

2-(2,7-Octadienyl)cyclohexanone.—A mixture of 150 ml of ethanol, 0.5 g of sodium metal, and 39.8 g of 2-acetyl-2-(2,7-octadienyl)cyclohexanone was heated at 80° for 2 hr. After the usual workup, the product was distilled; the first fraction had bp 110–120° (2 mm), 7.6 g, and the second fraction had bp 168–176° (2 mm), 27.0 g. Redistillations of both fractions gave 2-(2,7-octadienyl)cyclohexanone [bp 116° (3 mm); n_D^{20} 1.4809; ν_{\max} 1712 (>C=O), 1644, 990, and 910 (–CH=CH₂), and 970 cm⁻¹ (trans –CH=CH–)] and ethyl 6-acetyl-8,13-tetradecadienoate [bp 181° (3.5 mm); n_D^{20} 1.4635; ν_{\max} 1737 (ester), 1713 (>C=O), 1642, 993, and 910 (–CH=CH₂), and 970 cm⁻¹ (trans –CH=CH–)], respectively.

Anal. Calcd for C₁₄H₂₂O: C, 81.50; H, 10.75; mol wt, 206. Found: C, 81.23; H, 10.65; mol wt, 205. *Anal.* Calcd for C₁₈H₃₀O₂: C, 73.43; H, 10.27; mol wt, 294. Found: C, 73.57; H, 10.19; mol wt, 294.

2-(2,7-Octadienyl)cyclohexanone was also obtained by refluxing an aqueous sodium hydroxide solution of 1-(2,7-octadienyl)-2-oxocyclohexanecarbaldehyde in a 87% yield.

Platinum-Catalyzed Reaction of Acetylacetone with 1,3-Butadiene.—A mixture of 0.1 mol of acetylacetone, 0.5 mmol of Pt(Ph₃P)₄, 7 mmol of sodium phenoxide, and 0.3 mol of 1,3-butadiene was stirred at 85° for 16 hr. The product was com-

posed of 3-(1-methylallyl)-2,4-pentanedione (2.0 g, 13%), 1c (4.5 g, 21%), 3c (4.8 g, 24%), 3-(2-butenyl)-3-(2,7-octadienyl)-2,4-pentanedione (2.6 g, 10%), and 2c (3.3 g, 11%). The 1:1 adduct showed the following spectral characteristics: ν_{\max} 1722 sh and 1700 (ketone), 1644, 998, and 922 cm⁻¹ (–CH=CH₂); τ 9.0 (d, –CCH₃), 8.0 and 7.9 (CH₃CO–), 7.0 (m, =CCH–), 6.4 (d, –CHCO–), 4.8–5.2 (m, CH₂=C–), and 4.0–4.6 (m, –CH=C–). The 1:3 adduct exhibited the following spectral characteristics: ν_{\max} 1723 sh and 1702 (ketone), 1643, 991, and 910 (–CH=CH₂), 967 cm⁻¹ (trans –CH=CH–); τ 8.6 (m, =CCCH₂CC=), 8.3 (d, =CCH₃), ~8.0 (=CCH₂CCH₂C=), 8.0 (CH₃CO–), 7.5 (d, –CH₂CCO–), 4.0–5.2 (m, olefinic protons).

A mixture of 0.1 mol of acetylacetone, 0.5 mmol of PtCl₂(Ph₃P)₂, 7 mmol of sodium phenoxide, and 0.3 mol of 1,3-butadiene in 15 ml of benzene was stirred at 85° for 5 hr. The adducts 1c, 3c, and 2c were obtained in 18, 12, and 44% yields, respectively.

Registry No.—2-(2,7-Octadienyl)cyclohexanone, 29331-14-4; ethyl 6-acetyl-8,13-tetradecadienoate, 29331-15-5; 3-(2-butenyl)-3-(2,7-octadienyl)-2,4-pentanedione, 29331-16-6.

Preparation of Alkylmagnesium Fluorides¹

SIMON H. YU AND E. C. ASHBY*

School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia 30332

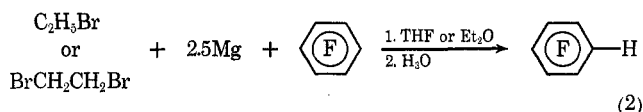
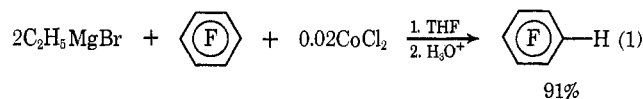
Received October 19, 1970

Alkylmagnesium fluorides have been prepared in high yield by the reaction of alkyl fluorides with magnesium in ether solvents in the presence of specific catalysts. The reaction rate was found to depend significantly on the solvent, reaction temperature, and catalyst. The best solvents for the reaction were found to be tetrahydrofuran and 1,2-dimethoxyethane and the best catalyst found was iodine. Under conditions of atmospheric pressure reflux using iodine as a catalyst, *n*-hexylmagnesium fluoride was produced in 90% yield in 14 days in diethyl ether, in 92% yield in 1.2 days in tetrahydrofuran, and in 92% yield in 4 hr in 1,2-dimethoxyethane. Under the most favorable conditions fluorobenzene and benzyl fluoride failed to react with magnesium.

For over half a century organic chemists have been interested in the preparation of organomagnesium fluorides; however, all attempts to prepare and isolate this class of compounds have been uniformly unsuccessful. The first attempt to prepare an organomagnesium fluoride was reported in 1921 by Swarts.² He found that the reaction of amyl fluoride with iodine-activated magnesium in diethyl ether after 100-hr reflux produced decane and magnesium fluoride. In 1931 Schiemann and Pillarsky³ reported that neither fluorobenzene nor its ortho methyl or para nitro derivatives reacted with magnesium to form the corresponding Grignard reagent. The same year Gilman and Heck⁴ reported that a small quantity of biphenyl was formed when fluorobenzene was heated with magnesium at 300° for 200 hr in a sealed tube without solvent. When fluorobenzene was sealed in a tube with activated magnesium-copper alloy⁵ in diethyl ether at room temperature for 6 months, the reaction mixture gave a negative color test⁶ for the presence of an active organometallic compound; however, at the end of 18 months the color test was positive. Several attempts were made by Bernstein and coworkers⁷ to prepare a Grignard reagent

from benzyl fluoride. At reflux temperature in diethyl ether, no reaction took place. Addition of an iodine crystal or of phenylmagnesium bromide failed to initiate reaction. Under more vigorous conditions in di-*n*-butyl ether, polymerization of the benzyl fluoride occurred. While ordinary magnesium gave no reaction, bibenzyl was obtained from the reaction of benzyl fluoride with activated magnesium in diethyl ether at 100° for 10 days in an autoclave. Thus all attempts to prepare fluoro Grignard reagents were frustrated either by a lack of reaction between the organo fluorides and magnesium or the formation of coupling product.

During our study the possible intermediacy of perfluoroarylmagnesium fluorides was indicated by the reaction of perfluoroaryl compounds with 2 molar equiv of ethylmagnesium bromide and a catalytic amount of certain transition metal halides in tetrahydrofuran⁸ (eq 1) and from the reaction of hexafluorobenzene with



magnesium and an equal molar amount of an entrainer such as ethyl or ethylene bromide in tetrahydrofuran

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(3) G. Schiemann and R. Pillarsky, *Chem. Ber.*, **64b**, 1340 (1931).

(4) H. Gilman and L. H. Heck, *J. Amer. Chem. Soc.*, **53**, 377 (1931).

(5) H. Gilman and N. B. St. John, *Recl. Trav. Chim. Pays-Bas*, **49**, 717 (1930).

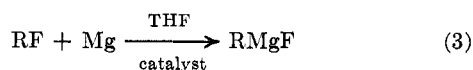
(6) H. Gilman and F. Schulze, *J. Amer. Chem. Soc.*, **47**, 2002 (1925).

(7) J. P. Bernstein, J. S. Roth, and W. T. Miller, *ibid.*, **70**, 2310 (1948).

(8) W. L. Respess and C. Tamborski, *J. Organometal. Chem.*, **18**, 263 (1969).

or diethyl ether⁹ (eq 2). The intermediacy of a fluoro Grignard compound was indicated by hydrolysis of the reaction product to produce pentafluorobenzene and by the reaction of the product with an organochlorosilane. However, no attempt was made to identify or isolate the possible intermediate fluoro Grignard compound.

In two preliminary communications we have reported the preparation of heretofore unknown hexylmagnesium fluoride in tetrahydrofuran by the reaction of hexyl fluoride with magnesium in the presence of suitable catalysts at reflux temperature¹ (eq 3) and the



preparation of both aliphatic and aromatic fluoro Grignard reagents by the reaction of dialkyl- and diaryl-magnesium compounds with metal halides such as BF_3 (eq 4), R_2AlF , etc.¹⁰ The present report describes



an investigation of the scope of the reaction represented by eq 3 with respect to the nature of the R group, the solvent, and the catalyst in an attempt to arrive at the optimum conditions for preparing fluoro Grignard compounds.

Experimental Section

All operations were carried out either in a Kewaunee nitrogen-filled glove box equipped with a recirculating system to remove oxygen and moisture or on the bench using typical Schlenk tube and syringe techniques.¹¹ All glassware was flash flamed and flushed with nitrogen prior to use. Triply sublimed magnesium (Dow Chemical) turnings and reflux conditions were employed in all syntheses except when stated otherwise.

Instrumentation.—All infrared spectra were obtained using a Perkin-Elmer 621 high resolution grating spectrophotometer and cesium iodide or potassium iodide absorption cells. Proton magnetic resonance spectra were obtained using a Varian A-60 magnetic resonance spectrometer (TMS standard). Glpc analyses were carried out using an F & M Model 720 gas chromatograph using 3-ft Polypak 2 columns (octane or toluene used as internal standard). Organometallic supernatant solutions were withdrawn at appropriate time intervals and quenched in a septum sealed bottle containing saturated MgSO_4 solution. The organic layer was subsequently analyzed by glpc for determination of per cent yield and per cent reaction.

Chemicals.—*n*-Hexyl fluoride was obtained from Columbia Organics. Its purity was checked by glpc analysis and found to be at least 99% pure. Fluorobenzene was obtained from Eastman Organics, benzyl fluoride from Pierce Chemical Co., and ethyl bromide and ethylene bromide (analytical grade) from Baker Chemicals. Gaseous methyl and ethyl fluorides were obtained from Pierce Chemical Co. All of the above were dried using molecular sieve 4A and employed without further purification.

Analytical grade iodine and bromine were obtained from Baker Chemical. Cobalt chloride and sodium iodide (Baker analyzed) were made anhydrous by heating under vacuum. Triply sublimed magnesium turnings (Dow Chemicals) and magnesium powder (Fisher Scientific) were dried under vacuum prior to use.

Anhydrous diethyl ether, tetrahydrofuran (THF), 1,2-dimethoxyethane (DME), and N,N,N',N' -tetramethylethylenediamine (TMED) were distilled from lithium or sodium aluminum hydride, and triethylamine (TEA) from calcium hydride prior to use.

Elemental Analyses.—Elemental analyses were carried out on hydrolyzed samples of the organometallic supernatant solution. Total alkalinity analysis, which gave the concentration of basic

magnesium (Mg_B) bonded to carbon, was determined by adding a known amount of acid and back-titrating with standard base using methyl red as an indicator.¹² The same sample was then analyzed for total magnesium (Mg_T) by conventional EDTA complexometric titration at pH 10 using Eriochrome Black T as an indicator; occasionally back-titration with zinc acetate was applied for sharper end points. Chloride, bromide, and iodide were determined by potentiometric titration. The same sample was then analyzed for fluoride by the method described by Hogen and Tortoric.¹³

Preparation of Hexylmagnesium Fluoride from Hexyl Fluoride and Magnesium in Tetrahydrofuran.—The standard procedure used for the preparation of hexylmagnesium fluoride is as follows. A weight of 2.5–5.0 g of magnesium turnings and a certain amount of solid activator (*e.g.*, CoCl_2 , I_2) were placed in a 100-ml, one-neck flask, with a side arm equipped with a three-way Teflon stopcock. To the neck was attached a water condenser and to the flask was added a magnetic stirring bar. Then 50–70 ml of freshly distilled THF, 2–3 ml of hexyl fluoride, and 2–3 ml of internal standard (toluene or octane) were added *via* syringe through the side-arm stopcock under strong nitrogen flow. The mixture was allowed to react at reflux temperature for a specified period of time. Liquid entrainers ($\text{C}_2\text{H}_5\text{Br}$, $\text{BrCH}_2\text{CH}_2\text{Br}$, or Br_2) were first dissolved in THF and added dropwise to the reaction mixture at reflux temperature. In some cases the magnesium was first activated by reaction with butyllithium or ethyl bromide in an appropriate solvent. The solution was then decanted prior to reaction.

A. Without Activator (Reaction 1).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 60 ml of THF for 13 days. After standing, analysis of the clear supernatant solution showed no soluble magnesium and the ratio of hexyl fluoride and octane was constant during the reaction.

B. Butyllithium as Activator (Reaction 2).—Magnesium (5 g, 206 mg-atoms) was activated by stirring with 15 ml of butyllithium-hexane solution (1.6 *N*) in 250 ml of distilled hexane for 1 day. Then the solution was decanted and hexyl fluoride (3 ml, 23 mmol) and THF (60 ml) were added. Analysis indicated that the solution contained no magnesium after 9 days of stirring at room temperature or after 3 days of additional reflux.

C. Bromine as Activator (Reaction 5).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 50 ml of THF with bromine (0.1 ml) as activator. A light brown solution was formed after 5 days. *Anal.* Mg_T , 0.529 *N*; F, 0.41 *N*; Br, 0.073 *N* (97% reaction, 72% yield.)

D. Ethylene Bromide as Activator (Reaction 6).—Hexyl fluoride (5 ml, 38 mmol) was allowed to react with magnesium powder (3 g, 123 mg-atoms) in 75 ml of THF with ethylene bromide (0.1 ml) as activator for 22 days. *Anal.* Mg_B , 0.879 *N*; Mg_T , 0.699 *N*; F, 0.578 *N*; Br, 0.011 *N* (100% reaction, 42% yield).

E. Ethyl Bromide as Activator (Reaction 7).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 50 ml of THF using ethyl bromide as activator.

Reaction 7a (1 drop of ethyl bromide was used). *Anal.* after 22 days. Mg_B , 0.458 *N*; Mg_T , 0.288 *N*; F, 0.199 *N*; Br, 0.02 *N* (100% reaction, 94% yield).

Reaction 7b [1 ml (13 mmol) of ethyl bromide was used]. *Anal.* after 8 days. Mg_B , 0.633 *N*; Mg_T , 0.550 *N*; F, 0.266 *N*; Br, 0.201 *N* (95% reaction, 92% yield).

Reaction 7c [2 ml (26 mmol) of ethyl bromide was used]. *Anal.* after 8 days. Mg_B , 0.936 *N*; Mg_T , 0.850 *N*; F, 0.257 *N*; Br, 0.567 *N* (99% reaction, 97% yield).

Reaction 7d [magnesium powder (4 g, 165 mg-atoms) was activated by ethyl bromide (4 ml, 53 mmol) followed by decantation of ethylmagnesium bromide solution]. *Anal.* after 8.5 days (63% reaction, 51% yield). *Anal.* after 20 days. Mg_B , 0.574 *N*; Mg_T , 0.409 *N*; F, 0.282 *N*; Br, 0.012 *N* (96% reaction, 63% yield).

F. Anhydrous Sodium Iodide as Activator (Reaction 3).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 60 ml of THF using sodium iodide (0.17 g, 1.1 mmol) as activator. No reaction took place after 11 days.

G. Anhydrous Cobalt Chloride as Activator (Reaction 4).—

(9) W. L. Respess, J. P. Ward, and C. Tamborski, *J. Organometal. Chem.*, **19**, 191 (1969).

(10) E. C. Ashby and J. A. Nackashi, *ibid.*, **24**, C17 (1970).

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

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

(13) J. M. Hogen and F. Tortoric, *Anal. Chem.*, **39**, 221 (1967).

Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 50 ml of THF using cobalt chloride (0.06 g, 0.5 mmol) as activator for 21 days. *Anal.* Mg_B , 0.504 *N*; Mg_T , 0.389 *N*; *F*, 0.313 *N*; *Cl*, 0.011 *N* (98% reaction, 95% yield).

H. Iodine as Activator (Reaction 8).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 70 ml of THF using iodine as the activator.

Reaction 8a [0.025 g (0.1 mmol) of iodine was used]. No reaction took place even after 24 days.

Reaction 8b [0.068 g (0.3 mmol) of iodine was used]. *Anal.* after 5 days. Mg_B , 0.338 *N*; Mg_T , 0.285 *N*; *F*, 0.232 *N*; *I*, 0.004 *N* (97% reaction, 95% yield).

Reaction 8c [0.26 g (1.0 mmol) of iodine was used]. *Anal.* after 5 days. Mg_B , 0.380 *N*; Mg_T , 0.340 *N*; *F*, 0.306 *N*; *I*, 0.01 *N* (100% reaction, 97% yield).

When reaction 8c using 0.26 g of iodine was repeated in 40 ml of THF for a longer period of time (reaction 8d), the yield did not decrease over a 6–14-day reflux period. *Anal.* Mg_B , 0.511 *N*; Mg_T , 0.473 *N*; *F*, 0.489 *N*; *I*, 0.014 *N* (100% reaction, 94% yield).

Reaction 8e [0.33 g (1.3 mmol) of iodine was used and the reaction was carried out in 60 ml of THF at 24°]. *Anal.* after 36 days. Mg_B , 0.306 *N*; Mg_T , 0.285 *N*; *F*, 0.256 *N*; *I*, 0.008 *N* (95% reaction, 93% yield).

I. Hexylmagnesium Fluoride Solution as Activator (Reaction 9).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 60 ml of THF using 10 ml of 0.285 *N* hexylmagnesium fluoride solution (from reaction 8b). *Anal.* after 12 days. Mg_B , 0.390 *N*; Mg_T , 0.264 *N*; *I*, 0.181 *N*; *I*, 0.002 *N* (97% reaction, 95% yield).

Preparation of Hexylmagnesium Fluoride from Hexyl Fluoride in Other Solvents.—The method used for the preparation of hexylmagnesium fluoride in other solvents is similar to that used for the preparation in THF.

A. Diethyl Ether (Reaction 10).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 70 ml of diethyl ether using iodine (0.251 g, 0.99 mmol) as activator. *Anal.* after 13 days. Mg_B , 0.346 *N*; Mg_T , 0.274 *N*; *F*, 0.195 *N*; *I*, 0.03 *N* (88% reaction, 83% yield).

B. Dimethoxyethane (Reaction 11).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 55 ml of DME using iodine (0.186 g, 0.73 mmol) as activator. *Anal.* after 7 hr. Mg_B , 0.327 *N*; Mg_T , 0.334 *N*; *F*, 0.295 *N*; *I*, 0.019 *N* (99% reaction, 95% yield).

C. *N,N,N',N'*-Tetramethylethylenediamine (Reaction 12) and Triethylamine (Reaction 13).—Hexyl fluoride (3 ml, 23 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 50 ml of TMED with iodine (0.20 g, 0.7 mmol) and in a separate experiment using 60 ml of TEA with iodine (0.30 g, 1.2 mmol) for 7 hr. Analyses showed in each case a negligible amount of magnesium in solution, and the formation of hexene.

Attempted Preparation of Phenylmagnesium Fluoride.—Fluorobenzene (3 ml, 32 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 75 ml of THF using iodine (0.36 g, 1.4 mmol) as activator (reaction 14a). After 14 days, analysis showed negligible reaction. The reaction also did not take place in 60 ml of DME using iodine (0.34 g, 1.3 mmol) as activator after 8 days (reaction 14b).

Attempted Preparation of Benzylmagnesium Fluoride (Reaction 15).—Benzyl fluoride (3 ml, 20.8 mmol) was allowed to react with magnesium (3 g, 123 mg-atoms) in 75 ml of THF using iodine (0.22 g, 0.87 mmol) as activator. After 13 days, analysis showed negligible reaction.

Preparation of Ethylmagnesium Fluoride (Reaction 16a).—Ethyl fluoride (4.9 g, 102 mmol) was passed through a tube of molecular sieve (4A) and then introduced through a side arm at the bottom of a Dry Ice condenser into the reaction flask containing magnesium (3 g, 123 mg-atoms), iodine (0.23 g, 0.9 mmol), and 75 ml of THF. *Anal.* after 2.5 days. Mg_B , 0.339 *N*; Mg_T , 0.300 *N*; *F*, 0.278 *N*; *I*, 0.014 *N* (36% yield).

Preparation of Methylmagnesium Fluoride and Other Alkylmagnesium Fluorides by Autoclave Techniques.—The preparation of methylmagnesium fluoride will illustrate the method employed. A weighed amount of magnesium was placed in the autoclave. The autoclave was flash flamed under nitrogen and kept under vacuum for 3 hr. Then the apparatus was cooled with Dry Ice-acetone and the desired solvent containing a certain amount of iodine was introduced under a nitrogen flow. After the solvent was cooled, methyl fluoride was passed through

a tube of molecular sieve and introduced into the autoclave. The autoclave was then sealed and the reaction carried out at the desired temperature with stirring.

When the reaction was carried out with excess methyl fluoride (32.4 g, 953 mmol), magnesium (5 g, 205 mg-atoms), and iodine (0.57 g, 2.2 mmol) in 100 ml of THF at 70° for 5 days (reaction 17a), analysis showed negligible magnesium in solution and glpc analysis of the solution indicated more than 25 peaks.

The reaction was then carried out with approximately equimolar quantities of methyl fluoride (8 g, 235 mmol) and magnesium (5 g, 205 mg-atoms) plus iodine (0.38 g, 1.5 mmol) in 100 ml of THF at 60° for 3 days (reaction 17b). Analyses showed the resultant solution to be 0.0295 *N* in Mg_B and 0.0175 *N* in Mg_T . Glpc analysis of the solution showed 10 peaks.

A similar reaction (reaction 17c) was carried out in 60 ml of DME with methyl fluoride (10 g, 290 mmol), magnesium (10 g, 410 mg-atoms), and iodine (0.47 g, 1.9 mmol) at 60° for 4 hr. *Anal.* Mg_B , 0.910 *N*; Mg_T , 0.519 *N*; *F*, 0.070 *N*; *I*, 0.039 *N*.

The reaction was then carried out under milder conditions with methyl fluoride (6.8 g, 200 mmol), magnesium (10 g, 410 mg-atoms), and iodine (0.54 g, 2.1 mmol) in 75 ml of THF at room temperature for 1.5 days (reaction 17d). *Anal.* Mg_B , 2.21 *N*; Mg_T , 2.23 *N*; *F*, 2.24 *N*; *I*, 0.03 *N*.

The reaction was also carried out in 70 ml of diethyl ether with methyl fluoride (6.7 g, 197 mmol), magnesium (10 g, 410 mg-atoms), and iodine (0.50 g, 1.8 mmol) at room temperature for 3 days (reaction 17e). Analyses showed it to be 0.36 *N* in Mg_B and to have a negligible *F* concentration.

An attempt was also made to prepare ethylmagnesium fluoride at room temperature in an autoclave (reaction 16b) by reaction of ethyl fluoride (7.48, 154 mmol), magnesium (10 g, 410 mg-atoms), and iodine (0.62 g, 2.4 mmol) in 75 ml of diethyl ether for 2 days. *Anal.* Mg_B , 0.270 *N*; Mg_T , 0.173 *N*; *F*, 0; *I*, 0.03 *N*.

An attempt was made (reaction 18) to prepare hexylmagnesium fluoride in diethyl ether at 90° in an autoclave by reaction of hexyl fluoride (2 ml, 15 mmol), magnesium (4 g, 164 mg-atoms), and iodine (0.21 g, 0.82 mmol) for 24 hr. *Anal.* Mg_B , 0.122 *N*; Mg_T , 0.0726 *N*; *F*, 0.0165 *N*; 0.009 *N* (98% reaction).

Stability of Alkylmagnesium Fluorides.—A THF solution of freshly prepared ethylmagnesium fluoride (reaction 16a) gave the following analysis: 0.339 *N* in Mg_B , 0.300 *N* in Mg_T , and 1.12 *N* in Mg_B - Mg_T . After the solution stood for 4 months, the analysis was 0.325 *N* in Mg_B , 0.298 *N* in Mg_T , and 1.09 *N* in Mg_B - Mg_T .

A diethyl ether solution of freshly prepared hexylmagnesium fluoride gave the following analysis: 1.290 *N* in Mg_B , 1.188 *N* in Mg_T , and 1.08 *N* in Mg_B - Mg_T . When 15 ml of the solution was heated at 85° for 15 days in a sealed tube, the following analysis was obtained: 1.514 *N* in Mg_B , 1.316 *N* in Mg_T , and 1.15 *N* in Mg_B - Mg_T .¹⁴

A THF solution of hexylmagnesium fluoride was 1.086 *N* in Mg_B , 0.998 *N* in Mg_T , and 1.09 *N* in Mg_B - Mg_T . After the solution stood for 4 months at room temperature the solution analyzed as 1.051 *N* in Mg_B , 1.044 *N* in Mg_T , and 1.01 *N* in Mg_B - Mg_T .

Results and Discussion

For the direct synthesis of difficultly formed Grignard reagents three modifications of the usual procedure for reacting an organic halide with magnesium have been employed: (1) use of a stronger coordinating solvent, (2) application of higher reaction temperatures, and (3) activation of the magnesium metal.¹⁵ The third method consists of activation of the magnesium by reduction of the size of the metal particles or by chemical reaction. The Gilman catalyst (a combination of magnesium and iodine) is a well-known example of chemical activation. Ethyl bromide or ethylene bromide is also used in catalytic amount to activate the magnesium surface and in molar quantities as an entrainer. Using

(14) The differences in concentration observed is probably due to evaporation of ether solvent during the handling of these highly volatile solutions under conditions of rapid nitrogen purge.

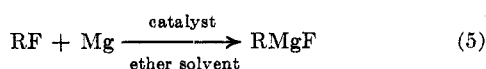
(15) E. Pearson, D. Cowan, and J. D. Becker, *J. Org. Chem.*, **24**, 504 (1959).

TABLE I
 PREPARATION OF HEXYLMAGNESIUM FLUORIDE^{a-c}

Reaction no.	Solvent	Catalyst	Mol % of catalyst ^d	Reaction time, day	% yield ^e	Mg _B :Mg _T :F ^f
1	THF	None	0	13	0	
2	THF	<i>n</i> -BuLi ^g		9	0	
3	THF	NaI	4.8	11	0	
4	THF	CoCl ₂	2.1	7	0	
				21	95	1.29:1:0.80
5	THF	Br ₂	8	5	72 (97)	...:1:0.92
6	THF	BrCH ₂ CH ₂ Br	1.1	7.5	88	
				22.5	42 (100)	1.26:1:0.84
7a	THF	C ₂ H ₅ Br	2.2	5	0	
				14	87	
				22	94	1.60:1:0.44
7b	THF	C ₂ H ₅ Br	58	1.5	86	
				2.5	91	
				8.0	92	1.24:1:0.76
7c	THF	C ₂ H ₅ Br	113	1.5	91	
				8.0	96	
				14.0	97	1.30:1:0.91
7d	THF	C ₂ H ₅ Br ^h	2.6	8.5	51 (63)	
				20	63 (96)	1.41:1:0.71
8a	THF	I ₂	0.4	24	0	
8b	THF	I ₂	1.3	1.2	48	1.18:1:0.82
				1.8	71	
				3.8	95	
				5	97	
8c	THF	I ₂	4.3	0.3	41	
				0.8	77	
				1.2	92	
				5	97	1.12:1:0.93
8d	THF	I ₂	4.3	6	95	
				14	94	1.06:1:1.06
8e	THF	I ₂	5.7	3	11	
				13	46	
				20	68	
				28	84	
				36	93	1.07:1:0.92
9	THF	<i>n</i> -C ₆ H ₁₃ MgF ^h	12.5	2	26	
				6	73	
				12	95	1.48:1:0.68
10	(C ₂ H ₅) ₂ O	I ₂	4.3	3	11	
				7	36	
				10	61	
				13	83	1.27:1:0.72
11	DME	I ₂	3.2	0.2	92	
				0.3	95	1.01:1:0.91
12	TMED ⁱ	I ₂	3.0	0.3	0	
13	TEA ⁱ	I ₂	5.2	0.3	0	

^a All reactions run at reflux temperatures and using magnesium turnings except reactions 8e at room temperature and reactions 6 and 7d using Mg powder. ^b Mg:RF, 5.4, except in reactions 2 and 6 where Mg:RF = 8.9 and 3.2 respectively. ^c ... indicate that no measurement was made. ^d Based on organo fluoride. ^e Based on the formation of hexane by glpc analysis. If the per cent yield is different from the per cent extent of reaction by more than 5%, the per cent reaction is given in parentheses. ^f Impurities introduced by catalyst are excluded: Mg_B, total alkalinity; Mg_T, total magnesium; F, fluoride. ^g After magnesium was activated, the solution was withdrawn before adding hexyl fluoride. ^h Hexylmagnesium fluoride (10 ml) from reaction 8b. ⁱ Dehydrohalogenation occurred.

a combination of all three methods (solvent, temperature, and catalyst), we have been able to prepare for the first time alkylmagnesium fluorides conveniently and in high yields (eq. 5). The following facts are most



certain evidences for the formation of the alkylmagnesium fluorides. First, elemental analyses show that the solutions produced on reaction of alkyl fluorides and magnesium contains C-Mg, Mg, and F in the ratio of approximately 1:1:1. Second, the formation of the C-Mg bond is indicated by both ir and nmr spectral

analysis and by the alkylating properties of the solutions. Third, molecular association studies show a behavior different from that of organomagnesium chlorides, bromides and iodides.

To investigate the effect of solvent, catalyst, temperature, reaction time, etc., on the formation of fluoro Grignard reagents from organo fluorides and magnesium, *n*-hexyl fluoride was allowed to react with magnesium under a variety of experimental conditions. Hexyl fluoride was chosen for this study since it is a liquid at room temperature and is commercially available. During the reactions to be studied, samples were withdrawn periodically. The yield was calculated from the amount

of hexane formed after hydrolysis as determined by glpc analysis. At the end of the reaction, the solution was subjected to elemental analyses (total alkalinity, EDTA titration, and fluoride and other halide determinations) and in addition, in some cases, ir and nmr spectra were obtained. The results are summarized in Table I.

Without a catalyst, no reaction was observed when hexyl fluoride was allowed to react with magnesium in tetrahydrofuran for 13 days (reaction 1). No reaction occurred even when attempts were made to activate the magnesium by stirring with *n*-butyllithium in hexane overnight before attempting to initiate the reaction (reaction 2). Addition of sodium iodide (reaction 3) or cobalt chloride (reaction 4) had no effect, except after an induction period of 7 days when cobalt chloride was used as a catalyst. Although the reaction is slow, the fluoro Grignard compound was produced in 95% yield after 21 days. Addition of a catalytic amount of bromine (reaction 5), ethylene bromide (reaction 6), ethyl bromide (reaction 7), or iodine (reaction 8) also catalyzed the formation of the fluoro Grignard. In an attempt to decrease the contamination of the product brought about by the addition of a catalyst, hexylmagnesium fluoride from reaction 8b was used as an activator (reaction 9). After 12.5 days, a 95% yield of soluble magnesium product was obtained; however, the reaction was slow and the reaction product exhibited a low Mg:F ratio, 1.0:0.68.

It is interesting to note that no coupling product, dodecane, or octane was observed except when ethylmagnesium bromide was used as the entrainer. On the other hand three unidentified peaks were observed by glpc analysis of a hydrolyzed sample of hexylmagnesium fluoride. Except when magnesium powder was used (reaction 6 and 7d), less than 5% by-product was observed. The amount of by-product did not vary substantially from experiment to experiment regardless of the nature of the catalyst or reaction time.

The best results in THF solvent were obtained when iodine (4%) was used as a catalyst. Hexylmagnesium fluoride (Mg:F, 1.0:0.93) was produced in 92% yield in only 1.2 days (reaction 8c). Iodine is not only the most efficient catalyst studied (Table II), but also the reac-

TABLE II
EFFECT OF CATALYST ON THE REACTION TIME^a

Reaction no.	Catalyst	Catalyst, %	Time, days
8b	I ₂	1.3	3
6	BrCH ₂ CH ₂ Br	1.1	6
7a	C ₂ H ₅ Br	2.2	13
4	CoCl ₂	2.1	20.5

^a For 90% reaction of hexyl fluoride with magnesium in THF.

tion product is less contaminated owing to the unusually low solubility of magnesium iodide in tetrahydrofuran (<3% based on RMgF). For this reason iodine was selected as the catalyst to be used in subsequent studies involving solvent and temperature effects in the preparation of hexyl- and other organomagnesium fluorides.

Reference to Table III shows that the solvent and reaction temperature have a dramatic effect on the reaction rate. For the same amount of iodide catalyst used, the time required for 90% reaction at reflux tem-

TABLE III
EFFECTS OF SOLVENT AND TEMPERATURE
ON REACTION RATE^a

Reaction no.	Solvent	Temp, °C	Time, days
10	(C ₂ H ₅) ₂ O	35	13.5
8c	THF	66	1.2
11	DME	90	<0.2
8e	THF	25	24
18	(C ₂ H ₅) ₂ O	90 ^b	<1

^a For 90% reaction of hexyl fluoride. ^b Only 25% of hexylmagnesium compound is fluoride.

perature became much less as the solvent was changed from diethyl ether to tetrahydrofuran to 1,2-dimethoxyethane. When the reaction was carried out in tetrahydrofuran at room temperature (24°), the time required for 90% reaction was longer than that required in diethyl ether at reflux temperature (>35°). When the reaction was carried out in diethyl ether at 90°, the rate was similar to that achieved in tetrahydrofuran at reflux temperature. These results clearly indicated that the reaction temperature, and to a lesser extent solvent, plays an important role in the rate of reaction. Attempts to prepare hexylmagnesium fluoride in *N,N,N',N'*-tetramethylethylenediamine and triethylamine failed (reactions 12 and 13). Dehydrohalogenation of hexyl fluoride by these solvents appeared to be a major reaction at reflux temperatures.

The data in Table IV show that, although reaction

TABLE IV
EFFECT OF CATALYST CONCENTRATION
ON REACTION RATE^a

Reaction no.	Catalyst	Catalyst, %	Time, days
7a	C ₂ H ₅ Br	2.2	17.5
7b	C ₂ H ₅ Br	58	2
7c	C ₂ H ₅ Br	113	1.4
8a	I ₂	0.4	∞
8b	I ₂	1.3	3
8c	I ₂	4.3	1.2

^a For 90% reaction of hexyl fluoride.

time can be substantially shortened by addition of larger amounts of catalyst, a low optimum catalyst concentration exists beyond which only a slight increase in reaction rate is observed.

All attempts to prepare phenyl- and benzylmagnesium fluoride failed (Table V). Even in the presence of iodine as a catalyst, fluorobenzene and benzyl fluoride failed to react with magnesium in tetrahydrofuran during a 13-day reflux period. However methyl- and ethylmagnesium fluoride were successfully prepared in tetrahydrofuran using iodine as activator. Because of the low boiling point of ethyl fluoride (-37.7°), the conventional apparatus using a Dry Ice condenser under conditions of tetrahydrofuran reflux was very inconvenient and only 36% yield of product was obtained owing to the escape of ethyl fluoride during the reaction. Because of this problem the synthesis of methylmagnesium fluoride from methyl fluoride (bp -78°) was carried out in an autoclave. The reaction was carried out using excess methyl fluoride since fluoride could be easily removed from the reaction mixture. A reaction was therefore carried out with excess methyl fluoride (MeF:Mg, 4.6) at 70° for 5 days (reaction 17a). How-

TABLE V
PREPARATION OF ORGANOMAGNESIUM FLUORIDES IN ETHER SOLVENTS USING IODINE AS A CATALYST^a

Reaction no.	Organo fluoride	Solvent	Reaction temp, °C	Mg:RF	Mol % of catalyst ^b	Reaction time, day	% yield ^c	Mg _B :Mg _T :F ^d
14a	PhF	THF	66	3.8	4.4	14	0	
14b	PhF	DME	90	3.8	4.1	8	0	
15	PhCH ₂ F	THF	66	6.1	4.2	13	0	
16a	C ₂ H ₅ F	THF	66	1.2	0.9	2.5	36	1.13:1:0.96
16b	C ₂ H ₅ F	THF	25	2.7	1.5	2	13	1.57:1:0
17a	CH ₃ F	THF	70	0.22	0.2	5	0	
17b	CH ₃ F	THF	60	0.88	0.6	3	1.2	1.68:1:...
17c	CH ₃ F	DME	60	1.4	0.6	0.2	19	1.82:1:0.15
17d	CH ₃ F	THF	25	2.1	1	1.5	95	0.99:1:1.02
17e	CH ₃ F	(C ₂ H ₅) ₂ O	25	2.1	1	3	13	2.12:1:0
18	<i>n</i> -C ₆ H ₁₃ F	(C ₂ H ₅) ₂ O	90	11	5.5	1	95	1.77:1:0.25

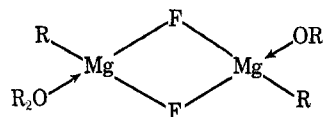
^a Reactions were carried out in an autoclave except for reactions 14, 15, and 16a. ^b Based on organo fluoride. ^c Yield determined by titration. ^d Impurities introduced by catalyst are excluded. Mg_B, total alkalinity; Mg_T, total magnesium; F, fluoride. ... indicated that no measurement was made.

ever, analysis showed negligible magnesium in solution and glpc analysis of the solution showed more than 25 different components to be present. The reaction was then carried out using a slight excess of methyl fluoride (MeF:Me, 1.1) at a lower temperature for 3 days (reaction 17b). Although glpc analysis of the solution showed only 10 peaks, magnesium analyses (Mg_B and Mg_T) showed that only a very small amount (1.2%) of dimethylmagnesium was formed. The failure of these reactions was probably due to the polymerization of methyl fluoride. The reaction was then carried out in 1,2-dimethoxyethane with excess magnesium at 60° for 4 hr (reaction 17c). Although 19% yield of a CH₃Mg compound was formed, only 15% of this was CH₃MgF. Finally the reaction was successfully carried out with excess magnesium in tetrahydrofuran at room temperature for 1.5 days (reaction 17d). Methylmagnesium fluoride was obtained in 95% yield. Attempts to prepare methyl- and ethylmagnesium fluorides in diethyl ether using autoclave techniques failed (reaction 17e and 16b); the reactions were slow; and only dialkylmagnesium compounds were obtained. Since the preparation of hexylmagnesium fluoride in diethyl ether is extremely slow, the reaction was carried out at 90° in an autoclave. The reaction was indeed accelerated dramatically at higher temperature and gave 95% yield based on soluble magnesium (reaction 18) in 24 hr. However, analyses indicated that the product contained only 25% fluoro Grignard.

The elemental analyses (Tables I and V) show that the products from the reactions of alkyl fluorides and magnesium contain in most cases a ratio of Mg_B:Mg_T of >1 and a Mg:F ratio of <1. The basic magnesium is obtained by acid-base titration (Mg_B for RMgF, 1; R₂Mg, 2) and total magnesium is obtained by EDTA analysis (Mg_T for RMgF, 1; R₂Mg, 1). These results clearly indicate that disproportionation occurs producing a product of low fluoride content and therefore high R₂Mg content. However, disproportionation was not complete in most cases and usually solutions had a Mg_B:Mg_T ratio between 1.3 and 1. It is presumed that disproportionation took place during the formation step since alkylmagnesium fluorides appear to be very stable in solution once formed. Magnesium analyses showed no change in concentration or Mg_B:Mg_T ratio for tetrahydrofuran solutions of ethyl- and hexylmag-

nesium fluoride after four months. Also hexylmagnesium fluoride in diethyl ether showed no change in the Mg_B:Mg_T ratio after heating at 85° for 15 days in a sealed tube.

The low Mg:F ratios are not surprising since disproportionation in Grignard systems is well known. For example, the attempted preparation of organomagnesium iodides in tetrahydrofuran results in the precipitation of MgI·6THF leaving the dialkyl magnesium compound in solution.¹⁶ The failure of the preparation of methyl- and ethylmagnesium fluoride in diethyl ether is probably due to the complete disproportionation in this solvent resulting in the precipitation of MgF₂ and solution of the dialkylmagnesium compound which is exactly what was observed. Presumably tetrahydrofuran being a more polar solvent solvates the reaction intermediates better during formation of the Grignard compound and lessens disproportionation. Once the fluoro Grignard compound is formed in either diethyl ether or tetrahydrofuran the compound is stable indefinitely. The lack of precipitation of the very insoluble MgF₂ from solution certainly indicates the absence of a Schlenk equilibrium. Molecular association and nmr studies to be reported on in detail elsewhere indicate the composition of primary alkylmagnesium fluorides in either diethyl ether or tetrahydrofuran solution as discrete dimers bound by a double fluorine bridge.



Registry No.—Hexylmagnesium fluoride, 25400-60-6; ethylmagnesium fluoride, 28596-49-8; methylmagnesium fluoride, 420-09-7.

Acknowledgment.—The authors wish to acknowledge preliminary studies by Mr. Robert G. Beach of this group, the generous support of the National Science Foundation (Grant No. SP-14795), and the Dow Chemical Co. for their generous supply of triply sublimed magnesium.

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