

Formation of phenylmagnesium halides in toluene

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Abstract

Formation reactions of phenylmagnesium chloride and bromide in toluene in the presence of one or two equivalents of diethyl ether or THF were investigated kinetically. Also, the reaction in diethyl ether and in chlorobenzene was addressed. Kinetic features of the reactions are similar to those found previously for the formation of alkylmagnesium halides in toluene and consist of rapid formation of a disolvated Grignard reagent followed by a slower formation of a monosolvated reagent. The latter is able of catalyzing the conversion of different halides into Grignard reagents. However, the contribution of Wurtz-type side reactions is considerable except when THF is used in toluene. Involving the kinetic data and the activation parameters some details of the reaction mechanism were discussed.

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1. Introduction

Organomagnesium compounds can be obtained not only in conventional ethers, but also in hydrocarbon media in the presence of minor amounts of donor solvents [1,2]. This has opened wide possibilities for industrial applications, as hydrocarbons are relatively cheap, non-hygroscopic and environmentally less hazardous solvents if compared with readily flammable ethers [3]. The significance of those factors becomes apparent with the importance of organomagnesium compounds in the synthesis of silicone monomers and other chemical processes [4].

In the presence of small amounts of complexing agents, e.g., ethers and tertiary amines, a great variety of organomagnesium compounds can be obtained in

hydrocarbon media [1,2]. Primary, secondary, and tertiary alkylmagnesium chlorides in toluene solutions, containing less than one equivalent of organic base, have been prepared recently [5,6]. Toluene has been proved to be a particularly suitable solvent for synthesis of such partially solvated Grignard reagents, as rather concentrated (1 M and above) solutions of these compounds can be obtained in this solvent.

Few decades ago, kinetics of formation of partially solvated alkylmagnesium halides in toluene was extensively investigated in this laboratory [7–9]. As the most important feature of the reaction, it was found that the formation of Grignard reagents in toluene in the presence of small amounts of an organic base (less than one mole per a mole of the organic halide) proceeds in two stages. After a rapid formation of the monosolvated (in average) Grignard reagent, a slow completion of the reaction occurs under the influence of the solvated alkylmagnesium halide.

By reason of recent revival of our interest in partially solvated Grignard reagents [10,11] we have addressed the formation of phenylmagnesium halides in toluene.

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Apart of numerous practical aspects to be solved, the kinetic features of this process were of particular interest because recent conclusions on the mechanism of Grignard reaction [12,13] point out different pathways for alkylmagnesium and arylmagnesium halide formations.

Two model reagents were chosen for the kinetic investigations into the formation reaction, phenylmagnesium bromide solvated with diethyl ether, and phenylmagnesium chloride solvated with THF. All the kinetic experiments largely imitated conventional preparation of Grignard reagents except that the sample of the organic halide was introduced all at once instead of dropwise addition as usual. In addition to the kinetic measurements, analyses of obtained reagents were carried out.

2. Experimental

2.1. Materials

Commercial reagents were carefully purified. Reagent grade magnesium shavings 99.8% Mg were purchased from Fluka. The reagents and solutions were operated under dry argon, and transferred by use of cannulas or syringes.

2.2. Kinetic measurements

For kinetic measurements the reaction was carried out in a 100 mL thermostated flask sealed with septa and equipped with a magnetic stirrer, a thermometer, and a reflux condenser capped with an inert gas balloon. The vessel was charged with calculated amounts of magnesium turnings activated prior to use by dry heating with few mg of iodine, of donor solvent, phenyl halide, and dry toluene.

After the reaction was initiated the course of the process was monitored by a withdrawing and analyzing the aliquots. For analyses, 1 mL samples were taken through a septum with a calibrated syringe and dissolved in an excess of standard sulphuric acid. The excess acid was back titrated against aqueous sodium hydroxide. The halide ion concentration was determined by the Mohr method in the same solution after the acidimetric analysis.

The concentrations of basic magnesium and the chloride ion were plotted against time. After the subtraction of the induction period the kinetic curves were treated according to the first-order rate law.

2.3. Analyses of Grignard reagents

For analyses, approximately 2 mL samples were withdrawn from the vigorously stirred reaction mixture. For analyses of the supernatant solution or the precipi-

tate, the samples were centrifuged. The precipitate obtained from centrifugation was washed with dry toluene and dissolved in a sample of sulphuric acid for determination of the basic magnesium–halide ion ratio.

For determination of diethyl ether content a calculated amount of *n*-heptane as GLC internal standard was added to the initial reagent solution. The samples of suspension or of supernatant solution were cautiously quenched with the 20% aq. solution of NH₄Cl. The organic layer was separated and analyzed by GLC.

3. Results and discussion

3.1. Bromobenzene in diethyl ether

In order to provide a comparison of the Grignard reagent formation in toluene solutions with a conventional preparation process, several kinetic experiments were carried out with bromobenzene in diethyl ether. Because of the great exothermicity of the reaction, severely aggravating the temperature control, kinetic measurements were performed in boiling ether (at 35 °C).

In a standard procedure the reaction flask was charged with 2 equiv. (relative to bromobenzene) of magnesium turnings, 50 mL of dry ether, and appropriate amount of bromobenzene. The reaction obeyed a neat first-order kinetics up to the end of the process. Calculated rate constants are presented in Table 1.

It has been established that the rate of Grignard reagent formation is proportional to the halide concentration and the surface area of magnesium metal ([12] and references therein):

$$v = kS_{\text{Mg}}[\text{RX}].$$

Thus, the reaction is of first-order in the organic halide and pseudo-zeroth-order in magnesium if a sufficient excess of the metal is provided. In our experiment, only double molar amount of magnesium was used. Although magnesium metal was taken in the form of shavings with a large surface area, a distinctive decrease

Table 1
Rate constants for the phenylmagnesium bromide formation in diethyl ether at 35 °C

Initial conc. of PhBr (M)	Initial amount of Mg (equiv.) ^a	$k \times 10^3$ (s ⁻¹)	Final [MgBr/PhMg] ^b
0.15	2	2.10	1.01
0.30	2	3.87	1.11
0.50	2	4.74	1.07
		4.82	1.12
		5.69	1.09
0.75	3	6.87	1.07
		7.40	1.10
1.00	2	9.19	1.15

^a Relative to bromobenzene.

^b The ratio indicates the extent of side reactions.

of the reaction rate during the experiment should have been observed. However, this was not the case. On the other hand, the rate constants appeared to be dependent on the initial concentration of the halide (Table 1) or obviously on the amount of magnesium metal. However, doubling of the amount of the metal, thus doubling the surface area of the shavings, did not lead to a twofold increase in the reaction rate. Rate data in Table 1 allow estimating an overall kinetic order of the reaction approximately equal to 1.67.

Our observations are consistent with and probably supporting the views of at least two groups of investigators [14–16], specifically the following. As the reaction proceeds, a finite number of discrete sites initiate. Following this stage, the reactive area increases by the growth of sites rather than by initiation of new sites. Pitting of the surface is an important feature and the reaction mainly proceeds in depth of the pits thus possibly increasing the active surface of the metal during the process while molar amount of the metal and its total surface area are decreasing.

3.2. Bromobenzene with diethyl ether in toluene

Because of the slow reaction, the kinetic measurements in toluene were carried out at elevated temperatures. The reaction was initiated by gradual raise of temperature. When the reaction had started, exothermicity of the process raised the temperature rapidly to a desired level (60–85 °C) controlled with a thermostat. Special GLC determinations using an internal standard revealed, somewhat unexpectedly, a practically negligible loss of diethyl ether in an amount of few percents during the measurements.

When diethyl ether was taken in a molar amount 2:1 relative to bromobenzene the reaction followed a neat

first-order kinetics (Fig. 1, curve A). In case of equimolar initial amounts of the reagents the reaction was of first-order up to consumption of the half amount of bromobenzene. Then a much slower reaction followed, also obeying a first-order kinetics (Fig. 1, curve B).

Calculated rate constants are presented in Table 2. From these data thermodynamic activation parameters were estimated for the first step of the reaction with $\text{Et}_2\text{O}/\text{PhBr} = 1$

$$\Delta H^\ddagger = 32.8 \pm 3.3 \text{ kJ mol}^{-1},$$

$$\Delta S^\ddagger = -218 \pm 10 \text{ J mol}^{-1} \text{ K}^{-1},$$

and for the ratio $\text{Et}_2\text{O}/\text{PhBr} = 2$,

$$\Delta H^\ddagger = 29.0 \pm 1.0 \text{ kJ mol}^{-1},$$

$$\Delta S^\ddagger = -224 \pm 3 \text{ J mol}^{-1} \text{ K}^{-1}.$$

It is seen from the data in Table 2 that the rate constants could be determined with a quite satisfactory repeatability. The reaction rate depends on the initial concentration of the halide, or more probably on the relative amount of magnesium metal similarly with the process in diethyl ether (see previous section).

The reaction in toluene is considerably slower than in pure diethyl ether (cf. Table 1). With $\text{Et}_2\text{O}/\text{PhBr} = 2$ the reaction is twice as fast as the first step of the reaction with equimolar amounts of the reagents, however, the activation parameters are statistically the same for both the cases.

It can be concluded that in the fast step of the reaction with equimolar initial amounts of the reagents the formation of disolvated phenylmagnesium bromide occurs. Then a much slower process follows leading to monosolvated reagent and accompanied with a precipitation of some species (vide infra). Such a monosolvated in average phenylmagnesium bromide reagent can

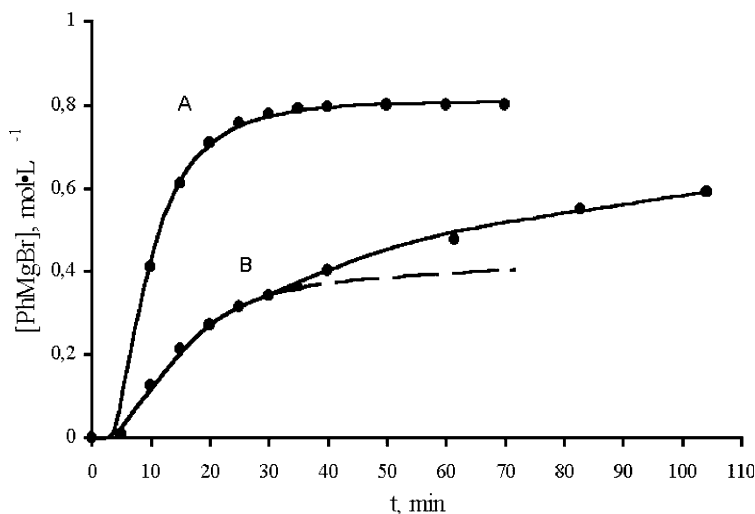


Fig. 1. Kinetic curves for the formation reaction of phenylmagnesium bromide in toluene at 70 °C. Initial conc. of bromobenzene 1 M. Molar amount of diethyl ether relative to bromobenzene 2:1 (curve A) and 1:1 (curve B).

Table 2
Rate constants $k \times 10^3$ (s^{-1}) for the phenylmagnesium bromide formation in toluene

Temperature (°C)	[PhBr] ₀	Mg (equiv.)	Et ₂ O/PhBr = 1		Et ₂ O/ PhBr = 2
			Fast step	Slow step	
60	1.0	2	0.83		1.72
70	1.0	2	1.27	0.27	2.40
			1.30	0.28	
	0.6	2	1.15		
			3.3	1.30	
0.4	5	1.95	0.21		
		1.60	0.20		
80	1.0	2			3.30
85	1.0	2	2.07	0.40	
			2.03	0.37	

convert a considerable amount of bromobenzene the turnover number being limited with thickness of the reaction mixture. However, the contribution of Wurtz coupling is remarkable. For example, in an experiment with 0.5 M diethyl ether and initial ratio PhBr/Et₂O = 8 at 65 °C, a 73% conversion of bromobenzene was attained in 70 h but the yield of the Grignard reagent was 52.5%.

Further, the possible catalytic action of solvated phenylmagnesium bromide was investigated. In kinetic experiments, monosolvated phenylmagnesium bromide was prepared in appropriate concentrations in toluene and the formation of Grignard reagents in the presence of the catalyst was followed as usual. The catalyzed reaction obeyed always the first-order reaction kinetics and was followed up to 80–90% conversion of added halide (1.5 equiv.).

As seen in Fig. 2, rate constants of Grignard reagent formation correlate with the concentration of the catalyst, monosolvated phenylmagnesium bromide. Actual concentration of phenylmagnesium bromide in the catalyst solution is by 30–33% lower than initial concentra-

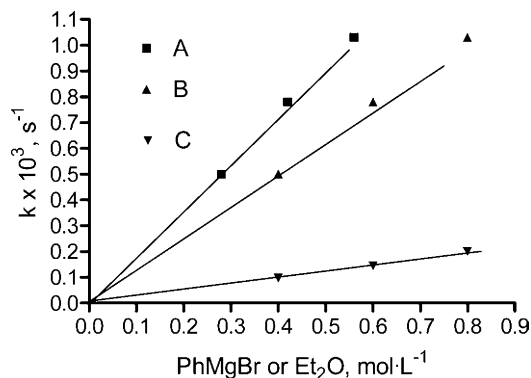


Fig. 2. Plots of catalytic rate constants at 70° for the formation of phenylmagnesium bromide vs. the concentration of solvated phenylmagnesium bromide (A) or vs. the molar content of diethyl ether in the system (B), and for the formation of *n*-butylmagnesium chloride (C). Initial amount of magnesium metal was 4 equiv. relative to the halide.

tion of bromobenzene because of extensive occurrence of Wurtz reaction during the synthesis (see below). The rate constants depend linearly on the concentrations of both phenylmagnesium bromide and diethyl ether in the system.

However, the slope of the line, k vs. PhMgBr concentration, is greater. These facts indicate that the catalysis is most probably exerted by solvated phenylmagnesium bromide, neither by free ether which concentration in the solution can be but negligible, nor by solvated magnesium halide. No catalytic effect of magnesium bromide–diethyl ether complex was detected in a previous work [9].

Remarkable is the catalytic action of the complex in the reaction of butyl chloride with magnesium metal although being considerably weaker than for the reaction of bromobenzene (Fig. 2). However, the catalyst appeared to be inactive towards chlorobenzene. No reaction was observed after 4 h heating of the mixture at 90 °C.

We considered the determination of composition of phenylmagnesium bromide solution to be relevant to discussion concerning the mechanism of the catalysis. Some partially solvated phenylmagnesium bromide solutions were analyzed (see Section 2.3). The results are presented in Table 3.

Evidently the contribution of Wurtz reaction in formation of these Grignard reagents is 30–33% independent of the concentration and halide–ether ratio. The precipitate is rich in magnesium halide and the relative content of magnesium bromide in the precipitate increases with increasing concentration of the reagent and with an increase in the ratio halide to ether. However, relative amount of the precipitate in a monosolvated reagent is very small. The results of diethyl ether determinations indicate that within the experimental errors practically all the ether contains in the solution. As almost insoluble in toluene, magnesium bromide in the solution must be entirely complexed with phenylmagnesium bromide and the latter in its turn binds up all the ether implicated in the system. Occurrence of free ether in the presence of these strong Lewis acids is unlikely. Consequently, only the solvated phenylmagnesium bromide seems to be responsible for the catalysis.

In former publications [7–9] we have stated that alkyl halides in the presence of minor additions of ether in toluene gave rapidly a monosolvated reagent which further catalyzed a slow zeroth-order Grignard formation. In light of present investigation, it seems plausible that in the fast reaction with alkyl halides initial formation of disolvated reagent and the subsequent reaction leading to a monosolvated product could not be distinguished. The zeroth-order kinetics of the catalyzed reaction of alkyl halides probably can be assigned to a mechanism entirely limited by the mass-transport.

Table 3
Results of the analysis of Grignard reagents

Initial conc. of PhBr (M)	Ratio PhBr/Et ₂ O	Stoichiometry PhMgBr · nMgBr ₂		Diethyl ether ^a	
		n in the reagent ^b	n in the precipitate	Reagent ^b	Supern. soln.
0.4	1	0.2	1	1.07	1.19
0.8	1	0.25	1.5	2.64	2.48
0.8	2	0.23	2	1.42	1.31
1.6	2	0.25	2	2.42	2.55

^a Arbitrary units.

^b A suspension of the precipitate in the solution.

The very slow catalytic reaction of bromobenzene can then be truly of first-order in the halide. However, this seems not to be the case for the formation of disolvated reagents. In toluene, the stoichiometric reagents are the halide, and the catalyst ether consumed by complexing with the product along with the reaction. Therefore, the kinetic order of the reaction should exceed unity considerably. Thus, the observed rate order can be an artifact due to a contribution of the mass-transport limitation under the conditions imitating a preparative procedure (cf. [12] p. 193 and references therein).

However, obtained rate constants still reflect the steps of the reaction not consisting in the mass-transport. The relatively low activation enthalpy is reasonably consistent with the values observed for related systems [16,17]. Remarkable is a great loss of entropy during the activation most probably pointing at the solvation of species in the rate-limiting step of the reaction.

The mechanism of catalysis in the reaction still remains obscure. However, an exchange of the organic base between a partially solvated organomagnesium compound in solution and an unsolvated alkyl- or arylmagnesium halide on the surface of the metal seems to be essential for the catalysis by the solvated Grignard reagent. Considering that the formation of a Grignard reagent is possible in the absence of organic bases provided a sufficiently high temperature, a vigorous stirring, etc. enable to remove the reaction products from the surface [1], the role of the organic base can consist in the solvation and dissolution of the organomagnesium compound.

3.3. Chlorobenzene with THF

Of the two most common solvents for Grignard reagents, THF has an advantage over diethyl ether due to the higher boiling point. As could be expected, chlorobenzene reacts more sluggishly in comparison with bromobenzene. Moreover, formation of *n*-butylmagnesium bromide in toluene in the presence of THF was 7 times slower than with diethyl ether [8]. The kinetic features of the process in toluene are rather similar

to those for bromobenzene–diethyl ether system, except the contribution of Wurtz reaction being less important.

In case of equimolar amounts of the reagents the initial stage of the reaction obeying the first-order kinetic law ends at approximately 60% extent of the reaction. The rate of the reaction seems to be almost independent on the initial concentration of the reagents (Table 4). The initial stage of the reaction is followed by a slow process of more complex kinetics further accompanied by formation of a precipitate. The stoichiometry of the supernatant solution is approximately 2Ph₂Mg · MgCl₂. One more equivalent of chlorobenzene added to a 1 M “monosolvated” PhMgCl solution reacted yielding a thick suspension of a solid rich in MgCl₂. The supernatant solution was 0.67 M in Ph–Mg and contained the stoichiometric complex 3Ph₂Mg · MgCl₂. An experiment with the ratio THF/chlorobenzene 2:1 gave a neat first-order kinetic curve for all the reaction with $k = 1.19 \times 10^{-4} \text{ s}^{-1}$ (at 110 °C and 0.5 M initial concentration of chlorobenzene).

Formerly, we found for alkyl chlorides [6] that stronger solvation of the reaction product generally enhanced the extent of the reaction, THF being an exception. This suggested that a solvated organomagnesium complex rather than the free donor substance in a very low concentration is responsible for the promotion of the reaction after the solvated Grignard reagent had been formed. In the presence of THF, the strong solvation of magnesium chloride accumulates the donor in the

Table 4
Rate constants for the phenylmagnesium chloride formation in toluene in the presence of equimolar amounts of THF

Temperature (°C)	Initial conc. of PhCl (M)	$k \times 10^4 \text{ (s}^{-1}\text{)}$	Conc. of the product by the end of the first stage (M)
90	1.0	0.433	
100	1.0	0.733	
110	0.6	1.00	<0.4
		1.05	<0.4
	0.8	1.20	~0.5
	1.0	1.08	~0.6
	1.2	1.07	~0.7

precipitate and deprives the supernatant solution of active species. In this context diethyl ether proves to be the most effective donor affording Grignard reagents with a very small content of the base.

From the data in Table 4 the activation parameters were estimated: $\Delta H^\ddagger = 49.9 \pm 3.8 \text{ kJ mol}^{-1}$, and $\Delta S^\ddagger = -129 \pm 10 \text{ J mol}^{-1} \text{ K}^{-1}$. The difference between the values of ΔH^\ddagger for chloro- and bromobenzene is not only statistically significant but also expected, based on the greater strength of the C–Cl bond. The considerably smaller entropy loss on comparison with the bromobenzene–diethyl ether system, if really ensuing from the solvation as speculated above, can be referred to lesser steric demands of THF in the complex.

In chlorobenzene, the reaction starts exothermically and is faster than in toluene solutions. The kinetics of the process follows the first-order law up to the consumption of a molar amount of chlorobenzene equivalent to the added THF. Then a slow reaction follows and formation of a precipitate begins. The process ends with formation of a thick paste which does not allow further agitation of the reaction mixture. The Grignard reaction is accompanied by remarkable formation of Wurtz-type by-products. For example, a reaction mixture 1 M in THF gave at 80 °C for the first step of the reaction $k = 3.25 \times 10^{-4} \text{ s}^{-1}$ and yielded reagents with stoichiometries $\text{Ph}_2\text{Mg} \cdot 1.28\text{MgCl}_2$ to $\text{Ph}_2\text{Mg} \cdot 1.32\text{MgCl}_2$. The conversion of chlorobenzene was 1.3 in respect of THF, however, the contribution of Wurtz reaction was up to 25%. In the supernatant solution diphenylmagnesium was dominating: $1.4\text{Ph}_2\text{Mg} \cdot \text{MgCl}_2$.

As in this experiment chlorobenzene is simultaneously the solvent and the reagent, the only variable is the concentration of THF. It can be concluded that the observed kinetic curves actually represent the consumption of THF in complexing with the formed Grignard reagents. It also follows that in the first stage of the process the stoichiometrically “monosolvated” phenylmagnesium chloride soluble in chlorobenzene is produced. Further reaction leads to formation of a less solvated reagent which partially precipitates with a disproportionation of the reagent yielding a supernatant solution rich in diphenylmagnesium.

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