A Kinetic Study of the Meerwein–Ponndorf–Verley Reaction

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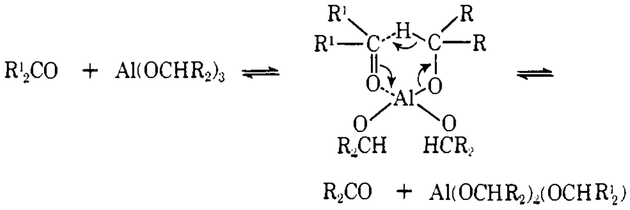
Abstract: Two steps of the Meerwein–Ponndorf–Verley (MPV) reaction have been studied in isolation by measuring the rates of exchange of deuterated acetone and deuterated isopropyl alcohol with aluminium isopropoxide. The results show that the "melt," which consists predominately of the trimeric form in equilibrium with a small concentration of dimeric form, is about 10^3 times more reactive than the tetrameric form in both reactions. In the presence of isopropyl alcohol the first step of the MPV reduction with the tetramer is probably its unimolecular conversion to a more reactive form. The initial step in the reaction of the "melt" forms probably involves rapid and reversible coordination of the acetone or alcohol with the aluminium *via* valency expansion.

The current view of the Meerwein–Ponndorf–Verley (MPV) reaction, summarized by Bradley,[1] is that it proceeds *via* the following steps: (1) coordination of the ketone to the alkoxide monomer; (2) hydride transfer; (3) separation from the complex of the ketone produced in step 2; (4) alcoholysis of the mixed alkoxide, liberating the free alcohol. Step 2 has generally been assumed to be rate determining. Meerwein[2a] proposed that the reaction involves coordination of ketone to metal, and Woodward[2b] that it proceeds through a cyclic transition state



The electronic[3] and steric[4] consequences of this mechanism have been verified; Williams and his coworkers[5] have established that the methine proton of aluminium isopropoxide is transferred during the reaction. Kinetic studies of the reaction,[6] however, have indicated that it may be more complicated than this simple picture indicates, and have shown[7] that in the reduction of acetophenone to α-phenylethanol, the ketone disappears more rapidly than the alcohol is produced, suggesting that the alcohol-exchange step of the reaction may be rate limiting.

Very little is known about the mechanism of the alcohol exchange reaction of alkoxides. It has been used extensively as a preparative technique,[8] but the only previous attempt to study the mechanism is that reported by Bains,[9] which showed that the exchange of ^{14}C-labeled isopropyl alcohol with aluminium isopropoxide in benzene at 20° is fast but measurable; details of this study have not yet been published.

The most common catalyst employed in MPV reactions is aluminium isopropoxide. This exists in three different polymeric forms, the dimer, trimer, and tetramer, which interconvert in solution and in the melt.[10] The gross structures of all three have been determined by cryoscopic and nmr studies.[10,11]

Experimental Section

Aluminium Isopropoxide. Commercial samples of aluminium isopropoxide were purified by distilling under reduced pressure, bp 108.5–109.5 (0.4 mm) and 115° (1.0 mm). Samples were allowed to solidify in a desiccator over a period of a month at room temperature, giving a white solid which nmr spectroscopy showed to be pure tetramer.

Solutions of the "melt" form were prepared by sealing solutions of the tetramer in the appropriate solvent in a Pyrex tube, heating to 110° for 16 hr, and cooling the tubes rapidly in ice water. (*Caution!* This treatment occasionally causes tubes to burst.) A detailed examination of the "melt"[10] produced in this way showed it to be initially almost pure dimer, but on standing over a period of about 2 hr (depending on concentration) the molecular weight rose until the average degree of polymerization of the alkoxide was 2.8. Further conversion of the "melt" to tetramer took place very slowly (over a period of weeks) at room temperature.[10] Throughout this work, "melt" refers to material at this preliminary equilibrium with average degree of polymerization of 2.8.

Deuterated Materials. Deuterated acetone was prepared by repeated sodium carbonate catalyzed exchange of acetone with deuterium oxide. The product had 99.6% of its hydrogen replaced by deuterium. Deuterated isopropyl alcohol was prepared by reduction of a sample of the above acetone with lithium aluminium hydride.[6] The proton spectrum of the product had a very broad methine proton peak and a split hydroxyl proton peak, but showed no trace of any hydrogen in the methyl groups.

Other Materials. Acetophenone was purified by distillation through a spinning-band column, bp 73.5° (7 mm); benzene solvent was purified by distillation from sodium, and the bases used in bonding studies were distilled before use, from sodium hydroxide pellets in the case of nitrogenous bases.

Nmr Spectroscopy. All kinetic data were measured on a Varian A-60 nmr spectrometer; reactions of the "melt" form of the alkoxide were measured by repeated scanning of a sample in an nmr tube, so that the reaction was carried out at the temperature of the

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[1] (a) D. C. Bradley, "Metal Alkoxides," Advances in Chemistry Series, No. 23, American Chemical Society, Washington, D. C., 1959, p 10; (b) D. C. Bradley, *Progr. Inorg. Chem.*, **2**, 303 (1960).

[2] (a) H. Meerwein, B. Bock, B. Kirschnick, W. Lenz, and A. Migge, *J. Prakt. Chem.*, **147**, 211 (1936); (b) R. B. Woodward, N. L. Wendler, and F. J. Brutschy, *J. Amer. Chem. Soc.*, **67**, 1425 (1945).

[3] J. C. McGowna, *Chem. Ind.* (London), 601 (1951).

[4] L. M. Jackman, A. K. Macbeth, and J. A. Mills, *J. Chem. Soc.*, 2641 (1949); L. M. Jackman, J. A. Mills, and J. S. Shannon, *J. Amer. Chem. Soc.*, **72**, 4814 (1950); W. von E. Doering and R. W. Young, *ibid.*, **72**, 631 (1950).

[5] E. D. Williams, K. A. Krieger, and A. R. Day, *ibid.*, **75**, 2404 (1953).

[6] L. M. Jackman and A. K. Macbeth, *J. Chem. Soc.*, 3252 (1952); W. N. Moulton, R. E. VanAtta, and R. R. Ruch, *J. Org. Chem.*, **26**, 290 (1961); M. S. Bains and D. C. Bradley, *Chem. Ind.* (London), 1032 (1961).

[7] V. J. Shiner, Jr., and D. Whittaker, *J. Amer. Chem. Soc.*, **85**, 2337 (1963.)

[8] R. C. Mehrotra, *J. Indian Chem. Soc.*, **30**, 585 (1953); W. Wayne and H. Adkins, "Organic Syntheses," Coll. Vol. III, John Wiley & Sons, Inc., New York, N. Y., 1955, p 48; M. S. Bains, *Can. J. Chem.*, **40**, 381 (1962).

[9] M. S. Bains, Ph.D. Thesis, University of London, 1959, quoted by D. C. Bradley, ref 1b, p 317.

[10] D. C. Kleinschmidt, V. J. Shiner, Jr., and D. Whittaker, to be published.

[11] V. J. Shiner, Jr., D. Whittaker, and V. P. Fernandez, *J. Amer. Chem. Soc.*, **85**, 2318 (1963).

probe, which was found to be steady at 31.4° over the period in which rates were being measured. Kinetic measurements of the other, slower reactions were carried out in sealed nmr tubes, which were kept in thermostated baths and removed for measurement as required; reaction during measurement of the spectra was negligible. Measurements of acetone peak positions were carried out on a Varian DP-60 spectrometer by the side-band technique and are considered accurate to ±0.1 Hz. All nmr data are given in cycles per second (Hz) from TMS at 60 MHz.

Kinetics. Both isotope exchange reactions studied in this work are reversible. First-order reversible reactions follow normal first-order kinetics,[12] with the equilibrium position considered as the complete reaction. For a second-order reaction, assuming the forward and back reactions to have the same rate constant, *i.e.*, ignoring isotope effects, the rate equation is

$$\mathrm{d}x/\mathrm{d}t = k_2(a - x)(b - x) - k_2x^2 \qquad (1)$$

where

$$k_2 = -\frac{1}{t(a + b)}\log[1 - (x/x_e)] \qquad (2)$$

where x_e is the equilibrium value of x. Thus, both first- and second-order reactions in these special conditions would follow the same kinetic form, and the order of the reaction can be found only by observing the variation in values of the first- and second-order rate coefficients as the concentrations of either or both reactants are varied.

Preliminary nmr measurements on a solution of acetone and tetrameric aluminium isopropoxide showed that the acetone peak lay between the peaks of the tetramer at 102 and 96 Hz downfield from TMS. Hence, in the studies of the acetone-exchange reaction it was necessary to compare the areas of these three peaks together with the area of the remaining methyl proton peaks of the alkoxide, from which ratio, the initial concentration of the alkoxide being known, it was possible to calculate the concentration of acetone. The method involves the assumption that the deuterated isopropyl groups are exchanged intramolecularly throughout the alkoxide structure more rapidly than they are taken up. To check this assumption, in one experiment aliquots were taken at intervals during exchange, the volatile components removed at reduced pressure, the alkoxide residue dissolved in benzene and the proton resonance spectra examined. These results, together with the nmr analysis of the complete sample, are listed in Table I.

Table I. Exchange of Deuterated Acetone with Aluminium Isopropoxide Tetramer in Benzene at 25.00°[a]

Time, hr	Integration of isolated alkoxide	Isopropyl alcohol, M	$(CH_3)_2CO$, M	10^6k_2, l. mol^{-1} sec^{-1}
0	3.07	0.000	0.000	...
24	3.04	0.029	0.031	0.42
72	...	0.029	0.143	0.23
96	3.10	0.057	0.176	0.22
168	...	0.064	0.345	0.29
216	3.42	0.064	0.379	0.25
∞(calcd)	...	...	0.760	...

[a] Aluminium isopropoxide is 0.794 M (as monomer); deuterated acetone is 1.115 M.

The figure in the second column gives for the isolated alkoxide (free of acetone) the ratio, (area of remaining methyl proton peaks)/(area of peaks at 102 and 96 Hz), which is equal to 3.00 for the pure tetramer. Any excessive incorporation of deuterium in the nonbridging isopropoxy groups would lead to a reduction in this figure and rearrangement to the "melt" form of the alkoxide would result in an increase in it. The two effects are near zero or balanced over the first 35% of the reaction, so that kinetic measurements subsequently were carried out only over this portion of reaction. Coincidental balance of these two effects seems unlikely, so we suggest that the rate of exchange is much faster than the rate of rearrangement to the "melt" form, and that the rate of internal scrambling of the labeled groups is faster than the rate of exchange with acetone. The final column of Table I gives second-order rate coefficients; although the data given here do not justify the conclusion that the reaction is second order, this justification is provided by the data in Table IV. The isopropyl alcohol observed to be produced in this reaction probably arose as a result of aldol condensation of the acetone, catalyzed by the alkoxide[13] followed by elimination of water which then hydrolyzed the alkoxide. Over the first 35% of the exchange reaction, the effect of this side reaction was relatively small, so that it was ignored in calculating rate coefficients.

The same nmr technique was used to study the exchange of isopropyl alcohol with aluminium isopropoxide. In this case, the methyl proton peaks of the alcohol occurred upfield from those of the alkoxide, so that the relative peak areas of the alkoxide could be examined without isolation of a sample of the material, and the kinetic method is valid regardless of whether the incorporated labeled material was scrambled or not. Detailed results for one experiment are given in Table II.

Table II. Exchange of Deuterated Isopropyl Alcohol with Aluminium Isopropoxide Tetramer in Benzene at 25.00°[a]

Time, hr	Integration of alkoxide	% tetramer converted to melt form	Isopropyl alcohol, M	10^6k_1, sec^{-1}
0	3.08	2.0	0.000	...
17	3.19	4.5	0.202	5.2
23	3.36	8.3	0.267	5.3
41	3.64	13.8	0.437	5.9
47	3.83	17.2	0.460	5.6
71	4.33	25.0	0.596	6.1
88	4.76	30.6	0.632	5.8
∞(calcd)	...	...	0.755	...

[a] Aluminium isopropoxide is 0.741 M (as monomer); deuterated isopropyl alcohol is 1.274 M.

The second column gives the same integration ratio as that recorded in Table I. In this case, the figure increases steadily throughout the reaction, suggesting that some conversion of the tetramer to the melt form may be occurring during the reaction. The figures in column three have been calculated on the assumption that the rearrangement is the only reaction of the alkoxide, and ignore any possible stereospecificity of deuterium incorporation. The rate coefficients in the fifth column are first order, based on the evidence in Table V, as the data for a single run provide no information on this point. The over-all accuracy of the rate constants measured by this nmr technique is estimated to be ±10%. The rate of alcohol exchange in the presence of ketone was measured, only over the first 10% reaction or less, because of the occurrence of a competing side reaction. The rate coefficients quoted in these examples must be considered only semiquantitative, the figures being accurate to approximately ±30%.

Results and Discussion

The bonding between aluminium isopropoxide and Lewis bases has been studied by means of nmr spectroscopy. In general, the shift in peak positions of the spectrum of either base or alkoxide on adding the other to the solution was small, and the best evidence for bonding was the broadening or splitting of the methyl proton peaks of the "melt" form of the alkoxide, probably as a result of coordination interfering with intramolecular alkoxide exchange.

Preliminary studies of a number of bases indicated that they could be divided into four main classes: (1) bases which cause breakdown of the alkoxide structure, *e.g.*, ethylenediamine;[14] (2) bases which displace acetone from the alkoxide, *e.g.*, acetophenone; (3) bases which do not affect the spectrum of the tetramer, but

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[12] A. A. Frost and R. E. Pearson, "Kinetics and Mechanism," John Wiley & Sons, Inc., New York, N. Y., 1953, p 172.

[13] W. Wayne and H. Adkins, *J. Amer. Chem. Soc.*, 62, 3401 (1940).

[14] V. J. Shiner, Jr., and D. Whittaker, *ibid.*, 87, 843 (1965).

cause broadening or splitting of the methyl proton peaks of the melt form of the alkoxide, *e.g.*, pyridine, diethylamine, and trimethylamine; (4) bases which have little or no effect on the spectra of either the tetrameric or melt forms of the alkoxide, *e.g.*, *t*-butylamine, triethylamine, N,N,N′,N′-tetramethylethylenediamine, dioxane, and tetrahydrofuran.

Of the second class of bases, the compounds which undergo the MPV reaction, only acetone can be easily studied directly, since it is only in this case that MPV reaction merely regenerates the starting materials. Since the position of the methyl proton peak of acetone in benzene solution was a function of acetone concentration the peak positions in Table III are values obtained by extrapolation to infinite dilution of acetone.

Table III. Effect of Tetrameric Aluminium Isopropoxide on the Position of the Methyl Proton Peak of Acetone at Infinite Dilution in Benzene Solution at 32.0°

Alkoxide, %	Peak position,[a] MHz	Alkoxide, %	Peak position,[a] MHz
0	93.7	0.260	94.1
0.104	93.6	0.649	94.9

[a] From TMS at 60 Mc.

These results indicate that the addition of the alkoxide affects the environment of the methyl protons of the acetone, but the effects involved are small, so that this method does not appear to be of quantitative value. Throughout these experiments, the alkoxide spectrum remained unchanged, suggesting that any coordination of acetone takes place directly to the tetramer rather than to a monomeric species, thus requiring the use of d orbitals of aluminium. If coordination is responsible for this small shift it is rapid and reversible, as we did not observe splitting into bonded and unbonded acetone peaks over a range of temperatures from +32 to −35°. Attempts to study the effect of the "melt" form of aluminium isopropoxide on acetone by this method were not successful, since the alkoxide catalyzes condensation of acetone.

Hydride Transfer Reaction between Acetone and Aluminium Isopropoxide. Second-order rate coefficients for the reaction between acetone and aluminium isopropoxide are given in Table IV. These results have been obtained from a study of the first 35–40% of the reaction.

Table IV. Second-Order Rate Coefficients for the Exchange of Tetrameric Aluminium Isopropoxide with Deuterated Acetone in Benzene Solution[a]

Concn of $Al(O\text{-}i\text{-}Pr)_3$[b]	Acetone, *M*	10^6k_2, l. mol^{-1} sec^{-1} 25.00°	35.00°	45.00°
0.426	1.346	0.22	0.52	1.22
0.639	1.342	0.22	0.49	1.25
0.852	1.315	0.21	0.45	1.39

[a] Mean energy of activation = 17.1 kcal/mol. [b] Moles of monomer.

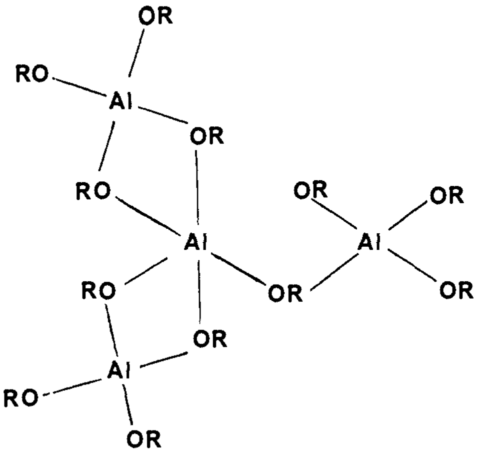
Exchange of the "melt" form of aluminium isopropoxide with deuterated acetone proceeds much more rapidly than exchange of the tetrameric form. The rate of formation of isopropyl alcohol is, however, increased to such an extent that it approaches the rate of acetone exchange. Thus, only the first 10–15% of the reaction can be used to measure the rate of exchange, and the results are less accurate than those listed in Table IV. The results obtained, listed in Table V, must be considered only semiquantitative, the errors involved being estimated at ±50%.

Table V. Second-Order Rate Coefficients for the Exchange of the "Melt" Form of Aluminium Isopropoxide with Deuterated Acetone in Benzene Solution at 31.4°

Concn of $Al(O\text{-}i\text{-}Pr)_3$[a]	Acetone, *M*	10^4k_2, l. mol^{-1} sec^{-1}
0.802	3.33	6.3
0.561	2.33	8.7
0.383	3.20	10.8

[a] Moles of monomer.

The kinetics of the exchange of acetone with the tetramer are consistent with a second-order reversible reaction, with intramolecular isopropoxy group exchange being faster than acetone exchange. We have proposed earlier[11] that intramolecular isopropoxide exchange in the "melt" form proceeds by formation of a new alkoxide bridge followed by opening of one of the original bridges. A similar mechanism is not possible in the tetrameric structure without increasing the coordination number of the central aluminium to seven, an unlikely possibility. In this case, the alternate mechanism, in which the first step of the reaction is fission of a bridging aluminium–oxygen bond to give a complex such as I, followed by formation of another alkoxide bridge, seems more likely to apply.



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An alternative hypothesis is that the reaction involves the monomeric form of the alkoxide, so that the deuterium would be evenly distributed when the monomer units repolymerized, the rate differences depending on the rates of formation of the monomer from the polymer species. We reject this hypothesis, since it is not consistent with the kinetic data, and is further inconsistent with our observation[10] that the rate of interconversion of the tetramer and melt species is considerably slower than the rate of exchange of acetone with either species.

We conclude, therefore, that the hydride-transfer step of the MPV reaction must involve the polymeric form of the alkoxide. The coordination step of Woodward's cyclic transition state mechanism for hydride transfer must then involve expansion of the coordination number of aluminium from four to five, hence, involving the use of the vacant d orbitals of aluminium, rather than expansion of coordination from three to four, as suggested earlier.[6a] This is consistent with reports that the alkoxides of other metals with similarly available orbitals may be used in the MPV reaction,[15] and also with reports that boron alkoxides are very poor reducing agents.[16]

Exchange Reaction between Isopropyl Alcohol and Aluminium Isopropoxide. First-order rate coefficients for the reaction between isopropyl alcohol and aluminium isopropoxide are given in Table VI. These results have been obtained from a study of the first 35–40% of the reaction.

Table VI. First-Order Rate Coefficients for the Exchange of Tetrameric Aluminium Isopropoxide with Deuterated Isopropyl Alcohol in Benzene Solution[a]

Concn of $Al(OR)_3$[b]	Isopropyl alcohol, *M*	$10^6 k_1$, sec^{-1}		
		25.00°	35.00°	45.00°
0.376	0.63	7.9	15.0	..
0.375	1.27	6.0	13.5	34
0.376	2.58	5.9	9.2	..
0.562	1.29	6.9	15.5	36
0.750	1.31	7.0	15.0	36
1.228	1.28	7.8	19.2	..

[a] Mean energy of activation = 15.1 kcal/mol. [b] Moles of monomer.

The exchange reaction between the "melt" form of aluminium isopropoxide and deuterated isopropyl alcohol was found to be complete in 4 min at 31.4° (the reaction was carried out in the nmr probe) so was not further studied.

The data quoted in Table VI are consistent with a first-order reaction, since variation of the rate coefficients occurs only at very high concentration of one or other of the reactants, when some deviation on account of the changing properties of the solvent would be expected. Since we have shown that the exchange of the melt form of the alkoxide is much faster than exchange of the tetramer, it is reasonable to assume that alcohol exchange with the tetramer is first order in alkoxide, and zero order in alcohol.

Clearly, the rate-determining step of this reaction must involve a rearrangement of the tetrameric alkoxide to a more reactive species. The evidence in Table II shows that the rate of exchange is very close to the rate of rearrangement of tetramer to melt over the range studied; since we have found that the melt form exchanges very rapidly, this seems a probable exchange route. By comparison of these data with those obtained from a study of the rearrangement of tetramer to melt in the absence of alcohol,[10] the alcohol is seen to increase the rate of rearrangement by a factor of approximately 15.

The first step of a unimolecular decomposition of a tetramer molecule seems most likely to be opening of one of the bridges between two aluminium atoms to give the species I, which was postulated as the intermediate in intramolecular alkoxide exchange. In the absence of alcohol, this does not necessarily lead to decomposition of the tetramer, so that the action of the alcohol is presumably to coordinate with the 5-coordinate aluminium atom, stabilizing it, and hence blocking reversal formation of the bridge. Since steric factors prevent coordination until after the bridge is opened, alcohol coordination should not affect the activation energy of bridge opening; hence we get good agreement for the E_a of alcohol exchange, 15.1 kcal/mol, with that for tetramer decomposition in benzene, 15.2 kcal/mol. On this hypothesis, I emerges as the intermediate in tetramer decomposition,[10] and also intra- and intermolecular alkoxide exchange. It is clear from our results, that the report that the exchange of isopropyl alcohol with aluminium isopropoxide is fast but measurable at 20° refers to the melt form of the alkoxide.

During an MPV reduction, the exchange of ketone and exchange of alcohol reactions proceed simultaneously; we therefore carried out a reaction in which the simultaneous exchange of deuterioacetone and deuterated isopropyl alcohol with tetrameric aluminium isopropoxide were studied. The reactions were studied for only the first 25% reaction, as the infinity readings for each reaction had to be calculated by neglecting the other reaction; consequently, the rate coefficients cannot be considered accurate to better than ±30%. For a 25.0° solution containing 0.813 *M* alkoxide (calculated as monomer), 1.413 *M* deuterioacetone, and 1.371 *M* deuterated isopropyl alcohol: k_1 (acetone exchange) $= 3.4 \times 10^{-6}$ sec^{-1}, k_2 (acetone exchange) $= 0.89 \times 10^{-6}$ l. mol^{-1} sec^{-1}, k_1 (alcohol exchange) $= 3.8 \times 10^{-6}$ sec^{-1}. The rates of the two reactions are thus equal within the limits of experimental error. The acetone exchange is accelerated by the presence of alcohol, and the alcohol exchange is retarded by the presence of acetone.

It does not seem reasonable to postulate that acetone bonds preferentially to the 5-coordinate aluminium in structure I excluding alcohol since the acetone exchange in the absence of alcohol is much slower than alcohol exchange. Since the results above show that alcohol accelerates the depolymerization of tetramer to the melt forms, it seems reasonable to assume that its accelerating effect in acetone exchange has to do with the same thing and that either alcohol stabilization of the ring-opened form I or the actual conversion to lower polymers provides the mechanism for accelerated acetone exchange. This conclusion is supported also by the indication from nmr line broadening that alcohol coordinates with the melt form. Acetone and alcohol competition for the lower coordinated aluminium atoms in the ring open or melt form probably accounts for the depressing effect of acetone on alcohol exchange. The fact that acetone and alcohol exchange rates are nearly the same when they are present together is probably coincidental.

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(15) H. Meerwein and R. Schmidt, *Ann.*, **444**, 221 (1925); M. Gomberg and W. E. Bachmann, *J. Amer. Chem. Soc.*, **52**, 4967 (1930); R. V. Shankland and M. Gomberg, *ibid.*, **52**, 4973 (1930); H. Meerwein, B. von Bock, B. Kirschnik, W. Lenz, and A. Migge, *J. Prakt. Chem.*, [2] **147**, 211 (1936).

(16) H. G. Kuivila, S. C. Slack, and P. K. Siiteri, *J. Amer. Chem. Soc.*, 73, 123 (1951); P. J. Gaston, unpublished results, quoted by A. G. Davies and C. D. Hall, *J. Chem. Soc.*, 1192 (1963).

Reaction of Acetophenone with Aluminium Isopropoxide. We have previously[7] reported the rate of MPV reduction of acetophenone in a solvent consisting of equal parts of benzene and isopropyl alcohol. The exchange reactions in benzene have now been studied, and are reported in Tables VII and VIII.

Table VII. Displacement of Acetone from Tetrameric Aluminium Isopropoxide by Acetophenone in Benzene at 25.00°[a]

Time, hr	Ketone composition, mol % Acetophenone	Acetone
0	100.0	0.0
24	98.5	1.5
72	94.5	5.5
96	93.2	6.8
168	86.1	13.9
216	79.7	20.3

[a] Initial alkoxide concentration, 0.431 *M* (as monomer); initial acetophenone concentration, 0.657 *M*.

Table VIII. Displacement of Acetone from the "Melt" Form of Aluminium Isopropoxide by Acetophenone in Benzene at 31.4°[a]

Time, min	Ketone composition, mol % Acetophenone	Acetone
0	100.0	0.0
1.3	97.4	2.6
3.5	94.1	5.9
10.1	86.2	13.8
13.4	81.9	18.1
17.4	78.2	21.8
21.5	72.7	27.3

[a] Initial alkoxide concentration, 0.993 *M* (as monomer); initial acetophenone concentration, 1.204 *M*.

The reaction with the "melt," which, on the basis of earlier results, we should expect to be a direct reaction between ketone and alkoxide, proceeds more rapidly in benzene than in the alcoholic solvent by a factor of 2. The acceleration probably results from removal of blocking of the aluminium by coordination of the alcohol. In the case of the tetramer, however, the effect of going from benzene to alcoholic benzene is to *increase* the rate of reaction by a factor of 100. This is difficult to understand if a direct reaction between alkoxide and ketone were involved, but can be readily understood if we now postulate that the rate-determining step of the reaction is rearrangement of the alkoxide to a more reactive form.

The effect of adding acetophenone to the exchange reaction between aluminium isopropoxide tetramer and deuterated isopropyl alcohol is to depress the rate of the exchange reaction. The reaction between 0.376 *M* aluminium isopropoxide and 0.630 *M* deuterated isopropyl alcohol in benzene at 25° has $k_1 = 7.9 \times 10^{-6}$ sec^{-1}; when 0.309 *M* acetophenone is added to the reaction mixture, the value of k_1 is reduced to 3.3×10^{-6} sec^{-1}.

Clearly, our results are consistent with the first step of MPV reduction with tetrameric aluminium isopropoxide in alcoholic solvent being rearrangement to a more reactive form of the alkoxide. This may then undergo the sequence of coordination, hydride transfer and separation as postulated by Meerwein. If the reaction is carried out with the "melt," the reaction with ketone occurs directly and more rapidly. The subsequent exchange between alkoxide and alcohol necessary to isolate the alcohol is, in some circumstances,[7,17] the slow step of the over-all reaction. The MPV reaction as normally run at reflux temperature would involve predominately the reaction of the "melt" forms, so our observations on these species are more pertinent to the synthetic reaction.

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(17) B. J. Yager and C. K. Hancock, *J. Org. Chem.*, **30**, 1174 (1965).