

[CONTRIBUTION FROM THE LABORATORY OF ORGANIC CHEMISTRY OF THE UNIVERSITY OF WISCONSIN]

A STUDY OF CATALYSIS IN THE PREPARATION OF ACETAL

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In connection with an investigation of the mechanism of certain aldehydic condensations a study has been made of the preparation of diethyl acetal. The claims for the known methods for the synthesis are neither in accord with one another nor with the experience of those who have attempted to use them. The standard text-book method is that of Fischer and Giebe¹ who used a 1% solution of anhydrous hydrogen chloride in alcohol and the required amount of acetaldehyde. They secured acetal in a yield of 50%. This method has not given such a good yield in the hands of many chemists. King and Mason² claim that acetal was prepared by treating acetaldehyde and 95% alcohol with the chlorides or nitrates of aluminum, beryllium, calcium, cerium, lithium, magnesium, manganese or thorium either with or without the addition of a little hydrochloric or other acid. They claim a yield of 90% through the use of calcium chloride. Dr. H. T. Clarke of the Eastman Kodak Company has supplied the authors with a description of the method used in their Laboratory for the preparation of acetal. Calcium chloride plus hydrochloric acid is used to bring about the condensation. Yields of 25% to 45% have been obtained. In a recent preparation they obtained 2.5 kg. of acetal from 4 kg. of acetaldehyde and 10 kg. of alcohol.

This investigation has involved a study of the efficiency of various catalysts, and of the optimum conditions for the use of calcium chloride as a condensing agent, as well as a determination of the solubility of acetal in alcoholic solutions, its vapor pressure at different temperatures, and the point of equilibrium between acetal and its products of hydrolysis.

Experimental Part

Purity and Analysis of Reagents.—The salts used as catalysts were of the usual "c. p." grade. The alcohol was either 95% or had been dehydrated by the use of lime. The resulting "absolute" alcohol was at least 99.8% ethyl alcohol. Acetaldehyde was prepared by the depolymerization of paraldehyde³ or was the 95% solution of acetaldehyde as supplied commercially. Acetaldehyde in these preparations as well as in other cases noted later was determined by a modification of the method of Seyewetz and Bardin.⁴ Ten cc. of a cold, approximately 5%, solution of the aldehyde (or an equivalent amount of a less concentrated solution) was added from a water-jacketed buret to about 40 cc. of a neutral (to phenolphthalein) 10% solution of sodium sulfite that was held at a temperature near 0°. The alkalinity developed by the addition

¹ Fischer and Giebe, *Ber.*, **30**, 3053; **31**, 545 (1898).

² King and Mason, *Brit. pat.* 101,423 (1916); *U. S. pat.* 1,312,186 (1919).

³ McLeod, *Am. Chem. J.*, **37**, 27 (1907).

⁴ Seyewetz and Bardin, *J. Soc. Chem. Ind.*, **25**, 202 (1906).

of the aldehyde was neutralized by the slow (not over 5 cc. per minute) addition of *N* sulfuric acid. The end-point was considered as reached when the pink color failed to return in 2 minutes. One cc. of *N* sulfuric acid is equivalent to 0.044 g. of acetaldehyde.

Standard Method for the Preparation of Acetal

After 30 preliminary experiments a standard method for the preparation of acetal was adopted. The justification for the various steps in this process is discussed later.

Twenty g. of anhydrous calcium chloride and 105 g. of 95% alcohol were placed in a 350cc. narrow neck bottle with spring-held stopper, and cooled to 8° or less. The bottle was then tared on a platform balance and 50 g. of cold 95% acetaldehyde slowly poured down the inside of the bottle to form a layer on the alcoholic solution. The bottle was then quickly closed, vigorously shaken, and allowed to stand with intermittent shaking for 12 hours or more. The perfectly clear upper layer was then separated and washed with 100 cc. of distilled water, used in 3 portions. The washed oil was then allowed to stand for several hours during which time a gram or more of water settled out. The oil was dried for 2 or 3 hours over 5 g. of potassium carbonate, and then fractionated.

The fractionation apparatus consisted of a 500cc. round-bottom flask connected to a Vigreux type of still-head which in turn was connected to a 75cm. water-cooled Liebig condenser. The lower end of the condenser tube was bent so that it delivered the distillate into a Gooch glass funnel (the so-called carbon filter tube). A 60cm. 31-spiral reflux condenser was attached to the Gooch funnel, the lower end of both condensers being held in the funnel by a paraffined cork stopper. The lower end of the funnel was attached to a 150cc. Erlenmeyer flask which served as a receiver for the distillate. The fractionating column had an internal diameter of 17 mm., an effective length of 30 cm., and had 16 paired, spiraled indentations. The distilling flask was heated in a small glycerin bath. Thermometers were placed at the outlet of the still-head and in the glycerin bath. The bath temperature was raised to 90° and kept there until distillation began. The temperature was allowed to rise very slowly so that the distillate came over at a rate of 1 or 2 drops per second. A good separation could not be made with a more rapid rate of distillation. Fractions were collected from 76–95° and from 95–106°. Each fraction was then separately fractionated, that fraction being considered as acetal that distilled from 100–103°.

A typical procedure is as follows.

When the acetaldehyde was added to the alcohol-calcium chloride solution the temperature of the reaction mixture rose from 8° to about 44° within 10 minutes. The pressure in the flask increased to about 10 cm. of mercury above that of the atmosphere within 5 minutes, and upon shaking decreased to atmospheric pressure within 10 minutes and slowly fell in the course of an hour and a half to 35 cm. of mercury below normal. Within 5 minutes of the beginning of the reaction there were formed 2 layers in the reaction flask, the upper one being approximately 3¹/₃ times the volume of the lower. After some hours the upper layer weighed about 128 g. and the salt layer 47 g. Upon washing with water the upper layer lost about 21 g.; 5 g. was absorbed by the potassium carbonate. The first fractionation of 101.6 g. gave 20.1 g. distilling at 75–95°, 76.2 g. from 95–106°, and 4.2 g. of residue. The second distillation at 736 mm. pressure

gave 18.5 g. from 78–100°, 72.3 g. from 100–103°, and 4.2 g. of residue. The product when kept over solid potassium hydroxide for 2 days gave a very light straw-yellow color to the alkali, showing the presence of very little aldehyde. The iodoform, calcium carbide and potassium permanganate tests indicated the absence of alcohol or water. It is believed that about 25 g. of acetal is not recovered in the process described. This loss is probably distributed as follows: in the wash water 6.0 g., in the salt layer 0.5 g., in the potassium carbonate 2.5 g., during distillation 2.5 g., in the low fraction 11.0 g., in the residue 2.5 g. These figures are based upon determinations made upon the solubility of acetal in calcium chloride solutions, pure water, alcohol-water mixtures and upon the absorption of acetal by potassium carbonate and refractionation of low- and high-boiling fractions. The alcohol was distributed as follows: 2.6 g. in the salt layer, and 21.4 g. in the upper layer about half of which was removed by the washing. There was 0.6 g. of acetaldehyde in the salt layer and 8.3 g. in the upper layer, 80% of which was removed by the washing process. Only 2.3 g. of the acetaldehyde originally used is unaccounted for. The actual yield of acetal by two fractionations was 72.3 g. or 54.6% (based on the amount of aldehyde used). By washing and refractionating the low-boiling distillate this yield may be increased to 83.3 g. or 65%. It is believed that 14.1 g. of acetal was lost in the wash water, in the high and low fractions, etc. The total amount of acetal formed was thus 97.4 g. or 75.9% of the theoretical amount. Certain references are made to "corrected percentage yield." In these cases account is taken of the loss of acetal, through washing, absorption and inefficient fractionation.

Preparation of Acetal on a Larger Scale

After this paper had been almost completely prepared for publication a preparation of acetal was made in which the quantities used were 10 times those specified in the standard method. The reaction in this case was carried out in an ordinary 4 liter cork-stoppered bottle, and 698 g. of acetal was obtained. This is a yield of 55%. By rewashing the low-boiling distillate of 185.7 g. with 200 cc. of water and fractionating the dried oil, 97.7 g. of acetal was obtained. By washing and refractionating the 78 g. of high-boiling residues, 18.6 g. more of acetal was obtained. The total amount of acetal obtained was thus 814.5 g. which is a 64% yield. The acetal in this case was collected over the range 100–103°. At least 90% of the distillate came over between 102.5° and 103° at 735 mm. pressure. The total working time required for the preparation of the 814.5 g. of acetal was 12 hours.

Physical Constants for Acetal

The purest samples of acetal obtained had d_4^{20} 0.8254, and $d_{20}^{15.6}$ 0.8334. Liebig⁵ gives d_4^{20} 0.823, and Stas⁶ gives $d_4^{22.4}$ 0.821; n_D^{25} in the Pulfrich refractometer was 1.3682.

The Vapor Pressure of Acetal.—The boiling point was 104.2° at 760 mm. pressure. Boiling points at other pressures are given in Table I. The values of the vapor pressure at all except the four higher temperatures given in the table were determined by the dynamic method. The

⁵ Liebig, *Ann.*, **5**, 26 (1833).

⁶ Stas, *Ann. chim. phys.*, [3] **19**, 146 (1872).

vapor pressures at the four higher temperatures were taken from determinations of the boiling point as made by the use of a barostat.

TABLE I
VAPOR PRESSURE OF ACETAL

Vapor pressure of acetal Mm. of Hg	Temperature ° C.	Vapor pressure of acetal Mm. of Hg	Temperature ° C.
52	33.9	432	86.6
121	52.8	499	90.5
178	62.0	553	93.3
218	67.1	586	95.1
244	71.0	720	101.2
301	76.3	736	102.4
365	81.7	745	103.0
...	...	760	104.2

Solubility of Acetal in Water and Alcoholic Solutions.—The solubility of acetal in grams per 100 cc. of an alcoholic solution as determined by observing the amount of acetal that must be added to the alcohol solution to produce a turbidity is given in Table II. This method for determining solubility seems a rather crude one, but in this case it gives quite accurate results, for when an amount of acetal very slightly in excess of the solubility is introduced there is an immediate separation of the solution into two layers.

TABLE II
SOLUBILITY OF ACETAL

% by vol. of alcohol	0	5	10	15	20	25	30	35	40	45	50	55	60
G. of acetal	5.0	5.1	5.3	5.5	5.6	6.4	7.3	8.5	10.0	11.8	14.0	17.2	∞

Results⁷

Calcium chloride, calcium nitrate and lithium chloride are about equally efficient and are the best catalysts that were used in these preparations. The average actual yield of acetal in experiments in which 20 g. of calcium chloride was used as the condensing agent was 56.9%. The average "corrected" yield was 76.7%. The yield obtained by the use of calcium nitrate was 2.0%, and with lithium chloride was 1.4% lower than with the calcium chloride. Aluminum chloride is almost as good a condensing agent as an equal weight of calcium chloride and much more rapid. The yield with this catalyst is 51.5%. The lower yield is probably due to the well-known activity of aluminum chloride in polymerizing acetaldehyde to paraldehyde. Ten g. of aluminum chloride is a better catalyst than an equal weight of calcium chloride. Eight other salts gave much lower yields of acetal. These salts and the percentage yields of acetal are: magnesium chloride, 27%; manganese chloride, 21%; cerium chloride, 17%;

⁷ Space in THIS JOURNAL was not available for the tabulation of the data of the 85 experiments upon which the reported results are based.

ammonium chloride, 11%; calcium bromide 10%; copper sulfate, 10%; zinc chloride, 9%; sodium iodide, 7%; and lithium iodide, 3%. Twenty g. of thorium chloride, barium chloride, calcium acetate, sodium chloride, potassium carbonate, calcium sulfate, cerium sulfate, magnesium nitrate, manganese nitrate, acetic acid, hydrochloric acid or sulfuric acid did not cause the formation of any isolable acetal.

As calcium chloride is the most readily obtainable and efficient catalyst, a more thorough study was made of its most effective use. Amounts of calcium chloride from 2 g. to 50 g. were used in the standard method. If 15 g. or less of the salt is used the yield is below the optimum, though there is an increase in yield with increase in the amount of catalyst. The use of more than 20 g. offers no advantage and, in fact, the larger amounts apparently lower the yield almost 2%. By the use of these larger quantities of calcium chloride the amount of alcohol and water removed in the subsequent washings is, of course, decreased. The larger amounts of catalyst greatly increase the speed of the reaction but produce a less pure product, as indicated by the test with potassium hydroxide described above. As the solubility of calcium chloride in the amount of alcohol used is approximately 17 g., there would seem to be no reason why more than this amount should be used. The addition of 20 g. of water or of the calcium chloride layer from a previous preparation to the reaction mixture cuts down the yield of acetal materially. No advantage seems to accrue through the substitution of absolute for 95% alcohol in the standard method. Increasing the temperature of the reaction to 100° has no effect upon the yield of acetal. Increasing the amount of alcohol in order to drive the equilibrium towards the formation of acetal is disadvantageous. This is due to the difficulty and loss in removing acetal from the excess alcohol either by washing or by fractional distillation. Even the conditions recommended by King and Mason give a lower yield of acetal than is obtained by using 1 mol. of aldehyde and 2 mols. of ethyl alcohol as in our standard method. The yield of acetal is reduced about $\frac{1}{3}$ when the crude material is distilled directly. Calcium chloride is not a good drying agent for acetal because it catalyzes the hydrolysis of the compound. It has, however, no effect upon the dried alcoholic solution of acetal. The reaction goes to completion with agitation within 2 hours but a yield of only 41% was obtained when the upper layer of the reaction mixture was separated from the calcium chloride layer 20 minutes after the reagents were mixed.

Since, according to Geuther,⁸ Fischer and Giebe,¹ and King and Mason,² acids promote the reaction, 2 cc. of conc. hydrochloric acid was used with 20 g. of calcium chloride in one experiment, and with 50 g. of the salt in another. The yield of acetal was low, being 29.7% in one case and 32.5%

⁸ Geuther, *Ann.*, 126, 65 (1862).

in the other. The second experiment involves essentially the method of the Eastman Kodak Company. It differs in procedure in that they used 15% more alcohol. They obtained yields of from 25 to 45%. We obtained a yield of 32.5% and there was formed 52.5% (corrected yield), a considerable part of which could be obtained by efficient fractionation. Our results in this experiment are much the same as those obtained by them on a larger scale. Attention should be called to what we regard as the impossibility of the 90% yield claimed by King and Mason. A study of their patent, a copy of which is in our possession, coupled with some experience in the fractionation of acetal-alcohol mixtures makes it evident that their product contained very considerable quantities of ethyl alcohol.

The inconsistent results that have sometimes been obtained in the use of various catalysts have probably been due in part to the fact that the reaction mixture was washed with a calcium chloride solution "to remove alcohol" or "dried" over calcium chloride. It is obvious from the work described in this paper that such a procedure might produce acetal no matter what condensing agent had originally been used. Confusion has also probably been caused by the fact that some salts, such as thorium chloride, cause a stratification to take place in a solution of alcohol, aldehyde and water but do not form any appreciable amounts of acetal. Because with most salts stratification is qualitatively associated with acetal formation, King and Mason were evidently led to believe that thorium chloride was a good catalyst.

The point of equilibrium between acetal and its products of hydrolysis has been approached from both sides. An equimolecular mixture of acetal (134 g.) and water (20.5 g.) was added to 20 g. of calcium chloride. After standing for the usual length of time, the acetal was worked up in the customary manner. The average "corrected" percentage yield was 76%. The average of 4 experiments in which acetal was prepared gave a "corrected yield" of 76.7%. It thus appears that the products of the reaction, $\text{CH}_3\text{CHO} + 2 \text{C}_2\text{H}_5\text{OH} \rightleftharpoons \text{CH}_3\text{CH}(\text{OC}_2\text{H}_5)_2 + \text{H}_2\text{O}$, are in equilibrium under the conditions of the standard method, when there is approximately 76% of the theoretically possible amount of acetal present. The "conditions of the standard method" are not easily interpreted. Roughly expressed they are as follows: the lower salt layer contains 19.4 g. of the calcium chloride, all except a trace of the water, 2.6 g. of alcohol, 0.6 g. of the aldehyde and 0.5 g. of acetal. The upper layer contains the remainder of the reaction materials.

We believe that this preparation involves a true case of catalysis and the function of the salt is not only that of a dehydrating agent. If the salt simply removes water from the sphere of the reaction no reason is seen why such good dehydrating agents as zinc chloride and calcium bromide

should not be good condensing agents.⁹ As a matter of fact these salts are of little value in preparing acetal. The divergence of catalytic and "salting out" or dehydrating action is illustrated by certain test-tube experiments. Two-g. portions of aluminum chloride, lithium chloride, sodium chloride and potassium carbonate were added to mixtures of 6 cc. of acetal, 6 cc. of alcohol and 2 cc. of water. An aqueous layer immediately separated in the tubes containing sodium chloride and potassium carbonate. No separation took place in the tubes containing the active catalysts, aluminum chloride and lithium chloride. When 3 cc. of acetaldehyde was now added to each test-tube, acetal was formed in the presence of the aluminum and lithium salts and an aqueous salt layer separated. When 6 cc. of alcohol was added to each test-tube, complete solution took place in the cases of these same 2 salts, but the sodium chloride and potassium carbonate still held to the water that they had abstracted from the solution. From this it is seen that the failure of sodium chloride and potassium carbonate to serve as catalysts is not due to the lack of ability to abstract water from an alcohol, acetal, aldehyde, water solution. The "salting out" of the acetal or the removal of water from the sphere of the reaction is quite probably one of the functions of the salt catalyst but before this function of the salt comes into play, its primary function in causing the reaction of the aldehyde and the alcohol must be manifested.

The data in this paper are inadequate for any proper interpretation of the mechanism of the action of the salt in the condensation of the alcohol and the aldehyde. Extensive investigations are being carried on in this Laboratory upon the condensations of aldehydes induced by salts and esters, from which it is hoped that some light will be shed upon the theoretical interpretation of these organic reactions.

Summary

1. Calcium, lithium, magnesium, cerium, ammonium, manganese, and zinc chlorides, calcium nitrate, calcium bromide, copper sulfate and sodium and lithium iodides serve as true catalysts and not merely as dehydrating agents in the preparation of acetal.
2. The point of equilibrium in the presence of calcium chloride between acetal and its products of hydrolysis has been established.
3. A method has been developed for the preparation of acetal on a moderately large scale in a yield of 65%.
4. The vapor pressure over a range of temperature and the solubility in water and alcohol have been determined. The density at 20°/4° was found to be 0.8254, and at 15.6°/15.6°, 0.8334. The index of refraction at 25° in sodium light was found to be 1.3682.

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⁹ Baxter and Warren, *THIS JOURNAL*, **33**, 340 (1911). Baxter and Starkweather, *ibid.*, **38**, 2038 (1916).