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I hereby recommend that the thesis prepared under my supervision by Jacob Wade Price

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be accepted as fulfilling this part of the requirements for the degree of Ph. D.

Approved by:

H. Shipley Fry

W. M. Burgess, Chairman

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OBSERVATIONS ON THE MECHANISM OF THE CANNIZZARO AND KLINGER REACTIONS

A dissertation submitted to the

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by

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PART A. THE CANNIZZARO REACTION

INTRODUCTION AND HISTORICAL

The interaction of aqueous alkalies with certain aldehydes, resulting in the formation of an acid and an alcohol, respectively, has long been known as the Cannizzaro reaction. It is represented by the general equation:

$$2RCHO + MOH \rightarrow RCH_2OH + RCOOM \qquad (c)$$

in which R represents either an alkyl or aryl radical, (subject to certain limitations; see theoretical discussion following), and MOH is a fairly strong base, usually sodium or potassium hydroxide.

Cannizzaro [1] first observed the reaction in his study of the alcohol produced by the action of potassium hydroxide on oil of bitter almonds. Although he could not, at that early date in the history of organic chemistry, formulate the reaction, he did demonstrate that the alcohol thus obtained could be reduced to a hydrocarbon which bore the same relation to it as does methane to methyl alcohol [2].

In 1887, Loew [3], in a study of catalytic effects, found that formaldehyde in 15% solution when treated with an equal volume of concentrated aqueous sodium hydroxide, produced sodium formate and a small amount of a gas. In the presence of cuprous oxide, a vigorous evolution of the

gas took place and it proved to be pure hydrogen. Other metallic oxides were without effect on the reaction although mercuric oxide was re duced to the free metal. Loew postulated the reaction represented by the following equation (a);

$$HCHO + NaOH \longrightarrow HCOONa + H_2 \qquad (a)$$

in which metallic copper reduced from the oxide was the catalyst. That such is the case is proved by the fact that the rate of evolution of the hydrogen increases after a few minutes as the reduced copper appears in the solution.

Some what later, Vanino [4] found that the silver oxide formed by adding silver nitrate to an alkaline solution of formaldehyde behaved similarly, the silver catalyzing the reaction as did the copper from cuprous oxide. These two metals seem to be the only ones with appreciable catalytic effect on the reaction.

Lieben [5], in 1901, presented the first quantitative data on the Cannizzaro reaction. By studying series of reactions between formaldehyde and potassium hydroxide of known concentrations he obtained the results embodied in the following table.

TABLE I.

YIELD OF FORMIC ACID FROM FORMALDEHYDE

BY CANNIZZARO REACTION ACCORDING TO LIEBEN.

$$2\ CH_2O + KOH \longrightarrow HCOOK + CH_3OH$$

RUN	HCOOH Produced	HCOOH Theory	% HCOOH	CONDITIONS
a	0.1925	0.2108	91.32	Stood open for 11 days at 10°.
b	0.2092	0.2108	99.24	Closed flask, 12 days at 10°, 17 days at about 15°, and 1 hr. at 30-40° in water bath.
c	0.213	0.2108	101.04	Closed flask, 12 days at 10°, 45 days at about 15°, and 3 3/4 hrs. at 50-60° in water bath.
d	0.2081	0.2108	98.72	Closed flask, 8-10° for 57 days.

Lieben's data show that the reaction becomes substantially complete in 11 days at the relatively low temperature of 10°. This work may be considered as establishing the reaction on a quantitative basis.

H. and A. Euler [6] studied the reaction of formaldehyde in dilute alkaline solutions and concluded that the former behaves as a very weak acid, yielding a monosodium salt, $H_2C(OH)(ONa)$, which is about 50% hydrolyzed in a normal solution. The salt is a binary electrolyte and formaldehyde itself as an acid has a dissociation constant of 1×10^{-14}. They also made a study of the rate of

reaction and determined that the formation of sodium or barium formate in dilute solutions of the respective bases is a reaction of the second order unless a large excess of formaldehyde is present, in which case the reaction is of the first order. Oxidation is not involved since the reaction takes place as readily in an atmosphere of hydrogen as it does in air. The alkali used is of considerable importance, calcium hydroxide, anomalously, reacting much more rapidly than either barium or sodium hydroxide. They also noted that concentrated sodium hydroxide causes a condensation of the formaldehyde to methylenitan as first pointed out by Butlerow [7]. (This is similar to the preparation of formose by Loew [8]).

Auerbach [9] objects to some of the points of the Euler theory.

The literature from 1905 has had little bearing upon the problem in question. The synthesis of sugars and the study of photosynthetic processes have involved formaldehyde from the standpoint of its condensations in alkali rather than its reactions with this agent. Birstein and Lobanov [10], however, have made a kinetic study of formate formation in strong sodium hydroxide solutions, (6.3 N). Their results show that the reaction is probably trimolecular, according to equation (c). There is a possibility, however, that two consecutive reactions take place, such as;

$$HCHO + NaOH \longrightarrow HCOONa + H_2 \qquad (a)$$

$$H_2 + HCHO \longrightarrow CH_3OH \qquad (b)$$

the data being not entirely conclusive that the former mechanism is the correct one. The reaction products, methyl alcohol and sodium formate, influence the reaction markedly, the former retarding and the latter accelerating it. The evolution of hydrogen gas due to the catalytic activity of copper and silver is additional evidence in favor of the latter explanation.

The chief purpose of the present study is to prove that the Cannizzaro reaction does involve reactions (a) and (b), noted above.

THEORETICAL

Aldehydes are conveniently classified by Lieben (11) as to the nature of the carbon atom in the alpha position to the aldehyde group. The reactions of the different groups toward alkaline condensing agents vary as follows:

GROUP	NATURE OF α-CARBON	REACTION WITH NaOH	EXAMPLE
I.	CH_3 or $-CH_2$	Gives aldols	$2CH_3CHO \rightarrow CH_3-CHOH-CH_2-CHO$ or $2CH_3CHO \rightarrow CH_2=CH-CH_2-CHO + H_2O$
II.	$-CH=$	Gives aldols	$2CH_2=CH-CHO \longrightarrow CH_2=CH-CHOH-CH=CH-CHO$
III.	$-C=$ or no C atom as in HCHO	Gives Cannizzaro reaction	$2HCHO + NaOH \longrightarrow HCOONa + CH_3OH$; $2C_6H_5CHO + NaOH \longrightarrow C_6H_5COONa + C_6H_5CH_2OH$

It will be noticed that only those aldehydes in which the aldehyde group is attached to a carbon atom not holding hydrogen atoms undergo the Cannizzaro reaction. The reactions of the first two groups are given by Lieben. It is with those aldehydes of the third group that we are interested. Typical of this group are:

Formaldehyde	HCHO
Benzaldehyde	C_6H_5CHO
Furfural	C_4H_3OCHO
Salicylaldehyde	$C_6H_4(OH)CHO$

Isobutyraldol	$(CH_3)_2CH\text{-}CHOH\text{-}C(CH_3)_2\text{-}CHO$
Formisobutyraldol	$CH_2OH\text{-}C(CH_3)_2\text{-}CHO$
Trimethyl acetaldehyde (pivalaldehyde)	$(CH_3)_3C\text{-}CHO$

Lieben concluded that all aldehydes were capable of undergoing the Cannizzaro reaction but that the aldol condensation took place more rapidly with those of the first two groups so as to mask completely or almost completely the former reaction.

Three types of Cannizzaro reaction have been described.

I. The ordinary reaction [11].

$$2RCHO + MOH \longrightarrow RCOOM + RCH_2OH$$

II. Mixed or cross reactions involving different aldehydes.[12]

$$R'CHO + R''CHO + MOH \rightarrow R'COOM + R''CH_2OH$$

or

$$R'CHO + R''CHO + MOH \longrightarrow R''COOM + R'CH_2OH$$

III. Nord [13] has postulated a third type wherein a metallic alcoholate is used instead of the simple alkali. An addition compound of the alcoholate and first aldehyde is formed:

$$R'CHO + ROM \longrightarrow R'CH(OM)OR$$

This compound then combines with the second aldehyde;

$R'CH(OM)OR + R''CHO \rightarrow R'CH(OR)OCHR''(OM)$

and the product decomposes giving an ester and the alcoholate:

$R'CH(OR)OCHR''(OM) \rightarrow R'CH_2OOCR'' + ROM$

Neuberg and Gorr [14] have shown that an aldehyde and a ketone as well as two aldehydes will undergo the Cannizzaro reaction. Benzaldehyde and methyl propyl ketone yielded benzoic acid and methyl propyl carbinol in the presence of aluminum ethylate:

$$C_6H_5CHO + \begin{matrix} CH_3 \\ \diagdown \\ C_3H_7 \end{matrix}\!\!\diagup CO \quad H_2O \rightarrow C_6H_5COOH + \begin{matrix} CH_3 \\ \diagdown \\ C_3H_7 \end{matrix}\!\!\diagup C \begin{matrix} \diagup H \\ \diagdown OH \end{matrix}$$

Certain physiological changes are assumed to be of this nature.

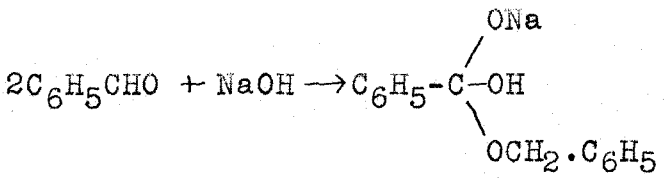
The object of this investigation is to study the mechanism of the first type of Cannizzaro reactions above mentioned. Several mechanisms have been postulated. Richter [15] assumes that the first step involves a union of two molecules of the aldehyde to form an ester which is subsequently saponified by the alkali present:

$2C_6H_5CHO \rightarrow C_6H_5COOCH_2C_6H_5$

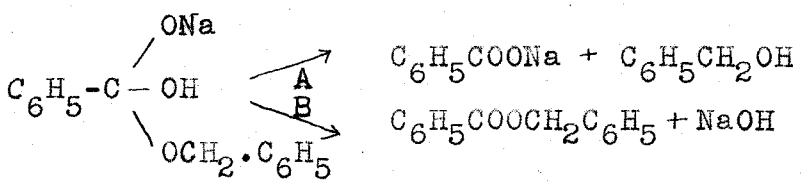
$C_6H_5COOCH_2C_6H_5 + MOH \rightarrow C_6H_5COOM + C_6H_5CH_2OH$

There is some evidence in support of this explanation of the reaction. Claisen [16] found that benzaldehyde treated with sodium methylate in methyl alcohol soon solidified to a crystalline mass which consisted mostly of benzoic acid and benzyl alcohol. However, if the mass

is heated for some time on a water bath and treated with glacial acetic acid followed by the addition of water, benzyl benzoate is the chief product. Kohn and Trantom (16) also found benzyl benzoate when carefully dried sodium hydroxide and benzaldehyde were used. They postulated the formation of an intermediate addition compound:

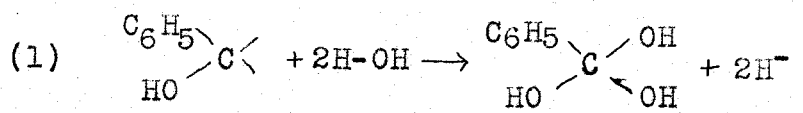


which might decompose in two ways:



Decomposition A is favored by the presence of water and base (and is the only reaction taking place in excess of water), while B is favored by excess of aldehyde.

Nef (17) has also advanced an interpretation which Kohn and Trantom consider unnecessary and yet which yields a possible explanation of the liberation of hydrogen. The mechanism of Kohn and Trantom would allow for the formation of methyl formate when formaldehyde is treated with an alkali but does not show how hydrogen could be liberated. Nef's explanation (for the action of benzaldehyde) involves the isomeric form of the aldehyde group:



$$\longrightarrow \begin{matrix} C_6H_5 \\ HO \end{matrix}\!\!>\!C{=}O + H_2O + 2H^-$$

$$(2)\quad 2H^- + \begin{matrix} C_6H_5 \\ HO \end{matrix}\!\!>\!C\!< \longrightarrow C_6H_5CH_2OH$$

(The free valence bonds merely indicate the free condition, not electrical charges.) It is conceivable in the above that the two free hydrogen atoms could unite to form a neutral hydrogen molecule which would be liberated as a gas, particularly if a catalyst were present.

The fact that hydrogen is evolved calls for an explanation which may be found in the assumption that the reaction takes place in two steps, the first involving the conversion of one molecule of aldehyde to the formate with the liberation of hydrogen:

$$HCHO + NaOH \longrightarrow HCOONa + 2H \qquad (a)$$

and the second involving the reduction of a second molecule of the aldehyde to methyl alcohol by the hydrogen thus liberated:

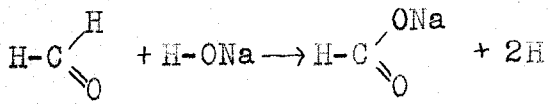
$$HCHO + 2H \longrightarrow CH_3OH \qquad (b)$$

The summation of these two equations gives the Cannizzaro reaction:

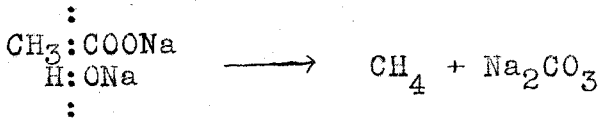
Σ (a) + (b)

$$2HCHO + NaOH \longrightarrow HCOONa + CH_3OH \qquad (c)$$

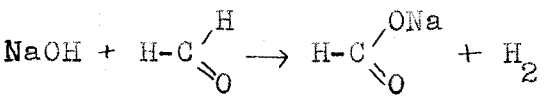
Equation (a) assumes the acidic dissociation of sodium hydroxide:



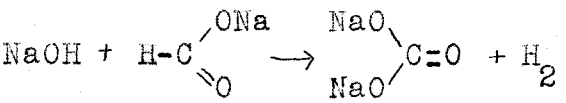
Work done in the past few years in this laboratory by Fry and co-workers [18] has shown that the reactions of many carbon compounds toward fused caustic alkalis are best explained in terms of the acidic dissociation of the alkalis. A familiar example is that afforded by the laboratory method of preparing methane:



When dry formaldehyde vapor is passed through fused mixtures of sodium and potassium hydroxides, carbonates and hydrogen are formed, the steps of the reaction being as follows:

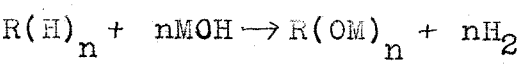


(a)



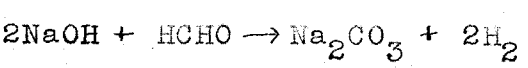
(1)

This corresponds to the type reaction which is followed in all cases by the fused alkali reactions:



(2)

the summation of equations (a) and (1) above giving:

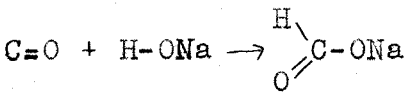


(3)

Apparently, if this is the mechanism of the Cannizzaro reaction, the reaction in aqueous solution stops at the

first stage (equation (a)) and is followed by the reduction of the second molecule of aldehyde or, in the presence of a catalyst, by the liberation of hydrogen.

The reaction of carbon monoxide and sodium hydroxide utilized in the manufacture of formic acid is another example of the acidic dissociation of the alkali and is analagous to the first step of the mechanism of the Cannizzaro reaction proposed above, (equation (a)).



The mechanism proposed for these reactions involving apparently the acidic dissociation of the caustic alkalis has also been extended to an explanation of the reduction of aromatic nitro-compounds by methyl alcohol solutions of sodium hydroxide (21).

Since cupric oxide and metallic copper have been shown to catalyze the liberation of hydrogen in the Cannizzaro reaction applied to formaldehyde, the oxide being simultaneously reduced to the metal, a method is afforded of studying the mechanism of the reaction. If the stoichiometrical relations between the yields of formate, methyl alcohol, hydrogen, and copper can be quantitatively determined, the reaction can then be shown to take place in the two stages noted above.

The purpose of the present investigation is to prove that the Cannizzaro reaction mechanism, in the case

of formaldehyde involves two consecutive reactions ((a) and (b), noted above), To this end, it was necessary to show that the first of these reactions, not confirmed by any previously published quantitative data, actually conforms to equation (a) which calls for the formation of hydrogen in the molecular ratio of 1:1.

The method followed (and more fully described in the following pages) was briefly as follows: The first reaction was shown to occur independently when sufficient copper was present to promote the liberation of measurable quantities of hydrogen. Moreover, both reactions (equations (a) and (b)) were concurrent as shown by the formation of sodium formate and hydrogen, products of the first reaction, and methyl alcohol, the product of the second reaction. Known amounts of $CuSO_4$ were added to a standardized formaldehyde--sodium hydroxide reaction mixture. On boiling, the precipitated cupric hydroxide was converted to cupric oxide which, in turn, was reduced to copper by some of the hydrogen liberated by reaction (a).

The extent of the occurence of reaction (a) was measured by the sodium formate produced and the equivalent amount of H_2 formed which is disposed of in three different ways. One fractional quantity, (x), would be liberated and determined as free hydrogen. Another fraction, (y), was assumed to be active in reducing cupric oxide to metallic copper.

$$CuO + 2H \rightarrow Cu + H_2O$$

The determination of the yield of copper would measure this fraction. The remainder of the total available hydrogen, fraction (z), would be active in reducing some of the formaldehyde to methyl alcohol, the yield of the latter serving simultaneously to measure the extent of the occurence of the second reaction and the hydrogen fraction (z). Accordingly, the sum of these fractional quantities of hydrogen (x+y+z), should equal the total amount of hydrogen formed in terms of the equivalent yield of sodium formate as given by equation (a). These assumptions were confirmed in the procedures to be described.

APPARATUS AND PROCEDURE

All runs were conducted in duplicate. The apparatus consisted of a round-bottom 500 c.c. distilling flask equipped with a Walther dropping funnel and a pressure equalizing device, (a glass tube connecting the flask with the upper neck of the funnel). This pressure equalizing tube had extending from and sealed to it, a glass side arm bearing a stop-cock so that the apparatus might be swept free of gases evolved in the reaction by passing in a current of nitrogen. The funnel stem extended to the bottom of the flask, so that the formaldehyde solution might be added to the reaction mixture without undue loss due to vaporization. The side arm of the flask was connected to a Liebig condenser and, in turn, to two gas washing bottles and a five liter bottle filled with water, inverted over a pneumatic trough. Precautions were taken that all of the connections be gas tight and all glass and rubber stoppers were wired in place to prevent leakage. Each gas washing bottle contained 50 c.c. of water which was sufficient to cover the tips of the inlet tubes.

Fifty c.c. of approximately 10 N sodium hydroxide and 100 c.c. of approximately 1 M copper sulphate of known strength were placed in the distilling flask. The cupric hydroxide formed is converted to the oxide by heating on a water bath. The black oxide settles leaving a clear, colorless supernatant liquid. The flask was then connected to the condenser, 25 c.c. of formaldehyde

solution and 25 c.c. of water placed in the dropping funnel, all connections made tight, and the distilling flask gently heated with a small Bunsen flame to the boiling temperature.

The dropping funnel was then adjusted to permit the formaldehyde to enter the reaction mixture drop by drop, about 2 hours being required to admit the entire 50 c.c. The dropping funnels and reaction flasks had to be watched very closely since the flow of formaldehyde solution was irregular, too rapid a flow causing the reaction to take place too violently with danger of explosion.

Methyl alcohol evolved in the reaction distills off, is condensed and collected in the gas washing bottles. Hydrogen evolved passes through the bottles and is collected in the 5 liter bottle over water. After all of the formaldehyde has been added, boiling is continued for about ten minutes to insure complete distillation of the alcohol. Nitrogen is then passed in through the side arm of the pressure equalizing tube as the apparatus cools to prevent back flow of water from the pneumatic trough and to sweep all of the hydrogen from the apparatus into the gas collecting bottle. About three liters of nitrogen is thus passed through.

The exit tube from the second gas washing bottle is then removed from the gas collecting bottle and the pneumatic trough, and carbon dioxide passed in for a sufficient length of time to convert the excess hydroxide to bicarbon-

ate. The reaction flask is again heated and distillation continued to insure complete removal of methyl alcohol which distills more readily from a bicarbonate than from a hydroxide solution.

The apparatus is then disconnected and the contents of the distilling flask filtered and washed carefully, the copper-copper oxide mixture being allowed to dry in a vacuum desiccator, and the filtrate containing the sodium formate and sodium bicarbonate, (Solution A) made up to 1000 c.c. in a volumetric flask. Care must be taken that all of the formate be washed from the precipitate, hot water being used for this purpose.

The contents of the two gas washing bottles are combined and their total volume made up to 500 c.c. in a volumetric flask (Solution B).

Hydrogen was evolved very slowly at first, but as the amount of copper increases, the rate of evolution increases markedly which indicates that metallic copper is the active catalyst. In support of this, copper reduced in previous reactions was also found to catalyze the reaction and copper reduced from cuprous iodide in liquid ammonia was an even more vigorous catalytic agent (22). This is, no doubt, due to the fact that the copper prepared in the liquid ammonia maintains its surface throughout the reaction while the copper reduced from cupric oxide by hydrogen evolved in the reaction coagulates and forms a spongy mass which causes a decrease in surface and consequent lowering of catalytic efficiency.

ANALYTICAL METHODS

(a) Gas Analysis: The gas collecting bottle (of known volume at room temperature) is filled with nitrogen and the percent of hydrogen determined by explosion of an aliquot portion with excess oxygen by the standard method of gas analysis.

(b) Determination of Sodium Formate: 100 c.c of Solution A (from reaction flask) are made up to 250 c.c. and 25 c.c of this are used for analysis by oxidation with 0.5 N permanganate by the standard method (23).

(c) Determination of Methyl Alcohol: 50 c.c of Solution B are made up to 250 c.c. and 25 c.c. used for analysis by oxidation with permanganate. Three Erlenmeyer flasks of 250 c.c. capacity are fitted with air condensers of 30 cm. length, clean rubber stoppers being used for the connections. Care must be taken that the stoppers fit tightly and that permanganate does not come in contact with them. 40 c.c. of 0.5 N permanganate and 25 c.c. of the methyl alcohol solution (which must not be stronger then 0.5% for this method of analysis), are placed in each flask, thoroughly mixed, 10 c.c of 6N sulphuric acid added, the condensers inserted and the flasks placed in a water bath for 3 hours at 85-90°. The condenser tubes are washed down occasionally with distilled water to insure complete reaction of the alcohol with the permanganate. When oxidation is complete, the excess permanganate is decolorized with 0.5 N oxalic acid and per-

manganate used to titrate to the end point. The amount of methyl alcohol is calculated from the equation:

$$5CH_3OH + 6KMnO_4 + 9H_2SO_4 \longrightarrow 3K_2SO_4 + 6MnSO_4 + 5CO_2 + 19H_2O$$

This method was checked with samples of methyl alcohol of known concentration and found to be quite satisfactory.

(d) Determination of Copper: (Modified method of Low [19]) A sample of the dried copper-copper oxide mixture weighing between 0.2000 g. and 0.2700 g. is dissolved in 5 c.c. of 1:1 nitric acid. Water is added to a volume of 50 c.c. and red fumes are expelled by boiling. Add 5 c.c. of strong bromine water and boil until bromine is completely expelled. Cool somewhat and add a slight excess of ammonium hydroxide, about 5 c.c. of the concentrated reagent. Boil off excess ammonia as shown by the change in color or partial precipitation of the copper as oxide or hydroxide, then add a slight excess of acetic acid (4-5 c.c. glacial), and boil to dissolve all of the copper. Cool to room temperature and add about 3 g. of potassium iodide or 6 c.c. of a solution containing 50 g. of potassium iodide per 100 c.c.

Titrate immediately with 0.1 N thiosulphate, until brown color becomes faint; then add sufficient starch paste to give a marked blue coloration and titrate carefully through a lilac color to colorless. Allow a few minutes interval between each drop when the lilac color

is reached and take care not to overstep the end-point. (0.1 N iodine can be used for back titration but this is not advisable.) The amount of total copper is thus determined by the iodine liberated by the reaction:

$$2Cu(C_2H_3O_2)_2 + 4KI \longrightarrow 2CuI + 4KC_2H_3O_2 + I_2$$

$$I_2 + 2Na_2S_2O_3 \longrightarrow 2NaI + Na_2S_4O_6$$

Knowing the weight of the Cu-Cuo mixture and having determined the total % of Cu, then the respective quantities of Cu and CuO can be readily calculated. In the procedure finally adopted, all of the CuO was reduced to metallic copper during the course of the reaction.

(e) Determination of formaldehyde: (Method of Blank and Finkenbeiner [20]) To a volume of 0.5 N sodium hydroxide are added 10-50 c.c. of neutral 3% hydrogen peroxide (depending on the concentration of the formaldehyde), and sufficient formaldehyde to leave 5-10 c.c. of the hydroxide in excess. (In the case of formalin, 50 c.c. of 0.5 N sodium hydroxide, 50 c.c. of 3% hydrogen peroxide, and not more than 1.6 c.c. of formalin.) The formaldehyde solution must be added carefully to the mixture of alkali and peroxide with continual shaking to avoid violent local action with consequent loss of material. A funnel is then placed in the neck of the flask and the mixture heated on a steam bath for 5 minutes with occasional shaking. It is then cooled to room temperature, the funnel and sides of the flask

washed down, and the excess hydroxide titrated with 0.5 N acid, using phenolphthalein as an indicator. The amount of base used up is a measure of the formaldehyde according to the equation:

$$H_2O_2 + 2HCHO + 2NaOH \longrightarrow 2HCOONa + 2H_2O + H_2$$

This method has been shown to be quite accurate in the determination of formaldehyde (Haywood and Smith).

PRELIMINARY QUANTITATIVE WORK

Some preliminary work was necessary before the standard procedure could be used.

Since the formaldehyde used in the reaction was a reagent grade of formalin and contained a considerable quantity of methyl alcohol, it was necessary to determine the amount present and correct for it in the later determinations of methyl alcohol. This was done in the following manner.

In each of 6 long neck, 500 c.c. round bottom flasks were placed 30 c.c. of approximately 1.0 N sodium hydroxide and 50 c.c. of neutral hydrogen peroxide. Exactly 1.5 c.c. of the formalin was then placed in each flask, the volume made up to about 200 c.c. and the flasks allowed to stand for 30 minutes at room temperature. They were then connected to reflux condensers, a small amount of silica added, and then heated to boiling until all of the hydrogen peroxide was decomposed. After cooling to room temperature, the contents of the flask were distilled until 100 c.c. had passed over. This was made up to a volume of 250 c.c. and 50 c.c. used for determination of methyl alcohol by the method given, using 35 c.c. of 0.5 N permanganate.

TABLE II.

DETERMINATION OF METHYL ALCOHOL IN FORMALIN.

FLASK	c.c. $KMnO_4$	$KMnO_4 \backsimeq H_2C_2O_4$	$KMnO_4$ used	g. CH_3OH present
1.	36.92	22.57	14.35	0.0423
2.	37.20	22.87	14.33	0.0422
3.	37.46	23.17	14.29	0.0422
4.	36.48	21.88	14.60	0.0431
5.	38.56	23.81	14.75	0.0436
6.	37.12	22.47	14.65	0.0433

1 c.c. $KMnO_4 \backsimeq$ 0.002955 g. CH_3OH

Average CH_3OH present = 0.04278 g.

CH_3OH in 1.5 c.c. formalin = 5×0.04278 = 0.214 g.

CH_3OH in 25 c.c. formalin (used in each run) = 3.566 g.

In using the Blank and Finkenbeiner method for the determination of formaldehyde in formalin, there is a possibility that the methyl alcohol present may be slowly oxidized by the hydrogen peroxide if too prolonged heating occurs. To this end, it was thought advisable to try the method both in the presence and absence of methyl alcohol and with varying times of heating. A solution of trioxymethylene of about 1% concentration was made up in dilute alkali and neutralized to phenolphthalein and 10 c.c. used in each case. The results are shown in the following table. The methyl alcohol used was a 0.5% solution neutral to phenolphthalein.

TABLE III.

DETERMINATION OF FORMALDEHYDE

IN PRESENCE OF METHYL ALCOHOL.

SAMPLE	c.c. 1% HCHO	c.c. NEUTRAL 3% H_2O_2	c.c. 0.5% CH_3OH	c.c. N/2 NaOH	c.c. N/2 HCl
1.	10	5	--	10.00	7.98
2.	10	5	--	10.00	6.54
3.	10	5	--	10.00	5.60
4.	10	5	--	10.00	5.55
5.	10	5	--	10.00	5.55
6.	10	10	--	10.00	5.53
7.	10	5	10	10.00	5.40
8.	10	5	10	10.00	5.38
9.	10	5	10	10.00	5.47
10.	10	5	10	10.00	5.57
11.	10	5	10	10.00	5.57
12.	10	5	10	10.00	5.57

CONDITIONS

1.---5 minutes at room temperature.
2.--10 minutes at room temperature.
3.--15 minutes at room temperature.
4, 5, and 6,---Heated 5 minutes on the water bath.
7, and 8.---5 minutes on the water bath.
9, and 10.---3 minutes on the water bath.
11.--20 minutes at room temperature.
12.--30 minutes at room temperature.

In the above table, no attempt was made to determine the exact amount of formaldehyde present since the amount of acid used in titrating the excess base is a sufficient index. Samples 4, 5, and 6 show the amount of acid necessary to neutralize excess base when no alcohol is present. Samples 1, 2, and 3 show that the reaction is approximately complete in 15 minutes at room temperature. Samples 7, and 8 show that the H_2O_2 must oxidize some of the alcohol to formaldehyde at the temperature of the water bath since a high aldehyde content is indicated. Samples 9, and 10 indicate that even three minutes on the water bath may give a high formaldehyde content. Samples 11, and 12 show that on standing for 20--30 minutes at room temperature, the reaction is essentially complete and the amount of base used is a true indication and measure of the formaldehyde present.

In order to determine whether or not the gas evolved contained gases other than hydrogen, gas analyses were made on two runs in which all of the air in the apparatus was first displaced with nitrogen. After the reaction, the apparatus was again swept out with nitrogen to insure complete removal of the reaction gases, the entire volume being subjected to analysis. No attempt was made to correlate the amounts of gas with the other reaction products, the purpose being to determine the presence or absence of gases other than hydrogen.

TABLE IV.

RESULTS OF GAS ANALYSIS.

RUN	CO_2 BEFORE COMBUSTION	CO	O_2	H_2	CO_2 AFTER COMBUSTION
1a.	NONE	NONE	NONE	47.3%	NONE
1b.	NONE	NONE	NONE	53.9%	NONE
2a.	NONE	NONE	NONE	46.6%	NONE
2b.	NONE	NONE	NONE	54.7%	NONE

As before stated, the percentages are merely relative and are not calculated to show the actual amount of hydrogen. The difference in the two runs lies in the difference in the sizes of the gas collecting bottles. The data of TABLE IV confirm Loew's statement that the hydrogen evolved in the reaction is mixed neither with carbon dioxide nor carbon monoxide.

EXPERIMENTAL

Although the earlier work of Lieben [5] had practically established the stoichiometric ratio 2HCHO : NaOH, it was deemed advisable to show that the ratio is realized in the absence of the catalyst and under the conditions of the present investigation. To this end, special runs were made in saponification flasks in which a volume of formalin containing approximately 0.1 mols of formaldehyde was accurately measured from a burette and heated with excess of standard sodium hydroxide at 100 for 30 minutes. At the end of this time, the flasks were cooled and the excess base determined. The mole ratio of formaldehyde to base was then calculated.

TABLE V.

DETERMINATION OF MOLECULAR RATIO OF FORMALDEHYDE TO HYDROXIDE IN ABSENCE OF CATALYST.

RUN	g. HCHO	MOLS HCHO	g. NaOH INITIALLY	g. NaOH REACTING	MOLS NaOH REACTING	MOLE RATIO HCHO : NaOH
1	3.1650	0.1055	4.1300	2.1076	0.0529	1.997
2	3.5264	0.1176	4.1300	2.3555	0.0589	1.996
3	3.2369	0.1079	4.1300	2.1448	0.0536	2.012
4	3. 2369	0.1079	4.1300	2.1610	0.0540	1.997
					AVERAGE	2.0005

The results given in Table V show the equation postulated by Lieben and others is correct and in conformity with the ratio 2HCHO : NaOH; i.e.,

$$2HCHO + NaOH \longrightarrow HCOONa + CH_3OH \qquad (c)$$

Data concerning the effect of a catalyst is given in later tables.

Although Loew[3] investigated the effect of various catalysts on the above reaction, he did not describe his apparatus nor did he furnish quantitative data. While the experimental method previously described was being developed, various catalysts other than copper reduced in the reaction flask were tried; ferric oxide, manganese dioxide, cuprous and cupric oxides, copper displaced from copper sulphate by zinc, and nickel mixed with kieselguhr, (catalyst employed in hydrogenation of oils). The only results worthy of mention were obtained with copper and its oxides and cupric oxide was finally chosen and used as described previously. Assuming the Cannizzaro reaction to take place in the two steps:

$$HCHO + NaOH \longrightarrow HCOONa + 2H \qquad (a)$$

$$HCHO + 2H \longrightarrow CH_3OH \qquad (b)$$

the extent of completion of the reaction in the various amounts of catalyst present in step (a), can be determined by measuring the amount of base used. This was done by Uber[22] in several quantitative experiments and the following data were given by him:

TABLE VI.

EFFECT OF DIFFERENT AMOUNTS OF COPPER OXIDE ON THE REACTION:

$$HCHO + NaOH \longrightarrow HCOONa + 2H$$

RUN	g. CuO PRESENT	g. NaOH USED	g. HCOONa ÷ NaOH USED	g. HCOONa ÷ HCHO THEORY	% COMPLETION OF REACTION
1a.	1.1606	8.5133	14.4723	22.3450	64.768
1b.	1.1606	8.6829	14.7718	22.3450	66.106
2a.	2.3212	10.2017	17.3521	22.3450	77.652
2b.	2.3212	10.0234	17.0394	22.3450	76.334
3a.	3.4818	11.7834	20.0318	22.3450	89.646
3b.	3.4818	11.5349	19.6095	22.3450	87.756
4a.	4.6424	12.9037	21.9525	22.3450	98.240
4b.	4.6424	12.9037	21.5650	22.3450	96.500
5a.	5.8030	13.0135	22.1222	22.3450	99.000
5b.	5.8030	13.4216	22.8133	22.3450	102.11

(9.858 g. of HCHO used)

From TABLE VI it is perfectly obvious that the percentage of completion of reaction (a) increases with the amount of copper present as catalyst and practically approaches 100% with large amounts of the catalyst.

On the basis of the preceding work, the method of procedure was developed and the following data obtained from a series of runs. Quite a bit of difficulty was met in avoiding bumping in the reaction flasks and in preventing the escape of hydrogen through rubber connections. The former difficulty was met fairly successfully by placing a rather large amount of broken porcelain in the flasks and

keeping the reaction mixture at a very slow boil. Loss of hydrogen was prevented by making glass seals of as many of the connections as possible and sealing elsewhere with de Khotinsky's cement. The concentration of the formaldehyde solution used was determined before the reaction in each case. The analytical results are embodied in the following table.

TABLE VII.

DATA SHOWING EXTENT OF OCCURENCE OF CONSECUTIVE REACTIONS

(a) AND (b)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
RUN	HCHO USED g.	HCOONa FOUND g.	HCHO⇨HCOONa (Eq. a) g.	CH_3OH FOUND g.	CH_3OH IN FORMALIN g.	CH_3OH PRODUCED g. 4--5	HCHO⇨CH_3OH PRODUCED (Eq. b) g.	% EXTENT REACTION (a) 3÷1	% EXTENT REACTION (b) 7÷1	% TOTAL HCHO ACCOUNTED FOR 8+9
Ia	10.075	19.0936	8.424	5.2802	3.566	1.7142	1.6071	83.61	15.95	99.56
Ib	10.075	18.3404	8.0913	5.6673	3.566	2.1013	1.9700	80.31	19.55	99.86
IIa	10.113	17.5119	7.726	6.1857	3.566	2.6197	2.4560	76.40	24.28	100.68
IIb	10.113	18.5852	8.1995	5.6467	3.566	2.0807	1.9507	81.07	19.29	100.36
IIIa	10.153	18.4534	8.1412	5.7214	3.566	2.1554	2.0207	80.18	19.90	100.08
IIIb	10.153	17.7190	7.8172	6.0134	3.566	2.4474	2.2944	76.99	22.60	99.59

$$HCHO + NaOH \longrightarrow HCOONa + H_2 \qquad (a)$$

$$HCHO + H_2 \longrightarrow CH_3OH \qquad (b)$$

$$\Sigma(a)+(b) \qquad 2\,HCHO + NaOH \longrightarrow HCOONa + CH_3OH \qquad (c)$$

The first seven columns of TABLE VII are self explanatory, being data obtained experimentally or calculated from experimental data. Column 8 shows the percentage of formaldehyde reacting according to equation (a) as indicated by the sodium formate formed. Column 9 shows the extent of reaction (b), determined from the methyl alcohol produced. The two reactions should account for all of the formaldehyde, which they do as is shown by column 10.

It will be noted that the figures in columns 8 and 9 are not in particularly close agreement within the columns, although corresponding values in the two columns give a practically quantitative accounting for all of the formaldehyde. The variation within the columns in probably due to differences in the surface conditions of the copper since liberation of hydrogen is due to this catalyst, the more efficient its action, the less the amount of methyl alcohol formed. It is obvious that a very high efficiency on the part of the catalyst would result in the formation of practically no methyl alcohol.

There remains to be correlated with the amount of hydrogen produced by reaction (a) and measured in terms of the equivalent amount of HCOONa, the hydrogen liberated as gas (x), that active in the reduction of CuO to Cu (y),

and that reacting with HCHO to produce CH_3OH (z). This is given by the data of the following table in which 100 c.c. of approximately 1 M $CuSO_4$ was converted to the equivalent amount of oxide to be reduced by the hydrogen fraction (y). In each case, all of the copper oxide was reduced to the metal.

TABLE VIII.

DISPOSITION OF TOTAL HYDROGEN FORMED ACCORDING TO EQUATION (a)

	1.	2.	3.	4.	5.	6.
RUN	H_2, GRAMS LIBERATED (x)	$H_2 \backsim$ Cu GRAMS (y)	$H_2 \backsim CH_3OH$ GRAMS (z)	TOTAL H_2 GRAMS (x+y+z)	$H_2 \backsim$ HCOONa GRAMS (EQUATION a)	% THEORY H_2 (x+y+z)
Ia	0.2439	0.1864	0.1071	0.5370	0.5577	96.29
Ib	0.2090	0.1864	0.1311	0.5265	0.5357	98.28
IIa	0.1502	0.1864	0.1618	0.4984	0.5115	97.45
IIb	0.2083	0.1864	0.1300	0.5247	0.5429	96.65
IIIa	0.2032	0.1864	0.1347	0.5243	0.5390	97.27
IIIb	0.1623	0.1864	0.1529	0.5016	0.5176	96.91

$$HCHO + NaOH \longrightarrow HCOONa + H_2 \qquad (x)$$

$$CuO + H_2 \longrightarrow Cu + H_2O \qquad (y)$$

$$HCHO + H_2 \longrightarrow CH_3OH \qquad (z)$$

Columns 1. 2, and 3 of TABLE VIII give respectively the hydrogen evolved as gas (x), hydrogen equivalent to the copper oxide reduced (y), and hydrogen equivalent to the methyl alcohol produced (z). These values are summed up in column 4 and compared with the amount of hydrogen theoretically produced by the reaction:

$$HCHO + NaOH \rightarrow HCOONa + H_2 \qquad (a)$$

as determined from the formate measurements recorded in TABLE VII. 96--98% of the hydrogen is accounted for, the loss probably being due to leakage before the gas was transferred to the collecting bottle.

SUMMARY

The data of TABLES VII and VIII show conclusively that the Cannizzaro reaction, in the case of formaldehyde, involves two distinct reactions:

$$HCHO + NaOH \rightarrow HCOONa + H_2 \quad (a)$$

$$HCHO + H_2 \rightarrow CH_3OH \quad (b)$$

$$2HCHO + NaOH \rightarrow HCOONa + CH_3OH \quad (c)$$

In the presence of copper, as a catalyst, 76--81% of the initial quantity of formaldehyde reacts in conformity with equation (a), while the remainder reacts in conformity with equation (b). In the uncatalyzed reaction, 50% of the initial formaldehyde reacts by (a) and 50% by (b), so that Σ(a)+(b), written as equation (c), expresses the stoichiometric relationships in the uncatalyzed reaction.

The results in TABLE VIII also serve to check the occurence of the two reaction from the standpoint of the hydrogen involved.

PART B. THE KLINGER REACTION

INTRODUCTION

The mechanism of the Cannizzaro reaction of formaldehyde having been established, it should be of interest to study reactions in which formaldehyde plays a part or in which formaldehyde, assumed to be an intermediate product, may function as a reducing agent in the presence of sodium hydroxide.

An admitable example of such a reaction is the reduction of nitrobenzene to azoxybenzene by sodium methylate. In this case the methylate is oxidized to sodium formate and the assumption may quite validly be made that formaldehyde, possessing as it does a state of oxidation midway between the methylate and the formate, exists as an intermediate oxidation product of the methylate. Other work carried out in this laboratory points to the correctness of this assumption, so a more detailed study of the reaction was made with the object of proving the presence of formaldehyde as an intermediate oxidation product in the Klinger reaction. The results of this study are embodied in the following discussion.

HISTORICAL

The action of various alkaline reducing agents on nitrobenzene has been the subject of much study since 1845 when Zinin [29] prepared azoxybenzene by the use of dry potassium hydroxide on an ethyl alcohol solution of nitrobenzene. The literature relative to this reaction has been well summarized by Cameron [25] and by Bowman [27], particularly with regard to the formation of azoxybenzene and will be but briefly touched upon here.

Zinin, as before stated, first mentioned the formation of azoxybenzene by the action of potash on alcoholic nitrobenzene although his work was purely of a qualitative nature.

Alexeyeff [30] added sodium amalgam as the reducing agent to alcoholic nitrobenzene and then acidified, obtaining an impure product which contained azoxybenzene. He also noted that zinc dust in the presence of alakli behaved similarly.

Rosenack [31] reported a method of obtaining the pure compound by modifying Zinin's procedure and he also stated that a trace of water is necessary for the commencement of the reaction, dry nitrobenzene being unattacked by either sodium or sodium amalgam.

Schmidt and Schultz [32] also used Zinin's method and mentioned the formation of aniline, oxalic acid, and a dark resinous substance similar to Michler's biazoxybenzoic acid, [33] as by-products of the reaction.

Klinger [24] first attempted to standardize the reaction so as to obtain the maximum yield of azoxybenzene. He found that ten parts of sodium dissolved in 250 parts of methyl alcohol and heated with 30 parts of nitrobenzene on a water bath for 5--6 hours gave an 85--89% reduction of the nitro- to the azoxy- compound. He also identified sodium formate as the oxidation product of the sodium methylate and postulated the equation:

$$4C_6H_5NO_2 + 3NaOCH_3 \rightarrow 2(C_6H_5N)_2O + 3HCOONa + 3H_2O$$

although he did not include experimental data to confirm it quantitatively.

Moltschanowsky [34] obtained the same results as Klinger but could not obtain as high yields.

Brühl [35] reported a quantitative yield of azoxybenzene when the sodium methylate used is free of alcohol of crystallization. This alcohol-free sodium methylate he prepared by adding just sufficient methyl alcohol to finely divided sodium in xylene. This product, when boiled with nitrobenzene for seven hours gave much better results than when methyl alcohol was used as a solvent.

Lachman [36] used Zinin's method employing sodium hydroxide and methyl alcohol in place of potassium hydroxide and ethyl alcohol. The reaction went smoothly and he reported 80--95% yields of product after 3 hours boiling. Acetone decreased the yield markedly but water had relatively little effect. These results are not in agreement with those of Cameron (25) who found that progressively increasing amounts

of water had a direct retarding effect on the reaction.

When Evans and Fetsch [37] heated a mixture of nitrobenzene, ethyl alcohol and magnesium amalgam, they obtained azobenzene as the chief product. Hydrogen was evolved, probably due to the action of the amalgam on water present. If the concentration of the amalgam is decreased and the volume of alcohol increased, Evans and Fry [38] found azoxybenzene to be the chief product. When methyl alcohol was used as solvent, azobenzene was obtained. The presence of magnesium methylate as the active reducing agent in the latter case was proved, its solubility in the corresponding alcohol rendering it a more active reducing agent than is the ethylate which is insoluble in ethyl alcohol. Hence azobenzene is obtained with methyl alcohol as solvent and azoxybenzene with ethyl alcohol as solvent.

Meisenheimer [39] distilled off the alcohol from a solution of nitrobenzene and alcoholic potassium hydroxide. Azoxybenzene was a product at intermediate temperatures, but, at 140--150°, a violent reaction takes place accompanied by the formation of a hard black mass, possibly similar to the black substance obtained by Lachman [36] on heating azoxybenzene with sulphuric acid of the approximate composition $H_2SO_4 \cdot H_2O$.

Allen [40] used ferrous sulphate in alkaline nitrobenzene as reducing agent. He obtained a variety of reduction products, among them azoxybenzene under certain conditions. Stirring and low current density favor the production of azoxybenzene electrolytically.

Snowden [41] gave a summary of the various methods for reducing nitrobenzene to azoxybenzene and proposed determining the percent of azo- and azoxy- compound in the product by means of melting point-compositon curve although Allen [40] believed the method to be unsatisfactory since small amounts of substances, other than the two being determined, greatly affect the results.

Rotarski [42] stated that the action of alcoholates on aromatic nitro-compounds was dependent on temperature. At low temperature:

$$2ArNO_2 + 3NaOMe \longrightarrow \begin{matrix} ArN\diagdown \\ ArN\!\rightarrow\! O \end{matrix} + 3NaOH + 3HCHO$$

At high temperature:

$$2ArNO_2 + 3NaOMe \longrightarrow \begin{matrix} ArN\diagdown \\ ArN\!-\!O \end{matrix} + 3HCOONa + 3H_2$$

At lower temperatures the action is simply that of hydrogen so theoretically there should be produced all of the possible reduction products from either one or two molecules of the nitro-compound. At higher temperatures, the reaction of the alcoholate is simply a taking away of oxygen so that only compounds poorer in oxygen can be obtained (azo-, azoxy-) and not compounds in which oxygen is replaced by hydrogen (hydrazo-, amino-). The temperature which is most favorable to the formation of a given compound depends on the nature of the alcohol and of the nitro-compound and also on the amount of alkali present. The author also summarizes the results of his work: Alkali and alcohol have no advantages over the metallic alcoholate for the reduction of aromatic nitro-compounds. Aldehydes do not reduce nitro-com-

pounds even in the presence of alkali. Barium oxide or hydroxide with an alcohol may often be used to advantage especially if the higher temperature necessary for the formation of azoxy-compounds results in decomposition when sodium hydroxide is present. Benzene or toluene may serve as a diluent as well as excess of the alcohol. The equations given by Rotarski for the reaction at different temperatures suggest the Cannizzaro reaction with formaldehyde to which reference will be made in a later section.

Heumann (43) used zinc dust and alkali to reduce nitrobenzene to azoxybenzene.

Dechen (44) reported that the presence of salts such as calcium and sodium chlorides increased the efficiency of the reducing action of zinc dust in acid solution.

Loessner (45) used sodium arsenite as the reducing agent, obtaining azoxybenzene.

Wohl and Aue (46) report the formation of azoxybenzene and o-nitro-phenol when nitrobenzene reacts with dry potassium hydroxide.

An investigation of these various methods shows that of Klinger to be the most satisfactory as a method of preparation and it is generally so given in text-books and laboratory manuals. Its chief advantages are ease of manipulation, smoothness of the reaction, and the fact that the azoxybenzene produced is not contaminated with other reduction products.

THEORETICAL

Fry and Cameron [26] established experimentally the stoichiometric ratios required by the Klinger equation:

$$4C_6H_5NO_2 + 3CH_3ONa \longrightarrow 2(C_6H_5N)_2O + 3HCOONa + 3H_2O$$

In addition, they also proposed a mechanism of the reaction, represented as follows:

$$3CH_3ONa + 3HOH \longrightarrow 3CH_3OH + 3HONa \qquad (x)$$

$$3CH_3OH + 3HONa \longrightarrow 3HCOONa + 12H \qquad (y)$$

$$4C_6H_5NO_2 + 12H \longrightarrow 2(C_6H_5N)_2O + 6H_2O \qquad (z)$$

$$\Sigma \quad 4C_6H_5NO_2 + 3CH_3ONa \longrightarrow 2(C_6H_5N)_2O + 3HCOONa + 3H_2O$$

Equation (x) assumes that sufficient water is initially present to start the reaction which will then increase in speed as more water is formed according to equation (z). This is true when the sodium alcoholate, the active reducing agent is prepared by the action of sodium hydroxide on methyl alcohol:

$$NaOH + CH_3OH \rightleftharpoons CH_3ONa + H_2O$$

Since, however, the reaction proceeds just as well or better when the sodium formate is produced by the action of metallic sodium on methyl alcohol;

$$Na + CH_3OH \longrightarrow CH_3ONa + 1/2H_2$$

it must be assumed that only an extremely small amount of water is necessary for starting the reaction.

Equation (y) involves the theory of the acidic dissociation of sodium hydroxide, a type reaction advanced by Fry and co-workers [41]. This theory is based largely

on the oxidizing action manifested by the fused caustic alkalies toward organic compounds. The type reactions expressing this oxidizing action are given by the equations:

$$R(H)_n + nMOH \longrightarrow R(OM)_n + nH_2$$

$$R(CH_3)_n + nMOH \longrightarrow R(OM)_n + nCH_4$$

where MOH represents a strong alkali and may be illustrated by the oxidation of methyl alcohol by fused sodium hydroxide [50]. The mechanism in the case of methyl alcohol was shown to conform to the following scheme.

$$CH_3OH + HONa \longrightarrow CH_3ONa + H_2O \qquad (a)$$

$$CH_3ONa + HONa \longrightarrow CH_2(ONa)_2 + H_2 \qquad (b)$$

$$CH_2(ONa)_2 + HONa \longrightarrow CH(ONa)_3 + H_2 \qquad (c)$$

$$CH(ONa)_3 + HONa \longrightarrow C(ONa)_4 + H_2 \qquad (d)$$

$$C(ONa)_4 + H_2O \longrightarrow Na_2CO_3 + 2NaOH \qquad (e)$$

$$\Sigma \qquad CH_3OH + 2HONa \longrightarrow Na_2CO_3 + 3H_2 \qquad (A)$$

This same mechanism may be employed to explain the oxidation of methyl alcohol to formate in strong alkaline solution with one notable difference. The fused alkali effects the complete oxidation of the alcohol, i.e., the carbonate is the end product, while the oxidation stops at step (c) of the above series of reactions when carried out in solution. Hydrolysis of the orthoformate then occurs:

$$CH(ONa)_3 + H_2O \longrightarrow HCOONa + 2NaOH \qquad (c')$$

and the summation of equations (a), (b), (c), (c'), gives:

$$CH_3OH + HONa \longrightarrow HCOONa + 2H_2$$

which is equation (y) of the mechanism postulated by Fry and Cameron and this mechanism is substantiated by experimental data.

Since the extent of completion of the Klinger reaction is conditioned chiefly by the extent to which sodium hydroxide undergoes acidic dissociation, any factors which tend to increase this dissociation should favor a larger yield of azoxybenzene while the reverse effect should be expected from the influence of those factors promoting basic dissociation of the hydroxide. Pyridine and water are examples respectively and Fry and Cameron found that pyridine, by promoting acidic dissociation of sodium hydroxide due to its own basic character, increased the extent of reduction of nitrobenzene to azoxybenzene and even carried it farther than the azoxy- stage with the formation of azobenzene. Water, on the other hand, promotes basic dissociation of sodium hydroxide and the yield of azoxybenzene is progressively cut down as water is added in increasing amounts, dropping from 88 to 19% when 3 mols of water are present.

From these results, the general conclusions may be drawn that Klinger's equation is a correct expression for the action of sodium methylate on nitrobenzene when no basic compounds are present, the extent of the reaction being measureable in terms of either the azoxybenzene or formate produced. When basic compounds are present, azobenzene may also be formed;

$$2(C_6H_5N)_2O + CH_3ONa \longrightarrow 2(C_6H_5N)_2 + HCOONa + H_2O$$

and the amount of formate produced is a measure of the simultaneous occurence of both reactions.

Fry and Bowman (28) continued the study of the effect of organic bases on the reduction of nitrobenzene and azoxybenzene, using aniline, mono- and di-methyl anilines, quinoline and iso-amyl amine. The order of these bases was chosen in order of increasing basicity and the extent of reduction of both nitrobenzene and azoxybenzene increased directly with the basicity of the nitrogen compound present. Iso-amyl amine, however, showed a peculiar behavior.

It was noted the 5 hours of refluxing of the reaction mixture in the presence of 1/8 mole of iso-amyl amine did not produce as much formate as was expected. Analysis of the formate indicated only 63.45% reduction whereas the results obtained with the other bases indicated that the result should have been in the neighborhood of 90-100%. With 1/4, 1/2, and 3/4 mols of the amine, the percentages of reduction measured in terms of the yield of sodium formate were respectively 40.70, 38.22, and 51.75. When the percent of reduction was measured in terms of the azoxybenzene yields, approximately normal yields (as based on the results when the other bases were present) were obtained. The iso-amyl amine odor persisted in the reaction mixture even after 3 hours of steam distillation, which is peculiar since the boiling point of the amine is 95°. The color of the solution was cherry-red, which disappeared when the benzene extract was treated with sulphuric acid and the odor of formaldehyde became quite apparent. When the acid solution was made alkaline, the

odor of the amine reappeared and an oil formed. This suggested the presence of an iso-amylamine-formaldehyde compound of the type discovered by Henry:

$$HCHO + H_2NR \longrightarrow H_2C\begin{matrix}\diagup NHR \\ \diagdown OH\end{matrix}$$

In the case of iso-amylamine, the reactions are as follows:

$$HCHO + \begin{matrix}CH_3\diagdown \\ \\ CH_3\diagup\end{matrix}CH\text{-}CH_2\text{-}CH_2\text{-}NH_2 \longrightarrow H_2C\begin{matrix}\diagup NHC_5H_{11} \\ \diagdown OH\end{matrix}$$

$$H_2C\begin{matrix}\diagup NHC_6H_{11} \\ \diagdown OH\end{matrix} \xrightarrow[\text{Alkali}]{\text{Strong}} CH_2{=}NC_5H_{11} + H_2O$$

$$CH_2{=}NC_5H_{11} + H_2O \xrightarrow{\text{Acid}} HCHO + C_5H_{11}NH_2$$

The formation of the formaldehyde in the mixture is easily understood since its intermediate formation was postulated in the proposed mechanism for the action of sodium hydroxide on methyl alcohol. Since water is present in the reaction mixture, it is logical to assume that the compound $CH_2(ONa)_2$ might hydrolyze as well as $CH(ONa)_3$, particularly if there were present a compound such as iso-amyl amine to combine with the formaldehyde as fast as it is formed. The reaction mechanism would then be represented as follows:

$$CH_3OH + HONa \longrightarrow CH_3ONa + H_2O \qquad (a)$$

$$CH_3ONa + HONa \longrightarrow CH_2(ONa)_2 + H_2 \qquad (b)$$

$$CH_2(ONa)_2 + H_2O \longrightarrow HCHO + 2NaOH \qquad (b')$$

When no iso-amyl amine is present, the formaldehyd would react with sodium hydroxide as previously indicated:

$$HCHO + HONa \longrightarrow HCOONa + H_2 \qquad (c'')$$

or $$CH_2(ONa)_2 + HONa \longrightarrow CH(ONa)_3 + H_2 \qquad (c)$$

This is additional evidence that the proposed mechanism for the oxidation of methyl alcohol due to the acidic dissociation of sodium hydroxide and involving the successive formation of formaldehyde, formic acid and carbonicacid is correct. But, it will also be noticed that reaction (c) or (c'') is the first step of the Cannizzaro reaction of formaldehyde as determined in Part A of this work. Another method is thus afforded by which it should be possible to show whether or not formaldehyde has a temporary existence in the Klinger reaction mixture as an intermediate oxidation product of methyl alcohol.

This might be assumed since Suter and Dains [49] found that benzaldehyde is formed when sodium dissolved in benzyl alcohol is used as the reducing agent for nitrobenzene. However, formaldehyde does not normally make its appearance in the Klinger reaction and is apparent only when conditions are such that carbon in the formaldehyde state of oxidation ($CH_2(ONa)_2$) can react more rapidly with a second substance present than it can react with acidic sodium hydroxide to produce carbon in the formic acid state of oxidation ($CH(ONa)_3$). This as just explained, was the case in Bowman's work when iso-amyl amine, which reacts quite rapidly with formaldehyde, was present.

The purpose of this work is to show that formaldehyde (by which name will be denoted either of the compounds HCHO and $CH_2(ONa)_2$) is actually present as an intermediate oxidation product of sodium methylate in the

Klinger reaction and, if copper be present, will react with sodium hydroxide to give sodium formate and hydrogen, a part of which should be liberated as a gas as was the case in the study of the Cannizzaro reaction. The reactivity of hydrogen in the presence of copper should be manifest in the yield of azoxybenzene, an increased yield indicating that it possesses more strongly reducing properties than does the hydrogen from the uncatalyzed reaction.

$$CH_2(ONa)_2 + HONa \longrightarrow CH(ONa)_3 + H_2 \qquad (c)$$

or $$HCHO + HONa \longrightarrow HCOONa + H_2 \qquad (c'')$$

Since reaction (c) or (c'') is identical with the first step of the Cannizzaro reaction of formaldehyde, an increased yield of azoxybenzene should indicate that copper acts catalytically in the reduction of nitrobenzene by hydrogen, thereby increasing the efficiency of the process.

To study this effect, five series of runs were conducted as follows:

(A). Sodium dissolved in methyl alcohol was used to reduce nitrobenzene in order to determine the "normal" percent of reduction under these conditions.

(B). A methyl alcohol solution of sodium hydroxide of the same molar concentration as the sodium methylate in (a), was used as the reducing agent in order to determine the "normal" percent of reduction by this method.

(C). Runs as in (A) were conducted in the presence of copper oxide in order to note whether or not a reduction to metallic copper takes place and, if so, to note

whether or not hydrogen is evolved as would be expected from the Cannizzaro reaction in the presence of copper.

(D). Runs as in (B) were conducted in the presence of copper oxide in order to note the same effects as in (C).

(E). Since copper oxide did not give very satisfactory results, metallic copper was used as catalyst for runs conducted as in (A) and (B) and its effect on the course of the reaction noted.

The results of these runs are then interpreted in terms of the previously postulated reaction mechanism.

EXPERIMENTAL METHODS

The runs were conducted according to the standard method developed by Cameron [25] and by Bowman [27] in this laboratory.

Where sodium in methyl alcohol was used as the reducing agent, it was freshly prepared for each run by dissolving Kahlbaum's "analytical grade" sodium in Merck's "C. P. grade, acetone free" methyl alcohol which is free from oxidizable material not volatile with steam. The sticks of sodium were scraped free of the surface layer of oxide under ligroin and 17.3 g. weighed under ligroin on an ordinary laboratory balance within 0.1 g. This is 5 times the amount of sodium required by 0.2 mols of nitrobenzene according to the Klinger equation. It was then cut into small strips and dropped through a reflux condenser into a 500 c.c. round-bottom flask containing 100 c.c. of the methyl alcohol. The reaction is sufficiently vigorous at first to cause the solution to boil but, as the methylate is formed, the vigor diminishes and heat must be applied. The sodium was added in thinner slices at the end and 50 c.c. additional alcohol added to effect more rapid solution. When cool, the sodium methylate solution was poured into a 250 c.c. volumetric flask containing 20.46 c.c. (24.6 g. or 0.2 mole) of Merck's "pure" nitrobenzene, redistilled after standing over calcium chloride. The flask was then filled up to the 240 c.c. mark (previously determined) with methyl

alcohol, some of which had been used to rinse out the flask which contained the sodium methylate. The contents of the volumetric flask, after shaking to effect complete solution of the nitrobenzene, were then transferred to a 500 c.c. round-bottom flask containing pieces of broken glass to prevent bumping. Ten c.c. of methyl alcohol were then used to rinse out the volumetric flask, the rinsings being added to the reaction flask to bring the total volume up to 250 c.c.

All runs were made in duplicate, the 500 c.c. flasks being as nearly identical as to length of neck, diameter, etc., as possible. The flasks were connected to reflux condensers and heated in a water bath large enough to contain both of them. In this way, differences in rate of reaction due to temperature differences were avoided. The flasks were immersed to the same depth in the water bath and the water was kept boiling vigorously. According to Bowman, special attention must be given to the condensers and his suggestions were followed. The condensers used were of the straight tube variety, of the same size and shape and with jackets about one meter long. Each was connected to a separate source of water so that the cooling effect might be uniform. These precautions are necessary to eliminate loss of the solvent due to bumping. The loss of solvent with smaller condensers is sufficient to change considerably the extent of reduction.

After 5 hours of boiling, the flasks are disconnected and the reaction stopped by the addition of 100 c.c.

of cold distilled water and cooling to room temperature. Azoxybenzene and the excess nitrobenzene then separated out as a reddish oil.

The reaction mixture is then steam distilled until all of the methyl alcohol and nitrobenzene have passed over. This requires about 75--100 minutes and the distillation must not be carried on too long or appreciable amounts of azoxybenzene will pass over.

At the end of the distillation, the reaction mixture was cooled to room temperature and the azoxybenzene separated from the strongly alkaline aqueous solution by extraction with benzene. Five extractions were sufficient, using 25, 20, 15, 15, and 15 c.c. of benzene. Since the formate is to be determined, care must be taken not to lose any of the aqueous solution and, at the end of the extraction, the combined benzene extracts are washed with water to remove any entrapped formate, the washings being combined with the aqueous solution.

The benzene extracts were dried over calcium chloride, the benzene evaporated, and the azoxybenzene weighed. No azobenzene was found in any of the runs.

The aqueous solution was then boiled carefully to drive off benzene, care being taken to avoid loss through bumping. It was then cooled to room temperature and made up to a volume of 1000 c.c. for formate determinations. This solution was always yellow, as mentioned by Bowman, but no attempt was made to determine the cause of the color.

Formate was determined in 25 c.c. of the aqueous solution by titration with approximately 0.25 N permanganate. Since determinations in the presence of hydroxides are difficult, the sample is made acid with sulphuric acid and sufficient sodium carbonate then added to make it slightly alkaline. The solution is heated to boiling and a slight excess of permanganate (as indicated by the pink color on settling of the manganeses dioxide) run in slowly. The solution is again heated almost to boiling and sufficient sulphuric acid slowly added to render the solution distinctly acid. A slight excess of standard oxalic acid over the amount necessary to react with all of the manganese dioxide is then added and the titration carried to the end-point with permanganate. The permanganate equivalent of the oxalic acid is subtracted from the total volume of permanganate and the amount of formate calculated from the permanganate used. No particular difficulty was experienced in getting duplicate results by this method.

When sodium hydroxide in methyl alcohol was used as reducing agent, the procedure was entirely similar. A saturated solution of sodium hydroxide in methyl alcohol was made up and siphoned from the insoluble sodium carbonate. Its concentration was then determined and a volume sufficient to contain 30 g. of sodium hydroxide (equivalent to 17.3 g. of sodium) added to the nitrobenzene (20.46 c.c.) in the 250 c.c. volumetric flask. The volume was then made up to 240 c.c. and the procedure from this point was identical.

Hydrogen was not given off in either of the above runs so no provision was made for colecting it.

When the above runs were repeated in the presence of copper-oxide and of metallic copper, the following changes were made in the procedure.

The copper oxide was prepared by precipitating the copper from the sulphate with a slight excess of sodium hydroxide. The blue precipitate was warmed on a water bath until it had turned black and settled out readily. It was then washed several times by decantation and then boiled for about an hour. After several more washings, it was filtered off on a Büchner funnel and dried in an air bath at 120°. The dried mass was then ground to a fine powder and once more boiled with water to dissolve any sulphates, etc., that might have been mechanically enclosed by the semi-gelatinous oxide. It was then again washed several times by decantation, filtered, washed, and dried as before. On analysis by the iodine-thiosulphate method, it showed a purity of 99.83%. It was kept in a vacuum desiccator over concentrated sulphuric acid.

The metallic copper was precipitated from copper sulphate by zinc dust, using a slight excess of the latter. The excess zinc was then dissolved by concentrated hydrochloric acid and the copper washed by decantation and filtering until all chlorides and sulphates were removed. After filtering, it was partially dried in a current of nitrogen free from oxygen in an oven at 120° and

completely dried in a vacuum desiccator over sulphuric acid. On analysis by the iodine-thiosulphate method, it showed 99.7% of copper.

The standard reaction mixtures as prepared by the previously given methods were used but to each reaction flask was added 4.000 g. of copper oxide or 4.000 g. of copper as catalyst. The procedure was then the same until after the steam distillation when the catalyst settled out at the bottom of the flask with the oily azoxybenzene. After cooling, the upper aqueous layer was decanted into a separatory funnel and the oily layer washed twice by decantation. The final small amount of formate was recovered by pouring the oily layer into a previously moistened filter paper and washing with hot water. The paper retains the azoxybenzene and copper and all of the formate solution is collected in the separatory funnel. Three extractions with 15 c.c. portions of benzene are sufficient to remove the small amount of azoxybenzene carried through by the aqueous solution after which the formate is determined as before.

The combined benzene extracts are placed in a 250 c.c. Erlenmeyer flask and the funnel holding the filter paper containing the azoxybenzene and copper is placed in the neck of the flask by means of a one-hole stopper. This is then used as an extraction apparatus by heating the flask on an electric hot plate and condensing the benzene vapors above the filter on the bottom of a

500 c.c. round-bottom flask resting lightly on the rim of the funnel and kept cool with running water. About half an hour is usually sufficient to remove all of the azoxybenzene as can be determined by the color of the condensate dripping from the stem of the funnel. After complete extraction, the azoxybenzene is recovered by evaporation of the benzene and weighed. The copper or copper oxide remaining on the filter may then be dried in a vacuum desiccator and analyzed.

When metallic copper is present in the reaction mixture, hydrogen gas is evolved in small but measureable quantities. In such runs, a gas delivery tube was led from the top of thereflux condenser to a gas collecting bottle in a pneumatic trough. The stopper by which the reaction flask was attached to the bottom of the reflux condenser also contained a small glass tube, closed with a stopcock, by which nitrogen could be passed into the apparatus at the end of a run to sweep all of the hydrogen into the gas collecting bottle. By this means the hydrogen was collected, together with nitrogen, in bottles of known capacity, (about 2 liters) and the amount could be determined by explosion with oxygen by the standard methods.

The results of these various runs are then summarized and discussed.

EXPERIMENTAL RESULTS

A. THE NORMAL PERCENT OF REDUCTION OF NITROBENZENE BY SODIUM METHYLATE

After several preliminary runs to standardize the methods of manipulation, a series of three runs, each in duplicate, was made to determine the normal percent of reduction of nitrobenzene by sodium dissolved in methyl alcohol. The percent was based upon the amount of sodium formate produced according to the Klinger reaction:

$$4C_6H_5NO_2 + 3CH_3ONa \longrightarrow 2(C_6H_5N)_2O + 3HCOONa + 3H_2O$$

The yields of azoxybenzene were not determined since Cameron [25] has shown that formate and azoxybenzene serve equally well to measure the extent of reaction, under the usual conditions the formate being somewhat more sensitive as a measure.

The results of these runs are embodied in the following table:

TABLE IX.

NORMAL PERCENT REDUCTION OF NITROBENZENE BY SODIUM METHYLATE

RUN	HCOONa TAKEN c.c.	HCOONa FOUND g.	TOTAL HCOONa g.	HCOONa ON COMPLETE REDUCTION (THEORY) g.	% THEORY REDUCTION
Ia	25	0.21860	8.744	10.200	85.72
Ib	25	0.21700	8.680	10.200	85.10
IIa	25	0.21842	8.737	10.200	85.65
IIb	25	0.22042	8.817	10.200	86.44
IIIa	25	0.21908	8.763	10.200	85.91
IIIb	25	0.21985	8.794	10.200	86.22
				AVERAGE	85.84

Fry and Cameron [26] report an average reduction under these same conditions of 86.43% and Fry and Bowman [28] give 88.45%. A number of slight variations in the experimental technique might give rise to this slight difference in results. The most probable cause, however, is the difference in water content of the methyl alcohol used in the runs. The work of Fry and Cameron [26] has shown that water produces the most marked effect when the first small amount is added, 0.5 mole decreasing the percent of reduction by almost one-third. This slight divergence from the results of the other investigators is of no consequence in this work, however, since the results are reproducible within one percent by using the same apparatus and reagents.

B. THE NORMAL PERCENT REDUCTION OF NITROBENZENE BY SODIUM HYDROXIDE IN METHYL ALCOHOL

The next series of runs was conducted in order to compare the reducing action of sodium hydroxide in methyl alcohol with that of an equivalent amount of sodium in methyl alcohol and to establish the "normal" percent of reduction by this method. The results are summarized in the following table:

TABLE X.

NORMAL PERCENT REDUCTION OF NITROBENZENE BY SODIUM HYDROXIDE IN METHYL ALCOHOL

RUN	HCOONa TAKEN c.c.	HCOONa FOUND g.	TOTAL HCOONa g.	HCOONa ON COMPLETE REDUCTION (THEORY) g.	% THEORY REDUCTION
IVa	25	0.15832	6.333	10.200	62.09
IVb	25	0.15648	6.259	10.200	61.36
Va	25	0.15655	6.262	10.200	61.40
Vb	25	0.15395	6.158	10.200	60.37
VIa	25	0.15535	6.214	10.200	60.92
VIb	25	0.15620	6.248	10.200	61.26
				AVERAGE	61.23

The percent reduction of nitrobenzene is seen to drop about 25% when the sodium hydroxide in methyl alcohol, equivalent to the sodium methylate, is used as the reducing agent.

It may be assumed that the reaction of sodium hydroxide with methyl alcohol results in an equilibrium:

$$NaOH + CH_3OH \rightleftharpoons CH_3ONa + HOH$$

The reaction from left to right would result in the formation of 0.75 mols of water from 30 g. of sodium hydroxide if the reaction went to completion. This being true, the extent of reduction of nitrobenzene should be the same as when 0.75 mols of water is added to the standard sodium methylate reaction mixture. The average percent reduction, however, is almost identical with that obtained by Cameron [25] when 0.5 mols of water was added (60.78%). Hence, it is quantitatively shown that the reaction of sodium hydroxide with methyl alcohol is an equilibrium reaction, proceding two-thirds to the formation of sodium methylate and water and one-third in the reverse direction.

The results obtained in this series of runs are also reproducible to the desired degree of accuracy.

C. THE REDUCTION OF NITROBENZENE BY SODIUM METHYLATE IN THE PRESENCE OF COPPER OXIDE

This series of runs was conducted in order to determine the effect of copper oxide on the course of the reaction. A preliminary run showed that sodium methylate in the absence of nitrobenzene exerts no reducing action on copper oxide.

Standard reaction mixtures were then made up and 4.000 g. of copper oxide added to each, the procedure being as before described. After the reaction was over and the products had been separated, the extent of reduction was determined by measurements of both the sodium formate and azoxybenzene produced. The sodium formate measurements indicated a slight increase in the extent of reduction but no constant values were obtained. However, the yields of azoxybenzene showed no increase in extent of reduction. The catalyst, when analyzed for copper content, proved to be copper oxide. The only explanation which suggests itself is that some copper oxide is reduced by the sodium methylate (in the presence of nitrobenzene) to metallic copper with the concurrent oxidation of the methylate to formate. The absence of metallic copper in the catalyst may be assumed to be due to oxidation during the processes preceding the analysis. The non-appearance of hydrogen from the reaction mixture, however,

seems to preclude the possibility of copper existing in the mixture, since it will be shown in a subsequent section that metallic copper promotes the liberation of hydrogen.

One item of interest was observed in this series of runs. Whereas the catalyst was generally black in color when ready for analysis for copper content, in one instance in was reddish brown in color and analysis showed it to contain the correct amount of oxygen required for cuprous oxide. As confirmation of the presence of this oxide, a sample dissolved in concentrated hydrochloric acid and poured in a large beaker of cold water gave a precipitate of cuprous chloride. The formate yield of this reaction indicated about 95% reduction but the azoxybenzene yield was normal. No hydrogen was detected as a reaction product. This shows conclusively either that some of the cupric oxide was reduced to metallic copper which was oxidized by subsequent treatment to cuprous oxide or that the cupric oxide was reduced directly to cuprous oxide. The non-appearance of hydrogen seems to favor the latter explanation but there is no explanation as to why cuprous oxide appeared in this single instance.

If the cupric oxide had been reduced to metallic copper, 4.000 g. would result in the formation of 1.700 g. of sodium formate by the reaction:

$$2CuO + CH_3ONa \longrightarrow HCOONa + 2Cu + H_2O$$

On the other hand, 4.000 g. of cupric oxide reduced to cuprous oxide would yield 0.850 g. of sodium formate according to the reaction:

$$4CuO + CH_3ONa \longrightarrow HCOONa + 2Cu_2O + H_2O$$

The total formate determined by analysis was 9.790 g. If 0.850 g. is subtracted from this value, 8.940 g. remain as the formate produced by the Klinger reaction. This is equivalent to a reduction of 86.65% which is close to the average value for the uncatalyzed reaction of 85.84%. When 1.700 g. is subtracted, the reduction is decreased to 79.31%. This also seems to indicate that the cupric oxide was reduced to cuprous oxide and would explain the non-appearance of hydrogen. This observation is quite interesting but it has little bearing on the problem in question.

The results of this series of runs are not tabulated here since they were so erratic and are of no value in the elucidation of the mechanism of the Klinger reaction as was hoped might be the case if copper oxide were reduced and were accompanied by the liberation of more or less hydrogen.

D. DETERMINATION OF THE EXTENT OF REDUCTION OF NITROBENZENE BY SODIUM HYDROXIDE IN METHYL ALCOHOL IN THE PRESENCE OF COPPER OXIDE

Although the previous series of runs gave no results of value, they were repeated with sodium hydroxide in methyl alcohol as the reducing agent. No hydrogen was detected in any of the runs but some of the cupric oxide was found to have been reduced to metallic copper:

$$2CuO + CH_3ONa \longrightarrow HCOONa + 2Cu + H_2O$$

The amount of formate produced by this reaction (as calculated from the copper determinations) was subtracted from the total formate before the extent of reduction on this basis was calculated. The results are summarized in the following table:

TABLE XI

THE PERCENT OF REDUCTION OF NITROBENZENE BY SODIUM HYDROXIDE IN METHYL ALCOHOL IN THE PRESENCE OF COPPER OXIDE

	1.	2.	3.	4.	5.	6.
RUN	HCOONa TAKEN c.c.	HCOONa FOUND g.	TOTAL HCOONa g.	LOSS OF O_2 FROM CuO g.	HCOONa=O_2 FROM CuO g.	HCOONa FROM REDUCTION $C_6H_5NO_2$ g.
VIIa	25	0.17650	7.060	0.3167	0.671	6.389
VIIb	25	0.18200	7.280	0.3368	0.716	6.564
VIIIa	25	0.18470	7.388	0.3454	0.734	6.654
VIIIb	25	0.17742	7.097	0.3507	0.745	6.352
IXa	25	0.18305	7.322	0.3555	0.755	6.567
IXb	25	0.18165	7.266	0.3464	0.736	6.530

	7.	8.	9.	10.	11.
RUN	HCOONa THEORY g.	% REDUCTION ON BASIS HCOONa	AZOXYBENZENE PRODUCED g.	AZOXYBENZENE THEORY g.	% REDUCTION ON BASIS AZOXYBENZENE
VIIa	10.200	62.64	11.7	19.8	59.1
VIIb	10.200	64.35	11.9	19.8	60.1
VIIIa	10.200	65.24	12.0	19.8	60.6
VIIIb	10.200	62.27	11.8	19.8	59.6
IXa	10.200	64.38	11.9	19.8	60.1
IXb	10.200	64.12	11.95	19.8	60.4

(The loss of 1 g. of oxygen from copper oxide corresponds to the formation of 2.125 g. of HCOONa by the reaction:

$$2CuO + CH_3ONa \rightarrow HCOONa + 2Cu + H_2O)$$

The yield of azoxybenzene serves to measure the extent of occurence of the Klinger reaction but not quite so accurately as does the yield of sodium formate under normal conditions (in the absence of a catalyst). In this series, the yields of azoxybenzene ranged from 59% to 61% which corresponds to the normal values. The yields as indicated by the formate are therefore somewhat high. This can also be accounted for by assuming that the treatment of the copper-copper oxide mixture before analysis results in a slight oxidation of some of the metal so that the loss of oxygen from copper oxide as determined analytically would be low. This would tend to make the values of column 5 low, and of columns 6 and 8 of Table XI high.

The conclusion may be drawn that copper oxide shows little or no effect on the reaction when sodium hydroxide in methyl alcohol is used as the reducing agent. Since, however, there is a possibility that here, as well as in the preceding series of runs, the conditions may not be just right for the production of metallic copper with the right catalytic activity, it was deemed advisable to use another method of preparing the catalytic copper than that of reduction from the oxide in the reaction mixture. Accordingly, metallic copper was prepared by the method described in a preceding section and used as the catalyst. This catalyst is discussed in the succeeding section.

E. THE REDUCTION OF NITROBENZENE BY SODIUM METHYLATE AND BY SODIUM HYDROXIDE IN METHYL ALCOHOL IN THE PRESENCE OF METALLIC COPPER

Four grams of the metallic copper prepared as before described were used as the catalyst in the succeeding runs. Both sodium methylate and sodium hydroxide in methyl alcohol were separately used as reducing agents as in the previous runs. It was noticed in case either reducing agent was used that hydrogen gas was evolved in measureable quantities. This was to be expected from the theoretical discussion already given and is assumed to be produced by the first step of the Cannizzaro reaction with formaldehyde:

$$HCHO + HONa \longrightarrow HCOONa + H_2$$

Hence, sodium formate equivalent, by the above reaction, to the hydrogen evolved must be subtracted from the total formate to give the formate produced solely by the Klinger reaction. This was done and the results are summarized in the following Table XII.

TABLE XII

THE PERCENT OF REDUCTION OF NITROBENZENE BY SODIUM METHYLATE AND BY SODIUM HYDROXIDE IN METHYL ALCOHOL IN THE PRESENCE OF METALLIC COPPER

	1.	2.	3.	4.	5.	6.
RUN	REDUCING AGENT	TOTAL HCOONa g.	H_2 EVOLVED g.	HCOONa $\rightarrow$ H_2 g. (Eq. a)	HCOONa FROM KLINGER REACTION (2)-(4) g.	HCOONa FROM KLINGER REACTION THEORY g.
Xa	CH_3ONa	9.673	0.00898	0.304	9.369	10.200
Xb	"	9.793	0.00938	0.317	9.476	10.200
XIa	"	9.714	0.00967	0.329	9.385	10.200
XIb	"	9.786	0.01123	0.382	9.404	10.200
XIIa	CH_3OH	7.967	0.01860	0.632	7.335	10.200
XIIb	+ NaOH	7.472	0.01180	0.401	7.071	10.200
XIIIa	"	7.676	0.01857	0.631	7.045	10.200
XIIIb	"	7.767	0.01246	0.424	7.343	10.200
XIVa	"	7.980	0.01952	0.664	7.316	10.200
XIVb	"	7.650	0.01388	0.472	7.178	10.200

	7.	8.	9.	10.	11.
RUN	% THEORY REDUCTION (KLINGER REACTION)	AZOXYBENZENE PRODUCED g.	AZOXYBENZENE THEORY g.	% THEORY REDUCTION (AZOXYBENZENE)	DIFFERENCE IN % BY 2 METHODS (7)-(10)
Xa	91.85	17.80	19.8	89.8	2.1
Xb	92.90	18.10	19.8	91.4	1.5
XIa	92.01	17.70	19.8	89.4	2.6
XIb	92.20	17.80	19.8	89.8	2.4
XIIa	71.91	13.80	19.8	69.7	2.2
XIIb	69.32	13.20	19.8	66.7	2.1
XIIIa	69.07	13.70	19.8	69.2	-0.1
XIIIb	71.99	13.80	19.8	69.7	2.3
XIVa	71.73	13.80	19.8	69.7	2.0
XIVb	70.37	13.58	19.8	68.6	1.8

It will be noticed that in the case of both reducing agents, the percent of reduction is greater than it is in the uncatalyzed reaction. With sodium methylate, the increase in from 4% to 6% above the normal 85.84% (See Table IX) while, with the sodium hydroxide in methyl alcohol, the increase is from 8% to 10% over the normal 61.23% (See Table X) although the percents calculated by the two methods vary slightly. Thus this shows conclusively that the first step of the Cannizzaro reaction, (Equation c'') plays a part in the reduction in the presence of metallic copper. The presence of formaldehyde as an intermediate oxidation product of the methylate is shown by its behavior toward the alkali in the presence of copper, producing sodium formate and free hydrogen by the previously demonstrated reaction:

$$HCHO + HONa \rightarrow HCOONa + H_2 \qquad (c'')$$

The hydrogen thus formed is, to a slight extent, evolved as the gas but a larger fraction of it must also function as a strong reducing agent since the extent of reduction is considerably increased when copper is present in the reaction mixture. This may be explained by reviewing the previously postulated series of reactions:

$$CH_3OH + HONa \rightarrow CH_3ONa + H_2O \qquad (a)$$

$$CH_3ONa + HONa \rightarrow CH_2(ONa)_2 + H_2 \qquad (b)$$

$$CH_2(ONa)_2 + HONa \rightarrow CH(ONa)_3 + H_2 \qquad (c)$$

Hydrolysis may occur after either reaction (b) or (c):

$$CH_2(ONa)_2 + H_2O \longrightarrow HCHO + 2NaOH \qquad (b')$$

$$CH(ONa)_3 + H_2O \longrightarrow HCOONa + 2NaOH \qquad (c')$$

In the normal course of the reaction, the hydrolysis indicated by (c') represents the termination of the oxidation of the methylate. In the catalyzed reaction, the formaldehyde produced by (b) reacts according to (c):

$$CH_2(ONa)_2 + HONa \longrightarrow CH(ONa)_3 + H_2 \qquad (c)$$

or $$HCHO + HONa \longrightarrow HCOONa + H_2 \qquad (c'')$$

but in the presence of the copper the liberation of the hydrogen is promoted in such a form that it is more active in the reduction of the nitrobenzene.

The actual existence of the intermediate formaldehyde stage is thus proved by the liberation of hydrogen gas in the presence of copper and the relationship of the first step of the Cannizzaro reaction with formaldehyde to the Klinger reaction definitely established.

SUMMARY

Additional evidence is adduced to show that the reaction mechanism postulated by Fry and Cameron (26) to explain the reducing action of sodium methylate on nitrobenzene (Klinger's reaction) is correct.

The proposed mechanism involves the oxidation of methyl alcohol successively to formaldehyde and formic acid (sodium salt). The formaldehyde normally shows only a transient existence in the reaction mixture, being immediately converted to the formate. This latter conversion, however, is the first step of the Cannizzaro reaction of formaldehyde as demonstrated in the first part of this work and it was found that metallic copper showed the same effect on the Klinger as on the Cannizzaro reaction.

In the presence of copper, the effect was not only to increase the yield of formate but also to cause the liberation of hydrogen, a portion of which is evolved as gas but the greater portion being active in the reduction of nitrobenzene to azoxybenzene. A comparison of the extent of reduction of the nitrobenzene, both with and without copper present, shows that the reduction increases somewhat in the presence of the metal, indicating that the hydrogen involved in the reduction is more active in the presence of copper.

The percent of reduction can be measured, under these conditions, by the amount of either formate or azoxybenzene produced, suitable correction being made for the excess

formate produced as measured in terms of the hydrogen evolved as gas.

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