

facts. Other evidence against the ion catalysis possibility is mentioned by Wood and Dickinson.

### Summary

The photochemical iodine-sensitized *cis-trans* isomerization of dichloroethylene in benzene solutions has been studied. Isomerization rates have been measured for various light intensities, iodine concentrations, temperatures, and area of

glass surface in contact with the solution. The results indicate that the reaction is homogeneous under the experimental conditions and that a mechanism involving catalysis of the isomerization by iodine atoms is probable.

A value for the activation energy of this photochemical reaction has been calculated from the results of these experiments.

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[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY AND CHEMICAL ENGINEERING OF THE UNIVERSITY OF PENNSYLVANIA]

## Effect of Structure on Reactivity.<sup>1</sup> II. Influence of Solvents on Ammonolysis of Esters

BY MAXWELL GORDON,<sup>2</sup> JOHN G. MILLER AND ALLAN R. DAY

In the first investigation of this series<sup>3</sup> the electron release effects of alkyl and aryl groups in the ammonolysis of esters were studied. All of the reaction media employed contained about 18% water because it had been found that most esters will not react appreciably with ammonia in anhydrous dioxane or methanol over a period of several weeks at room temperature. The question of the effect of water on the ammonolysis of esters is subject to more difference of opinion<sup>4</sup> than any other phase of this work. On the basis of the references cited,<sup>4</sup> the work in this paper probably offers the first general method for the ammonolysis of esters in the absence of water.

From the earlier investigations and from the work in this laboratory, it may be stated that in general simple esters will not react with ammonia at a useful rate in anhydrous media. The notable effect of water on the rate of ammonolysis suggested that the use of hydroxylated organic solvents might also promote the ammonolysis of esters. Investigation of a series of such solvents has shown this assumption to be correct. Certain of the glycols and related compounds were found to be more effective than water. Furthermore, the results show the same qualitative structure-reactivity correlations as those reported in the first paper<sup>3</sup> for aqueous solutions.

### Experimental

The experimental method employed for ammonolysis in this investigation was identical with

(1) From a thesis submitted in December, 1947, by M. Gordon to the Department of Chemistry and Chemical Engineering of the University of Pennsylvania in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

(2) National Institute of Health Predoctoral Research Fellow, 1946-1948.

(3) Gordon, Miller and Day, *THIS JOURNAL*, **70**, 1946 (1948).

(4) Fischer and Dilthey, *Ber.*, **35**, 844 (1902); McKenzie and Wren, *J. Chem. Soc.*, 311 (1908); Morrell, *ibid.*, 2701 (1914); Blair, *THIS JOURNAL*, **48**, 37 (1926); Grant and Hinshelwood, *J. Chem. Soc.*, 1351 (1933); Hughes and Ingold, *ibid.*, 252 (1935); Haworth, Haslop, Salt and Smith, *ibid.*, 222 (1944).

that used in the first paper of this series.<sup>3</sup> At this point in the work it became apparent that the choice of dioxane as a diluent was particularly fortunate, since it was found that ammonolysis proceeds more slowly in dioxane than in any other solvent tested. On this account dioxane could reasonably be used as a diluent in evaluating the catalytic effects of other solvents.

In addition to the compounds used in the previous work,<sup>3</sup> the following were employed: ethylene glycol, b.p. 72° at 1 mm.,  $n_D^{20}$  1.4316; diethylene glycol, 101° at 1 mm., 1.4472 at 20°; trimethylene glycol, 88° at 1 mm., 1.4398 at 20°; ethylene glycol monomethyl ether, 43° at 20 mm., 1.4074 at 20°; diethylene glycol monomethyl ether, 68° at 1 mm., 1.4264 at 27°; glycerol, 1.4729 at 20°; propylene glycol, 65° at 1 mm., 1.4293 at 27°; ethylene glycol monoacetate, 61° at 1 mm., 1.4278 at 20°; 1,3-butane-diol, 74° at 0.5 mm., 1.4410 at 20°; isobutylene glycol, 58° at 1 mm., 1.4350 at 20°. The anhydrous ammonia used was controlled with a steel needle valve and metered by means of a bubble counter.

### Results

The promoting effect of water on the ammonolysis of ethyl acetate was found to be dependent on its concentration. Thus with no water present there was no measurable ammonolysis in 400 hours, with 5 moles of water/l. the rate constant was 0.000220 l. mole<sup>-1</sup> hour<sup>-1</sup>, with 10 moles of water/l., 0.000450, and with 20 moles of water/l., 0.000750. The concentration of ammonia was 0.809-1.172 moles/l. The lack of ammonolysis in the anhydrous diluent (dioxane) is notable. Further preliminary measurements revealed that other solvents similarly showed an increase in rate of ammonolysis beyond the point where the ammonia-catalyst ratio is 1:1. Other solvents tried were methanol, *t*-butanol, ethylene glycol and glycerol.

Because of the striking effects of the various

solvents used in the preliminary work and in view of the desirability of making the comparisons on the basis of the number of moles of solvent added, the experiments summarized in Table I were performed. Here, in the ammonolysis of methyl acetate, the data shown are for systems containing ten moles of water/l. in each case and five moles of additional solvent. In all instances the reaction mixtures were made up to volume with dioxane. The use of water was required because some of the solvents will not promote ammonolysis in the absence of water. The particular sample in which water was the additional solvent contained, of course, a total of fifteen moles of water/l.

In these experiments the rate constants were measured over rather long periods of time and, in general, showed a slight decrease as the reaction progressed, similar to the behavior reported in the previous investigation.<sup>3</sup> For comparison of the catalytic effects of the solvents, Table I lists the rate constants at the half-time in each case.

The order of listing in this table shows the relative catalytic effects of the solvents. Similar results were obtained in the ammonolysis of ethyl acetate, methyl benzoate and methyl lactate.

The values for per cent. ammonolysis for most of the experiments summarized in Table I are plotted against time in Fig. 1. Two of the curves 6 and 10, are important reference curves, the latter representing the behavior of the system containing the same constituents as all the rest, without any additional solvent, while the former shows the effect of additional water. Between these curves are found those of all the solvents which have a lower catalytic effect, mole for mole, than water. It is in these solvents that ammonolysis would not be expected to proceed appreci-

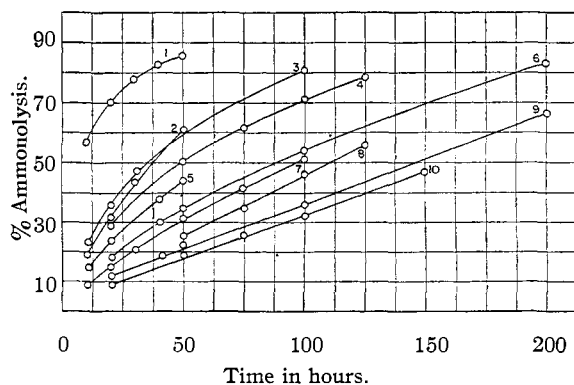


Fig. 1.—Effect of additional solvent on the ammonolysis of methyl acetate: 1, glycerol; 2, diethylene glycol; 3, ethylene glycol; 4, propylene glycol; 5, diethylene glycol monomethyl ether; 6, water (15 moles/l.); 7, ethylene glycol monoethyl ether; 8, *t*-butanol; 9, methanol; 10, water (10 moles/l.) All concentrations are 5 moles/l. with the exception of water.

ably in the absence of water. This conclusion was verified experimentally when ammonolysis failed to take place in anhydrous methanol or *t*-butanol.

TABLE I  
EFFECT OF ADDITIONAL SOLVENT ON AMMONOLYSIS<sup>a</sup> OF METHYL ACETATE AT 30°

Additional solvent	<i>k</i>	Additional solvent	<i>k</i>
None	0.0014	Water	0.00391
Methanol	.00172	Diethylene glycol-	
<i>t</i> -Butanol	.0025	monomethyl	
1,3-Butanediol	.00262	ether	.00527
Trimethylene glycol	.00330	Propylene glycol	.00600
Ethylene glycol	.00339	Ethylene glycol	.0100
monoethyl ether		Diethylene glycol	.0100
Isobutylene glycol	.0038	Glycerol	.0285

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.463–2.537 moles/l.

Of course, ammonolysis of most esters would not be anticipated in anhydrous dioxane since replacement of a portion of dioxane by any of the other solvents tested resulted in an increase in rate, thus showing dioxane to be at the bottom of the scale of catalytic activity. Ethylene glycol monoethyl ether and trimethylene glycol lie below the level of water in catalytic activity, but are so close to it that they would be expected to promote ammonolysis in the absence of water. This conclusion was verified experimentally. All of the solvents corresponding to the curves above that of 15 moles of water/l. would be expected to promote ammonolysis readily in the absence of water, and this was found to be the case.

To corroborate the results shown in Table I and Fig. 1, the ammonolysis of methyl acetate was studied in the following anhydrous solvents at 30°: ethylene glycol, diethylene glycol, propylene glycol and trimethylene glycol. The concentration of ester was 0.7 mole/l. and that of the ammonia was 2.52 to 2.61 moles/l. Due to the high viscosity of these glycols, the experimental error was higher than in the experiments in which dioxane or alcohol diluent was used and the downward drift of the constants was slightly more pronounced. For this reason, only the values of the reaction constants measured at twenty hours reaction time are reported here: 0.0421, 0.0286, 0.0175, and 0.00216 l. mole<sup>-1</sup> hour<sup>-1</sup>, respectively.

A more complete representation of the experiments is shown in Fig. 2 where the per cent. ammonolysis in each case is plotted over a period of time. This graph shows the variety of solvents in which ammonolysis can take place under anhydrous conditions. These results verify the prediction made in discussion of Table I, that solvents which exert a catalytic activity in the ammonolysis of esters equal to or greater than that of water would cause ammonolysis to proceed in

the absence of water. The relative catalytic effects of these anhydrous solvents follow the same order as that found with ten moles of water/l. present in each case.

The effect of sodium hydroxide on the ammonolysis of methyl acetate at 30° is shown by the two experiments reported in Table II. The concentration of sodium hydroxide was 0.07 mole/l. in one run, and the base was absent in the other. Ten moles of water/l. was present in each case. Dioxane was used as the diluent. The application of the second analytical method for ammonia described earlier<sup>3</sup> showed that about 50% of the ester was hydrolyzed. Without additional comment at this point, we note that the extent of hydrolysis prevents practical application of the use of sodium hydroxide in ammonolysis.

TABLE II

EFFECT OF SODIUM HYDROXIDE ON THE AMMONOLYSIS<sup>a</sup> OF METHYL ACETATE AT 30°

Concn. of NaOH	Hours				
	1	25	50	75	100
None					
% Ammonolysis		10.5	18.8	25.8	33.3
Rate constant		0.00185	0.00178	0.00176	0.00148
0.07 Mole NaOH/l.					
% Ammonolysis	14.5	27.5	39.0	44.0	47.0
Rate constant	0.0705	0.00600	0.00350	0.00205	0.00145

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.276–2.474 moles/l.

The values found for the relative rates, using the rate for methyl acetate (0.0418) as unity, for the ammonolysis of acetates in anhydrous ethylene glycol are listed in Table III.

TABLE III

AMMONOLYSIS<sup>a</sup> OF ACETATES IN ANHYDROUS ETHYLENE GLYCOL AT 30°

Ester	Relative rate
Phenyl acetate	17.9
Vinyl acetate	4.33
Methyl acetate <sup>b</sup>	1.00
<i>n</i> -Amyl acetate	0.91
Isobutyl acetate	.87
Isopropyl acetate	.65
<i>s</i> -Butyl acetate	.21
$\alpha$ -Naphthyl acetate	.18
$\beta$ -Naphthyl acetate	.18
<i>t</i> -Butyl acetate	.036

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.411–2.416 moles/l. <sup>b</sup> The rates for methyl, ethyl, *n*-propyl, *n*-butyl and benzyl acetates were practically the same in anhydrous ethylene glycol.

The values found for the relative rates, using the rate for methyl benzoate (0.00280) as unity, for the ammonolysis of benzoic acid esters in anhydrous ethylene glycol are shown in Table IV.

The values found for the relative rates, using the rate for methyl lactate (0.599) as unity, for the ammonolysis of lactic acid esters in anhydrous ethylene glycol are listed in Table V.

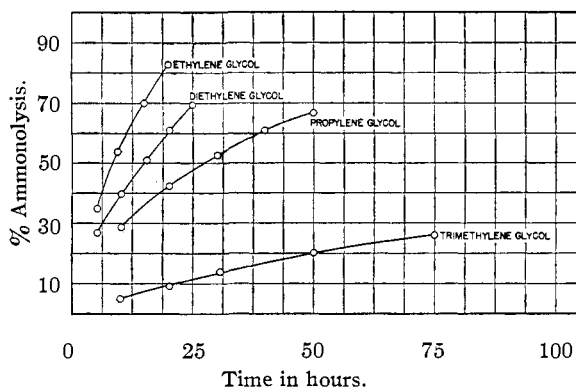


Fig. 2.—Ammonolysis of methyl acetate in anhydrous solvents.

TABLE IV

AMMONOLYSIS<sup>a</sup> OF BENZOATES IN ANHYDROUS ETHYLENE GLYCOL AT 30°

Ester	Relative rate
Phenyl benzoate	1.01
Methyl benzoate	1.00
Ethyl benzoate	0.92
Benzyl benzoate	.82
<i>n</i> -Propyl benzoate	.64
Isopropyl benzoate	.30
<i>t</i> -Butyl benzoate	.057

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.385 moles/l.

TABLE V

AMMONOLYSIS<sup>a</sup> OF LACTATES IN ANHYDROUS ETHYLENE GLYCOL AT 30°

Ester	Relative rate
Methyl lactate	1.00
Allyl lactate	0.91
Ethyl lactate	.88
<i>n</i> -Propyl lactate	.70
<i>n</i> -Butyl lactate	.57
<i>n</i> -Amyl lactate	.55
Isobutyl lactate	.47
Isopropyl lactate	.22
<i>s</i> -Butyl lactate	.21
<i>n</i> -Butyl hydracrylate <sup>b</sup>	.038
<i>t</i> -Butyl lactate	.016

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.458 moles/l. <sup>b</sup> Inserted for comparison with *n*-butyl lactate.

Table VI lists similar data, using the rate for methyl acetate as unity, for the ammonolysis of methyl esters of various acids in anhydrous ethylene glycol. It should be noted that in the case of methyl crotonate principally addition to the double bond, with very little ammonolysis, took place. These results confirm those obtained in aqueous dioxane solution.<sup>3</sup>

In the ammonolysis of four homologous series of esters in anhydrous ethylene glycol the same general effects were noted as were observed earlier in aqueous dioxane–ammonia solutions.<sup>3</sup> Of course, most of the esters ammonolyzed much

TABLE VI

AMMONOLYSIS<sup>a</sup> OF METHYL ESTERS IN ANHYDROUS ETHYLENE GLYCOL AT 30°

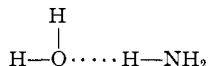
Ester	Relative rate
Methyl formate	66.4
Methyl lactate	14.3
Methyl acetate	1.00
Methyl phenylacetate	0.85
Methyl propionate	.650
Methyl crotonate	.25
Methyl isobutyrate	.13
Methyl benzoate	.08
Methyl trimethylacetate	.003

<sup>a</sup> Concentration of ester 0.7 mole/l., concentration of ammonia 2.510 moles/l.

more rapidly in ethylene glycol solution than in aqueous dioxane. The only characteristic feature about the ammonolysis of esters in anhydrous ethylene glycol (Tables III, IV, V and VI) was the much smaller difference in reactivity between the different esters. While ammonolysis in anhydrous ethylene glycol has excellent possibilities for the preparation of amides, it should not be used in comparative studies without using a diluent such as dioxane to avoid the manipulative difficulties in working quantitatively with viscous solutions.

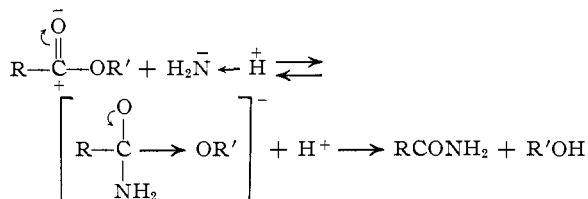
### Discussion

The mechanism of activation of the ammonia pictured earlier for water<sup>3</sup> is probably also in effect



with the alcohols. While the free amide ion is not postulated in any case, polarization of the hydrogen-nitrogen bond in the case of water and some of the other solvents is sufficient to make the ammonia molecule more reactive as a nucleophilic agent.

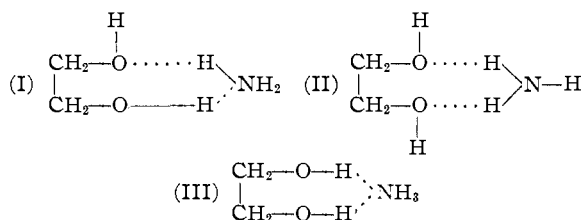
The effect of sodium hydroxide on the ammonolysis of methyl acetate (Table II) is strong evidence for the mechanism of ammonolysis involving addition of an amide ion, rather than molecular ammonia.



The presence of hydroxyl ions would favor the formation of amide ions and the precipitous initial rate of ammonolysis in sodium hydroxide solution bears this out. The rate constants drop off after 10% reaction. This would be expected from the low concentration of sodium hydroxide used and its consumption by the competing hydrolysis.

The catalysis by water and the other solvents continues increasingly even beyond the point where there is a 1:1 ratio of solvent to ammonia. This points to the association of only a fraction of the solvent molecules with ammonia. It is difficult, therefore, to assign a specific structure to the ammonia-solvent complex in most cases. However, for purposes of discussion of relative effects, a simple addition complex involving one molecule of ammonia and one of solvent will be considered.

In view of the results obtained for the ammonolysis of esters in various media a cyclic structure for the complex of ammonia with ethylene glycol, one of the most active of catalysts, seems probable. The three possible structures for this hydrogen-bonded complex are as follows:



In formula (I) for this complex the two hydrogen bonds are probably of unequal strength. Spectroscopic evidence has been found by Gordy<sup>5</sup> for this conclusion. In his studies Gordy used methanol containing a deuterium atom in the hydroxyl group, and he measured the shift in O-D infrared absorption as a result of hydrogen bonding to various compounds. From these data he concluded that the acceptor properties of the amine hydrogen are much weaker than those of the hydroxyl hydrogen. Huggins<sup>6</sup> has likewise emphasized the improbability of strong hydrogen bonds being formed through an amine hydrogen. From these investigations it is apparent that the N-H...O bond is weaker than the N...H-O bond in Formula I.

Formula II of the ammonia-ethylene glycol complex, although present in smaller amounts than Formula I due to its weak bonds, is probably the more active in ammonolysis because it contains two N-H...O bonds which are the ones making a NH<sub>2</sub><sup>-</sup> ion available. However, a strong bond is not necessary to implement the mechanism of ammonolysis. All that is needed is an attractive force which will polarize the covalent nitrogen-hydrogen bond sufficiently. In form (II) both hydrogen-nitrogen bonds involved would be weakened somewhat, and it is statistically possible for fission of either bond to occur upon approach of the nitrogen to the carbonyl carbon of the ester.

In ammonolysis it is not necessary to postulate that the nitrogen-hydrogen bond breaks before the nitrogen-carbon bond is formed. These

(5) Gordy, *J. Chem. Phys.*, **7**, 93 (1939).

(6) Huggins, *J. Org. Chem.*, **1**, 407 (1936).

bonds could be broken and formed simultaneously,<sup>7</sup> after the nucleophilic center in the ammonia complex and the electrophilic center of the ester have approached one another through the action of electrostatic forces or by random motion.

An additional form of the ammonia-ethylene glycol complex may be drawn (III), but it was ruled out for two reasons: first, because it is difficult to see how it could contribute to the formation of potential amide ions and, second, because of the unlikelihood of two hydrogen bonds forming on a single nitrogen. In this connection Huggins<sup>6</sup> has stated that attempts to find two O-H...N bridges to the same nitrogen were unsuccessful.

The reasons for the postulate of a cyclic and not a linear hydrogen bonded ammonia-solvent complex are obvious from the data. The monohydric alcohols, for which no simple cyclic hydrogen bonded structure is possible, show a comparatively low order of catalytic activity. The 1,2-glycols and glycerol, on the other hand, exhibit an increase in catalytic effect that is far out of proportion to the additional molecular concentration of hydroxyl groups introduced. For example, the rate of ammonolysis of methyl acetate in the presence of 5 moles of ethylene glycol/l. is over five times the rate in a similar molecular concentration of methanol. The disproportionate increase in the catalytic activity of glycerol over ethylene glycol is probably due to the combination of inter- and intramolecular hydrogen bonded complexes with ammonia which are possible.

Trimethylene glycol, which differs from ethylene glycol only by one CH<sub>2</sub> group, has a catalytic activity only one-third that of ethylene glycol. Similarly 1,3-butanediol has a much lower order of catalytic activity than would be anticipated. In fact, on the basis of equivalent molecular concentrations of hydroxyl groups, the catalytic activity of these 1,3-glycols is of the order of magnitude of methanol. This phenomenon points very strongly to a structure like (II), containing a seven-membered ring, for the ethylene glycol-ammonia complex. A similar structure for trimethylene glycol or 1,3-butanediol would require an eight-membered ring, which is less likely on steric grounds. Wall and Claussen have stated,<sup>8</sup> on the basis of spectrographic evidence, that the most stable rings involving hydrogen bonds contain six or seven atoms, including the hydrogen. These numbers are greater by one than those usually given for rings involving only ordinary electron pair types of bonds.

Substitution of one of the hydrogens in ethylene glycol by an ethyl group reduced the catalytic activity in ammonolysis to one-third of the former value. The fact that ethylene glycol was three times as effective as ethylene glycol monoethyl

ether indicates that the hydroxyl oxygen is much more effective in promoting hydrogen bonding, and hence ammonolysis, than the ether oxygen. Independent confirmation for these results was obtained by Gordy<sup>9</sup> from measurements of the shift in the infrared absorption spectra of hydroxyl groups. The shift in the oxygen-deuterium absorption maximum of CH<sub>3</sub>OD was more than twice as great in propylene glycol as in dioxane.

Gordy further stated that a cyclic ether is not as effective an electron donor solvent as an open chain ether. Errera<sup>10</sup> and Freymann<sup>11</sup> similarly commented on the comparatively low associating ability of dioxane. Their observations corroborate the results of this laboratory on the very low order of catalytic activity of dioxane. In this particular instance there is the additional steric factor which makes ring formation, involving the two ether oxygens of dioxane, improbable.

From all of the foregoing experiments we may generalize that the grouping -O-C-C-O- is the basic one involved in most of the pronounced catalytic effects noted in this study. If the groups attached to the terminal ends of the oxygens are hydrogens, the greatest activity is observed. Conversion of the hydroxyl oxygens to ether oxygens reduces the catalytic activity, particularly if the ether grouping is part of a ring. In diethylene glycol, which was found to have the same catalytic effect on ammonolysis as ethylene glycol, two hydroxyl groups are present, but they are separated by five atoms, the center one being an ether oxygen. In this molecule the possibility of bonding of ammonia to either half of the molecule increases its catalytic activity to the point where it equals that of ethylene glycol.

The catalytic activity of diethylene glycol monomethyl ether was about half that of diethylene glycol, showing again the reduced catalytic activity of the ether oxygen when compared with the hydroxyl oxygen. However, diethylene glycol monomethyl ether showed about 55% greater catalytic activity than ethylene glycol monoethyl ether, indicating that the ether oxygen must make some contribution, if a small one, to the catalytic activity of the solvent.

On the basis of the relative catalytic effects of methanol and *t*-butanol on the ammonolysis of esters, it might be anticipated that propylene glycol, containing a secondary alcohol group, would show a greater catalytic activity than ethylene glycol. A similar conclusion might be reached for the relative catalytic effects of trimethylene glycol and 1,3-butanediol, or ethylene glycol and isobutylene glycol.

In this Laboratory the catalytic effect of propylene glycol was found to be 40% less than that of ethylene glycol. Empirical confirmation for these

(7) London, *Z. Elektrochem.*, **35**, 552 (1929).

(8) Wall and Claussen, *This Journal*, **61**, 2679 (1939).

(9) Gordy, *J. Chem. Phys.*, **8**, 170 (1940).

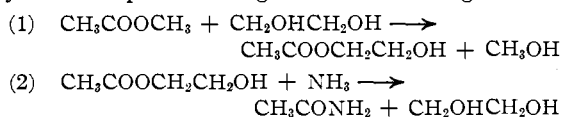
(10) Errera, Gaspard and Sack, *ibid.*, **8**, 63 (1940).

(11) Freymann, *Compt. rend.*, **204**, 41 (1937).

results can be obtained from the work of Gordy and Stanford<sup>12</sup> and Wall and Claussen.<sup>8</sup> These investigators found that there was no intramolecular hydrogen bonding in ethylene glycol, while in propylene glycol the internal association was noted in the shift in the oxygen-deuterium absorption band. Therefore these investigators concluded that ethylene glycol shows a greater proton attracting ability than propylene glycol.

Similarly, it was found in this Laboratory that ethylene glycol had greater catalytic activity in ammonolysis than isobutylene glycol, and it was found that the effect of trimethylene glycol was greater than 1,3-butanediol. From all of these results on glycols a generalization is apparent. All symmetrical glycols have a greater catalytic activity in ammonolysis than the corresponding unsymmetrical glycols due to the presence of intramolecular hydrogen bonding in the latter. Thus:  $\text{CH}_2\text{OHCH}_2\text{OH} > \text{CH}_3\text{CHOHCH}_2\text{OH} > (\text{CH}_3)_2\text{COHCH}_2\text{OH}$ , and  $\text{CH}_2\text{OHCH}_2\text{CH}_2\text{OH} > \text{CH}_3\text{CHOHCH}_2\text{CH}_2\text{OH}$ . In other words, in unsymmetrical glycols the intramolecular hydrogen bonding results in a reduced over-all ability to associate with ammonia or other compounds. The more basic an atom, the more readily it acts as an acceptor for hydrogen; the more acidic the atom, the more readily it acts as a proton donor. Therefore in a glycol the greater the difference in electronegativities of the oxygens, the greater will be the intramolecular hydrogen bonding. The relative effects of ethylene glycol, propylene glycol, and isobutylene glycol, noted above, agree with these predictions. Wall and Claussen<sup>8</sup> postulated intramolecular hydrogen bonding in propylene glycol, in preference to intermolecular bonding, because of the small change in the frequency of hydroxyl absorption encountered upon dilution of carbon tetrachloride solutions of propylene glycol.

Consideration was given the possibility that catalysis of the ammonolysis of esters by ethylene glycol takes place through ester interchange.



Demonstration that either of these two steps proceeds more slowly than the ammonolysis of methyl acetate in the presence of ethylene glycol rules out the mechanism involving ester interchange. The first of these steps was too difficult to study experimentally. The second step was followed experimentally, and the ammonolysis of  $\beta$ -hydroxyethyl acetate ( $k = 0.00700$ ) was found to proceed more slowly than the ammonolysis of

(12) Gordy and Stanford, *J. Chem. Phys.*, **9**, 204, 215, 440 (1941).

methyl acetate ( $k = 0.0100$ ) in the presence of ethylene glycol. In addition, the ammonolysis of  $\beta$ -hydroxyethyl acetate was much slower in ethylene glycol than would be anticipated in comparison with other esters.

It should not be inferred from the above discussion that a sharp demarcation exists between those solvents which catalyze ammonolysis in the absence of water and those which do not. On the basis of experimental evidence the ammonolysis of all esters may be said to proceed in all solvents although the extent of reaction in some cases is too small to be measurable with any degree of accuracy. Justification for this statement is found in the behavior of phenyl acetate in various ammonia solutions. Phenyl acetate ammonolyzed completely in the presence of water in about half an hour. This ester was then shown to undergo ammonolysis almost completely in anhydrous dioxane or alcohol in about twenty-four hours. In comparison, the ammonolysis of methyl acetate takes place to the extent of only a few per cent. in anhydrous dioxane or alcohol over a period of three months. The magnitude of the experimental error involved in working with anhydrous solutions of alcohol or dioxane, particularly the latter, is so great that the results are of value in qualitative comparisons only. Experimental error in these cases is due to the low solubility of ammonia in these solvents, and to the volatility of the solvents themselves.

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### Summary

A general method has been developed for the ammonolysis of esters in the absence of water.

The catalytic effect of water and other solvents on the ammonolysis of esters has been found to increase with concentration, even beyond the point where the ammonia-catalyst ratio is 1:1.

The relative catalytic effects of solvents on the ammonolysis of esters has been investigated and the following order of reactivity was determined: glycerol > ethylene glycol, diethylene glycol > propylene glycol > diethylene glycol monomethyl ether > water > isobutylene glycol > ethylene glycol monoethyl ether > trimethylene glycol > 1,3-butanediol > *t*-butanol > methanol > dioxane.

A mechanism has been postulated for the ammonolysis of esters in various solvents.

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