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MECHANISM OF THE HYDROLYSIS OF LACTAMS IN AQUEOUS SOLUTIONS OF POTASSIUM HYDROXIDE

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Abstract—The subject of this study was the kinetics of the hydrolysis of γ-butyrolactam, δ-valerolactam, ε-caprolactam and enantholactam in strong aqueous solutions of potassium hydroxide.

It has been shown that the average thermodynamic activity of aqueous solutions of potassium hydroxide is a function of alkalinity. Ionization of lactams yields singly and doubly ionized forms of reactive lactams. The processes of interaction of these ions with the water molecule are the rate-limiting steps.

AQUEUOS and non-aqueous solutions of alkali metal hydroxides are widely used as catalysts in organic syntheses. The mechanism of alkaline catalysis is becoming increasingly important in connection with the problem of the relationship between structure and reactivity of organic compounds.

The mechanism of chemical reaction in a liquid phase is defined as the sum total of data on the equilibrium of various forms of a substance in a reactive medium and on the mechanism of slow elementary steps which limit the rate of the process.

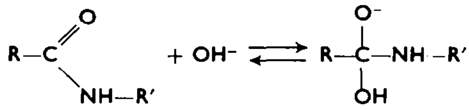
The detailed mechanism of a chemical process can be established if, in addition to kinetic measurements, some method is applied to estimate the equilibrium concentrations of various forms of the reagent in the given medium. In the study of reactions catalysed by acids and bases, it is interesting to identify the ionized form of the reagent and to determine the ionization constants. This research will be successful if the kinetic investigations are undertaken under conditions in which the catalyst (acid or alkali) concentration varies within a wide range reaching such values when practically all the reagent attains reactive form. This permits calculation of the true activation energy and the true pre-exponential factor characteristic of the reactivity of the chemical substance.

The object of this investigation was the study, using a model reaction, of the catalytic effect of aqueous solutions of potassium hydroxide within a wide range of alkali concentrations and to determine the parameter characterizing the catalytic activity of these media.

Hydrolysis of ε-caprolactam, δ-valerolactam, enantholactam, γ-butyrolactam and N-methylacetamide was chosen as a model process; the alkali concentration varied from 1 to 50·4% potassium hydroxide by weight.

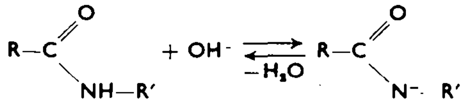
Mechanism of the ionization of lactams and amides in alkali media

It is usually assumed that the ionization of amides and lactams in alkali media proceeds by one of the following two courses:



$$\mathrm{R{-}C({=}O){-}NH{-}R'} + \mathrm{OH^-} \rightleftarrows \mathrm{R{-}C(O^-)(OH){-}NH{-}R'}$$

(I)



$$\mathrm{R{-}C({=}O){-}NH{-}R'} + \mathrm{OH^-} \underset{-\mathrm{H_2O}}{\rightleftarrows} \mathrm{R{-}C({=}O){-}N^-{-}R'}$$

(II)

According to (I) the hydroxyl ion adds to the amide group. According to (II) the interaction between the hydroxyl ion and the amide or lactam produces an ion with a negative charge on the nitrogen atom and a molecule of water. It is common knowledge that the hydrogen of the amide group is mobile and displays acid properties. In γ-butyrolactam the hydrogen of the "NH" group is replaceable by sodium with the formation of a salt.[1] The exchange of the hydrogen of the amide group in alkali media can also serve as an indicator of acidity.[2] On the other hand, there is evidence showing that the amides ionize by (I). For example, the oxygen of the carbonyl group readily exchanges in alkaline media.[3]

To gain an insight into the mechanism of lactam ionization the authors studied the I.R. spectra of γ-butyrolactam and ε-caprolactam in aqueous solutions of potassium hydroxide of varying concentrations.[4] In view of the fact that water shows intensive bands in the region of lactam absorption the lactam spectra in solutions of KOD in D_2O were also investigated only in solutions containing up to 20% KOD. In stronger solutions the solubility of lactam is exceedingly low. In dilute alkali and in strong KOD solutions the I.R. spectra of ε-caprolactam absorption are

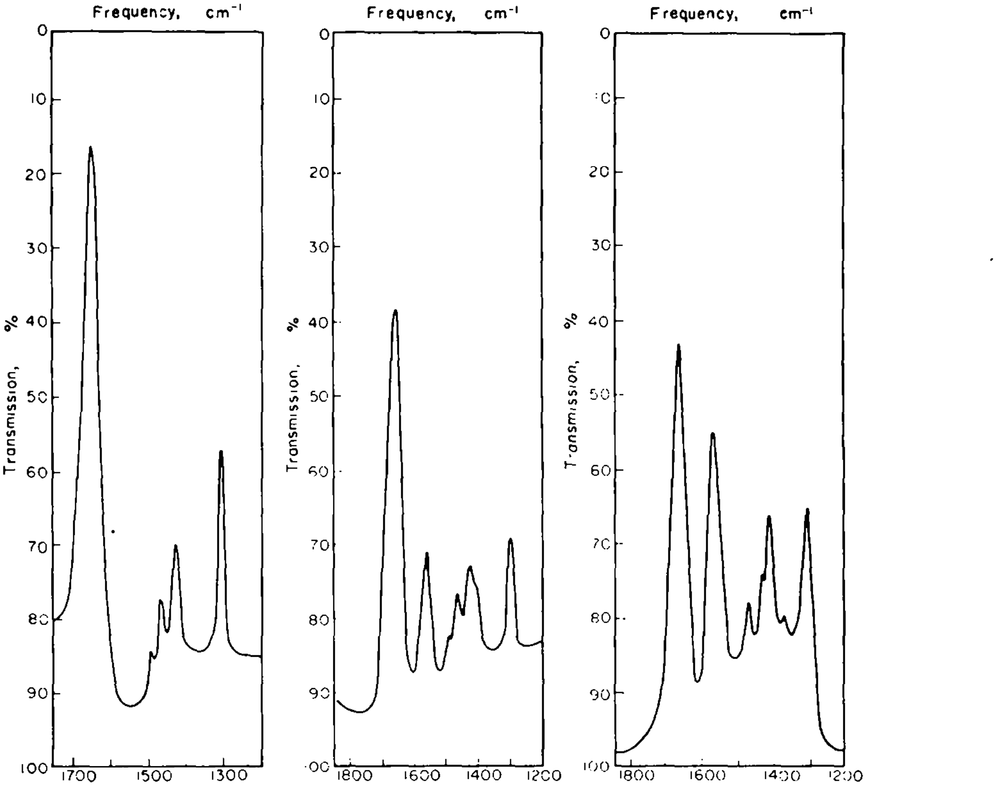


FIG. 1. Infra-red spectra of γ-butyrolactam in D_2O (1), in 22% KOD (2) and in 30% KOD (3).

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[1] J. Fabel and O. Wassmuth, *Ber. Dtsch. Chem. Ber* III, 2831 (1907).

[2] A. Berger, A. Zoeweristein and S. Meiboom, *J. Amer. Chem. Soc.* **81**, 62 (1959).

[3] M. Z. Bender and R. O. Zingu, *J. Amer. Chem. Soc.* **77**, 348, (1955).

[4] M. I. Vinnik, Y. V. Moiseyev and A. V. Palagina, *Dokl. Akad. Nauk SSSR* **143**, 1127 (1962).

practically the same. From this may be concluded that ε-caprolactam in the above solutions is almost completely in a non-ionized form and concentration of the ionized form can therefore be neglected.*

In the case of γ-butyrolactam essential changes were observed to take place in the I.R. spectrum when the strength of the alkali changed. γ-Butyrolactam shows an absorption band of 1,665 cm^{-1} in H_2O and 1,650 cm^{-1} in D_2O which belongs to the stretching vibration of the "C=O" group. As the alkali concentration increases the intensity of this band weakens while in a saturated alkali solution (about 50% KOH by weight) this band is absent altogether. Instead, there appears a band with a frequency of 1,555 cm^{-1} the intensity of which increases as the alkali concentration becomes greater. Solutions containing more than 30% alkali show two more bands with frequencies of 1,740 cm^{-1} and 1,395 cm^{-1}. Spectra of γ-butyrolactam absorption in solutions of varying strength are shown in Fig. 1. The absorption coefficients for γ-butyrolactam bands at 1,395 cm^{-1}, 1,555 cm^{-1}, 1,665 cm^{-1} and 1,740 cm^{-1} as a function of potassium hydroxide concentration at 25° are shown in Fig. 2. It is obvious that the band with the frequency of 1,665 cm^{-1} belongs to the non-ionized form of lactam. The absorption bands with the frequency of 1,555 cm^{-1} are ascribed to the ion which forms when the OH^- ion adds to the carbonyl group of the lactam

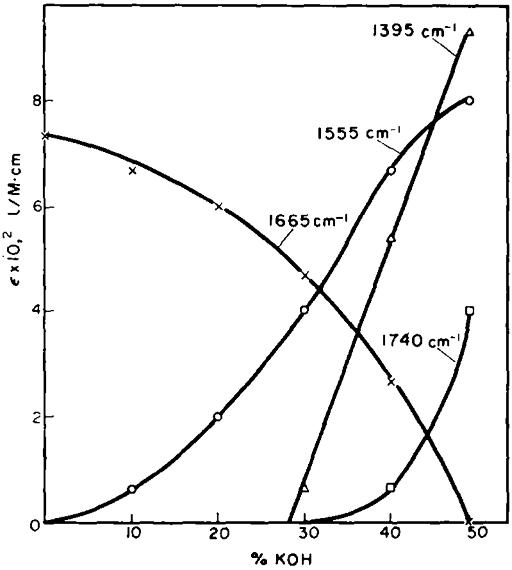
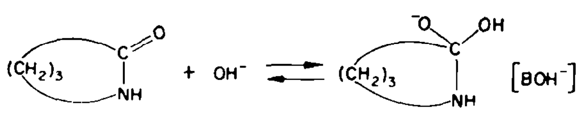


FIG. 2. Change in the absorption coefficients of γ-butyrolactam bands at 1,395 cm^{-1}, 1,555 cm^{-1}, 1,665 cm^{-1} and 1,740 cm^{-1} as a function of alkali concentration.



III

while the frequencies of 1,740 cm^{-1} and 1,395 cm^{-1} are due to the doubly ionized form produced by the interaction between a singly charged ion and the hydroxyl ion.

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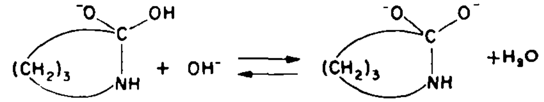
* The absence of any noticeable ionization can also be judged by the decreasing solubility of ε-caprolactam as the strength of the potassium hydroxide increases.

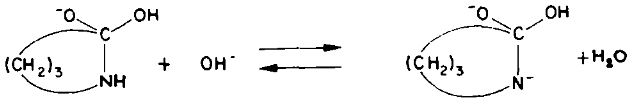
In a paper[4] published, it was assumed that the dianion of lactam was formed as follows:



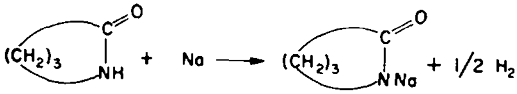
IV

The reason for accepting this structure of the dianion is provided by the spectrum of the carbonate group $CO_3^=$ of strontium carbonate which reveals bands with frequencies of 1,740 cm^{-1}, 1,555 cm^{-1} and 1,400 cm^{-1}.

The dianion may also be formed as follows:

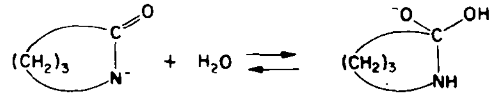


It will be subsequently shown that a singly charged ion with a negative charge on the nitrogen atom shows an intensive absorption band at 1,470 cm^{-1}. It can be assumed, therefore, that the appearance of a strong band with a frequency of 1,395 cm^{-1} in strong solutions of potassium hydroxide is due to the formation of dianion with a negative charge on the nitrogen atom. As evidence is insufficient for establishing the structure of the dianion, the lactam dianion is designated $BOO^=$.

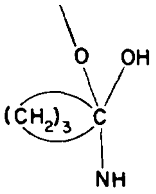


VI

The sodium salt of γ-butyrolactam was synthesized using the methods described by Fabel and Wassmuth.[1] The absorption spectrum of the dry salt pressed into a pellet with potassium bromide retains the entire absorption and band corresponding to the carbonyl group while the band with the frequency of 1,555 cm^{-1} is practically absent (Fig. 3). Solution of the salt in absolute alcohol possesses an identical spectrum. It can, therefore, be concluded that the lactam salt shows an entirely different spectrum from the ionized form produced by dissolving γ-butyrolactam in strong aqueous solutions potassium hydroxide. When this salt is dissolved in water and in aqueous solutions of potassium hydroxide, a rapid recombination of water occurs with the formation of γ-butyrolactam and a hydroxyl ion which interact according to (III) yielding a BOH^- ion. It is possible that an equilibrium between the ions is rapidly attained in aqueous alkali solutions.



VII

However equilibrium is practically shifted towards the  ion.

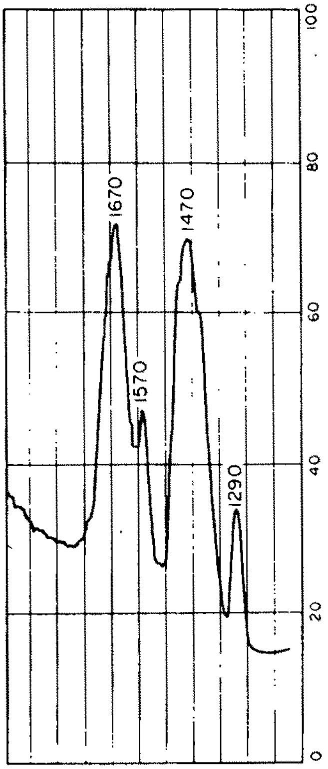
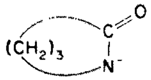


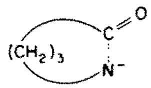
FIG. 3. Infra-red spectrum of Na-salt of γ-butyrolactam in a KBr pellet.

The presence of type



ions can explain the exchange of amide hydrogen in aqueous alkali solutions.

Thus, when γ-butyrolactam dissolves in aqueous alkali solutions there is a singly charged BOH^- ion and BOO^{--} dianion in equilibrium with the non-ionized form, in which form a considerable portion of lactam can be present, possibly with



ions. However, spectral data show that the concentration of such ions is low as compared with BOH^- and BOO^{--} concentrations.

Alkaline function of aqueous solutions of potassium hydroxide

In a chemical reaction which proceeds under the influence of an alkaline catalyst, it is assumed that the slowest step is unimolecular and that the degree of ionization of the reagent is low. When the ratio between the activity coefficients of the ionized form and the activated complex is constant, the observed rate constant K_{eff} will be expressed by the equation:

$$K_{\text{eff}} = \frac{K_{\text{true}}}{K_r} \times Q_{\text{OH}^-} \times \frac{f_{\text{B}}}{f_{\text{BOH}^-}} \tag{1}$$

where K_r is the reagent ionization constant;

f_{B} and f_{BOH^-} are the activity coefficients of the non-ionized and the ionized forms of the reagent;

K_{true} is the true rate constant.

The value $Q_{\text{OH}^-} \times (f_{\text{B}}/f_{\text{BOH}^-})$ should specify the catalytic activity of alkaline media in the same way as the function $h_0 = a_{\text{H}}{}^+ \times (f_{\text{B}}/f_{\text{BH}}{}^+)$ specifies the catalytic activity of acid media. It is therefore termed the alkalinity of the medium. An equation similar to [1] is valid for processes where the rate-limiting step is effected upon the collision of the non-ionized molecule of the reagent with the hydroxyl ion. However, the alkalinity of the medium is characterized in such cases by the $Q_{\text{OH}^-} (f_{\text{B}}/f^*)$ value where f^* is the activity coefficient of the activated complex.

The application of the function proved useful when treating the reaction mechanism in aqueous media of strong acids.[5] Not infrequently, the dependence of K_{eff} on H_0 is useful in concluding the mechanism of the rate-limiting step and in determining the constant of the K_{B} basicity and the true rate constant K_{true}.[6]

The acidity function is determined by the indication method, employed to determine the alkalinity function of aqueous solutions of hydrazine[7] and diethylamine.[8] Schwarzenbach[9] attempted to design an acidity scale for aqueous solutions of potassium hydroxide and sodium hydroxide by the indicator method. However, the data he provides cannot be used for a quantitative estimation of alkaline media since during experiments the indicator was partly in a solid phase due to poor solubility.

The authors decided to determine the alkalinity of aqueous solutions of potassium hydroxide by using the kinetic method. In order to select a chemical reaction for establishing the alkalinity of solutions, the mechanism of its rate-limiting step must be known; besides, the degree of ionization of the reagent must remain low throughout the entire investigated range of alkali concentrations. The alkalinity of aqueous solutions of potassium hydroxide was determined by the dependence of K_{eff} of ε-caprolactam hydrolysis on the strength of potassium hydroxide

It follows from the I.R. spectra that practically all ε-caprolactam is in a non-ionized form even in strong solutions of potassium hydroxide and the concentration of the ionized form can, therefore, be disregarded. As well be shown further the ion provided by addition of the hydroxyl ion to the carbonyl group is one of the reactive components appearing during the hydrolysis of lactams, and the rate-limiting act is reduced to the interaction of the ion with the water molecule. Therefore

$$K_{\text{eff}} = \frac{K_{\text{true}}}{K_r} \times Q_{\text{OH}^-} \times \frac{f_{\text{B}}}{f_{\text{BOH}^-}} \times Q_{\text{H}_2\text{O}} \tag*{[2]}$$

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[5] Z. P. Hammett, *Phys. Org. Chem.* N.Y. and London (1940).

[6] M. I. Vinnik, R. S. Ryabova and I. M. Chirkov, *Zh. Fiz. khim*, **33**, 1992 (1959).

[7] N. C. Deno, *J. Amer. Chem. Soc.* **74**, 2039 (1954).

[8] R. Schall, *C.R. Acad. in Paris*, **238**, 2157 (1954).

[9] D. Schwarzenbach and R. Sulzberger, *Helv. Chim. Acta* **27**, 348 (1944).

When the strength of the alkali is increased from 1·037 to 45·78% potassium hydroxide (by weight) K_{eff} becomes 416 times higher and the $K_{\text{eff}}/Q_{\text{H}_2\text{O}}$ ratio increases by a factor of 1,580.[10] It was found that the change in $K_{\text{eff}}/Q_{\text{H}_2\text{O}}$ coincides quantitatively with the change in the average ion activity $Q_{\pm} = Q_{\text{KOH}}^{1/2}$ of aqueous solutions of potassium hydroxide. Figure 4. shows the value of log $K_{\text{eff}}/Q_{\text{H}_2\text{O}}$ as a function of log $Q_{\pm}$ at 25°. It may be concluded that for aqueous solutions of potassium hydroxide, the alkalinity of the medium $Q_{\text{OH}^-} \times (f_{\text{B}}/f_{\text{BOH}^-})$ corresponds quantitatively to the average ion activity. According to Bernal and Fowler,[11] K^+ and OH^- ions have identical radii in aqueous solutions. Since the electronic shell of these ions is completely filled, it can be assumed that when the properties of the medium change, their thermodynamic activity will change in the same way. When the activities of the K^+ and OH^- ions change in the same way and the alkalinity of the medium corresponds to $Q_{\pm}$ it may be expected that the ratio between the activity coefficients $f_{\text{B}}/f_{\text{BOH}^-}$ will be constant for solutions of alkali of various concentrations. It was verified that the alkalinity values calculated by the above method are applicable to other processes as well. A number of experiments on the kinetics of δ-valerolactam and enantholactam hydrolysis were carried out for this purpose.

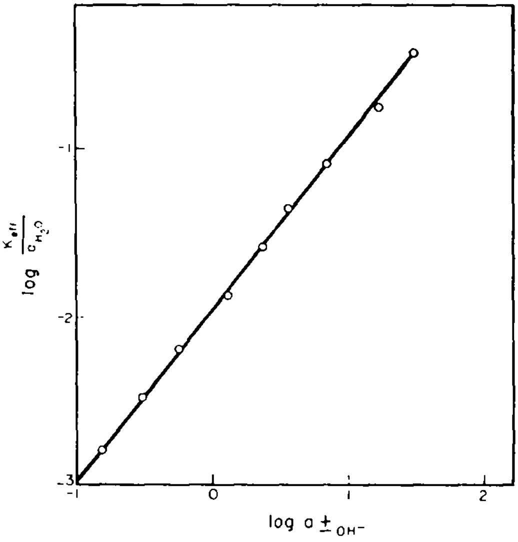

FIG. 4. The value of log $K_{\text{eff}}/Q_{\text{H}_2\text{O}}$ as a function of log $Q_{\pm}$ for ε-caprolactam at 25°.

The values of K_{eff} for δ-valerolactam and enantholactam hydrolysis in potassium hydroxide solutions at various temperatures are summarized in Table 1. The K_{eff}, Q_{OH^-} and $Q_{\text{H}_2\text{O}}$ values at 25° as well as the effective activation energies E_{eff} are given in Table 2. The rate constants for potassium hydroxide solutions at 25° were obtained by extrapolation from higher temperatures. The data in Table 2 show that the value of $K_{\text{eff}}/Q_{\text{OH}^-}\text{-}Q_{\text{H}_2\text{O}}$ for δ-valerolactam and enantholactam remains constant over a very wide range of potassium hydroxide concentrations. This indicates that in this case also the average ion activity of potassium hydroxide is a measure of

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[10] M. I. Vinnik, Y. V. Moiseyev and L. V. Palagina, *Dok. Akad. Nauk SSSR* **138**, 149 (1961).

[11] J. O. Bernal and R. H. Fowler, *J. Chem. Phys.* **1**, 515 (1933).

Table 1

% KOH by weight	t°C	K_{eff}/min⁻¹/	% KOH by weight	t°C	K_{eff}/min⁻¹/
δ-valerolactam					
1·037	60	0·175 × 10^{-1}	12·41	25	0·242 × 10^{-1}
	70	0·310 × 10^{-1}		40	0·785 × 10^{-1}
	80	0·493 × 10^{-1}		50	0·155
	90	0·875 × 10^{-1}		60	0·298
2·250	60	0·366 × 10^{-1}		70	0·451
	70	0·749 × 10^{-1}		80	0·851
	80	0·115	15·76	25	0·357 × 10^{-1}
4·184	40	0·176 × 10^{-1}		40	0·115
	50	0·391 × 10^{-1}		50	0·219
	60	0·785 × 10^{-1}		60	0·395
	70	0·123	20·45	25	0·563 × 10^{-1}
8·056	25	0·125 × 10^{-1}		50	0·391
	40	0·414 × 10^{-1}		60	0·670
	50	0·766 × 10^{-1}	26·95	25	0·127
	60	0·144		40	0·365
	70	0·263		50	0·675
	80	0·426	33·16	15	0·106
	90	0·634		25	0·205
enantholactam					
5·75	96	6·09 × 10^{-3}	19·90	96	3·40 × 10^{-2}
	90	3·35 × 10^{-3}		90	1·93 × 10^{-2}
10·10	96	1·36 × 10^{-2}		80	6·65 × 10^{-3}
	90	7·60 × 10^{-3}	29·40	90	4·71 × 10^{-2}
	80	2·70 × 10^{-3}		80	2·26 × 10^{-2}
				70	7·10 × 10^{-3}

alkalinity and that water enters into the kinetic equation of the rate-limiting reaction step.

Wilmarth and Fluornoy[14] studied the dependence of the rate of *para*hydrogen conversion on the strength of aqueous solutions of potassium, sodium and lithium hydroxides. The experiments were carried out over a wide range of potassium hydroxide concentrations and comparison made between K_{eff} constants and the average ion activity $Q_{\pm}$.

The rate constants of *para*hydrogen conversion at 70° allowing for the ratio between the volumes of the gaseous and liquid phases may be found in the work of reference.[14] However, for a comparison with the alkalinity of the medium account must be taken of the change in the hydrogen solubility with increasing concentration of potassium hydroxide. Unfortunately, the solubilities of hydrogen in aqueous solutions of potassium hydroxide are known only for 0·5 and 1 M potassium hydroxide at 25°. The solubilities of hydrogen in aqueous solutions of sodium hydroxide[15] for 25° are known up to 4 M sodium hydroxide.

From these data,[15] it can be tentatively assumed that as compared to the solubility in water the solubility of H_2 in 2, 3 and 4 M solutions of sodium hydroxide decreases

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[14] W. K. Wilmarth and J. M. Fluornoy, *J. Amer. Chem. Soc.* **83**, 2257 (1961).

[15] Landolt and Bernstein, *Phys. Chem.* Tabellen, **1**, 77, Berlin (1923).

TABLE 2

δ-valerolactam

% KOH by weight	log K_{eff}	log Q_{OH^-}	log Q_{H_2O}	log $\frac{K_{eff}}{Q_{OH^-} - Q_{H_2O}}$	$E \frac{kcal}{-mole}$
1·037	−2·80	−0·81	−0·002	−1·99	13·5
2·250	−2·48	−0·52	−0·005	−1·95	13·5
4·184	−2·21	−0·25	−0·011	−1·95	13·5
8·056	−1·91	0·105	−0·025	−1·99	13·5
12·41	−1·62	0·38	−0·040	−1·95	13·5
15·76	−1·44	0·575	−0·054	−1·96	13·5
20·45	−1·21	0·85	−0·030	−1·98	13·5
26·95	−0·90	1·235	−0·134	−2·01	13·5
33·16	−0·66	1·61	−0·240	−2·03	13·5

enantholactam

% KOH by weight	log K_{eff}	log Q_{OH^-}	log Q_{H_2O}	log $\frac{K_{eff}}{Q_{OH}Q_{H_2O}}$	$E \frac{kcal}{mole}$
5·75	−5·95	−0·08		−5·90	25·5
10·10	−5·63	0·25	−0·02	−5·80	25·5
19·90	−5·23	0·82	−0·08	−5·97	25·5
29·40	−4·71	1·36	−0·17	−5·90	25·5

Note: The values of Q_{KOH} are taken from ref. 12 and of Q_{H_2O} from ref. 13.

in inverse proportion to the alkali molarity. Assuming that this regularity is also observed for concentrated solutions of potassium hydroxide at 70°, the effective constants of *para*hydrogen conversion, K_{eff}, which can be compared with the alkalinity of the medium can be calculated. It may be seen from data of Table 3 that the change in K_{eff} of *para*hydrogen conversion is determined by $Q_{\pm}$.

The dependence of K_{eff} on $Q_{\pm}$ of diacetone alcohol decomposition within the potassium hydroxide concentration range from 0·50 to 17·53%; K also follow the equation:

$$\log K_{eff} + \log Q_{\pm} = \text{const} \quad [3]$$

The $Q_{\pm}$ value of aqueous solutions of potassium hydroxide are termed the alkalinity of the medium and denoted by Q_{OH^-} log Q_{OH^-} is the alkalinity function.

TABLE 3*

KOH molality	log $Q_{\pm}$	$K \times 10^3$	$K_{eff} \times 10^3$	$K_{eff}/Q_{\pm} \times 10^3$
3·0	+0·44	1·70	5·1	1·8
5·4	+0·90	3·4	18·4	2·3
10·60	+1·66	8·8	93	2·0
18·0	+2·46	55·8	1,000	3·6

* The values of $Q_{\pm}$ at 70°C are taken from the work of reference.[14] K is the experimental rate constant corrected for the ratio between the volumes of the gaseous and liquid phases. K_{eff} is the rate constant with account taken of the change in the solubility of hydrogen relative to the solubility in water.

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[12] R. A. Robinson and R. M. Stokes, *Trans. Faraday Soc.* **45**, 612 (1949).

[13] E. Shibata, J. Kobayaschi and S. Furukawa, *J. Chem. Soc., Japan* **52**, 404 (1931).

[14] G. Akerlof and P. Bender, *J. Amer. Chem. Soc.* **70**, 2366 (1948).

Mechanism of the elementary rate-limiting step of the hydrolysis of lactams and amides

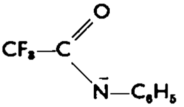
In order to establish the mechanism of the slowest elementary step of the hydrolysis of lactams and amides, it is necessary to determine

(a) which of the ionized forms of lactam is reactivative and

(b) whether the rate-limiting step is unimolecular or bimolecular, i.e., whether water enters in the kinetic equation for the rate-limiting step.

It follows from the I.R. data that ionization of γ-butyrolactam in concentrated aqueous solutions of potassium hydroxide produces a singly charged BOH^- ion and a dianion.

When Taft and Biechler[18] investigated the mechanism of amide hydrolysis they considered the formation of ions with a negative charge on the nitrogen atom. The authors based their conclusions solely on kinetic investigations. Studying the hydrolysis of trifluoroacetanilide in aqueous and aqueous-dioxane solutions of sodium hydrate, Taft and Biechler[18] found that when the concentrations of sodium hydroxide exceed 0·28 N the rate constant of hydrolysis no longer depends on the catalyst concentration. This result can be obtained if all the amide is in an ionized form. The authors give the ion the formula



where the negative charge is on the nitrogen atom. Since such ions are unreactive during hydrolysis the authors assume that other reactive ions also exist in equilibrium with such ions at low concentrations. The results obtained by other researchers[19] show that considerable ionization of the reagent may be surmized from the dependence of K_{eff} on the strength of the alkali. However, the reactivity is ascribed to other ions which, in the opinion of these authors, are present in low concentrations. The question of the role of various equilibria is extremely important for establishing the kinetic equation of the rate-limiting elementary act, and for calculating the true activation energies and the pre-exponential factors.

γ-Butyrolactam clearly shows that in lactam hydrolysis only the ions present in high concentrations possess reactivity. Although, opposite cases are possible, the application of kinetic methods and independent identification of the equililbrium forms of the reagent in the solution, have determined the detailed mechanism of the limiting act of the process with a high degree of accuracy.

As anticipated, a complex dependence of K_{eff} on the concentration of potassium hydroxide is observed for γ-butyrolactam. As the concentration of potassium hydroxide from 1·037 to 40·86%, K_{eff} increases, but decreases in more concentrated alkali solutions.[4] (Fig. 5).

Lactam hydrolysis in a KOD medium at 40° were carried out in order to compare the hydrolysis rate constants with the concentrations of singly charged BOH^- ions. The hydrolysis rate constant and at the same time the concentration of the

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[19] J. T. Edwards and K. A. Terry, *J. Chem. Soc.* 3527 (1957).

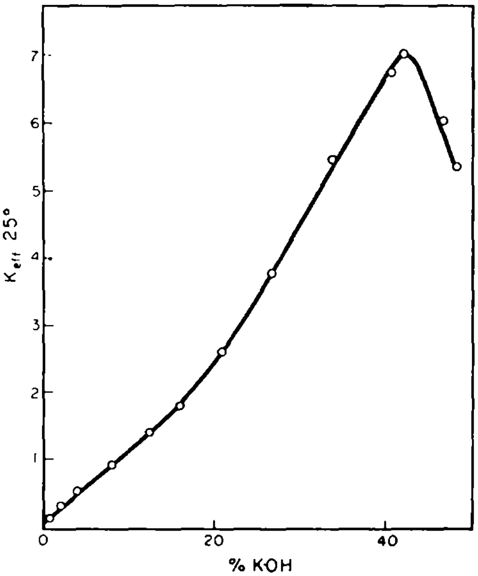

FIG. 5. K_{eff} as a function of potassium hydroxide concentration for γ-butyrolactam at 25°.

non-ionized form of C_B and ions C_{BOD^-} were determined from I.R. spectra. The concentration of γ-butyrolactam in these experiments amounted to about 0·8 mole/litre. Table 4 shows that the K_{eff}/C_{BOD^-} and $K_{eff}/C_{BOD^-}Q_{D_2O}$ ratios do not remain constant for 18·98 and 28·02% KOD solutions where the concentrations of the components are determined accurately.

TABLE 4*

% KOD by weight	K_{eff}/min^{-1}	Q_{D_2O}	C_B	C_{BOD^-}	$\frac{K_{eff}}{C_{BOD^-}}$	$\frac{K_{eff}}{C_{BOD^-}Q_{D_2O}}$
9·06	$1·5 \times 10^{-3}$	0·18	0·96	0·04	$3·7 \times 10^{-2}$	$4·6 \times 10^{-2}$
18·98	$4·7 \times 10^{-3}$	0·61	0·83	0·17	$2·7 \times 10^{-2}$	$4·5 \times 10^{-2}$
28·02	$2·5 \times 10^{-2}$	0·41	0·59	0·41	$6·1 \times 10^{-2}$	$1·5 \times 10^{-1}$

* The activity Q_{D_2O} of water was measured by the tension of water vapour over solutions of lactam in KOD.

The increase in these ratios in concentrated solutions is due to the appearance of a doubly ionized form in noticeable concentrations. It will, therefore, be assumed that both singly and doubly charged ions are reactive during the hydrolysis of amides and lactams. These data show that the doubly charged ion possesses greater reactivity than the singly charged ion. Taft and Biecher[18] demonstrated that reactive dianions form in concentrated solutions of alkali. Other researchers[20] also support to this viewpoint.

As the hydrolysis rate constant of γ-butyrolactam drops in alkali solutions exceeding 40·86% potassium hydroxide (by weight), the equilibrium constants K_r and K_r' show that in such solutions all the γ-butyrolactam is present in the form of BOH^- and $BOO^=$ ions and the concentration of dianions exceeds that of BOH^- ions. The decrease in K_{eff} for such solutions is due to the fact that in the rate-limiting step the $BOO^=$ dianion reacts with the water molecule. Similarly, the rate of conversion of the BOH^- ion into hydrolysis products is likewise determined by the interaction of the ion and the water molecule. In the hydrolysis of N-phenylurethanesulphamide in aqueous solutions of sodium hydroxide, Palm and Kubar[21] showed that the K_{eff} maximum depends on the alkali concentration. Since the ionization of the reagent in their experiments was only the formation of a singly charged ion, the decrease in K_{eff} for concentrated solutions of sodium hydroxide was due to a decrease in H_2O activity.

The mechanism of lactam hydrolysis may, therefore, be represented as on opposite page.

The dependence of K_{eff} on the solution properties is expressed by the equation:

$$K_{eff} = \frac{K_{true} \cdot Q_{H_2O} \times K_2' \dfrac{Q_{H_2O}}{Q_{OH^-}} + K'_{true} \times Q_{H_2O}}{1 + K_2' \dfrac{Q_{H_2O}}{Q_{OH^-}} + K_2 \times K_2' \dfrac{Q_{H_2O}}{(Q_{OH^-})^2}} \qquad [4]$$

K'_{true} is the true rate constant of the interaction of the $BOO^=$ dianion and a water molecule.

$$K_2' = \frac{Q_{BOH^-} \times Q_{OH^-}}{Q_{BOO^=} \times Q_{H_2O}}$$

K_{true} is the true rate constant of the interaction of the BOH^- ion and a water molecule

$$K_2 = \frac{Q_B \times Q_{OH^-}}{Q_{BOH^-}}$$

The experimental values of K_{eff} for γ-butyrolactam hydrolysis are satisfactorily described by the equation [4]. This equation was used to calculate $K_{true} = 4 \times 10^{-3}$ min^{-1} and $K'_{true} = 2{\cdot}62 \times 10^{-2}$ min^{-1} for 25° as well as $K_r = 4$ and $K_r' = 190$. The constants K_r and K_r' calculated by this equation show fair agreement with those obtained from the data of I.R. and U.V. spectra.

The same equation describes the dependence of K_{eff} of N-methylacetamide hydrolysis on the alkalinity and activity of water in 2–50·4% potassium hydroxide

TABLE 5

Lactam or amide	$\log \frac{K_{true}}{K_r}$	$E \frac{kcal}{mole}$
γ-Butyrolactam	−3·0	14·2
δ-Valerolactam	−2·0	13·4
ε-Caprolactam	−3·6	16·7
Enantholactam	−5·9	25·5
N-Methylacetamide	−3·25	15·7
Acetamide[20]	−2·65	14·8

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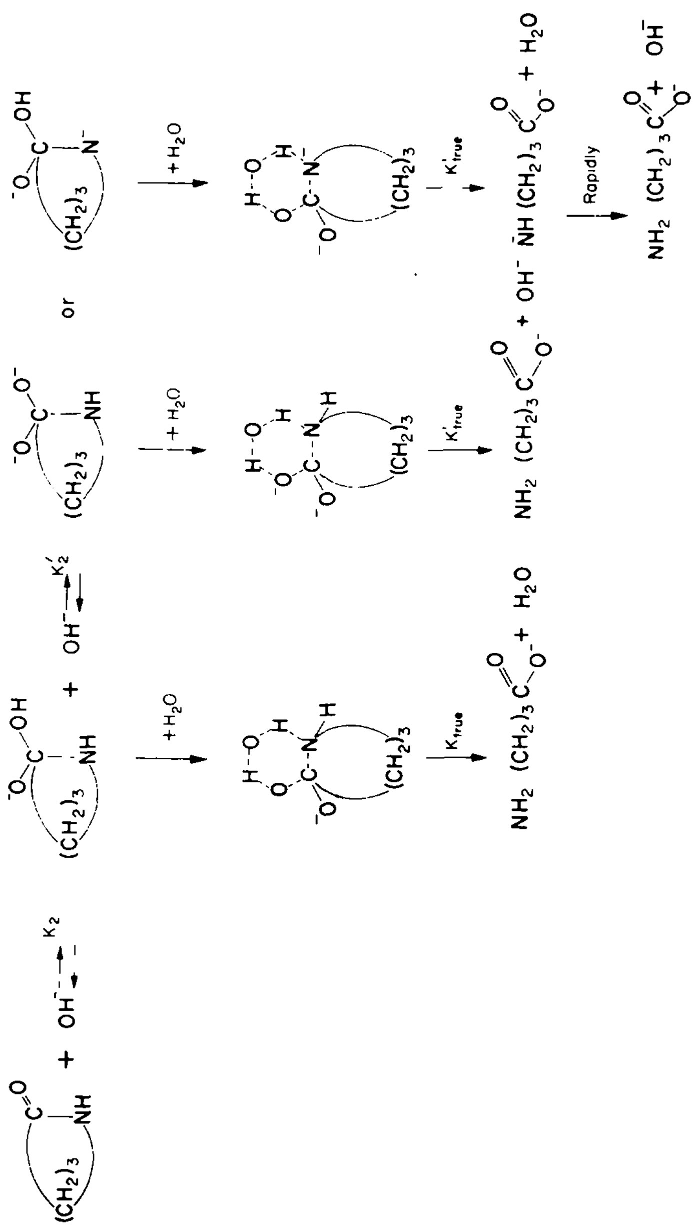
K2
K'2
+H2O
K_true
K'_true
Rapidly
or

solutions.[22] The hydrolysis of amides and lactams may be assumed to follow the same course. For N-methylacetamide at 25°, $K_{\text{true}} = 2{\cdot}5 \times 10^{-2}$ min^{-1} and $K'_{\text{true}} = 0{\cdot}71$ min^{-1}. The ionization constants of N-methylacetamide in aqueous solutions of potassium hydroxide are calculated by the equation [4]. $K_r = 42{\cdot}5$, $K_r' = 1{\cdot}43 \times 10^4$.

It was impossible to find separately the true rate and ionization constants of ε-caprolactam, δ-valerolactam and enantholactam. To estimate the effect of the chemical structure of the reagent on the formation equilibrium constant and the reactivity of singly charged BOH^- ions, the known values of K_{true}/K_r for 25° and the effective activation energies are compared.

EXPERIMENTAL

The kinetics of the hydrolysis of lactams and N-methylacetamide was investigated by the change in the absorption in the ultra-violet using a spectrophotometer СФД-I with diffraction grating. The quartz vessels were controlled thermostatically to an accuracy of ±0·1°. The concentration of lactams and N-methylacetamide amounted to 10^{-1}–10^{-3} mole/litres. KOD was obtained by evaporating a dil. KOH solution in D_2O in a platinum crucible. The I.R. spectra were obtained on a type double-beam spectrophotometer of the Russian mark "ИКС-14". Some of the kinetic experiments on the hydrolysis of γ-butyrolactam were based on absorption variations in the I.R. region of the spectrum. The degree of conversion of lactam into amino acid was determined by the change in the intensity of the absorption band with a frequency of 1,650 cm^{-1}. Hydrolysis of lactams and N-methylacetamide is unimolecular with respect to the reagent and irreversible. The effective rate constant K_{eff} was calculated by the equation for unimolecular reactions. The rate constant did not change until complete conversion of the reagents.

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