ENAMINES. V.*

STUDY OF THE MECHANISM OF THE POLAROGRAPHIC REDUCTION OF 4-HYDROXYMETHYLENE-3-OXOCAPROLACTAM

M. K. Polievktov, A. B. Grigor'ev,
R. A. Dubinskii, and V. G. Granik

UDC 543.253:547.891

The two-electron electrical reduction of 4-hydroxymethylene-3-oxocaprolactam in aqueous solutions at pH < 3 proceeds reversibly to give the corresponding enediol, from which 4-formyl-3-hydroxycaprolactam (the principal pathway) and 4-hydroxymethylene-3-oxocaprolactam are formed by a protropic shift. An increase in the pH of the medium leads to acceleration of the subsequent chemical steps and determines the irreversibility of the reduction at pH > 4.

A polarographic method has previously [2] been used for the study of the kinetics of hydrolysis of 4-dimethylaminomethylene-3-oxocaprolactam to 4-hydroxymethylene-3-oxocaprolactam I. The present research was devoted to the study of the mechanism of the reduction of enol I on a dropping mercury electrode in an aqueous medium. In a 1.0 M HCl base electrolyte one reduction wave is formed (Fig. 1, curve 1). The height of this wave corresponds to the transfer of two electrons, and the $\Delta E/\Delta[\log(i/i_{\text{lim}} - i)$ value is 28 mV. When the pH is increased to 3, the height of this wave and its slope remain constant, whereas $E_{1/2}$ is shifted to negative potentials, with $\Delta E_{1/2}\Delta pH$ equal to 81 mV. In addition to the principal reduction wave at more negative potentials, a second markedly stretched out wave, which initially increases and then vanishes as the acidity decreases is observed in the same pH range (≤ 3). The height of the second wave reaches its maximum value in a 0.25 M HCl base electrolyte (Fig. 1, curve 2). At pH 3-5 the polarograms of enol I contain only one reduction wave, the height of which remains constant, but the slope decreases sharply, whereas a discontinuity appears on the curve of the dependence of $E_{1/2}$ on the pH of the medium. When pH > 5.5, this wave begins to decrease and vanishes completely at pH > 10 with the simultaneous appearance at more negative potentials of a new reduction wave (Fig. 1, curves 5 and 6). The total current at pH > 8 exceeds the value corresponding to the transfer of two electrons and increases as the pH increases, during which the wave in the upper portion of the curve is split (Fig. 1, curve 7). The dependences of the heights of the observed waves and of $E_{1/2}$ on the pH of the medium are presented in Fig. 2.

Enol I is a relatively strong acid (pK_a 4.11) [2] and is therefore, found practically completely in the anionic form in solutions with pH ≅ 6, and the wave with $E_{1/2} = -1.60$ V corresponds to its reduction. The rate of protonation of this anion is quite high in buffered media, and, in addition to the reduction wave of the anion, a wave whose height is determined by the rate of protonation is observed in the region of more positive potentials at pH < 10. At pH < 5.5 the rate of this process becomes so high that there is only one reduction wave of enol I on the polarograms. As in the case of buffered media with pH ≅ 5.5, the polarograms of enol I in unbuffered KCl solutions contain two waves, but the first wave is observed at considerably more positive potentials; this is associated with the low pH of the unbuffered solutions of enol I. As the ionic strength (μ) of the solution increases, the height of this wave decreases because of an increase in the pH of the near-cathode layer as potential ψ' decreases, during which the second wave is shifted to more positive potentials. The $\Delta E_{1/2}/\Delta\log \mu$ value is 80 mV, i.e., as one should expect in the case of reduction of anions [3], it exceeds the change in the ψ potential.

It should be noted that in media in which the first wave of enol I has kinetic character, it consists of two portions (see Fig. 1, curves 5 and 6). This evidently associated with the possibility of protonation of the anion of enol I to give two different products:

---

*See [1] for communication IV.

S. Ordzhonikidze All-Union Scientific-Research Pharmaceutical-Chemistry Institute, Moscow 119021. Translated from Khimiya Geterotsiklicheskikh Soedinenii, No. 4, pp. 486-490, April, 1977. Original article submitted March 29, 1976.

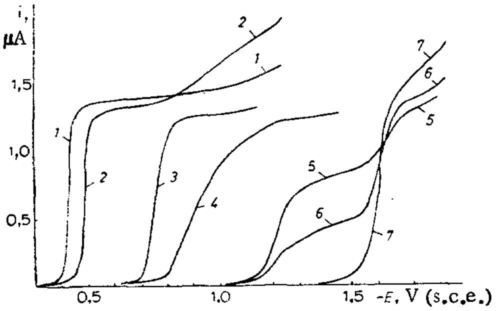


Fig. 1

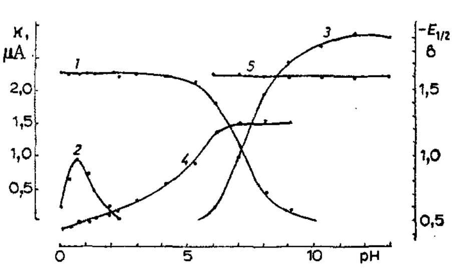


Fig. 2

Fig. 1. Polarograms of a 0.57 mM solution of 4-hydroxymethylene-3-oxocaprolactam in a 1.0 M HCl base electrolyte (1), in a 0.25 M HCl base electrolyte (2), in buffered media with pH 4.12 (3), 5.27 (4), 6.94 (5), and 8.03 (6), and in a 0.1 M NaOH base electrolyte (7).

Fig. 2. Dependence of the $\varkappa = i_{\lim}/c$ (1, 2, and 3) and $E_{1/2}$ (4, 5) values of the reduction waves of 4-hydroxymethylene-3-oxocaprolactam on the pH of the medium.

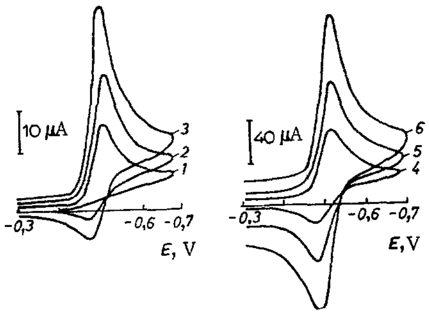
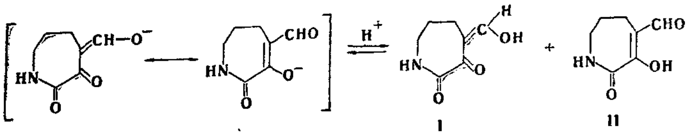


Fig. 3. Cyclical voltamperograms of a 0.5 mM solution of 4-hydroxymethylene-3-oxocaprolactam in a 0.1 M HCl base electrolyte at potential-scanning rates of: 1) 0.2; 2) 0.5; 3) 1.0; 4) 2.0; 5) 5.0; 6) 10.0 V/sec.

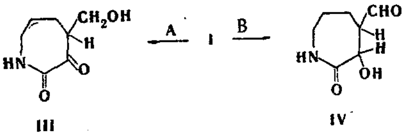


I

II

Enol I is indisputably the thermodynamically favorable form [2], but it may be assumed that the II → I transformation is relatively slow and that there is not enough time for it to occur under the polarographic conditions; the kinetic wave therefore, corresponds to the reduction of both enol I and II.

The surpassing of the total current at pH > 8 of the two-electron level and the splitting of the wave are apparently explained by subsequent reduction under these conditions of substances formed after the transfer of two electrons to the I molecule. It follows from general considerations that the two-electron reduction of I may proceed via two pathways (A and B) to give 4-hydroxymethyl-3-oxocaprolactam III or 4-formyl-3-hydroxycaprolactam IV.



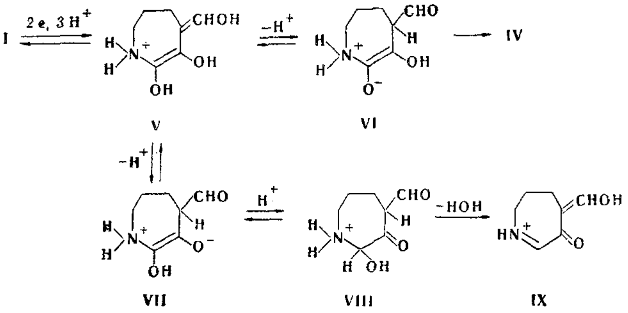
III

IV

A model compound — 3-oxocaprolactam — is reduced in one step in both acidic and alkaline media (the $E_{1/2}$ values of the reduction waves of 3-oxocaprolactam in 1 M HCl, 0.1 M HCl, and 0.1 M KOH base electrolytes are, respectively, -0.52, -0.58, and -1.19 V). It follows from a comparison of these data with the $E_{1/2}$ values of the waves observed on the polarograms of I (see Fig. 1) that pathway A is not realized and that the final product of reduction of enol I is aldehyde IV.

Thus the increase in the limiting current of the reduction wave of enol I in alkaline media is due to subsequent reduction of aldehyde IV, the wave of which is observed in the same range of potentials as observed for other aliphatic aldehydes, whereas the limiting current increases as the pH increases; this is determined by the increase in the rate of dehydration of the aldehyde group [3].

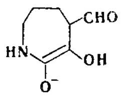
The appearance of a second reduction wave over a narrow range of pH values of acid solutions is evidently associated with chemical side processes that accompany the two-electron reduction of I. In fact, as we have already pointed out above, the slope of the wave in semilogarithmic coordinates constitutes evidence for the reversible character of the reduction of enol I; this is also confirmed by cyclical voltamperometric data (Fig. 3). As seen from Fig. 3, the anode oxidation peak is observed at a potential-scanning rate of 0.5 V/sec, and is is also apparent that the higher the rate, the greater the ratio of the height of the anode peak to the height of the cathode peak. However, enol I and hydroxy aldehyde IV cannot constitute a reversible redox pair, and an intermediate that has time under the polarographic conditions to undergo conversion to give polargraphically active compounds that form the second wave at pH ≤ 3 consequently should exist. In our opinion, the first product of the two-electron reduction of enol I is relatively unstable enediol V, the pathways of the subsequent conversion of which can be represented in general form by the following scheme:



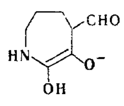
Thus the chemical transformations of V provide for the formation of two zwitterions (VI and VII). Dipolar ion VI is subsequently protonated at 3-C to give aldehyde IV (the principal pathway of the process), while ion VII adds a proton to 2-C, and the resulting carbinol amine VIII undergoes subsequent relatively slow dehydration to imine IX. In conformity with the theory in [3], in the case of a reversible two-electron process that occurs with the consumption of two protons, the $\Delta E_{1/2}/\Delta pH$ value at 25° should be 59 mV, as compared with 88.5 mV in the case of consumption of three protons. The experimentally determined $\Delta E_{1/2}/\Delta pH$ value for enol I is 81 mV; this is also in good agreement with both theory and the scheme presented above, which requires the consumption of three protons and two electrons for the reduction of I. An examination of the structures of zwitterions VI and VII makes it possible to assume that 3-C protonation of ion VI will predominate over 2-C protonation of ion VII, since there would be greater ion—ion repulsion of the ring NH_2^+ group and the hydronium cation in the latter case.

Thus the V → IV pathway is the principal transformation of V. The height of the second wave at pH < 3 is therefore relatively low (under these conditions the wave of aldehyde IV is covered by the discharge current of the base electrolyte) and can be ascribed to reduction of carbinol amine VIII, which does not have time under the polarographic conditions to undergo dehydration to imine IX. In fact, the latter should be reduced more readily than the starting depolarizer and should give an increase in the current above the level corresponding to the transfer of two electrons.

As the pH of the medium increases, the rate of detachment of a proton from the intermediate of the two-electron reduction of enol I increases sharply, as a result of which the reduction becomes irreversible. It may be assumed that the transformations of the initial reduction product proceed through the formation of anions X and XI,



X



XI

whereas C-protonation becomes more selective as compared with strongly acidic media, in which the hydronium ion acts as the protonating agent. We also note that the electron density on the 3-C atom in X is substantially higher than on the 2-C atom of XI due to the effect of two electron-donor groups (:NH and O^-), and the 3-C protonation process therefore, should be preferable. As a result, the rate of the X → IV transformation is much higher than the rate of formation of the carbinol amine during 2-C protonation of anion XI, so that one pathway, i.e., the formation of IV, is realized in the irreversible reduction of enol I.

Coulometric measurement of the number of electrons during the electrical reduction of enol I in 1 M HCl solution gave $n = 2.7$, during which if the electrolysis is interrupted and the polarographic curve is recorded, a new small wave appears in front of the principal reduction wave of I. These data are in good agreement with the scheme presented above, since in the case of electrolysis (in contrast to polarography) there is time for dehydration of carbinol amine VIII, as a result of which one observes an increase in the number of electrons, and interruption of the electrolysis makes it possible to record the formation of imine IX, which is reduced more readily than starting depolarizer I. After prolonged electrolysis, the polarographic curve does not differ from the curve of the base electrolyte, and a wave with $E_{1/2} = -1.65$ V is observed when the reduction products are transferred to an alkaline medium. The reduction wave of the electrolysis products increases and is shifted to positive potentials ($E_{1/2} = -1.36$ V) when the electrolysis products are transferred to a buffered solution with pH 10.5 made up of NaOH and hexamethylenediamine adipate [4]. All of this constitutes evidence in favor of the formation of aldehyde IV during electrolysis. It should be noted that coulometric measurements in a buffered solution with pH 5.27 give $n = 1.85$, whereas the reduction products also form a wave with $E_{1/2} = -1.36$ V in the above-indicated buffer solution. Thus these data confirm the scheme presented above for the electrical reduction of enol I and selectivity of the direction of the process in media in which enol I is reversed irreversibly.

EXPERIMENTAL

Polarography was carried out in a thermostatted cell at 25 ± 0.1°. The dropping mercury electrode with a spatula for forced detachment of the drops had the following characteristics: $m = 0.82$ mg/sec and $t = 0.4$ sec. An external saturated calomel electrode served as the anode. The polarograms were recorded with a Radiometer PO-4 polarograph. A PAR-170 "electrochemical system" and an OH-404 coulometric analyzer (Radelkis) were used for the coulometric measurements and the degree of cyclical voltamperograms.

LITERATURE CITED

1. A. B. Grigor'ev, V. G. Granik, and M. K. Polievktov, Zh. Obshch. Khim., 46, 404 (1976).
2. R. G. Glushkov, O. Ya. Belyaeva, V. G. Granik, M. K. Polievktov, A. B. Grigor'ev, V. E. Serokhvostova, and T. A. Vlasova, Khim. Geterotsikl. Soedin., No. 12, 1640 (1976).
3. S. G. Mairanovski, Catalytic and Kinetic Waves in Polarography [in Russian], Nauka, Moscow (1966).
4. M. P. Strukova, Yu. S. Ignat'ev, L. N. Smirnov, and G. P. Smirnova, Zh. Anal. Khim., 27, 1647 (1972).