Electroanalytical Chemistry and Interfacial Electrochemistry, 48 (1973) 277–283

ELECTROCHEMICAL REDUCTION OF AZOMETHINE DERIVATIVES OF α-DIKETONES

III. 1,2-DIHYDROPYRROLIZINE-1,2-DIONE DIOXIME

MARIO E. CARDINALI, ITALO CARELLI and ANTONIO TRAZZA

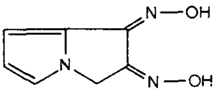
Istituto di Chimica della Facoltà di Ingegneria, Università di Roma and Centro di Elettrochimica e Chimica Fisica delle Interfasi del Consiglio Nazionale delle Ricerche, Rome (Italy)

(Received 30th May 1973)

INTRODUCTION

This paper is concerned with a study on the polarographic behaviour of 1,2-dihydropyrrolizine-1,2-dione dioxime (I), which was supported by spectrophotometric and coulometric determinations. This study should be considered a part of a more comprehensive research on those derivatives of 1,2-dihydropyrrolizine which contain substituents in both positions 1 and 2[1]; these compounds are of some biological interest[2].

Very scanty data are found in the literature about the electrochemistry of *vic*-dioximes in aqueous media. Most data are concerned with *vic*-dioximes of aliphatic, or aryl-aliphatic, or alicyclic, α-diketones[3–7], which generally are reduced to the corresponding amines in acidic media, either via a single eight-electron step or via a six-electron intermediate.



(I)

EXPERIMENTAL

The electrochemical and spectrophotometric apparatus described in a previous paper[1] was used for the measurements. The compound (I) was prepared[2] and recrystallized from water (m.p. 235°C, dec.). All other products were A.R. grade; Britton and Robinson buffer solutions[8] were used to provide media with stable pH values. The solutions were de-oxygenated with 99.99% pure nitrogen. The temperature was controlled within ±0.1°C. Potentials were measured against a saturated calomel electrode. The characteristic of the capillary was $m^{\frac{2}{3}}t^{\frac{1}{6}} = 1.74$ mg$^{\frac{2}{3}}$ s$^{-\frac{1}{2}}$, when measured at $E = -0.70$ V and $T = 21.3$°C, under a mercury head of 80.0 cm in a buffer solution at pH = 2.98, where compound (I) was present at 1.054×10^{-4} M concentration.

RESULTS AND DISCUSSION

(a) Polarography

The reduction of compound (I) at a dropping mercury electrode produces several waves, whose height and/or potential vary according to pH (Fig. 1). The height of wave A (the least cathodic wave) is almost constant up to $\text{pH} \simeq 7.5$. At higher pH values, its limiting current gradually decreases; when pH is 12 or more, it completely disappears (Fig. 2). A plot of the half-wave potential $(E_{\frac{1}{2}})_A$ against pH is linear up to $\text{pH} \simeq 9$, according to the relation $(E_{\frac{1}{2}})_A = -0.33_5 - 0.06_3$ pH. At pH values higher than 9, the half-wave potential shows a constant value $(E_{\frac{1}{2}})_A = -0.95$ V, practically independent of pH. At those pH values ($\text{pH} < 7.5$) where the height of A is constant, its limiting current is diffusion-controlled. The Ilkovic constant is $(I_d)_A = 10.15$ when determined at $T = 21.3°\text{C}$ and $h = 80.0$ cm in a $\text{pH} = 3$ buffer solution containing (I) at 1.05×10^{-4} *M* concentration. A comparison of this value with the same datum relative to the four-electron reduction step of 2-oxyimino-1,2-dihydropyrrolizin-1-one[1] suggests that the reduction step which gives rise to wave A involves six electrons per molecule of (I).

At potentials more cathodic than $(E_{\frac{1}{2}})_A$, the polarogram shows a second wave (wave B, Fig. 1). Its limiting current is equal to about $\frac{1}{3}$ $(i_l)_A$ and remains

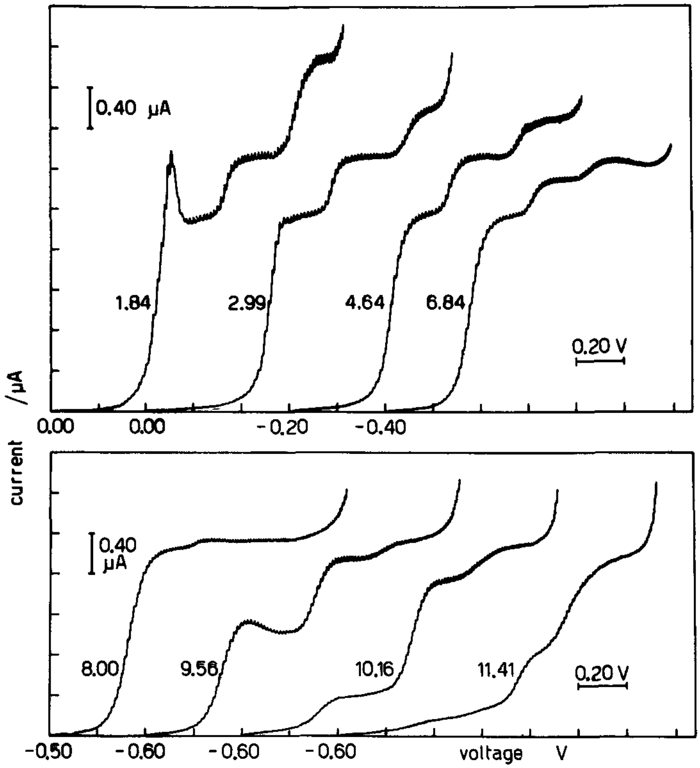


Fig. 1. Typical reduction polarogram of 1,2-dihydropyrrolizine-1,2-dione dioxime at 9.9×10^{-5} *M* concn. in buffer solns. at pH values indicated (mercury head = 80.0 cm, $T = 22.0°\text{C}$).

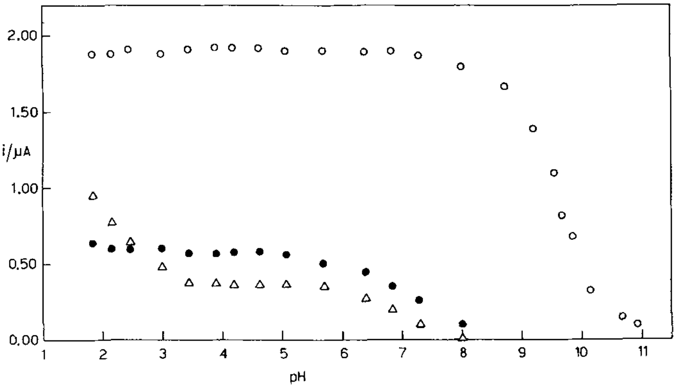


Fig. 2. Dependence of limiting current values of reduction waves of (I) on pH; exptl. conditions are as in Fig. 1. (○) wave A, (●) wave B, (△) wave C.

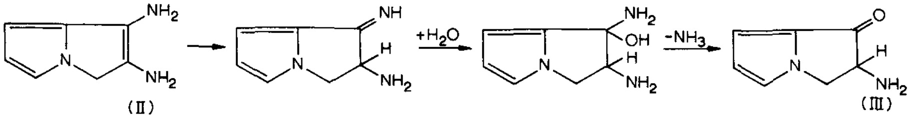
constant and diffusion-controlled up to pH$\simeq$5. At higher pH values it gradually decreases, to disappear at pH$\simeq$8.5 (Fig. 2). Up to pH$\simeq$3.5, the half-wave potential $(E_{\frac{1}{2}})_B$ depends on pH according to the relation $(E_{\frac{1}{2}})_B = -0.67_5 - 0.04$ pH, while at pH$>$3.5, $\Delta(E_{\frac{1}{2}})_B/\Delta$ pH$= -68$ mV.

At potentials more negative than wave B, a third wave is observed (wave C in Fig. 1), whose limiting current is about $\frac{1}{2}$ $(i_l)_A$ at the most acidic pH values investigated. It rapidly decreases up to pH$\simeq$3.5; then it attains a constant value up to pH$\simeq$5.5 (about $\frac{1}{6}$ $(i_l)_A$), to decrease again in less acidic media and finally to vanish at pH$\simeq$8 (Fig. 2). The half-wave potential is related to pH by means of the equation $(E_{\frac{1}{2}})_C = -0.99 - 0.04_3$ pH. The dependence of $(i_l)_C$ on the mercury head points out a partially kinetic character for the electrode process. At pH$\simeq$2, where $(i_l)_C$ attains its highest values, the addition of increasing quantities of a cationic surfactant, such as phenyltrimethylammonium bromide, to a solution of (I), causes wave C to undergo a proportional decrease, and its half-wave potential to be shifted towards remarkably more negative values, so that when the surfactant-to-depolarizer concentration ratio is about 100, wave C disappears, since it is masked by the base electrolyte discharge.

Therefore, at pH$\simeq$8.5, only wave A can be observed in the reduction polarogram of (I) (Fig. 1). At more alkaline pH values, wave A gradually decreases, as previously stated, and two new waves (A′ and A″) are formed at more negative potentials, whose limiting currents increase with pH, while their half-wave potentials exhibit the values -1.32 V and and -1.58_5 V respectively, both almost independent of pH. However, the decrease of A, and the corresponding increases of A′ and A″, are not such that the total limiting current, $(i_l)_A + (i_l)_B + (i_l)_C$, is constant with pH; namely a progressive lowering of its value is observed as pH is increased, so that in 0.2 *M* NaOH it is equal to about a half of the value shown by $(i_l)_A$ in acidic or neutral media.

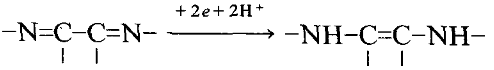
(b) Controlled potential reduction

In a buffer solution at pH$\simeq$3–4, the reduction of (I) involves six electrons per molecule when performed at a potential value E_A corresponding to the plateau of wave A. This result could be inferred from the value of $(I_d)_A$. The polarogram recovered after completion of the analysis shows that waves B and C have disappeared, as well as wave A, while a new wave (D) is present. It is about $\frac{1}{3}$ as high as wave A, and its half-wave potential is not very different from wave C. Therefore, it can be concluded that, during the electrolysis, the six-electron reduction product of (I) (henceforth called (II)) is turned into a compound which is no more reducible at the potentials of wave B, but only at more negative values. After the completion of the electrolysis, the u.v. spectrum is superimposable onto the spectrum of 1,2-dihydro-2-aminopyrrolizin-1-one (III)[1], if recorded under the same conditions. Furthermore, some qualitative tests, performed on the solution after the electrolysis, showed the presence of NH_3. These results suggest that (III) is the transformation product of the species formed at the electrode by means of the six-electron reduction of (I). Compound (III) can be reduced at the potentials of wave *D*, thus producing 1,2-dihydropyrrolizin-1-one (IV)[1]. Therefore, a formula can be attributed to (II), which should give rise to (III) according to the reaction



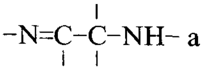
(II) (III)

This kind of reaction is shown by most ene-diamines. The reduction mechanism proposed for the formation of the unstable ene-diamine (II) from (I), can be compared with the reduction mechanism of *o*-benzoquinone dioxime, which is ultimately turned into *o*-phenylenediamine[9] after using up six electrons. Other similar mechanisms are argued for some quinoxalines, dihydro-5,6-pyrazines, and diimines of α-diketones. For all these compounds a reduction scheme



$$-\underset{|}{N}=\underset{|}{C}-\underset{|}{C}=N- \xrightarrow{+2e+2H^+} -NH-\underset{|}{C}=\underset{|}{C}-NH-$$

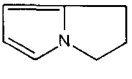
is reported[10]; sometimes transpositions to



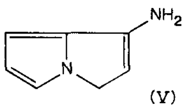
$$-N=\underset{|}{C}-\overset{|}{\underset{|}{C}}-NH-$$

and hydrolyses are admitted.

When (II) is further reduced without undergoing a chemical transformation into (III), that is when the reduction of (I) is carried out at a potential value E_B corresponding to the plateau of wave B, a number of electrons slightly lower than eight is observed to be used up per molecule of (I). After the electrolysis, the u.v. spectrum shows a main band with $\lambda_{max} = 313$ nm and $\varepsilon = 17578$ l mol^{-1} cm^{-1}; wave C is still present on the polarogram. These facts seem to exclude that, at the potentials of wave B, 1,2-dihydro-1,2-diaminopyrrolizine is formed, since its u.v. spectrum should be similar to 1,2-dihydropyrrolizine



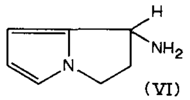
where no significant band can be observed at $\lambda > 220$ nm (ref. 2). It seems more probable that the reduction product is



(V)

(V) and that its formation is caused by a reductive cleavage of the C–N bond present in the molecule of the intermediate compound (II) in position 2. This opinion can be supported by the presence of NH_3 in the solution at potential E_B, and by a comparison between the u.v. spectra of 3-H pyrrolizine as well as some derivatives containing substituents in position 1 or 2 (ref. 11) and the spectrum of the eight-electron reduction product of (I).

After a further reduction at the potentials of wave C, the u.v. spectrum shows a slight absorption at 294 nm ($\varepsilon = 1800$ l mol^{-1} cm^{-1}) and a band with a maximum at 220 nm ($\varepsilon = 5300$ l mol^{-1} cm^{-1}). Instead of a stepwise reduction at potentials E_B and E_C, a straight one can be carried out at potential E_C; in the latter case, after the electrolysis the absorption in the u.v. spectrum at 294 nm almost vanishes, while the band at 220 nm is increased. These results suggest that the process which causes wave C should be mainly a saturation of the double bond in position 1,2 in the ring; compound (VI)



(VI)

should be produced[2]. The adsorption at 294 nm is typical for ketone (IV)[1]; it seems likely that the formation of small quantities of such compound can be ascribed to a reduction of (III) at E_C ($E_D = E_C$), if we admit that, besides a reduction as such, (II) can undergo a chemical transformation of some kinetic importance into (III). Obviously, as already observed, this side reaction will be less effective if the electrolysis is carried out directly at E_C, instead of stepwise at E_B and E_C. Therefore, the results previously shown can be summarized in the following scheme

$$(\mathrm{I})+\mathrm{H}^+ \xrightarrow[\text{for pH}>7.5]{\text{rate controlling}} (\mathrm{IH}^+) \xrightarrow{+6e+5\mathrm{H}^+} (\mathrm{II}) \qquad \text{(i)}$$

$$(\mathrm{II})+\mathrm{H}^+ \xrightarrow[\text{for pH}>5]{\text{rate controlling}} (\mathrm{IIH}^+) \xrightarrow[-\mathrm{NH}_3]{+2e+\mathrm{H}^+} (\mathrm{V}) \qquad \text{(ii)}$$

$$(\mathrm{V})+\mathrm{H}^+ \xrightarrow[\text{for pH}>5.5]{\text{rate controlling}} (\mathrm{VH}^+) \xrightarrow{+2e+\mathrm{H}^+} (\mathrm{VI}) \qquad \text{(iii)}$$

$$(\mathrm{II}) \xrightarrow{+\mathrm{H}_2\mathrm{O};\,-\mathrm{NH}_3} (\mathrm{III}) \qquad \text{(iv)}$$

$$(\mathrm{III}) \xrightarrow[-\mathrm{NH}_3]{+2e+2\mathrm{H}^+} (\mathrm{IV}) \qquad \text{(v)}$$

according to which, in an acidic and/or neutral medium, the three polarographic waves A, B and C are caused by processes (i), (ii) and (iii) respectively. In these processes, a protonation precedes the electronic transfer, as suggested by the dependence of $i_{\lim}$ and $E_{\frac{1}{2}}$ of the three waves on pH[12]. Moreover, at $\mathrm{pH} < 3.5$, the process of wave C seems to be accompanied by catalytic hydrogen evolution[1]. In the controlled potential electrolysis, if the reduction is carried out at E_A, mechanisms (i) and (iv) will predominate; step (v)[1] will follow, because of a further reduction of (III) at the potentials of the new wave D. Finally, if the reduction is carried out directly at E_C or stepwise at E_B and E_C, nearly the same sequence of reductive steps observed under polarographic conditions will take place. If the reduction of (I) is carried out at $\mathrm{pH} \simeq 8$, that is under such conditions that waves B and C nearly vanish, different results will be obtained according to the reduction potential. Namely, if this potential is about -1 V (at the beginning of the plateau of wave A), (III) will be formed, as in acidic media, via steps (i) and (iv); then the further reduction at -1.5 V (wave D) will produce (IV) via step (v). On the other hand, if the electrolysis is carried out at -1.5 V (end of the plateau of wave A), a compound whose absorption is about 220 nm will be formed in addition to (IV); the latter is produced via steps (i), (iv) and (v). It seems likely that, under these conditions, there may be kinetic competition between the protonation of (II) and the chemical transformation of (II) to (III), so that a reduction process of the protonated form of (II) to yield the corresponding saturated *vic*-diamine may be partially effective.

Finally, at $\mathrm{pH} > 8$, the ionization equilibria of the oximinic function of (I) and the splitting of wave A into three waves (A, A′ and A″) suggest that the reduction of the protonated form of (I) is gradually replaced by the reduction of the neutral or anionic forms (waves A′ and A″ respectively) at much more negative and pH-independent potentials. Moreover, the gradual decrease of the total limiting current shows that, as the proton supply to the interphase becomes increasingly difficult, the reduction process of (I) is no longer able to keep the current up to the diffusion levels observed in acidic or neutral media.

As a conclusion, because of the six-electron reduction product (ene-diamine), the polarographic reduction behaviour of (I) is reminiscent of the behaviour of the *ortho* and *para*-quinone dioximes[9,13], and emphasizes the activating role played by protonation in the reductive cleavage of the C–N bond, as a consequence of the larger number of basic sites in the molecule of (I).

ACKNOWLEDGEMENTS

The authors thank Mr. G. Vaccaro for technical help. This work was supported by the Consiglio Nazionale delle Ricerche.

SUMMARY

The electrochemical behaviour of 1,2-dihydropyrrolizine-1,2-dione dioxime (I) in aqueous buffered media has been studied by polarographic, coulometric and spectrophotometric means.

The main feature of the polarogram in acidic media is the presence of three waves (A, B and C). Wave A is caused by the reduction of (I) to the corresponding ene-diamine (II), which is then reduced to ene-amine (V) (wave B) and to amine (VI) (wave C). In a controlled potential electrolysis, performed at potentials of the plateau of wave A, the reduction yields 1,2-dihydro-2-aminopyrrolizin-1-one (III),

formed via hydrolysis of (II); a further reduction of (III) yields ketone (IV). When pH is increased, waves B and C are progressively lowered, and finally vanish at pH$\simeq$8, because of a slowing down of the pre-protonation steps. At pH$>$8, wave A is split into three waves (A, A′ and A″), the first of which increases, and the second and third decrease, as pH attains higher and higher values; this behaviour can be ascribed to the reduction of the protonated, neutral, and anionic form of (I).

REFERENCES

1 M. E. Cardinali, I. Carelli, G. Ceccaroni and A. Trazza, *J. Electroanal. Chem.*, 42 (1973) 49.
2 V. Carelli, M. Cardellini and F. Morlacchi, *Ann. Chim. (Rome)*, 57 (1967) 1462.
3 C. L. Perrin, *Progress in Physical Organic Chemistry, Vol. 3*, Interscience, New York, 1965, p. 248.
4 M. Spritzer and L. Meites, *Anal. Chim. Acta*, 26 (1962) 58.
5 R. I. Gelb and L. Meites, *J. Phys. Chem.*, 68 (1964) 2599.
6 M. E. Cardinali, I. Carelli and A. Trazza, *Ric. Sci.*, 39 (1969) 640.
7 P. Souchay and S. Ser, *J. Chim. Phys.*, 49 (1952) C172.
8 H. T. S. Britton, *Hydrogen Ions*, Chapman-Hall, London, 1932, p. 225.
9 C. D. Thompson and R. T. Foley, *J. Electrochem. Soc.*, 119 (1972) 177.
10 J. Pinson and J. Armand, *Bull. Soc. Chim. Fr.*, (1971) 1764.
11 V. Carelli, M. Cardellini and F. Morlacchi, *Ann. Chim. (Rome)*, 53 (1963) 309.
12 P. Zuman, *The Elucidation of Organic Electrode Processes*, Academic Press, New York, 1969, Ch. 2.
13 J. Bonastre and A. Castelbon, *Bull. Soc. Chim. Fr.*, (1972) 366.