Anodic Oxidation of 2,3-Diphenylindole

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The anodic (oxidative) electrochemical behavior of 2,3-diphenylindole (1) has been investigated with a view toward elucidating the decomposition pathway(s) of the initially generated cation radical. In acetonitrile with tetraethylammonium perchlorate as supporting electrolyte, the one-electron transfer step at platinum is followed by a rapid coupling of two 1 cation radicals to give the dimeric species 2. From the various spectral data, primarily ^{13}C NMR, of 2 it appears that 2 is an indole–indolenine dimer, the dimeric bond being formed between the 3 position in the indolenine moiety and, most probably, the 5 position in the indole portion of the dimer. This is in contrast to the analogous coupling patterns for various carbazole derivatives, whose cation radicals form simple carbazole–carbazole dimers.

The indole nucleus, with its widespread occurrence in natural systems,[1] has been the object of much chemical investigation. In this communication we wish to report the results of an anodic (oxidative) electrochemical study of 2,3-diphenylindole (1). The anodic electrochemical behavior of indole and its derivatives has only briefly been investigated, but these studies indicate that reactivity may be centered both in the benzene ring[2] and in the pyrrole ring.[3] Electrochemical studies of the structurally similar carbazole system in acetonitrile have revealed dimerization as the dominant process upon anodic oxidation.[4] The present study was directed toward determining which of these possibilities might pertain to the indole system under investigation.

Previous studies on indole itself[3] had shown that the electrochemistry was quite involved, but was concerned mainly with reactivity centered in the area of the 2,3 double bond. It was anticipated that protection of the double bond with phenyl groups might lead to less complicated behavior and that useful information on indole itself could be inferred from the "model" behavior of this compound; the results of this study are presented herein.

Results and Discussion

Initial information about the 2,3-diphenylindole system was obtained from a cyclic voltammetric study. The cyclic voltammogram (Figure 1) shows two waves; the first of these corresponds to the initial oxidation of 1, while the further anodic wave apparently is due to the oxidation of a product formed from the initially generated species. From a comparison of the cyclic voltammograms of 1 and its electrolysis product, it may be seen that the oxidation wave for this product corresponds fairly closely with the further anodic wave in the cyclic voltammogram of 1, there being an approximately 70 mV cathodic shift of the former with respect to the latter. This shift is most probably due to the presence of protons in the unreduced electrolysis mixture. In a study of the peak potential shift as a function of scan rate, an anodic shift of 20 mV per decade scan rate increase was found. A shift of this magnitude corresponds theoretically to a reversible (fast) electron transfer followed by a rapid second-order reaction.[5] The parameter $i_p/v^{1/2} C$ should also remain constant with scan rate;[6] a decrease of only 1% in this value over the range 0.5–60 V/min was observed. Previous work on various substituted carbazoles has indicated that the initial formation of a cation radical upon anodic oxidation is a reversible one-electron process.[7] Thus, it seems reasonable to suppose that the initial oxidation of 1 also produces the cation radical, which then undergoes a rapid dimerization (i.e., a subsequent second-order reaction). A coulometrically determined *n* value for this oxidation lends additional support for this one-electron process, the *n* value found being 1.05 (corrected for background current).

An approximate value for the rate constant of the dimerization reaction was determined by the method of Olmstead et al.[5] This method involves correlating the shift in peak potential from the standard potential $E°$ of the system (as a function of scan rate) with the kinetic parameter (i.e., the rate constant) of the system, thus requiring a value for $E°$. This value, a characteristic of the one-electron cation radical system in the absence of any kinetic complications, was obtained by scanning at a high rate (250 V/min) using oscilloscopic recording. The cyclic voltammogram obtained was that of a reversible system, having equal anodic and cathodic peak currents with no evidence of the second anodic wave; the $E°$ value was +1.08 V. A value of 2×10^6 M^{-1} s^{-1} for the rate constant was obtained from extrapolation of the working curve given by Olmstead et al.[5]

This value must be regarded as approximate because of possible errors in relating oscilloscopically recorded traces to conventionally recorded values of potential and because of the difficulty of obtaining an extremely accurate value from the oscilloscope abscissa. Nevertheless, the results serve to indicate that the following reaction is very rapid, an aspect also observed in the structually similar carbazole systems.[4]

The nature of the species finally formed in the electrochemical reaction was determined by spectral characterization of the mass electrolysis product. In general, as evidenced by the data in the Experimental Section, the spectral properties of 1 and of its electrolysis product are quite similar, suggesting similar structures for the two compounds. From the mass spectral data (peak at *m/e* 536), it appears that the compound is indeed a dimer of 1, with two hydrogens lost in the coupling reaction. The composition $C_{40}H_{28}N_2$ indicates that the electrolysis product is a simple dimer; in other words, apparently no further oxidation or gross structural changes in the basic indole nucleus have occurred. The infrared spectral data also support this conclusion, there being no bands present in the carbonyl region (1650–1800 cm^{-1}).

Especially useful in characterizing the dimer was its ^{13}C NMR spectrum. The spectral data for the dimer are presented in Table I, along with data for 1 and for 2,3,3-trimethylindolenine,[8] a model compound for the proposed dimer structure (cf. **2**, Figure 2c). The assignments for 1 were made on the basis of those for 2- and 3-phenylindole[9] as well as for various methylated indole derivatives.[10] It should be noted that there is some ambiguity regarding the assignments for both the 4 and 6 carbons and the 2 and 9 carbons, the reverse assignments also being possible. The corresponding 2 and 9 carbons, as well as the 4, 6, and 7′ carbons, in the dimer also cannot be given with great certainty because several resonances in the 133–136-ppm and 120–122-ppm regions, respectively, were present in the dimer spectrum. The same situation holds for the 8 position in both 1 and 2 since this resonance usually occurs at approximately 126 ppm[10] and there are several

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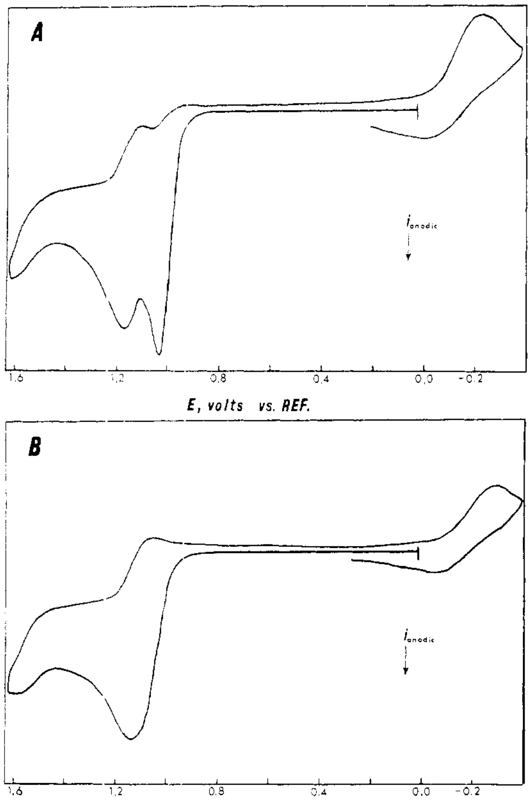

Figure 1. (A) Cyclic voltammogram of 2,3-diphenylindole (1.0×10^{-3} M) in MeCN/TEAP at platinum, sweep rate = 100 mV/s. (B) Cyclic voltammogram of the isolated electrolysis product under the same conditions.

closely spaced resonances in this region of the spectra. Tabular values given only to the nearest integral number imply the existence of several resonances in close proximity to one another near the value indicated.

As seen from the data in Table I, the spectrum of the dimer contained many of the peaks present in **1** as well as several other peaks corresponding to carbon atoms in widely different environments from those in **1**. Thus, the dimer is obviously unsymmetrical, one half of it consisting of an apparently intact **1** moiety. The furthest peaks downfield (181.9 ppm) and upfield (72.1 ppm) suggest a change in structure in the other half of the dimer in which one carbon is now doubly bonded to either an oxygen or a nitrogen atom while another carbon now becomes saturated. Since evidence has already been presented against the presence of a carbonyl group, it appears that the most likely explanation for the ^{13}C NMR spectral data is a shift of the double bond in the pyrrole ring from the 2,3 position to the 1,2 position, thus forming an indolenine. A comparison of the resonances of 2,3,3-trimethylindolenine with those in the nonindole half of the dimer supports the characterization of this portion of the dimer as having an indolenine structure since the two sets of resonances can be seen to consist of rather similar values. The assignments for the resonances in the indolenine half of the dimer were then made on the basis of those given for the model compound.

The formation of the indole–indolenine dimer may be visualized (Figure 2) as the coupling of two **1** cation radicals, the resonance structures indicating positions of high reactivity, to form the dimer **2** with elimination of two protons. The reaction at the C-3 position of the cation radical is supported not only by the creation of an apparently aliphatic carbon atom (appearance of upfield peak at 72.1 ppm) but also by the fact that in many cases the reactivity of indoles is centered at the 3 position.[11]

Table I. ^{13}C NMR Spectral Data of 2,3-Diphenylindole (1) and Its Electrolysis Product (2)

	Chemical shifts, ppm from Me_4Si		
Carbon assignments	**1**[d]	**2**[a]	2,3,3-Trimethylindolenine[b]
2	135.7	135.8	189.0
3	114.9	114.6 s	—
4	120.3	121 d[c]	123.4
5	122.5	—	129.2
6	119.5	119.6 d	126.8
7	110.8	110.8 d	121.2
8	—	—	147.9
9	134.9	134.8	155.6
2′		181.9 s	
3′		72.1 s	
4′		123.8 d	
5′		129	
6′		126–127 d[c]	
7′		121 d[c]	
8′		148.9 s	
9′		153.6 s	

[a] For numbering scheme of dimer see Figure 2. Registry no.: **2**, 64728-25-2. [b] In Me_2SO; original data converted using $\delta_c^{CS_2}$ 192.8. [c] All of the peaks in each of the regions indicated appeared to be doublets under SFORD conditions. [d] Registry no.: **1**, 3469-20-3.

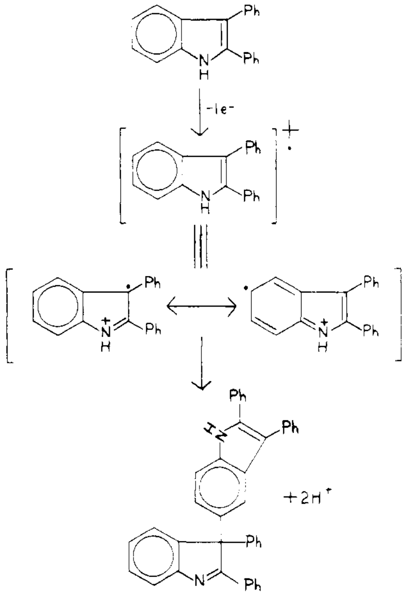

Figure 2. Proposed coupling scheme for the formation of the indole–indolenine dimer (**2**).

That the position of substitution in the indole nucleus is in the benzene ring of the molecule was inferred from the fact that a resonance corresponding to the 3 position was still present in the ^{13}C NMR spectrum of **2**, suggesting that the pyrrole ring in this half of the dimer remained unaltered. Further, based on considerations of greatest electron density (from HMO calculations) in the indole ring at the 1, 3, 5, and 7 positions,[3] the 5 and 7 positions now seemed to be most likely positions for substitution. A single-frequency off-resonance ^{1}H-decoupled (SFORD) ^{13}C NMR study of **2** indicated that the 4, 6, and 7 positions were unsubstituted, the resonances corresponding to these positions being split into doublets in the SFORD study, as indicated in Table I. Thus, these positions apparently are not those at which coupling occurs, leaving the

5 position as the only remaining possibility. Indeed, the ^{13}C NMR spectrum of **2** contained no resonances within ±1 ppm of 122.5 (C-5 in **1**), again suggesting that coupling involves the 5 position since this process should shift the resonance considerably downfield. The exact value of this shift is rather uncertain since there still remain unassigned resonances in the spectrum of **2** both at 140.3 ppm and (one resonance) in the 135-ppm region. To make a meaningful choice between these two values, a model compound involving a similarly substituted indole would be necessary.

The infrared data also support the structure assignment since the diminished intensity of the N–H band (3400 cm^{-1}) in the product spectrum suggests that only one of the dimer components contains the N–H functionality. The band at 1520 cm^{-1} (6.58 μm), assigned to the imine stretching vibration of the indolenine nucleus, falls somewhat outside the usual range for this vibration (6.10–6.30 μm), but shifts to longer wavelengths have been noted when the double bond is further conjugated.[12]

The UV spectra of **1** and its dimer **2** are, as stated before, quite similar. However, the molar absorptivities of the two compounds at approximately 310 nm are quite different, that for the dimer **2** being almost twice that for **1**. This would seem to be evidence for a dimeric structure consisting of two coupled indole rings until one considers that the UV spectrum for 3,3-dimethyl-2-phenylindolenine, which should be very similar to that for the indolenine in the proposed dimer **2**, also exhibits an absorbance at 306 nm (log a = 4.177).[13] Thus, due to the similarity of absorbance characteristics, both in wavelength and in strength, of the indole and indolenine chromophores in this instance, it is not possible to ascertain whether the electrolysis product of **1** is an indole–indole or an indole–indolenine dimer on the basis of the UV spectral data.

Finally, the mass spectrum of the dimer may now be explained as arising from the loss of a phenyl substituent to give a fragment at m/e 459, followed by loss from this fragment of either benzonitrile or HCN to give fragments at m/e 356 or m/e 432, respectively, these latter eliminations probably depending upon which phenyl (2 or 3) substituent is lost in the first elimination. Fragments resulting from the loss of these entities have been previously noted in the mass spectrum of **1**.[14] The peak at m/e 268 would, of course, correspond to cleavage of the dimeric bond.

Experimental Section

Melting points are uncorrected. The IR spectra were taken with a Perkin-Elmer Model 621 grating infrared spectrophotometer. The ^{13}C NMR spectra were recorded in CDCl$_3$ on a JEOL JNM-PS-100 instrument. A Hitachi Perkin-Elmer RMU-6 mass spectrometer was used to obtain a mass spectrum of **1**, while the spectrum of the electrolysis product of **1** was recorded with a Hewlett-Packard 5930A mass spectrometer. With both instruments, a direct solid probe was used for sample introduction, the ionization energy being 70 eV. UV spectra were taken with a Cary 15 spectrometer.

1 was prepared by the Bischler indole synthesis, as outlined by Szmuszkovicz et al.,[15] and was purified by column chromatography on Fisher activated alumina followed by recrystallization first from ethanol and then from ether–hexane to give colorless crystals, mp 122–123 °C (lit.[16] 123 °C); IR (KBr) 3400 s (NH), 1599 cm^{-1} m (C=C); UV max (MeOH) 308 nm (log ϵ 4.24), 250 (4.42); mass spectrum, m/e 269 (M$^+$, base peak). These spectral data were in good agreement with the published spectral data.[14,17]

The electrochemical instrumentation used to obtain cyclic voltammetric and chronoamperometric data has been described previously.[4] A Hewlett-Packard 7045A X-Y recorder was used with this instrument.

Mass electrolyses and coulometric determinations were carried out at controlled potential using a Wenking Model 68 FR 0.5 potentiostat. Electrolyses were at a platinum gauze working electrode in acetonitrile with 0.1 M tetraethylammonium perchlorate (TEAP) as supporting electrolyte, using a SCE (NaCl) reference electrode. The same medium was used for obtaining the cyclic voltammetric data. The purification of acetonitrile and TEAP have been described previously.[18] Two types of electrolysis cells were used in this study; one was a standard "H-type" two-compartment Sargent cell and the other was a 500-mL beaker with the auxiliary electrode compartment separated from the working electrode compartment by a porous ceramic cup. These cells gave equivalent results. The current passed during the electrolysis was integrated by voltage–frequency conversion of the *IR* drop across a standard resistor in the auxiliary electrode circuit, followed by counting of the frequency pulses.

Preparative Electrolysis of 2,3-Diphenylindole (1). An approximately 9 mM solution of **1** in acetonitrile was electrolyzed at a potential about 100 mV anodic of the primary oxidation wave in the cyclic voltammogram of **1**, the electrolysis being continued until 1 equiv of electricity had been passed through the cell (n = 1). After oxidation the solution was reduced to a potential of −0.6 V in order to reduce any protons formed in the oxidation and to take any electrolysis products back to the neutral form.

The electrolysis product was obtained as a benzene solution by either extracting the evaporated electrolysis mixture (leaving as residue the product and TEAP) or partitioning the electrolysis mixture between benzene and deionized water. Evaporation of the benzene solution yielded the same crude product in either case. Chromatography of this product on activated alumina (Matheson Coleman and Bell) showed the presence of only one component, the purified yield being 90–95%. Recrystallization from ethanol–ether yielded small light yellow crystals, mp 225–226 °C; IR (KBr) 3400 m (NH), 1595 m (C=C), 1520 cm^{-1} m-w (C=N); UV$_{max}$ (MeOH) 314 nm (log ϵ 4.49), 257 (4.67); mass spectrum, m/e 536 (M$^+$, 100), 459 (14), 432 (21), 356 (25), 268 (14). Anal. Calcd for C$_{40}$H$_{28}$N$_2$: C, 89.52; H, 5.26; N, 5.22. Found: C, 89.33; H, 5.29; N, 5.18.

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References and Notes

(1) W. J. Houlihan, "Indoles: Part One", Wiley-Interscience, New York, N.Y., 1972, p 6.
(2) M. J. Allen and V. J. Powell, *J. Electrochem. Soc.*, **105**, 541 (1958).
(3) C. J. Nielsen, M. S. Thesis, California State University, Sacramento, Calif., 1974.
(4) J. F. Ambrose and R. F. Nelson, *J. Electrochem. Soc.*, **115**, 1159 (1968).
(5) M. L. Olmstead, R. G. Hamilton, and R. S. Nicholson, *Anal. Chem.*, **41**, 260 (1969).
(6) E. R. Brown and R. F. Large in "Techniques of Chemistry", Vol. 1, Part 11A, A. Weissberger and B. W. Rossiter, Ed., Wiley-Interscience, New York, N.Y., 1971, p 476.
(7) J. F. Ambrose, L. L. Carpenter, and R. F. Nelson, *J. Electrochem. Soc.*, **122**, 876 (1975).
(8) E. Kleinpeter and R. Borsdorf, *J. Prakt. Chem.*, **315**, 765 (1973).
(9) Thomas L. Gilchrist, Charles W. Rees, and Colin Thomas, *J. Chem. Soc., Perkin Trans. 1*, 8 (1975).
(10) J. B. Stothers, "Carbon-13 NMR Spectroscopy", Academic Press, New York, N.Y., 1972, pp 266–268.
(11) W. J. Houlihan, ref 1, pp 70–126.
(12) B. Witkop and J. B. Patrick, *J. Am. Chem. Soc.*, **73**, 713 (1951).
(13) B. Witkop, J. B. Patrick, and H. M. Kissman, *Chem. Ber.*, **85**, 949 (1952).
(14) J. C. Powers, *J. Org. Chem.*, **33**, 2044 (1968).
(15) J. Szmuszkovicz, et al., *J. Med. Chem.*, **9**, 527 (1966).
(16) R. C. G. Fennel and S. G. P. Plant, *J. Chem. Soc.*, 2872 (1932).
(17) C. F. H. Allen and J. A. Van Allan, *J. Am. Chem. Soc.*, **73**, 5851 (1951).
(18) E. T. Seo, et al., *J. Am. Chem. Soc.*, **88**, 3498 (1966).