Reaction of (*S*)-(+)-1-Ferrocenylethanol (8) with Acetic Acid in Benzene.—A solution of glacial HOAc (6 g, 0.1 mol) and (*S*)-(+)-**8** [4.6 g, 0.02 mol, $[\alpha]^{25}\text{D}$ +29.3° (*c* 1.7, benzene)] in 130 ml of dry benzene is refluxed for 4 hr while water separates (Dean-Stark trap). The solvent is removed *in vacuo* and the crude acetate (**9**) (4.9 g, 90%) is purified by chromatography (activated alumina, 5.5 × 20 cm, MCB, 80–325 mesh, eluent-Skelly B). The resulting yellow solid is sublimed: 35° (1 Torr), $[\alpha]^{25}\text{D}$ 0 (ethanol).

Registry No.—**2,** 11136-56-4; **9,** 11136-55-3.

Nucleophilic Substitutions Initiated by Electrochemical Oxidation. I. Intramolecular Nucleophilic Substitutions

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The overcrowded 8-*tert*-butyl-1-(2-pyridyl)naphthalenes **1a–c** have been anodically oxidized to give the zwitterions **2a–c** after treatment of the initial reaction mixtures with aqueous base. The initial product of the two-electron oxidation of **1a** was the isolable perchlorate **3**, which slowly eliminates the *tert*-butyl group. The overall mechanism of the formation of zwitterions **2a–c** can be viewed as an electrochemically initiated intramolecular nucleophilic substitution reaction.

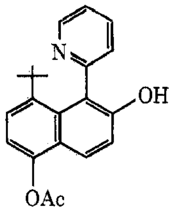
Anodic substitution reactions have been the subject of research for many years, with numerous investigations being described in the literature and summarized in review articles.[1-4] There has been much discussion of the mechanism of these reactions; recent studies have been concerned mainly with the pyridination of substituted anthracenes. Mechanisms proposed for these reactions include (a) the initial formation of a dication and subsequent attack by the nucleophile;[5-7] (b) the formation of a radical cation, attack of this species by the nucleophile, and further electron transfer (ECE mechanism);[8] and (c) disproportionation of the initial radical cation and attack of the resulting dication by the nucleophile.[9]

In all these mechanisms the proton can be considered as the leaving group. Reports of anodic substitution reactions with leaving groups other than the proton are scarce, but such reactions might prove more tractable and thereby offer useful mechanistic insight. The anodic nucleophilic displacement of bromine has been reported for 9,10-dibromoanthracene.[10] However, the authors did not elaborate on the chemical nature of the leaving group. Other communications have dealt with the replacement of a *tert*-butyl group during the course of the anodic oxidation of 2,4,5-tri-*tert*-butylphenol[11] and of 2,4,6-tri-*tert*-butylaniline[12] in acetonitrile solution.

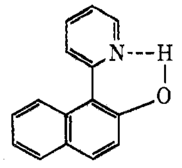
We have investigated intramolecular nucleophilic substitution reactions of highly sterically hindered 8-*tert*-butyl-1-(2-pyridyl)naphthalenes[13] initiated *via* electrochemical oxidation. The leaving group in this case is also the *tert*-butyl group. However, when the oxidations are carried out under suitable reaction conditions, the intermediate cationic species, which still incorporate the *tert*-butyl group, can be isolated as their perchlorate salts. Decomposition of these salts yields isobutylene and zwitterions as the final products. One of these novel zwitterions was observed earlier[13] when 2-hydroxy-5-acetoxy-8-*tert*-butyl-1-(2-pyridyl)-naphthalene was treated with cupric chloride in refluxing ethanol. Although a two-electron oxidation product was obtained from this reaction, the polarographic oxidation was then described as a one-electron exchange. The suggested mechanism included the hitherto unprecedented oxidative coupling of a pyridyl radical through nitrogen rather than carbon. Our own studies on the anodic substitution of a *tert*-butyl group of 2,4,6-tri-*tert*-butylphenol by pyridine, which we shall describe in another paper, led us to the assumption that this intramolecular reaction may also proceed *via* a nucleophilic substitution. Therefore, the objective of this work was to explore the scope and mechanism of the oxidative formation of the zwitterions from their pyridyl naphthol precursors.

Results and Discussion

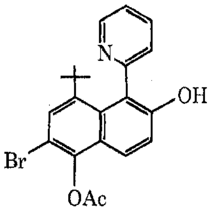
Cyclic Voltammetric Studies.—Upon scanning anodically from 0.0 V, compounds **1a–c**, all of which have



1a



1b



1c

a free hydroxyl group, show three "irreversible" responses A, B, and C, the peak potentials of which are given in Table I. Response C, which is near the solvent cutoff, is often ill-defined; therefore, no effort was made to elucidate its nature.

Compounds **1a–c** do not show a cathodic response between 0 and −2.0 V if the scan is started at 0 V.

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TABLE I

PEAK POTENTIALS OF CYCLIC VOLTAMMETRIC RESPONSES[a]

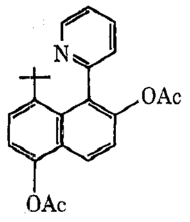
Compound	Response A	B	C	D	E
1a	0.98	1.60	1.9	−0.55	−1.35
1b	1.05	1.75	2.1	−0.52	−1.45
1c	1.00	1.70	2.1	−0.47	−1.25

[a] Scan rate, 0.1 V/sec; Pt electrode; 0.1 *M* TBAP in CH_3CN; potential *vs.* ssce.

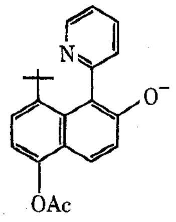
However, if the scan is started at potentials corresponding to the diffusion plateau of the first oxidation response A, two reductive responses D and E (Table I) can be observed. Preoxidation at potentials corresponding to the diffusion plateau of response B produces only responses D and E.

Both acetylation of the hydroxyl group of **1a** and removal of the hydroxyl proton of **1a** change the cyclic voltammetric behavior drastically.

The first oxidative response of the diacetylated compound **1d** occurs at +1.48 V and a second response is observed at +1.80 V. Reduction responses, which are again present only after preoxidation at potentials corresponding to the diffusion plateau of the first oxidation wave, occur at −0.50 and −0.95 V.



1d



1e

Compared with the parent naphthol, the anion **1e**, which can be generated *in situ* from **1a** with tetramethylguanidine, is oxidized much more easily. At slow scan rates (~0.05 V/sec) only one broad oxidation response can be observed with a peak potential of approximately +0.24 V. If the scan rate is increased, this broad response becomes better defined and, at a scan rate of 0.5 V/sec, two separate responses at the potentials +0.17 and +0.43 V can be clearly distinguished. A further increase in scan rate does not increase the definition of these two responses appreciably. A current maximum at +0.35 V in the reverse scan, which could indicate some reversibility of the second response, also shows no improvement in definition at scan rates greater than 0.5 V/sec.

If cyclic voltammetric studies are performed in the presence of perchloric acid, response A decreases with increasing concentration of the acid, whereas response B increases. The addition of pyridine reconstitutes response A to its original height. Furthermore, cyclic voltammetric scans of the salt **1c** $HClO_4$ in the presence of equimolar amounts of **1c** show clearly that responses B and D are the result of oxidation and reduction, respectively, of protonated starting material.

Scan-rate studies reveal no basic difference in the voltammetric behavior of the compounds with hydroxyl groups and their diacetylated derivatives. Plots of $i_pA/V^{1/2}$ *vs.* log *V* of compounds **1a**, **1b**, and **1d** give horizontal straight lines over a scan rate of three decades.

Coulometric Data.—Coulometry (on a time scale of approximately 15 min) at potentials corresponding to the diffusion plateau of response A resulted in an exchange of one electron per molecule of starting material for compounds **1a–d**. If the oxidation is performed at potentials corresponding to the diffusion plateau of response B, the number of electrons exchanged per molecule of starting material is two.

Addition of pyridine to the coulometry solution changes the apparent one-electron process of response A to a two-electron process.

The results of coulometric studies of the anion **1e** are dependent on potential. A voltammogram of a stirred solution of **1e** exhibits a broad wave with a diffusion plateau attained at +0.5 V. Coulometry at this potential results in an exchange of two electrons per molecule of starting material. If the oxidation is performed at +0.2 V, 1.54 F are exchanged per mole of starting material and at +0.1 V a one-electron process is observed.

The results of the coulometric studies are summarized in Table II.

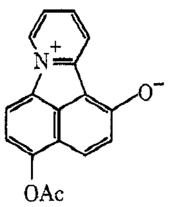
TABLE II

RESULTS OF COULOMETRY AT CONTROLLED POTENTIALS

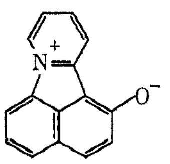
	Electrons/molecule					
				1e		
	1a	**1b**	**1c**	+0.5 V	+0.2 V	+0.1 V
Response A	1	1	1	2.0	1.54	1.0
Response B	2	2	2			
1a + 5% pyridine	2					

Macroelectrolyses.—Macroelectrolyses have been performed on a gram scale at potentials corresponding to the diffusion plateau of the first oxidation response in an acetonitrile–sodium perchlorate medium.

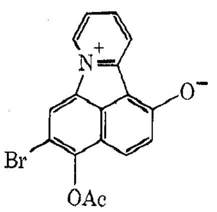
The oxidation of **1a** was carried out at +1.15 V until the current had decayed to 5% of its original value. Starting material and the zwitterion **2a** were isolated from the reaction mixture in approximately 50 and 40% yields, respectively. The current yield of **2a** was 80%. The characteristic data of **2a** are shown in Table III. Oxidation of **1b** was performed at +1.15 V until the current had decayed to 5% of its original value. Besides 50% starting material, zwitterion **2b** was isolated in 4% yield from the reaction mixture. A second product of the formula $C_{30}H_{20}N_2O_2$ was obtained in 40% yield. The current yield for **2b** and the second product was approximately 4 and 40%, respectively. The mass spectrum of the unknown compound displayed a parent peak at *m/e* 440, and the fragmentation pattern suggested an unsymmetrical dimer of **1b** having a C–O–C bridge and a hydroxyl group. These results were supported by ¹H nmr spectroscopy. How-



2a



2b



2c

TABLE III

CHARACTERISTIC DATA OF ZWITTERIONS **2a–c**

Compd	Mp, °C	Mass spectrum	Uv spectrum, nm (ϵ 10^{-3})	C_V peak pot in CH_3CN–TBAP, 0.1 V/sec
2a[a]	211	277 m$^+$	489 (11.1) (2)[b]	E_{p1} = +1.20 V
		235 m − CH_2CO	451 (8.6)	(irreversible)
			430 (4.0)	
			405	
			335 (4.7)	E_{p2} = −1.43 V
			270 (6.65)	(reversible)
			262 (9.8)	
			242 (21.4)	
2b	135	219 m$^+$	498 (4.95) (1)	E_{p1} = +1.10 V
		191 m − CO	459 (4.30)	(irreversible)
		190 m − HCO	433 (2.20)	
			418 (0.85)	E_{p2} = −1.47 V
			335 (2.95)	(reversible)
			265 (19.0)	
			243 (17.1)	
			227	
2c[a]	235–240	355 m$^+$	491 (9.4) (1)	E_{p1} = +1.22 V
	dec	315 m − CH_2CO	462 (7.25)	(irreversible)
			437 (3.19)	
			410 (sh)	E_{p2} = −1.32 V
			333 (3.77)	(reversible)
			278 (11.6)	
			268 (11.6)	
			246 (17.0)	

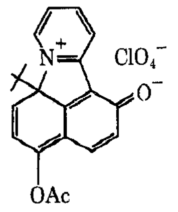
[a] Prepared also through oxidation with $CuCl_2$ by D. L. Fields. [b] (1) In acetonitrile; (2) in methanol.

ever, a conclusion about the exact position of the C–O–C linkage could not be reached. The characteristic data of zwitterion **2b** are presented in Table III.

Compound **1c** was similarly oxidized at +1.1 V, giving unchanged starting material (50% yield) and the zwitterion **2c** in approximately 45% yield. The current yield of **2c** was 90% and its characteristic data can be found in Table III.

When compound **1a** was electrolyzed at +1.3 V in acetonitrile–sodium perchlorate in the presence of pyridine (6% by volume) at 0°, two electrons were exchanged per molecule of starting material and an orange solution was obtained. From this solution a red-brown compound was isolated which decomposed at 160° with the evolution of gas. ^1H nuclear magnetic resonance spectra in DMSO-d_6 together with mass spectral data showed that the compound still contained a *tert*-butyl group. The ^1H nmr spectrum exhibited broad absorptions for aromatic protons in the region of τ 1.8–3.0. A relatively broad signal at τ 9.02 (area 9) was assigned to a *tert*-butyl group, and two sharp absorptions of equal intensity at τ 8.08 (area 0.5) and at τ 7.92 (area 0.5) were attributed to acetyl groups on the assumption of the existence of two isomers. Mass spectra, recorded as a function of increasing probe temperature, showed that the compound thermally decomposed to form isobutylene, the zwitterion **2a**, and, probably because of reducing conditions in the spectrometer, 1-(2-pyridyl)-2-hydroxy-5-acetoxynaphthalene. The zwitterion **2a** was also isolated as the main product of both the thermal decomposition at 160° and the photolytic decomposition of an acetonitrile solution of this red-brown material in the beam of a xenon high-pressure lamp.

The ir spectrum in a KBr pellet exhibited, among others, absorptions at 1100 (attributable to ClO_4^-), 1650 (possible quinoid carbonyl group), and 1740 cm^{-1} (acetyl group). This combined information suggests that the isolated oxidation product has the structure **3**



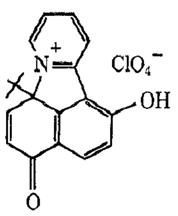
3

which was further supported by elemental analysis.

A uv–visible spectrum of **3** in acetonitrile showed maxima at 540 nm (ϵ 1000), 454 (8500), 430 (9000), and 350 (8900).

When a solution of **3** in acetonitrile was treated with 5% aqueous potassium hydroxide, a deep-red solution was formed. Immediate dropwise addition of 35% perchloric acid solution yielded a brownish red precipitate, which decomposed at 170° with the evolution of gas. As for compound **3**, this composite proved to be a perchlorate salt (ir absorption in KBr at 1100 cm^{-1}), the cation of which contained a *tert*-butyl group (broad absorption in the ^1H nmr spectrum at τ 9.08 and the appearance of abundant isobutylene in the mass spectrum). Probes for the presence of an acetyl group by ^1H nmr, ir, and mass spectroscopy were negative. A band at 1640 cm^{-1} in the infrared spectrum indicated the presence of a quinoid carbonyl group. The following structure (**4**) was accordingly assigned to the compound.

A uv–visible spectrum of **4** in acetonitrile showed maxima at 540 nm (ϵ 3000), 478 (260), 445 (5700), and 365 (6600). When **4** was thermally decomposed, the uv–visible spectrum of the major reaction product was



4

identical with that of the hydrolysis product of zwitterion **2a**.

Both **3** and **4** also decomposed on standing at room temperature, with the formation of the same products. Cyclic voltammetric scans of **3** in an acetonitrile–sodium perchlorate medium show that response E (see Table I) is the result of the reduction of **3**.

The oxidation of the diacetylated compound **1d** at +1.7 V led to a yellow solution, which yielded a brown residue when the solvent was evaporated. Treatment of this residue with aqueous sodium bicarbonate gave a bright-red fluorescent solution and an insoluble yellow material. The yellow material was identified after chromatography as unchanged starting material ($\sim$50% of the initial amount). On standing, the bright-red aqueous solutions turned yellow and exhibited a green fluorescence. The major component of these solutions was the zwitterion **2a**. However, all attempts to elucidate the structure of the red fluorescent intermediate failed.

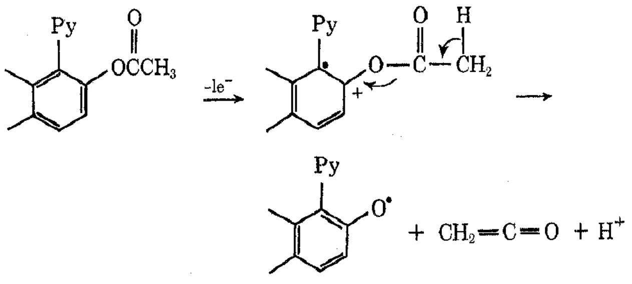
Cyclic voltammetric studies together with coulometric experiments and product characterization of macroelectrolyses show that in aprotic media the apparently one-electron process under response A is, in reality, a two-electron oxidation. The electrolysis product is, for example, the cyclic perchlorate **3** when **1a** is oxidized at potentials corresponding to the diffusion plateau of response A. The formation of this material requires the loss of two electrons and one proton from the starting material. The protons generated in this oxidation are accepted by starting material, thus giving rise to response B in the cyclic voltammograms of **1a–c**. The isolation of the perchlorate **3** after exhaustive electrolysis demonstrates furthermore that ring closure occurs prior to the ejection of the *tert*-butyl group. Thus, the formation of the zwitterions **2a–c** can be formally considered as an electrochemically initiated nucleophilic substitution reaction.

More detailed aspects of the electrochemical oxidation mechanism are less clearly defined and need some further discussion. The question of whether or not the naphthols are oxidized and the resulting radical cations deprotonate or a dissociation of the naphthols occurs before electron transfer cannot be answered on the basis of the collected data. Deprotonation of both the radical cation and the naphthol are expected to be very fast reactions[14] and would therefore be of no major consequence in determining the pathway of the overall reaction. The product in either case is an uncharged radical, which may be oxidized further to a cation or undergo chemical reactions.

Cyclic voltammetric and coulometric studies of the anion **1e** shed some light on the reactions of the uncharged radical. At potentials of approximately +0.1 V, **1e** is oxidized in a one-electron process, which appears to be irreversible even when studied by fast-sweep cyclic voltammetry. Thus, a rapid chemical reaction seems to come into play after one electron has been removed from the anion. Among the reactions which can be expected are an intermolecular dimerization or an intramolecular attack of the pyridine nitrogen atom on carbon-8 of the naphthalene moiety. The isolation of the dimer from the oxidation of **1b** and the observation that the yield of zwitterion increases when **1e** is oxidized at potentials increasing from +0.1 to +0.5 V support the idea of dimerization of the intermediate radical. The intermediate radical from the oxidation of **1b** appears to be much more reactive toward dimerization than the comparable radicals from **1a** and **1c**. Therefore, dimerization can compete effectively with the transfer of the second electron and, as a result, zwitterion **2b** is obtained only in low yield.

The data for the oxidation of the diacetylated compound **1d** reveal that there is no basic mechanistic difference between the oxidation of it and that of the hydroxyl derivatives. Exhaustive electrolysis of **1d** at potentials corresponding to the diffusion plateau of the first oxidation response in aprotic solvent leaves 50% starting material, and the second oxidative response corresponds to electron transfer from protonated starting material. In addition, ^{1}H nmr studies show that acetic acid is produced during the electrolysis and the zwitterion **2a** was isolated as the final product of the reaction.

In view of these observations, a reasonable mechanistic picture for this oxidation process can be visualized through the loss of ketene from the initial radical cation.



The remaining reaction steps are analogous to those for the oxidation of the hydroxyl derivatives. Since the plot of $i_p/V^{1/2}$ *vs.* log V is a horizontal straight line, the loss of ketene appears also to be a very fast reaction. Deketenization of acetyl compounds is a common fragmentation process in mass spectrometry[15–17] and can therefore also be expected from an electrochemically generated cation radical of a short enough lifetime to exclude solution chemistry.

Since the mechanistic studies have been performed mainly with compound **1a**, a mechanism for the electrochemical oxidation of this compound is outlined in Scheme I.

Experimental Section

Chemicals.—Acetonitrile (Eastman X488) was used after drying for several days over a molecular sieve.

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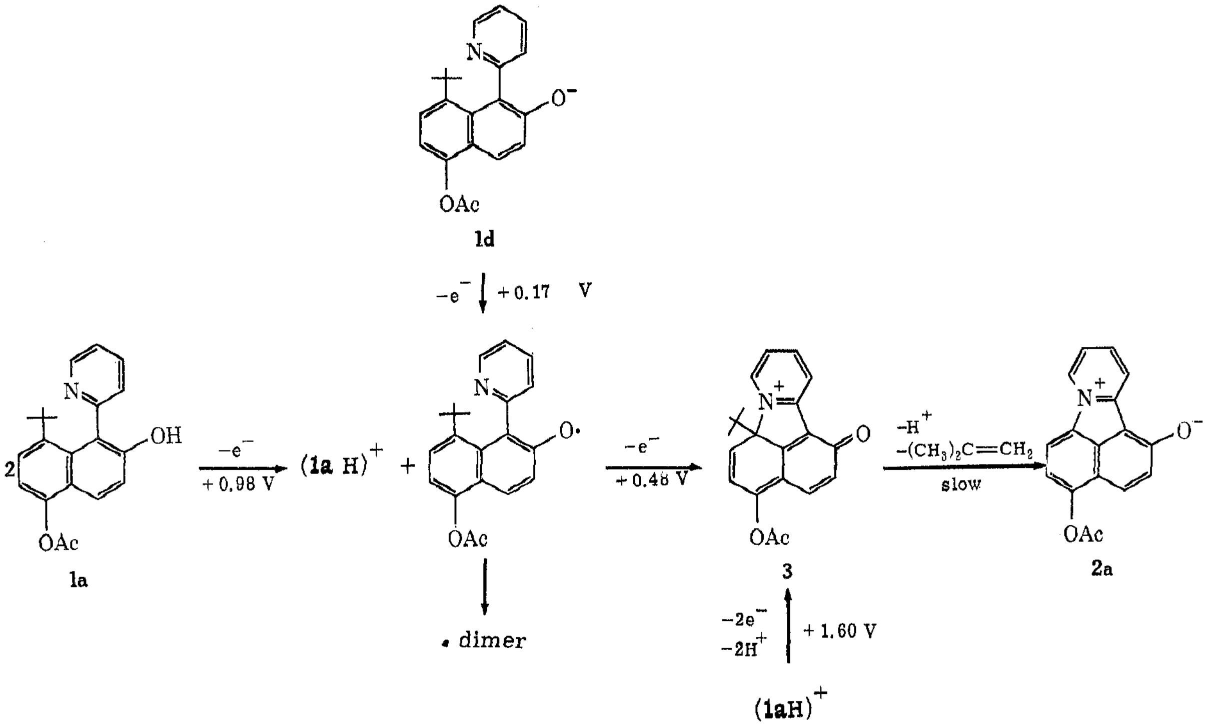
Scheme I



Tetrabutylammonium perchlorate (TBAP) (Southwestern Analytical Chemicals) was dried under vacuum before use. For macroelectrolyses, sodium perchlorate (G. Fredrick Smith Chemical Co., recrystallized from acetone–methylene chloride) was used as supporting electrolyte.

Apparatus.—Cyclic voltammetric experiments were performed in a conventional three-electrode cell (design after that marketed by Brinkmann) with an Electrochemistry System Model 170 from the Princeton Applied Research Corp. All potentials are referred to an aqueous saturated sodium chloride calomel reference electrode (ssce).

Controlled potential coulometry and preparative oxidations were carried out in conventional two-compartment cells at platinum-working electrodes. The potentiostat was either the Model 170 from Princeton Applied Research Corp. or a Model AS100 from Tacussel Electronique.

^{1}H nuclear magnetic resonance spectroscopy was performed with a Varian A-60 instrument, mass spectroscopy was performed with the Hitachi RMS-4 spectrometer, and uv–visible and ir spectra were obtained with the Cary Model 14 and Perkin-Elmer Model 137 instruments, respectively.

Preparations. Zwitterions 2a–c.—After the acetonitrile solutions of the starting materials had been electrolyzed exhaustively at the proper potentials, the reaction mixture was filtered and acetonitrile was evaporated under reduced pressure. The residue was treated with 5% aqueous sodium bicarbonate solution, the resulting mixture was extracted with dichloromethane, and the organic phase was dried over anhydrous sodium sulfate. After evaporation of the dichloromethane, the oxidation products were separated on a Florisil column with acetone–methanol mixtures as eluents.

Compounds 3 and 4.—Solutions of 1a at 2–5 m*M* concentration in acetonitrile–sodium perchlorate were oxidized exhaustively at 0° in the presence of 6% pyridine. The orange solution was filtered and evaporated to approximately $^1/_{10}$ of the original volume. The remaining solution was diluted with distilled water and a red-brown precipitate was collected on a filter. After repeated washings with cold water the precipitate was dried at room temperature under high vacuum. Reprecipitation from acetone–hexane and drying under high vacuum yielded a red-brown powder, which decomposed at 160°. Yields were 60–70% of **3**.

Anal. Calcd for: C, 58.2; H, 4.64; N, 3.57; Cl, 8.18. Found: C, 57.6; H, 4.5; N, 3.7; Cl, 8.0.

When a solution of **3** in acetonitrile was treated with 5% aqueous potassium hydroxide solution, a deep-red solution was formed. Immediate dropwise addition of 35% perchloric acid yielded a brownish red precipitate, which was collected by filtration. After several washings with cold water, this precipitate was dried under high vacuum at room temperature. After reprecipitation from acetone–hexane and drying under high vacuum, brown-red **4** was obtained, which decomposed at 170°.

Registry No.—**1a,** 30310-07-7; **1b,** 23825-09-4; **1c,** 35026-49-4; **2a,** 30310-10-2; **2b,** 35026-51-8; **2c,** 35026-52-9; **3,** 35026-53-0; **4,** 35026-54-1.

Acknowledgment.—I am indebted to Dr. D. L. Fields for supplying the starting materials and for many helpful discussions. I also wish to thank Mr. D. P. Maier for his patience in recording and interpreting the mass spectra and Mr. R. L. Young for supplying the ^{1}H nmr spectral data. Discussions with Drs. J. Chang and R. F. Large are gratefully acknowledged.