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Studies on Sulfenamides. XII.[1] Anodic Oxidation of *N*-(*o*-Nitrophenylthio)-1,2,3,4-tetrahydroquinoline and *N*-(*o*-Nitrophenylthio)-1,2,3,4-tetrahydroisoquinoline

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The paramagnetic species formed by anodic oxidation of *N*-(*o*-nitrophenylthio)-1,2,3,4-tetrahydroquinoline (**3**) in acetonitrile has been identified as the radical cation of 1,1′,2,2′,3,3′,4,4′-octahydro-1,1′-di-(*o*-nitrophenylthio)-6,6′-biquinoline by isolating the radical cation perchlorate. The perchlorate separated out from the electrolyzed solution and its structure was confirmed by converting it to 1,1′,2,2′,3,3′,4,4′-octahydro-6,6′-biquinoline. Anodic oxidation of *N*-(*o*-nitrophenylthio)-1,2,3,4-tetrahydroisoquinoline (**4**) in methanol gave an almost quantitative yield of 3,4-dihydroisoquinoline (**7**) and a 56% yield of methyl 2-nitrobenzenesulfenate (**9**). In acetonitrile, electrolysis of **4** gave a 33% yield of **7** and no **9**. These results were interpreted in terms of a much faster rate of deprotonation of the sulfenamide radical cation in methanol than in acetonitrile.

Keywords——ESR; anodic oxidation; *in situ* electrolysis; benzenesulfenamide; sulfenamide radical cation; 3,4-dihydroisoquinoline; methyl 2-nitrobenzenesulfenate; radical cation perchlorate; 1,1′,2,2′,3,3′,4,4′-octahydro-6,6′-biquinoline

In the previous papers[1,2] we reported electron spin resonance (ESR) studies on the radical cations electrochemically generated from *N*-(*o*-nitrophenylthio) alicylic amines (**1**) and *N*-(*o*-nitrophenylthio) secondary aromatic amines in acetonitrile. The paramagnetic species formed by *in situ* anodic oxidation of **1** and three *N*-methyl-4′-substituted 2-nitrobenzenesulfenanilides have been identified as the radical cations derived from the parent sulfenamides by one-electron transfer. On the other hand, the radicals generated from three 4′-unsubstituted *N*-alkyl-2-nitrobenzenesulfenanilides (**2**) have been identified as the radical cations of *N*,*N*′-dialkyl-diphenoquinone-diimines formed by dimerization of the sulfenanilide radical cations and subsequent oxidation of the dimers. From the voltammetric data, it is proposed that the dimerization takes place before the cleavage of the S–N bond in the sulfenanilide radical cations.

In order to clarify the mechanism of the dimerization of the sulfenanilide radical cations, we carried out cyclic voltammetry and anodic oxidation studies of *N*-(*o*-nitrophenylthio)-1,2,3,4-tetrahydroquinoline (**3**) and *N*-(*o*-nitrophenylthio)-1,2,3,4-tetrahydroisoquinoline (**4**) in both acetonitrile and methanol, and attempted to identify the products.

Results

Cyclic Voltammetry

The cyclic voltammogram of **3** in acetonitrile containing 0.1 M $NaClO_4$ showed an irreversible anodic peak at 1.02 V at a potential scan rate (v) of 50 mV/s. The value of $i_p \cdot C^{-1} \cdot v^{-1/2}$ of the anodic peak, where i_p is the peak current in μA and C is the concentration of **3** in mM, was 3.9. Upon reversal of the scan direction at 1.3 V, a cathodic wave was observed at 0.7 V. These characteristics are similar to those of **2**, except that the value of

$i_p \cdot C^{-1} \cdot v^{-1/2}$ is only about 80% of that of **2**.

The voltammetric behavior of **3** in methanol containing 0.1 M $NaClO_4$ was similar to that in acetonitrile.

The voltammogram of **4** in acetonitrile showed two irreversible anodic waves at 1.19 and 1.70 V. The value of $i_p \cdot C^{-1} \cdot v^{-1/2}$ of the first anodic wave was 2.25. Upon reversal of the scan direction at 1.4 or 2.0 V, no cathodic wave was observed at v of 50 mV/s. The voltammogram of **4** in methanol showed three anodic waves at 1.12, 1.37, and 1.7 V. The value of $i_p \cdot C^{-1} \cdot v^{-1/2}$ of the first anodic wave was 3.33, which is about 1.5 times that of the first anodic wave in acetonitrile. Upon reversal of the scan direction at 2.0 V, a cathodic wave was observed at 0.1 V. No cathodic wave was observed when the scan direction was reversed at 1.2 V.

ESR Spectroscopy

In situ electrolysis of **3** in acetonitrile at ambient temperature gave a partially resolved ESR spectrum, as shown in Fig. 1. When the electrolytic current was turned off, the ESR signal intensity decayed very slowly ($t_{1/2} > 5$ h). The spectrum was reasonably well simulated by the following ESR parameters: $g = 2.0026$, $A_1 = 5.0$ (2N), $A_2 = 5.0$ (2H), $A_3 = 2.6$ (4H), $A_4 = 1.3$ G (4H), and a line width of 2.5 G (Lorentzian line shape). Comparison of the data with those reported for the *N*-alkyl-2-nitrobenzenesulfenanilides[1] suggests that the observed paramagnetic species is not the radical cation of the parent sulfenamide but a secondary radical which is formed by the dimerization of the radical cation followed by oxidation.

In situ electrolysis of **4** in acetonitrile gave no ESR signal even at −40 °C.

Controlled Potential Electrolysis

A 5 mM solution of **3** in acetonitrile containing 0.1 M $NaClO_4$ was subjected to electrolysis at a glassy-carbon anode at 1.0 V. The quantity of electricity consumed corresponded to $n = 1.89$. A black powder was precipitated from the solution during the electrolysis; it was filtered off and identified as the perchlorate of 1,1′,2,2′3,3′4,4′-octahydro-1,1′-di(*o*-nitrophenylthio)-6,6′-biquinoline radical cation (**5**) on the basis of the elemental analysis data, and infrared (IR) and ESR spectra. The ESR spectrum of **5** dissolved in acetonitrile (dark purple solution) was identical with that obtained by *in situ* electrolysis of **3**. The perchlorate **5** was stable for at least a few days in the dark and under reduced pressure. Treatment of **5** with aqueous acetonitrile solution of Na_2CO_3 gave red crystals, which were identified as 1,1′,2,2′,3,3′,4,4′-octahydro-1,1′-di(*o*-nitrophenylthio)-6,6′-biquinoline (**6**) from the IR, nuclear magnetic resonance (NMR), and mass spectra (MS), and by converting **6** to 1,1′,2,2′,3,3′,4,4′-octahydro-6,6′-biquinoline.

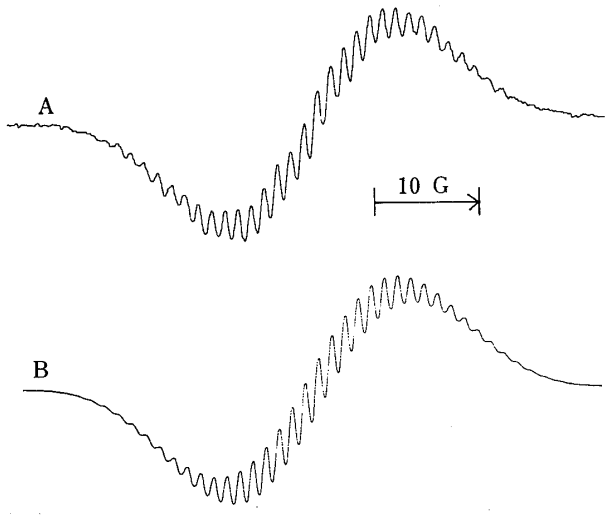

Fig. 1. ESR Spectrum of an *in Situ*-Electrolyzed Solution of the Sulfenamide **3** (5 mM) at 25 °C (A) and a Computer Simulation (B)

Instrumental settings: power 0.2 mW; modulation amplitude 0.5 G; scan rate 6.25 G/min; gain 1.6× 1000; time constant 1 s.

Anodic oxidation of **4** in acetonitrile (10 mM) at 1.19 V gave 3,4-dihydroisoquinoline (**7**) and a trace amount of 2,2′-dinitrodiphenyldisulfide (**8**). The structure of **7** was confirmed by analysis of the ^{1}H- and ^{13}C-NMR and MS, and by the melting point of the picrate.[3] The yields of **7** and **8** as determined by high-performance liquid chromatography (HPLC) were 33 and 1%, and the coulometric *n*-value was 0.92.

Electrolysis of **4** in methanol (10 mM) at 1.19 V gave an almost quantitative yield of **7** and a 56% yield of methyl 2-nitrobenzenesulfenate (**9**). The *n*-value was 1.46.

Discussion

The following scheme is proposed for the formation of the cation radical **5** (Chart 1). Isolation of **5** as the perchlorate substantiates the proposed mechanism for the oxidation of **2**, that is, the dimerization of the radical cations of **2** takes place before the S–N bond fission.[1] Although the paramagnetic species observed on *in situ* electrolysis of **2** were assigned as the radical cations of *N*,*N*′-dialkyl-diphenoquinone-diimines (**10**),[1] in which the *o*-nitrophenylthio groups are not retained, the cation radical perchlorate obtained in the present study retains the *o*-nitrophenylthio groups. Since the perchlorate of **5** is scarcely soluble in acetonitrile, it separates out from the electrolyzed solution and hence the oxidation of **3** does not proceed beyond **5**. On the other hand, the corresponding perchlorate derived from **2** is soluble in the solution and is subjected to decomposition and further oxidation. The fact that the value of A_N of **5** (5.0 G) is much larger than that of **10** (3.7—3.9 G) indicates that the two radicals have greatly different structures.

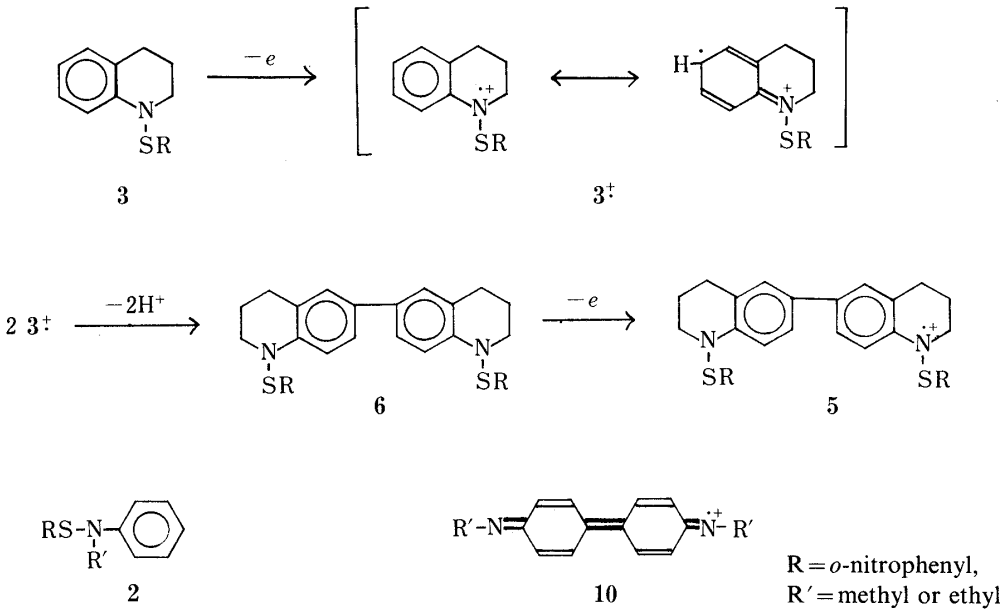

Chart 1

The mechanism shown in Chart 2 is proposed for the anodic oxidation of **4**. Although **4**$^{+}$ was not detected by ESR spectroscopy, one-electron oxidation of **4** to form **4**$^{+}$ is considered to be the first step of the anodic oxidation of **4** by analogy with that of the other sulfenamides. Failure to detect **4**$^{+}$ on electrolysis of **4** is considered to be due to the exceptionally high instability of **4**$^{+}$.

In methanol, which is an amphiprotic solvent, **4**$^{+}$ is deprotonated immediately to give A on the surface of the anode, and about a half of A is oxidized further to B, which undergoes heterolysis to C and **7**. The sulfenyl ion reacts with methanol to form **9**. The rest of A which

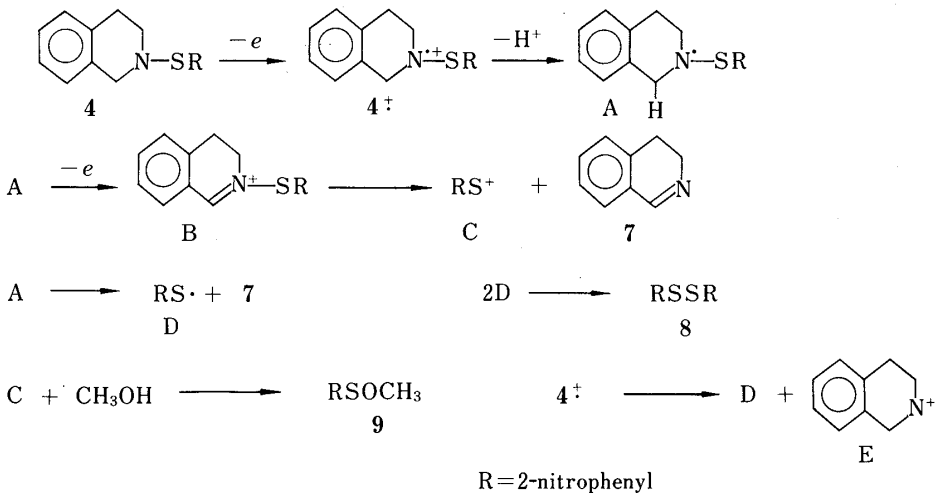

Chart 2

escaped oxidation undergoes homolysis to D and **7**. The yields of **7** (nearly 100%) and **9** (56%), and an *n*-value of 1.46 substantiate this conclusion.

In acetonitrile, which is an aprotic solvent, deprotonation of $\mathbf{4}^{+\cdot}$ is slower than in methanol, and hence only about one-third of $\mathbf{4}^{+\cdot}$ is deprotonated, and A exclusively undergoes homolysis to D and **7**. The rest of $\mathbf{4}^{+\cdot}$ is assumed to undergo homolysis to D and E. The fate of E, however, is unclear at present.

Experimental

Materials——Sulfenamides were prepared by the same method as reported by Capron *et al.*[4] Compound **3** was purified by recrystallization from acetone, giving orange crystals, mp 179.5—180 °C. Compound **4** was recrystallized from ethanol, yielding yellow crystals, mp 93—94 °C. The structures of **3** and **4** were confirmed by analysis of the ^{1}H-NMR spectra. Compound **7** was prepared by the method of Wehrli and Schaer.[5] Acetonitrile were purified as described previously.[6] Methanol was dried with activated magnesium and distilled.

Apparatus——Cyclic voltammetry,[7] controlled potential electrolysis,[7] and ESR spectroscopy[2] were carried out as described previously. All potentials were measured against a saturated calomel electrode. IR, NMR, and MS were obtained on Hitachi 260-30, Bruker AM-400, and Hitachi M-60 spectrometers, respectively. HPLC was carried out with a Waters Associates M-510 solvent delivery system, U6K universal LC injector, Z-module radial compression separation system, and Japan Spectroscopic Co. Uvidec 100-IV UV detector.

Isolation of 5——Compound **3** (143.7 mg) was subjected to electrolysis in acetonitrile (100 ml) containing 0.1 M $NaClO_4$ at 1.0 V at room temperature until the current fell below 1% of the initial value. A black powder precipitated from the electrolyzed solution was filtered off and weighed after being washed with acetonitrile and water, and dried in a desiccator (129.0 mg). It was identified as the perchlorate of **5** on the basis of the elemental analysis data, and IR and ESR spectra: mp 129—131 °C (dec.). *Anal.* Calcd for $C_{30}H_{26}O_8N_4S_2Cl$: C, 53.77; H, 3.91; N, 8.36. Found: C, 53.50; H, 3.65; N, 8.34. IR ν_{max}^{KBr} cm^{-1}: 1510 (NO_2), 1310 (NO_2), 1120 (Cl–O).

A mixture of **5** (108 mg), Na_2CO_3 (100 mg) and acetonitrile (10 ml) containing water (0.5 ml) was stirred overnight. A brown precipitate was separated from the mixture by filtration, and the precipitate was transferred to a separatory funnel together with 100 ml of $CHCl_3$ and 100 ml of water. The funnel was shaken well and then the chloroform layer was separated, dried with Na_2SO_4, and evaporated to dryness under reduced pressure. The residue was subjected to column chromatography on silica gel with $CHCl_3$ as an eluent. The red fraction was collected. Concentration of the red fraction gave a red solid (33.9 mg), which was identified as **6** on the basis of the IR, NMR, and MS; mp 256—257 °C. IR ν_{max}^{KBr} cm^{-1}: 1510 (NO_2), 1335 (NO_2). NMR ($CDCl_3$) δ : 2.13 (4H, m, CH_2), 2.93 (4H, t, CH_2), 3.76 (4H, q, CH_2), 7.19—7.56 (12H, m, aromatic proton), 8.35 (2H, q, aromatic proton). MS *m/e*: 263 ($M^+ - 1 - 2(O_2NC_6H_4S^+)$), 154 ($O_2NC_6H_4S^+$). The structure of **6** was further confirmed by the following procedures. **6** (53.2 mg) was dissolved in 30 ml of anhydrous tetrahydrofuran and the solution was filtered. Hydrogen chloride was introduced into the filtrate, and the white precipitate obtained was filtered off and washed with anhydrous tetrahydrofuran. The precipitate was dissolved in saturated Na_2CO_3 solution and the solution was extracted with $CHCl_3$. The $CHCl_3$ layer was separated and dried over anhydrous Na_2SO_4, then evaporated. The residual oil was identified as 1,1′,2,2′,3,3′,4,4′-octahydro-6,6′-biquinoline on the basis of the NMR and MS and the elemental

analysis data of its dipicrate. NMR ($CDCl_3$) δ: 1.58 (2H, br s, NH), 1.92—1.98 (4H, m, CH_2), 2.80 (4H, t, J=6.4 Hz, CH_2), 3.31 (4H, br t, J=5.4 Hz, CH_2), 6.49 (2H, d, J=8.0 Hz, aromatic proton), 7.11—7.14 (4H, m, aromatic proton). MS *m/e*: 264 (M^+).

Determination of 7——A 5 μl aliquot of electrolyzed solution was injected into a NOVA-PAK cartridge column. The mobile phase was 0.05 M borate buffer (pH 8.3)–MeOH (1 : 2), and the detector was operated at 254 nm.

Determination of 8 and 9——Compounds **8** and **9** were determined as described previously.[8]

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