ELECTRON-TRANSFER PROCESSES: THE ELECTROCHEMICAL REDUCTION OF N,N-DIMETHYL- AND p-CYANOBENZENESULFONAMIDE

by

CARLOS G. SANTELICES

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Approved by:

M. Dale Hawley
Major Professor

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INTRODUCTION

The chemical and electrochemical reduction of sulfonamides have been previously reported to occur by several different pathways. Manousek et al.[1] reduced substituted benzenesulfonamides at mercury electrodes in aqueous borate buffers. By polarographic and coulometric techniques they found that p-cyanobenzenesulfonamides are reductively cleaved in the pH range 7-11 at the carbon-sulfur bond. The process, which involves two electrons and is pH independent, was suggested to occur by the reaction scheme indicated in equations (1) and (2)

$$ArSO_2NH_2 + 2\ e + H^+ \longrightarrow ArH + SO_2NH_2^- \qquad (1)$$

$$SO_2NH_2^- + H_2O \longrightarrow HSO_3^- + NH_3 \qquad (2)$$

However, in contrast to the results obtained in aqueous media, Closson et al.[2] reported that reductive cleavage of sulfonamides by means of electron transfer from arene anion radicals in tetrahydrofuran (THF) and 1,2-dimethoxyethane (DME) occurred at the sulfur-nitrogen bond. The stoichiometry of these reactions at room temperature was variable, requiring from two to almost six equivalents of anion radical for complete cleavage to the anion of the corresponding amine. At low temperatures (-60 to -80°C), however, complete cleavage of tertiary arenesulfonamides required exactly

two equivalents of aromatic hydrocarbon radical anion. A typical example is the reduction of N-methyl-N-phenyl-p-toluenesulfonamide at -70°C (Equation 3)

$$p\text{-}CH_3C_6H_4SO_2N(C_6H_5)(CH_3) + 2Ar^{\cdot-} + H^+ \longrightarrow p\text{-}CH_3C_6H_4SO_2^- + C_6H_5NH(CH_3) \qquad (3)$$

Although the resulting products were stable at this temperature, warming of the solution to room temperature resulted in the further reduction of the p-toluenesulfinate by the hydrocarbon radical anion to produce toluene and several inorganic sulfur compounds.

The redox behavior of primary and secondary sulfonamides is more complicated. For example, whereas reaction of N-tolyl-p-toluenesulfonamide with sodium naphthalene occurs with simple deprotonation to give the corresponding sodium salt of the sulfonamide, stronger reducing agents, such as sodium biphenyl, readily cleave the sulfur-nitrogen bond in this anion, even at -70°C.[2]

Electrochemical reduction of a variety of sulfonamides also results in cleavage of the sulfur-nitrogen bond[3,4]. The reaction scheme outlined by equations (4) - (7) was proposed by Cottrell and Mann[4] for the reduction of the p-cyanobenzenesulfonamides containing an acidic hydrogen.

$$p\text{-}NCC_6H_4SO_2NHR + 2e \longrightarrow [p\text{-}NCC_6H_4SO_2NHR]^{2-} \qquad (4)$$

$$[p\text{-}NCC_6H_4SO_2NHR]^{2-} \longrightarrow p\text{-}NCC_6H_4SO_2^- + RNH^- \qquad (5)$$

$$p\text{-}NCC_6H_4SO_2NHR + RNH^- \longrightarrow p\text{-}NCC_6H_4SO_2NR^- + RNH_2 \qquad (6)$$

$$p\text{-}NCC_6H_4SO_2^- + e \rightleftharpoons [p\text{-}NCC_6H_4SO_2]^{2-\cdot} \qquad (7)$$

The first of the two cathodic peaks observed by Cottrel and Mann was attributed to the irreversible two-electron reduction of the sulfonamide to the corresponding sulfinate anion (eq. 4 and 5). The more negative of the two processes was proposed to correspond to the quasi-reversible one electron reduction of the sulfinate to its dianion radical (eq. 7). The formation of the latter species is supported by an E.S.R. signal which appeared during the controlled potential electrolysis of the N-propyl- and p-toluenesulfonamides at the potential of the second cathodic wave.

A report in our laboratory has postulated nitrogen-hydrogen bond cleavage for the decomposition of the primary p-nitrobenzenesulfonamide radical anion[5]. However, the protonation of the radical anion by the parent compound and further reduction of the nitro group competed with the nitrogen-hydrogen bond cleavage in the p-nitrobenzenesulfonamide radical anion. In order to eliminate proton transfer as a competing reaction, we have reexamined the electrochemical behavior of N,N-dimethyl- and p-cyanobenzenesulfonamide in nonaqueous, aprotic media. We have found that the decomposition mode is dependent upon both potential and the degree of substitution on the amide moiety.

EXPERIMENTAL

INSTRUMENTATION

Cyclic Voltammetry. The cyclic voltammetric experiments were performed on a transitorized, three electrode potentiostat[6,7]. A digitally controlled, multipurpose function generator and a circuit for electronic compensation of ohmic potential loss between the reference and working electrodes were incorporated into the instrument. Readout in relatively slow cyclic voltametric experiments (scan rates of 0.4 v/s or less) was to a Tektronix model 564 oscilloscope. The latter was equipped with two type 2A63 plug-ins and a model C-12 polaroid camera.

Chronoamperometry and coulometry. The three-electrode potentiostat used two inverting amplifiers in parallel configuration for the measurement of cell current and for the electronic compensation of ohmic potential loss between the reference and working electrodes[7]. Stabilization of the potentiostat was effected by means of a 20 pf capacitor connected between the output and the inverting input of the control amplifier (model 48J, analog devices). Since oscillation of the potentiostat could be triggered by high-frequency noise spikes when compensation of ohmic potential loss approached 100%, the outputs of the IR compensation and the current sense amplifiers (model 48J) were each filtered with a multi-frequency cutoff frequency network (100 KHz, 10 KHz, or 1 KHz). The cutoff frequency was software controlled and was a function of the time range selected (0.1 to 10 ms, 1 ms to 100 ms, etc., in one decade steps to a maximum of t = 10s). The rolloff of the filter above the selected frequency was 40 db/decade. Control of the potentiostat and

the acquisition of data were effected by a laboratory digital computer (Lab 8/e, Digital Equipment Corporation).

A similar circuit was used for the controlled potential coulometer. The control amplifier of this instrument was modified to deliver currents up to 100 mA at ± 100V. Circuits were also incorporated for digital integration of the cell current and the digital display of the number of coulombs passed[8]. A strip-chart recorder was used to record the current-time curve.

Chromatography. Analysis of the exhaustively electrolyzed solutions was performed in part by high-performance liquid chromotography. The instrument consisted at a 6000 psi pump (Waters Associates, Inc., Model 6000A), a variable wavelength absorption detector (Schoeffel Instruments, Inc., Models GM770 and SF770), a 7000 psi sample injection valve (Valco Model CV-6-UHPa-C-20) with various size sample loops, and a 25-cm column containing Lichrosorb Si-60 (prepared by CCl_4 Slurry Packing Techniques).

Gas chromatographic analyses were performed with a Hewlett-Packard chromatograph Model 5750. The columns (6 ft 10% UC-W 98) were operated at a temperature of 150°C and a helium flow rate of 25 ml/min.

Cells and electrodes. All electrochemical experiments were performed on an all-glass vacuum line[9]. The solvent (DMF or AN) was distilled into the cell on the vacuum line; traces of oxygen, if present, were removed by several freeze-pump-thaw cycles. After the cell and its contents were brought to room temperature (22.5 ± 0.5°C), helium was introduced until normal atmospheric pressure was attained. The helium was purified by successive passage of the gas through columns of BTS catalyst and anhydrous

magnesium perchlorate and a trap cooled to liquid nitrogen temperature.

The reference electrode was a saturated calomel electrode (SCE). The SCE compartment was separated from the working and auxiliary electrodes in all studies by a glass frit and bridge in order to minimize the contamination of the cell solution by water. The solution in this bridge was a small volume of the solution being investigated.

A small piece of platinum foil served as the auxiliary electrode for the cyclic and chronoamperometric experiments. The auxiliary electrode was placed about 1/2 to 1 centimeter from and parallel to the surface of the working electrode. For coulometric studies the auxiliary electrode was a large, coiled platinum wire which was isolated from the working electrode compartment by means of a glass frit.

A planar platinum button electrode (Beckman number 39273), having a geometric area of 0.25 cm^2, was used as the working electrode for all chronoamperometric experiments. Although most cyclic voltammetric experiments were also performed on this planar platinum electrode, the working electrode used to monitor the progress of the controlled-potential electrolyses was a small spherical platinum bead. A large cylindrical platinum gauze served as the working electrode in coulometric determinations. Stirring of the cell contents was accomplished by means of a water powered magnetic stirrer. For the chronoamperometric measurements the cell was placed inside a Faradaic cage to minimize noise and other interferences.

Chemicals. N,N-Dimethylformamide (DMF) was purified according to the procedure of Faulkner and Bard[10]. DMF of 99% purity was dried over anhydrous $CuSO_4$ and distilled twice at reduced pressure on a vigreux column.

In the purification of acetonitrile (AN)(Fisher) the method described by Walter and Ramaley[11] was employed. All solvents were collected over activated molecular sieves (Linde type 4A) and immediately transferred to the vacuum line for further use. The method of Kolthoff and Coetzee[12] was used for the preparation of tetraethylammonium perchlorate (TEAP). Tetrabutylammonium perchlorate (TBAP) was commercially available (Fisher Scientific Co.). Both supporting electrolytes were recrystalized several times, dried and stored in a vacuum desiccator before being used.

N,N,-Dimethyl-p-bromobenzenesulfonamide. A solution of 20 ml of 40% aqueous dimethylamine (0.180 mole) and 25 grams of sodium carbonate (0.236 mole) in 150 ml of water was added slowly, with stirring, to 11 grams (0.043 mole) of p-bromobenzenesulfonyl chloride (Eastman Kodak Co.) in 40 ml of diethyl ether. The reaction mixture was then heated until the ether had boiled off and a white precipitate had formed. After cooling, separation of the desired compound was achieved by extraction with two 100 ml portions of benzene. The benzene layer was then washed with 100 ml of 5% sodium hydroxide, washed twice with water, and dried over anhydrous sodium sulfate. The benzene was then evaporated under reduced pressure. Crystallization of the residue from methylene chloride/hexane (1:5, v/v) afforded 10.0 grams (88% yield) of N,N-dimethyl-p-bromobenzenesulfonamide, m.p. 93-93.2°C (Lit[13] 94°C); p.m.r. (CCl_4, internal TMS): τ 2.41 (S, C_6H_4,4) 7.35 (S, $N(CH_3)_2$,6).

p-Bromobenzenesulfonamide. 42 grams (0.164 mole) of p-bromobenzenesulfonyl chloride (Eastman Kodak Co.) were dissolved in 100 ml of diethyl ether. 70 ml of concentrated aqueous ammonia were then added slowly to the stirred solution. The resulting solution was then boiled for about 20 minutes.

After this period of time another 70 ml of concentrated aqueous ammonia was added and heating was continued for 30 minutes. Cooling of the reaction mixture to 5°C produced a white precipitate which was collected in a Buchner funnel. Crystallization from hot water yielded .36 grams (93%), colorless needles of p-bromobenzenesulfonamide, m.p. 164-165°C, Lit[14] 166°C, p.m.r. (acetone-d_6, internal TMS): τ 2.24 (m,C_6H_4,4), 3.34 (broad S, NH_2,2).

N,N-Dimethyl-p-cyanobenzenesulfonamide. To 9.6 grams (0.0364 mole) of N,N-dimethyl-p-bromobenzenesulfonamide in 15 ml of dry (distilled from BaO) dimethylformamide was added 4.88 grams (0.0545 mole) of cuprous cyanide. The contents of the reaction flask were stirred under nitrogen for 10 minutes at room temperature and then heated under reflux for 12 hours. The yellow-brown reaction mixture was cooled, diluted with 100 ml of benzene and washed with three 100 ml portions of aqueous sodium cyanide (10 grams sodium cyanide in 300 ml of water). The yellow benzene layer was washed once with water, dried over anhydrous sodium sulfate and then treated with decolorizing carbon. Evaporation of the benzene afforded 6.6 grams (87% yield) of N,N-dimethyl-p-cyanobenzenesulfonamide. Crystallization from chloroform-hexane (1:5, v/v) gave colorless needles, m.p. 125°C, Lit[15] 124-127°C; p.m.r. (CCl_4 + $CDCl_3$, internal TMS): τ 2.13 (S, C_6H_4,4), 7.25 (S,$N(CH_3)_2$,6).

p-Cyanobenzenesulfonamide. To 10.8 grams (0.0457 mole) of p-bromobenzenesulfonamide in 8 ml of dry dimethylformamide (distilled from BaO) was added 6.2 grams (0.069 mole) of cuprous cyanide. The mixture was stirred under nitrogen sweep for about 10 minutes and then heated under reflux for a 13-hour period.

The resulting brown reaction mixture was then cooled and diluted with 200 ml of ethyl acetate. The cuprous cyanide complexes formed were dissolved by stirring the mixture with a solution of 8.5 grams (0.17 mole, 2.5 equivalents) of NaCN in 150 ml of water. The excess sodium cyanide was carefully neutralized with 10% HCl (under a hood) and stirred for 5 minutes.

The aqueous layer was washed with two 100-ml portions of ethyl acetate and the combined ethyl acetate layers were washed with three 150-ml portions of water. Anhydrous sodium sulfate was then used to dry the resulting ethylacetate solution.

After the solvent was evaporated 6.2 grams (79% yield) of p-cyanobenzenesulfonamide were obtained. The solid residue was recrystalized from hot water producing colorless needles. m.p. 169-169.5°C, Lit[16] 168-169°C, p.m.r. (acetone-d_6, internal TMS): τ 1.99 (q,C_6H_4,4), 3.19 (broad S, NH_2,2).

p-Cyanobenzenesulfonyl chloride. p-Cyanobenzenesulfonyl chloride was synthesized from phosphorous pentachloride [J.T. Baker Chemical Co.] and parasulphaminebenzoic acid [Eastman Organic Chemicals] according to the procedure of Remsen, Hartman, and Muckenfuss[16]. A typical preparation is as follows: 27 grams [0.1295 mole] of phosphorous pentachloride and 13 grams [0.0647 mole] of parasulfaminebenzoic acid were thoroughly mixed and brought into a two-neck round bottom flask. A thermometer was then placed in the flask to measure the temperature of the reaction mixture. Stirring was maintained throughout the reaction.

The flask, along with its contents, was set in an oil bath and the temperature increased slowly. At about 70-80°C the solid mixture began

to soften and the reaction commenced with the evolution of HCl and the liquification of the contents. The temperature was then raised again until the reaction continued, as previously, with the evolution of HCl and the production of phosphorous oxychloride. The reaction mixture was maintained at about 120°C until all the oxychloride distilled off. Raising of the temperature to about 170°C started a second reaction which produced additional phosphorous oxychloride. Heating of the mixture reaction was continued until the thermometer indicated a temperature of about 200°C; the temperature was kept at this level until no more oxychloride distilled off. Better yields of p-cyanobenzenesulfonyl chloride were observed when the reaction mixture was kept at ~200°C for an extended period of time even if formation of phosphorus oxychloride was no longer noticeable.

The resulting brown liquid was poured into a suitable flask. Upon cooling, the solution crystallized, rendering well-defined prisms. This impure product was treated with water to separate the phosphorus compounds and the remaining solid was dissolved with benzene, heated, and treated with decolorizing carbon.

Crystallization from benzene/carbon tetrachloride produced large, perfectly transparent, rhombic prisms of p-cyanobenzenesulfonyl chloride. 12.35 grams were obtained [95% yield]. m.p. 110°C, Lit[16] 111-112°C. p.m.r. [$CDCl_3$, internal TMS]: τ 1.93 [q, C_6H_4,4].

p-Cyanobenzenesulfinic acid. p-Cyanobenzenesulfinic acid was prepared from p-cyanobenzenesulfonyl chloride and sodium sulfite according to the method of Cymerman, Koebner, and Short[17]. The following is a typical preparation: 6 grams (0.03 mole) of p-cyanobenzenesulfonyl chloride dissolved

in 10 ml of hot acetone were added slowly to a stirred solution of 7.5 grams (0.06 mole) of sodium sulfite in 30 ml of water. The temperature of the reaction mixture was kept between 75-80°C. Sodium carbonate was added to maintain an alkaline reaction. After the addition of the p-cyanobenzenesulfonyl chloride stirring of the solution was continued for 30 minutes. The reaction mixture was then cooled to 0°C, acidified with concentrated hydrochloric acid, and extracted immediately with ethyl acetate (immediate extraction is essential to prevent the formation of Bis[p-cyanophenyl] disulfoxide, as observed by Cymerman, Koebner and Short[17]. It was also noted that if the ethyl acetate extract containing the sulfinic acid were allowed to stand, then ethyl p-cyanobenzenesulfinate would form).

After the evaporation of the solvent, 4.1 grams (82.5% yield) of p-cyanobenzenesulfinic acid were obtained. Crystallization of the product from hot water produced transparent needles, m.p. 127-128°C (Lit[17] 128-129°C).

RESULTS

CYCLIC VOLTAMMETRY

p-Cyanobenzenesulfonamide. The cyclic voltammetric behavior of p-cyanobenzenesulfonamide in dimethylformamide with tetraethylammonium perchlorate as the supporting electrolyte is shown in Figure 1. On the first cathodic sweep two reduction processes are observed near -1.80 V and -2.36 V. Upon reversal of the potential scan at -2.80 V a single oxidation wave corresponding to the reoxidation of the product of the second cathodic process is seen near -2.15 V. Subsequent cycles show that the first wave decreases in magnitude while the second wave increases in magnitude relative to that of the first cathodic peak. The first reduction process is irreversible, as evidenced by the absence of an anodic wave at all sweep rates in the scan range from 0.1 V/s to 50 V/s. Furthermore, switching of the cathodic sweep between the first and second reduction processes did not reveal reversibility. The second cathodic process is reversible as evidenced by a $i_{p,a}/i_{p,c}$ ratio (ratio of anodic peak current to cathodic peak current) of unity.

N,N-Dimethyl-p-cyanobenzenesulfonamide. The cyclic voltammogram of N,N-dimethyl-p-cyanobenzenesulfonamide in dimethylformamide is illustrated in Figure 2. On the cathodic sweep two principal reduction peaks are seen near -1.70 V and -2.42 V. In addition, a shoulder appears on the second cathodic peak when tetraethylammonium perchlorate is used as the supporting electrolyte. Decreasing the scan rate causes the shoulder to

become more clearly defined. It is not observed at these scan rates if TBAP is used as the supporting electrolyte (compare Fig. 2 and 3).

The first cathodic process is attributed to the reduction of N,N-dimethyl-p-cyanobenzenesulfonamide to its radical anion. Total reversibility of this process was demonstrated by reversing the direction of the potential sweep between the first and second cathodic processes (Fig. 4). As expected for a reversible process, a ratio of unity for $i_{p,a}/i_{p,c}$ was obtained. Reduction of the radical anion to its dianion at more negative potential is irreversible, however, as evidenced by the facts that (1) two distinct cathodic processes are discernible near -2.4 V; (2) the peak height for the combined processes significantly exceeds that for the reduction of the tertiary sulfonamide to its radical anion; and (3) the magnitude of the anodic wave (-1.62 V) for the reoxidation of the radical anion (9) is reduced by the occurrence of the second reduction process (Fig. 2). The presence of an anodic wave near -2.26 V on the reverse, positive-going sweep also indicates that the decomposition of the dianion must afford a product which is reduced reversibly at the applied potential.

p-Cyanobenzenesulfinic acid. Cyclic voltammetric behavior of p-cyanobenzenesulfinic acid in DMF and TEAP as the supporting electrolyte is shown in Figure 5. Two reduction reaction waves are observed near -1.04 V and -2.42 V on the cathodic sweep. Only a single oxidation wave corresponding to the reoxidation of the second reduction product is obtained on the anodic scan.

The first cathodic peak corresponds to the reduction of the sulfinic acid to its unstable radical anion. The latter decomposes with a loss of

Figure 1. Cyclic voltammogram of 2.43×10^{-3} M p-cyanobenzenesulfonamide in dimethylformamide with 0.1 M tetraethylammonium perchlorate as the supporting electrolyte. The scan rate was 0.2 V/s on the 0.25 cm^2 planar platinum electrode.

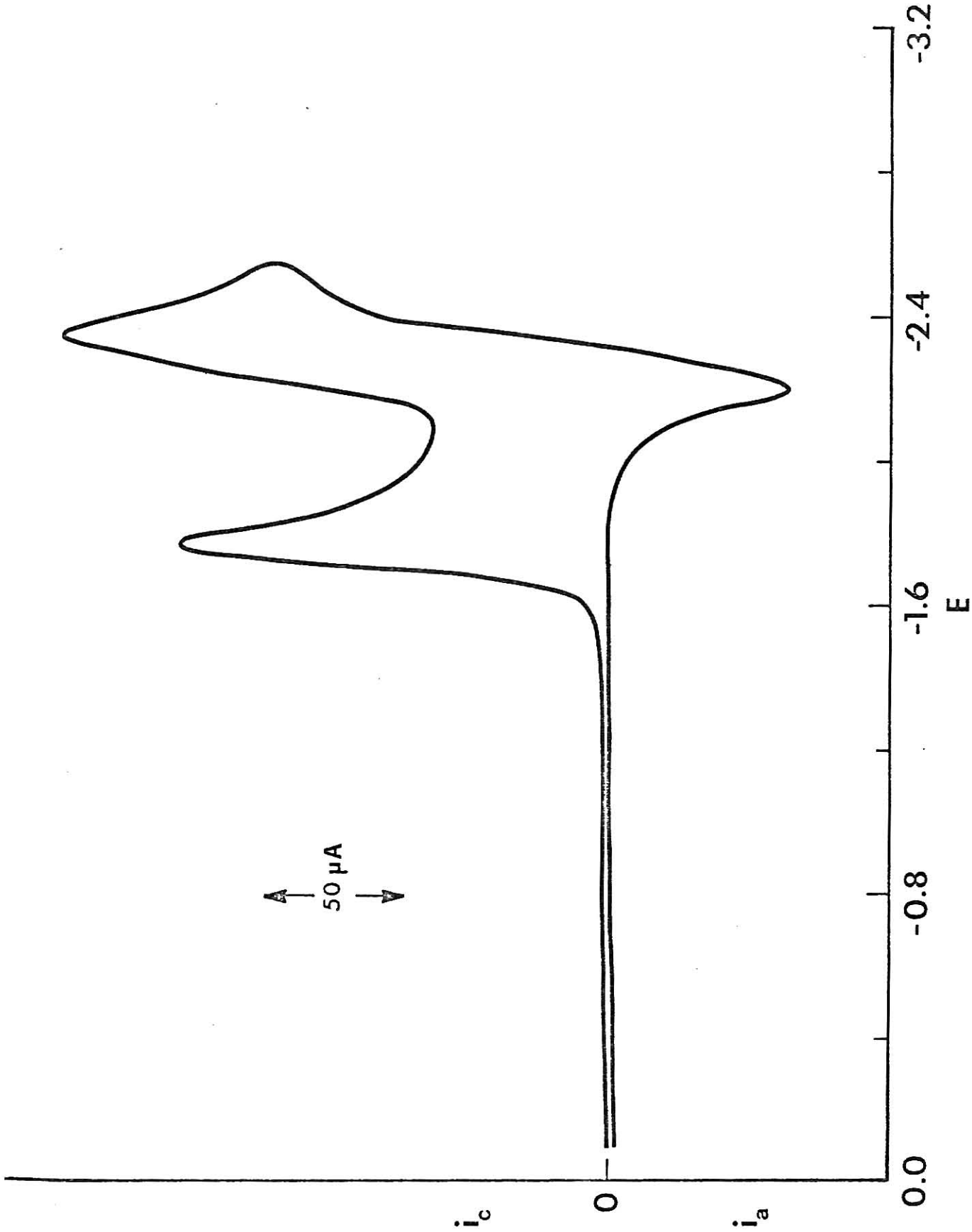

50 μA
i_c
0
i_a
0.0
-0.8
-1.6
-2.4
-3.2
E

Figure 2. Cyclic voltammogram of 4.2×10^{-3} M N,N-dimethyl-p-cyanobenzenesulfonamide in DMF with 0.1 M tetraethylammonium perchlorate at a scan rate of 0.2 V/s on the 0.25 cm^2 planar platinum electrode.

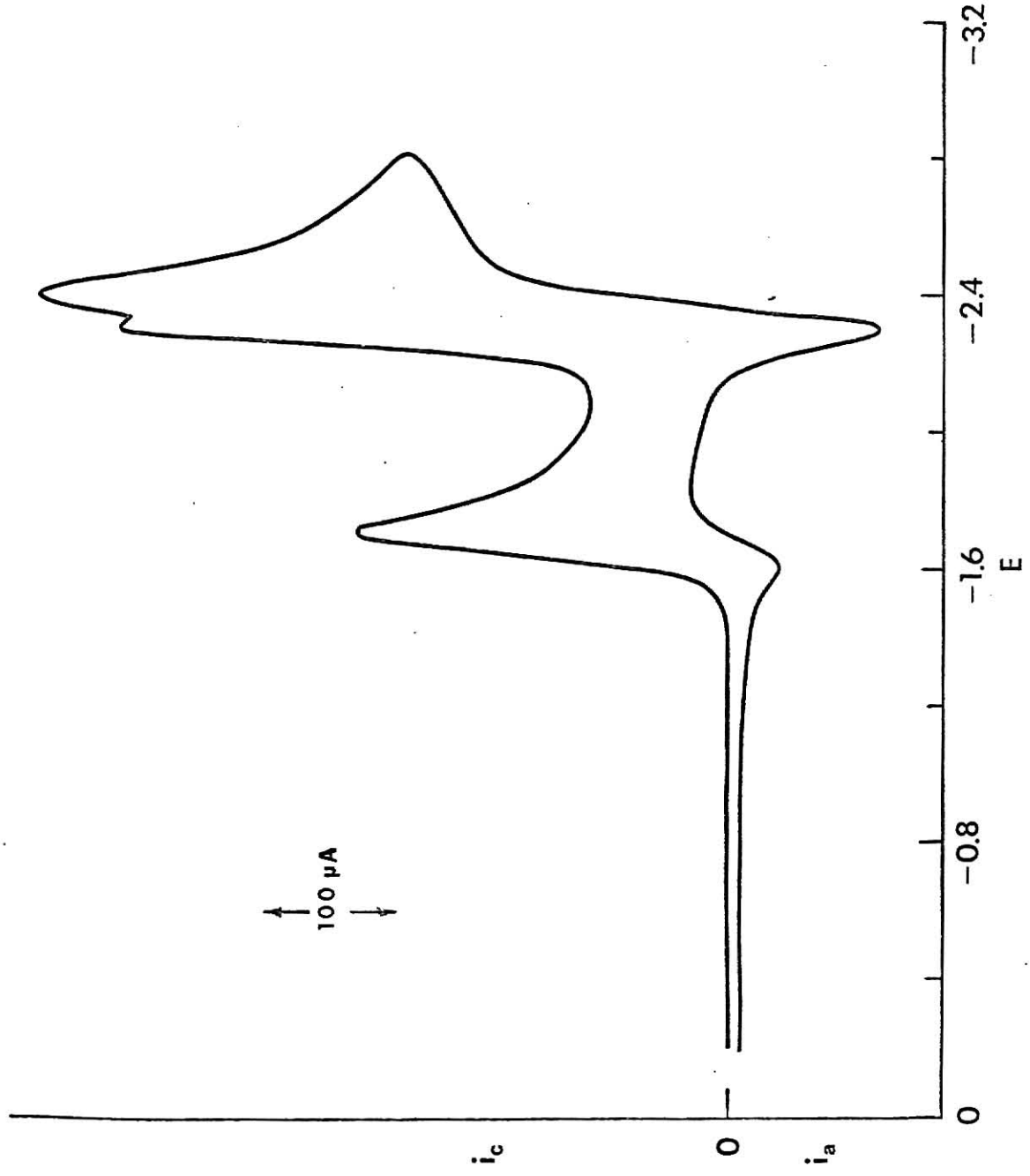

100 μA
i_c
0
i_a
0
−0.8
−1.6
−2.4
−3.2
E

Figure 3. Cyclic voltammogram of 1.86×10^{-3} M N,N-dimethyl-p-cyanobenzenesulfonamide in DMF with 0.1 M tetrabutylammonium perchlorate as the supporting electrolyte. The scan rate on the 0.25 cm^2 planar platinum electrode was 0.2 V/s.

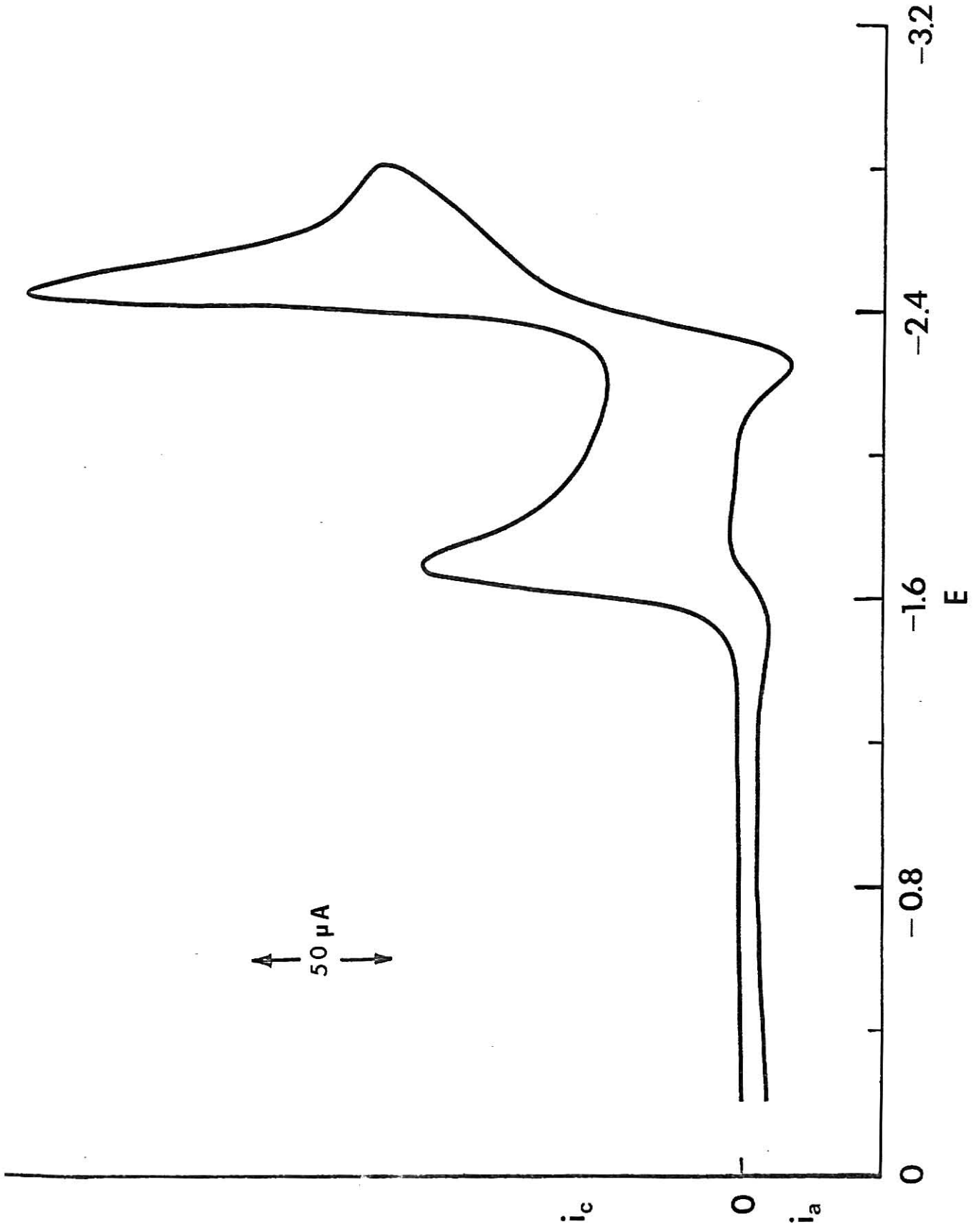
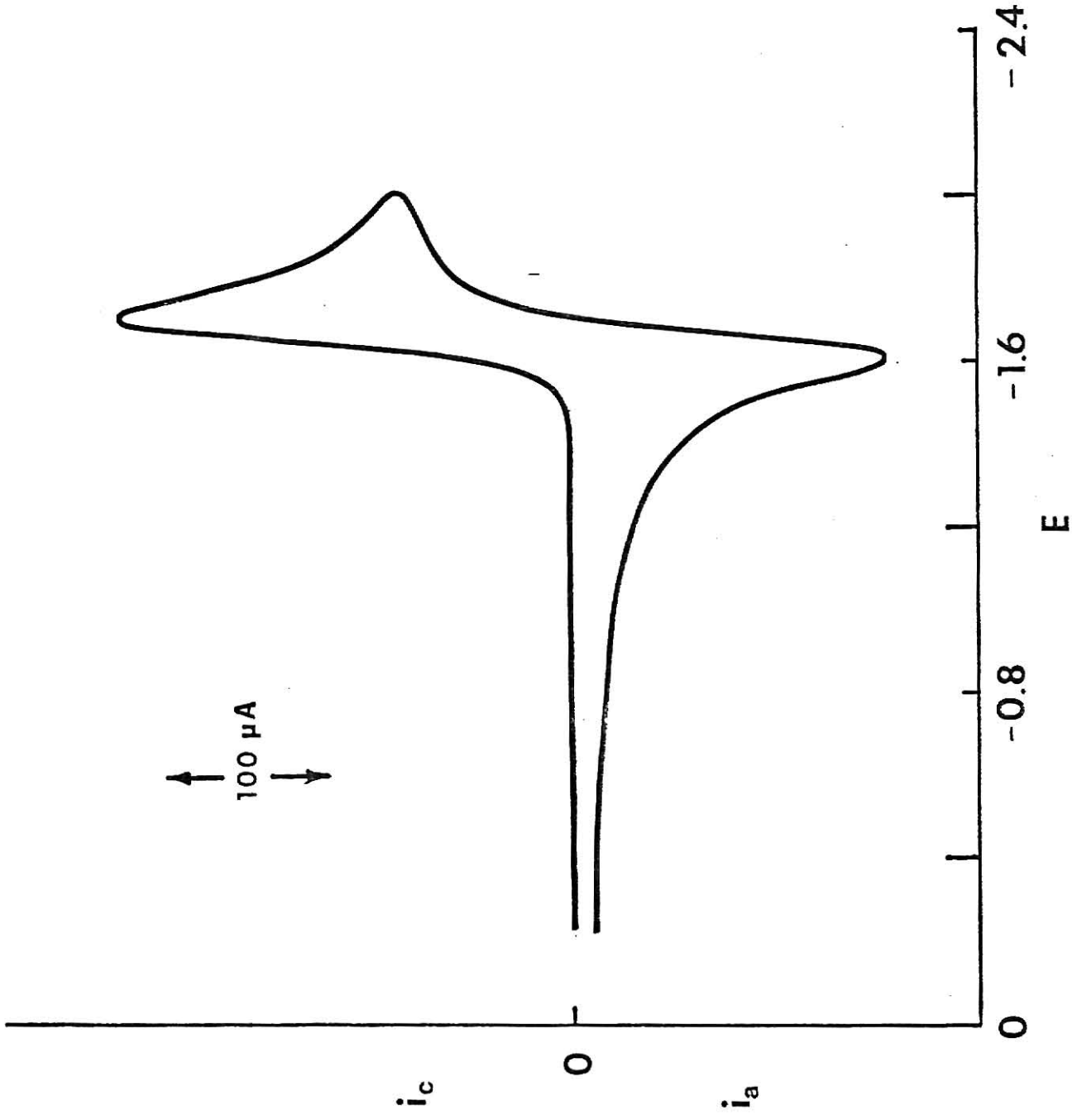

50 μA
i_c
0
i_a
0
−0.8
−1.6
−2.4
−3.2
E

Figure 4. Cyclic voltammogram of 4.2×10^{-3} M N,N-dimethyl-p-cyanobenzenesulfonamide in DMF with 0.1 M tetraethylammonium perchlorate. The scan rate on the 0.25 cm^2 planar platinum electrode was 0.2 V/s.


100 μA
i_c
0
i_a
0
-0.8
-1.6
-2.4
E

hydrogen and the production of the corresponding sulfinate anion. The instability of the radical anion is evidenced by the absence of an anodic wave corresponding to the reoxidation of the reduction product.

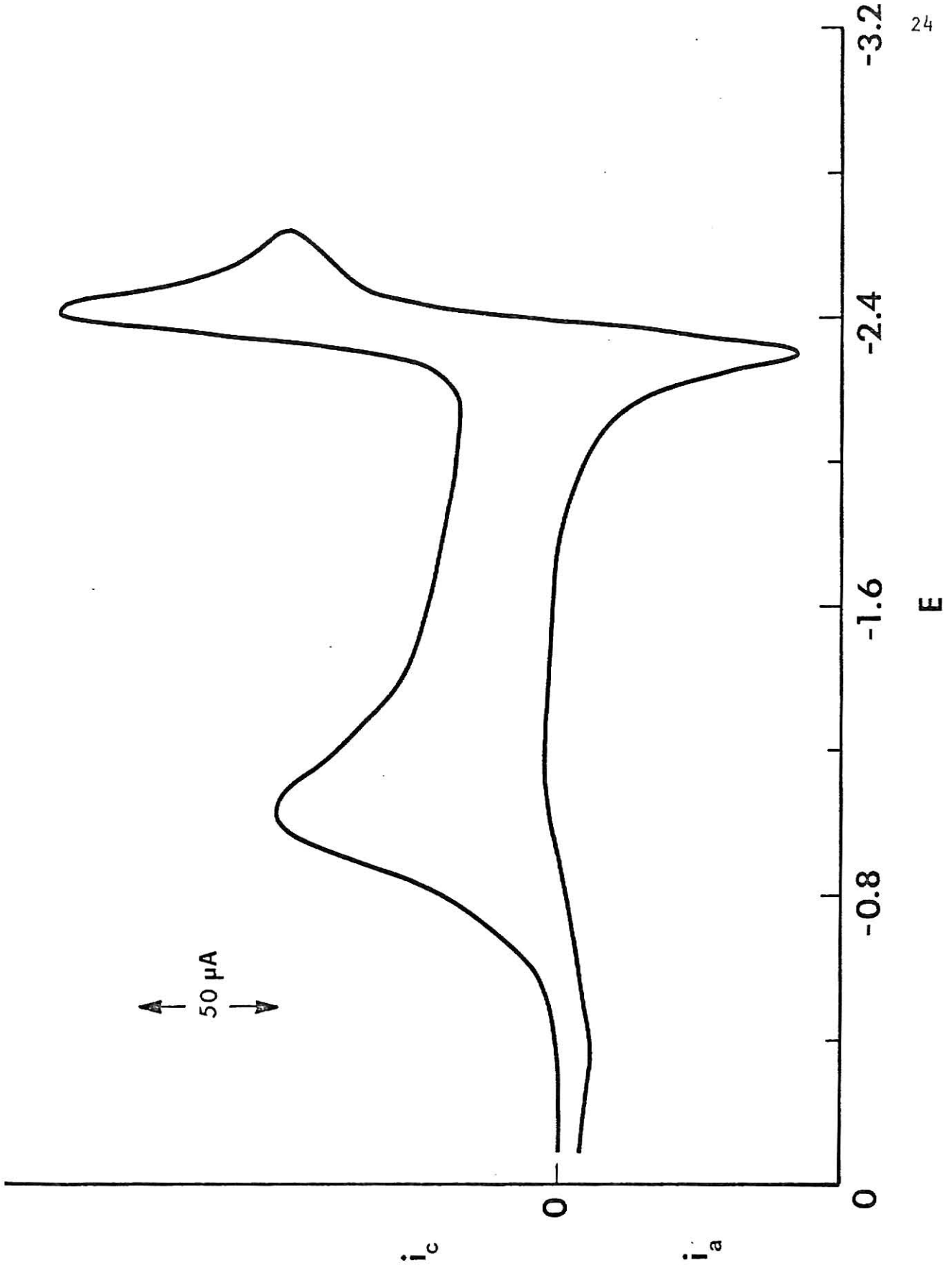
Reversibility of the second reduction process is based on the ratio $i_{p,a}/i_{p,c}$. This reversible couple appears at nearly the same potential as the second cathodic wave for the reduction of the tertiary sulfonamide and corresponds to the reduction of the sulfinate to its stable radical anion.

The reaction scheme outlined in Equations (8) - (9) describes the electrochemical reduction of p-cyanobenzenesulfinic acid

$$\underline{p}\text{-}NCC_6H_4SO_2H + e \longrightarrow \frac{1}{2} H_2 + \underline{p}\text{-}NCC_6H_4SO_2^- \qquad (8)$$

$$\underline{p}\text{-}NCC_6H_4SO_2^- + e \rightleftharpoons NCC_6H_4SO_2^{2-\cdot} \qquad (9)$$

Figure 5. Cyclic voltammogram of 2.18×10^{-3} M p-cyanobenzenesulfinic acid in dimethylformamide and 0.1 M tetraethylammonium perchlorate as the supporting electrolyte. The scan rate on the 0.25 cm^2 planar platinum electrode was 0.2 V/s.


50 μA
i_c
0
i_a
0
-0.8
-1.6
-2.4
-3.2
E

CHRONOAMPEROMETRY

p-Cyanobenzenesulfinic acid. Since the stepwise reduction of p-cyanobenzenesulfinic acid to its conjugate base and then to its dianion radical is known to involve one and two electrons, respectively, this chemical system was used to estimate the number of electrons in each of the several reductions of the two sulfonamides. As shown in Figure 6, the chronoamperometric reductions of p-cyanobenzenesulfinic acid at -1.84 and -2.60 are both diffusion controlled for $t \geq 50$ ms.

N,N-Dimethyl-p-cyanobenzenesulfonamide. Chronoamperometric $it^{1/2}/c$ values were obtained for the reduction of the tertiary sulfonamide at two different potential settings.

Initially the potential was stepped from a value where no electrochemical reaction occurs (-1.20 V) to a potential which is sufficiently negative (-2.00 V) to cause only the initial reduction of N,N-dimethyl-p-cyanobenzenesulfonamide. A diffusion controlled value of about 34 μA $s^{1/2}$ $mmol^{-1}$ l was obtained for $it^{1/2}/c$ in a time range of 5ms $\leq t \leq$ 10s (Fig. 6).

In a second experiment the potential was made sufficiently negative (-2.84 V) so as to cause all cathodic processes to occur concurrently. The value obtained for $it^{1/2}/c$ remained diffusion controlled in the same time range, but approximately tripled in magnitude: $it^{1/2}/c$ = 100 μA $s^{1/2}$ $mmol^{-1}$ l (Fig. 6).

From a comparison of these values with the data obtained from the reduction of p-cyanobenzenesulfinic acid, we conclude that the reduction

of the tertiary sulfonamide at the potentials of -2.10 V and -2.84 V involves one and three electrons per molecule, respectively.

In order to verify the reversibility of the first redox process double-potential-step chronoamperometry (DPSCA) technique was employed. In this technique the potential is first stepped to a value sufficiently negative (-2.00 V) to cause the diffusion controlled reduction of N,N-dimethyl-p-cyanobenzenesulfonamide to its radical anion. After a predetermined cathodic electrolysis time, τ, the potential was then stepped to a value sufficiently anodic (-1.20) to cause the oxidation of N,N-dimethyl-p-cyanobenzenesulfonamide radical anion.

Double potential step chronoamperometric data (Table 1) establish unequivocally that the product of this reaction, the N,N-dimethyl-p-cyanobenzenesulfonamide radical anion, is stable at this potential and that it can be reoxidized quantitatively to starting material on the reverse potential step. Neither a change in the concentration of the sulfonamide nor different values of τ altered appreciably the results obtained by DPSCA. All data were in close agreement with the theoretical values corresponding to a reversible process (see Table 1).

p-Cyanobenzenesulfonamide. The chronoamperometric reduction of p-cyanobenzenesulfonamide at -2.10 V is a diffusion-controlled, one electron process in the time range 3 ms $\leq t \leq$ 10 s. Unlike the tertiary sulfonamide, however, the initially formed p-cyanobenzenesulfonamide radical anion decomposes so rapidly that no anodic current can be observed for its reoxidation in double-potential-step experiments of 10 ms duration. Reduction of p-cyanobenzenesulfonamide at more negative potential (-2.84 V)

gives $it^{1/2}/c$ data slightly in excess of what might be expected for an overall two-electron process. The absence of diffusion control for $t < 30$ ms results in large part from the rapid decomposition of the dianion of p-cyanobenzenesulfonamide (3) and our inability to apply a sufficiently negative potential so as to render the concentration of p-cyanobenezenesulfonamide zero at the electrode surface for all $t > 0$. The limit of -2.84 V vs. SCE is imposed by the onset of solvent-electrolyte breakdown on the platinum working electrode.

Figure 6. Single potential step chronoamperometric data for the reduction of: p-cyanobenzenesulfinic acid at (△) -1.84 V and (▲) -2.60 V; p-cyanobenzenesulfonamide at (◑) -2.10 V and (◐) -2.84 V; and N,N-dimethyl-p-cyanobenzenesulfonamide at (○) -2.10 V and (●) -2.84 V.

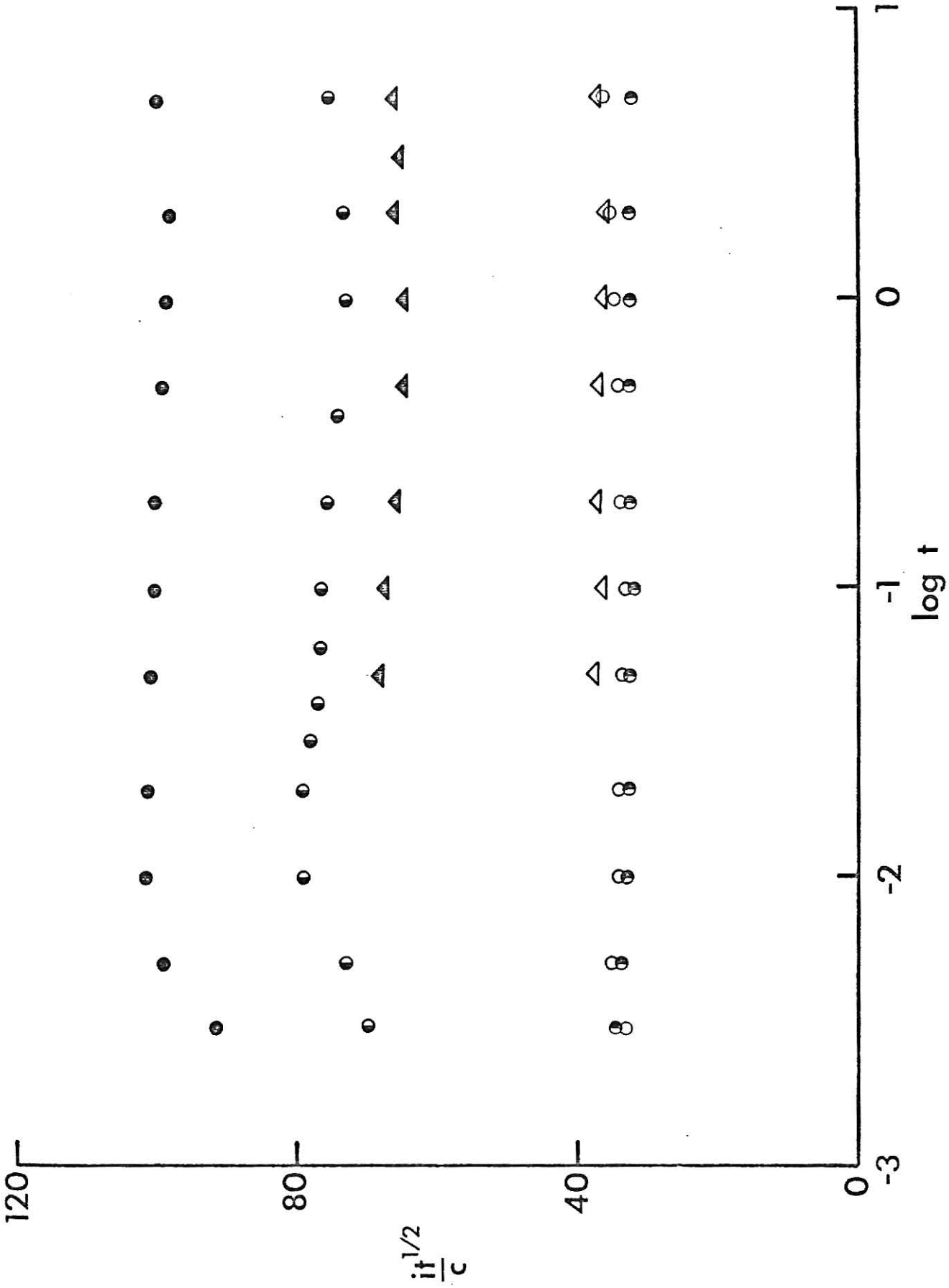

120
80
40
0
-3
-2
-1
0
1
log t
$\frac{it^{1/2}}{c}$

Table 1. Double potential step chronoamperometric data for N,N-dimethyl-*p*-cyanobenzenesulfonamide in 0.1 *M* TEAP-DMF.

Initial potential = -1.20 V

Forward potential = -2.00 V

Reverse potential = -1.20 V

Tau = 0.2 s

TABLE 1

Ratio Time	Ratio Current (Experimental)	Ratio Current (Theoretical)
0.1	2.31	2.21
0.2	1.35	1.32
0.3	0.95	0.95
0.4	0.73	0.74
0.5	0.60	0.60
0.6	0.51	0.50
0.7	0.44	0.43
0.8	0.37	0.37
0.9	0.33	0.33
1.0	0.30	0.29

COULOMETRY

N,N-Dimethyl-p-cyanobenzenesulfonamide. Decomposition of the N,N-dimethyl-p-cyanobenzenesulfonamide dianion by the cleavage of the carbon-sulfur and sulfur-nitrogen bonds would produce benzonitrile and p-cyanobenezenesulfinate, respectively, as the main product of electrolysis. Since the one-electron reductions of benzonitrile and p-cyanobenzenesulfinate are chemically reversible and occur approximately at the same potential, cyclic voltammetry does not permit the unequivocal identification of the electrolysis product.

Chronoamperometric results obtained are also consistent for either pathway. Hence, in order to make the distinction, millimolar solutions of N,N-dimethyl-p-cyanobenzenesulfonamide in DMF were electrolyzed at a potential of -2.40 V. Electrolysis was halted after the addition of 2 faradays/mole of starting material. The electrolyzed solution was transferred to a suitable round bottom flask which was then connected to the vacuum line. By application of the method used in the distillation of solvent into the cell, separation of the supporting electrolyte was obtained. The distillate was then examined by gas chromatography. Standards of benzonitrile in DMF were prepared for each analysis.

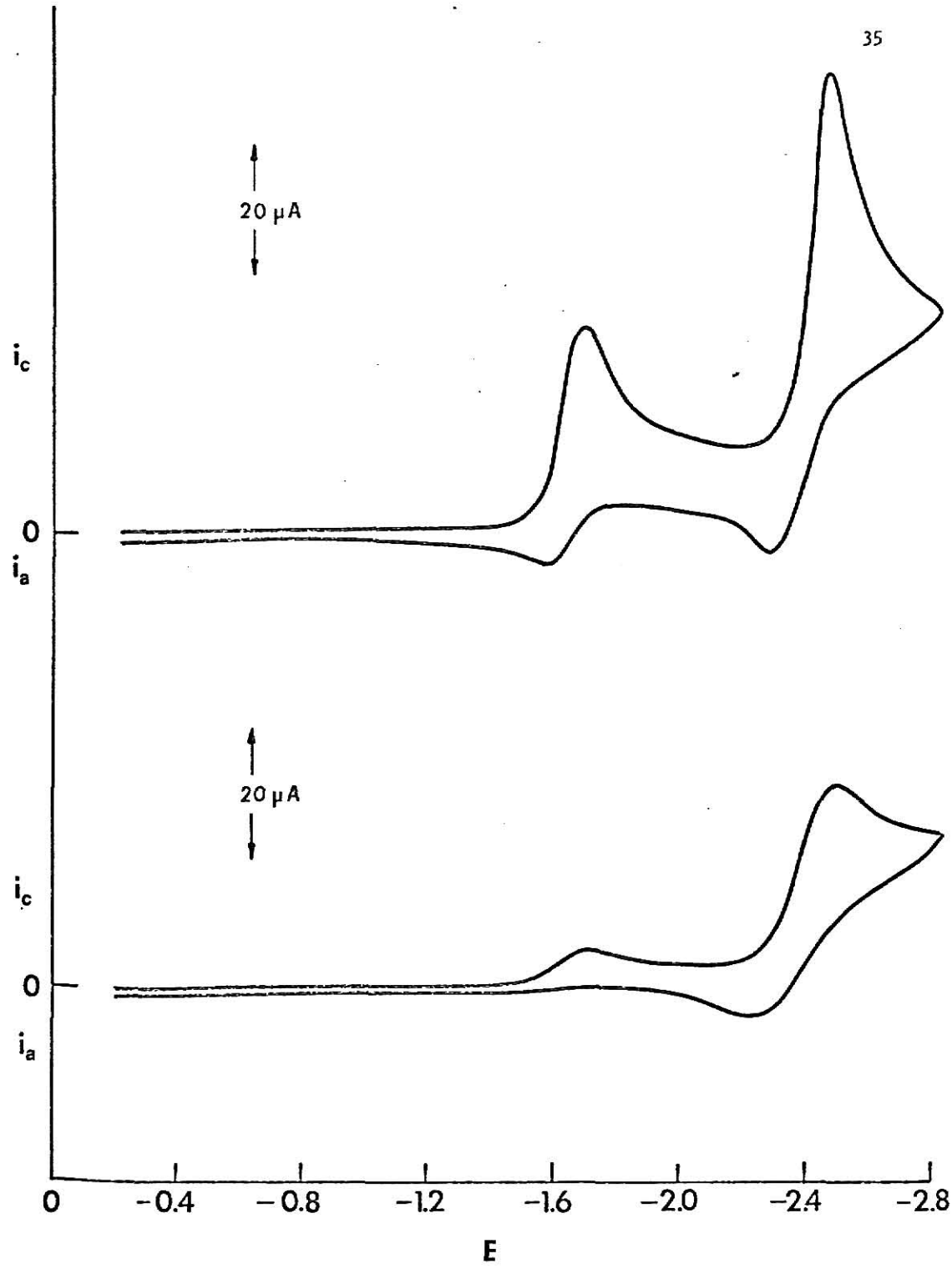
Gas chromatography gave no indication of the formation of benzonitrile. In addition, no other compound with retention greater than that of the DMF was observed. Thus, if any benzonitrile was actually formed, it could not have been in excess of 5% of the starting material.

The dry solid residue that remained after distillation in the vacuum line was tested for sulfinate using the Smiles test[18]. The results obtained were positive, indicating the presence of sulfinate. No quantitative determinations were attempted.

Examination of the peak height in the cyclic voltammograms of N,N-dimethyl-p-cyanobenzenesulfonamide before and after electrolysis (Fig. 7) shows that more than 80% of the starting material was consumed. Furthermore, the potential at which the second reversible couple (-2.46V) appears does not correspond to that of benzonitrile ($E_{p,c}$ = -2.38 V in 0.1 M TBAP-DMF). The peak height of this second reversible cathodic process before and after electrolysis corresponded approximately to two and one electron processes, respectively, when compared to the peak height of the first cathodic process.

p-Cyanobenzenesulfonamide. It was suggested by Cottrell and Mann[4] that the first of the two reduction peaks observed corresponded to the irreversible two-electron reduction of p-cyanobenzenesulfonamide to the corresponding sulfinate anion. However, the results of performed studies by Asirvatham and Hawley[5] on p-nitrobenzenesulfonamides suggest that the decomposition of the primary sulfonamide radical anion occurs in part with loss of hydrogen and the formation of the corresponding sulfonamide anion. Hence, p-cyanobenzenesulfonamide was exhaustively electrolyzed (at -1.90 V) in solution of DMF and AN for the purpose of product identification. Thus, if cleavage of either N-H or S-N bond occurred, then acidification of the electrolyzed solution would produce either starting material or p-cyanobenzenesulfinic acid, respectively.

Figure 7. Cyclic voltammograms of N,N-dimethyl-p-cyanobenzenesulfonamide in 0.1 M TBAP-DMF. The scan rate on the spherical platinum bead electrode was 0.2 V/s. Upper curve: before electrolysis; lower curve: after electrolysis. The electrolysis was halted when two electrons per molecule of sulfonamide had been passed.

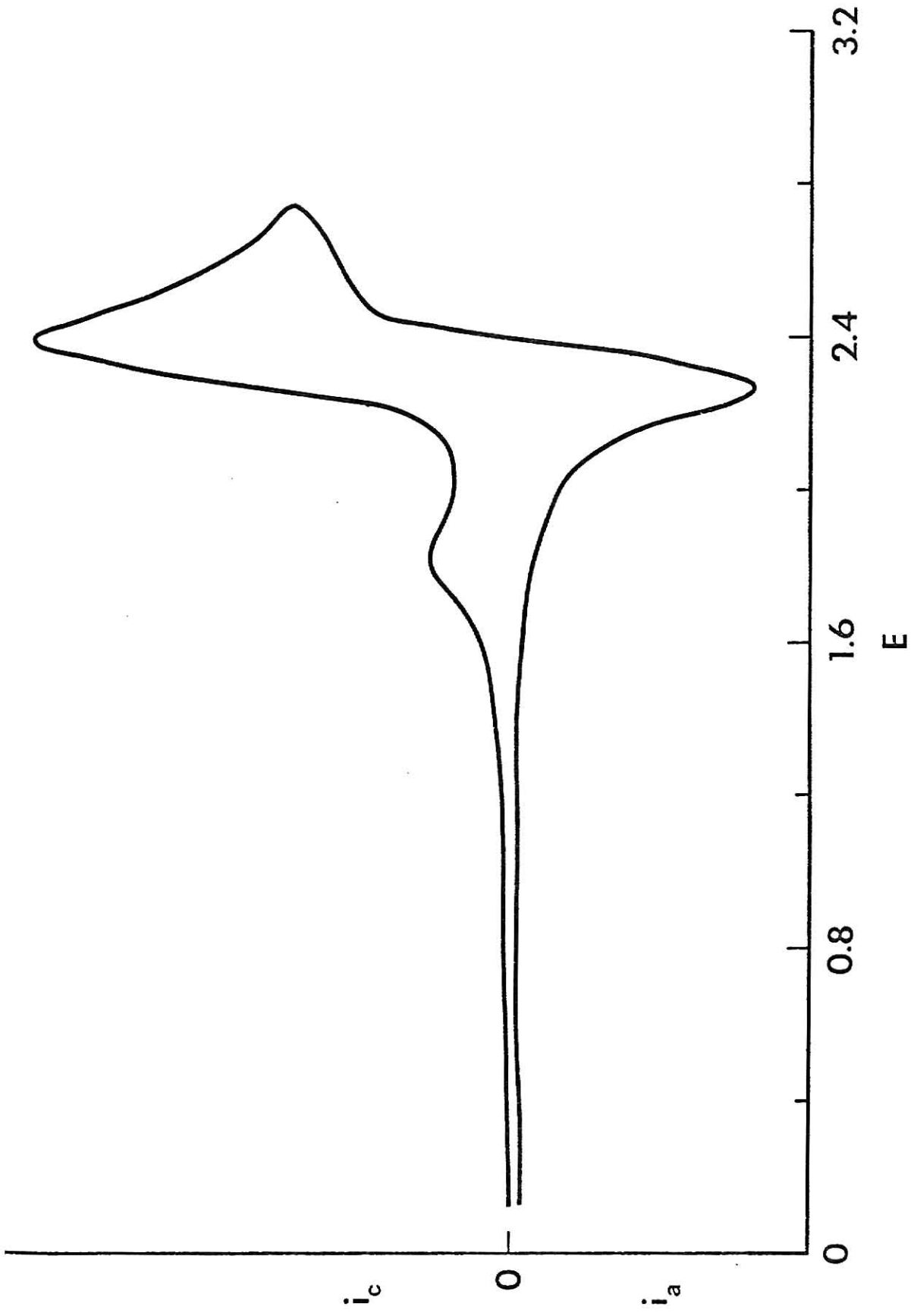

20 μA
i_c
0
i_a
20 μA
i_c
0
i_a
0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
-2.8
E

From a comparison of peak heights before and after electrolysis, we conclude that approximately 80% of starting material is consumed by the passage of one electron per molecule of p-cyanobenzenesulfonamide (Fig. 8).

After acidification of the electrolyzed solution with perchloric acid, careful neutralization with sodium carbonate and sodium bicarbonate followed. The resulting solution was evaporated to dryness under reduced pressure. Ethyl acetate was first added to the residue to extract the product from most of the supporting electrolyte (TEAP). In order to maximize the recovery of p-cyanobenzenesulfonamide, 95% ethanol was used due to the greater solubility of the extract in this solvent. The combined ethyl acetate and ethanol solutions were then evaporated to dryness. Washing the dry residue with portions of the eluent (5% wt. absolute ethanol in chloroform) prepared the sample for high performance liquid chromatography analysis. (TEAP has only limited solubility in the chosen mobile phase). All samples were then diluted to 25 ml.

HPLC results showed that the p-cyanobenzenesulfonamide was recovered in 75 $\pm$ 2.4% absolute yield. When the absolute yields are divided by the recovery factor of 84 $\pm$ 3.4%, p-cyanobenzenesulfonamide is recovered in 89 $\pm$ 3% effective yield. We conclude, therefore, that electrolysis of p-cyanobenzenesulfonamide at the potential of the first wave is a one-electron process which gives the corresponding conjugate base, p-$NCC_6H_4SO_2\overline{N}H$, as the principal product.

Figure 8. Cyclic voltammogram of an electrolyzed solution of p-cyanobenzenesulfonamide in 0.1 M TEAP-DMF. The scan rate on the spherical platinum bead electrode was 0.2 V/s. The electrolysis was terminated when one electron per molecule of sulfonamide had been passed.


3.2
2.4
1.6
0.8
0
E
i_c
0
i_a

DISCUSSION

The reaction scheme described by Eqs. 10-18 is proposed for the reduction of the primary sulfonamide, 1. The cyclic voltammetric and chronoamperometric data show that 1 is reduced to its radical anion at the potential of the first cathodic wave. The radical anion is unstable, as evidenced by the absence of an anodic wave for its reoxidation at scan rates up to 100 V/s, and rapidly decomposes by loss of hydrogen (Eq. 12) to give the conjugate base, 6. This species then may be protonated to regenerate 1 or it may be reduced reversibly to its dianion radical (7) at more negative potential ($E_{p,c}$ = -2.36 V) (Eq. 12).

The most complex behavior occurs when the potential is made sufficiently negative so as to cause the reduction of the radical anion, 2, to the dianion, 3 (Eq. 11). Initially, the dianion is suggested to undergo rapid sulfur-nitrogen bond cleavage to give equal molar quantities of amide ion and p-cyanobenzenesulfinate, 4 (Eq. 11). The latter species is electroactive at the applied potential ($E_{p,c}$ = -2.42 V) and is reduced reversibly to its dianion radical, 5 (Eq. 13).

Although the formation of p-cyanobenzenesulfinate dianion radical from 1 requires three electrons, subsequent solution reactions involving amide ion, the dianion radical (5), and starting material (1) reduce the observed n value. First, abstraction (Eq. 15) of a proton from the primary sulfonamide (pK_a = 9.3)[19] by amide ion ($pK_a \tilde{=} 34$)[20] would yield the conjugate base (6), a species which is reduced reversibly to its dianion radical (7) at the applied potential. Second, diffusion of the dianion radical of the sulfinate (5) from the electrode surface is presumed to result also in electron transfer

Scheme I

$$RSO_2NH_2 + e \xrightarrow[\underline{E}_1]{} [RSO_2NH_2]^{\cdot-} \text{ , where R = } \underline{p}\text{-}NCC_6H_4 \qquad (10)$$

$\underline{1}$ $\underline{2}$

$$\underline{2} \xrightarrow{e,\ \underline{E}_2 << \underline{E}_1} [RSO_2NH_2]^{2-} \xrightarrow{fast} RSO_2^- + \bar{N}H_2 \qquad (11)$$

$\underline{3}$ $\underline{4}$

$$\underline{2} \xrightarrow{fast} 1/2\ H_2 + RSO_2\bar{N}H \underset{e}{\overset{e}{\rightleftharpoons}} RSO_2NH^{2-\cdot} \qquad (12)$$

$\underline{6}$ $\underline{7}$

$$\underline{4} + e \rightleftharpoons RSO_2^{2-\cdot} \qquad (13)$$

$\underline{5}$

$$\bar{N}H_2 \xrightarrow{SH} NH_3 + S^- \qquad (14)$$

$$\bar{N}H_2 \xrightarrow{\underline{1}} NH_3 + \underline{6} \qquad (15)$$

$$\underline{5} + \underline{1} \longrightarrow \underline{2} + \underline{4} \qquad (16)$$

$$\underline{7} + \underline{1} \longrightarrow \underline{2} + \underline{6} \qquad (17)$$

$$\underline{5} \text{ or } \underline{7} + \underline{2} \longrightarrow \underline{3} + \underline{4} \text{ or } \underline{6} \qquad (18)$$

Scheme II

$$RSO_2N(CH_3)_2 + e \rightleftharpoons RSO_2N(CH_3)_2^{\cdot -} \xrightarrow{e} RSO_2N(CH_3)_2^{2-} \quad (19)$$

$\underline{\underline{8}}$ $\underline{\underline{9}}$ $\underline{\underline{10}}$

$$\underline{\underline{10}} \xrightarrow{\text{fast}} N(CH_3)_2^- + \underline{\underline{4}} \quad (20)$$

$$\underline{\underline{4}} + e \rightleftharpoons \underline{\underline{5}} \quad (21)$$

$$\underline{\underline{5}} + \underline{\underline{8}} \longrightarrow \underline{\underline{4}} + \underline{\underline{9}} \quad (22)$$

$$N(CH_3)_2^- \xrightarrow{SH} S^- + HN(CH_3)_2 \quad (23)$$

from 5 to the starting material, 1 (Eq. 16). Since the radical anion of p-cyanobenzenesulfonamide is then formed in the bulk of solution rather than at the electrode surface, decomposition of the radical anion by loss of hydrogen affords 6, a species which is reduced slightly more easily than p-cyanobenzenesulfinate (Eq. 12). Because the subsequent solution redox reaction (Eq. 17) between 7 and 1 also gives 2 in the bulk of solution, the reduction of 1 at the potential of its second cathodic wave gives the dianion radical 7 as the principal product in an overall two-electron process.

Support for the two-electron reduction of 1 to 7 at -2.84 V is provided by single-potential-step chronoamperometry experiments. The slightly larger apparent n value of two, especially for $t \leq 30$ ms, is consistent with the inclusion of Eqs. 11, 13, 14 and 18 in the reaction scheme. The formation of a small amount of the sulfinate 4 is discernible in the cyclic voltammogram of 1 as a slight splitting near the peak of the second cathodic wave (Fig. 1). In addition, ammonia and sulfinate were detected as products of the reduction of 1 by Cottrell and Mann[4] when they electrolyzed 1 at the potential of the second cathodic wave.

The redox behavior of the tertiary sulfonamide (8) is less complex. As evidenced by the cyclic voltammetric and chronamperometric results, the reduction of 8 to its radical anion (9) is chemically reversible. The second cathodic wave arises when the radical anion is further reduced to the dianion (10) (Eq. 19). This species is unstable and decomposes rapidly by nitrogen-sulfur bond cleavage (Eq. 20). One product of this reaction, the p-cyanobenzenesulfinate anion (4), is electroactive at the applied potential and is reduced reversibly to its dianion radical, 5 (Eq. 21). The remaining

reactions in the redox scheme involve the abstraction of a proton from a component of the solvent-electrolyte system by the dimethylamide anion (Eq. 23) and a solution redox reaction (Eq. 22) between the sulfinate dianion radical $\underline{\underline{5}}$ and the tertiary sulfonamide $\underline{\underline{8}}$. This scheme correctly predicts the experimentally observed chronoamperometric $\underline{n}$ values of one and three at -2.84 V, respectively. In addition, $\underline{p}$-cyanobenzenesulfinate was identified as one of the reduction products when $\underline{\underline{8}}$ is electrolyzed at the potential of the second cathodic wave.

Rapid nitrogen-hydrogen bond cleavage in the primary sulfonamide radical anion and the marked stability for the corresponding tertiary sulfonamide radical anion were unrecognized in a previous electrochemical study of the several $\underline{p}$-cyanobenzenesulfonamides.[4] The ease with which nitrogen-hydrogen bond cleavage occurs in the primary sulfonamide radical anion may be rationalized on the basis of the acidity of the primary sulfonamide (pK_a = 9.3[19]). This nitrogen-centered acid behaves very similarly to $\underline{p}$-nitrobenzyl cyanide, a carbon-centered acid which has been shown to lose hydrogen from its radical anion to give the stable $\underline{p}$-nitrobenzyl cyanide anion.[21,22] We have also reported nitrogen-hydrogen bond cleavage in $\underline{p}$-nitrobenzenesulfonamide radical anion.[5] In that case, however, protonation of the radical anion by the parent compound and further reduction of the nitro group competed with loss of hydrogen from the radical anion.

LITERATURE CITED

1. O. Manousek, O. Exner, and P. Zuman, Collect. Czeck. Chem. Commun., 33 (1968) 4000.
2. W. D. Closson, S. Ji, and S. S. Schulenberg, J. Amer. Chem. Soc., 92 (1970) 650.
3. L. Horner and H. Neumann, Chem. Ber., 98 (1965) 3462.
4. P. T. Cottrell and C. K. Mann, J. Amer. Chem. Soc., 93 (1971) 3579.
5. M. R. Asirvatham and M. D. Hawley, J. Electroanal. Chem., 53 (1974) 293.
6. D. E. Bartak, H. K. Hundley, M. van Swaay, and M. D. Hawley, Chem. Instr., 4 (1972) 1.
7. W. E. Ryan, Ph.D. Dissertation, Kansas State University, Manhattan, Ks., 1976.
8. M. van Swaay, *Submitted for publication.*
9. J. L. Sadler and A. J. Bard, J. Amer. Chem. Soc., 90 (1968) 1979.
10. L. R. Faulkner and A. J. Bard, J. Amer. Chem. Soc., 90 (1968) 6284.
11. M. Walter and L. Ramaley, Anal. Chem., 45 (1973) 165.
12. I. M. Kolthoff and J. F. Coetzee, J. Amer. Chem. Soc., 79 (1957) 870.
13. C. S. Marvel and F. E. Smith, J. Amer. Chem. Soc., 45 (1923) 2696.
14. Handbook of Chemistry and Physics, The Chemical Rubber Company, 50th Edition.
15. E. L. Eliel and K. W. Nelson, J. Org. Chem., 20 (1955) 1657.
16. I. Remsen, R. N. Hartman, and A. M. Muckenfuss, J. Amer. Chem. Soc., 18 (1896) 150.

17. J. Cymerman, A. Koebner, and W. F. Short, J. Chem. Soc., (1948) 381.

18. A. I. Vogel, "Practical Organic Chemistry," 3rd Ed., Wiley, New York, N. Y., 1962, 1078.

19. G. S. Supin, A. L. Itskova, and Ya. A. Mandel'baum, Zh. Obsheh. Khim., 42 (1972) 1186.

20. J. March, "Advanced Organic Chemistry: Reactions, Mechanisms, and Structures," McGraw-Hill Book Co., New York, N. Y., 1969, 221.

21. A. R. Metcalfe and W. A. Waters, J. Chem. Soc. B, (1969) 918.

22. D. E. Bartak and M. D. Hawley, J. Amer. Chem. Soc., 94 (1972) 640.

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ELECTRON-TRANSFER PROCESSES: THE ELECTROCHEMICAL REDUCTION OF N,N-DIMETHYL- AND p-CYANOBENZENESULFONAMIDE

by

CARLOS G. SANTELICES

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ABSTRACT

The redox behavior of N,N-dimethyl- and p-cyanobenzenesulfonamide has been studied in dimethylformamide by electroanlytical methods. The tertiary sulfonamide is reduced in successive one-electron steps to give first its stable radical anion and then its dianion. The latter species is unstable and rapidly decomposes by sulfur-nitrogen bond cleavage to give dimethylamide anion and p-cyanobenzenesulfinate ion. One-electron reduction of the sulfinate to its stable dianion radical occurs at the applied potential and completes the reduction pathway.

The reduction pathway for the primary sulfonamide is potential dependent. At the potential of the first cathodic wave, the primary sulfonamide is reduced irreversibly to its radical anion. This species undergoes nitrogen-hydrogen bond cleavage and affords hydrogen and the conjugate base of the primary sulfonamide as products. The base is then reduced to its stable dianion radical at more negative potential. Reduction of the primary sulfonamide at the potential of the second cathodic wave gives its dianion, a species which rapidly undergoes decomposition by nitrogen-sulfur bond cleavage to give amide anion and p-cyanobenzenesulfinate. Subsequent chemical and electrochemical reactions involving these species and the primary sulfonamide formally give $p\text{-}NCC_6H_4SO_2NH^{2-\cdot}$ as the principal product in an overall two-electron step.