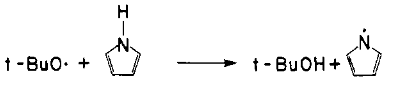
J. Org. Chem. 1983, 48, 3707-3712 3707

reactions are readily reversible. No EPR signals were detected when pyrrole or *N*-methylpyrrole were used. This was most probably due to the fact that on photolysis peroxide/pyrrole mixtures quickly went brown, thus screening further photodecomposition.

In laser flash photolysis experiments where sample discoloration presents less significant problems both pyrrole and *N*-methylpyrrole were found to react with *tert*-butoxyl radicals. While the reaction products have not been identified, because of discoloration during preparative photolysis, it seems likely that hydrogen abstraction is the dominant reaction since the experience with thiophene and furan suggests that additions to the double bonds are slow or rapidly reversible (reactions 19 and 20).



(19)

(20)

The rate constants for these reactions were measured by using benzhydrol as a probe molecule[24] and were found to be $k_{19} = 8.7 \times 10^6$ M^{-1} s^{-1} and $k_{20} = 4.9 \times 10^6$ M^{-1} s^{-1}. These rate constants are similar to those for the reaction of *tert*-butoxyl with dimethylamine where the rate constant for N–H abstraction is 1.1×10^7 M^{-1} s^{-1} while that for C–H abstraction is 6.6×10^7 M^{-1} s^{-1}.[32]

Optical signals due to phenylthiyl radicals generated from diphenyldisulfide were not quenched by addition of thiophene, furan, or pyrrole, indicating that the addition of this radical must be relatively slow ($<10^5$ M^{-1} s^{-1}) or readily reversible.

Summary

The kinetic data obtained in this work indicate that thiophene and furan have reactivities toward radical addition that are intermediate between those of normal olefins and benzene.

Acknowledgment. We thank Dr. J. C. Scaiano of these laboratories for the use of the laser flash photolysis equipment.

Registry No. Ia, 86885-42-9; Ib, 86885-43-0; $(EtO)_2\dot{P}O$, 31682-65-2; Ph·, 2396-01-2; $Et_3Si\cdot$, 24669-77-0; furan, 110-00-9; thiophene, 110-02-1; 1-hexene, 592-41-6; benzene, 71-43-2.

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Neighboring Group Participation in Organic Redox Reactions. 8.[1] Kinetics and Products of the Aqueous Iodine Oxidation of 3-Hydroxy- and 3-Methoxy-1,5-dithiacyclooctanes

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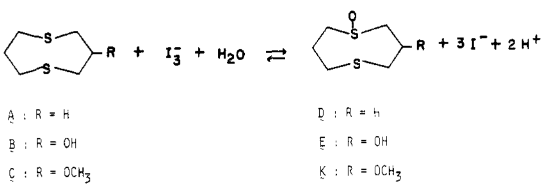
The aqueous iodine oxidation of 3-hydroxy- and 3-methoxy-1,5-dithiacyclooctanes (B and C) occurs about 10^4 times faster than the similar reaction of thiacyclooctane but about 10^2 times slower than the oxidation of the parent compound 1,5-dithiacyclooctane (A). These observations are consistent with the formation of a dicationic intermediate. The *cis*- and *trans*-sulfoxides are formed in roughly equal amounts. Single-crystal X-ray diffraction of *trans*-3-methoxy-1,5-dithiacyclooctane 1-oxide (*trans*-K) and of *cis*-3-hydroxy-1,5-dithiacyclooctane 1-oxide (*cis*-E) reveals a transannular sulfur–sulfur close contact of 3.175 (2) and 3.135 (2) Å, respectively, and S···S–O angles of 176.9 (1) and 175.4 (1)°. As predicted by the S···S–O alignment, the reverse reaction, the HI reduction of *trans*-3-methoxy-1,5-dithiacyclooctane 1-oxide (*trans*-K), is accelerated over that of a simple sulfoxide but is ca. 10 times slower than the reduction of 1,5-dithiacyclooctane 1-oxide. The equilibrium constant is ca. 150 for the reaction $K + 2H^+ + 3I^- \rightleftharpoons H_2O + I_3^- + C$. Cyclic voltammetric measurements show that both B and C have low oxidation potentials but that, although the oxidation of B is reversible, that of C is quasi-reversible.

Introduction

We previously reported the remarkable redox characteristics of the eight-membered ring dithioether 1,5-dithiacyclooctane (A). For example, A forms both a long-lived cation radical and dication on treatment with $NOBF_4$,[2a] its oxidation potential is almost a volt lower than that of the cyclic monothioether 1-thiacyclooctane, and it exhibits a completely reversible cyclic voltammogram in acetonitrile.[2b] As shown in eq 1, A is oxidized with aqueous iodine to the monosulfoxide D reversibly[3a] and at a rate that is about one million times faster than that of 1-thiacyclooctane. This unusual behavior can be attributed to the facile transannular oxidative coupling reaction between the two thioether groups to give intermediates containing a sulfur–sulfur bond.



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0022-3263/83/1948-3707$01.50/0

If the 1,5-dithiacyclooctane ring could be derivatized at the 3-position, it should be possible to attach a variety of redox active and photoactive substituents and to study the cooperative effects in these multifunctional systems. The preparation of 3-hydroxy-1,5-dithiacyclooctane (B), 3-methoxy-1,5-dithiacyclooctane (C), and their sulfoxides and the assessment of the effect of the β-substituents on facilitation of their redox reactions are the initial phase of this investigation.

Experimental Section

Equipment. a. Gas chromatography was performed with SE-30 on Chromosorb P (AW, HMDS) in a 6-ft glass column in an Aerograph Model A-90-P3 instrument.

b. HPLC was performed on an MCH-10 column using 1.3 mL/min of 90% aqueous CH_3CN in a Varian 5000 liquid chromatograph with a 240-nm UV detector.

c. EM Reagents silica gel 60 F_{254} precoated TLC sheets, 0.2 mm thick, were used for all TLC work with the indicated solvents.

d. Columns were prepared for chromatography with silica gel 60 from E. Merck, Darmstadt, West Germany, and the indicated solvent systems. A Gilson FC 80K microfractionator was used to collect fractions from the column.

e. Analyses were performed by Microanalytical Laboratories, University of California, Berkeley, CA.

f. Deionized water was degassed and equilibrated under a N_2 atmosphere.

g. A Radiometer Copenhagen PHM 82 standard pH meter was used alone or in combination with a Model ABU 80 autoburette and TTT60 titrator.

h. NMR spectra were recorded either on a Varian EM 360 or on a Varian EM 390 NMR spectrometer.

i. Low-resolution mass spectra were recorded on a CEC 21-104. High-resolution mass spectra were recorded at the Midwest Center for Mass Spectrometry, University of Nebraska—Lincoln.

j. Cyclic voltammetry was performed with a Princeton Applied Research Model 173 potentiostat, Model 175 Universal programmer, Model 178 electrometer, and Model RE0074 X-Y recorder.

k. UV and visible spectra were recorded on a Beckman DU spectrometer with a Gilford 6051 recorder and the cell compartment thermostated with a Lauda K-2/R circulator.

Electrochemical Oxidations. Electrochemical oxidations were carried out by cyclic voltammetry. Sample preparation was carried out under a nitrogen atmosphere in a drybox. Electrochemical grade tetrabutylammonium perchlorate was the supporting electrolyte (0.1 M) in dry acetonitrile (Burdick and Jackson, Inc.).

A three-compartment electrochemical cell consisted of two outer arms containing a silver reference electrode (Ag|0.1 M $AgNO_3$ in CH_3CN) and a platinum counterelectrode. The platinum working electrode was cleaned in 10 M HNO_3, heated in a flame, and oven-dried before each experiment. A 100-mV/s scan rate was used. Sample concentrations were 2.0×10^{-3} M.

Kinetic Measurements. Procedures have been described previously.[1,3] The pseudo-first-order rate constants, k_{obsd}, were obtained by monitoring the monitoring the absorbance of I_3^- at 353 nm.

Synthesis. Reagents. The following reagents were obtained from the indicated sources: Chloromethyloxirane (epichlorohydrin), 1,3-propanedithiol, and iodomethane from Aldrich Chemical Co., Wilwaukee, WI; sodium hydride, 50% dispersion in oil, from Ventron, Alfa Division, Danvers, MA; all other chemicals were reagent grade from Mallinckrodt Inc., Paris, KY.

a. 3-Hydroxy-1,5-dithiacyclooctane (B). The synthesis was based on a modification of Corey et al.[4] A high-speed stirrer with a flexible shaft was placed on a 500-mL, three-necked, mortonized, round-bottom flask. Absolute ethanol (150 mL) and sodium hydroxide (8.80 g, 220 mmol) were added to the reaction flask with stirring. Chloromethyloxirane (9.25 g, 100 mmol) was diluted to 50 mL with absolute ethanol; 1,3-propanedithiol (10.82 g, 100 mmol) was diluted to 50 mL with absolute ethanol. The two ethanol solutions were added to the reaction flask over a 1-h period, using two syringes in a syringe pump. The reaction mixture turned cloudy during the addition of the reactants. After stirring of the mixture overnight, water (200 mL) and saturated sodium chloride solution (100 mL) were added, and the mixture was extracted with ether. The ether layer was first washed with water and saturated sodium chloride solution and then dried over anhydrous sodium sulfate. The ether was removed by rotoevaporation to give a yellow oil. The oil was vacuum distilled (101–105 °C (0.050 torr)) to give 5.92 g (28.8% yield) of a very viscous, slightly yellow oil. This material was further purified by column chromatography: ^1H NMR ($CDCl_3/Me_4Si$) δ 2.07 (m, 2 H, CCH_2C), 2.57 (t, 4 H, SCH_2C), 2.81 (d, 4 H, SCH_2C), 3.04 (m, 1 H, CHO), 3.77 (m, COH); TLC R_f 0.55 with 5% ethanol in chloroform; MS (70 eV), m/z (relative intensity) 164.2 (100, $C_6H_{12}OS_2$), 122.0 (51, $C_3H_6OS_2$), 106.0 (81, $C_3H_6S_2$).

b. 3-Methoxy-1,5-dithiacyclooctane (C). A reflux condenser, an addition funnel, and a nitrogen inlet were placed on a 300-mL, three-necked, mortonized round-bottom flask. A 50% dispersion of sodium hydride in oil (4.60 g, 100 mmol) was washed with pentane to give a gray powder. The washed sodium hydride, tetrahydrofuran (60 mL), and a magnetic stirring bar were added to the reaction flask, which was purged with nitrogen for 1 h before the methyl iodide (17.0 g, 120 mmol) was added. A solution of B (9.86 g, 60.0 mmol) in tetrahydrofuran (25 mL) was added to the mixture dropwise over a 30-min period. Moderate gas evolution was observed during the addition. The reaction mixture was refluxed for 30 min and then cooled to room temperature. Upon completion of stirring and cooling, the reaction mixture was separated into two layers; the organic layer was washed with saturated solutions of sodium chloride and then dried over anhydrous sodium sulfate. The solvent was removed from the dried organic layer by rotoevaporation to give a yellow oil. Pentane washed sodium hydride (0.125 g, 5.21 mmol) was added to the oil and the mixture was distilled (93–95 °C (0.035 torr)) to give 5.58 g (52.2% yield) of a slightly yellow oil. This material was further purified by preparation GLC: ^1H NMR ($CDCl_3/Me_4Si$) δ 2.15 (m, 2 H, CCH_2C), 2.74 (t, 4 H, SCH_2C), 2.98 (d, 4 H, SCH_2C), 3.33 (s, 3 H, OCH_3), 3.47 (m, 1 H, CHO); TLC R_f 0.66 (5% ethanol in chloroform). Anal. Calcd for $C_7H_{14}OS_2$: C, 47.15; H, 7.91. Found: C, 47.55; H, 7.85.

c. 3-(Benzoyloxy)-1,5-dithiacyclooctane. The benzoate derivative, mp 45–48 °C, was prepared from B, benzoyl chloride, and pyridine:[5] ^1H NMR ($CDCl_3/Me_4Si$) δ 2.30 (m, 2 H, $SCHCH_2CS$), 2.82 (t, 4 H, SCH_2C), 3.20 (d, 4 H, SCH_2C), 5.33 (p, 1 H, CHO), 7.47 (m, 3 H, protons at meta and para positions), 8.07 (m, 2 H, protons at ortho position); IR (film) ν 1715 (C=O), 1270 (CO) cm^{-1}, no OH stretch; TLC R_f 0.86 (5% ethanol in chloroform). Anal. Calcd for $C_{13}H_{16}O_2S_2$: C, 58.18; H, 6.01. Found: C, 58.18; H, 5.96.

d. 2-(Chloromethyl)-1,4-dithiacycloheptane. 3-Hydroxy-1,5-dithiacyclooctane (1.00 g, 6.09 mmol), triphenylphosphine (1.60 g, 6.10 mmol), and 15 mL of carbon tetrachloride were added to a 25-mL round-bottom flask containing molecular sieves and a reflux condenser.[6] The reaction was refluxed in the steam bath for 3 h and then kept at -5 °C overnight. The mixture was suction filtered twice and washed with carbon tetrachloride. After the excess carbon tetrachloride and chloroform were removed under reduced pressure, the product (0.238 g, 21% yield) was distilled at 83–87 °C (0.050 torr): ^1H NMR ($CDCl_3/Me_4Si$) δ 2.05 (p, 2 H, CCH_2C), 3.05 (m, 7 H, protons α to sulfur), 3.76 (d, 2 H, CCH_2Cl); TLC R_f 0.76 (5% ethanol in chloroform).

Products of the Aqueous I_2 Oxidation of B and C. The autoburette filled with 0.25 M NaOH was connected to a three-necked flask containing 50 mL of 50% aqueous methanol and a magnetic stir bar. The solution was maintained at pH 7 during the alternate additions of the two reactants, 1 mmol of the thioether in 10 mL of methanol and 1 mmol of I_2 in 2.54 mL of methanol. When the reaction was complete, the solution was evaporated to dryness.

***cis*- and *trans*-3-Methoxy-1,5-dithiacyclooctane 1-Oxide**

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Table I. Crystal Data

	3-methoxy-1,5-dithiacyclooctane 1-oxide	3-hydroxy-1,5-dithiacyclooctane 1-oxide
formula	$C_7H_{14}S_2O_2$	$C_6H_{12}S_2O_2$
fw	194.32	180.29
a, Å	10.057 (2)	7.931 (2)
b, Å	10.233 (3)	11.915 (2)
c, Å	9.602 (2)	8.737 (3)
β, deg	116.43 (2)	101.25 (2)
V, Å^3	884.8 (4)	809.9 (3)
Z	4	4
d(calcd) g/cm^3	1.46 (140 K)	1.48 (140 K)
d(measd) g/cm^3	1.44 (298 K)	1.45 (298 K)
space group	Cc	$P2_1/c$
cryst dimens, mm	0.25 × 0.10 × 0.25	0.37 × 0.80 × 1.3
temp, K	140	140
radiation	Mo Kα	Mo Kα
μ(Mo Kα), cm^{-1}	5.9	5.7
2θ limits, deg	0–50	0–50
final no. variables	107	94
no. unique data	824	1429
no. unique data with $I > 2.5\sigma(I)$	726	1271
R	0.040	0.030

(K). The organic product from C was dissolved in CH_2Cl_2. Since the products had R_f values of 0.38 and 0.25 on TLC, they were separated by liquid chromatography on 10 g of Merck silica gel, using 5% ethanol in $CHCl_3$. Single-crystal X-ray diffraction identified the slower eluting compound as *trans*-3-methoxy-1,5-dithiacyclooctane 1-oxide (*trans*-K).

Compound *cis*-K, 0.026 g, was a solid: IR 3430, 2930, 1660, 1450, 1400, 1175, 1095, 1020 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 3.7 (m, 1), 3.45 (s, 3), 3.05 (m, 4), 2.7 (m, 2), 2.35 (m, 3), 2.10 (m, 1); TLC R_f 0.38; HPLC retention time ~6 min.

Compound *trans*-K, 0.029 g, was a solid: mp 89–91 °C; IR 2910, 1450, 1400, 1210, 1085, 1035, 1010 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.05 (m, 1), 3.4 (s, 3), 3.25 (d, 2), 3.1 (m, 2), 2.7 (m, 2), 2.4 (m, 2), 2.2 (m, 2); TLC R_f 0.25; HPLC retention time ~7 min.

***cis*- and *trans*-3-Hydroxy-1,5-dithiacyclooctane 1-Oxide (E).** The organic product from B was extracted into warm $CHCl_3$, using a Soxhlet extractor over 12 h. The product had R_f values of 0.1 and 0.16 on TLC, using 10% C_2H_5OH in $CHCl_3$. Areas on the HPLC were in the ratio 0.37:0.63 for the 6.0- and 6.8-min peaks, respectively.

Single-crystal X-ray diffraction identified the slower eluting compound as *cis*-3-hydroxy-1,5-dithiacyclooctane 1-oxide (*cis*-E).

From a solution of $CHCl_3$, large crystals, *cis*-E, mp 142–143 °C, formed on evaporation over a few days: IR (KBr Pellet) 3250, 2950, 2910, 2480, 1450, 1400, 1300, 1050, 980 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.5 (m, 1), 3.4–2.0 (overlapping m, 9). The more rapidly eluting product *trans*-E was not obtained pure; ^{1}H NMR of a mixture of *cis*- and *trans*-E ($CDCl_3$) δ 4.5 (m, 1), 4.1 (m, 3) 3.4–2.0 (overlapping m, 9).

Oxidation of B with $NaIO_4$ was carried out by the standard procedure and yielded a mixture that had HPLC areas of 42:58 for *trans*- and *cis*-E, respectively.

Equilibrium Constant. Two solutions were made up containing 4.7×10^{-5} M *trans*-K, 0.042 M NaI, 0.184 M $NaClO_4$, and $HClO_4$. The final concentration of I_3^- generated by reduction of *trans*-K was measured spectroscopically. In the solution where $[HClO_4] = 0.05$ M, $[I_3^-]_\alpha = 2.5 \times 10^{-5}$ M and in the solution where $[HClO_4] = 0.10$ M, $[I_3^-]_\alpha = 3.5 \times 10^{-5}$ M. The average value for $K_{\text{redn}} = 145 \pm 7$ (eq 1, reversed).

X-ray Data Collection and Structure Solution. The crystal-structure determination for both compounds followed the same procedure. Crystal data are summarized in Table I. Data were collected on a $P2_1$ diffractometer using a low-temperature apparatus, ω scans, in the quadrant $h, k, \pm l$. No decay was noted during data collection. The structures were solved by direct methods. Crystallographic programs were those of the SHELXTL (version 3 package).[7] Scattering factors and corrections for anomalous dispersion were from ref 8. No absorption correction was applied. All non-hydrogen atoms were assigned anisotropic thermal parameters. For the methoxy derivative the methyl hydrogens and for the hydroxy derivative the hydroxyl hydrogen were allowed to refine freely with $U_{\text{iso}} = 0.04$ Å^2. The remaining hydrogen atoms were included in the refinement, using a riding model and $U_{\text{iso}} = 1.2$ times the equivalent isotropic value for the bonded carbon atom. Final positional parameters and thermal parameters, bond distances, angles, and torsion angles are available as supplementary material.

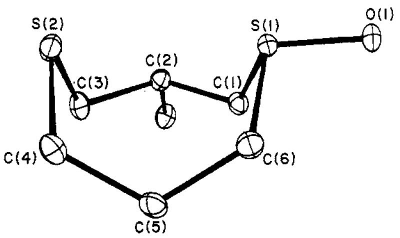

Figure 1. A drawing of *cis*-3-hydroxy-1,5-dithiacyclooctane 1-oxide, showing anisotropic thermal ellipsoids at the 40% level and the atom numbering scheme.

Results and Discussion

3-Hydroxy-1,5-dithiacyclooctane (B) was prepared in 30% yield in a one-step reaction between (chloromethyl)oxirane and 1,3-propanedithiolate in ethanol.[4] The methyl ether C was prepared by treating the alkoxide of B with methyl iodide in THF. An attempted conversion of B to 3-chloro-1,5-dithiacyclooctane using triphenylphosphine and CCl_4 gave the ring-contracted product 2-(chloromethyl)-1,4-dithiacycloheptane. Similar rearrangements of β-substituted sulfides are often observed[9,10] due to a facile intramolecular displacement reaction that gives an episulfonium intermediate. Nucleophilic attack of chloride ion on the intermediate gives the rearranged product.

The products of the aqueous I_2 oxidation of B and C are the corresponding *cis*- and *trans*-sulfoxides E and K. The structure of the specific isomers could only be assigned after an X-ray crystal-structure determination.

Structure Determinations. 3-Hydroxy-1,5-dithiacyclooctane 1-Oxide. A drawing of the molecule showing the cis arrangement is given in Figure 1. The conformation of the eight-membered ring is boat–chair. Neighboring molecules are linked by a hydrogen bond between the hydroxyl hydrogen and the sulfoxide oxygen with O(2)···O(1)′ of 2.732 (2) Å and O(2)–H···O(1)′ of 167 (1)°. Of particular interest is the relatively short S(1)···S(2) contact of 3.135 (2) Å and O(1)–S(1)···S(2) angle of 175.4 (1)°.[11] In a series of 1,5-dithiacyclooctane derivatives this S···S distance is next to the shortest (3.121 (5) Å in 1-acetonyl-1-thionia-5-thiacyclooctane perchlorate[12]). The S–O distance of 1.519 (2) Å is the longest reported for a sulfoxide. Most of these distances range from 1.48 to 1.50 Å.[13] A similar lengthening was observed in *endo*-3-(ben-

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Table II. Oxidation of 3-Methoxy-1,5-dithiacyclooctane (C; 26.0 °C, $[I_3^-]_0 \simeq 3 \times 10^{-5}$ M, pH 6.0)

run	10^4[C], M	[KI], M	[KCl], M	[buffer],[a] M	k_{obsd}, s^{-1}	k',[b] M^{-1} s^{-1}
1	5.01	0.0625	0.437	0.0125	0.175 ± 0.001	350 ± 2
2	5.01	0.100	0.400	0.0125	0.046 ± 0.002	92 ± 4
3	5.01	0.125	0.375	0.0125	0.028 ± 0.002	56 ± 4
4	5.01	0.250	0.250	0.0125	0.0043 ± 0.0001	8.6 ± 0.2
5	5.01	0.330	0.170	0.0125	0.002098 ± 0.00004	4.15 ± 0.08
6	5.01	0.50		0.0125	0.00098 ± 0.00005	2.0 ± 0.1
7	5.01	0.0625	0.437	none[c]	0.170	340
8	5.01	0.125	0.375	none[c]	0.0304	61
9	5.01	0.250	0.250	none[c]	0.0036	7.2
10	5.01	0.50		none[c]	0.00046	0.92
11	3.75	0.125	0.375	0.0125	0.0198 ± 0.0008	53 ± 2
12	2.50	0.125	0.375	0.0125	0.013 ± 0.001	52 ± 4

[a] Phosphate buffer. [b] $k' = k_{obsd}/[C]$ M^{-1} s^{-1}. [c] Final pH = 6.

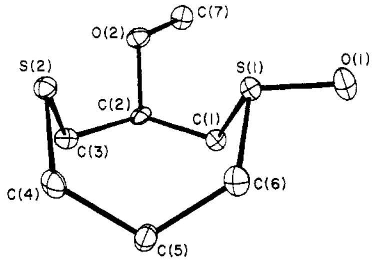

Figure 2. A drawing of *trans*-3-methoxy-1,5-dithiacyclooctane 1-oxide, showing anisotropic thermal ellipsoids at the 40% level and the atom numbering scheme.

zylsulfinyl)bicyclo[2.2.1]heptane-*endo*-2-carboxylic acid,[14] in which there is an intermolecular hydrogen bond between the sulfoxide oxygen and a carboxyl group and an intramolecular nonbonded close contact of 2.80 Å between the sulfur atom and the carbonyl oxygen with O–S···O of 173° and S–O of 1.517 (3) Å.

3-Methoxy-1,5-dithiacyclooctane 1-Oxide. The trans arrangement of this molecule is depicted in Figure 2. As was true for the 3-hydroxy derivative, the ring is in the boat–chair conformation. There are no short intermolecular contacts. Bond distances and angles are similar to those found in the 3-hydroxy derivative except for the S–O bond length of 1.496 (4) Å, the shorter value presumably arising from the lack of hydrogen bonding. However, its length is still on the high end of the values found for sulfoxide bonds. Like the 3-hydroxy species, there is a transannular interaction that contributes to S–O bond weakening. In this compound the S(1)··S(2) distance is 3.175 (2) Å and the O(1)–S(1)···S(2) angle is 176.9 (1)°.

Electrochemical Data. The electrochemical oxidation data reveal that compounds A–C have oxidation peak potentials of 0.42, 0.45, and 0.52 V, respectively. These values are low relative to the monothioether thiacyclooctane, which has an oxidation peak potential of +1.2 V under the same conditions. The differences in potential of the oxidation and reduction peaks are 0.050 V for A and for B, which classifies these redox reactions as reversible by standard electrochemical criteria. Compound C has a cyclic voltammogram with the same qualitative features as has A and B. However, the +0.19-V difference between oxidation and reduction peaks for C is slightly too large to be judged as reversible by these same criteria and the reaction of C must be classified as quasi-reversible.

Aqueous Iodine Oxidation of C. Data for the oxidation of C are reported in Table II and shown in Figures 3 and 4. In runs 3, 11, and 12 (Table II), the concentration of C was varied and the pseudo-first-order rate constants

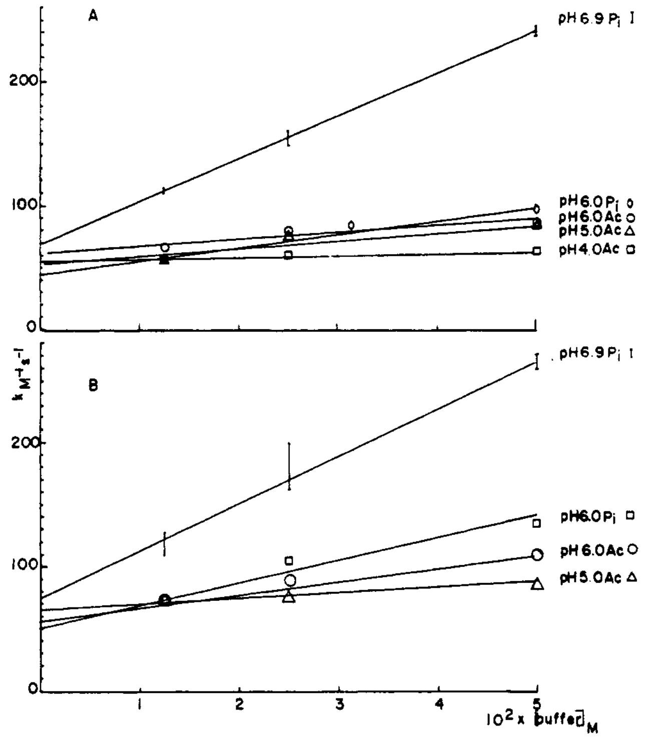

Figure 3. Effect of buffer concentration on the rate constants for oxidation with aqueous I_2; 26.0 °C, 0.125 M KI, 0.375 M KCl, $[I_3^-]_0 \leq 3 \times 10^{-5}$ M; phosphate buffer (P_i), and acetate buffer (Ac): (A) 5.01×10^{-4} M C, (B) 6.27×10^{-4} M B.

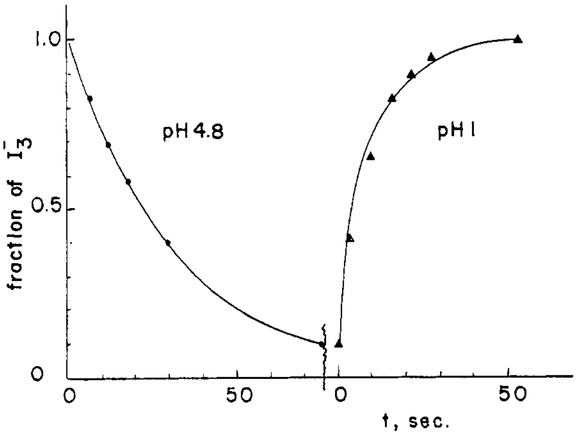

Figure 4. Reversible oxidation and reduction in the system C + $I_2 \rightleftharpoons$ K + $2I^-$, 26.0 °C. Fraction of I_3^- lost at pH ~4 and regenerated at pH 1 vs. time. Oxidation of 5.01×10^{-4} M C with 6.0×10^{-5} M I_3^- in 0.125 M KI, 0.375 M KCl and reduction of 3.0×10^{-5} M K with 0.125 M KI.

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Table III. Pseudo-First-Order Rate Constant k_1 for the Reaction between ~10^{-5} M *trans*-K and I^- in $HClO_4$ at 26.0 °C

run	$HClO_4$, M	NaI, M	$NaClO_4$, M	10^3k_1, s^{-1}
1	0.025	0.30		5.83 ± 0.07
2	0.050	0.30		20 ± 2
3	0.10	0.30		100 ± 10
4	0.10	0.20	0.10	88 ± 3
5	0.10	0.10	0.20	85 ± 1

are proportional to the concentration of C. Therefore the last column in the table displays the second-order rate constants $k' = k_{obsd}/[C]$ M^{-1} s^{-1}.

The dependence of the rate of oxidation on iodide is inverse third order in runs 7–10 where no buffer has been used, $k' \propto [I^-]^{2.9}$, coefficient of correlation = 0.999. When pH 6.0, 0.125 M phosphate buffer is used as in runs 1–6, the relationship (coefficient of correlation = 0.992) appears to be $k' = (0.29[I^-]^{-2} + 0.067\ [I^-]^{-3})$ M^{-1} s^{-1} and the rate law is

$$\frac{-d[I_3^-]}{dt} = \frac{-d[C]}{dt} = [C][I_3^-]\{0.29[I^-]^{-2} + 0.067[I^-]^{-3}\}\ M\ s^{-1} \tag{2}$$

Figure 3 shows the sensitivity of the rate of reaction to buffer concentrations in solutions of pH 4–6.9. The extrapolated rate constants are 44–62 M^{-1} s^{-1} in the range pH 4–6 and 70 M^{-1} s^{-1} at pH 6.9. A similar effect of buffer concentrations and pH on the I_2 oxidation was seen in the behavior of A, reflecting the intramolecular nature of the catalysis.

In order to compare the rate constants for A and C, it is convenient to use the extrapolated rate constants in pH 6 phosphate at 0.5 M KI. For A the rate constant is 80 M^{-1} s^{-1}.[3a] The extrapolated rate constant for C (Figure 3A) is 45 M^{-1} s^{-1} at 0.125 M KI. The rate constant at 0.5 M KI may be calculated by use of the inverse third order in iodide and it has the value of 70 × 10^{-2} M^{-1} s^{-1}. The oxidation of A is 80 ÷ (70 × 10^{-2}) or 100 times faster than the oxidation of C.

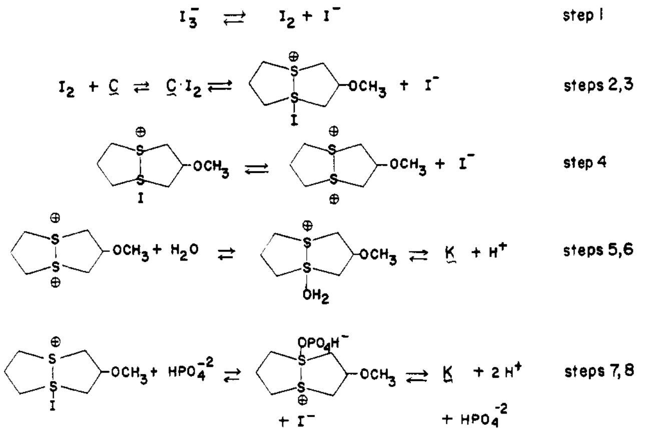
The NMR and IR of the products from the I_2 oxidation of C indicate that the *cis*- and *trans*-sulfoxides are produced in about equal amounts. The NMR spectra differ primarily in the value of δ of the tertiary proton, which is at 3.7 ppm for *cis*-K and at 4.05 ppm for *trans*-K.

Aqueous HI Reduction of *trans*-K. The ease of reversibility of the reaction is demonstrated in Figure 4, which shows a plot of the fraction I_3^- observed spectrophotometrically vs. time. The decay in I_3^- represents the oxidation of C, and when the solution is acidified, I_3^- and C are regenerated.

The data for the reduction of *trans*-K with HI are given in Table III. From runs 3–5, the zero-order dependence of the rate constant, k_1, on iodide is seen, and from runs 1–3, $\log k_1 = 2.05 \log [H^+]$ is determined with a coefficient of correlation of 0.997. The second-order dependence on $[H^+]$ for *trans*-K is the same as observed for the HI reduction of D.[3b] By comparison of the rate constants of *trans*-K to the rate constants for D at 0.050 and 0.10 M $HClO_4$, D is faster by 20. The rate law is

$$\frac{d[I_3^-]}{dt} = \frac{d[C]}{dt} = k_{redn}\,[K][H^+]^2 \tag{3}$$

Scheme I



The reduction of *trans*-K goes to completion under the conditions given in Table III. However, by lowering the NaI concentrations, the reaction does not go to completion and the equilibrium constant can be measured. Its value is 147 ± 6 at 25.0 °C. The equilibrium constant for the reduction reaction of D is only 14.[3b]

Aqueous Iodine Oxidation of 3-Hydroxy-1,5-dithiacyclooctane (B). Data for the oxidation of B are reported in Table IV and shown in Figure 3. The concentration of B was varied in runs 3, 6, and 7. A first-order dependence on [B] is observed so that the pseudo-first-order rate constants k_{obsd} were divided by [B] to give k' in M^{-1} s^{-1}. The iodide dependence of runs 1–5 is summarized at pH 6.0, 0.125 M phosphate buffer as $k' = (0.27[I^-]^{-2} + 0.11[I^-]^{-3})$ M^{-1} s^{-1} and the rate law is

$$\frac{-d[I_3^-]}{dt} = \frac{-d[B]}{dt} = [B][I_3^-]\{0.27[I^-]^{-2} + 0.11[I^-]^{-3}\}\ M\ s^{-1} \tag{4}$$

Equation 4 is similar to eq 2 with the rates for B being 50–100% higher than for C.

The effect of the buffer concentration and pH on the rates of B are shown in Figure 3. The extrapolated rate constants are almost identical with the rate constants for C and are 50–66 M^{-1} s^{-1} in the range pH 4–6 and 76 M^{-1} s^{-1} at pH 6.9.

The oxidation of B was not carried out below pH 5 because of the tendency of β-hydroxy sulfides to rearrange in acid.[9,10]

The NMR and IR of the products from the I_2 oxidation of B indicate that they are the *cis*- and *trans*-sulfoxides that are produced in about equal amounts. Only *cis*-E was obtained in the pure form by crystallization from $CHCl_3$. The tertiary proton of *cis*-E (δ 4.5) was downfield from the tertiary proton of *trans*-E (δ 4.1). Intermolecular hydrogen bonding between S–O and HO is shown in the X-ray

Table IV. Oxidation of 3-Hydroxy-1,5-dithiacyclooctane (B; 26.0 °C, $[I_3^-]_0 \simeq 3 \times 10^{-5}$ M, pH 6.0, 0.125 M Phosphate)

run	10^4[B], M	[KI], M	[KCl], M	k, s^{-1}	k', M^{-1} s^{-1}
1	6.27	0.0625	0.437	0.34 ± 0.03	534
2	6.27	0.100	0.400	0.080 ± 0.008	127
3	6.27	0.125	0.375	0.046 ± 0.001	73
4	6.27	0.250	0.250	0.0065 ± 0.0009	10.4
5	6.27	0.50		0.00162 ± 0.00001	2.58
6	3.18	0.125	0.375	0.023 ± 0.003	72
7	4.77	0.125	0.375	0.0328	69

analysis and is responsible[15] for the low S–O stretch in the IR.

Reaction Mechanism. In the absence of buffer the reversible reaction of C is inverse third order in iodide and has the reaction sequence similar to that which we have proposed previously for A^{3b} (Scheme I).

Thus if step 4 is rate determining in the oxidation of C, the rate law for the oxidation has the form given in eq 5 and is observed in the oxidation in the absence of buffer.

$$\begin{aligned}\frac{d[C]}{dt} &= -(K_I[I_3^-]/[I^-])([C]K_1)(K_2/[I^-])(K_3/[I^-])k_4 \\ &= -k_{oxidn}[I_3^-][I^-]^{-3}[C]\end{aligned} \tag{5}$$

In eq 2 the experimental rate law for the oxidation in pH 6.0, 0.0125 M phosphate buffer has an additional term in $[I^-]^{-2}$ that represents 34% of the rate when $[I^-] = 0.125$ M. This increase in the rate due to buffer is also apparent in Figure 3A. Mechanistically, the inverse second order in iodide could be attributed to the reaction of the buffer with the intermediate formed in step 3, and the buffer-dependent sequence could be steps 1–3, followed by rate-determining attack of the buffer in step 7 and hydrolysis in step 8. Although HPO_4^{2-} has been shown in step 7, other buffer species may also be involved. Equation 6 is the corresponding rate law (b oxidn = buffer oxidation). The experimental rate law in eq 2 is the summation of eq 5 and 6.

$$\begin{aligned}\frac{d[C]}{dt} &= -(K_I[I_3^-]/[I^-])([C]K_1)(K_2/[I^-])[\text{buffer}]k_6 \\ &= -k_{b\,oxidn}[I_3^-][I^-]^{-2}[C]\end{aligned} \tag{6}$$

The mechanism of oxidation of B is similar to that of C. Unfortunately, the tendency of E to rearrange in acid prevented a study of the reversibility of this system.

The reduction of sulfoxide *trans*-K to C has the rate law given in eq 3 and follows the series of reactions 1–6 in reverse. The formation of an S–S bond prior to or in the rate-determining step is facilitated by the short S···S distance and the S···S–O angle of 176.9° in *trans*-K. The adjacent positive charges in the diprotonated sulfoxide in steps 5 and 6 can be separated if sulfurane formation occurs ($^+S–S–^+OH_2$).

Summary and Conclusion

The 3-hydroxy and 3-methoxy derivatives of 1,5-dithiacyclooctane display the same versatile redox characteristics as does their parent compound. The sulfoxide products from B and C are formed with little, if any, stereoselectivity via dicationic and sulfurane intermediates. It appears that the presence of electron-withdrawing substituents in the 3-position of A causes only slight modifications in its redox chemistry.

Acknowledgment. The National Institutes of Health and the National Science Foundation have supported this research.

Registry No. B, 86944-00-5; B benzoate, 86944-01-6; C, 86944-02-7; *cis*-E, 86944-03-8; *trans*-E, 86944-04-9; *cis*-K, 86944-05-0; *trans*-K, 86944-06-1; 2-(chloromethyl)-1,4-dithiacycloheptane, 86944-07-2.

Supplementary Material Available: Final positional parameters, thermal parameters, bond distances, angles, and torsion angles (4 pages). Ordering information is given on any current masthead page.

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