Intramolecular Photoinduced Rearrangements via Electron-Transfer-Induced, Concerted Bond Cleavage and Cation Radical/Radical Coupling

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Abstract: Intramolecular photoinduced electron-transfer concerted bond cleavage has been observed in both a phenylanthracene and a phenylnaphthacene sulfonium salt derivative to produce a singlet phenylaryl cation radical/radical pair. Subsequent, cation radical/radical coupling produces photorearrangement, which appears to be a kinetic process due to the correlation of the product distribution with spin densities in the phenylaryl cation radical. In the phenylanthracene derivative, amide and sulfide products are also formed, presumably from electron transfer from the radical to the cation radical within the solvent cage. The efficacy of the photoinduced electron transfer/bond cleavage and radical coupling is attributed to the concerted nature of the bond cleavage, close proximity of the aryl π system to the sulfonium moiety, as well as to the favorable thermodynamics for electron transfer.

Introduction

The photochemical behavior of onium salts is of considerable scientific and technological interest especially as it relates to the photoproduction of Bronsted acids.[1] Understanding the mechanism of Bronsted acid generation from the photoactivated onium salts will provide the basis for the design of more efficient "photoacid" systems. Although *stepwise* photoinduced electron-transfer bond-cleavage reactions are well-known for both one-electron oxidative[1b,2] and reductive[1b,3,4] processes, concerted electron-transfer bond-cleavage reactions have, to the best of our knowledge, not been reported.[1b] We report a photoinduced electron-transfer bond cleavage involving a *concerted* reductive cleavage process that subsequently leads to molecular rearrangement by radical/cation radical coupling.

Background

Direct irradiation of some arylalkyl sulfonium salt derivatives, which undergo a concerted one-electron reductive cleavage due to the σ^* nature of the lowest unoccupied molecular orbital (LUMO),[5] were found to photorearrange by a fragmentation-recombination mechanism. A singlet cation radical/radical pair intermediate has been proposed.[6,7] Similar radical coupling products have been observed more recently in the photolysis of triaryl sulfonium salts.[1a] Evidence for this mechanism was obtained from product studies. For example, 9-anthrylmethyl(*p*-cyanobenzyl)sulfonium hexafluorophosphate (**1**) (Scheme I) provided five regioisomers when irradiated in acetonitrile, consistent with the involvement of a singlet radical pair.[8]

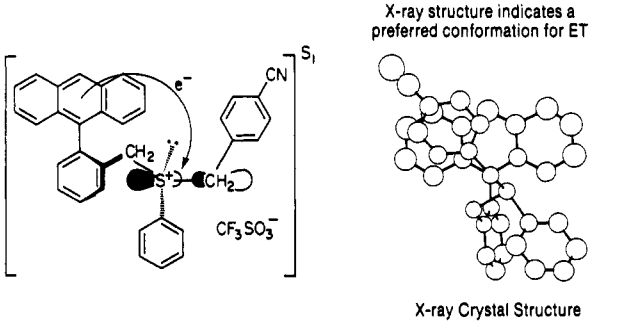
In further support of the singlet radical pair intermediate, the photolysis of onium salts containing a heteroatom with a substantial nuclear spin, i.e., N, P, provides only out-of-cage products.[7] On the other hand, an onium salt containing S, which does not have a nuclear spin, provides only in-cage radical coupling products. Furthermore, an onium salt containing As, with a modest nuclear spin, provides both in-cage and out-of-cage photoproducts.[7] These results are consistent with an enhancement of the rate of intersystem crossing from a singlet to a triplet radical cation/radical pair by a nuclear hyperfine interaction.[7]

In addition, when the LUMO for the sulfonium salt derivative is π^* rather than σ^*, as with 5-naphthacenylmethyl(*p*-cyanobenzyl)sulfonium trifluoromethanesulfonate, photochemical irradiation does not produce either bond cleavage or photorearrangement.[9]

Results and Discussion

An intramolecular electron-transfer scheme was devised to utilize chromophores with a π^* LUMO to generate a singlet cation radical/radical pair intermediate similar to that generated from direct excitation of an arylsulfonium chromophore. A general scheme demonstrating the concept is provided in Scheme II, where the light-absorbing chromophore and the sulfonium moiety are separated by an electronically insulating group. In this concept, the LUMO of the sulfonium moiety is at lower energy than the π^* LUMO of the chromophore in order for the thermodynamics for electron transfer from the photoexcited chromophore to the sulfonium moiety to be exothermic. In addition, it would be desirable to have the highest occupied molecular orbital (HOMO) sites in the chromophore and σ^* LUMO in the sulfonium moiety in close proximity to allow for efficient through-space or through-bond electron-transfer-induced, concerted bond cleavage.

Phenylanthracene Sulfonium Salt. In the phenylanthracene derivative **3**, the 9-phenyl group has restricted rotation and is oriented orthogonal to the plane of the anthracene ring system. This conformational feature is shown in the X-ray crystal structure[10] of **3**. The lowest energy conformation in the single crystal places the sulfonium moiety directly over the anthracene ring.



The absorption spectrum of **3** is virtually identical with that of phenylanthracene except for a modest ~5-nm shift to the red

(1) (a) Dektar, J. L.; Hacker, N. P. *J. Am. Chem. Soc.* **1990**, *112*, 6004 and references cited therein. (b) Saeva, F. D. Chapter in *Topics in Current Chemistry*; Springer-Verlag: New York, 1990; Vol. 156, p 59 and references cited therein.

(2) (a) Lee, L. Y. C.; Ci, X.; Giannotti, C.; Whitten, D. G. *J. Am. Chem. Soc.* **1986**, *108*, 175 and references cited therein. (b) Schuster, G. B.; Chatterjee, S.; Cottschalk, P.; Davis, P. D. *J. Am. Chem. Soc.* **1988**, *110*, 2326.

(3) Rossi, R. A.; DeRossi, R. H. *Aromatic Substitution by the $S_{RN}1$ Mechanism*; ACS Monograph Series 178; American Chemical Society: Washington, DC, 1983.

(4) Rossi, R. A.; Bunnett, J. F. *J. Org. Chem.* **1973**, *38*, 1407.

(5) Saeva, F. D.; Morgan, B. P. *J. Am. Chem. Soc.* **1984**, *106*, 4121.

(6) Saeva, F. D.; Morgan, B. P.; Luss, H. R. *J. Org. Chem.* **1985**, *50*, 4360.

(7) Breslin, D. T.; Saeva, F. D. *J. Org. Chem.* **1988**, *53*, 713.

(8) Saeva, F. D.; Breslin, D. T. *J. Org. Chem.* **1989**, *54*, 712.

(9) Saeva, F. D.; Breslin, D. T.; Martic, P. A. *J. Am. Chem. Soc.* **1989**, *111*, 1328.

(10) Programs for the X-ray study of **3** were from the Structure Determination Package, SDP-PLUS V 3.0; Enraf-Nonius Corp.: Delft, Holland, 1985.

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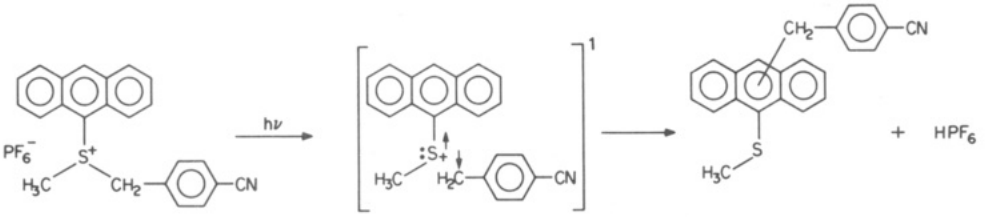
Scheme I



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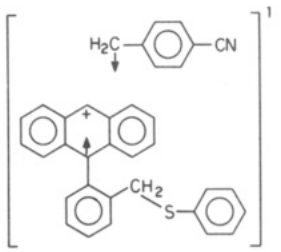
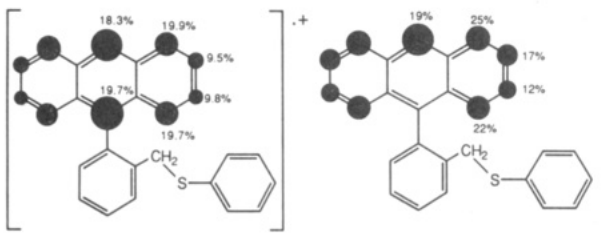
in acetonitrile solvent. Compound **3** is relatively nonfluorescent, with a fluorescent quantum yield (ϕ_f) less than 10^{-3}. The lack of fluorescence is consistent with the introduction of a rate process such as electron transfer, which competes effectively with fluorescence. The phenylanthracene sulfide derivative **5**, on the other hand, exhibits intense blue fluorescence. Photoinduced electron transfer from the anthracene ring system to the sulfonium moiety is highly exothermic, with $\Delta G_{ET}^{\circ} = -24$ kcal/mol.[11] Photolysis of **3** in acetonitrile, i.e., $h\nu > 360$ nm, so that only anthracene can be electronically excited, provided both rearrangement and products derived from heterolytic bond cleavage (Scheme III).

Photorearrangement to produce **4** occurs in 44% yield with a quantum yield of 0.15. The rearrangement product **4** is composed of five regioisomers, which differ in the position of the *p*-cyanobenzyl group on the anthracene ring. The *p*-cyanobenzyl group has migrated from sulfur to all possible carbon sites that contain a proton on the anthracene ring system. The observation of photoproduct **4** is consistent with the involvement of a singlet cation radical/radical pair formed from photoinduced electron transfer from the photoexcited singlet state of anthracene to the sulfonium moiety.



A comparison of the product distribution with AM1-calculated spin densities[12] for the cation radical clearly demonstrate that, in general, the spin densities determine the product distribution and that radical–radical coupling is a kinetic process.

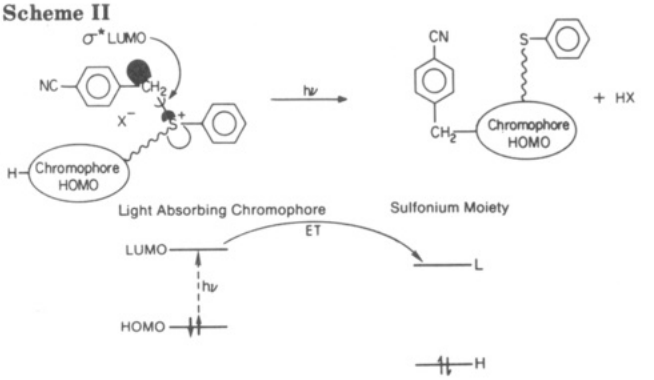


Spin Densities Product Distribution

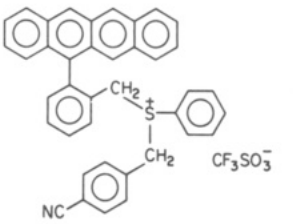
The phenylanthracene sulfide **5** and amide **6** are produced in 56% yield with a quantum yield of $\phi = 0.17$. We believe that **5** and **6** arise from electron transfer from the *p*-cyanobenzyl radical to the phenylanthracene cation radical within the singlet pair to produce *p*-cyanobenzyl carbocation, which reacts with acetonitrile and trace water.

Phenylnaphthacene Sulfonium Salt. The corresponding (5-phenylnaphthacenyl)sulfonium salt **7** was synthesized in 40% overall yield. Compound **7** absorbs out to ~520 nm in CH_2Cl_2

Scheme II



and exhibits fluorescence with a quantum yield of 0.25. The absorption spectrum of **7** is similar to the electronic absorption of the 5-[2-[(phenylthio)methyl]phenyl]naphthacene.

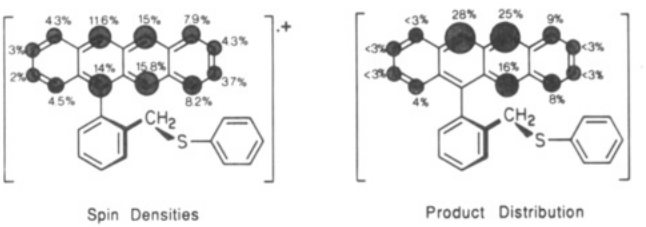


7

The free energy change for photoinduced electron transfer from the naphthacenyl to the sulfonium moiety is −15 kcal/mol, approximately 9 kcal/mol less favorable than for **3**.

Photolysis of **7** under conditions identical with those of **3** provides photoinduced rearrangement in quantitative yield with a quantum yield of 0.25 (Scheme IV). The lack of formation of the sulfide and amide products, in this case, is attributed to the inability of the phenylnaphthacene cation radical to oxidize the *p*-cyanobenzyl radical. The *p*-cyanobenzyl radical with an oxidation potential[13] of 1.0 V (CH_3CN, SCE) is capable of being oxidized by the cation radical of the phenylanthracenyl sulfide derivative ($E_p^{ox} = 1.04$ V) and *not* by the cation radical of the phenylnaphthacenyl sulfide derivative ($E_p^{ox} = 0.78$ V).

All eleven possible regioisomers are formed in the photorearrangement process. A comparison of the product distribution with the AM1[12]-calculated spin densities in the phenylnaphthacenyl cation radical further demonstrate that the product distribution is determined by spin densities and is kinetically controlled.



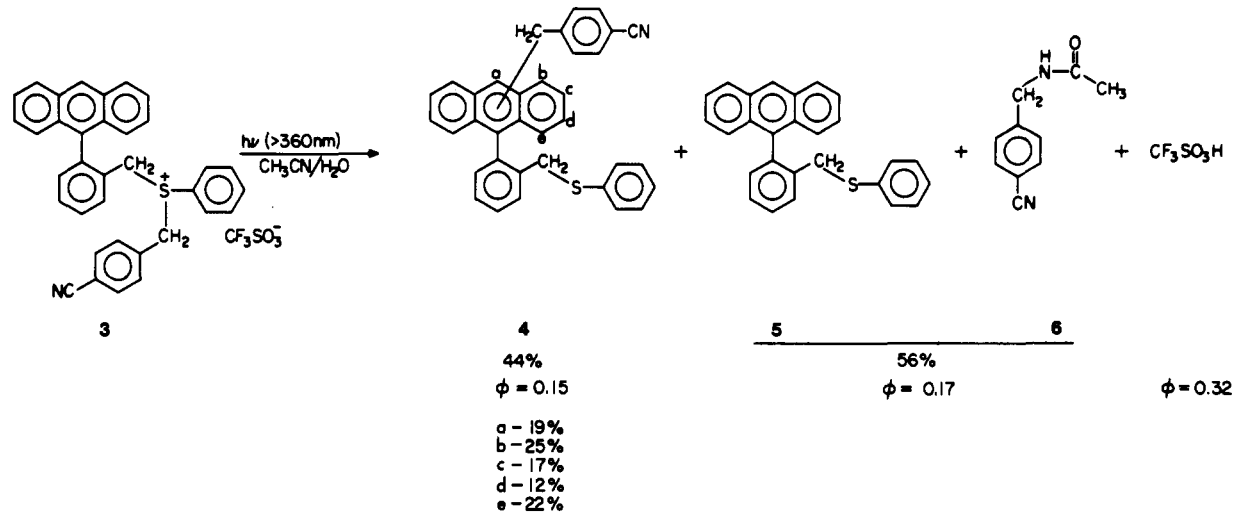
Spin Densities Product Distribution

The efficacy of the photoinduced bond cleavage and cation radical/radical recombination reactions of **3** and **7**, we feel, is due

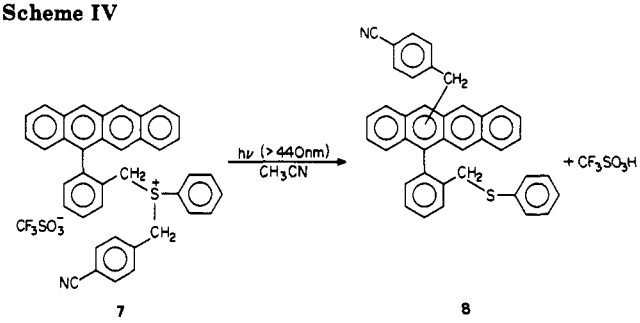
(11) Rhem, D.; Weller, A. *Ber. Bunsen-Ges. Phys. Chem.* **1969**, *73*, 834.
(12) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Steward, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.

(13) The oxidation potential for the *p*-cyanobenzyl radical was measured in acetonitrile by D. Wayner and D. Griller, private communication.

Scheme III



Scheme IV



to the concerted nature of the electron-transfer-induced bond cleavage. This process eliminates the energy-wasting back electron transfer from the reduced acceptor to the oxidized electron donor. In addition, the close proximity of the aryl π^* system and σ^* LUMO site on the sulfonium moiety would tend to enhance the efficiency for both photoinduced electron-transfer concerted bond cleavage and radical–radical coupling.

In summary, intramolecular photoinduced electron-transfer concerted bond cleavage has been observed for both a phenylanthracene and a phenylnaphthacene sulfonium salt derivative. Subsequent cation radical/radical coupling appears to be a kinetic process as indicated by the correlation of the product distribution with spin densities in the phenylaryl radical cation. In the phenylanthracene derivative, amide and sulfide products accompany photorearrangement, presumably resulting from electron transfer from the radical to the cation radical within the solvent cage.

The efficiency of the photoinduced electron transfer/bond cleavage and radical coupling is attributed to the concerted nature of the bond cleavage, close proximity of the aryl π system to the sulfonium moiety, as well as to the favorable thermodynamics for electron transfer.

Experimental Section

Equipment. A Princeton Applied Research Model 173 potentiostat and Model 175 universal programmer were used in the standard three-electrode configuration to obtain redox potentials by cyclic voltammetry. A platinum-inlay electrode was used as the working electrode along with a platinum auxiliary electrode and a standard calomel electrode (SCE). The electrolyte was 0.1 N tetrabutylammonium fluoroborate (TBAF) previously recrystallized from an ethyl acetate/pentane solvent mixture in dry acetonitrile. The electrochemical peak potentials (E_p) were measured in volts vs SCE at 100 mV/s scan rate.

Absorption spectra were run on a Perkin-Elmer Model Lambda 9 spectrophotometer equipped with a Perkin-Elmer 7700 professional computer and a Hewlett-Packard ColorPro eight-pen plotter. ^{1}H NMR spectra were run on a GE Nicolet 300-MHz spectrometer. The sulfonium salts were photolyzed with an Oriel 200-W Hg–Xe lamp in combination with an Ealing 4880- and 4050-Å interference filter for quantum efficiency studies. Actinometry was performed with Aberchrome 540 to determine the flux (photons/s) of the 200-W Hg–Xe lamp.[14] The determination of quantum yields is included in the supplementary material. Combustion analyses and mass spectrometry were performed by the Analytical Technology Division of the Eastman Kodak Co. Fluorescence excitation and emission spectra were measured by using a Perkin-Elmer Model LS-5 spectrofluorimeter equipped with a Perkin-Elmer Model 7500 Laboratory Computer and a Hewlett-Packard two-pen plotter.

Materials. 9-[2-(Methoxymethyl)phenyl]anthracene. 2-(Methoxymethyl)bromobenzene (10.0 g, 50 mmol) and magnesium metal (1.33 g, 55 mmol) were added to 200 mL of anhydrous tetrahydrofuran (THF) in a 500-mL three-neck flask equipped with an argon gas purge and heated at reflux for 3 h to form the corresponding Grignard reagent. To this mixture was added anthrone (9.71 g, 50 mmol) as a solid. The reaction mixture was heated at reflux for 15 h before being hydrolyzed by the addition of 10 mL of 6 N HCl. Once cooled to room temperature, the reaction mixture was extracted with three 300-mL portions of diethyl ether. The combined ether fractions were dried over anhydrous $MgSO_4$, filtered, and flash evaporated. The crude product was dissolved in chloroform and run through silica gel (~10 g) to provide the crude product in 80% yield by using chloroform as eluant. Recrystallization from ethanol provided the purified product in 72% yield: mp 142–3 °C; ^{1}H NMR ($CDCl_3$) δ 3.92 (s, 2 H), 7.2–8.6 (m, 13 H, Ar), 3.00 (s, 3 H). Anal. Calcd for $C_{22}H_{18}O$: C, 88.88; H, 6.11. Found: C, 88.68; H, 6.08.

9-[2-(Bromomethyl)phenyl]anthracene. 9-[2-[(Methoxymethyl)-phenyl]anthracene (4.5 g, 15 mmol) was dissolved in 250 mL of dry chloroform and placed in a 500-mL three-neck, round-bottom flask. Hydrogen bromide gas was bubbled through the solution for 7.5 h, and then the solution was stirred for 15 h to produce a quantitative yield of crude product (5.2 g). Recrystallization from cyclohexane provided the purified product in 98% yield: mp 95–7 °C; ^{1}H NMR ($CDCl_3$) δ 4.17 (s, 2 H), 8.5 (s, 1 H, Ar), 7.2–8.2 (m, 12 H, remaining Ar). Anal. Calcd for $C_{21}H_{15}Br$: C, 72.74; H, 4.31. Found: C, 72.64; H, 4.35.

9-[2-[(Phenylthio)methyl]phenyl]anthracene. 9-[2-(Bromomethyl)-phenyl]anthracene (1.1 g, 3.17 mmol) in 25 mL of anhydrous tetrahydrofuran (THF) was added dropwise to a solution of sodium phenylthiolate (0.35 g, 3.2 mmol) in 50 mL of anhydrous THF. The reaction mixture was stirred at room temperature for 1 h before the addition of 100 mL of 5% HCl. The reaction mixture was extracted with three 100-mL portions of diethyl ether, and the combined ether extract was then extracted with two 50-mL portions of 10% sodium carbonate to remove unreacted thiophenol. The ether layer was then dried over magnesium sulfate, filtered, and flash evaporated to provide 1.17 g (98.6% yield) of product. Recrystallization from 2-propanol provided 1.12 g of purified product: mp 128–130 °C, mass spectrum (FDMS) *m/e* 374; ^{1}H NMR (CD_2Cl_2) δ 3.65 (s, 2 H), 8.50 (s, 1 H, Ar), 6.81–8.20 (m, 17 H, remaining Ar).

9-[2-[[Phenyl-*p*-(cyanobenzyl)sulfonium]methyl]phenyl]anthracene Trifluoromethanesulfonate (3). 9-[2-[(Phenylthio)methyl]phenyl]-anthracene (0.435 g, 1.16 mmol) was dissolved in 50 mL of dichloromethane along with *p*-cyanobenzyl bromide (0.227 g, 1.16 mmol). Silver trifluoromethanesulfonate–(dioxane)$_2$ complex (0.503 g, 1.16 mmol) was added to the reaction mixture as a solid, and the reaction mixture was stirred for 15 h at room temperature before being filtered into a 100-mL

(14) Heller, H. G.; Langan, J. R. *J. Chem. Soc., Perkin Trans.* **1981**, *1*, 341.

round-bottom flask. The filtrate was flash evaporated and dissolved in a minimum amount of CH_3CN. This solution was added dropwise to 200 mL of anhydrous ether to obtain the crude product as an off-white solid. Recrystallization from an acetonitrile–diethyl ether mixture provided the purified product: mp 127–130 °C (dec); ^1H NMR (CD_3CN) δ 4.50 (q, 2 H), 4.70 (q, 2 H), 8.78 (s, 1 H, Ar), 6.80–8.50 (m, 21 H, remaining Ar); mass spectrum (FDMS) m/e 492.

5(12*H*)-Naphthacenone. 5,12-Naphthacenequinone (20 g, 7.75 mmol) was placed in a 1-L single-neck, round-bottom flask along with tin metal (40 g) and 500 mL of acetic acid. The mixture was heated at reflux for 1.5 h at which time 40 mL of concentrated HCl was added. The reaction mixture was then allowed to cool, and the crude product (17 g, 90% yield) was collected by suction filtration. Recrystallization from toluene provided (15 g, 80% yield) of purified product: mp 196–5 °C;[15] ^1H NMR ($CDCl_3$) δ 4.50 (s, 2 H), 7.20–9.00 (m, 10 H, Ar).

2-[(Phenylthio)methyl]iodobenzene. Sodium hydride (26 g) was placed in a 250-mL three-neck, round-bottom flask. The sodium hydride–mineral oil dispersion was washed with cyclohexane and then suspended in 100 mL of anhydrous tetrahydrofuran (THF). A solution of thiophenol (4.4 g) in 50 mL of THF was added dropwise to the suspension of the hydride in THF over a period of $^1/_2$ h. After the reaction mixture was stirred at room temperature for an additional $^1/_2$ h, a solution of 2-iodobenzyl chloride (10 g, Aldrich) in 50 mL of THF was added dropwise to the reaction mixture. After 30 min, the reaction was quenched with 10 mL of 10% aqueous HCl. Diethyl ether (200 mL) was added to the reaction mixture and extracted with 10% aqueous NaOH and then with water. The ether layer was dried over $MgSO_4$, filtered, and flash evaporated to yield 13 g of crude product. The purified product was obtained in 97% yield (12.5 g) by vacuum distillation: bp 145–150 °C at 0.5 mmHg; ^1H NMR ($CDCl_3$) δ 4.22 (s, 2 H), 6.90–7.90 (m, 9 H, Ar); mass spectrum (EIMS) m/e 326.

5-[2-[(Phenylthio)methyl]phenyl]naphthacene. 2-[(Phenylthio)-methyl]iodobenzene (5.0 g, 15.3 mmol), Mg (0.37 g, 15.3 mmol), and 50 mL of anhydrous THF were placed in a 100-mL round-bottom flask, and the mixture was heated at reflux for 4 h to form the corresponding Grignard reagent. The reaction mixture was allowed to cool for 15 min before the addition of 5(12*H*)-naphthacenone (3.4 g, 14.0 mmol) as a solid, and the purple reaction mixture was heated at reflux for 3 h. The mixture was stirred for 15 h at room temperature before addition of 10 mL of concentrated HCl. The reaction mixture was then heated at reflux for 15 min and cooled to room temperature. The reaction mixture was extracted with diethyl ether (3 × 100 mL), and the combined ether layers were then extracted with 100 mL of 10% sodium carbonate and then with water. The ether solution was dried over $MgSO_4$, filtered, and flash evaporated. The crude product (4.3 g, 72% yield) was recrystallized from nitromethane to provide 3.7 g, 62% yield; mp 164–5 °C, mass spectrum (FDMS) m/e 426; ^1H NMR ($CDCl_3$) δ 3.92 (s, 2 H), 6.80–9.00 (m, 20 H, Ar).

4-(Cyanobenzyl)[2-(5-naphthacenyl)benzyl]phenylsulfonium Trifluoromethanesulfonate (7). 5-[2-[(Phenylthio)methyl]phenyl]-naphthacene (1.0 g, 2.3 mmol) was placed in a 50-mL single-neck, round-bottom flask along with *p*-cyanobenzyl bromide (0.46 g, 2.3 mmol) and 30 mL of dry methylene chloride. Silver trifluoromethanesulfonate–(dioxane)$_2$ complex (1.01 g, 2.3 mmol) was added to the reaction mixture as a solid rapidly to minimize exposure to moisture. The reaction mixture was stirred for 24 h and the AgBr filtered off before the solvent was evaporated by flash evaporization. Chloroform (10 mL) was added to the crude product and the solution filtered into 200 mL of anhydrous diethyl ether. The crude product that precipitated from ether was collected by suction filtration (1.6 g, 51% yield). The purified product was obtained by recrystallization with an acetonitrile–diethyl ether mixture: mp 120 °C (dec); ^1H NMR ($CDCl_2$) δ 4.96 (m, 2 H, diastereotopic protons), 4.30 (m, 2 H diastereotopic protons), 6.70–8.90 (m, 24 H, Ar), mass spectrum (FDMS) m/e 542.

Photochemistry. Photolysis of 3 and Characterization of Photoproducts. Compound **3** (1.0 g) was dissolved in 50 mL of dry CH_3CN previously distilled from CaH_2 and placed in a Pyrex glass vessel. Cyclohexane (50 mL) also was added to the glass vessel, forming two immiscible layers. Only the acetonitrile solution layer was irradiated with an Oriel 200W Hg–Xe lamp using a Corning 0–52 cut-off filter, i.e., $h\nu$ > 340 nm. The solution was continuously purged with argon during the irradiation. The cyclohexane layer (upper layer) was removed periodically and replenished with fresh cyclohexane, thus removing the nonionic photoproducts in order to eliminate secondary photochemistry. The combined cyclohexane extract was flash evaporated and subjected to silica gel chromatography using a Harrison Research Chromatotron (Model 7924) to remove **4** from **5**. Compound **6**, which remained in the acetonitrile, was characterized by ^1H NMR and compared to an authentic sample that was synthesized independently. The mixture of photoisomers was obtained from careful Chromatotron chromatography, and each photoisomer was characterized by a combination of high-resolution ^1H NMR in $CDCl_3$ and mass spectrometry.

(15) Fieser, L. F. *J. Am. Chem. Soc.* **1931**, *53*, 2329.

Table I. Summary of Crystal Data and Refinement Parameters for Structure **3**

formula	$S_2F_3O_3NC_{36}H_{26}$
MW	641.74
space group	I
cell constants at 23 (1) °C:	
a, Å	11.377 (4)
b	11.903 (2)
c	23.521 (4)
α, deg	92.04 (1)
β	93.06 (2)
γ	90.20 (2)
V, Å^3	3179 (2)
no. molecules/unit cell (Z)	4
D calcd, g cm^{-3}	1.341
crystal dimensions, mm	0.13 × 0.20 × 0.46
absorption coeff (μ, Mo Kα) cm^{-1}	2.1
scan technique	ω-2θ
scan rate, deg 2θ min^{-1}	2–10
2θ limit, deg	46
h, k, l range	0 to 12, −13 to 13, −25 to 25
no. of unique data measured	8816
no. of data used in refinement ($I > \sigma(I)$)	4518
no. of parameters	811
$R = \sum\|\|F_o\| - \|K\|F_c\|\|/\sum\|F_o\|$	0.083
$R_w = (\sum w(\|F_o\| - K\|F_c\|)^2/\sum wF_o^2)^{1/2}$	0.079
$S = [(\sum w(\|F_o\| - K\|F_c\|)^2/(n_o - n_v)]^{1/2}$	1.29
wtg parameters ($w^{-1} = \sigma^2(F_o) + (pF_o)^2 + q$):	
p	0.02
q	1.0
scale factor, K	0.875 (1)
maximum shift in final cycle, (Δ/σ)	0.14
residual electron density in final difference Fourier synthesis (e/Å^3)	−0.31 to +0.45

^1H NMR and Mass Spectral Characterization of Photoproducts 4. 1-(*p*-Cyanobenzyl)-9-[2-[(phenylthio)methyl]phenyl]anthracene (4a): ^1H NMR ($CDCl_3$) δ 4.70 (s, 2 H), 3.65 (s, 2 H), 8.54 (s, 1 H, Ar), 6.84–8.10 (m, 20 H, remaining Ar); mass spectrum (FDMS) m/e 491.

2-(*p*-Cyanobenzyl)-9-[2-[(phenylthio)methyl]phenyl]anthracene (4b): ^1H NMR ($CDCl_3$) δ 4.12 (s, 2 H), 3.65 (s, 2 H), 8.20 (s, 1 H, Ar), 6.84–8.10 (m, 20 H, remaining Ar); mass spectrum (FDMS) m/e 491.

3-(*p*-Cyanobenzyl)-9-[2-[(phenylthio)methyl]phenyl]anthracene (4c): ^1H NMR ($CDCl_3$) δ 4.10 (s, 2 H), 3.65 (s, 2 H), 8.18 (s, 1 H, Ar), 6.84–8.10 (m, 20 H, remaining Ar); mass spectrum m/e 491.

4-(*p*-Cyanobenzyl)-9-[2-[(phenylthio)methyl]phenyl]anthracene (4d): ^1H NMR ($CDCl_3$) δ 3.70 (s, 2 H), 3.65 (q, 2 H, $\Delta\nu_{AB}$ = 16 Hz), 8.31 (s, 1 H, Ar), 6.84–8.10 (m, 20 H, remaining Ar); mass spectrum (FDMS) m/e 491.

9-(*p*-Cyanobenzyl)-10-[2-[(phenylthio)methyl]phenyl]anthracene (4e): ^1H NMR ($CDCl_3$) δ 5.13 (s, 2 H), 3.65 (s, 2 H), 6.84–8.10 (m, 21 H, Ar); mass spectrum (FDMS) m/e 491.

Photolysis of 7 and Characterization of Photoproducts. Compound **7** was photolyzed as previously described for compound **3** to obtain the photoproducts **8a–k**.

^1H NMR and Mass Spectral Characterization of Photoproducts 8. 1-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8a): ^1H NMR ($CDCl_3$) δ 4.28 (s, 2 H), 3.77 (s, 2 H), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) m/e 541.

2-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8b): ^1H NMR ($CDCl_3$) δ 4.18 (s, 2 H), 3.77 (s, 2 H), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) m/e 541.

3-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8c): ^1H NMR ($CDCl_3$) δ 4.27 (s, 2 H), 3.77 (s, 2 H), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) m/e 541.

4-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8d): ^1H NMR ($CDCl_3$) δ 4.14 (s, 2 H), 3.50 (q, 2 H, $\Delta\nu_{AB}$ = 14 Hz), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) m/e 541.

6-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8e): ^1H NMR ($CDCl_3$) δ 4.10 (s, 2 H), 3.75 (s, 2 H), 8.71 (s, 2 H, Ar), 8.13 (d, 1 H, Ar), 8.19 (d, 1 H, Ar), 7.0–7.9 (m, 19 H, remaining Ar); mass spectrum (FDMS) m/e 541.

7-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8f): ^{1}H NMR ($CDCl_3$) δ 4.65 (s, 2 H), 3.77 (s, 2 H), 7.95 (d, 1 H, Ar), 7.0–8.72 (m, 22 H, remaining Ar); mass spectrum (FDMS) *m/e* 541.

8-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8g): ^{1}H NMR ($CDCl_3$) δ 4.08 (s, 2 H), 3.77 (s, 2 H), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) *m/e* 541.

9-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8h): ^{1}H NMR ($CDCl_3$) δ 4.19 (s, 2 H), 3.77 (s, 2 H), 7.0–8.7 (m, 23 H, Ar); mass spectrum (FDMS) *m/e* 541.

10-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8i): ^{1}H NMR ($CDCl_3$) δ 4.69 (s, 2 H), 3.77 (s, 2 H), 8.67 (s, 1 H, Ar), 8.78 (s, 1 H, Ar), 8.15 (s, 1 H, Ar), 8.00 (d, 1 H, Ar), 7.0–7.88 (m, 19 H, remaining Ar); mass spectrum (FDMS) *m/e* 541.

11-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8j): ^{1}H NMR ($CDCl_3$) δ 5.28 (s, 2 H), 3.77 (s, 2 H), 8.86 (s, 1 H, Ar), 7.99 (s, 1 H, Ar), 8.26 (d, 1 H, Ar), 7.0–7.88 (m, 20 H, remaining Ar); mass spectrum (FDMS) *m/e* 541.

12-(*p*-Cyanobenzyl)-5-[2-[(phenylthio)methyl]phenyl]naphthacene (8k): ^{1}H NMR ($CDCl_3$) δ 5.30 (s, 2 H), 3.77 (s, 2 H), 8.26 (s, 1 H, Ar), 8.82 (s, 1 H, Ar), 7.0–8.02 (m, 21 H, remaining Ar); mass spectrum (FDMS) *m/e* 541.

X-ray Crystallography.[6] A clear tabular crystal of **3** was mounted in a glass capillary and used for data collection on an Enraf-Nonius CAD4 diffractometer using graphite-monochromated Mo Kα radiation.[6] A summary of unit-cell data and refinement parameters are given in Table I. Unit-cell data were determined by least-squares refinement of 25 reflections ($12.0 < 2\theta < 20.6°$). Three standard reflections were remeasured every hour of X-ray exposure. Data were corrected for a maximum 8% variation in intensity over time.

The structure was solved by direct methods by using MULTAN 11/82. There are two molecules (A & B) in the assymetric unit. Refinement was by the full-matrix least-squares method. Hydrogen atoms were input at calculated positions in the final cycles of refinement but not refined.

Supplementary Material Available: Determination of the quantum yields of **4**, **5**, **6**, and **8** (2 pages). Ordering information is given on any current masthead page.

The Chemistry of Cyclic Vinyl Ethers. 6. Total Synthesis of Polyether Ionophore Antibiotics of the Calcimycin (A-23187) Class

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Abstract: An extremely convergent (longest linear sequence, 16 steps), fully stereoselective, and potentially general synthesis of the antibiotic ionophores of the Calcimycin (A-23187) class was devised. The key steps involve a coupling reaction between the chiral nonracemic subunits dihydropyran **41** (as the α-lithio anion) and bromide **49**. Subsequent acid-promoted cyclization directly produces the spirocyclic ring system found in the ionophore X-14885A (**3**). Alternatively, cyclopropanation of substituted vinyl ether **55** followed by acid treatment afforded the spiroketal **58** that was subsequently converted into the polyether ionophore Calcimycin (**1**) and also Cezomycin (**2**).

The first polyether ionophore antibiotics were isolated in 1951;[1] however, as a result of their structural complexities and the lack of sufficiently powerful spectroscopic techniques, 16 years passed before the first structure of a member of the class, Monensin, was elucidated.[2] The discovery in the late 1960's that these compounds possessed interesting biological and ionophoric properties resulted in a tremendous increase in interest in this class of substances. Over 80 new members of this class have been isolated and most of the structures fully established since that time.[3] Their remarkable structural complexities have stimulated the development of a variety of new synthetic methodologies based on acyclic stereocontrol for the efficient construction of these polyacetate and/or polypropionate derived materials.[4] In this paper, we present a full account of our efforts to apply new methodology, developed in our laboratories, involving the generation and subsequent reactions of cyclic vinyl ether anions to the enantioselective total synthesis of (−)-A-23187 and other members of that class such as Cezomycin (**2**).[5,6]

The antibiotic Calcimycin (**1**), also called A-23187, was isolated in 1974 by Chaney from the cultures of *Streptomyces chartreusis* (NRRL 3882) as a mixed calcium–magnesium salt.[7] Its structure was determined by a single-crystal X-ray analysis on the free acid. The absolute configuration was unequivocally established by the first total synthesis of (−)-**1** by Evans and co-workers in 1979, and several additional total syntheses of **1**, both in racemic and nonracemic form, have been recorded since that time.[8] Calcimycin (**1**) is active against Gram-positive bacteria and fungi, and the acute toxicity in mice is 10 mg/kg (intraperitoneal).[9] More importantly, Calcimycin was shown to form a 2:1 (antibiotic–cation) neutral complex with divalent metal cations and also to complex Ca^{2+} selectively over monovalent cations.[10] This unique

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