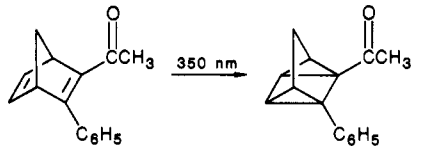
absorption at λ_{max} 294 nm. Irradiation with 350-nm light gave a quantitative yield of **2a**. The $E_{1/2}^{ox}$ for **2a** was 0.90



1a **2a**

V vs. SCE. Thus, while the substituents dramatically changed the photoefficiency with which **1a** could be converted into **2a** with 350-nm light as compared to the parent hydrocarbons, the substituents had a balanced electronic effect on the HOMO of **2a** in comparison to quadricyclane itself ($E_{1/2}^{ox}$ = 0.91 V vs. SCE). Utilization of the electrochemical "switching" process with tri-*p*-tolylamine as the cation-radical precursor gave **1a** from **2a** in analogy to the process outlined above.

In summary, we have developed an electrically driven "on–off switch" for the release of thermal energy in the conversion of **2** to **1**. This switch is highly efficient. However, we stress that while the chemical efficiency approaches 100%, *it is not 100%* since the conversion of **2** into **1** eventually ceases after the applied current is turned off (indicating the presence of a very minor side reaction). Clearly, considerable developmental work would be required before this concept could be utilized in a practical solar energy storage cell.[17]

Experimental Section[18]

Quadricyclane (Tetracyclo[3.2.0.0^{2,7}.0^{4,6}]heptane, 1). Compound **1** (R = R′ = H) was prepared according to the literature procedure.[19]

2-Acetyl-3-phenylbicyclo[2.2.1]hepta-2,5-diene (1a). A solution of 4.82 g (35 mmol) of 4-phenyl-3-butyn-2-one, ca. 50 mg of *p*-methoxyphenol (to inhibit polymer formation), and 3.3 g (25 mmol) of distilled dicyclopentadiene was placed in a round-bottomed flask equipped with a reflux condenser, and the reaction mixture was heated to 160 °C under a nitrogen atmosphere for 10 h. The resulting amber oil was distilled to give 6.0 g (82% yield) of **1a**: bp 93–95 °C (0.05 mm); ^{1}H NMR ($CDCl_3$) δ 7.25 (s, 5 H), 6.90 (br s, 2 H), 4.03 (m, 1 H), 3.72 (m, 1 H), 2.30–2.00 (m, 2 H), 1.94 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 196.6, 166.4, 149.6, 143.9, 141.4, 137.3, 128.6, 128.4, 127.3, 70.4, 59.4, 52.3, 29.1; IR (neat) 3060, 2980, 2938, 2865, 1655, 1595, 1560, 1495, 1448, 1363, 1334, 1300, 1240, 810, 760, 723, 700 cm^{-1}; UV $\lambda_{max}^{acetonitrile}$ = 294 nm (ϵ 4000); exact mass, *m/e* 210.1036 (calcd for $C_{15}H_{14}O$, 210.1045).

Anal. Calcd for $C_{15}H_{14}O$: C, 85.68; H, 6.71. Found: C, 85.34; H, 6.75.

1-Acetyl-5-phenyltetracyclo[3.2.0.0^{2,7}.0^{4,6}]heptane (2a). A solution of 3.0 g (14 mmol) of **1a** in 35 mL of hexane in a Pyrex tube was purged with nitrogen and irradiated for 12 h at ambient temperature in a Rayonet reactor equipped with 16 350-nm lamps. Removal of the solvent gave a quantitative yield of **2a**, which varied from having no detectable impurities (including **1a**) to material that was contaminated with up to 5% of **1a** as the only detectable impurity. Similar results were obtained when chloroform was used as solvent and in the absence of solvent. For irradiation in the absence of solvent, neat **1a** was sealed in a Pyrex tube under vacuum. Compound **2a** had the following physical properties: ^{1}H NMR ($CDCl_3$) δ 7.24 (s, 5 H), 2.74–2.09 (m, 6 H), 1.72 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 203.8, 137.2, 129.2, 128.0, 126.6, 42.1, 39.2, 33.4, 32.3 (2C), 31.7, 27.4, 20.7; IR (neat) 3060, 2930, 2860, 1674, 1610, 1510, 1454, 1386, 1310, 1300, 1235, 1170, 1160, 1075, 1020, 955, 910, 830, 750, 700 cm^{-1}.

Anal. Calcd for $C_{15}H_{14}O$: C, 85.68; H, 6.71. Found: C, 85.31; H, 6.78.

Conversion of Quadricyclane (2) to Norbornadiene (1) Using an Electrochemical Switch. In a typical experiment, 1.00 mL (0.92 g, 10 mmol) of **2** (R = R′ = H) and tri-*p*-tolylamine[20] (0.10 g, 0.34 mmol) were dissolved in 30 mL of methylene chloride containing 0.20 M tetra-*n*-hexylammonium perchlorate in the working compartment of a divided preparative electrolysis cell. The solution was purged with nitrogen at ambient temperature, and an anodic current of about 1 mA was passed through the solution while controlling the working electrode potential at +0.30 V vs. a saturated-NaCl–SCE electrode. The formation of **1** (R = R′ = H) was monitored by GLC. After the passage of 3.9 C, the conversion of **2** to **1** was complete. The electrochemical catalytic turnover number (mol of product/faraday) was 247. Similar results were obtained by using tetraethylammonium tetrafluoroborate as electrolyte.

Conversion of 2a to 1a Using an Electrochemical Switch. In the working compartment of a divided preparative electrolysis cell were placed 0.50 g (2.4 mmol) of **2a** and 0.034 g (0.12 mmol) of tri-*p*-tolylamine in 30 mL of methylene chloride containing 0.05 M tetraethylammonium tetrafluoroborate. The nitrogen-purged solution was subjected to controlled-potential oxidation at 0.50 V vs. a saturated-NaCl–SCE until 1.3 C of current had passed. Workup of the reaction mixture showed that **2a** had been completely converted into **1a**.

In a repeat of the same experiment, the progress of the reaction was monitored by IR spectroscopy utilizing the carbonyl frequencies at 1665 cm^{-1} and 1641 cm^{-1} of **2a** and **1a**, respectively.[21] These studies indicated a catalytic turnover number of 290 for the conversion of **2a** to **1a**.

Acknowledgment. We are indebted to the National Science Foundation for a grant that supported this investigation.

(17) We are continuing to investigate applications of this concept. For an initial disclosure, see: Gassman, P. G.; Hershberger, J. W. U.S. Pat. 4 582 578, April 18, 1986.

(18) ^{1}H NMR and ^{13}C NMR spectra were recorded on Varian EM-360 and Bruker WH-90 spectrometers, respectively. IR spectra were obtained with a Beckman IR 4240 spectrophotometer. A Perkin-Elmer Lambda 3B was used for UV measurements. Elemental analyses were done by Galbraith Analytical Laboratories, Inc. Cyclic voltammetry was performed on a Princeton Applied Research Model 174A polarographic analyzer. A typical solution consisted of 10^{-3} M substrate dissolved in acetonitrile which contained 0.1 M tetraethylammonium tetrafluoroborate at ambient temperature with a scan rate of 100 mV/s. A platinum bead working electrode and a saturated-NaCl–SCE reference electrode were employed. Preparative electrolyses were performed in a three-compartment cell equipped with a platinum gauze working electrode.

(19) Smith, C. D. *Org. Synth.* **1971**, *51*, 133.

(20) Walter, R. I. *J. Am. Chem. Soc.* **1955**, *77*, 5999.

(21) The values used here are those observed in methylene chloride containing electrolyte. They are considerably shifted from those observed for the neat liquid.

Radical Spirocyclization: Synthesis of an Appropriately Oxygenated Spiro Compound Related to the Antitumor Antibiotic Fredericamycin A

Derrick L. J. Clive,* A. Gaëtan Angoh, and Sharon M. Bennett

Department of Chemistry, University of Alberta, Edmonton, Alberta, T6G 2G2, Canada

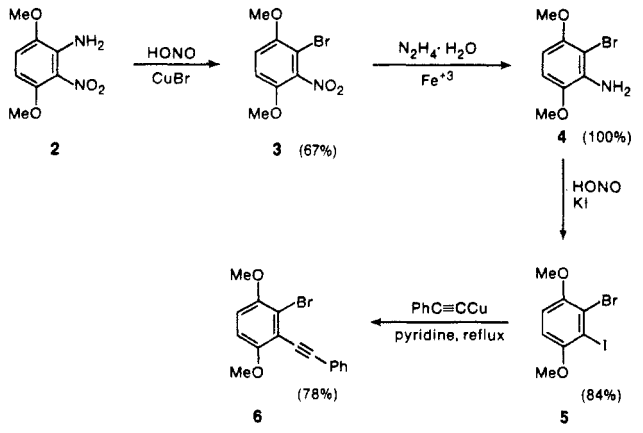
Received September 8, 1986

As judged by the number of very recent publications on the subject,[1] there is appreciable interest in the synthesis

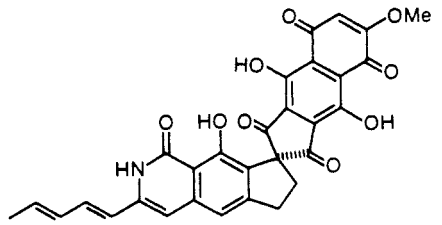
(1) (a) Rama Rao, A. V.; Reddeppa Reddy, D.; Deshpande, V. H. *J. Chem. Soc., Chem. Commun.* **1984**, 1119. (b) Parker, K. A.; Koziski, K. A.; Breault, G. *Tetrahedron Lett.* **1985**, *26*, 2181. (c) Eck, G.; Julia, M.; Pfeiffer, B.; Rolando, C. *Ibid.* **1985**, *26*, 4723. (d) Eck, G.; Julia, M.; Pfeiffer, B.; Rolando, C. *Ibid.* **1985**, *26*, 4725. (e) Kende, A. S.; Ebetino, F. H.; Ohta, T. *Ibid.* **1985**, *26*, 3063. (f) Braun, M.; Veith, R. *Ibid.* **1986**, *27*, 179. (g) Bach, R. D.; Klix, R. C. *Ibid.* **1986**, *27*, 1983. (h) Bach, R. D.; Klix, R. C. *J. Org. Chem.* **1986**, *51*, 749. (i) Parker, K.; Breault, G. A. *Tetrahedron Lett.* **1986**, *27*, 3835. (j) Bennett, S. M.; Clive, D. L. J. *J. Chem. Soc., Chem. Commun.* **1986**, 878. (k) The first total synthesis has recently been completed: Kelly, T. R., personal communication.

0022-3263/87/1952-1339$01.50/0

Scheme I



of the bacterial metabolite fredericamycin A.[2] Viewed as a chemical problem, the structure of the compound (see 1) is sufficiently complex that a total synthesis is not a simple undertaking;[1k] however, the development of synthetic routes to fredericamycin A could prove to be a medically useful achievement: the substance is a very powerful antitumor agent,[2] and the fact that its spiro structure is unique raises the significant possibility that new molecular mechanisms relevant to tumor inhibition may be discovered through a structure–activity study. Chemical synthesis does, of course, provide access to suitable analogues for biological evaluation.



1

We report here the use of our radical spirocyclization[1j,3] to prepare compound **16** (Scheme II), which represents the unusual central portion of the antibiotic together with the correct oxygenation pattern.

The synthetic route is convergent and is based on two components: the methoxy aldehyde **7**[1j] (Scheme II) and the dimethoxy bromide **6** (Scheme I). The latter was made by the sequence of operations summarized in Scheme I, the route shown being the best of several that we examined. Amine **2**[4] was subjected to a Sandmeyer reaction[5] (**2** → **3**), and then the nitro group was reduced with hydrazine.[6] Another Sandmeyer reaction[7] served to generate the iodo bromide **5**, and coupling[8] with copper(I) phenylacetylide proceeded chemospecifically to the desired bromo acetylene **6**. This compound underwent metal–halogen exchange, and the resulting organolithium **8** was allowed to react (Scheme II) with the aldehyde **7**. Epimeric alcohols **9** were produced in 89% yield and were oxidized (75%) to the ketone **10**. Phenylselenation (**10** → **11**) was achieved by treating the ketone, at a low temperature, first with LDA and then with an excess of phenylselenenyl chloride. Although the reaction is efficient (83% yield), the α-phenylseleno ketone is not particularly stable and was best used within a few days. The compound was dissolved in benzene containing a trace of AIBN. The solution was refluxed, and an excess (1.7-fold) of triphenyltin hydride was added in one portion. Refluxing was continued overnight, and it was then possible to isolate the desired spiro compound **14** (Scheme II) in 79% yield as a single isomer. These conditions represent an optimized procedure and differ from the high-dilution technique often found essential in radical cyclizations. Evidently, the α-keto radical **12** cyclizes more rapidly than it abstracts hydrogen from triphenyltin hydride. We have found[1j] that a benzyloxy group in a syn relationship to the vinylic radical undergoes intramolecular 1,6-hydrogen migration. Therefore, the success of the present spirocyclization (**11** → **14**) is due to the greater C–H bond dissociation energy for H–CH_2O than for H–CH(Ph)O.

For cleavage of the olefinic double bond in **14**, ozonolysis was successful, but the reaction requires close monitoring to avoid overoxidation. Finally, the *O*-methyl groups of **15** were removed (**15** → **16**, 85%) by the action of boron tribromide at room temperature.

Experimental Section

Infrared spectra were recorded on a Perkin-Elmer Model 297 spectrophotometer. Mass spectra were recorded on an A.E.I. MS50 mass spectrometer at an ionizing voltage of 70 eV. NMR spectra were measured with a Bruker WH200 or WH400 spectrometer. Elemental analyses were carried out in the Microanalytical Laboratory of the University of Alberta.

2-Bromo-1,4-dimethoxy-3-nitrobenzene (3). Sodium nitrite (1.72 g, 24.90 mmol) in water (5.0 mL) was added with stirring over 15 min to a cold (0 °C) solution of 3,6-dimethoxy-2-nitroaniline **2**[4] (4.50 g, 22.7 mmol) in acidic methanol [from concentrated sulfuric acid (20 mL), methanol (10 mL), and water (30 mL)]. The mixture was stirred at 0 °C for a further 30 min and then added over 1 h to a stirred, warm (60 °C) solution of copper(I) bromide (1.80 g, 12.71 mmol), 48% w/v hydrogen bromide (6 mL), and water (30 mL). At the end of the addition the mixture was refluxed for 1 h more, cooled, and filtered. The precipitate was washed with water (10 mL) and dried under vacuum. Purification by flash chromatography over silica gel (6 × 15 cm) with 1:1 hexane–dichloromethane gave bromide **3** (4.0 g, 67%): IR ($CHCl_3$) 1540, 1365 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 3.84 (s, 3 H), 3.90 (s, 3 H), 6.95 (s, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 150.6, 145.4, 143.3, 113.4, 112.5, 104.2, 57.1, 57.0; exact mass, *m/z* 260.9640, 262.9621 (calcd for $C_8H_8BrNO_4$, 260.9633, 262.9613). Anal. Calcd for $C_8H_8BrNO_4$: C, 36.64; H, 3.07; N, 5.34; O, 24.42. Found: C, 36.70; H, 3.03; N, 5.33; O, 24.58.

2-Bromo-3,6-dimethoxyaniline (4). A mixture of bromide **3** (4.1 g, 15.2 mmol), activated carbon (600 mg, 50–200 mesh, Fisher Scientific Co.), ferric chloride hexahydrate (250 mg), and methanol (50 mL) was refluxed for 10 min with stirring. Hydrazine hydrate (3.0 g, 60.2 mmol, 99.1%) was added over 30 min to the boiling solution. The mixture was stirred under reflux for an additional 12 h, cooled, and evaporated. The resulting slurry was dissolved in dichloromethane (50 mL), washed with water (2 × 20 mL), and dried ($MgSO_4$). Evaporation of the solvent and flash chromatography of the residue over silica gel (5 × 15 cm) with 1:1 hexane–dichloromethane gave amine **4** (3.52 g, 100%): IR ($CHCl_3$) 3490, 3395, 1605 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 3.80 (s, 3 H), 3.81 (s, 3 H), 4.30 (br s, 2 H), 6.22 (d, *J* = 8 Hz, 1 H), 6.65 (d, *J* = 8 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 151.1, 142.1, 136.4, 109.3, 99.6, 98.9, 56.5, 56.4; exact mass *m/z* 232.9853 (calcd for $C_8H_{10}{}^{80}BrNO_2$, 232.9871). Anal. Calcd for $C_8H_{10}BrNO_2$: C, 41.38; H, 4.34; N, 6.03; O, 13.78. Found: C, 41.40; H, 4.30; N, 5.94; O, 13.83.

2-Bromo-1,4-dimethoxy-3-iodobenzene (5). Sodium nitrite

(2) (a) Misra, R.; Pandey, R. C.; Silverton, J. B. *J. Am. Chem. Soc.* **1982**, *104*, 4478. (b) Pandey, R. C.; Toussaint, M. W.; Stroshane, R. M.; Kalita, C. C.; Aszalos, A. A.; Garretson, A. L.; Wei, T. T.; Byrne, K. M.; Geoghegan, R. E., Jr.; White, R. J. *J. Antibiot.* **1981**, *34*, 1390. (c) Warnick-Pickle, D. J.; Byrne, K. M.; Pandey, R. C.; White, R. J. *Ibid.* 1402. (d) Byrne, K. M.; Hilton, B. D.; White, R. J.; Misra, R.; Pandey, R. C. *Biochemistry* **1985**, *24*, 478.

(3) Set, L.; Cheshire, D. R.; Clive, D. L. J. *J. Chem. Soc., Chem. Commun.* **1985**, 1205.

(4) Rees, C. W.; West, D. E. *J. Chem. Soc. C* **1970**, 583.

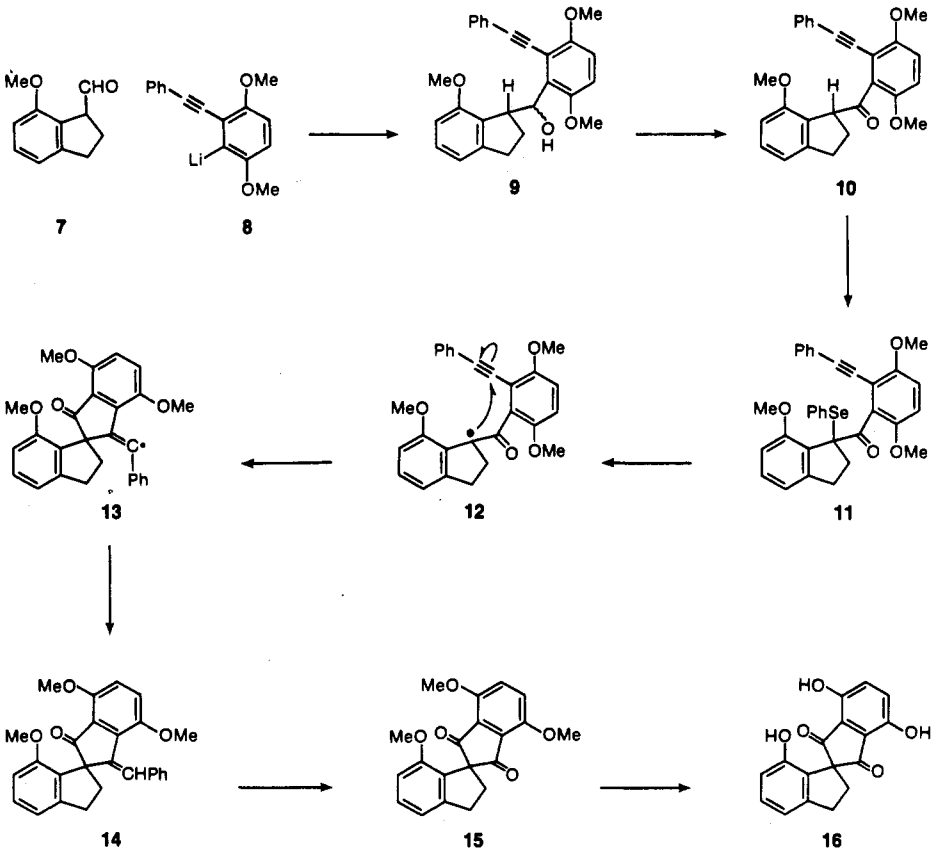
(5) Cf.: Ando, M.; Enoto, S. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2437.

(6) Cf.: Hirashima, T.; Manabe, O. *Chem. Lett.* **1975**, 259.

(7) Cf.: Heaney, H.; Millar, I. T. *Org. Synth.* **1973**, *5*, 1120.

(8) Owsley, D. C.; Castro, C. E. *Org. Synth.* **1972**, *52*, 128.

Scheme II



(1.11 g, 16.17 mmol) in water (5.0 mL) was added with stirring over 15 min to a cold (0 °C) solution of amine **4** (3.41 g, 14.7 mmol) in concentrated hydrochloric acid (7 mL) and ice (10 g). The mixture was stirred at 0 °C for a further 20 min, and the cold solution, maintained at 0 °C in a jacketed addition funnel, was added over 30 min to a stirred solution (room temperature) of potassium iodide (24.4 g, 0.146 mol) in water (30 mL). The mixture was left standing at room temperature overnight and extracted with dichloromethane (2 × 50 mL). The combined organic extracts were washed successively with 10% w/v aqueous sodium hydroxide, 5% w/v aqueous sodium bicarbonate, and water and dried ($MgSO_4$). Evaporation of the solvent and flash chromatography of the residue over silica gel (6 × 15 cm) with 1:1 hexane–dichloromethane gave iodide **5** (4.21 g, 84%): ^1H NMR ($CDCl_3$, 200 MHz) δ 3.83 (s, 3 H), 3.84 (s, 3 H), 6.75 (d, J = 8 Hz, 1 H), 6.89 (d, J = 8 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 154.5, 151.5, 121.3, 112.5, 110.3, 96.7, 57.4, 57.3; exact mass, m/z 341.8756, 343.8736 (calcd for $C_8H_8BrIO_2$, 341.8750, 343.8730). Anal. Calcd for $C_8H_8BrIO_2$: C, 27.99; H, 2.35; Br, 23.30; O, 9.33. Found: C, 28.20; H, 2.32; Br, 23.90; O, 9.43.

2-Bromo-1,4-dimethoxy-3-(phenylethynyl)benzene (6). Pyridine (25 mL) was added to a mixture of copper(I) phenylacetylide[8] (1.72 g, 10.5 mmol) and iodide **5** (2.40 g, 7.0 mmol). The mixture was stirred under reflux for 12 h, cooled to room temperature, and diluted with ether (100 mL). The solution was washed successively with 1 M hydrochloric acid, saturated aqueous sodium bicarbonate, water, and brine and dried ($MgSO_4$). Evaporation of the solvent and flash chromatography of the residue over silica gel (6 × 15 cm) with 20% ethyl acetate–hexane gave bromide **6** (1.73 g, 78%): ^1H NMR ($CDCl_3$, 200 MHz) δ 3.88 (s, 3 H), 3.89 (s, 3 H), 6.70 (d, J = 2 Hz, 2 H), 7.35 (m, 3 H), 7.62 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 155.5, 151.0, 131.78, 131.72, 128.4, 128.3, 123.5, 117.0, 112.7, 110.6, 98.5, 84.9, 57.1, 58.8; exact mass, m/z 317.9983 (calcd for $C_{16}H_{13}{}^{80}BrO_2$, 318.0075). Anal. Calcd for $C_{16}H_{13}BrO_2$: C, 60.56; H, 4.13; O, 10.09. Found: C, 60.28; H, 4.05; O, 10.24.

2,3-Dihydro-7-methoxy-1*H*-indene-1-carboxaldehyde (7). Potassium *tert*-butoxide (3.47 g, 30.9, mmol) was added over 30 min, via a side-arm addition funnel to a suspension of (methoxymethyl)triphenylphosphonium chloride (10.59 g, 30.9 mmol) in dioxane (75 mL) under argon. The mixture was stirred at room temperature for 1.5 h, and then a solution of 2,3-dihydro-7-methoxy-1*H*-inden-1-one[9] (2.00 g, 12.4 mmol) in dioxane (10 mL + 5 mL rinse) was added over ca. 5 min. Stirring at room temperature was continued for 22 h. Water (ca. 50 mL) was then added, and the aqueous solution was extracted with ether (2 × 100 mL). The combined organic extracts were washed with brine, dried, and evaporated. The residue was taken up in 15% ethyl acetate–hexane which contained just enough dichloromethane to dissolve the triphenylphosphine oxide. The solution was loaded onto a column of silica gel (5 × 15 cm), and the column was developed with 15% ethyl acetate–hexane. This procedure allowed separation of most of the triphenylphosphine oxide from the derived enol ethers. The crude product was used directly in the preparation of the corresponding aldehyde **7**.

p-Toluenesulfonic acid monohydrate (300 mg, 1.58 mmol) was added to a solution of the crude enol ethers in aqueous dioxane [dioxane (30 mL) + water (10 mL)], and the mixture was stirred under reflux for 14 h. It was then cooled to room temperature, diluted with water (20 mL), and extracted with ether (2 × 80 mL). The combined organic extracts were washed with 5% aqueous sodium bicarbonate (30 mL) and brine (30 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (5 × 15 cm) with 10% ethyl acetate–hexane gave **7** (1.74 g, 79.9%). Kugelrohr distillation afforded an analytical sample: bp 67 °C (0.02 mm); IR (CCl_4) 1725, 1480, 1265, 1080 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.10–2.52 (m, 2 H), 2.98 (m, 2 H), 3.82 (s, 3 H), 4.08 (m, 1 H), 6.72 (d, J = 8.0 Hz, 1 H), 6.89 (d, J = 8.0 Hz, 1 H), 7.23 (t, J = 8.0 Hz, 1 H), 9.73 (d, J = 3.0 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 200.5, 156.5, 146.9, 129.6, 126.7, 117.3, 108.2, 55.8, 55.2, 32.2, 25.3; exact mass, m/z 176.0840 (calcd for $C_{11}H_{12}O_2$, 176.0837). Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.74; H, 6.78.

2,3-Dihydro-7-methoxy-1-[hydroxy(3,6-dimethoxy-2-(phenylethynyl)phenyl)methyl]-1*H*-indene (9). *n*-Butyllithium

(9) (a) Wagatsuma, S.; Higuchi, S.; Ito, H.; Nakano, T.; Naoi, Y.; Sakai, K.; Matsui, T.; Takahashi, Y.; Nishi, A.; Sano, S. *Org. Prep. Proc. Int.* **1973**, *5*, 65; (b) Loudon, J. D.; Radzan, R. K. *J. Chem. Soc.* **1954**, 4299. We used dimethyl sulfate instead of methyl iodide (93%).

(1.5 M in hexane, 0.73 mL, 1.09 mmol) was injected dropwise into a stirred and cooled (-78 °C) solution of bromide **6** (348 mg, 1.09 mmol) in ether (8 mL). The mixture was stirred for an additional 20 min, and aldehyde **7** (176 mg, 1.0 mmol) in ether (3 mL + 1 mL rinse) was then added at -78 °C over ca. 3 min. The reaction mixture was allowed to warm to 0 °C over 2 h. Saturated aqueous ammonium chloride (10 mL) was added, and the mixture was extracted with ether (2 × 15 mL). The combined organic extracts were washed with brine and dried ($MgSO_4$). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 1% ethyl acetate–dichloromethane gave alcohols **9** (371 mg, 89%): IR (neat) 3540, 2240, 1585 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.22 (m, 1 H), 2.55–2.92 (m, 2 H), 3.15 (m, 1 H), 3.33 (2s, 1:2, 3 H), 3.95 (m, 7 H), 5.32 (m, 1 H), 6.45 (d, J = 8 Hz, 1 H), 6.68–6.90 (m, 3 H), 7.05 (t, J = 7.5 Hz, 1 H), 7.34 (m, 5 H); exact mass, m/z 414.1827 (calcd for $C_{27}H_{26}O_4$, 414.1824). Anal. Calcd for $C_{27}H_{26}O_4$: C, 78.22; H, 6.32. Found: C, 78.06; H, 6.38.

1-[3,6-Dimethoxy-2-(phenylethynyl)benzoyl]-2,3-dihydro-7-methoxy-1*H*-indene (10). Alcohols **9** (371 mg, 0.896 mmol) in dichloromethane (5 mL + 1 mL rinse) were added at room temperature to a stirred mixture of pyridinium chlorochromate (772 mg, 3.58 mmol) and 3-Å molecular sieves (1.79 g, 8–12 mesh) in dichloromethane (15 mL). Stirring was continued for 4 h, ether (50 mL) was added, and the brown suspension was filtered through a pad of Celite (3 × 6 cm) which was washed well with 1:1 ether–dichloromethane. The combined filtrates were evaporated, and flash chromatography of the residue over silica gel (2 × 15 cm) with dichloromethane gave ketone **10** (280 mg, 75%): IR (neat) 1690, 1580 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.10–2.33 (m, 1 H), 2.60–2.92 (m, 2 H), 3.05–3.35 (m, 1 H), 3.45 (s, 3 H), 3.64 (s, 3 H), 3.82 (s, 3H), 4.8 (dd, J = 8, 2 Hz, 1 H), 6.51 (d, J = 8 Hz, 1 H), 6.8 (d, J = 8 Hz, 1 H), 6.89 (s, 2 H), 7.10 (t, J = 7.5 Hz, 1 H), 7.32 (m, 5 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 204.0, 156.3, 154.2, 150.2, 147.0, 135.6, 131.6, 128.8, 128.7, 128.0, 127.9, 123.2, 116.8, 112.1, 112.0, 111.1, 107.7, 97.0, 83.1, 56.7, 56.3, 55.6, 54.7, 32.3, 29.1; exact mass, m/z 412.1682 (calcd for $C_{27}H_{24}O_4$, 412.1668). Anal. Calcd for $C_{27}H_{24}O_4$: C, 78.60; H, 5.86. Found: C, 78.68; H, 5.88.

1-[3,6-Dimethoxy-2-(phenylethynyl)benzoyl]-2,3-dihydro-7-methoxy-1-(phenylseleno)-1*H*-indene (11). Ketone **10** (390 mg, 0.94 mmol) in THF (3 mL + 1 mL rinse) was added over 5 min to a cold (-78 °C) solution of LDA [from diisopropylamine (0.26 mL, 1.88 mmol) and n-butyllithium (1.5 M in hexane, 1.06 mL, 1.59 mmol)] in THF (8 mL). The yellow mixture was stirred at -78 °C for 1 h, and phenylselenenyl chloride (574 mg, 2.82 mmol) in THF (3 mL + 1 mL rinse) was added over 2 min. The mixture was stirred at -78 °C for 1 h and then warmed to -20 °C over 30 min. Saturated aqueous ammonium chloride (10 mL) was added followed by water (5 mL). The mixture was extracted with ether (2 × 20 mL), and the combined extracts were washed with brine and dried ($MgSO_4$). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 30% ethyl acetate–hexane gave selenide **11** (434 mg, 83%): IR ($CHCl_3$) 2300, 1670, 1585, 1460 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.45–3.05 (m, 4 H), 3.28 (s, 3 H), 3.43 (s, 3 H), 3.90 (s, 3 H), 6.40 (d, J = 8 Hz, 1 H), 6.55 (d, J = 7.5 Hz, 1 H), 6.67 (d, J = 7.5 Hz, 1 H), 6.80 (d, J = 8 Hz, 1 H), 7.00–7.71 (m, 11 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 202.7, 156.2, 154.7, 150.1, 146.9, 137.7, 134.6, 131.9, 130.4, 129.4, 128.0, 123.9, 116.4, 112.8, 111.1, 108.2, 97.2, 84.4, 66.9, 60.2, 57.2, 55.4, 54.4, 39.0, 31.3, 20.8, 14.1; mass spectrum, m/z 568 (M), 411 (M - PhSe).

2,3-Dihydro-7-methoxy-1*H*-indene-1-spiro-2′-(3′-benzylidene-4′,7′-dimethoxy-2*H*-inden-1′-one) (14). Triphenyltin hydride (456 mg, 1.30 mmol) in benzene (3 mL + 1 mL rinse) was added in one portion to a refluxing solution of selenide **11** (425 mg, 0.765 mmol) and AIBN (12 mg, 0.073 mmol) in benzene (15 mL). Refluxing was continued for 12 h, and the solvent was evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 40% ethyl acetate–hexane gave **14** (252 mg, 79%): IR ($CHCl_3$) 1700, 1585 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.05–2.50 (m, 3 H), 4.0 (m, 1 H), 3.49 (s, 3 H), 3.91 (s, 3 H), 3.99 (s, 3 H), 6.40–7.25 (m, 10 H), 8.09 (s, 1 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 205.0, 155.6, 151.9, 150.9, 148.1, 142.7, 139.6, 137.3, 134.4, 129.0, 128.6, 127.3, 126.1, 124.2, 118.3, 117.3, 110.9, 108.3, 63.8, 56.2, 55.9, 55.8, 36.3, 32.0; exact mass, m/z 412.1666 (calcd for $C_{27}H_{24}O_4$, 412.1668). Anal. Calcd for $C_{27}H_{24}O_4$: C, 78.60; H, 5.86. Found: C, 78.22; H, 5.71.

2,3-Dihydro-7-methoxy-1*H*-indene-1-spiro-2′-(4′,7′-dimethoxy-2*H*-inden-1′,3′-dione) (15). An ozone–oxygen stream was bubbled through a solution of olefin **14** (200 mg, 0.485 mmol) in dry methanol (7 mL) at -78 °C until the starting material had just disappeared [2.5 min, TLC (silica gel, 40% ethyl acetate–hexane)]. Argon was passed through the solution for 5 min to remove the excess of ozone, and trimethyl phosphite (0.17 mL, 1.45 mmol) was injected. The cold bath was removed, and the solution was stirred overnight. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 40% ethyl acetate–hexane gave diketone **15** (100 mg, 61%): IR ($CHCl_3$) 1740, 1705, 1590 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.43 (t, J = 7.5 Hz, 2 H), 3.22 (t, J = 7.5 Hz, 2 H), 3.51 (s, 3 H), 4.03 (s, 6 H), 6.65 (d, J = 8 Hz, 1 H), 6.92 (d, J = 8 Hz, 1 H), 7.20 (t, J = 8 Hz, 1 H), 7.32 (s, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 200.4, 155.1, 151.0, 148.4, 129.9, 129.6, 128.2, 119.9, 117.2, 108.3, 65.3, 56.6, 55.2, 35.3, 32.3; exact mass, m/z 338.1148 (calcd for $C_{20}H_{18}O_5$, 338.1149). Anal. Calcd for $C_{20}H_{18}O_5$: C, 70.98; H, 5.36. Found: C, 70.65; H, 5.53.

2,3-Dihydro-7-methoxy-1*H*-indene-1-spiro-2′-(4′,7′-dihydroxy-2*H*-inden-1′,3′-dione) (16). Boron tribromide (1 M in dichloromethane, 0.61 mL, 0.61 mmol) was injected over a period of 5 min to a cold (-78 °C) solution of diketone **15** (23 mg, 0.068 mmol) in dichloromethane (2 mL). The cold bath was removed, and stirring was continued overnight. Water (10 mL) was added, and the mixture was extracted with dichloromethane (2 × 5 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (1 × 10 cm) with dichloromethane gave **16** (17.3 mg, 85%): IR (CH_2Cl_2) 1720, 1671, 1595, 1483 cm^{-1}; ^1H NMR (acetone-d_6, 400 MHz) δ 2.44 (t, J = 8 Hz, 2 H), 3.17 (t, J = 8 Hz, 2 H), 6.59 (d, J = 8 Hz, 1 H), 6.80 (d, J = 8 Hz, 1 H), 7.08 (t, J = 8 Hz, 1 H), 7.23 (s, 2 H); ^{13}C NMR (acetone-d_6, 100.6 MHz) δ 204.1, 153.5, 149.7, 149.1, 130.5, 128.2, 126.5, 124.6, 116.5, 113.3, 78.8, 35.1, 32.7; exact mass, m/z 296.0693 (calcd for $C_{17}H_{12}O_5$, 296.0681). Anal. Calcd for $C_{17}H_{12}O_5$: C, 68.90; H, 4.08. Found: C, 68.56; H, 4.02.

Acknowledgment. We thank the Natural Sciences and Engineering Research Council of Canada for financial support and the Alberta Heritage Foundation for Medical Research for a Postgraduate Scholarship (to S.M.B.).

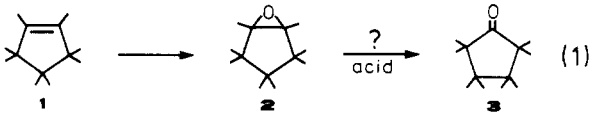
Acid- and Base-Catalyzed Ring-Opening Reactions of a Sterically Hindered Epoxide

Herbert Mayr,* Rainer Koschinsky, Elfriede Will, and Englbert Bäuml

Institut für Chemie der Medizinischen Universität zu Lübeck, D-2400 Lübeck 1, Federal Republic of Germany

Received September 29, 1986

Epoxides are known to rearrange to carbonyl compounds under acidic conditions.[1] When we tried to employ this reaction for the synthesis of octamethylcyclopentanone (**3**)[2] via the sequence shown in eq 1, unexpected rearrangements took place, which we report in this paper.



(1)

(1) Bartok, M.; Lang, K. L. In *The Chemistry of Heterocyclic Compounds*; (Eds. Weissberger, A., Taylor, E. C., Eds.; Wiley: New York, 1985; Vol. 42/III, Chapter 1.

(2) Fitjer, L.; Wehle, D.; Scheuermann, H.-J. *Chem. Ber.* **1986**, *119*, 1162.

0022-3263/87/1952-1342$01.50/0