Silicon in Organic Synthesis. 26. Expedient Synthesis of Dicyclopropylideneethane via Functionalized 1-(Trimethylsilyl)cyclopropanes[1,2]

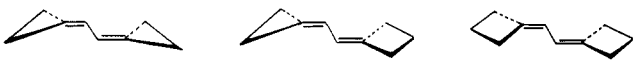
Leo A. Paquette,* Gregory J. Wells, and Geoffrey Wickham[3]

Evans Chemical Laboratories, The Ohio State University, Columbus, Ohio 43210

Received April 12, 1984

Dicyclopropylideneethane (1) has been prepared from two different 1-(trimethylsilyl)cyclopropane derivatives. In the first, aldehyde 4 is coupled in the presence of zerovalent titanium to give olefin 5 which is readily epoxidized. The alternative methodology features conversion of bromide 6 to sulfide 7 and subsequent application of Ramberg-Bäcklund methodology to arrive at 5. Treatment of epoxide 9 with tetra-*n*-butylammonium fluoride delivers allylic alcohol 10 whose conversion to 1 simply requires activation to the chloride and reexposure to fluoride ion. The target diene exhibits a proclivity for polymerization when kept as a neat solid. This tendency is reduced in dilute solution under an inert atmosphere and is almost entirely inhibited at −70 °C. As expected, 1 is a reactive diene in Diels-Alder reactions despite the obvious steric congestion at its bonding centers.

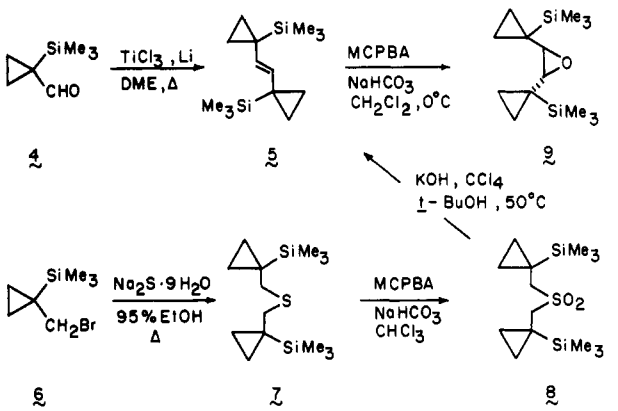
The homologous series of conjugated hydrocarbons represented by 1–3 offers a smooth gradation of electronic and steric properties that is certaih to contribute new insight into our understanding and appreciation of 1,3-butadiene chemistry. Although the chemical reactivity of methylenecyclopropanes and methylenecyclobutanes is presently rather well understood, the effect of juxtapositioning these structural elements with extension of the π-conjugation has not been investigated. The resulting spectral consequences would be interesting, though perhaps predictable. Less clear is the inherent ability of these 1,1,4,4-tetrasubstituted 1,3-butadienes to enter into Diels-Alder reactions. For some time, it has been recognized that 1,1-disubstitution of butadiene with simple alkyl groups introduces a marked reluctance to engage in [4 + 2] cycloaddition.[4] More recently, constraining this pair of substituents into a small ring,[5] and especially into a cyclopropane unit,[6] for the purpose of reducing the steric size of the appendages was shown to have a facilitating influence on this reaction. Notwithstanding, the problem should be exacerbated when both terminal carbon atoms of the diene are fully substituted. The question as to whether 1–3 would be subject to a significant steric barrier, thereby prohibiting attainment of a planar (or at least quasi-planar) cisoid conformation, remained to be answered.



1 2 3

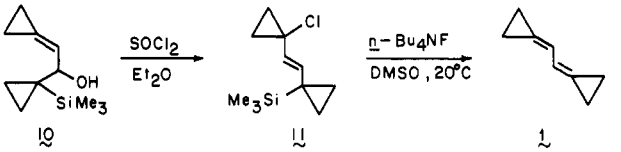
The development of viable synthetic approaches to 1–3 could obviously shed light on this and several allied issues. Heinrich and Lüttke have previously observed 1 to be a minor product in the mixture of 12 possible mono- and bis-adducts that arise from reaction of diazomethane with biallenyl.[7] However, this approach holds no preparative potential. This paper describes two efficient routes to 1

Scheme I



4 5 9 6 7 8

Scheme II



10 11 1

and provides some indication of the reactivity level of this diene toward various dienophiles.

Synthetic Considerations. The first synthetic sequence commences with the readily available bifunctional aldehyde 4,[8] reductive coupling of which in the presence of zerovalent titanium[9] afforded the symmetrically disposed *trans*-1,2-bis[1-(trimethylsilyl)cyclopropyl]ethylene (5) in 38% yield (Scheme I). This stable colorless oil features a ^{1}H NMR spectrum (in $CDCl_3$) consisting of singlets at δ 5.4 (2 H) and 0.0 (18 H) in addition to the cyclopropane multiplet at δ 0.55–0.35 (8 H). Its ^{13}C NMR spectrum consists of the expected four lines at 133.80, 10.08, 9.53, and −3.16 ppm. Köbrich and Merkel have described a more circuitous route to the cis isomer of 5 that was isolated as a crystalline solid [mp 38 °C; ^{1}H NMR (CCl_4) δ 5.37 (s, 2 H), 0.67 (A_2B_2, 8 H), −0.07 (s, 18 H)] following Lindlar reduction of the corresponding acetylene.[10]

(1) For Part 25, see: Paquette, L. A.; Yan, T.-H.; Wells, G. J. *J. Org. Chem.*, in press.
(2) Presented in part at the 7th National Convention, Royal Australian Chemical Institute, Canberra, A.C.T., 22–27 August 1982.
(3) Ohio State University Postdoctoral Fellow, 1983–1984.
(4) (a) Stewart, C. A., Jr. *J. Am. Chem. Soc.* **1982**, *84*, 117; *J. Org. Chem.* **1963**, *28*, 3320. (b) Fisch, J. J.; Husk, G. R. *Ibid.* **1966**, *31*, 589. (c) Bartlett, P. D. *Q. Rev. Chem. Soc.* **1973**, *24*, 473. (d) Kataoka, F.; Shimizu, N.; Nishida, S. *J. Am. Chem. Soc.* **1980**, *102*, 711.
(5) Paquette, L. A.; Klinger, F. *J. Org. Chem.* **1982**, *47*, 272.
(6) Zutterman, F.; Krief, A. *J. Org. Chem.* **1983**, *48*, 1135.
(7) Heinrich, F.; Lüttke, W. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 234.
(8) (a) Yan, T.-H.; Paquette, L. A. *Tetrahedron Lett.* **1982**, *23*, 3227. (b) Wells, G. J.; Yan, T.-H.; Paquette, L. A. *J. Org. Chem.*, in press.
(9) (a) McMurry, J. E.; Krepski, L. R.; Fleming, M. P.; Kees, K. L. *J. Org. Chem.* **1978**, *43*, 3255. (b) McMurry, J. E.; Krepski, L. R. *Ibid.* **1976**, *41*, 3929.
(10) Köbrich, G.; Merkel, D. *Liebigs Ann. Chem.* **1972**, *761*, 50.

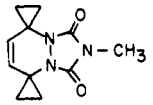
0022-3263/84/1949-3618$01.50/0

At this juncture, the inefficiency of the McMurry coupling caused us to focus attention upon the development of an alternative higher yielding pathway to **5** that was also not as scale restricted. That the application of Ramberg–Bäcklund methodology[11] to bromide **6**[8b] serves this purpose well can be seen from the high overall yield (80%) achieved in its conversion to sulfone **8** via sulfide **7**. When **8** was subsequently exposed to the action of potassium hydroxide and carbon tetrachloride in anhydrous *tert*-butyl alcohol at 50 °C,[12,13] **5** was reproducibly obtained in 53% yield following distillation.

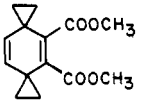
Treatment of **5** with *m*-chloroperbenzoic acid cleanly gave rise to epoxide **9** (86%). Furthermore, allylic alcohol **10** was produced in 81% yield following monodesilylation of **9** with tetra-*n*-butylammonium fluoride in refluxing tetrahydrofuran and chromatography on basic alumina (Scheme II). When all attempts to apply Peterson olefination chemistry[14] to this β-hydroxy silane under acidic or basic conditions[15] proved unsuccessful, **10** was allowed to react instead with thionyl chloride in ether solution. Under these conditions, chlorination proceeded readily with allylic rearrangement to provide the pivotal intermediate **11** (85%) whose trans geometry was apparent from the coupling constant of its olefinic protons (J = 14.8 Hz).

The stage was now set for the vinylogous elimination of chlorotrimethylsilane in **11**. To this end, this chloride was stirred with tetra-*n*-butylammonium fluoride in dry dimethyl sulfoxide solution at ambient temperature for 24 h. The target diene **1** was obtained as a colorless crystalline solid in nearly quantitative yield after extraction into and isolation from pentane. Whereas **1** is prone to polymerize when stored neat, this propensity can be retarded by storage in dilute solution under an inert atmosphere. At −70 °C, the material persists for considerable periods of time. The unique electronic character of **1** is revealed most clearly by its electronic spectrum that features intense absorptions at 247, 238, and 230 nm.

Cycloaddition Behavior. When *N*-methyltriazolinedione was added to **1** in chloroform solution at −60 °C, rapid reaction occurred as judged by the immediate disappearance of the pink color of the dienophile. Surprisingly, however, the yield of isolated urazole **12** was quite low, being only 17% after chromatography on neutral alumina. No other recognizable substance could be isolated.



12

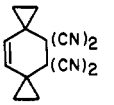


13

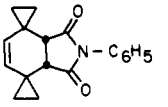
No observable cycloaddition resulted when equimolar amounts of **1** and dimethyl acetylenedicarboxylate in dichloromethane solution were allowed to stand for 21 h at room temperature or overnight at the reflux temperature. In refluxing benzene, a 12% yield of **13** resulted after overnight heating.

Upon admixture of **1** and tetracyanoethylene in degassed carbon tetrachloride solution at room temperature, a bright mauve color was observed. After 2 days, workup provided **14** in 27% yield. No tetracyanocyclobutane derivative was observed.

A notably smooth reaction occurred when equimolar amounts of **1** and *N*-phenylmaleimide were heated overnight in benzene at the reflux temperature. These conditions sufficed to provide **15** in 74% yield after chromatographic purification.



14



15

In each example, the structural assignment to the adduct followed convincingly from ^{1}H (ref 16) and ^{13}C NMR considerations. As expected from the spiro arrangement of the two three-membered rings, the cyclopropyl protons are of at least two types. The structural features of **12–14** are such that they are inherently more symmetric than **15**. The gradations are most apparent in the ^{13}C NMR spectra (see Experimental Section).

Discussion

Schemes I and II outline new protocols by which strained cycloalkane rings may be conjoined via a butadiene unit. The use of desilylation methodology to effect stepwise introduction of the pair of double bonds in **1** has proven to be quite serviceable. Other methods for gaining access to somewhat related 1,3-dienes have been reported. Prinzbach's approach to pentafulvadiene, while novel, is entirely dependent on cyclopentadienide nucleophilicity.[17] Unfortunately, this feature is restricted to the fully unsaturated five-membered ring. More recently, Walborsky and Wüst have developed a titanium-promoted reductive 1,3-elimination scheme applicable to (*E*)- and (*Z*)-2-ene-1,4-diols.[18] Since the latter are readily available from the coupling of cyclanones with acetylene followed by controlled reduction, the process may have considerable generality. However, the requirement of starting with cyclopropanone is obviously prohibitive. Similar restrictions do not apply to aldehyde **4** or bromide **6** as demonstrated herein.

Dicyclopropylideneethane (**1**) gives evidence of being a more reactive diene than 2,5-dimethyl-2,4-hexadiene toward dienophiles. The latter affords no adduct when treated with di-*tert*-butyl acetylenedicarboxylate.[19] More drastic conditions (toluene, reflux, 7 days) serve to induce [4 + 2] cycloaddition with diethyl azodicarboxylate (26% yield).[20] A more quantitative comparison would clearly be of interest and will be carried out when homologous dienes **2** and **3** also become available. A complete mapping of the dynamic conformational behavior of **1** awaits detailed variable-temperature spectral analysis.

Experimental Section

Reductive Coupling of 4. Into a dry argon-blanketed flask fitted with a gas inlet tube and serum cap was placed 18.0 g (117 mmol) of anhydrous titanium trichloride. Dry peroxide-free glyme (100 mL) was introduced via syringe. To this dark, stirred slurry

(11) Paquette, L. A. *Org. React. (N.Y.)* **1977**, *25*, 1.
(12) (a) Meyers, C. Y.; Malte, A. M.; Matthews, W. S. *J. Am. Chem. Soc.* **1969**, *91*, 7510. (b) Meyers, C. Y.; Yo, L. L. *Tetrahedron Lett.* **1972**, 4319.
(13) Koenig, K. E.; Felix, R. A.; Weber, W. P. *J. Org. Chem.* **1974**, *39*, 1539.
(14) Peterson, D. J. *J. Organomet. Chem.* **1972**, *7*, 295.
(15) Colvin, E. W. "Silicon in Organic Synthesis", Butterworths: London, 1981; Chapter 12.
(16) For ^{1}H NMR spectra of related molecules, see ref 6 and Nishida, S.; Moritani, I.; Ito, K.; Sakai, K. *J. Org. Chem.* **1967**, *32*, 939. Tsuji, T.; Nishida, S. *J. Chem. Soc., Chem. Commun.* **1972**, 284.
(17) (a) Sauter, H.; Prinzbach, H. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 296. (b) Sauter, H.; Gallenkamp, B.; Prinzbach, H. *Chem. Ber.* **1977**, *110*, 1382.
(18) Walborsky, H. M.; Wüst, H. H. *J. Am. Chem. Soc.* **1982**, *104*, 5807.
(19) Weber, G.; Menke, K.; Hopf, H. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 483.
(20) Duismann, W.; Rüchardt, C. *Chem. Ber.* **1978**, *111*, 596.

was added 1.6 g (233 mmol) of lithium wire freshly cut into small pieces. The reaction mixture was gently refluxed overnight (ca. 16 h). After being cooled to ambient temperature, a solution of **4**[8b] (1.5 g, 10.5 mmol) in glyme (10 mL) was added via syringe in one portion. The mixture was stirred at room temperature for 2 h, refluxed for 20 h, diluted with 250 mL of pentane, and filtered with suction through a bed of silica gel over Celite. The adsorbants were washed with pentane and ether, and the combined filtrates were concentrated to leave the crude product as a yellow oil. Distillation on a Kugelrohr apparatus at 90 °C and 0.2 torr gave 0.50 g (38%) of **5** as a nearly colorless oil. Further purification for analysis was effected by VPC (6 ft × 0.25 in. SE-30 on Chromosorb G; 150 °C): IR (cm^{-1}, neat) 3060, 2985, 2950, 2890, 1423, 1392, 1243, 1182, 1040, 977, 959, 830, 740, 630; ^1H NMR ($CDCl_3$) δ 5.4 (s, 2 H), 0.55–0.35 (m, 8 H), 0.0 (s, 18 H); ^{13}C NMR ($CDCl_3$) ppm 133.80, 10.08, 9.53, -3.16; MS, m/z calcd (M^+) 252.1729, obsd 252.1735.

Anal. Calcd for $C_{14}H_{28}Si_2$: C, 66.56; H, 11.20. Found: C, 66.75; H, 11.20.

[1-(Trimethylsilyl)cyclopropyl]methyl Sulfide (7). A solution of **6**[8b] (23.2 g, 112 mmol) and sodium sulfide nonahydrate (16.2 g, 67.3 mmol) in 95% ethanol (232 mL) was heated at reflux for 2.75 h, cooled to room temperature, and diluted with ether. The resulting solution was washed with water, dried, and evaporated at reduced pressure. Distillation of the residue provided 12.9 g (81%) of **7**, bp 92 °C at 0.15 torr, as a colorless oil: ^1H NMR ($CDCl_3$) δ 2.50 (s, 4 H), 0.40 (m, 8 H), -0.007 (s, 18 H); ^{13}C NMR ($CDCl_3$) ppm 42.24, 9.43, 5.27, -2.49; MS, m/z 271 ($M^+ - CH_3$, 1.64) 257 (3.77), 213 (3.16), 158 (21.3) 143 (16.9), 99 (19.7), 85 (7.33), 73 (100), 59 (11.1).

[1-(Trimethylsilyl)cyclopropyl]methyl Sulfone (8). A solution of **7** (12.9 g, 45.1 mmol) in chloroform (320 mL) was stirred rapidly with 0.5 M aqueous sodium bicarbonate solution (377 mL) while *m*-chloroperbenzoic acid (28.2 g of 80–85% purity, ca. 163 mmol) was added in small portions over 3 h. Upon completion of the addition, stirring was continued for 19.5 h. The aqueous phase was separated and the chloroform layer was washed twice with 5% sodium hydroxide solution and once with water prior to drying. Solvent removal left a colorless oil which crystallized upon standing in the freezer. There was obtained 14.05 g (98%) of **8** as a colorless solid: mp 58–59 °C (from hexane); IR (cm^{-1}, neat) 1313, 1117; ^1H NMR ($CDCl_3$) δ 2.84 (s, 4 H), 0.65 (s, 8 H), 0.044 (s, 18 H); ^{13}C NMR ($CDCl_3$) ppm 62.40, 10.24, 0.24, -2.29; MS, m/z 303 ($M^+ - CH_3$, 1.63), 249 (6.61), 210 (1.21), 177 (5.28), 147 (7.91), 127 (16.5), 99 (33.9), 73 (100).

Anal. Calcd for $C_{14}H_{30}O_2SSi_2$: C, 52.77; H, 9.49. Found: C, 52.85; H, 9.35.

***trans*-1,2-Bis[1-(trimethylsilyl)cyclopropyl]ethylene (5). Ramberg–Bäcklund Rearrangement of 8.** Sulfone **8** (7.0 g, 22.1 mmol), powdered potassium hydroxide (62 g, 1.11 mol), anhydrous *tert*-butyl alcohol (308 mL), and carbon tetrachloride (728 mL) were combined and heated at 50 °C with stirring for 17 h. After being cooled to room temperature, the reaction mixture was washed with water and brine, dried, and evaporated at reduced pressure. The residue was combined with that obtained from a preparation involving 6.5 g (20.4 mmol) of **8** and the lot was vacuum distilled to provide 5.69 g (53%) of **5**, bp 75 °C (0.8 torr). This material was identical with that prepared earlier.

***trans*-1,2-Bis[1-(trimethylsilyl)cyclopropyl]ethylene Oxide (9).** Expoxidation of **5** (1.0 g, 3.97 mmol) was effected with *m*-chloroperbenzoic acid (910 mg of 80–85% purity, ca. 4.22 mmol) in dichloromethane (40 mL) and 0.5 M aqueous sodium bicarbonate solution (5 mL). After 2 h, the usual workup was applied and the residual oil was chromatographed on basic alumina (elution with pentane). There was isolated a 64% yield of **9** as a colorless oil: IR (cm^{-1}, neat) 2970, 2890, 1800, 1776, 1425, 1321, 1250, 1210, 1051, 989, 875, 825, 740, 680, 600; ^1H NMR ($CDCl_3$) δ 2.70 (s, 2 H), 0.65–0.30 (m, 8 H), 0.05 (s, 18 H); ^{13}C NMR ($CDCl_3$) ppm 59.50, 6.20, 4.72, -2.73; MS, m/z calcd (M^+) 268.1679, obsd 268.1687.

1-[1-(Trimethylsilyl)cyclopropyl]-2-cyclopropylideneethanol (10). Into a solution of anhydrous tetra-*n*-butylammonium fluoride (1.5 g, 5.6 mmol) in dry tetrahydrofuran (20 mL) was syringed a solution of **9** (0.60 g, 2.2 mmol) in 5 mL of the same solvent. After being refluxed overnight (12 h), the reaction mixture was poured into a separatory funnel containing water (10 mL) and ether (50 mL). The organic phase was washed with water and brine before being dried, filtered, and concentrated. The crude light yellow oil was chromatographed on basic alumina (elution with 20% ether in hexene) to give 0.29 g (65%) of **10** as a colorless oil: IR (cm^{-1}, neat) 3300, 3060, 2980, 2950, 1420, 1285, 1250, 1200, 1010, 950, 830, 735, 675; ^{1h} NMR ($CDCl_3$) δ 5.80 (m, 1 H), 0.45 (m, 4 H), 3.85 (d, J = 7 Hz, 1 H), 1.70 (s, 1 H), 1.05 (m, 4 H), 0.45 (m, 4 H), 0.0 (s, 9 H); ^{13}C NMR ($CDCl_3$) ppm 122.59, 120.51, 79.18, 7.83, 5.75, 2.15, 1.38, -1.68; MS, m/z calcd (M^+) 196.1283, obsd 196.1267.

***trans*-1-(1-Chlorocyclopropyl)-2-[1-(trimethylsilyl)-cyclopropyl]ethylene (11). Procedure A.** A cold (0 °C) solution of **10** (0.53 g, 1.7 mmol) in carbon tetrachloride (25 mL) was treated with freshly distilled thionyl chloride (0.42 g, 3.5 mmol) via syringe. The reaction mixture was stirred while being allowed to warm slowly to ambient temperature over 2 h. Concentration at 30 torr gave a clear yellow oil which was chromatographed on basic alumina (elution with hexane) to afford 0.46 g (80%) of **11** as a colorless oil. Further purification for analysis was accomplished by VPC (6 ft × 0.25 in. SE-30 on Chromosorb G, 115 °C); ^1H NMR ($CDCl_3$) δ 5.83 (d, J = 14.8 Hz, 1 H), 5.30 (d, J = 14.8 Hz, 1 H), 1.30 (m, 2 H), 1.05 (m, 2 H), 0.65 (m, 4 H), 0.10 (s, 9 H); ^{13}C NMR ($CDCl_3$) ppm 135.08, 130.98, 42.06, 17.40, 9.85 (2C), -3.21; MS, m/z calcd (M^+) 214.0945, obsd 214.0950.

Anal. Calcd for $C_{11}H_{19}ClSi$: C, 61.49; H, 8.93. Found: C, 61.76; H, 8.96.

Procedure B. To a cold (0 °C) solution of purified thionyl chloride (0.99 g, 8.35 mmol) in anhydrous diethyl ether (10 mL) was added **10** (1.62 g, 8.27 mmol) dissolved in ether (2 mL) in one portion. After the solution was stirred at ice temperature for 30 min, the ether was removed in vacuo. Kugelrohr distillation of the residue (75 °C and 0.08 torr) provided 1.50 g (85%) of **11** identical in all respects with the material isolated above.

Dicyclopropylideneethane (1). To a solution of anhydrous tetra-*n*-butylammonium fluoride (0.64 g, 2.4 mmol) in dry dimethyl sulfoxide (3 mL) was syringed a solution of **11** (0.21 g, 0.98 mmol) in 2 mL of the same solvent. The reaction mixture was stirred at room temperature under an argon atmosphere for 24 h. Water (10 mL) was added and the product was extracted into pentane (3 × 10 mL). The combined pentane extracts were washed with water and brine before being dried, filtered, and concentrated by distillation at atmospheric pressure. The last few milliliters of pentane were removed by sweeping the recovery flask with dry argon or nitrogen to provide 94 mg (90%) of **1** as a white, powdery solid which was stored under argon at -78 °C; IR (Cm^{-1}, KBr) 3030, 2925, 2850, 1780, 1490, 1450; ^1H NMR ($CDCl_3$) δ 6.45 (m, 2 H), 1.25 (m, 8 H); ^{13}C NMR ($CDCl_3$) ppm 124.66, 118.21, 2.58, 2.20; MS, m/z calcd (M^+) 106.0782, obsd 106.0787; UV (λ_{max} nm, cyclohexane) 247, 238, 230.

These spectral properties coincide with a somewhat more limited data set reported earlier.[7]

Diels–Alder Reactions of 1. A. With *N*-Methyltriazolinedione. To a cold (-60 °C) solution of **1** (85 mg, 0.80 mmol) in $CDCl_3$ (2 mL, deoxygenated with a stream of argon) was added dropwise under argon via syringe a solution of *N*-methyltriazolinedione (90.4 mg, 0.80 mmol) in the same solvent (4 mL). The pink color of the dienophile was instantly discharged. The reaction mixture was allowed to warm slowly (ca. 2 h) to room temperature and freed of solvent under reduced pressure. The resulting crystalline solid was chromatographed on neutral alumina (chloroform elution) to give 30 mg (17%) of **12**. Recrystallization from hexane afforded colorless irregular prisms: mp 106–106.5 °C; ^1H NMR ($CDCl_3$) δ 5.21 (s, 2 H), 2.98 (s, 3 H), 2.05 (dd, J = 7.9 and 6.5 Hz, 4 H), 0.93 (dd, J = 7.9 and 6.5 Hz, 4 H); ^{13}C NMR ($CDCl_3$) ppm 211.46, 128.24, 40.76, 24.68, 12.29; MS, m/z (M^+, 79.8) 204 (16.9) 192 (100), 161 (13.9), 147 (36.9) 135 (39.1) 119 (11.0), 106 (27.0), 91 (32.2), 79 (34.8), 65 (19.0).

Anal. Calcd for $C_{11}H_{13}N_3O_2$: C, 60.26; H, 5.98. Found: C, 60.26; H, 6.17.

B. With Dimethyl Acetylenedicarboxylate. A solution of **1** (105 mg, 0.99 mmol) and dimethyl acetylenedicarboxylate (141 mg, 0.99 mmol) in benzene (4 mL, distilled from calcium hydride) was stirred at the reflux temperature under an argon atmosphere overnight. The reaction mixture was cooled to room temperature and evaporated under reduced pressure to leave a viscous yellow oil. This material was passed down a short column of neutral

alumina (chloroform elution) to give 30 mg (12%) of **13** as a colorless crystalline solid: mg 92.5–93 °C (from hexane); ^{1}H NMR ($CDCl_3$) δ 4.84 (s, 2 H), 3.66 (s, 6 H), 1.39 (dd, J = 7.3 and 4.9 Hz, 4 H), 0.77 (dd, J = 7.3 and 4.9 Hz, 4 H); ^{13}C NMR ($CDCl_3$) ppm 166.80, 136.97, 129.94, 51.88, 21.15, 17.83; MS, m/z 248 (M^+, 16.6) 233 (100), 201 (95.7) 185 (55.9), 184 (45.1) 157 (39.9), 156 (29.0), 130 (49.8), 128 (52.1) 115 (36.4), 102 (22.7), 91 (15.4), 77 (23.5).

Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.50. Found: C, 67.87; H, 6.63.

C. With Tetracyanoethylene. A solution of **1** (105 mg, 0.99 mmol) in carbon tetrachloride (2 mL) was added under argon to a solution of freshly sublimed tetracyanoethylene (127 mg, 0.99 mmol) in the same solvent (2 mL) at room temperature. Initially, a bright mauve color was observed. After being stirred for 2 days, the reaction mixture was filtered through a bed of Celite, which was rinsed with carbon tetrachloride. Evaporation of the filtrate provided 63 mg (27%) of **14** as a white crystalline solid. Following recrystallization from chloroform and sublimation (90 °C and 0.05 torr), the adduct exhibited a decomposition point of 182 °C: ^{1}H NMR ($CDCl_3$) δ 5.30 (s, 2 H), 1.62 (m, 4 H), 1.25 (m, 4 H); ^{13}C NMR ($CDCl_3$) ppm 128.17, 109.88, 46.55, 22.70, 14.14; MS, m/z 234 (M^+, 63.3), 219 (30.1), 206 (69.9), 192 (100), 181 (35.7), 179 (47.9), 167 (99.5).

Anal. Calcd for $C_{14}H_{10}N_4$: C, 71.78; H, 4.30. Found: C, 71.52; H, 4.47.

D. With *N*-Phenylmaleimide. A solution of **1** (94.1 mg 0.89 mmol) and *N*-phenylmaleimide (154 mg, 0.89 mmol) in benzene (3.5 mL) was deoxygenated by bubbling argon through and heated at reflux under an argon atmosphere overnight. The solvent was evaporated under reduced pressure and the pale yellow crystalline residue (246 mg) was purified by MPLC on silica gel (elution with 21% ethyl acetate in petroleum ether). There was isolated 185 mg (74%) of **15** as fine white needles which were sublimed at 102 °C and 0.05 torr: mp 102–104 °C; ^{1}H NMr ($CDCl_3$) δ 7.50–7.23 (m, 5 H), 5.32 (s, 2 H), 2.81 (s, 2 H), 1.40 (m, 2 H), 0.88 (m, 4 H), 0.67 (m, 2 H); ^{13}C NMR ($CDCl_3$) ppm 176.69, 133.45, 129.05, 128.39, 126.48, 48.40, 17.54, 14.69, 12.45; MS, m/z 279 (M^+, 44.7) 132 (100), 117 (59.7).

Anal. Calcd for $C_{18}H_{17}NO_2$: C, 77.40; H, 6.13. Found: C, 77.37; H, 6.26.

Acknowledgment. This research has been supported in large part by a grant from the National Science Foundation.

Registry No. **1**, 36336-98-8; **4**, 81236-83-1; **5**, 91606-47-2; **6**, 91606-48-3; **7**, 91606-49-4; **8**, 91606-50-7; **9**, 91606-51-8; **10**, 91606-52-9; **11**, 91606-53-0; **12**, 91606-54-1; **13**, 91606-55-2; **14**, 91606-56-3; **15**, 91606-57-4; *N*-methyltriazolinedione, 13274-43-6; dimethyl acetylenedicarboxylate, 762-42-5; tetracyanoethylene, 670-54-2; *N*-phenylmaleimide, 941-69-5.

Synthesis and Absolute Configuration of the Bacterial *cis*-1,2-, *cis*-8,9-, and *cis*-10,11-Dihydrodiol Metabolites of Benz[*a*]anthracene Formed by a Strain of *Beijerinckia*

D. M. Jerina,*[1a] P. J. van Bladeren,[1a] H. Yagi,[1a] D. T. Gibson,[1b] V. Mahadevan,[1b] A. S. Neese,[1c] M. Koreeda,[1c] N. D. Sharma,[1d] and D. R. Boyd[1d]

Laboratory of Bioorganic Chemistry, NIADDK, The National Institutes of Health, Bethesda, Maryland 20205, Center for Applied Microbiology and Department of Microbiology, The University of Texas at Austin, Austin, Texas 78712, Department of Chemistry, The Johns Hopkins University, Baltimore, Maryland 21218, and Department of Chemistry, The Queen's University of Belfast, Belfast BT95AG, Northern Ireland

Received January 10, 1984

Metabolism of the environmental contaminant benz[*a*]anthracene has been examined with the bacterium *Beijerinckia* B8/36. This organism is a mutant strain of the wild type, which lacks the ability to oxidize further initially formed *cis*-dihydrodiol metabolites of aromatic hydrocarbons. The main isolated metabolites of benz[*a*]anthracene consist of the *cis*-1,2-, *cis*-8,9-, and *cis*-10,11-dihydrodiols in a ratio of 73:15:12, respectively. Synthesis of the dihydrodiols in optically pure form from precursors whose configurations were previously known or have been assigned in the present study has established that the metabolites are of very high enantiomeric purity and have 1*R*,2*S*, 8*R*,9*S*, and 10*S*,11*R* absolute configurations. In the course of these assignments, the (+)-isomer of 1,2-epoxy-1,2,3,4-tetrahydrobenz[*a*]anthracene has been established to have 1*R*,2*S* absolute configuration, and a prior assignment of (−)-*trans*-(1*R*,2*R*)-1,2-dihydroxy-1,2-dihydrobenz[*a*]anthracene has been confirmed. The chemical interrelationships of absolute configuration have been done in such a manner that the *cis*-1,2-, *cis*-8,9-, and *cis*-10,11-dihydrodiols formed by the bacterium are tied directly to structures which have been used to assign the corresponding *trans*-1,2-, *trans*-8,9-, and *trans*-10,11-dihydrodiols formed from benz[*a*]anthracene in mammalian liver.

Introduction

Polycyclic aromatic hydrocarbons such as benz[*a*]anthracene represent a widespread class of environmental contaminants. Their identification in soils and ancient marine sediments[2] has led to the suggestion that they have been present in the environment during geological periods of time.[3] It is therefore not surprising that microbial flora have developed enzyme systems capable of their metabolism. Sisler and Zobell,[4] for example, have reported the release of carbon dioxide during the oxidation of benz[*a*]anthracene. Although conventional enrichment culture techniques in mineral salts media failed to identify organisms capable of growth on polycyclic aromatic hydrocarbons, a *Beijerinckia* species was isolated based on its

(1) (a) Authors at NIH. (b) Authors at University of Texas. (c) Authors at Johns Hopkins University. (d) Authors at Queen's University of Belfast. The present address for M. K. is Department of Chemistry, University of Michigan, Ann Arbor, MI 48109.

(2) Blumer, M. *Science (Washington, D.C.)* **1961**, *134*, 474–475. Kern, W. *Helv. Chim. Acta* **1947**, *30*, 1595–1599.

(3) Blumer, M.; Youngblood, W. W. *Science (Washington, D.C.)* **1975**, *188*, 53–55. Giger, W.; Blumer, M. *Anal. Chem.* **1974**, *46*, 1663–1667.

(4) Sisler, F. D.; Zobell, C. E. *Science (Washington, D.C.)* **1947**, *106*, 521–522.

0022-3263/84/1949-3621$01.50/0