Photocycloaddition of Methylcyclobutene and (-)-Piperitone: Synthesis of (-)-Shyobunone and Related Sesquiterpenes[1]

John R. Williams* and James F. Callahan

Department of Chemistry, Temple University, Philadelphia, Pennsylvania 19122

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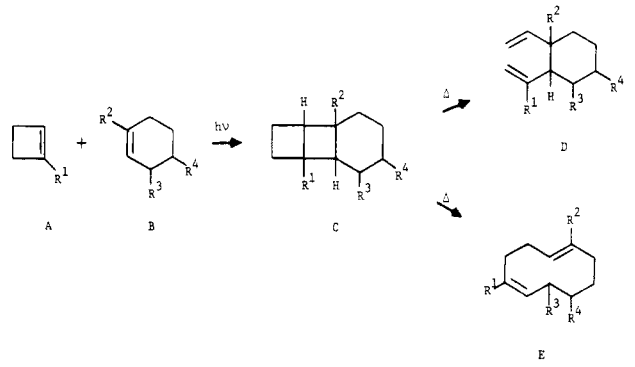
Photocycloaddition of methylcyclobutene to (-)-piperitone affords the photoadduct **3a**. Flash vacuum pyrolysis of the photoadduct **3a** affords (-)-shyobunone (**4a**), 2-epi-(-)-shyobunone (**5a**), 3-epi-(-)-shyobunone (**6a**), 2,3-diepi-(-)-shyobunone (**7a**), and (*R*)-(+)-isoacoragermacrone (**8a**) in 5, 9, 13, 2, and 19% yields, respectively. Reduction of **3a** followed by thermolysis (190 °C, 1 h) and oxidation yields (-)-shyobunone (**4a**), 2-epi-(-)-shyobunone (**5a**), and 3-epi-(-)-shyobunone (**6a**). The aldehyde **13** also obtained from the thermolysis, when treated with $SnCl_4$ and oxidized, yields (-)-shyobunone (**4a**). Thermolysis of the photoadduct **3a** (250 °C, 30 min) affords the cadinane **10a** via isoacoragermacrone **8a**. The ^{13}C NMR data on the cadinanes **10a,b**, **11a**, and **12** are discussed.

Sesquiterpenes as a class of natural products[2] have been extensively studied due to the fact that many of them possess a broad-base activity as pheromones,[3a-d] antitumor agents,[3e] and antibiotics.[3f] Since many of these sesquiterpenes are thought to be derived biogenetically from germacranes,[4a,b] an efficient means of synthesizing germacranes should yield potentially many other sesquiterpenes such as elemanes and cadinanes.

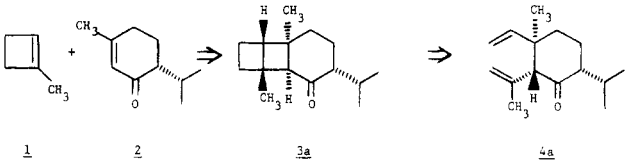
Our previous experience in the use of the $[2_\pi + 2_\pi]$ photocycloaddition of cyclobutenes A[5] suggested a potential synthesis of elemane and germacrane sesquiterpenes (see Scheme I). Since many monoterpenes are readily available in optically active form, they are ideal chiral templates for the stereospecific synthesis of optically active sesquiterpenes. The photochemical $[2_\pi + 2_\pi]$ cycloaddition of such a terpene, B, preferably containing an enone to facilitate the photocycloaddition to a cyclobutene, A, should lead to a highly strained tricyclo[4.4.0.$0^{2,5}$]decane, C. Thermolysis of the photoadduct C would be expected to give a 1,2-divinylcyclohexane, D, and/or a cyclodecadiene E, depending on the reaction conditions (see Scheme I). Therefore, if the photocycloaddition is both regio- and stereospecific, a single optically active photoadduct may be prepared which upon thermolysis should afford optically active products.

To test this hypothesis, the stereospecific synthesis of (-)-shyobunone (**4a**) was planned as shown in Scheme II with the knowledge that thermolysis of tricyclo[4.4.0.$0^{2,5}$]decane systems afforded both *cis*- and *trans*-1,2-divinylcyclohexanes.[5] Since we initiated our studies, other groups have reported various reactions on similar systems.[6a-g]

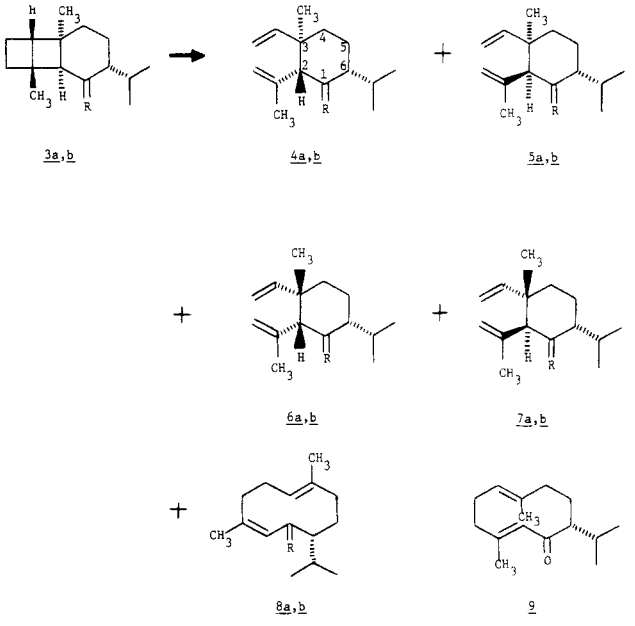
Scheme I



Scheme II



Scheme III[a]



[a] a, R = O; b, R = α-H, β-OH.

Photocycloaddition of (-)-piperitone (**2**) to the isoprene synthon methylcyclobutene (**1**) at low temperatures gave

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one product, the tricyclo[4.4.0.0^{2,5}]decanone **3a**, in an excellent isolated yield (71%). The low temperature both afforded the control of any thermal reaction of the methylcyclobutene and limited the number of isomers formed in the cycloaddition. The structure of **3a** was determined in a number of ways. The head-to-head nature of the adduct was confirmed in the proton NMR which showed H-1 as a singlet at δ 2.76. Reduction of the photoadduct **3a** using $NaBH_4$ gave the alcohol **3b** as the only isolated product. The relative stereochemistry of the crystalline, racemic alcohol **3b** was determined by X-ray crystallography.[8] Since the absolute stereochemistry of (−)-piperitone (**2**) is known,[9] **3a** depicts the absolute stereochemistry of the photoadduct. The positive Cotton effect exhibited by the photoadduct **3a** also confirmed its absolute stereochemistry.

Flash vacuum pyrolysis of the photoadduct **3a** at 500 °C afforded a mixture of four elemanes (29%) and a *trans*-1(10)-*cis*-4-germacrane (19%), which were separated by silica gel chromatography (see Scheme III). The structures of the elemane isomers were determined by spectral data and confirmed by comparison with the data on known compounds.[10,11] Their absolute stereochemistry was confirmed by comparison of the circular dichroism spectra of the elemanes to the optical rotatory dispersion data of the naturally occurring compounds.[10,11] The ratio of the elemanes identified as (−)-shyobunone (**4a**), 2-epi-(−)-shyobunone (**5a**), 3-epi-(−)-shyobunone (**6a**), and 2,3-diepi-(−)-shyobunone (**7a**) was 17:30:47:6.

The germacrane isolated was assigned the structure (*R*)-(+)-isoacoragermacrone (**8a**) since it was identical with (±)-isoacoragermacrone previously prepared by Still.[12] The absolute stereochemistry was derived from the known absolute stereochemistry of **3a**. (±)-Isoacoragermacrone has been isomerized via organotin addition followed by an oxidation sequence to yield (±)-acoragermacrone (**9**).[12] Since the chiral carbon should not be affected during the olefin isomerization, the above sequence constitutes a formal four-step stereospecific synthesis of optically active (*R*)-acoragermacrone (**9**). Furthermore, isoacoragermacrone undergoes acid-catalyzed stereospecific cyclizations to give cadinane- and guaiane-type sesquiterpenes.[13]

Thermolysis of the photoadduct **3a** in a sealed tube at 250 °C for 30 min yielded the *trans*-decalin **10a**, and no elemane or isoacoragermacrone was isolated. To explain the formation of this unexpected product, it was reasonable to assume that thermolysis of **3a** did yield a *trans*-1(10)-*cis*-4-germacrone intermediate, **8a**.[5,6] However, since the reaction was carried out at high temperatures, none of the germacrone **8a** survived but underwent an intramolecular ene reaction to give the observed product, **10a**. This was proven by converting **8a** into **10a** under these reaction conditions. This transannular intramolecular reaction has precedent in similar systems.[13,14]

Scheme IV

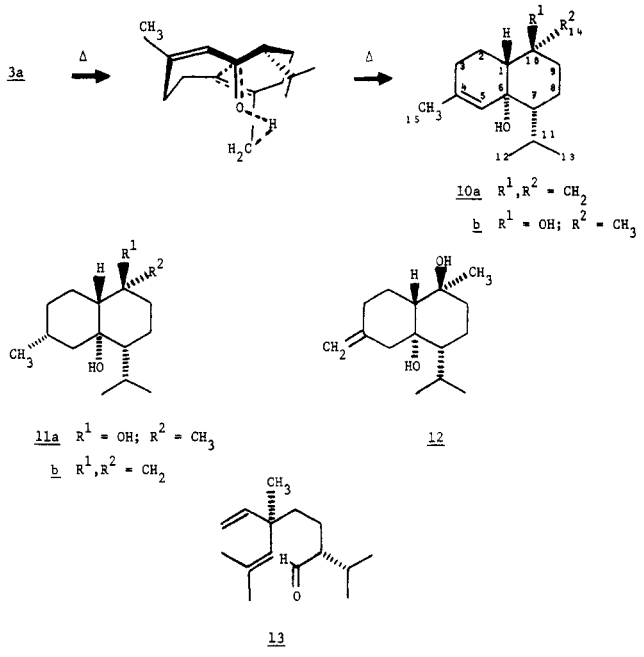

Table I. ^{13}C NMR Spectral Data of Cadinanes

	compd			
carbon	10a	10b	11a	12
1	48.9	52.9	55.1	54.1
2	20.3	17.6	15.6	22.9
3	30.5	31.4	31.7	34.7
4	138.4	138.3	27.1	146.0
5	124.1	126.3	42.8	46.9
6	72.2	72.2	75.7	74.9
7	50.2	50.0	52.6	51.4
8	22.8	19.6	18.8	19.4
9	35.9	42.9	43.1	43.1
10	149.6	72.5	72.4	72.5
11	25.5	25.2	24.8	25.3
12	23.4[a]	22.9[a]	23.1[a]	23.1[a]
13	18.0[a]	18.7[a]	18.4[a]	18.4[a]
14	107.3	24.1	24.1	24.0
15	23.7	23.7	21.1	111.4

[a] Interchangable.

In order to confirm the structure of **10a**, we related it to the known cadinane **11b** which can be derived from (+)-isocalamendiol (**12**).[15] Treatment of **10a** (Scheme IV) with 1 equiv of $Hg(OAc)_2$ followed by basic $NaBH_4$[16] gave the ene diol **10b**. This was then reduced by using PtO_2/EtOAc to give the diol **11a**. This diol was then converted via dehydration with $POCl_3$[15b] to **11b**, confirming the relative stereochemistry of the intermediates except at C-10. The stereochemistry of C-10 was confirmed by comparing the ^{13}C NMR spectra of (+)-isocalamendiol (**12**) to those of **10b** and **11a**[17] (see Table I). Hydration of the C-10(14) olefin in **10a** shifts the C-10 carbon to higher field as expected in **10b**, **11a**, and **12**. Similarly, C-1 and C-9 in **10b**, **11a**, and **12** are deshielded relative to **10a**.

(7) (−)-Piperitone used had a 14% ee ($[\alpha]_D$ −6.9° (*c* 0.313 g/mL)) except in the case of the flash vacuum pyrolysis where the (−)-piperitone used to synthesize **3a** had a 61% ee ($[\alpha]_D$ −30.5° (*c* 0.339 g/mL)).

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Since the sealed-tube thermolysis of the keto photoadduct **3a** did not yield the desired elemane product, the reduced photoadduct **3b** was thermalized in order to avoid the intramolecular ene reaction. Heating of **3b** in a sealed tube at 190 °C for 1 h followed by rapid cooling yielded two major structural isomers as well as a trace of a third (see Scheme III). The proton NMR showed one set of isomers to be the elemane alcohols **4b**, **5b**, and **6b**. These were isolated in 48% yield in the ratio 21:26:54. In order to identify these isomers, we oxidized them to the ketones (−)-shyobunone (**4a**), 2-epi-(−)-shyobunone (**5a**), and 3-epi-(−)-shyobunone (**6a**), respectively. The mixture was then separated first by using 15% silver nitrate impregnated silica gel[18] and then by using normal silica gel chromatography, and the products were identified by their spectral data.[10,11]

The second product of the thermolysis was found to be the aldehyde **13** which was isolated in 43% yield. The aldehyde **13** was converted to the elemane alcohol **4b** by using $SnCl_4$[19] via an acid-catalyzed ene reaction. Its absolute stereochemistry was confirmed by converting the alcohol **4b** to the ketone **4a**. This established the absolute stereochemistry of the aldehyde **13**.[10] The aldehyde **13** is formed via a thermal ene reaction of the elemane alcohols at the elevated temperature of this reaction. This reaction sequence is useful since it affords increased yields of the *trans*-1,2-divinylcyclohexane systems.

The third isomer from the thermolysis afforded spectral data consistent with the germacrane alcohol **8b**, but not enough of the material could be isolated to confirm this structure.

As can be seen, thermolysis of the highly strained photoadduct **3** affords a variety of products, depending upon the reaction conditions. In those cases where a number of products are formed, the reaction probably proceeds via a radical process whereas **8a** is formed via a concerted cycloreversion process or orbital overlap controlled fragmentation of a 2,5-diradical intermediate.[20]

In conclusion it can be seen that an optically active monoterpene can undergo photocycloaddition regio- and stereospecifically to afford one product which may be further converted into other optically active systems. If the temperature of the photocycloaddition is increased, then traces of other photoadducts start to be observed.

Experimental Section

Melting points were determined with a Thomas-Hoover apparatus and are uncorrected. IR spectra were taken with a Perkin-Elmer 137 Infracord spectrophotometer. ^{13}C NMR spectra were recorded at 25.16 MHz on a Varian XL-100 spectrometer fitted with a Nicolet 1180 pulse system, and ^1H NMR spectra were recorded at 90 MHz on a Perkin-Elmer R32 spectrometer. Chemical shifts are reported in δ units from the internal standard Me_4Si in chloroform-*d*. Optical rotations were measured at the sodium D line on a Perkin-Elmer 241 polarimeter using a 1-dm cell with chloroform as the solvent. Circular dichroism spectra were measured on a JASCO J-41A spectropolarimeter using methanol as the solvent. High-resolution mass spectra were taken with a Hitachi Perkin-Elmer RMH-2. TLC was carried out on silica gel GF plates, and column chromatography was performed by using Woelm silica gel.

2,6-Dimethyl-9-(1-methylethyl)tricyclo[4.4.0.0^{2,5}]decan-10-one (3a). Methylcyclobutene used in the photolysis was synthesized by the catalytic isomerization of commercially available methylenecyclobutane using the method of Shabtai et al.[21] This resulted in a mixture of endocyclic–exocyclic isomers which contained 75–80% methylcyclobutene, and this mixture was used in all photolysis reactions.

A typical photolysis reaction follows. (−)-Piperitone [**2**; 1.50 g (9.85 mmol), $[\alpha]_D$ −6.9° (*c* = 0.313 g/mL), 14% ee] was added to CH_2Cl_2 (3.0 mL) in a quartz test tube. Then 0.895 g (13.1 mmol) of the mixture of methylcyclobutene–methylenecyclobutane from above was added, and the tube was sealed under Ar. It was then photolyzed at −78 °C (2-propanol–dry ice bath) by using a 450-W Hanovia medium-pressure mercury lamp in a quartz immersion well until all the methylcyclobutene was exhausted (proton NMR). Then 0.300 g (4.40 mmol) of the methylcyclobutene–methylenecyclobutane mixture was added, and the reaction was continued until all the (−)-piperitone was exhausted. The solvent was then evaporated under reduced pressure, and the crude product was separated on a 200-g silica gel column eluted with 2% ether–hexane to give 1.54 g (71%) of isolated product **3a**: IR (neat) 1688 cm^{-1}; NMR δ 2.76 (s, 1 H), 1.16 (s, 3 H), 1.10 (s, 3 H), 0.95 (d, 3 H, *J* = 7.6 Hz), 0.80 (d, 3 H, *J* = 7.6 Hz); CD $[\Theta]_{311}$ +5660.

Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.74; H, 10.89.

2,6-Dimethyl-9-(1-methylethyl)tricyclo[4.4.0.0^{2,5}]decan-10-ol (3b). The photoadduct **3a** (0.100 g, 0.454 mmol) was added to dry methanol (5 mL), and to this was added $NaBH_4$ (0.069 g, 1.82 mmol). The solution was then stirred at room temperature for 16 h, after which time the excess $NaBH_4$ was destroyed with water, and the mixture was extracted several times with ether. The combined ether fractions were then evaporated. Silica gel chromatography resulted in 0.071 g (70%) of pure **3b**: mp 72–72.5 °C (racemic **3b**); IR (KBr) 3313 cm^{-1}; NMR δ 3.71 (dd, 1 H, *J* = 8, 12 Hz), 2.77 (d, 1 H, *J* = 8 Hz), 1.38 (s, 3 H), 1.01 (s, 3 H), 0.97 (d, 3 H, *J* = 8 Hz), 0.78 (d, 3 H, *J* = 8 Hz).

Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.79. Found: C, 81.28; H, 11.80.

Flash Vacuum Pyrolysis of 2,6-Dimethyl-9-(1-methylethyl)tricyclo[4.4.0.0^{2,5}]decan-10-one (3a). Photoadduct **3a** (2.292 g, 10.4 mmol; 61% ee)[7] in pentane (6 mL) was passed over hot quartz chips at 500 °C under vacuum. Silica gel chromatography yielded 0.436 g (19%) of (*R*)-(+)-isoacoragermacrone (**8a**) and a mixture of (−)-shyobunone (**4a**), 2-epi-(−)-shyobunone (**5a**), 3-epi-(−)-shyobunone (**6a**), and 2,3-diepi-(−)-shyobunone (**7a**) (0.657 g, 29%, ratio of 17:30:47:6) as well as 0.616 g of recovered starting material **3a**.

Repeated chromatography using silica gel and 15% $AgNO_3$ impregnated silica gel[18] resulted in the isolation of pure compounds.

(*R*)-(+)-Isoacoragermacrone (**8a**): IR (neat) 1682, 1635 cm^{-1}; ^1H NMR δ 6.06 (s, 1 H), 5.03 (t, 1 H, *J* = 8 Hz), 1.80 (s, 3 H), 1.48 (s, 3 H), 0.94 (d, 6 H, *J* = 7 Hz); $[\alpha]_D$ +93.6 (*c* 0.024 g/mL, CH_3OH); ^{13}C NMR δ 206.0 (s), 144.7 (s), 138.1 (s), 130.5 (d), 124.3 (d), 58.3 (d), 40.5 (t), 31.1 (d), 29.4 (t), 27.7 (t), 24.3 (t), 24.0 (q), 20.6 (q), 20.2 (q), 14.6 (q).

(−)-Shyobunone (**4a**): IR (neat) 1712, 1641 cm^{-1}; NMR δ 5.68–6.05 (dd, 1 H, *J* = 10, 16 Hz), 4.65–5.15 (m, 4 H), 3.03 (s, 1 H), 1.78 (s, 3 H), 1.08 (s, 3 H), 0.94 (d, 3 H, *J* = 7 Hz), 0.91 (d, 3 H, *J* = 7 Hz); CD $[\Theta]_{297}$ −5340.

2-Epi-(−)-shyobunone (**5a**): IR (neat) 1702, 1641 cm^{-1}; NMR δ 6.20–5.82 (dd, 1 H, *J* = 10, 17 Hz), 5.32–4.80 (m, 4 H), 2.96 (s, 1 H), 1.73 (s, 3 H), 1.12 (s, 3 H), 0.95 (d, 3 H, *J* = 6 Hz), 0.87 (d, 3 H, *J* = 6 Hz); CD $[\Theta]_{299}$ +2500.

3-Epi-(−)-shyobunone (**6a**): IR (neat) 1708, 1646 cm^{-1}; NMR δ 6.18–5.80 (dd, 1 H, *J* = 10, 18 Hz), 5.24–4.67 (m, 4 H), 2.98 (s, 1 H), 1.75 (s, 3 H), 1.17 (s, 3 H), 0.94 (d, 3 H, *J* = 6 Hz), 0.88 (d, 3 H, *J* = 6 Hz); CD $[\Theta]_{297.5}$ −5780.

2,3-Diepi-(−)-shyobunone (**7a**): NMR δ 5.90–5.55 (dd, 1 H, *J* = 8, 18 Hz), 5.25–4.70 (m, 4 H), 3.13 (s, 1 H), 1.81 (s, 3 H), 1.12 (s, 3 H), 0.93 (d, 3 H, *J* = 6.4 Hz), 0.88 (d, 3 H, *J* = 6.4 Hz); CD $[\Theta]_{305}$ +551.

Thermolysis of 2,6-Dimethyl-9-(1-methylethyl)tricyclo-[4.4.0.0^{2,5}]decan-10-one (3a). All thermolyses were done in a sealed tube at 250 °C in xylene. A typical thermolysis follows.

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Photoadduct **3a** (0.090 g, 0.408 mmol) was added to xylene (0.7 mL, 0.58 M) and sealed in a tube under argon. This tube was then placed in an oven (encased in a metal-sand bath) for 0.5 h. The crude material from nine of these reactions was combined and separated via silica gel chromatography to give **10a** as the only identifiable product in 40% yield: IR (neat) 3500, 1639 cm^{-1}; NMR δ 5.86 (s, 1 H), 4.87 (s, 1 H), 4.61 (s, 1 H), 1.70 (s, 3 H), 0.94 (d, 6 H, J = 7.8 Hz); mass spectrum, calcd for $C_{15}H_{24}O$ m/e 220.1827, found m/e 220.1830.

1,6-Dimethyl-4-(1-methylethyl)-1,2,3,4,7,8-hexahydro-1,4a-naphthalenediol (10b). Mercuric acetate (0.453 g, 1.42 mmol) was added to a flask along with H_2O (3.0 mL) and THF (3.0 mL) to give a yellow solution. Addition of **10a** (0.314 g, 1.42 mmol) caused the yellow color to disappear, and the solution was stirred for 15 min. Then 3 M NaOH (2.2 mL, aqueous) and 0.5 M $NaBH_4$ in 3 M NaOH (1.42 mL, aqueous) were added, and the resulting mercury was allowed to settle. Extraction of the decanted solution with water and ether gave 0.316 g of the ene diol **10b**. This could be used in the next reaction without further purification: IR (neat) 3424, 1661 cm^{-1}; NMR δ 5.84 (s, 1 H), 1.69 (s, 3 H), 1.24 (s, 3 H), 0.97 (d, 6 H, J = 8 Hz); mass spectrum, calcd for $C_{15}H_{26}O_2$ m/e 238.1932, found m/e 238.1930.

1,6-Dimethyl-4-(1-methylethyl)octahydro-1,4a-naphthalenediol (11a). The crude product (0.316 g) from above was added to ethyl acetate (31 mL) with PtO_2 (0.043 g, 0.189 mmol). This solution was hydrogenated at room temperature and 1 atm pressure for 16 h. The crude product after filtration and evaporation was purified by column chromatography to give 0.076 g of **11a** (24% yield from **10a**): mp 67–68 °C; IR (KBr) 3366 cm^{-1}; NMR δ 1.23 (s, 3 H), 1.14 (d, 3 H, J = 6.6 Hz), 0.94 (d, 3 H, J = 7 Hz), 0.88 (d, 3 H, J = 7 Hz).

Anal. Calcd for $C_{15}H_{28}O_2$: C, 74.95; H, 11.74. Found: C, 74.68; H, 11.57.

1-Methylene-4-(1-methylethyl)-6-methyloctahydro-4a-naphthalenol (11b). The diol **11a** (0.070 g, 0.291 mmol) was added to dry pyridine (1.4 mL) and cooled to −20 °C. Phosphorus oxychloride (0.124 mL, 1.32 mmol) was added, and the reaction was brought to room temperature and stirred for 18 h. The solution was poured onto ice and extracted with several portions of ether which were combined, dried, and evaporated. Separation by silica gel chromatography (hexane) gave 0.048 g (74%) of **11b**: IR (neat) 3557, 1648 cm^{-1}; NMR δ 4.86 (s, 1 H), 4.67 (s, 1 H), 1.15 (d, 3 H, J = 6 Hz), 0.89 (d, 3 H, J = 8 Hz), 0.87 (d, 3 H, J = 8 Hz).

Thermolysis of 2,6-Dimethyl-9-(1-methylethyl)tricyclo[4.4.0.0^{2,5}]decan-10-ol (3b). A typical thermolysis reaction follows. Purified but not recrystallized **3b** (0.075 g, 0.337 mmol) was added to xylene (0.7 mL), and this solution was heated in a sealed tube at 190 °C for 1.0 h. Six of the above reactions were pooled and separated by column chromatography. The first product eluted from the column was the aldehyde **13**: 0.193 g (43% yield); IR (neat) 1729, 1630 cm^{-1}; NMR δ 9.56 (d, 1 H, J = 2.4 Hz), 5.66–6.05 (m, 1 H), 5.10 (br s, 1 H), 4.8–5.1 (m, 2 H), 1.68 (d, 3 H, J = 1 Hz), 1.6 (d, 3 H, J = 1 Hz), 1.13 (s, 3 H), 0.97 (d, 6 H, J = 7.6 Hz); mass spectrum, calcd for $C_{15}H_{26}O$ m/e 222.1984, found m/e 222.2001.

Next was eluted a mixture of three isomeric elemane alcohols, **4b**, **5b**, and **6b** (0.217 g, 48% yield). The relative ratios were determined by gas chromatography to be 21:26:54 of **4b**, **5b**, and **6b**, respectively. These were converted to their respective ketones **4a**, **5a**, and **6a** without separation of the isomers.

A trace of what seems to be the germacrene alcohol, **8b**, was then isolated but in quantities too small to be completely characterized: NMR δ 4.90–5.35 (m, 2 H), 4.20 (t, 1 H, J = 10 Hz), 1.63 (s, 3 H), 1.62 (s, 3 H), 0.97 (d, 3 H, J = 8 Hz), 0.79 (d, 3 H, J = 8 Hz).

Oxidation of the Elemene Alcohols 4b, 5b, and 6b. A mixture of isomers **4b**, **5b**, and **6b** (0.265 g, 1.19 mmol) was added to acetone (8 mL), and to this solution was added Jones reagent (CrO_3/H_2SO_4) until it remained a light brown. The solution was stirred for 30 min, diluted with water, and extracted with several portions of ether which were combined and evaporated. The crude product was separated by using $AgNO_3$-impregnated silica gel in a gravity column (15% $AgNO_3$ by weight, addition of $AgNO_3$ to silica gel in a methanolic solution which was then dried at 120 °C for 24 h)[18] and eluted with 1:1 benzene–hexane to give 0.025 g (9.5%) of (−)-shyobunone (**4a**): $[\alpha]_D$ −16° (c 0.272 g/mL); 14% ee; CD $[\Theta]_{296.5}$ −1510. The other two isomers were eluted together but were then separated by using silica gel chromatography (hexane). 3-Epi-(−)-shyobunone (**6a**): 0.040 g (15 %); IR (neat) 1708, 1646 cm^{-1}; NMR δ 6.18–5.80 (dd, 1 H, J = 10, 18 Hz), 5.24–4.67 (m, 4 H), 2.98 (s, 1 H), 1.75 (s, 3 H), 1.17 (s, 3 H), 0.94 (d, 3 H, J = 6 Hz), 0.88 (d, 3 H, J = 6 Hz); CD $[\Theta]_{297.5}$ −1830. 2-Epi-(−)-shyobunone (**5a**): 0.020 g (7.6%); IR (neat) 1702, 1641 cm^{-1}; NMR δ 6.20–5.82 (dd, 1 H, J = 10, 17 Hz), 5.32–4.80 (m, 4 H), 2.96 (s, 1 H), 1.73 (s, 3 H), 1.12 (s, 3 H), 0.95 (d, 3 H, J = 6 Hz), 0.87 (d, 3 H, J = 6 Hz); CD $[\Theta]_{301.5}$ +3040.

Shyobunone (4a). The aldehyde **13** (0.150 g, 0.67 mmol) was added to benzene (60 mL) followed by 0.473 mL (0.236 mmol) of 0.5 M $SnCl_4$ in benzene. The solution was stirred for 1 h at room temperature, diluted with ether, and extracted with saturated $NaHCO_3$(aq) and 5% HCl(aq). The aqueous washes were then extracted with two portions of ether. The crude product upon evaporation was treated with excess Jones reagent in acetone, allowed to stir for 0.5 h, diluted with water, and extracted with several portions of ether. The combined organic extracts were dried and evaporated. Purification via silica gel chromatography gave 0.032 g (22%) of pure (−)-shyobunone (**4a**), CD $[\Theta]_{296.5}$ −1429.

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