The NMR solvent was $CDCl_3$. The workup of each reaction culminated in drying the organic phase over $MgSO_4$, filtering, and removing the solvent at reduced pressure on a rotary evaporator. Unless otherwise noted, distillations were bulb-to-bulb distillations performed with a Kugelrohr oven at the temperature and pressure indicated. Microanalyses were performed by the Microanalytical Laboratory of the College of Chemistry, University of California, Berkeley.

Ethyl (*Z*)-2,3-Dideuterioacrylate (2). The starting material was prepared as described by Hill and Newkome[5] and was shown by high-field NMR to contain 96% of the desired isomer.

Ethyl (2*R,3*S**)-2,3-Dideuterioepoxypropanoate (3).** A solution of 2.5 g (24.5 mmol) of the deuterioacrylate **2** and 12.3 g (54 mmol) of 3,5-dinitroperoxybenzoic acid[6] in 50 mL of $CHCl_3$ was heated at reflux for 8 h. The mixture was cooled to 0 °C, diluted with CH_2Cl_2, and filtered. The precipitate was washed with CH_2Cl_2, and the combined filtrates were washed with 20% aqueous $NaHSO_3$ and two portions of saturated aqueous $NaHCO_3$, dried, and distilled through a short-path apparatus to afford **3**: 1.98 g (68% yield); bp 76–80 °C (30 torr); IR (film) 1741, 1420, 1390, 1255, 1201, 1030 cm^{-1}; NMR δ 1.31 (t, 3, J = 7), 3.0 (s, 1), 4.25 (dq, 2, J = 2.2, 7). Anal. Calcd for $C_6H_6D_2O_3$: C, 51.72; H, 6.95. Found: C, 51.49; H, 6.88.

Ethyl (2*R,3*S**)-2,3-Dideuterio-2-hydroxy-3-(phenylseleno)propanoate (4).** A solution of diisobutylaluminum phenylselenide in hexane was prepared by the addition of 1.32 g (4.25 mmol) of diphenyl selenide to 6.0 mL of a 1.41 M solution (8.5 mmol) of diisobutylaluminum hydride in hexane. This reagent was added to a solution of 1.0 g (8.5 mmol) of glycidate **3** in 60 mL of hexane at −78 °C, and the solution was stirred for 2 h and then allowed to warm to 21 °C over an 8-h period. The mixture was washed with phosphate buffer (pH 3), and the aqueous layer was back-extracted with three portions of CH_2Cl_2. The combined organic layers were washed with saturated aqueous $NaHCO_3$, dried, and concentrated, and the crude product was purified by chromatography (ether/hexane, 1:1) to give **4**: 1.5 g (64% yield); IR 3560, 1730, 1480, 1080, 905 cm^{-1}; NMR δ 1.19 (t, 3, J = 7.1), 3.14 (s, 1), 3.33 (s, 1), 3.97 (dq, 1, J = 7.13, 7.15), 4.12 (dq, 1, J = 7.09, 7.14), 7.2–7.6 (m, 5). Anal. Calcd for $C_{11}H_{12}D_2O_3Se$: C, 48.36; H, 5.17. Found: C, 48.19; H, 5.13.

Ethyl (2*R,3*S**)-2,3-Dideuterio-2-[(dimethoxyphosphinyl)oxy]-3-(phenylseleno)propanoate (5).** To a solution of 0.98 g (3.56 mmol) of selenoalcohol **4** in 100 mL of THF at −78 °C was added a solution of 3.56 mol of lithium diisopropylamide in 25 mL of THF. After 15 min at −78 °C, 0.57 g (3.96 mmol) of dimethyl phosphorochloridate was added, and the mixture was allowed to warm to 21 °C over a 12-h period. After addition of 25 mL of saturated aqueous NH_4Cl, the aqueous layer was extracted four times with CH_2Cl_2, and the combined organic layers were washed with 2.5 N HCl and saturated $NaHCO_3$, dried, and evaporated to give 1.3 g (95% yield) of **5**, which was of sufficient purity to be carried on to the next step: IR 1750, 1270, 1045, 1020 cm^{-1}; NMR δ 1.25 (t, 3, J = 7.1), 3.36 (s, 1), 3.77 (d, 3, J = 18.1), 3.81 (d, 3, J = 18.2), 4.16 (m, 2), 7.2–7.6 (m, 5). A sample was purified for analysis by preparative TLC (silica gel; EtOAc/hexane, 70:30). Anal. Calcd for $C_{13}H_{17}D_2O_6PSe$: C, 40.96; H, 5.02; P, 8.12. Found: C, 40.93; H, 5.12; P. 8.01.

Ethyl (*Z*)-3-Deuterio-2-[(dimethoxyphosphinyl)oxy]-propenoate ((*Z*)-6). To a solution of 1.3 g (3.4 mmol) of phosphate ester **5** in 140 mL of CH_2Cl_2 at 21 °C was added 1.0 mL (8.8 mmol) of 30% H_2O_2. The mixture was stirred vigorously for 1 h, diluted with CH_2Cl_2, and washed with $NaHCO_3$. The organic layer was dried and evaporated to give *Z* enol ester **6**: 0.714 g (94% yield); IR 1730, 1635, 1310, 1280, 1170, 1040, 1005, 850, 820 cm^{-1}; NMR δ 1.34 (t, 3, J = 7.1), 3.88 (d, 6, J = 11.2), 4.29 (q, 2, J = 7.1), 5.97 (d, 1, J = 2.5). A sample was purified for analysis by preparative TLC (silica gel; EtOAc/hexane, 70:30). Anal. Calcd for $C_7H_{13}O_6P$: C, 37.51; H, 5.85; P, 13.82. Found: C, 37.35; H, 5.94; P, 13.64.

Cyclohexylammonium (*Z*)-3-Deuteriophosphoenolpyruvate ((*Z*)-1). A solution of 0.71 g (3.17 mmol) of triester (*Z*)-**6** and 1.05 mL (7.9 mmol) of bromotrimethylsilane in 25 mL of CH_2Cl_2 was kept at 21 °C for 2 h. After evaporation at reduced pressure, the residue was dissolved in 16 mL of 1 N KOH, washed with CH_2Cl_2, and desalted by elution through a column of Dowex 50W-X8 resin in the H^+ form. Addition of 0.33 mL (3.17 mmol) of cyclohexylamine to the eluant, lyophilization, and recrystallization from 1:1 methanol/ether gave 0.59 g (69% yield) of colorless product, mp 153–154 °C dec (lit.[8] mp 144–146 °C). Analysis of the olefinic proton signals at δ 5.76 (*E* isomer) and δ 6.06 (*Z* isomer) (CD_3OD solvent) indicated that this material was contaminated by less than 8% of the *E* isomer.

Ethyl (2*R,3*S**)-2,3-Dideuterio-3-bromo-2-hydroxypropanoate (7).** To a solution of 0.90 g (7.63 mmol) of labeled glycidate **3** and 1.0 mL (9.1 mmol) of bromotrimethylsilane in 75 mL of CH_2Cl_2 at −78 °C was added 0.174 g (0.76 mmol) of zinc bromide. The mixture was stirred at −78 °C for 6 h and then allowed to warm to 21 °C over a 12-h period. After hydrolysis of the trimethylsilyl ether with 2.8 mL of 2.5 N HCl, the mixture was partitioned between additional CH_2Cl_2 and saturated aqueous $NaHCO_3$, and the organic layer was dried and evaporated to give the bromohydrin **7** as analytically pure, colorless crystals: 1.39 g (92% yield); mp 49–50 °C; IR 3400, 1730, 1390, 1320, 1240, 1060 cm^{-1}; NMR δ 1.33 (t, 3, J = 7), 3.24 (br s, 1), 3.66 (s, 1), 4.30 (q, 2, J = 7). Anal. Calcd for $C_5H_7D_2BrO_3$: C, 30.48; H, 4.60; Br, 40.55. Found: C, 30.33, H, 4.50; Br, 40.78.

Ethyl (*E*)-3-Deuterio-2-[(dimethoxyphosphinyl)oxy]-propenoate ((*E*)-6). To a solution of 1.19 g (5.98 mmol) of bromohydrin **7** in 150 mL of THF at −78 °C was added a solution of 5.98 mmol of LDA in 30 mL of THF. After 15 min, 0.72 mL (6.58 mmol) of dimethyl phosphorochloridate was added, and the solution was allowed to warm to −20 °C over 14 h. After 3 h at 0 °C, the reaction mixture was partitioned between saturated aqueous NH_4Cl and CH_2Cl_2. The aqueous layer was washed twice with CH_2Cl_2, and the combined organic layers were washed with 2.5 N HCl and saturated $NaHCO_3$, dried, and evaporated to give the *E* enol phosphate (*E*)-**6**: 1.36 g (quantitative yield); NMR δ 1.34 (t, 3, J = 7.1), 3.88 (d, 6, J = 11.5), 4.29 (q, 2, J = 7.1), 5.61 (d, 1, J = 2.48).

Cyclohexylammonium (*E*)-3-Deuteriophosphoenolpyruvate ((*E*)-1). A 1.345 g sample of the *E* triester (*E*)-**6** was hydrolyzed and purified as described above for the *Z* isomer to give (*E*)-**1**: 1.15 g (72% yield); mp 150–151 °C dec. NMR analysis indicated that less than 6% of the *Z* stereoisomer was present.

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Registry No. (*E*)-**1**, 87115-14-8; (*Z*)-**1**, 87115-16-0; **2**, 87115-17-1; **3**, 87115-18-2; **4**, 87115-19-3; **5**, 87115-20-6; (*E*)-**6**, 87115-21-7; (*Z*)-**6**, 87115-22-8; **7**, 87115-23-9; **8**, 87115-24-0.

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(Arene)chromium Tricarbonyl Complexes in Organic Synthesis: Stereoselective Synthesis of *cis*- and *trans*-7-Hydroxycalamenenes[1]

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In the previuos papers, we have reported that nuclear lithiation of some arene compounds can be controlled regiochemically by complexation of the arene ring with chromium tricarbonyl group.[2,3] For example, (η^6-7-methoxy-1-tetralol)chromium tricarbonyl and the related

(1) Dedicated to Emeritus Prof. Takeo Sakan on the 70th anniversary of his birth.

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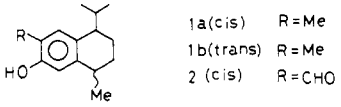
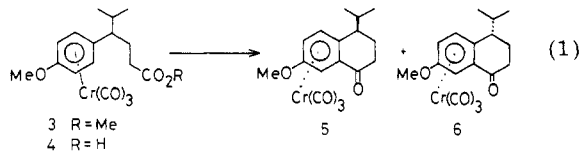
complexes are selectivity lithiated at the 6-position, complementarily to the lithiation of the corresponding chromium-free arene compounds at the 8-position. The same type of complexation would be applicable to the stereoselective introduction of various substituents into an alicyclic ring adjacent to the arene ring. Since the coordination by the $Cr(CO)_3$ group confers a third dimension on the molecular structure which has stereochimical consequences, electrophilic or nucleophilic attack at the reactive center of an alicyclic ring ortho-condensed to an aromatic moiety always occurs stereospecifically in an exo fashion. This report provides evidence on the stereochemical control at the benzylic position by employing the (η^6-arene)-chromium tricarbonyl intermediate, which was converted to *cis*- and *trans*-7-hydroxycalamenenes[4] (**1a,b**).



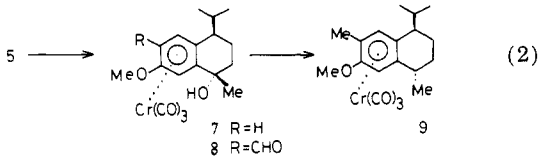
Refluxing of methyl 4-(*p*-methoxyphenyl)-5-methylhexanoate, readily available from methyl 3-(*p*-methoxybenzoyl)propionate by two steps, with $Cr(CO)_6$ in heptane and dibutyl ether gave a yellow (η^6-arene)chromium tricarbonyl complex, **3**, which was hydrolyzed with KOH to afford an acid **4** in 72% overall yield. Although a reaction of the complex **4** with polyphosphoric acid[5] was not successful, Friedel–Crafts cyclization with $AlCl_3$ of the corresponding acid chloride afforded the *exo*-isopropyltetralone complex **5** (eq 1) in 60.5% yield, along with a



(1)

trace of the *endo*-isopropyl isomer **6**. Methyl signals of the isopropyl group of the less polar,[6] major product **5** (mp 90 °C) appeared at higher field[7] (δ 1.02 and 1.08) than the corresponding signals of the more polar, minor product **6** (mp 133 °C) at δ 1.06 and 1.18. Usually, the exo complex shows a lower melting point and higher mobility on chromatography than the corresponding endo isomer. The cyclization proceeded in such way that the isopropyl group at the chiral benzylic position was oriented far from the bulky tricarbonylchromium group and afforded the exo isomer **5** predominantly.

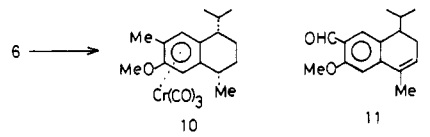
Reaction of the complex **5** with methyllithium gave a single exo-methylated[8] product, **7**, in 68% yield (eq 2).



(2)

Directed lithiation[2] of the complex **7** with butyllithium, followed by quenching with DMF, gave the 6-formyl complex **8** in 85% yield without formation of regioisomeric formyl complexes. Ionic hydrogenolysis[9] of the complex **8** with an excess of triethylsilane and trifluoroacetic acid resulted in the stereoselective hydride displacement at the benzylic position along with the exhaustive reduction of the formyl group, giving the complex **9** in 82% yield without stereoisomeric contamination. Decomplexation of the $Cr(CO)_3$ group (exposure to sunlight) and subsequent demethylation gave *trans*-7-hydroxycalamenene (**1b**) in good yield.

On the other hand, *endo*-isopropyltetralone complex **6** was converted into *cis*-7-hydroxycalamenene (**1a**) through the *exo*-isopropyl and *exo*-methyl complex **10** by the similar reaction sequence in 45% overall yield (eq 3). Both



(3)

of the trans and cis isomers were identical with the authentic samples in NMR and IR spectra. *cis*-7-Hydroxycalamenene (**1a**) was also prepared stereoselectively from the complex **8** by the following procedure. Exposure to sunlight (decomplexation) and dehydration with *p*-TsOH gave a dihydronaphthalene derivative **11**, which was converted to **1a** in 78% overall yield without contamination of the trans isomer **1b** by catalytic reduction with 10% Pd/C and subsequent demethylation. Catalytic reduction with 5% $Pd/BaSO_4$ and subsequent demethylation of the compound **11** gave *cis*-7-hydroxycalamenal[10] without reduction of the formyl group.

Experimental Section

Melting points were determined on a Yanagimoto Model MPJ-2 micro melting point apparatus and are uncorrected. ^1H NMR spectra were recorded on a JEOL Model PS-100, and IR spectra were measured by a JASCO Model A-102 spectrometer. Mass spectra were determined on a JEOL D-300 in the EI mode (30 eV). Elemental analysis was performed on a Perkin-Elmer Model 240 automatic elemental analyzer. Ether and THF were distilled under nitrogen from benzophenone ketyl imediately before use. TMEDA was purified by distillation from CaH_2. Methylene chloride was distilled from P_2O_5.

Preparation of (η^6-Methyl 4-(*p*-methoxyphenyl)-5-methylhexanoate)chromium Tricarbonyl (3). A mixture of methyl 4-(*p*-methoxyphenyl)-5-methylhexanoate (5.00 g, 20 mmol), chromium hexacarbonyl (6.60 g, 30 mmol) in heptane (100 mL) and butyl ether (200 mL) was heated at reflux under nitrogen in a 500 mL round-bottom flask equiped with a Strohmeier-type apparatus[11] for 36 h. The yellow solution was allowed to cool, and the precipitate was filtered. After evaporation of the filtrate in vacuo, a crude product was purified by SiO_2 chromatography with ether–petroleum ether. Crystalization from ether–hexane gave 6.05 g (78.3%) of **3** as yellow crystals: mp 53–54 °C; ^1H NMR ($CDCl_3$) δ 0.85 (6 H, t, J = 6 Hz), 1.70–2.60 (6 H, m), 3.72 (3 H, s), 3.76 (3 H, s), 5.10 (2 H, m), 5.44 (2 H, m); IR ($CHCl_3$) 1970, 1880, 1740, 1550 cm^{-1}. Anal. Calcd for $C_{18}H_{22}O_6Cr$: C, 55.96; H, 5.74. Found: C, 56.19; H, 5.74.

Preparation of (η^6-4-(*p*-Methoxyphenyl)-5-methylhexanoic acid)chromium Tricarbonyl (4). A solution of the complex **3** (5.22 g, 13.52mmol) and KOH (2.31 g, 41mmol) in MeOH (195 mL) and water (42 mL) was refluxed for 1 h under nitrogen. After evaporation of the MeOH in vacuo, the aquous solution was acidified with HCl and then extracted with ether. The extract was washed with saturated aquous sodium chloride and dried over

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sodium sulfate. Evaporation in vacuo and recrystalization from ether–hexane gave 4.64 g (92.3%) of **4** as yellow crystals: mp 143–144 °C; ^{1}H NMR ($CDCl_3$) δ 0.91 (6 H, t, J = 6 Hz), 1.70–2.60 (6 H, m), 3.76 (3 H, s), 5.10 (2 H, m), 5.44 (2 H, m); IR ($CHCl_3$) 3600–2400, 1960, 1880, 1710, 1510 cm^{-1}. Anal. Calcd for $C_{17}H_{20}O_6Cr$: C, 54.84; H, 5.41. Found: C, 54.83; H, 5.41.

Cyclization of 4 To Give 5 and 6. A mixture of the complex **4** (6.01 g, 16.1 mmol) and oxalyl chloride (12.0 g, 94.5 mmol) in dry benzene (500 mL) was heated at 50 °C for 2 h under nitrogen. The solvent and excess reagent were evaporated in vacuo to give an acid chloride complex as a yellow oil, which was used for next step without purification. To a solution of acid chloride in dry methylene chloride (400 mL) was added anhydrous $AlCl_3$ (25 g, 18.4 mmol) all at once at 0 °C under nitrogen. The reaction mixture was stirred at 0 °C for 30 min and then at room temperature for 2 h under nitrogen. After addition of water (300 mL) at 0 °C, the reaction mixture was extracted with methylene chloride. The extract was washed with aquous sodium bicarbonate and sodium chloride and dried over sodium sulfate. Rotary evaporation of the solvent gave a red oil which showed two spots on TLC. Coloum chromatography (SiO_2 200 g) with ether/petroleum ether (1:3) gave as a first eluate 3.45 g (60.5%) of **(η^6-4-*exo*-isopropyl-7-methoxy-1-tetralone)chromium tricarbonyl (5)** as red crystals: mp 90 °C; ^{1}H NMR ($CDCl_3$) δ 1.02 (3 H, d, J = 6.3 Hz), 1.08 (3 H, d, J = 6.3 Hz), 1.62–3.63 (6 H, m), 3.72 (3 H, s), 5.44 (2 H, s), 5.60 (1 H, s); IR ($CHCl_3$) 1980, 1900, 1690, 1540 cm^{-1}. Anal. Calcd for $C_{17}H_{18}O_5Cr$: C, 57.63; H, 5.12. Found: C, 57.76; H, 5.14.

The second eluate gave 166 mg (2.5%) of **(η^6-4-*endo*-isopropyl-7-methoxy-1-tetralone)chromium tricarbonyl (6)** as red crystals: mp 132–133 °C; ^{1}H NMR ($CDCl_3$) δ 1.06 (3 H, d, J = 6.3 Hz), 1.18 (3 H, d, J = 6.3), 1.24–2.74 (6 H, m), 3.66 (3 H, s), 5.32 (1 H, dd, J= 2, 5 Hz), 5.64 (1 H, d, J = 2 Hz), 5.68 (1 H, d, J = 5 Hz); IR ($CHCl_3$) 1980, 1910, 1690 cm^{-1}. Anal. Calcd for $C_{17}H_{18}O_5Cr$: C, 57.63; H, 5.12. Found: C, 57.59; H, 5.14.

Reaction of 5 with MeLi To Give 7. To a solution of **5** (3.41 g, 9.57 mmol) in dry ether (200 mL) was added 7.6 mL of MeLi (11.4 mmol, 1.5 M in ether) at −78 °C under nitrogen. After stirring at 0 °C for 1.5 h, water was added. The reaction mixture was extracted with ether, washed with aquous sodium chloride, dried over sodium sulfate, and rotary evaporated. The resulting oil was purified by SiO_2 chromatography with ether–petroleum ether to give **7** as yellow crystals: 2.23g (63%); mp 122 °C; ^{1}H NMR ($CDCl_3$) δ 0.68 (3 H, d, J = 7 Hz), 0.94 (3 H, d, J = 7 Hz), 1.52 (3 H, s), 3.68 (3 H, s), 5.27 (1 H, dd, J = 3, 7 Hz), 5.52 (1 H, d, J = 3 Hz), 5.63 (1 H, d, J = 7 Hz); IR ($CHCl_3$) 3640, 1980, 1900, 1540 cm^{-1}. Anal. Calcd for $C_{18}H_{22}O_5Cr$: C, 58.37; H, 5.99. Found: C, 58.51; H, 6.00.

Conversion of 7 To Give 8. To a mixture of **7** (1.47 g, 3.96 mmol) and TMEDA (1.44 mL, 9.5 mmol) in dry ether (42 mL) was added 7.34 mL of *n*-BuLi (1.3 M in hexane, 9.5 mmol) with stirring at −78 °C under nitrogen. After the mixture was stirred for 2.5 h, 1.5 mL of DMF (20 mmol) was added all at once at −78 °C. The reaction mixture was warmed to 0 °C for 2 h. After addition of water, the reaction mixture was extracted with ether, washed with aquous sodium chloride, dried over sodium sulfate, and rotary evaporated. The resulting product was purified by SiO_2 chromatography to give **8** as red crystals: 1.34g (85%); mp 142–143 °C; ^{1}H NMR ($CDCl_3$) δ 0.82 (3 H, d, J = 6 Hz), 1.06 (3 H, d, J = 6 Hz), 1.60 (3 H, s), 3.80 (3 H, s), 5.42 (1 H, s), 6.39 (1 H, s), 10.01 (1 H, s); IR ($CHCl_3$) 3640, 1970, 1890, 1680, 1540 cm^{-1}. Anal. Calcd for $C_{19}H_{22}O_6Cr$: C, 57.29; H, 5.57. Found: C, 57.46; H. 5.62.

Prepation of (η^6-*trans*-7-Methoxycalamenene)chromium Tricarbonyl (9). To a mixture of **8** (200 mg, 0.50 mmol) and triethylsilane (350 mg, 3.0 mmol) was added trifluoroacetic acid (350 μL, 4.5 mmol) at 0 °C under nitrogen. The reaction mixture was heated at 50–60 °C for 4.5 h with stirring. The reaction mixture was decomposed with water and worked up as usual. Purification by SiO_2 chromatography gave **9** as a yellow oil: 151 mg (82%); ^{1}H NMR ($CDCl_3$) δ 0.72 (3 H, d, J = 7 Hz), 0.96 (3 H, d, J = 7 Hz), 1.38 (3 H, d, J = 6 Hz), 2.17 (3 H, s), 3.71 (3 H, s), 5.26 (1 H, s), 5.43 (1 H, s); IR ($CHCl_3$) 1970, 1800 cm^{-1}.

Preparation of *trans*-7-Hydroxycalamenene (1b). A solution of **9** (151 mg, 0.41 mmol) and ether (10 mL) was exposed to sunlight until the yellow color of the solution was disappeared. The precipitate was filtered and washed ether. Evaporation of ether in vacuo gave *trans*-7-methoxycalamenene: 97 mg (100%); colorless oil; ^{1}H NMR ($CDCl_3$) δ 0.84 (3 H, d, J = 7 Hz), 1.10 (3 H, d, J = 7 Hz), 1.39 (3 H, d, J = 6 Hz), 2.28 (3 H, s), 1.58–3.00 (7 H, m), 3.88 (3 H, s), 6.72 (1 H, s), 7.00 (1 H, s); IR ($CHCl_3$) 1610, 1500, 1460, 1255 cm^{-1}; MS, calcd for $C_{16}H_{24}O$ m/e 232.1827, found 232.1828.

To a solution of *trans*-7-methoxycalamene (93 mg, 0.40 mmol) and methylene chloride (5 mL) was added boron tribromide (210 mg, 0.83 mmol) at −78 °C. The reaction mixture was warmed to room temperature for 7 h. The mixture was decomposed with water and worked up as usual. Purification by SiO_2 chromatography gave **1b**: 80 mg (90%); colorless oil; ^{1}H NMR ($CDCl_3$) δ 0.72 (3 H, d, J = 7 Hz), 1.01 (3 H, d, J = 7 Hz), 1.24 (3 H, d, J = 6 Hz), 2.29 (3 H, s), 4.68 (1 H, s), 6.66 (1 H, s), 6.96 (1 H, s); IR (neat) 3400, 1610, 1590 cm^{-1}; MS, calcd for $C_{15}H_{22}O$ m/e 218.1671, found 218.1671.

Preparation of (η^6-*cis*-7-Methoxycalamenene)chromium Tricarbonyl (10). Compound **6** was converted into **10** overall 50% yield by similar method mentioned above. ^{1}H NMR ($CDCl_3$) δ 1.04 (3 H, d, J = 7 Hz), 1.12 (3 H, d, J = 7 Hz), 1.36 (3 H, d, J = 6 Hz), 2.14 (3 H, s), 3.78 (3 H, s), 5.10 (1 H, s), 5.52 (1 H, s); IR ($CHCl_3$) 1970, 1800 cm^{-1}.

Preparation of *cis*-7-Hydroxycalamenene (1a). The complex **10** gave *cis*-7-methoxycalamenene with quantitative yield by sunlight exposure: ^{1}H NMR ($CDCl_3$) δ 0.76 (3 H, d, J = 7 Hz), 1.03 (3 H, d, J = 7 Hz), 1.28 (3 H, d, J = 7 Hz), 2.18 (3 H, s), 1.44–3.04 (7 H, m), 3.78 (3 H, s), 6.52 (1 H, s), 6.90 (1 H, s); IR ($CHCl_3$) 1610, 1460, 1250 cm^{-1}; MS, calcd for $C_{16}H_{24}O$ m/e 232.1827, found: 232.1834.

Demethylation of *cis*-7-methoxycalamenene with boron tribromide gave **1a** in a 90% yield by a method similar to that mentioned above: ^{1}H NMR ($CDCl_3$) δ 0.88 (3 H, d, J = 7 Hz), 1.03 (3 H, d, J = 7 Hz), 1.24 (3 H, d, J = 7 Hz), 2.12 (3 H, s), 4.66 (1 H, s), 6.57 (1 H, s), 6.96 (1 H, s); IR (neat) 3400, 1610, 1590 cm^{-1}; MS, calcd for $C_{15}H_{22}O$ m/e 216.1671, found 218.1680.

Preparation of 11. A solution of **8** (600 mg, 1.51 mmol) of ether (100 mL) was exposed to sunlight until a red color was disappeared. The precipitate was filtered, and washed with ether. Evaporation of ether gave 369mg (94%) of β-4-isopropyl-β-1-methyl-6-formyl-7-methoxy-1-tetralol: mp 133–134 °C; ^{1}H NMR ($CDCl_3$) δ 0.64 (3 H, d, J = 7 Hz), 1.04 (3 H, d, J = 7 Hz), 1.49 (3 H, s), 3.91 3 H, s), 7.23 (1 H, s), 7.63 (1 H, s), 12.31 (1 H, s); IR ($CHCl_3$) 3640, 1680 cm^{-1}. Anal. Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. Found: C, 73.14; H, 8.48.

A mixture of the above tetralol derivative (165 mg, 0.63 mmol) and a catalytic amount of *p*-TsOH in benzene (20 mL) was refluxed for 2 h. The reaction mixture was washed with aquous sodium bicarbonate and sodium chloride. Evaporation in vacuo and purification by SiO_2 gave **11**: 137mg (86%); mp 63–64 °C; ^{1}H NMR ($CDCl_3$) δ 0.90 (3 H, d, J = 7 Hz) 0.98 (3 H, d, J = 7 Hz), 2.10 (3 H, br s), 3.94 (3 H, s), 5.56 (1 H, m), 6.81 (1 H, s), 7.35 (1 H, s), 10.02 (1 H, s). Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.65; H, 8.25. Found: C, 78.80, 8.27.

Catalytic Reduction of 11 with Pd/C. A mixture of **11** (137 mg, 0.50 mmol) and 10% Pd/C (30 mg) in 95% EtOH (10 mL) was stirred at room temperature for 10 h under a hydrogen atmosphere. The precipitate was filtered. Evaporation and purification by SiO_2 gave pure *cis*-7-methoxycalamenene (107 mg, 82%).

Preparation of *cis*-7-Hydroxycalamenal (2). A mixture of **11** (50 mg, 0.21 mmol) and 5% Pd/$BaSO_4$ (25 mg) in 95% EtOH (10 mL) was stirred at 0 °C for 2 h under hydrogen atmosphere. Filtration, rotary evaporation, and purification by SiO_2 chromatography gave *cis*-7-methoxycalamenal: 47 mg (90%); mp 77–78 °C; ^{1}H NMR ($CDCl_3$) δ 0.74 (3 H, d, J = 7 Hz), 1.00 (3 H, d, J = 7 Hz), 1.12 (3 H, d, J = 7 Hz), 3.86 (3 H, s), 6.67 (1 H, s), 7.10 (1 H, s), 10.30 (1 H, s); IR ($CHCl_3$) 1670 cm^{-1}. Anal. Calcd for $C_{16}H_{22}O_2$: C, 78.01; H, 9.00. Found: C, 78.10; H, 9.02.

Treatment of *cis*-7-methoxycalamenal (20 mg, 0.08 mmol) with boron tribromide (0.02 mL, 0.21 mmol) gave *cis*-7-hydroxycalamenal (**2**) by the usual method: 18 mg (96%); ^{1}H NMR ($CDCl_3$) δ 0.80 (3 H, d, J = 7 Hz), 1.04 (3 H, d, J = 7 Hz), 1.28 (3 H, d, J = 7 Hz), 6.78 (1 H, s), 7.36 (1 H, s), 9.82 (1 H, s), 10.07 (1 H, s); IR (neat) 3280, 1660, 1580 cm^{-1}; MS, calcd for $C_{15}H_{20}O_2$ m/e 232.1463, found 232.1449.

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Registry No. **1a**, 24406-03-9; **1b**, 87302-52-1; **2**, 68926-81-8; **3**, 87249-20-5; **4**, 87249-21-6; **5**, 87249-22-7; **6**, 87304-45-8; **7**, 87249-23-8; **8**, 87249-24-9; **9**, 87249-25-0; **10**, 87304-46-9; **11**, 87226-67-3; $Cr(CO)_6$, 13007-92-6; methyl 4-(*p*-methoxyphenyl)-5-methylhexanoate, 87226-68-4; *trans*-7-methoxycalamenene, 87226-69-5; *cis*-7-methoxycalamenene, 87226-70-8; β-4-isopropyl-β-1-methyl-6-formyl-7-methoxy-1-tetralol, 87226-71-9; *cis*-7-methoxycalamenal, 87226-72-0.

Efficient Synthesis of Barbaralane

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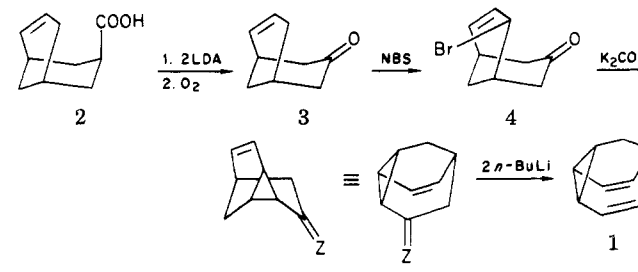
The properties of the barbaralane (tricyclo[3.3.1.$0^{2,8}$]-nona-3,6-diene) system (**1**) and its derivatives have been

1

of substantial interest since the ring system was first reported in 1963.[1] This system is one of several with fluxional character,[2,3] in which a degenerate Cope rearrangement occurs at ambient temperatures. Recently there has been renewed interest in the chemistry of these systems, particularly **1**, in which derivatives of the parent molecule have been used as substrates for spectroscopic[4–6] and mechanistic[7] investigations. Several groups have investigated the electronic states of derivatives of **1**, in light of the prediction[8,9] that with suitable substituents the system may exhibit homoaromatic character. While attempts to synthesize such a system are ongoing,[10,11] a derivative of **1** that shows this property has not yet been observed.

The two most widely recognized syntheses of **1** have not been especially convenient.[12,13] In both syntheses cyclopropanation is accomplished by carbene insertion into a preformed double bond. These approaches are characterized by one or more low-yield intermediate steps and the necessity of one or more complex separation steps. Other recent entries into the barbaralane system include the rearrangement of bicyclo[3.3.2] iron tricarbonyl cations[14] and the rearrangement of norbornadiene–carbene adducts,[15] but these routes do not proceed to the parent compound **1**.

Scheme I



5a, Z = O
b, Z = NNHTs

We now report a more generally useful synthesis of **1** and its derivatives under very mild conditions, one which does not depend on a carbenoid intermediate (Scheme I). The cyclopropane ring system is formed by way of a transannular ring closure before the diene system is in place. Thus treatment of 2-adamantanone (Aldrich) with sodium azide in methanesulfonic acid produced carboxylic acid **2** by the method of Sasaki, Eguchi, and Toru[16] in 80% yield. Using a variation of the method of Krishnamurthy and Fort,[17] oxidative decarboxylation of **2** was accomplished in 70% yield by treatment with 2.5 equiv of LDA at 0 °C followed by oxygenation of the resulting dianion at −78 °C. The intermediate α-hydroperoxy carboxylate was not isolated. Acid workup[16] afforded bicyclic ketone **3**. The remaining 30% of the product was unchanged **2**, which was recycled.

Allylic bromination of **3** with *N*-bromosuccinimide gave bromo ketone **4** as the only product in nearly quantitative yield. Successful bromination required the use of properly purified NBS. The use of recrystallized NBS that had been allowed to air-dry for at least 3 days afforded essentially only **4**. However, if either unpurified reagent or rigorously purified reagent was used, quantities of product resulted (20–30% of the product mixture) in which bromination occurred at the ketone α-positions. Such a mixture could not be purified by simple recrystallization but had to be subjected to a chromatographic separation. The stereochemical assignment of the bromine as exo was made on the basis of previous reports,[11] which have shown that allylic bromination in related systems proceeds by exclusive exo attack, and on the basis of NMR evidence, i.e., no evidence of epimers in the ^{13}C NMR spectrum.

Bromo ketone **4** is ideally set up for base-catalyzed ring closure to tricyclic ketone **5a**, which is a direct precursor to **1**. Indeed, treatment of **4** with any of several bases, including NaOMe or K_2CO_3, produced **5a** in >95% isolated yield. Conversion of **5a** to **1** in 59% purified yield was then easily accomplished by using *n*-BuLi in THF by way of a Bamford–Stevens type elimination[18] of the corresponding

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