Anomalous Products from the Thermal Diels−Alder Reaction of a (*E*)-2-Thiophenyl Butadiene Tethered to 3-Methallyl Cyclohexenone

Paul A. Grieco*,[1] and Michael D. Kaufman

Department of Chemistry and Biochemistry, Montana State University, Bozeman, Montana 59717, and Department of Chemistry, Indiana University, Bloomington, Indiana 47405

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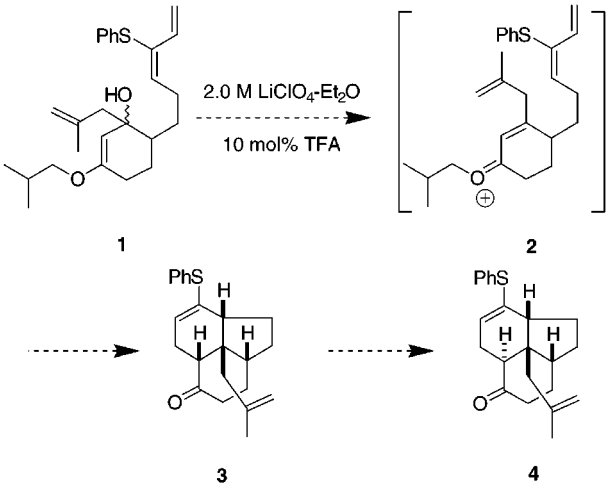
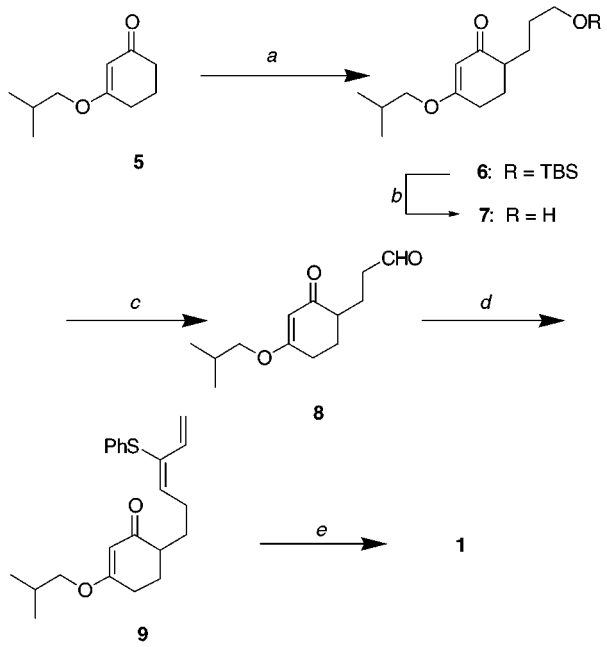
In connection with our interest in the intramolecular Diels−Alder reaction of in situ-generated, heteroatom-stabilized allyl cations in polar media,[2] we set out to extend this chemistry by employing a terminal (*E*)-2-thiophenyl group on the terminal butadiene unit and incorporating a methallyl group at the γ carbon of the intermediate allyl cation (cf. **2**) so as to generate a quaternary carbon atom within a carbocyclic array (cf. **1** → **4**).

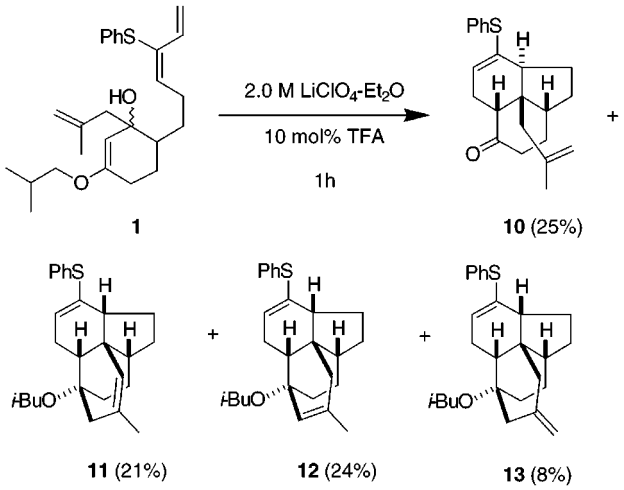


On the basis of previous work from our laboratory,[2] it was anticipated that substrate **1** would undergo facile cycloaddition with formation of **3** via an exo transition state followed by equilibration[3] adjacent to the carbonyl leading exclusively to **4**. Upon exposure (1 h, ambient temperature) of **1** (for the synthesis of **1**, see Scheme 1) to 2.0 M lithium perchlorate in diethyl ether containing 10 mol % trifluoroacetic acid, neither the expected product **4** nor **3** could be detected. Workup provided four cycloadducts **10**−**13** in a combined yield of 78%. The structure of tricyclic ketone **10**, which presumably arises via a stepwise, endo-like transition state, was readily confirmed by ^{1}H NMR and NOE measurements. The ^{1}H NMR spectra of **11**−**13** were strikingly similar in that they all possessed an isobutyl group and had lost the methallyl functionality. The structure of **11** was unambiguously established by single-crystal X-ray analysis.[4] The structures of **12** and **13** were derived from their respective ^{1}H NMR spectra and by comparison with the spectrum of **11**.

Scheme 1[a]



[a] Reagents and conditions: (*a*) LDA, THF-HMPA, -78 °C to 0 °C; *t*-Bu(Me)$_2$SiOCH$_2$CH$_2$CH$_2$I (56%); (*b*) TBAF, THF (99%); (*c*) vinyl-MgBr, THF, -78 °C; ADDP, THF, 0 °C (79%); (*d*) 9-Me$_3$Si(PhS)C=CHCH$_2$BBN, THF, 0 °C, 3h; 5.0 N NaOH, 3.5h (79%); (*e*) methallyl-MgCl, THF-TMEDA, -78 °C (96%).



Extensive experimentation was undertaken in an effort to obtain tricyclic ketone **4** by modifying the conditions

(1) Address correspondence to this author at Montana State University.

(2) Grieco, P. A.; Kaufman, M. D.; Daeuble, J. F.; Saito, N. *J. Am. Chem. Soc.* **1996**, *118*, 2095. Grieco, P. A.; Dai, Y. *J. Am. Chem. Soc.* **1998**, *120*, 5128.

(3) Complete equilibration of **3** to **4** was anticipated because MMX calculations indicated **4** is more stable than **3** by 2.1 kcal.

(4) Cycloadduct **11**, mp 74.5−76.5 °C, crystallizes in space group *Pcan* with cell dimensions at −172 °C of a = 14.120(11) Å, b = 14.598(15) Å, c = 21.349(11) Å, and Z = 8. The volume of the crystal was 4400.50 Å^3 with a density of 1.191 g cm^{-3}. All atoms, including hydrogens, were located and refined to final residuals of R(F) = 0.0571 and R_w(F) = 0.0472. Complete crystallographic data can be obtained from the Molecular Structure Center, Indiana University, Bloomington, IN 47405 (report 96072).

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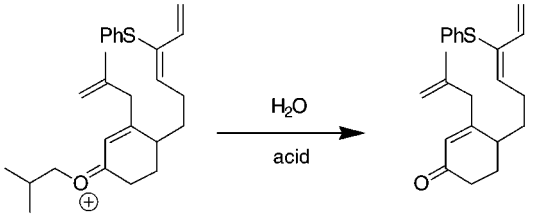
Table 1. Product Distribution in the Cycloaddition of Substrate 1[a]

					yield (%)[b]				
entry	solvent	catalyst	T (°C)	time (min)	**10**	**11**	**12**	**13**	**14**
1	2.0 M $LiClO_4$−Et_2O	10 mol % TFA	rt	60	25	21	24	8	
2	2.0 M $LiClO_4$−Et_2O	10 mol % TFA	0	25	21	24	31	10	
3	1.0 M $LiClO_4$−Et_2O	20 mol % TFA	0	60	21	22	25	5	
4	1.0 M $LiClO_4$−Et_2O	15 mol % HOAc	rt	40	14	17	20	6	30
5	0.5 M $LiClO_4$−Et_2O	10 mol % TFA	0	60	13	13	16	5	32
6	1.0 M $LiClO_4$−EtOAc	10 mol % TFA	0	60	9	4	5	1	49
7	1.0 M $LiClO_4$−EtOAc	10 mol % HOAc	0	120					80
8[c]	CH_2Cl_2	BF_3·Et_2O	−78	90					66
9[d]	CH_2Cl_2	TMSOTf	0	60					71

[a] All of reactions were carried out at 0.01 M in the indicated solvent. [b] Isolated yields. [c] 1.1 equiv of BF_3·Et_2O was employed. [d] Reaction was conducted initially at −78 °C employing 1.1 equiv of 2,6-lutidine and 2.0 equiv of TMSOTf.

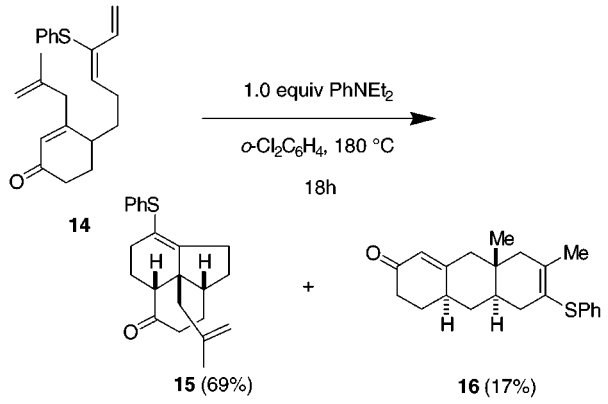
for the cycloaddition of substrate **1** (see Table 1). When various acidic polar media were employed, neither adduct **3** nor **4** could be detected. The table reveals that reducing the polar nature of the medium serves to promote hydrolysis of the intermediate heteroatom-stabilized allyl cation **2**, at the expense of cycloaddition, thus leading to the formation of cyclohexenone **14**. Attempts to promote the Diels−Alder reaction with Lewis acids led exclusively to cyclohexenone formation.



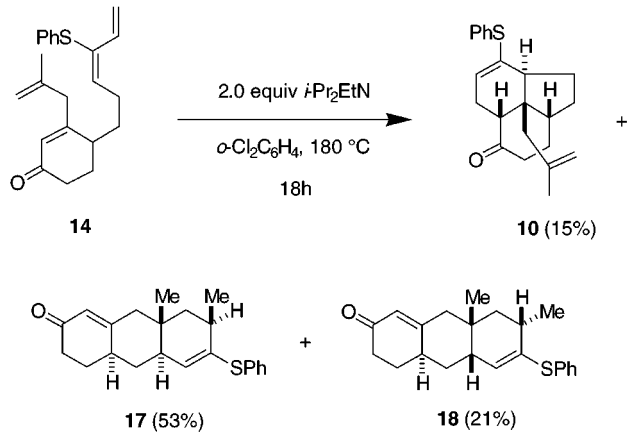
2 **14**

Having been unsuccessful in our attempts to prepare tricyclic ketone **4** from **1**, we directed our attention to the thermal cycloaddition of enone **14**.[5] In an initial experiment, a 0.02 M solution of **14** in 1,2-dichlorobenzene containing 1.0 equiv of diethylaniline was heated at 180 °C in a sealed tube [presilylated with *N*,*O*-bis(trimethylsilyl)acetamide] for 18 h. Workup provided a 69% yield of tricyclic ketone **15**, wherein the enol phenylthioether of the originally formed cycloadduct had migrated, and a 17% yield of crystalline octahydroanthracenone **16**, mp 164.5−165.0 °C, whose structure was established by single-crystal X-ray analysis.[6] Once again, the equilibrated tricyclic ketone **4** or the all-cis cycloadduct **3** could not be detected. The isolation of both **15** and **16** was surprising and raised a number of questions. Of particular concern was the origin of these cycloadducts.

The formation of cycloadduct **15** presumably arises from either **10** or the elusive cycloadduct **3** via isomerization of the enol phenylthioether. To address this issue, the cycloaddition was repeated in the presence of the more basic diisopropylethylamine (DIPEA). Thus, a 0.02 M solution of **14** in 1,2-dichlorobenzene containing 2.0 equiv of DIPEA was heated at 180 °C for 18 h in a sealed



tube which had been pretreated with *N*,*O*-bis(trimethylsilyl)acetamide. As anticipated, the stronger base inhibited migration of the enol phenylthioether in all of the cycloadducts (**10**, **17**, and **18**). We were surprised to find, however, that tricyclic ketone **10**, mp 96.5−97.5 °C, was isolated in only 15% yield, with no trace of the endo-derived product **3** or the more stable equilibrated adduct **4**. Remarkably, the anomalous Diels−Alder adducts **17** and **18** were isolated in a ratio of ca. 2.5:1, respectively, in a combined yield of 74%. The structures of **17** and **18** follow from their respective ^{1}H NMR spectra and difference NOE spectroscopy.



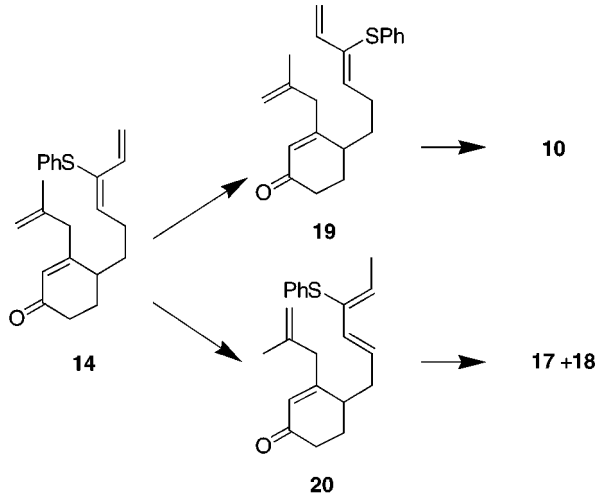
The above results reveal the difficulties associated with the use of (*E*)-thiophenyl butadienes such as **14** in thermal Diels−Alder reactions.[7] It would appear that the

(5) Enone **14** can be prepared in 80% yield employing 1.0 M $LiClO_4$·EtOAc containing 10 mol % acetic acid at 0 °C for 2 h (see Experimental Section).

(6) Cycloadduct **16** crystallizes in space group $P2_1/c$ with cell dimensions at −169 °C of a = 11.776(2) Å, b = 11.812(2) Å, c = 13.535(3) Å, β = 107.10(1)°, and Z = 4. The volume of the crystal was 1799.37 Å^3 with a density of 1.250 g cm^{-3}. All atoms, including hydrogens, were located and refined to final residuals of R(F) = 0.0409 and R_w(F) = 0.0364. Complete crystallographic data can be obtained from the Molecular Structure Center, Indiana University, Bloomington, IN 47405 (report 96116).

(7) The thermal isomerization of thiophenyl-substituted butadienes has been noted previously: Voyle, M.; Kyler, K. S.; Arseniyadis, S.; Dunlap, N. K.; Watt, D. S. *J. Org. Chem.* **1983**, *48*, 470. Grieco, P. A.; Lis, R.; Zelle, R. E.; Finn, J. *J. Am. Chem. Soc.* **1986**, *108*, 5908.

activation energy for the cycloaddition of **14** is sufficiently high that diene isomerization occurs leading to the formation of **19**, the precursor to **10**, and **20**, which gives rise to the octahydroanthracenones **17** and **18**. Further studies are underway to examine the scope of this novel Diels−Alder reaction.



Experimental Section[8]

6-[3-*tert*-Butyldimethylsilyloxy)-propyl)]-3-isobutoxy-2-cyclohexen-1-one (6). A 2.5 M solution of *n*-butyllithium in hexanes (24.0 mL, 60.0 mmol) was slowly added over 6 min to a solution of diisopropylamine (8.41 mL, 60.0 mmol) in 120 mL of THF cooled to −20 °C. After 25 min, the resultant solution was cooled to −78 °C. A solution of vinylogous ester **5**[9] (8.41 g, 50.0 mmol) in 10 mL of THF was added, and the reaction mixture was stirred at −78 °C. After 30 min, HMPA (21.0 mL, 121 mmol) was added. After an additional 5 min, a solution of 3-iodo-*tert*-butyldimethylsilyloxy propane[10] (15.5 g, 51.7 mmol) in 20 mL of THF was added. The reaction mixture was allowed to warm to −20 °C. After 10 h at −20 °C, the reaction mixture was quenched with 5 mL of H_2O and was concentrated to about $^1/_3$ volume. The remaining solution was partitioned between 200 mL of hexanes and 100 mL of H_2O. The aqueous layer was extracted with hexanes, and the combined organic extracts were washed with saturated aqueous brine solution, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The residue was chromatographed on 400 g of silica gel. Elution with hexanes−ethyl acetate (9:1) afforded 9.50 g (56%) of **6** as a colorless oil: R_f 0.59 (hexanes−ethyl acetate, 3:1); IR ($CHCl_3$) 1635, 1605 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.28 (s, 1 H), 3.61 (m, 2 H), 3.56 (d, J = 6.6 Hz, 2 H), 2.46−2.39 (m, 2 H), 2.17 (m, 1 H), 2.06 (m, 1 H), 2.00 (m, 1 H), 1.84 (m, 1 H), 1.72 (m, 1 H), 1.65−1.46 (m, 2 H), 1.40 (m, 1 H), 0.95 (d, J = 6.9 Hz, 6 H), 0.87 (s, 9 H), 0.03 (s, 6 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.5, 176.8, 102.1, 74.6, 63.3, 44.9, 30.3, 27.8, 27.7, 26.2, 25.9, 25.8, 19.0, 18.3, −5.3; HRMS (CI) calcd for $C_{19}H_{37}O_3Si$ (M + 1) *m/e* 341.25131, found 341.25157.

6-(3-Hydroxy-propyl)-3-isobutoxy-2-cyclohexen-1-one (7). To a solution of silyl ether **6** (6.30 g, 18.5 mmol) in 20 mL of THF cooled to 0 °C was added a 1.0 M solution of TBAF in THF (28 mL, 28 mmol). The resultant solution was allowed to warm to ambient temperature overnight. The reaction mixture was poured into 75 mL of H_2O. The aqueous layer was extracted with Et_2O. The combined organic extracts were washed with H_2O and saturated aqueous brine solution, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The residue was chromatographed on 150 g of silica gel. Elution with ethyl acetate−hexanes (3:1) containing 0.1% triethylamine afforded 4.14 g (99%) of alcohol **7** as a colorless oil: R_f 0.42 (ethyl acetate); IR ($CHCl_3$) 3640, 3430, 1650, 1615 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.31 (s, 1 H), 3.63 (q, J = 6.0 Hz, 2 H), 3.58 (d, J = 6.6 Hz, 2 H), 2.45 (dd, J = 7.2, 5.4 Hz, 2 H), 2.24 (m, 1 H), 2.11−1.97 (m, 3 H), 1.87 (m, 1 H), 1.76 (m, 1 H), 1.71−1.49 (m, 3 H), 0.97 (d, J = 6.4 Hz, 6 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.9, 177.3, 102.1, 74.7, 62.3, 44.7, 30.1, 28.0, 27.7, 26.5, 25.5, 19.0; HRMS (CI) calcd for $C_{13}H_{23}O_3$ (M + 1) *m/e* 227.16483, found 227.16431.

3-(4-Isobutoxy-2-oxo-cyclohex-3-enyl)-propionaldehyde (8). A solution of alcohol **7** (1.79 g, 7.90 mmol) in 30 mL of THF was cooled to −78 °C and degassed, back-filling with argon. To this solution was added a 1.0 M solution of vinylmagnesium bromide (8.5 mL, 8.5 mmol) in THF. After 30 min at −78 °C, 1,1′-(azodicarbonyl)dipiperidine[11] (2.16 g, 8.56 mmol) was added in 30 mL of THF. The resultant deep red solution was allowed to slowly warm to 0 °C over 3 h. The reaction was quenched with H_2O (5.0 mL) and acidified with 1 N HCl (6 mL). The resultant mixture was partitioned between hexanes (100 mL) and H_2O (50 mL). The aqueous layer was extracted with ethyl acetate, and the combined organic extracts were washed with saturated aqueous brine, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The product was purified by chromatography on 150 g of silica gel. Elution with hexanes−ethyl acetate (2:1) afforded 1.40 g (79%) of aldehyde **8** as a colorless oil: R_f 0.60 (ether); IR ($CHCl_3$) 1730, 1650, 1615 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 9.77 (t, J = 1.6 Hz, 1 H), 5.28 (s, 1 H), 3.56 (m, 2 H), 2.57 (td, J = 7.6, 1.6 Hz, 2 H), 2.44 (m, 2 H), 2.22 (m, 1 H), 2.13−1.96 (m, 3 H), 1.80−1.68 (m, 2 H), 0.97 (d, J = 6.6 Hz, 3 H), 0.95 (d, J = 6.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.2, 200.5, 177.0, 102.1, 74.7, 44.2, 41.6, 28.0, 27.6, 26.8, 22.3, 19.0; HRMS (EI) calcd for $C_{13}H_{20}O_3$ (M+) *m/e* 224.1413, found 224.1414.

3-Isobutoxy-6-(4-phenylsulfanyl-hexa-3(*E*),5-dienyl)-2-cyclohexen-1-one (9). A solution of freshly distilled 1-phenylthio-1-trimethylsilyl allene (1.54 g, 7.00 mmol) in 7.0 mL of THF was treated with a 0.5 M solution of 9-borabicyclo[3.3.1]-nonane in THF (9.75 mmol, 4.88 mmol).[12] The resultant solution was heated in an oil bath for 12 h at 35 °C. After the mixture cooled to 0 °C, a solution of aldehyde **8** (1.51 g, 6.72 mmol) in 12 mL of THF was added, and stirring was continued at 0 °C. After 3 h, 5.0 N aqueous sodium hydroxide solution (3.0 mL) was added, and the reaction mixture was warmed to ambient temperature. After an additional 3.5 h, the reaction was poured into 150 mL of pentane and washed with water and saturated aqueous brine solution. The organic layer was dried over anhydrous $MgSO_4$ and concentrated in vacuo. The residue was chromatographed on 200 g of silica gel. Elution with hexanes−dichloromethane−ethyl acetate (15:4:1) afforded 1.90 g (79%) of (*E*)-diene **9** as a colorless oil: R_f 0.48 (hexanes−ethyl acetate, 3:1); IR($CHCl_3$) 1645, 1610 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.24−7.21 (m, 4 H), 7.15 (m, 1 H), 6.72 (ddd, J = 16.7, 10.7, 0.8 Hz, 1 H), 6.17 (t, J = 7.2 Hz, 1 H), 5.65 (br d, J = 16.7 Hz, 1 H), 5.31 (s, 1 H), 5.21 (br d, J = 10.7 Hz, 1 H), 3.58 (m, 2 H), 2.48−2.38 (m, 4 H), 2.22 (m, 1 H), 2.12−1.97 (m, 3 H), 1.75 (m, 1 H), 1.51 (m, 1 H), 0.97 (d, J = 6.6 Hz, 6 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.9, 176.9, 141.9, 130.2, 128.7, 128.1, 125.6, 118.8,

(8) Proton and carbon nuclear magnetic resonance spectra were recorded on Varian VXR 400 MHz or Bruker DPX 300 MHz spectrometers. Chemical shifts are reported in parts per million (δ) relative to tetramethylsilane (δ 0.0). Infrared spectra were taken on a Perkin-Elmer Model 298 spectrophotometer, a Mattson Galaxy 4020 series FTIR spectrometer, or a Perkin-Elmer model 1600 FTIR. High-resolution mass spectra were obtained on a VG Instuments 70E-HF mass spectrometer. Elemental analyses were performed by Robertson Microlit Laboratories, Inc., Madison, NJ. Melting points were obtained on a Fisher-Johns hot-stage or a MEL-TEMP capillary melting point apparatus and are uncorrected. Reactions were monitored by thin-layer chromatography using E. Merck precoated silica gel 60 F-254 (0.25 mm) plates. Plates were visualized by immersion in *p*-anisaldehyde solution or phosphomolybdic acid solution. E. Merck precoated silica gel 60 F-254 (0.50 mm) plates were used for preparative plate chromatography. E. Merck silica gel 60 (230−400 mesh) was used for chromatography. Anhydrous lithium perchlorate was purchased and was further dried at 180 °C under high vacuum for 24 h prior to use.

(9) Cf. Stork, G.; Danheiser, R. L. *J. Org. Chem.* **1973**, *38*, 1775.

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(11) Narasaki, K.; Morikawa, A.; Saigo, K.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1997**, *500*, 2773.

(12) Pearson, W. H.; Lin, K.-C.; Poon, Y.-F. *J. Org. Chem.* **1989**, *54*, 5814.

102.3, 74.8, 44.5, 29.3, 28.1, 27.7, 26.6, 26.6, 19.1; HRMS (EI) calcd for $C_{22}H_{28}O_2S$ (M+) *m/e* 356.18114, found, 356.18096.

8b*β*-(2-Methyl-allyl)-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6,-8aα,8b*β*-octahydro-1*H*-acenaphthylene-5-one (10), 5α-Isobutoxy-10-methyl-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6,8aα,8b*β*-octahydro-1*H*-5*β*,8b*β*-prop-9-enoacenaphthylene (11), 5α-Isobutoxy-10-methyl-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6, 8aα,-8b*β*-octahydro-1*H*-5*β*,8b*β*-prop-10-enoacenaphthylene (12), and 5α-Isobutoxy-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6,8aα,8b*β*-octahydro-1*H*-5*β*,8b*β*-propanoacenaphthylen-10-ylidene (13). A 25 mL round-bottom flask was charged with magnesium turnings (82 mg, 3.3 mmol). THF (3.0 mL) was added, and the mixture was chilled to 0 °C. Freshly distilled 3-chloro-2-methylpropene (0.30 mL, 3.04 mmol) was added portionwise over 90 min, and the resultant solution was allowed to stir at 0 °C. After 1 h, the Grignard solution was cooled to −78 °C. TMEDA (1.0 mL, 6.62 mmol) was added, and the resultant slurry was stirred 30 min at −78 °C followed by the addition of a solution of vinylogous ester **9** (200 mg, 0.56 mmol) in 7.1 mL of THF. After 15 min, the bright yellow reaction mixture was quenched with H_2O and poured into 40 mL of Et_2O. The organic layer was washed with H_2O, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was taken up in pentane and washed with H_2O and saturated aqueous brine solution. The organic layer was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure to afford 224 mg (96%) of alcohol **1** as a colorless oil, which was used directly in the next reaction.

A solution of the above alcohol **1** (109 mg, 0.264 mmol) in anhydrous Et_2O (1.3 mL) was added dropwise via syringe pump over 9 min to 2.0 M $LiClO_4$−Et_2O (13.0 mL) containing TFA (2.0 mL, 0.026 mmol). After a total of 1 h, the reaction was quenched by the addition of Et_3N (25 mL). The reaction mixture was diluted with H_2O, and the product was extracted with CH_2Cl_2. The combined organic extracts were dried over anhydrous $MgSO_4$ and concentrated in vacuo. The residue was chromatographed on 25 g of silica gel. Elution with hexanes−ether (9:1) afforded 59 mg of a mixture of **11**−**13**. Further elution afforded 25 mg (25%) of cycloadduct **10**. Separation of **11**−**13** by preparative thin-layer chromatography (hexanes−ether, 49:1) afforded 22.1 mg (21%) of **11**, 24.5 mg (24%) of **12**, and 7.9 mg (8%) of **13**.

10: R_f 0.45 (hexanes−ether, 3:1); IR ($CHCl_3$) 1710, 1640, 1590 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.31−7.24 (m, 4 H), 7.18 (m, 1 H), 5.83 (q, J = 3.5 Hz, 1 H), 4.97 (s, 1 H), 4.75 (s, 1 H), 3.05 (dt, J = 19.7, 3.2 Hz, 1 H), 2.89 (d, J = 7.8 Hz, 1 H), 2.60 (m, 1 H), 2.52 (dt, J = 10.9, 7.0 Hz, 1 H), 2.39 (td, J = 13.0, 5.6 Hz, 1 H), 2.27 (dt, J = 13.0, 3.7 Hz, 1 H), 2.14 (d, J = 14.1 Hz, 1H), 2.13 (m, 1 H), 2.04−1.95 (m, 2 H), 1.93 (d, J = 14.2 Hz, 1 H), 1.92 (s, 3 H), 1.65−1.54 (m, 3 H), 1.27 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 212.0, 143.0, 135.3, 131.0, 130.1, 130.0, 128.9, 126.4, 115.7, 53.0, 48.2, 44.4, 39.9, 38.8, 38.3, 31.9, 27.6, 25.5, 23.8, 23.3. An analytical sample was prepared by recrystallization from hexanes, mp 96.5−97.5 °C. Anal. Calcd for $C_{22}H_{26}OS$: C, 78.06; H, 7.74. Found: C, 77.91; H, 7.64.

11: IR ($CHCl_3$) 1590, 1465 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.33−7.24 (m, 4 H), 7.17 (m, 1 H), 6.21 (dd, J = 6.8, 1.7 Hz, 1 H), 5.28 (s, 1 H), 3.20 (m, 2 H), 2.50−2.42 (m, 2 H), 2.26−2.14 (m, 2 H), 2.05−1.98 (m, 3 H), 1.90 (dd, J = 12.3, 5.0 Hz, 1 H), 1.82 (m, 9 H), 1.47 (m, 1 H), 1.18 (m, 1 H), 0.92(d, J = 6.6 Hz, 3 H), 0.91(d, J = 6.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.4, 136.3, 135.8, 135.7, 129.5, 128.9, 127.2, 126.8, 75.1, 67.4, 49.6, 47.2, 46.8, 45.3, 43.3, 32.8, 31.4, 29.3, 26.0, 23.1, 23.0, 19.6, 19.5. An analytical sample was prepared by recrystallization from hexanes, mp 74.5−76.5 C. Anal. Calcd for $C_{26}H_{34}OS$: C, 79.14; H, 8.68. Found: C, 79.15; H, 8.67.

12: IR ($CHCl_3$) 1590, 1470 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.34 (br d, J = 8.1 Hz, 2 H), 7.30 (br t, J = 8.1 Hz, 2 H), 7.20 (br t, J = 7.0 Hz, 1 H), 6.16 (dd, J = 6.3, 2.1 Hz, 1 H), 5.26 (s, 1 H), 3.09 (m, 2 H), 2.34 (br d, J = 8.1 Hz, 1 H), 2.22 (dt, J = 18.0, 6.0 Hz, 1 H), 2.11 (m, 1 H), 2.08 (br d, J = 16.9 Hz, 1 H), 1.97 (dd, J = 11.3, 6.0 Hz, 1 H), 1.94 (m, 1 H), 1.85−1.63 (m, 7 H), 1.66 (s, 3 H), 1.48 (m, 2 H), 1.27 (m, 1 H), 0.92 (d, J = 6.5 Hz, 3 H), 0.91 (d, J = 6.5 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.2, 135.5, 135.4, 133.2, 130.2, 130.1, 128.9, 126.3, 78.7, 68.3, 49.8, 49.7, 46.1, 45.0, 39.2, 34.4, 33.1, 29.6, 29.1, 25.5, 25.3, 23.1, 19.7 (2C). An analytical sample was prepared by recrystallization from pentane, mp 58.5−59.5 °C. Anal. Calcd for $C_{26}H_{34}OS$: C, 79.14; H, 8.68. Found: C, 79.18; H, 8.69.

13: IR ($CHCl_3$) 1590, 1460 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, J = 7.6 Hz, 2 H), 7.28 (t, J = 7.6 Hz, 2 H), 7.18 (t, J = 7.6 Hz, 1 H), 6.20 (br d, J = 6.0 Hz, 1 H), 4.76 (s, 1 H), 4.67 (s, 1 H), 3.17 (m, 2 H), 2.48 (dt, J = 18.9, 6.0 Hz, 1 H), 2.32 (br d, J = 7.6 Hz, 1 H), 2.30 (ABquartet, J = 12.3 Hz, $\Delta\nu$ = 36.7 Hz, 2 H), 2.12 (dd, J = 18.9, 11.3 Hz, 1 H), 2.04 (dd, J = 12.6, 5.4 Hz, 1 H), 1.97 (ABquartet, J = 12.6 Hz, $\Delta\nu$ = 14.5 Hz, 1 H), 1.86 (dd, J = 11.3, 6.0 Hz, 1 H), 1.80−1.49 (m, 7 H), 1.39 (m, 1 H), 0.92 (d, J = 6.6 Hz, 3 H), 0.91 (d, J = 6.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.5, 135.7, 134.9, 134.5, 129.9, 128.9, 126.2, 111.8, 77.0, 67.3, 52.1, 50.3, 48.0, 46.1, 44.2, 42.4, 34.6, 30.9, 30.1, 29.3, 26.7, 25.4, 19.7, 19.6; HRMS (EI) calcd for $C_{26}H_{34}OS$ (M+) *m/e* 394.23322, found, 394.23409.

3-(2-Methyl-allyl)-4-(4-phenylsulfanyl-hexa-3(*E*),5-dienyl)-2-cyclohexen-1-one (14). To a solution of substrate **1** (80 mg, 0.19 mmol) in anhydrous EtOAc (12.0 mL) cooled to 0 °C was added 3.0 M $LiClO_4$−EtOAc (6.0 mL) followed by glacial acetic acid (1.1 mL). After 2 h at 0 °C, the reaction was quenched with Et_3N (15 mL). The reaction mixture was poured into H_2O, and the product was isolated by extraction with CH_2Cl_2. The combined organic extracts were washed with brine, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The crude enone was chromatographed on silica gel. Elution with hexanes−ether (2:1) afforded 53 mg (80%) of pure **14** as an oil: R_f 0.31(hexanes−ethyl acetate, 4:1); IR ($CHCl_3$) 1670, 1625, 1590 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.26−7.23 (m, 4 H), 7.15 (m, 1 H), 6.67 (ddd, J = 16.7, 10.7, 0.6 Hz, 1 H), 6.11 (t, J = 7.6 Hz, 1 H), 5.90 (d, J = 16.7 Hz, 1 H), 5.86 (s, 1 H), 5.26 (d, J = 10.7 Hz, 1 H), 4.90 (s, 1 H), 4.78 (s, 1 H), 2.96 (d, J = 15.1 Hz, 2 H), 2.86 (d, J = 15.1 Hz, 2 H), 2.53−2.29 (m, 5 H), 2.09−1.94 (m, 2 H), 1.77−1.59 (m, 2 H), 1.68 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.2, 166.4, 141.1, 140.0, 136.1, 131.8, 129.9, 128.8, 128.5, 127.1, 125.9, 119.5, 114.4, 44.7, 36.6, 33.2, 29.8, 27.2, 25.6, 22.2; HRMS (EI) calcd for $C_{22}H_{26}OS$ (M+) *m/e* 338.17058, found 338.17111.

8b*β*-(2-Methyl-allyl)-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6,7,-8b*β*-octahydro-1*H*-acenaphthylene-5-one (15) and 7,8a*β*-Dimethyl-6-phenylsulfanyl-4,4aα,5,8,8a*β*,9,10,10aα-octahydro-3*H*-anthracen-2-one (16). A 10 mL culture tube with a Teflon-lined cap was charged with 1 mL of *N*,*O*-bis-(trimethylsilyl)acetamide and heated to 180 °C for 2 h. The cooled tube was rinsed thoroughly with CH_2Cl_2 and dried in vacuo. A solution of enone **14** (34.5 mg, 0.102 mmol) in 5.1 mL of anhydrous 1,2-dichlorobenzene was added followed by the addition of diethylaniline (18.0 μL, 0.114 mmol). The tube was sealed and heated to 180 °C. After 18 h, the reaction mixture was cooled to room temperature and applied directly to 45 g of silica gel. Elution with hexanes afforded a forerun of 1,2-dichlorobenzene. Further elution with hexanes−ethyl acetate (8:1) afforded 24.0 mg (69%) of cycloadduct **15** as a colorless film: R_f 0.45 (hexanes−ether, 3:1); IR ($CHCl_3$) 1705, 1645, 1590 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.27−7.23 (m, 2 H), 7.17−7.13 (m, 3 H), 4.98 (s, 1 H), 4.78 (s, 1 H), 2.74 (dd, J = 4.3, 3.2 Hz, 1 H), 2.68 (m, 1 H), 2.57−2.29 (m, 5 H), 2.29−2.21 (m, 3 H), 2.11 (m, 1 H), 2.00 (m, 1 H), 1.91−1.72 (m, 2 H), 1.88 (s, 3 H), 1.45 (m, 1 H), 1.36 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.5, 149.7, 142.5, 135.0, 129.3, 128.8, 125.9, 123.4, 116.0, 53.9, 46.7, 44.5, 41.4, 40.5, 29.6, 27.3, 26.9, 25.2, 18.9; HRMS (EI) calcd for $C_{22}H_{26}OS$ (M+) *m/e* 338.17058, found 338.17048.

Further elution with hexanes−ethyl acetate (3:1) afforded 6.0 mg of **16** as a crystalline solid: R_f 0.30 (hexanes−ethyl acetate, 3:1); IR ($CHCl_3$) 1665, 1640, 1590 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.28−7.19 (m, 4 H), 7.15 (br t, J = 7.3 Hz, 1 H), 5.84 (s, 1 H), 2.39 (dt, J = 16.4, 4.6 Hz, 1 H), 2.37−2.24 (m, 3 H), 2.23−1.98 (m, 5 H), 1.97 (s, 3 H), 1.94−1.76 (m, 2 H), 1.71 (m, 1 H), 1.61 (m, 1 H), 1.06 (dt, J = 13.1, 12.0 Hz, 1 H), 0.77 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.7, 164.5, 139.7, 136.4, 128.9, 128.4, 126.0, 125.5, 121.8, 49.7, 48.7, 40.3, 37.4, 36.6, 36.2, 35.7, 35.0, 29.0, 21.7, 17.3. An analytical sample was prepared by recrystallization from ether, mp 164.5−166.0 °C. Anal. Calcd for $C_{22}H_{26}SO$: C, 78.06; H, 7.74. Found: C, 77.97; H, 7.82.

8b*β*-(2-Methyl-allyl)-8-phenylsulfanyl-2,2a*β*,3,4,5a*β*,6,-8aα,8b*β*-octahydro-1*H*-acenaphthylene-5-one (10), 7*β*,8a*β*-Dimethyl-6-phenylsulfanyl-4,4aα,7,8,8a*β*,9,10,10aα-octahydro-3*H*-anthracen-2-one (17), and 7α,8a*β*-Dimethyl-6-phenylsulfanyl-4,4aα,7,8,8a*β*,9,10,10a*β*-octahydro-3*H*-

anthracen-2-one (18). A 20 mL culture tube with a Teflon-lined cap was charged with 4.0 mL of *N*,*O*-bis(trimethylsilyl)acetamide and heated to 180 °C for 2 h. The cooled tube was rinsed thoroughly with CH_2Cl_2 and dried in vacuo. A solution of enone **14** (22 mg, 0.065 mmol) in 6.5 mL of anhydrous 1,2-dichlorobenzene was added to the culture tube followed by diisopropylethylamine (23 μL, 0.13 mmol). The tube was sealed and heated to 180 °C. After 18 h, the reaction mixture was cooled to ambient temperature, and the solvent was removed in vacuo with gentle heating (40−45 °C). The residue was purified by preparative thin-layer chromatography. Elution with hexanes−ethyl acetate (4:1) afforded 3.3 mg (15%) of **10**, which was identical in all respects with the sample of **10** prepared above, 4.7 mg (21%) of **18**, and 11.7 mg (53%) of **17**.

17: R_f 0.30 (hexanes−ethyl acetate, 3:1); IR ($CHCl_3$) 1660, 1630, 1590 cm^{-1}; ^{1}H NMR (500 MHz, C_6D_6) δ 7.44 (d, J = 7.8 Hz, 2 H), 7.06 (t, J = 7.7 Hz, 2 H), 6.96 (t, J = 7.8 Hz, 1 H), 5.87 (s, 1 H), 5.65 (s, 1 H), 2.43 (m, 1 H), 2.31 (dt, J = 16.2, 3.7 Hz, 1 H), 1.96 (td, J = 16.2, 5.3 Hz, 1 H), 1.76 (br d, J = 13.4 Hz, 1 H), 1.69 (d, J = 14.1 Hz, 1 H), 1.60 (m, 1 H), 1.45 (d, J = 14.1 Hz, 1 H), 1.41 (dq, J = 13.4, 4.9 Hz, 1 H), 1.34 (dd, J = 13.7, 8.2 Hz, 1 H), 1.23 (d, J = 7.4 Hz, 3 H), 1.17−1.04 (m, 3 H), 0.66 (dt, J = 11.6, 13.4 Hz, 1 H), 0.53 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.6, 164.9, 137.1, 135.0, 134.3, 130.8, 128.9, 127.4, 126.7, 49.5, 44.9 (2 C), 37.9, 37.2, 34.7, 34.3, 32.1, 29.4, 21.2, 18.9. An analytical sample was prepared by recrystallization from pentane−ether, mp 134.0−136.0 °C (dec). Anal. Calcd for $C_{22}H_{26}SO$: C, 78.06; H, 7.74. Found: C, 77.97; H, 7.70.

18: R_f 0.35 (hexanes−ethyl acetate, 3:1); IR ($CHCl_3$) 1660, 1630, 1590 cm^{-1}; ^{1}H NMR (500 MHz, C_6D_6) δ 7.41 (d, J = 7.4 Hz, 2 H), 7.05 (t, J = 7.7 Hz, 2 H), 6.94 (t, J = 7.4 Hz, 1 H), 5.86 (s, 1 H), 5.76 (dd, J = 3.5, 2.1 Hz, 1 H), 2.31 (dt, J = 15.7, 3.7 Hz, 1 H), 2.30 (m, 1 H), 1.98 (ddd, J = 15.5, 14.1, 5.1 Hz, 1 H), 1.90 (br d, J = 13.4 Hz, 1 H), 1.75 (m, 1 H), 1.52 (m, 1 H), 1.42 (br, d, J = 13.0 Hz, 1 H), 1.30−1.12 (m, 4 H), 1.14 (d, J = 6.4 Hz, 3 H), 1.04 (dd, J = 13.4, 6.8 Hz, 1 H), 0.95 (ddd, J = 13.7, 6.0, 3.9 Hz, 1 H), 0.63 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.6, 166.8, 137.5, 135.2 (2 C), 130.6, 129.0, 126.6, 126.1, 44.9, 43.5, 41.8, 37.3, 35.4, 34.8, 34.5, 30.9, 29.2, 26.3, 20.5. An analytical sample was prepared by recrystallization from pentane−ether, mp 175.0−177.0 °C. Anal. Calcd for $C_{22}H_{26}SO$: C, 78.06; H, 7.74. Found: C, 77.80; H, 7.75.

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Supporting Information Available: Photocopies of the ^{1}H and ^{13}C NMR spectra for compounds **6**−**9**, **13**, and **14**. This material is available free of charge via the Internet at http://pubs.acs.org.

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