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Oxidative Cyclization of Unsaturated Ketene Dithioacetals with Ceric Ammonium Nitrate to Form Bicyclic Lactones

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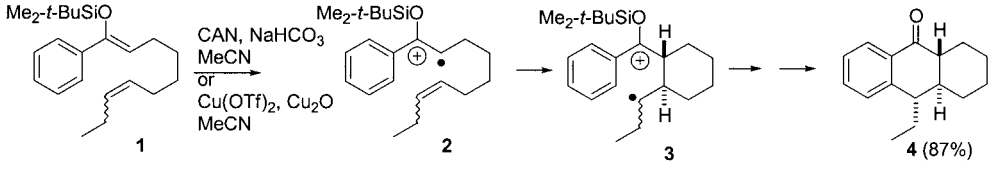
Abstract—Ceric ammonium nitrate oxidizes unsaturated ketene dithioacetals in wet MeCN to give cation radicals that cyclize to trisubstituted double bonds and styrenes by cation-like cyclizations leading to cyclic cation radicals that are transformed by further oxidation, hydrolysis and cyclization to bicyclic lactones in moderate to good yield.

Introduction

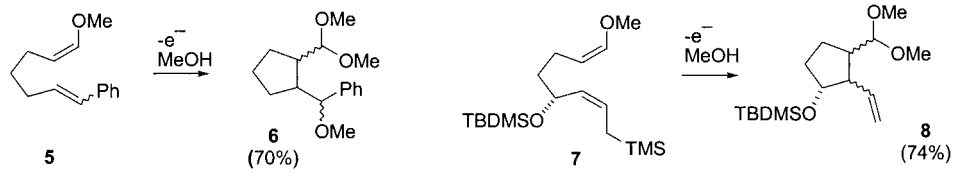
Oxidation of both alkyl and silyl enol ethers provides an attractive route to cation radicals that can be trapped intramolecularly with alkenes, enol ethers, vinylsilanes, allylsilanes, and electron rich aromatic rings.[1] These oxidations can be carried out with one-electron oxidants, electrochemically,[1c] or by photochemical electron transfer by irradiation in the presence of dicyanoanthracene. For instance, we found that oxidation of silyl enol ether **1** with either ceric ammonium nitrate (CAN) and $NaHCO_3$ or $Cu(OTf)_2$ and Cu_2O in MeCN generated cation radical **2** that cyclized to give cation radical **3**. Desilylation, cyclization and oxidation afforded **4** stereoselectively in 87% yield (Scheme 1).[2] Livinghouse has recently shown that $(CF_3CH_2O)VOCl_2$ is a very effective oxidant for related cyclizations and oxidative coupling of enol silyl ethers.[3]

Moeller has developed electrochemical oxidative cyclizations of unsaturated enol ethers.[1c,4,5] For instance, oxidation of styrene enol ether **5** afforded 70% of cyclopentane **6** as a mixture of isomers,[4] while oxidation of allylsilane enol ether **7** provided 74% of **8** as a mixture of isomers (Scheme 2).[5]

Mattay has developed photochemical electron transfer (PET) as a method for generation of cation radicals from enol ethers.[6] Irradiation of silyl enol ether **9** and dicyanoanthracene (DCA) formed cation radical **10** by electron transfer to the excited state of DCA. Cyclization gave **11**, which lost TMS to give ketone radical **12**. Unfortunately, radical **12** was reduced to afford 25% of decalone **13** by the DCA radical anion generated by the oxidation of **10**, so that the radical functionality is lost by reduction in PET oxidative cyclization of unsaturated silyl enol ethers (Scheme 3).



Scheme 1.



Scheme 2.

Keywords: cation-like cyclization; ceric ammonium nitrate; bicyclic lactones.

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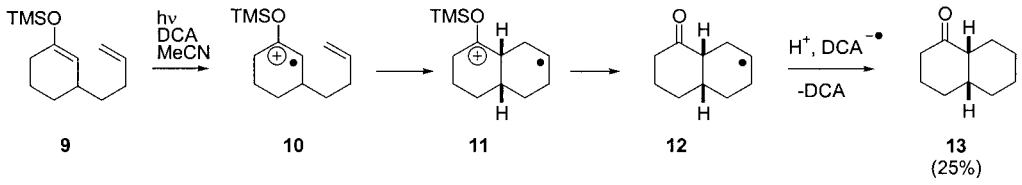


Scheme 3.

Strong oxidants are required for the oxidation of enol ethers. Ketene acetals are more electron rich than enol ethers and should therefore be more readily oxidized. Unfortunately, they are very hydrolytically unstable and initial attempts at oxidative cyclizations of unsaturated ketene acetals resulted only in hydrolysis to the ester.[2] Readily available ketene dithioacetals are relatively stable but should be more easily oxidized than enol ethers because the double bond is substituted by two sulfur atoms that are electron donating by resonance. We therefore prepared a variety of unsaturated ketene dithioacetals and examined their oxidative cyclizations with a variety of one-electron oxidants.

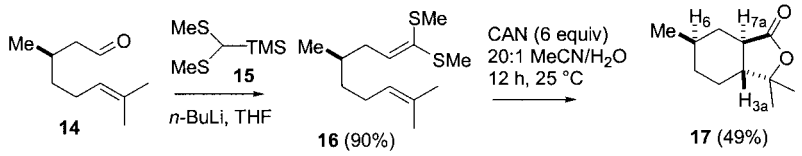
Results and Discussion

Ketene dithioacetal **16** was prepared in one step in 90% yield by Seebach's procedure from citronellal (**14**) by a Peterson reaction with the lithium salt of bis(methylthio)trimethylsilylmethane (**15**).[7] Slow addition of ketene dithioacetal **16** over 4 h to 6 equiv. of CAN in 19:1 MeCN/H_2O and stirring overnight afforded 49% of bicyclic lactone **17** stereoselectively as the only characterizable product. Rapid addition of **16** gave 30% of **17**, suggesting that dimerization may be a side reaction in concentrated solution. Although the oxidation requires only 2 equiv. of CAN in principal, excess CAN was needed since the sulfur byproducts were oxidized by CAN. $MeSSO_2Me$,[8] which can be formed by oxidation of MeSH with 6 equiv. of CAN, was obtained as a minor byproduct in some reactions. Since the two oxygens of **17** are derived from water, lower yields of **17** were obtained if water was not added as a cosolvent. Comparable yields of **17** were obtained in MeCN containing 2–10% water. The reaction was most successfully carried out in air. For reasons that are not clear, lower yields were obtained under either N_2 or O_2 atmospheres (Scheme 4).

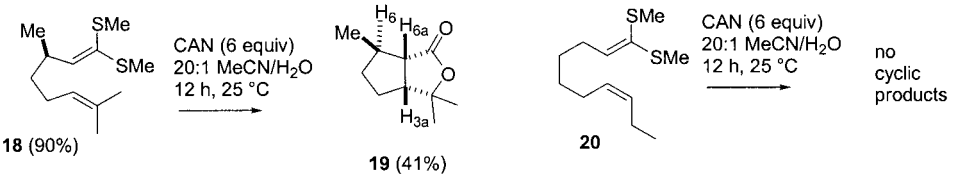
Lower yields were obtained using $Mn(OAc)_3 \cdot 2H_2O$ in 17:2:1 MeCN/TFA/H_2O.[9] Oxidative cyclization does not occur with $Cu(NO_3)_2$, $K_3Fe(CN)_6$, $[FeCl_2(DMF)_2][FeCl_4]$, or Ag_2CO_3 on celite. $Cu(OTf)_2$,[2] $VOCl_3$, and (CF_3CH_2O)-$VOCl_2$ were not investigated since these oxidants are not compatible with water. Lower yields of lactone **17** were obtained from the ketene dithioacetal obtained by Peterson reaction of **14** with 2-trimethylsilyl-1,3-dithiane.[7] These oxidative cyclizations also gave more complex mixtures because the byproducts derived from 1,3-propanedithiol were not volatile or water soluble. The ketene dithioacetal obtained by a Peterson reaction with bis(phenylthio)trimethylsilane was less electron rich and did not react with CAN to give lactone **17**.

Ketene dithioacetal **18** was prepared analogously to **16** in 85% yield. Slow addition over 4 h to excess CAN in 19:1 MeCN/H_2O afforded 40% of the known lactone **19**[10] stereoselectively as the only isolable product. No cyclic products were obtained by oxidation of ketene dithioacetal **20**, which was prepared analogously from 6-nonenal, indicating that a moderately electron rich double bond is needed for oxidative cyclization to occur (Scheme 5).

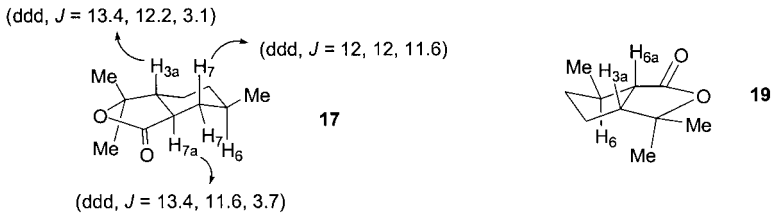
The stereochemistry of lactone **17** was unambiguously established by analysis of the coupling constants. The 13.4 Hz coupling constant between H_{3a} and H_{7a} established that both of these hydrogens are axial on the cyclohexane ring. The axial H_7 absorbs at δ 1.00 (ddd, 1, J=12, 12, 11.6 Hz). The large geminal and two large vicinal coupling constants indicate that the methyl group is equatorial on the cyclohexane ring. The stereochemistry of **19** was established by a 1D NOESY experiment. Irradiation of the methyl doublet at δ 1.15 showed strong NOEs to H_6 at δ 2.4 and H_{6a} at δ 2.76 and a weak NOE to H_{3a} at δ 2.58, indicating that the methyl group, H_{3a}, and H_{6a} are on the same face of **19** (Scheme 6).



Scheme 4.



Scheme 5.



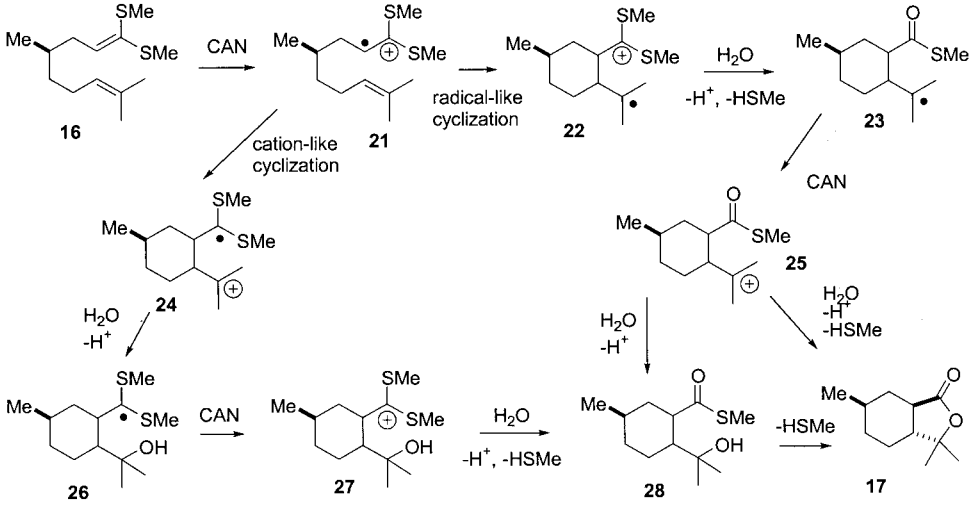
Scheme 6.

There are two fundamentally different mechanisms by which these cyclizations can occur, which are discussed for **16** as a representative example. Oxidation of **16** will give cation radical **21**, which can undergo a radical-like cyclization to give **22** as occurs in the oxidative cyclization of enol silyl ether **1** and PET cyclization of **9**. Reaction of **22** with water and loss of a proton and MeSH will give thioester radical **23**, which can be oxidized to thioester cation **25**. Reaction with water to give alcohol thioester **28** and cyclization will provide lactone **17**.

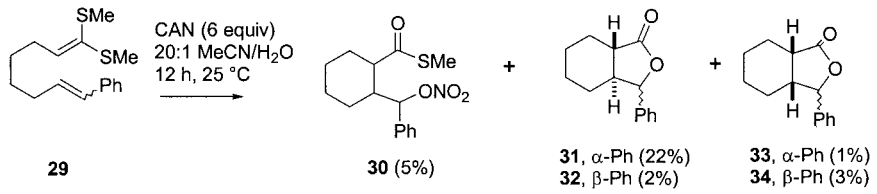
Alternatively, cation radical **21** can undergo a cation-like cyclization to give **24**, which will react with water to give alcohol radical **26**. Oxidation of **26** will afford alcohol cation **27**, which will react with water with loss of a proton and MeSH to afford alcohol thioester **28**. The failure of the less nucleophilic 1,2-disubstituted alkene of **20** to cyclize suggests that cation radical **21** cyclizes by the cation-like pathway to provide **24** since the electronic character of the double bond should be less important in radical-like cyclizations. The reactivity of cation radicals obtained from ketene dithioacetals are thus very different from the cation radicals obtained from enol ethers, which add to 1,2-disubstituted double bonds as in the formation of **4**.[2] This suggests that cation-radicals obtained from ketene dithioacetals undergo cation-like cyclizations, while cation-radicals obtained from enol ethers undergo radical-like cyclizations (Scheme 7).

Styrenes are sufficiently nucleophilic to react with the cation radicals obtained from ketene dithioacetals. Ketene dithioacetals **29** and **35** were obtained in 85 and 82% yield from 7-phenyl-6-heptenal[4] and 6-phenyl-5-hexenal,[4] respectively, as mixtures of stereoisomers. Slow addition of **29** to CAN in 19:1 MeCN/H_2O afforded 22% of the known lactone **31**[11] and traces of the known lactones **32**–**34**[11] in the yields indicated. Nitrate thioester **30** was also isolated in 5% yield. Similar product mixtures were obtained from the pure *cis* and *trans* isomers of **29**.

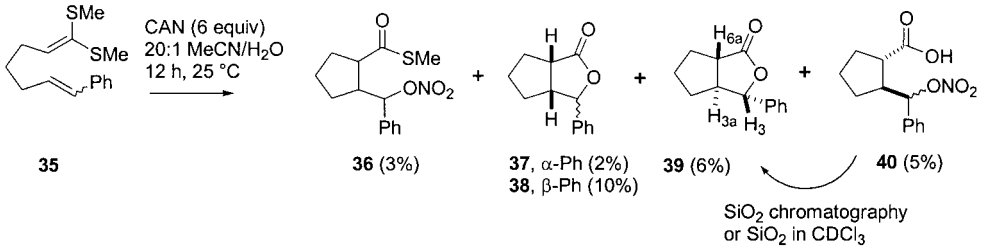
The presence of the thioester of **30** was established by the methyl singlet at δ 2.36, the carbonyl carbon at δ 202.2, and the carbonyl absorption at 1686 cm^{-1}. The presence of the nitrate of **30** was established by the absorptions at 1637 and 1281 cm^{-1}. The isolation of the nitrate indicates that the benzylic cation analogous to either **24** or **25** can be trapped



Scheme 7.



Scheme 8.



Scheme 9.

by nitrate instead of water. Formation of nitrate esters in CAN oxidations is well known (Scheme 8).[2,12]

Slow addition of **35** to CAN in 19:1 MeCN/H_2O afforded 3% of the analogous nitrate thioester **36**, 10% of the known lactone **38**,[13] 2% of lactone **37**, 6% of the strained *trans*-fused lactone **39**, and 5% of the nitrate acid **40**. Examination of the ^{1}H NMR spectrum of the crude product indicated the absence of *trans*-fused lactone **39** and that >10% of nitrate acid **40** was present. This suggested that **40** cyclized to lactone **39** during chromatography. This was confirmed by the slow conversion of **40** to **39** in $CDCl_3$ containing silica gel. Presumably the reactive benzylic nitrate undergoes solvolysis to give a cation which cyclizes to give the *trans*-fused lactone with the more stable pseudoequatorial phenyl group.

The stereochemistry of lactone **39** was established by the 14.7 Hz vicinal coupling constant between the ring fusion hydrogens H_{3a} and H_{6a}, the 10.1 Hz vicinal coupling constant between H_3 and H_{3a}, the NOE between H_3 and H_{6a}, and the absence of an NOE between H_3 and H_{3a}. The stereochemistry of lactone **37** was established by the 8.5 Hz coupling constant between the ring fusion hydrogens H_{3a} and H_{6a}, and an NOE and 6.7 Hz vicinal coupling constant between H_3 at δ 5.73 and H_{3a} at δ 3.14 (Scheme 9).

In conclusion, we have demonstrated that CAN oxidizes ketene dithioacetals in wet MeCN to cation radicals that will cyclize to trisubstituted double bonds and styrenes leading to lactones and nitrate thioesters and acids. Cyclizations forming cyclohexanes give primarily or exclusively the *trans*-fused lactones **17** and **31**, while cyclizations forming cyclopentanes give primarily or exclusively the *cis*-fused lactones **18** and **38**. The requirement for electron rich double bonds suggests that these cyclizations are cation-like as in the cyclization of **21** to **24** and are mechanistically quite different from the cyclizations of cation-radicals derived from enol ethers, which appear to be radical-like. Further development and application of this reaction is currently underway.

Experimental

General

NMR spectra were recorded at 400 MHz in $CDCl_3$. Chemical shifts are reported in δ ppm and coupling constants in Hz. IR spectra are reported in cm^{-1}.

4,8-Dimethyl-1,1-bis(methylthio)-1,7-nonadiene (16). 2.5 M *n*-BuLi in hexanes (0.44 mL, 1.10 mmol) was added to a solution of bis(methylthio)trimethylsilylmethane[7] (180 mg, 1.00 mmol) in 10 mL of dry THF under N_2 at −40°C. The solution was warmed to rt, stirred for 1 h, and recooled to −40°C. Citronellal (185 mg, 1.20 mmol) was added and the solution was warmed to rt and stirred for 2 h. Distilled water (10 mL) was added and the THF was removed under reduced pressure. The remaining aqueous solution was extracted with hexanes. The combined organic layers were dried over Na_2SO_4 and concentrated. Flash chromatography of the residue on silica gel (hexanes) gave 220 mg (90%) of ketene dithioacetal **16** as a colorless liquid: ^{1}H NMR 5.93 (dd, 1, *J*=7.3, 7.3 Hz), 5.09 (br t, 1, *J*=7.3 Hz), 2.34 (ddd, 1, *J*=14.1, 7.3, 6.1 Hz), 2.28 (s, 3), 2.27 (s, 3), 2.22 (ddd, 1, *J*=14.1, 7.9, 7.9 Hz), 2.07–1.91 (m, 2), 1.68 (s, 3), 1.61 (s, 3), 1.58–1.51 (m, 1), 1.34 (dddd, 1, *J*=13.4, 9.2, 6.1, 6.1 Hz) 1.18 (dddd, 1, *J*=13.4, 9.2, 7.3, 6.1 Hz), 0.89 (d, 3, *J*=6.1 Hz); ^{13}C NMR 134.4, 132.7, 131.2, 124.7, 37.6, 36.7, 33.0, 25.7, 25.6, 19.5, 17.7, 16.9, 16.7; IR (neat) 1676, 1582.

(3aα,6α,7aβ)-Hexahydro-3,3,6-trimethyl-1(3*H*)-isobenzofuranone (17). A solution of freshly prepared **16** (110 mg, 0.45 mmol) in 10 mL of MeCN was added over 4 h by syringe pump to a solution of CAN (1.483 g, 2.70 mmol) in 40 mL of 95:5 MeCN/water at rt. Additional CAN (109 mg, 0.20 mmol) was added when the solution turned colorless. (For the other three substrates, no additional CAN was needed.) The yellow solution was stirred overnight and 20 mL of H_2O was added. MeCN was removed under reduced pressure. 10 mL of EtOAc and 1 mL of saturated Na_2SO_3 aqueous solution were added to the solution, which was stirred for 5 min to reduce the excess Ce(IV) to give a colorless solution. (More Na_2SO_3 aqueous solution was needed for the other three substrates. However, too much will cause the formation of emulsions that are extremely hard to break.) The solution was extracted with three portions of EtOAc. The combined organic layers were dried over Na_2SO_4 and concentrated to give 105 mg of crude product. Flash chromatography on silica gel (9:1 hexanes/EtOAc) gave 40 mg (49%) of pure lactone **17** as a white solid. Elution with EtOAc and then MeOH gave 28 mg (35%) of unidentified polar compounds.

Data for lactone **17**: mp 68–70°C; ^{1}H NMR 2.23 (ddd, 1, *J*=13.4, 11.6, 3.7 Hz), 2.15 (dddd, 1, *J*=12.8, 3.7, 3.7, 1.2 Hz), 1.89–1.82 (br d, 1, *J*=13.4 Hz), 1.79 (dddd, 1, *J*=12.2, 3.3, 3.3, 3.3 Hz), 1.67 (ddd, 1, *J*=13.4, 12.2, 3.1 Hz), 1.50–1.38 (m, 1), 1.43 (s, 3), 1.26 (s, 3), 1.24 (dddd, 1, *J*=12, 12, 12, 3.7 Hz), 1.00 (ddd, 1, *J*=12, 12,

11.6 Hz), 0.99 (d, 3, J=6.7 Hz), 0.97 (dddd, 1, J=13, 13, 13, 3 Hz); ^{13}C NMR 176.5, 85.5, 52.3, 44.1, 34.2, 33.7, 32.6, 27.3, 25.7, 21.9, 20.7; IR (CH_2Cl_2) 1762.

$MeSSO_2Me$ present in some reaction mixtures coeluted with **17**. It was removed by stirring a solution of **17** or the crude reaction mixture with EtSH in a two phase mixture of EtOAc and water, which formed volatile MeSSEt and water soluble $MeSO_2H$.[14]

3,7-Dimethyl-1,1-bis(methylthio)-1,6-octadiene (18). (389 mg, 85%) was prepared from 2,6-dimethyl-5-heptenal (236 mg, 2.20 mmol) and bis(methylthio)trimethylsilylmethane (360 mg, 2.00 mmol) as a colorless liquid as described above for **16**: ^{1}H NMR 5.70 (d, 1, J=9.8 Hz), 5.10 (br t, 1, J=7.3 Hz), 2.94–2.83 (m, 1), 2.29 (s, 3), 2.27 (s, 3), 1.97–1.89 (br dt, 2, J=7.3, 7.5 Hz), 1.68 (d, 3, J=1.2 Hz), 1.59 (s, 3), 1.41–1.24 (m, 2), 0.97 (d, 3, J=6.7 Hz); ^{13}C NMR 141.7, 131.4, 131.1, 124.5, 37.3, 34.9, 26.0, 25.7, 20.8, 17.7, 16.94, 16.85; IR (neat) 1674, 1582.

(3aα,6α,7aα)-Hexahydro-3,3,6-trimethyl-1*H*-cyclopenta-[*c*]furanon-1-one (19). Oxidation of **18** (276 mg, 1.20 mmol) with CAN as described above for **16** gave 220 mg of crude product. Flash chromatography on silica gel (9:1 hexanes/EtOAc) gave 84 mg (41%) of **19**. Elution with EtOAc and then MeOH gave 80 mg (38%) of unidentified polar compounds.

Data for **19**: mp 45–46°C (lit.[10] 15–19°C); ^{1}H NMR 2.76 (dd, 1, J=8.5, 4.3 Hz), 2.58 (ddd, 1, J=8.5, 8.5, 8.5 Hz), 2.43–2.33 (m, 1), 1.91 (dddd, 1, J=12.2, 6.7, 6.7, 3.7 Hz), 1.84–1.76 (m, 1), 1.55 (dddd, 1, J=12.8, 9.8, 9.8, 6.7 Hz), 1.40 (s, 3), 1.39 (s, 3), 1.22 (dddd, 1, J=12.2, 10.4, 8.5, 6.1 Hz), 1.15 (d, 3, J=6.7 Hz); ^{13}C NMR 179.9, 84.1, 53.8, 50.2, 38.2, 35.4, 29.9, 28.0, 23.6, 21.2; IR (CH_2Cl_2) 1759. A 1D NOESY experiment with irradiation of the methyl doublet at δ 1.15 showed strong NOEs to H_6 at δ 2.4 and H_{6a} at δ 2.76 and a weak NOE to H_{3a} at δ 2.58.

1,1-Bis(methylthio)-8-phenyl-1,7-octadiene (29). A 1:2 mixture of *cis*- and *trans*-7-phenyl-6-heptenals[4] (450 mg, 2.4 mmol) was treated with bis(methylthio)trimethylsilylmethane (360 mg, 2.00 mmol) as described above for the preparation of **16** to give 680 mg of crude product. Flash chromatography on silica gel (0.5% Et_2O in hexanes) gave 18 mg (6%) of *cis*-**29**, followed by 418 mg (75%) of a 1:2 mixture of *cis*- and *trans*-**29**, and 39 mg of 50% pure *trans*-**29**. Flash chromatography of the impure *trans*-**29** (hexanes) gave 12 mg (4%) of *trans*-**29**.

Data for *cis*-**29**: ^{1}H NMR 7.35–7.19 (m, 5), 6.41 (d, 1, J=11.6 Hz), 5.88 (t, 1, J=7.3 Hz), 5.65 (dt, 1, J=11.6, 7.3 Hz), 2.38–2.30 (m, 4), 2.27 (s, 3), 2.26 (s, 3), 1.52–1.38 (m, 4); ^{13}C NMR 137.7, 135.1, 132.8, 132.3, 128.9, 128.7 (2 C), 128.1 (2 C), 126.4, 30.3, 29.4, 28.9, 28.4, 16.83, 16.79; IR (neat) 1682.

Data for *trans*-**29**: ^{1}H NMR 7.36–7.26 (m, 4), 7.19 (tt, 1, J=7.0, 1.5 Hz), 6.38 (d, 1, J=15.9 Hz), 6.21 (dt, 1, J=15.9, 6.7 Hz), 5.91 (t, 1, J=7.3 Hz), 2.35 (dt, 2, J=7.3, 7 Hz), 2.29 (s, 3), 2.27 (s, 3), 2.22 (ddt, 2, J=7, 1.2, 6.7 Hz), 1.54–1.40 (m, 4); ^{13}C NMR 137.8, 135.1, 132.3, 130.8, 129.9, 128.5 (2 C), 126.8, 125.9 (2 C), 32.8, 30.3, 28.82, 28.79, 16.83 (2 C); IR (neat) 1680.

Oxidative cyclization of 29. Oxidation of a 1:2 mixture of *cis*- and *trans*-**29** (305 mg, 1.10 mmol) with CAN as described above for **16** gave 250 mg of crude product. Flash chromatography on silica gel (1:1 hexanes/CH_2Cl_2) gave 11 mg (5%) of **30**. Elution with 9:1 to 4:1 hexanes/EtOAc gave 16 mg (7%) of a 3:6:2:10 mixture of lactones **31, 32, 33**, and **34**, followed by 44 mg (21%) of lactone **31**. Elution with EtOAc and then MeOH gave 78 mg (36%) of polar products. Similar mixtures of products were obtained from either pure *cis*- or *trans*-**29**.

Data for *S*-methyl 2-(α-nitrooxyphenylmethyl)cyclohexanecarbothioate (**30**): ^{1}H NMR 7.40–7.30 (m, 5), 5.60 (d, 1, J=6.7 Hz), 2.48–2.36 (m, 2), 2.36 (s, 3), 1.99–1.92 (m, 1), 1.78–1.63 (m, 2), 1.54–1.47 (m, 2), 1.24–1.12 (m, 3), 0.95–0.84 (m, 1); ^{13}C NMR 202.2, 135.8, 128.9, 128.5 (2 C), 127.4 (2 C), 87.6, 55.5, 42.3, 31.0, 27.3, 25.0, 24.5, 11.6; IR (CH_2Cl_2) 1686, 1637, 1281.

Data for (3α,3aβ,7aα)-hexahydro-3-phenyl-1(3*H*)-isobenzofuranone (**31**): mp 80–83°C (lit.[11] 86–88°C); ^{1}H NMR 7.42–7.32 (m, 5), 4.98 (d, 1, J=9.8 Hz), 2.26–2.19 (m, 1), 2.18 (ddd, 1, J=13.1, 11.3, 3.4 Hz), 1.94–1.76 (m, 4), 1.42–1.22 (m, 3), 1.15 (ddddd, 1, J=13, 13, 13, 4, 4 Hz); the ^{13}C NMR spectrum is identical to that previously reported.[11]

Partial data for (3α,3aα,7aβ)-hexahydro-3-phenyl-1(3*H*)-isobenzofuranone (**32**)[11] were determined from the mixture: ^{1}H NMR 5.61 (d, 1, J=7.9 Hz).

Partial data for (3α,3aβ,7aβ)-hexahydro-3-phenyl-1(3*H*)-isobenzofuranone (**33**)[11] were determined from the mixture: ^{1}H NMR 5.48 (d, 1, J=4.5 Hz).

Partial data for (3α,3aα,7aα)-hexahydro-3-phenyl-1(3*H*)-isobenzofuranone (**34**)[11] were determined from the mixture: ^{1}H NMR 5.22 (d, 1, J=3.1 Hz).

***cis* and *trans*-1,1-Bis(methylthio)-7-phenyl-1,6-heptadiene (35).** A 1:1 mixture of *cis*- and *trans*-6-phenyl-5-hexenal[4] (630 mg, 3.6 mmol) was treated with bis(methylthio)trimethylsilylmethane (540 mg, 3.00 mmol) as described above for the preparation of **16** to give 892 mg of crude product. Flash chromatography on silica gel (1% Et_2O in hexanes) gave 2 mg (0.2%) of *cis*-**35**, followed by 650 mg (82%) of a 1:1 mixture of *cis*- and *trans*-**35**, and 2 mg (0.2%) of *trans*-**35**.

Data for *cis*-**35**: ^{1}H NMR 7.36–7.20 (m, 5), 6.43 (d, 1, J=11.6 Hz), 5.87 (t, 1, J=7.3 Hz), 5.67 (dt, 1, J=11.6, 7.3 Hz), 2.41–2.32 (m, 4), 2.27 (s, 3), 2.23 (s, 3), 1.55 (tt, 2, J=7.6, 7.6 Hz).

Data for *trans*-**35**: ^{1}H NMR 7.36–7.26 (m, 4), 7.19 (tt, 1, J=7.0, 1.5 Hz), 6.40 (br d, 1, J=15.9 Hz), 6.22 (dt, 1, J=15.9, 6.7 Hz), 5.92 (t, 1, J=7.3 Hz), 2.41 (dt, 2, J=7.3, 7.3 Hz), 2.29 (s, 3), 2.27 (s, 3), 2.23 (ddt, 2, J=6.7, 1.2, 7.3 Hz), 1.58 (tt, 2, J=7.3, 7.3 Hz); IR (neat) 1680.

Oxidative cyclization of 35. Oxidation of **35** (430 mg, 1.62 mmol) with CAN as described above for **16** gave 306 mg of crude product. Flash chromatography on silica gel (1:1 hexanes/CH_2Cl_2) gave 11 mg (3%) of nitrate thioester **36**. Elution with 9:1 to 4:1 hexanes/EtOAc gave 33 mg (10%) of lactone **38**, 12 mg (4%) of a 3:1:1 mixture of **37**, **38**, and **39**, and 25 mg (8%) of 70% pure **39**. Elution with 1:1 hexanes/EtOAc gave 16 mg (5%) of nitrate acid **40**. Elution with MeOH gave 136 mg (41%) of unidentified polar products. Rechromatography of the 3:1:1 mixture of **37**, **38** and **39** (40:1 hexanes/EtOAc) gave 6 mg (2%) of **37**. Rechromatography of the impure **39** (40:1 hexanes/EtOAc) gave 16 mg (6%) of **39**.

Data for *S*-methyl 2-(α-nitrooxyphenylmethyl)cyclopentanecarbothioate **(36)**: ^{1}H NMR 7.40–7.30 (m, 5), 5.60 (d, 1, *J*=9.2 Hz), 2.98–2.88 (m, 2), 2.33 (s, 3), 2.09–1.99 (m, 1), 1.92–1.82 (m, 1), 1.72–1.56 (m, 3), 1.33 (dddd, 1, *J*=12, 8, 8, 8 Hz); ^{13}C NMR 202.1, 136.7, 129.1, 128.7 (2 C), 127.1 (2 C), 88.3, 56.7, 47.0, 32.1, 29.6, 24.8, 11.8; IR (CH_2Cl_2) 1684, 1634, 1277.

Data for (3aα,6β,7aα)-hexahydro-3-phenyl-1*H*-cyclopenta[*c*]furanon-1-one **(37)**: ^{1}H NMR 7.41–7.26 (m, 5), 5.73 (d, 1, *J*=6.7 Hz), 3.26 (ddd, 1, *J*=8.5, 8.5, 3.1 Hz), 3.14 (dddd, 1, *J*=8.5, 8, 8, 6.7 Hz), 2.14 (dddd, 1, *J*=13.4, 6.7, 6.7, 3.1 Hz), 2.04–1.94 (m, 1), 1.57–1.49 (m, 2), 1.40–1.31 (m, 1), 1.22–1.13 (m, 1); ^{13}C NMR 180.5, 137.4, 128.5 (2 C), 127.7, 124.9 (2 C), 81.5, 46.8, 45.5, 29.7, 27.8, 25.8; IR (neat) 1771.

Data for (3aα,6α,7aα)-hexahydro-3-phenyl-1*H*-cyclopenta[*c*]furanon-1-one **(38)**:[13] ^{1}H NMR 7.41–7.27 (m, 5), 5.11 (d, 1, *J*=3.7 Hz), 3.17 (ddd, 1, *J*=9.5, 9.5, 2.5 Hz), 2.87 (dddd, 1, *J*=9.5, 7.5, 3.7, 3.7 Hz), 2.21–2.13 (m, 1), 2.03–1.90 (m, 2), 1.90–1.83 (m, 1), 1.84–1.75 (m, 1), 1.72–1.62 (m, 1); ^{13}C NMR 180.5, 140.9, 128.8 (2 C), 128.2, 124.9 (2 C), 86.4, 48.4, 44.8, 33.6, 30.7, 25.4; IR (neat) 1770.

Data for (3aα,6α,7aβ)-hexahydro-3-phenyl-1*H*-cyclopenta[*c*]furanon-1-one **(39)**: ^{1}H NMR 7.42–7.33 (m, 5), 5.26 (d, 1, *J*=10.1 Hz), 2.84 (ddd, 1, *J*=14.7, 11.6, 6.7 Hz), 2.49 (dddd, 1, *J*=14.7, 11.5, 10.1, 6.1 Hz), 2.30–2.11 (m, 2), 1.92 (dddd, 1, *J*=10.4, 8.5, 6.7, 3.1 Hz), 1.81 (dddd, 1, *J*=11.6, 7.9, 6.1, 2.4 Hz), 1.73–1.56 (m, 2); ^{13}C NMR 173.2, 137.6, 128.6 (2 C), 128.5, 125.6 (2 C), 84.5, 57.3, 53.6, 28.9, 24.0, 20.4; IR (neat) 1782.

Data for 2-(α-nitrooxyphenylmethyl)cyclopentanecarboxylic acid **(40)**: ^{1}H NMR 7.40–7.31 (m, 5), 5.64 (d, 1, *J*=9.2 Hz), 2.87 (dddd, 1, *J*≈8.4, 8.4, 8.4, 8.4 Hz), 2.72 (ddd, 1, *J*≈8, 8, 8 Hz), 2.14–2.04 (m, 1), 1.95 (dddd, 1, *J*≈14, 7, 7, 7 Hz), 1.74–1.59 (m, 3), 1.35 (dddd, 1, *J*≈12.8, 8.5, 8.5, 8.5 Hz); ^{13}C NMR 180.5, 136.7, 129.1, 128.7 (2 C), 127.1 (2 C), 88.2, 47.3, 46.7, 31.1, 29.4, 24.8; IR (CH_2Cl_2) 3400–2600 (br), 1705, 1636, 1273.

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