

## Answers to Chapter 5 Problems.

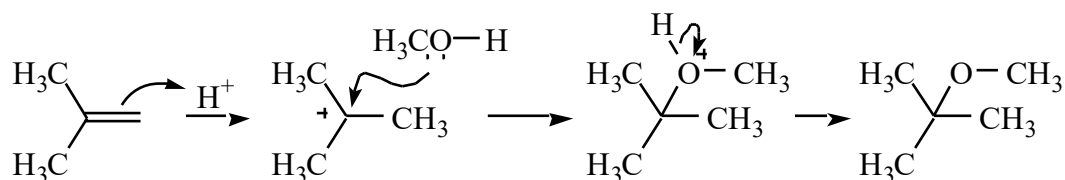
1. (a) MTBE is less prone to autoxidize than ether and THF. In MTBE, only one C attached to O bears H atoms, and abstraction of one of these H atoms gives a 1° radical. In ether and THF, both C atoms bear H atoms, and abstraction of one of these H atoms gives a 2° radical. 2° Radicals are much more stable than 1° radicals, so ether and THF are more prone to autoxidize.

(b) ETBE is of less interest than MTBE because it is more prone to autoxidize. Abstraction of H· from the H-bearing C adjacent to O gives a 2° radical of comparable stability to the radical derived from ether and THF.

Incidentally, MTBE also forms an azeotrope with H<sub>2</sub>O (like benzene does), so there is no need to dry it over MgSO<sub>4</sub> or 4 Å molecular sieves after an extraction, as must be done with both ether and THF.

MTBE also has a much higher flash point than ether.

(c) Acidic conditions are required.



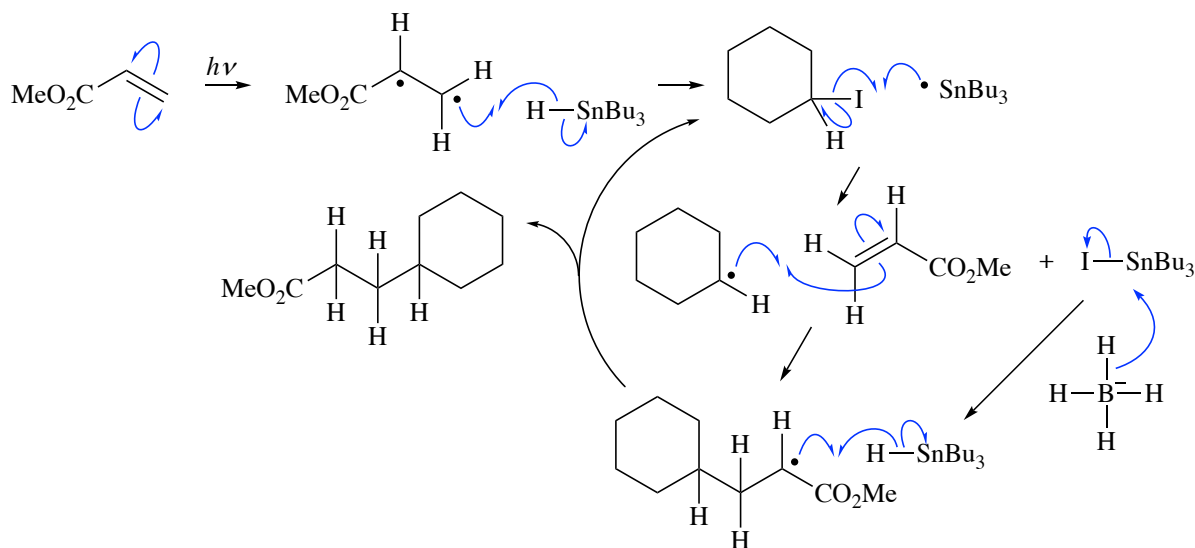
(d) Ethanol is made from corn — hence the name, grain alcohol. If ETBE were required to be used in gasoline, it would mean megabucks for corn producers.

(e) MTBE has a smaller C/O ratio than ETBE, so MTBE is more soluble in water. MTBE is also less prone to undergo H· abstraction, a major decomposition pathway for ETBE.

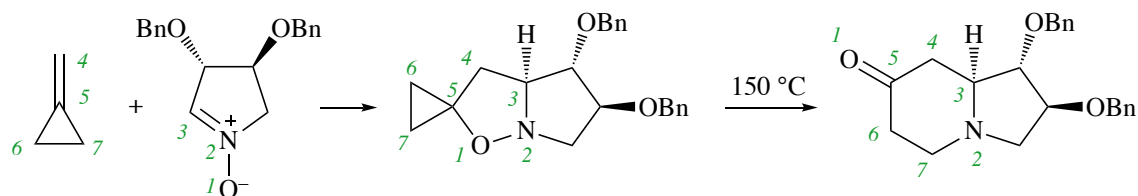
2. (a) CFCs decompose most readily during the Antarctic spring and in the stratosphere. This suggests that their decomposition is catalyzed by UV light. The action of UV light on CFCs is likely to cause homolysis of a C–Cl bond. In fact, Cl· radicals are the agents that catalyze ozone depletion.

(b) HCFCs have a C–H bond, whereas CFCs don't. In the lower atmosphere, O<sub>2</sub> (actually, HO·) can abstract H· from an HCFC to give an alkyl radical, which can then undergo further reactions. This decomposition pathway is not open to CFCs, so they remain intact until they reach the stratosphere.

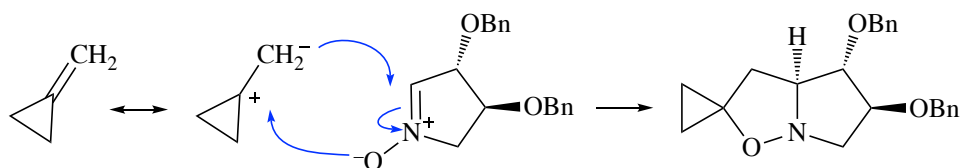
3. (a) This is a standard free-radical addition reaction. In the propagation part of the mechanism, Bu<sub>3</sub>Sn· abstracts I· from the alkyl iodide, the alkyl radical adds to the acrylate ester, and abstraction of H· from HSnBu<sub>3</sub> completes the chain. The Bu<sub>3</sub>SnI produced in the course of the reaction is reduced by NaBH<sub>4</sub> back to HSnBu<sub>3</sub>, allowing the HSnBu<sub>3</sub> to be used in catalytic quantities. Initiation steps other than the one shown (e.g., C–I bond homolysis) may be envisioned. The termination steps are the usual radical–radical combination and disproportionation reactions.



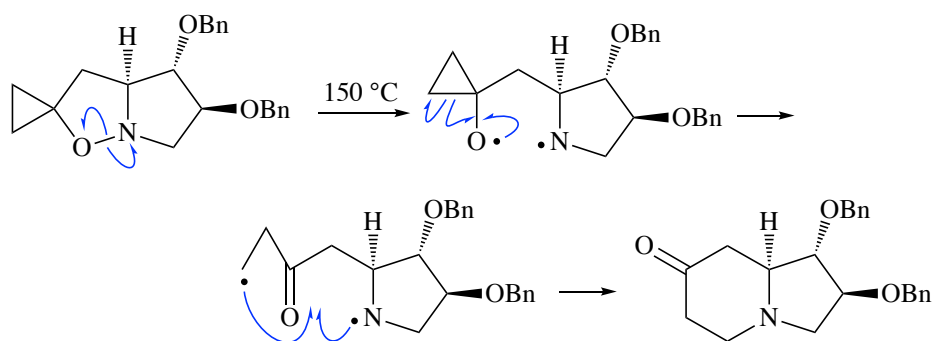
(b) Number the atoms.



The first reaction is a 1,3-dipolar cycloaddition. The best resonance structure for the dipolarophile puts the positive charge on C5 and the negative charge on C4. This makes C5 most likely to be attacked by O1.

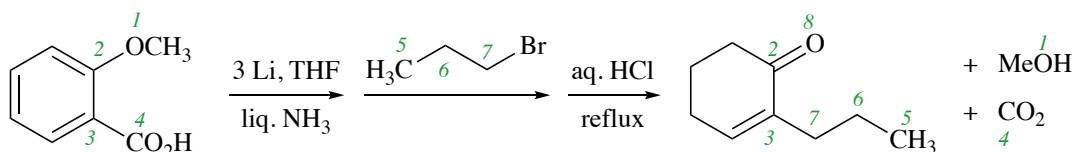


Now the second step. Make: C7–N2. Break: O1–N2, C5–C7. Heating the tricyclic compound causes thermolysis of the weak O1–N2 bond. The cyclopropyloxy radical quickly ring-opens to put the radical center at C7; then radical–radical recombination between C7 and N2 gives the product.

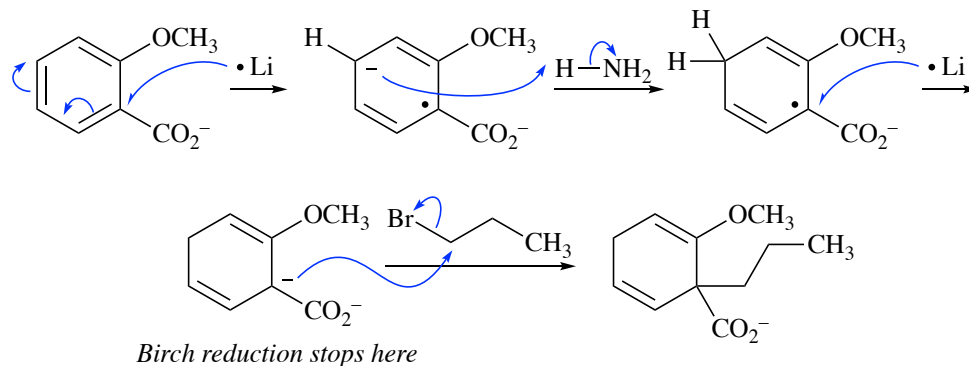


(c) The coproducts are MeOH and CO<sub>2</sub>, and the O in the product most likely comes from workup.

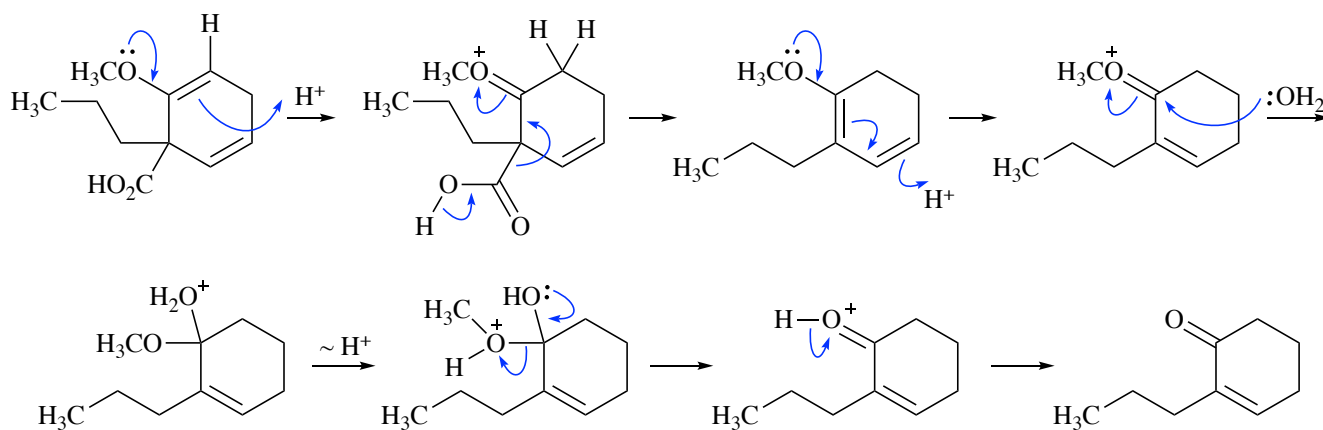
Make: C3–C7, C2–O8. Break: O1–C2, C3–C4.



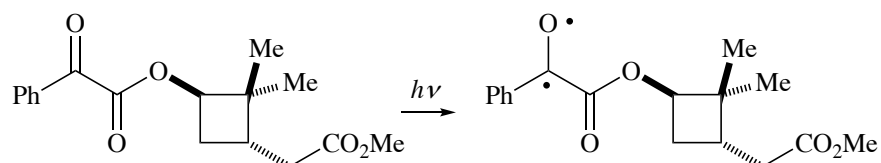
The first part is a Birch reduction, with  $\text{NH}_3$  as the proton source. It gives the carboxylate enolate as the initial product. When the alkyl halide is added, the enolate acts as a nucleophile to give the C3–C7 bond in an  $\text{S}_{\text{N}}2$  reaction.



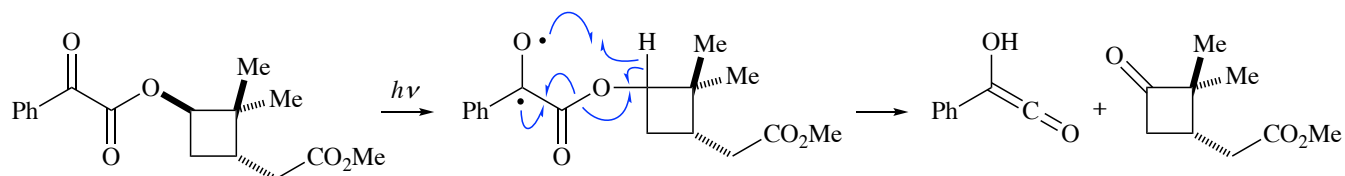
Refluxing in acid protonates the enol ether to give a nice stable carbocation. Loss of  $\text{CO}_2$  from this carbocation gives a new dienol ether. Acidic hydrolysis of this dienol ether gives the product enone in the usual fashion.



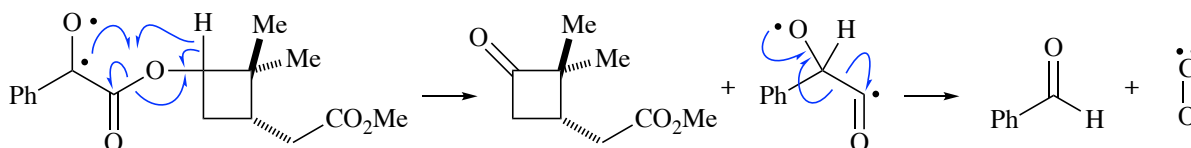
(d) Light promotes an electron from the  $\pi$  to the  $\pi^*$  orbital in the aromatic  $\text{C}=\text{O}$  bond to give a 1,2-diradical.



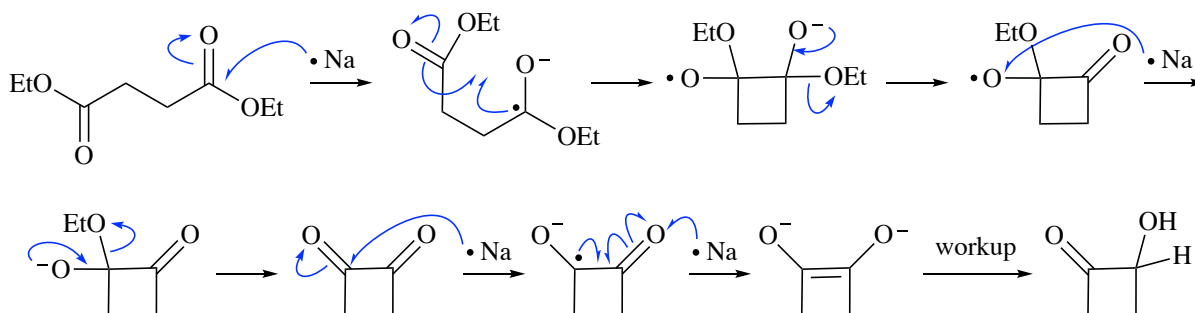
The O radical can then undergo Norrish type II cleavage, abstracting H· from C1 in a six-membered TS, to give the cyclobutanone and the ketenol.



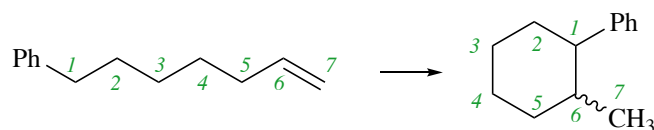
Alternatively, the C radical can abstract H· from C1 in a five-membered TS to give the cyclobutanone, CO, and PhCHO.



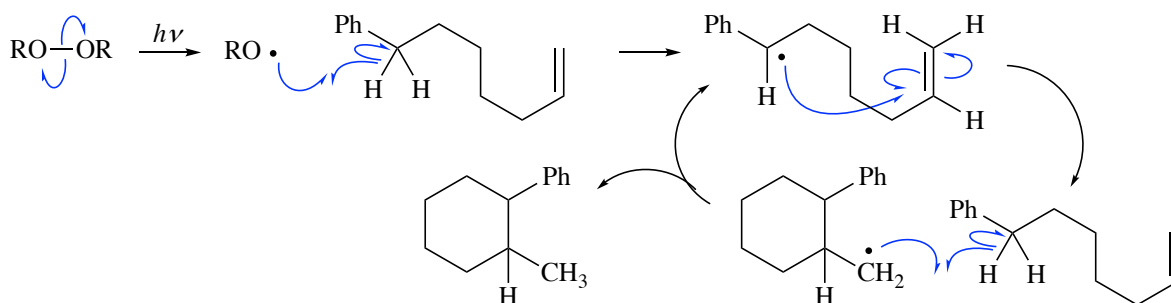
(e) This is an acyloin condensation. The two ketones are reduced to ketyls, which couple and lose EtO<sup>-</sup>. The 1,2-dione is then reduced further by Na to give an ene-1,2-diolate, which after workup gives the  $\alpha$ -hydroxyketone.



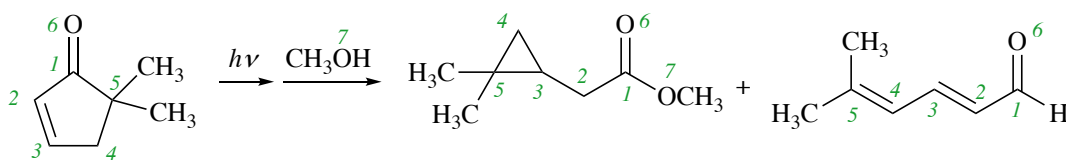
(f) A new C1–C6 bond is formed.



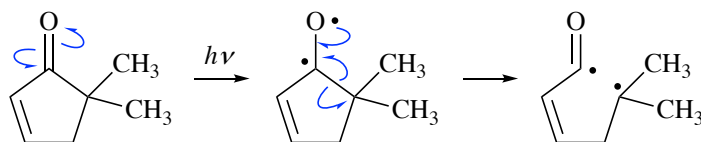
Initiation has an alkoxy radical abstract H· from the C1–H bond to make a benzylic radical. Propagation consists of cyclization, then H· abstraction by C7 from a C1–H bond.



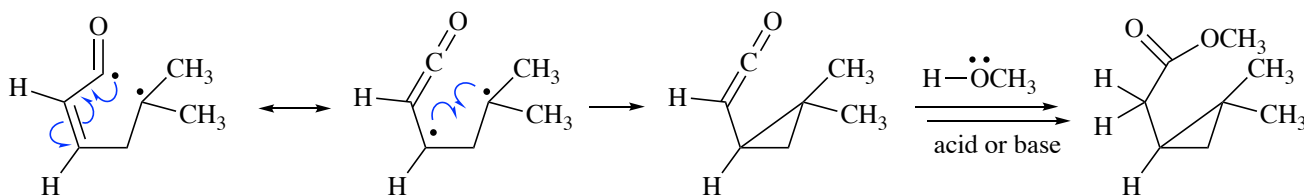
(g) Product 1: Make: C1–O7, C3–C5. Break: C1–C5. Product 2: Make: C1–H. Break: C1–C5. In both compounds, the C1–C5 bond is broken, suggesting that the first step in both cases is Norrish type I cleavage.



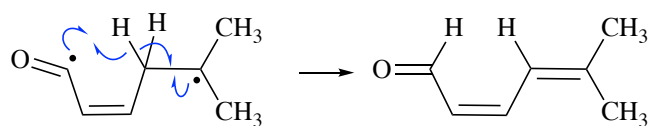
Light induces formation of a 1,2-diradical. Norrish type I cleavage to give the more stable of the two possible 1,5-diradicals then occurs.



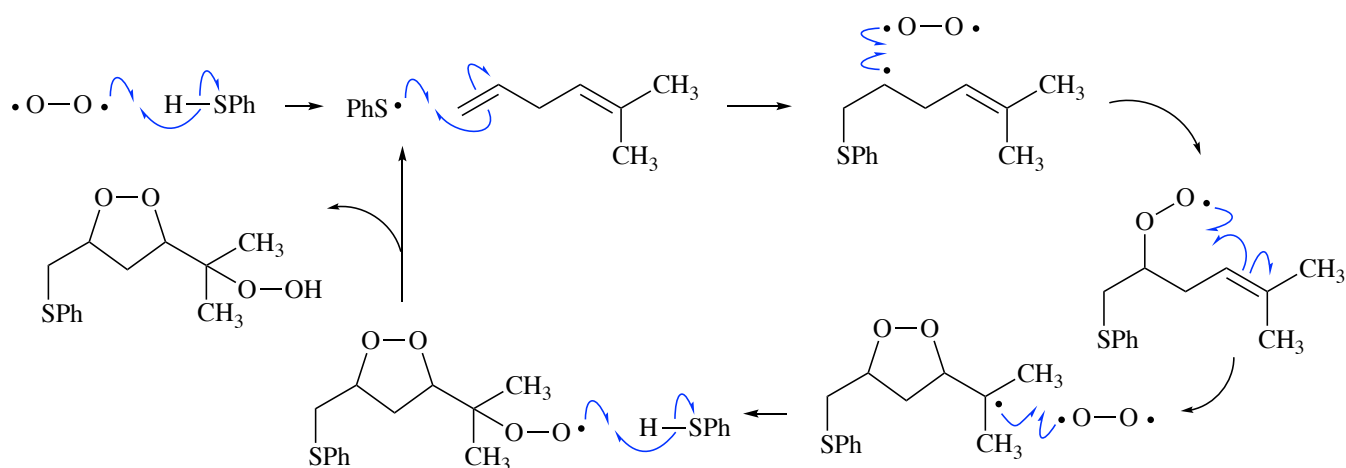
The diradical can undergo radical–radical recombination at C3–C5 to give a ketene, which reacts with  $\text{CH}_3\text{OH}$  to give the ester product via an acid- or base-catalyzed reaction.



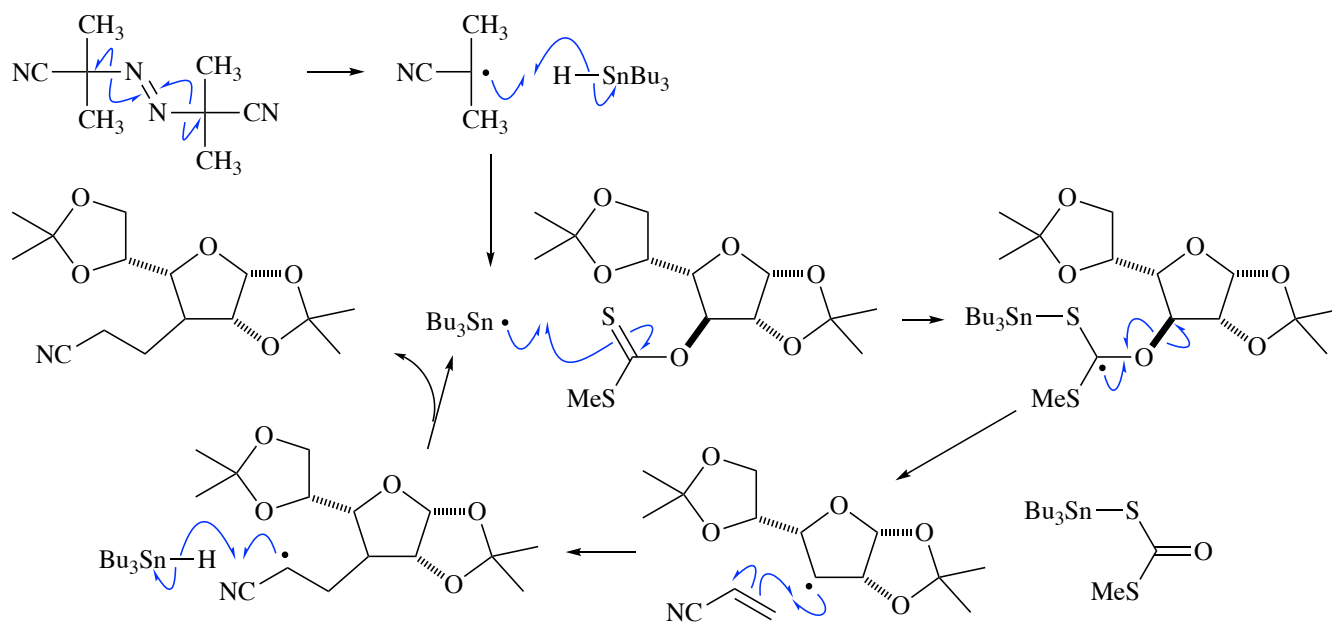
Alternatively, C1 of the diradical can abstract H• from C4 in a disproportionation reaction to give the diene product.



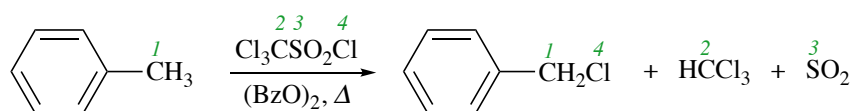
(h) *Two* equivalents of  $O_2$  are incorporated into this autoxidation product, in addition to one equivalent of PhSH. Initiation proceeds by  $H\cdot$  abstraction from PhSH by  $O_2$ . Propagation has PhS $\cdot$  add to the less substituted alkene to give an alkyl radical, which reacts with  $O_2$  to give a peroxy radical. This adds in intramolecular fashion to the other alkene to give a new alkyl radical, which combines with  $O_2$  again to give a new peroxy radical. The peroxy radical abstracts  $H\cdot$  from PhSH to complete the chain.



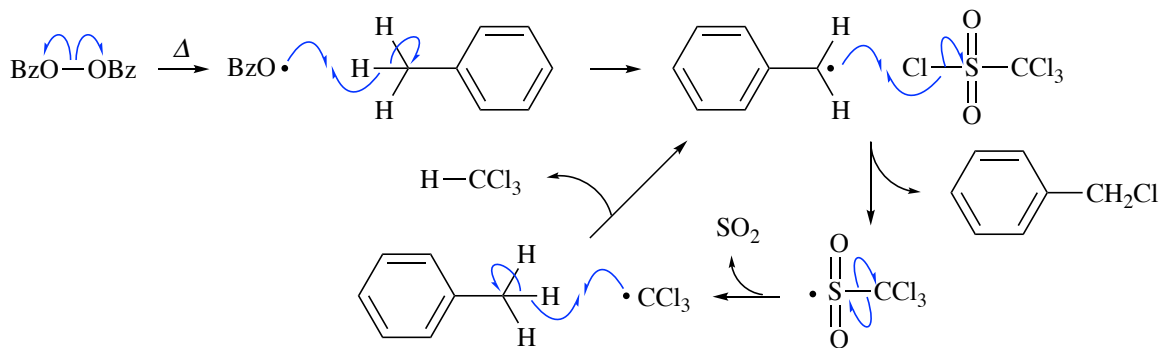
(i) This reaction combines the Barton deoxygenation with an addition reaction. In the propagation part,  $Bu_3Sn\cdot$  adds to S of the  $C=S$  bond to give an alkyl radical, which fragments to give the dithiocarbonate and a new alkyl radical. The alkyl radical then adds to acrylonitrile to give yet another alkyl radical, which abstracts  $H\cdot$  from  $Bu_3SnH$  to complete the chain.



(j) In principle, the Cl in the product could come from either the S–Cl bond or the C–Cl bond, but since C still has three Cl atoms attached in the product, it probably comes from the S–Cl bond. Make: C1–Cl4. C2–H. Break: C1–H, C2–S3, S3–Cl4.

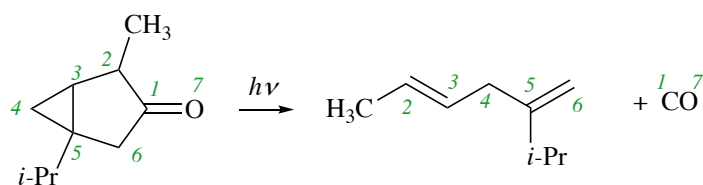


BzO• is generated in the initiation. It abstracts H• from toluene to give a benzyl radical, which abstracts Cl4 from S3 to give benzyl chloride and Cl<sub>3</sub>CSO<sub>2</sub>• radical. This radical then fragments to give SO<sub>2</sub> and •CCl<sub>3</sub>, which then abstracts H• from toluene to complete the chain.

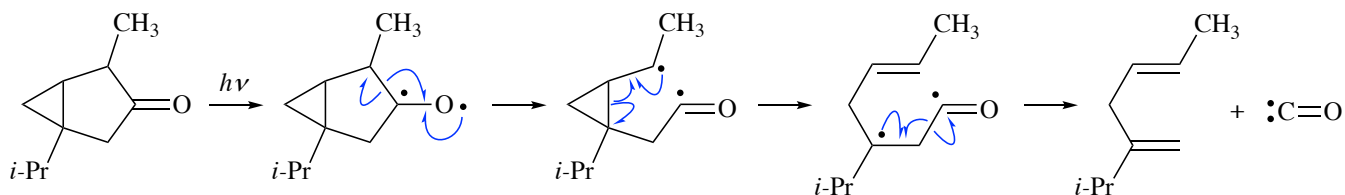




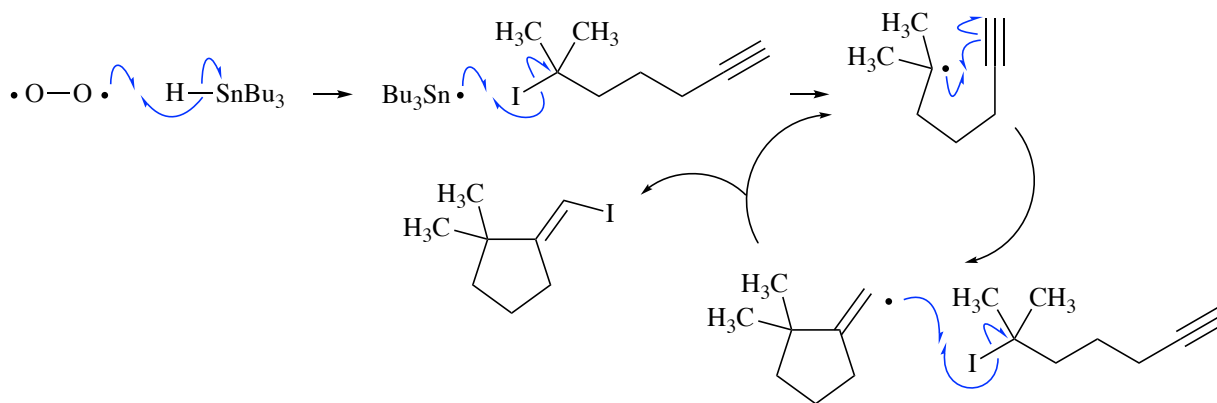
(k) The coproduct is CO. Make: none. Break: C1–C2, C1–C6, C3–C5.



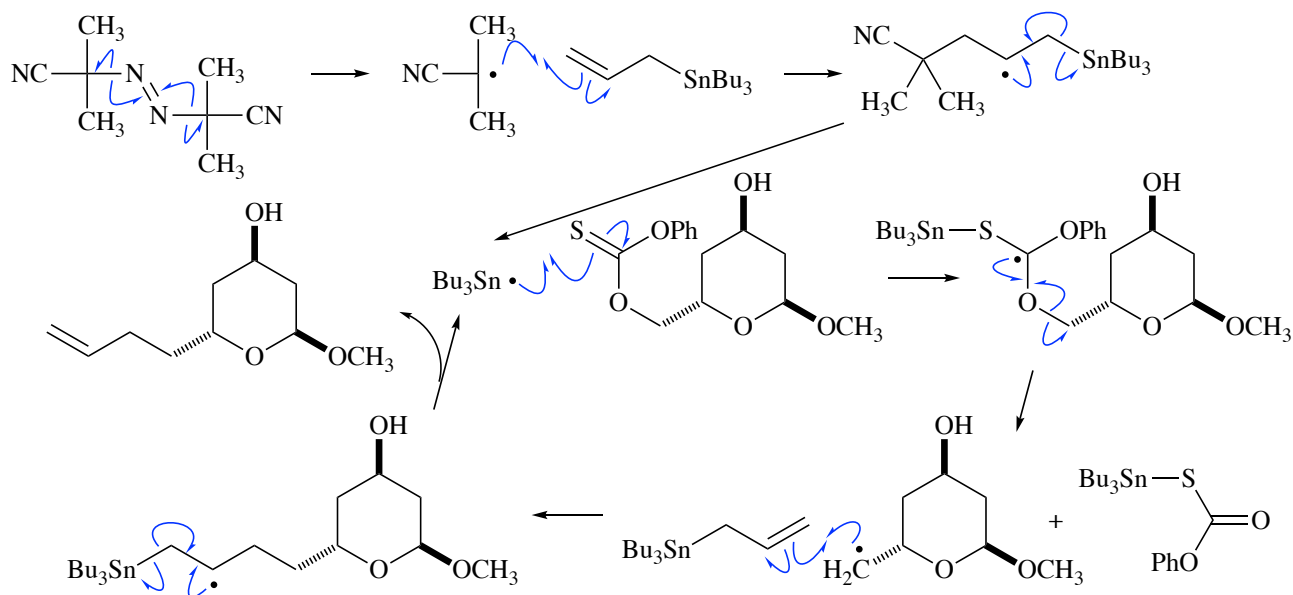
Photoexcitation of the ketone gives a 1,2-diradical, which undergoes Norrish type I cleavage of the C1–C2 bond to give a 1,5-diradical. The cyclopropylcarbinyl radical opens up to give a 1,3-diradical, which finally loses CO to give the observed diene. Some of these steps may be concerted.



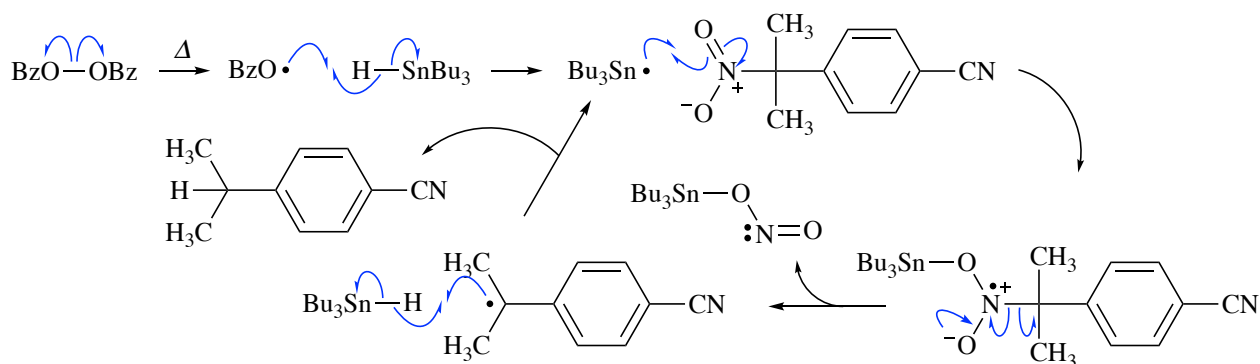
(l) This radical-catalyzed isomerization reaction is a variation of the  $\text{Bu}_3\text{SnH}$ -promoted reductive cyclization of haloalkenes that we've seen before.  $\text{Bu}_3\text{SnH}$  is no longer a stoichiometric starting material, so it cannot appear in the propagation part of the mechanism. Instead, it is an initiator that is used to generate small amounts of the alkyl radical by abstraction of I $\cdot$  from the starting material. In the propagation part of the mechanism, the alkyl radical adds to the triple bond to give a vinyl radical, which abstracts I $\cdot$  from the starting material to give the product and to complete the chain.



(m) This reaction combines a Barton deoxygenation with a free-radical allylation.  $\text{Bu}_3\text{Sn}\cdot$  is the chain-carrying species.

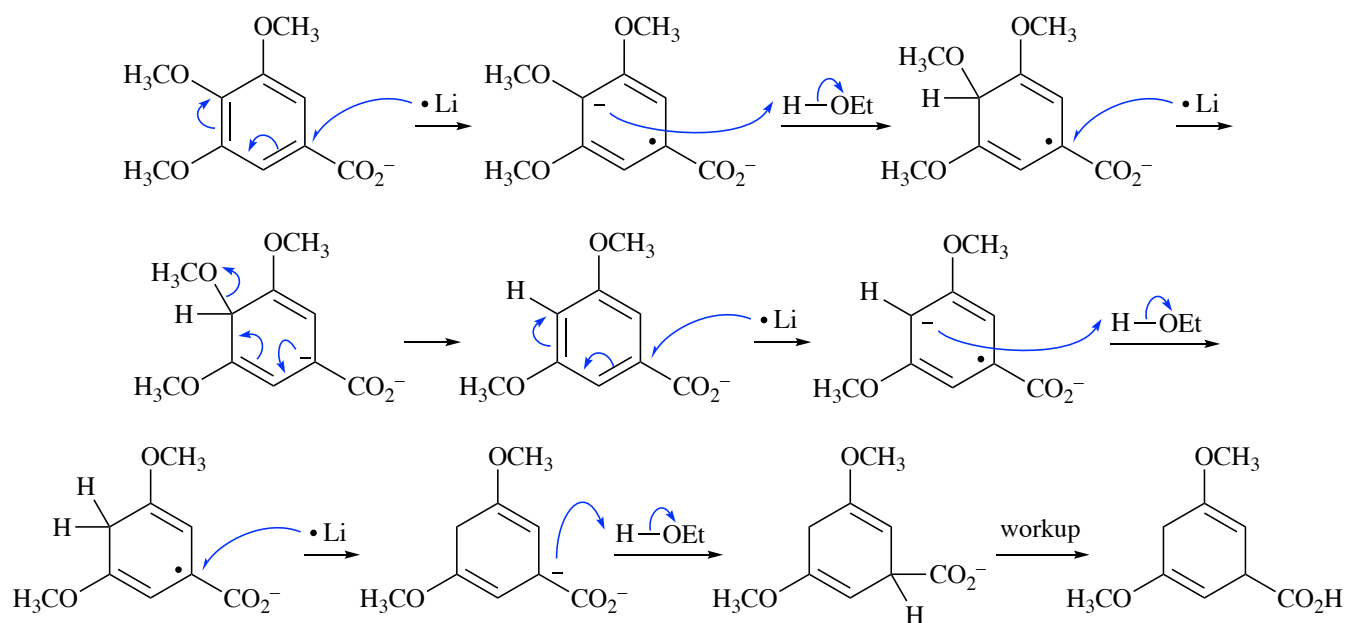


(n) This free-radical substitution appears to proceed by direct attack of  $\text{Bu}_3\text{Sn}\cdot$  on the C–N bond to give a Sn–N bond and a C radical. However, the N atom is quite sterically encumbered, and direct abstraction of a light atom by  $\text{Bu}_3\text{Sn}\cdot$  is quite rare. A better mechanism has the  $\text{Bu}_3\text{Sn}\cdot$  add to O of the N=O  $\pi$  bond to give a N-centered radical. Fragmentation of the C–N bond then gives a nitrite and the requisite alkyl radical, which abstracts  $\text{H}\cdot$  from  $\text{Bu}_3\text{SnH}$  to complete the chain.

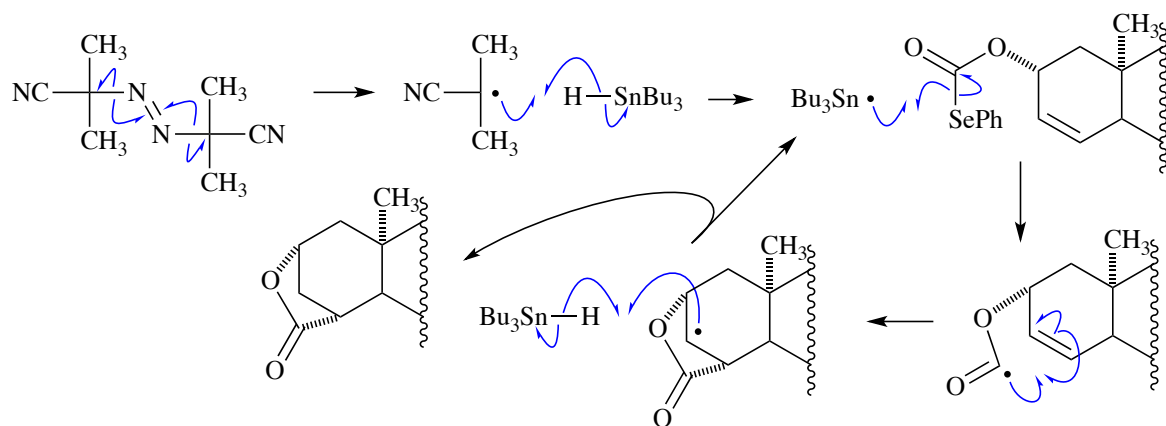


(o) In this Birch reduction, the first equivalent of Li reduces the acid to a carboxylate. The Birch reduction then proceeds normally until after the second electron transfer step, when elimination of  $\text{MeO}^-$

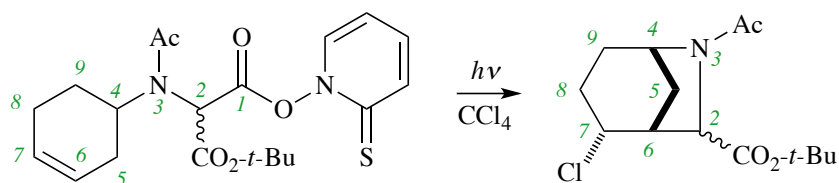
occurs to give a new aromatic compound. Now Birch reduction proceeds again normally to give the observed product.



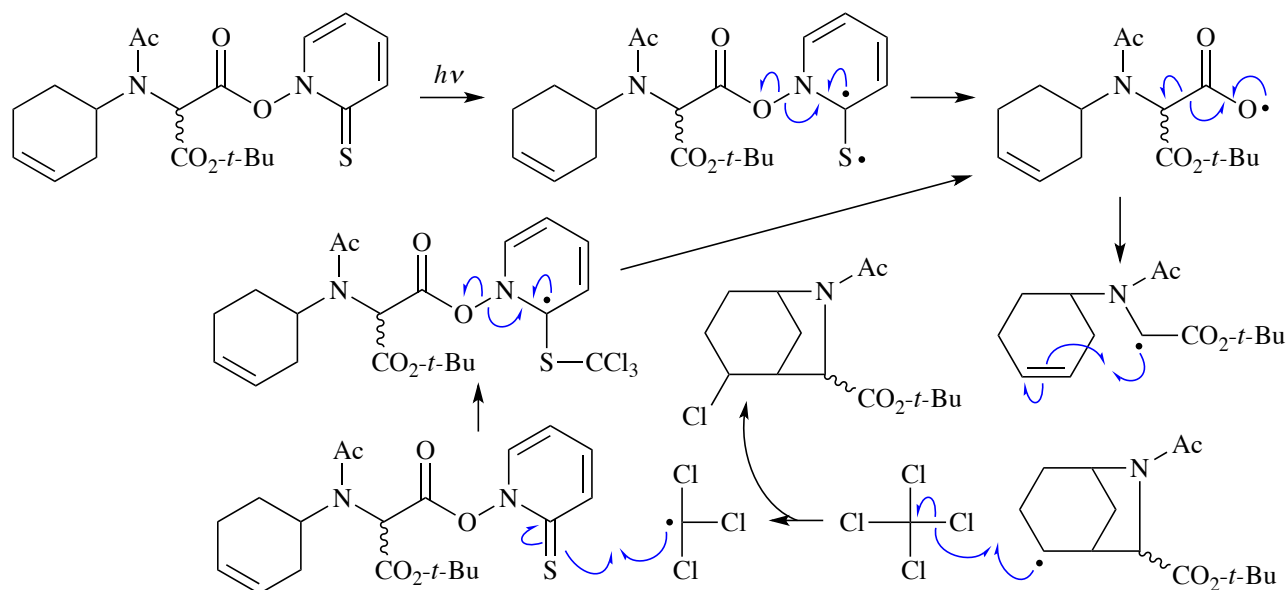
(p) This reaction is a standard free-radical addition reaction, except that  $\text{Bu}_3\text{Sn}\cdot$  abstracts  $\text{PhSe}$  instead of a halogen, and the addition reaction takes place in an intramolecular fashion.



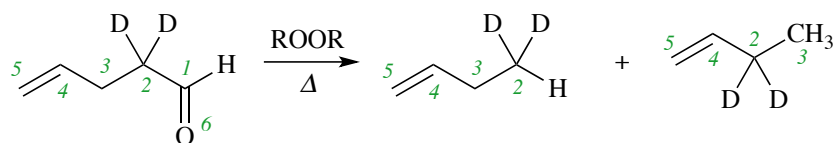
(q) Make: C2–C6, C7–C1. Break: C1–C2. Note that the elements of  $\text{CO}_2$  are missing, as is the pyridinethione.



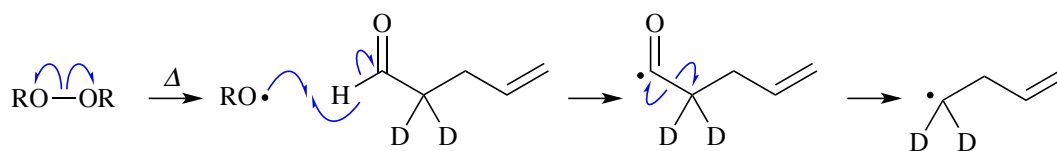
The weakest bond, the C=S  $\pi$  bond, will be selectively photoexcited. Fragmentation of the weak N–O bond (Norrish type I cleavage) gives a carboxy radical, which can fragment to break the C1–C2 bond and give a C2 radical, which adds to the C6=C7  $\pi$  bond to give a C7 radical, which abstracts Cl $\cdot$  from CCl<sub>4</sub> to give the product. The reaction may or may not be drawn as a chain reaction, depending on whether the rate of addition of the Cl<sub>3</sub>C $\cdot$  radical to S of the C=S  $\pi$  bond is comparable in rate to the Norrish cleavage.



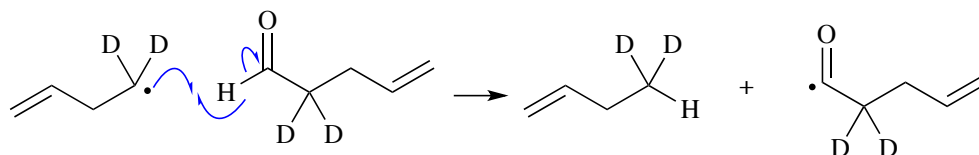
(r) First compound: Make: C2–H. Break: C1–C2. Second compound: Make: C2–C4, C3–H. Break: C1–C2, C3–C4.



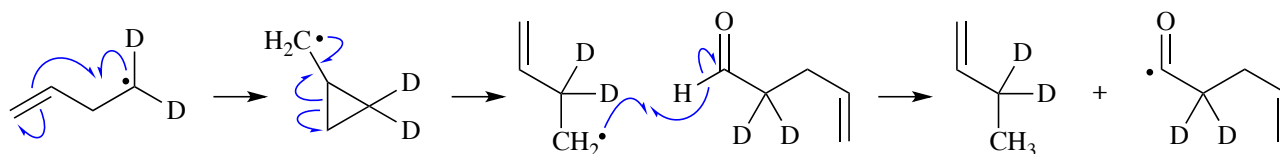
In both products, the C1–C2 bond has broken. This bond can break by fragmentation of a C1 radical to give the C2 radical and CO. The C1 radical is generated by abstraction of H $\cdot$ .



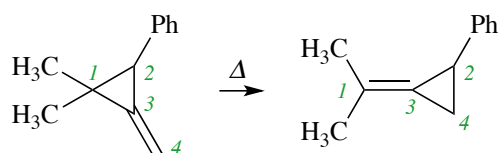
The first product is obtained by abstraction of H $\cdot$  from the starting material to complete the chain.



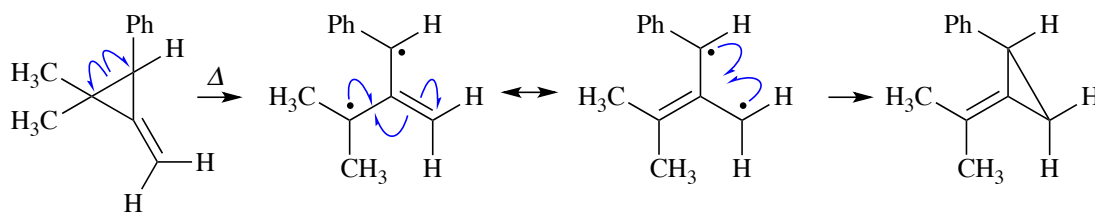
The second product still requires formation of the C2–C4 bond and cleavage of the C3–C4 bond. Addition of C2 to C4 is followed by fragmentation of the C2–C3 bond. The C3 radical then abstracts H $\cdot$  from the starting material to give the second product and to complete the chain.



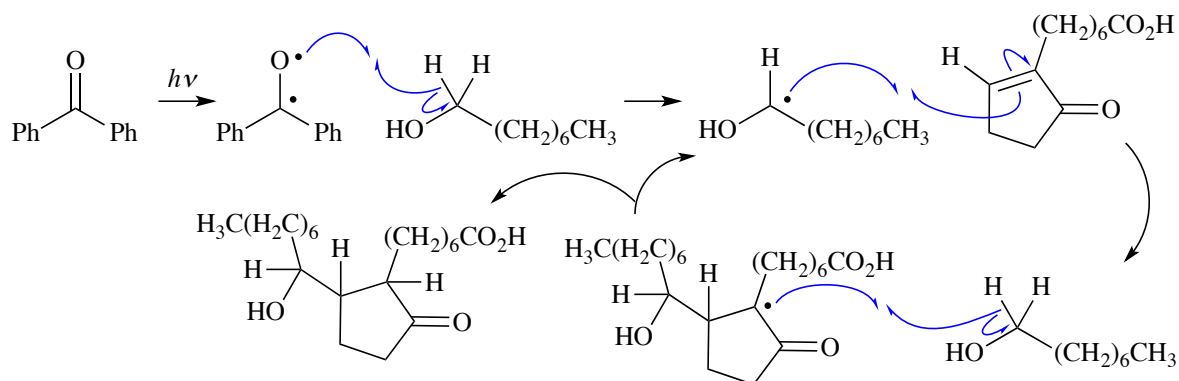
(s) Make: C2–C4. Break: C1–C2.



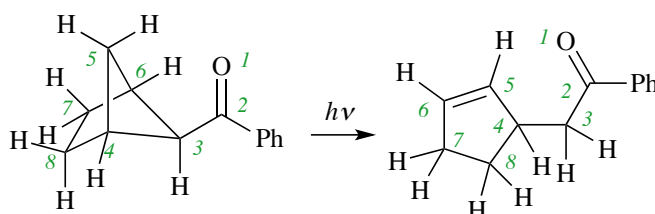
The C1–C2 bond is quite weak. Homolysis of this bond gives a 1,3-diradical at C1 and C2. The C1 radical is allylicly delocalized onto C4, also. Combination of the C2 radical with with the C4 radical gives the product.



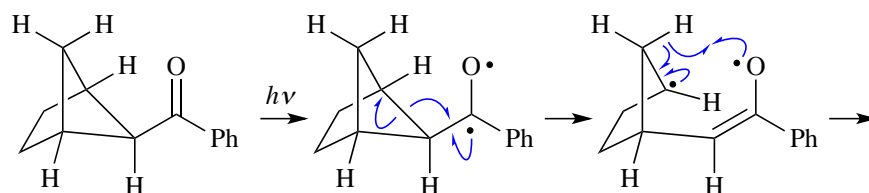
(t) Another free-radical addition reaction. The initiator is benzophenone in its photoexcited state. It abstracts  $\text{H}\cdot$  from the alcohol C adjacent to the OH group to give a 1-hydroxyalkyl radical, the first radical of the propagation part of the mechanism.

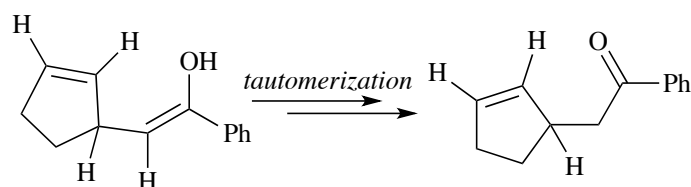


(u) As always, numbering is key. If we preserve as many C–C bonds as possible, we get the numbering shown. Make: C3–H. Break: C3–C6, C5–H.

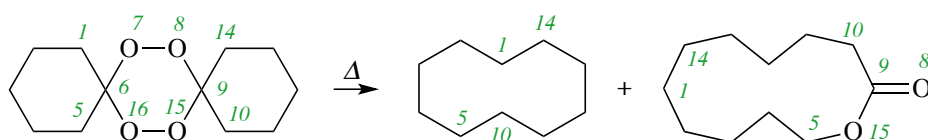


Photoexcitation of the ketone gives a 1,2-diradical. Fragmentation of the C3–C6 bond then occurs to relieve strain in the four-membered ring, giving a new diradical. (This mode of bond-breaking is neither Norrish type I nor type II.) A disproportionation reaction (six-membered TS) then gives an unsaturated enol, which tautomerizes (acid or base catalysis) to give the observed product.

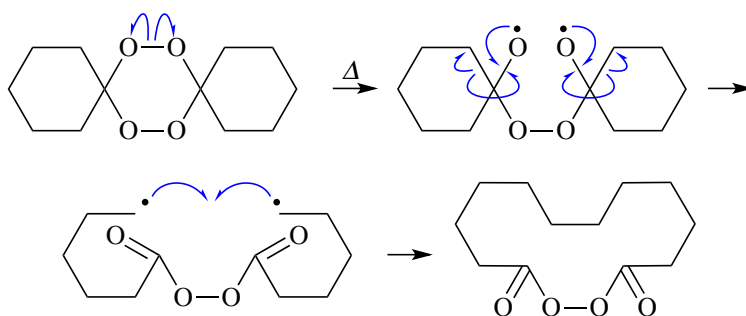




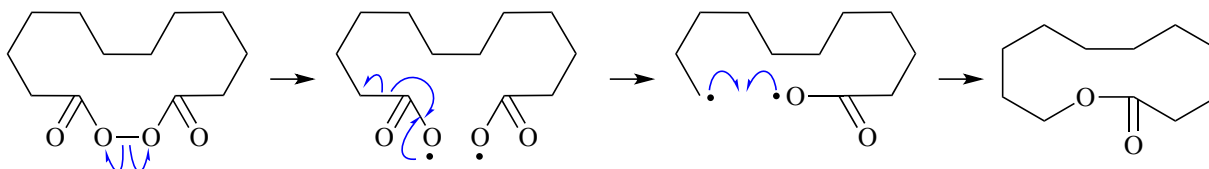
(v) From starting material to first product, two equivalents of  $\text{CO}_2$  are missing. First product: Make: C1–C14, C5–C10. Break: C1–C6, C5–C6, O7–O8, C9–C10, C9–C14, O15–O16. From starting material to second product, one equivalent of  $\text{CO}_2$  is missing. Second product: Make: C1–C14, C5–O15. Break: C1–C6, C5–C6, O7–O8, C9–C14, O15–O16.



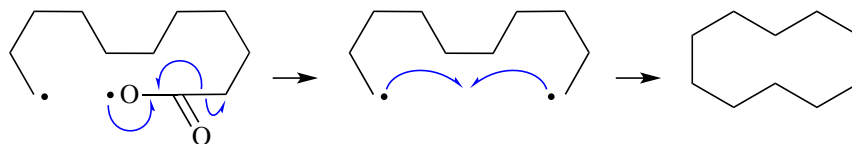
Heating cleaves a weak O–O bond homolytically to give two oxy radicals. Fragmentation of the C1–C6 and C9–C14 bonds gives two radicals which recombine to give a cyclic diacyl peroxide.



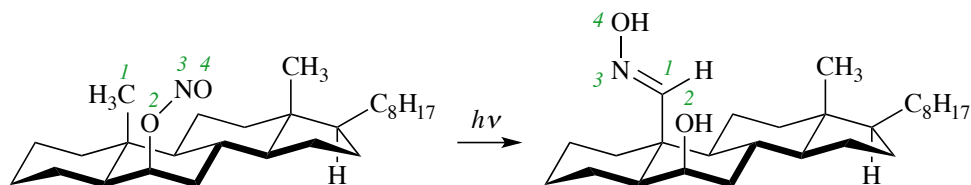
Homolytic cleavage of the O15–O16 bond gives a new diradical. This can lose either one or two equivalents of  $\text{CO}_2$  before recombination to give the two observed products.



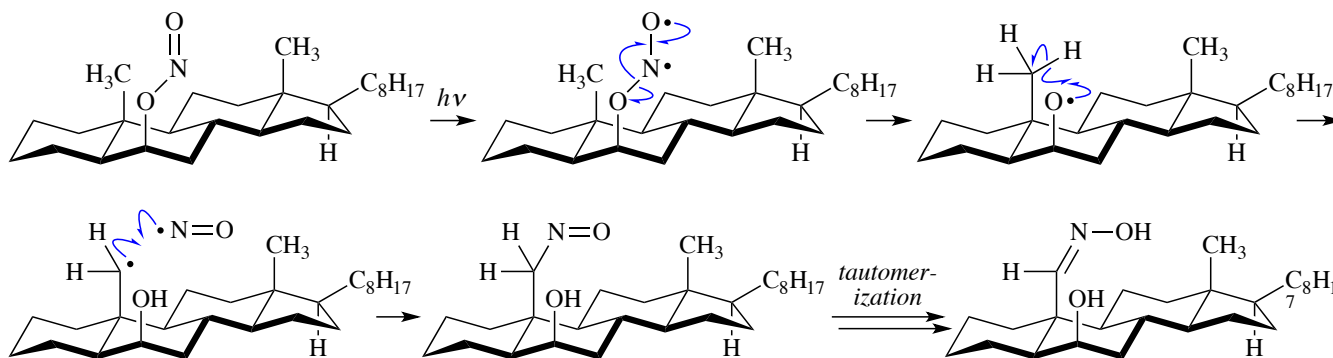
OR



(w) Make: C1–N3. Break: O2–N3.

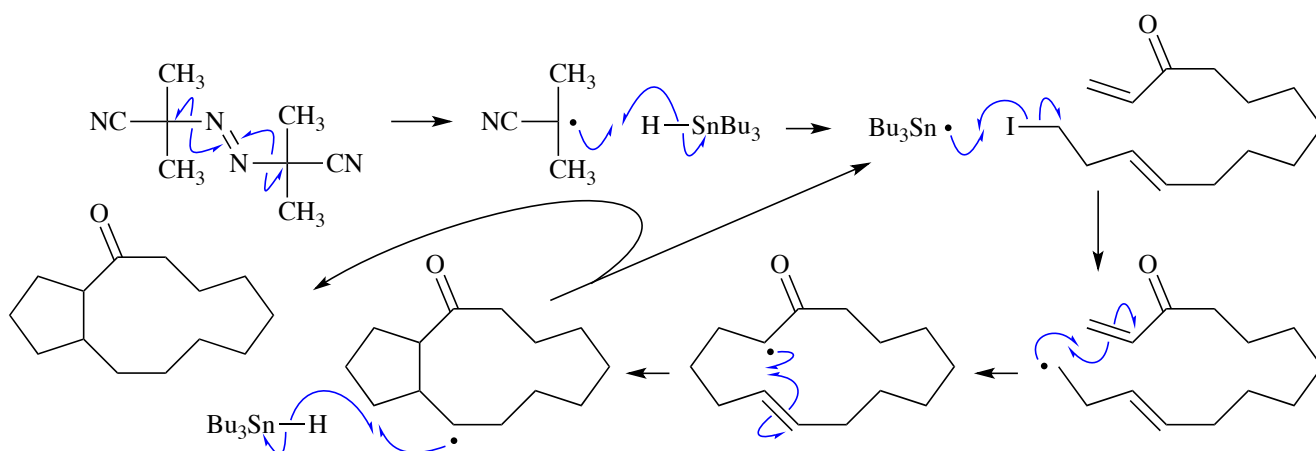


This is a Barton reaction. Photoexcitation of the N=O  $\pi$  bond is followed by fragmentation of the O–NO bond gives an oxy radical, which abstracts H $\cdot$  from the nearby C1. Combination of this radical with NO, then acid- or base-catalyzed tautomerization, gives the oxime.

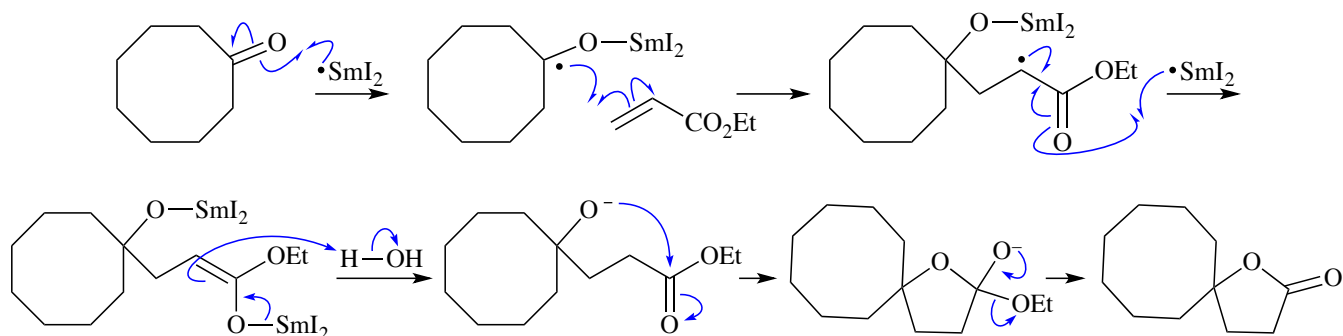




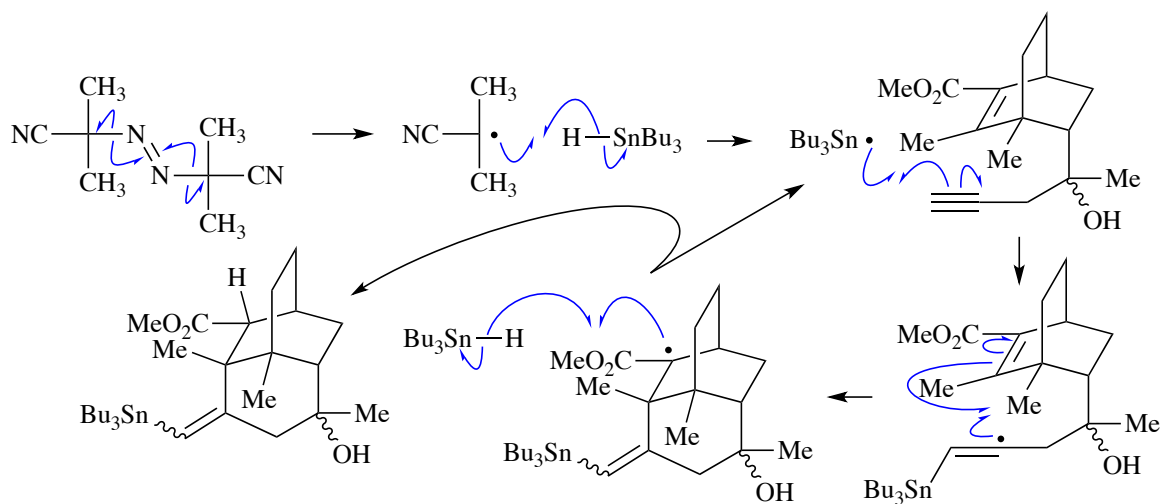
(x) Two sequential free-radical addition reactions occur. They may be stepwise or concerted.



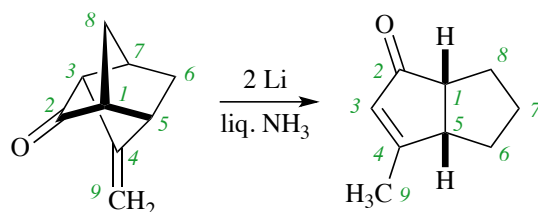
(y) Reduction of the ketone by  $\text{SmI}_2$  gives the ketyl. Addition of the C radical to ethyl acrylate gives a new radical, which undergoes further reduction by  $\text{SmI}_2$  to give the ester enolate. Workup gives a  $\gamma$ -hydroxyester alcohol, which closes up to the lactone (cyclic ester).



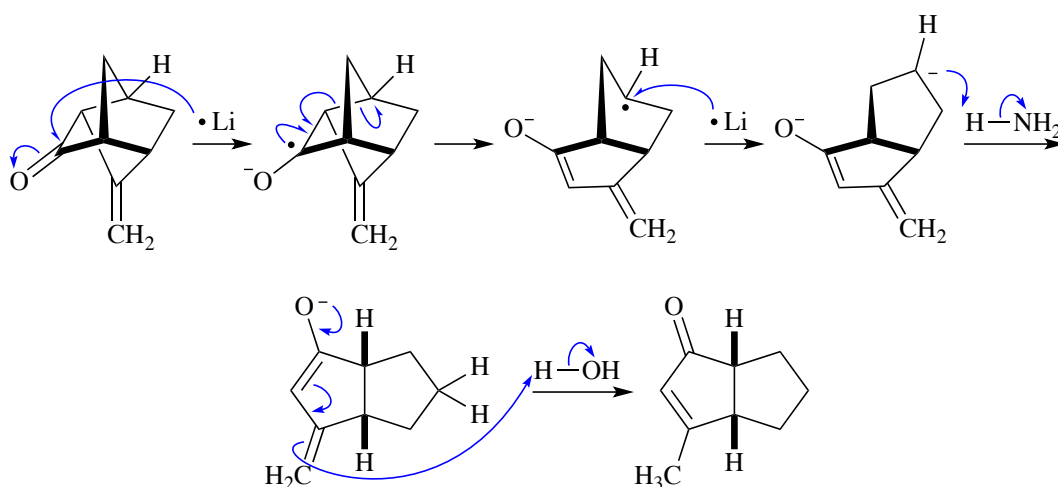
(z) The  $\text{Bu}_3\text{Sn}\cdot$  adds to the alkyne to give an alkenyl radical, which then undergoes intramolecular addition to give an alkyl radical. This radical is quenched from the less hindered side to put the carboxylate group in the more sterically hindered position.



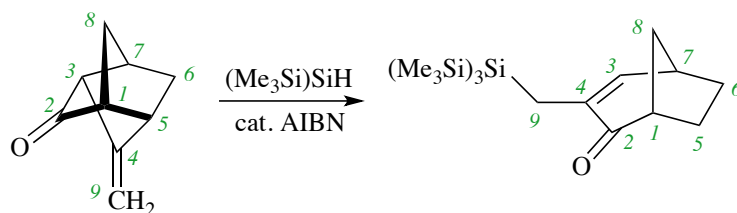
(aa) The easiest atoms to assign in the product are C2, C9 and C4. Break: C3–C7.



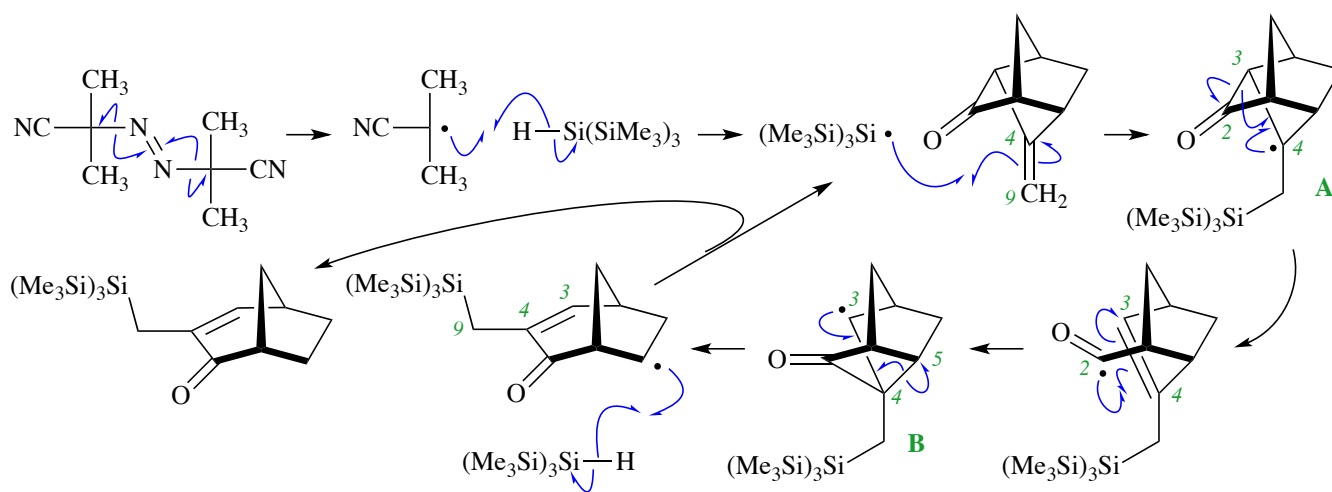
The first step is electron transfer to the C=O  $\pi^*$  orbital to make the ketyl. This undergoes C3–C7 fragmentation to give a dienolate and a radical at C7. Under the reaction conditions, this radical is reduced by a second equivalent of Li to give a carbanion, which is protonated by  $\text{NH}_3$ . The dienolate is protonated on C9 upon workup.



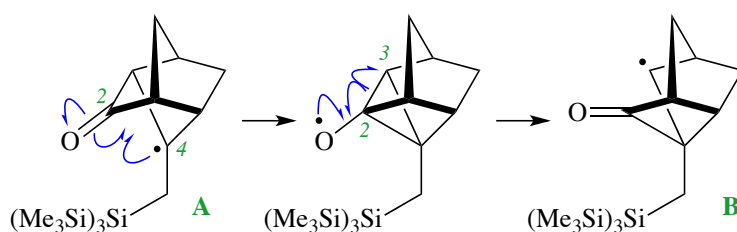
(bb) Again, the easiest atoms to number in the product are C2, C9, and C4. In the product, the bridgehead C next to the carbonyl C2 is going to be either C1 or C3; this C is more likely to be C1, because it is bound to two CH<sub>2</sub> groups, and in the starting material C1 is bound to one CH and one CH<sub>2</sub> while C3 is bound to no CH<sub>2</sub> groups. From there the numbering is clear. Make: Si–C9, C4–C2. Break: C2–C3, C4–C5.



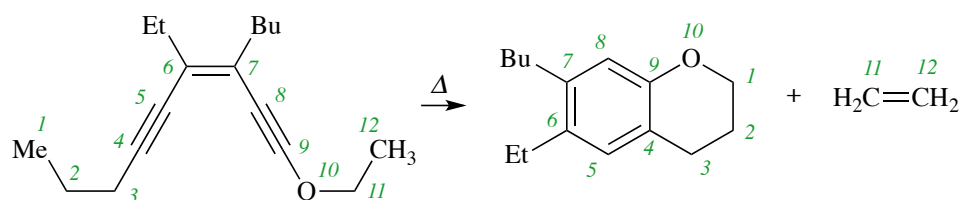
This is an intermolecular reaction, so it's going to be a chain process. Initiation has the AIBN-derived radical remove H from Si. In the propagation, the Si radical adds to C9 to give intermediate **A**. From **A**, two pathways to intermediate **B** are possible. *Either* we can cleave C2–C3, then make C4–C2, *or* we can make C4–C2, then cleave C3–C2. Either way, the final steps are the fragmentation of C4–C5 in **B**, then abstraction of H· from Si–H to start the propagation again.



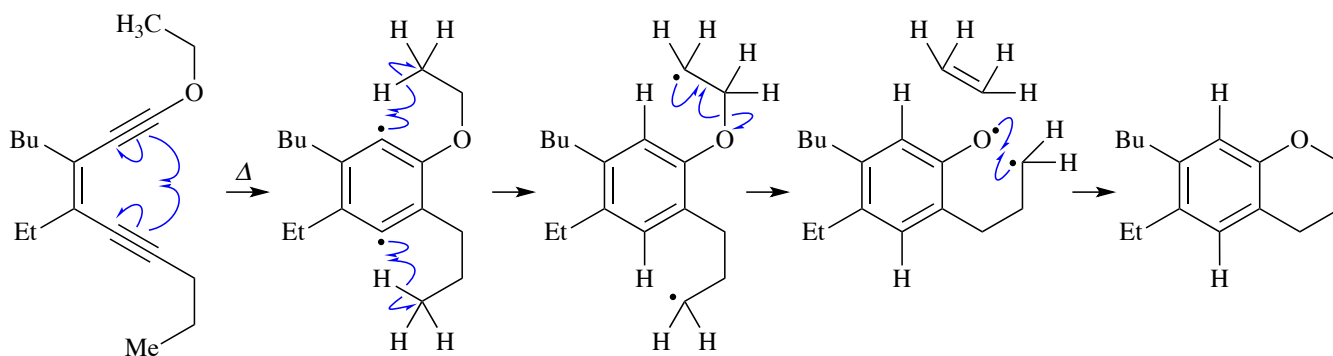
OR



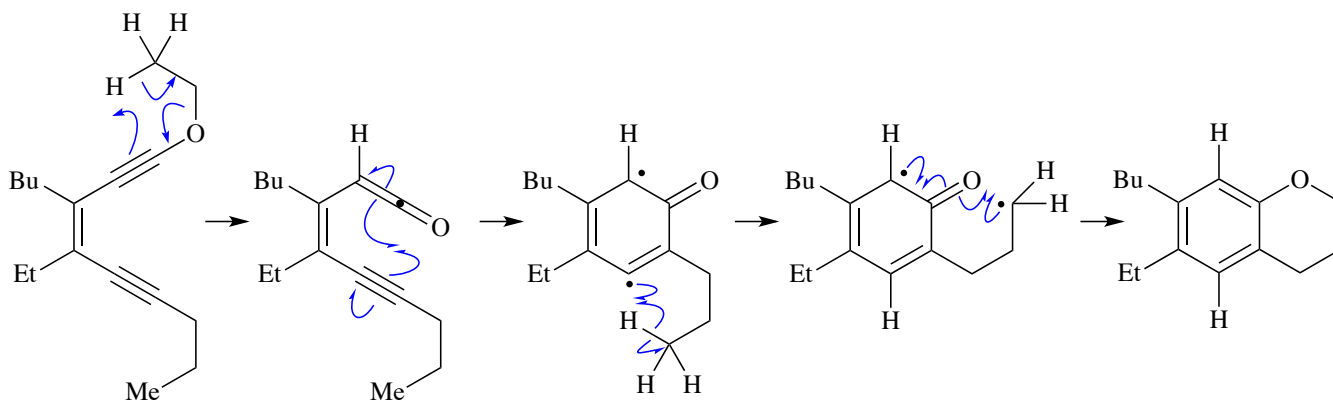
(cc) A molecule of ethylene is lost. Make: C1–O10, C4–C9. Break: O10–C11.



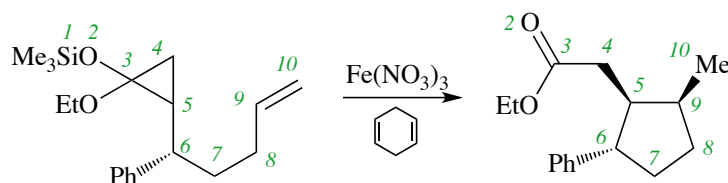
Enediyne tend to undergo Bergman cyclizations, and the C4–C9 bond can be made in this way. The C5 and C8 radicals produced thereby can each abstract H $\cdot$  from C1 and C12, respectively. Fragmentation of the C10–C11 bond, then radical–radical combination gives the product.



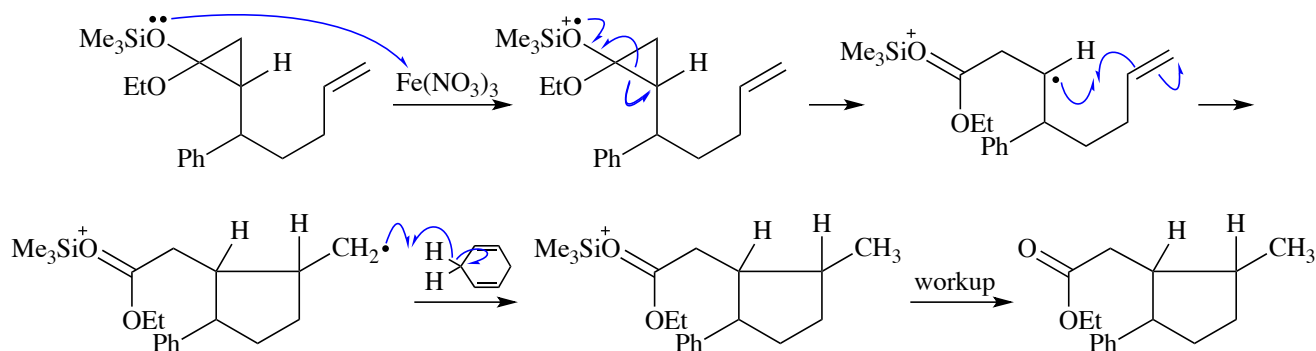
Alternatively, a retro-ene reaction cleaves the O10–C11 bond and gives a highly unsaturated ketene. The ketene can undergo cycloaromatization to give a diradical intermediate. H $\cdot$  abstraction and radical–radical recombination then give the product.



(dd) Make: C5–C9. Break: Si1–O2, C3–C5.



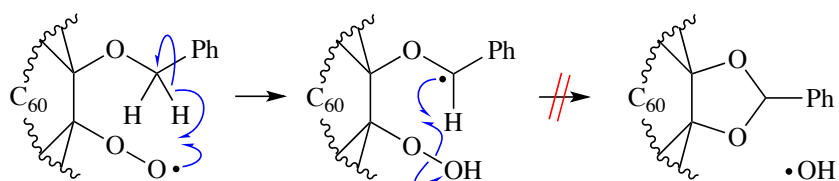
$\text{Fe}(\text{NO}_3)_3$  has the same reactivity as CAN, a one-electron oxidizing agent. The  $\text{Fe}(\text{NO}_3)_3$  will remove the electron highest in energy from the substrate. Such an electron would have to be one of the unshared electrons of the O atoms. After removal of an electron from O2, the C3–C5 bond can fragment to give a C5 radical, which can add to C9 and generate a new radical at C10. The C10 radical then abstracts  $\text{H}\cdot$  from 1,4-cyclohexadiene. Si1 is lost from O2 upon aqueous workup.



4. (a) The third step, combination of  $\text{O}_2$  with a radical, is reasonable. The fourth step, abstraction of  $\text{H}\cdot$  from an O–H bond by  $\text{ROO}\cdot$ , is *not* reasonable, because the alkylperoxy radical is much more stable than the alkoxy radical. The radical could abstract  $\text{H}\cdot$ , but not from an O–H bond. The fifth step is reasonable, assuming that the benzyloxy radical could be formed in the first place. The sixth step, abstraction of  $\text{RO}\cdot$  from an RO–OH bond by a stable alkyl radical, is *very doubtful*.  $\text{HO}\cdot$  is a very high energy species that is only very rarely seen in organic reactions, and reaction mechanisms claiming  $\text{HO}\cdot$  as an intermediate or coproduct must be viewed with great skepticism. (It is, however, an important biological radical.) Also, abstractions of first row atoms are not common, and the proposed  $\cdot\text{OH}$  abstraction reaction is expected to be quite slow.

(b) The fourth and fifth steps could be combined to give a reasonable step. That is, the peroxy radical could directly abstract  $\text{H}\cdot$  from the benzylic bond in an intramolecular fashion to give a benzylic radical and the hydroperoxy compound. This would require a seven-membered TS, but at least the  $\text{H}\cdot$  would be

abstracted from a relatively weak bond. Unfortunately, this would not solve the problem of the sixth step.



A better possibility:  $\text{PhCH}_2\text{O}^-$  adds to  $\text{C}_{60}$ . Then autoxidation of a benzylic C-H bond occurs to give the hydroperoxide. Then the  $\text{C}_{60}$  carbanion displaces  $\text{OH}^-$  from the hydroperoxide to give the product.

