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The Intermediacy of Oxycyclobutenes in the Synthesis and Reactions of Cyclobutenones and Cyclobutenols

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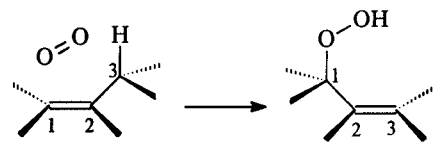
Abstract: Vinylcyclobutenol **7**, generated *via* the singlet oxygenation of alkylidenecyclobutene **5**, rearranges at room temperature to a solvent dependent mixture of isomeric dienones **10** and **11**. Alkylidenecyclobutene **5** was prepared in turn *via* an inverse Wittig addition of the isopropyl ylide to cyclobutenone **4**; in a normal addition of ketone to ylide, vinylallene **12** is also obtained. Finally, the corresponding Wittig reaction of 4,4-dichlorocyclobutenone **3** yields only the 2,4-dichloro isomer **13**. When this reaction is carried in the presence of *n*-butoxide, dienone **32** is generated. © 1999 Elsevier Science Ltd. All rights reserved.

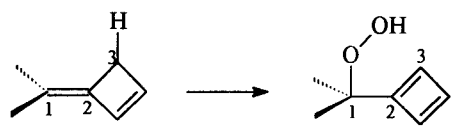
Keywords: Cyclobutenes; Rearrangements; Oxygen, Singlet; Wittig Reactions

Introduction

In the $^1O_2$ ene reaction, olefins containing an allylic hydrogen are oxidized to the corresponding allylic hydroperoxides in which the double bond has shifted to a position adjacent to the original double bond (equation 1).[1] Previous research in this laboratory has explored the effect of ring-strain on the mode, rate and direction of singlet oxygen attack.[2] In particular, we have focused on various small ring olefin systems in which ring-strain decreases or develops as we proceed to product. These studies indicate that, in the transition state leading to product, $^1O_2$ is essentially insensitive to strain considerations.[1a,1b] This conclusion is consistent with prior reports that singlet oxygen reactions have very small activation energies (0.5-8 kcal/mol)[3] and that the product-determining transition state is reactant-like and occurs quite early.[1] In light of this, we speculated as to whether singlet molecular oxygen reactions might even be used to obtain access to anti-aromatic species,[4] converting, for example, alkylidenecyclobutenes into cyclobutadiene derivatives (eq. 2).



(eq. 1)



(eq. 2)

To this end, we explored the synthesis and photosensitized oxygenation of 1-isopropylidene-3-phenylcyclobut-2-ene **5** (as well as several other alkylidenecyclobutenes), as outlined in Scheme 1.[4b] Cycloaddition of dichloroketene **2** with phenyl acetylene generated dichlorocyclobutenone **3**,

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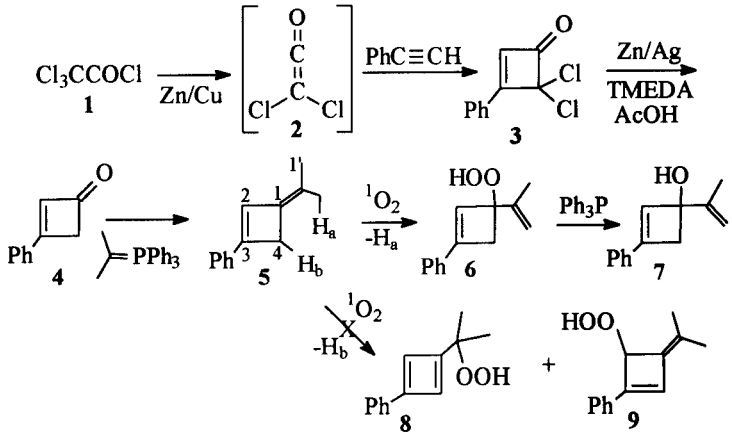
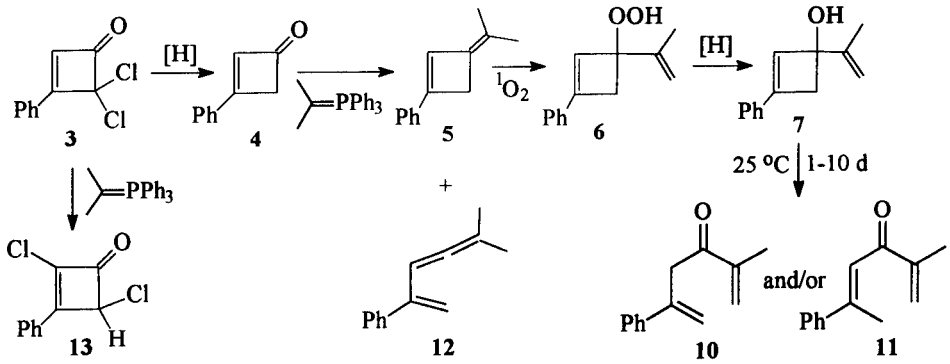
which was reduced to dihydro analog **4**, and converted to alkylidenecyclobutene **5** *via* a Wittig reaction. Singlet oxygenation gave exclusively hydroperoxide **6** which was reduced to the corresponding alcohol **7**. We found no evidence for either the formation of the antiaromatic cyclobutadiene **8** or diallylic hydroperoxide **9**, whose formation would have involved abstraction of the endocyclic allylic hydrogen H_b. The reason for their absence deserves further elucidation.

Scheme 1: Synthesis and Photosensitized Oxygenation of Isopropylidenecyclobutene **5**



We have recently reinvestigated the preparation of cyclobutenol **7** and, as summarized in Scheme 2, have revealed several very curious results which required further investigation and elucidation: (1) Firstly, we discovered that vinylcyclobutenol **7** rearranges at room temperature to a mixture of products (ultimately identified as isomeric dienones **10** and **11**), with the exact product distribution and rate of reaction depending on the solvent conditions. (2) Secondly, the Wittig reaction of cyclobutenone **4** generates not only the desired alkylidenecyclobutene **5**, but also variable (10-30%) yields of vinylallene **12**. (3) Finally, the corresponding Wittig reaction of 4,4-dichlorocyclobutenone **3** yields only the 2,4-dichloro isomer **13**. As we hope to demonstrate in this paper, a common underlying mechanism involving oxycyclobutenes links these varied transformations.

Scheme 2: Side Reactions in the Preparation of Cyclobutenol **7**



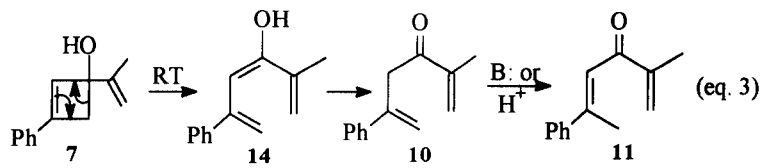
Results and Discussion

(A) Rearrangement of Vinylcyclobutenol 7. Frimer and Weiss[4] report that hydroperoxide **6**, formed in the photosensitized oxygenation of diene 5, proves to be relatively stable at ambient temperatures; nevertheless, the corresponding allylic alcohol 7, obtained upon Ph_3P reduction of **6** in $CDCl_3$, undergoes facile rearrangement at 25 °C to a mixture of undetermined products. Our reexamination of this system revealed that when the reduction of hydroperoxide **6** was effected by thiourea in methanol at -10 °C, cyclobutenol **7** could be obtained pure and stored at this temperature (freezer) essentially without change for extended periods of time.
We also discovered that the product distribution and rate of rearrangement are solvent dependent. As Table 1 shows, in the aprotic solvent benzene or in $CDCl_3$ containing 5% of the mildly basic pyridine, a single product is obtained, which was identified as the partially conjugated dienone **10**. On the other hand, the fully conjugated dienone **11** is formed exclusively in $CDCl_3$ containing 5% of the more strongly basic triethylamine. A variable mixture of these dienones is obtained in chloroform, the extent of whose mild acidity depends on the supplier and the age of the solvent sample.

Table 1: Solvent Dependence in the Rearrangement of Cyclobutenol **7**

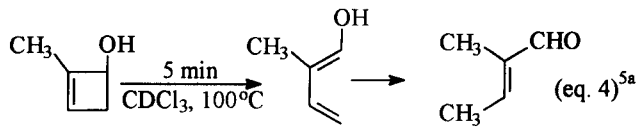
SOLVENT	BASE	RXN TIME (d)	PRODUCT
$CDCl_3$	---	4-10	**10** and **11** (variable ratio)
Benzene	---	3	**10**
$CDCl_3$	Pyridine	1	**10**
$CDCl_3$	Et_3N	1	**11**

These results can be easily rationalized by assuming a well precedented[5,6] electrocyclic opening of vinylcyclobutenol **7** to trienol **14**, which tautomerizes in turn to the partially conjugated kinetic product dienone **10**, or, under acid or base catalysis, to the fully cross-conjugated dienone **11** (eq. 3).

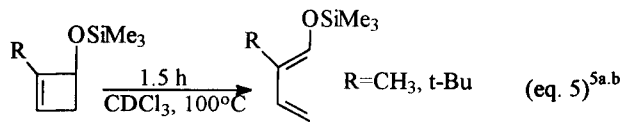


(eq. 3)

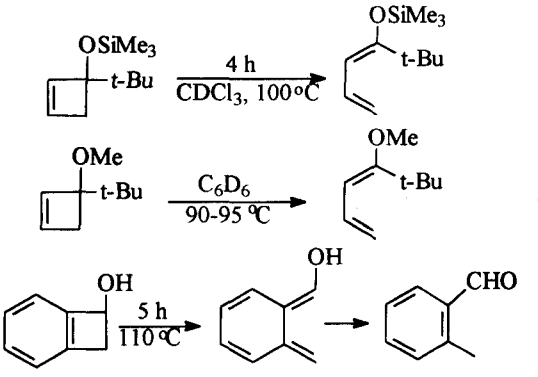
What is somewhat surprising, however, is that this rearrangement is relatively facile, occurring at room temperature. By comparison, other hydroxy-, alkoxy-, and silyloxycyclobutenes are stable at ambient temperatures, with electrocyclic openings generally observed only at much higher temperatures, *ca.* 100 °C (see eqs. 4-7). In the corresponding benzocyclobutene series (eq. 8), such openings are even slower.



(eq. 4)[5a]

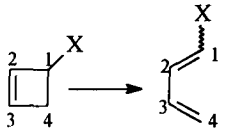


(eq. 5)[5a,b]



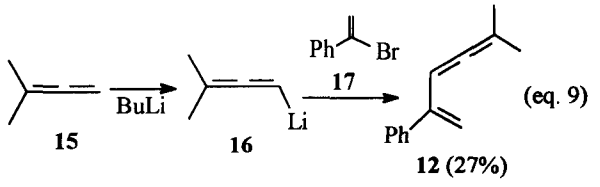
The room temperature opening of 7 can be easily rationalized, based on the relative activation energies for such processes calculated by Houk and coworkers[5c,5d] and summarized in Table 2.[7] It is clear from these E_a values that not only electron donors such as a hydroxyl group (ΔE_a = -8.8 kcal), but also a vinyl moiety (ΔE_a = -5 kcal), effect a sizable lowering of the energy of activation for the electrocyclic opening of substituted cyclobutenes. Hence, it is not surprising that our vinylcyclobutenol 7, with a cumulative effect of ΔE_a = -13.8 kcal, should open at room temperature. Note also that the Table predicts that conversion of the hydroxyl group to an oxyanion (ΔE_a = -18.4 kcal) will have a dramatic effect on accelerating this process (*vide infra*).

Table 2: Houk's Calculated Relative Energies of Activation, ΔE_a (kcal/mol), for the Electrocyclic Opening of Substituted Cyclobutenes[5d]

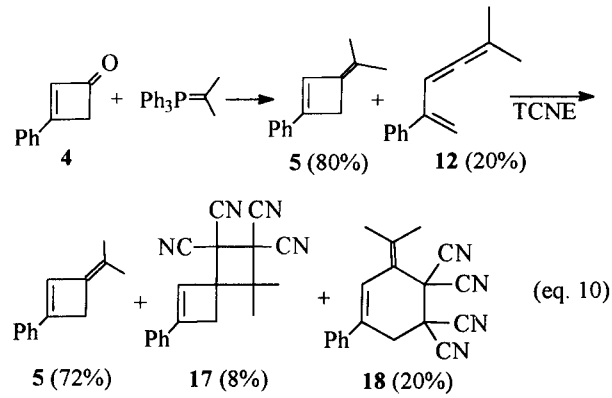


Substituent	O^-	NH_2	OH	CH_3	$CH{=}CH_2$	H
ΔE_a	-18.4	-11.5	-8.8	-1.7	-5	[0]

(B) Formation of Vinylallene 12. As noted above and outlined in Scheme 2, we attempted to prepare the singlet oxygenation substrate, isopropylidenecyclobutene 5, *via* the Wittig reaction of cyclobutenone 4 with isopropylidenetriphenylphosphine. We discovered, however, that the desired product was contaminated with varying amounts (10-30%) of vinylallene 12, which we were unsuccessful in removing by column chromatography. The vinylallene was identified by its spectral data and independently synthesized by coupling bromostyrene (17) with the lithium salt of 1,1-dimethylallene (16, eq. 9).[8]



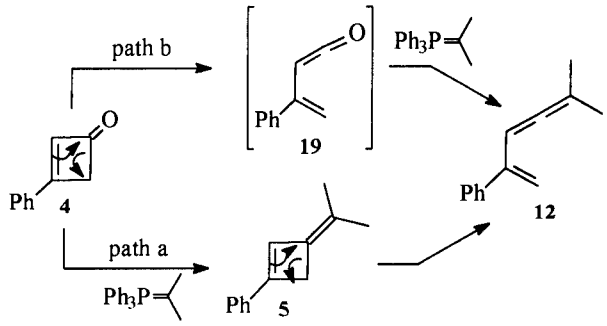
We did discover, however, that we could obtain **5** essentially pure by reacting the isomer mixture of **5** and **12** with tetracyanoetheylene (TCNE; 1.4 equivalents based on **12**) at room temperature. The [2+4] cycloaddition of vinylallene **12** leading to **17** proceeded substantially faster than the [2+2] cycloaddition to the exocyclic double bond of alkylidenecyclobutene **5**, converting the vinylallene to TCNE-adduct **18** (eq. 10). The non-polar alkylidenecyclobutene **5** could then be readily isolated by column chromatography.



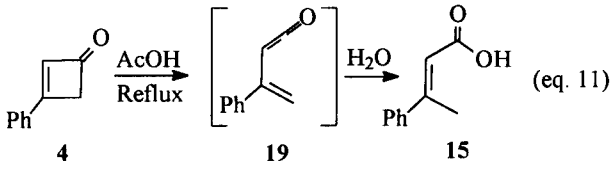
(eq. 10)

Although this TCNE derivatization method allowed us to obtain pure **5**, we desired a more fundamental understanding of *how* and *why* vinylallene **12** was formed in the first place. A priori, one would be tempted to suggest that perhaps alkylidenecyclobutene **5** itself opens to the allene **12** (Scheme 3, path a).

Scheme 3: Rejected Mechanisms for the Formation of Vinylallene **12**



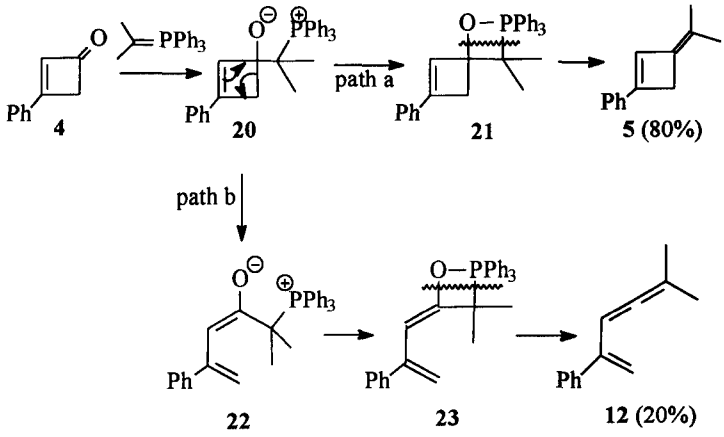
However, **5** is known to be thermally stable even at temperatures above 160 °C.[8b,9] Alternatively, allene **12** might result from electrocyclic opening of cyclobutenone **4** to vinylketene **19**,[10] which then undergoes Wittig reaction[11] to **12** (Scheme 3, path b). Indeed, Hassner and Dillon[12] report that ketene formation from **4** can be detected; nevertheless, it occurs only at temperatures above 100 °C (eq. 11).



(eq. 11)

Based on our experience with vinylcyclobutenol **7** we would like to suggest an alternate possibility, outlined in Scheme 4. Addition of the Wittig reagent to cyclobutenone **4** is expected to yield betaine **20**. Rapid closure of the zwitterion to oxaphosphetane **21** would yield the expected alkylidenecyclobutene **5**. However, betaine **20** is an oxycyclobutene and a facile electrocyclic opening to betaine **22** is not unexpected. Closure of the latter to oxaphosphetane **23** would then yield allene **12**.

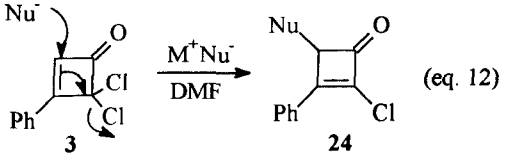
Scheme 4: Proposed Mechanism for the Formation of Vinylallene **12**



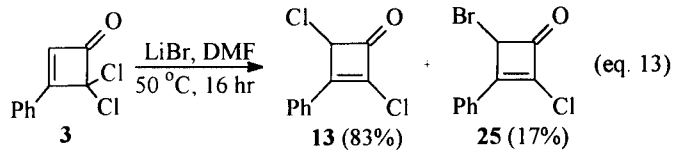
It should be noted that allene **12** is formed in only a 20% yield, which suggests that the immediate closure of betaine **20** (path a) is preferred to electrocyclic opening (path b). We postulated that if the above mechanism is correct, the reason betaine **22** is formed at all is because, under normal Wittig reaction conditions, we add the ketone to the Wittig reagent solution. The latter is highly polar, containing a high concentration of lithium salts. Under such conditions, the open form betaine **20** is stabilized and exists long enough to undergo electrocyclic opening to betaine **22**. However, were we to carry out an inverse addition of the Wittig reagent to the ketone, the amount of allene formed would be negligible.

This is in fact the case: when an inverse addition is performed we could detect only traces of allene. Furthermore, if we carry out an inverse addition - but add to the ketone solution a high concentration of LiBr - we again obtain a 20% yield of vinylallene. All this is consistent with the mechanism proposed in Scheme 4.

(C) Wittig Reaction of 4,4-Dichlorocyclobutenone 3. Having explained the formation of **12** from cyclobutenone **4**, we wanted to explore the corresponding Wittig reaction of the 4,4-dichloro analog **3**. Much to our surprise, the 2,4-dichloro isomer **13** was formed exclusively (Scheme 2). Searching the literature, we came across the report of Dillon and Gao[13] who studied the S_N2' reaction of various nucleophiles upon cyclobutenone **3** (eq. 12).

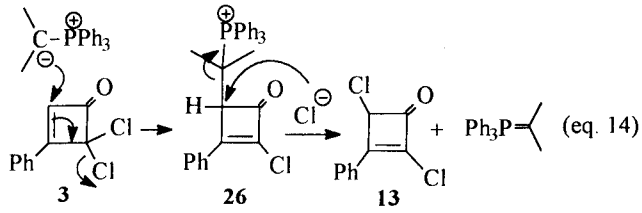


In particular, they report that heating a DMF solution of enone **3** with lithium bromide at 50 °C generated an 83% yield of the dichloro isomer **13** along with a 13% yield of the bromochloro analog **25** (eq. 13).



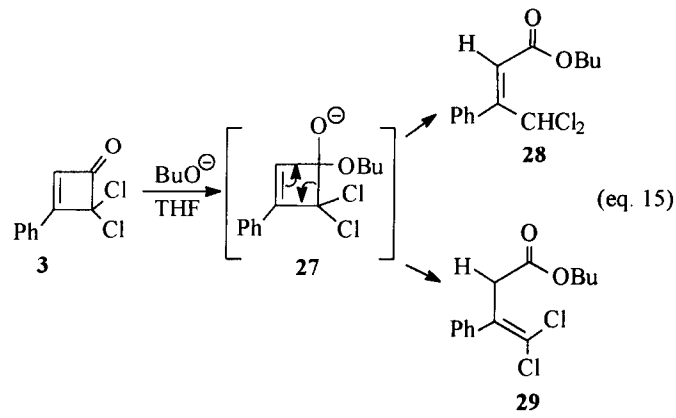
(eq. 13)

We thought that perhaps in our case too, the LiBr generated in the preparation of the Witting reagent might be catalyzing the isomerization of **3** to **13**. Nevertheless, when we tried to isomerize **3** with LiBr in THF, the solvent of the Wittig reaction, **3** was recovered unchanged. These results lead us to consider an alternative mechanism. As shown in eq. 14, we believe it is the Wittig reagent itself which reacts at the double bond *via* an S_N2' reaction, yielding intermediate **26**, which then undergoes chloride attack yielding **13**.



(eq. 14)

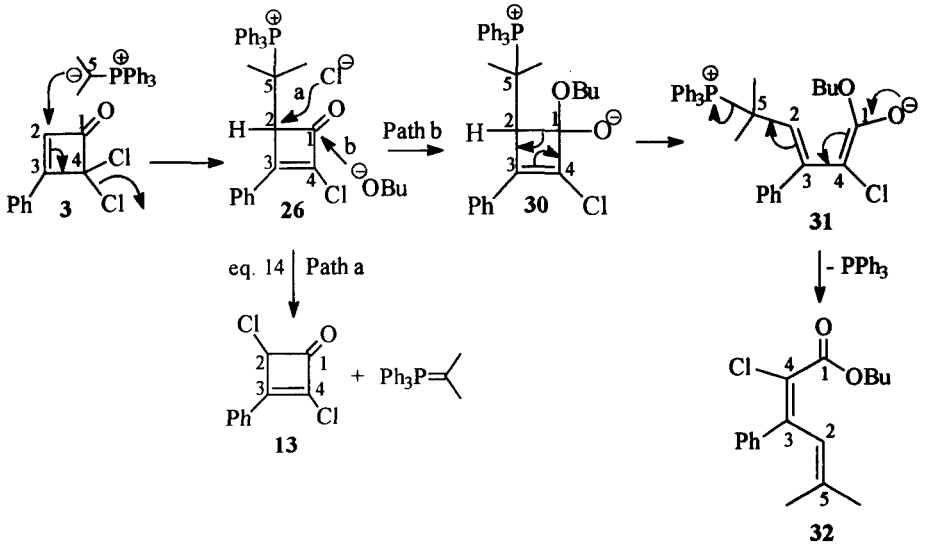
In order to provide evidence for this mechanism, we were interested in trying to intercept **26** before it expels the Wittig reagent leaving group. In this regard, Hassner and Dillon[12] report that *n*-butoxide reacts with **3**, not at the double bond, but at the carbonyl (eq. 15). The resulting oxycyclobutenone **27** undergoes facile electrocyclic opening to enones **28** and **29**. We hoped that if we now carried out the Wittig reaction on 4,4-dichlorocyclobutenone **3** in the presence of *n*-butoxide we might now succeed in intercepting the phosphorane S_N2' reaction intermediate **26**.



(eq. 15)

As shown in Scheme 5, when we carried out the Wittig reaction on 4,4-dichlorocyclobutenone in the presence of *n*-butoxide, we obtained diene ester **32** as the exclusive product. We believe that prior to chloride attack on the sterically hindered C-2 position of **26** to give **13** (as already outline in eq. 14), rapid *n*-butoxide attack at the C-1 carbonyl once again generates an oxycyclobutene (**30**). Facile electrocyclic opening of the latter produces dienolate **31**, which expels triphenylphoshine yielding the observed dienone **32**.

Scheme 5: Trapping of Intermediate **26**

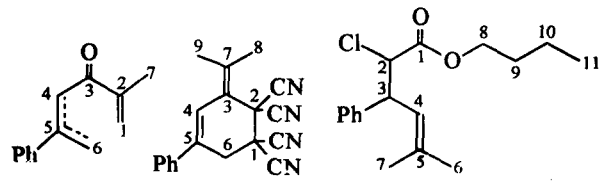


Conclusion

We began our study in search of antiaromaticity, but discovered instead the curious formation of a whole group of unexpected products, **10-13** and **32**. The evidence presented in this paper strongly suggests that, despite the variety of products, there really is a common simple intermediate in all these cases: the labile oxycyclobutene.

Experimental

NMR spectra were obtained on Bruker DMX-600, DPX-300 and AC-200 Fourier transform spectrometers. Assignments were facilitated with DEPT (DPX-300), by correlating proton and carbon chemical shifts through analysis of residual couplings in off-resonance decoupled spectra (AC-200), and *via* long range hetero COSY and NOESY experiments (DMX-600) as needed. In all cases, TMS served as the internal standard. EI and CI (CH_4) mass spectra were run on a Finnigan-4021 GC/MS machine (at 70 eV, unless otherwise indicated), except where exact mass data is given. In the latter instance, the EI data reported is based on the high resolution mass spectra (HRMS), performed on a VG-Fison AutoSpecE High Resolution Spectrometer. Preparative thin layer chromatography (PTLC) was carried out on Merck silica gel F_{254} precoated plates and the products were extracted from the silica by stirring overnight in dichloromethane. For column chromatography separation, Merck silica gel 230-400 mesh was used. All "dried" solvents were distilled from sodium benzophenone ketyl immediately before use. We report here experimental details for the substantially improved preparation of the known[4b] cyclobutyl compounds **3-7**. The spectroscopic data of the latter proved to be essentially identical to those reported previously by Frimer and Weiss.[4b] For the assignments of NMR signals, the compounds have been numbered as shown below.



10-11 18 32

4,4-Dichloro-3-phenyl-2-cyclobuten-1-one (3): A flame-dried three-necked flask, fitted with a magnetic stirrer, two glass stoppers and an gas inlet adapter, was charged with activated zinc (5.2 g, 87 mmol),[14] that had been heated to 140 °C overnight. The flask was maintained under an argon cloud and cooled to room temperature, and a solution of phenylacetylene (3 g, 24.9 mmol) in dry ether (100 mL) was added. The flask was then equipped with pressure equalizing addition funnel topped with an argon inlet adapter. To the vigorously stirred mixture, a dry ether solution (50 mL) containing trichloroacetyl chloride (6.6 mL, 58 mmol) and phosphorous oxychloride (5.4 mL) was added over a 30 min. period. After 4 hours, the resulting brown mixture was filtered through a pad of Celite. The filtrate was washed successively with 100 mL portions of ice water, 5% ice cold sodium hydroxide (until the liquor had a brandy color), and saturated sodium chloride, and then dried over magnesium sulfate. Removal of the ether *in vacuo* yielded a solid which was recrystallized from hot petroleum ether (40-60 °C) and identified as the desired dichlorocyclcbutenone **3** (4.5 g, 21.0 mmol, 84% yield).[4b]

3-Phenyl-2-cyclobuten-1-one (4): A flame-dried three-necked flask, fitted with a rubber septum, pressure-equalizing dropping funnel and nitrogen inlet adapter, was charged with a magnetically stirred suspension of zinc/silver couple[15] (5.26 g, 80 mmol) and tetramethylethylenediamine (TMEDA, 12.1 mL) in 100 mL absolute ethanol. Glacial acetic acid (4.6 mL) was then injected through the septum. The reaction mixture was maintained at 0 °C while a solution of 4,4-dichloro-3-phenyl-2-cyclobuten-1-one (2.94 g, 14 mmol) in dry ether (20 mL) was added over 10 min *via* the dropping funnel. After 15 min, the ice bath was removed, and the reaction mixture was stirred at room temperature and monitored by TLC. When all the starting material had reacted (*ca.* 1 h), the reaction mixture was vacuum filtered with the aid of ether. The filtrate was washed successively with a 5% sodium hydroxide solution and saturated sodium chloride solution, dried over magnesium sulfate, filtered, and concentrated at reduced pressure to give a good yield of 3-phenylcyclobutenone (**4**, 1.74 g, 88%).[4b]

1-Isopropylidene-3-phenyl-2-cyclobutene (5): A flame-dried three-necked flask equipped with a rubber septum, a gas inlet adapter and a glass stopper, was charged with the above isopropyltriphenylphosphonium bromide[16] (4.8 g ,10.3 mmol) in dry THF (150 mL) and the reaction mixture was magnetically stirred under an argon cloud. *n*-Butyllithium (4.8 mL, 2.6M solution in hexane, 12 mmol) was injected through the septum yielding a red ylide solution, which was stirred at room temperature for another 15 min. Meanwhile, another flame-dried three-necked flask equipped with a rubber septum, an gas inlet adapter and a glass stopper was charged with a solution of 3-phenylcyclobutenone (**4**) (1.4 g, 9.7 mmol) in dry THF (50 mL) which was magnetically stirred under an argon cloud. The ylide was transferred by syringe into the ketone solution ("inverse addition"), and the resulting mixture was stirred for another 0.5 h at room temperature. The reaction mixture was diluted with 50 mL CH_2Cl_2, washed successively with 100 mL portions of H_2O, and saturated sodium chloride solution and dried over anhydrous $MgSO_4$. Removal of the solvent *in vacuo* gave a thick dark brown oil which was purified by column chromatography eluting with petroleum ether (40-60 °C) giving cyclobutene **5** as a white, rose smelling solid (0.66 g , 3.88 mmol, 40% yield).[4b]

Photooxidation of Cylobutene 5; 1-Isopropenyl-3-phenyl-2-cylobuten-1-ol (7): The photooxidation of **5** was carried out in the vessel previously described.[17] The light source was two 600 W halogen lamps, each cooled by compressed air and water. Two straw-colored filters (360 nm UV cutoff) were placed between the photooxidation vessel and the lamps in order to exclude UV irradiation. The photooxidation vessel, equipped with a magnetic stirring bar and flushed with oxygen, was charged with pure olefin (*ca.* 250 mg) dissolved in 5 mL of $CHCl_3$ to which a spatula tipful of polymer-based Rose Bengal (P-RB) was added. The apparatus was closed with two rubber septa and connected *via* a syringe needle to an oxygen gas burette. The sample was irradiated until oxygen uptake essentially ceased (*ca.* 2 h). The amount of the oxygen absorbed was generally close to 100% of the theoretical oxygen uptake (*ca.* 22.4 mL per mmol of substrate). NMR and TLC confirmed that the photooxidation of cyclobutene **5** proceeded to completion yielding hydroperoxide **6**[4b] as the sole product. The latter could be isolated essentially pure by filtering off the P-RB and evaporating the solvent under reduced pressure. If alcohol **7**[4b] is desired, the hydroperoxide was dissolved in a 10% solution of thiourea in methanol and kept at -10 °C for 2 hours. The solvent was removed *in vacuo*, 20 mL chloroform were added, and the remaining solid was removed by filtration. Allylic alcohol 7 was quickly separated on PTLC eluting with 15% 2-methyl-2-butanone in petroleum ether (40-60 °C). The pure alcohol could be stored essentially unchanged for extended periods of time in the freezer at -10 °C.

2-Methyl-4-phenylhexa-1,5-dien-3-one (10) and 2-Methyl-4-phenylhexa-1,4-dien-3-one (11): When alcohol 7 is allowed to stand at room temperature (see Table 1 for various conditions), it yielded hexadienones **10** and/or **11.** The isomers were separated by preparative TLC, eluting with 10% acetone in hexane. The configuration of enone **11** was determined in part based on the observation that the chemical shift of the two C_1-hydrogens are essentially the same ($\Delta\delta$ = 0.2 ppm); hence there are no ring current effects.

10: ^{1}H NMR ($CDCl_3$) δ: 7.35 (m, 5H, aryl), 6.04 (broad s, 1H, H_1), 5.77 (qd, J 1.5 Hz, 0.5 Hz, 1H, H_1), 5.55 (broad s, 1H, H_6), 5.13 (broad s, 1H, H_6), 3.91 (d, J 0.5 Hz, 2H, H_4), 1.87 (bs, 3H, H_7); ^{13}C NMR ($CDCl_3$) δ 199.40 (C_3), 144.35, 142.25 and 140.39 (C_5, C_2 and *ipso*), 128.38 (*meta*), 127.68 (*para*) 125.83 (*ortho*), 125.27 (C_1), 116.40 (C_6), 44.38 (C_4), 17.8 (C_7); MS (CI, 70 eV): m/z 187 (MH^+, 9.30%), 85 (MH^+ - $PhCH{=}CH_2$, 100%); HRMS: calcd (MH^+, $C_{13}H_{15}O$) 187.1122, obsd 187.1140.

11: ^{1}H NMR ($CDCl_3$) δ: 7.49 (m, 2H, *ortho*), 7.38(m, 3H, *para* + *meta*), 6.89 (q, J 1Hz, 1H, H_4) 5.98 (quint, J 1Hz, 1H, H_1), 5.78 (qd, J 1.5 Hz, 1.0 Hz, 1H, H_1), 2.48 (d, J 1Hz, 3H, H_6), 1.97 (dd, J 1.5 Hz, 1.0 Hz, 3H, H_7); ^{13}C NMR ($CDCl_3$) δ 193.78 (C_3), 153.20, 146.61 and 142.91 (C_5, C_2 and *ipso*), 128.84 (*para*), 128.53 (*meta*), 126.37 (*ortho*), 123.89 (C_1), 121.73 (C_4), 18.58 and 17.80 (C_6 and C_7); MS (DCI, CH_4, 70 eV): m/z 187 (MH^+, 100%), 145 (MH^+ - C_3H_6, 5.49%); HRMS: calcd (MH^+, $C_{13}H_{15}O$) 187.1122, obsd 187.1136

2-Methyl-5-phenylhexa-2,3,5-hexatriene (12): This is a modification of the procedure previously described.[8] A flame-dried three-necked flask equipped with gas inlet adapter, glass stopper and rubber septum, was charged with dimethylallene (0.73 g , 7.65 mmol) and TMEDA (2.5 mL, 16.5 mmol) in 50 mL dry THF. The solution was magnetically stirred under a nitrogen cloud and the flask was cooled to –78 °C in a dry ice - acetone bath. A solution of *n*-butyllithium (6 mL, 1.6 M in hexanes) was then added dropwise by syringe through the rubber septum over 10 min. Meanwhile, another flame-dried three-necked flask, equipped with a gas inlet adapter, glass stopper, rubber septum and magnetic stirrer, was maintained under an argon cloud and charged with α-bromostyrene (1.21 g, 6.61 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4 g, 0.34 mmol) in dry THF (50 mL). After 30 min the allenic solution was added dropwise over 1 h *via* a syringe canula to the styrene solution, and the mixture was allowed to stir for an additional hour. The solution was diluted with 50 mL pentane, and extracted twice with water. The organic layer dried over magnesium sulfate and concentrated by rotary evaporation to give a brown solid. The crude product was flash chromatographed,

eluting with hexanes, to give the desired vinylallene (**12**; 300 mg, 1.76 mmol, 26.6% yield). The spectroscopic data of the latter proved to be identical to those previously reported.[8]

2,4-Dichloro-3-phenyl-2-cyclobuten-1-one (13). In an attempt to prepare the 4,4-dichloro analog of cyclobutene **5**, 4,4-dichloroketone **3** was reacted with isopropyltriphenylphosphonium bromide according to the procedure described above for the preparation of cyclobutene **5.** The crude product was chromatographed over silica gel, eluting with 3% ethyl acetate in petroleum ether (40-60 °C), yielding 2,4-dichlorocyclobutenone **13** in moderate yield (0.65 g, 3 mmol, 65% yield). The spectral data was identical to that reported previously by Hassner and Dillon.[12]

3,3-Dimethyl-6-phenyl-spiro[3.3]hept-5-ene-1,1,2,2-tetracarbonitrile (17): A two-necked round bottomed flask equipped with a magnetic stirring bar, gas inlet adapter and glass stopper, was charged with alkylidenecyclobutene **5** (106 mg, 0.62 mmol) in dichloromethane. The solution was magnetically stirred and maintained under a nitrogen cloud and tetracyanoethylene (230 mg, 1.69 mmol) was added at once. The color of the solution changes from dark blue to green after several minutes, and gradually to yellow during 16 h. The solvent was then removed and the residue was column chromatographed, eluting with 20% ethyl acetate in hexane, yielding the desired tetranitrile **17** (170 mg, 0.57 mmol, 92% yield).

17: ^{1}H NMR ($CDCl_3$) δ: 7.44 (s, 5H, aryl), 6.48 (s, 1H, H_2), 3.23 (s, 2H, H_4), 1.69 and 1.64 (each s, each 3H, C_6 and C_7 methyls); ^{13}C NMR ($CDCl_3$) δ 152.52 (C_3), 130.68 (*para*), 131.02 (*ipso*), 128.85 (*meta*), 125.76 (*ortho*), 121.40 (C_2), 109.45, 110.06 and 110.40 (CN), 57.08 (C_1), 50.76 (C_5), 41.68 and 42.98 ($C[CN]_2$), 35.31 (C_4), 24.27 (C_6 and C_7); MS (CI, 70 eV): m/z 299 (MH^+, 6.56%), 193 (MH^+ - $C(CN)_2C(CH_3)_2$, 30.67%), 170 (MH^+ - $C(CN)_2C(CN)_2$, 100%); HRMS: calcd ($C_{19}H_{15}N_4$, MH^+) 299.1296, obsd 299.1270.

3-(1-Isopropylidene)-5-phenyl-4-cyclohexene-1,1,2,2-tetracarbonitrile (18): The title compound was independently synthesized from allene **12,** by reacting the latter with TCNE, as described above for **17**. PTLC, eluting with 20% ethyl acetate in hexane, gave cyclohexene **18** in 56% yield.

18: ^{1}H NMR ($CDCl_3$) δ: 7.45-7.40 (m, 5H, aryl), 6.96 (s, 1H, H_4), 3.51(s, 2H, H_6), 2.37 and 2.16 (each one s,each one 3H, C_7 and C_8); ^{13}C NMR ($CDCl_3$) δ: 146.07 (C_3) 137.66 (*ipso*), 129.34 (C_3 and *para*), 129.20 (*meta*), 125.34 (C_7 and *ortho*), 116.45 (C_4), 110.42 and 110.88 (C_1 and C_2), 41.96 and 41.33 (CN), 33.83 (C_6), 24.28 and 22.93 (C_8 and C_9); MS (EI, 70 eV): m/z 298 (M^+, 100%), 283 (M^+ - CH_3, 17.21), 270 (M^+ - C_2H_4, 12.11%), 256 (M^+ - CH_3 - HCN, 50.11%), 244 (M^+ - C_2H_4 - CN, 33.80%), 229 (M^+ - CH_3 - 2HCN, 10.63%), 155 (M^+ - $CH_2C(CN)_2C(CN)_2$, 34.57%); HRMS: calcd for $C_{19}H_{14}N_4$ 298.1200, obsd 298.1218

Butyl 2-Chloro-5-methyl-3-phenyl-2,4-hexadienoate (32). A flame-dried three-necked flask was equipped with a rubber septum, an gas inlet adapter and pressure-equalizing addition funnel filled with 4,4-dichlorocyclobutenone **3** (1.0 g., 4.7 mmol) in 50 mL dry THF. The flask, maintained under an argon cloud, was charged with *n*-butanol (0.36 ml, 4.8 mmol) and isopropyltriphenylphosphonium bromide (1.8g, 4.7 mmol). After the reaction mixture was magnetically stirred for 0.5 h, *n*-butyllithium (2.0 mL of a 1.6 M solution in hexane, 3.12 mmol) was injected through the rubber septum dropwise over 20 min. The dichlorocyclobutenone solution was then added over a 5 min period. After an additional hour of stirring, the reaction mixture was diluted with 50 mL CH_2Cl_2, washed successively with water, 20 mL 30% hydrogen peroxide solution (to oxidize the triphenylphosphine into triphenylphosphine oxide), and saturated sodium chloride solution, and dried over anhydrous magnesium sulfate. Removal of the dichloromethane *in vacuo* gave a brown oil. The resulting crude product was purified by column chromatography over silica gel eluting with 3% ethyl acetate in hexane yielding the desired ester **32** (0.85 g, 62% yield).

32: ^{1}H NMR ($CDCl_3$) δ: 7.38-7.32 (m, 5H, aryl), 6.32 (q, J 1Hz, 1H, H_4), 4.25 (t, J 7 Hz , 2H, H_8), 1.83 (d, J 1Hz, 3H, H_7), 1.70 (sextet, J 7Hz, 2H, H_9), 1.43 (quintet, J 7Hz, 2H, H_{10}), 1.34 (d, J 1Hz, 3H, H_6), 0.97 (t, J 7 Hz, 3H,H_{11}); ^{13}C NMR ($CDCl_3$) δ: 164.65 (C_1), 146.42 (C_3), 140.85 (C_5), 139.24 (*ipso*), 129.09 (*ortho*), 128.15 (*ortho*), 128.06 (*para*), 126.55 (C_2), 123.84 (C_4), 65.78 (C_8), 30.60 (C_9), 26.84 and 19.82 (C_6 and C_7), 19.16 (C_{10}), 13.68 (C_{11}); FTIR ($CHCl_3$) 1731.25 (s, C=O); MS(CI,CH_4, 70 eV): m/z 295 (MH^+ + 2, 9%), 293 (MH^+, 27%), 239 (MH^+ - C_4H_8 + 2, 33%) 237 (MH^+ - C_4H_8, 100%) 219 (MH^+ - C_4H_8 - H_2O, 30%), 201 (MH^+ - C_4H_8 - HCl, 8%); HRMS: calcd ($C_{17}H_{22}O_2Cl$, MH^+) 293.1308, obsd 293.1330.

References and Footnotes

1. For reviews see: a) Frimer, A.A. *Chem. Rev.* **1979**, *79*, 359. b) Frimer, A.A. In "The Chemistry of Peroxides"; Patai, S. Ed.; Wiley, New York, 1983; pp. 201-234. c) Frimer, A.A.; Stephenson, L.M. In "Singlet O_2" - Volume II: "Reaction Modes and Products - Part I", Frimer, A.A. Ed.; Chemical Rubber Company, Boca Raton, Florida, 1985; pp. 67-91. d) Frimer, A.A. In *The Chemistry of Enones* - Part 2, Patai, S. and Rappoport, Z. Eds.; Wiley, Chichester, 1989; pp. 781-921.
2. a) Frimer, A.A.; Roth, D.; Sprecher, M. *Tetrahedron Lett.* **1977**, 1927. b) Frimer, A.A.; Farkash, T.; Sprecher, M. *J. Org. Chem.* **1979**, *44*, 989. c) Frimer, A.A.; Roth, D. *J. Org. Chem.* **1979**, *44*, 3882. d) Frimer, A.A.; Antebi, A. *J. Org. Chem.* **1980**, *45*, 2334. e) Frimer, A.A. *Israel J. Chem.* **1981**, *21*, 194. f) Frimer, A.A. *J. Photochem.* **1984**, *25*, 211.
3. a) Koch, E. *Tetrahedron* **1968**, *24*, 6295. b) Ashford, R.D.; Ogryzlo, E.A. *J. Am. Chem. Soc.* **1975**, *97*, 3604.
4. a) Frimer, A.A.; Weiss, J. *J. Org. Chem.* **1993**, *58*, 3660. b) Frimer, A.A.; Weiss, J.; Gottlieb, H.E.; Wolk, J.L. *J. Org. Chem.* **1994**, *59*, 780.
5. a) Jefford, C.W.; Boschung, A.F.; Rimbault, C.G. *Tetrahedron Lett.* **1974**, 3387. b) Houk, K.N.; Spellmeyer, D.C.; Jefford, C.W.; Rimbault, C.G.; Wang, Y.; Miller, R.D. *J. Org. Chem.* **1988**, *53*, 2125. c) Niwayama, S.; Kallel, E.A.; Sheu, C.; Houk, K.N. *J. Org. Chem.* **1996**, *61*, 2517. d) Niwayama, S.; Kallel, E.A.; Sheu, C.; Spellmeyer, D.C.; Houk, K.N. *J. Org. Chem.* **1996**, *61*, 2813, and references cited therein.
6. a) Arnold, B.J.; Sammes, P.G.; Wallace, T.W. *J. Chem. Soc. Perkin Trans. I* **1974**, 409. b) *ibid.*, 415. c) Moss, R.J.; White, R.O.; Rickborm, B. *J. Org. Chem.* **1985**, *50*, 5132and references cited therein. d) Azadi-Ardakani, M.; Wallace, T.W. *Tetrahedron* **1988**, *44*, 5939. e) Azadi-Ardakani, M.; Hayes, Roy; Wallace, T.W. *Tetrahedron* **1990**, *46*, 6851. f) Hickman, D.N.; Hodgetts, K.J.; Mackman, P.S.; Wallace, T.W.; Wardelworth, J.M. *Tetrahedron* **1996**, *52*, 2235.
7. As far as the benzocyclobutene systems are concerned, their E_a seems to lie 7-8 kcal/mole higher than the corresponding cyclobutene system.[6c]
8. a) Tuyet, J.L.; Linstrumelle. G. *Synthesis* **1982**, 738. b) Pasto, D.J.; Kong. W. *J. Org. Chem.* **1989**, *54*, 4028.
9. a) Pasto, D.J.; Kong. W. *J. Org. Chem.* **1988**, *53*, 4807. b) Lopez, S.; Rodriguez, J.; Gracia Rey, G. J.; De Lera, A.R. *J. Am. Chem. Soc.* **1996**, *118*, 1881.
10. Mayr, H.; Huisgen, R. *J. Chem. Soc. Chem. Comm.* **1976**, 57.
11. Hamlet, Z.; Barker, W.D. *Synthesis.* **1970**, 543.
12. Hassner, A.; Dillon, J.L. Jr. *J. Org. Chem.* **1983**, *48*, 3382.
13. Dillon J.L.; Gao Q. *J. Org. Chem.* **1994**, *59*,6868.
14. Danheiser, R.L.; Savariar, S.; Cha, D.D. *Org. Synth.* **1989**, *68*, 32.
15. Clark, R.D.; Heathcock, C.H. *J. Org. Chem.* **1973**, *38*, 3658.
16. Fagerlund, U.H.M.; Idler, D.R. *J. Am. Chem. Soc.* **1957**, *79*, 6473.
17. Frimer, A.A.; Bartlett, P.D.; Boschung, A.F.; Jewett, J.G. *J. Am. Chem. Soc.* **1977**, *99*, 7977.