Synthesis and Thermal Rearrangements of 4-Allyl-4-arylcyclobutenones

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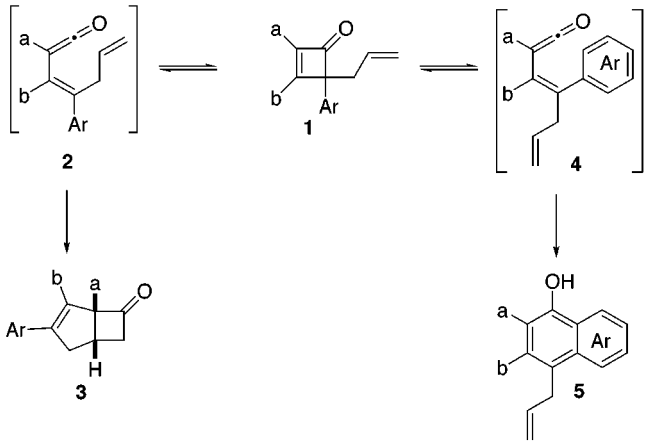
The synthesis and thermolysis of 4-allyl-4-arylcyclobutenones are detailed. Allylcyclobutenones were prepared through the trapping of the cyclobutenonium cation generated by treatment of 4-hydroxycyclobutenones with Lewis acids. A study of the nucleophilic trapping revealed the following mechanistic highlights: the most likely intermediate is the cyclobutenonium cation, the regioselectivity of the allylation reaction is dictated by attack at the site most suited to stabilize the cation, and the rate of allylation is dependent on carbocation formation. Thermolysis of 4-allyl-4-arylcyclobutenones made possible a study of the competitive [2 + 2] cycloaddition and 6π electrocyclization. A judicious choice of substituents allows some control of the selectivity between the two pathways. The substituents control this selectivity through a combination of imposed electronics in the dienylketene intermediate, the relative ketenophilicity of the 4-position substituent, and the relative contortion substituents in the 2- and 3-positions impose on the transition state of the respective ring-closure processes. The scope of the cyclobutenonium cation trapping with silylated carbon nucleophiles was explored, producing 4-allenylcyclobutenones from the use of propargylsilane and 4-spirocyclobutenones from triisopropylsilane. Thermolysis studies of these precursors are also detailed.

Introduction

Reported here is a study concerning the synthesis and thermal rearrangements of cyclobutenones bearing two different ketenophilic substituents at the 4-position. Specifically, the synthesis and thermolysis of 4-allyl-4-arylcyclobutenones and selected related compounds are presented. Although much is known of the synthetic utility and mechanisms of rearrangements of cyclobutenones, until now no systematic study has appeared in which two groups are positioned to competitively intercept the corresponding vinylketene intermediates.[1] The generalized results arising from this study are outlined in Scheme 1. Thermolyses (refluxing toluene) of cyclobutenones **1** induce a rapid and reversible electrocyclic ring opening to the corresponding vinylketenes **2** and **4**. In the rate-limiting steps, the former undergoes an intramolecular [2 + 2] cycloaddition to give bicyclo[3.2.0]-heptenones **3**, and the latter proceeds to allylated naphthols **5** via 6π electrocyclic ring closure followed by tautomerization.[1−3] Both products are formed from the examples presented here. However, because the intermediate ketenes equilibrate under the reaction conditions, a judicious choice of substituents allows some control of the selectivity of the slower product-forming ring-closure steps. Details of this investigation are presented below.

Scheme 1



Synthesis of 4-Allyl-4-arylcyclobutenones and Related Compounds. Syntheses of the required 4-allyl-4-arylcyclobutenones stem from our continuing study of the synthetic utility of cyclobutenonium ions, which are readily generated from appropriately substituted cyclobutenones.[4] In this regard, we previously reported that 4-aryl-4-hydroxycyclobutenones give high yields of the 4-protio derivatives when treated with BF_3·Et_2O in the presence of trialkylsilanes.[5] For example, **6** gave **8** in 94% yield where cation **7** is envisaged as a reaction intermediate (Scheme 2). When **8** was subjected to thermolysis

(1) For selected reviews on the synthetic utility of cyclobutenones see: (a) Moore, H. W.; Yerxa, B. R. *Advances in Strain in Organic Chemistry*; JAI Press: Greenwich, 1995; Vol. 4, pp 81−162. (b) Moore, H. W.; Yerxa, B. R. *Chemtracts* **1992**, *5*, 273. (c) Liebeskind, L. S. *Tetrahedron* **1989**, *45*, 3053. (d) Bellus, D.; Ernst, B. *Angew. Chem.* **1988**, *100*, 820. (e) Moore, H. W.; Decker, O. H. W. *Chem. Rev.* **1986**, *86*, 821.

(2) Xu, S. L.; Moore, H. W. *J. Org. Chem.* **1989**, *54*, 6018. Xu, S. L.; Xia, H.; Moore, H. W. *J. Org. Chem.* **1991**, *56*, 6094.

(3) For an excellent review on intramolecular ketene/alkene cycloadditions see: Snider, B. B. *Chem. Rev.* **1989**, *88*, 793.

(4) Xu, S. L.; Moore, H. W. *J. Org. Chem.* **1989**, *54*, 4024.

(5) Turnbull, P.; Moore, H. W. *J. Org. Chem.* **1995**, *60*, 644. Turnbull, P.; Heileman, M. J.; Moore, H. W. *J. Org. Chem.* **1996**, *61*, 2584.

(6) For examples see: (a) Yamamoto, Y.; Noda, M.; Ohno, M.; Eguchi, S. *J. Org. Chem.* **1997**, *62*, 1292. (b) Yamamoto, Y.; Ohno, M.; Eguchi, S. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1353. (c) Yamamoto, Y.; Nunokawa, K.; Okamoto, K.; Ohno, M.; Eguchi, S. *Synthesis* **1995**, 571. (d) Yamamoto, Y.; Ohno, M.; Eguchi, S. *Tetrahedron* **1994**, *50*, 7783. (e) Ohno, M.; Yamamoto, Y.; Eguchi, S. *Syntlett* **1998**, 1167.

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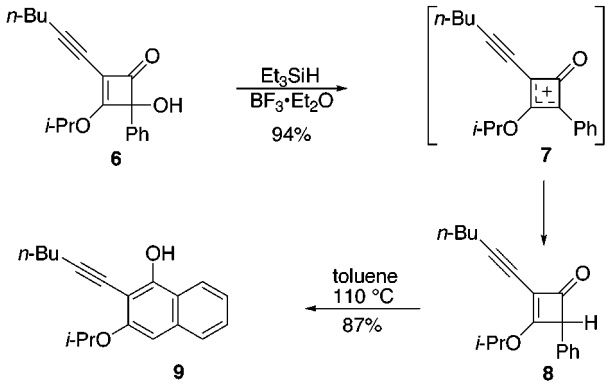
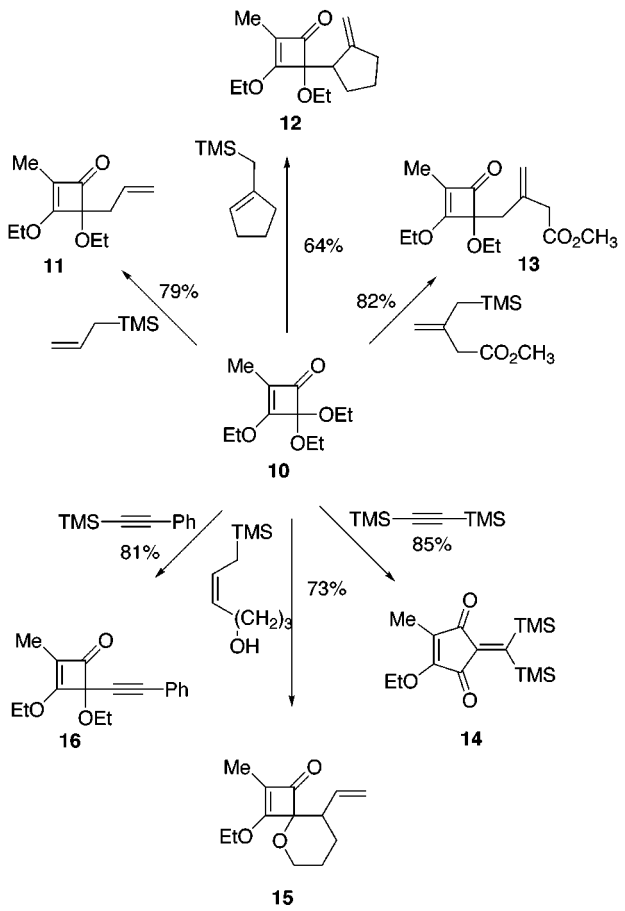
Scheme 2



Scheme 3

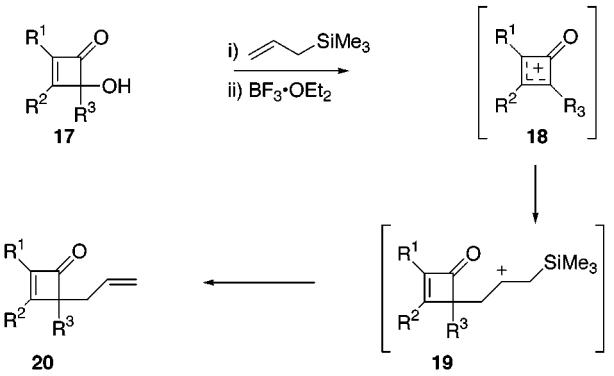


(refluxing toluene) the ring-expanded naphthol **9** was obtained in 87% yield. In a related and more extensive study, Eguchi and co-workers[6] generated analogous cyclobutenonium ions from cyclobutenedione monoketals[7] and utilized these in a number of potentially useful transformations, selected examples of which are provided in Scheme 3. Specifically, various allyltrimethylsilanes were observed to react with 3,4,4-triethoxy-2-methylcyclobutenone (**10**) in the presence of Lewis acids to give allylated products such as **11**−**13** and **15**. Under similar conditions, 1-trimethylsilyl-2-phenylethyne gave the 4-alkynyl-4-ethoxycyclobutenone **16**, and ditrimethylsilylethyne gave the rearranged cyclopentene-1,3-dione **14**.

Syntheses of the 4-allyl-4-arylcyclobutenones required for the present study start with 4-hydroxycyclobutenones,

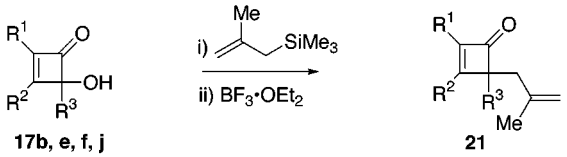
(7) Gayo, L.; Moore, H. W. *J. Org. Chem.* **1992**, *57*, 6896.

Scheme 4



20	R^1	R^2	R^3	time	% yield
a	≡—*n*-Bu	O*i*-Pr	3-$MeOC_6H_3$	2 h	95
b	≡—*n*-Bu	O*i*-Pr	4-$MeOC_6H_3$	15 min	96
c	≡—*n*-Bu	O*i*-Pr	3,4-$(MeO)_2C_6H_3$	10 min	96
d	Ph	OMe	Ph	28 h	84
e	Ph	O*i*-Pr	Ph	48 h	95
f	4-$MeOC_6H_3$	O*i*-Pr	4-$MeOC_6H_3$	2 h	98
g	3-$MeOC_6H_3$	O*i*-Pr	3-$MeOC_6H_3$	48 h	98
h	*n*-Bu	O*i*-Pr	Ph	12 h	70
i	*s*-Bu	O*i*-Pr	Ph	19 h	98
j	*t*-Bu	OMe	Ph	14 d	80
k	Ph	Me	Ph	5 min	88
l	Ph	*i*-Bu	Ph	5 min	99

Scheme 5



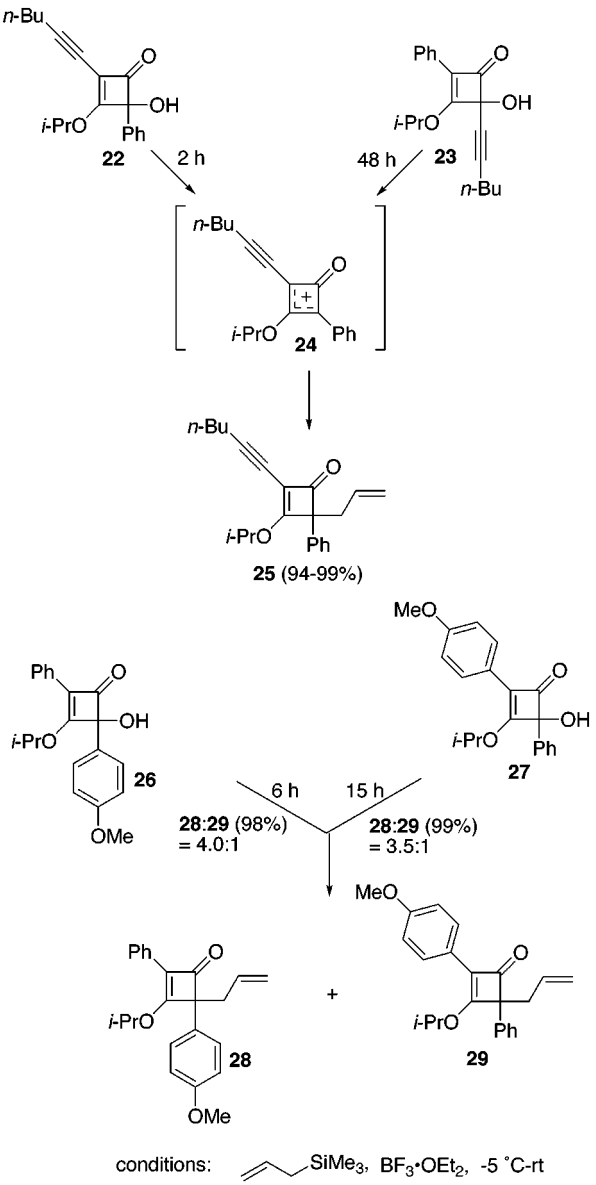
21	R^1	R^2	R^3	time	% yield
a	≡—*n*-Bu	O*i*-Pr	4-$MeOC_6H_3$	2.5 h	98
b	Ph	O*i*-Pr	Ph	48 h	99
c	4-$MeOC_6H_3$	O*i*-Pr	4-$MeOC_6H_3$	2 h	93
d	*t*-Bu	OMe	Ph	18 d	76

a class of compounds readily prepared from squaric acid (Schemes 4−7).[1,8] As exemplified in Scheme 4, methylene chloride solutions of 4-aryl-4-hydroxycyclobutenones **17a**−**l** and allyltrimethylsilane were slowly treated with BF_3·Et_2O at −5 °C and then allowed to warm to ambient temperature. These reaction conditions are envisaged to induce the formation of cyclobutenonium ions **18**, which are intercepted by allyltrimethylsilane to give **19**, the ultimate precursors to **20**. Under similar conditions, **17b,e,f,j** gave adducts **21a**−**d** in good to excellent yields upon treatment with 2-methyl-3-trimethylsilylpropene (Scheme 5).

Even though cyclobutenonium ions such as **18** are resonance hybrids and, thus, allylation could conceivably take place at either position 2 or 4, the major products,

(8) For lead references concerning the synthesis of substituted cyclobutenones see: Schmidt, A. H.; Ried, W. *Synthesis* **1978**, 1. Knorr, H.; Ried, W. *Synthesis* **1978**, 649. Schmidt, A. H.; Ried, W. *Synthesis* **1978**, 869. Reed, M. W.; Pollart, D. J.; Perri, S. T.; Foland, L. D.; Moore, H. W. *J. Org. Chem.* **1988**, *53*, 2477. Liebeskind, L. S.; Fengl, R. W.; Wirtz, K. R.; Shawe, T. T. *J. Org. Chem.* **1988**, *53*, 2482. Liebeskind, L. S.; Fengl, R. W. *J. Org. Chem.* **1990**, 5359. Liebeskind, L. S.; Wirtz, K. R. *J. Org. Chem.* **1990**, 5350. Liebeskind, L. S.; Wang, J. *Tetrahedron Lett.* **1990**, 4293.

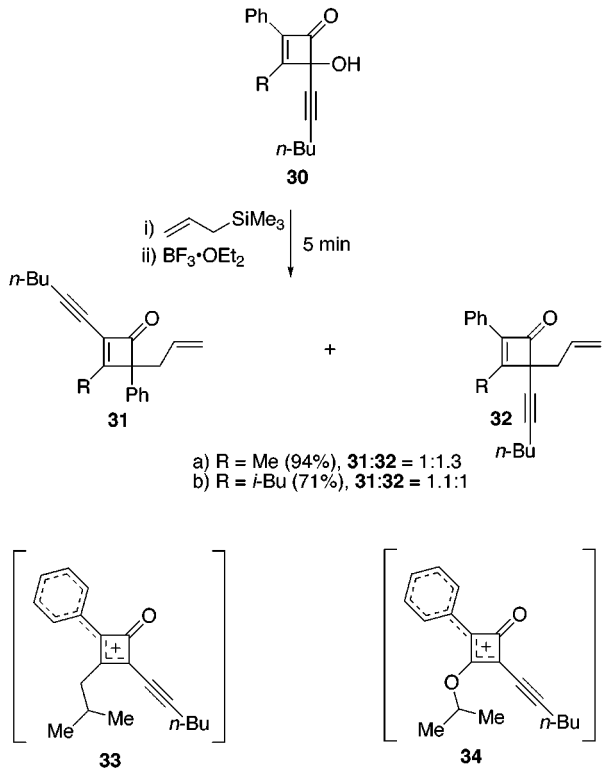
Scheme 6



with few exceptions, are those resulting from attack of the silane at the position bearing the aryl group, i.e., the site better able to support the positive charge.[4,5] For example, allylation of differentially substituted hydroxycyclobutenones **17a**−**c** gave the corresponding 4-allyl-4-aryl-2-hexynyl-3-isopropoxycyclobutenones **20a**−**c** in yields ranging from 95% to 96%. Analogously, **17h**−**j** gave only 3-alkoxy-2-alkyl-4-allyl-4-phenylcyclobutenones **20h**−**j** in 70−98% yields.

Further details concerning the mechanism of the allylation reactions were obtained when the regioisomeric cyclobutenones **22** and **23** were subjected to the allylation conditions (Scheme 6). Both were observed to give a nearly quantitative yield of a single allylated cyclobutenone **25**, a result in agreement with a mechanism involving the common intermediacy of cyclobutenonium ion **24**. The same conclusion was drawn from a related study starting with the regioisomeric diarylcyclobutenones **26** and **27**, which were observed to give a mixture of the allylated regioisomers **28** and **29** in ratios (averaged) of 4.0:1.0 and 3.5:1.0, respectively, as determined by ^{1}H NMR analysis of the crude products for two different runs.

Scheme 7

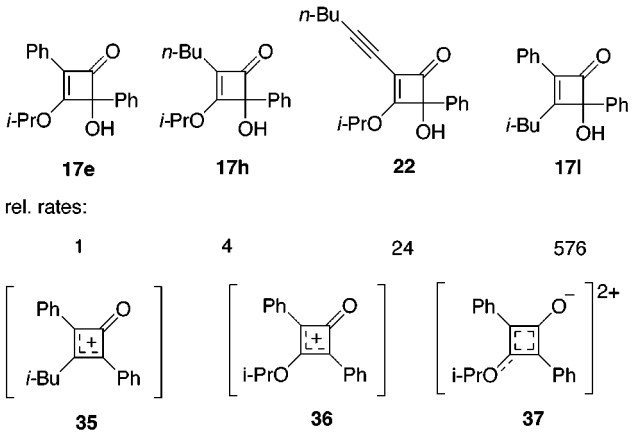


Structure assignments of the products resulting from these studies are based upon characteristic spectral properties, as well as a complete X-ray crystal structure of **28**. Knowing the structure of **28** allows the unambiguous assignment of the structure of its regioisomer **29**. Once again, the major isomer, **28**, is the one arising from allylation at the benzylic site better able to stabilize the cationic charge in the intermediate. By analogy, the structure of **25** is assigned, i.e., allylation takes place at the benzylic position as opposed to the propargylic site. Further structural information is gleaned through analysis of the thermolysis products and will be discussed later.

Significant compromised selectivity was observed for the allylation of the 3-alkyl-4-hexynyl-4-hydroxy-2-phenylcyclobutenones **30a** and **30b** (Scheme 7). The former gave **31a** and **32a** in a respective ratio of 1:1.3, and the latter gave **31b** and **32b** in a ratio of 1.1:1. For these cases, formation of both regioisomers was not anticipated because, as previously described, the closely related 4-hexynyl-4-hydroxy-2-phenyl-3-isopropoxycyclobutenone **23** gave nearly a quantitative yield of only **25** (Scheme 6). Clearly, the 3-alkyl groups of **30a,b**, as compared to the 3-alkoxy group in **23**, cause a significant reduction in the allylation selectivity. This is likely due to greater steric congestion for attack at the benzylic position in, for example, carbenium ion intermediate **33** as compared to **34** because alkyl groups are sterically more encumbering than alkoxy substituents (e.g., A_{Me} = 1.74 kcal/mol and A_{t-OBu} = 0.75 kcal/mol).[9] Apparently, this difference is great enough to allow the seemingly less stable propargylic site in the carbocations arising from **31a,b** to favorably compete with the benzylic position for allylation, a situation not observed for 3-alkoxy analogues **22** and **23**.

(9) Eliel, E.; Wilen, S. H.; Mander, L. N. *Stereochemistry of Carbon Compounds*; John Wiley and Sons: New York, 1994; pp 695−696.

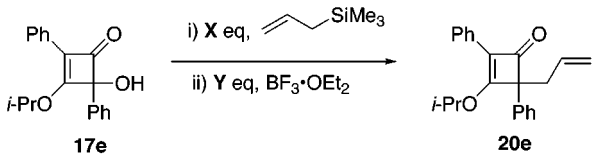
Scheme 8



Further mechanistic information is gleaned from the qualitative relative allylation rates listed in Schemes 4−7. Reaction rates generally correlate with carbocation stability and thus suggest ionization as the rate-limiting step of the reaction. The following specific examples are illustrative of this point: (1) 4-Hydroxy-3-methoxy-2,4-diphenylcyclobutenone (**17d**) reacts nearly twice as fast as its 3-isopropoxy analogue **17e**. The smaller methoxy group imparts less steric constraints, and thus both phenyl groups can participate more fully in cation stabilization, i.e., coplanarity of both phenyl groups is conceivably allowed for **18d** but not for **18e**. (2) 4-Hydroxy-3-isopropoxy-4-(4-methoxyphenyl)-2-phenylcyclobutenone (**26**) reacts approximately twice as fast as its regioisomer **27**. Here again, coplanarity of both aryl groups is apparently partially impeded during the ionization step as a result of steric interaction of the isopropyl group with the 2-aryl substituent. Thus, formation of the cation from **26** gains more assistance from the 4-methoxyphenyl group than does the ionization of **27**. (3) 3-Isopropoxy-2,4-di(4-methoxyphenyl)cyclobutenone (**17f**) reacts approximately 24 times faster than the 2,4-diphenyl- (**17e**) or 2,4-di(3-methoxyphenyl)- (**17g**) analogues. (4) 2-Hexynyl-3-isopropoxy-4-(4-methoxyphenyl)-cyclobutenone (**17b**) and 2-hexynyl-3-isopropoxy-4-(3,4-dimethoxyphenyl)-cyclobutenone (**17c**) react 8−12 times faster than the 4-(3-methoxyphenyl) analogue **17a**.

Similar relative rate comparisons are summarized in Scheme 8, in which four selected cyclobutenones (**17e**, **17h**, **22**, and **17l**) representing the general structural types are presented along with their respective qualitative relative allylation rates. Steric inhibition for coplanarity of the two phenyl groups during the ionization step would account for **17e** having the slowest rate. This is, however, of particular note in comparison to **17l**, which reacts more than 500 times faster even though noncoplanarity of the phenyl groups should be even more pronounced because the isobutyl group is sterically more encumbering than an isopropoxy group. Apparently, the controlling factor is that cyclobutenonium ions such as **35** bearing σ-donating 3-alkyl groups are more stable than the corresponding examples bearing σ-withdrawing 3-alkoxy groups, e.g., **36**. This is, of course, expected if structures **35** and **36** best represent the hybrid structure, because the cationic center would not experience direct π-donation by the cross-conjugated alkoxy group. However, if pseudoaromatic cyclobutadienium dication structures such as **37** made major contributions to the hybrid, direct π-donation of the alkoxy group would be important and **36** would be expected to be formed at a faster rate than **35**. The fact that this is not the case argues against significant contributions from structures such as **37**.

Scheme 9



time (h)	X = 5, Y = 5 **17e**:**20e**	X = 20, Y = 5 **17e**:**20e**	X = 20, Y = 20 **17e**:**20e**
0.5	**17e** only	**17e** only	**17e** only
1	42:1	trace of **20e**	43:1
4	3.9:1	4.6:1	3.2:1
10	1:2.2	no data	1:1.8
24	1:19	1:18	1:21
48	**20e** only	**20e** only	**20e** only

These data favor a mechanism of allylation in which the rate-limiting step is carbocation formation. Indeed, this possibility was confirmed in one case by a rate/concentration study that showed the reaction rate to be independent of the allylsilane concentration. Specifically, the rate of allylation of **17e** was observed to be unaffected when the concentration of allylsilane was varied. As summarized in Scheme 9, the ratio of starting cyclobutenone **17e** to product **20e** at ambient temperature remained essentially constant (^{1}H NMR analysis) over a period of 48 h, even though the equivalents of allyltrimethylsilane and BF_3•Et_2O were varied from 5 to 20. On the basis of these results, it is assumed that all other examples behave analogously.

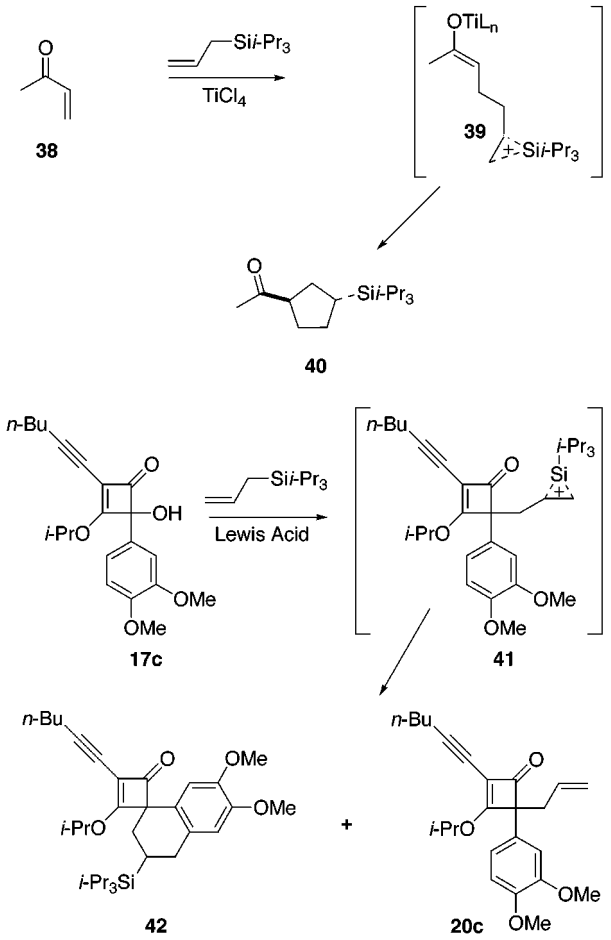
In summary, 4-aryl-4-hydroxycyclobutenones serve as valuable precursors to allylated derivatives. The data provided above not only point to the synthetic utility of this reaction but also support a mechanism in which Lewis acid induced ionization of the 4-hydroxy group in 4-aryl-4-hydroxycyclobutenones is the rate-limiting step. Allylation then arises via the kinetically faster trapping of the cyclobutenonium ion intermediate. In the absence of steric encumbrances, allylation of such hybrid cations ions takes place at the site better able to stabilize a positive charge.

Further Studies Concerning the Synthetic Scope

Danheiser, Dixon, and Gleason reported the reaction of enones such as **38** with allyltriisopropylsilane in the presence of $TiCl_4$ to give cyclopentenones **40** via intramolecular trapping of the cationic center in **39** by the enol moiety (Scheme 10).[10] It was reasoned that under similar conditions the bulky silicon-stabilized cation resulting from the reaction of 4-aryl-4-hydroxycyclobutenones with allyltriisopropylsilane would be intercepted by the proximal aromatic group, to give spiro-fused cyclobutenones. This reaction was initially studied by treating cyclobutenone **17c** with allyltriisopropylsilane and BF_3•Et_2O. Under these conditions, a 90% yield of a 1:1.1 mixture of, respectively, the spiroannulated cyclobutenone **42** and the allylated product **20c** was realized. This ratio changed to 1:1.5 when $TiCl_4$ was employed. The most efficient

(10) Danheiser, R. L.; Dixon, B. R.; Gleason, R. W. *J. Org. Chem.* **1992**, *57*, 6094.

Scheme 10

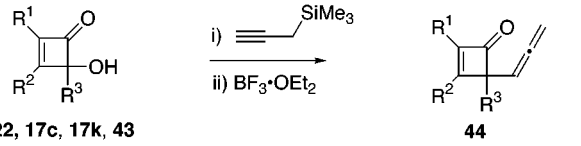


Lewis acid	% **42**	% **20c**	% yield
BF_3•OEt_2	47	53	90
$TiCl_4$	40	60	88
$AlCl_3$	79	21	85

spiroannulation was realized when $AlCl_3$ was employed, resulting in an 85% yield of **42** and **20c** in a ratio of 4:1. The spiroannulation appears to be limited to cyclobutenones bearing electron-rich aryl groups at position 4. For example, when **17b** and **22** were treated with allyltriisopropylsilane/$AlCl_3$, the products detected were the 4-allyl derivatives **20b** and **25**, respectively, in yields ranging from 40% to 73%.

Finally, the results of a limited study of the Lewis acid promoted reactions of propargyltrimethylsilane with 4-aryl-4-hydroxycyclobutenones are summarized in Scheme 11. This study was directed to the synthesis of 4-allenylcyclobutenones and is based on the well-established route to allenes arising from electrophilic substitution of propargylsilanes.[11] The reaction proceeds as expected starting with 4-hydroxycyclobutenones **22**, **17c,k**, and **43** to give the corresponding 4-allenylcyclobutenones **44a**−**d**, members of a class of compounds of interest because they have been shown to undergo thermal ring

Scheme 11



44	R^1	R^2	R^3	time	% yield
44a	≡—*n*-Bu	O*i*-Pr	Ph	3 h	70
44b	≡—*n*-Bu	O*i*-Pr	3,4-$(MeO)_2C_6H_3$	15 min	83
44c	Ph	Me	Ph	5 min	70
44d	3,4$(MeO)_2C_6H_3$	OMe	3,4-$(MeO)_2C_6H_3$	30 min	49

expansion to synthetically useful *ortho*-quinone methide intermediates.[12,13]

Thermolysis Studies

As noted earlier (Scheme 1), 4-allyl-4-arylcyclobutenones **1** would be expected to undergo thermal electrocyclic ring opening to the corresponding vinylketenes **2** and/or **4**. On the basis of torquoselectivity arguments, one would expect **2** to be preferentially formed, i.e., the outward rotation of the aryl group is favored over an alkyl group.[14] This could then lead to the prediction that intramolecular [2 + 2] cycloaddition to give bicyclo[3.2.0]heptenones would be favored over the electrocyclic ring closure to naphthols. However, as it was previously shown that vinylketenes can equilibrate with their precursor cyclobutenones, it is difficult to predict product distribution in the absence of experimental data.[5] To probe this in detail, the thermolysis of a number of the cyclobutenones synthesized herein were investigated, and the data are provided below.

In general, it was found that 4-allyl-4-arylcyclobutenones undergo facile rearrangements in refluxing toluene to give mixtures of the corresponding naphthols and bicyclo[3.2.0]heptenones. For example, **25** and **20b**−**l** gave good to excellent yields (83−97%) of mixtures of the corresponding naphthols **45** and bicyclo[3.2.0]heptenones **46** (Scheme 12). Among these examples slight, but significant, selectivities in product formation were observed. Specifically, **25**, **20b**, and **20c** constitute a similarly substituted series in which thermolysis results in the preferential formation of the naphthol **45a**−**c** over the bicyclo[3.2.0]heptenone **46a**−**c** in respective ratios varying from 1.5:1 to 3:1. This preference is reversed for those cyclobutenones bearing 2-aryl and 3-alkoxy groups, i.e., **20d**−**f** gave **45d**−**f** and **46d**−**f** in ratios varying from 1:2 to 1:2.6. Interestingly, the naphthol:bicyclo[3.2.0]-heptenone ratio reverts to one favoring the naphthol (1.3:1 to 2:1) for **20k,l**, both of which are 3-alkyl-2-phenylcyclobutenones as compared to the 3-alkoxy analogues.

Conclusions drawn from these data include the following: 1) Naphthol formation increases as the ketene

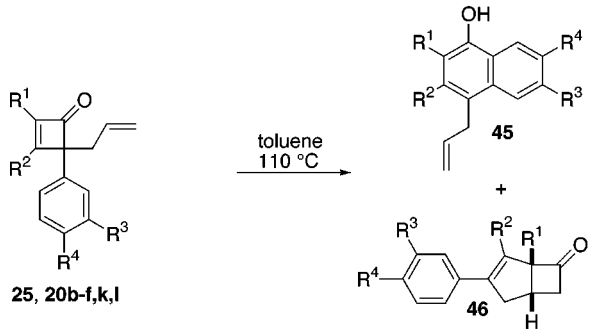
(11) For reviews see: (a) Fleming, I. In *Comprehensive Organic Synthesis*; Heathcock, C. H., Ed.; Pergamon Press: Oxford, 1991; Vol. 2, pp 563−593. (b) Schinzer, D. *Synthesis* **1988**, 263.

(12) Taing, M.; Moore, H. W. *J. Org. Chem*. **1996**, *61*, 329.

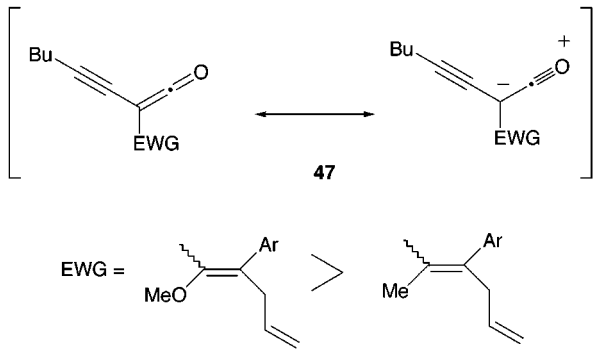
(13) For reviews on the chemistry of quinone methides see: Veciana, J.; Martinez, A. D.; Armet, O. *Rev. Chem. Intermed*. **1988**, *10(1)*, 35−70. Volod′kin, A. A.; Ershov, V. V. *Usp. Khim*. **1988**, *57(4)*, 595−624. Also see the following and references therein: Angle, S. R.; Arnaiz, D. O. *J. Org. Chem*. **1990**, *55*, 3708−10. Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc*. **1990**, *112*, 3698−700. Angle, S. R.; Yang, W. *J. Am. Chem. Soc*. **1990**, *112*, 4524−8. Angle, S. R.; Louie, M. S.; Mattson, H. L.; Yang, W. *Tetrahedron Lett*. **1989**, *30*, 1193−6. Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc*. **1989**, *111*, 1136−8.

(14) Houk, K. N.; Rondan, N. G. *J. Am. Chem. Soc*. **1985**, *107*, 2099. Niwayama, S.; Kallel, E. A.; Sheu, C.; Houk, K. N. *J. Org. Chem*. **1996**, *61*, 2517.

Scheme 12



45/46	R^1	R^2	R^3	R^4	ratio 45:46	% yield
a	≡—*n*-Bu	O*i*-Pr	H	H	2:1	88
b	≡—*n*-Bu	O*i*-Pr	H	OMe	1.5:1	90
c	≡—*n*-Bu	O*i*-Pr	OMe	OMe	3:1	84
d	Ph	OMe	H	H	1:2.6	83
e	Ph	O*i*-Pr	H	H	1:2.1	92
f	4-$MeOC_6H_3$	O*i*-Pr	H	OMe	1:2	92
g	Ph	Me	H	H	2:1	96
h	Ph	*i*-Bu	H	H	1.3:1	97

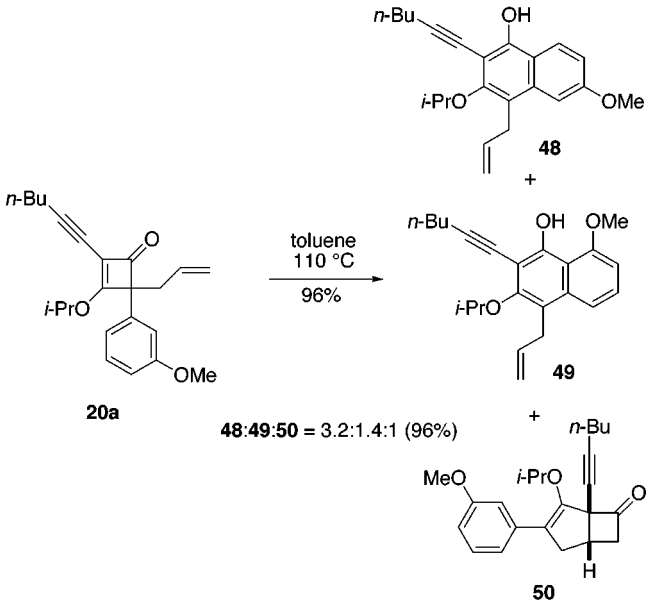


becomes more electrophilic. Thus, assuming the resonance structures in Scheme 12 adequately represent the ketene,[15] the alkynyl ketenes **47** should be more electrophilic than the corresponding aryl ketenes, i.e., anion delocalization into the alkynyl groups would be favored. Additionally, the 2-aryl-1-methoxy-1,5-pentadienyl group would be a stronger electron-withdrawing group (EWG) than the 1-methyl analogue and thereby would increase the electrophilic nature of the respective ketene arising from 3-alkoxy- vs 3-alkylcyclobutenones. (2) Naphthol formation is also increased as the 4-aryl group increases in nucleophilic character. This is particularly true if the π-donating methoxy group is in position 3 of the aryl substituent, i.e., R^3 = OMe. In this regard, it is noteworthy that **20c** gives a 3:1 ratio of naphthol **45c** to bicyclo[3.2.0]heptenone **46c**. Even higher selectivity was observed for the thermolysis of 4-allyl-2-hexynyl-3-isopropoxy-4-(3-methoxyphenyl)-cyclobutenone **20a** (Scheme 13). Here the ratio of naphthols **48** and **49** to bicyclo[3.2.0]heptenone **50** was 3.2:1.4:1. It is of interest to note that both regioisomeric naphthols **48** and **49** were formed, the former from attack of the ketene *para* to the methoxy group and the latter from *ortho* attack.

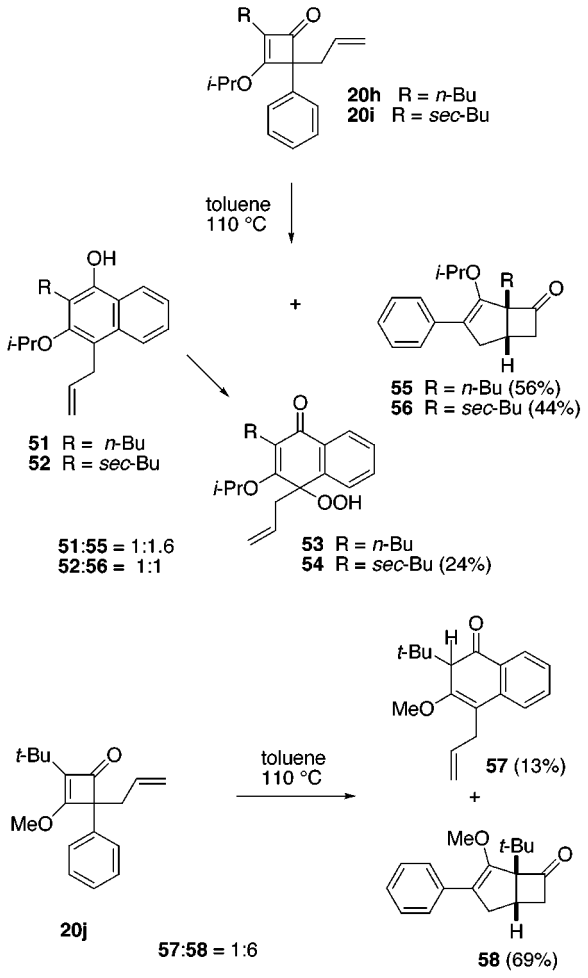
Thermolysis (toluene, 110 °C) of 2-alkylcyclobutenones **20h,i** also gave mixtures of the corresponding naphthols

(15) For a discussion of ketene stability and reactivity see: (a) Gong, L.; McAllister, M. A.; Tidwell, T. T. *J. Am. Chem. Soc.* **1991**, *113*, 6021. (b) Tidwell, T. T. *Ketenes*; John Wiley and Sons: New York, 1995.

Scheme 13

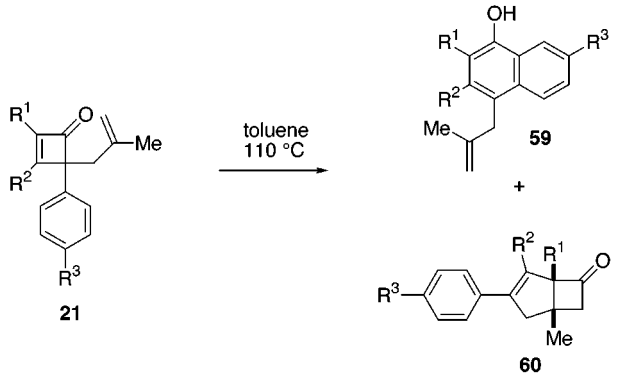


Scheme 14



and bicyclo[3.2.0]heptenones. The former gave the respective products (**51**:**55**) in a ratio of 1:1.6, and the latter gave a ratio (**52**:**56**) of 1:1 (Scheme 14). It was necessary to determine these ratios by ^{1}H NMR of the crude product mixture because the naphthols readily undergo oxidation to the corresponding hydroperoxides **53** and **54** (24%) upon attempted purification.

Scheme 15



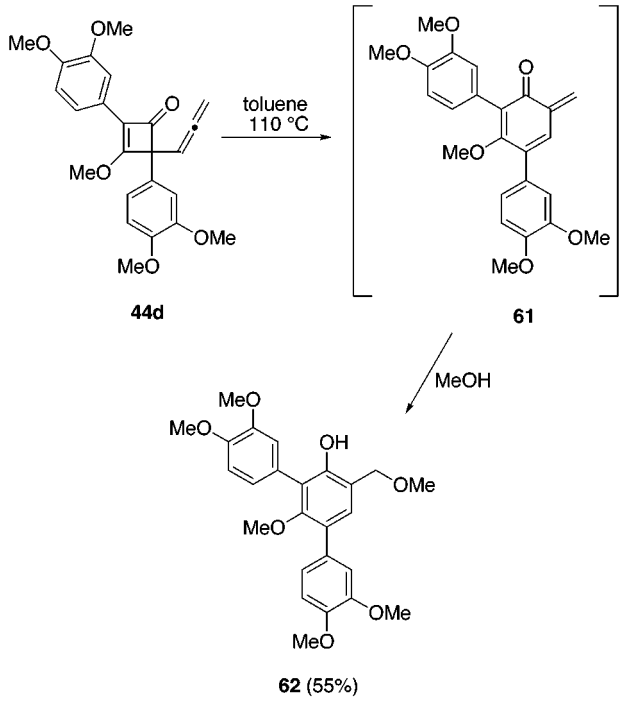
59/60	R^1	R^2	R^3	ratio 59:60	% yield
a	≡—*n*-Bu	O*i*-Pr	OMe	1.4:1	99
b	Ph	O*i*-Pr	H	1:4	99
c	4-MeOC_6H_3	O*i*-Pr	OMe	1:4.3	95
d	*t*-Bu	OMe	H	**60** only	98

The highest selectivity was observed when 4-allyl-2-*tert*-butyl-3-methoxy-4-phenylcyclobutenone **20j** was subjected to the above thermolysis conditions. Here, an 82% yield of a mixture of the keto tautomer of the naphthol **57** (13%) and the bicyclo[3.2.0]heptenone **58** (69%) was realized. In this case, the bulky *tert*-butyl group apparently disfavors the planar or helical transition state associated with the electrocyclic ring closure as compared to the nonplanar transition state associated with the orthogonal arrangement required for an assumed concerted intramolecular [2 + 2] ketene alkene cycloaddition. That the keto tautomer **57** is isolated rather than the aromatic naphthol is of interest and is apparently due to less steric strain associated with having the bulky *tert*-butyl group attached to an sp^3 hybridized carbon atom.

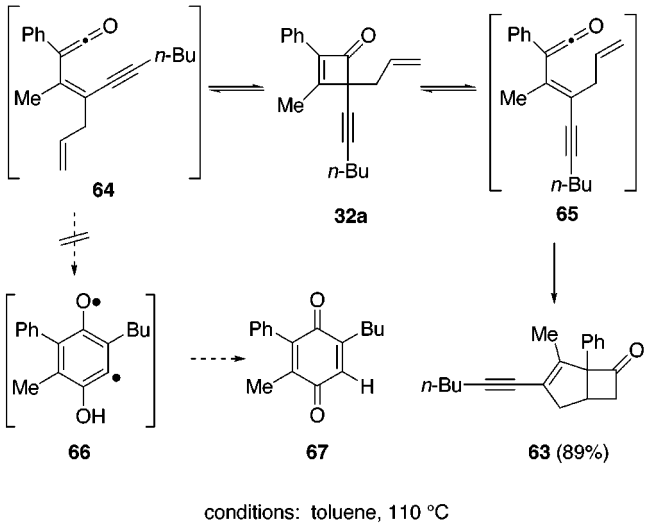
A modification of the 4-allyl group was observed to have some influence on the selectivity of the thermal ring expansion. Specifically, **21a**−**d** all bear a 4-(2-methylallyl) group. The methyl group is so placed that it would stabilize presumed cationic or radical character in the transition state for a [2 + 2] cycloaddition but should have little influence on the competitive electrocyclic ring-closure process.[3] Thus, one would anticipate an increase in the amount of the bicyclo[3.2.0]heptenones relative to the naphthols in the thermolysis of **21a**−**d** as compared to their respective desmethyl analogues, **20b,e,f,j**. This was not observed for **21a**, which again would result in the more electrophilic vinylketene, i.e., the ratio of **59a** to **60a** was 1.4:1 as compared to 1.5:1 for **20b** (Scheme 15). However, a clear increase in the expected selectivity was observed for the remaining examples: **21b** gave **59b** and **60b** in a respective ratio of 1:4 (cf. 1:2.1 for **20e**); for **21c** the ratio **59c** to **60c** was 1:4.3 (cf. 1:2 for **20f**); and for **21j** the only product detected was the bicyclo[3.2.0]-heptenone **60d**.

Previously, we reported that 4-allenyl-4-hydroxycyclobutenones undergo facile thermal ring expansion to *o*-quinone methide intermediates, which can be trapped via intra- or intermolecular processes.[12,13] The synthetic and pharmacological potential of this ring expansion is significantly expanded because previously unknown 4-allenyl-4-arylcyclobutenones are now readily available as outlined in Scheme 11. Such compounds would, of course, also have the potential for competitive ring expansion to

Scheme 16



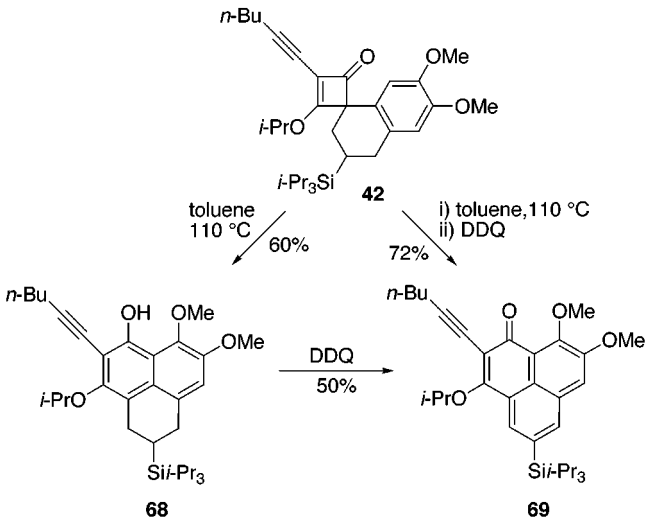
Scheme 17



naphthols or to reactive *o*-quinone methide intermediates.[13] To gain some insight into these possibilities, **44d** was subjected to thermolysis in refluxing acetonitrile containing methanol (Scheme 16). In this case, the only product isolated was the phenol **62** (55%), a product that must arise through methanol trapping of the *o*-quinone methide **61**.

The above thermolyses employ cyclobutenones bearing aryl and allyl groups at position 4. In general, such compounds lead to competitive reactions in which the intermediate vinylketenes undergo electrocyclic ring closure to provide the corresponding naphthol or proceed to bicyclo[3.2.0]heptenones via intramolecular [2 + 2] ketene/alkene cycloadditions. An example in which the competition is between an alkynyl group and an allyl group is outlined in Scheme 17. Here, **32a** was subjected to thermolysis in refluxing toluene, and the only detected product was the bicyclo[3.2.0]heptenone **63** (89%), the product arising from the intramolecular cycloaddition of

Scheme 18



vinylketene **65**. Apparently, ring closure of ketene **64** to the diradical **66**, a known precursor to the quinone **67**, is kinetically unfavorable in comparison to the intramolecular cycloaddition.[1a]

Finally, a transformation of potential synthetic importance as a route to phenalenones, useful precursors to a variety of natural products and drug templates, is outlined in Scheme 18.[16,17] Here the mixture of diastereomeric spirocyclobutenones **42** was subjected to the standard thermolysis conditions (toluene, 110 °C), resulting in the formation of phenalene **68** in 60% isolated yield. Oxidation using 2.1 equiv of DDQ afforded phenalenone **69** in 50% yield. Significantly higher yields of this product were realized when the initial thermolysate was treated directly with the oxidizing agent to give **69** in 72% overall yield.

Conclusions

In conclusion, we wish to note the following significant points arising from the study outlined herein: (1) The thermal rearrangements of appropriately substituted cycobutenones provides one of the most versatile routes to highly condensed ring systems.[1] The most obvious limitation to this methodology is the availability of the starting cyclobutenones. The work outlined here helps to minimize this problem and adds to the rapidly growing number of viable synthetic routes to such compounds. Specifically, readily available 4-aryl-4-hydroxycyclobutenones are efficiently allylated upon treatment with BF_3·Et_2O and allyltrialkylsilanes. (2) The selectivity of the allylation is dependent upon the structure of the intermediate cyclobutenonium cation. In general, allylation takes place predominantly at that site better able to stabilize the positive charge. (3) The 4-aryl-4-allylcyclobutenones available by this route undergo electrocyclic ring opening to the corresponding intermediate vinylketenes. These, in turn, proceed to bicyclo[3.2.0]heptenones ([2 + 2] cycloaddition mode) or to 4-allylnaphthols (electrocyclic ring-closure mode). Although both reaction pathways are operative, selectivity can be slightly enhanced by a judicious choice of substituents.

(16) For a synthesis of a phenalenone-based natural product see: Danheiser, R. L.; Helgason, A. L. *J. Am. Chem. Soc.* **1994**, *116*, 9471.

(17) For phenalenone-based drug templates see: Von Voigtlander, P. F.; Athaus, J. S.; Ochoa, M. C.; Neff, G. L. *Drug Dev. Res.* **1989**, *17*, 71. Tang, A. H.; Franklin, S. R.; Code, R. A.; Athaus, J. S.; Von Voigtlander, P. F.; Darlington, W. H.; Szmuszkaovicz, J. *Drug Dev. Res.* **1990**, *21*, 53.

Experimental Section

General Methods and Materials. All reactions were carried out in flame-dried glassware under a positive pressure of dry nitrogen. Tetrahydrofuran (THF) was dried by passing it through two 4 × 36 in.^{2} columns of anhydrous neutral A-2 alumina to remove H_2O. Toluene and CH_2Cl_2 were distilled from calcium hydride. All solids were recrystallized from CH_2Cl_2/pentane. Removal of solvents was accomplished on a rotary evaporator at approximately 20 Torr. All reactions were followed by TLC using E. Merck silica gel 60 F-254 coated on glass. Flash column chromatography was performed using E. Merck silica gel (230−400 mesh). Radial chromatography was performed on rotors coated with Merck 7749 silica gel. ^{1}H NMR (300 and 500 MHz) and ^{13}C NMR (75 and 125 MHz) spectra were recorded in $CDCl_3$ as solvent; coupling constants are given in hertz. Melting points are uncorrected.

Representative Procedure for the Allylation of 4-Hydroxycyclobutenones. 4-Allyl-2-(1-hexynyl)-3-isopropoxy-4-(3-methoxyphenyl)-2-cyclobutenone (20a). 2-(1-Hexynyl)-4-hydroxy-3-isopropoxy-4-(3-methoxyphenyl)-2-cyclobutenone (**17a**) (0.164 g, 0.5 mmol, 1 equiv) was dissolved in dry CH_2Cl_2 (8 mL) under a positive pressure of N_2. The resulting solution was treated with allyltrimethylsilane (0.40 mL, 2.5 mmol, 5.0 equiv) and cooled to ca. −5 °C prior to dropwise addition of BF_3·OEt_2 (0.31 mL, 2.5 mmol, 5.0 equiv). The ice bath was removed after 15 min, and after an additional 1.75 h, the reaction mixture was quenched with saturated aqueous sodium bicarbonate (3 mL). Further dilution with CH_2Cl_2 (10 mL) was followed by extraction. The organic layer was washed with saturated aqueous sodium chloride (5 mL), and the combined aqueous layers were extracted with CH_2Cl_2 (2 × 10 mL). The combined organic portions were dried ($MgSO_4$) and concentrated to give a yellow oil. Flash silica gel chromatography (9:1 hexanes/EtOAc) provided 0.167 g (95%) of **20a** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.22 (t, J = 8.0, 1H), 7.01−6.97 (m, 2H), 6.79−6.77 (m, 1H), 5.80−5.71 (m, 1H), 5.28 (septet, J = 6.1, 1H), 5.09 (d, J = 18.1, 1H), 5.08 (d, J = 9.5, 1H), 3.78 (s, 3H), 2.71 (dd, J = 14.3, J = 6.8, 1H), 2.60 (dd, J = 14.3, J = 8.0, 1H), 2.30 (t, J = 7.0, 2H), 1.53−1.44 (m, 8H), 1.38 (hextet, J = 7.3, 2H), 0.89 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 187.5, 181.2, 159.5, 140.4, 132.7, 129.4, 118.6, 118.1, 112.6, 111.4, 102.5, 92.3, 78.2, 69.8, 67.7, 55.0, 38.5, 30.4, 22.3, 22.3, 21.8, 19.0, 13.4; IR (neat) 1767, 1606 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O_3$ (M^+) 352.2038, found 352.2037.

2-(1-Hexynyl)-3-isopropoxy-4-(4-methoxyphenyl)-4-(2-methylallyl)-2-cyclobutenone (21a). Prepared in the same manner as described for **20a**. A CH_2Cl_2 solution of 2-(1-hexynyl)-4-hydroxy-3-isopropoxy-4-(4-methoxyphenyl)-2-cyclobutenone (**17b**) (0.164 g, 0.5 mmol, 1 equiv) was treated with (2-methylallyl)trimethylsilane (0.320 g, 2.5 mmol, 5 equiv) followed by BF_3·OEt_2 (0.31 mL, 2.5 mmol, 5 equiv) and stirred at room temperature for 2.5 h. Workup and purification by flash silica gel chromatography (12:1 hexanes/EtOAc) gave 0.179 g (98%) of **21a** as a pale yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 (d, J = 8.5, 2H), 6.83 (d, J = 8.5, 2H), 5.27 (septet, J = 6.1, 1H), 4.85 (s, 1H), 4.72 (s, 1H), 3.77 (s, 3H), 2.65 (d, J = 14.0, 1H), 2.60 (d, J = 14.0, 1H), 2.31 (t, J = 7.0, 2H), 1.71 (s, 3H), 1.52−1.46 (m, 2H), 1.47 (d, J = 6.1, 6H), 1.38 (hextet, J = 7.3, 2H), 0.89 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 188.4, 181.6, 158.6, 141.1, 131.5, 126.9, 115.4, 113.7, 102.4, 92.2, 78.2, 69.4, 67.9, 55.2, 42.6, 30.5, 23.7, 22.4, 22.3, 21.9, 19.1, 13.5; IR (neat) 1766, 1606 cm^{-1}; HRMS (CI) calcd for $C_{24}H_{30}O_3$ (M^+) 366.2195, found 366.2192.

4-Allyl-2-(1-hexynyl)-3-isopropoxy-4-phenyl-2-cyclobutenone (25) from 22. Prepared as described for **20a**. A CH_2Cl_2 solution of 2-(1-hexynyl)-4-hydroxy-3-isopropoxy-4-phenyl-2-cyclobutenone (**22**) (0.503 g, 1.69 mmol, 1 equiv) was treated with allyltrimethylsilane (1.34 mL, 8.44 mmol, 5 equiv)

followed by $BF_3{\cdot}OEt_2$ (1.04 mL, 8.44 mmol, 5 equiv) and stirred at room temperature for 2 h. Workup and purification by flash silica gel chromatography (9:1 hexanes/EtOAc) gave 0.513 g (94%) of **25** as a pale yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43−7.41 (m, 2H), 7.33−7.30 (m, 2H), 7.26−7.24 (m, 1H), 5.81−5.72 (m, 1H), 5.30 (septet, J = 6.5, 1H), 5.12−5.08 (m, 2H), 2.75−2.71 (m, 1H), 2.64−2.60 (m, 1H), 2.31 (t, J = 7.0, 2H), 1.52−1.47 (m, 8H), 1.39 (hextet, J = 7.3, 2H), 0.89 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 187.8, 181.4, 139.0, 132.8, 128.4, 127.1, 125.8, 118.7, 102.4, 92.3, 78.3, 69.8, 67.8, 38.6, 30.5, 22.4, 22.3, 21.9, 19.0, 13.5; IR (neat) 1766, 1608 cm^{-1}; HRMS (EI) calcd for $C_{22}H_{26}O_2$ (M^+) 322.1933, found 322.1936.

4-Allyl-3-isopropoxy-4-(4-methoxyphenyl)-2-phenyl-2-cyclobutenone (28) and 4-Allyl-3-isopropoxy-2-(4-methoxyphenyl)-4-phenyl-2-cyclobutenone (29) from 26. Prepared as described for **20a**. A CH_2Cl_2 solution of 4-hydroxy-3-isopropoxy-4-(4-methoxyphenyl)-2-phenyl-2-cyclobutenone (**26**) (0.324 g, 1.0 mmol, 1 equiv) was treated with allyltrimethylsilane (0.80 mL, 5 mmol, 5 equiv) followed by $BF_3{\cdot}OEt_2$ (0.61 mL, 5 mmol, 5 equiv) and stirred at room temperature for 6 h. Workup was followed by ^{1}H NMR analysis which showed a 4.3:1 ratio of products favoring **28** over **29**. This ratio was observed to be 3.7:1 in another run, giving an average of 4.0:1. Radial chromatography (30:1 hexanes/EtOAc) gave as first fraction 0.064 g (18%) of **29** as a white crystalline solid: mp 108 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (d, J = 8.6, 2H), 7.47 (d, J = 7.7, 2H), 7.37 (t, J = 7.7, 2H), 7.28 (d, J = 7.3, 1H), 6.90 (d, J = 8.6, 2H), 5.97−5.88 (m, 1H), 5.23 (d, J = 16.8, 1H), 5.15 (d, J = 10.1, 1H), 4.58 (septet, J = 6.1, 1H), 3.82 (s, 3H), 3.13 (dd, J = 14.5, J = 6.5, 1H), 2.84 (dd, J = 14.5, J = 7.7, 1H), 1.39 (d, J = 6.1, 3H), 1.12 (d, J = 6.1, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 186.5, 175.9, 158.8, 138.7, 133.3, 128.7, 128.6, 127.4, 126.2, 121.9, 121.3, 118.7, 113.8, 78.0, 71.5, 55.3, 36.3, 23.0, 22.7; IR (neat) 1749, 1632, 1601 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{24}O_3$ (M^+) 348.1725, found 348.1728.

Second fraction, 0.278 g (80%) of **28** as a pale yellow crystalline solid: mp 115 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.72 (d, J = 7.6, 2H), 7.41 (d, J = 8.7, 2H), 7.38 (t, J = 7.7, 2H), 7.27 (t, J = 7.4, 1H), 6.92 (d, J = 8.7, 2H), 5.99−5.91 (m, 1H), 5.26 (d, J = 16.8, 1H), 5.17 (d, J = 10.2, 1H), 4.60 (septet, J = 6.1, 1H), 3.80 (s, 3H), 3.15 (dd, J = 14.6, J = 6.5, 1H), 2.86 (dd, J = 14.6, J = 7.7, 1H), 1.41 (d, J = 6.1, 3H), 1.13 (d, J = 6.1, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 186.7, 177.5, 158.8, 133.2, 130.2, 129.1, 128.3, 127.3, 127.2, 126.9, 121.2, 118.7, 114.0, 78.2, 71.1, 55.1, 36.0, 22.9, 22.6; IR (neat) 1747, 1642, 1632, 1597 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{24}O_3$ (M^+) 348.1725, found 348.1726.

4-Allyl-2-(1-hexynyl)-3-methyl-4-phenyl-2-cyclobutenone (31a) and 4-Allyl-4-(1-hexynyl)-3-methyl-2-phenyl-2-cyclobutenone (32a). Prepared as described for **20a**. A CH_2Cl_2 solution of 4-(1-hexynyl)-4-hydroxy-3-methyl-2-phenyl-2-cyclobutenone (**30a**) (0.254 g, 1.0 mmol, 1 equiv) was treated with allyltrimethylsilane (0.80 mL, 5.0 mmol, 5 equiv) followed by $BF_3{\cdot}OEt_2$ (0.61 mL, 5.0 mmol, 5 equiv) and stirred at −5 °C for 5 min. Workup was followed by ^{1}H NMR analysis which showed a 1.3:1 ratio of products favoring **32a** over **31a**. Radial chromatography (200:1 hexanes/EtOAc) gave as first fraction 0.149 g (54%) of **32a** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.66 (d, J = 7.5, 2H), 7.39 (t, J = 7.5, 2H), 7.32 (t, J = 7.5, 1H), 5.91−5.83 (m, 1H), 5.14 (dd, J = 16.8, J = 1.0, 1H), 5.09 (d, J = 10.3, 1H), 2.60 (d, J = 7.2, 2H), 2.43 (s, 3H), 2.23 (t, J = 7.0, 2H), 1.51−1.45 (m, 2H), 1.40 (hextet, J = 7.3, 2H), 0.90 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 188.0, 172.5, 143.5, 133.4, 129.8, 128.7, 128.6, 127.2, 118.2, 87.8, 76.8, 64.3, 39.0, 30.9, 21.9, 18.6, 13.8, 13.6; IR (neat) 1764, 1639, 1599 cm^{-1}; HRMS (CI) calcd for $C_{20}H_{22}O$ (M^+) 278.1671, found 278.1671.

Second fraction, 0.112 g (40%) of **31a** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35−7.24 (m, 5H), 5.77−5.68 (m, 1H), 5.12 (d, J = 17.0, 1H), 5.08 (d, J = 10.1, 1H), 2.85 (dd, J = 14.6, J = 6.9, 1H), 2.74 (dd, J = 14.6, J = 7.4, 1H), 2.38 (t, J = 7.1, 2H), 2.28 (s, 3H), 1.58−1.52 (m, 2H), 1.43 (hextet, J = 7.4, 2H), 0.92 (t, J = 7.4, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 189.8, 181.3, 139.0, 133.3, 130.9, 128.6, 127.2, 126.1, 118.5, 98.2, 73.2, 67.9, 37.6, 30.4, 22.0, 19.3, 14.5, 13.5; IR (neat) 2221, 1766, 1641, 1619 cm^{-1}; HRMS (CI) calcd for $C_{20}H_{23}O$ (MH^+) 279.1749, found 279.1753.

4-Allyl-2-(1-hexynyl)-3-isobutyl-4-phenyl-2-cyclobutenone (31b) and 4-Allyl-4-(1-hexynyl)-3-isobutyl-2-phenyl-2-cyclobutenone (32b). Prepared as described for **20a**. A CH_2Cl_2 solution of 4-(1-hexynyl)-4-hydroxy-3-isobutyl-2-phenyl-2-cyclobutenone (**30b**) (0.142 g, 0.48 mmol, 1 equiv) was treated with allyltrimethylsilane (0.38 mL, 2.4 mmol, 5 equiv) followed by $BF_3{\cdot}OEt_2$ (0.3 mL, 2.4 mmol, 5 equiv) and stirred at −5 °C for 5 min. Workup was followed by ^{1}H NMR analysis which showed a 1.1:1 ratio of products favoring **31b** over **32b**. Radial chromatography (100:1 hexanes/EtOAc) gave as first fraction 0.050 g (33%) of **32b** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.68 (d, J = 7.5, 2H), 7.38 (t, J = 7.4, 2H), 7.32 (t, J = 7.1, 1H), 5.94−5.86 (m, 1H), 5.14 (d, J = 16.9, 1H), 5.10 (d, J = 10.1, 1H), 2.81 (dd, J = 14.0, J = 8.7, 1H), 2.66−2.61 (m, 3H), 2.39 (septet, J = 6.6, 1H), 2.22 (t, J = 7.0, 2H), 1.47 (quintet, J = 7.0, 2H), 1.39 (hextet, J = 7.0, 2H), 1.07 (d, J = 6.6, 6H), 0.89 (t, J = 7.1, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 188.6, 175.6, 144.3, 133.4, 129.7, 128.7, 128.5, 127.3, 118.1, 87.6, 77.5, 63.7, 39.4, 38.7, 30.7, 27.2, 23.7, 23.0, 21.9, 18.6, 13.5; IR (neat) 1764, 1634, 1598 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O$ (M^+) 320.2140, found 320.2142.

Second fraction, 0.059 g (38%) of **31b** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35−7.23 (m, 5H), 5.78−5.70 (m, 1H), 5.12 (d, J = 17.1, 1H), 5.08 (d, J = 10.1, 1H), 2.86 (dd, J = 14.5, J = 7.0, 1H), 2.75 (dd, J = 14.5, J = 7.5, 1H), 2.43 (d, J = 7.1, 2H); 2.38 (t, J = 7.1, 2H), 2.34 (septet, J = 6.7, 1H), 1.54 (quintet, J = 7.0, 2H), 1.43 (hextet, J = 7.2, 2H), 1.00 (d, J = 6.7, 3H), 0.99 (d, J = 6.7, 3H), 0.92 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 190.4, 184.0, 138.8, 133.3, 129.8, 128.6, 127.2, 126.2, 118.6, 97.8, 73.0, 68.8, 39.3, 37.2, 30.3, 25.8, 23.2, 23.2, 21.9, 19.3, 13.5; IR (neat) 2224, 1768, 1642, 1609 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O$ (M^+) 320.2140, found 320.2138.

4-Allyl-3-isopropoxy-2,4-diphenyl-2-cyclobutenone (20e). Kinetic Studies. 4-Hydroxy-3-isopropoxy-2,4-diphenyl-2-cyclobutenone (**17e**) (0.147 g, 0.5 mmol, 1 equiv) was dissolved in dry CH_2Cl_2 (8 mL) under a positive pressure of N_2. The resulting solution was treated with allyltrimethylsilane (X equiv, X = 5, 20) and cooled to ca. −5 °C prior to dropwise addition of $BF_3{\cdot}Et_2O$ (Y equiv, Y = 5, 20). The ice bath was removed after 15 min. After 30 min and 1, 4, 10, 24, and 48 h, aliquots were taken out of the reaction mixture. Workup of the aliquots was followed by ^{1}H NMR analysis (see Scheme 9).

Spiro[3-(1-hexynyl)-4-isopropoxy-2-oxo-3-cyclobutene-1,1′(2′*H*)-3′,4′-dihydro-6′,7′-dimethoxynaphthalene] (42) and 4-Allyl-2-(1-hexynyl)-3-isopropoxy-4-(3,4-dimethoxyphenyl)-2-cyclobutenone (20c). Prepared in the same manner as described for **20a**. A CH_2Cl_2 solution of 2-(1-hexynyl)-4-hydroxy-3-isopropoxy-4-(3,4-dimethoxyphenyl)-2-cyclobutenone (**17c**) (0.179 g, 0.5 mmol, 1 equiv) was treated with allyltriisopropylsilane (0.36 mL, 1.5 mmol, 3 equiv) followed by $AlCl_3$ (200 mg, 1.5 mmol, 3 equiv) and stirred at −5 °C for 10 min. Workup gave a yellow oil. ^{1}H NMR analysis of the crude product showed a 3.7:1 ratio of products favoring **42** over **20c**. Purification by flash silica gel chromatography (4:1 hexanes/EtOAc) gave as first fraction 0.181 g (67%) of **42** as a pale yellow amorphous solid (mixture of diastereomers 1.2:1*): ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.69, 6.65* (each s, 1H), 6.60*, 6.58 (each s, 1H), 5.33−5.20 (m, 1H), 3.83, 3.82, 3.80 (each s, 6H), 2.86−2.71 (m, 2H), 2.362, 2.360* (each t, J = 7.0, 2H), 2.21−1.86 (m, 2H), 1.58−1.36 (m, 10H), 1.22−1.08 (m, 22H), 0.92 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 190.4, 188.7, 184.9, 182.4, 148.4, 148.3, 147.4, 147.3, 132.9, 132.4, 123.9, 123.6, 111.8, 111.5, 109.4, 108.9, 103.5, 92.6, 78.1, 77.7, 68.2, 68.0, 66.6, 66.3, 56.1, 55.9, 55.7, 55.7, 31.9, 31.8, 31.7, 31.5, 30.5, 22.1, 22.1, 21.9, 21.9, 19.1, 19.1, 19.0, 17.5, 17.3, 13.5, 10.9, 10.8; IR (neat) 1766, 1606 cm^{-1}; HRMS (EI) calcd for $C_{33}H_{50}O_4Si$ (M^+) 538.3478, found 538.3487.

Second fraction, 34 mg (18%) of **20c** as a yellow oil.

Representative Procedure for the Allenylation of 4-Hydroxycyclobutenones. 4-Allenyl-2-(1-hexynyl)-3-iso-

propoxy-4-phenyl-2-cyclobutenone (44a). 2-(1-Hexynyl)-4-hydroxy-3-isopropoxy-4-phenyl-2-cyclobutenone (**22**) (0.107 g, 0.36 mmol, 1 equiv) was dissolved in dry CH_2Cl_2 (5 mL) under a positive pressure of N_2. The resulting solution was treated with propargyltrimethylsilane (0.16 mL, 1.08 mmol, 3.0 equiv) and cooled to ca. −5 °C prior to the dropwise addition of $BF_3{\cdot}OEt_2$ (0.13 mL, 1.08 mmol, 3.0 equiv). The ice bath was removed after 15 min, and after an additional 2.75 h, the reaction mixture was quenched with saturated aqueous sodium bicarbonate (10 mL). Further dilution with CH_2Cl_2 (5 mL) was followed by extraction. The organic layer was washed with saturated aqueous sodium chloride (5 mL), and the combined aqueous layers were extracted with CH_2Cl_2 (2 × 10 mL). The combined organic portions were dried ($MgSO_4$) and concentrated to give a brown oil. Flash silica gel chromatography (19:1 hexanes/EtOAc) provided 0.080 g (70%) of **44a** as a pale yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.44−7.41 (m, 2H), 7.35−7.28 (m, 3H), 5.48 (t, J = 6.5, 1H), 5.30 (septet, J = 6.5, 1H), 4.86 (d, J = 6.5, 2H), 2.33 (t, J = 7.0, 2H), 1.54−1.39 (m overlapping with d, J = 6.0, 10H), 0.91 (t, J = 7.0, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 208.4, 185.8, 180.3, 137.4, 128.4, 127.5, 126.4, 102.9, 93.0, 90.5, 78.6, 78.2, 67.8, 30.5, 22.3, 21.9, 19.1, 13.5; IR (neat) 1946, 1768, 1607 cm^{-1}; HRMS (EI) calcd for $C_{22}H_{24}O_2$ (M^+) 320.1776, found 320.1774.

Representative Procedure for the Thermolysis of 4-Allylcyclobutenones. 4-Allyl-2-(1-hexynyl)-3-isopropoxynaphthol (45a) and 5-(1-Hexynyl)-4-isopropoxy-3-phenylbicyclo[3.2.0]hept-3-en-6-one (46a). A solution of **25** (0.251 g, 0.78 mmol) in toluene (16 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 3 h. Removal of the volatile components was followed by ^{1}H NMR analysis which showed a 2:1 ratio of products favoring the naphthol over the bicycloheptenone. Flash silica gel chromatography (50:1 hexanes/EtOAc) gave as first fraction 0.127 g (51%) of naphthol **45a** as an off-white oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.19 (dd, J = 8.5, J = 0.5, 1H), 7.86 (d, J = 8.5, 1H), 7.48 (ddd, J = 8.0, J = 6.5, J = 1.0, 1H), 7.40 (ddd, J = 8.0, J = 6.5, J = 1.0, 1H), 6.41 (s, 1H), 6.41−5.96 (m, 1H), 5.04−4.95 (m, 2H), 4.77 (septet, J = 6.0, 1H), 3.82−3.81 (m, 2H), 2.59 (t, J = 7.0, 2H), 1.68 (quintet, J = 7.5, 2H), 1.54 (hextet, J = 7.5, 2H), 1.35 (d, J = 6.0, 6H), 0.99 (t, J = 7.5, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 153.9, 152.0, 137.2, 132.9, 127.3, 124.5, 123.9, 122.6, 120.5, 118.6, 115.3, 101.9, 100.7, 75.8, 72.9, 30.8, 29.7, 22.6, 22.1, 19.6, 13.6; IR (neat) 3487, 1620, 1574 cm^{-1}; HRMS (CI) calcd for $C_{22}H_{26}O_2$ (M^+) 322.1933, found 322.1929.

Second fraction, 0.093 g (37%) of **46a** as a white crystalline solid: mp 52−53 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75−7.70 (m, 2H), 7.39−7.31 (m, 2H), 7.24−7.19 (m, 1H), 4.83 (septet, J = 6.0, 1H), 3.39 (dd, J = 18.0, J = 9.0, 1H), 3.28 (dd, J = 15.5, J = 7.5, 1H), 3.08 (dd, J = 18.5, J = 6.5, 1H), 2.89−2.84 (m, 1H), 2.70 (d, J = 15.5, 1H), 2.27 (t, J = 7.0, 2H), 1.51 (quintet, J = 7.0, 2H), 1.42 (hextet, J = 7.0, 2H), 1.39 (d, J = 6.0, 3H), 1.17 (d, J = 6.0, 3H), 0.91 (t, J = 7.0, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.1, 147.2, 135.5, 128.0, 126.8, 126.5, 117.0, 89.9, 74.0, 73.8, 73.1, 52.5, 37.0, 32.2, 30.7, 23.0, 22.8, 21.9, 18.7, 13.5; IR (neat) 1779, 1620 cm^{-1}; HRMS (CI) calcd for $C_{22}H_{26}O_2$ (M^+) 322.1933, found 322.1926.

4-Allyl-2-(1-hexynyl)-3-isopropoxy-6-methoxynaphthol (48), 4-Allyl-2-(1-hexynyl)-3-isopropoxy-8-methoxynaphthol (49), and 5-(1-Hexynyl)-4-isopropoxy-3-(3-methoxyphenyl)-bicyclo[3.2.0]hept-3-en-6-one (50). A solution of **20a** (0.162 g, 0.46 mmol) in toluene (9.2 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 3 h. Removal of the volatile components was followed by ^{1}H NMR analysis which showed a 3.2:1.4:1 ratio (**48**:**49**:**50**). Radial chromatography (30:1 hexanes/EtOAc) gave as first fraction 0.088 g (54%) of naphthol **48** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, J = 9.1, 1H), 7.18 (s, 1H), 7.06 (d, J = 9.1, 1H), 6.38 (s, 1H), 5.98 (ddt, J = 16.6, J = 10.6, J = 5.6, 1H), 5.06 (d, J = 10.6, 1H), 5.04 (d, J = 16.6, 1H), 4.79 (septet, J = 6.1, 1H), 3.89 (s, 3H), 3.79 (d, J = 5.6, 2H), 2.58 (t, J = 7.1, 2H), 1.67 (quintet, J = 7.4, 2H), 1.53 (hextet, J = 7.3, 2H), 1.35 (d, J = 6.1, 6H), 0.98 (t, J = 7.2, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 158.8, 153.9, 152.8, 137.2, 134.6, 124.3, 117.5, 115.7, 115.6, 115.2, 103.8, 101.2, 98.5, 75.7, 72.9, 55.1, 30.8, 30.0, 22.5, 22.1, 19.6, 13.6; IR (neat) 3485, 1626, 1580 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O_3$ (M^+) 352.2038, found 352.2031.

Second fraction, 0.028 g (17%) of **50** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 (s, 1H), 7.24−7.22 (m, 2H), 6.79−6.76 (m, 1H), 4.84 (septet, J = 6.0, 1H), 3.82 (s, 3H), 3.39 (dd, J = 18.1, J = 9.0, 1H), 3.26 (dd, J = 15.5, J = 7.9, 1H), 3.07 (dd, J = 18.1, J = 6.4, 1H), 2.89−2.83 (m, 1H), 2.69 (d, J = 15.5, 1H), 2.26 (t, J = 7.0, 2H), 1.53−1.36 (m, 4H), 1.39 (d, J = 6.0, 3H), 1.17 (d, J = 6.0, 3H), 0.90 (t, J = 7.2, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.1, 159.3, 147.4, 136.8, 128.9, 119.4, 117.0, 112.6, 112.2, 90.0, 74.0, 73.7, 73.1, 55.1, 52.6, 37.1, 32.1, 30.7, 23.1, 22.9, 21.9, 18.8, 13.6; IR (neat) 1783, 1623, 1599 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O_3$ (M^+) 352.2038, found 352.2029.

Third fraction, 0.040 g (25%) of **49** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 10.08 (s, 1H); 7.48 (d, J = 8.6, 1H), 7.30 (t, J = 8.2, 1H), 6.73 (d, J = 7.8, 1H), 5.95 (ddt, J = 17.4, J = 9.9, J = 5.6, 1H), 5.00 (dd, J = 9.9, J = 1.5, 1H), 4.93 (dd, J = 17.4, J = 1.5, 1H), 4.88 (septet, J = 6.1, 1H), 4.03 (s, 3H), 3.77 (dt, J = 5.6, J = 1.5, 2H), 2.58 (t, J = 7.2, 2H), 1.70−1.64 (m, 2H), 1.53 (hextet, J = 7.3, 2H), 1.32 (d, J = 6.1, 6H), 0.96 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 156.3, 156.0, 154.5, 137.2, 134.5, 126.3, 118.8, 117.8, 115.2, 111.9, 103.4, 102.7, 99.1, 75.4, 73.9, 56.3, 31.1, 30.1, 22.5, 22.2, 19.8, 13.7; IR (neat) 3364, 1621, 1606, 1581 cm^{-1}; HRMS (CI) calcd for $C_{23}H_{28}O_3$ (M^+) 352.2038, found 352.2036.

4-Allyl-2-*n*-butyl-3-isopropoxynaphthol (51), 4-Allyl-2-*n*-butyl-4-hydroperoxy-3-isopropoxy-4*H*-naphthalen-1-one (53), and 5-*n*-Butyl-4-isopropoxy-3-phenylbicyclo-[3.2.0]hept-3-en-6-one (55). A solution of **20h** (0.186 g, 0.62 mmol) in toluene (12 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 2 h. Removal of the volatile components was followed by ^{1}H NMR analysis which showed a 1.6:1 ratio of products favoring the bicycloheptenone **55** over the naphthol **51**. Flash silica gel chromatography (19:1 hexanes/EtOAc) gave as first fraction 0.104 g (56%) of bicycloheptenone **55** as a water white oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.77−7.74 (m, 2H), 7.35−7.32 (m, 2H), 7.22−7.19 (m, 1H), 4.51 (septet, J = 6.0, 1H), 3.20 (dd, J = 18.0, J = 9.0, 1H), 3.09 (dd, J = 16.0, J = 8.0, 1H), 2.97 (dd, J = 17.5, J = 6.0, 1H), 2.75 (d, J = 16.0, 1H), 2.59−2.55 (m, 1H), 1.83−1.80 (m, 1H), 1.75−1.70 (m, 1H), 1.36−1.22 (m, 7H), 1.08 (d, J = 6.0, 3H), 0.89 (t, J = 7.0, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.1, 148.7, 135.8, 128.1, 126.9, 126.5, 119.3, 83.3, 71.8, 51.5, 37.5, 29.4, 28.2, 26.4, 23.03, 22.98, 22.3, 13.9; IR (neat) 1767, 1622 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{26}O_2$ (M^+) 298.1933, found 298.1938.

Second fraction, **53**. Isolated from attempts to purify the corresponding naphthol **51** as a white crystalline solid: mp 84−86 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, J = 8.0, 1H), 7.88 (s, 1H), 7.64−7.62 (m, 2H), 7.47−7.43 (m, 1H), 5.15 (septet, J = 6.0, 1H), 5.12−5.05 (m, 1H), 4.83−4.80 (m, 2H), 2.90 (dd, J = 12.5, J = 7.5, 1H), 2.59−2.49 (m, 3H), 1.47 (m, 10H), 0.92 (t, J = 7.5, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 185.4, 164.3, 140.7, 132.7, 132.5, 130.2, 129.5, 128.5, 126.6, 124.2, 120.0, 86.2, 75.5, 42.3, 30.8, 24.0, 23.44, 23.41, 23.0, 13.9; IR (neat) 3316, 1631, 1599, 1572 cm^{-1}; HRMS (CI) calcd for $C_{20}H_{27}O_4$ (MH^+) 331.1909, found 331.1910.

4-Allyl-2-*sec*-butyl-3-isopropoxynaphthol (52), 4-Allyl-2-*sec*-butyl-4-hydroperoxy-3-isopropoxy-4*H*-naphthalen-1-one (54), and 5-*sec*-Butyl-4-isopropoxy-3-phenylbicyclo-[3.2.0]hept-3-en-6-one (56). A solution of **20i** (0.166 g, 0.56 mmol) in toluene (11.1 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 5 h. Removal of the volatile components was followed by ^{1}H NMR analysis which showed a 1:1 ratio of **52** and **56**. Radial chromatography (50:1 hexanes/EtOAc) gave as first fraction 0.073 g (44%) of bicycloheptenone **56** as a pale yellow oil (mixture of diastereomers 1.3:1): ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.77 (d, J = 7.4, 2H), 7.34 (t, J = 7.8, 2H), 7.21 (t, J = 7.4, 1H), 4.62−4.54 (m, 1H), 3.14, 3.13 (each dd, J = 18.1 and J = 9.0, J = 18.0 and J = 9.0, 1H), 3.01 (dd, J = 15.7, J = 8.1, 1H), 2.89, 2.86 (each dd, J = 18.1 and J = 5.9, J = 18.0 and J = 5.9, 1H), 2.75 (d, J = 15.8, 1H), 2.71−2.65 (m, 1H), 2.06−1.98 (m, 1H), 1.62−1.50 (m, 1H), 1.34 (d, J = 6.2, 3H), 1.08, 1.07 (each d, J = 5.7, J = 5.1, 3H), 1.00−0.93 (m, 4H), 0.89, 0.88 (each t, J = 7.2, J = 6.6, 3H); ^{13}C NMR (125 MHz,

$CDCl_3$) δ 209.8, 209.5, 148.3, 148.1, 135.81, 135.77, 128.0, 127.0, 126.9, 126.4, 120.2, 120.1, 88.24, 88.15, 71.6, 51.8, 51.4, 37.8, 37.6, 34.7, 34.1, 25.1, 25.0, 24.6, 23.9, 23.0, 22.2, 14.3, 13.3, 12.2 11.8; IR (neat) 1769, 1622, 1598 cm^{-1}; HRMS (CI) calcd for $C_{20}H_{26}O_2$ (M^+) 298.1933, found 298.1936.

Second fraction, 0.043 g (24%) of **54**. Isolated from attempts to purify the corresponding naphthol **52** as a yellow crystalline solid (mixture of diastereomers 1.8:1): mp 73−74 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.09−8.04 (m, 1H), 7.95, 7.85 (each br s, 1H), 7.63−7.58 (m, 2H), 7.46−7.40 (m, 1H), 5.28−5.05 (m, 2H), 4.86−4.79 (m, 2H), 3.22−3.11 (m, 1H), 2.90, 2.88 (each dd, J = 12.3, J = 7.6, 1H), 2.59, 2.57 (each dd, J = 12.8, J = 7.1, 1H), 1.86−1.58 (m, 2H), 1.46 (d, J = 6.1, 3H), 1.43, 1.42 (each d, J = 6.2, 3H), 1.27, 1.22 (each d, J = 7.1, J = 7.0, 3H), 0.86, 0.81 (each t, J = 7.5, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 185.3, 164.4, 163.9, 140.5, 140.4, 134.1, 134.0, 133.1, 132.9, 132.6, 129.6, 129.5, 128.5, 128.4, 126.53, 126.46, 124.1, 123.9, 120.1, 120.0, 86.3, 75.7, 75.5, 42.7, 42.4, 33.0, 32.9, 29.7, 27.6, 27.1, 23.6, 23.4, 23.3, 18.6, 18.5, 13.0, 12.9; IR (neat) 3348, 1644, 1606, 1574 cm^{-1}; HRMS (CI) calcd for $C_{20}H_{27}O_4$ (MH^+) 331.1909, found 331.1908.

4-Allyl-2-*tert*-butyl-3-methoxy-2*H*-naphthalen-1-one (57) and 5-*tert*-Butyl-4-methoxy-3-phenylbicyclo[3.2.0]hept-3-en-6-one (58). A solution of **20j** (0.216 g, 0.80 mmol) in toluene (16 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 14 d. Removal of the volatile components was followed by ^1H NMR analysis which showed a 6:1 ratio of products favoring the bicycloheptenone over the naphthalenone. Radial chromatography (100:1 hexanes/EtOAc) gave as first fraction 0.149 g (69%) of bicycloheptenone **58** as a yellow oil: ^1H NMR (500 MHz, $CDCl_3$) δ 7.64−7.62 (m, 2H), 7.37 (t, J = 7.8, 2H), 7.25 (t, J = 7.6, 1H), 3.59 (s, 3H), 3.14 (dd, J = 17.9, J = 9.1, 1H), 3.00 (dd, J = 16.1, J = 7.8, 1H), 2.86 (dd, J = 18.1, J = 5.8, 1H), 2.73−2.67 (m, 2H), 1.12 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.5, 152.1, 135.4, 128.2, 127.3, 127.0, 122.9, 88.8, 58.4, 51.1, 37.1, 34.6, 26.4, 26.3; IR (neat) 1763, 1618, 1596 cm^{-1}; HRMS (CI) calcd for $C_{18}H_{22}O_2$ (M^+) 270.1620, found 270.1623.

Second fraction, 0.029 g (13%) of **57** as a yellow oil: ^1H NMR (500 MHz, $CDCl_3$) δ 7.77 (dd, J = 7.8, J = 1.4, 1H), 7.48 (dt, J = 7.8, J = 1.4, 1H), 7.33 (d, J = 7.6, 1H), 7.21 (dt, J = 7.6, J = 1.0, 1H), 5.92 (ddt, J = 17.1, J = 10.1, J = 5.6, 1H), 5.13 (dq, J = 17.1, J = 1.6, 1H), 5.04 (dq, J = 10.1, J = 1.6, 1H), 3.63 (s, 3H), 3.45 (ddt, J = 15.9, J = 5.4, J = 2.0, 1H), 3.34−3.28 (m, 1H), 3.20 (s, 1H), 0.97 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.9, 155.5, 139.8, 136.2, 133.8, 131.3, 126.1, 125.8, 124.1, 118.6, 115.5, 58.8, 58.0, 37.9, 29.1, 28.4; IR (neat) 1682, 1644, 1634, 1598 cm^{-1}; HRMS (EI) calcd for $C_{18}H_{22}O_2$ (M^+) 270.1620, found 270.1620.

2-(1-Hexynyl)-3-isopropoxy-7-methoxy-4-(2-methylallyl)-naphthol (59a) and 5-(1-Hexynyl)-4-isopropoxy-3-(4-methoxyphenyl)-1-methyl-bicyclo[3.2.0]hept-3-en-6-one (60a). A solution of **21a** (0.175 g, 0.48 mmol) in toluene (9.5 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 3 h. Removal of the volatile components was followed by ^1H NMR analysis which showed a 1.4:1 ratio of products favoring the naphthol over the bicycloheptenone. Radial chromatography (100:1 pentane/EtOAc) gave as first fraction 0.103 g (59%) of naphthol **59a** as a yellow oil: ^1H NMR (500 MHz, $CDCl_3$) δ 7.70 (d, J = 9.3, 1H), 7.47 (d, J = 2.5, 1H), 7.13 (dd, J = 9.2, J = 2.5, 1H), 6.37 (s, 1H), 4.76 (s, 1H), 4.68 (septet, J = 6.1, 1H), 4.36 (s, 1H), 3.93 (s, 3H), 3.69 (s, 2H), 2.59 (t, J = 7.1, 2H), 1.82 (s, 3H), 1.68 (quintet, J = 7.3, 2H), 1.54 (hextet, J = 7.4, 2H), 1.34 (d, J = 6.2, 6H), 0.99 (t, J = 7.3, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 156.3, 152.6, 150.6, 144.7, 128.5, 126.4, 121.2, 119.5, 118.8, 111.1, 101.8, 101.3, 100.7, 75.7, 73.1, 55.3, 33.8, 30.8, 23.2, 22.5, 22.1, 19.7, 13.6; IR (neat) 3486, 1599, 1575 cm^{-1}; HRMS (CI) calcd for $C_{24}H_{30}O_3$ (MH^+) 366.2195, found 366.2191.

Second fraction, 0.071 g (40%) of **60a** as a yellow oil: ^1H NMR (500 MHz, $CDCl_3$) δ 7.67 (d, J = 8.8, 2H), 6.87 (d, J = 8.8, 2H), 4.80 (septet, J = 6.0, 1H), 3.81 (s, 3H), 3.29 (d, J = 17.7, 1H), 2.91 (d, J = 17.7, 1H), 2.88 (s, 2H), 2.29 (t, J = 7.0, 2H), 1.51 (quintet, J = 7.0, 2H), 1.42 (hextet, J = 7.2, 2H), 1.40 (s, 3H), 1.38 (d, J = 6.0, 3H), 1.14 (d, J = 6.0, 3H), 0.90 (t, J = 7.2, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 202.2, 158.0, 145.6, 128.3, 128.1, 117.3, 113.4, 91.3, 72.5, 72.1, 58.4, 55.2, 44.8, 36.1, 30.8, 23.0, 22.7, 22.2, 21.8, 18.7, 13.5; IR (neat) 1779, 1632, 1607 cm^{-1}; HRMS (CI) calcd for $C_{24}H_{30}O_3$ (M^+) 366.2195, found 366.2193.

3-Methoxy-6-methoxymethyl-2,4-(3,4-dimethoxyphenyl)-phenol (62). 4-Allenyl-3-methoxy-2,4-(3,4-dimethoxyphenyl)-2-cyclobutenone (**44d**) (0.103 g, 0.25 mmol, 1 equiv) was dissolved in acetonitrile (6 mL, 0.03 M) and treated with anhydrous methanol (1.02 mL, 25.2 mmol, 100 equiv). The resulting solution was heated to gentle reflux for 2 h. Removal of the volatile components provided an orange oil which was purified by flash silica gel chromatography (19:1 CH_2Cl_2/EtOAc) to furnish 0.061 g (55%) of **62** as a white crystalline solid: mp 158−159 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.14−7.13 (m, 2H), 7.07 (dd, J = 8.0, J = 2.0, 1H), 7.03−6.99 (m, 3H), 6.91 (d, J = 8.0, 1H), 6.79 (s, 1H), 4.64 (s, 2H), 3.94 (s, 3H), 3.92 (s, 3H), 3.903 (s, 3H), 3.900 (s, 3H), 3.48 (s, 3H), 3.21 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.6, 152.6, 148.9, 148.5, 148.4, 147.9, 131.3, 129.8, 126.5, 125.7, 123.2, 122.7, 121.2, 118.7, 113.6, 112.4, 111.1, 110.9, 72.4, 60.5, 58.4, 55.94, 55.90, 55.8; IR (neat) 3436, 1592 cm^{-1}; HRMS (EI) calcd for $C_{25}H_{28}O_7$ (M^+) 440.1835, found 440.1830.

3-(1-Hexynyl)-4-methyl-5-phenylbicyclo[3.2.0]hept-3-en-6-one (63). A solution of **32a** (0.147 g, 0.53 mmol) in toluene (11 mL, 0.05 M) was heated to reflux under a blanket of N_2 for 3 h. Removal of the volatile components followed by radial chromatography (20:1 hexanes/EtOAc) furnished 0.131 g (89%) of **63** as a water white oil: ^1H NMR (500 MHz, $CDCl_3$) δ 7.34−7.23 (m, 5H), 3.35−3.28 (m, 1H), 3.20−3.15 (m, 1H), 2.92−2.85 (m, 2H), 2.58 (d, J = 16.7, 1H), 2.40 (t, J = 7.0, 2H), 1.67 (s, 3H), 1.56 (quintet, J = 7.0, 2H), 1.46 (hextet, J = 7.4, 2H), 0.95 (t, J = 7.2, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 206.1, 142.8, 138.2, 128.4, 127.0, 125.8, 120.8, 95.6, 87.7, 76.7, 51.2, 43.2, 34.2, 30.8, 21.9, 19.2, 13.6, 12.7; IR (neat) 2217, 1770, 1602 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{22}O$ (M^+) 278.1671, found 278.1684.

5-(1-Hexynyl)-2,3-dihydro-6-hydroxy-4-isopropoxy-2-triisopropylsilyl-7,8-dimethoxy-1*H*-phenalene (68). A solution of **42** (0.067 g, 0.13 mmol) in toluene (6 mL, 0.02 M) was heated to reflux under a blanket of N_2 for 45 min. Removal of the solvent was followed by flash silica gel chromatography (9:1 hexanes/EtOAc) which furnished 0.057 g (60%) of **68** as a water white oil: ^1H NMR (500 MHz, $CDCl_3$) δ 10.29 (s, 1H), 6.96 (s, 1H), 4.73 (septet, J = 6.0, 1H), 4.04 (s, 3H), 3.95 (s, 3H), 3.49−3.45 (m, 1H), 3.09−3.01 (m, 2H), 2.69−2.63 (m, 1H), 2.59 (t, J = 7.0, 2H), 1.67 (quintet, J = 7.5, 2H), 1.55−1.46 (m, 3H), 1.33 (d, J = 6.0, 6H), 1.31−1.18 (m, 3H), 1.15 (d, J = 7.0, 18H), 0.96 (t, J = 7.5, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 154.2, 150.1, 146.0, 140.7, 134.5, 126.1, 119.1, 114.7, 113.6, 103.1, 99.1, 75.2, 73.9, 62.1, 56.8, 34.1, 31.1, 26.7, 22.7, 22.5, 22.2, 19.9, 19.2, 13.7, 11.0; IR (neat) 3297, 1606 cm^{-1}; HRMS (EI) calcd for $C_{33}H_{50}O_4Si$ (M^+) 538.3478, found 538.3464.

2-(1-Hexynyl)-3-isopropoxy-5-triisopropylsilyl-8,9-dimethoxy-phenalenone (69). A solution of **42** (0.045 g, 0.08 mmol) in toluene (3.3 mL, 0.5 *M*) was heated to reflux under a blanket of N_2 for 45 min. After cooling to room temperature, the pale yellow reaction mixture was treated with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (0.040 g, 0.18 mmol). After 5 min, the crude, red reaction mixture was filtered through a silica plug and concentrated to afford a dark yellow solid. Flash silica gel chromatography (4:1 hexanes/EtOAc) furnished 0.032 g (72%) of **69** as a yellow crystalline solid: mp 168−170 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.28 (d, J = 1.0, 1H), 8.02 (d, J = 1.0, 1H), 7.51 (s, 1H), 4.52 (septet, J = 6.0, 1H), 4.09 (s, 3H), 4.04 (s, 3H), 2.58 (t, J = 7.0, 2H), 1.66 (quintet, J = 7.0, 2H), 1.56−1.48 (m, 5H), 1.43 (d, J = 6.5, 6H), 1.15 (d, J = 7.0, 18H), 0.95 (t, J = 7.0, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 183.0, 166.0, 156.0, 153.4, 138.3, 132.3, 131.2, 128.4, 125.1, 122.5, 119.8, 113.7, 111.7, 101.7, 76.0, 73.7, 61.4, 56.2, 30.9, 22.9, 22.2, 19.9, 18.6, 13.7, 10.8; IR (neat) 1631, 1577, 1562 cm^{-1}; HRMS (CI) calcd for $C_{33}H_{47}O_4Si$ (MH^+) 535.3243, found 535.3233.

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Supporting Information Available: Procedures and additional compound characterization data, X-ray data for compound **28**, copies of ^{1}H and ^{13}C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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