Intramolecular [4 + 3]-Cycloadditions of Photochemically Generated Oxyallyl Zwitterions: A Route to Functionalized Cyclooctanoid Skeletons[1]

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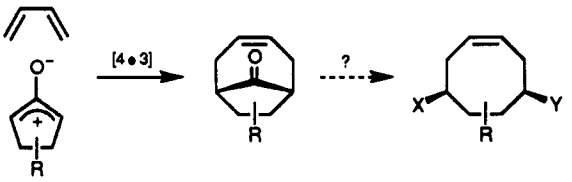
[4 + 3]-Cycloaddition of photochemically generated, 4-pyrone derived oxyallyl zwitterions and furans was examined as a potential approach to keto-bridged cyclooctenes. In one case, intermolecular cycloaddition proceeded to give adduct **3** with complete diastereoselectivity and in moderate yield, but the reaction was not general. Substrates **5a–i** were then prepared in one to three steps from either 3-methyl-4*H*-pyran-4-ones or 3-hydroxy-2-methyl-4*H*-pyran-4-one, and their viability in intramolecular [4 + 3]-cycloadditions was examined. Substrates **5a–e**, in which the tether was attached to the incipient zwitterion via a carbon, underwent cycloaddition to give [4 + 3]-cycloadducts **7** and **8** in varying yields, along with small amounts of cage compound **9**. In contrast, **5f–i**, in which the tether was attached to the incipient zwitterion via an oxygen, gave only solvent-trapping products **10**. In one case (**5e**), isomeric pyran-2-ones **11e/12e** were produced in addition to [4 + 3]-cycloadduct **8e** and cage compound **9e**. Moreover, it was found that **11e** and **12e** both underwent subsequent photochemical crossed [4 + 4]-cycloadditions to give lactone-bridged cyclooctadienes **13e** and **14e**. The structures of **11e/12e** and their [4 + 4]-cycloadducts were confirmed by synthesis of each of the 2-pyrones via alternative routes.

Introduction

The growing number of structurally interesting and biologically important natural products isolated which contain cyclooctane rings has prompted numerous approaches to the construction of this challenging skeleton.[2] Direct ring formation by closure of an acyclic precursor is usually disfavored[3] due to the significant entropic and enthalpic barriers to ring-closure. As a result, elegant indirect approaches involving fragmentation,[4] ring-expansion,[5] or other rearrangements[6] have been developed. Cyclooctanoid assembly via cycloaddition is an attractive mode of construction, and successful [4 + 4]-cycloadditions[7] and [6 + 2]-cycloadditions[8] are known. [4 + 3]-Cycloaddition of a 1,3-diene and an oxyallyl zwitterion constrained within a cyclopentane ring might also be considered to be a formal [4 + 4]-type construction, as it would yield a cyclooctene with a potentially cleavable one-carbon ketone bridge (eq 1).[9] We report here our preliminary results in this area.



(1)

We have found that bicyclic oxyallyl zwitterions **1** are readily generated from 4-pyrone precursors upon photolysis (Scheme I), and the appropriate internal nucleophile tethered at position 2 can then intercept the transient zwitterion to yield fused bi- and tricyclic products in good yield.[10] Given the known ability of oxyallyl zwitterions to participate as $2\pi e$ partners in concerted cycloadditions,[11] we sought to extend the trapping protocol to include diene moieties.[12,13] Such a process would involve the generation of three new carbon–carbon bonds and up to six stereocenters from simple achiral precursors. Intermolecular trapping using a large excess of furan was moderately

† All inquiries regarding crystallographic data should be directed to this author.

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(1) Presented in preliminary form: West, F. G.; Hartke-Karger, C. *Abstracts of Papers.* 203rd National Meeting of the American Chemical Society, San Fransisco, CA, April 1992; American Chemical Society: Washington, DC, 1992; ORGN 519.

(2) For a recent review of cyclooctanoid synthesis, see: Petasis, N. A.; Patane, M. A. *Tetrahedron* **1992**, *48*, 5757.

(3) (a) Mandolini, L. in *Adv. Phys. Org. Chem.* **1986**, *22*, pp. 1–111. (b) Illuminati, G.; Mandolini, L. *Acc. Chem. Res.* **1981**, *14*, 95. For exceptions, see: (c) Schreiber, S. L.; Sammakia, T.; Crowe, W. E. *J. Am. Chem. Soc.* **1986**, *108*, 3128. (d) Deslongchamps, P.; Roy, B. L. *Can. J. Chem.* **1986**, *64*, 2068. (e) McMurry, J. E.; Rico, J. G. *Tetrahedron Lett.* **1989**, *30*, 1169.

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(10) (a) West, F. G.; Fisher, P. V.; Willoughby, C. A. *J. Org. Chem.* **1990**, *55*, 5936. (b) West, F. G.; Fisher, P. V.; Arif, A. M. *J. Am. Chem. Soc.* **1993**, *115*, 1595. (c) West, F. G.; Willoughby, D. W. *J. Org. Chem.* **1993**, *58*, 3796.

(11) (a) Harmata, M.; Herron, B. F. *Tetrahedron Lett.* **1993**, *34*, 5381. (b) Harmata, M.; Fletcher, V. R.; Claassen, R. J., II. *J. Am. Chem. Soc.* **1991**, *113*, 9861. (c) Ohno, M.; Mori, K.; Hattori, T.; Eguchi, S. *J. Org. Chem.* **1990**, *55*, 6086. (d) Murray, D. H.; Albizati, K. F. *Tetrahedron Lett.* **1990**, *31*, 4109. Reviews: (e) Noyori, R.; Hayakawa, Y. *Org. React.* **1983**, *29*, 163. (f) Hoffmann, H. M. R. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 1. (g) Mann, J. *Tetrahedron* **1986**, *42*, 4611. (h) Hosomi, A.; Tominaga, Y. In *Comprehensive Organic Synthesis, Vol. 5: Combining C-C π-Bonds*, Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991, Chapter 5.1.

(12) For an earlier example of furan trapping of a 4-pyrone-derived oxyallyl zwitterion, see: Barltrop, J. A.; Day, A. C.; Samuel, C. J. *J. Am. Chem. Soc.* **1979**, *101*, 7521.

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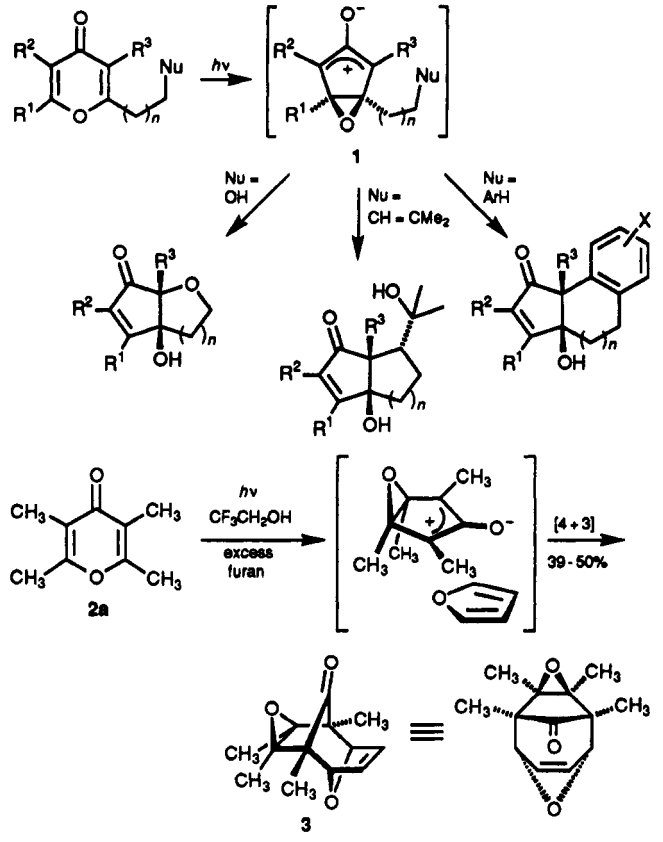
Scheme I

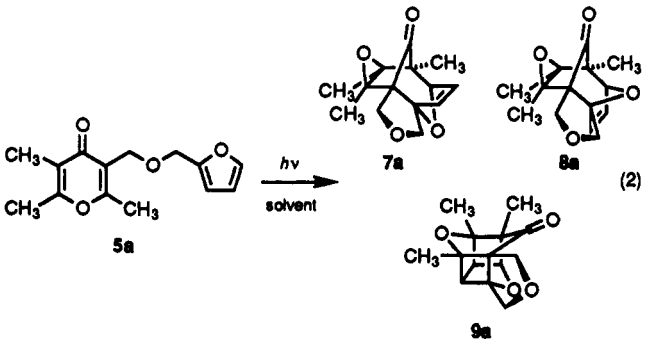


effective in the case of 2,3,5,6-tetramethyl-4*H*-pyran-4-one (**2a**), yielding cycloadduct **3** as a single diastereomer in modest yield. The structure of **3** was confirmed by X-ray diffraction analysis,[14] and it derives from approach of the diene and the zwitterion in an "endo" or "compact" transition state.[11e] However, the reaction was complicated by furan-derived photochemistry and could not be generalized to other 4-pyrone and diene partners. Our previous success with intramolecular nucleophilic trapping[10] suggested that a tethered diene might be more effective in intercepting the short-lived zwitterion before it could suffer alternative nonproductive rearrangements.

Results and Discussion

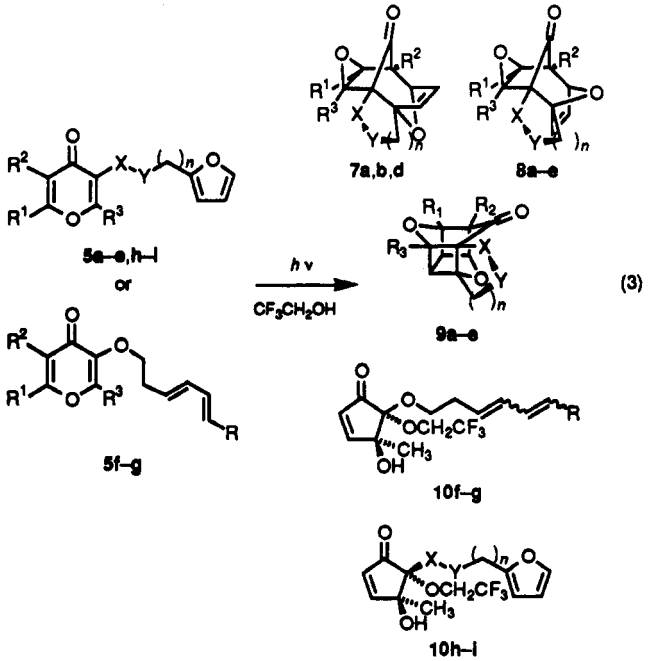
Attachment of a diene containing tether at position 3 of 4-pyrone starting materials required the presence of an appropriate functionality handle. Two complementary approaches proved to be successful (Scheme II). A brief sequence utilizing simple 3-methyl-4-pyrones **2a–c** could be employed. Radical bromination at the C-3 methyl, followed by displacement with furyl-substituted nucleophiles such as furfuryl alcohol or 1,1-bis(phenylsulfonyl)-2-(2′-furyl)ethane (**4**) under phase-transfer catalysis gave unsymmetrical ethers **5a,c,d** or the corresponding bis(sulfones), which could be reduced with Na(Hg) to give **5b,e**. Alternatively, the readily available 3-hydroxy-4-pyrone **2d** could be easily alkylated at the hydroxyl group with diene containing electrophiles **6a–e** to yield substrates **5f–i**.

With substrates **5a–i** in hand, we sought to examine a variety of photolysis conditions using ether **5a** as a test case (eq 2). In analogy to earlier studies,[10] we found that



nonpolar organic solvents such as CH_2Cl_2 were unsuitable due to inefficient formation of zwitterion. Irradiation in dilute aqueous solutions or methanol (Table I) led to a mixture consisting of the desired cycloadducts **7a** and **8a** in low yields, along with apparent solvent capture products[12,15] (*vide infra*) and cage structure **9a**, which presumably arises from two sequential intramolecular photochemical [2+2]-cycloadditions.[16] Isomers **7a** and **8a** were distinguished by, *inter alia*, the upfield shift of the epoxide methyls in **8a** as a result of their proximity to the dihydrofuran π system. Assignments were confirmed by single-crystal X-ray diffraction analysis.[14] Optimum results were obtained using either trifluoroethanol or acetonitrile containing 1.0 M $LiClO_4$[17] as solvent.

Photocycloaddition results for all substrates under standard conditions (eq 3) are shown in Table II. It is



(13) For similar [4 + 3]-cycloadditions involving oxyallyl zwitterions derived photochemically from cross-conjugated dienones, see: (b) Schultz, A. G.; Macielag, M.; Plummer, M. *J. Org. Chem.* **1988**, *53*, 391. (c) Samuel, C. J. *J. Chem. Soc., Perkin Trans. 2* **1981**, 736. (d) Chapman, O. L.; Clardy, J. C.; McDowell, T. L.; Wright, H. E. *J. Am. Chem. Soc.* **1973**, *95*, 5086. (e) Crandall, J. K.; Haseltine, R. P. *J. Am. Chem. Soc.* **1968**, *90*, 6251.

(14) The authors have deposited atomic coordinates for **3**, **7a**, and **8a** with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.

(15) West, F. G.; Fisher, P. V.; Gunawardena, G. U.; Mitchell, S. *Tetrahedron Lett.* **1993**, *34*, 4583.

(16) Analogous intermolecular 4-pyrone photodimerizations are well precedented: Yates, P.; Jorgensen, M. J. *J. Am. Chem. Soc.* **1963**, *85*, 2956 and references cited therein.

(17) For discussions of the unique properties of ethereal and other solutions of $LiClO_4$, see: (a) Kaiser, R.; Föhlisch, B. *Helv. Chim. Acta* **1990**, *73*, 1504. See also: (b) Grieco, P. A. *Aldrichim. Acta* **1991**, *24*, 59. (c) Waldmann, H. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1306.

Scheme II

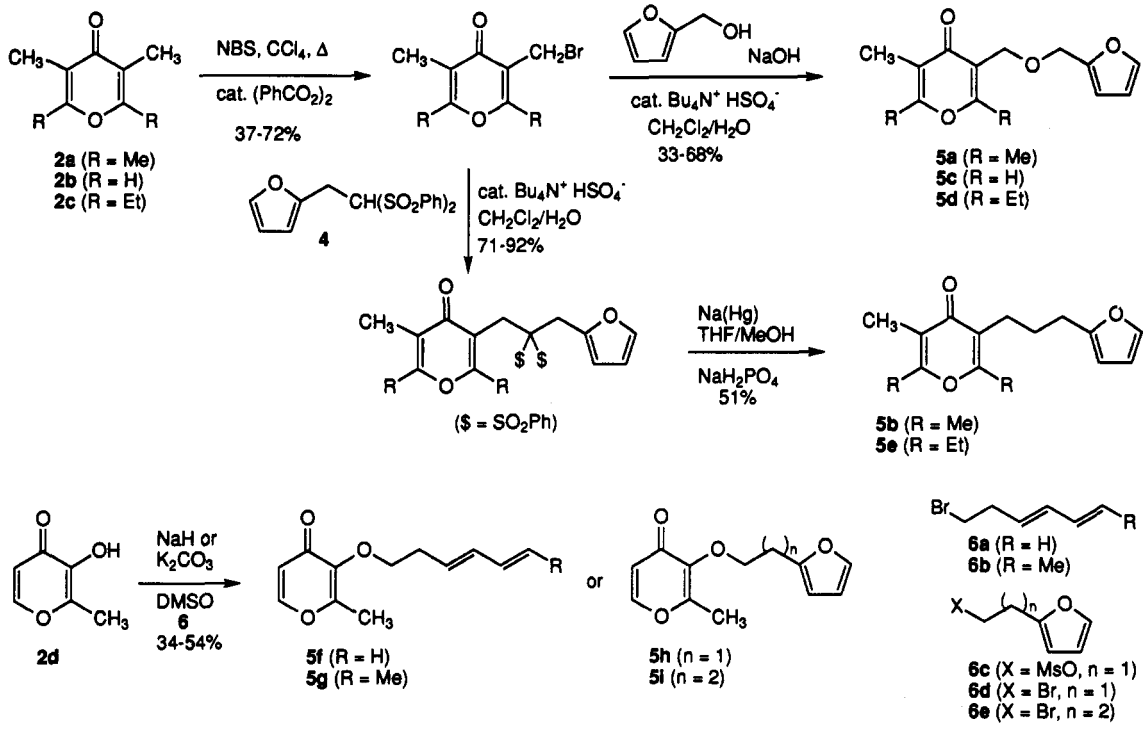


Table I. Effect of Solvent on Photocycloaddition of 5a[a]

solvent	yield of 7a[b] (%)	yield of 8a[b] (%)	yield of 9a[b] (%)
CH_2Cl_2			10
H_2O	12	14	4
MeOH	10		15
CH_3CN	5	5	14
$CH_3CN/LiClO_4$[c]	25	25	10
CF_3CH_2OH	30	20	5

[a] See eq 2. Standard conditions: Substrate was dissolved in solvent (2–4 mM), and the solution was deoxygenated by bubbling with dry N_2 and then irradiated (Vycor) for 1–2 h. [b] Isolated yields after chromatography. Satisfactory IR, ^1H and ^{13}C NMR, and HRMS or combustion analyses were obtained on 5–9. [c] Dry $LiClO_4$ (1.0 M) in CH_3CN.

interesting to note that while the intermolecular case cited above yielded only the endo diastereomer, endo/exo mixtures were seen in nearly all intramolecular cases. We imagine that this erosion of the inherent endo selectivity may arise from unfavorable steric interactions in the endo transion state between the tether and the alkyl substituent at C-2 (Figure 1). There also appears to be significant requirement for extensive alkyl substitution about the pyrone ring, in contrast to our earlier results with nucleophilic trapping. Overall, **5a–e** are converted into cycloadducts **7a–e** and **8a–e**, in which three new carbon–carbon bonds, several new rings, and six new contiguous stereocenters have been formed from simple linked pairs of heterocycles. The modest chemical yields are largely mitigated by the substantial increase in molecular complexity[18] which is created in the cycloadditions.

Surprisingly, O-tethered substrates **5f–i** did not yield any cycloadduct, producing instead mixed ketals **10f–i** in good yield, with concurrent diene cis/trans isomerization for **10f–g**. We had reasoned that the presence of an oxygen substituent on the intermediate zwitterion would confer additional stability, permitting efficient diene trapping. Rapid consumption of **5f–i** and clean formation of solvent adducts **10f–i** suggest that while zwitterion formation may be enhanced, reaction via ionic pathways dominates over cycloaddition, perhaps as a result of the polarizing effect of the ether substituent on one terminus.

In the case of **5e**, significant quantities of 2-pyrones **11e** and **12e** were isolated (Scheme III). These compounds presumably arose via the known[12a,19] competing rearrangement of the zwitterion intermediates to epoxycyclopentenones, followed by conversion to the isomeric 2-pyrones via secondary photochemistry. More interesting was the isolation of another minor product ultimately identified as lactone-bridged cyclooctadiene **13e**. This product was presumed to arise from an intramolecular crossed photochemical [4 + 4]-cycloaddition between the 2-pyrone and the furan moieties of **11e** following rearrangment from 4-pyrone to 2-pyrone. Intermolecular [4 + 4]-photodimerization of 2-pyrones is precedented,[20] as is intramolecular [4 + 4]-cycloaddition of linked bis(pyridones).[6b] Recent studies in our laboratories have confirmed that related 2-pyrones bearing pendant furans undergo efficient photocycloaddition.[7c] Interestingly, although 2-pyrone **12d** was isolated from the photolysis of **5d**, none of the corresponding [4 + 4]-adduct was seen.

Careful irradiation of a mixture of **11e** and **12e** until consumption of **11e** led to a mixture of unconsumed **12e**, **13e**, and traces of a second apparent [4 + 4]-cycloadduct assigned as **14e** (eq 4). This result provided indirect evidence that **13e** arose from **11e**. However, the isomeric 2-pyrones and their photocycloadducts could not initially be rigorously distinguished, since the photochemically generated mixture of **11e** and **12e** was inseparable. In addition, [4 + 4]-cycloadducts **13e** and **14e** were not formed in sufficient quantity to completely rule out diastereomeric structures **13e′** and **14e′**. Preliminary assignment as the

(18) Bertz, S. H. *J. Am. Chem. Soc.* **1982**, *104*, 5801.

(19) (a) Pavlik, J. W.; Kwong, J. *J. Am. Chem. Soc.* **1973**, *95*, 7914. (b) Ishibe, N.; Sunami, M.; Odani, M. *J. Am. Chem. Soc.* **1973**, *95*, 463. (c) Padwa, A.; Hartman, *J. Am. Chem. Soc.* **1966**, *88*, 1518.

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Table II. Effect of Ring Substituents, Tether, and Diene Trap[a]

substrate	R^1	R^2	R^3	X	Y	n	R	yield of 7[b] (%)	yield of 8[b] (%)	yield of 9[b] (%)	yield of 10[b] (%)
5a	Me	Me	Me	CH_2	O	1		30	20	5	
5b	Me	Me	Me	CH_2	CH_2	1		17[c]	52[c]	5[c]	
5c	H	Me	H	CH_2	O	1			10[c]	15[c]	
5d	Et	Me	Et	CH_2	O	1		19[d]	19[d]	10[d]	
5e	Et	Me	Et	CH_2	CH_2	1			27[c,d]	5[c,d]	
5f	H	H	Me				H				66
5g	H	H	Me				Me				67
5h	H	H	Me	O	CH_2	1					58
5i	H	H	Me	O	CH_2	2					58

[a] See eq 3. Standard conditions: Substrate was dissolved in trifluoroethanol (2–4 mM), and the solution was deoxygenated by bubbling with dry N_2 and then irradiated (Vycor) for 1–2 h. [b] Isolated yields after chromatography. Satisfactory IR, ^1H and ^{13}C NMR, and HRMS or combustion analyses were obtained on **5–13**. [c] Starting material also recovered in the case of **5b** (16%), **5c** (11%), and **5e** (18%). [d] Pyran-2-one **12d** (19%), pyran-2-ones **11e** and **12e** (18% combined yield), and [4 + 4]-cycloadduct **13e** (4%) were also isolated. See Scheme III.

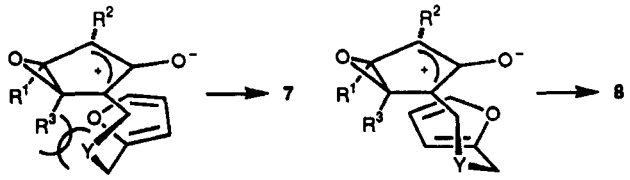
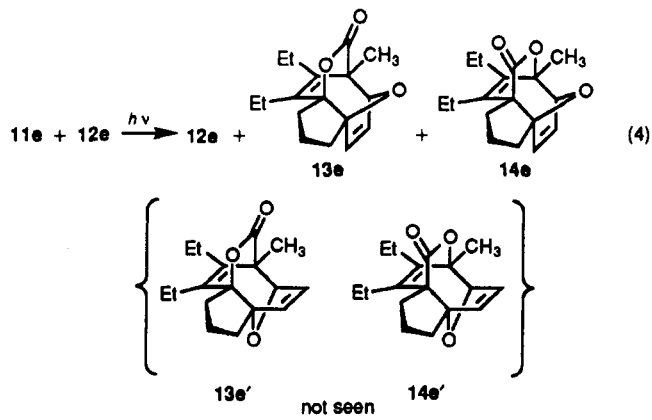


Figure 1. Endo (compact) and exo transition states for intramolecular [4 + 3]-cycloadditions.

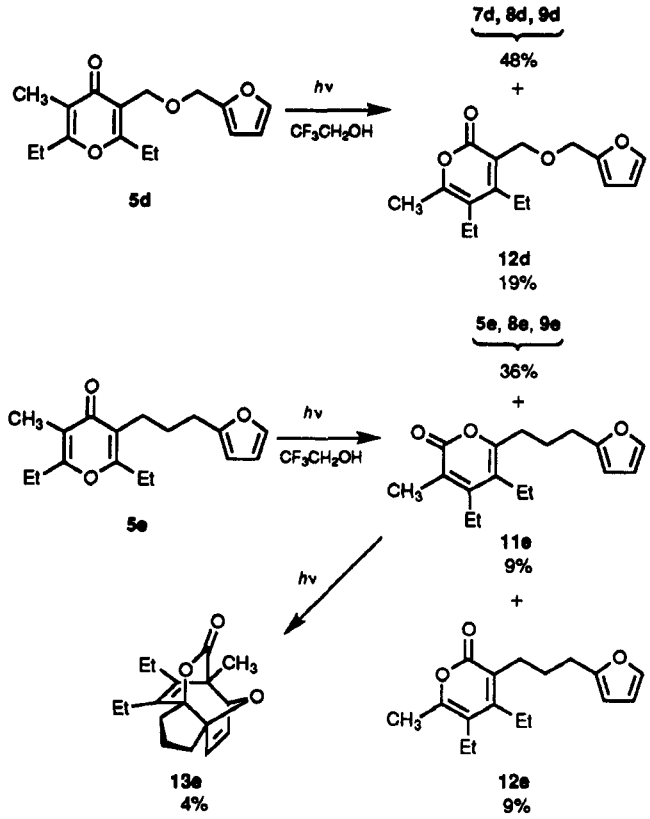
endo diastereomers was based on spectral analogy to structurally related 2-pyrone/furan [4 + 4]-cycloadducts.[7c]



Ultimately, the structures of **11e** and **12e** were determined by independent synthesis of each isomer via nonphotochemical routes (Scheme IV). 3,5-Diethyl-2,6-dimethylpyran-4-one (**2c**) could be converted to 4,5-diethyl-3,6-dimethylpyran-2-one (**15**) in gram quantities via photochemical rearrangement in trifluoroethanol. Radical bromination of **15** gave an inseparable mixture of isomeric bromomethyl pyrones **16** and **17**, which underwent displacement by bis(sulfone) **4** under phase-transfer catalysis to give separable adducts **18** and **19**. Reductive desulfonylation of **19** with sodium amalgam gave **12e** in modest yield, but the analogous transformation of **18** to **11e** could not be effected. Fortunately, **11e** could be obtained, albeit in low yield, by metalation of **15** followed by alkylation with bromide **6d**.

Irradiation of pure **11e** led cleanly to endo [4 + 4]-cycloadduct **13e**, with traces of a second isomer, presumed to be exo [4 + 4]-cycloadduct **13e'** (Scheme V). In contrast to earlier studies,[7c] [2 + 2]-adduct **20e** was not isolated. However, it could be formed as the minor component in an equilibrium mixture via cyclooctadiene/divinylcyclobutane [3,3]-sigmatropic shift upon warming **13e** in toluene, thus confirming the endo stereochemical assignment for **13e**. Irradiation of **12e** gave a 2:1 mixture of [4 + 4]-cycloadducts, assigned as **14e/14e'**, but consumption of the starting 2-pyrone required substantially longer irradiation times.

Scheme III



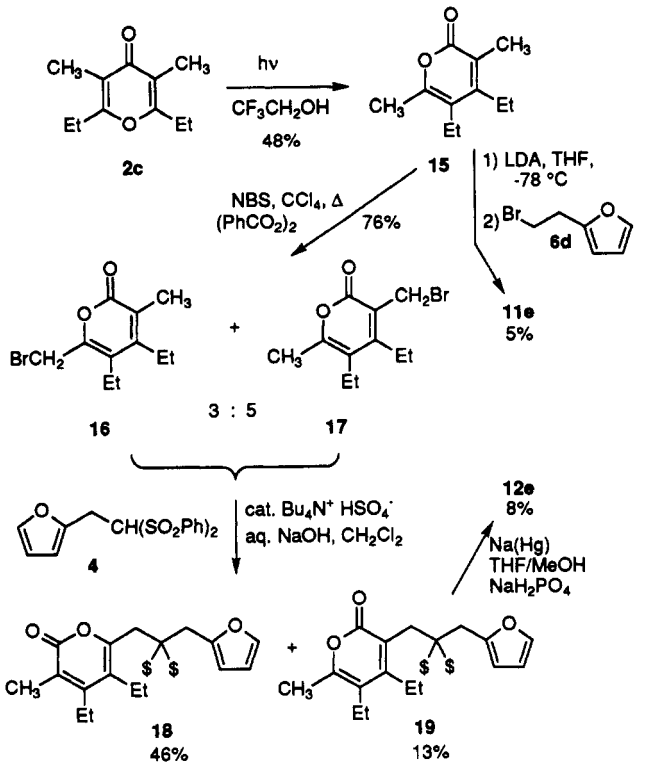
Conclusions

In summary, we have reported a new class of reactions involving intramolecular cycloaddition between photochemically generated 5-membered oxyallyl zwitterions and pendant furans. This transformation can be considered to be a formal [4 + 4]-type construction between the four diene carbons and four of the carbons of the cyclic zwitterions, generating a keto-bridged cyclooctene. The efficiency of the process is quite sensitive to substitution on the pyran-4-one ring, particularly the presence of an ether oxygen at C-3. In one case, pyran-2-one secondary photoproducts underwent further photochemical conversion to [4 + 4]-cycloadducts **13e** and **14e**. Further work involving subsequent elaboration of the highly functionalized cycloadducts will be reported elsewhere.

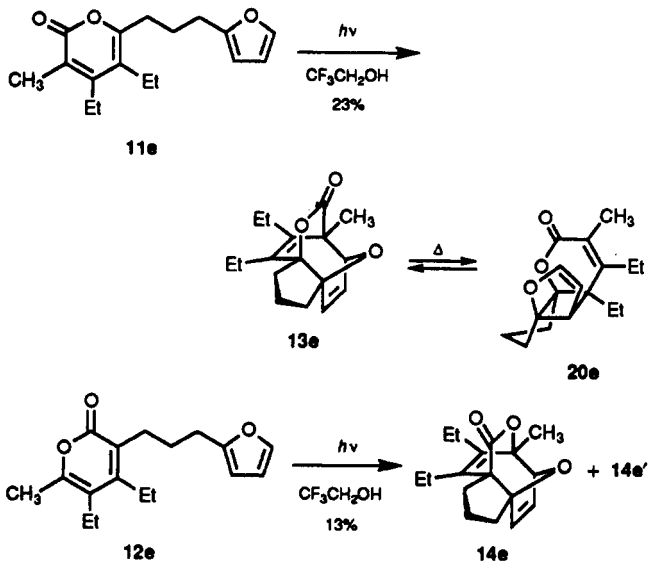
Experimental Section

General. Reactions were conducted in oven-dried (120 °C) or flame-dried glassware under a positive nitrogen atmosphere unless otherwise stated. Photolyses were carried out using an

Scheme IV



Scheme V



Ace-Hanovia photochemical reactor equipped with a 450-W medium-pressure Hg lamp in a water-cooled quartz jacket and a Vycor filter sleeve. Small-scale reactions were performed in quartz tubes placed approximately 10 cm from the lamp, and large-scale reactions were carried out using an immersion well. Reaction mixtures were deoxygenated with slow bubbling of dry N_2 for 20–30 min.

Thin layer chromatography (TLC) was performed on plates of silica precoated with 0.25-mm Kieselgel 60 F_{254} (Merck). Medium-pressure liquid chromatography (MPLC) was carried out using Ace Michel–Myers columns and an FMI pump (Model QSY), with detection at 254 nm using an ISCO UA-5 detector. Flash chromatography and MPLC columns were packed with 230–400-mesh silica gel (Merck or Baxter). All solvents were distilled before use. Melting points were obtained on a Thomas-Hoover apparatus in open capillary tubes and are uncorrected.

Proton nuclear magnetic resonance spectra (^{1}H NMR) were recorded on Varian XL-300 or Unity-300 (300 MHz) instruments. The chemical shifts are reported on the δ scale (ppm) downfield from tetramethylsilane. Coupling constants (J) are reported in hertz (Hz). Carbon nuclear magnetic resonance spectra (^{13}C NMR) were obtained at 75 MHz on Varian XL-300 or Unity-300 instruments and are reported (ppm) relative to the center line of a triplet at 77.0 ppm for deuteriochloroform. Infrared (IR) spectra were measured with Perkin-Elmer 298 or Mattson FTIR 3000 infrared spectrophotometers. Mass spectra were determined on a Finnigan MAT 95 high-resolution gas chromotograph/mass spectrometer with Finnigan MAT ICIS II operating system.

Intermolecular Cycloadduct 3. 2,3,5,6-Tetramethyl-4*H*-pyran-4-one[21] (**2a**) (152 mg, 1.0 mmol) was dissolved in a mixture of dry trifluoroethanol (30 mL) and furan (30 mL) in a 75-mL quartz tube, and dry N_2 gas was bubbled through the solution for 20 min. The reaction mixture was irradiated using a 450-W medium-pressure Hg lamp fitted with a corex sleeve in a quartz cooling jacket until the pyrone starting material was consumed (7 h). After removal of solvent under reduced pressure, the crude product was purified by flash chromatography (silica gel, hexanes/EtOAc (90:10)) to give 85 mg (39%) of **3** as a pale yellow crystalline solid (X-ray quality crystals could be obtained by recrystallization from hexanes.): mp 139–141 °C; R_f 0.30 (hexanes/EtOAc (70:30)); IR 1730 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.30 (s, 2H), 4.45 (s, 2H), 1.40 (s, 6H), 1.02 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 206.2, 135.2, 84.6, 69.3, 60.3, 10.4, 8.0. Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.77; H, 7.38.

3-[[(2′-Furyl)methoxy]methyl]-2,5,6-trimethyl-4*H*-pyran-4-one (5a). 2,3,5,6-Tetramethyl-4*H*-pyran-4-one (**2a**) (1.20 g, 7.9 mmol) and dry *N*-bromosuccinimide (NBS, 1.55 g, 8.7 mmol) were dissolved in dry CCl_4 (20 mL). Benzoyl peroxide (45 mg) was added, and the mixture was heated at reflux for 2 h. After being cooled to rt, the mixture was filtered through glass wool and the filtrate concentrated. The crude product was purified by MPLC (silica gel, hexanes/CH_2Cl_2/Et_2O (80:15:5)) to give 1.3 g (72%) of 3-(bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one, along with 105 mg (4%) of 3,5-bis(bromomethyl)-2,6-dimethyl-4*H*-pyran-4-one, 65 mg (3%) of 2-(bromomethyl)-3,5,6-trimethyl-4*H*-pyran-4-one, and 140 mg (12%) of recovered starting material. 3-(Bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one (crystalline solid): mp 82–84 °C; R_f 0.38 (hexanes/Et_2O/CH_2Cl_2 (2:2:1)); IR (KBr) 3043, 1658, 1610, 1425 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.39 (s, 2H), 2.35 (s, 3H), 2.27 (s, 3H), 1.95 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.4, 163.9, 160.6, 120.2, 119.9, 23.8, 17.7, 17.6, 9.9. Anal. Calcd for $C_9H_{11}O_2Br$: C, 46.78; H 4.80. Found: C, 46.87; H, 4.77. 3,5-Bis(bromomethyl)-2,6-dimethyl-4*H*-pyran-4-one (crystalline solid): mp 123–124 °C; R_f 0.28 (hexanes/Et_2O/CH_2Cl_2 (2:2:1)); IR (KBr) 2980, 2922, 1659, 1622, 1423, 1199 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.34 (s, 4H), 2.35 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.1, 164.8, 121.6, 22.7, 17.6. 2-(Bromomethyl)-3,5,6-trimethyl-4*H*-pyran-4-one (crystalline solid): mp 69–70 °C; R_f 0.44 (hexanes/Et_2O/CH_2Cl_2 (2:2:1)); IR (KBr) 2986, 2926, 1659, 1607, 1433, 1194 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.24 (s, 2H), 2.28 (s, 3H), 1.98 (s, 3H), 1.92 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.1, 160.8, 157.0, 120.9, 119.6, 25.5, 17.7, 9.9, 9.6.

3-(Bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one (1.0 g, 4.3 mmol) was dissolved in CH_2Cl_2 (6 mL) and the solution cooled to 0 °C. Furfuryl alcohol (0.43 mL, 5.0 mmol) was added, followed by 6.25 M aqueous NaOH (4.0 mL) and tetrabutylammonium hydrogen sulfate (85 mg, 0.25 mmol), and the resulting two-phase mixture was stirred vigorously for 6 h at 0 °C. The reaction was poured into saturated aqueous NH_4Cl (10 mL), and the aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were washed with water and dried ($MgSO_4$), and the solvent was removed. The resulting material was passed through a short plug of basic alumina (CH_2Cl_2/Et_2O (1:1)) and then purified by MPLC (silica gel, hexanes/CH_2Cl_2/Et_2O (12:7:1)) to give 650 mg (50%) of **5a** as colorless needles: mp 67 °C; R_f 0.35 (Et_2O/CH_2Cl_2/hexanes (12:5:3)); IR (KBr) 3134, 3113, 2947, 2918, 2874, 2843, 1668, 1610, 1433 cm^{-1}; UV (MeOH) λ_{max} 262 nm (10^{-5} M; ϵ 4960); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40–7.39 (m, 1H), 6.36–6.33 (m, 2H), 4.49 (s, 2H), 4.45 (s, 2H), 2.30 (s, 3H), 2.25 (s, 3H), 1.93 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.1, 164.9, 160.3, 151.7, 142.5, 119.8, 119.3, 110.1, 109.2, 64.2, 61.6, 17.7, 17.5, 10.0. Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.49. Found: C, 67.80; H, 6.48.

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2,2-Bis(phenylsulfonyl)-1-(2′-furyl)ethane (4). Sodium borohydride (265 mg, 7.0 mmol) was added to a 0 °C suspension of 2,2-bis(phenylsulfonyl)-1-(2′-furyl)ethene[22] (2.58 g, 6.89 mmol; prepared by condensation of bis(phenylsulfonyl)methane with 2-furaldehyde) in methanol (50 mL). The mixture was warmed to rt and stirred for 1 h. The resulting clear, colorless solution was poured into saturated NH_4Cl solution (50 mL), and the aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL). The combined organic layers were dried ($MgSO_4$) and evaporated, and the residue was recrystallized from EtOH to give 2.58 g (99%) of 4 as colorless needles: mp 119 °C; IR (KBr) 3078, 2937, 1323, 1151 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.90–7.51 (m, 10H), 7.10 (dd, J = 1.9, 0.7 Hz, 1H), 6.17 (dd, J = 3.2, 1.9 Hz, 1H), 6.00 (dd, J = 3.2, 0.7 Hz, 1H), 4.95 (t, J = 6.3 Hz, 1H), 3.60 (d, J = 6.2 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.8, 141.9, 138.0, 134.5, 129.4, 129.1, 110.7, 108.3, 81.6, 24.9. Anal. Calcd for $C_{18}H_{16}O_5S_2$: C, 57.43; H, 4.29. Found: C, 57.53; H, 4.30.

3-[3-(2′-Furyl)propyl]-2,5,6-trimethyl-4*H*-pyran-4-one (5b). 3-(Bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one (693 mg, 3.00 mmol) was dissolved in CH_2Cl_2 (5 mL), the solution was cooled to 0 °C, and 4 (1.13 g, 3.00 mmol), a solution of NaOH (0.60 g, 15 mmol) in water (2.5 mL), and tetrabutylammonium hydrogen sulfate (85 mg, 0.25 mmol) were added. The resulting mixture was stirred vigorously at rt in the dark for 12 h. The mixture was poured into saturated NH_4Cl solution (5 mL), and the aqueous layer was extracted with CH_2Cl_2 (3 × 5 mL). The combined organic layers were washed with water (10 mL), dried ($MgSO_4$), and evaporated, and the crude product was purified by MPLC (silica gel, hexanes/CH_2Cl_2/Et_2O (16:3:1)) to give 1.26 g (92%) of 3-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)propyl]-2,5,6-trimethyl-4*H*-pyran-4-one as colorless needles: mp 177 °C dec; R_f 0.42 (Et_2O/CH_2Cl_2/hexanes (12:5:3)); IR (KBr) 3155, 3101, 2993, 1658, 1612, 1143 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87–7.42 (m, 10H), 7.25 (dd, J = 1.9, 0.8 Hz, 1H), 6.47 (dd, J = 3.3, 0.8 Hz), 6.18 (dd, J = 3.3, 1.9 Hz, 1H), 4.01 (s, 2H), 3.49 (s, 2H), 2.44 (s, 3H), 2.25 (s, 3H), 1.80 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.4, 165.4, 160.2, 147.3, 141.0, 138.0, 134.0, 131.1, 128.3, 119.1, 117.4, 111.9, 111.0, 91.3, 31.1, 28.1, 19.3, 17.6, 10.0. Anal. Calcd for $C_{27}H_{26}O_7S_2$: C, 61.58; H, 4.98. Found: C, 61.64; H, 5.02.

3-[3-(2′-Furyl)-2,2-bis(phenylsulfonyl)propyl]-2,5,6-trimethyl-4*H*-pyran-4-one (950 mg, 1.80 mmol) was dissolved in dry THF (30 mL), and then MeOH (30 mL) and NaH_2PO_4 (1.7 g, 14.4 mmol) were added. Sodium amalgam (5%, 6.4 g, 14 mmol) was added in portions over 6 h with vigorous stirring. The remaining Hg was filtered, the filtrate was concentrated, and the residue was dissolved in CH_2Cl_2 (25 mL). The resulting solution was washed with saturated NH_4Cl (3 × 10 mL) and water (10 mL), dried ($MgSO_4$), and evaporated, and the crude product was purified by MPLC (silica gel, hexanes/CH_2Cl_2/Et_2O (14:5:1)) to give 226 mg (51%) of **5b** as a colorless crystalline solid: mp 36–37 °C; R_f 0.48 (Et_2O/CH_2Cl_2/hexanes (12:5:3)); IR (KBr) 3105, 2935, 1662, 1597, 1431, 1182 cm^{-1}; UV (MeOH) λ_{max} 264 nm (10^{-5} M; ε 8060); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28 (dd, J = 1.8, 0.8 Hz, 1H), 6.26 (dd, J = 3.1, 1.9 Hz, 1H), 6.02 (dd, J = 3.1, 0.8 Hz, 1H), 2.67 (t, J = 7.4 Hz, 2H), 2.45 (t, J = 7.8 Hz, 2H), 2.24 (s, 3H), 2.20 (s, 3H), 1.92 (s, 3H), 1.83–1.78 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.8, 160.5, 160.0, 155.9, 140.5, 122.6, 119.1, 110.0, 104.8, 27.8, 26.6, 24.2, 17.6, 17.3, 9.9. Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.36. Found: C, 73.30; H, 7.39.

3-[[(2′-Furyl)methoxy]methyl]-5-methyl-4*H*-pyran-4-one (5c). The procedure outlined above for the preparation of 3-(bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one was carried out using 3,5-dimethyl-4*H*-pyran-4-one[23] (**2b**) (515 mg, 4.15 mmol) and dry NBS (812 mg, 4.56 mmol) to give 478 mg (57%) of 3-(bromomethyl)-5-methyl-4*H*-pyran-4-one, along with 109 mg (9%) of 3,5-bis(bromomethyl)-4*H*-pyran-4-one and 140 mg (27%) of recovered starting material. 3-(Bromomethyl)-5-methyl-4*H*-pyran-4-one (colorless crystalline solid): mp 118 °C; R_f 0.32 (hexanes/CH_2Cl_2/Et_2O (3:5:2)); IR (KBr) 3068, 3032, 2984, 1651, 1620, 1323 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.97 (s, 1H), 7.68 (s, 1H), 4.28 (s, 2H), 1.97 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.0, 154.8, 152.0, 125.8, 125.2, 23.1, 10.8. Anal. Calcd for $C_7H_7O_2Br$: C, 41.41; H 3.48. Found: C, 41.50; H, 3.47. 3,5-Bis(bromomethyl)-4*H*-pyran-4-one (colorless crystalline solid): mp 101–102 °C; R_f 0.38 (hexanes/CH_2Cl_2/Et_2O (3:5:2)); IR (KBr) 3076, 3040, 1655, 1620, 1325 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.99 (s, 2H), 4.25 (s, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.5, 155.1, 126.4, 22.3. Anal. Calcd for $C_7H_6O_2Br_2$: C, 29.82; H, 2.15. Found: C, 29.92; H, 2.18.

3-(Bromomethyl)-5-methyl-4*H*-pyran-4-one (450 mg, 2.22 mmol) was subjected to the procedure described above for the preparation of **5a** to give 330 mg (68%) of **5c** as colorless needles: mp 94 °C; R_f 0.21 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (KBr) 3142, 3111, 2868, 1656, 1604, 1091 cm^{-1}; UV (MeOH) λ_{max} 260 nm (10^{-5} M; ε 4700); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.85 (s, 1H), 7.68 (s, 1H), 7.42–7.41 (m, 1H), 6.38–6.34 (m, 2H), 4.57 (s, 2H), 4.43 (s, 2H), 1.93 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.0, 153.1, 151.7, 151.2, 143.0, 125.0, 125.0, 110.3, 109.7, 65.0, 63.6, 10.8. Anal. Calcd for $C_{12}H_{12}O_4$: C, 65.45; H, 5.49. Found: C, 65.53; H, 5.47.

2,6-Diethyl-3-[[(2′-furyl)methoxy]methyl]-5-methyl-4*H*-pyran-4-one (5d). The procedure outlined above for the preparation of 3-(bromomethyl)-2,5,6-trimethyl-4*H*-pyran-4-one was carried out using 2,6-diethyl-3,5-dimethyl-4*H*-pyran-4-one[24] (**2c**) (1.08 g, 6.00 mmol) and dry NBS (1.17 g, 6.60 mmol) to give 580 mg (37%) of 3-(bromomethyl)-2,6-diethyl-5-methyl-4*H*-pyran-4-one, along with 750 mg (48%) of 2-(1′-bromoethyl)-6-ethyl-3,5-dimethyl-4*H*-pyran-4-one and 260 mg (17%) of recovered starting material. 3-(Bromomethyl)-2,6-diethyl-5-methyl-4*H*-pyran-4-one (colorless crystalline solid): mp 70 °C; R_f 0.50 (hexanes/Et_2O/CH_2Cl_2 (3:2:5)); IR (KBr) 2968, 2876, 1655, 1610, 1431, 1417 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.41 (s, 2H), 2.71 (q, J = 7.6 Hz, 2H), 2.62 (q, J = 7.6 Hz, 2H), 2.01 (s, 3H), 1.31 (t, J = 7.6 Hz, 3H), 1.24 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.3, 168.1, 165.0, 119.5, 119.1, 24.8, 24.7, 23.3, 11.2, 11.0, 9.4. Anal. Calcd for $C_{11}H_{15}O_2Br$: C, 50.98; H 5.83. Found: C, 51.09; H, 5.80. 2-(1′-Bromoethyl)-6-ethyl-3,5-dimethyl-4*H*-pyran-4-one (crystalline solid): mp 57–58 °C; R_f 0.37 (hexanes/Et_2O/CH_2Cl_2 (3:2:5)); IR (KBr) 2986, 2828, 1651, 1609, 1422, 1084 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.51 (q, J = 7.0 Hz, 1H), 2.60 (q, J = 7.4 Hz, 2H), 1.93 (s, 3H), 1.90 (d, J = 6.7 Hz, 3H), 1.89 (s, 3H), 1.21 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.5, 164.6, 159.5, 118.5, 118.2, 40.6, 24.7, 22.2, 11.2, 9.5, 9.2.

3-(Bromomethyl)-2,6-diethyl-5-methyl-4*H*-pyran-4-one (311 mg, 1.20 mmol) was subjected to the procedure described above for the preparation of **5a** to give 90 mg (33%) of **5d** as a colorless oil: R_f 0.37 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2978, 2939, 1658, 1618, 1425 cm^{-1}; UV (MeOH) λ_{max} 264 nm (10^{-5} M; ε 5090); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.85 (s, 1H), 7.39–7.38 (m, 1H), 6.36–6.33 (m, 2H), 4.50 (s, 2H), 4.46 (s, 2H), 2.63 (q, J = 7.6 Hz, 2H), 2.59 (q, J = 7.5 Hz, 2H), 1.94 (s, 3H), 1.22 (t, J = 7.5 Hz, 3H), 1.21 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.8, 169.3, 164.8, 151.9, 142.6, 119.0, 118.4, 110.2, 109.3, 64.2, 61.3, 24.7, 24.6, 11.6, 11.2, 9.4. Anal. Calcd for $C_{16}H_{20}O_4$: C, 69.55; H, 7.29. Found: C, 69.49; H, 7.20.

2,6-Diethyl-3-[3-(2′-furyl)propyl]-5-methyl-4*H*-pyran-4-one (5e). 3-(Bromomethyl)-2,6-diethyl-5-methyl-4*H*-pyran-4-one (400 mg, 1.54 mmol) was subjected to the procedure described above for **5b** to give 395 mg (71%) of 2,6-diethyl-3-[3-(2′furyl)-2,2-bis(phenylsulfonyl)propyl]-5-methyl-4*H*-pyran-4-one as colorless needles: mp 159 °C dec; R_f 0.34 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (KBr) 2976, 2941, 1655, 1612, 1143 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.86–7.43 (m, 10H), 7.28–7.27 (m, 1H), 6.49 (d, J = 3.3 Hz), 6.19 (dd, J = 3.3, 1.9 Hz, 1H), 4.04 (s, 2H), 3.50 (s, 2H), 2.85 (q, J = 7.6 Hz, 2H), 2.60 (q, J = 7.6 Hz, 2H), 1.80 (s, 3H), 1.24 (t, J = 7.6 Hz, 3H), 1.22 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 180.0, 169.2, 164.5, 147.5, 141.1, 138.1, 134.1, 131.2, 128.4, 118.2, 116.5, 112.0, 111.1, 91.5, 31.1, 27.3, 25.5, 24.6, 11.3, 11.2, 9.5; HRMS calcd for $C_{23}H_{25}O_5S$ [(M - SO_2Ph)$^+$] m/e 413.1423, found m/e 413.1401.

2,6-Diethyl-3-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)propyl]-5-methyl-4*H*-pyran-4-one (395 mg, 0.713 mmol) was subjected to the Na(Hg) conditions described above for **5b** to give 100 mg (51%) of **5e** as a colorless oil: R_f 0.37 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2976, 2939, 1658, 1612, 1421 cm^{-1}; UV (MeOH) λ_{max} 264 nm (10^{-5} M; ε 8790); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.27–7.26 (m, 1H), 6.27 (dd, J = 3.1, 1.9 Hz, 1H), 6.03 (dd, J = 3.1, 0.8

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Hz, 1H), 2.71–2.44 (m, 8H), 1.94 (s, 3H), 1.84–1.74 (m, 2H), 1.22 (t, J = 7.6 Hz, 3H), 1.21 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.4, 164.8, 164.4, 156.0, 140.6, 121.7, 118.1, 110.0, 104.8, 27.8, 27.1, 24.7, 24.3, 23.8, 11.8, 11.2, 9.3. Anal. Calcd for $C_{17}H_{22}O_3$: C, 74.42; H, 8.08. Found: C, 74.51; H, 8.11.

3-(Hexa-3,5-dienyloxy)-2-methyl-4*H*-pyran-4-one (5f). 3-Hydroxy-2-methyl-4*H*-pyran-4-one (**2d**) (378 mg, 3.00 mmol) and NaH (340 mg 60% suspension, 8.50 mmol) were suspended in dry DMSO (10 mL), and the mixture was stirred at rt for 0.5 h. The reaction flask was placed in a water bath, and 6-bromohexa-1,3-diene[25] (**6a**) (837 mg, 5.2 mmol) was added dropwise by syringe. After the mixture was stirred for 1 h at rt, additional bromo diene (258 mg, 1.6 mmol) was added, and after another 1 h both bromo diene (258 mg, 1.6 mmol) and NaH (96 mg 60% suspension, 2.4 mmol) were added. After a further 1 h of stirring, the reaction mixture was partitioned between Et_2O and H_2O (10 mL each), the aqueous layer was extracted with Et_2O (2 × 5 mL), and then the combined organic layers were washed with H_2O (10 mL), dried ($MgSO_4$), concentrated, and purified by flash chromatography (CH_2Cl_2/Et_2O (2:1), silica gel, 3-cm × 15-cm column) to give 210 mg (34%) of **5f** as a colorless oil: R_f 0.30 (CH_2Cl_2/Et_2O (2:1)); IR (CCl_4) 3081, 3005, 1650, 1427, 1250 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.53 (d, J = 5.4 Hz, 1H), 6.27 (d, J = 5.7 Hz, 1H), 6.26–6.08 (m, 2H), 5.66 (dt, J = 14.9, 7.5 Hz, 1H), 5.05 (d, J = 17.7 Hz, 1H), 4.93 (d, J = 10.5 Hz, 1H), 4.07 (t, J = 6.6 Hz, 2H), 2.43 (q, J = 6.9 Hz, 2H), 2.22 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.7, 158.8, 153.2, 144.3, 136.6, 132.9, 130.2, 116.9, 115.5, 71.1, 33.2, 14.7; HRMS calcd for $C_{12}H_{15}O_3$ (M + 1) m/e 207.1026, found m/e 207.1025.

3-(Hepta-3,5-dienyloxy)-2-methyl-4*H*-pyran-4-one (5g). 3-Hydroxy-2-methyl-4*H*-pyran-4-one (**2d**) (378 mg, 3.00 mmol) and 7-bromohepta-2,4-diene[25] (**6b**) (696 mg, 3.98 mmol) were subjected to the conditions described above for the synthesis of **5f** to give after workup 230 mg (35%) of **5g** as a colorless oil: R_f 0.30 (CH_2Cl_2/Et_2O (3:1)); IR (CCl_4) 3080, 3030, 1652, 1430, 1253 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.52 (d, J = 5.7 Hz, 1H), 6.23 (d, J = 5.7 Hz, 1H), 6.02–5.88 (m, 2H), 5.54–5.44 (m, 2H), 4.02 (t, J = 6.7 Hz, 2H), 2.37 (q, J = 6.8 Hz, 2H), 2.20 (s, 3H), 1.63 (d, J = 6.7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.9, 158.9, 153.3, 144.5, 132.6, 131.2, 127.8, 126.8, 117.0, 71.4, 33.1, 17.9, 14.7; HRMS calcd for $C_{13}H_{17}O_3$ (M + 1) m/e 221.1169, found m/e 221.1168.

3-[2-(2′-Furyl)ethoxy]-2-methyl-4*H*-pyran-4-one (5h). 3-Hydroxy-2-methyl-4*H*-pyran-4-one (**2d**) (509 mg, 4.03 mmol) and K_2CO_3 (835 mg, 6.05 mmol) were suspended in dry DMSO (10 mL), and the mixture was stirred at rt for 15 min. 2-(Mesyloxy)-1-(2′-furyl)ethane[26] (**6c**) (767 mg, 4.03 mmol) in DMSO (5 mL) was added dropwise to the mixture. After being stirred at rt for 12 h, the reaction mixture was poured into saturated aqueous NH_4Cl (10 mL), the aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL), and then the combined organic layers were washed with H_2O (10 mL), dried (Na_2SO_4), concentrated, and purified by radial chromatography (4-mm silica gel plate, EtOAc/hexanes (3:1)) to give 485 mg (54%) of **5h** as a colorless oil: R_f 0.42 (EtOAc/hexanes (3:1)); IR (CCl_4) 2962, 1641, 1429, 1253, 1190 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.59 (d, J = 5.7 Hz, 1H), 7.57–7.27 (m, 1H), 6.34 (d, J = 5.7 Hz, 1H), 6.31–6.29 (m, 1H), 6.15–6.13 (m, 1H), 4.36 (t, J = 6.6 Hz, 2H), 3.05 (t, J = 6.6 Hz, 2H), 2.16 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.9, 159.2, 153.3, 152.4, 144.5, 141.1, 117.1, 110.3, 106.4, 69.7, 28.9, 14.7. Anal. Calcd for $C_{12}H_{12}O_4$: C, 65.45; H, 5.49. Found: C, 65.53; H, 5.54.

3-[[3-(2′-Furyl)propyl]oxy]-2-methyl-4*H*-pyran-4-one (5i). 3-Hydroxy-2-methyl-4*H*-pyran-4-one (**2d**) (333 mg, 2.64 mmol) and K_2CO_3 (547 mg, 3.96 mmol) were suspended in dry DMSO (10 mL), and the mixture was stirred at rt for 15 min. 3-Bromo-1-(2′-furyl)propane[27] (**6e**) (499 mg, 2.64 mmol) in DMSO (5 mL) was added dropwise to the mixture. After being stirred at rt for 12 h, the reaction mixture was worked up as described for **5h** and purified by radial chromatography (4-mm silica gel plate, EtOAc/hexanes (3:1)) to give 323 mg (52%) of **5i** as a colorless oil: R_f 0.41 (EtOAc/hexanes (3:1)); IR (CCl_4) 2957, 1647, 1429, 1253, 1190 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.57 (d, J = 5.4 Hz, 1H), 7.26–7.25 (m, 1H), 6.29 (d, J = 5.7 Hz, 1H), 6.24–6.23 (m, 1H), 5.99–5.98 (m, 1H), 4.05 (t, J = 6.3 Hz, 2H), 2.77 (t, J = 7.5 Hz, 2H), 2.28 (s, 3H), 2.06–1.97 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.9, 158.9, 155.2, 153.3, 144.7, 140.9, 117.1, 110.0, 105.0, 71.1, 28.4, 24.3, 14.6. Anal. Calcd for $C_{13}H_{14}O_4$: C, 66.66; H, 6.02. Found: C, 66.61; H, 6.07.

Representative Photocycloaddition Procedure: Irradiation of 5a in Trifluoroethanol. Preparation of 7a, 8a, and 9a. Substrate **5a** (100 mg, 0.40 mmol) was dissolved in trifluoroethanol (TFE, 100 mL), the solution was placed in a quartz test tube (3 × 24 cm), and dry N_2 was bubbled through for 0.5 h. The reaction vessel was clamped 10 cm away from a Hanovia 450-W medium-pressure Hg lamp with a quartz cooling jacket, and the reaction was irradiated for 2 h. Solvent was removed, and the residue was purified by MPLC (silica gel, hexanes/Et_2O/CH_2Cl_2 (16:3:1)) to give 30 mg (30%) of **7a** (recrystallized from EtOH/hexanes), 20 mg (20%) of **8a** (recrystallized from EtOH/hexanes), and 5 mg (5%) of **9a** (recrystallized from EtOAc/hexanes). **7a** (colorless cubes): mp 124 °C; R_f 0.56 (hexanes/CH_2Cl_2/Et_2O (3:5:12)); IR (KBr) 3070, 2984, 2941, 2879, 1764, 1384, 964 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.45 (dd, J = 6.0, 1.5 Hz, 1H), 6.22 (d, J = 6.0 Hz, 1H), 4.56 (d, J = 1.7 Hz, 1H), 4.13 (d, J_{AB} = 9.4 Hz, 1H), 4.11 (d, J_{AB} = 9.1 Hz, 1H), 4.07 (d, J_{AB} = 9.4 Hz, 1H), 3.98 (d, J_{AB} = 9.4 Hz, 1H), 1.57 (s, 3H), 1.45 (s, 3H), 1.09 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.1, 137.3, 136.4, 94.7, 86.4, 70.2, 68.2, 68.0, 67.7, 62.8, 59.2, 12.3, 10.2, 7.8. Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.49. Found: C, 67.77; H, 6.49. **8a** (colorless cubes): mp 124 °C; R_f 0.41 (hexanes/CH_2Cl_2/Et_2O (3:5:12)); IR (KBr) 3086, 2980, 2864, 1772, 1450, 842 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.71 (dd, J = 5.9, 2.0 Hz, 1H), 6.45 (d, J = 5.9 Hz, 1H), 4.43 (d, J = 2.1 Hz, 1H), 4.41 (d, J_{AB} = 10.0 Hz, 1H), 3.86 (d, J_{AB} = 11.0 Hz, 1H), 3.80 (d, J_{AB} = 11.3 Hz, 1H), 3.75 (d, J_{AB} = 10.3 Hz, 1H), 1.24 (s, 3H), 1.23 (s, 3H), 1.18 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 195.8, 136.9, 134.5, 96.5, 86.1, 72.3, 71.2, 70.1, 68.5, 63.9, 58.6, 13.1, 12.9, 11.3. Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.49. Found: C, 67.70; H, 6.49. **9a** (colorless needles): mp 96 °C; R_f 0.60 (hexanes/CH_2Cl_2/Et_2O (3:5:12)); IR (KBr) 2980, 2879, 1699, 1384, 1031 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.40 (d, J = 5.7 Hz, 1H), 4.17 (d, J_{AB} = 10.0 Hz, 1H), 4.11 (d, J_{AB} = 10.7 Hz, 1H), 4.02 (d, J_{AB} = 10.6 Hz, 1H), 3.78 (d, J_{AB} = 10.2 Hz, 1H), 3.71 (dd, J = 9.8, 5.7 Hz, 1H), 3.42 (d, J = 9.8 Hz, 1H), 1.53 (s, 3H), 1.43 (s, 3H), 1.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.4, 89.4, 84.1, 82.5, 80.4, 69.7, 68.3, 66.2, 60.1, 57.5, 56.5, 18.1, 16.3, 12.1. Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.49. Found: C, 67.73; H, 6.46.

Irradiation of 5b. Substrate **5b** (400 mg, 1.63 mmol) was dissolved in TFE (500 mL), the solution was placed in the immersion well (1000 mL) of an Ace-Hanovia photochemical reactor, and dry N_2 was bubbled through for 0.5 h. Photolysis, followed by standard workup and MPLC (silica gel, hexanes/Et_2O/CH_2Cl_2 (16:3:1)), gave 70 mg (17%) of **7b**, 210 mg (52%) of **8b**, 20 mg (5%) of **9b**, and 64 mg (16%) of recovered **5b**. **7b** (colorless needles): mp 140 °C; R_f 0.79 (hexanes/CH_2Cl_2/Et_2O (4:5:1), four elutions); IR (KBr) 3003, 2972, 1714, 1363, 1222 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.34 (dd, J = 5.9, 1.7 Hz, 1H), 6.06 (d, J = 5.9 Hz, 1H), 4.48 (d, J = 1.7 Hz, 1H), 2.11–2.01 (m, 4H), 1.90–1.82 (m, 2H), 1.51 (s, 3H), 1.43 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.6, 138.8, 135.7, 97.3, 86.0, 70.7, 69.7, 68.3, 59.3, 30.4, 21.8, 18.0, 13.3, 10.7, 8.4. Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.36. Found: C, 73.10; H, 7.37. **8b** (colorless needles): mp 133 °C; R_f 0.74 (hexanes/CH_2Cl_2/Et_2O (4:5:1), four elutions); IR (KBr) 3084, 2966, 1761, 1070 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.67 (dd, J = 5.7, 2.1 Hz, 1H), 6.42 (d, J = 5.7 Hz, 1H), 4.42 (d, J = 2.0 Hz, 1H), 2.31–2.26 (m, 1H), 1.94–1.81 (m, 4H), 1.61–1.55 (m, 1H), 1.27 (s, 3H), 1.22 (s, 3H), 1.21 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.3, 137.7, 135.3, 97.4, 85.8, 72.5, 70.3, 70.0, 58.9, 34.4, 25.8, 23.2, 13.2, 13.0, 11.5. Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.36. Found: C, 73.08; H, 7.41. **9b** (colorless oil): R_f 0.87 (hexanes/CH_2Cl_2/Et_2O (4:5:1), four elutions); IR (CCl_4) 2968, 1707, 1383, 1080, 1049 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.31 (d, J = 5.8 Hz, 1H), 3.67 (dd, J = 9.8, 5.8 Hz, 1H), 3.30 (d, J = 9.8 Hz, 1H), 2.28–2.22 (m, 1H), 2.09–1.78 (m, 5H), 1.46 (s, 3H), 1.40 (s, 3H), 1.20 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 206.4, 92.1, 83.5, 82.7, 79.6, 70.1, 59.2,

(25) Bromodienes were prepared from cyclopropylmagnesium bromide and either acrolein or crotonaldehyde via the procedures outlined in: (a) Descoins, C.; Henrick, C. A. *Tetrahedron Lett.* **1972**, 2999. (b) Julia, M.; Julia, S.; Guegan, R. *Bull. Soc. Chim. Fr.* **1960**, 1072.

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58.4, 57.2, 32.2, 25.8, 24.2, 18.2, 17.9, 12.5; HRMS calcd for $C_{15}H_{18}O_3$ *m/e* 246.1256, found *m/e* 246.1253.

Irradiation of 5c. Substrate **5c** (100 mg, 0.45 mmol) was dissolved in TFE (100 mL) and subjected to the procedure described for **5a** to give 10 mg (10%) of **8c**, 15 mg (15%) of **9c**, and 11 mg (11%) of recovered **5c**. **8c** (colorless solid): mp 144 °C; R_f 0.34 (hexanes/CH_2Cl_2/Et_2O (4:5:1), four elutions); IR (KBr) 2968, 2876, 1768, 920 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.75 (dd, J = 5.9, 1.9 Hz, 1H), 6.51 (d, J = 5.9 Hz, 1H), 4.61 (d, J = 1.9 Hz, 1H), 4.54 (d, J_{AB} = 10.2 Hz, 1H), 3.95 (s, 2H), 3.81 (d, J_{AB} = 10.2 Hz, 1H), 3.43 (d, J = 4.0 Hz, 1H), 3.37 (d, J = 3.9 Hz, 1H), 1.39 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.1, 136.7, 135.1, 97.1, 86.4, 71.4, 68.8, 66.0, 60.1, 58.1, 55.2, 13.2; HRMS calcd for $C_{12}H_{12}O_4$ *m/e* 220.0736, found *m/e* 220.0726. **9c** (colorless needles): mp 96 °C; R_f 0.58 (hexanes/CH_2Cl_2/Et_2O (4:5:1), four elutions); IR (KBr) 2982, 2866, 1701, 1076 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.66 (dd, J = 4.9, 1.2 Hz, 1H), 4.45 (d, J = 5.4 Hz, 1H), 4.44 (m, 1H), 4.17 (d, J_{AB} = 10.0 Hz, 1H), 4.08 (d, J_{AB} = 10.4 Hz, 1H), 4.07 (d, J_{AB} = 10.4 Hz, 1H), 4.01 (m, 1H), 3.76 (d, J_{AB} = 9.8 Hz, 1H), 3.72 (dd, J = 9.9, 4.2 Hz, 1H), 1.31 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 202.4, 90.2, 81.3, 80.6, 78.1, 69.4, 68.9, 66.8, 59.0, 51.5, 49.6, 14.7. Anal. Calcd for $C_{12}H_{12}O_4$: C, 65.45; H, 5.49. Found: C, 65.26; H, 5.50.

Irradiation of 5d. Substrate **5d** (160 mg, 0.58 mmol) was dissolved in TFE (200 mL) and subjected to the procedure described for **5c** to give 30 mg (19%) of **7d**, 30 mg (19%) of **8d** (recrystallized from EtOAc/hexanes), 10 mg (6%) of **9d**, and 30 mg (19%) of 4,5-diethyl-3-[[(2'-furyl)methoxy]methyl]-6-methyl-2*H*-pyran-2-one (**12d**). **7d** (colorless needles): mp 98–100 °C; R_f 0.65 (hexanes/CH_2Cl_2/Et_2O (4:5:1), three elutions); IR (KBr) 2976, 2883, 1766, 1467 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.42 (dd, J = 5.7, 1.8 Hz, 1H), 6.23 (d, J = 5.7 Hz, 1H), 4.65 (d, J = 1.8 Hz, 1H), 4.20 (d, J_{AB} = 10.3 Hz, 1H), 4.08 (d, J_{AB} = 9.5 Hz, 1H), 4.05 (d, J_{AB} = 10.4 Hz, 1H), 4.04 (d, J_{AB} = 9.9 Hz, 1H), 2.24–2.14 (m, 1H), 1.96–1.78 (m, 3H), 1.13 (s, 3H), 1.12 (t, J = 7.7 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.3, 137.7, 136.6, 94.6, 86.8, 71.2, 70.7 (2C), 68.4, 63.7, 59.6, 20.0, 18.9, 9.4, 9.3, 8.7. Anal. Calcd for $C_{16}H_{20}O_4$: C, 69.55; H, 7.29. Found: C, 69.46; H, 7.26. **8d** (colorless needles): mp 144 °C; R_f 0.51 (hexanes/CH_2Cl_2/Et_2O (4:5:1), three elutions); IR (KBr) 3105, 2978, 2874, 1766, 1465 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.71 (dd, J = 5.9, 2.0 Hz, 1H), 6.43 (d, J = 5.9 Hz, 1H), 4.52 (d, J_{AB} = 10.1 Hz, 1H), 4.49 (d, J = 2.0 Hz, 1H), 3.90 (s, 2H), 3.85 (d, J_{AB} = 10.1 Hz, 1H), 1.62–1.53 (m, 4H), 1.36 (s, 3H), 0.96 (t, J = 7.6 Hz, 3H), 0.95 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.2, 136.7, 134.5, 96.8, 86.4, 73.4, 72.5, 72.0, 71.6, 64.6, 59.2, 20.6, 19.8, 12.5, 9.8, 9.7. Anal. Calcd for $C_{16}H_{20}O_4$: C, 69.55; H, 7.29. Found: C, 69.50; H, 7.25. **9d** (colorless oil): R_f 0.70 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2974, 2877, 1707, 1460, 1284 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.37 (d, J = 5.8 Hz, 1H), 4.15 (d, J_{AB} = 10.3 Hz, 1H), 4.13 (d, J_{AB} = 10.7 Hz, 1H), 4.03 (d, J_{AB} = 10.6 Hz, 1H), 3.80 (d, J_{AB} = 10.1 Hz, 1H), 3.74 (dd, J = 9.8, 5.8 Hz, 1H), 3.44 (d, J = 9.8 Hz, 1H), 1.98–1.84 (m, 3H), 1.70–1.66 (m, 1H), 1.23 (s, 3H), 0.95 (t, J = 7.3 Hz, 3H), 0.94 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.9, 89.6, 86.6, 85.1, 80.5, 69.9, 68.5, 66.2, 60.4, 54.6, 53.7, 23.9, 22.0, 11.7, 7.1 (2C); HRMS calcd for $C_{16}H_{21}O_4$ (M + 1) *m/e* 277.1440, found *m/e* 277.1438. **12d**: (colorless oil): R_f 0.63 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2970, 2933, 2877, 1709, 1547, 1062 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.39–7.38 (m, 1H), 6.35–6.31 (m, 2H), 4.51 (s, 2H), 4.45 (s, 2H), 2.49 (q, J = 7.6 Hz, 2H), 2.23 (q, J = 7.6 Hz, 2H), 2.22 (s, 3H), 1.10 (t, J = 7.6 Hz, 3H), 1.05 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.7, 161.7, 157.6, 151.8, 142.8, 118.1, 117.4, 110.3, 109.5, 64.4, 63.4, 22.6, 19.8, 17.4, 14.5, 14.3; HRMS calcd for $C_{16}H_{20}O_4$ *m/e* 276.1351, found *m/e* 276.1350.

Irradiation of 5e. Substrate **5e** (100 mg, 0.36 mmol) was dissolved in TFE (100 mL) and subjected to the procedure described for **5a** to give 27 mg (27%) of **8e**, 5 mg (5%) of **9e**, 18 mg (18%) of an inseparable mixture of 2-pyrones **11e** and **12e**, and 4 mg (4%) of **13e**. **8e** (colorless needles): mp 124 °C; R_f 0.62 (hexanes/CH_2Cl_2/Et_2O (4:5:1), two elutions); IR (KBr) 2972, 2937, 1764, 981 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.61 (dd, J = 5.9, 2.1 Hz, 1H), 6.36 (d, J = 5.9 Hz, 1H), 4.42 (d, J = 2.1 Hz, 1H), 2.36–2.30 (m, 1H), 1.89–1.84 (m, 4H), 1.68–1.46 (m, 5H), 1.32 (s, 3H), 0.95 (t, J = 7.6 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.7, 137.6, 135.1, 97.6, 86.0, 73.6, 73.2, 72.5, 59.3, 34.5, 25.9, 24.1, 20.6, 19.8, 12.6, 9.8, 9.7. Anal. Calcd for $C_{17}H_{22}O_3$: C, 74.42; H, 8.08. Found: C, 74.46; H, 8.04. **9e** (colorless solid): mp 95 °C; R_f 0.75 (hexanes/CH_2Cl_2/Et_2O (4:5:1), two elutions); IR (KBr) 2968, 2935, 1709, 1058, cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.28 (d, J = 5.9 Hz, 1H), 3.70 (dd, J = 9.8, 5.9 Hz, 1H), 3.31 (d, J = 9.8 Hz, 1H), 2.32–2.27 (m, 1H), 2.05-2.00 (m, 2H), 1.89–1.63 (m, 7H), 1.20 (s, 3H), 0.94 (t, J = 7.3 Hz, 3H), 0.93 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 206.7, 92.2, 86.1, 85.5, 79.6, 70.4, 59.5, 55.4, 54.2, 32.5, 26.4, 24.0 (2 C), 23.9, 12.1, 7.4, 7.2; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1569, found *m/e* 274.1560. **11e/12e** (colorless oil): R_f 0.47 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); individual spectral data for **11e** and **12e** are given below in the procedures for their independent preparation. **13e** (colorless needles): mp 101 °C; R_f 0.56 (hexanes/CH_2Cl_2/Et_2O (4:5:1), two elutions); IR (KBr) 2966, 1732, 1464, 1400, 1217, 1157 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.18 (d, J = 5.7 Hz, 1H), 5.97 (dd, J = 5.7, 1.9 Hz, 1H), 4.35 (d, J = 1.9 Hz, 1H), 2.21–1.69 (m, 10H), 1.40 (s, 3H), 0.99 (t, J = 7.6 Hz, 3H), 0.90 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.7, 142.4, 140.4, 139.0, 130.5, 95.0, 94.6, 87.8, 56.2, 34.1, 33.2, 23.6, 21.9, 20.9, 18.3, 14.5, 14.1; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1543, found *m/e* 274.1556.

Irradiation of 5f. Substrate **5f** (50 mg, 0.24 mmol) was dissolved in TFE (50 mL) and subjected to the procedure described for **5a**. Standard workup and purification by flash chromatography (silica gel, 1.8 × 14 cm column, hexanes/EtOAc (1:3)) gave 48 mg (66%) of **10f** as a yellow oil: R_f 0.70 (hexanes/EtOAc (1:3)); IR (CCl_4) 3450, 2960, 1732, 1281, 1160 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.34 (d, J = 6.3 Hz, 1H), 6.57–6.11 (m, 2H), 6.07 (d, J = 6.6 Hz, 1H), 5.62 (dt, J = 15.3, 7.6 Hz, 1H), 5.08 (d, J = 17.9 Hz, 1H), 4.96 (d, J = 9.9 Hz, 1H), 4.11–3.61 (m, 4H), 3.02 (q, J = 0.9 Hz, 1H), 2.38 (q, J = 6.9 Hz, 2H), 1.39 (d, J = 0.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.4, 165.7, 136.5, 133.5, 129.5, 128.9, 123.2 (q, J_{CF12} = 277 Hz, CF_3), 116.1, 99.2, 77.4, 63.7, 61.4 (q, J_{CF13} = 36 Hz, CCF_3), 32.8, 23.1; HRMS calcd for $C_{14}H_{18}O_4F_3$ (M + 1) *m/e* 307.1159, found *m/e* 307.1158.

Irradiation of 5g. Substrate **5g** (50 mg, 0.23 mmol) was dissolved in TFE (60 mL) and subjected to the procedure described for **5a**. Standard workup and purification by radial chromatography (2-mm silica gel plate, hexanes/EtOAc (5:3)) gave 49 mg (67%) of **10g** as a yellow oil: R_f 0.53 (hexanes/EtOAc (5:3)); IR (CCl_4) 3460, 2965, 1734, 1285, 1162 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38 (d, J = 6.3 Hz, 1H), 6.41–6.36 (m, 1H), 6.11 (d, J = 6.6 Hz, 1H), 6.07–5.94 (m, 1H), 5.64–5.42 (m, 2H), 4.13–3.63 (m, 4H), 3.09 (q, J = 0.9 Hz, 1H), 2.53–2.34 (m, 2H), 1.72 (d, J = 6.8 Hz, 3H), 1.43 (d, J = 0.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.7, 165.9, 133.1, 131.1, 128.9, 128.4, 126.0, 123.4 (q, J_{CF12} = 277 Hz, CF_3), 99.2, 78.7, 63.9, 61.3 (q, J_{CF13} = 36 Hz, C-CF_3), 32.8, 23.0, 17.9; HRMS calcd for $C_{15}H_{20}O_4F_3$ (M + 1) *m/e* 321.1304, found *m/e* 321.1304.

Irradiation of 5h. Substrate **5h** (115 mg, 0.52 mmol) was dissolved in TFE (100 mL) and subjected to the procedure described for **5a**. Standard workup and purification by flash chromatography (silica gel, 1.8 × 19 cm column, hexanes/EtOAc (1:1)) gave 98 mg (58%) of **10h** as a yellow oil: R_f 0.55 (hexanes/EtOAc (1:1)); IR (CCl_4) 3445, 2980, 1732, 1282, 1165 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.37 (d, J = 6.6 Hz, 1H), 7.30–7.29 (m, 1H), 6.28–6.26 (m, 1H), 6.11 (d, J = 6.6 Hz, 1H), 6.10–6.09 (m, 1H), 4.09–3.81 (m, 4H), 3.07 (q, J = 1.2 Hz, 1H), 2.96 (t, J = 6.7 Hz, 2H), 1.37 (d, J = 1.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.6, 165.9, 151.8, 141.4, 128.9, 123.4 (q, J_{CF12} = 277 Hz, CF_3), 110.4, 106.9, 99.1, 78.7, 62.4, 61.1 (q, J_{CF13} = 36 Hz, C-CF_3), 28.5, 22.7; HRMS calcd for $C_{14}H_{15}O_5F_3$ *m/e* 320.0860, found *m/e* 320.0859.

Irradiation of 5i. Substrate **5i** (100 mg, 0.43 mmol) was dissolved in TFE (100 mL) and subjected to the procedure described for **5a**. Standard workup and purification by flash chromatography (silica gel, 3.0 × 23 cm column, hexanes/EtOAc (1:1)) gave 84 mg (58%) of **10i** as a yellow oil: R_f 0.56 (hexanes/EtOAc (1:1)); IR (CCl_4) 3439, 2957, 1730, 1282, 1165 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38 (d, J = 6.3 Hz, 1H), 7.28–7.27 (m, 1H), 6.27–6.25 (m, 1H), 6.11 (d, J = 6.3 Hz, 1H), 5.99–5.98 (m, 1H), 4.08–3.64 (m, 4H), 3.10 (q, J = 1.1 Hz, 1H), 2.74 (t, J = 7.3 Hz, 2H), 1.98 (quintet, J = 7.1 Hz, 2H), 1.42 (d, J = 0.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.7, 165.9, 154.9, 141.1, 128.9, 123.4 (q, J_{CF12} = 277 Hz, CF_3), 110.1, 105.3, 99.2, 78.7, 62.9, 61.3 (q, J_{CF13} = 36 Hz, C-CF_3), 27.9, 24.2, , 22.9; HRMS calcd for $C_{15}H_{17}O_5F_3$ *m/e* 334.1018, found *m/e* 334.1017.

4,5-Diethyl-3,6-dimethyl-2*H*-pyran-2-one (15). 2,6-Diethyl-3,5-dimethyl-4*H*-pyran-4-one[23] (**2c**) (1.20 g, 6.65 mmol) was dissolved in dry CH_3CN (1 L), the solution was placed in the immersion well (1100 mL) of an Ace-Hanovia photochemical reactor, and dry N_2 was bubbled through for 0.5 h. Irradiation, followed by standard workup, and purification by flash chromatography (hexanes/CH_2Cl_2/Et_2O (5:1:3), silica gel, 5 × 17 cm) gave 580 mg (48%) of pyran-2-one **15**: colorless oil; R_f 0.29 (hexanes/CH_2Cl_2/Et_2O (5:1:3)); IR (CCl_4) 2972, 2936, 1705, 1554, 1053 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.46 (q, J = 7.6 Hz, 2H), 2.32 (q, J = 7.5 Hz, 2H), 2.21 (s, 3H), 2.04 (s, 3H), 1.08 (t, J = 7.5 Hz, 3H), 1.05 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.9, 155.8, 154.0, 118.0, 116.7, 22.4, 19.8, 16.8, 14.3, 12.7, 11.9.

4,5-Diethyl-3-methyl-6-[3-(2′-furyl)propyl]-2*H*-pyran-2-one (11e). A 2.5 M solution of n-BuLi in hexanes (0.57 mL, 1.42 mmol) was added dropwise to a cold solution (−78 °C) of diisopropylamine (0.21 mL, 1.48 mmol) in dry THF (5 mL). After the mixture was stirred for 0.5 h at −78 °C, a solution of **15** (470 mg, 2.6mmol) in dry THF (5 mL) was added dropwise via cannula. After the mixture was stirred for an additional 0.5 h at −78 °C, 2-bromo-1-(2′-furyl)ethane (**6d**)[25] (695 mg, 3.9 mmol) in dry THF (5 mL) was added dropwise via cannula. The reaction mixture was allowed to warm to rt over a period 2.5 h and was poured into saturated aqueous NH_4Cl (10 mL), and the aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were washed with water, dried ($MgSO_4$), and evaporated, and the crude product was purified by flash chromatography (hexanes/EtOAc (4:1), silica gel, 3-cm × 19-cm column) to give 35 mg (5%) of **11e** as a colorless oil: R_f 0.48 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2970, 2936, 1703, 1552, 1456 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.28-7.27 (m, 1H), 6.25 (dd, J = 3.0, 1.8 Hz, 1H), 5.99–5.98 (m, 1H), 2.67 (t, J = 7.3 Hz, 2H), 2.54–2.41 (m, 4H), 2.28 (q, J = 7.5 Hz, 2H), 2.04–1.97 (m, 5H), 1.08 (t, J = 7.8 Hz, 3H), 1.03 (t, J = 7.6Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.2, 157.2, 156.0, 155.1, 141.0, 118.9, 116.9, 110.1, 105.3, 30.0, 27.5, 26.2, 22.7, 19.8, 15.3, 13.0, 12.3; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1568, found *m/e* 274.1556.

4,5-Diethyl-6-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)propyl]-3-methyl-2*H*-pyran-2-one (18) and 4,5-Diethyl-3-[3-(2′-furyl)-2,2-bis(phenyl-sulfonyl)propyl]-6-methyl-2*H*-pyran-2-one (19). The procedure described for the bromination of **2a** was carried out using **15** (1.42 g, 8.14 mmol), dry NBS (1.59 g, 8.89 mmol), and benzoyl peroxide (50 mg) in CCl_4 (20 mL). After being cooled to rt, the mixture was filtered through glass wool and the filtrate concentrated. The crude product was purified by radial chromatography (1% Et_2O in CH_2Cl_2, 4-mm silica plate) to give 1.60 g (76%) of an inseparable mixture of isomeric bromides **16** and **17** in a 3:5 ratio (determined by ^1H NMR integration): ^1H NMR (300MHz, $CDCl_3$) for **16** δ 4.23 (s, 2H), 2.49–2.40 (m, 4H), 2.07 (s, 3H), 1.18 (t, J = 7.5Hz, 3H), 1.07 (t, J = 7.4Hz, 3H); for **17** δ 4.41 (s, 2H), 2.57 (q, J = 7.6 Hz, 2H), 2.34 (q, J = 7.5 Hz, 2H), 2.24 (s, 3H), 1.20 (t, J = 7.5 Hz, 3H), 1.07 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75MHz, $CDCl_3$) **16** + **17**: δ 161.9, 160.9, 160.1, 159.2, 158.1, 151.1, 122.5, 122.4, 120.2, 120.1, 25.7, 25.6, 25.0, 24.7, 22.7, 22.6, 20.1, 19.9, 14.7 (2 C), 13.6, 12.6.

The mixture of **16** and **17** (480 mg, 1.85 mmol) was subjected to the conditions outlined above for **5b** to give 176 mg (46%, based on **16**/**17** ratio of 3:5) of 4,5-diethyl-6-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)propyl]-3-methyl-2H-pyran-2-one (**18**) and 82 mg (13% based on **16**/**17** ratio of 3:5) of 4,5-diethyl-3-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)propyl]-6-methyl-2H-pyran-2-one (**19**). **18** (pale yellow solid): mp 153–155 °C dec; R_f 0.23 (hexanes/CH_2Cl_2/Et_2O (5:1:3)); IR (KBr) 2974, 1707, 1339, 1146 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.81 (d, J = 7.5 Hz, 4H), 7.64 (t, J = 7.5 Hz, 2H), 7.46 (t, J = 7.7 Hz, 4H), 7.31 (dd J = 1.8, 0.9 Hz, 1H), 6.47 (dd, J = 3.3, 0.6 Hz, 1H), 6.28 (dd, J = 3.3, 1.8 Hz, 1H), 4.08 (s, 2H), 3.60 (s, 2H), 2.50 (q, J = 7.7 Hz, 2H), 2.48 (q, J = 7.7 Hz, 2H), 1.96 (s, 3H), 1.15 (t, J = 7.5 Hz, 3H), 1.12 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.5, 155.0, 150.1, 146.7, 142.3, 137.1, 134.6, 130.9, 128.7, 120.9, 120.4, 111.6, 110.7, 90.9, 29.7, 29.4, 22.8, 19.9, 14.7, 12.8, 12.4; HRMS calcd for $C_{29}H_{30}O_7S_2$ *m/e* 554.1433, found *m/e* 554.1432. **19** (white solid): mp 167–168 °C dec; R_f 0.18 (hexanes/CH_2Cl_2/Et_2O (5:1:3)); IR (KBr) 2972, 1701, 1331, 1144 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.80 (d, J = 7.2 Hz, 4H), 7.61 (t, J = 7.5Hz, 2H), 7.46 (t, J = 7.8 Hz, 4H), 7.28–7.27 (m, 1H), 6.56 (d, J = 3.3 Hz, 1H), 6.25 (dd, J = 3.3, 1.8 Hz, 1H), 4.18 (s, 2H), 3.53 (s, 2H), 2.65 (q, J = 7.6 Hz, 2H), 2.33 (q, J = 7.5 Hz, 2H), 2.19 (s, 3H), 1.09 (t, J = 7.6 Hz, 3H), 1.04 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.5, 161.7, 156.2, 147.4, 141.6, 137.8, 134.3, 131.2, 128.4, 117.5, 116.1, 111.9, 110.9, 91.9, 31.5, 28.0, 22.9, 20.4, 17.2, 14.5, 13.8. Anal. Calcd for $C_{29}H_{30}O_7S_2$: C, 62.80; H, 5.45. Found: C, 62.70; H, 5.52.

4,5-Diethyl-6-methyl-3-[3-(2′-furyl)propyl]-2*H*-pyran-2-one (12e). 4,5-Diethyl-3-[3-(2′-furyl)-2,2-bis(phenylsulfonyl)-propyl]-6-methyl-2*H*-pyran-2-one (**19**) (275 mg, 0.50 mmol) was subjected to the Na(Hg) conditions described above for **5b** to give 11 mg (8%) of **12e** as a colorless oil: R_f 0.46 (hexanes/CH_2Cl_2/Et_2O (4:5:1)); IR (CCl_4) 2971, 2936, 1703, 1549, 1454 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.27 (d, J = 1.5 Hz, 1H), 6.27 (dd, J = 3.0, 1.8 Hz, 1H), 6.00 (d, J = 3.2 Hz, 1H), 2.69 (t, J = 7.5 Hz, 2H), 2.51–2.46 (m, 2H), 2.38 (q, J = 7.6 Hz, 2H), 2.31 (q, J = 7.5 Hz, 2H), 2.19 (s, 3H), 1.89–1.78 (m, 2H), 1.05 (t, J = 7.6 Hz, 3H), 1.04 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.8, 156.1, 155.9, 154.8, 140.7, 122.5, 116.9, 110.1, 104.9, 28.0, 27.1, 26.5, 22.3, 20.0, 17.1, 14.6, 14.0; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1568, found *m/e* 274.1557.

Irradiation of 11e. Pyran-2-one **11e** (35 mg, 0.13 mmol) was dissolved in dry TFE (35 mL) and subjected to the photolysis procedure described for **5a** followed by standard workup and purification by flash chromatography (hexanes/EtOAc (8:1), silica gel, 1 cm × 13 cm column) to give 8 mg (23%) of **13e** as a white solid: mp 98-100 °C; R_f 0.30 (hexanes/EtOAc (4:1)); IR (KBr) 2965, 1732, 1456, 1217, 1159 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.18 (d, J = 5.7 Hz, 1H), 5.97 (dd, J = 5.7, 2.1 Hz, 1H), 4.35 (d, J = 1.8 Hz, 1H), 2.20–1.69 (m, 10H), 1.40 (s, 3H), 1.00 (t, J = 7.6 Hz, 3H), 0.90 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.7, 142.6, 140.4, 138.9, 130.5, 95.0, 94.6, 87.8, 56.2, 34.1, 33.2, 23.6, 21.9, 20.9, 18.3, 14.5, 14.1; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1568, found *m/e* 274.1564.

[4 + 4]-Cycloadduct **13e** (5 mg, 0.02 mmol) was dissolved in dry toluene (3 mL), the reaction mixture was refluxed for 3 h, and the solvent was evaporated to give a 2:1 ratio of **13e**/**20e**. Partial spectral data for **20e**: IR (CCl_4) 1705 cm^{-1}; ^1H NMR (300MHz, $CDCl_3$) δ 6.36 (d, J = 2.7 Hz, 1H), 4.77 (t, J = 2.8 Hz, 1H), 2.76 (d, J = 3.3 Hz, 1H).

Irradiation of 12e. Pyran-2-one **12e** (23 mg, 0.08 mmol) was dissolved in dry TFE (30 mL) and subjected to the photolysis procedure described for **5a** followed by standard workup and purification by flash chromatography (hexanes/EtOAc (8:1), silica gel, 1-cm × 13-cm column) to give 4 mg (13%) of **14e** (2:1 endo/exo mixture) as a white solid: mp 94–95 °C; R_f 0.27 (hexanes/EtOAc (4:1)); IR (KBr) 2967, 2932, 1736, 1452, 1074 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) endo isomer δ 6.42 (d, J = 5.7 Hz, 1H), 6.34 (dd, J = 5.7, 1.8 Hz, 1H), 4.27 (d, J = 1.8 Hz, 1H), 2.43–1.66 (m, 10H), 1.44 (s, 3H), 1.12 (t, J = 7.6 Hz, 3H), 0.98 (t, J = 7.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.9, 139.8, 138.6, 137.2, 132.5, 87.1, 86.9, 84.2, 43.2, 33.4, 27.1, 23.0, 21.3, 21.1, 20.8, 14.7, 14.5; HRMS calcd for $C_{17}H_{22}O_3$ *m/e* 274.1568, found *m/e* 274.1563.

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Supplementary Material Available: ORTEP structures for **3**, **7a**, and **8a**, ^1H NMR spectra of **5f**, **5g**, **10g**, **10h**, and **14e**, and ^{13}C NMR spectra of **8c**, **9b**, **9d**, **9e**, **10f**, **10i**, **11e**, **12d**, **12e**, and **13e** (18 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.