Tetrahedron Vol. 49, No. 25, pp. 5495-5506, 1993
Printed in Great Britain

0040-4020/93 $6.00+.00

Chromium(0) Promoted [6π+2π] Cycloaddition Reactions

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(*Received in USA* 23 *December* 1992; *accepted* 6 *April* 1993)

Abstract: The chromium(0) mediated [6+2] cycloaddition reactions of a variety of cyclic trienes with substituted alkenes is detailed. The reactions can be effected either photochemically or thermally. Reactions promoted with catalytic quantities of chromium(0) are also described.

So-called higher-order cycloaddition reactions (i.e., those involving 6π+2π, 6π+4π and 4π+4π reactant combinations, Figure 1) display many characteristics normally associated with synthetically attractive processes. They proceed with an attendant rapid increase in molecular complexity, can accommodate extensive functionalization in both addends, and are highly stereoselective.[1a] Unfortunately, these transformations often exhibit poor periselectivity that translates into low chemical yields of the higher-order cycloadducts. As a consequence, most of these reactions have been relegated to the status of laboratory curiosities.

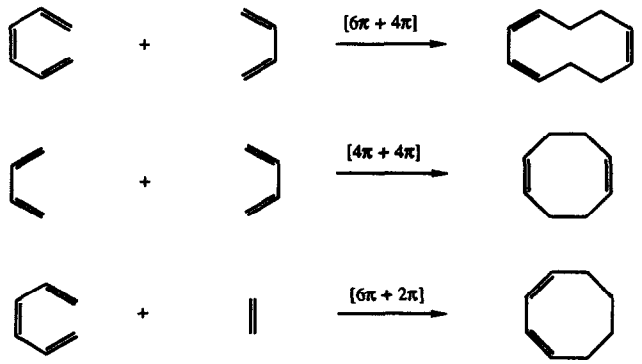


Figure 1. Generalized examples of typical higher-order cycloaddition reactions.

Convinced that higher-order cycloadditions could become important synthetic transformations if a means for controlling periselectivity could be identified, we embarked on a study of transition metal-promoted cycloaddition processes. It was envisioned that an appropriate metal center could serve as a template, which

would pre-complex with the two participants rendering the reaction temporarily intramolecular in nature. This concept as applied to the [6π+2π] combination is depicted in Figure 2. At the outset of this investigation, it was anticipated that metal intervention in the cycloaddition process would serve to limit the options available to the reactants for pericyclic interaction, although predicting which of the many possible pathways would prevail was not obvious. While metal-mediated cycloaddition reactions have been successfully implemented in a variety of situations,[1b-d] only a few useful instances of metal-promoted higher-order processes have surfaced.[1e-h] Among these, the Ni(0) catalyzed intramolecular [4π+4π] process as described by Wender and co-workers was a notable advance, particularly with regard to synthetic utility.[1g,h] As part of ongoing studies in this area, we have

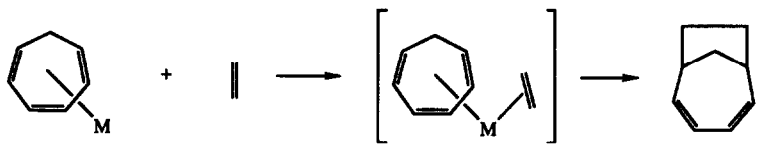
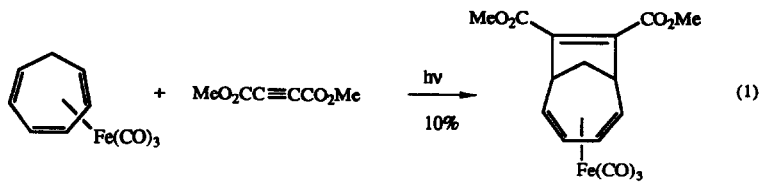


Figure 2. The metal-template effect in the [6π+2π] cycloaddition reaction

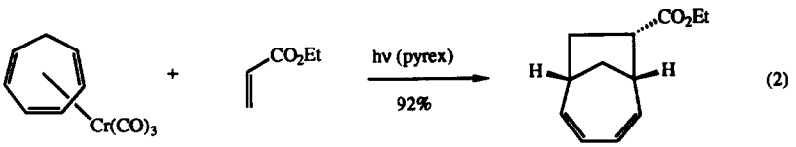
recently demonstrated that a wide range of [6π+4π] cycloadditions can be effectively mediated by chromium(0) and yields of the resultant bicyclo[4.4.1]undecatriene adducts in this series routinely exceed 90%.[2] Exceptionally high levels of stereocontrol is a noteworthy feature of these transformations. We now provide an account of the successful implementation of the corresponding chromium(0) promoted [6π+2π] cycloaddition process.[3]



(1)

When this investigation began relatively few examples of metal-free [6+2] cycloadditions had been reported and in most instances the higher-order pathway was of minor importance.[4] An exception was the work of Feldman who demonstrated that protonated tropones undergo effective photoinduced, intramolecular [6+2] cycloaddition.[5] Prior to our work, only a few examples of metal-mediated [6+2] cycloaddition reactions had appeared and these were of relatively limited scope.[6] Of particular note in this regard was the work of Pettit and co-workers who were among the first investigators to recognize the potential of metal templating for promotion of higher-order cycloaddition reactions.[6a,c] The use of iron(0) for effecting the [6+2] process was a major development in this area although the yields of adducts were modest (Eq. (1)). Subsequent to our preliminary disclosure of the chromium(0) promoted [6π+2π] cycloaddition,[3] reports of a related cycloaddition of substituted acetylenes with (η^6-cycloheptatriene)tricarbonylchromium(0) by Grevels[7a] and Sheridan[7b] appeared.

The metal-promoted [6π+2π] cycloaddition reaction evolved as a natural extension of the corresponding [6π+4π] process and working mechanistic models of the metal-mediated cycloaddition could easily accommodate



(2)

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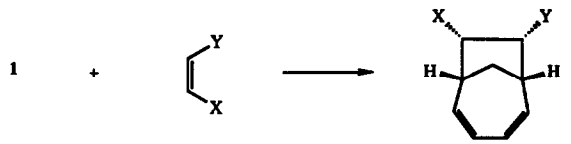
the [6+2] combination.[2c] The photoinduced engagement of readily available (η^6-1,3,5-cycloheptatriene)tricarbonylchromium(0) (1)[8] with ethyl acrylate embodies the basic characteristics of the cycloaddition process as developed in our laboratory. The chemical efficiency of these transformations is quite high, normally providing adduct yields in excess of 90%. Furthermore, the bicyclo[4.2.1]nonadiene products are diastereomerically homogeneous resulting from an exclusive endo approach of the 2π partner.[9,10] In contrast to the corresponding metal-promoted [6π+4π] reaction,[2a] adducts are isolated in a metal-free state directly from the reaction mixture. The results of several representative cycloadditions are compiled in Table I.

Table I. Representative [6π+2π] Cycloaddition Reactions.



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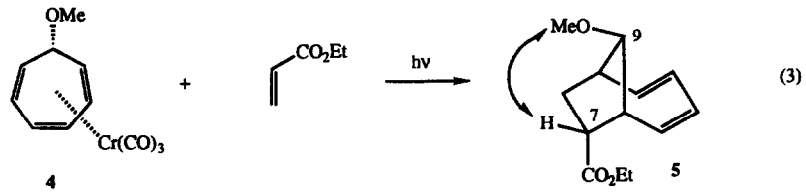
Entry	Product	Alkene	Yield (%)[a]
1	**3a**	X=H, Y=COMe	97[b]
2	**3b**	X, Y=CO_2Et	80
3	**3c**	X=H, Y=SOPh	39[c]
4	**3d**	X=H, Y=SO_2Ph	49
5	--	X=H, Y=n-BuO	0

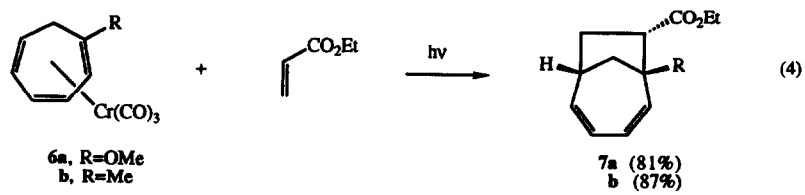
[a] All irradiations performed with a pyrex filter unless otherwise indicated. [b] The product rapidly epimerizes to the β-isomer on standing. [c] Obtained as a 1:1 mixture of diastereomers.

Interestingly, electron rich 2π addends do not participate in the [6+2] cycloaddition process (Entry 5), which is in direct contrast to the insensitivity displayed by the [6+4] reaction toward the electronic nature of the reactants.[2] This phenomenon may be related to the strength of the metal-alkene bond in the intermediate complex between a triene-metal species and the alkene that is presumably involved in these transformations. The interaction of alkenes and zero valent transition metals is primarily via d-π* backbonding and the presence of electron withdrawing groups on the 2π partner lowers the energy of π*, thus enhancing this interaction. The [6+2] reaction is not restricted to carbonyl deactivated alkenes as evidenced by the successful, albeit relatively inefficient, cycloadditions of phenyl vinyl sulfoxide and sulfone (Entries 3 and 4).

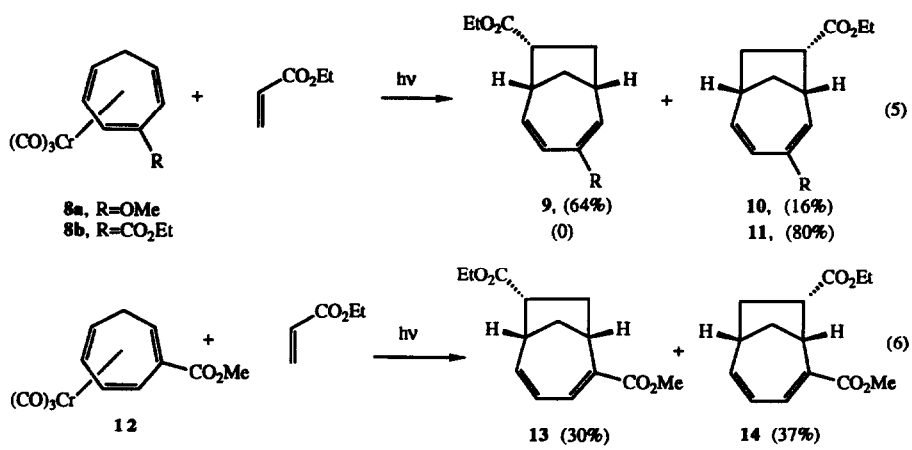
Considerable stereochemical information can be created in the bicyclic adducts emerging from these reactions by judicious selection of participants. Either 7-endo or exo-substituted complexes[11] can be employed as 6π



partners giving rise to products rich in well-defined stereochemistry (Eq. (3)). NOE experiments on **5**, in which irradiation of the 9-methoxy signal resulted in a 7.6% enhancement of the C-7 exo proton signal, provided additional evidence that the acrylate approaches complex **4** from the face proximate to the metal center.

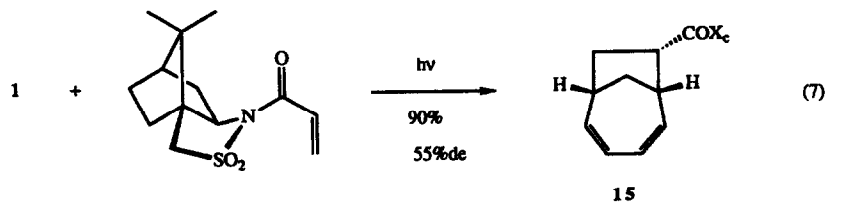


Regiochemical studies have also been conducted on the photoinduced [6π+2π] reaction to more fully understand electronic and steric influences on the course of these transformations. Substituents situated at one of the bond forming centers in the triene complex have a strong influence on the orientation of the addition providing only the more hindered adducts with good efficiency (Eq. (4)). Substituents located at the C-3

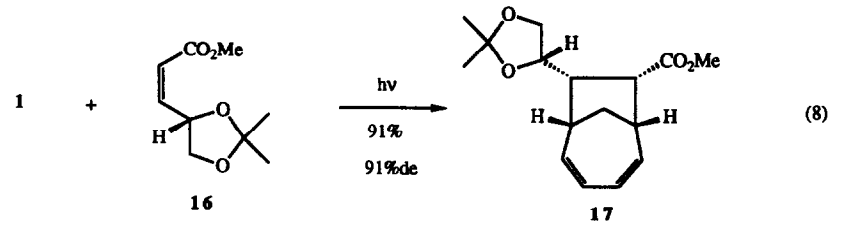


position of the triene also provide for regiochemical discrimination in the resultant products (Eq.(5)). However, the corresponding reactions with complexes substituted at the C-2 position exhibited little discernible selectivity (Eq. (6)). A fully satisfactory rationale for these observations awaits additional examples so that a more complete trend can be identified.

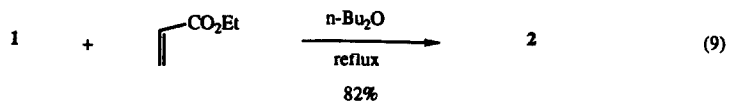
A series of chiral induction studies was also performed. After an extensive screening process, the Oppolzer sultam emerged as the most effective chiral auxiliary on simple acrylate partners (Eq. (7)) and substantial asymmetric induction was evident when the commercially available ester **16** was employed as the 2π



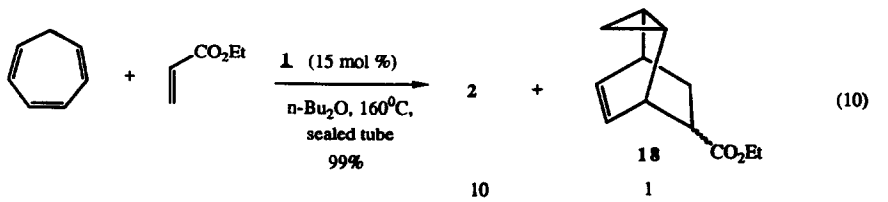
partner (Eq. (8)). The absolute configurations have not been firmly established in either example and the product structures are depicted arbitrarily. Invoking simple steric approach models[12] to predict the sense of asymmetric induction in these transformations is risky due to uncertainties surrounding the mechanistic details of the metal-promoted cycloaddition reaction.



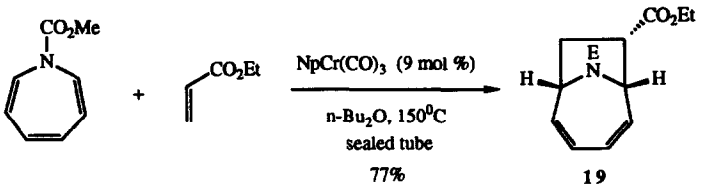
One of the more intriguing and useful aspects of the [6π+2π] cycloaddition process is that it can be effected with more or less equal efficiency using either photochemical or thermal activation. In a typical thermal reaction, a mixture of the triene complex and alkene partner is heated in an ether solvent at reflux. The resultant bicyclic adducts are isolated in yields often exceeding 80% (Eq. (9)). These materials are identical in every respect with those obtained from the corresponding photochemical reaction and, once again, are isolated metal-free.[13]



The apparent efficiency of the thermal version of the [6+2] reaction as well as the metal-free nature of the resultant adducts suggested that the reaction would also be amenable to employing sub-stoichiometric quantities of the "$Cr(CO)_3$" source. Heating a mixture of cycloheptatriene, ethyl acrylate and complex **1** (15 mol%) in n-Bu_2O at 160 °C in a sealed tube provided the anticipated bicyclo[4.2.1]nonadiene adduct **2** in high yield. This compound was accompanied by a small quantity of the normal (metal-free) cycloaddition product between



cycloheptatriene and ethyl acrylate, compound **18**.[4,14] It is noteworthy that performing the same reaction in the absence of the chromium(0) catalyst provided a 65% yield of **18** with only a trace amount of the [6+2] adduct evident. Heterocyclic trienes also are effective participants in the catalytic version of the [6+2] cycloaddition (Eq. (11)). The development of the catalytic version of the metal-promoted [6π+2π] cycloaddition process renders the transformation experimentally convenient and economically attractive and further investigations in these directions are currently underway in our laboratory.



(11)

Np= naphthalene
E = COOMe

Experimental Section

General. All reactions were conducted under a nitrogen atmosphere unless otherwise indicated. Melting points were taken on a Thomas Hoover apparatus and are uncorrected. A General Electric QE-300 NMR spectrometer was used for obtaining the 300 MHz ^{1}H NMR and 75 MHz ^{13}C NMR spectra. IR spectra were recorded on a Nicolet 30 DX spectrophotometer. Photolysis reactions were conducted using a Canrad-Hanovia medium-pressure mercury vapor lamp operating at 450 W, which was placed in a water-cooled immersion well constructed of either quartz or pyrex glass. A sleeve made of uranium glass available from the Houde Glass Co., 1177 McCarter Hwy., Newark, NJ 07104 was also used in certain cases. Combustion analyses were performed by Midwest Microanalytical Laboratories, Indianapolis, IN. Tetrahydrofuran was distilled from sodium-benzophenone ketyl under a nitrogen atmosphere. Hexane (technical grade) was distilled at atmospheric pressure. Chromium hexacarbonyl (Pressure Chemical) was used without further purification.

General Procedure for the Photochemical [6+2] Cycloaddition of (η^6-1,3,5-cycloheptatriene)tricarbonylchromium(0) Complexes. To a dry photochemical reaction vessel, equipped with a pyrex immersion well were added hexanes (350 mL), (η^6-1,3,5-cycloheptatriene)tricarbonylchromium(0) (**1**)[8] (1 mmol) and the alkene (1.5 mmol). The resultant red-orange solution was irradiated (Canrad-Hanovia medium pressure Hg vapor lamp) with a concomitant argon purge until no starting material remained (TLC) (10-90 min). The resultant yellow solution was stirred in air for 10 min giving a colorless solution and green precipitate, which was filtered, concentrated *in vacuo*, and purified by flash chromatography (silica gel).

7α-Ethoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (2). Prepared from complex **1** (228 mg, 1.0 mmol) and ethyl acrylate (150 mg, 1.5 mmol) in hexanes (350 mL) by irradiation for 15 min (uranium glass filter). Chromatography (silica gel, hexanes/diethyl ether, 9:1) afforded 177 mg (92%) of a colorless oil: bp (0.3 Torr): 69-70 °C, IR (film) ν 2938, 1735, 1447, 1190, 1045, 714 cm^{-1}; ^{1}H NMR (300

MHz, $CDCl_3$) δ 1.24 (t, J=7.2 Hz, 3H), 1.98 (d, J=12.3 Hz, 1H), 2.04 (m, 1H), 2.17 (m, 1H), 2.27 (m, 1H), 2.69 (m, 1H), 2.98 (m, 1H), 3.11 (m, 1H), 4.12 (m, 2H), 5.57 (m, 1H), 5.73 (m, 2H), 6.07 (dd, J=8.5, 10.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.47, 33.19, 36.75, 37.22, 43.14, 59.40, 60.27, 123.52, 126.89, 133.55, 140.42, 173.08; mass spectrum: m/e (rel. intensity) 192 (22), 163 (2), 119 (38), 91 (100); HRMS: calcd. for $C_{12}H_{16}O_2$: 192.1150, found, 192.1154; Anal. calcd. for $C_{12}H_{16}O_2$: C, 74.97, H, 8.39, found, C, 74.38, H, 8.34.

7α-Methylcarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (3a). Prepared from complex 1 (228 mg, 1 mmol) and methyl vinyl ketone (140 mg, 2 mmol) in hexanes (350 mL) by irradiation for 15 min (pyrex immersion well) chromatography (silica gel, hexanes/diethyl ether, 95:5) provided 156 mg (97%) of a colorless oil which rapidly epimerized to a mixture of the 7α and 7β isomers on standing for several hours at room temperature: IR ($CDCl_3$) ν 2937, 1705, 1359, 1167 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.91 (m, 1H), 2.03 (d, J=12 Hz, 1H), 2.15 (s, 3H), 2.24 (m, 1H), 2.34 (m, 1H), 2.71 (m, 1H), 3.09 (m, 1H), 3.21 (m, 1H), 5.56 (dd, J=6.2, 10.9 Hz, 1H), 5.73 (m, 2H), 6.10 (dd, J=8.4, 9.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.25, 33.50, 35.99, 36.94, 43.20, 68.69, 123.38, 127.34, 132.88, 140.75, 207.72; mass spectrum: m/e (rel. intensity) 162 (32), 119 (27), 104 (20), 91 (100); HRMS: calcd. for $C_{11}H_{14}O$: 162.1044, found, 162.1043.

7α,8α-Bis(ethoxycarbonyl)-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (3b). Prepared from complex 1 (228 mg, 1 mmol) and diethyl maleate (258 mg, 1.5 mmol) in hexanes (350 mL) by irradiation (17 min, pyrex). Chromatography (silica gel, hexanes/diethyl ether; 85:15) provided 210 mg (80%) of colorless crystals: mp = 32-33 °C (hexanes); IR (film) ν 2943, 1734, 1161, 1032, 735 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.20 (t, J=7.2 Hz, 6H), 2.11 (m, 2H), 2.99 (m, 2H), 3.26 (dd, J=2.5, 5.5 Hz, 2H), 4.06 (q, J=7.2 Hz, 4H), 5.59 (dd, J=3.0, 9.1 Hz, 2H), 5.93 (dt, J=3.3, 8.4 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.23, 32.87, 40.76, 56.61, 60.12, 125.91, 135.02, 171.50; mass spectrum: m/e (rel. intensity) 264 (32), 219 (22), 190 (26), 145 (19), HRMS: calcd. for $C_{15}H_{20}O_4$: 264.1361, found, 264.1357: Anal. calcd. for $C_{15}H_{20}O_4$: C, 68.16, H, 7.63, found, 68.35, H, 7.70.

7α-Phenylsulfinyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (3c). Prepared from complex 1 (241 mg, 1.05 mmol) and phenyl vinyl sulfoxide (159 mg, 1.04 mmol) in hexanes (350 mL) by irradiation (1.5 h, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 4:1) afforded starting sulfoxide (30 mg) and two products in nearly equal amounts: isomer #1: 35 mg (17%); IR ($CDCl_3$) ν 3057, 3019, 1638, 1030 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.75 (m, 1H), 1.87 (d, J=12.3 Hz, 1H), 2.13 (m, 1H), 2.28 (m, 1H), 2.75 (m, 1H), 3.10 (m, 1H), 3.22 (m, 1H), 5.63 (m, 2H), 5.89 (m, 1H), 6.01 (m, 1H), 7.40-7.59 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 32.17, 37.91, 40.35, 40.77, 72.32, 123.81, 124.19, 125.40, 128.93, 130.64, 136.90, 138.03, 142.93; mass spectrum: m/e (rel. intensity) 243 (0.3), 119 (81), 118 (27); HRMS calcd. for $C_{15}H_{16}OS$ - (PhSO): 119.0860, found, 119.0863. Isomer #2: 45 mg (22%); IR ($CDCl_3$) ν 3057, 3019, 1644, 1036 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.72 (m, 2H), 2.10-2.30 (m, 2H), 2.50 (m, 1H), 2.80 (m, 1H), 3.42 (m, 1H), 5.70 (m, 1H), 5.90-6.30 (m, 3H), 7.48 (m, 3H), 7.69 (m, 1H), 7.74 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 33.05, 36.80, 37.00, 37.53, 80.44, 124.93, 124.97, 127.94, 129.06, 129.22, 131.30,

131.91, 140.16; mass spectrum: m/e (rel. intensity) 244 (19), 167 (1), 119 (73); HRMS: calcd. for $C_{15}H_{16}OS$: 244.0921, found, 244.0919.

7α-Phenylsulfonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (3d). Prepared from complex 1 (240 mg, 1.04 mmol) and phenyl vinyl sulfone (184 mg, 1.09 mmol) in hexanes (350 mL) by irradiation (45 min, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 9:1) provided 132 mg (49%) of a colorless oil: IR ($CDCl_3$) ν 3060, 3016, 1983, 1958, 1594, 1306, 1144 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.95 (d, J=12.2 Hz, 1H), 2.28 (m, 3H), 2.80 (m, 1H), 3.28 (m, 1H), 3.72 (m, 1H), 5.65 (m, 2H), 5.88 (m, 2H), 7.58 (m, 3H), 7.89 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.98, 38.78, 40.68, 42.24, 72.69, 124.19, 125.60, 127.95, 128.27, 129.16, 133.52, 136.72, 137.22; mass spectrum: m/e (rel. intensity) 260 (6), 141 (0.4), 119 (100); HRMS: calcd. for $C_{15}H_{16}O_2S$, 260.0871, found, 260.0870.

7α-Ethoxycarbonyl-9α-methoxy-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (5). Prepared from complex **4**[11] (258 mg, 1 mmol) and ethyl acrylate (150 mg, 1.5 mmol) in hexanes (350 mL) by irradiation (20 min, pyrex). Chromatography (silica gel, hexanes/diethyl ether, 94:6) afforded 151 mg (68%) of a colorless oil: bp (0.77 Torr) = 88-89 °C; IR (film) ν 2941, 1737, 1455, 1179, 1095 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.25 (t, J=7.2 Hz, 3H), 2.18 (m, 1H), 2.46 (m, 1H), 2.61 (m, 1H), 3.02 (m, 1H), 3.35 (s, 3H), 3.53 (m, 1H), 4.14 (m, 2H), 4.17 (s, 1H), 5.53 (m, 2H), 5.70 (dd, J=7.0, 11.8, Hz, 1H), 5.90 (dd, J=9.4, 10.6 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.48, 35.82, 42.56, 47.15, 56.38, 57.26, 60.37, 87.87, 124.19, 127.17, 128.08, 134.43, 173.59; mass spectrum: m/e (rel. intensity) 222 (42), 177 (6), 149 (28), 117 (100); HRMS: calcd. for $C_{13}H_{18}O_3$: 222.1256, found: 222.1250; Anal. calcd. for $C_{13}H_{18}O_3$: C, 70.25, H, 8.16, found, C, 70.62, H, 8.22.

8α-Ethoxycarbonyl-1β-methoxy-(6Hβ)-bicyclo[4.2.1]nona-2,4-diene (7a). Prepared from complex **6a**[11c] (516 mg, 2.0 mmol) and ethyl acrylate (300 mg, 3.0 mmol) in hexanes (350 mL) by irradiation (90 min, quartz). Chromatography (silica gel; hexanes/diethyl ether, 95:5) afforded 361 mg (81%) of a colorless oil: bp (0.4 Torr)= 100-101 °C; IR (film) ν 2938, 1735, 1371, 1096, 1047, 756 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.23 (t, J=7.2 Hz, 3H), 2.19 (m, 2H), 2.47 (m, 1H), 2.49 (d, J=11.7 Hz, 1H), 2.61 (m, 1H), 3.19 (dd, J=7.9, 11.0 Hz, 1H), 3.36 (s, 3H), 4.16 (m, 2H), 5.54 (dd, J=6.8, 11.1 Hz, 1H), 5.76 (m, 2H), 5.99 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.48, 33.75, 35.88, 37.03, 53.04, 60.51, 62.65, 87.32, 123.13, 125.50, 136.25, 139.47, 172.30; mass spectrum: m/e (rel. intensity) 222 (23), 177 (8), 149 (13), 122 (100); HRMS: calcd. for $C_{13}H_{18}O_3$: 222.1256, found, 222.1258.

8α-Ethoxycarbonyl-1β-methyl-(6Hβ)-bicyclo[4.2.1]-nona-2,4-diene (7b). Prepared from complex **6b**[11c] (171 mg, 0.705 mmol) and ethyl acrylate (150 mg, 1.5 mmol) in hexanes (350 mL) by irradiation (25 min, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 5:1) afforded 127 mg (87%) of a colorless oil: IR ($CDCl_3$) ν 3033, 2951, 2869, 1729, 1606, 1335, cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.25 (t, J=7.2 Hz, 3H), 1.35 (s, 3H), 2.10 (m, 3H), 2.40 (m, 1H), 2.60 (m, 1H), 2.75 (dd, J=9.2, 10.1 Hz, 1H), 4.10 (q, J=7.2 Hz, 2H), 5.40 (d, J=11.6 Hz, 1H), 5.50 (dd, J=7.2, 10.9 Hz, 1H), 5.65 (dd, J=7.4, 12.3 Hz, 1H), 6.05 (dd, J=8.8; 10.8 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.31, 26.27, 35.39, 38.00, 42.30,

48.25, 59.95, 64.89, 122.97, 124.79, 138.85, 140.15, 172.73; mass spectrum: m/e (rel. intensity) 206 (61), 165 (10), 133 (60), 117 (21), 106 (66); HRMS: calcd. for $C_{13}H_{18}O_2$: 206.1306, found, 206.1302.

7α-Ethoxycarbonyl-3-methoxy-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (9) and 8α-Ethoxycarbonyl-3-methoxy-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (10). Prepared from complex **8a**[11c] (150 mg, 0.58 mmol) and ethyl acrylate (100 mg, 1.0 mmol) in hexanes (350 mL) by irradiation (15 min, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 20:1) afforded 104 mg (80%) consisting of a mixed fraction of the two isomers and a fraction containing only the major isomer **9**: IR ($CDCl_3$) ν 2862, 1734, 1648, 1622, 1474, 1376, 1047 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.14 (t, J=7.1 Hz, 3H), 1.90 (d, J=12 Hz, 1H), 2.15 (m, 3H), 2.70 (dd, J=3.4, 8.6 Hz, 1H), 2.95 (dd, J=6.0, 11.8 Hz, 1H), 3.05 (t, J=9.4 Hz, 1H), 3.39 (s, 3H), 4.10 (q, J=7.1 Hz, 2H), 5.13 (dd, J=1.8, 9.3 Hz, 1H), 5.67 (dd, J=2.3, 12.5 Hz, 1H), 5.77 (dd, J=6.8, 12.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.23, 32.82, 34.66, 37.25, 42.66, 54.25, 58.24, 60.14, 107.66, 127.18, 133.39, 153.57, 172.81; mass spectrum: m/e (rel. intensity) 222 (32), 177 (13), 122 (100), 109 (76); HRMS: calcd. for $C_{13}H_{18}O_3$: 222.1258, found: 222.1256.

Decoupling experiments on this isomer substantiated the structure assigned to compound **9** and the minor product was assumed to be the other regioisomer, **10**.

8α-Ethoxycarbonyl-3-methoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (11). Prepared from complex **8b**[11d] (90 mg, 0.32 mmol) and ethyl acrylate (60 mg, 0.6 mmol) in hexanes (350 mL) by irradiation (20 min, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 6:1) provided 60 mg (80%) of a colorless oil: IR ($CDCl_3$) ν 2957, 2871, 1735, 1702, 1603, 1483, 1430, 1384, 1330 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.24 (t, J=7.1 Hz, 3H), 2.00 (d, J=12.2 Hz, 1H), 2.10-2.30 (m, 3H), 2.75 (m, 1H), 3.20 (m, 2H), 3.70 (s, 3H), 4.10 (q, J=7.1 Hz, 2H), 6.20 (m, 2H), 7.10 (d, J=6.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.37, 32.56, 37.10, 37.77, 42.33, 52.15, 58.39, 60.58, 121.03, 130.21, 140.84, 143.56, 168.06, 172.55; mass spectrum: m/e (rel. intensity) 250 (54), 218 (27), 190 (31), 157 (69), 137 (77); HRMS: calcd. for $C_{14}H_{18}O_4$: 250.1205, found, 250.1209.

2-Methoxycarbonyl-7α-ethoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (13) and 2-Methoxycarbonyl-8α-ethoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (14). Prepared from complex **12**[15] (217 mg, 0.76 mmol) and ethyl acrylate (130 mg, 1.3 mmol) in hexanes (350 mL) by irradiation (15 min, pyrex). Chromatography (silica gel, hexanes/ethyl acetate, 20:1) afforded 56 mg (30%) of **13** and 69 mg (37%) of the isomeric **14**: **13**: IR ($CDCl_3$) ν 1735, 1701, 1437, 1269, 1247, 1196 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.24 (t, J=6.8 Hz, 3H), 1.90 (d, J=12.5 Hz, 1H), 2.20 (m, 3H), 3.02 (m, 1H), 3.15 (m, 1H), 3.47 (m, 1H), 3.72 (s, 3H), 4.10 (q, J=6.9 Hz, 1H), 5.90 (dd, J=7.4, 11.6 Hz, 1H), 6.15 (dd, J=7.3, 11.7 Hz, 1H), 6.80 (d, J=7.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.27, 32.53, 35.03, 36.58, 43.32, 51.93, 59.42, 60.30, 125.00, 132.09, 141.34, 168.11, 172.35; mass spectrum: m/e (rel. intensity) 250 (43), 218 (24), 177 (23), 150 (16), 117 (95); HRMS: calcd. for $C_{14}H_{18}O_4$: 250.1204, found, 250.1200. **14**: IR ($CDCl_3$) ν 2952, 1719, 1592, 1436, 1198 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.23 (t, J=7.0 Hz, 3H), 1.80 (m, 1H), 2.25 (m, 3H), 3.05 (m, 1H), 3.10 (m, 1H), 3.50 (m, 1H), 3.73 (s, 3H), 4.10 (q, J=7.0 Hz, 2H), 5.80 (dd, J=7.7, 11.2 Hz, 1H), 6.40 (dd, J=8.3, 11.1 Hz, 1H), 6.85 (d, J=7.7 Hz, 1H); ^{13}C NMR (75

MHz, $CDCl_3$) δ 14.16, 31.39, 38.67, 42.87, 43.02, 51.95, 55.81, 60.56, 123.06, 132.71, 139.60, 144.96, 168.221, 174.47; mass spectrum: m/e (rel. intensity) 250 (25), 177 (23), 150 (75), 137 (44), 135 (39), 117 (100); HRMS: calcd. for $C_{14}H_{18}O_4$: 250.1204, found, 250.1199.

7α-{[3aS-(3aα,6α,7aβ)]-Hexahydro-8,8-dimethyl-3H-3a,6-methano-2,1-benzisothiazole-2,2-dioxide}carbonyl-(1Hβ,6Hβ)-bicyclo-[4.2.1]nona-2,4-diene (15). Prepared from complex **1** (227 mg, 1.0 mmol) and [3aS-(3aα,6α,7aβ)]-hexahydro-8,8-dimethyl-3H-3a,6-methano-2,1-benzisothiazole-2,2-dioxide-1-prop-2-enoate[12] (188 mg, 1.1 mmol) in hexanes (350 mL) by irradiation (40 min, pyrex). Chromatography (silica gel, hexanes/diethyl ether, 1:1) afforded 157 mg (90%) (55% de) of a colorless oil: IR ($CDCl_3$) ν 3016, 2964, 2886, 1700, 1330, 1265, 1236, 1165, 1132 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.96 (s, 3H), 1.15 (m, 1H), 1.19 (s, 3H), 1.41 (m, 2H), 1.88 (m, 4H), 2.05 (m, 2H), 2.31 (m, 1H), 2.55 (m, 1H), 2.69 (m, 1H), 3.31 (m, 1H), 3.46 (d, J=9.2 Hz, 2H), 3.68 (m, 1H), 3.88 (m, 1H), 5.57 (m, 2H), 5.77 (dd, J=7.1, 11.6 Hz, 1H), 6.08 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.06, 20.82, 26.64, 32.94, 33.89, 37.20, 38.70, 44.51, 44.72, 47.86, 48.18, 53.33, 60.41, 65.73, 123.57, 127.83, 132.60, 140.45, 171.53.

7α-Methoxycarbonyl-8α-(S)-(2,2-dimethyl-1,3-dioxolanyl)-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (17). Prepared from compound **16** (279 mg, 1.5 mmol) and complex **1** (228 mg, 1.0 mmol) in hexanes (350 mL) by irradiation (25 min, pyrex). Chromatography (silica gel, hexanes/diethyl ether, 97:3) afforded 242 mg (91%) (91% de) of a colorless oil: IR (film) ν 2986, 1743, 1379, 1259, 706 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.33 (s, 3H), 1.40 (s, 3H), 2.16 (d, J=12.0 Hz, 1H), 2.28 (m, 2H), 2.84 (m, 1H), 3.22 (m, 2H), 3.42 (dd, J=5.4, 8.1 Hz, 1H), 3.54 (s, 3H), 4.03 (dd, J=6.3, 8.1 Hz, 1H), 5.06 (m, 1H), 5.67 (m, 2H), 5.77 (m, 1H), 5.98 (dd, J=7.61, 11.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.30, 27.43, 32.38, 42.22, 43.26, 51.11, 54.21, 58.06, 69.14, 74.20, 108.49, 125.99, 126.65, 133.33, 135.39, 172.86; mass spectrum: m/e (rel. intensity) 278 (25), 263 (24), 221 (32), 188 (21), 143 (23); HRMS: calcd. for $C_{16}H_{22}O_4$: 278.1518, found, 278.1521; Anal. calcd. for $C_{16}H_{22}O_4$: C, 69.04, H, 7.97, found: C, 68.96, H, 8.07.

7α-Ethoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (2) (Thermal activation). To an oven-dried Carius tube was added complex **1** (150 mg, 0.66 mmol), ethyl acrylate (0.5 mL, 4.6 mmol) and freshly distilled n-Bu_2O (15 mL). The solution was degassed by the "freeze-pump-thaw" technique, sealed under vacuum, and heated at 140 °C (6 h). After cooling, the mixture was concentrated *in vacuo* and the residue purified by chromatography (silica gel, chloroform/hexanes, 1:10) to afford compound **2** (104 mg, 82%). The spectral data for this material was identical in all regards with the compound derived from the photochemical reaction.

7α-Ethoxycarbonyl-(1Hβ,6Hβ)-bicyclo[4.2.1]nona-2,4-diene (2) (Catalytic reaction). An oven-dried Carius tube was charged with complex **1** (159 mg, 0.7 mmol) ethyl acrylate (1.0 mL, 9.2 mmol) cycloheptatriene (0.55 mL, 4.8 mmol) and freshly distilled (from $LiAlH_4$) n-Bu_2O (10 mL). The contents were degassed as before, sealed and heated at 160 °C (15 h). After cooling, the green mixture was filtered through Celite, concentrated *in vacuo* and purified by chromatography (silica gel, chloroform/hexanes, 1:10) to afford

compound **2** (948 mg, 90%) and compound **18**[14] (96 mg, 9%). The spectral data of **2** were identical to authentic material.

7α-Ethoxycarbonyl-9-methoxycarbonyl-(1Hβ,6Hβ)-9-azabicyclo[4.2.1]nona-2,4-diene (19). Prepared by heating a mixture of (N)-methoxycarbonylazepine[16] (254 mg, 1.68 mmol), ethyl acrylate (254 mg, 2.54 mmol), (η^6-naphthalene)tricarbonylchromium(0)[17] (41 mg, 0.15 mmol) in n-Bu_2O (10 mL) at 150 °C (20 h) in a sealed tube as above. Chromatography (silica gel, hexanes/ethyl acetate, 9:1) afforded 195 mg (77% based on recovered starting material) of a white solid which exists as N-(CO)OMe rotamers: mp 63-63.5 °C (hexanes, Et_2O); IR ($CDCl_3$) ν 3015, 1734, 1690, 1096 cm^{-1}; ^1H NMR (300 mHz, $CDCl_3$) δ 1.15 (t, J=7.1 Hz, 3H), 2.40 (m, 2H), 3.45 (m, 1H), 3.65 (s, 3H), 4.14 (m, 2H), 4.45 (m, 1H), 4.84 (m, 1H), 5.68 (m, 1H), 5.84 (m, 2H), 6.20 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.13, 36.12, 37.41, 52.41, 54.94, 57.72, 58.63, 58.69, 58.78, 60.75, 123.63, 126.65, 126.89, 132.88, 133.03, 138.62, 138.91, 154.45, 170.26, 170.42, mass spectrum: m/e (rel. intensity) 251 (43), 222 (2), 206 (7), 192 (2), 178 (22), 151 (100); HRMS: calcd. for $C_{13}H_{17}NO_4$: 251.1158, found, 251.1160; Anal calcd. for $C_{13}H_{17}NO_4$: C, 62.13, H, 6.82, N, 5.57, found, C, 62.30, H, 6.82, N, 5.52.

Acknowledgment: The authors wish to thank the National Institutes of Health (GM-30771) for their generous support of this research.

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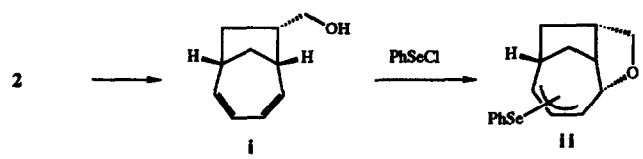

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