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Investigation of Bicyclic Thioketones as Triggers for Liquid Crystal Optical Switches

Rochelle Fisher Bradford and Gary B. Schuster*

School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, Georgia 30332

gschuster@cosdean.cos.gatech.edu

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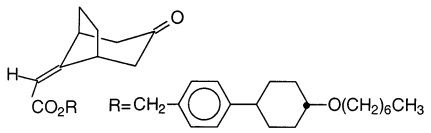
The axially chiral bicyclic thioketones **11** and **15** were prepared and investigated for suitability as chiroptical triggers in a liquid crystal optical switch. Irradiation of partially resolved **15** with unpolarized light leads to its conversion to the racemic form (photoracemization). However, irradiation of racemic thioketones **11** and **15** with circularly polarized light does not lead to detectable photoresolution. The lack of photoresolution was traced to inefficiency in intramolecular, through-bond triplet energy transfer. These thioketones are not suitable for use as phototriggers.

Introduction

There is widespread interest in the development of materials that can be switched by light between independent, stable states and can be detected optically without their destruction or interconversion.[1−8] Such materials have potential for incorporation in devices that may be useful for display or memory applications. We have been developing a series of chiroptical triggers for liquid crystalline materials that may be useful for such devices.[1,9−11]

A chiroptical trigger is an optically active compound whose enantiomers are interconverted by irradiation with visible or ultraviolet light. Irradiation of one enantiomer of such a compound with unpolarized light will convert it to the racemic mixture (photoracemization). Irradiation of the racemic mixture with circularly polarized light (CPL) will cause a partial photoresolution with the enantiomeric excess at the photostationary state ($[\gamma]_{pss}$) determined by the Kuhn anisotropy factor ($g_\lambda = \Delta\epsilon_\lambda/\epsilon_{\lambda avg}$) according to $[\gamma]_{pss} = g_\lambda/2$, where $\Delta\epsilon_\lambda$ is the difference between molar extinction coefficients for an enantiomer with right- and left-handed CPL at wavelength λ, determined by circular dichroism (CD) spectroscopy, and $\epsilon_{\lambda avg}$ is the average extinction coefficient of the two enantiomers determined by absorption spectroscopy.[12−16]



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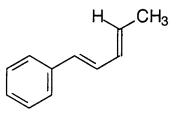

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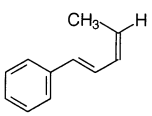

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Incorporation of an optically active form of such a trigger in an achiral liquid crystalline material will usually produce a cholesteric texture.[17−21] In a functioning chiroptical switch, irradiation of the racemic trigger with CPL in a nematic liquid crystal will convert the liquid crystal to its cholesteric texture; irradiation of the trigger with normal light will racemize it and result in the reformation of the nematic texture. The difference between nematic and cholesteric liquid crystals is readily sensed nondestructively by optical methods.[22]

We have developed chiroptical triggers based on these principles and we have shown their utility in the development of an optical switch.[1] In this earlier report, the chiroptical trigger compound is a ketone linked by a bicyclic unit to a photoisomerizable olefin, see structure **1**. Irradiation of the ketone chromophore with either CPL or unpolarized light in a liquid crystal solution causes through-bond triplet energy transfer and isomerization of the olefinic group, which triggers the reversible conversion of nematic and cholesteric textures. In this system, the lowest energy nπ* ketone chromophore absorbs light at ca. 300 nm, which is a spectral region where most liquid crystalline materials also absorb. This

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property of the known chiroptical triggers limits their utility because overlap of the trigger and liquid crystalline material absorption spectra at the irradiation wavelength cannot be tolerated in a switch. Consequently, we have sought chiroptical triggers that absorb in the visible region of the spectrum where few liquid crystalline materials absorb light. The attempt to develop such a trigger based on the thiocarbonyl chromophore (λ_{max} = 480 nm for the nπ* absorption band) is reported here.

Results

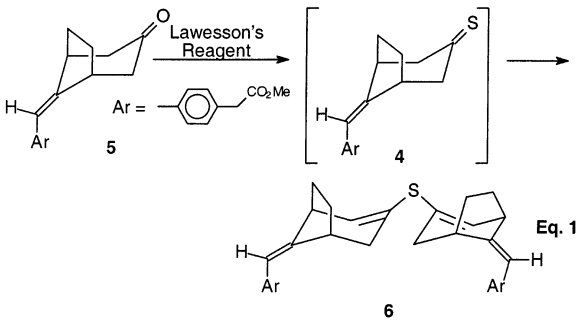
1. Thioketones as Photosensitizers for Olefin Isomerization. It is generally known that triplet−triplet energy transfer from a sensitizer to an olefinic compound occurs efficiently and causes double bond isomerization when the triplet energy of the sensitizer is greater than that of the olefin by at least ca. 2−3 kcal/mol.[23] The triplet energy of the thiocarbonyl chromophore in aliphatic compounds is ca. 57 kcal/mol.[24] The spectroscopic (vertical) triplet energy of *trans*-β-methylstyrene, a model for the isomerizable component of previously studied chiroptical triggers, is estimated to be ca. 60.5 kcal/mol by O_2 perturbation of its absorption spectrum, but the triplet energy of its relaxed, twisted conformation is estimated to be 53 kcal/mol.[25] Hence, we studied the ability of 2-adamantanethione (a model for the bicyclic thioketone chromophore of possible chiroptical triggers) to sensitize the isomerization of β-methylstyrene by a "non-vertical energy transfer" mechanism.

Irradiation of 2-adamantanethione (0.04 M) in a deoxygenated benzene-d_6 solution (for ease of analysis by NMR spectroscopy) containing *trans*-β-methylstyrene (0.2 M) with visible light for 3 h did not result in the formation of a detectable amount of *cis*-β-methylstyrene. A control experiment showed that irradiation (at 300 nm) of a solution containing 2-adamantanone (triplet energy = 80 kcal/mol[24]) in place of the thioketone results in efficient isomerization of the olefin. Evidently, sensitization of the styrene isomerization by 2-adamantanethione is inefficient, probably because its triplet energy is too low.

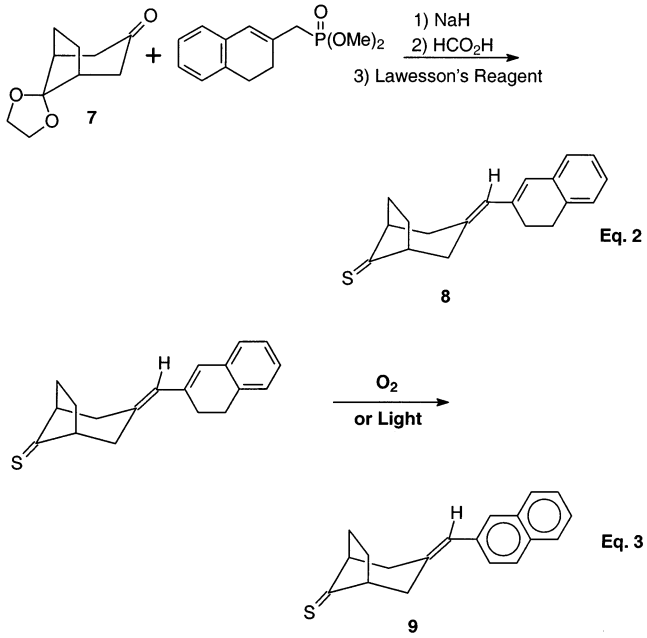
The vertical triplet energies of *trans*-piperylene and *cis*-piperylene are reported to be 54 and 53 kcal/mol, respectively, based on triplet sensitization experiments.[24] We find that irradiation of 2-adamantanethione in solutions containing piperylene causes the isomerization of the cis isomer but not the trans form. From this result, we assume that dienes with vertical triplet energies of 53 kcal/mol or lower will be isomerizable by triplet sensitization with thioketones. To confirm this hypothesis, we studied the sensitized isomerization of a mixture of *E* and *Z* isomers of 1-phenyl-4-methyl-1,3-butadiene (structure **2** and **3**). We find that this mixture of olefins is isomerized by both 2-adamantanethione and 2-adamantanone. On this basis, we conclude that aryl-substituted dienes have suitable triplet energies for sensitization by thioketones and we designed a series of possible chiroptical triggers that incorporate these groups into a bicyclic structure.

2. Design and Synthesis of Thioketone-Containing Chiroptical Triggers. Our first attempt to develop a thioketone-containing trigger compound focused on bicyclic compound **4**, which incorporates a substituted styrene group appended to the 6-position of a bicyclo[3.2.1]octane framework. This structure was selected as a model for the conversion of a rigid aliphatic ketone to a thioketone because it mimics the bicyclic core of previously prepared triggers.

Ketone **5** was prepared according to a procedure that has been described previously.[11] Its treatment with Lawesson's reagent, $C_{14}H_{14}O_2P_2S_4$, or any of a number of other thionating reagents, yields primarily the dimeric sulfide **6** (eq 1) or no reaction at all. Formation of dimeric



sulfides is a common decomposition route for aliphatic thioketones having enolizable protons.[26,27] Consequently, we modified the structure of the target compounds to avoid this problem. The 7-thiocarbonylbicyclo[3.2.1]octane structure shown in eq 2 will not dimerize to the sulfide readily because formation of the enol violates Bredt's rule.[28] This skeleton forms the core of a family of potential trigger compounds we prepared and investigated.



Our synthesis of the racemic bicyclo[3.2.1]octane-containing triggers begins with monoprotected diketone

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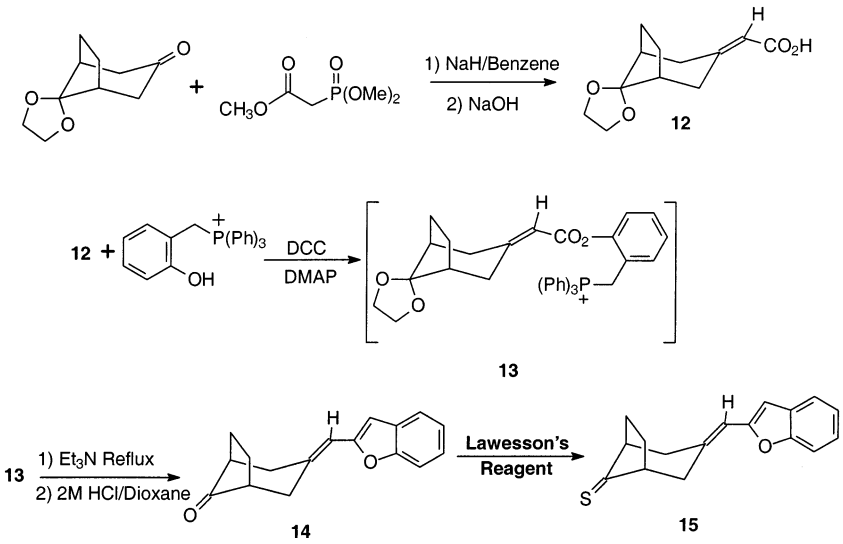
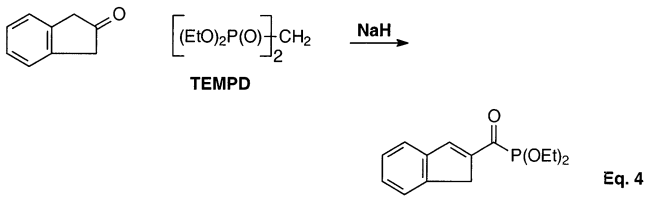
SCHEME 1



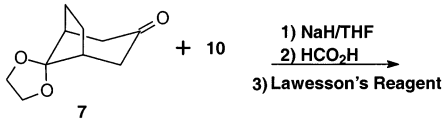
7, which has been prepared previously.[11] The Horner−Wadsworth−Emmons reaction of **7** to form the benzo-substituted diene was followed by deprotection and conversion to the thioketone **8** with Lawesson's Reagent, as is shown in eq 2. Other methods to convert the ketone to the thioketone gave mostly trithiolane byproducts.[29] Unfortunately, thioketone **8** is prone to O_2 and light-initiated oxidation to the naphthalene compound, **9**, which made its isolation in pure form difficult and reduces its value as a potential chiroptical trigger (eq 3). Hence, we turned our attention to indene-containing potential trigger compounds which cannot oxidize in this way.

The reaction of tetraethylmethylenediphosphonate (TEMPD) with 2-indanone and NaH gives diethylphosphonate ester (**10**) in 76% yield (eq 4). The Horner−Wadsworth−Emmons reaction of **10** with the protected diketone (**7**) followed by deprotection and thionation with Lawesson's reagent gives racemic thioketone **11** in 40% overall yield (eq 5). Optically active thioketones are



Eq. 4

10



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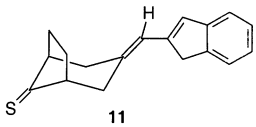

Eq. 5

11

required for assessment of their utility as chiroptical triggers. We attempted to resolve thioketone **11** by chiral chromatographic methods; however, all attempts failed. Similarly, attempts to separate diastereomeric derivatives of the ketone precursor to **11** failed to provide material that could be transformed into optically active thioketone.

We designed and prepared a potential chiroptical trigger containing a benzofuran group on the hypothesis that heteroatoms in the aryl-substituted diene portion would provide an additional interaction for resolution using chiral chromatographic methods and increase the likelihood of its success. In addition, the synthetic route selected for preparation of this trigger proceeds through an intermediate carboxylic acid that provides an opportunity for the classical resolution of enantiomers by formation of diastereomeric salts. The target compound (**15**) and the synthetic route are shown in Scheme 1. It was discovered that thioketone **15** could not be resolved into enantiomers by chromatographic procedures. Consequently, carboxylic acid **12** was partially resolved by forming its diastereomeric salts with quinine and the preferential precipitation of one compound. The CD spectrum of partially resolved **12** is shown in Figure 1. Optically active **12** was converted to optically active **15** by following the route shown in Scheme 1.

3. Optical Characterization and Photochemistry of Potential Triggers 11 and 15. One objective for the preparation of thioketone-containing triggers is to move the action spectrum of a chiroptical switch to the visible region. Figure 2 shows the region of the spectrum of thioketone **11** from 350 to 600 nm. As is typical of aliphatic thioketones, it exhibits a weak ($n\pi^*$) band with λ_{max} at ca. 480 nm. The absorption spectrum of **15** is similar.

A successful chiral trigger will be partially photoresolved by irradiation with CPL. The irradiation of racemic thioketones **11** and **15** with CPL (λ > 400 nm) in deoxygenated benzene solution was monitored by absorption and CD spectroscopy. These thioketones were consumed very slowly during the course of the irradiation (by monitoring its absorption spectrum), but even after several days of irradiation the CD spectrum showed no

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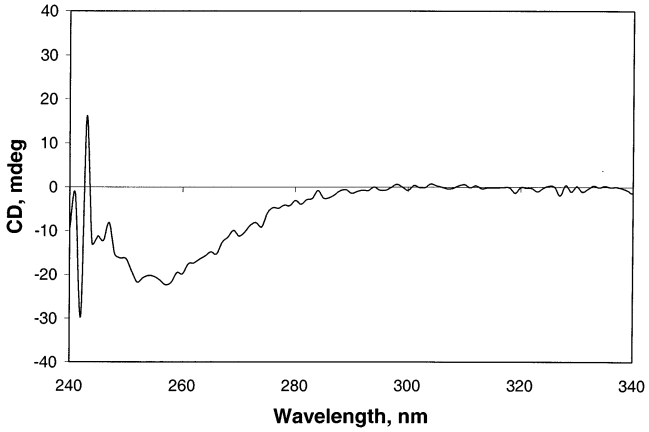

FIGURE 1. CD spectrum of partially resolved **12** (4.4 mM in CH_2Cl_2 solution in a 1.0 cm path length cell).

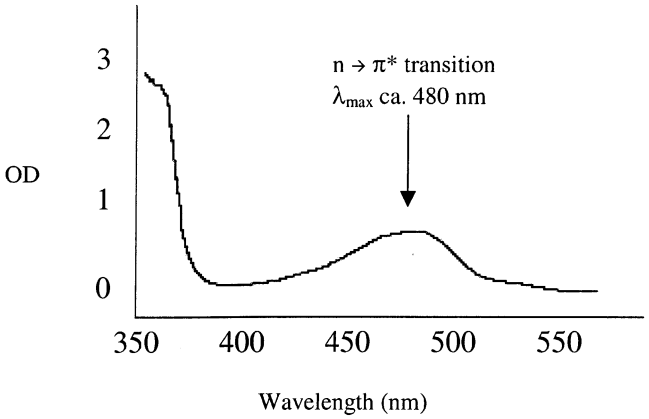

FIGURE 2. Absorption spectrum of **11** (30 mM in deuterated benzene solution in a 1.0 cm path length cell).

sign of partial photoresolution. The failure to detect photoresolution could be a consequence of either an inadequate g_λ value or inefficient intramolecular triplet energy transfer from the thioketone to the isomerizing group.

We determined the quantum efficiency for the photoracemization of optically active thioketone **15**. Irradiation of a deoxygenated benzene solution prepared from partially resolved **15** in the visible spectral region results in the slow loss of optical activity that is revealed by analysis of the CD spectrum in Figure 3. The quantum yield for photoracemization (Φ_{rac}) of **15** at 450 nm was determined to be 0.04 by using a Reinecke's salt actinometer.[30] This is about 10% of the value measured for intramolecular through-bond triplet−triplet energy transfer when the sensitizer is a ketone.[9]

Discussion

The goals of this work were to prepare and characterize a chiroptical trigger that absorbs in the visible spectral region. Thioketone-containing compounds were prepared that could have fulfilled this objective. These compounds are chiral and are theoretically capable of partial photoresolution and photoracemization. However, the efficiency of photoresolution is exponentially dependent on the Φ_{rac}, which means that a low value for this parameter

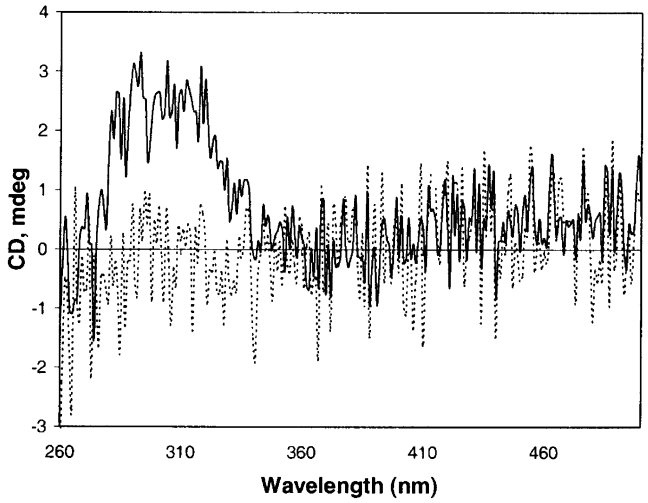

FIGURE 3. A photoracemization of partially resolved **15** (1.4 mM deuterated benzene solution in a 1.0 cm path length cell): (−) before irradiation and (--) after irradiation with unpolarized light for 24 h.

will cause the trigger to be useless.[31] We find that the Φ_{rac} of the thioketone-containing triggers is approximately an order of magnitude less than their ketone-containing counterparts, which explains why no photoresolution was detected when **11** or **15** was irradiated with CPL.

It is worthwhile to speculate briefly about the reasons that underlie the inefficient triplet−triplet energy transfer in the thioketone triggers. We demonstrated that 2-adamantanethione is an effective sensitizer of diene **2**, which shows that the energy criterion for energy transfer is met. However, this model reaction proceeds by an exchange mechanism, which requires a collision between the triplet sensitizer and the diene acceptor.[32] In fact, exchange energy transfer cannot lead to photoresolution because its efficiency is independent of the handedness of the CPL absorbed. Triggers **11** and **15** were designed to avoid this problem by providing a rigid, through-bond framework for intramolecular energy transfer. Evidently, the through-bond transfer mechanism is less effective for thioketones than for ketones. This may be a result of the fact that sulfur is a second-row element and that the orbital overlap of its nπ* state with carbon−carbon bond orbitals of the bridging bicyclic group, which is required for the through bond process, is less.

Experimental Section

General. ^{1}H and ^{13}C NMR spectra were recorded at 300 and 75 MHz, respectively, in $CDCl_3$ unless otherwise specified. Chemical shifts are reported in parts per million (δ) downfield from TMS. The following compounds were synthesized according to procedures reported previously: 2-adamantanethione,[33,34] 1-phenyl-4-methyl-1,3-butadiene (**2** and **3**),[35] methyl 2-[4-(3-oxo-bicyclo[3.2.1]oct-8-ylidenemethyl)phenyl]acetate, **5**,

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bicyclo[3.2.1]octane-3,8-dione 8-ethylene ketal, **7**,[11] and 2-(bromomethyl)-3,4-dihydronaphthalene.[36]

General Method for Deprotection of Bicyclic Ketals. An excess of formic acid was added to the ketal and the mixture was heated at reflux for 4 h. The reaction mixture was cooled to room temperature and poured over ice water. The solution was neutralized with 2 M NaOH and extracted into ether. The combined organic layers were washed with brine and dried with $MgSO_4$ to give the ketone.

General Method for the Conversion of Bicyclic Ketones to Thioketones. Lawesson's reagent (0.5 mmol) was added slowly to a room temperature solution of the bicyclic ketone in toluene (3 mL, 0.8 mmol). For preparation of racemic thioketones, the mixture was heated at reflux until the reaction was complete as determined by thin-layer chromatography. If optically active thioketone was sought, the mixture was kept at 70 °C for 6−12 h until the starting ketone had been consumed. The crude product mixture was separated by chromatography on a silica gel column eluted with a mixture of EtOAc and hexane (1:3). The isolated thioketone was purified by sublimation, which yields bright orange crystals. The reaction of ketone **5** under these conditions gives sulfide **6**, which was not purified further. ^{1}H NMR δ 1.2 (s, 6H), 1.8−2.0 (m, 8H), 2.2−2.4 (m, 2H), 2.5−2.9 (m, 4H), 3.1−3.2 (m, 1H), 3.3 (m, 1H), 3.5 (d, 2H), 3.7 (d, 2H), 6.1−6.3 (d, 4H), 7.1−7.3 (m, 8H); GC/MS *m*/*z* 566 (M^+), 537, 507, 403, 337, 267, 239, 207, 179, 155, 117, 91.

Dimethyl 3,4-Dihydronaphthalen-2-ylmethylphosphonate. Trimethyl phosphite (4.5 g, 36 mmol) was added to 3-bromomethyl-1,2-dihydronaphthalene (1 g, 4.5 mmol) and stirred overnight at 50 °C. The crude product was purified by column chromatography (silica gel EtOAc/hexane 1:3, followed by MeOH) to yield 0.74 g (65%) of phosphonate ester. ^{1}H NMR δ 2.5−2.6 (m, 2H), 2.9−3.0 (m, 4H), 4.8 (s, 3H), 4.9 (s, 3H), 6.5 (d, 1H), 7.1−7.4 (m, 4H); GC/MS *m*/*z* 252 (M^+), 141, 124.

3-(3,4-Dihydronaphthalen-2-ylmethylene)bicyclo[3.2.1]-octan-8-one. A THF solution of dimethyl 3,4-dihydronaphthalen-2-ylmethylphosphonate (ca. 1 mL, 0.28 g, 1.1 mmol) was added slowly to a slurry of NaH in THF (2 mL, 0.052 g, 2.2 mmol) at room temperature. The mixture was stirred for 15 min and then a THF solution (3 mL, 0.1 g, 0.55 mmol) of bicyclo[3.2.1]octane-3,8-dione 8-ethylene ketal was added dropwise. When addition was completed, the reaction mixture was heated at reflux for 8 h. Water (ca. 1 mL) was added slowly to the reaction mixture and then the product was extracted into ether. The combined organic layers were washed with brine and dried with $MgSO_4$. The crude material was purified by column chromatography (silica gel 1:3 EtOAc/hexane) to give a white solid in 15% yield. ^{1}H NMR δ 1.2−2.8 (m, 14H), 3.9 (m, 4H), 5.9 (s, 1H), 6.3 (s, 1H), 6.9−7.2 (m, 4H); GC/MS *m*/*z* 308 (M^+), 280, 235, 193, 181, 142, 129, 99. The ketal protecting group was removed by means of the standard procedure to give the ketone in 52% yield. ^{1}H NMR δ 1.4−2.0 (m, 4H), 2.2−2.6 (m, 6H), 2.7−2.9 (m, 3H), 3.0−3.2 (m, 1H), 6.1 (s, 1H), 6.3 (s, 1H), 7.0−7.2 (m, 4H); GC/MS *m*/*z* 264 (M^+), 221, 181, 165, 128, 91.

Preparation of Thioketone 8. The thioketone was prepared by means of the standard procedure and isolated in 33% yield. ^{1}H NMR δ 1.2−3.2 (m, 14H), 6.1 (s, 1H), 6.3 (s, 1H), 7.0−7.3 (m, 4H); GC/MS *m*/*z* 280 (M^+), 247, 181, 168, 150, 115, 91. Upon exposure to air and/or light, **8** oxidizes to give 3-(2-naphthylmethylene)bicyclo[3.2.1]octane-8-thione (**9**), which was identified by NMR and mass spectroscopy and not characterized further. ^{1}H NMR δ 1.4−2.8 (m, 10H), 6.3 (s, 1H), 7.0−7.4 (m, 7H); GC/MS *m*/*z* 278 (M^+), 245, 128.

Diethyl 1*H*-Indene-2-ylmethylphosphonate (10). A THF solution of tetraethylmethylenediphosphonate (10 mL, 0.52 g, 1.8 mmol) was added slowly at room temperature to a THF slurry of NaH (ca. 2 mL, 0.04 g, 1.6 mmol). The mixture was stirred for 15 min and then a THF solution of 2-indanone (2 mL, 0.2 g, 1.5 mmol) was added dropwise. The mixture was stirred overnight at room temperature and then water (ca. 3 mL) was added and the product was extracted into ether. The combined organic layers were washed with brine and then dried with $MgSO_4$. The crude product was purified by column chromatography (silica gel 1:3 EtOAc/hexane, followed by MeOH) to give a yellow oil in 68% yield. This material was used without further purification. ^{1}H NMR δ 1.2−1.4 (t, 6H), 3.0−3.1 (d, 2H), 3.5 (s, 2H), 4.0−4.2 (m, 4H), 6.7−8.8 (d, 1H), 7.1−7.5 (m, 4H); ^{13}C NMR δ 16.6, 28.8, 30.6, 42.3, 62.2, 120.6, 123.7, 124.5, 126.5, 130.9, 138.8, 143.7, 145.0; ^{31}P (121 MHz, $CDCl_3$) 26.3; GC/MS *m*/*z* 266 (M^+), 238, 210, 156, 128.

Preparation of Thioketone 11. A THF solution of phosphonate ester **10** (2 mL, 0.35 g, 1.3 mmol) was added dropwise to a THF slurry of NaH (2.5 mL, 0.04 g, 1.7 mmol) and the mixture was stirred at room temperature for 15 min. A THF solution of ketal **7** (2 mL, 0.2 g, 1.1 mmol) was slowly added to this mixture and then it was heated at reflux for 8 h. Water (ca. 2 mL) was added to the reaction mixture and the product was extracted into ether. The combined organic layers were washed with brine and dried with $MgSO_4$. The crude material was purified by column chromatography (silica gel 1:6 EtOAc/hexane) to give the protected ketone as a white solid in 84% yield. Mp 136 °C; ^{1}H NMR δ 1.2−2.2 (m, 7H), 2.5−2.9 (m, 3H), 2.8−2.9 (m, 2H), 3.4−3.7 (m, 2H), 4.0 (s, 4H), 6.25 (s, 1H), 6.65 (s, 1H), 7.1−7.4 (m, 4H); ^{13}C NMR δ 25.30, 25.56, 34.33, 39.68, 40.01, 41.54, 41.88, 63.88, 64.93, 116.80, 120.39, 123.47, 124.17, 126.43, 130.14, 137.83, 143.04, 144.98, 145.31; GC/MS 294 (M^+), 266, 249, 221, 205, 179, 151, 128, 99. The ketal protecting group was removed by means of the standard procedure to give the ketone in quantitative yield. Mp 103−104 °C; ^{1}H NMR δ 1.5−2.0 (m, 4H), 2.5−2.7 (s, 2H), 2.9−3.0 (m, 1H), 3.1 (m, 2H), 3.2−3.4 (m, 1H), 3.4−3.7 (m, 2H), 6.3 (s, 1H), 6.7 (s,1H), 7.0−7.4 (m, 4H); ^{13}C NMR δ 22.99, 23.26, 39.78, 41.41, 44.13, 44.94, 47.96, 120.81, 123.50, 124.76, 126.10, 126.65,131.79, 134.43, 143.07, 144.31, 144.57, 221.60; GC/MS *m*/*z* 250 (M^+), 207, 167, 152, 130, 115, 91. The ketone was converted to the thioketone in 40% yield using the standard procedure. ^{1}H NMR δ 1.4−2.0 (m, 4H), 2.5−2.7 (m, 2H), 2.8−3.0 (m, 1H), 3.1 (s, 2H), 3.2−3.3 (m, 1H), 3.4−3.7 (m, 2H), 6.4 (1, 1H), 6.7 (s, 1H), 7.1−7.4 (m, 4H); GC/MS *m*/*z* 266 (M^+), 233, 191, 167, 152, 137, 115.

3*H*-Spiro[bicyclo[3.2.1]octane-8,2′-[1,3]dioxolan]-3-ylideneacetic Acid (12). Solid NaH (0.18 g, 7.8 mmol) was added slowly at room temperature to a benzene solution of trimethylphosphonoacetate (10 mL, 1.35 g, 7.4 mmol). The mixture was stirred for 10 min and then a toluene solution of ketone **7** (3 mL, 0.5 g, 2.8 mmol) was added over a 15-min period. The mixture was heated at reflux overnight then water (ca. 4 mL) was added and the solution was neutralized with 1 M HCl. The organic layer was extracted into methylene chloride, washed with brine, and then dried with $MgSO_4$. The crude product was purified by column chromatography (silica gel 1:3 EtOAc/hexane) to give methyl 3*H*-spiro[bicyclo[3.2.1]octane-8,2′-[1,3]dioxolan]-3-ylideneacetate as a white solid in 83% yield. Mp 135−136 °C; ^{1}H NMR δ 1.3−1.5 (m, 2H), 1.8 (m 2H), 2.0 (m, 2H), 2.1−2.2 (m, 1H), 2.4−2.6 (m, 1H), 2.8−3.0 (m, 1H), 3.6 (m, 1H), 3.7 (s, 3H), 4.0 (s, 4H), 5.8 (s, 1H); GC/MS *m*/*z* 238 (M^+), 223, 206, 179, 164, 134, 119, 99, 79. This ester was hydrolyzed by reaction in 3 M NaOH for 12 h at room temperature. The reaction mixture was acidified with 6 M HCl and the organic layer was extracted into methylene chloride, washed with brine, and then dried with $MgSO_4$ to give carboxylic acid **12** in racemic form in 75% yield. ^{1}H NMR δ 1.3−1.5 (m, 2H), 1.8−1.9 (m, 2H), 2.0 (m, 2H), 2.1−2.2 (d, 1H), 2.4−2.6 (d, 1H), 2.8−3.0 (d, 1H), 3.6 (m, 1H), 4.0 (s, 4H), 5.8 (s, 1H); ^{13}C (75 MHz, $CDCl_3$) δ 25.66, 25.82, 34.37, 40.01, 40.44, 42.31, 64.48, 65.43, 116.59, 117.42, 162.50, 171.72; GC/MS *m*/*z* 224 (M^+), 206,179, 150, 134, 105, 99, 79.

Bicyclic Ketone 14. Solid (2-hydroxybenzyl)phosphonium bromide (1.24 g, 2.8 mmol) and dicyclohexylcarbodiimide (0.5

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g, 2.5 mmol) were added to a CH_2Cl_2 solution of acid **12** (10 mL, 0.44 g, 2 mmol). Solid (dimethylamino)pyridine (0.04 g, 0.3 mmol) was added all at once to the reaction solution and the mixture was stirred at room temperature until acid **12** was consumed (5−10 h) as indicated by thin-layer chromatography. The solvent was removed from the reaction mixture and toluene (5 mL) was added. Triethylamine (1.53 mL) was added to the toluene solution, which was then heated at reflux until **13** was consumed (3−5 h) as indicated by TLC. The cooled reaction mixture was filtered and purified by column chromatography (silica gel 1:3 EtOAc/hexane) to give the coupled ketal in 67% yield as a white solid. Mp 106 °C; ^{1}H NMR δ 1.2−1.6 (m, 2H), 1.6−1.8 (m, 2H), 1.9−2.0 (m, 2H), 2.1−2.2 (m, 1H), 2.5−2.7 (m, 1H), 2.8−3.0 (m, 1H), 3.0−3.2 (m, 1H), 3.8−4.0 (m, 4H), 6.2 (s, 1H), 6.4 (s, 1H), 7.0−7.2 (m, 2H), 7.3−7.5 (m, 2H); GC/MS *m*/*z* 296 (M^+), 268, 251, 223, 207, 181, 165, 152, 131, 99, 77. The ketal was added to an excess of 2 M HCl in dioxane, and the mixture was stirred at 50 °C until starting material was consumed as indicated by TLC to give ketone **14** in 87% yield. Mp 73−74 °C; ^{1}H NMR δ 1.6−2.0 (m, 4H), 2.4 (s, 2H), 2.6 (m, 1H), 2.8 (m, 1H), 3.0 (m, 1H), 3.6−3.8 (m, 1H), 6.4 (s, 1H), 6.6 (s, 1H), 7.2−7.3 (m, 2H), 7.4 (d, 1H), 7.5 (d, 1H); GC/MS 252 (M^+), 224, 209, 195, 183, 169, 157, 144, 131, 115. Anal. Calcd for $C_{17}H_{16}O_2$: C, 80.91; H, 6.39. Found: C, 80.64, 6.40. A similar procedure was followed with partially resolved **12** except that the esterification to form **13** and the Wittig coupling reaction were carried out at 50 °C.

Preparation of Thioketone 15. The thioketone was prepared by means of the standard procedure and isolated in 72% yield. ^{1}H NMR δ 1.5−2.0 (m, 4H), 2.6−2.8 (m, 1H), 2.9−3.1 (m 2H), 3.1 (s, 2H), 3.5−3.7 (m, 1H), 6.4 (s, 1H), 6.6 (s, 1H), 7.1−7.4 (m, 2H), 7.4−7.6 (m, 2H); GC/MS *m*/*z* 268 (M^+), 236, 221, 195, 170, 131, 91. When preparing optically active **15** from partially resolved **14** the reaction was carried out at 50 °C. Formation of partially resolved **15** was confirmed by CD spectroscopy.

Resolution of 12. A solid portion of racemic acid **12** (5.4 g, 24.0 mmol) was added to a solution of quinine in methanol (20 mL, 7.8 g, 24.0 mmol). The mixture was stirred at room temperature for ca. 1 h. Most of the methanol was evaporated and 10 mL of acetone was added to the concentrated solution. The resulting solution was heated at reflux for 2 h and cooled overnight, and the white precipitate that formed was isolated by filtration. The partially resolved acid **12** was liberated from its quinine salt by addition of HCl (2 M, final pH ca. 2) and extracted into CH_2Cl_2. The solution was dried with $MgSO_4$ and the resolved acid (ca. 2.5 g) was isolated by evaporation of the solvent. Resolution was confirmed by recording the CD spectrum of **12**. The crude, partially resolved acid was recrystallized from a methanol/acetone solution. The resolution procedure was repeated until an enantiomeric excess sufficient for conversion to optically active **15** was obtained.

Photoracemization of Ketone 14 and Thioketone 15. Deoxygenated benzene (d_6, to permit analysis by NMR spectroscopy) solutions of ketone **14** or thioketone **15** (absorbance at 300 nm = 2) were irradiated with UV (in the case of **14**, λ > 300 nm) or visible (in the case of **15**, λ > 400 nm) light from an Oriel 1000 W Hg−Xe arc lamp. The racemization reaction was monitored by CD spectroscopy and the chemical composition of the solutions was confirmed by GC/MS and NMR spectroscopy. Ketone **14** was fully racemized after 36 h of irradiation and thioketone was racemized after 24 h. There was no significant decomposition of either the ketone or the thioketone. The quantum yield for racemization of thioketone **15** was determined by comparison with a Reinecke's salt actinometer.[30]

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Supporting Information Available: ^{1}H NMR spectra of **10**−**12**, **14**, and **15**. This material is available free of charge via the Internet at http://pubs.acs.org.

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