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1,4-Hydroxybiradical Behavior Revealed through Crystal Structure−Solid-State Reactivity Correlations

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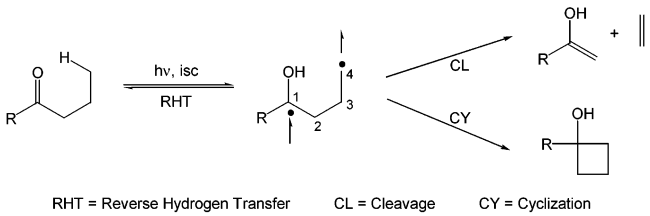
Abstract: Structure−reactivity correlations for triplet 1,4-hydroxybiradicals in solution are made difficult by the presence of multiple reactive conformers and the possibility of conformation-dependent intersystem crossing. These problems can be overcome by working in the crystalline state, where the conformations of the 1,4-hydroxybiradicals are fixed and determinable by X-ray crystallography of the parent ketones, assuming that hydrogen atom abstraction occurs with little or no change in conformation. This approach is applied to 15 bi- and tricyclic ketones designed to have slightly different biradical conformations, so that the effect of small and incremental changes in geometry on biradical behavior can be tested. The results indicate that, while geometry does have a strong influence on 1,4-hydroxybiradical partitioning between cyclization, cleavage, and reverse hydrogen transfer, a full understanding of the results requires that the strain involved in forming the cyclization products be taken into account.

1,4-Biradicals are formed as intermediates in a wide variety of ground- and excited-state reactions and continue to be the subject of intense experimental[1] and theoretical[2] interest. Triplet 1,4-biradicals are particularly common in photochemical reactions and have been identified as intermediates in enone-alkene photocycloadditions,[3] the Paterno−Büchi reaction,[4,5] and the Norrish/Yang type II reaction.[6] It is with this last reaction that the present Article is concerned.

Triplet 1,4-hydroxybiradicals formed in the first step of the photochemical Norrish/Yang type II reaction have three fates: reverse hydrogen transfer to regenerate the starting ketone in its ground state, cleavage of the central carbon−carbon bond to form an alkene and an enol, and Yang cyclization to form a cyclobutanol derivative.[6,7]



These reactions are necessarily accompanied by triplet to singlet intersystem crossing, and this has given rise to two subtly different schools of thought concerning mechanism. The first, espoused by Wagner and co-workers,[8,9] views triplet hydroxybiradical partitioning as being controlled by conventional kinetic barriers in which intersystem crossing accompanies product formation. The second, more widely accepted view, advanced originally by Scaiano et al.[10] and subsequently elaborated by Griesbeck and co-workers,[11] pictures biradical behavior as being controlled by intersystem crossing. In this scenario, the singlet biradical is viewed as reacting immediately following intersystem crossing from the triplet. As a result, the conformation in which the singlet is born (and from which it reacts) will be the one that was most favorable for intersystem crossing − a geometry that may be quite different from that conventionally thought to favor cleavage, cyclization, or reverse hydrogen transfer.[12] Consequently, while some structural features of biradical reactivity are well established, such as the requirement for good overlap during cleavage between the C_2-C_3 bond and

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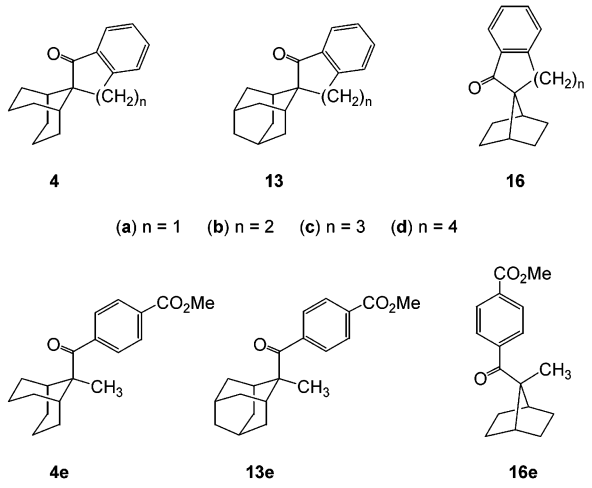
(1) *Kinetics and Spectroscopy of Carbenes and Biradicals*; Platz, M. S., Ed.; Plenum: New York, 1990.
(2) Klessinger, M. *Theor. Comput. Chem.* **1998**, *5*, 581.
(3) Andrew, D.; Weedon, A. C. *J. Am. Chem. Soc.* **1995**, *117*, 5647 and references therein.
(4) Griesbeck, A. G.; Mauder, H.; Stadtmüller, S. *Acc. Chem. Res.* **1994**, *27*, 70.
(5) Griesbeck, A. G.; Buhr, S.; Fiege, M.; Schmickler, H.; Lex, J. *J. Org. Chem.* **1998**, *63*, 3847.
(6) For a general review of the Norrish type II reaction, see: Wagner, P.; Park, B.-S. In *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1991; Vol. 11, Chapter 4.
(7) Cyclobutanol products in Norrish type II photochemistry were first reported by: Yang, N. C.; Yang, D. H. *J. Am. Chem. Soc.* **1958**, *80*, 2913.
(8) Wagner, P. J. *Acc. Chem. Res.* **1989**, *22*, 83.
(9) Wagner, P. J.; Meador, M. A.; Zhou, B.; Park, B. S. *J. Am. Chem. Soc.* **1991**, *113*, 9630. For related work supporting the idea of intersystem crossing accompanying product formation, see: Michl, J. *J. Am. Chem. Soc.* **1996**, *118*, 3568.
(10) Scaiano, J. C. *Tetrahedron* **1982**, *38*, 819.
(11) (a) Griesbeck, A. G.; Heckroth, H. *J. Am. Chem. Soc.* **2002**, *124*, 396. (b) Griesbeck, A. G. *Synlett* **2003**, 451.
(12) The spin−orbit coupling contribution to intersystem crossing in triplet biradicals is greatest when the radical-containing orbitals are othogonal to one another, a geometry that may not be well arranged for cleavage or cyclization and may even correspond to a nonminimum energy conformation.[4] See also: Carlacci, L.; Doubleday, C., Jr.; Furlani, T. R.; King, H. F.; McIver, J. W., Jr. *J. Am. Chem. Soc.* **1987**, *109*, 5323.

the radical-containing orbitals at C_1 and C_4,[13] there is still no general understanding of how biradical structure affects partitioning among the three possible reaction pathways. To add to the problem, triplet 1,4-hydroxybiradicals are sufficiently long-lived to allow conformational equilibration, making identification of reactive conformers difficult. For all of the above reasons, it is apparent that further research correlating 1,4-hydroxybiradical structure and reactivity is needed.

By working in the crystalline state, the problems of multiple reactive conformers and conformation-dependent intersystem crossing can be avoided, because most organic compounds crystallize in and are restricted to their lowest energy conformations. Furthermore, because it is likely that γ-hydrogen abstraction in the crystalline state occurs with very little motion of the associated heavy atoms,[14,15] the structures of the conformationally locked 1,4-hydroxybiradicals can be inferred from the X-ray crystal structures of the parent ketones, and this allows direct structure−reactivity relationships to be established for these reactive intermediates. In a preliminary communication, we used this approach to analyze the Norrish/Yang type II photochemistry of spirocyclic ketones **13a**−**c**.[16] In the present Article, we report an extension of this work to the eight-ring homologue **13d**, as well as to the homologous series **4a**−**d** and **16a**−**d**.



These compounds were chosen for investigation because the conformation of the 1,4-biradicals formed by γ-hydrogen atom abstraction could be varied in a regular and incremental fashion by changing the size of the ketone-containing spiro ring. For comparison purposes, we also report the results of photolyzing the nonspirocyclic analogues **4e**, **13e**, and **16e** in the solid state. The results obtained paint a remarkable picture of how relatively subtle conformational changes can profoundly affect 1,4-hydroxybiradical partitioning among cleavage, reverse hydrogen transfer, and cyclization.[17]

Results and Discussion

Synthesis of Starting Materials and X-ray Crystallography. Scheme 1 shows the approach taken for the synthesis of ketones **4a**−**e** from the known compound, methyl bicyclo[3.3.1]-nonane-9-carboxylate (**1**).[18] Analogous procedures were used for the preparation of ketones **13a**−**e** and **16a**−**e**, and the details of the synthesis of these compounds are given in the Supporting Information. All 15 ketones proved to be crystalline solids, and each had its crystal and molecular structure determined by direct methods. Crystallographic information files for all 15 starting ketones (as well as five photoproducts) are provided in the Supporting Information. Figure 1 presents ORTEP drawings of ketones **4a**−**e** at the 30% ellipsoid probability level showing the conformational differences between them as a function of spiro ring size.

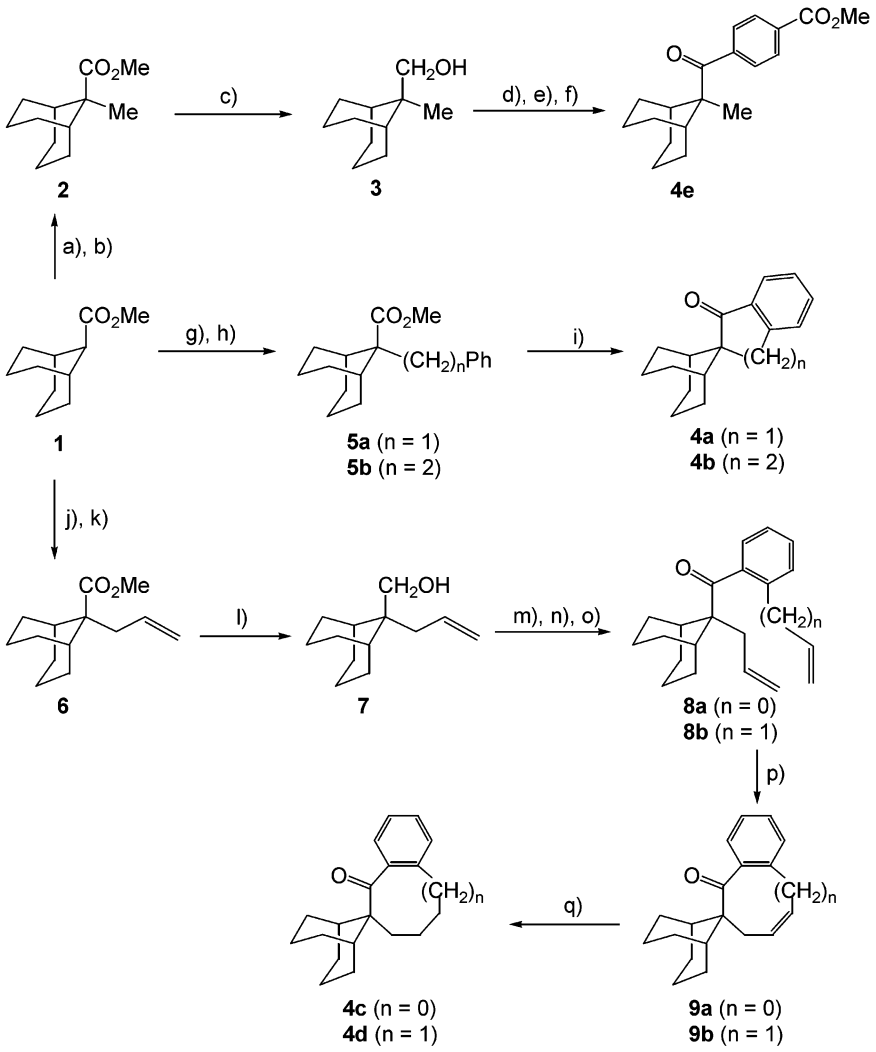
Photochemistry. Each of the 15 ketones was irradiated in the crystalline state. The procedure consisted of crushing ca. 5 mg of the ketone to be photolyzed between two Pyrex microscope slides, taping the plates together, sealing the resulting sandwiches under nitrogen in polyethylene bags, and irradiating the ensembles with the output from a water-cooled 450 W medium-pressure mercury lamp. Conversions were generally kept below ca. 25% to minimize crystal melting during photolysis. Preparative scale photolyses for the purpose of product isolation and characterization were carried out in solution, which led to results essentially identical to those observed in the solid state. The photoproducts were isolated by column chromatography, and their structures were established by high-resolution NMR and other spectroscopic methods. In some cases (photoproducts **11d**, **15c**, **15d**, **19**, and **20**), the structures were corroborated by X-ray crystallography. The workup and photoproduct isolation and characterization procedures for the photolysis of ketones **4a**−**e** are given in the Experimental Section. Details of the photolysis of ketone **13e** have been published,[15] and, for the remaining nine photolyses, this information is provided in the Supporting Information.

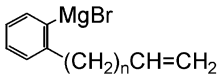
With a specificity and internal consistency that is little short of astonishing, the five-membered ring spiroketones **4a**, **13a**, and **16a** all underwent exclusive cleavage to afford the corresponding ring-opened photoproducts **10a**, **14a**, and **17a** (Scheme 2) as an approximately 1:1 mixture of two diastereomers. These are formed by nonstereoselective ketonization of the intermediate enols, which could be detected by ^{1}H NMR in the photolysis of ketones **4a** and **13a**. Figure 2a shows the vinyl region of the ^{1}H NMR spectrum of ketone **13a** following photolysis at 0 °C in 2:1 *tert*-butyl alcohol-d_{10}/benzene d_6. The resonances at δ 5.42 and 5.79 ppm are assigned to the vinyl hydrogens of the enol formed by cleavage of the 1,4-hydroxybiradical. Figure 2b shows a second spectrum taken immediately after the addition of a trace amount of trifluoroacetic acid. This spectrum contains vinylic signals for the enol as well as four new resonances (δ 5.34, 5.38, 5.60, and 5.72 ppm) assigned to the two newly formed epimers of ketone **14a**. Another spectrum (Figure 2c) acquired 5 min later contained no enol signals, indicating that complete conversion to the keto tautomers had occurred.

Unlike the five-ring spiroketones, the seven-ring, eight-ring, and nonspirocyclic ketones **4c**/**13c**/**16c**, **4d**/**13d**/**16d**, and **4e**/**13e**/**16e** reacted predominantly to form cyclized products **11c**/**15c**/**18c**, **11d**/**15d**/**18d**, and **19**/**21**/**22**, respectively. In those cases where crystal structures were lacking, the stereochemistry at the hydroxyl-bearing carbon atom was established by ^{1}H NOE difference nuclear magnetic resonance spectroscopy (see Sup-

(13) Wagner, P. J.; Kemppainen, A. E. *J. Am. Chem. Soc.* **1968**, *90*, 5896.
(14) Gudmundsdottir, A. D.; Lewis, T. J.; Randall, L. H.; Scheffer, J. R.; Rettig, S. J.; Trotter, J.; Wu, C.-H. *J. Am. Chem. Soc.* **1996**, *118*, 6167.
(15) Leibovitch, M.; Olovsson, G.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1998**, *120*, 12755.
(16) Cheung, E.; Netherton, M. R.; Scheffer, J. R.; Trotter, J. *Org. Lett.* **2000**, *2*, 77.
(17) For related studies carried out in solution, see: (a) Lewis, F. D.; Hilliard, T. A. *J. Am. Chem. Soc.* **1972**, *94*, 3852. (b) Lewis, F. D.; Johnson, R. W.; Ruden, R. A. *J. Am. Chem. Soc.* **1972**, *94*, 4292.
(18) House, H. O.; Cronin, T. H. *J. Org. Chem.* **1965**, *30*, 1061.

Scheme 1



a) LDA; b) MeI, DMPU; c) LAH; d) PCC; e) *i*-PrMgCl, IC_6H_4COOMe; f) PCC; g) LDA, BuLi, h) $Ph(CH_2)_nBr$, DMPU; i) BCl_3; j) LDA, BuLi; k) CH_2=CH-CH_2Br, DMPU; l) LAH; m) PCC; n)  ; o) PCC; p) Grubbs' catalyst (benzylidene-bis(tricyclohexylphosphine)dichlororuthenium); q) H_2, Pd/C.

porting Information). In the case of ketones **4c**, **4d**, and **4e**, small amounts (5−10%) of a second photoproduct (**12c**, **12d**, and **20**, respectively) were also isolated and characterized. These are presumably formed by a novel disproportionation of the intermediate 1,4-hydroxybiradicals in which a hydrogen atom on C_5 is transferred to the radical center on C_1 (Figure 3a).[19]

In striking contrast to all of the above results, the six-membered ring spiroketones **4b**, **13b**, and **16b** proved to be photochemically inert, giving only trace amounts (<1%) of unidentified short retention time peaks on GC. The overall results are summarized in Table 1.

As outlined in the preliminary communication,[16] the lack of photoproduct formation in the case of ketone **13b** was shown by deuterium labeling studies (in solution) to be due to efficient reverse hydrogen transfer of the 1,4-hydroxybiradical intermediate rather than to a failure of initial γ-hydrogen abstraction. Based on the fact that the γ-hydrogen atom abstraction distances and angles are nearly identical for all three six-ring spiroketones,[20] the same can be confidently assumed for compounds **4b** and **16b**, even though in these cases attempted trapping of the biradicals was unsuccessful.[21]

Based on the crystallographic results, the 1,4-hydroxybiradicals may be modeled as shown in Figure 3. The crystallographic data reveal that the $C_1-C_2-C_3-C_4$ torsion angle is essentially

(19) As far as we are aware, this type of disproportionation is unknown for 1,4-hydroxybiradicals, although it has been observed in the case of a 1,5-hydroxybiradical. See: Wagner, P. J.; Laidig, G. *Tetrahedron Lett.* **1991**, *32*, 895.

(20) In fact, all 15 ketones have similar γ-hydrogen atom abstraction geometries, with d (the C═O···H_γ distance) = 2.47 ± 0.10 Å and ω (the γ-hydrogen out-of-plane angle) = 43 ± 16°. These values are typical of ketones known to take part in the Norrish/Yang type II reaction in the crystalline state. For a review on this topic, see: Ihmels, H.; Scheffer, J. R. *Tetrahedron* **1999**, *55*, 885.

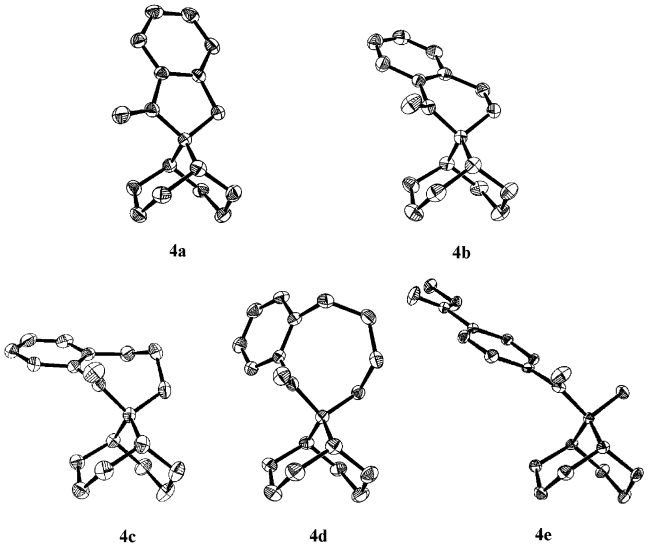


Figure 1. Molecular conformation of ketones **4a**−**e** in the crystalline state.

constant at 63.4 ± 1.8° (gauche) for all 15 compounds investigated and that the $C_1 \cdots C_4$ distance is likewise invariant at 3.00 ± 0.06 Å. The major structural difference between homologues lies in the extent of rotation about the C_1-C_2 bond, which varies with the presence or absence of the spiro ring and the ring size. The effect of this difference is to change the overlap of the p-orbital on C_1 with both the C_2-C_3 bond and the p-orbital on C_4, and this, we believe, is the key structural feature affecting biradical reactivity in these systems. Our hypothesis is that cleavage is favored by good overlap between the p-orbitals on C_1 and C_4 with the C_2-C_3 bond, cyclization is favored by good overlap of the p-orbitals on C_1 and C_4 with each other, and reverse hydrogen transfer dominates when neither of the above conditions is met and the OH group is close to C_4 (as it is in every case). As we shall see, the crystallographic data support this hypothesis, but, as will also become apparent, a full interpretation of the results requires that the strain involved in forming the cyclization products be taken into account.

For the purposes of discussion, we define φ_1 and φ_4 as the dihedral angles between the C_2-C_3 bond and the p-orbitals on C_1 and C_4, respectively. The overlap between these orbitals is proportional to cos φ_1 and cos φ_4,[22] and, as mentioned earlier, the best geometry for cleavage can be expected when φ_1 and $\varphi_4 = 0°$ and cos φ_1 = cos $\varphi_4 = 1$. The values of cos φ_1 and cos φ_4 for the 15 ketones investigated in the present study are given in Table 1. Also shown in Table 1 are the values of the angle β, defined as the dihedral angle between the p-orbital on C_1 and the C_2-C_4 vector (Figure 3b). The most favorable geometry for cyclization exists when $\beta = 0°$, that is, when the p-orbital on C_1 is pointing directly at the p-orbital on C_4.

As can be seen from Table 1, the three five-ring ($n = 1$) ketones **4a**, **13a**, and **16a** undergo exclusive cleavage from biradicals in which there is reasonably good overlap between both radical-containing p-orbitals and the central C_2-C_3 bond. The overlap is ≥80% of maximum for **4a** and **13a** and somewhat less for **16a** (79% and 58% of maximum). At the same time that cleavage is favored, cyclization of these biradicals is disfavored by the poor overlap between the p-orbitals on C_1 and C_4 ($\beta = 60-71°$). Furthermore, cyclization would lead to a highly strained pentacyclic ring system,[23] and it is thus not surprising that cleavage is the exclusive mode of reaction detectable for the five-ring spirocycles.

In contrast, the six-ring ($n = 2$) ketones **4b**, **13b**, and **16b** lead to biradicals in which only the p-orbital on C_4 is reasonably oriented for cleavage, the other (on C_1) being very poorly aligned (2−7% of maximum overlap). The subsequent failure of these biradicals to cleave is clear evidence that cleavage requires overlap of both p-orbitals with the cleaving C_2-C_3 bond. While the geometry for cyclization in these cases is by no means ideal ($\beta = 53-61°$), it is, as we shall see, adequate. More important is the fact that cyclization would lead to the very strained *trans*-fused 6/4 ring junction-containing photoproducts **11b**, **15b**, and **18b**. The overall result is that both cleavage and cyclization are disadvantaged relative to reverse hydrogen transfer, and this becomes the sole process undergone by these biradicals.

Cyclization is the preferred mode of reaction of the biradicals formed by photolyzing the seven-ring ($n = 3$) spiroketones **4c**, **13c**, and **16c**, and this can be understood as being due to three factors: relatively poor cleavage geometry (cos $\varphi_1 = 34-47\%$), relatively favorable cyclization geometry ($\beta = 29-39°$), and formation of a *trans*-fused 7/4 ring system that is no longer prohibitively strained. The same reasoning applies to the nonspirocyclic systems **4e**, **13e**, and **16e**, which have biradical geometries similar to those of the seven-ring compounds and likewise undergo mainly Yang photocyclization in the crystalline state.

Finally, from Table 1 it can be seen that the geometry of the biradicals formed by photolysis of the eight-ring ($n = 4$) ketones **4d**, **13d**, and **16d** is nearly identical to that of their six-ring ($n = 2$) counterparts, yet the former cyclize while the latter react exclusively via reverse hydrogen transfer. The logical conclusion from these results is that cyclization is slowed in the six-ring case, not only by the biradical geometry, but also by the difficulty in forming a *trans*-fused 6/4 product, a rate-retarding effect that is lessened in the eight-ring case.

In summary, the fact that the effect of spirocyclic ring size on biradical partitioning is the same for three separate ring systems (**4**, **13**, and **16**) argues very strongly for a common interpretation of the results. This interpretation is based on two factors: the geometry of the intermediate 1,4-hydroxybiradicals as deduced from X-ray crystallography of the parent ketones, and the increase in strain energy accompanying cyclization (ΔE_{strain}). Molecular mechanics calculations indicate that ΔE_{strain} is greatest when $n = 1$ and least when $n = 4$.[24] As a result, the relative rate of biradical cyclization would be expected to decrease with decreasing n.[25] In agreement with this analysis,

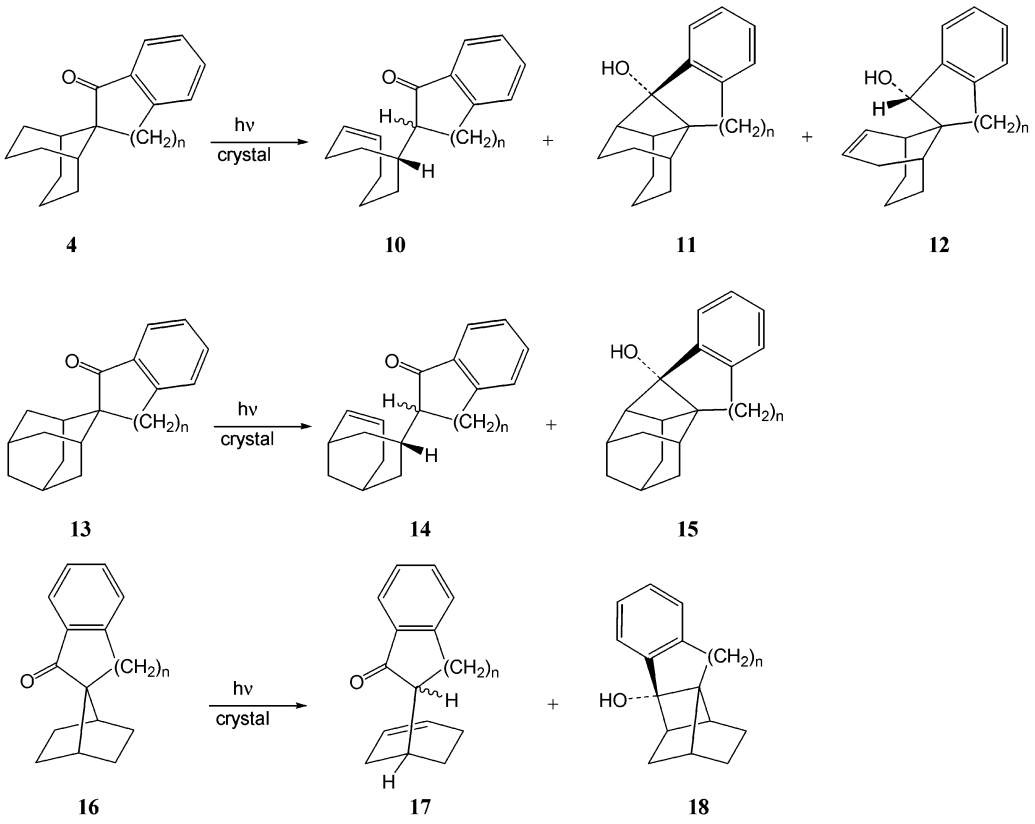
(21) The trapping experiment consisted of irradiating ketones **4b** and **16b** in 2:1 *tert*-BuOD/benzene and looking for deuterium incorporation at the γ-position. While successful in the case of **13b**,[16] no exchange was detectable for ketones **4b** and **16b**. Attempts to observe such exchange in γ,γ-d_2-nonaphenone were similarly unsuccessful. See: Wagner, P. J.; Kelso, P. A.; Kemppainen, A. E.; McGrath, J. M.; Schott, H. N.; Zepp, R. G. *J. Am. Chem. Soc.* **1972**, *94*, 7506.

(22) Burdett, J. K. *Molecular Shapes*; Wiley-Interscience: New York, 1980; p 6.

(23) The expected cyclization products are cyclobutanols **11a**, **15a**, and **18a** in which a prohibitively strained *trans*-fused 5/4 ring system is added to an existing and moderately strained bi- or tricyclic carbon skeleton.

(24) For example, the increase in strain energy in going from ketone **4a** to cyclobutanol **11a** was calculated to be 72.6 kcal/mol. In the case of the **4b** to **11b** conversion, $\Delta E_{strain} = 46.4$ kcal/mol, which decreased to 29.8 kcal/mol for the **4c**/**11c** pair and 28.7 kcal/mol for the **4d**/**11d** pair. Calculations were carried out using the HyperChem/ChemPlus software package, version 5.11/2.0.

Scheme 2


O
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10
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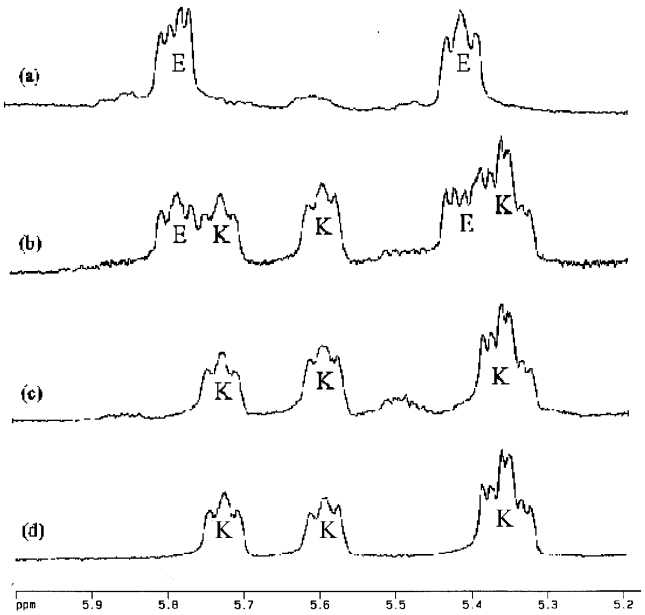

Figure 2. ^{1}H NMR vinyl region (δ 5−6 ppm) after photolysis of ketone **13a** showing signals due to the intermediate enol (E) and the two diastereomers of ketone **14a** (K): (a) after photolysis; (b) immediately following addition of catalytic trifluoroacetic acid; (c) 5 min post addition; (d) purified sample of **14a**.

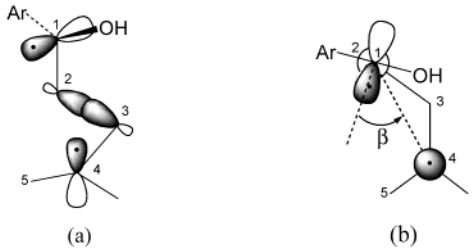

Figure 3. (a) The gauche 1,4-hydroxybiradical model; (b) the angle β.

Table 1. Solid-State Photolysis Results and Geometric Data for Ketones **4a**−**e**, **13a**−**e**, and **16a**−**e**[a]

n	ketone	product	cos φ_1	cos φ_4	β (deg)	reaction[b]
1	**4a**	**10a**	0.81	0.80	60	CL
	13a	**14a**	0.85	0.87	61	CL
	16a	**17a**	0.79	0.58	71	CL
2	**4b**	none	0.02	0.75	61	RHT
	13b	none	0.05	0.86	59	RHT
	16b	none	0.07	0.53	53	RHT
3	**4c**	**11c** (trace **12c**)	0.41	0.80	37	CY
	13c	**15c**	0.34	0.87	39	CY
	16c	**18c**	0.47	0.53	29	CY
4	**4d**	**11d** (trace **12d**)	0.17	0.81	49	CY
	13d	**15d**	0.09	0.86	55	CY
	16d	**18d**	0.14	0.53	48	CY
acyclic	**4e**	**19** (trace **20**)	0.52	0.81	28	CY
	13e	**21**	0.48	0.87	29	CY
	16e	**22**	0.57	0.54	21	CY

[a] Assumes abstraction of the more favorably oriented γ-hydrogen in each case. This is unambiguous for the majority of the ketones studied, but for compounds **4a**, **13a**, and **16a**, where the γ-hydrogens are nearly equidistant from the carbonyl oxygen, the data represent average values for both γ-hydrogens. The γ-hydrogen abstraction distances and angles for each compound are tabulated in the Supporting Information. [b] CL = cleavage; RHT = reverse hydrogen transfer; CY = cyclization.

no cyclization is observed when $n = 1$ or 2. The effect of ring strain is most clearly seen in the different behavior of the $n = 2$ and $n = 4$ biradicals. The X-ray data show that these biradicals have very similar geometries in the crystalline state, yet the latter cyclize while the former undergo reverse hydrogen transfer.

The added effect of varying the spiro ring size is to change the orientation of the p-orbital on C_1 of the 1,4-hydroxybiradical with respect to the C_2-C_3 σ bond involved in cleavage as well as the p-orbital on C_4 involved in cyclization. For $n = 1$, geometric factors favor cleavage, and, because cyclization is strongly disfavored by ring strain, cleavage predominates.[26] When $n = 2$, cleavage is strongly disfavored by geometry because the C_2-C_3 bond is well aligned with only one of the two p-orbitals, and cyclization, while geometrically feasible, is disfavored by ring strain. The result is exclusive reverse hydrogen transfer. When $n = 3$, 4, or acyclic, geometric factors favor cyclization over cleavage, and, because cyclization is no longer prohibited by ring strain, this becomes the dominant observable pathway.[26]

Experimental Section

General Methods. Commercial spectral grade solvents were used for photochemical experiments unless otherwise stated. For synthetic use, tetrahydrofuran and diethyl ether were dried over the sodium ketyl of benzophenone; dichloromethane was dried over calcium hydride; acetonitrile was distilled from P_2O_5. All reactions were performed under a nitrogen atmosphere unless otherwise noted. Melting points were determined on a Fisher−Johns hot-stage apparatus and uncorrected. Analytical TLC was performed on 0.20 mm silica gel 60-F plates and visualized under UV light and/or by staining with I_2 or phosphomolybdic acid. Preparative chromatography was performed using either the flash column method with silica gel (particle size 230−400 mesh) or radial elution chromatography on a Harrison Research Chromatotron (model 7924T) with self-coated silica gel plates (1 mm or 2 mm thickness with EM Science silica gel 60 PF254 containing gypsum 7749−3). Infrared spectra were recorded on a Perkin-Elmer 1710 Fourier transform spectrometer. Ultraviolet spectra were recorded on a Perkin-Elmer Lambda-4B UV/vis spectrometer at 25 °C. High-resolution mass spectra were obtained from a Kratos MS 50 instrument using electron impact (EI) ionization at 70 eV, or chemical ionization (CI) with the ionization gas noted. Elemental analyses were performed by the UBC microanalytical service on a Carlo Erba CHN Model 1106 analyzer. ^{1}H NMR spectra were obtained at either 300 or 400 MHz on Bruker AV-300 or Bruker AV-400 instruments. ^{13}C NMR spectra were recorded at either 75 or 100 MHz.

Methyl 9-Methylbicyclo[3.3.1]nonane-9-carboxylate (2). General Procedure A. To a cold (−78 °C) solution of LDA (prepared from 19.5 mmol of DIPA and 18.1 mmol of *n*-butyllithium) in THF (60 mL) was added methyl bicyclo[3.3.1]nonane-9-carboxylate (**1**)[18] (2.54 g, 13.9 mmol) in THF (30 mL) over 15 min. After the mixture was stirred in the cold for 1.5 h, an additional portion of *n*-butyllithium (9.6 mL of a 1.6 M solution in *n*-hexane, 15.3 mmol) was added dropwise. The reaction was stirred for 30 min, followed by the addition of DMPU (5.0 mL, 42 mmol). After 5 min, methyl iodide (9.89 g, 69.7 mmol) was added, and the reaction was stirred in the cold for 3 h before warming slowly to room temperature and stirring overnight. The reaction was quenched with water and extracted with Et_2O. The combined ethereal extracts were washed with brine, dried ($MgSO_4$), and the solvent was removed in vacuo. Vacuum distillation afforded

(25) This analysis is based on the reasonable assumption that $\Delta S^{\ddagger}$ does not change appreciably with spiro ring size because (a) a four-membered ring is being formed in each case, and (b) cyclization occurs in each case from a fixed conformation with relatively few degrees of freedom. As a result, $\Delta H^{\ddagger}$ (difference in strain energy) is expected to be the determining factor in the rate of ring closure.

(26) Because it is undetectable, the extent of reverse hydrogen transfer in the photochemistry of ketones **4a**,**c**,**d**,**e**; **13a**,**c**,**d**,**e**; and **16a**,**c**,**d**,**e** is unknown.

the title compound as a colorless liquid (2.24 g, 82%). bp: 96−99 °C/6 mmHg. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.23 (s, 3H), 1.34−2.05 (m, 14H), 3.67 (s, 3H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.30, 20.87, 23.83, 26.40, 29.39, 33.260, 46.17, 51.22, 178.80 ppm. IR (neat): 2988, 2914, 2867, 1731, 1453, 1267, 1232, 1119, 1098 cm^{-1}. HRMS (EI) calcd for $C_{12}H_{20}O_2$ 196.1463, found 196.1460.

9-Hydroxymethyl-9-methylbicyclo[3.3.1]nonane (3). General Procedure B. To a solution of ester **2** (2.18 g, 11.1 mmol) in THF (40 mL) was added lithium aluminum hydride (6.1 mL of a 1.0 M solution in THF, 6.1 mmol). The reaction was allowed to reflux for 16 h. The reaction was cooled and carefully quenched with aqueous saturated sodium sulfate solution until large particles of white precipitate were formed. The reaction mixture was filtered, and removal of THF in vacuo gave an aqueous residue, which was extracted with Et_2O. The combined ethereal extracts were washed with brine and dried over $MgSO_4$. Removal of solvent in vacuo gave alcohol **3** (1.85 g, 99%) as a white solid. mp: 117−119 °C (EtOAc/petroleum ether). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.07 (s, 3H), 1.18 (br, 1H), 1.40−2.04 (m, 14H), 3.61 (s, 2H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.66, 21.43, 21.48, 27.22, 27.50, 32.91, 36.76, 69.45 ppm. IR (KBr): 3299 (br), 2950, 2911, 2868, 1453, 1024 cm^{-1}. HRMS (EI) calcd for $C_{11}H_{20}O$ 168.1514, found 168.1507. Anal. Calcd for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.91; H, 12.10.

9-(*p*-Carbomethoxybenzoyl)-9-methylbicyclo[3.3.1]nonane (4e). General Procedure C. A mixture of PCC (3.71 g, 17.2 mmol) and Celite 545 (5.00 g) was ground in a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **3** (1.81 g, 10.8 mmol) in anhydrous dichloromethane (120 mL) and stirred for 2 h at room temperature. The reaction mixture was filtered through a column of Florisil, and the remaining solids were triturated well with anhydrous Et_2O. Removal of solvent in vacuo gave the corresponding aldehyde (1.79 g, 99%) as a colorless oil, which was used without further purification.

To a cold (−40 °C) solution of methyl 4-iodobenzoate (2.85 g, 10.9 mmol) in THF (60 mL) was added isopropylmagnesium chloride (5.7 mL of a 2.0 M solution in THF, 11.4 mmol) over 10 min. The reaction was stirred in the cold for 1 h. A solution of the aldehyde (1.73 g, 10.4 mmol) obtained above in THF (20 mL) was added dropwise. The reaction was stirred in the cold for 3 h and quenched with 5% aqueous NH_4Cl. THF was removed in vacuo, and the resultant aqueous phase was extracted with Et_2O. The combined ethereal extracts were washed with brine, followed by drying ($MgSO_4$) and removal of the solvent in vacuo. Silica gel chromatography (14% EtOAc in petroleum ether) afforded corresponding alcohol (2.82 g, 90%) as a white powder.

A mixture of PCC (3.09 g, 14.3 mmol) and Celite 545 (5.0 g) was ground in a mortar and pestle until homogeneous. This solid was added to a solution of the alcohol (2.71 g, 8.96 mmol) obtained above in anhydrous dichloromethane (100 mL), and the reaction was stirred for 12 h at room temperature. The reaction mixture was filtered through a column of Florisil, and the remaining solids were triturated well with anhydrous Et_2O. Removal of solvent in vacuo gave ketone **4e** (2.69 g, 100%) as a white solid. mp: 137−138 °C (EtOAc/hexanes). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.48 (s, 3H), 1.32−1.94 (m, 10H), 2.08 (m, 2H), 2.29 (br, 2H), 3.92 (s, 3H), 7.74 (d, J = 8.5 Hz, 2H), 8.03 (d, J = 8.5 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.10, 20.89, 23.64, 26.71, 29.03, 33.74, 51.04, 52.32, 127.69, 129.27, 131.89, 143.20, 166.36, 209.71 ppm. IR (KBr): 2950, 2906, 2857, 1722, 1666, 1435, 1279, 1190, 1108, 862, 738 cm^{-1}. UV/vis (1.46×10^{-4} M, MeOH): 285 (1459), 330 (194) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{19}H_{24}O_3$ 300.1725, found 300.1729. Anal. Calcd for $C_{19}H_{24}O_3$: C, 75.97; H, 8.05. Found: C, 75.80; H, 8.00.

Methyl 9-Benzylbicyclo[3.3.1]nonane-9-carboxylate (5a). Compound **5a** was prepared by General Procedure A using 3.56 mmol of LDA, 500 mg (2.74 mmol) of methyl bicyclo[3.3.1]nonane-9-carboxylate,[18] *n*-butyllithium (1.9 mL of a 1.6 M solution in *n*-hexane, 3.01 mmol), 662 μL (5.48 mmol) of DMPU, and 937 mg (5.48 mmol) of benzyl bromide. The crude product was purified by silica gel chromatography (3% Et_2O in petroleum ether) to give the title compound (680 mg, 91%) as a white solid. mp: 65−66 °C (Et_2O/hexanes). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.38−2.30 (m, 14H), 3.01 (s, 2H), 3.45 (s, 3H), 7.02−7.26 (m, 5H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.26, 21.02, 26.79, 29.52, 32.22, 41.78, 50.62, 52.18, 126.40, 127.94, 129.33, 138.01, 175.84 ppm. IR (KBr): 2960, 2913, 2866, 1737, 1723, 1490, 1227, 1045, 740, 700 cm^{-1}. HRMS (EI) calcd for $C_{18}H_{24}O_2$ 272.1776, found 272.1782. Anal. Calcd for $C_{18}H_{24}O_2$: C, 79.37; H, 8.88. Found: C, 79.18; H, 8.79.

Spiro[2*H*-indene-2,9′-bicyclo[3.3.1]nonan]-1(3*H*)-one (4a). General Procedure D. To a cold (−78 °C) solution of ester **5a** (416 mg, 1.53 mmol) in anhydrous dichloromethane (10 mL) was added boron trichloride (15.3 mL of a 1.0 M solution in dichloromethane, 15.3 mmol) over 10 min. The reaction was slowly warmed to 0 °C and stirred for 3 h before being poured onto crushed ice (15 g). Dichloromethane (125 mL) was added, and the mixture was stirred until all of the ice melted. The organic phase was separated and successively washed with 5% aqueous sodium carbonate, water, and brine, then dried ($MgSO_4$) and concentrated in vacuo. Silica gel chromatography (3% Et_2O in petroleum ether) afforded the title compound (323 mg, 88%) as a white solid. mp: 105.5−107.5 °C (hexanes). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.48−2.12 (m, 12H), 2.52 (m, 2H), 3.16 (s, 2H), 7.28−7.69 (m, 4H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.48, 20.55, 26.78, 29.37, 33.51, 38.94, 53.16, 123.94, 125.99, 127.10, 134.13, 136.87, 151.15, 209.99 ppm. IR (KBr): 2947, 2917, 2876, 1693, 1281, 936, 764, 727 cm^{-1}. UV/vis (1.75×10^{-4} M, MeOH): 294 (2851), 340 (65) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{17}H_{20}O$ 240.1514, found 240.1514. Anal. Calcd for $C_{17}H_{20}O$: C, 84.96; H, 8.39. Found: C, 84.59; H, 8.66.

Methyl 9-(2-Phenylethyl)bicyclo[3.3.1]nonane-9-carboxylate (5b). Compound **5b** was prepared by General Procedure A using 7.31 mmol of LDA, 1.03 g (5.62 mmol) of methyl bicyclo[3.3.1]nonane-9-carboxylate,[18] *n*-butyllithium (3.9 mL of a 1.6 M solution in *n*-hexane, 6.18 mmol), 1.36 mL (11.3 mmol) of DMPU, and 1.14 mL (11.3 mmol) of 2-bromo-1-phenylethane. The crude product was purified by silica gel chromatography (3% Et_2O in petroleum ether) to give the title compound (1.31 g, 81%) as a colorless oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.41−2.05 (m, 14H), 2.15 (br, 2H), 2.42 (m, 2H), 3.73 (s, 3H), 7.12−7.31 (m, 5H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.04, 21.29, 26.29, 29.46, 29.99, 31.97, 37.82, 49.74, 51.19, 125.79, 128.28, 128.36, 142.42, 177.03 ppm. IR (neat): 3025, 2950, 2914, 2867, 1728, 1455, 1239, 1197, 1163, 1050, 759, 699 cm^{-1}. HRMS (CI) calcd for $C_{19}H_{30}NO_2$ (M + NH_4^+) 304.2277, found 304.2276. Anal. Calcd for $C_{19}H_{26}O_2$: C, 79.68; H, 9.15. Found: C, 79.61; H, 9.43.

3,4-Dihydrospiro[naphthalene-2(1*H*),9′-bicyclo[3.3.1]nonan]-1-one (4b). Compound **4b** was prepared by General Procedure D using 1.09 g (3.81 mmol) of ester **5b** and 20.0 mL (20.0 mmol, 1.0 M in dichloromethane) of boron trichloride. The crude product was purified by silica gel chromatography (3% Et_2O in petroleum ether) to give the title compound (691 mg, 71%) as a white solid. mp: 92−93 °C (Et_2O/petroleum ether). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.45−1.65 (m, 6H), 1.75−2.24 (m, 10H), 2.97 (t, J = 6.3 Hz, 2H), 7.14 (d, J = 7.6 Hz, 1H), 7.24 (dt, J = 7.7, 0.9 Hz, 1H), 7.38 (dt, J = 7.6, 1.5 Hz, 1H), 7.76 (dd, J = 7.7, 1.1 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.66, 21.62, 24.24, 27.46, 28.71, 30.74, 31.55, 47.35, 126.39, 127.46, 127.87, 132.00, 134.23, 141.92, 206.80 ppm. IR (KBr): 2926, 2857, 1685, 1286, 1226, 900, 757, 738 cm^{-1}. UV/vis (1.89×10^{-4} M, MeOH): 285 (2466), 330 (150) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{18}H_{22}O$ 254.1671, found 254.1671. Anal. Calcd for $C_{18}H_{22}O$: C, 84.99; H, 8.72. Found: C, 85.15; H, 8.66.

Methyl 9-(2-Propenyl)bicyclo[3.3.1]nonane-9-carboxylate (6). Compound **6** was prepared by General Procedure A using 21.9 mmol of LDA, 3.07 g (16.8 mmol) of methyl bicyclo[3.3.1]nonane-9-carboxylate,[18] *n*-butyllithium (11.6 mL of a 1.6 M solution in *n*-hexane, 18.5 mmol), 4.1 mL (34 mmol) of DMPU, and 2.9 mL (34 mmol) of allyl bromide. The crude product was purified by silica gel chroma-

tography (3% Et_2O in petroleum ether) and bulb-to-bulb distillation to give the title compound (3.49 g, 93%) as a colorless liquid. bp: 125−127 °C/6 mmHg. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.40−2.00 (m, 12H), 2.05 (br, 2H), 2.43 (d, J = 7.5 Hz, 2H), 3.68 (s, 3H), 4.98 (m, 2H), 5.65 (m, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.07, 21.16, 26.26, 29.42, 31.80, 40.13, 50.48, 51.00, 117.03, 133.58, 176.52 ppm. IR (neat): 2960, 2912, 2866, 1731, 1460, 1214, 1186, 1120, 912 cm^{-1}. HRMS (EI) calcd for $C_{14}H_{22}O_2$ 222.1620, found 222.1620. Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.97; H, 10.14.

9-Hydroxymethyl-9-(2-propenyl)bicyclo[3.3.1]nonane (7). Compound **7** was prepared by General Procedure B using 3.36 g (15.1 mmol) of ester **6** and 8.3 mL (8.3 mmol, 1.0 M solution in THF) of lithium aluminum hydride. The crude product was purified by silica gel chromatography (25% Et_2O in petroleum ether) to give the title compound (2.67 g, 91%) as a white solid. mp: 51−52 °C (Et_2O/pentane). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.38−2.10 (m, 14H), 2.37 (d, J = 7.5 Hz, 2H), 3.75 (s, 2H), 5.02−5.17 (m, 2H), 5.89 (m, 1H) ppm. ^{13}C NMR ($CDCl_3$, 100 MHz): δ 20.86, 21.07, 26.97, 27.24, 31.02, 37.03, 39.66, 65.10, 116.89, 135.56 ppm. IR (KBr): 3371 (br), 3072, 2911, 2876, 1637, 1487, 1463, 1048, 1009, 910 cm^{-1}. HRMS (CI) calcd for $C_{13}H_{26}NO$ ($M + NH_4^+$) 212.2015, found 212.2015. Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.06; H, 11.54.

9-(2-Propenyl)-9-(*o*-vinylbenzoyl)bicyclo[3.3.1]nonane (8a). General Procedure E. A mixture of PCC (1.42 g, 6.59 mmol) and Celite 545 (3.09 g) was ground in a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **7** (927 mg, 4.77 mmol) in anhydrous dichloromethane (150 mL) and stirred for 2 h at room temperature. The reaction mixture was filtered through a column of Florisil, and the remaining solids were triturated well with anhydrous Et_2O. Removal of solvent in vacuo gave the corresponding aldehyde (915 mg, 99%) as a colorless oil, which was used without further purification.

To a suspension of Mg turnings (570 mg, 23.8 mmol) in THF (30 mL) was added 1,2-dibromoethane (50 $\mu\mu$L). The mixture was gently heated for 2 min. 2-Bromostyrene (1.83 g, 10.0 mmol) was then added slowly so as to maintain a gentle reflux, and the reaction was stirred for 1 h. The aldehyde (915 mg, 4.76 mmol) obtained above in THF (20 mL) was added dropwise, and the reaction was stirred for 2 h at room temperature. The reaction was quenched with 1 M HCl and diluted with Et_2O. The organic phase was separated and washed successively with water and brine. The organic layer was dried ($MgSO_4$), and the solvent was removed in vacuo. Silica gel chromatography (5% Et_2O in petroleum ether) afforded the corresponding alcohol (1.12 g, 79% from **7**) as a white solid (mp: 80−82 °C Et_2O/petroleum ether).

A mixture of PCC (1.20 g, 5.57 mmol) and Celite 545 (2.50 g) was ground in a mortar and pestle until homogeneous. This solid was added to a solution of the alcohol (1.10 g, 3.71 mmol) obtained above in anhydrous dichloromethane (150 mL), and the resulting mixture was stirred for 12 h at room temperature. The reaction mixture was filtered through a column of Florisil, and the remaining solids were triturated well with anhydrous Et_2O. Removal of solvent in vacuo and silica gel chromatography (5% Et_2O in petroleum ether) gave ketone **8a** (673 mg, 61%) as a colorless oil, which solidified upon standing. mp: 53−54 °C (Et_2O/petroleum ether). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.34−1.71 (m, 8H), 1.83 (m, 2H), 2.08 (m, 2H), 2.29 (br, 2H), 2.78 (d, J = 7.3 Hz, 2H), 5.04 (m, 2H), 5.27 (dd, J = 11.2 and 11.0 Hz, 1H), 5.70 (m, 2H), 7.00 (dd, J = 11.0 and 17.4 Hz, 1H), 7.21 (dt, J = 7.6 and 1.2 Hz, 1H), 7.36 (dt, J = 7.8 and 1.2 Hz, 1H), 7.55 (dd, J = 7.8 and 1.2 Hz, 1H), 7.61 (d, J = 7.9 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 19.81, 20.99, 26.71, 28.94, 32.38, 39.60, 55.20, 116.32, 117.18, 124.85, 126.26, 127.46, 129.82, 133.57, 135.09, 137.63, 139.16, 209.75 ppm. IR (KBr): 3075, 2916, 2867, 1672, 1475, 1216, 994, 914, 769, 739 cm^{-1}. HRMS (EI) calcd for $C_{21}H_{26}O$ 294.1984, found 294.1984. Anal. Calcd for $C_{21}H_{26}O$: C, 85.67; H, 8.90. Found: C, 85.39; H, 8.94.

Spiro[6*H*-benzocycloheptene-6,9′-bicyclo[3.3.1]nonan]-5(7*H*)-one (9a). General Procedure F. To a solution of ketone **8a** (472 mg, 1.60 mmol) in degassed anhydrous dichloromethane (110 mL) was added a solution of Grubbs' catalyst (benzylidene-bis(tricyclohexylphosphine)dichlororuthenium) (63 mg, 5 mol %) in degassed anhydrous dichloromethane over 10 min. The initial purple color was replaced by a light golden brown color. The reaction was stirred at room temperature for 12 h. The reaction solution was filtered through Florisil, and the solvent was removed in vacuo. Silica gel chromatography (8% Et_2O in petroleum ether) afforded the enone **9a** (416 mg, 97%) as a pale yellow solid. Further purification by recrystallization from EtOAc/petroleum ether provided colorless crystals. mp: 101−102 °C (EtOAc/petroleum ether). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.38−2.03 (m, 12H), 2.19 (br, 2H), 2.62 (dd, J = 2.8, 5.2 Hz, 2H), 5.81 (dt, J = 5.2 and 12.2 Hz, 1H), 6.38 (d, J = 12.2 Hz, 1H), 7.11 (d, J = 7.5 Hz, 1H), 7.26 (dt, J = 7.5 and 1.0 Hz, 1H), 7.36 (dt, J = 7.5 and 1.5 Hz, 1H), 7.50 (d, J = 7.5 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.25, 21.48, 26.97, 28.96, 31.31, 35.37, 49.69, 127.21, 127.52, 129.35, 130.01, 130.73, 130.83, 132.87, 138.21, 209.72 ppm. IR (KBr): 3019, 2911, 2869, 1677, 1460, 1261, 925, 779, 764 cm^{-1}. UV/vis (1.95×10^{-4} M, MeOH): 270 (4049), 310 (2466) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{19}H_{22}O$ 266.1671, found 266.1671. Anal. Calcd for $C_{19}H_{22}O$: C, 85.67; H, 8.32. Found: C, 85.71; H, 8.44.

8,9-Dihydrospiro[6*H*-benzocycloheptene-6,9′-bicyclo[3.3.1]nonan]-5(7*H*)-one (4c). General Procedure G. A suspension of 10% palladium on charcoal (18 mg) and enone **9a** (186 mg, 0.70 mmol) in EtOAc (25 mL) was placed under an atmosphere of H_2. The mixture was stirred for 4 h and filtered through Celite 545. Removal of the solvent in vacuo afforded ketone **4c** (180 mg, 96%) as a white solid. Recrystallization from Et_2O/hexanes provided colorless crystals. mp: 75−76 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.37−1.58 (m, 6H), 1.68−2.10 (m, 12H), 2.84 (m, 2H), 7.08 (m, 1H), 7.18−7.33 (m, 3H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.06, 21.07, 23.69, 26.53, 28.95, 32.59, 35.77, 36.26, 53.48, 126.03, 128.18, 128.53, 129.25, 137.69, 141.96, 213.51 ppm. IR (KBr): 2914, 2864, 1679, 1446, 1260, 951, 770, 740 cm^{-1}. UV/vis (1.49×10^{-4} M, MeOH): 275 (1294), 315 (338) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{19}H_{24}O$ 268.1827, found 268.1827. Anal. Calcd for $C_{19}H_{24}O$: C, 85.03; H, 9.01. Found: C, 85.29; H, 9.17.

9-(2-Propenyl)-9-[*o*-(2-propenyl)benzoyl]bicyclo[3.3.1]nonane (8b). Compound **8b** was prepared by General Procedure E. PCC (1.50 g, 6.96 mmol) was used to oxidize alcohol **7** (1.08 g, 5.56 mmol) to give the corresponding aldehyde (1.04 g, 97%) as a colorless oil; Mg turnings (649 mg, 27.0 mmol), 2-propenylbromobenzene[27] (2.26 g, 11.5 mmol), and this aldehyde (1.04 g, 5.41 mmol) reacted to afford the corresponding alcohol (1.29 g, 75%) as a colorless oil. Oxidation of this alcohol (1.20 g, 3.86 mmol) with PCC (1.25 g, 5.80 mmol) was followed by silica gel chromatography (6% Et_2O in petroleum ether) to give the title compound (988 mg, 83%) as a colorless oil, which solidified upon standing. mp: 54−56 °C (Et_2O/petroleum ether). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.35−1.71 (m, 8H), 1.84 (m, 2H), 2.09 (m, 2H), 2.30 (br, 2H), 2.80 (d, J = 7.3 Hz, 2H), 3.44 (d, J = 6.8 Hz, 2H), 5.07 (m, 4H), 5.74 (m, 1H), 6.02 (m, 1H), 7.14 (m, 1H), 7.32 (d, J = 3.9 Hz, 2H), 7.55 (d, J = 7.8 Hz, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 19.83, 20.97, 26.70, 28.95, 32.33, 37.44, 39.64, 55.17, 115.95, 117.10, 124.77, 124.97, 129.67, 131.27, 133.63, 137.64, 139.61, 139.78, 209.89 ppm. IR (KBr): 3074, 2915, 2868, 1672, 1637, 1460, 1217, 995, 914, 743 cm^{-1}. HRMS (EI) calcd for $C_{22}H_{28}O$ 308.2140, found 308.2139. Anal. Calcd for $C_{22}H_{28}O$: C, 85.66; H, 9.15. Found: C, 86.00; H, 9.27.

Spiro[6*H*-benzocyclooctene-6,9′-bicyclo[3.3.1]nonan]-5(7*H*,10*H*)-one (9b). Compound **9b** was prepared by General Procedure F using 670 mg (2.17 mmol) of ketone **8b** and 54 mg (3 mol %) of Grubbs' catalyst (benzylidene-bis(tricyclohexylphosphine)dichlororuthenium).

(27) Boymond, L.; Rottländer, M.; Cahiez, G.; Knochel, P. *Angew. Chem., Int. Ed.* **1998**, *37*, 1701.

The crude product was purified by silica gel chromatography (5% Et_2O in petroleum ether) to give the title compound (578 mg, 95%) as an off-white solid. Recrystallization from hexanes provided colorless crystals. mp: 83−84 °C (hexanes). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.50−1.75 (br m, 6H), 1.80−2.05 (br m, 6H), 2.21 (br, 1H), 2.45 (br m, 3H), 3.48 (br m, 2H), 5.57−5.75 (m, 2H), 7.05−7.26 (m, 4H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.01, 21.38, 26.81 (br), 28.10 (br), 28.32 (br), 30.10 (br), 31.05 (br), 31.73, 32.88 (br), 35.69, 57.33, 124.90, 125.46, 125.89, 128.26, 128.93, 129.84, 135.43, 141.14, 213.58 ppm, slow conformational exchange at room temperature has broadened and split some of the carbon signals. IR (KBr): 2912, 2867, 1694, 1458, 1120, 951, 936, 772, 727 cm^{-1}. UV/vis (1.78×10^{-4} M, MeOH): 265 (286), 315 (118) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{20}H_{24}O$ 280.1827, found 280.1828. Anal. Calcd for $C_{20}H_{24}O$: C, 85.67; H, 8.63. Found: C, 85.59; H, 8.80.

8,9-Dihydrospiro[6*H*-benzocyclooctene-6,9′-bicyclo[3.3.1]nonan]-5(7*H*,10*H*)-one (4d). Compound **4d** was prepared by General Procedure G using 249 mg (0.89 mmol) of ketone **9b** and 25 mg of 10% palladium on charcoal. Filtration gave the title compound (241 mg, 96%) as a white solid. Recrystallization from hexanes provided colorless crystals. mp: 102−103 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.22−2.32 (br m, 18H), 2.52−2.96 (br m, 2H), 7.05−7.25 (m, 4H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 19.74, 21.76, 22.06, 25.77 (br), 27.87 (br), 28.10 (br), 29.18, 29.42 (br), 31.80 (br), 32.61, 33.12 (br), 34.04, 55.44, 124.59, 124.92, 128.29, 130.17, 139.70, 140.78, 215.29, slow conformational exchange at room temperature has broadened and split some of the carbon signals. IR (KBr): 2911, 2867, 1685, 1448, 935, 753 cm^{-1}. UV/vis (1.56×10^{-4} M, MeOH): 265 (247), 315 (95) nm (M^{-1} cm^{-1}). HRMS (EI) calcd for $C_{20}H_{26}O$ 282.1984, found 282.1983. Anal. Calcd for $C_{20}H_{26}O$: C, 85.06; H, 9.28. Found: C, 84.94; H, 9.59.

Photochemical Studies. General Considerations. Both solution and solid-state photolyses were carried out by using a 450 W Hanovia medium-pressure mercury lamp in a water-cooled immersion well. Light from the lamp was filtered through a Pyrex ($\lambda \geq 290$ nm) immersion well.

For preparative scale solution-state photolyses, samples were dissolved in HPLC grade or spectral grade solvents and were purged with nitrogen for at least 15 min prior to irradiation. In the case of ketones **4a**, **13a**, and **16a**, anhydrous barium oxide was added to scavenge any acidic impurities that might promote the tautomerization of intermediate enols to ketone epimers. By doing so, secondary photocleavage of the ketone epimers was kept to a minimum. The reactions were performed either in sealed reaction vessels or under a positive pressure of nitrogen. Yields and conversions were calculated on the basis of the mass of the isolated products.

For analytical solid-state photolyses, ground solid samples (5−10 mg) were sandwiched between two microscopic slides. The sample plates were then fixed to one another with tape and placed in a polyethylene bag, and heat-sealed under a positive pressure of nitrogen. Following irradiation, the samples were quantitatively washed from the plates with an appropriate solvent and concentrated in vacuo. The samples were analyzed directly by GC and/or NMR spectroscopy. Yields and conversions of the solid-state reactions were determined on the basis of the average integration of at least two GC analyses. The overall precision of the reported GC results is estimated to be ±1%. In the case of ketones **13c** and **13d**, where GC analyses were hampered by the thermal lability of the photoproducts, ^{1}H NMR and ^{13}C NMR analyses of the crude solid-state photosylates were conducted to determine their composition.

Photolysis of Spiroketone 4a. A solution of ketone **4a** (51 mg, 0.21 mmol) in 2:1 *tert*-butyl alcohol/benzene (20 mL) containing anhydrous barium oxide (14 mg) was irradiated (Pyrex filter, 450 W Hanovia lamp) for 2.5 h at room temperature. Removal of solvent and silica gel chromatography (5% Et_2O in petroleum ether) afforded starting material **4a** (19 mg, 37%) and ketone epimers (~1:1 by ^{1}H NMR) **10a** (18 mg, 35%; 56% based on recovered starting material) as a colorless oil. Also isolated was 1-indanone (3 mg, 11%, 17% based on recovered starting material) resulting from secondary photocleavage of ketone **10a**.

Ketone 10a (Equal Mixture of Two Epimers). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.98−1.67 (m, 6H), 1.97−2.43 (m, 5H), 2.63 (m, 1H), 2.87 (m, 1H), 3.16 (m, 1H), 5.64 (m, 2H), 7.33 (m, 1H), 7.43 (m, 1H), 7.55 (m, 1H), 7.72 (m, 1H) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ 24.75, 24.86, 25.68, 25.71, 27.93, 28.16, 28.88, 28.94, 29.67, 30.38, 31.30, 34.62, 37.57, 38.63, 54.30, 54.51, 123.56, 123.69, 126.42, 126.47, 127.18 (two accidentally equivalent), 129.66, 130.01, 130.12, 130.57, 134.48 (two accidentally equivalent), 137.89, 138.04, 154.27, 154.67, 208.70, 208.88 ppm. IR (neat): 3013, 2923, 2853, 1709, 1610, 1464, 1282, 750, 732 cm^{-1}. HRMS (EI) calcd for $C_{17}H_{20}O$ 240.1514, found 240.1516. Anal. Calcd for $C_{17}H_{20}O$: C, 84.96; H, 8.39. Found: C, 85.06; H, 8.61.

Ketone **10a** was also found to be the major product (67%, at 6% conversion) resulting from irradiation of crystals of spiroketone **4a**; compounds 1-indanone, 1,4-cyclooctadiene, and 1,5-cyclooctadiene were also observed by GC-MS, presumably through the competitive enol−keto tautomerization and secondary photolysis seen in solution (GC).

Photolysis of Spiroketone 4b. Irradiation (>24 h) of a 2:1 *tert*-butyl alcohol/benzene or acetonitrile solution of spiroketone **4b** resulted in only trace amounts (<1%) of unidentified short retention time peaks on GC. Photolysis of spiroketone **4b** in the solid state (>48 h) also led to no detectable photoproducts.

Photolysis of Spiroketone 4c. A solution of ketone **4c** (70 mg, 0.26 mmol) in 2:1 *tert*-butyl alcohol/benzene (50 mL) was purged with nitrogen for 30 min and irradiated (Pyrex filter, 450 W Hanovia) for 56 h. Removal of solvent in vacuo followed by silica gel chromatography (6% Et_2O in petroleum ether) afforded starting material **4c** (14 mg, 20%) and cyclobutanol **11c** (37 mg, 53%; 66% based on recovered starting material) as a colorless oil. Also isolated was a mixture of two components (2 mg, 3%). Careful examination of the ^{1}H NMR spectrum of this mixture revealed that one component was cyclobutanol **11c** and another component was an alkene (**12c**) bearing characteristic vinyl proton signals similar to those of alkene **20**. Further attempts to purify **12c** were not successful because of its small quantity and polarity similar to that of **11c**.

***endo*-Arylcyclobutanol 11c.** ^{1}H NMR (C_6D_6, 400 MHz): δ 0.93 (m, 1H), 1.02 (br, 1H), 1.15 (m, 1H), 1.30−1.79 (m, 9H), 1.91 (m, 1H), 2.04 (m, 2H), 2.20 (m, 1H), 2.44 (m, 1H), 2.59 (m, 1H), 2.79 (m, 1H), 3.25 (m, 1H), 7.01 (m, 3H), 7.19 (m, 1H) ppm. ^{13}C NMR (C_6D_6, 100 MHz): δ 18.93, 20.98, 22.37, 23.46, 25.72, 27.69, 30.01, 31.90, 36.77, 37.91, 48.21, 48.70, 83.01, 125.39, 125.88, 127.16, 131.57, 142.27, 143.21 ppm. IR (KBr): 3459, 2927, 2874, 1006, 968, 757, 740 cm^{-1}. HRMS (EI) calcd for $C_{19}H_{24}O$ 268.1827, found 268.1829. Anal. Calcd for $C_{19}H_{24}O$: C, 85.03; H, 9.01. Found: C, 85.08; H, 9.38.

endo-Arylcyclobutanol **11c** and alkene **12c** were also found to be the only two products (96% and 4%, respectively, at 18% conversion) resulting from irradiation of crystals of spiroketone **4c** (GC).

Photolysis of Spiroketone 4d. A solution of ketone **4d** (179 mg, 0.63 mmol) in 2:1 *tert*-butyl alcohol/benzene (50 mL) was irradiated (Pyrex filter, 450 W Hanovia) for 156 h. Removal of the solvent in vacuo followed by silica gel chromatography (8% Et_2O in petroleum ether) gave starting material **4d** (47 mg, 26%) and an oily mixture of **11d** and **12d** (92 mg, 51%; 69% based on recovered starting material). Attempts to separate **11d** and **12d** failed due to similar polarity of these two compounds. NMR analysis revealed that this mixture consisted of one secondary alcohol and one tertiary alcohol. The oxidizing reagent TPAP (tetrapropylammonium perruthenate)/NMO (4-methylmorpholine *N*-oxide)[28] was used to oxidize the secondary alcohol component to the corresponding ketone **12do**, which showed a significant difference in polarity to the tertiary alcohol component. Silica gel chromatography

(28) Ley, S. V.; Norman, J.; Griffith, W. P.; Marsden, S. P. *Synthesis* **1994**, *7*, 639.

(8% Et_2O in petroleum ether) provided **11d** (73 mg, 41%; 55% based on recovered starting material) and **12do** (17 mg, 9%; 13% based on recovered starting material). Oily compound **11d** solidified upon standing, while compound **12do** remained an oil.

***endo*-Arylcyclobutanol 11d.** mp: 62−64 °C (hexanes). ^{1}H NMR (C_6D_6, 400 MHz): δ 0.99 (m, 1H), 1.04 (br, 1H), 1.21 (m, 1H), 1.30−1.50 (m, 4H), 1.51−1.70 (m, 5H), 1.75−1.90 (m, 3H), 2.00 (m, 1H), 2.36 (m, 2H), 2.51 (1H, m), 2.61 (m, 1H), 2.70 (m, 1H), 2.90 (m, 1H), 6.98 (m, 1H), 7.04 (m, 2H), 7.13 (m, 1H) ppm. ^{13}C NMR (C_6D_6, 100 MHz): δ 18.79, 20.75, 22.87, 25.37, 25.69, 27.15, 27.24, 27.80, 32.76, 34.63, 36.57, 48.25, 49.82, 82.17, 126.17, 127.25, 127.26, 131.82, 141.92, 143.48 ppm. IR (KBr): 3471, 2928, 2870, 1455, 983, 964, 771, 740 cm^{-1}. HRMS (EI) calcd for $C_{20}H_{26}O$ 282.1984, found 282.1985. Anal. Calcd for $C_{20}H_{26}O$: C, 85.06; H, 9.28. Found: C, 85.03; H, 9.63.

Ketone 12do. ^{1}H NMR (C_6D_6, 400 MHz): δ 1.02−1.80 (m, 13H), 2.32 (br, 2H), 2.46 (br, 1H), 2.81 (m, 1H), 3.14 (m, 1H), 5.60 (m, 1H), 5.86 (m, 1H), 6.90−6.99 (m, 2H), 7.05 (m, 1H), 7.35 (m, 1H) ppm. ^{13}C NMR (C_6D_6, 100 MHz): δ 16.97, 19.27, 23.32, 29.37, 30.55, 30.82, 31.32, 32.56, 34.56, 54.42, 125.00, 125.80, 128.42, 129.88, 130.41, 132.08, 137.82, 142.89, 212.72 ppm. IR (neat): 3015, 2914, 2865, 1683, 1446, 972, 756, 710 cm^{-1}. HRMS (EI) calcd for $C_{20}H_{24}O$ 280.1827, found 280.1831. Anal. Calcd for $C_{20}H_{24}O$: C, 85.67; H, 8.63. Found: C, 85.67; H, 8.65.

The structure of photoproduct **12d** was deduced on the basis of the spectral data of its derivative ketone **12do**.

endo-Arylcyclobutanol **11d** and alkene **12d** were also found to be the only two products (81% and 19%, respectively, at 9% conversion) resulting from irradiation of crystals of spiroketone **4d** (GC).

Photolysis of Ketone 4e. A solution of ketone **4e** (501 mg, 1.67 mmol) in acetonitrile (50 mL) was irradiated (Pyrex filter, 450 W Hanovia) for 6 h. Removal of the solvent in vacuo followed by silica gel chromatography (11% EtOAc in petroleum ether) afforded cyclobutanol **19** (446 mg, 89%) and alkene **20** (27 mg, 5%).

***endo*-Arylcyclobutanol 19.** mp: 149−150 °C (EtOAc/petroleum ether). ^{1}H NMR (C_6D_6, 400 MHz): δ 0.85 (m, 1H), 0.98 (m, 1H), 1.20 (s, 3H), 1.21−1.35 (m, 3H), 1.45−1.65 (m, 5H), 1.83 (m, 2H), 2.52 (m, 1H), 2.66 (m, 1H), 3.53 (s, 3H), 7.09 (d, J = 8.2 Hz, 2H), 8.11 (d, J = 8.2 Hz, 2H) ppm. ^{13}C NMR (C_6D_6, 100 MHz): δ 17.70, 18.61, 20.46, 22.87, 24.61, 27.73, 36.19, 37.62, 46.42, 46.79, 51.61, 81.87, 125.73, 129.45, 130.32, 149.34, 166.64 ppm. IR (KBr): 3482, 2958, 2927, 2879, 1723, 1609, 1439, 1279, 1106, 861, 781, 712 cm^{-1}. HRMS (EI) calcd for $C_{19}H_{24}O_3$ 300.1725, found 300.1726. Anal. Calcd for $C_{19}H_{24}O_3$: C, 75.97; H, 8.05. Found: C, 75.96; H, 8.28.

Alkene 20. mp: 148−150 °C ($CHCl_3$/hexanes). ^{1}H NMR (C_6D_6, 400 MHz): δ 0.85 (s, 3H), 1.03−1.12 (m, 2H), 1.20−1.30 (m, 3H), 1.48−1.80 (m, 4H), 2.35 (br, 1H), 2.53(br, 1H), 3.53 (s, 3H), 4.30 (s, 1H), 5.62 (m, 1H), 5.83 (m, 1H), 7.29 (d, J = 8.3 Hz, 2H), 8.13 (d, J = 8.3 Hz, 2H) ppm. ^{13}C NMR (C_6D_6, 75 MHz): δ 15.71, 16.52, 24.57, 29.36, 32.11, 32.90, 36.16, 40.09, 51.57, 75.22, 128.05, 128.55, 129.04, 129.19, 129.35, 148.50, 166.82 ppm. IR (KBr): 3524, 3017, 2921, 2862, 1723, 1706, 1610, 1436, 1281, 1111, 1016, 860, 772, 724 cm^{-1}. HRMS (CI) calcd for $C_{19}H_{28}NO_3$ ($M + NH_4^+$) 318.2069, found 318.2069. Anal. Calcd for $C_{19}H_{24}O_3$: C, 75.97; H, 8.05. Found: C, 75.89; H, 8.36.

endo-Arylcyclobutanol **19** and alkene **20** were also observed (92% and 6%, respectively, at 25% conversion) in the solid-state photolysis of ketone **4e** (GC).

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Supporting Information Available: Crystallographic information files (CIF) for previously unreported crystal structures, experimental details of the synthesis and photochemistry of ketones **13a**−**e** and **16a**−**e**, table of geometric data showing the hydrogen atom abstraction geometries for ketones **4a**−**e**, **13a**−**e**, and **16a**−**e**, and a figure showing the NOE interactions used in establishing the stereochemistry of photoproducts **11c**, **18c**−**d**, **21**, and **22** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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