Photochemistry of 9-methylbicyclo[3.3.1]nonyl aryl ketones — A novel 1,5-disproportionation of 1,4-hydroxy biradicals and asymmetric induction using the solid-state ionic chiral auxiliary method[1]

Shuang Chen, Brian O. Patrick, and John R. Scheffer

Abstract: A novel 1,5-disproportionation reaction has been discovered for 1,4-hydroxy biradicals derived from the photolysis of 9-methylbicyclo[3.3.1]nonyl phenyl ketones (**1**), which undergo mainly Yang cyclization both in solution and the solid state. By applying the solid-state ionic chiral auxiliary method of asymmetric synthesis to the Yang cyclization, enantiomeric excesses as high as 95% were achieved at high reaction conversions. The origin of the reaction selectivity is discussed with the help of X-ray crystallography. In addition, the solid-state photoreaction of ketone **1b** was found to occur in a single crystal-to-single crystal fashion.

Key words: photochemistry, 1,4-hydroxy biradical, disproportionation, asymmetric induction, ionic chiral auxiliary, single crystal-to-single crystal reaction.

Résumé : On a découvert une nouvelle réaction de dismutation pour les 1,4-dihydroxy biradicaux obtenus par photolyse des 9-méthylbicyclo[3.3.1]nonyl (phényl) cétones (**1**) qui subissent principalement une cyclisation de Yang tant en solution qu'à l'état solide. En appliquant à la cyclisation de Yang la méthode de l'auxiliaire chiral ionique en phase solide, il a été possible d'obtenir des excès énantiomériques pouvant atteindre 95 % avec des taux de conversion élevés. On discute de l'origine de la sélectivité de la réaction à l'aide de la cristallographie des rayons X. De plus, on a trouvé que, à l'état solide, la réaction de la cétone **1b** s'effectue d'une façon allant d'un cristal unique à un cristal unique.

Mots clés : photochimie, 1,4-dihydroxy biradical, dismutation, induction asymétrique, auxiliaire chiral ionique, réaction d'un cristal unique à un cristal unique.

[Traduit par la Rédaction]

Introduction

Triplet 1,4-hydroxy biradicals formed in the γ-hydrogen abstraction step of the photochemical Norrish–Yang type II reaction have three possible 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 (Scheme 1) (1). In this paper, we report a fourth reaction pathway, a novel 1,5-disproportionation, observed for the 1,4-hydroxy biradicals derived from hydrogen abstraction of 9-methylbicyclo[3.3.1]nonyl phenyl ketones (**1**). The study of the photochemistry of 9-methylbicyclo[3.3.1]nonyl phenyl ketones (**1**) complements our earlier studies on the solid-state Norrish–Yang type II photochemistry of adamantyl phenyl ketones and norbornyl phenyl ketones (**2** and **3**) (Scheme 1) (2, 3). In these two previous systems, hydrogen abstraction occurred from either a rigid six-membered ring or a rigid five-membered ring, while in the bicyclo[3.3.1]nonyl phenyl ketone system hydrogen abstraction occurs from a relatively flexible six-membered ring, allowing for the effects of small changes in ring geometry on the hydrogen abstraction process and the reaction outcome to be examined. Moreover, 9-methylbicyclo[3.3.1]nonyl phenyl ketones (**1**) are achiral molecules that give mainly chiral Yang photocyclization products upon photolysis. As hydrogen abstraction of either of the two enantiotopic γ-hydrogen atoms could occur, this allows the enantioselectivity of the reaction to be studied using the solid-state ionic chiral auxiliary method (4).

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Results and discussion

9-Methylbicyclo[3.3.1]nonyl phenyl ketones (**1a** and **1b**) were prepared by standard synthetic methods (Scheme 2) from the known compound 9-methylbicyclo[3.3.1]nonyl methanol (**4**) (5). Hydrolysis of ester **1b** afforded the corresponding keto acid **1c**, which was then reacted with various optically pure amines to form chiral salts **1d**–**1j** through acid–base chemistry. All these compounds were fully characterized by ^{1}H and ^{13}C NMR, FT-IR, HR-MS, UV, and elemental analysis (see details in the Experimental section).

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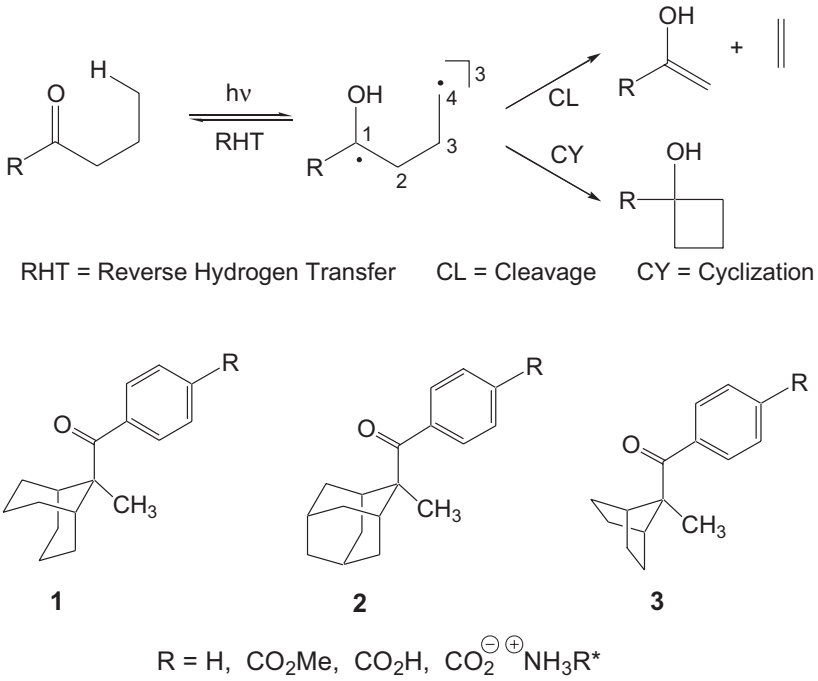
Scheme 1.



Scheme 2.

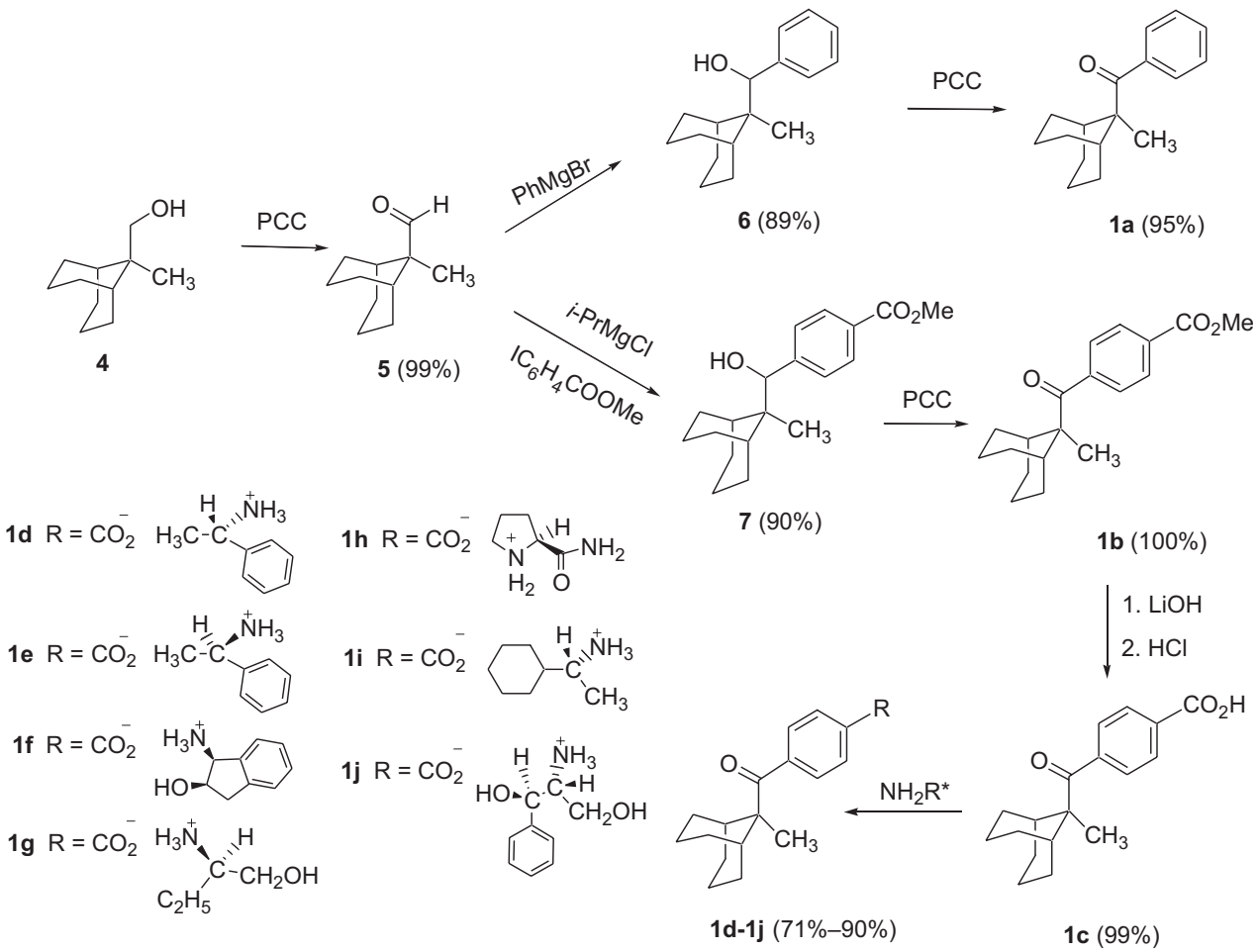
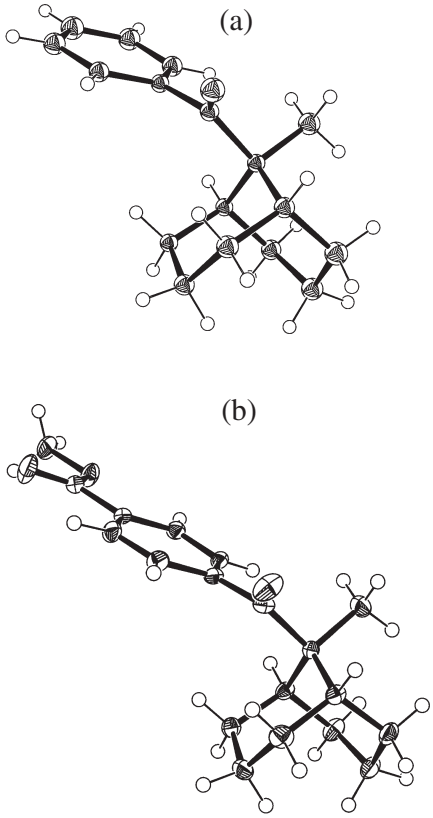


Fig. 1. ORTEP representation of (*a*) ketone **1a** and (*b*) ketone **1b**.



Single crystal X-ray crystallographic determinations were also performed for compounds **1a** and **1b** (Fig. 1).

The photochemistry of aryl ketones **1a** and **1b** was explored in both solution and the crystalline state. The reaction products were readily obtained by preparative scale solution photolysis and the solid-state reactions were performed on an analytical scale to determine the mode of reactivity in that medium. The details of the experiments as well as the apparatus used are given in the Experimental section. Table 1 and Scheme 3 summarize the photochemical results in both media. As shown in Scheme 3 and Table 1, like the analogous compounds **2** and **3** (2, 3), solution photolysis of ketones **1a** and **1b** primarily yielded Yang photocyclization products **9a** and **9b**.

Interestingly, photolysis of ketones **1a** and **1b** also afforded small amounts (<5%) of the unusual 1,5-disproportionation products **10a** and **10b** (Scheme 3). These minor products are presumably formed by a novel disproportionation of the intermediate 1,4-hydroxy biradical **8** in which a hydrogen atom on C5 is transferred to the radical center on C1. As far as we are aware, this type of disproportionation reaction is unknown for 1,4-hydroxy biradicals, although the corresponding process has been observed for a 1,5-hydroxy biradical (6). The stereochemistry of the major photoproducts (**9a** and **9b**) was later determined to be that in which the aryl group is in the endo position, although generation of *exo*-aryl products is theoretically possible. It is interesting to note that in the photochemistry of 9-methyl substituted ketones **1a** and **1b**, no Norrish type I or type II photocleavage products could be identified, although traces (<1%) of several unknown photoproducts could be detected by GC. The

Table 1. Photolysis of ketones **1a** and **1b** in solution and the crystalline state.

				Products (%)[b]			
Ketone	Medium	Time (h)	Conversion (%)[a]	**9a**	**10a**	**9b**	**10b**
1a	CH_3CN[c]	1	65	62	2		
		2	89	85	3		
		8	100	92	3		
	Crystal[c]	24	100	92	5		
1b	CH_3CN[c]	1	98			91	4
	Crystal[c]	24	100			90	5

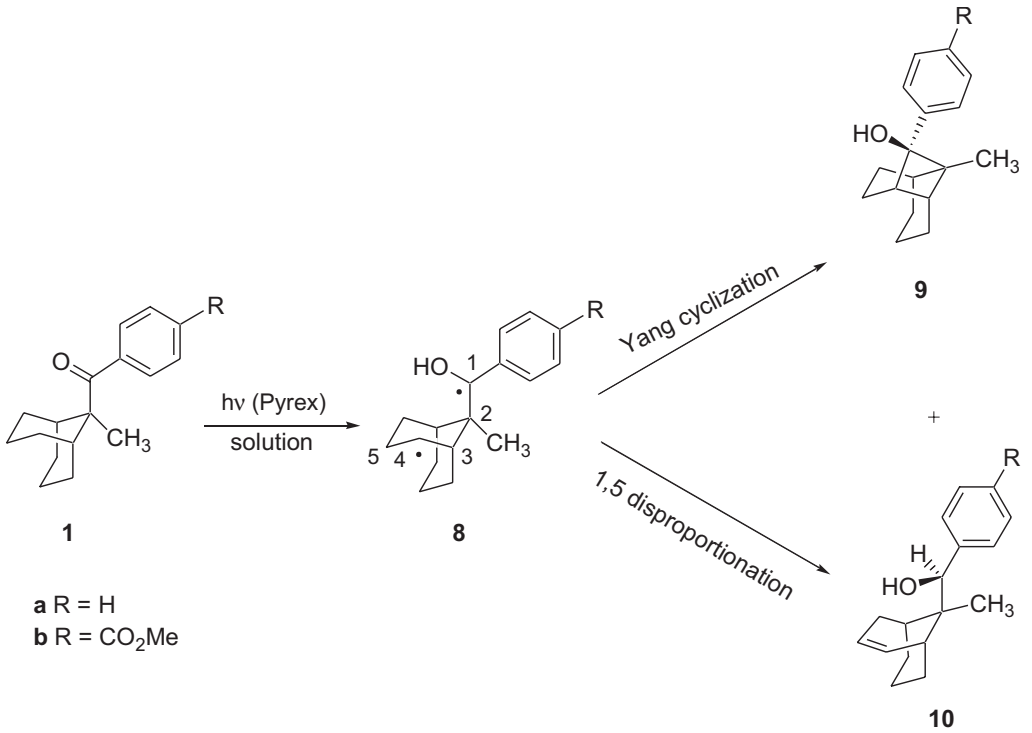
[a]Percentage of total GC integral owing to the disappearance of the corresponding starting material.
[b]Percentage of total GC integral owing to the corresponding product.
[c]The combined percentage of the reported compounds is less than unity because of some unidentified GC peaks.

results of solid-state photolysis of ketones **1a** and **1b** were strikingly similar to their solution counterparts, with **1a** and **1b** affording photoproducts **9a** and **9b** (90%–92%) and **10a** and **10b** (5%). All the photoproducts were fully characterized by 1D ^1H and ^{13}C (BB and APT) NMR, 2D ^1H–^1H COSY, ^1H–^{13}C HMQC, HMBC and NOESY, FT-IR, HR-MS, as well as by elemental analysis. The structures of photoproducts **10a**, **9b**, and **10b** were also confirmed by X-ray crystallography (Fig. 2). The details of the separation conditions along with the analytical data for each of the products are given in the Experimental section.

As described above, 9-methylated bicyclo[3.3.1]nonyl phenyl ketones **1a** and **1b** underwent Yang photocyclization and yielded *endo*-aryl cyclobutanols **9a** and **9b** as major photoproducts, both in solution and the solid state. In this case, it is relevant to ask why neither *exo*-aryl cyclobutanols nor photocleavage products were obtained. To answer this question, consider the idealized reaction pathway shown in Scheme 4. X-ray crystallography shows that in the crystalline state ketones **1a** and **1b** adopt chair–chair conformations in which the benzoyl group is in the axial position and the mean plane of the carbonyl group is roughly orthogonal to the plane bisecting the bicyclo[3.3.1]nonane ring between γ-hydrogen atoms H_x and H_y. In this case, H_x is in closer proximity to the carbonyl oxygen than H_y (for H_x: d = 2.50 Å in ketone **1a**, and 2.52 Å in ketone **1b**; for H_y: d = 3.49 Å in ketone **1a**, and 3.69 Å in ketone **1b**). The other γ-hydrogen abstraction parameters (ω, Δ, and θ) in Table 2 also suggest that H_x is in a more favorable position for hydrogen abstraction than H_y (7).

Upon photoexcitation and hydrogen abstraction, 1,4-hydroxy biradical intermediate **11** will be generated. Since hydrogen abstraction in the solid state is considered to occur with minimum movement of the heavy atoms, geometric data derived from the ground-state ketone can be used to analyze the behavior of the corresponding 1,4-hydroxy biradical intermediate (8). For this purpose, we define two torsional angles with reference to Fig. 3*a*, which is a depiction of the 1,4-hydroxy biradicals derived from ketones **1a** and **1b**. Angle φ_1 is defined as the dihedral angle between the C2—C3 bond and the p orbital on C1, and the angle φ_4 is likewise defined as the analogous angle between the C2—C3 bond and the p orbital on C4. The p orbitals at C1 and

Scheme 3.



Scheme 4.

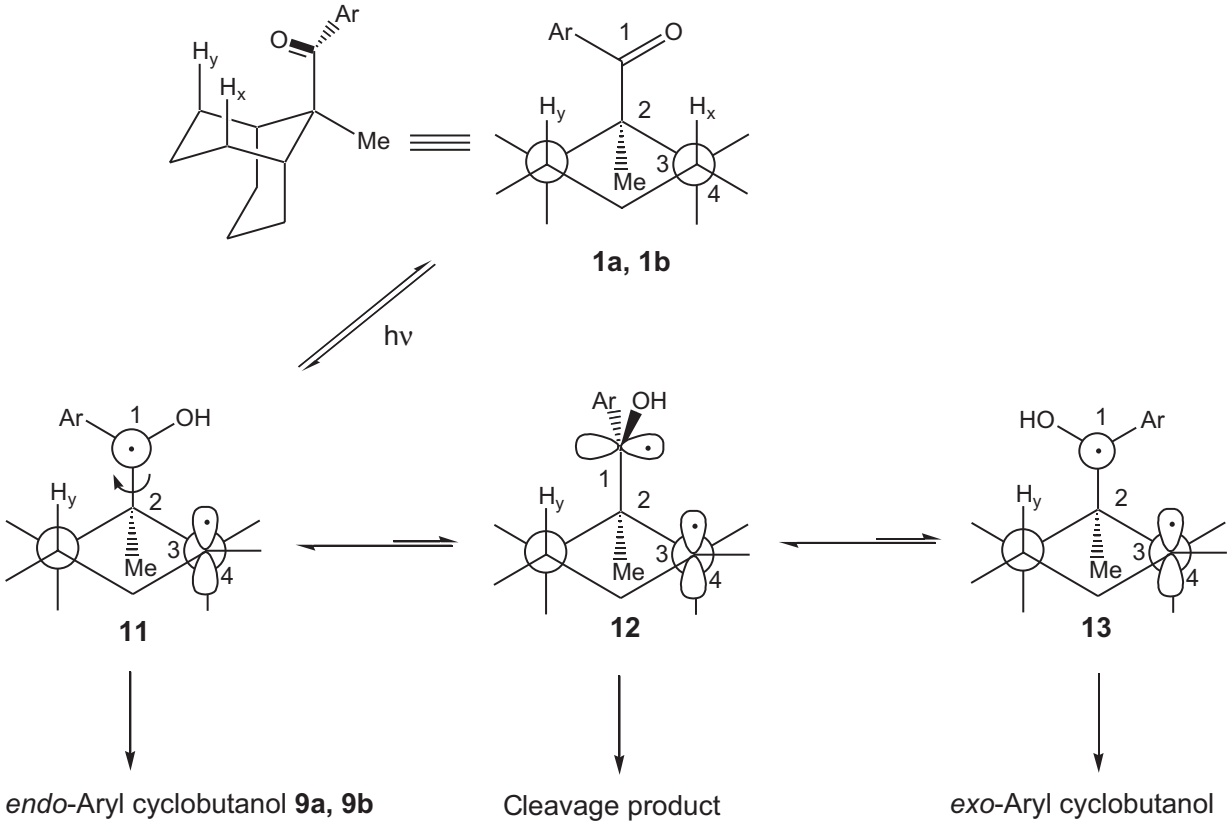
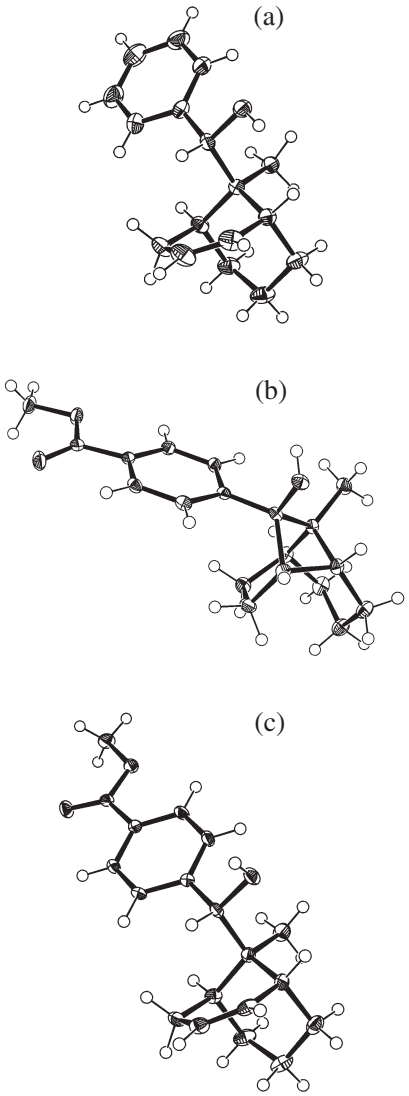


Fig. 2. ORTEP representation of photoproducts (*a*) **10a**, (*b*) **9b**, and (*c*) **10b**.



C4 are assumed to be orthogonal to the O-C1-C2 and C3-C4-C5 planes, respectively. It is generally believed that cleavage of 1,4-hydroxy biradicals is favored by good overlap between the p orbitals on C1 and C4 with the C2—C3 bond (9). The overlap between these orbitals is proportional to $\cos\varphi_1$ and $\cos\varphi_4$ (10), and the best geometry for cleavage can be expected when φ_1 and $\varphi_4 = 0°$ and $\cos\varphi_1 = \cos\varphi_4 = 1$. The values of $\cos\varphi_1$ and $\cos\varphi_4$ for the two ketones investigated in the present study are given in Table 3. Also shown in Table 3 are the values of the angle β, defined as the dihedral angle between the p orbital on C1 and the C2–C4 vector (Fig. 3*b*). The most favorable geometry for cyclization exists when $\beta = 0°$, i.e., when the p orbital on C1 is pointing directly at the p orbital on C4. Table 3 also gives the values of the distance (*D*), defined as the distance between C1 and C4. For Yang photocyclization to be successful, the radical-containing carbon atoms C1 and C4 must be close to one another, i.e., $D < 3.4$ Å, which is the sum of the van der Waals radii for two carbon atoms (11).

Table 2. Hydrogen atom abstraction parameters for compounds **1a** and **1b**.

Ketone	H	*d* (Å)[a]	ω (°)[b]	Δ (°)[c]	θ (°)[d]
1a	H_x	2.50	57	86	118
	H_y	3.49	91	41	105
1b	H_x	2.52	63	78	119
	H_y	3.69	94	35	105
Ideal value		2.7±0.2	0	90–120	180

[a]C=O···H_γ distance.
[b]Deviation of H_γ from the mean plane of the carbonyl group.
[c]C=O···H_γ angle.
[d]C-H_γ···O angle.

Fig. 3. (*a*) Idealized 1,4-hydroxybiradical intermediate. (*b*) Depiction of the angle β.

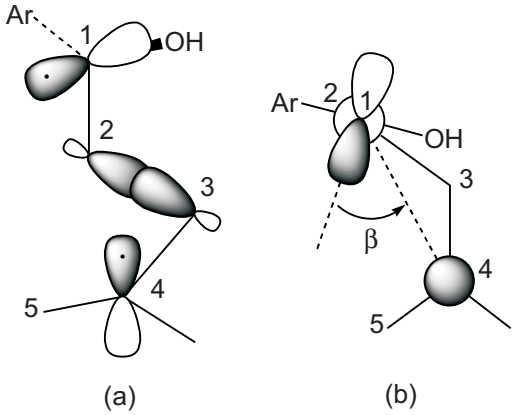
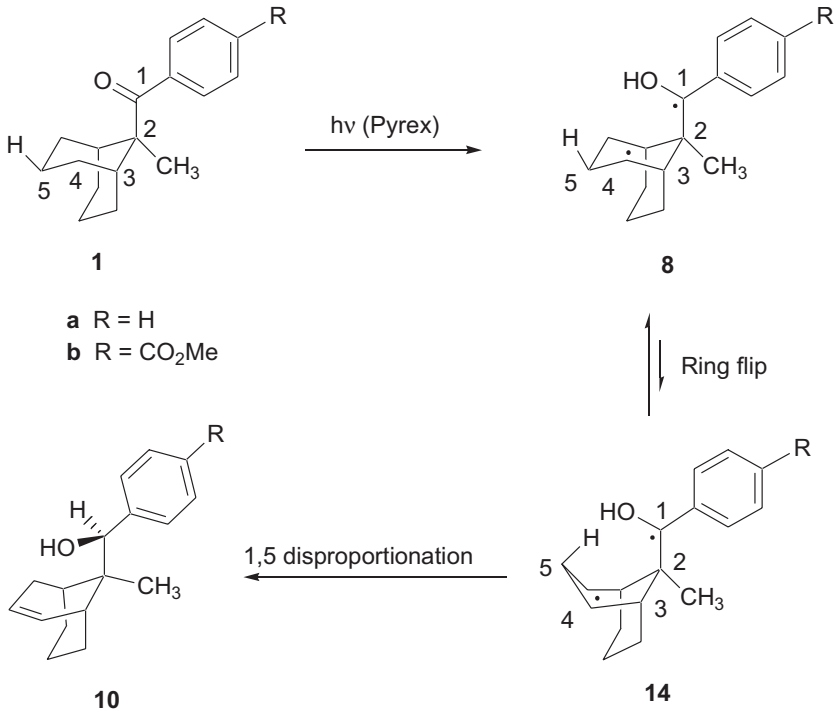


Table 3. Geometric data for ketones **1a** and **1b**.

Ketone	φ_1 (°)	$\cos\varphi_1$	φ_4 (°)	$\cos\varphi_4$	β (°)	*D* (Å)
1a	65	0.42	35	0.82	35	3.01
1b	59	0.52	36	0.81	28	2.90

With $\cos\varphi_4 \approx 80\%$ and $\cos\varphi_1 \approx 50\%$ (only 50% of maximum overlap between the p orbital on C1 and the C2—C3 bond), the geometry of biradical intermediate **11** is poor for cleavage, as cleavage requires good overlap of both p orbitals with the cleaving C2—C3 bond. But this biradical has a good geometry for cyclization, with $\beta \approx 30°$ (indicating there is reasonably good overlap of the two p orbitals at C1 and C4) and $D = 2.90$ Å in ketone **1b**, and 3.01 Å in ketone **1a**. As a result, cyclization of biradical **11** with retention of configuration at C1 and C4 leads to the predominant *endo*-aryl photoproducts **9a** and **9b**. On the other hand, for cleavage to occur, an approximate 90° rotation of the aryl and hydroxyl groups about the C1—C2 bond of biradical **11** is required to align the p orbital on C1 with the C2—C3 σ bond (see Scheme 4, structure **12**). An additional 90° rotation of the aryl and hydroxyl groups about the C1—C2 bond leads to biradical **13**, closure of which would give *exo*-aryl cyclobutanol products. Both processes require rotations about the C1—C2 bond and are unfavorable because of Ar/α-CH_3 eclipsing, a phenomenon known as the "α-alkyl group effect" (12). Therefore, *endo*-aryl cyclobutanols **9a**

Scheme 5.



and **9b** are the major products formed in the photoreaction of ketones **1a** and **1b**.

Formation of minor photoproducts **10a** and **10b** observed in the photolysis of ketones **1a** and **1b** can be seen to be the result of a 1,5-disproportionation of biradical intermediate **14**, which in turn is formed by a ring flip of initially formed biradical **8** (Scheme 5).[3] X-ray crystallographic analysis showed that the distance between C1 and the equatorial hydrogen atom on C5 in ketones **1a** and **1b** is 4.08 and 4.02 Å, respectively. It is unlikely that 1,5-disproportionation could take place directly from the chair–chair biradical **8** without a significant geometry change of the bicyclic ring. On the other hand, a ring flip of biradical **8** at the C5 end leads to the boat–chair biradical **14** in which the flagpole hydrogen atom on C5 is brought close to the radical center on C1 (13), and a 1,5-disproportionation process should easily occur. Because this ring-flipping process is energetically unfavorable, in an established equilibrium, the population of biradical **14** is less than that of biradical **8**. Moreover, because 1,5-disproportionation requires breaking a C—H bond, it is likely to be a slower process than Yang cyclization. Therefore, only small amounts of disproportionation products **10a** and **10b** were observed in the photolysis of ketones **1a** and **1b**.

In comparison with our previous studies on the photochemistry of adamantyl phenyl and norbornyl phenyl ketones (**2** and **3**) in which Yang cyclization was found to be the sole reaction pathway (no 1,5-disproportionation product was obtained owing to the rigidity of adamantyl and norbornyl ring skeletons) (2, 3), the present study not only corroborates this main reaction pattern for bicyclic and tricyclic phenyl ketones, but also shows that small changes in the flexibility of the bicyclic ring system can lead to a new reaction pattern, in this case a novel 1,5-disproportionation reaction.

To apply the solid-state ionic chiral auxiliary method to asymmetric induction in the photochemistry of 9-methylbicyclo[3.3.1]nonyl phenyl ketones, a number of crystalline salts (**1d–1j**, Scheme 2) were prepared by reaction of keto acid **1c** with commercially available optically pure amines. The amines were selected according to two criteria: (*i*) the pK_a of the reacting acid should be lower than that of the protonated amine by about 3 pK_a units (14, 15) because this ensures complete proton transfer from the acid to the amine instead of formation of a neutral hydrogen bonded complex; (*ii*) the amine selected should not possess chromophores that interfere with the aryl ketone absorption at 320–330 nm. The formation of an ammonium carboxylate linkage between the acid and amine was confirmed by the melting point and FT-IR spectrum of each salt. The melting points of all the salts are different from both those of keto acid **1c** and the corresponding amines. In the IR spectrum of keto acid **1c**, the C=O stretches of the ketone and carboxylic acid exist as broadened bands at 1695 and 1680 cm^{-1}, respectively. In the spectra of the salts, these absorptions are replaced by a single sharper band at ~1675 cm^{-1} corresponding to the C=O stretch of the ketone. At the same time, two new intense bands (1300–1600 cm^{-1}) owing to the symmetric and asymmetric stretches of the carboxylate anion are observed (16). The 1:1 acid–base stoichiometry of all the salts was confirmed by ^{1}H NMR spectroscopy, ESI (or LSI-MS) mass spectrometry, and elemental analysis.

[3] An alternative mechanism for the formation of minor photoproducts **10a** and **10b** involving initial δ-hydrogen atom abstraction followed by disproportionation is deemed unlikely on two counts: the general and well-established kinetic preference for γ over δ-hydrogen abstraction (1*a*), and in the specific case of ketones **1a** and **1b**, impossibly long C=O···H_δ distances (4.40 and 4.38 Å, respectively).

To determine whether the ionic chiral auxiliary has any effect on the product distribution or the steric course of the photoreaction in solution, a number of the optically active salts were photolyzed in a mixture of acetonitrile and water. Following irradiation, the reaction mixture was treated with excess ethereal diazomethane solution to form the corresponding methyl esters **9b** and **10b**. All the solution-state reactions essentially afforded the same product ratio of cyclobutanol **9b** and alkene **10b** as that observed in the solution photolysis of keto ester **1b**. Photoproduct **9b** was subsequently determined to be racemic. The enantiomeric excess of photoproduct **10b** was not measured owing to its small quantity in the reaction mixture. These results show that, in solution, the anisotropy of the chiral ammonium ion has no influence on the reaction selectivity.

Each of the salts listed in Scheme 2 was irradiated in the crystalline state. No color change or melting of the crystals was observed during the reaction, and following irradiation, the crystals were dissolved in ethyl acetate or methanol and treated with excess ethereal diazomethane to form the corresponding methyl esters **9b** and **10b**. Following diazomethane treatment, the organic layer containing the esterified photoproducts and starting material was washed with water and filtered through a short-path silica gel column to remove the chiral auxiliary. The mixture was then analyzed by GC for yield and conversion. Owing to the overlap of the product and starting ketone peaks in the chiral HPLC analysis, achiral preparative HPLC was used to isolate photoproduct **9b** (Waters Radialpak™ μPorasil™ silica column, 10% EtOAc in hexanes, 5 mL/min). Following purification, the enantiomeric excess of photoproduct **9b** was measured using chiral HPLC (Chiralcel® OC column, 2% isopropanol in hexanes, 0.5 mL/min). The results of the solid-state photolysis of chiral salts **1d**–**1j** are summarized in Table 4. Irradiation of the salts in the crystalline state leads to asymmetric induction with product ees ranging from 3% to 95%. The highest ee was observed for salt **1i** formed between acid **1c** and (*R*)-(–)-1-cyclohexylethylamine, where an enantiomeric excess of 95% was achieved at 38% reaction conversion.

Photolysis of the (*S*)-(–)-1-phenylethylamine and (*R*)-(+)-1-phenylethylamine salts (**1d** and **1e**) afforded nearly equal optical yields of the enantiomers of cyclobutanol **9b** (after diazomethane workup). This allows direct access to both enantiomers by simple exchange of the ionic chiral auxiliary. Table 4 also shows that the product ee declines with increasing reaction conversion. This is not unexpected, since the salts react to give products that presumably do not "fit" into the original crystal lattice, and defect sites are generated. As the reaction proceeds, the rigidity and regularity of the crystal lattice is gradually lost. As a result, the topochemical control is reduced and enantioselectivity declines. Low-temperature photolysis can be used to partially compensate this effect. As shown in Table 4, for reactions conducted at reduced temperature (–20 °C), enantioselectivities are better than those obtained at room temperature. Specifically, at –20 °C, quantitative conversion to cyclobutanol **9b** from salt **1d** occurred in 81% ee in comparison to 70% ee at room temperature. Further reducing the reaction temperature to –70 °C provided limited improvement in enantioselectivity, while much longer irradiation times were required.

To date, salts **1d**–**1j** have resisted attempts to determine their X-ray crystal structures; thus, we were not able to correlate the observed enantioselectivity with the solid-state structure. Nevertheless, the high ees observed in the solid state can be explained by a conformational effect, a situation that has been seen in other solid-state enantioselective Norrish–Yang type II reactions (17). In the solid state, the role of the ionic chiral auxiliary is to preorganize the photoreactant in a homochiral conformation in which the carbonyl group of the substrate is positioned to abstract only one of the two diastereotopic γ hydrogens in the initial step of the photoreaction. With topochemical control persisting in the solid state, formation of a single enantiomer of the product is achieved following removal of the chiral auxiliary, thereby transforming conformational chirality into configurational chirality.

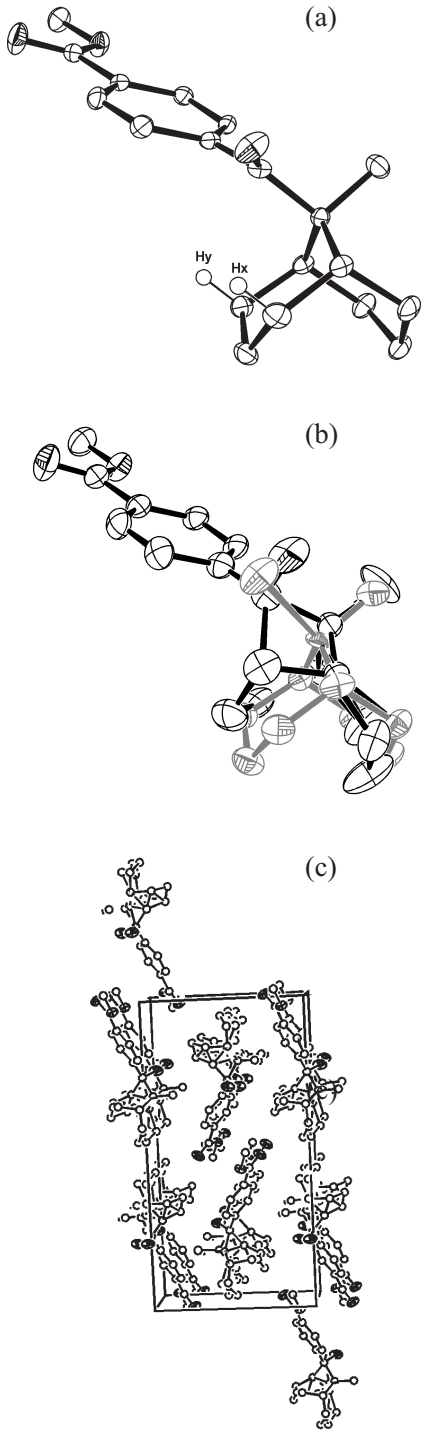
Among the salts studied, salt **1j** showed a particularly low enantioselectivity (3% ee). The low enantioselectivity observed is likely due to the phenomenon of *conformational enantiomerism* (18) in which equal amounts of both enantiomeric conformers of the photolabile carboxylate exist within the crystal lattice. Each conformer abstracts one of the two diastereotopic γ hydrogens and forms opposite enantiomers of the same photoproduct after workup. In addition,

Table 4. Solid-state photolysis of optically pure salts **1d**–**1j**.

Salt	Temp. (°C)	Time (min)	Conv. (%)[a]	ee (%)[b]	[α][c]
1d	r.t.[d]	120	>99	70	+
	–20	15	31	91	+
	–20	30	60	86	+
	–20	240	>99	81	+
	–70	180	44	86	+
1e	r.t.[d]	120	>99	73	–
	–20	15	36	90	–
	–20	30	72	86	–
	–20	60	89	86	–
	–70	120	93	80	–
1f	r.t.[d]	120	83	49	+
	–20	60	55	86	+
	–20	180	73	60	+
	–20	300	95	54	+
1g	r.t.[d]	120	98	25	–
	–20	30	21	38	–
	–20	240	81	29	–
1h	r.t.[d]	120	94	60	+
	–20	30	26	94	+
	–20	180	87	77	+
	–70	180	56	93	+
1i	r.t.[d]	120	>99	36	–
	–20	10	38	95	–
	–20	30	64	84	–
	–20	120	97	70	–
1j	r.t.[d]	120	>99	3	+
	–20	60	35	17	+
	–20	240	84	7	+
	–70	180	68	6	+

[a]Percentage of total GC integral owing to the disappearance of the corresponding starting material.
[b]The enantiomeric excess for photoproduct **9b** was determined using a Chiralcel® OC HPLC column.
[c]Sign of rotation of **9b** at the sodium D-line.
[d]Room temperature.

Fig. 4. ORTEP representation of: (*a*) ketone **1b** showing γ hydrogens H_x and H_y; (*b*) mixed crystal composed of 75% of ketone **1b** (gray) and 25% of photoproduct **9b** (black); (*c*) crystal packing diagram of the mixed crystal.



crystal disorder could also be a cause for the low enantioselectivity observed in the photolysis of salt **1j**. In a disordered crystal, two or more conformations of the reactive ion are distributed randomly throughout the crystal (static disorder) or are thermally interconverting (dynamic disorder). Since attempts to grow crystals of salt **1j** suitable for X-ray analysis were not successful, the exact reason for the low enantioselectivity of salt **1j** remains to be determined.

During our photochemical studies, we noticed that crystals of ketone **1b** did not change in appearance upon irradiation. This suggested the occurrence of a single-crystal-to-single-crystal reaction (19), which allowed the structures of both reactant and product to be obtained at various stages of reaction. Figure 4*a* shows the crystal structure of ketone **1b** prior to photolysis, and Fig. 4*b* depicts the superposition of ketone **1b** and its photoproduct in the mixed crystal following 25% conversion to the corresponding cyclobutanol **9b**. The extent of conversion was determined through refinement of the atom site occupancy factors in the X-ray crystallographic study. Figure 4*a* predicts preferential abstraction of H_x over H_y, and in agreement with this, the molecular structure of the photoproduct shows that the carbon atom to which H_x was attached is in fact part of the newly formed four-membered ring. The crystal structures also reveal that closure of the biradical does occur with "retention of configuration" at the carbonyl carbon. The reactant and product have similar geometries in which the aryl group portion of the molecule remains essentially unchanged during photolysis, while an upward movement of the γ carbon occurs to allow for cyclobutane ring formation. The corresponding alteration of the bicyclic ring skeleton is significant but a close atom-for-atom correspondence between the photoreactant and photoproduct is maintained. Also observed was a change in the orientation of the carbon–oxygen bond during the change in hybridization at the carbonyl carbon from sp^2 to sp^3. Accompanying this was a change in the length of the C—O bond from 1.22 to 1.33 Å. While these motions are significantly greater than those accompanying other unimolecular single crystal-to-single crystal photoreactions,[4] the overall packing arrangement of the crystal (Fig. 4*c*) remains unchanged, and as a result, the process still occurs in a topochemical fashion.

Summary

The photochemistry of several 9-methylbicyclo[3.3.1]-nonyl phenyl ketones was studied in solution and the solid state. In both media, Yang photocyclization was found to be the major process for α-methylated bicyclo[3.3.1]nonyl phenyl ketones (**1a** and **1b**), with *endo*-aryl cyclobutanols (**9a** and **9b**) being the major products. An unusual 1,4-hydroxy biradical disproportionation reaction was also observed during the photolysis of ketones **1a** and **1b**, although it was a minor process (<5%). By utilizing the *ionic chiral auxiliary* method, high enantioselectivities (up to 95%) were achieved for a number of the optically active salts on photolysis in the solid state. In addition, structure–reactivity correlation studies were performed based on the crystal structure data of ketones **1a** and **1b** to rationalize their photochemical behavior. The solid-state photoreaction of ketone **1b** was found to occur in a topochemically controlled, single crystal-to-single crystal fashion.

[4] For examples of unimolecular single-crystal-to-single-crystal photochemical reactions, see refs. 2 and 3.

Experimental section

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, and 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 were 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 Chromatron (model 7924T) with self-coated silica gel plates (1 or 2 mm thickness with EM Science silica gel 60 PF254 containing gypsum 7749-3). IR spectra were recorded on a PerkinElmer 1710 Fourier transform spectrometer. UV spectra were recorded on a PerkinElmer 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, a Kratos MS 80 spectrometer using desorption chemical ionization (CI) with the ionizing gas noted, a Kratos Concept IIHQ hybrid spectrometer using liquid secondary ionization (LSI-MS), or a Micromass LCT spectrometer using electrospray ionization (ESI). Elemental analyses were performed by the University of British Columbia (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. Some spectra are supported by data from the attached proton test (APT). Where these are given, (-ve) denotes a negative APT peak corresponding to a methine (CH) or methyl (CH_3) carbon centre, while no assignment signifies a quaternary or methylene (CH_2) carbon center.

9-Methylbicyclo[3.3.1]nonyl carboxaldehyde (5) and 9-methylbicyclo[3.3.1]nonyl phenyl methanol (6)

A mixture of PCC (1.40 g, 6.48 mmol) and Celite® 545 (2.79 g) was ground with a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **4** (5) (545 mg, 3.24 mmol) in anhydrous dichloromethane (40 mL) and the mixture stirred for 2 h at room temperature. The reaction mixture was filtered through a column of Florisil® and the remaining solids triturated well with anhydr. Et_2O. Removal of solvent in vacuo gave aldehyde **5** (538 mg, 100%) as colorless oil, which was found to be unstable and was used without further purification. To a cold (0 °C) solution of phenyl magnesium bromide in THF (25 mL) was added aldehyde **5** (538 mg, 3.24 mmol in 5 mL of THF). The reaction was stirred in the cold (0 °C) for 2 h and quenched with 5% aq. NH_4Cl solution (15 mL). THF was removed and the resultant aqueous phase was extracted with Et_2O (3 × 20 mL). The combined ethereal extracts were washed with H_2O (20 mL) and brine (20 mL), followed by drying ($MgSO_4$) and removal of the solvent in vacuo. Silica gel chromatography (5% EtOAc in petroleum ether) afforded alcohol **6** (706 mg, 89%) as a white solid, mp 118–118.5 °C (EtOAc – petroleum ether). IR (KBr, cm^{-1}): 3395, 2943, 2912, 2868, 1491, 1461, 1020, 892, 761, 732, 703, 567. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 0.85 (s, 3H), 1.27 (br, 1H), 1.39 (m, 1H), 1.50–1.62 (m, 4H), 1.66 (s, 1H), 1.68–1.99 (m, 5H), 2.00–2.20 (m, 2H), 2.37 (m, 1H), 5.40 (s, 1H), 7.23 (m, 1H), 7.29 (m, 2H), 7.37 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 16.54 (-ve), 20.58, 20.87, 27.20, 27.60, 27.74, 27.85, 32.24 (-ve), 32.92 (-ve), 39.65, 74.13 (-ve), 126.93 (-ve), 127.47 (-ve), 127.55 (-ve), 142.45. HR-MS (CI) calcd. for $C_{17}H_{24}O$: 244.1827; found: 244.1834. Anal. calcd. for $C_{17}H_{24}O$: C 83.55, H 9.90; found: C 83.95, H 10.02.

9-Benzoyl-9-methylbicyclo[3.3.1]nonanes (1a)

A mixture of PCC (1.15 g, 5.33 mmol) and Celite® 545 (2.30 g) was ground with a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **6** (651 mg, 2.66 mmol) in anhydrous dichloromethane (30 mL) and the reaction mixture was stirred for 10 h at room temperature. The reaction mixture was filtered through a column of Florisil® and the remaining solids well triturated with anhydr. Et_2O. Removal of solvent in vacuo and silica gel chromatography (3% Et_2O in petroleum ether) gave ketone **1a** (612 mg, 95%) as a white solid, mp 67 to 68 °C (EtOAc – petroleum ether). UV–vis (2.39×10^{-4} mol/L, MeOH, nm ((mol/L)$^{-1}$ cm^{-1})): 285 (1178), 330 (720). IR (KBr, cm^{-1}): 2960, 2913, 2865, 1672, 1444, 1266, 1232, 1216, 1124, 963, 932, 721, 696, 663. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 1.30–1.93 (m, 13H), 2.02–2.17 (m, 2H), 2.34 (br, 2H), 7.33–7.46 (m, 3H), 7.70–7.75 (m, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 20.20, 20.98, 23.63 (-ve), 26.82, 29.02, 33.90 (-ve), 50.79, 127.84 (-ve), 127.97 (-ve), 130.83 (-ve), 139.34, 209.84. HR-MS (EI) calcd. for $C_{17}H_{22}O$: 242.1671; found: 242.1670. Anal. calcd. for $C_{17}H_{22}O$: C 84.25, H 9.15; found: C 84.45, H 9.13. This structure was confirmed by X-ray crystallographic analysis.

(9-Methyl)bicyclo[3.3.1]non-9-yl (*p*-carbomethoxy)phenyl methanol (7)

A mixture of PCC (3.71 g, 17.2 mmol) and Celite® 545 (5.00 g) was ground with a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **4** (5) (1.81 g, 10.8 mmol) in anhydrous dichloromethane (120 mL) and the mixture was stirred for 2 h at room temperature. The reaction mixture was filtered through a column of Florisil® and the remaining solids well triturated with anhydr. Et_2O. Removal of solvent in vacuo gave aldehyde **5** (1.79 g, 99%) as 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 mol/L solution in THF, 11.4 mmol) over 10 min. The reaction was stirred in the cold (–40 °C) for 1 h. A solution of aldehyde **5** (1.73 g, 10.4 mmol) previously obtained in THF (20 mL) was added. The reaction was stirred at –40 °C for 3 h and quenched with 5% aq. NH_4Cl (100 mL). THF was removed in vacuo and the resultant aqueous phase was extracted with Et_2O (3 × 70 mL). The combined ethereal extracts were washed with brine (2 × 100 mL), followed by drying ($MgSO_4$) and removal of the solvent in vacuo. Silica gel chromatography (14% EtOAc in petroleum ether) afforded alcohol **7** (2.82 g, 90%) as a white powder, mp 135–137 °C (EtOAc – petro-

leum ether). IR (KBr, cm^{-1}): 3516 (br), 2950, 2913, 2868, 1724, 1610, 1490, 1460, 1436, 1283, 1192, 1111, 1034, 1018, 909, 869, 812, 770, 736, 715, 573. ^1H NMR ($CDCl_3$, 300 MHz) δ: 0.79 (s, 3H), 1.90–2.40 (m, 15H), 3.88 (s, 3H), 5.43 (s, 1H), 7.42 (d, *J* = 8.4 Hz, 2H), 7.93 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 16.56 (-ve), 20.48, 20.78, 27.15, 27.62 (br), 27.76, 32.19 (-ve), 32.90 (-ve), 39.91, 52.00 (-ve), 73.82 (-ve), 127.49 (-ve), 128.68 (-ve), 147.91 (br), 167.07. HR-MS (CI) calcd. for $C_{19}H_{30}NO_3$: 320.2226 $(M + NH_4)^+$; found: 320.2222. Anal. calcd. for $C_{19}H_{26}O_3$: C 75.46, H 8.67; found: C 75.48, H 8.73.

9-(*p*-Carbomethoxybenzoyl)-9-methylbicyclo[3.3.1]nonane (1b)

A mixture of PCC (3.09 g, 14.3 mmol) and Celite® 545 (5.0 g) was ground with a mortar and pestle until homogeneous. This solid was added to a solution of alcohol **7** (2.71 g, 8.96 mmol) in anhydrous dichloromethane (100 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 triturated well with anhydr. Et_2O. Removal of solvent in vacuo gave ketone **1b** (2.69 g, 100%) as a white solid, mp 137 to 138 °C (EtOAc–hexanes). ^1H 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). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 20.10, 20.89, 23.64 (-ve), 26.71, 29.03, 33.74 (-ve), 51.04, 52.32 (-ve), 127.69 (-ve), 129.27 (-ve), 131.89, 143.20, 166.36, 209.71. IR (KBr, cm^{-1}): 2950, 2906, 2857, 1722, 1666, 1497, 1435, 1401, 1279, 1235, 1190, 1108, 1017, 960, 934, 862, 738, 703. UV–vis (1.46×10^{-4} mol/L, MeOH, nm ($(mol/L)^{-1}$ cm^{-1})): 285 (1459), 330 (194). HR-MS (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. This structure was confirmed by X-ray crystallographic analysis.

9-(*p*-Carboxybenzoyl)-9-methylbicyclo[3.3.1]nonane (1c)

To a solution of ester **1b** (2.45 g, 8.16 mmol) in THF (50 mL) was added a solution of lithium hydroxide monohydrate (3.42 g, 81.6 mmol, in 25 mL of water). The reaction was stirred at room temperature for 20 h. The reaction solution was diluted with Et_2O (200 mL) and extracted with water (3 × 100 mL). The combined aqueous extracts were acidified with concd. HCl and extracted with Et_2O (3 × 100 mL). The combined organic extracts were washed with water (100 mL) and brine (100 mL), then dried over $MgSO_4$. Removal of solvent in vacuo yielded acid **1c** (2.31 g, 99%) as a white powder, mp 224–226 °C (EtOH–H_2O). IR (KBr, cm^{-1}): 3080–2720 (br), 2950, 2906, 2863, 1695, 1680, 1568, 1505, 1431, 1401, 1316, 1295, 1214, 1126, 968, 933, 860, 807, 761, 731, 698, 543. ^1H NMR (DMSO, 300 MHz) δ: 1.20–2.16 (m, 15H), 2.22 (br, 2H), 7.82 (d, *J* = 8.2 Hz, 2H), 7.98 (d, *J* = 8.2 Hz, 2H). (No COOH signal was observed owing to proton exchange with a trace amount of water in the solvent). ^{13}C NMR (DMSO, 75 MHz) δ: 19.66, 20.41, 23.05 (-ve), 26.16, 28.47, 33.10 (-ve), 50.22, 127.71 (-ve), 129.12 (-ve), 132.78, 142.24, 166.66, 209.02. UV–vis (1.68×10^{-4} mol/L, MeOH, nm ($(mol/L)^{-1}$ cm^{-1})): 285 (2994), 335 (333). HR-MS (EI) calcd. for $C_{18}H_{22}O_3$: 286.1569; found: 286.1567. Anal. calcd. for $C_{18}H_{22}O_3$: C 75.50, H 7.74; found: C 75.23, H 7.67.

(*S*)-(–)-1-Phenylethylamine salt (1d)

Keto acid **1c** (86 mg, 0.30 mmol) and (*S*)-(–)-1-phenylethylamine (40 μL, 38 mg, 0.31 mmol) were dissolved in a hot mixture of acetonitrile and methanol. Upon cooling to room temperature, filtration gave salt **1d** as colorless needles (98 mg, 80%), mp 211–213 °C (MeOH–CH_3CN). IR (KBr, cm^{-1}): 3447, 2915, 2862, 2767, 1667, 1615, 1518, 1455, 1395, 1232, 1219, 1124, 1092, 965, 932, 844, 825, 764, 745, 695, 539. ^1H NMR (CD_3OD, 300 MHz) δ: 1.30–2.25 (m, 18H), 2.33 (br, 2H), 4.42 (q, *J* = 6.8 Hz, 1H), 7.41 (m, 5H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.95 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 20.96 (-ve), 21.26, 22.01, 24.16 (-ve), 27.80, 30.11, 35.25 (-ve), 52.05, 52.26 (-ve), 127.60 (-ve), 128.44 (-ve), 129.89 (-ve), 130.05 (-ve), 130.26 (-ve), 140.11, 141.37, 141.99, 173.98, 212.09. HR-MS (LSI-MS) calcd. for $C_{26}H_{34}NO_3$: 408.2539 $(M + H^+)$; found: 408.2538. Anal. calcd. for $C_{26}H_{33}NO_3$: C 76.62, H 8.16, N 3.44; found: C 76.34, H 8.15, N 3.43.

(*R*)-(+)-1-Phenylethylamine salt (1e)

Keto acid **1c** (57 mg, 0.20 mmol) and (*R*)-(+)-1-phenylethylamine (27 μL, 25 mg, 0.21 mmol) were dissolved in a hot mixture of acetonitrile and methanol. Upon cooling to room temperature, filtration gave salt **1e** as colorless needles (64 mg, 79%), mp 211–213 °C (MeOH–CH_3CN). IR (KBr, cm^{-1}): 3446, 2915, 2864, 2766, 1668, 1615, 1519, 1456, 1396, 1232, 1219, 1124, 1092, 966, 933, 844, 825, 764, 744, 695, 539. ^1H NMR (CD_3OD, 300 MHz) δ: 1.30–2.25 (m, 18H), 2.33 (br, 2H), 4.42 (q, *J* = 6.8 Hz, 1H), 7.41 (m, 5H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.95 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 20.96 (-ve), 21.26, 22.01, 24.16 (-ve), 27.80, 30.11, 35.25 (-ve), 52.05, 52.26 (-ve), 127.60 (-ve), 128.44 (-ve), 129.89 (-ve), 130.05 (-ve), 130.26 (-ve), 140.20, 141.37, 141.99, 173.98, 212.09. HR-MS (ESI) calcd. for $C_{26}H_{34}NO_3$: 408.2539 $(M + H^+)$; found: 408.2544. Anal. calcd. for $C_{26}H_{33}NO_3$: C 76.62, H 8.16, N 3.44; found: C 76.35, H 8.46, N 3.47.

(1*S*,2*R*)-(–)-*cis*-1-Amino-2-indanol salt (1f)

Salt **1f** was prepared by dissolving 57 mg (0.20 mmol) of keto acid **1c** and 31 mg (0.21 mmol) of (1*S*,2*R*)-(–)-*cis*-1-amino-2-indanol in a hot mixture of acetonitrile and methanol. Upon cooling to room temperature, filtration gave salt **1f** as an off-white powder (71 mg, 81%), mp 190 °C (dec) (MeOH–CH_3CN). IR (KBr, cm^{-1}): 3235, 2913, 2862, 2625, 1670, 1619, 1580, 1535, 1452, 1397, 1267, 1216, 1093, 966, 932, 844, 823, 803, 741, 567. ^1H NMR (CD_3OD, 300 MHz) δ: 1.28–2.00 (m, 13H), 2.18 (m, 2H), 2.33 (br, 2H), 3.01 (dd, *J* = 5.9, 16.3 Hz, 1H), 3.22 (dd, *J* = 6.4, 16.3 Hz, 1H), 4.54 (d, *J* = 5.9 Hz, 1H), 4.70 (dd, *J* = 5.9, 11.3 Hz, 1H), 7.31 (m, 3H), 7.46 (d, *J* = 7.3 Hz, 2H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.96 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 21.24, 22.00, 24.15 (-ve), 27.80, 30.10, 35.24 (-ve), 40.09, 52.05, 58.71 (-ve), 72.08 (-ve), 126.14 (-ve), 126.64 (-ve), 128.40 (-ve), 129.44 (-ve), 129.89 (-ve), 130.77 (-ve), 138.47, 141.28, 141.99, 142.77, 174.11, 212.11. HR-MS (ESI) calcd. for $C_{27}H_{34}NO_4$: 436.2488 $(M + H^+)$; found: 436.2486. Anal.

calcd. for $C_{27}H_{33}NO_4$: C 74.45, H 7.64, N 3.22; found: C 74.38, H 7.68, N 3.23.

(*R*)-(–)-2-Amino-1-butanol salt (1g)

Salt **1g** was prepared by dissolving 57 mg (0.20 mmol) of keto acid **1c** and 19 mg (0.21 mmol) of (*R*)-(–)-2-amino-1-butanol in hot methanol. Upon cooling to room temperature, filtration gave salt **1g** as an off-white powder (53 mg, 71%), mp 159–162 °C (MeOH). IR (KBr, cm^{-1}): 3367, 2960, 2910, 2871, 1681, 1667, 1595, 1524, 1463, 1387, 1263, 1232, 1217, 1124, 1083, 964, 931, 869, 803, 747, 570. ^{1}H NMR (CD_3OD, 300 MHz) δ: 1.01 (t, *J* = 7.6 Hz, 3H), 1.25–2.00 (m, 15H), 2.18 (m, 2H), 2.33 (br, 2H), 3.08 (m, 1H), 3.54 (dd, *J* = 6.7, 11.7 Hz, 1H), 3.75 (dd, *J* = 3.7, 11.7 Hz, 1H), 7.73 (d, *J* = 8.5 Hz, 2H), 7.96 (d, *J* = 8.5 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 10.16 (-ve), 21.25, 22.00, 23.67, 24.16 (-ve), 27.81, 30.11, 35.25 (-ve), 52.05, 55.98 (-ve), 61.99, 128.44 (-ve), 129.88 (-ve), 141.43, 141.96, 174.17, 212.11. HR-MS (ESI) calcd. for $C_{22}H_{34}NO_4$: 376.2488 (M + H^+); found 376.2488. Anal. calcd. for $C_{22}H_{33}NO_4$: C 70.37, H 8.86, N 3.73; found: C 70.28, H 8.90, N 3.76.

L-Prolinamide salt (1h)

Salt **1h** was prepared by dissolving keto acid **1c** (57 mg, 0.20 mmol) and L-prolinamide (24 mg, 0.21 mmol) in a hot mixture of acetonitrile and methanol. Upon cooling to room temperature, filtration gave salt **1h** (72 mg, 90%) as a white powder, mp 210–211.5 °C (MeOH–CH_3CN). IR (KBr, cm^{-1}): 3365, 3232, 2935, 2909, 2871, 1715, 1680, 1631, 1591, 1544, 1383, 1217, 1015, 963, 931, 827, 804, 744, 668, 641, 567. ^{1}H NMR (CD_3OD, 300 MHz) δ: 1.20–2.00 (m, 16H), 2.17 (m, 2H), 2.33 (br, 2H), 2.39, (m, 1H), 3.31 (m, 2H), 4.19 (dd, *J* = 6.4, 8.4 Hz, 1H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.97 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 21.23, 21.99, 24.15 (-ve), 25.38, 27.79, 30.10, 31.25, 35.24 (-ve), 47.34, 52.07, 60.99 (-ve), 128.48 (-ve), 129.93 (-ve), 140.68, 142.21, 173.01, 173.71, 212.07. HR-MS (ESI) calcd. for $C_{23}H_{33}N_2O_4$: 401.2440 (M + H^+); found: 401.2451. Anal. calcd. for $C_{23}H_{32}N_2O_4$: C 68.97, H 8.05, N, 6.99; found: C 69.10, H 8.09, N 6.98.

(*R*)-(–)-1-Cyclohexylethylamine salt (1i)

Salt **1i** was prepared by dissolving keto acid **1c** (57 mg, 0.20 mmol) and (*R*)-(–)-1-cyclohexylethylamine (31 μL, 27 mg, 0.21 mmol) in hot methanol. Upon cooling to room temperature, filtration gave salt **1i** as a white powder (71 mg, 86%), mp 192–195 °C (MeOH). IR (KBr, cm^{-1}): 3443, 2929, 2862, 2603, 2551, 2361, 2342, 2203, 1666, 1635, 1578, 1537, 1450, 1382, 1263, 1232, 1216, 1126, 964, 932, 868, 821, 804, 745, 568. ^{1}H NMR (CD_3OD, 300 MHz) δ: 0.98–2.00 (m, 27H), 2.18 (m, 2H), 2.33 (br, 2H), 3.06 (m, 1H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.96 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 16.07 (-ve), 21.24, 22.00, 24.15 (-ve), 26.92, 27.00, 27.08, 27.81, 28.82, 30.01, 30.11, 35.26 (-ve), 42.75 (-ve), 52.05, 53.39 (-ve), 128.42 (-ve), 129.85 (-ve), 141.61, 141.90, 174.20, 212.09. HR-MS (ESI) calcd. for $C_{26}H_{40}NO_3$: 414.3008 (M + H^+); found: 414.3009. Anal. calcd. for $C_{26}H_{39}NO_3$: C 75.50, H 9.50, N 3.39; found: C 75.31, H 9.55, N 3.46.

(1*R*,2*R*)-(–)-2-Amino-1-phenyl-1,3-propanediol salt (1j)

Salt **1j** was prepared by dissolving keto acid **1c** (57 mg, 0.20 mmol) and (1*R*,2*R*)-(–)-2-amino-1-phenyl-1,3-propanediol (35 mg, 0.21 mmol) in a hot mixture of acetonitrile and methanol. Upon cooling to room temperature, filtration gave salt **1j** as a white powder (76 mg, 84%), mp 142 to 143 °C (MeOH–CH_3CN). IR (KBr, cm^{-1}): 3367, 2914, 2864, 1668, 1582, 1542, 1493, 1453, 1386, 1229, 1124, 1039, 968, 960, 932, 868, 840, 803, 746, 700, 572, 540. ^{1}H NMR (CD_3OD, 300 MHz) δ: 1.25–1.73 (m, 8H), 1.51 (s, 3H), 1.89 (m, 2H), 2.17 (m, 2H), 2.33 (br, 2H), 3.26 (m, 1H), 3.47 (m, 2H), 4.73 (d, *J* = 8.6 Hz, 1H), 7.37 (m, 5H), 7.72 (d, *J* = 8.6 Hz, 2H), 7.96 (d, *J* = 8.6 Hz, 2H). ^{13}C NMR (CD_3OD, 75 MHz) δ: 21.23, 21.98, 24.15 (-ve), 27.81, 30.10, 35.26 (-ve), 52.06, 60.23, 60.29 (-ve), 72.54 (-ve), 127.86 (-ve), 128.42 (-ve), 129.51 (-ve), 129.74 (-ve), 129.89 (-ve), 141.38, 141.97, 142.23, 174.13, 212.15. HR-MS (ESI) calcd. for $C_{27}H_{36}NO_5$: 454.2593 (M + H^+); found: 454.2599. Anal. calcd. for $C_{27}H_{35}NO_5$: C 71.50, H 7.78, N 3.09; found: C 71.34, H 8.05, N 3.41.

Photochemistry

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 (λ ≥ 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. The reactions were performed either in sealed reaction vessels or under a positive pressure of nitrogen. Yields and conversions were calculated based on the mass of the isolated products. For analytical solid-state photolyses, the procedure consisted of crushing ca. 5 mg of the salt to be photolyzed between two Pyrex microscope slides, taping the plates together, sealing the resulting sandwiches in polyethylene bags under a positive nitrogen atmosphere, and irradiating the ensembles with the output from a water-cooled 450 W medium-pressure mercury lamp. Photolyses were generally carried out at room temperature. For some runs that required low temperature during photolysis, a Cryocool CC-100 II immersion cooling system (Neslab Instrument Inc.) was used with ethanol as the coolant. The salts were irradiated for varying lengths of time to determine the dependence of the ee values on the extent of conversion. To achieve high conversions it was usually necessary to rotate the sample 180° midway through the irradiation, exposing the rear side of the slide to the light and allowing as much of the sample as possible to react. For neutral molecules, the sample was directly analyzed by GC. The reaction mixtures containing chiral organic salts were first derivatized to their corresponding methyl esters by treatment with excess ethereal diazomethane solution and then washed with water and subjected to short-path silica gel chromatography to remove the chiral auxiliary. The mixtures were then analyzed by GC for conversion as well as product composition. Yields and conversions of the solid-state reactions were determined based on the average integration of at least two GC analyses. The overall precision of the reported GC results is estimated to be ±1%.

Preparative photolysis of ketone 1a

A solution of ketone **1a** (485 mg, 2.00 mmol) in acetonitrile (40 mL) was purged with nitrogen for 30 min and irradiated for 7 h. Removal of the solvent in vacuo followed by silica gel chromatography (6% EtOAc in petroleum ether) afforded starting material **1a** (17 mg, 4%), cyclobutanol **9a** (442 mg, 91%), and alkene **10a** (19 mg, 4%).

Data for cyclobutanol 9a

Colorless oil. IR (KBr, cm^{-1}): 3441, 3027, 2923, 2874, 1479, 1452, 996, 882, 775, 702. ^{1}H NMR (C_6D_6, 400 MHz) δ: 0.89 (m, 1H), 1.14 (m, 1H), 1.23–1.27 (m, 1H), 1.28 (s, 3H), 1.33–1.39 (m, 2H), 1.52–1.77 (m, 5H), 1.82–1.97 (m, 2H), 2.60 (m, 1H), 2.71 (m, 1H), 7.07–7.18 (m, 5H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 17.77 (-ve), 18.29, 20.23, 22.55, 24.53, 27.56, 36.11 (-ve), 37.62 (-ve), 46.26, 46.37 (-ve), 82.64, 125.29 (-ve), 127.17 (-ve), 128.65 (-ve), 144.04. HR-MS (EI) calcd. for $C_{17}H_{22}O$: 242.1671; found: 242.1672. Anal. calcd. for $C_{17}H_{22}O$: C 84.25, H 9.15; found: C 84.00, H 9.13.

Data for alkene 10a

Melting point: 55–56.5 °C (EtOAc – petroleum ether). IR (KBr, cm^{-1}): 3431, 3057, 3015, 2940, 2918, 2864, 1492, 1472, 1453, 1015, 899, 763, 712, 608. ^{1}H NMR (CD_2Cl_2, 300 MHz) δ: 0.90 (s, 3H), 1.18–1.43 (m, 4H), 1.52–2.04 (m, 5H), 2.48 (m, 1H), 2.70 (m, 1H), 4.97 (br, 1H), 5.73 (m, 1H), 6.00 (m, 1H), 7.20–7.40 (m, 5H). ^{13}C NMR (CD_2Cl_2, 75 MHz) δ: 15.77 (-ve), 16.57, 24.75, 29.52, 32.32, 33.22 (-ve), 35.48 (-ve), 40.04, 75.92 (-ve), 127.23 (-ve), 127.77 (-ve), 128.12 (-ve), 128.97 (-ve), 129.16 (-ve), 143.07. HR-MS (EI) calcd. for $C_{17}H_{22}O$: 242.1671 (M^+); found: 242.1672. Anal. calcd. for $C_{17}H_{22}O$: C 84.25, H 9.15; found: C 84.05, H 9.15. This structure was confirmed by X-ray crystallographic analysis.

Preparative photolysis of ketone 1b

A solution of ketone **1b** (501 mg, 1.67 mmol) in acetonitrile (50 mL) was purged with nitrogen for 30 min and irradiated for 6 h. Removal of the solvent in vacuo followed by silica gel chromatography (11% EtOAc in petroleum ether) afforded cyclobutanol **9b** (446 mg, 89%) and alkene **10b** (27 mg, 5%).

Data for cyclobutanol 9b

Melting point: 149 to 150 °C (EtOAc – petroleum ether). IR (KBr, cm^{-1}): 3482, 2958, 2927, 2879, 1723, 1609, 1439, 1279, 1106, 1007, 861, 781, 712. ^{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). ^{13}C NMR (C_6D_6, 100 MHz) δ: 17.70 (-ve), 18.61, 20.46, 22.87, 24.61, 27.73, 36.19 (-ve), 37.62 (-ve), 46.42, 46.79 (-ve), 51.61 (-ve), 81.87, 125.73 (-ve), 129.45, 130.32 (-ve), 149.34, 166.64. HR-MS (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. This structure was confirmed by X-ray crystallographic analysis.

Data for alkene 10b

Melting point: 148–150 °C ($CHCl_3$–hexanes). IR (KBr, cm^{-1}): 3524, 3017, 2950, 2921, 2862, 1723, 1706, 1610, 1436, 1281, 1111, 1016, 860, 772, 724, 705, 612. ^{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). ^{13}C NMR (C_6D_6, 75 MHz) δ: 15.71 (-ve), 16.52, 24.57, 29.36, 32.11, 32.90 (-ve), 36.16 (-ve), 40.09, 51.57 (-ve), 75.22 (-ve), 128.05 (-ve), 128.55 (-ve), 129.04 (-ve), 129.19 (-ve), 129.35, 148.50, 166.82. HR-MS (CI) calcd. for $C_{19}H_{28}NO_3$: 318.2069 ($M + NH_4^+$); 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. This structure was confirmed by X-ray crystallographic analysis.

X-ray crystal structure analyses

Crystal data for compounds **1a**, **1b**, **9b**, **10a**, and **10b** were collected using a Rigaku/AFC7 four-circle diffractometer equipped with an ADSC Quantum CCD detector. The X-ray source was graphite-monochromated Mo Kα radiation (λ = 0.710 73 Å). Structures were solved by means of direct methods (SHELXS-97 (20) for **1a**, SIR92 (21) for **1b**, **9b**, **10a**, and **10b**), and all refinements were carried out by full-matrix least-squres procedures (SHELXL-97) (22) using anisotropic displacement parameters for all non-hydrogen atoms. Hydrogen atoms were introduced in calculated positions and only one overall isotropic displacement parameter was refined. The CCDC reference numbers are CCDC 255968–255972 for compounds **1a**, **1b**, **9b**, **10a**, and **10b**, respectively, and 260038 for the mixed crystal resulting from partial solid-state photolysis of ketone **1b**.[5]

Crystal structure determination of ketone 1a

Single crystals of **1a** were recrystallized from EtOAc – petroleum ether, mounted in inert oil, and transferred to the cold nitrogen stream of the diffractometer. Crystal data: $C_{17}H_{22}O$, MW = 242.35, triclinic, a = 6.938 Å, b = 10.104 Å, c = 10.197 Å, α = 101.473°, β = 98.041°, γ = 104.520°, V = 664.48 Å^3, T = 173 K, space group P, Z = 2, μ(Mo Kα) = 0.073 mm^{-1}, reflections measured = 4092, unique = 2552, $R1$ = 0.0402, $wR2$ = 0.1053, GoF = 1.046.

Crystal structure determination of ketone 1b and its single crystal-to-single crystal reaction

Single crystals of **1b** were recrystallized from EtOAc–hexanes, mounted in inert oil and transferred to the cold nitrogen stream of the diffractometer. Crystal data: $C_{19}H_{24}O_3$, MW = 300.38, monoclinic, a = 6.5508(3) Å, b = 11.0233(6) Å, c = 21.4693(13) Å, β = 92.627(2)°, V =

[5] Supplementary data for this article are available on the Web site or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0S2, Canada. DUD 4027. For more information on obtaining material refer to http://cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml. CCDC 255968–255972 and 260038 contain the crystallographic data for this manuscript. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).

1548.70(14) Å^3, T = 173 K, space group $P2_1/c$, Z = 4, μ(Mo Kα) = 0.085 mm^{-1}, reflections measured = 13 627, unique = 3307, $R1$ = 0.0411, $wR2$ = 0.1059, GoF = 1.046. Same crystal photolyzed to 25% conversion: $C_{19}H_{24}O_3$, MW = 300.38, monoclinic, a = 6.5305(2) Å, b = 11.2200(4) Å, c = 21.4348(7) Å, β = 91.892(1)°, V = 1569.72(1) Å^3, T = 173 K, space group $P2_1/c$, Z = 4, μ(Mo Kα) = 0.085 mm^{-1}, reflections measured = 24 848, unique = 2768, $R1$ = 0.0424, $wR2$ = 0.1125, GoF = 1.058.

Crystal structure determination of ketone 9b

Single crystals of **9b** were recrystallized from EtOAc – petroleum ether, mounted in inert oil, and transferred to the cold nitrogen stream of the diffractometer. Crystal data: $C_{19}H_{24}O_3$, MW = 300.38, triclinic, a = 6.2815(4) Å, b = 7.2477(6) Å, c = 18.7120(17) Å, α = 79.329(9)°, β = 82.478(10)°, γ = 69.225(8)°, V = 780.75(11) Å^3, T = 173 K, space group P, Z = 2, μ(Mo Kα) = 0.085 mm^{-1}, reflections measured = 3144, unique = 3144, $R1$ = 0.0367, $wR2$ = 0.1027, GoF = 1.086.

Crystal structure determination of ketone 10a

Single crystals of **10a** were recrystallized from EtOAc – petroleum ether, mounted in inert oil, and transferred to the cold nitrogen stream of the diffractometer. Crystal data: $C_{17}H_{22}O$, MW = 242.35, monoclinic, a = 10.4796(10) Å, b = 19.2773(18) Å, c = 13.6457(13) Å, β = 93.507(3)°, V = 2751.5(5) Å^3, T = 173 K, space group $P2_1/c$, Z = 8, μ(Mo Kα) = 0.070 mm^{-1}, reflections measured = 23 886, unique = 5933, $R1$ = 0.0618, $wR2$ = 0.1553, GoF = 1.128.

Crystal structure determination of ketone 10b

Single crystals of **10b** were recrystallized from $CHCl_3$–hexanes, mounted in inert oil, and transferred to the cold nitrogen stream of the diffractometer. Crystal data: $C_{19}H_{24}O_3$, MW = 300.38, monoclinic, a = 15.1864(11) Å, b = 6.8150(5) Å, c = 14.9981(10) Å, β = 90.383(4)°, V = 1552.20(19) Å^3, T = 173 K, space group $P2_1/n$, Z = 4, μ(Mo-K_α) = 0.085 mm^{-1}, reflections measured = 3331, unique = 3331, $R1$ = 0.0378, $wR2$ = 0.0949, GoF = 0.928.

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