Singlet-Triplet Reactivity of 1-Methyl-2-Cyclohexenyl Aryl Ketones: Racemization *vs* 1,3-Acyl Shift in the Excited States[1]

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Received February 12, 1990

The photochemistry of 1-Methyl-2-cyclohexenyl aryl ketones (phenyl ketone **7a**, *p*-toluyl ketone **7b**, biphenyl ketone **7c** and -naphthyl ketone **7d**) is reported. The aryl ketone **7a, 7b** and **7c** undergo photo-racemization with efficiencies of 0.75, 0.79 and 0.76 respectively on direct irradiation. Direct irradiation of the ketone **7d**, however, undergoes 1,3-shift with an efficiency of 0.02. Triplet states are responsible for the racemizations and singlet state is responsible for 1,3-shift as in general. The ketone **7a, 7b** and **7c** are good example of a few β ,γ-unsaturated ketones which undergo efficient intersystem crossing on direct irradiation.
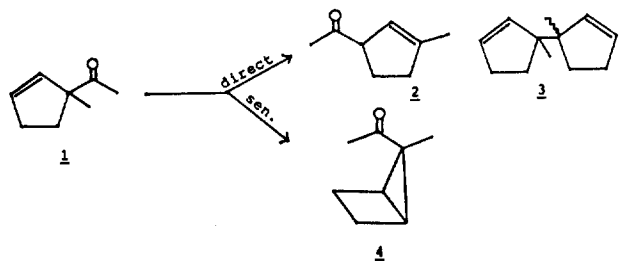
Introduction

A variety of photochemical reactions[2] has been found for both singlet and triplet excited states of β, γ-unsaturated ketones. Particular interest has been directed toward the nature of the two major rearrangement reactions, the 1,3-acyl shift (1,3-AS) and the oxadi-π-methane (ODPM) rearrangement.

The conclusion[3] from earlier studies was that the 1,3-AS reaction occurred primarily from the n,π^* singlet, whereas the ODPM reaction occurred exclusively from the π, π^* triplet state of β, γ-unsaturated ketones.

Effort to study both reactions have been severely limited because of the absence of ODPM products on direct irradiation and of phosphoresence from β, γ-unsaturated ketones in general.

Our approach to explore the structural modification which would enhance the intersystem crossing efficiency has led to examine the effect of migrating groups and of olefinic moieties on the reactivity of a series of β, γ-unsaturated ketones.

Of the several β, γ-unsaturated ketones studied, one of the structurally least complicated is 1-acetyl-1-methyl-2-cyclopentene (1). Neywick[4] has studied the singlet and triplet photochemistry of **1** and observed that photolysis of **1** resulted in the formation of two products, **2** and **3**, which mechanistically are equivalent to a 1,3-AS. Acetone sensitized irradiation of **1** afforded product, endo-**4**.


Schaffner[5] and coworkers have introduced the benzoyl group to the olefinic moiety of **1** to investigate the migrating group effect on the excited state of ketone **5**.
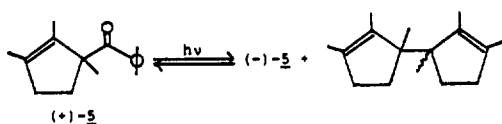

Irradiation of optically active ketone **5** gave primarily racemic mixture, along with some α-cleavage and no appreciable 1,3-AS product was observed.

Lee[6] has studied the photochemistry of benzoyl cyclohexadiene derivatives **6**. The cyclic β ,γ,δ,ϵ-unsaturated ketone **6** is a system in which 1,5-shift seems more likely. However, direct photolysis of **6** gave only the 1,3-AS product.
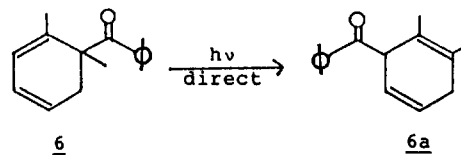

Since the migrating groups and the olefinic moieties showed variety of photoreactions, we have decided to investigate the migrating group effect and singlet-triplet reactivity of 1-methyl-2-cyclohexenyl aryl keontes (**7a–7d**) which are analogous to ketone **6**.
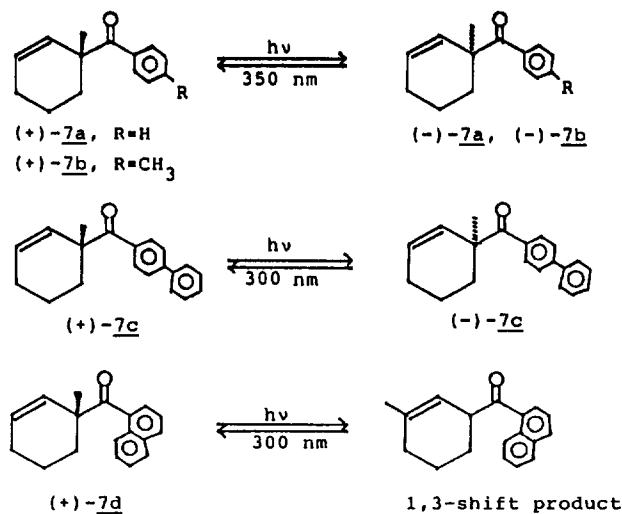

7a,	Ar =	phenyl
7b,	Ar =	p-toluyl
7c,	Ar =	4-biphenyl
7d,	Ar =	α-naphthyl
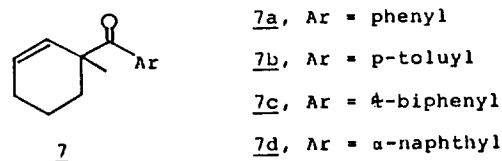
Results and Discussion

The ketones **7a–7d** were synthesized by the Grignard reactions of 1-cyano-1-methyl-2-cyclohexene.[7] Each of the
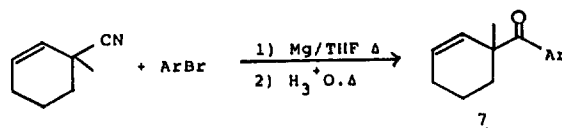
Ar = phenyl, p-toluyl, biphenyl, α-naphthyl

ketone (**7a–7d**) was irradiated in diethyl ether at 350 nm(direct irradiation) for 40 to 120 min. Isolation procedures which would detect even small amounts of ODPM products did not reveal any of the tricyclic ketone and 1,3-AS product from the direct irradiations. NMR and GC analyses revealed that there were neither 1,3-AS nor decomposition during the direct irradiation. α-Naphthyl ketone **(7d)**, however, showed 1,3-AS product under the direct irradiation.

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Scheme 1

(+)-**7a**, R=H
(+)-**7b**, R=CH₃

(-)-**7a**, (-)-**7b**

(+)-**7c**

(-)-**7c**

(+)-**7d**

1,3-shift product

Table 2. Quantum Efficiencies for Racemization and 1,3-AS

Ketones	ϕ_{rac}	$\phi_{1,3}$	k/min
7a	0.75[a]	0.00[b]	1.72×10^{-2}
7b	0.79	0.00[b]	2.15×10^{-3}
7c	0.76	0.00[b]	2.79×10^{-2}
7d	------[c]	0.06[d]	--------------[c]
		0.02[e]	

[a] Data from ref. (1). [b] No appreciable 1,3-AS for the first 40, 120, 30 min irradiation respectively. [c] Not determined. [d] Quantum yield for disappearance. [e] Quantum yield for appearance.

Table 1. Change in Specific Rotations and Kinetic Treatments of **7a–7c** as a function of Irradiation Time

Time (min)	Specific Rotations at 546 nm			$\ln \alpha_o/\alpha_t$		
	7a[a]	**7b**	**7c**	**7a**[a]	**7b**	**7c**
0	+36.47	−22.63	+30.84	0	0	0
5	+33.06	−21.75	+27.95	0.098	0.040	0.098
10	+30.78	−21.23	+24.78	0.170	0.064	0.218
20	+25.08	−20.35	+18.16	0.375	0.106	0.529
30	+21.66	−19.47	+15.56	0.521	0.150	0.648
40	+18.24			0.693		
45		−19.30				0.159
60		−18.86				0.182
80		−17.89				0.235
100		−17.54				0.255
120		−17.19				0.279

[a] Data from Ref. (1).

Figure 1. Stern–volmer quenching of the photo–racemization and 1,3–AS. (Values of k_q for **7a**, **7b** and **7c** are 30.8, 17.1 and 28.1 respectively).

The racemic ketones (**7a–7c**) were resolved to see if the photo–racemizations occur under the direct irradiation conditions. Optical resolution of (±) ketones were performed by selective ketalization[8] with (2R,3R)–2,3–butandiol and since the photo–racemization follows first–order kinetics, optical purities and absolute configurations were not determined.

Direct irradiations of ketones at 350 nm for **7a,b** and 300 nm for **7c**, showed predominant racemizations with high quantum efficiencies (Table 2). Irradiation of the ketone **7d** at 300 nm, however, produced 1,3–AS product only. The results of irradiations were summarized in Scheme 1 and Table 1.
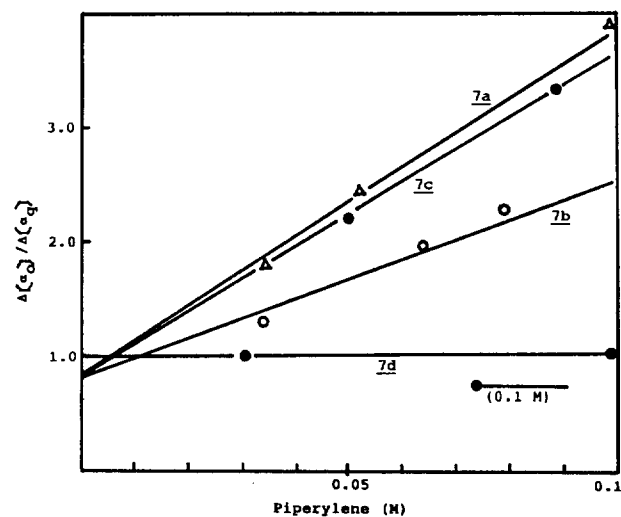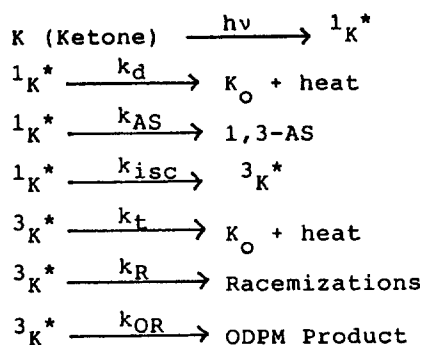
Quantum efficiencies of each ketones, **7a–7c** under direct irradiation are given in Table 2. As noted in Table 2, both 1,3–As and racemization were monitored under the direct irradiation.

For determination of the racemization quantum efficiency of the ketone **7a–c**, the change in optical rotation of the partially resolved ketone was followed as a function of the absorbed radiation. Table 1 presents the experimental rotations monitored at 546 nm. The quantum efficiencies for the racemizations were obtained from the expression, employing the

integrated rate expression for a unimolecular racemization first employed by Givens[9] for the racemization of bicyclo–[3,2,1]oct–2–ene–7–one.

$$\phi_{rac} = \frac{C_o}{2E_t} \ln \frac{\alpha_o}{\alpha_t} \qquad (1)$$

To express the efficiency of the degenerate rearrangement as a quantum yield for racemization (ϕ_{rac}), the first–order rate constant must be converted to the reaction efficiency, *i.e.*, the equation (1), where C_o is the total number of moles of ketone presents: E_t is the total number of photons (einstein) absorbed by the ketone and α_o and α_t are the initial and final rotations, respectively. With use of the equation (1) and the data in Table 1, quantum yields were obtained and the values are in Table 2.

A quenching experiment employing various concentrations of *trans*–piperylene in a 0.02–0.13 M solution of each ketones were examined (Figure 1). Figure 1 reveals that no quenching could be detected in 1,3–AS of ketone **7d** even when the high concentration of piperylene was used. Photo–racemizations, however, were quenched by the addition of *trans*–piperylene and the linear Stern–Volmer relations were observed as shown in Figure 1.

Acetophenone and(or) benzophenone sensitized irradiations of the ketones **7a–7d** showed racemization, but there were neither 1,3–AS nor ODPM rearrangements.

$$K \text{ (Ketone)} \xrightarrow{\text{hv}} {}^1K^*$$

$${}^1K^* \xrightarrow{k_d} K_O + \text{heat}$$

$${}^1K^* \xrightarrow{k_{AS}} 1,3\text{-AS}$$

$${}^1K^* \xrightarrow{k_{isc}} {}^3K^*$$

$${}^3K^* \xrightarrow{k_t} K_O + \text{heat}$$

$${}^3K^* \xrightarrow{k_R} \text{Racemizations}$$

$${}^3K^* \xrightarrow{k_{OR}} \text{ODPM Product}$$

Scheme 2

Since the photo-racemizations were quenched by *trans*-piperylene and sensitized by acetophenone or benzophenone, the responsible excited state for the racemization of the ketone (**7a-7c**) could be a triplet state, and a singlet excited state could be responsible for the 1,3-AS of the ketone (**7d**).

Based upon the sensitization and quenching experiments, the photochemical mechanism presenting the elementary processes outlined as shown in Scheme 2.

Since the photo-racemizations of ketone **7a-7c** are very efficient, intersystem crossing efficiencies of these ketones must be at least 0.75, 0.76, 0.79 respectively.

$$\phi_{rac} = \frac{k_R}{k_R + k_t + k_{OR}} \times \phi_{isc} \approx 0.75 \sim 0.79$$

$$0.75 < \phi_{isc} < 1.0$$

This high efficiency of intersystem crossing would prevent fluorescence and 1,3-AS which generally comes from singlet state. It appears that photo-racemization which predominates over ODPM rearrangement comes from triplet state of ketones **7a-7c** and 1,3-AS product comes from singlet state of ketone **7d**. The phenyl ketone **7a**, *p*-toluyl ketone **7b** and biphenyl ketone **7c** are good examples of a few[10-14] β, γ-unsaturated ketones which intersystem cross under the direct irradiation.

Experimental

Gas chromatographic analyses were performed by a Varian Aerograph M-2800 using a 1/8 in × 6*ft*, 5% SE-30 column. Mass spectra were obtained using HP-5985A, GC-Mass System. Element analyses were performed by Yanaco MTT-2. The following spectrophotometers were used: NMR, Varian-EM-360; IR, JASCO-810; UV, Shimadzu-2600; Polarimeter, Bellinhgam M-D2.

1-Methyl-2-cyclohexenyl Phenyl Ketone (7a). To a 500 m*l* round-bottomed flask fitted with a reflux condenser with outlet to an oil seal, a dropping funnel, and a inlet tube for nitrogen was introduced 30 m*l* of anhydrous ether and 4.86g of magnesium. A solution of 30.8g (0.2 mol) of bromobenzene in 30 m*l* of ether was added in a small portions until the reaction started, and then, at such a rate as to maintain gentle refluxing of ehter. After addition of all bromobenzene (required two hours), the solution was refluxed for an additional hour. A solution of 9.17 g (0.08 mol) of 1-cyano-1-methyl-2-cyclohexene in 30 m*l* of ether was added dropwise to the mechanistically stirred Grignard solution. The reaction mixture was refluxed for 5 hours. After cooled the

solution by an ice-bath, the mixture was poured slowly into a mixture of about 300g of ice and excess of 50% aqueous sulfuric acid. The aqueous layer was separated and refluxed for 15 hours. The resulting solution was cooled and then extracted with ether. The extracts were washed with water and saturated sodium thiosulfate solution, and then dried over sodium sulfate. Vacuum distillation gave 13.52 g (0.07 mol, 89%, Bp 143 °C at 4.5 mmHg) of pure ketone **7a**. The spectral data were: NMR (CCl$_4$) δ 1.3 (s, 3H), 1.5-2.5 (m, 6H), 5.9-6.1 (d, 2H) and 7.3-8.3 (m, 5H); IR (neat) 3050, 1700, 1680, 1620 cm^{-1}; Mass *m/e* (relative intensity) 65 (20), 77 (36.0), 95 (10.0), 105 (100), 200 (M$^+$, 2.1). Anal. Calcd. for C$_{14}$H$_{16}$O: C, 83.96; H, 8.05. Found: C, 83.60; H, 8.12.

1-Methyl-2-cyclohexenyl *p*-toluyl Ketone (7b). The procedure used for the synthesis of the ketone **7a** was employed. Vaccum distillation gave 13.0 g (0.061 mol, 76%, bp 117 °C at 0.7 mmHg) of pure ketone **7b**. The spectral data were: NMR (CDCl$_3$) δ 1.5 (s, 3H), 1.6-2.4 (m, 6H), 2.5 (s, 3H), 6.0 (d, 2H) and 7.2-8.0 (q, 4H); IR (neat) 3020, 1670 and 1610 cm^{-1}; Mass *m/e* (relative intensity) 65 (21.1), 91 (35.4), 95 (13.5), 119 (100), 214 (M$^+$, 2.0). Anal. Calcd. for C$_{15}$H$_{18}$O: C, 84.11; H, 8.41. Found: C, 83.69; H, 8.71.

1-Methyl-2-cyclohexenyl Biphenyl Ketone (7c). The procedure used for the synthesis of the ketone **7a** was employed using THF for Grignard reaction. Vacuum distillation gave 3.12 g (0.011 mol, 23%) of ketone **7c**. The spectral data were: NMR (CDCl$_3$) δ 1.5 (s, 3H), 1.6-2.4 (m, 6H), 6.0 (d, 2H) and 7.0-8.1 (m, 9H); IR (neat 3020, 1670, 1615 cm^{-1}; Mass *m/e* (relative intensity) 95 (7.3), 152 (36.8), 153 (15.6), 181 (100), 182 (14.5), 276 (M$^+$, 3.2).

1-Methyl-2-cyclohexenyl α-naphthyl Ketone (7d). The procedure used for the synthesis of the ketone **7a** was employed. Vacuum distillation gave 15.66 g (0.06 mol, 76%, bp 160 °C at 4.5 mmHg) of pure ketone **7d**. The spectral data were: NMR (CDCl$_3$) δ 1.3 (s, 3H), 1.5-2.5 (m, 6H), 5.5-6.0 (d, 2H) and 7.2-8.0 (m, 7H); IR (neat) 3050, 1690, 1650 and 1595 cm^{-1}; Mass *m/e* (relative intensity) 95 (9.8), 127 (63.6), 155 (100), 250 (M$^+$, 3.3).

Resolution of Racemic Ketones. Selective ketalization of **7a**: To a solution of 2.0 g (10 mmol) of (±) ketone **7a** and 1.4 m*l* (15.3 mmol) of (2R,3R)-butandiol in 40 m*l* of benzene was added a small amount of anhydrous *p*-toluensulfonic acid. After fitting a Dean-Stark trap, the mixture was vigorously refluxed for 30 hours. The solution was washed three times with 40 m*l* of water, then dried and concentrated. Unreacted ketone **7a** was separated by column chromatography and polarimetric analysis of this ketone **7a** showed optical rotation [α] = +36.47°. Hydrolysis of ketal: In a 250 m*l* round-bottomed flask was placed a solution of 1.01 g (3.71 mmol) of (-)-ketal and 30 m*l* of 15% aqueous hydrochloric acid in 50 m*l* of ethyl alcohol. The mixture was stirred and gently heated for 42 hours. After cooling the solution, the mixture was extracted with ether. The ether solution was washed with water and saturated sodium carbonate solution. The solution was then dried and distilled by vacuum to obtain 0.52 g (2.62 mmol, 71%) of (-)-ketone **7a**. Polarimetric analysis of the resolved ketone **7a** showed optical rotation, [α] = -30.50°. Ketalization of ketones, **7a-7c**, by optically active 2,3-butandiol occurs stereoselectively when sterrically hindered ketones such as phenyl ketone (**7a**), *p*-toluyl ketone (**7b**) and biphenyl ketone (**7c**) are used.

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Resolved 1-Methyl-2-cyclohexenyl *p*-toluyl ketone (7b) and resolved 1-Methyl-2-cyclohexenyl biphenyl ketoen (7c). The optically active ketals of racemic ketones were hydrolyzed to obtain resolved ketones. (Table 1 for optical rotations).

Irradiation of Resolved Ketones (7a-7c). Direct irradiation of 1-Methyl-2-cyclohexenyl phenyl ketone (7a): A solution of 320 mg of (+)-ketone, 7a in 15 m*l* of anhydrous ether was degassed with purified nitrogen and irradiated with 16 RPR-3500 Å lamps for 40 min in pyrex tubes. The optical rotation during the irradiation was determined at 5-10 min intervals. NMR and GC analysis indicated that there were neither 1,3-AS product nor ODPM product.

Direct irradiation of 1-Methyl-2-cyclohexenyl *p*-toluyl ketone (7b). A solution of 570 mg of (-)-ketone, 7b in 15 m*l* of anhydrous ether was degassed with purified nitrogen and irradiated with 4 RPR-3500 Å lamps for 120 min in pyrex tubes. The optical rotation during the irradiation was determined at 5-20 min intervals. NMR and GC analysis indicated no 1,3-AS and no ODPM product.

Direct irradiation of 1-Methyl-2-cyclohexenyl biphenyl ketone (7c). A solution of 312 mg of (+)-ketone, 7c in 20 m*l* of methylene chloride was degassed with purified nitrogen and irradiated with 4 RPR-3000 Å lamps for 30 min in pyrex tubes. The optical rotation during the irradiation was determined at 5 min intervals. NMR and GC analysis indicated no 1,3-AS and no ODPM product.

Direct Irradiation of 1-Methyl-2-Cyclohexenyl α-Naphthyl Ketone (7d). A solution of 1.50 g of (±) ketone, 7d in 300 m*l* of anhydrous ether was divided into sixteen pyrex tubes and degassed with purified nitrogen and irradiated with 15 RPR-3000 Å lamps for 4 hours, affording 1,3-AS product, 3-Methyl-2-cyclohexenyl naphthyl ketone. The spectral data were: NMR (CDCl₃) 1,3 (s, 3H), 1.5-2.7 (m, 6H), 3.8-4.3 (s, 1H), 5.4-5.7 (s, 1H) and 7.1-8.2 (m, 7H); IR (neat) 3050, 1690, 1650 and 1595 cm⁻¹; Mass *m/e* (relative intensity) 95 (10.2), 127 (100), 155 (98.8), 250 (3.5).

Acetophenone and Benzophenone Sensitized Irradiation of Ketones (7a-7d). A solution of 1.7 g (6.8 mmol) of 1-Methyl-2-cyclohexenyl-naphthyl ketone (7d) and 250 mg of benzophenone in 340 m*l* of anhydrous ether was degassed with purified nitrogen and irradiated with 15 RPR-3500 Å lamps for 20 hours. NMR and GC analysis revealed that there were neither 1,3-AS nor ODPM product. Resolved ketone 7d, however, showed photo-racemization under the same irradiation condition. Acetophenone-sensitized irradiations of ketones (7a-7c) with 16-RPR-3500 Å lamps showed that there were neither 1,3-AS nor ODPM rearrangement. Resolved ketone (7a-7c), however, showed photo-racemizations under the same irradiation conditions.

Quantitative Investigations, Quantum Yield Determinations. Quantum yield determinations were performed by the following general procedures. A solution of between 100 and 300 mg of the ketones in 10-15 m*l* of a solvent was placed in a pyrex tube and degassed with purified nitrogen. Irradiation were carried out with 15 or 16 RPR-3000 Å and RPR-3500 Å lamps. Light out-put was monitored by potas-

sium ferrioxalate[14] actinometry according to the method of Hatchard and Parker. After irradiation, the contents were determined by one of the following methods. The results are given in Table 2.

Method A. The solution of 1-Methyl-2-cyclohexenyl α-naphthyl ketone (7d) was analyzed directly by GC using hexadecane as an internal standard. A 1/8 in × 6 ft 5% SE-30 column was used.

Method B. The Quantum yield for the photoracemization of the ketone, 7a-7d were analyzed by polarimeter at 5-20 min intervals.

Quenching Experiments. Several solutions of 100-190 mg of ketones and various concentration of piperylene in 15-20 m*l* of anhydrous ether were degassed with purified nitrogen and irradiated with 15 RPR-3000 and 3500 Å lamps. The irradiated samples were analyzed by polarimeter and GC using 1/8 in × 6 ft 5% SE-30 column. The results are given in Figure 1.

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