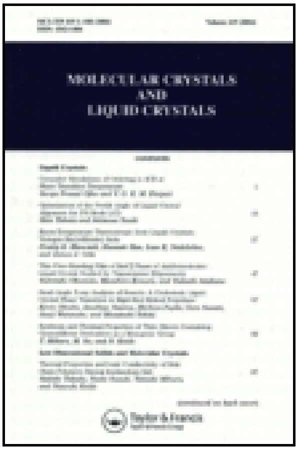


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

Crystal Lattice Control of Unimolecular Photo-Rearrangements. Medium-Dependent Photochemistry of Cyclohexenones

John R. Scheffer [a], James Trotter [a], Wolfgang K. Appel [a], Trevor J. Greenhough [a], Z. Q. Jiang [a], Anthony S. Secco [a] & Leueen Walsh [a]

[a] Department of Chemistry, University of British Columbia, Vancouver, Canada

Version of record first published: 17 Oct 2011.

To cite this article: John R. Scheffer , James Trotter , Wolfgang K. Appel , Trevor J. Greenhough , Z. Q. Jiang , Anthony S. Secco & Leueen Walsh (1983): Crystal Lattice Control of Unimolecular Photo-Rearrangements. Medium-Dependent Photochemistry of Cyclohexenones, Molecular Crystals and Liquid Crystals, 93:1, 1-15

To link to this article: http://dx.doi.org/10.1080/00268948308073511

Mol. Cryst. Liq. Cryst., 1983, Vol. 93, pp. 1–15
0026-8941/83/9304-0001/$18.50/0

Printed in the United States of America

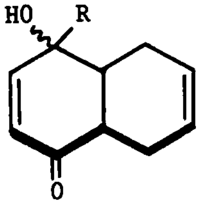
CRYSTAL LATTICE CONTROL OF UNIMOLECULAR PHOTOREARRANGEMENTS. MEDIUM-DEPENDENT PHOTOCHEMISTRY OF CYCLOHEXENONES

JOHN R. SCHEFFER,* JAMES TROTTER,* WOLFGANG K. APPEL,
TREVOR J. GREENHOUGH, Z.Q. JIANG, ANTHONY S. SECCO, and
LEUEEN WALSH
Department of Chemistry, University of British Columbia,
Vancouver, Canada

Abstract The solid state and solution photochemistry of nine compounds possessing the basic cis-4a,5,8,8a-tetrahydronaphthoquin-1-one-4-ol structure are reported. Two main points are addressed: (1) The reasons for the differences observed between the solution and solid state results, and (2) the source of the solid state reactivity differences among the nine substrates studied.

INTRODUCTION

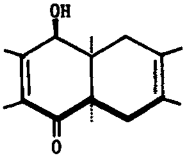
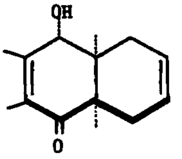
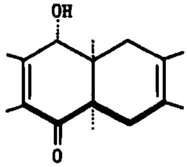
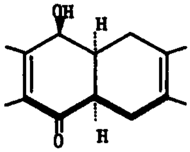
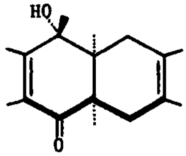
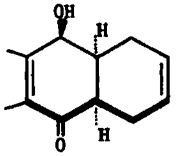
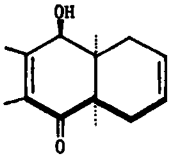
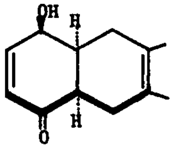
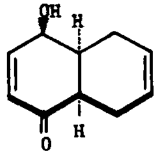
This paper describes our investigation into the solution and solid state photochemistry of the cyclohexenone system possessing the general structure shown below. Altogether, nine substrates were studied. In all nine cases, the crystal structure of the reactant was determined by X-ray diffraction methods and the data derived therefrom used to elucidate the solid state photorearrangement mechanisms. The results correspond to a situation in which the solid state medium limits reaction to one stable conformational isomer of a given substrate in contrast to the liquid phase where a minor, higher energy conformational isomer is the reacting species.



COMPOUNDS STUDIED

Table I shows the structures of the compounds studied, their melting points, their crystallographic space groups, and the R factor associated with each crystal structure determination. The substrates were prepared by sodium borohydride reduction of the corresponding ene-dione compounds which are, in turn, readily available via well precedented Diels-Alder adduct chemistry.[1,2] In the case of substrate **3**, preparation was by reaction with methyllithium rather than sodium borohydride.

Table I Compounds studied.†

1		136.5-137.5° $P\bar{1}$ R = 0.043 Conformation A	**5**		118.5-119° $P2_1/n$ R = 0.048 Conformation B
2		170.5-171° $P2_1/n$ R = 0.041 Conformation B	**6**		138-138.5° $C2/c$ R = 0.058 Conformation A
3		156-157° $P2_1/c$ R = 0.041 Conformation A	**7**		109.5-110.5° $P2_12_12_1$ R = 0.031 Conformation A
4		115-116° $P\bar{1}$ R = 0.041 Conformation A	**8**		122-122.5° $P2_1/c$ R = 0.032 Conformation A
			9		128-128.5° $P\bar{1}$ R = 0.042 Conformation A

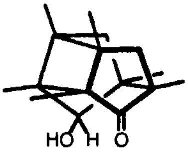
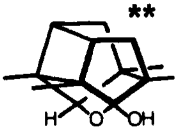
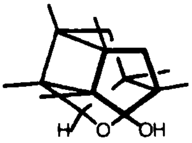
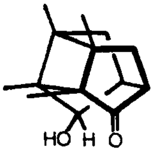
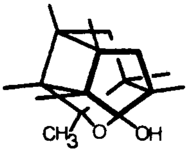
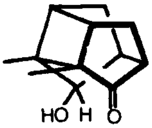
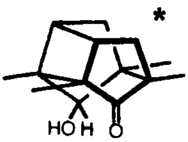
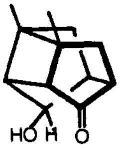
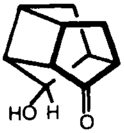
---

† Open-ended heavy and dotted lines refer to methyl groups.

RESULTS

Table II shows the major products obtained when each of the substrates was photolyzed in benzene solution at ambient temperature, either in the presence or absence of benzophenone as a sensitizer. In every case, the predominant course of events proved to be intramolecular [2+2] photocycloaddition. Only in the case of substrates 4 and 5 were significant amounts of a second photoproduct observed. The structure and probable origin of these products will be discussed later in the paper.

Table II Liquid phase (L) photoproducts.

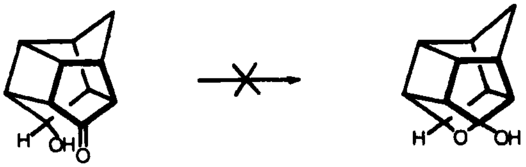
1L		5L	
2L		6L	
3L		7L	
4L		8L	
		9L	

*6% of photoproduct 4C
**24% of photoproduct 5C

Cage photoproducts in which the hydroxyl group is syn with respect to the carbonyl functionality were invariably isolated in the hemiacetal form (Eq. 1). This contrasts with the results of Sasaki, et. al.,[3] who found that ketol 10 did not undergo intramolecular hemiacetal formation (Eq. 2). We attribute this to a greater separation between the reacting centers in 10 induced by the bridging methylene group.

(1)

10



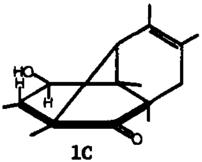
(2)

Table III summarizes the solid state photochemical results. Particularly noteworthy in these results is the fact that no [2+2] photocycloaddition, other than small amounts attributable to sample melting and/or traces of solvent, was observed. Also intriguing is the solid state photoproduct structure variation within the series.

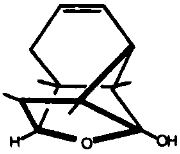
DISCUSSION

First we turn our attention to the solid state results and the reasons for the reactivity differences observed among the nine substrates studied. The crystal structure data provide the key. They show that reactants 1 - 9 crystallize in one of two possible conformations which we designate as A or B. Both conformations may be described as a half-chair cyclohexene ring cis-fused to a half-chair-like cyclohexenone moiety. A half-chair to half-chair ring flip interconverts

Table III Crystalline phase (C) photoproducts.



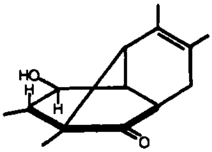
1C



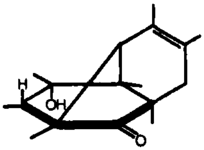
5C

[No Reaction]

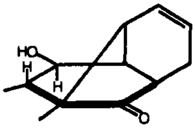
2C



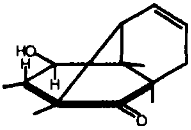
6C



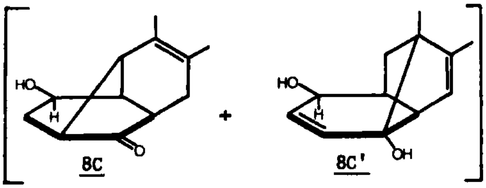
3C



7C

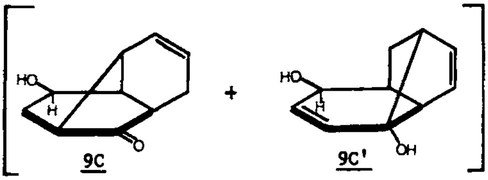


4C



8C

8C'



9C

9C'

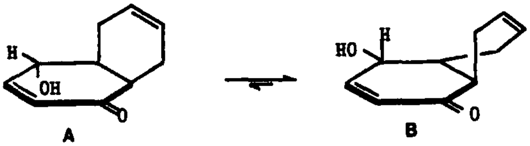
A and B. Conformers A and B and their interconversion are shown in Eq. 3. Substrates 1, 3, 4, 6, 7, 8, and 9 adopt conformation A in the solid state, whereas reactants 2 and 5 crystallize in conformation B (*cf.*, Table I). This is readily explicable using the principles of organic confor-

(3)

Bulkier substituent at C(4) prefers equatorial position.
Molecule crystallizes in more stable conformation.

mational analysis. *The conformations are determined by the preference for the bulkier substituent at C(4) to adopt the pseudo-equatorial position.* This is illustrated in Eq. 4 for the three situations encountered in this study. The methyl substituents have been omitted for clarity.

(4a)

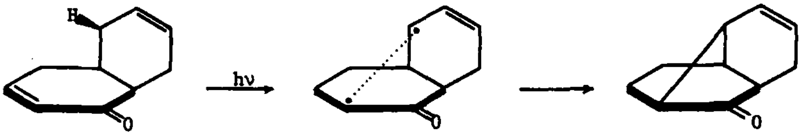


(4b)

(4c)

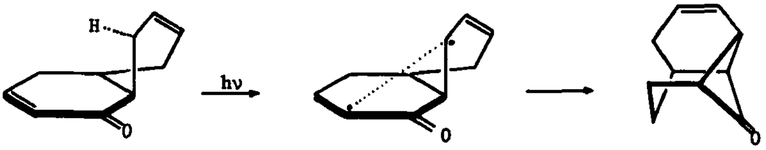
With this information we are in a position to understand the solid state photochemical reaction mechanisms. Substrates which exist in conformation A in the solid state react via initial allylic hydrogen atom abstraction (five-membered transition state!) by enone β-carbon atom followed by biradical collapse (Eq. 5a, substituents omitted for clarity). In the case of conformation B, reaction occurs by way of abstraction of the C(8) allylic hydrogen atom through a six membered transition state followed by biradical coupling (Eq. 5b). The actual compound isolated, 5C, is once again an internal hemiacetal of the initially formed ketol (Eq. 5c). Both primary processes are labeled (π,π^*) in analogy with other photoreactions involving hydrogen abstraction by enone carbon.[4] Preliminary crystal phosphorescence studies on substrate 5 confirm this assignment.

Conformation A Reactivity ($\pi\rightarrow\pi^*$)

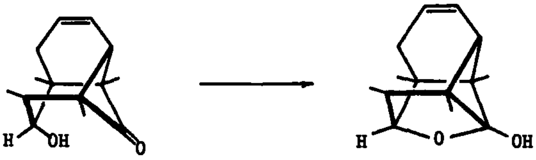


(5a)

Conformation B Reactivity ($\pi\rightarrow\pi^*$)



(5b)



(5c)

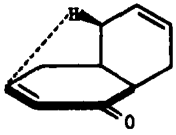
5C

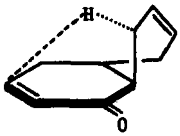
Structure-Reactivity Correlations

Are the suggested hydrogen atom transfers and subsequent carbon-carbon bond formations in fact geometrically feasible?

Tables IV - VII summarize the ground state abstraction and bonding distances and angles as determined by X-ray crystallography for the nine substrates studied. The data indicate

Table IV Hydrogen abstraction distances, d.

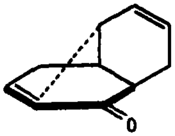


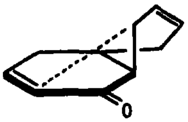


Conformation A	Conformation B
1: 2.72(2) Å	2: 2.92(2) Å (Unreactive)
3: 2.81(2)	5: 2.85(4)
4: 2.78(2)	
6: 2.84(5)	
7: 2.84(4)	
8: 2.82(3)	
9: 2.81(2)	

Sum of the van der Waals radii for carbon and hydrogen = 2.90 Å.

Table V Carbon-carbon distances, α.



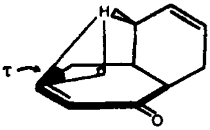


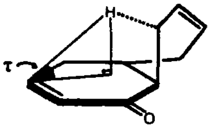
Conformation A	Conformation B
1: 3.30 Å	2: 3.23 Å (Unreactive)
3: 3.35	5: 3.17
4: 3.30	
6: 3.42	
7: 3.42	
8: 3.35	
9: 3.39	

Sum of the van der Waals radii for two carbon atoms = 3.40 Å.

that both steps of the postulated two step mechanisms are topochemically allowed. In particular, the abstraction and bonding distances are generally within the van der Waals radii sums of the atoms involved. The one unreactive substrate, 2, has the greatest abstraction distance, 2.92(2) Å. Whether this is the factor responsible for its unreactivity will have to await further experimentation. It should be pointed out that the values of α, τ, Δ, and θ for compound 2 do not appear capable of explaining its lack of reactivity.

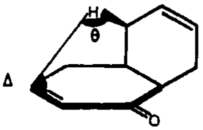
Table VI Hydrogen abstraction angle τ (ideal = 90°).

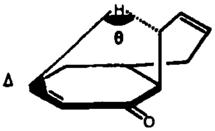




Conformation A	Conformation B
1: 53.2°	2: 49.5° (Unreactive)
3: 50.0°	5: 50.6°
4: 51.9°	
6: 53.5°	
7: 54.1°	
8: 56.7°	
9: 55.7°	

Table VII
Hydrogen abstraction angles Δ (ideal = 90°) and θ (ideal = 180°).





Conformation A

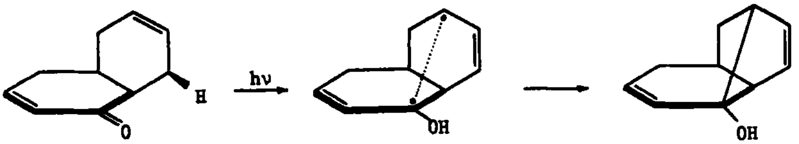
	Δ	θ
1:	78.5°	107°
3:	78.3°	104°
4:	77.5°	105°
6:	79.0°	122°
7:	79.7°	101°
8:	80.9°	
9:	82.2°	

Conformation B

	Δ	θ	
2:	75.2°	108°	(Unreactive)
5:	71.6°	107°	

For the time being, we suggest the rule of thumb that hydrogen atom abstraction by carbon has an upper limit of approximately 2.90 Å, which is also the van der Waals radii sum. A van der Waals radii sum upper limit also appears to be valid for hydrogen atom abstraction by carbonyl oxygen. We believe this to be the primary step involved in the solid state formation of photoproducts 8C' and 9C'(Table III). This is represented schematically in Eq. (6). The involvement of (n,π^*) excited states in analogous hydrogen abstraction processes is well established.[5] Thus substrates 8 and 9 exhibit dual excited state reactivity. This can reasonably be attributed to the absence in these compounds of methyl substituents on the enone double bonds. Such methyl substitution is known to favor (π,π^*) relative to (n,π^*) excited states.[6]

Conformation A Reactivity ($n \rightarrow \pi^*$)

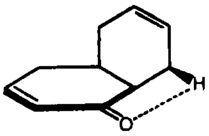


(6)

The distance and geometric parameters associated with the formation of photoproducts 8C' and 9C' are beautifully consistent with the suggestion of carbonyl oxygen n-orbital hydrogen atom abstraction (Table VIII). Not only are the abstraction distances well under the van der Waals radii sum of 2.72 Å for oxygen and hydrogen, but the angles τ and Δ are very near the optimum values of 0° and 90° respectively for n-orbital participation.

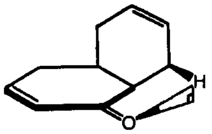
Additional examples of (π,π^*) reactivity from conformation B and (n,π^*) reactivity from A may be found in previously published work from our laboratory.[1] In every case, the van

Table VIII Distance and geometric parameters involved in formation of photoproducts 8C' and 9C'.

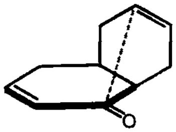


Abstraction Distances $\underline{8}$: 2.49(4) Å; $\underline{9}$: 2.49(2)

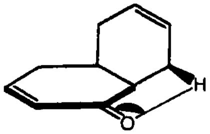
van der Waals radii sum = 2.72 Å



Angle τ $\underline{8}$: 1.0°; $\underline{9}$: 0.6° (Ideal = 0°)



Carbon-Carbon Distances $\underline{8}$: 3.41 Å; $\underline{9}$: 3.40



Angle Δ $\underline{8}$: 81.1°; $\underline{9}$: 81.8° (Ideal = 90°)

der Waals radii sum upper limit rule of thumb for hydrogen atom abstractability is adhered to. To date there are no exceptions in nineteen separate cases studied including one by Mohr.[7]

Solution versus Solid State Reactivity

We turn now to the question of why the photochemical results in solution differ from those obtained in the solid state. The answer to this question is two-fold. First of all, [2+2] photocycloaddition from either conformation A or B is topochemically disallowed in the solid state. In both conformers the carbon-carbon double bonds are neither close nor parallel and are prevented from becoming so by the restraints imposed by the crystal lattice. Thus internal [2+2] cycloaddition in solution almost certainly occurs from a conformation different from A or B. Conformer C (Fig. 1), in which the reacting double bonds are parallel and in close proximity to one another,

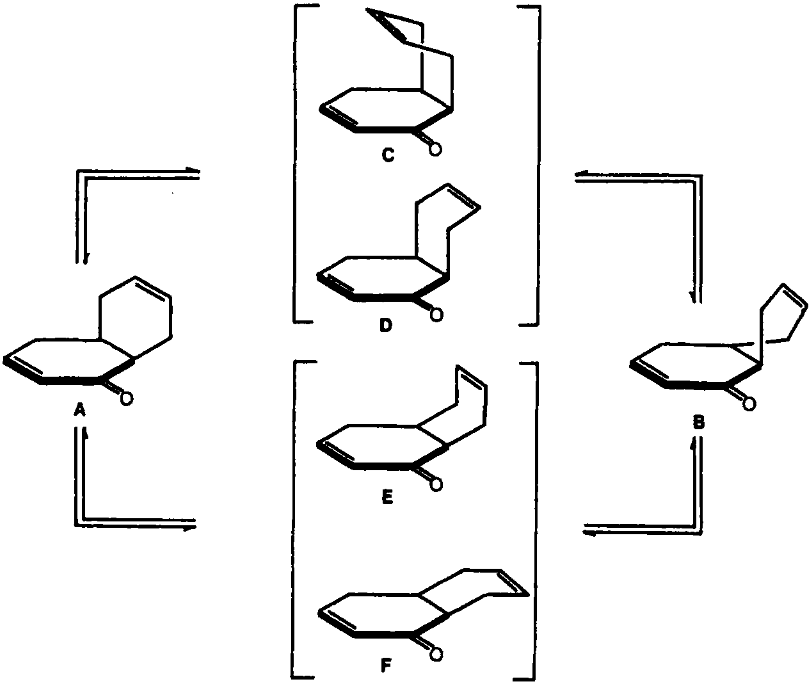
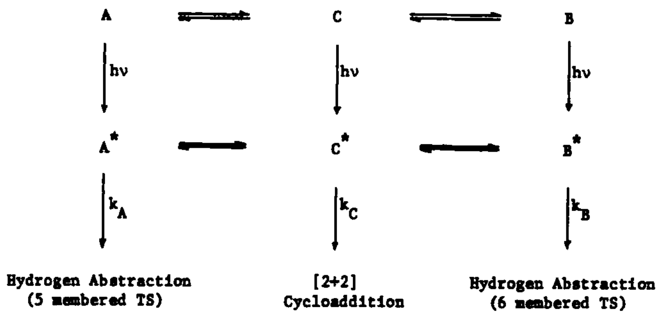


FIGURE 1. Solution conformational isomers.

is the logical choice for the reactive species. Figure 2 summarizes the situation: We postulate three distinct conformational isomers (A, B, and C), each possessing unique photochemical reactivity. In the solid state, reaction (hydrogen abstraction) occurs only from conformers A or B since C is not present. We may choose between A and B by selecting substituents which favor one or the other according to the principles of conformational analysis.

The solution situation is more complex and has been analyzed (for two reactive conformers) by Lewis, et. al.[8] Applied to the three conformer case of Figure 2, two limiting scenarios, termed Case I and Case II, are possible. In case II, conformational isomerism in the excited state between A^*, B^*, and C^*



Case I

Conformational isomerism
in excited state faster
than photochemical reactions.

Result

Product ratio determined
by relative k_A, k_B, k_C.
($k_C >> k_A, k_B$)

Case II

Conformational isomerism
in excited state slower
than photochemical reactions.

Result

Product ratio determined
by ground state conformer
distribution.

FIGURE 2. Kinetic scheme in solution.

is much slower than photochemical reaction. This would result in a photoproduct ratio directly proportional to the ground state conformer distribution in solution.[8] Because C is responsible for [2+2] photocycloaddition, yet is certainly a very minor conformer in solution (eclipsing), Case II must be ruled out. The alternative, Case I, considers the situation in which excited state conformational isomerization is rapid relative to photoreaction. This results in the photoproduct ratio being determined by the relative magnitudes of k_A, k_B, and k_C and of course, to explain the predominance of [2+2] photocycloaddition, requires that $k_C >> k_A$, k_B. We suggest that this is the situation which obtains in the solution photochemistry of the substrates studied in the present work.

We are currently testing this hypothesis through studies on the temperature dependence of the solution photoproduct ratios. Lowering the temperature might be expected to increase the proportion of type A or B reactivity observed in solution by decreasing the rate of excited state conformational isomerism. A similar effect may account for the occurrence of solid state photoproducts 4C (6%) and 5C (24%) in the solution photolysis of substrates 4 and 5 respectively (cf., Table II). In this case, a decrease in the rate of excited state conformational isomerism may have been brought about by the ring junction methyl groups which necessarily eclipse one another in the process.

Conclusion

We feel the work described goes far toward achieving the goal of "crystal engineering" for the systems studied. That is, we have developed a theoretical framework which allows for the design and synthesis of new analogues of the naphthoquinol system whose solid state (and solution) photoreactions can be predicted with a high degree of certainty. Such investigations are the subject of ongoing research in our laboratory.

ACKNOWLEDGMENTS

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research. Financial support by the Natural Sciences and Engineering Research Council of Canada is also gratefully acknowledged.

REFERENCES

1. (a) W.K. Appel, T.J. Greenhough, J.R. Scheffer, J. Trotter, and L. Walsh, J. Am. Chem. Soc., 102, 1158 (1980); (b) W.K. Appel, T.J. Greenhough, J.R. Scheffer, J. Trotter, and L. Walsh, J. Am. Chem. Soc., 102, 1160 (1980); (c) W.K. Appel, Z.Q. Jiang, J.R. Scheffer, and L. Walsh, J. Am. Chem. Soc., submitted for publication.
2. Z.Q. Jiang, J.R. Scheffer, A.S. Secco, and J. Trotter, Tetrahedron Lett., 891 (1981).
3. T. Sasaki, S. Eguchi, T. Kiriyama, and O. Hiroaki, Tetrahedron, 30, 2707 (1974).
4. W. Herz, V.S. Iyer, M. Nair, and J. Saltiel, J. Am. Chem. Soc., 99, 2704 (1977).
5. N.J. Turro, "Modern Molecular Photochemistry," Benjamin/ Cummings, Menlo Park, California, 1978.
6. R.L. Cargill, W.A. Bundy, D.M. Pond, A.B. Sears, J. Saltiel, J. Winterle, Mol. Photochem., 3, 123 (1971).
7. (a) S. Mohr, Tetrahedron Lett., 593 (1980); (b) S. Mohr, personal communication.
8. F.D. Lewis, R.W. Johnson, and D.E. Johnson, J. Am. Chem. Soc., 96, 6090 (1974).