Entropic Control of Photochemical Reactivity. The Transition State for γ-Hydrogen Abstraction of Alkyl Phenyl Ketones[1]

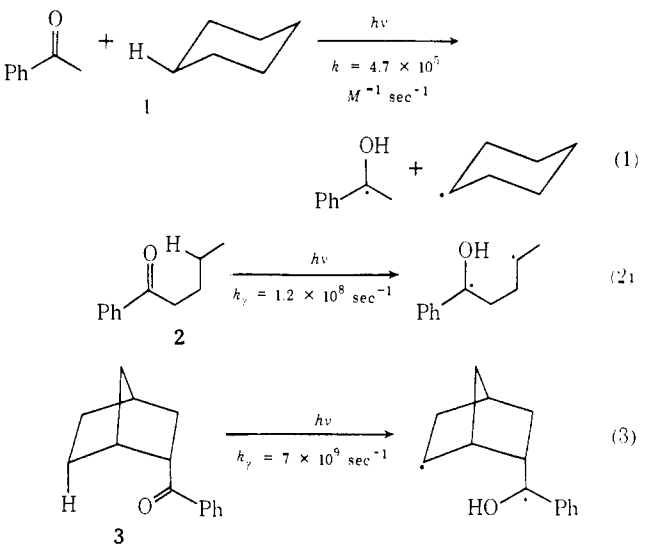
Frederick D. Lewis,[2]* Richard W. Johnson, and Daniel R. Kory

Contribution from the Department of Chemistry, Northwestern University, Evanston, Illinois 60201. *Received March 30, 1974*

Abstract: The photochemical reactivity of several alkyl phenyl ketones, having similar n,π* triplet energies and γ C–H bond strengths but differing in conformational mobility, has been investigated. Measurements of Arrhenius activation parameters show that the rate enhancements in conformationally restricted molecules are entirely entropic in origin. Rate factors of 5–8 for each internal rotation which must be frozen in the transition state are observed. Primary and secondary kinetic deuterium isotope effects have been measured for photochemical γ-hydrogen abstraction. The results are consistent with an unsymmetrical transition state with less than 50% γ C–H bond breaking. The transition state model for γ-hydrogen abstraction is in accord with experimental results and recent theoretical predictions.

Rate constants for intramolecular and enzyme-catalyzed reactions are often much larger than those for analogous nonenzymatic, bimolecular reactions.[3-6] Since restriction of conformational freedom may be one source of rate enhancement in enzyme-catalyzed reactions, there has been considerable recent interest in the effects of conformational restriction on reactivity in model systems. Rate enhancements in intramolecular reactions have been attributed to changes in entropies of activation,[4] orientation of reactive centers,[5] and changes in the reaction mechanism.[6] Since the model systems studied involve complex ionic reactions, it is often difficult to assess the importance of the possible sources of rate enhancement.

In the evolution of structure–reactivity relationships in organic photochemistry[7] little attention has been given to the possible importance of conformational mobility. A comparison of the rate constants for intermolecular hydrogen abstraction by acetophenone (eq 1)[8] and intramolecular γ-hydrogen abstraction by valerophenone (eq 2) and bicycloalkyl phenyl ketones (eq 3)[9] led us to suspect that conformational freedom might influence photochemical reactivity. Our study of the effects of molecular conformation upon competitive α cleavage and γ-hydrogen abstraction in *tert*-alkyl phenyl ketones also led to the hypothesis that the rate constant for a conformationally restricted photochemical reaction such as γ-hydrogen abstraction is dependent upon conformational populations.[10]



In order to provide more detailed information about the relationship between molecular conformation and photochemical reactivity, the photochemical behavior of a series of alkyl phenyl ketones differing in conformational mobility has been investigated.[11] The effects of temperature and deuteration upon the rate constants for γ-hydrogen abstraction have also been examined. Our results have important implications both for the understanding of photochemical reactivity and for the more general question of rate enhancements in intramolecular reactions.

Results

Quantum Yields and Kinetics. Irradiation of 2-propyl-1-tetralone (**4**) results in the formation of tetralone and a mixture of isomeric cyclobutanols (eq 4). The elimination/cyclization ratio increased from 3:1 in benzene to 12:1 in 1-propanol solution. No

(1) (a) The authors thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, and PPG Industries for support of this research. (b) Presented in part at the 166th National Meeting of the American Chemical Society, Chicago, Ill., Aug 1973, ORGN 72.

(2) Camille and Henry Dreyfus Teacher–Scholar, 1973–1978.

(3) (a) W. P. Jencks, "Catalysis in Chemistry and Enzymology," McGraw-Hill, New York, N. Y., 1969, Chapter 1; (b) M. L. Bender, "Mechanisms of Homogeneous Catalysis from Protons to Proteins," Wiley-Interscience, New York, N. Y., 1971, Chapter 9.

(4) M. I. Page and W. P. Jencks, *Proc. Nat. Acad. Sci. U. S.*, **68**, 1678 (1971).

(5) (a) D. R. Storm and D. E. Koshland, Jr., *Proc. Nat. Acad. Sci. U. S.*, **66**, 445 (1970); (b) D. R. Storm and D. E. Koshland, Jr., *J. Amer. Chem. Soc.*, **94**, 5805 (1972); (c) T. C. Bruice, A. Brown, and D. O. Harris, *Proc. Nat. Acad. Sci. U. S.*, **68**, 658 (1971).

(6) (a) R. Hershfield and G. L. Schmir, *J. Amer. Chem. Soc.*, **94**, 6788 (1972); (b) S. Milstien and L. A. Cohen, *ibid.*, **94**, 9158 (1972); (c) D. F. DeTar, *ibid.*, **96**, 1255 (1974).

(7) For pertinent reviews, see (a) J. C. Dalton and N. J. Turro, *Annu. Rev. Phys. Chem.*, 21, 499 (1970); (b) P. J. Wagner, *Accounts Chem. Res.*, **4**, 168 (1971).

(8) L. Giering, M. Berger, and C. Steel, *J. Amer. Chem. Soc.*, **96**, 953 (1974).

(9) F. D. Lewis, R. W. Johnson, and R. A. Ruden, *ibid.*, **94**, 4292 (1972).

(10) F. D. Lewis, R. W. Johnson, and D. E. Johnson, *J. Amer. Chem. Soc.*, **96**, 6090 (1974).

(11) F. D. Lewis, R. W. Johnson, and D. R. Kory, *J. Amer. Chem. Soc.*, **95**, 6470 (1973).

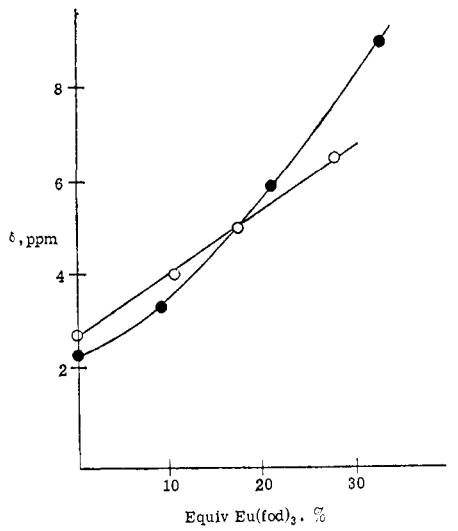
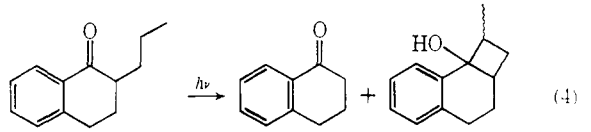


Figure 1. Lanthanide-induced chemical shifts of the methine protons H_e for cyclobutanols **6** (○) and **7** (●).

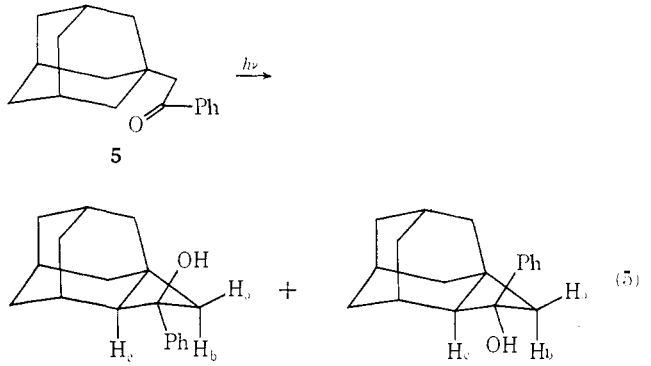


(4)

4

C_6H_6	3	1
PrOH	12	1

effort was made to separate and characterize the mixture of cyclobutanols. Irradiation of α-adamantylacetophenone (**5**) gave only the isomeric cyclobutanols **6** and **7** (eq 5). The product ratio is only moderately solvent



(5)

5 **6** **7**

C_6H_6	1.3	1
PrOH	0.6	1

dependent. The absence of photoelimination products is consistent with previous reports for α-adamantylacetone.[12,13] The two cyclobutanol products were separated by chromatography on silica gel. The nmr spectra of **6** and **7** showed an AB quartet for the cyclobutyl methylene and a broad doublet for the cyclobutyl methine (see Experimental Section). Cyclobutanol **7** had the longer retention time on silica gel and the lower field OH nmr chemical shift,[12] both of which are indicative of the less hindered equatorial OH stereochemistry. This assignment is supported by the larger lanthanide induced shift for the methine proton H_e in cyclobutanol **7** (Figure 1).

(12) R. B. Gagosian, J. C. Dalton, and N. J. Turro, *J. Amer. Chem. Soc.*, **92**, 4752 (1970).
(13) R. R. Sauers, M. Gorodetsky, J. A. Whittle, and C. K. Hu, *J. Amer. Chem. Soc.*, **93**, 5520 (1971).

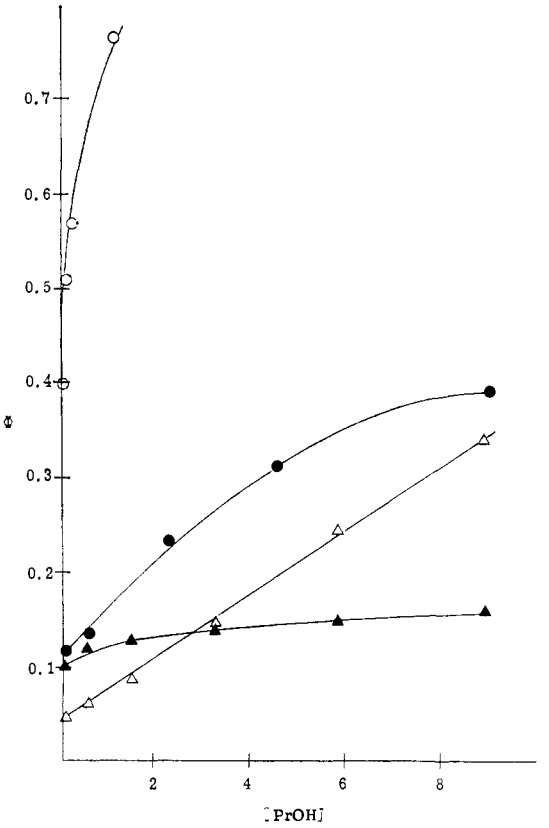


Figure 2. Variation in quantum yields for type II product formation in benzene with added 1-propanol for valerophenone (○), 2-propyl-1-tetralone (●), α-adamantylacetophenone (△), and *endo*-2-benzoylnorbornane (▲).

Quantum yields for product formation from *endo*-2-benzoylnorbornane,[9] 2-propyl-1-tetralone, and α-adamantylacetophenone were measured in benzene and 1-propanol–benzene solutions. The results are shown in Table I and Figure 2. Wagner's[14a] results for valerophenone (**2**) in *tert*-butyl alcohol–hexane are included for purposes of comparison. The increase in quantum yield with added alcohol is attributed to biradical solvation, which suppresses reversion of the biradical to

Table I. Quantum Yield[a] and Kinetic Data for *endo*-2-Benzoylnorbornane (**3**), 2-Propyl-1-tetralone (**4**), and α-Adamantylacetophenone (**5**)

Ketone	Solvent	Φ_{elim}	Φ_{cy}	$k_q\tau$,[b] M^{-1}	$10^8(1/\tau)$, sec^{-1}
3	C_6H_6	0.10		0.7[c]	70
	PrOH	0.16			
4	C_6H_6	0.09	0.03	8.5	5.9
	PrOH	0.36	0.03		
5	C_6H_6		0.04	5.5	9.2
	PrOH		0.34		

[a] Quantum yields for type II elimination and cyclization products measured at 23 ± 2° in benzene or 8.9 *M* 1-propanol–benzene solvent. [b] Least-squares slope of linear Stern–Volmer plots in benzene solution at 23 ± 2° using *trans*-1,3-pentadiene quencher, limits of reproducibility ±5%. [c] Data from ref 9.

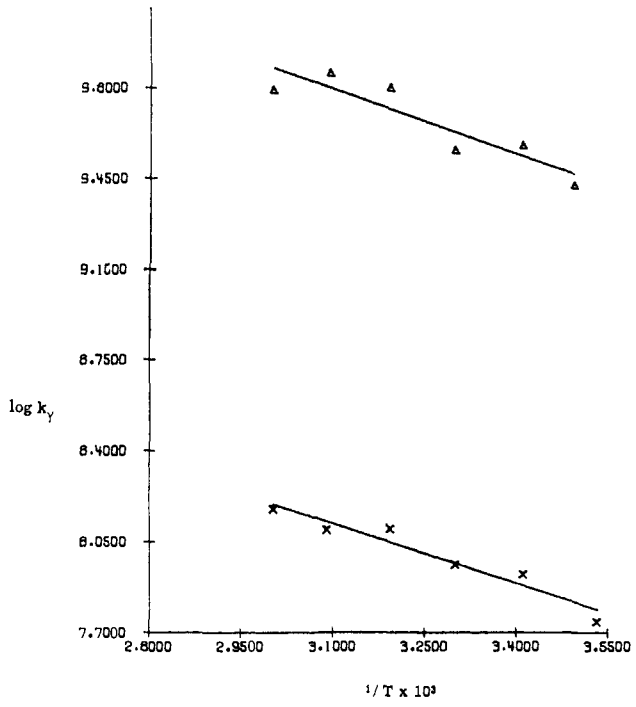


Figure 3. Plot of log k_γ *vs.* $1/T$ for valerophenone (×) and *endo*-2-benzoylnorbornane (△).

ground state ketone.[14] For ketones **3–5** the quantum yields are still increasing with alcohol concentration at 8.9 *M* 1-propanol–benzene. The sensitivity of the quantum yield to added alcohol decreases in the order valerophenone > 2-propyl-1-tetralone ~ adamantyl-acetophenone > *endo*-2-benzoylnorbornane. This order is best explained by steric hindrance of biradical solvation.[14c]

Rate constants for γ-hydrogen abstraction were determined by standard Stern–Volmer quenching experiments in degassed benzene solution using *trans*-1,3-pentadiene as the triplet quencher. From the slopes of the linear Stern–Volmer plots ($k_q\tau$) and the assumption that $k_q = 5 \times 10^9\ M^{-1}\ \text{sec}^{-1}$ in benzene solution,[15] values of the triplet lifetime (τ) are obtained (Table I). In view of the short triplet lifetimes ($\tau < 10^{-8}$ sec) it is unlikely that radiationless triplet decay competes with γ-hydrogen abstraction. Thus the triplet lifetime is determined by the rate of γ-hydrogen abstraction ($1/\tau = k_\gamma$). The quantum inefficiency for product formation is assumed to be due to biradical reversion to ground state ketone rather than inefficient biradical formation.

Arrhenius Activation Parameters. Activation parameters have previously been determined for valerophenone in benzene solution.[16] Cyclooctane was chosen for the present study because the observed and calculated rates of diffusion controlled quenching are nearly identical in this solvent.[17] Stern–Volmer quenching experiments were performed on 0.03 *M* solutions of valerophenone or *endo*-2-benzoylnorbornane in cyclooctane solution between 10 and 60°. Viscosities were measured for solutions containing one-half the maximum 1,3-pentadiene concentration used in a given run. Rates of diffusion were calculated using the Debye equation.[18] The results are given in Tables II and III. Computer-generated Arrhenius plots of the

$$k_{\text{diff}} = \frac{8RT}{3000\eta}$$

Table II. Kinetic Data for Valerophenone (**2**)

T, °C	$k_q\tau$, M^{-1}	$10^9 k_{\text{diff}}$, M^{-1} sec^{-1}	$10^7(1/\tau)$, sec^{-1}
10	40.1	2.22	5.54
20	34.8	2.92	8.39
30	38.3	3.53	9.21
40	35.2	4.42	12.6
50	44.2	5.51	12.5
60	43.3	6.48	15.0

Table III. Kinetic Data for *endo*-2-Benzoylnorbornane (**3**)

T, °C	$k_q\tau$, M^{-1}	$10^9 k_{\text{diff}}$, M^{-1} sec^{-1}	$10^8(1/\tau)$, sec^{-1}
13	1.10	2.94	2.67
20	0.924	3.18	3.44
30	1.10	4.01	3.65
40	0.806	5.14	6.38
50	0.875	6.35	7.26
60	1.10	6.89	6.22

Table IV. Arrhenius Activation Parameters[a] for Hydrogen Abstraction

Ketone	E_a, kcal/mol	$\Delta S^{\ddagger}$,[b] gibbs	r[c]
Acetophenone[d] (**1**)	3.3	−23.9	
Valerophenone (**2**)	3.5 ± 0.5	−12.5 ± 1.5	0.97
endo-2-Benzoyl-norbornane (**3**)	3.7 ± 0.9	−4.0 ± 2.8	0.91

[a] Error limits are deviations from least squares. [b] Entropies of activation calculated for 25°. [c] Correlation coefficient of least-squares plot. [d] Data from ref 8.

data in Tables II and III are shown in Figure 3 and the resulting activation parameters are given in Table IV along with the results of Steel and coworkers[8] for acetophenone intermolecular hydrogen abstraction from cyclohexane.

Deuterium Isotope Effects. Catalytic hydrogenation and deuteration of *endo*-5-benzoylnorbornene afforded the protiated and exo-deuterated ketones **3** and **8** (eq 6). Similarly, ketones **9** and **10** were obtained from *endo*-5-benzoylnorbornene-*1,2,3,4,7,7-d*$_6$ (eq 7). Hydrogenation of norbornene-type molecules is known to give predominantly exo,cis addition products.[19] Within the limits of nmr detection, only the exo,cis products **8** and **9** are obtained. The three protons in **10** and its norbornene precursor comprise a readily analyzed ABX system (see Experimental Section). Long range

(14) (a) P. J. Wagner, *J. Amer. Chem. Soc.*, **89**, 5898 (1967); (b) P. J. Wagner, I. E. Kochevar, and A. E. Kemppainen, *ibid.*, **94**, 7489 (1972); (c) P. J. Wagner, P. A. Kelso, A. E. Kemppainen, J. M. McGrath, H. N. Schott, and R. G. Zepp, *ibid.*, **94**, 7506 (1972).

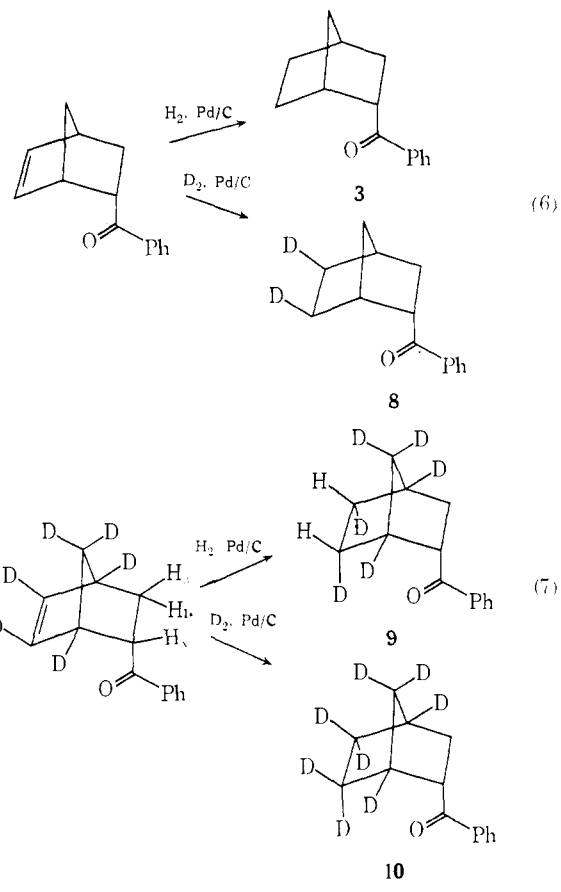
(15) (a) P. J. Wagner and I. Kochevar, *J. Amer. Chem. Soc.*, **90**, 2232 (1968); P. J. Wagner, J. M. McGrath, and R. G. Zepp, *ibid.*, **94**, 6883 (1972).

(16) (a) F. D. Lewis, *Mol. Photochem.*, **4**, 501 (1972); (b) J. C. Scaiano, J. Grotewold, and C. M. Previtali, *J. Chem. Soc., Chem. Commun.*, 390 (1972).

(17) P. J. Wagner and I. Kochevar, *J. Amer. Chem. Soc.*, **90**, 2232 (1968).

(18) W. P. Helman, *Chem. Phys. Lett.*, **17**, 306 (1972).

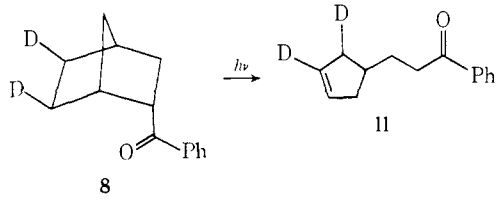
(19) (a) D. R. Arnold, D. J. Trecker, and E. B. Whipple, *J. Amer. Chem. Soc.*, **87**, 2596 (1965); (b) P. G. Gassman, K. T. Mansfield, and T. J. Murphy, *ibid.*, **91**, 1684 (1969); (c) W. C. Baird, B. Frangus, and J. Surridge, *J. Org. Chem.*, **34**, 2944 (1969).



(6)

(7)

coupling of H_x to the 6-exo proton is observed for **9** but not for **8**. Further evidence for the stereospecificity of deuteration in **8** was provided by analysis of the photoelimination product **11** (eq 8). Integration of the aro-



(8)

matic and vinyl regions of the nmr spectrum gave a ratio of 5.04:1. Endo deuteration at C_6 would result in a smaller aromatic/vinyl ratio.

Quantum yields for photoelimination and Stern–Volmer quenching constants were measured in cyclooctane solvent at 20° (Table V). Rate constants for

Table V. Deuterium Isotope Effects on γ-Hydrogen Abstraction for *endo*-2-Benzoylnorbornane

Ketone	Φ_{elim}[a]	$k_q\tau$,[b] M^{-1}	$10^9 k_\gamma$, sec^{-1}	k_H/k_D
3	0.11	0.924	3.44	
8	0.11	1.19	2.7	1.26
9	0.16	2.94	1.1	3.18
10	0.16	3.35	0.86	4.0

[a] Quantum yields for photoelimination and quenching constants measured at 20 ± 1° in cyclooctane solutions. [b] Least-squares slope of linear Stern–Volmer plot, limits of reproducibility ±5%.

γ-hydrogen or deuterium abstraction were calculated assuming $k_q = 3.2 \times 10^9$ M^{-1} sec^{-1} (Table III). The 5-endo deuterated ketones **9** and **10** have larger photoelimination quantum yields than those for ketones **3** and **8**. The small inverse isotope effect on the quantum yield ($\Phi_H/\Phi_D = 0.69$) probably is due to the larger kinetic isotope effect for reversion of the biradical to ground state ketone than for product formation.[20]

Discussion

The triplet lifetime of an aryl alkyl ketone is determined by the rate of γ-hydrogen abstraction ($1/\tau = k_{ab}$) when the abstraction reaction occurs with unit efficiency. Investigations of the variation in triplet lifetime with both aryl and alkyl substituents have provided a number of useful structure–reactivity relationships for both inter- and intramolecular hydrogen abstraction (eq 1 and 2). For example, triplet lifetimes are known to be dependent upon the configuration and energy of the triplet state as well as the strength of the C–H bond being broken.[7] These and other structure–reactivity relationships provide a fairly good understanding of *relative* photochemical reactivities in acyclic ketones. However, they do not explain the observed rate enhancements in some cycloalkyl and bicycloalkyl phenyl ketones (*cf.* eq 2 and 3).[9,10] A more serious problem with existing structure–reactivity relationships is that they provide little information about *absolute* photochemical reactivity.[21]

A number of theoretical models for photochemical hydrogen abstraction reactions have recently been advanced.[22–26] There has been some debate as to whether the rate determining step should be treated as a radiationless transition[21,22] or the transfer of a hydrogen atom across a potential energy barrier.[24–28] A model based on radiationless transition theory with the rate of abstraction determined by Franck–Condon factors for electronic-to-vibrational energy transfer has been proposed by Heller.[22] This model, in its present form, does not adequately explain much of the experimental data for inter-[24,27] and intramolecular[28] hydrogen abstraction and also has been criticized on theoretical grounds.[24,27a]

The theoretical models presented by Michl[25] and Salem[26] provide a basis both for understanding photochemical hydrogen abstraction reactions and interpreting structure–reactivity data. Salem has shown that the ketone n,π^* excited state correlates with the biradical product while the ketone ground state correlates with a zwitterionic excited state (Figure 4). If the carbonyl is a symmetry plane for the abstraction, the surface crossing is rigorously allowed. In practice the crossing is weakly avoided due to the absence of a symmetry plane. However, internal conversion at the avoided crossing should be extremely rapid as a result of the small energy gap between the ground and excited state surfaces. Thus the excited state lifetime may depend on the height of small potential barriers on the excited state surface leading to the surface crossing rather than

(20) T. R. Darling, M. J. Turro, R. H. Hirsch, and F. D. Lewis, *J. Amer. Chem. Soc.*, **96**, 434 (1974), and references therein.
(21) G. S. Hammond, *Advan. Photochem.*, 7, 373 (1969).
(22) A. Heller, *Mol. Photochem.*, 1, 257 (1969).
(23) R. C. Dougherty, *J. Amer. Chem. Soc.*, **93**, 7187 (1971).
(24) (a) C. M. Previtali and J. C. Scaiano, *J. Chem. Soc., Perkin Trans 2*, 1667 (1972); (b) *ibid.*, 1672 (1972).
(25) J. Michl, *Mol. Photochem.*, 4, 243 (1972); (b) *ibid.*, 257 (1972).
(26) L. Salem, W. G. Dauben, and N. J. Turro, *J. Chim. Phys.*, 70, 694 (1973).
(27) (a) R. W. Yip and W. Siebrand, *Chem. Phys. Lett.*, 13, 209 (1972); (b) J. P. Blanchi, *J. Chim. Phys.*, 70, 905 (1973).
(28) P. J. Wagner, P. A. Kelso, A. E. Kemppainen, and R. G. Zepp, *J. Amer. Chem. Soc.*, **94**, 7500 (1972).

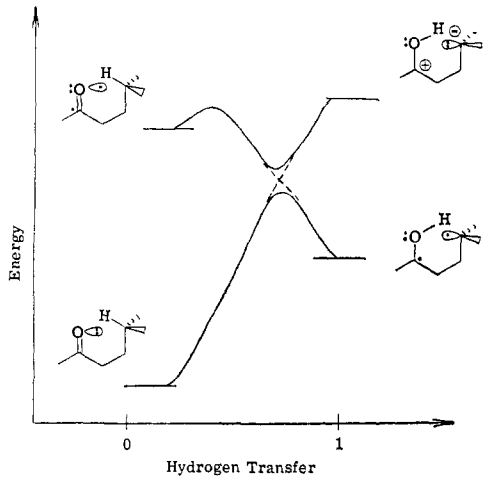


Figure 4. Energy surfaces for carbonyl ground and n,π^* excited states showing the weakly avoided surface crossing (dashed lines).

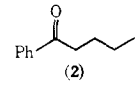
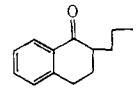
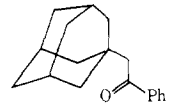
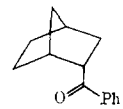
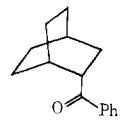
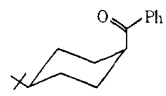
the rate of internal conversion.[25] If this interpretation is correct, it is not necessary to assume that hydrogen atom transfer is an adiabatic process in order to apply transition state theory to such reactions. It should therefore be possible to measure activation parameters and kinetic isotope effects for hydrogen abstraction and to use this information to provide a detailed description of the transition state.

Activation Parameters. The Arrhenius activation energies for valerophenone and *endo*-2-benzoylnorbornane intramolecular hydrogen abstraction (Table IV) are the same, within the experimental error. The activation energy for valerophenone (3.5 kcal/mol) is somewhat smaller than two previously reported values (4.2[16a] and 4.7 kcal/mol[16b]). The value reported by Steel[8] for intermolecular hydrogen abstraction by acetophenone with cyclohexane (3.3 kcal/mol) is similar to that for valerophenone intramolecular abstraction. Ketones **1**–**3** all have similar ^{3}n,π^* energies and spin distributions and the secondary C–H bonds broken have similar bond strengths. Thus it is not surprising that the activation energies are the same. Scaiano, *et al.*,[16b] have demonstrated that the activation energy is dependent upon C–H bond strength. Their activation energy for butyrophenone is 2.0 kcal/mol larger than that for valerophenone, while there is little difference in the entropies of activation.

Since the activation energies for the hydrogen abstraction reactions shown in eq 1–3 are the same, the large variation in rate constants is due entirely to differences in entropy of activation. The entropy of activation for acetophenone intermolecular hydrogen abstraction is normal for a bimolecular reaction and demonstrates that there are no "unusual" conformational requirements for the intermolecular abstraction. The entropy of activation for valerophenone is also about normal for a strain-free six-center transition state.[4,29] The entropy change for forming a cyclic transition state is estimated to be 4–5 gibbs per internal rotation which must be frozen out.[29] The entropies of activation for valerophenone (three internal rotations) and *endo*-2-benzoylnorbornane (one internal rotation) are both in agreement with this estimate. Thus the 60-fold rate increase for *endo*-2-benzoylnorbornane *vs.* valerophenone is due to the two fewer internal rotations which must be frozen out in going from the ketone excited state to the transition state.

The relative reactivities of a number of alkyl phenyl ketones with similar n,π^* triplet energies and γ C–H bond strengths can be explained on the basis of conformational mobility (Table VI). Ketones **4** and **5** both have two internal rotations which must be frozen in the transition state and have rate constants intermediate between those for valerophenone and *endo*-2-benzoylnorbornane. Ketones **11** and **12** have one internal rotation and rate constants similar to that for *endo*-2-benzoylnorbornane. A completely rigid ketone ($\Delta S^{\ddagger} = 0$) with an activation energy of 3.5 kcal/mol would have a rate constant for γ-hydrogen abstraction of 4×10^{10} sec^{-1}. Since rate constants this rapid cannot be measured by conventional quenching techniques, no effort was made to synthesize such a ketone. It is interesting to note that the rate constant for valerophenone is slower than the enthalpy-controlled maximum by a factor of 3×10^2. Thus variations in activation entropy are as important as γ C–H bond strength[7] in determining photochemical reactivity.

Table VI. Kinetic Data for Alkyl Phenyl Ketones

Ketone	$k_q\tau$, M^{-1}	k_{rel}
 (2)	40	1.0
 (4)	8.5	4.9
 (5)	5.5	7.7
 (3)	0.7	58
 (11)	0.5[a]	83
 (12)	0.74[b]	57

[a] Value from ref 9. [b] Value from ref 10.

Kinetic Isotope Effects. The results for the deuterated *endo*-2-benzoylnorbornanes (Table V) indicate that secondary as well as primary isotope effects influence the rate constant for γ-hydrogen abstraction. A secondary isotope effect of 1.3 can be obtained by

(29) H. E. O'Neal and S. W. Benson, *J. Phys. Chem.*, 71, 2903 (1967).

comparing the values of k_γ for ketones **3** *vs.* **8** or **9** *vs.* **10**. This value is outside the error limits of the kinetic data and is close to the maximum value predicted by Streitwieser for a change from sp^3 to sp^2 hybridization.[30] Interpretation of the secondary isotope effect is complicated by the possible operation of both α and β secondary isotope effects in the norbornane system.[31] Although there is no unique explanation of the large secondary isotope effect, it may result from relief of nonbonded repulsion of the eclipsed exo protons in the transition state for γ-hydrogen abstraction.[32] A large steric isotope effect could be related to the unusual nonplanar geometry of the 2-norbornyl free radical.[33]

Primary kinetic isotope effects have been reported for several alkyl phenyl ketones with values of k_H/k_D ranging from 1.7 to 5.5 (Table VII).[20,34,35] The value

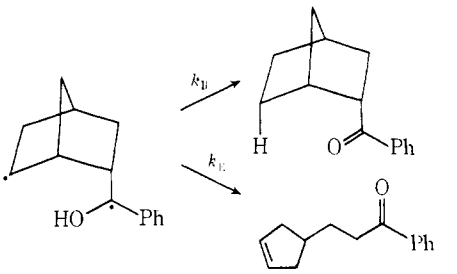
Table VII. Kinetic Isotope Effects for Alkyl Phenyl Ketones

Ketone	k_γ, sec^{-1}	k_H/k_D
endo-2-Benzoylnorbornane (**3**)	3.4×10^9	3.2
Phenyl *n*-octyl ketone	1.7×10^8	4.8[a] (3.0)[b]
α-Methoxylacetophenone	3.1×10^9	5.5[c] (3.0)[d]
γ-Hydroxy-γ-phenyl-butyrophenone	6.7×10^8	1.7[e]

[a] Value from ref 34 corrected for incomplete deuteration and δ hydrogen abstraction. [b] Uncorrected. [c] Value from ref 20. [d] Value calculated using $k_\gamma = 1.7 \times 10^9$ sec^{-1} from P. J. Wagner and A. E. Kemppainen, *J. Amer. Chem. Soc.*, **90**, 5896 (1968). [e] Value from ref 35.

for α-methoxyacetophenone[20] depends upon the choice of literature values for the nondeuterated ketone and the value for phenyl *n*-octyl ketone[34] contains corrections for competing reactions and incomplete deuteration. Neither of these values is corrected for secondary isotope effects. In view of the limited data available, no significance can be attached to the variation in isotope effect with structure. Deuterium isotope effects in the range 2–4 are consistent with an unsymmetrical transition state.[36] An uncertainty affecting interpretation of the isotope effect is the nonlinearity of the C–H–O atoms in the transition state (*vide infra*). Increasing nonlinearity decreases the isotope effect for proton transfer reactions: however, the effect for hydrogen atom transfer is not known.[37]

The primary kinetic isotope effect for reversion of the biradical intermediate to ground state ketone can be estimated from the quantum yield data in Table V. Since reversion to ground state ketone (k_R) and elimination (k_E) are the only reactions of the biradical (eq 9),[9] the quantum yield expressions (eq 10 and 11) can be



(9)

$$\Phi_{EH} = k_{EH}/(k_{EH} + k_{RH}) = 0.11 \quad (10)$$

$$\Phi_{ED} = k_{ED}/(k_{ED} + k_{RD}) = 0.16 \quad (11)$$

simplified to provide eq 12. The secondary isotope

$$k_{RH}/k_{RD} = 1.54(k_{EH}/k_{ED}) \quad (12)$$

effect for photoelimination (k_{EH}/k_{ED}) must be less than 1.3.[30] Thus the isotope effect for reverse hydrogen transfer is less than 2.0. The smaller isotope effect for reverse hydrogen transfer *vs.* γ-hydrogen abstraction implies an earlier transition state for the former reaction (Figure 4).

Transition State for Hydrogen Abstraction. Several lines of evidence lead to the conclusion that the transition state for secondary alkyl hydrogen abstraction by an aromatic carbonyl $^3n,\pi^*$ excited state resembles the excited state more than the biradical intermediate. The heat of reaction for formation of the biradical from the ground state ketone is estimated to be 57 ± 3 kcal/mol.[38,39] Thus formation of the biradical from the n,π^* triplet state (73 kcal/mol) is approximately 16 kcal/mol exothermic. The moderate exothermicity and low activation energy indicate an early transition state, if Hammond's postulate[40] is applicable.[41] The primary kinetic isotope effects are also consistent with an unsymmetrical transition state.[36] Pryor[42] has recently observed that the kinetic isotope effect for a series of hydrogen-transfer reactions has a maximum value of $k_H/k_D \sim 6.7$ for slightly endothermic reactions. The isotope effects for γ-hydrogen abstraction ($k_H/k_D \sim 3$) and calculated heat of reaction ($\Delta H \sim 16$ kcal/mol) correlate well with Pryor's results.[42] An additional line of evidence for an early transition state is the absence of significant rate enhancement by γ substituents which can stabilize a biradical intermediate by resonance.[43] The rate constant for γ-hydrogen abstraction for γ-phenylbutyrophenone is actually smaller than that for γ-methylvalerophenone. Such behavior is common in very exothermic homolytic reactions[44] and has been noted for intermolecular hydrogen abstraction by aromatic ketones from alkyl benzenes.[8,24]

Further evidence for a nonplanar transition state[9,28] is provided by the present study. The nonplanar transition state has a longer $O–H_\gamma$ distance[45] and

(30) (a) A. Streitwieser, Jr., R. H. Jagow, R. C. Fahey, and S. Suzuki, *J. Amer. Chem. Soc.*, **80**, 2326 (1958). (b) Secondary α isotope effects on the order of 1.10–1.15 per deuterium have been reported for several homolytic reactions: S. Seltzer and S. G. Mylonakis, *J. Amer. Chem. Soc.*, **89**, 6584 (1967).

(31) H. Tanida and T. Tsushima, *J. Amer. Chem. Soc.*, **93**, 3011 (1971).

(32) H. C. Brown and G. J. McDonald, *J. Amer. Chem. Soc.*, **88**, 2514 (1966).

(33) T. Kawamura, T. Koyama, and T. Yonezawa, *J. Amer. Chem. Soc.*, **95**, 3220 (1973).

(34) P. J. Wagner, P. A. Kelso, and R. G. Zepp, *J. Amer. Chem. Soc.*, **94**, 7480 (1972).

(35) F. D. Lewis, *J. Amer. Chem. Soc.*, **92**, 5602 (1970).

(36) N. A. Bergman, W. H. Saunders, Jr., and L. Melander, *Acta Chem. Scand.*, **26**, 1130 (1972).

(37) R. A. More O'Ferrall, *J. Chem. Soc. B*, 785 (1970).

(38) F. D. Lewis and T. A. Hilliard, *J. Amer. Chem. Soc.*, **94**, 3852 (1972).

(39) D. R. Kory, Ph.D. Thesis, Northwestern University, 1974.

(40) G. S. Hammond, *J. Amer. Chem. Soc.*, **77**, 334 (1955).

(41) It is not clear what the effect of a surface crossing occurring after formation of the transition state would have on this assumption.

(42) W. A. Pryor and K. G. Kneipp, *J. Amer. Chem. Soc.*, **93**, 5584 (1971).

(43) P. J. Wagner and A. E. Kemppainen, *J. Amer. Chem. Soc.*, **94**, 7495 (1972).

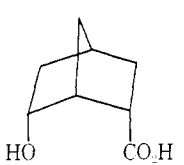
(44) C. Rüchardt, *et al.*, XXII IInternational Congress on Pure and Applied Chemistry, Special Lectures, Vol. 4, Butterworths, London, 1971, p 223.

(45) F. P. Boer, T. W. Shannon, and F. W. McLafferty, *J. Amer. Chem. Soc.*, **90**, 7239 (1968).

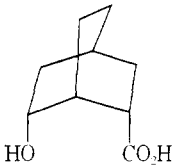
smaller O–H–C_γ angle than the planar transition state but does not have the unfavorable methylene eclipsing interactions present in the planar transition state. Eclipsing interactions would result in a higher activation energy for intramolecular abstraction by valerophenone *vs.* intermolecular abstraction by acetophenone.[46] This is in fact not the case (Table IV). The O–H–C_γ angle for the nonplanar transition state is near the optimal angle of 120° for ground state carbonyl hydrogen bonding predicted by "lone-pair" theory.[47] If a linear transition state were energetically more favorable, the activation energy for intermolecular abstraction should be lower than that for intramolecular abstraction.

Conformational Rate Enhancement. Restriction of conformational mobility can result in rate enhancements for intramolecular reactions. Conformational mobility has been restricted by incorporating the reactive centers into rigid molecules (*e.g.*, Table VI),[4,5] by interlocking of substituents,[6b] and by associating with a model enzyme.[48] Such perturbations can affect the electronic and steric properties of the reaction, the solvation of reactants and transition state, and even the reaction mechanism. It has proven difficult to separate conformational mobility from one or more such attendant effects. Thus the contribution of entropy to rate acceleration is difficult to evaluate. Jencks[4] has predicted a rate enhancement of about 5 from the loss of entropy for freezing one internal rotation (~4–5 gibbs), whereas Bruice[5c] has predicted a rate enhancement as large as 160.

Photochemical hydrogen abstraction of alkyl phenyl ketones provides a model system for evaluating the contribution of conformational entropy to intramolecular rate acceleration. The rate-limiting step is a simple transfer of a hydrogen atom across a small potential energy barrier. The rate constants for both inter-[8] and intramolecular[17] abstraction are independent of solvent. Orientational requirements[5a,b] do not appear to be important for the model ketones in Table VI. Orbital overlap of the half-vacant nonbonding orbital on oxygen with the γ-hydrogen should be comparable for all of these ketones. Small changes in bond angles and O–H_γ distances do not appear to affect the rate constant. For example, the rate constants for *endo*-2-benzoylnorbornane and 2-benzoylbicyclo[2.2.2]octane are nearly identical while the rate constants of lactonization for the bicyclic acids **13** and **14** differ by a factor of



13

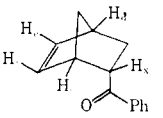
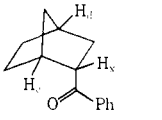
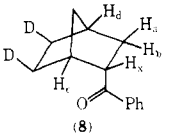
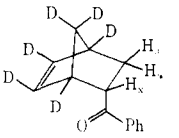
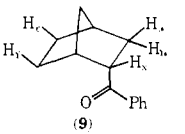
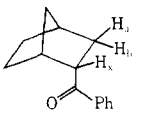


14

10^3.[5b,49] The effects of alkyl substituents upon the rate constants for intramolecular hydrogen abstraction are also readily explained. For acyclic ketones, α- and β-methyl substituents have little effect on the rate constant.[28,38] This is consistent with a nonplanar transition state having minimized eclipsing interactions. α-Methyl substituents decrease the rate constant for bicycloalkyl and cycloalkyl phenyl ketones **3**, **11**, and **12**.[9,10] Eclipsing interactions between the α-methyl and phenyl groups cannot be avoided in the transition states for these ketones.

In conclusion, the rate acceleration which accompanies decreased conformational mobility for the ketones in Table VI is entropic in origin. The rate factors of 5–8 for each internal rotation correspond to a $\Delta\Delta S^{\ddagger}$ of 4–5 gibbs. This result is in good agreement with recent predictions for six-membered transition states.[4,27] The significantly larger rate factors which have previously been reported for ionic reactions most likely are due to enthalpic as well as entropic changes. Whether these larger differences are due to changes in orbital overlap[5a,b] or other factors[4,6] remains an open question.

Table VIII. Nmr Data for Norbornyl Ketones

Ketone	δ, ppm	*J*, Hz
	x 3.62 (m) c 3.17 (m) d 2.80 (m) e,f 5.8 (m)	
 (1)	x 3.65 (m) c 2.60 (m) d 2.33 (m)	
 (8)	x 3.62 (m)[a] c 2.55 (m) d 2.26 (m)	J_{ax} = 10.6 $J_{bx} = J_{cx}$ = 4.8
	x 3.65 a 1.63 b 1.75	J_{ab} = 11.5 J_{ax} = 9.4 J_{bx} = 4.8
 (9)	x 3.67 (m) a 1.76 b 1.82 e,f 1.3 (m)	J_{ab} = 12.0
 (10)	x 3.62 a 1.65 b 1.80	J_{ab} = 12.8 J_{ax} = 10.7 J_{bx} = 4.8

[a] Doublet of triplets.

Experimental Section

2-Propyl-1-tetralone (4). Ethyl 1-keto-1,2,3,4-tetrahydro-2-naphthoate was prepared by the method of Bachmann and Wendler.[50] To a cooled solution of the β-keto ester (4.36 g, 0.02 mol)

(46) K. J. Mintz and D. J. LeRoy, *Can. J. Chem.*, **51**, 3534 (1973).
(47) P. A. Kollman, *J. Amer. Chem. Soc.*, **94**, 1837 (1972).
(48) D. W. Griffiths and M. L. Bender, *J. Amer. Chem. Soc.*, **95**, 1679 (1973).
(49) Several of the hydroxycarboxylic acids studied by Storm and Koshland were assigned incorrect structures; however, the structural assignments for 13 and 14 have been confirmed. R. M. Moriarty and T. Adams, *J. Amer. Chem. Soc.*, **95**, 4070 (1973).
(50) W. E. Bachmann and N. L. Wendler, *J. Amer. Chem. Soc.*, **68**, 2583 (1946).

and sodium (0.53 g, 0.023 mol) in 45 ml of ethanol was added 1-bromopropane (3.7 g, 0.03 mol). The mixture was stirred under reflux for 20 hr and then poured into water and extracted with ether and the ether removed. The residue was refluxed for 21 hr with a mixture of 40 ml of acetic acid, 5 ml of sulfuric acid, and 25 ml of water. The solvents were removed, and the residue was extracted with ether, washed with dilute hydroxide, dried, and distilled. Ketone **4** was obtained as a colorless solid (2.5 g, 67%): mp 41°; nmr (CCl_4) δ 0.93 (t, 3 H), 1.4 (m, 4 H), 2.0 (m, 3 H), 2.9 (t, 3 H), 7.2 (m, 3 H), 7.9 (m, 1 H); uv spectrum (hexane) λ_{max} 326 nm, ϵ_{max} 38.

α-(1-Adamantyl)acetophenone (5). To a solution of 1-adamantaneacetic acid (Aldrich, 2.0 g, 0.01 mol) in 100 ml of anhydrous ether was added 2 equiv of phenyllithium. Aqueous work-up followed by distillation (135–137°, 0.2 mm) and chromatography on alumina gave 1.0 g (40%) ketone **5**: mp 64–65° (hexane); ir spectrum (CCl_4) 1680 cm^{-1}; nmr spectrum (CCl_4) δ 1.65 (m, 12 H), 1.93 (m, 3 H), 2.60 (s, 2 H), 7.4 (m, 3 H), 7.8 (m, 2 H); uv spectrum (hexane) λ_{max} 324 nm, ϵ_{max} 52.

Cyclopentadiene-d_6. The most satisfactory of the several methods employed was the exchange reaction of cyclopentadiene in DMSO–D_2O–NaOD.[51] After four exchanges mass spectral analysis (CEC 21-104 with an ionization voltage of 6.2 eV) showed 83.6% d_6, 14.2% d_5, 1.5% d_4, <0.7% d_3–d_0.

***exo,exo*-5,6-Dideuterio-*endo*-2-benzoylnorbornane (8).** Catalytic deuteration of *endo*-5-benzoylnorbornene[9] (1.4 g, 0.0068 mol) in 15 ml of 95% ethanol over 0.06 g of 10% palladium on carbon followed by chromatography on silica gel (1% ethyl acetate–hexane) and evaporative distillation gave **8** as a colorless oil (0.7 g, 50%) (Table VIII).

1,4,*exo*-5,*exo*-6,7,7-Hexadeuterio-*endo*-2-benzoylnorbornane (9). Diels–Alder reaction of cyclopentadiene-d_6 with acrylic acid followed by treatment of the crude product with 2 equiv of phenyllithium gave 1,2,3,4,7,7-hexadeuterio-*endo*-5-benzoylnorbornane.

Catalytic hydrogenation of hexadeuterio-*endo*-5-benzoylnorbornene (1.36 g, 0.0065 mol) in 20 ml of 95% ethanol over 0.06 g of 10% palladium on carbon, after chromatography and distillation, gave **9** as a colorless oil (0.9 g, 66%) (Table VIII).

1,4,5,5,6,6,7,7-Octadeuterio-*endo*-2-benzoylnorbornane (10). Catalytic deuteration of hexadeuterio-*endo*-5-benzoylnorbornene gave **10** as a colorless oil (Table VIII).

Irradiation of 2-Propyl-1-tetralone (4). A solution of 0.8 g of ketone in 80 ml of benzene was bubbled with argon and irradiated through Pyrex for 4.5 hr. Chromatography on silica gel (hexane–benzene) gave recovered starting material (10%), 1-tetralone (75%), and an alcoholic product (15%): ir spectrum (film) 3550 cm^{-1}; nmr (CCl_4) δ 1.10 (d, 2 H, J = 7 Hz), 1.6–3.0 (m, 9 H), 7.2 (m, 4 H).

Irradiation of α-(1-Adamantyl)acetophenone (5). A solution of 0.60 g of ketone in 50 ml of 1-propanol–benzene was bubbled with argon and irradiated for 45 min through Pyrex. Gc on a 5 ft × 1/8 in. column of 5% SF 96 on Chromosorb G at 210° showed >90% conversion to two products of shorter retention time than starting ketone. Chromatography on silica gel (2% ethyl acetate–hexane) resulted in elution of the product with longer gc retention time (**6**, 0.19 g, mp 82–83°) followed by the product with shorter gc retention time (**7**, 0.14 g, mp 106–107°). The ir spectra of **6** and **7** were similar and both showed only a free OH stretch at 3610 cm^{-1} (0.03 M, CCl_4). Nmr spectra (CCl_4): for **6**, δ 1.4–2.2 (m, 15 H), 2.1 (d, H_a), 2.2 (d, H_b), 2.9 (m, H_e), 2.3 (m, OH), 7.2 (m, 5 H); for **7**, 1.4–2.2 (m, 15 H), 1.95 (d, H_a), 2.65 (d, H_b), 2.5 (m, H_e), 2.8 (m, OH), 7.2 (m, 5 H).

Irradiation of *exo,exo*-5,6-Dideuterio-*endo*-2-benzoylnorbornane (8). A solution of 0.2 g of ketone **8** in 25 ml of benzene was bubbled with argon and irradiated through Pyrex for 200 min. Analysis by gc showed ~50% conversion of starting ketone. Chromatography on silica gel (hexane–benzene) gave the photoelimination product as a colorless oil: nmr (CCl_4) δ 1.6–2.7 (m, 6 H), 2.90 (t, 2 H), 5.62 (s, 1 H), 7.4 (m, 3 H), 7.8 (m, 2 H).

General Procedures for preparative irradiations, quantum yields, and rate constants are described in the accompanying manuscript. Viscosities of ketone–piperylene–cyclooctane solutions were measured using an Ostwald viscosimeter. A merry-go-round apparatus immersed in a thermostated water bath (±0.5°) was used for the variable temperature studies.

Acknowledgments. The authors wish to thank Professors W. H. Saunders, Jr., M. S. Silver, M. A. Winnik, and J. Michl for stimulating discussions and C. Steel for informing us of his results prior to publication.

(51) S. McLean, C. J. Webster, and R. J. D. Rutherford, *Can. J. Chem.*, 47, 1556 (1969).

Photoisomerization of Cyclohexadienyl Cations. Stereochemistry of Bicyclohexenyl Cation Formation[1]

James W. Pavlik*[2] and Robert J. Pasteris[3]

Contribution from the Department of Chemistry, University of Wisconsin—River Falls, River Falls, Wisconsin 54022. *Received January 30, 1974*

Abstract: The photoisomerization of cyclohexadienyl cations **1–5** has been studied under conditions which allowed direct observation of bicyclohexenyl cations **6–9** by nmr spectroscopy. Although most reported isomerizations of this type have been reported to yield the bicyclohexenyl cation with the larger group in the endo position, photolysis of cations **1** and **3** yielded cations **6** or **8** as a mixture of stereoisomers in which the *endo*-methyl cation predominates. Although increasing the size of R_2 had no effect on the stereochemistry of the ring closure in **2**, steric interaction in **4** was sufficient to favor formation of the *endo*-CCl_3 cation. This suggests that the stereochemistry of these ring closures is determined not only by interaction between R_1 and R_2 but also by repulsion between the C-1 OH group and R_1. In view of this it was surprising that photolysis of **5** resulted in the *endo*-methyl cation as the major product. Molecular models suggest that hydrogen bonding between the C-1 OH and R_1 may affect the stereochemistry of the ring closure in **5**.

Photolysis of cyclohexadienyl cations **1** and **5** has previously been shown[4] to result in the formation of the same product, 5-hydroxy-2-methylbenzaldehyde, **10**. Although at that time the existence of bicyclohexenyl cation **6** was only postulated as a common intermediate in the conversion of **1** and **5** to **10**, similar work

(1) Presented in part at the 167th National Meeting of the American Chemical Society, Los Angeles, Calif., Apr 1974.

(2) Department of Chemistry, Worcester Polytechnic Institute, Worcester, Mass. 01609.

(3) ACS–PRF Undergraduate Research Participant, 1972–1973.

(4) N. Filipescu and J. W. Pavlik, *J. Amer. Chem. Soc.*, **92**, 6062 (1970).