(47) G. S. Pawley, W. N. Lipscomb, and H. H. Freedman, *J. Am. Chem. Soc.*, **86**, 4725 (1964).
(48) D. A. Forsyth and G. A. Olah, *J. Am. Chem. Soc.*, **98**, 4086 (1976).
(49) (a) R. R. Ernst, *Adv. Magn. Reson.*, **2**, 74 (1966); (b) A. Abragam, "Principles of Magnetic Resonance", Oxford University Press, London, 1961, p 114; (c) R. R. Ernst and W. A. Anderson, *Rev. Sci. Instrum.*, **37**, 93 (1966).
(50) G. A. Olah, P. W. Westerman, and J. Nishimura, *J. Am. Chem. Soc.*, **96**, 3548 (1974).

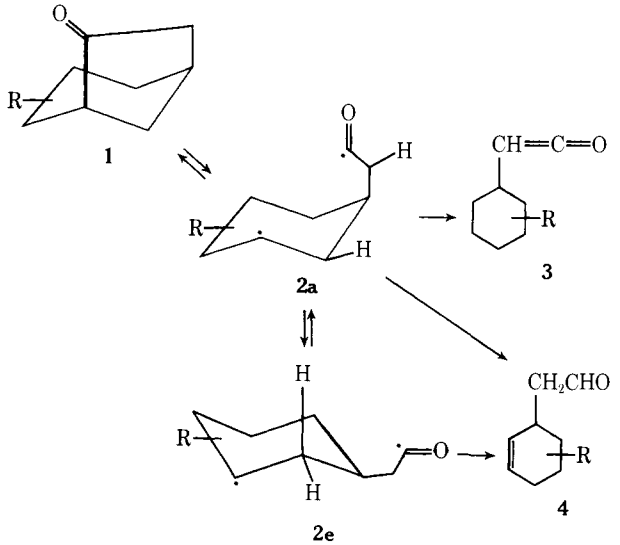
Photochemistry of Bicyclo[3.2.1]octan-6-ones. Stereoselectivity of Hydrogen Transfer in Disproportionation of Biradical Intermediates[1,2]

William C. Agosta* and Steven Wolff*

Contribution from the Laboratories of The Rockefeller University, New York, New York 10021. *Received December 13, 1976*

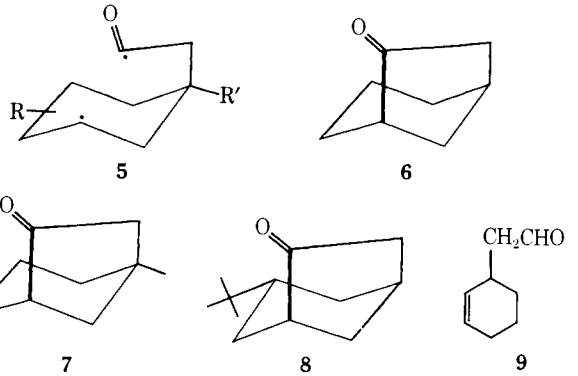
Abstract: The stereoselectivity of disproportionation of biradicals derived from three bicyclo[3.2.1]octan-6-ones, **6–8**, has been investigated through preparation and photolysis of the stereospecifically deuterated species **10**, **11**, and **24–27**. The results collected in Table I indicate that in disproportionation of **2e** (R = H) to aldehyde **4** (R = H) axial hydrogen is transferred ~95% of the time, and it is suggested that this is primarily a stereoelectronic effect favoring scission of the carbon–hydrogen bond lying closest to the plane of the adjacent p orbital bearing free spin. The results in Tables II, III, and IV show an important element of steric control in disproportionation of **2a** to form ketene **3** and aldehyde **4**. In **46** with a geminal methyl substituent at C(1) this occurs ~94% from **48** (transfer of exo hydrogen) and ~6% from **49** (transfer of endo hydrogen). In biradical **47** with only hydrogen at C(1) the side chain has more freedom of rotation, and hydrogen is transferred from all three possible rotational conformers, ~52% from **48**, ~19% from **49**, and 29% from **50** (transfer of ring hydrogen).

In earlier investigations of substituted bicyclo[3.2.1]-octan-6-ones (**1**) we showed that **2a**, the biradical intermediate formed on photochemical α-cleavage of these ketones, undergoes conformational relaxation before disproportionation.[3] Thus in ketones for which the inverted conformer **2e** is more stable, all disproportionation occurs from **2e** and leads only to aldehyde **4**. For systems in which the initially formed



conformer **2a** is the more stable, the situation is somewhat more complicated, since disproportionation to either ketene **3** or aldehyde **4** is geometrically possible. In practice, however, both **3** and **4** are formed only when the geminal substituent (R′ in **5**) is hydrogen. The ketones examined which disproportionate solely from **2a** and in which this substituent was an alkyl group (methyl or *tert*-butyl) yielded only ketene **3** on irradiation. This result was ascribed to a steric effect of the geminal substituent, acting to disfavor certain conformations of the acyl radical side chain. The behavior of ketones for which significant populations of both **2a** and **2e** could be expected on conformational grounds also was qualitatively consistent with these principles. In addition to these conformational and steric factors, we suggested that stereoelectronic effects might play a role in disproportionation of **2a** and **2e**.

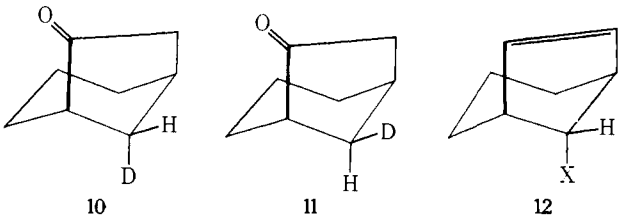
With this fund of information at hand we undertook deuterium labeling experiments designed to explore the stereoselectivity for transfer of hydrogen in disproportionation of **2a** and **2e**. We were interested not only in a more complete description of the rearrangements of specific bicyclo[3.2.1]-octan-6-ones but also more broadly in the possibility of defining the roles of both steric and stereoelectronic effects in such hydrogen transfer processes. Previous studies[4–6] in other systems have shown that intramolecular disproportionation of acyl alkyl biradicals is sometimes quite stereoselective, but in general the reasons for this stereoselectivity are poorly understood and the question of thermodynamic or kinetic control is unanswered. In this report we describe the preparation and photolysis of appropriate deuterated isomers of **6–8**, three bi-



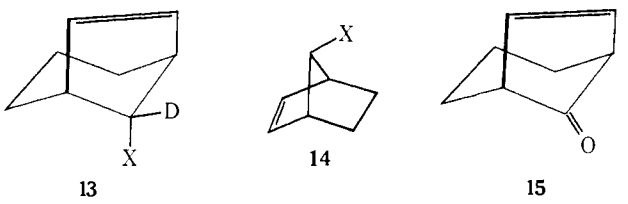
cyclooctanones from our earlier work[3] which were chosen for the present study. The results demonstrate that highly stereoselective behavior can result from operation of both steric and stereoelectronic factors in these intermediates. Furthermore, they provide qualitative evidence that the rates of ring inversion and side chain rotation can be faster or slower than

disproportionation, depending on the specific substitution pattern of the ketone. Biradicals continue to attract intense interest,[7] and we believe that the present observations contribute an understanding of their behavior that should be generally interesting and useful.

Preparative Experiments. The parent bicyclooctanone **6** exemplifies those ketones for which **2e** is the stable conformer of the biradical intermediate. Photochemical isomerization of **6** yields 2-cyclohexene-1-acetaldehyde (**9**, 93%) with <0.5% of any other volatile product, and there is good evidence that this occurs through disproportionation in conformer **2e** (R = H).[3] In this conformer both an axial and an equatorial hydrogen atom are accessible for transfer to the side chain, and in order to study the stereochemistry of this disproportionation we have prepared **10** and **11**, two monodeuterated isotopic isomers of **6**. Starting material for these syntheses was the known[8] bicyclooctenol **12a.** The derived tosylate **12b** undergoes solvolysis with retention of configuration due to participation of the double bond,[8] and we took advantage of this fact for stereospecific introduction of deuterium. The reaction conditions employed were those developed for trapping of carbonium ions with sodium borohydride[9] and previously used in conversion of *anti*-7-norbornenyl tosylate (**14b**) to the deuterated olefin **14c.**[10] Thus **12b** reacted with excess sodium borodeuteride in 65% diglyme–35% D_2O containing NaOD at 50 °C to furnish labeled olefin **12c.** In order to introduce deuterium into the epimeric position **12a** was oxidized to ketone **15**[8] using chromium trioxide–pyridine complex[11] and then reduced back with lithium aluminum deuteride at −78 °C to form **13a.** This reduction was stereospecific, and only deuterated alcohol **13a** (or **12a** using lithium aluminum hydride) was obtained.[12] The

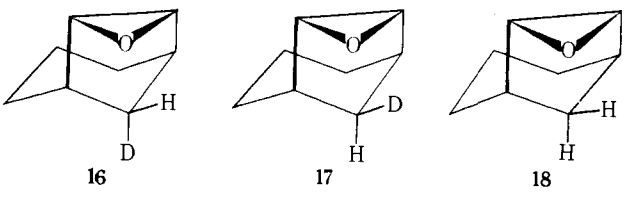


10 11 12



13 14 15

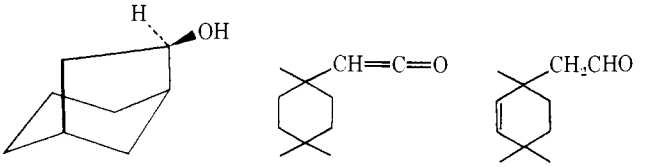
a, X = OH c, X = D
b, X = OTs d, X = H



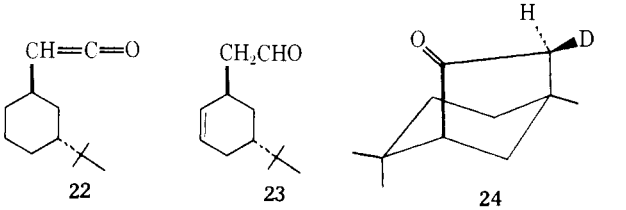
16 17 18

derived tosylate **13b** was now reduced as described above, but with sodium borohydride, to furnish labeled olefin **13d.** Similar treatment of **12b** with sodium borohydride gave the unlabeled bicyclooctene **12d.** The melting point, as well as IR[13] and NMR[14] spectra, of this material were compatible with those previously reported for **12d** prepared by other routes. Mass spectrometric determination of the deuterium content of the labeled isomers indicated that **12c** was 92% d_1, 8% d_0, and that **13d** was 98% d_1, 2% d_0. The stereospecificity of deuteration was verified through NMR measurements on the related epoxides **16** and **17.** These compounds, along with **18**, were available upon oxidation of the olefins **12c, 13d,** and **12d,** respectively, with *m*-chloroperbenzoic acid. The exo orientation shown for the epoxides is that expected on steric grounds, since endo approach to the olefin is impaired by the endo axial hydrogen at C(3). This stereochemistry was confirmed by hydride reduction of **18** to yield known *exo*-bicyclo[3.2.1]octan-6-ol (**19**).[14] In **18** the signal for the axial proton at C(8), anti to the epoxide ring, is shifted upfield to δ 0.92 ppm and may be integrated without difficulty.[15] Integration of the spectra of **16** and **17** therefore permitted determination of the stereospecificity of deuteration at C(8); in each case there was no evidence of scrambling. Within experimental error then the described reduction of tosylates **12b** and **13b** and the resulting labeling of **12c** and **13d** are completely stereospecific.[16] Hydroboration and peroxide oxidation[17] of these olefins, followed by treatment of the intermediate alcohols with chromium trioxide,[11] then gave the desired deuterated ketones **10** and **11.**

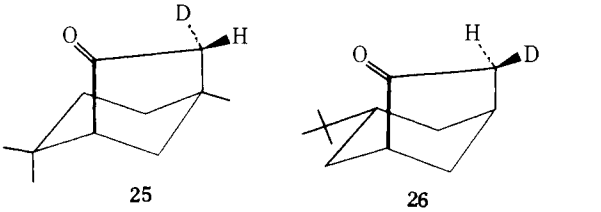
The other two bicyclooctanones chosen for this study, **7** and **8**, exemplify disproportionation of the biradical in initial conformation **2a.** At 30 °C **7** is photochemically isomerized to ketene **20** (87%),[18] while the *tert*-butyl compound **8** yields **22** (51%) and **23** (20%).[3] We wished to examine both **7** and **8**, since they differ in the nature of the geminal substituent (R′ in **5**). As we noted above, substitution in this position appears to affect the product distribution through influence over the conformation of the acyl side chain.[19] In each case disproportionation of **2a** presents the opportunity for stereoselectivity in transfer of hydrogen from side chain to ring, and we were curious whether the size of the geminal substituent would influence the stereochemistry of this disproportionation leading to ketenes **20** and **22.** The deuterated species required to examine this question are **24–27.** These were prepared from the



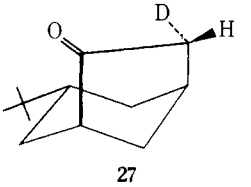
19 20 21



22 23 24



25 26

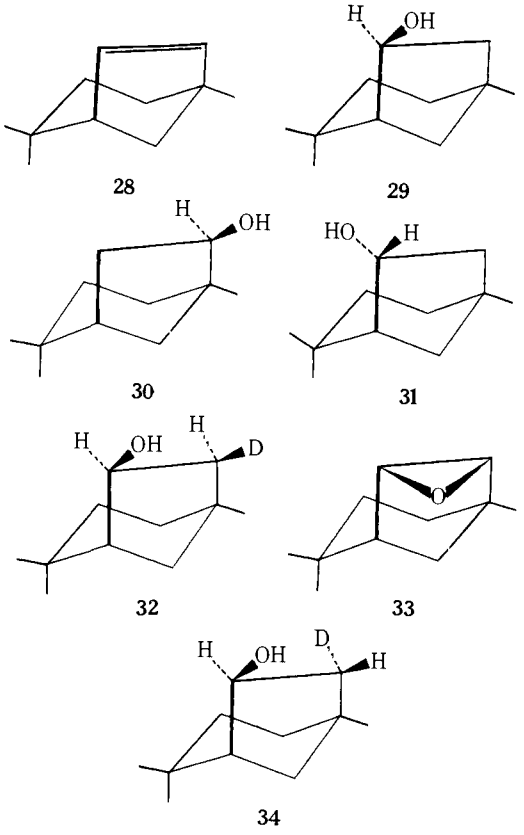


27

corresponding unlabeled compounds **7** and **8** through intermediates described below.

Ketone **7** was converted to the related olefin **28** on reaction of the derived tosylhydrazone with methyllithium.[20] Hydroboration of **28** with the highly selective bis-3-methyl-2-butylborane (disiamylborane),[17,21] followed by peroxide

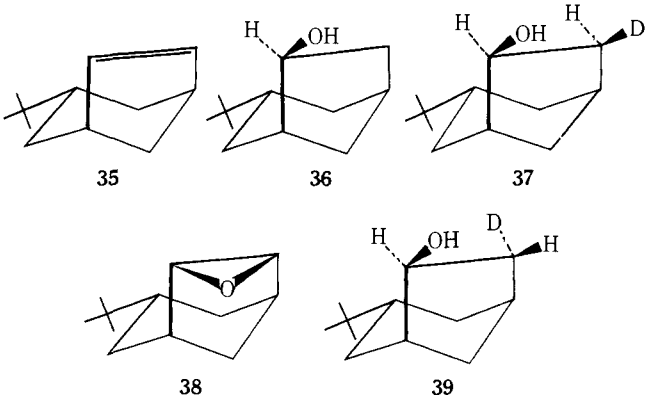
oxidation, furnished a 6:1 mixture of two alcohols which were separated by preparative vapor phase chromatography (VPC). Exo attack on **28** should be greatly favored sterically, and the end of the double bond away from the bridgehead methyl group should be somewhat more accessible to the bulky alkylborane. The two alcohols formed then are expected to be **29** (major) and **30** (minor). This assignment is supported by



the oxidation of **29** to give back **7**, and by the observation that neither of these alcohols is the previously known[22] endo isomer **31.** Hydroboration of **28** was now repeated using deuterated disiamylborane, and the major alcohol **32** was oxidized to **24** with ruthenium tetroxide.[23]

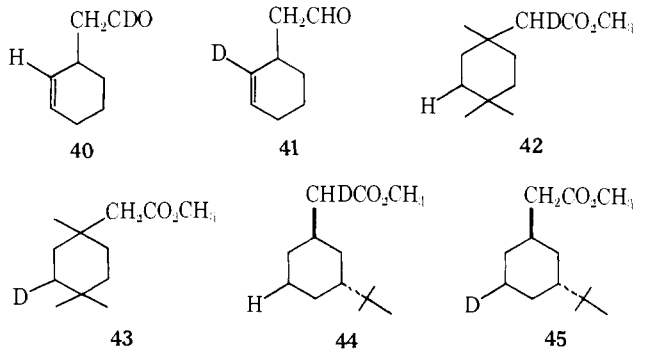
For preparation of **25**, olefin **28** was first converted to epoxide **33** using *m*-chloroperbenzoic acid. The configuration of **33** follows by analogy from the oxidation of the parent olefin **12d** to **18** described above and is confirmed by hydride reduction of **33** to alcohol **29.** This reduction is slow, since it requires endo attack on the epoxide. After 2 days with excess lithium aluminum hydride in refluxing dioxane (101 °C), 40% of the starting material remained unreacted. The reaction is quite regioselective, however, and **29** is virtually the sole product. In models it appears that attack at the other endo position (which would lead to **30**) is effectively precluded by the equatorial methyl group at C(4). Use of lithium aluminum deuteride in this reduction gave the deuterated alcohol **34**, and oxidation with ruthenium tetroxide now gave **25.**

A parallel set of transformations from the *tert*-butyl ketone **8** to **26** and **27** is simplified by the symmetry of olefin **35.** Hydroboration and deuterioboration of **35** furnished alcohols **36** and **37**, respectively. Similarly peracid oxidation of **35** leads to the epoxide **38**, which is opened by hydride or deuteride reduction to yield **36** or **39,** respectively. The endo alcohol epimeric with **36** was formed stereospecifically on reduction of **8** with lithium aluminum hydride at −78 °C. Oxidation of the deuterated alcohols **37** and **39** then gave **26** and **27.** The deuterium content of **24–27**, was measured mass spectrometrically with the following results: **24**, 94% d_1, 6% d_0; **25**, 98% d_1, 1% d_0, 1% d_2; **26**, 92% d_1, 8% d_0; **27**, 92% d_1, 1% d_0, 7% d_2.



NMR spectra[24] (220 MHz) of these ketones confirmed the stereochemistry of labeling.

Photochemical Results. The six deuterated ketones were irradiated in benzene containing ~3.5% methanol (v/v, ~0.87 M) at 30 ± 0.5 °C. From ketones **10** and **11** the aldehyde produced is a mixture of the isotopically isomeric species **40** and **41,** while the products formed on trapping the initial ketenes from trimethyl ketones **24** and **25** are methyl esters **42** and **43** and those from *tert*-butyl ketones **26** and **27** are esters **44** and **45.** In each case the desired product was isolated and



purified by preparative vapor phase chromatography. All these procedures were carried out as previously described in detail.[3] The deuterated products were analyzed by integration of NMR spectra, and the results, corrected for total deuterium content, are presented in Tables I–III. Also presented are the corresponding ratios of the rates of transfer of the two hydrogen atoms involved in each case. In Table I k_{ax} and k_{eq} refer to the rates of transfer of axial and equatorial hydrogen from the inverted conformer **2e**; in Tables II and III k_{en} and k_{ex} refer respectively to the rate of transfer of the hydrogen which was originally endo or exo on the bicyclo[3.2.1]octane skeleton. For each pair of ketones the rate ratios reflect both the inherent stereoselectivity and the deuterium kinetic isotope effect in disproportionation. The magnitude of each of these factors can be calculated from the ratios using the formalism of Curtin,[25] with the assumptions that only these two factors are operative, and that within each pair of labeled ketones the isotope effects for the two epimerically deuterated species are identical. The results of these simple calculations are also given in the tables. The isotope effects are sensitive functions of the small amount of the minor isotopic isomer obtained in each case and therefore are not determined accurately.

Discussion

We note first that in all three cases the calculated isotope effects are small. Our results are in general agreement with earlier quantitative data on radical disproportionations in the gas phase, which lead to a value of ~1.5.[26] Most previous studies of biradical disproportionations in solution have yielded only the qualitative conclusion that the deuterium isotope effect is small,[4,6,27] but in a recent investigation the isotope effect for

Table I. Stereoselectivity in Disproportionation of Ketone **6**

Deuterated isomer of **6**	% aldehyde formed **40**	**41**	k_{ax}/k_{eq}	k_H/k_D	Stereoselectivity for axial H
10	2	90	45	~2	~95%
11	88	10	8.8		

Table II. Stereoselectivity in Disproportionation of Ketone **7** to Ketene **20**

Deuterated isomer of **7**	% ester formed **42**	**43**	k_{ex}/k_{en}	k_H/k_D	Stereoselectivity for exo H
24	9	85	9.4	~1.6	~94%
25	93	4	23		

Table III. Stereoselectivity in Disproportionation of Ketone **8** to Ketene **22**

Deuterated isomer of **8**	% ester formed **44**	**45**	k_{ex}/k_{en}	k_H/k_D	Stereoselectivity for exo H
26	40	52	1.3	~2	~73%
27	14	78	5.6		

hydrogen transfer in an acyl α-alkoxyalkyl biradical was found to be 1.5–2.1.[5] For the small number of cases available then, structure and reaction conditions have shown little influence on the magnitude of the isotope effects observed in hydrogen disproportionations.

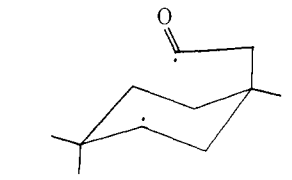
The results in Table I indicate that in disproportionation of **2e** (R = H) axial hydrogen is transferred ~95% of the time. In part this high selectivity may be steric in origin; although the acyl radical can approach the axial and equatorial hydrogens of **2e** equally closely, there may well be small energy differences in the favorable geometry for each transfer.[28] We consider, however, that the most important factor leading to selective transfer of axial hydrogen is stereoelectronic control arising from interaction of the carbon–hydrogen bond being broken with the adjacent p orbital of the unpaired electron. Such stereoelectronic control in β-scission of radicals and in the reverse addition of radicals to olefins has been discussed for several years, and there is now considerable evidence that, in homolytic cleavage of a carbon–carbon bond adjacent to a radical center (β-alkyl scission), the bond preferentially broken is the one lying closest to the plane of the p orbital bearing free spin.[29] Similarly, in the reverse reaction, there are independently derived results favoring the same geometric arrangement in certain intramolecular additions of carbon radicals to double bonds.[29] Such a requirement applied now to cleavage of a carbon-hydrogen bond adjacent to a radical center (β-hydrogen scission) would lead to preferential transfer of axial hydrogen in **2e.** We are unaware of prior experimental evidence implicating stereoelectronic control in such hydrogen transfer reactions.

The influence of this principle is presumably felt elsewhere. Disproportionation of **2a** leads preferentially to ketene through hydrogen transfer from side chain to ring. We suggested earlier that a stereoelectronic effect might operate here,[3] and our present interpretation of the results in Table I supports this suggestion. Disproportionation of **2a** to form aldehyde **4** necessarily involves transfer of equatorial hydrogen from ring to side chain, and this transfer cannot conform to the stereoelectronic requirement discussed above. On the other hand, in the disproportionations to be discussed below in which hydrogen adjacent to the acyl radical center is transferred to the ring, stereoselectivity is expected not to be influenced by this stereoelectronic consideration; it seems likely that in **2a** rotation about the acyl-C(α) bond (that is, the C(6)–C(7) bond as numbered in the starting ketone) is sufficiently free that transfer to the ring of either C(7) hydrogen may occur with an energetically favorable orientation of the adjacent orbital on C(6) bearing the unpaired electron.

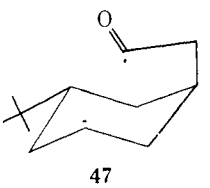
Shortly after our initial communication[2] on this matter there appeared an interesting CIDNP study of the disproportionation of cyclohexyl radical itself.[30] Here it was found that formation of cyclohexene occurs with selective transfer of equatorial rather than axial hydrogen. As the authors pointed out,[30] this is a surprising result that may reflect greater steric hindrance to intermolecular transfer of axial hydrogen in this system. This observation serves to emphasize that stereoelectronic factors are not the sole determinants of the stereochemistry of radical disproportionation.

Indeed the results in Tables II and III provide strong evidence of an important role for steric factors in these disproportionations. They indicate an appreciably higher degree of selectivity in hydrogen transfer to form ketene in **7** than in **8.** In addition it should be kept in mind that hydrogen transfer from ring conformer **46** gives only ketene, while **47** yields both ketene **22** (51%) and aldehyde **23** (20%). These earlier observations[3] may be combined with our present findings to yield the overall results recorded in Table IV. The difference in selectivity of hydrogen transfer in the two intermediates is quite striking.

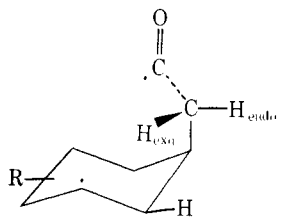
This significant difference in the specific fates of biradicals from **7** and **8** can be reasonably explained only by the difference in the geminal substituent at C(1) (R′ in **5**). The other ring substituents are too distant to have effects of such magnitude, whereas the size of the geminal substituent has a direct bearing on the rotational freedom of the axial two-carbon side chain and thus can influence the population of rotational conformers **48–50.** The straightforward explanation for our



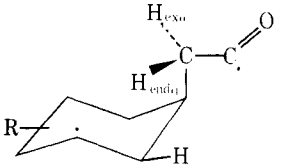
46



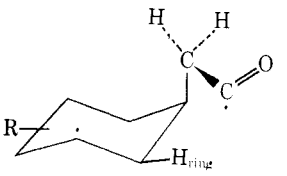
47



48



49



50

results is that the C(1) methyl substituent in **46** sufficiently inhibits rotation of the side chain that disproportionation occurs selectively from **48** under kinetic control. The side chain of **47,** however, is considerably more free to rotate before disproportionation, so that **48–50** all become populated, and this

Table IV. Overall Selectivity in Disproportionation of Ketones 7 and 8

Ketone	Observed hydrogen transfer, % H_{exo} to ring via **48**	H_{endo} to ring via **49**	H_{ring} to side chain via **50**
7	94	6	0
8	52	19	29

leads to the nonselective hydrogen transfer observed. It is unnecessary to assume complete rotational equilibrium in **47**, since the results require only a greater degree of rotational exploration in **47** than in **46** before disproportionation. While this simple explanation is the best available to us, it would be more attractive if examination of models revealed that **48** is the rotational isomer of **46** and **47** most readily reached after α-cleavage of the ketones. The reasons for the observed preference, however, are not obvious.

It would also be worthwhile to discuss these various competitive processes in a quantitative fashion, but presently available information permits only the following simple observations. The rotational barrier in **47** should be 6–7 kcal/mol, similar to or a little higher than that in butane,[31] and the additional geminal methyl group should increase this by ~1.5 kcal/mol[32] to 7.5–8.5 kcal/mol in **46.** We previously noted that the barrier to inversion of **2a** to **2e** is ~5 kcal/mol,[33] and that an increase of this to 6–7 kcal/mol was also accompanied by a change in the fate of **2a.**[3] Substituent effects on both ring inversion and side chain rotation then suggest that such motions cease to be rapid relative to disproportionation when their activation energies are as high as ~7 kcal/mol. This leads to an estimate of some 6–8 kcal/mol for the activation energies of the disproportionations available to **2a.** Such an estimate is reasonable, since activation energies for bimolecular disproportionation of simple alkyl radicals in solution lie in this range while those for bimolecular abstraction of secondary hydrogen by an alkyl radical are around 8–10 kcal/mol.[34]

In closing we note that our studies of the photochemical isomerization of bicyclo[3.2.1]octan-6-ones provide a more detailed analysis of factors influencing intramolecular disproportionation than has been available in the past. Efforts to predict the course of similar reactions envisaged as key transformations in projected synthetic sequences have not always been successful,[35] and photochemical processes in general still retain a reputation for unpredictability. Our results attest to the control exercised over disproportionation by energetically small effects, but they also suggest that examination of these effects should improve our predictive ability.[36]

Experimental Section

Materials and Equipment. These have been previously described.[3] The VPC columns used in the present work were A, 25 ft, 25% QF-1; B, 10 ft, 25% QF-1; C, 25 ft, 25% NPGS; D, 16 ft, 25% FFAP; E, 5 ft, 25% QF-1; F, 15 ft, 25% DEGS. Columns A, B, C, and E were prepared using 40/60 Chromosorb W and D and F with 60/80 Chromosorb P, all 0.25 in. aluminum tubing.

All melting points were obtained for samples in sealed capillaries and are corrected. In general, reaction products were kept in solution to avoid handling losses and yields were not determined.

Bicyclo[3.2.1]oct-6-ene (12d). *endo*-Bicyclo[3.2.1]oct-6-en-8-yl tosylate[8] was reduced by $NaBH_4$ in 65% aqueous diglyme according to the procedure of Bell and Brown.[9] The reaction was carried out in a Carius tube for 17 h. The product was obtained by pentane extraction of the reaction after dilution with water and passage through an alumina column to remove a small amount of unreacted tosylate. VPC analysis of the eluent on column A (120 °C) indicated only one product which was collected and identified as **12d,** mp 111.5–112.5 °C (lit. mp 106–108[13] and 111–112 °C[14]).

***exo*-3-Oxatricyclo[3.3.1.0^{2,4}]nonane (18).** The epoxide was formed by treatment of the olefin with an excess of a solution of *m*-chloroperbenzoic acid in CH_2Cl_2 for 0.5 h at 0 °C and 1 h at 25 °C. The reaction mixture was washed with saturated $NaHCO_3$, 10% Na_2SO_3, and saturated $NaHCO_3$ and dried. The solvent was removed by distillation through a Vigreux column and the residue was passed through a column containing alumina (activity V) with pentane. VPC analysis on column A (160 °C) indicated one major peak which was collected and identified as **18:** mp 185–186 °C; IR 3005 (w), 2925 (s), 2845 (m), 1452 (w), 1360 (m), 1230 (w), 1205 (w), 1082 (w), 980 (w), 940 (m), 837 cm^{-1} (s); NMR (220 MHz) δ 3.15 (s, 2 H), 2.23 (br s, 2 H), 1.78–1.33 (m, 7 H), 0.92 (d, J = 11 Hz, 1 H); mass spectrum *m/e* 124.0891 (M^+, calcd for $C_8H_{12}O$, 124.0888).

Reduction of this epoxide with $LiAlH_4$ in Et_2O (4 h at reflux, 15 h at 25 °C) gave, after VPC purification on column B (135 °C), **19,** mp 144.5–146 °C (lit.[14] mp 143–144.5 °C, lit.[14] mp 192–194 °C for endo isomer).

Bicyclo[3.2.1]oct-6-en-8-one (15). The alcohol **12a**[8] (124.4 mg, 1 mmol) was oxidized with chromium trioxide–pyridine complex according to the method of Ratcliff and Rodehorst.[11] After removal of solvent 126.7 mg of crude crystalline ketone was obtained. VPC analysis on column B (135 °C) indicated only one component: mp 110–111 °C (lit.[8] mp 108–110, 110.5–111 °C); IR 3045 (w), 2930 (s), 2848 (m), 1768 (s), 1440 (m), 1255 (m), 1162 (w), 1070 (m), 705 cm^{-1} (m); NMR δ 6.20 (t, J = 2 Hz, 2 H), 2.67 (br s, 2 H) 2.10–1.17 (m, 6 H).

Reduction of 15. The enone was reduced with $LiAlH_4$ in dry ether −78 °C for 0.75 h, then allowed to warm to 25 °C. After destruction of excess reagent with saturated Na_2SO_4 and filtration, VPC analysis of the product (column B, 130 °C) indicated only one component. This was collected and identified as **12a.**

***endo*-8-*d*-Bicyclo[3.2.1]octan-6-one (10).** Tosylate **12b** was reacted with $NaBD_4$ in 65% diglyme–35% D_2O containing NaOH as described above. Mass spectrometric analysis of the olefin obtained indicated 92% d_1, 8% d_0. The 220-MHz NMR spectrum of the derived epoxide **16** showed the following signals: δ 3.16 (s, 2 H), 2.23 (br s, $W_{1/2}$ = 11 Hz, 2 H), 1.78–1.33 (m, 7 H). A small signal at δ 0.92 (d, J = 11 Hz) was visible and could be accounted for by incomplete labeling.

The labeled bicyclooctene **12d** was hydroborated according to the procedure of Brown[17] and the alcohol was oxidized with chromium trioxide–pyridine complex.[11] The ketone was purified by preparative VPC on column D (190 °C) prior to photolysis.

***exo*-8-*d*-Bicyclo[3.2.1]octan-6-one (11).** Alcohol **12a** (1.001 g, 8.06 mmol) was oxidized to the ketone according to the procedure of Ratcliff and Rodehorst.[11] VPC analysis of the crude product indicated 100% conversion. Reduction with $LiAlD_4$ (359 mg) in ether (100 mL) at −78 °C of the unpurified ketone afforded crystalline alcohol **13a** (0.905 g, 90% overall).

Conversion to tosylate **13b** by reaction with a twofold excess of *p*-TsCl in pyridine at 4 °C for 4 days and subsequent reduction of the crude tosylate with $NaBH_4$ in 65% aqueous diglyme as described above gave bicyclooctene **13d.** Mass spectrometric determination of the isotopic content indicated 98% d_1, 2% d_0. The epoxide **17** had the following NMR spectrum (220 MHz): δ 3.15 (s, 2 H), 2.23 (br s, $W_{1/2}$ = 6 Hz, 2 H), 1.78–1.33 (m, 6 H), 0.91 (br s, 1 H).

The olefin was converted to the ketone by hydroboration and oxidation of the alcohol as previously described. The ketone was purified by VPC on column D.

Photolysis of 10. A benzene solution of the ketone containing 3.5% methanol was irradiated through Pyrex as previously described.[3] The photolysis was stopped when VPC analysis indicated >90% conversion. The aldehyde was obtained by preparative VPC on column B (137 °C). Integration of the aldehyde and olefinic protons gave values of 0.987 H and 1.093 H, respectively.

Photolysis of 11. Ketone **11** was photolyzed in the same fashion. Integration of the aldehyde proton gave 0.12 H and the olefinic protons, 1.90 H.

1,4,4-Trimethylbicyclo[3.2.1]oct-6-ene (28). A mixture of **7** (963 mg, 5.8 mmol) and *p*-toluenesulfonylhydrazide (1.160 g, 6.24 mmol) in ethanol (15 mL) containing 1 drop of acetic acid was heated to reflux overnight. Cooling yielded 654 mg of crystalline material and a second crop of 201 mg was obtained (44%). Recrystallization from ethanol afforded an analytical sample, mp 186–188.5 °C.

Anal. Calcd for $C_{18}H_{26}N_2O_2S$: C, 64.65; H, 7.84; N, 8.38. Found: C, 64.69; H, 7.87; N; 8.34.

Treatment of the tosylhydrazone with methyllithium following the method of Shapiro[20] gave the olefin. The dried organic extracts of the

reaction were passed through an alumina (activity I) column with pentane. VPC analysis (column A, 134 °C) of the eluent after concentration indicated one peak which was collected and identified as **28**: IR 3040 (w), 2942 (s), 2907 (s), 2850 (s), 1450 (m), 1377 (w), 1368 (w), 1358 (m), 1350 (m), 1177 (w), 1088 (m), 788 cm^{-1} (m); NMR (60 MHz) δ 5.92 (dd, J = 3, 6 Hz, 1 H), 5.48 (d, J = 6 Hz, 1 H), 2.08 (br s, 1 H), 1.63–1.08 (m, 6 H), 1.05 (s, 3 H), 0.99 (s, 3 H), 0.80 (s, 3 H); mass spectrum m/e 150.1410 (M^+, calcd for $C_{11}H_{18}$, 150.1408).

Hydroboration of 28. Hydroboration of the olefin with disiamylborane according to the procedure of Brown[21] afforded two products as indicated by VPC analysis on column C (175 °C). The major, first eluted component was identified as *exo*-1,4,4-trimethylbicyclo-[3.2.1]octan-6-ol (29): mp 26–29 °C; IR 3605 (w), 3550–3100 (br), 2940 (s), 2907 (5), 2852 (m), 1452 (m), 1386 (m), 1368 (m), 1088 (m), 1040 (m), 985 (w), 900 cm^{-1} (w); NMR (60 MHz) δ 4.12 (dd, J, 3, 7 Hz, 1 H), 2.00 (s, 1 H) 1.93–1.06 (m, 9 H), 1.05 (s, 3 H), 0.95 (s, 3 H), 0.90 (s, 3 H); mass spectrum m/e 168.1514 (M^+, calcd for $C_{11}H_{20}O$, 168.1513). The second component was identified as *exo*-1,4,4-trimethylbicyclo[3.2.1]octan-7-ol (**30**): IR 3610 (w), 2955 (s), 2915 (s), 2860 (m), 1460 (m), 1377 (w), 1360 (w), 1045 cm^{-1} (m); NMR (60 MHz) δ 3.56 (dd, J = 3, 7 Hz, 1 H), 2.42–1.05 (m, 10 H), 0.93 (s, 6 H), 0.82 (s, 3 H); mass spectrum m/e 168.1500.

Oxidation of 29. A solution of RuO_4 was prepared by vigorously stirring a mixture of RuO_2 (63.7 mg), suspended in CCl_4 (16 mL), and 0.25 M $NaIO_4$ (8 mL). The yellow CCl_4 layer was separated and dried over Na_2SO_4. After decanting, the alcohol (29.4 mg) was added to the solution of RuO_4, magnetically stirred at room temperature. A black precipitate formed immediately and after 10 min, excess oxidant was destroyed with a few drops of 2-propanol. After filtration and concentration, the residue was analyzed by VPC (column B, 155 °C) indicating only one component. This was collected and identified as **7** on the basis of identical IR and NMR spectra and VPC retention time.

***exo*-3-Oxa-1,6,6-trimethyltricyclo[3.3.1.$0^{2,4}$]nonane (33).** The trimethyl substituted epoxide was prepared and purified by the same procedure described for **18**. VPC analysis (column A, 178 °C) of the crude product indicated only one peak, which was collected and identified as **33**: IR 3012 (w), 2948 (s), 2910 (s), 2855 (m), 1455 (m), 1379 (m), 1368 (m), 998 (m), 862 (w), 852 (m), 832 cm^{-1} (m); NMR (60 MHz) δ 3.24 (dd, J = 0.5, 3 Hz, 1 H), 2.74 (d, J = 3 Hz, 1 H), 1.83 (br s, 1 H), 1.70–0.77 (m, 6 H), 1.03 (s, 3 H), 0.98 (s, 3 H), 0.95 (s, 3 H).

Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.92. Found: C, 79.50; H, 10.86.

Reduction of 33. A mixture of the epoxide and $LiAlH_4$ in dioxane was heated at refux for 1 week. The reaction mixture was worked up as usual and the product analyzed by VPC (column B, 153 °C) indicating one component, ~98% pure. This was collected and identified as **29** on the basis of identical IR and NMR spectra.

Preparation and Photolysis of 24. Ketone **24** was prepared by deuterioboration of **28** with labeled disiamylborane, VPC purification of the derived alcohol, and oxidation with RuO_4. The 220-MHz NMR spectrum indicated that the exo proton (δ 1.74, dd) was lacking, and the endo proton (δ 1.92) had collapsed to a singlet. Mass spectrometric analysis indicated ~94% d_1, ~6% d_0.

The ketone was irradiated under standard conditions and the ester obtained was purified by VPC on column F (153 °C). Integration of the protons α to the carbonyl gave 1.905 H.

Preparation and Photolysis of 25. Reduction of epoxide **33** with $LiAlD_4$ and oxidation with ruO_4 of VPC purified alcohol gave the endo-7-*d* ketone (**25**). The 220-MHz NMR spectrum indicated the absence of the endo proton and the exo proton as a broad singlet. Mass spectrometric analysis indicated 1% d_2, 98% d_1, 1% d_0.

Ketone **25** was photolyzed as above and produced the desired ester. The integral of the protons α to the carbonyl was 1.026 H.

***exo*-3-*tert*-Butylbicyclo[3.2.1]oct-6-ene (35).** The tosylhydrazone was prepared in the usual fashion, mp 194.5–198 °C.

Anal. Calcd for $C_{19}H_{28}N_2O_2S$: C, 64.49; H, 8.10; N, 8.40. Found: C, 65.86; H, 8.18; N, 8.07.

The olefin **35** was prepared and purified as described above for **28**. A sample for spectra was obtained by preparative VPC on column A (148 °C): IR 3045 (m), 2930 (s), 2850 (s), 1648 (w), 1585 (w), 1475 (m), 1455 (m), 1390 (m), 1360 (s), 1300 (w), 1232 (m), 1222 (m), 1100 (w), 1075 (w), 970 (w), 913 (w), 825 (w), 720 (w), 688 cm^{-1} (m); NMR (60 MHz) δ 5.77 (s, 2 H), 2.58 (br s, 2 H), 2.10–0.90 (m, 7 H), 0.80 (s, 9 H); mass spectrum m/e 164.1565 (M^+, calcd for $C_{12}H_{20}$, 164.1564).

***exo*-3-*tert*-Butylbicyclo[3.2.1]octan-*exo*-6-ol (36).** The olefin was hydroborated with an excess of disiamylborane as described above. Analytical VPC on column A (190 °C) indicated formation of only one alcohol which was collected: mp 79–81 °C; IR 3605 (w), 3550–3100 (br), 2930 (s), 2855 (m), 1475 (w), 1382 (w), 1360 (s), 1052 (w), 1025 (m), 1012 cm^{-1} (s); NMR (60 MHz) δ 4.00 (m, 1 H), 2.49–0.92 (m, 12 H), 0.78 (s, 9 H); mass spectrum m/e 182.1682 (M^+, calcd for $C_{12}H_{22}O$, 182.1665).

***exo*-3-*tert*-Butylbicyclo[3.2.1]octan-*endo*-6-ol.** Reduction of ketone **8** with $LiAlH_4$ in ether at −78 °C gave only one alcohol as determined by analytical VPC on column A (190 °C). Preparative VPC afforded pure material: mp 98.5–99.5 °C; Ir 3615 (w), 2935 (s), 2855 (m), 1475 (m), 1360 (s), 1077 (m), 1047 cm^{-1} (m); NMR (60 MHz) δ 4.30 (m, 1 H), 2.34–1.00 (m, 12 H), 0.83 (s, 9 H); mass spectrum m/e 182.1659 (M^+).

***exo*-3-Oxa-*exo*-7-*tert*-butyltricyclo[3.3.1.$0^{2,4}$]nonane (38).** Oxirane **38** was prepared by reaction of **35** with excess *m*-chloroperbenzoic acid. Purification was achieved by alumina (activity V) chromatography and preparative VPC on column E (150 °C): mp 82–83 °C; IR 3010 (w), 2930 (s), 2860 (m), 1475 (m), 1456 (m), 1387 (s), 1362 (s), 1240 (m), 1226 (m), 988 (m), 924 (m), 837 cm^{-1} (s); NMR (60 MHz) δ 3.10 (s, 2 H), 2.25 (br s, 2 H), 1.90–0.90 (m, 7 H), 0.82 (s, 9 H); mass spectrum m/e 180.1523 (M^+, calcd for $C_{12}H_{20}O$, 180.1514).

Preparation and Photolysis of 26. Ketone **26** was prepared by deuterioboration with labeled disiamylborane and subsequent oxidation of the crude alcohol with RuO_4 as described for **24**. The 220-MHz NMR spectrum of **26** indicated that the doublet of doublets at δ 2.11 was absent and the signal for the endo proton at δ 1.94 had collapsed to a broad singlet. Mass spectrometric analysis indicated 92% d_1, 8% d_0.

After photolysis of the ketone and collection of the ester by VPC on column E, the integral of the multiplet between δ 2.38–2.22 (which includes the two protons α to the carbonyl and the equatorial tertiary proton) was 2.581.

Preparation and Photolysis of 27. Epoxide **38** was reduced with $LiAlD_4$ in refluxing dioxane for 1 week. The alcohol was purified by VPC on column A (190 °C) after analysis indicated ~3% of the endo isomer. Oxidation with RuO_4 afforded the ketone, whose NMR spectrum (220 MHz) indicated the absence of the endo proton at 1.94; the exo proton appeared as a broad singlet at 2.10. Mass spectrometric analysis showed an isotopic contact of 92% d_1, 1% d_0, 7% d_2.

Ketone **27** was photolyzed and the product was obtained as above. Integration of the signal between δ 2.58–2.22 gave 2.151 H.

Acknowledgments. We thank Mr. William Rosenstein for technical assistance; Mr. S. T. Bella for microanalyses; The Rockefeller University Mass Spectrometry Laboratory, supported by NIH Grant RR-00862, as well as Dr. W. Benz of Hoffmann-La Roche, Inc., Nutley, N.J., for mass spectra; and the National Science Foundation for partial support of this research through Grant CHE74-21436. The 220-MHz NMR spectra were obtained on an instrument at The Rockefeller University and operated by a consortium supported in part by NSF Grant PCM74-12247.

References and Notes

(1) This paper is dedicated with pleasure to Professor R. B. Woodward on the occasion of his sixtieth birthday, April 10, 1977.
(2) A portion of this work has appeared as a preliminary communication: W. C. Agosta and S. Wolff, *J. Am. Chem. Soc.*, **98**, 4316 (1976).
(3) W. C. Agosta and S. Wolff, *J. Am. Chem. Soc.*, **97**, 456 (1975); **98**, 4182 (1976).
(4) J. Meinwald, R. A. Schneider, and A. F. Thomas, *J. Am. Chem. Soc.*, **89**, 70 (1967).
(5) R. O. Duthaler and C. Ganter, *Helv. Chim. Acta*, **59**, 415 (1976).
(6) W. C. Agosta and W. L. Schreiber, *J. Am. Chem. Soc.*, **93**, 3947 (1971).
(7) References to reviews on various aspects of the subject are given in ref 3.
(8) B. A. Hess, Jr., *J. Am. Chem. Soc.*, **93**, 1000 (1971). See also R. L. Cargill and J. W. Crawford, *J. Org. Chem.*, **35**, 356 (1970).
(9) H. M. Bell and H. C. Brown, *J. Am. Chem. Soc.*, **88**, 1473 (1966).
(10) A. P. Marchand and J. E. Rose, *J. Am. Chem. Soc.*, **90**, 3724 (1968).
(11) R. Ratcliff and R. Rodehorst, *J. Org. Chem.*, **35**, 4000 (1970). These conditions gave **15** essentially quantitatively, a considerable improvement over

the previous acidic conditions (37%).[8]
(12) Reduction and other reactions of norbornen-7-one proceed similarly, although the reported stereospecificity is somewhat lower: R. S. Bly, C. M. Dubose, Jr., and G. B. Konizer, *J. Org. Chem.*, **33**, 2188 (1968), and references cited therein. From examination of models it would appear that the axial hydrogens at C(2) and C(4) provide effective additional hindrance to approach to the carbonyl group of **15** from that side of the molecule, and this may account for the greater stereoselectivity observed in the bicyclooctenone system.
(13) H. Krieger, *Suom. Kemistil. B*, **38**, 260 (1965).
(14) R. A. Appleton, J. C. Fairlee, R. McCrindle, and W. Parker, *J. Chem. Soc. C*, 1716 (1968).
(15) Assignment of this upfield signal to the anti proton at C(8) in **18** is required by the observed spectra of **16** and **17** taken with the fact that **12b** is known[8] to react under solvolysis conditions with retention of configuration. It is also in line with earlier assignments for the anti proton at C(7) in various norbornene epoxides: K. Tori, K. Kitahonoki, Y. Takano, H. Tanida, and T. Tsuji, *Tetrahedron Lett.*, 559 (1964); J. E. Franz, C. Osuch, and M. W. Dietrich, *J. Org. Chem.*, **29**, 2922 (1964); R. Huisgen, L. Moebius, G. Mueller, H. Stangl, G. Szeimies, and J. M. Vernon, *Chem. Ber.*, **98**, 3992 (1965). The only previous observations concerning bicyclo[3.2.1]oct-6-ene epoxides known to us are those of P. R. Jefferies, R. S. Rosich, and D. E. White [*Tetrahedron Lett.*, 1853 (1963)] on oxiranes derived from the diterpene alcohol beyerol and its esters. This was the original report that epoxides cause an upfield shift of suitably located nearby hydrogens, but in this work the unique upfield signal was attributed to the C(8) proton syn rather than anti to the epoxide ring. The subsequent results with norbornene epoxides cited above, along with our present findings with **16–18**, suggest that this original assignment by Jefferies et al. should be reversed.
(16) In contrast, reduction of **12b** with lithium aluminum deuteride in refluxing ether gave ~15% inversion and ~85% retention from similar analysis of the derived epoxide.
(17) H. C. Brown, "Organic Syntheses via Boranes", Wiley, New York, N.Y., 1975.
(18) A small amount (8%) of aldehyde **21** is also formed, but this is believed to arise from inverted conformer **2e**. See ref 3 for discussion.
(19) Such substitution also has an important effect in related ground state reactions: W. C. Agosta and S. Wolff, *J. Org. Chem.*, **40**, 1027 (1975).
(20) R. H. Shapiro, *Org. React.*, **23**, 405 (1976).
(21) H. C. Brown and G. Zweifel, *J. Am. Chem. Soc.*, **83**, 1241 (1961).
(22) S. Wolff, W. L. Schreiber, A. B. Smith, III, and W. C. Agosta, *J. Am. Chem. Soc.*, **94**, 7797 (1972).
(23) H. O. House, "Modern Synthetic Reactions", 2nd ed, W. A. Benjamin, Menlo Park, Calif., 1972, pp 412–414, and references cited therein.
(24) Spectral assignments for these ketones are given by W. C. Agosta and S. Wolff, *J. Org. Chem.*, **40**, 1665 (1975).
(25) D. Y. Curtin and D. B. Kellom, *J. Am. Chem. Soc.*, **75**, 6011 (1953).
(26) P. J. Boddy and E. W. R. Steacie, *Can. J. Chem.*, **38**, 1576 (1976); J. H. Current and B. S. Rabinovitch, *J. Chem. Phys.*, **38**, 783 (1963).
(27) W. B. Hammond and T. S. Yeung, *Tetrahedron Lett.*, 1173 (1975), and references cited therein.
(28) Only a small steric effect is anticipated since ΔG°_{25} for *cis*- and *trans*-hydrindan is only ~0.3 kcal/mol and actually favors the trans isomer. For discussion and references see E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis", Wiley, New York, N.Y., 1965, pp 228–230.
(29) A. L. J. Beckwith and G. Phillipou, *Aust. J. Chem.*, **29**, 123 (1976); A. L. J. Beckwith, *Chem. Soc., Spec. Publ.*, **No. 24**, 239 (1970); J. W. Wilt in "Free Radicals", Vol. 1, J. K. Kochi, Ed., Wiley, New York, N.Y., 1973, Chapter 8. These articles contain extensive references to earlier literature.
(30) P. Livant and R. G. Lawler, *J. Am. Chem. Soc.*, **98**, 6044 (1976).
(31) E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis", Wiley, New York, N.Y., 1965, p 9, and references cited therein.
(32) C. H. Bushweller and W. G. Anderson, *Tetrahedron Lett.*, 1811 (1972).
(33) N. Ya. Buben, Yu. N. Molin, A. I. Pristupa, and V. N. Shamshev, *Dokl. Akad. Nauk SSSR*, **152**, 352 (1963); S. Ogawa and R. W. Fessenden, *J. Chem. Phys.*, **41**, 994 (1964).
(34) K. U. Ingold in "Free Radicals", Vol. 1, J. K. Kochi, Ed., Wiley, New York, N.Y., 1973, Chapter 2.
(35) See, for example, P. D. Hobbs and P. D. Magnus, *J. Am. Chem. Soc.*, **98**, 4594 (1976).
(36) For a recent study of substituent effects that are interpreted as introducing barriers to conformational change in biradicals arising in a rather different kind of photochemical reaction see J. R. Scheffer, B. M. Jennings, and J. P. Louwerens, *J. Am. Chem. Soc.*, **98** (1976).

The Photochemistry of Chloroaromatic Compounds. Is "π-Chlorobenzene" an Intermediate?[1]

D. R. Arnold* and P. C. Wong

Contribution from the Photochemistry Unit, Department of Chemistry, University of Western Ontario, London, Ontario, Canada N6A 5B7.
Received October 18, 1976

Abstract: In 1973 Lemal and co-workers[2a] reported that irradiation of dilute solutions of chlorobenzene in cyclohexane gave significant amounts of chlorocyclohexane (53%). To account for this unexpected observation they proposed a mechanism involving hydrogen abstraction from cyclohexane by a phenyl radical which is complexed with a chlorine atom ("π-chlorobenzene"). The cyclohexyl radical and the chlorine atom then couple in the solvent cage. We have reexamined this reaction and our results lead us to propose an alternative explanation. We present evidence that the chlorocyclohexane derives from the photosensitized addition of hydrogen chloride to cyclohexene and that the cyclohexene is formed by disproportionation of cyclohexyl radicals.

In 1973 Lemal and co-workers reported that irradiation of dilute solutions of chlorobenzene (I) in cyclohexane (II) gave chlorocyclohexane (III, 53%) as a major product.[2] They recognized that formation of this product could not simply be explained as the reaction of the phenyl and chlorine radical, which would result upon bond homolysis, since both the phenyl radical and the chlorine atom are relatively reactive radicals and would abstract hydrogen, predominantly from the solvent. Benzene was a major product but there was less than an equivalent amount of hydrogen chloride. To account for this unexpected result they proposed a mechanism, the key step of which was a hydrogen abstraction from cyclohexane by the phenyl radical moiety of a chlorine atom–phenyl radical complex (V, "π-chlorobenzene") giving a chlorine atom (complexed with benzene)–cyclohexyl radical pair in a solvent cage (Scheme I).

We were attracted to this area by the unusual nature of this suggested mechanism and particularly by the possibility that reactions involving this type of intermediate (V) might offer a synthetically useful procedure for functionalizing an unactivated, saturated, proximate alkyl position. For example, *o*-chloropropylbenzene (VI) would be expected to yield 3-chloropropylbenzene (VII) since the hydrogen abstraction from the terminal methyl group by the phenyl radical moiety is favored in a six-membered transition state as shown in Scheme II.

This type of intramolecular hydrogen abstraction has been observed by Beckwith and co-workers using electron spin resonance (ESR) techniques.[3] We recognized that this particular example puts a heavy demand upon the intramolecular reactivity of the intermediate VIII since the hydrogen being abstracted is attached to a terminal carbon (i.e., primary hy-