

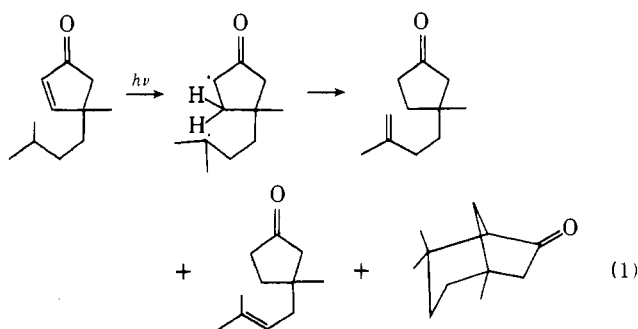
Photochemistry of 4-Isobutyl-4-methyl- and
4-(2-Methoxyethyl)-4-methyl-2-cyclopentenone.
Stereochemical Effects in Intramolecular Abstraction
of Hydrogen by the β -Carbon Atom of Cyclopentenones

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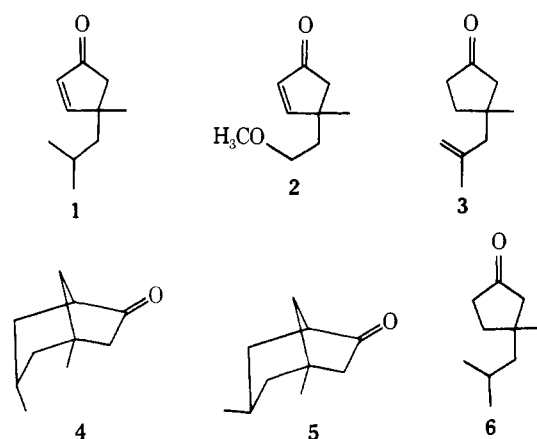
Abstract: Photochemical rearrangement of ketone **1** furnishes **3-5** by way of the diastereomeric biradicals **11** and **12**. Through use of **1e** and **1f**, isotopic isomers of **1** specifically labeled in one or the other of the diastereotopic methyl groups, the contribution of **11** and **12** as reaction intermediates was investigated. Results summarized in Scheme III show that 92% of the rearrangement proceeds through **11** and only 8% through **12**. Experiments with deuterium-labeled **1d** and with the methoxy-substituted ketone **2** indicate that 1,5-hydrogen transfer (six-membered intermediate) is preferred, that 1,6-transfer is possible but slow, and that there is no evidence for 1,4-hydrogen transfer in these systems. Preparation of the various substrates and proofs of structure of products are described.

Irradiation of various 4-substituted cyclopentenones leads to rearrangements involving intramolecular transfer of hydrogen from side chain to the β -carbon atom of the unsaturated ketone,^{1,2} and the typical products are simply explained as resulting from disproportionation and/or collapse of a biradical intermediate. An example leading to both types of products is shown in eq 1. Related reactions occur with other unsatu-

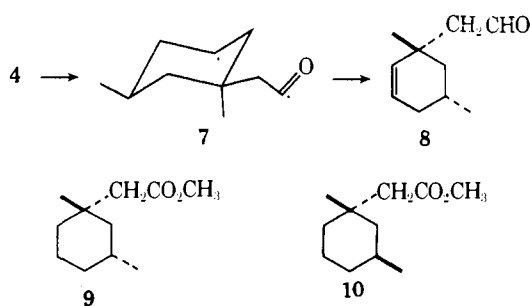


rated ketones having a relatively constrained carbon-carbon double bond.³⁻⁵ In the present work we have investigated stereochemical effects in the formation and reactions of these biradicals through study of the photochemistry of two new cyclopentenones, 4-isobutyl-4-methylcyclopentenone (**1**) and 4-(2-methoxyethyl)-4-methylcyclopentenone (**2**). Photochemical results and discussion are given first, followed by preparative experiments.

On photolysis ketone **1** undergoes rearrangement to three products, the methallylcyclopentanone **3** and the two dimethylbicyclooctanones **4** and **5**. At 8.5% conversion the yields of these isomers are **3** (31%), **4** (31%), and **5** (3%), for a total of 65%.⁷ The structure of **3** was apparent from its spectroscopic properties and hydrogenation to **6**, an authentic sample of which was on hand. In addition **3** was independently prepared by a route which will be described later. It was fairly simple to infer from spectroscopic data and analogy that the remaining two ketones were the bicyclooctanones **4** and **5**;⁸ however, it was less certain which ketone was which. The NMR signal for the C(3)-methyl group appears at δ 0.905 ppm in one and at 1.01 ppm in the other. On this basis a provisional assignment was possible, since an equatorial methyl group is expected^{9,10} to appear slightly upfield from its axial counterpart, and the effect of the carbonyl group in **4** and **5** probably is to enhance this difference. This tentative conclusion was confirmed and the major bicyclic ketone was proved to be **4** by



means of the photochemical degradation which we have employed previously.^{1,10} Photolysis of **4** ($\lambda > 2800 \text{ \AA}$) led via α -cleavage (**7**) and subsequent hydrogen transfer to the cyclohexeneacetaldehyde **8**. This was characterized and converted into the related saturated ester by catalytic reduction of the olefinic double bond, Jones oxidation¹¹ of the aldehyde, and esterification of the acid thus formed. This final methyl ester was identical with authentic **9** and readily distinguishable from its diastereomer **10**.¹² The preparation and assignment of

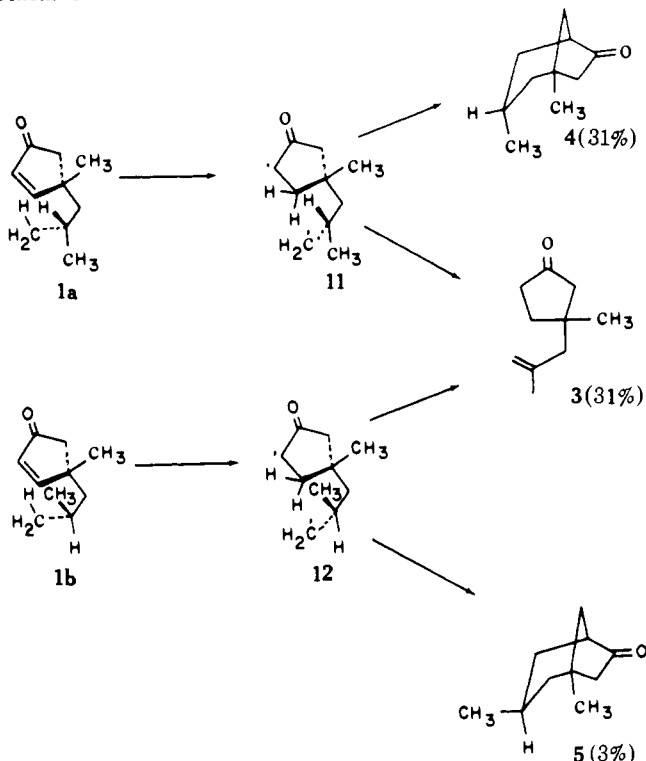


stereochemistry to **9** and **10** have been described previously.¹⁰

These rearrangements of **1** afford an opportunity to examine two different stereochemical problems. We discuss first the question raised by bicyclic ketones **4** and **5**, which differ only in the stereochemistry of the methyl group at C(3). These are the products anticipated from collapse of one or the other of the diastereomeric biradicals **11** and **12**, and the general

question to be considered concerns the factors leading to the observed amounts of **4** (31%) and **5** (3%) from these intermediates. Collapse of **11** leads to **4**, and **12** leads to **5**. The differing stereochemistry at C(3) in these products is thus determined by way of hydrogen abstraction from one or the other of the two diastereotopic methyl groups of the isobutyl side chain of **1**, and the dissimilar yields of **4** and **5** indicate that the stereochemical differences involved in formation and/or reaction of **11** and **12** are somehow significant. It is clear that an understanding of this significance is desirable in connection with improvement of our appreciation of the factors controlling formation and reactions of biradical intermediates. The specific considerations involved in rearrangement of **1** are displayed in Scheme I, where **1a** and **1b** are rotational conformers of **1**

Scheme I

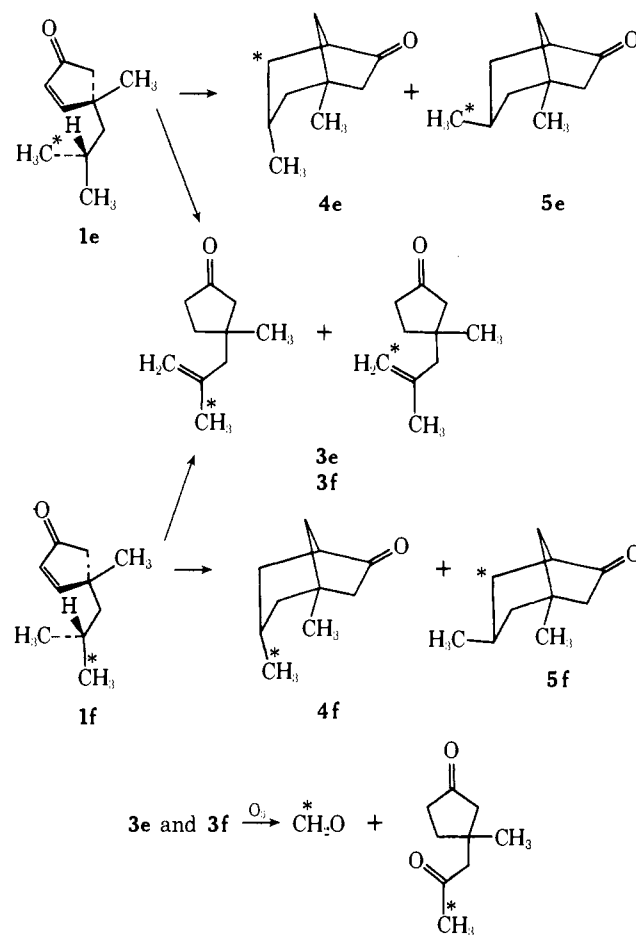


appropriate for hydrogen transfer and formation of **11** and **12**, respectively. It is apparent that steric differences could lead to one or more of the following: (1) preferential formation of **11** rather than **12**; (2) preferential reversion of **12** to **1**; (3) unequal partitioning of **11** and **12** among coupling (**4** or **5**), disproportionation (**3**), and nonvolatile products. If only (1) and/or (2) were operative, all rearrangement would proceed preferentially by way of **11**, and ~90% of **3** would arise from this intermediate. On the other hand, if only (3) were operative, both **11** and **12** would contribute equally to the total reaction, but all of **3** could come from **12**. It will be seen then that evaluation of the relative importance of these possible effects requires a knowledge of what fraction of **3** arises from each of the precursors **11** and **12**.¹⁴ Evaluation of the relative contribution of **11** and **12** necessitates a distinction between the diastereotopic methyl groups of **1** and then determination of the contribution of each of these methyl groups to the methyl and methylene carbon atoms of the methallyl side chain of **3**. In chemical terms this calls for the solution of two problems, preparation of **1** stereospecifically labeled in one of the diastereotopic methyl groups and demonstration of which methyl group is so labeled. We have in fact prepared two isotopic isomers of **1**, each stereospecifically labeled with both ¹³C and ¹⁴C in one of the diastereotopic methyl groups. Details of the synthesis and the stereochemical assignment, as well as the

reasons for this particular choice of label, are deferred to a later paragraph, and here we will proceed to the photolysis of these two labeled compounds **1e** and **1f**.

Each of these ketones **1e** and **1f** will react by way of **11** and **12** as already presented in Scheme I. The result is that each substrate will give rise to discretely labeled isomers of **4** and **5**, and to a mixture of isomers of **3** in which the label is distributed between methyl and methylene groups of the side chain. This is summarized in Scheme II, where **3e** and **3f**

Scheme II



designate the mixtures, not necessarily identical, of the two labeled species shown and obtained from **1e** and **1f**, respectively. Ketones **1e** and **1f** were irradiated and the major products (**3e**, **4e**, **3f**, and **4f**) were isolated and purified as for unlabeled material. In order to determine the distribution of label in **3e** and **3f** these cyclopentanones were cleaved at the side chain double bond and the extent of labeling in the resulting fragments was separately measured. Pilot experiments with unlabeled **3** showed that a satisfactory procedure was ozonolysis at -78 °C in ethyl acetate and treatment with zinc and water, followed by extraction with pentane. From the organic extract 3-acetyl-3-methylcyclopentanone could be obtained and purified by preparative VPC. From the aqueous solution remaining after extraction with pentane, formaldehyde could be isolated directly as its dimedone derivative. This ozonolysis was then applied to **3e** and **3f**, and the ¹⁴C content of the diketone and derivatized formaldehyde from each series was determined in standard fashion. The results of duplicate determinations are summarized in Table I. The activities of **3e** and **3f** differ somewhat because **1e** and **1f** were diluted with unequal amounts of unlabeled material during synthesis. The reasons for the apparently incomplete recovery of activity from ozonolysis of **3e** have not been identified conclusively but may

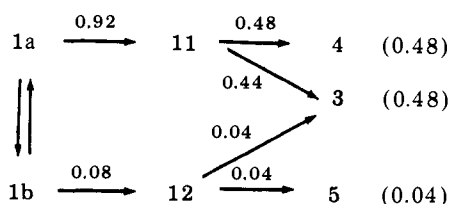
Table I. Radioactivity of **3e**, **3f**, and Ozonolysis Products

Compd	(Cpm/mol) × 10 ⁻⁶		% recovered activity	
	From 1e	From 1f	From 1e	From 1f
3	814.7	930.3		
	810.8	927.7		
3-Acetyl-3-methyl-cyclopentanone	53.2	895.3	7.4	92.1
	53.4	895.5		
Derivatized formaldehyde	661.7	74.7	92.6	7.9
	663.5	78.9		

be due to failure to dry thoroughly the dimedone derivative in this series before weighing.

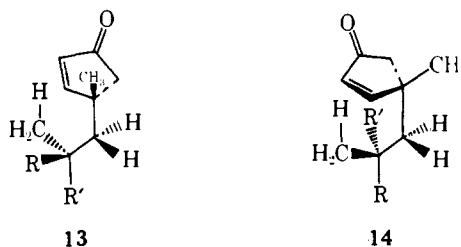
Combination of these data with the yields of **3-5** leads to the desired information on the origin of the three isomeric products. The results are presented in Scheme III, where the

Scheme III



product fractions have been normalized to total 1.00. Over each arrow is given the fraction of rearrangement of ketone **1** that proceeds by that transformation. As already indicated above, it is not possible to assess reversal of **11** and **12** to **1** with these data, so that the figures given for formation of **11** and **12** (0.92 and 0.08) necessarily refer to net processes for biradicals leading to volatile products. It is clear that isomerization of **1** proceeds overwhelmingly by way of **11** rather than **12**, and that this behavior is responsible for the observed product distribution. For each biradical the ratio of disproportionation to coupling is approximately unity. We cannot assess what portion of nonvolatile products (35% total) derives from **11** and/or **12**. It seems unlikely, however, that one or the other of these biradicals is preferentially diverted to polymer.

The results themselves afford no basis for explaining this striking selectivity, but an examination of molecular models suggests the following tentative interpretation. There are two possible staggered conformations of the isobutyl side chain which bring a given methyl group within range for hydrogen transfer to the β -carbon atom. These are shown in **13** and **14**. That is to say, **1a** can be represented in greater detail by **15** or **18**, while **1b** is **16** or **17**. Only one of these conformations, however, is feasible for abstraction from each methyl group; **15**, which leads to **11**, and **16**, which leads to **12**, are possible, but both **17** and **18** have unacceptable nonbonded interactions of the methyl group not involved in hydrogen transfer. The detailed representations of conformations **1a** and **1b** thus are



15, R = H; R' = CH₃
17, R = CH₃; R' = H

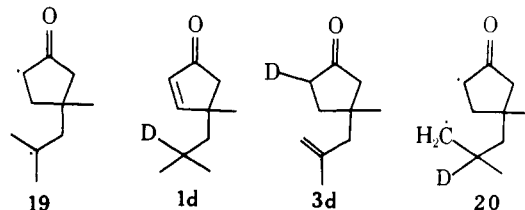
16, R = CH₃; R' = H
18, R = H; R' = CH₃

expected to be **15** and **16**, respectively, and abstraction from the diastereotopic methyl groups should then occur in conformations which differ in detail in the two cases and which present hydrogen at a somewhat different distance and angle to the β -carbon atom in each case. Such steric factors are known to play a decisive role in the rates of abstraction of hydrogen by alkoxy radicals¹⁵ and by oxygen in triplet ketones,¹⁶ and therefore it is reasonable to assume that conformational differences between **15** and **16** will be kinetically important. In models conformer **15**, which leads to biradical **11** and thence to most of the observed rearrangement, actually appears less favorable for hydrogen transfer than does **16**. This suggests that the preponderance of rearrangement of **1** by way of **11** may reflect not preferential formation of this biradical but rather easier back transfer of hydrogen from **12** to re-form **1** and/or steric retardation of the forward reactions of **12**. Clarification of these mechanistic points will depend on reliable physical data not yet available; for the present the findings presented in Scheme III provide instructive evidence of highly discriminating behavior in the hydrogen abstraction reactions of cyclopentanone **1**.

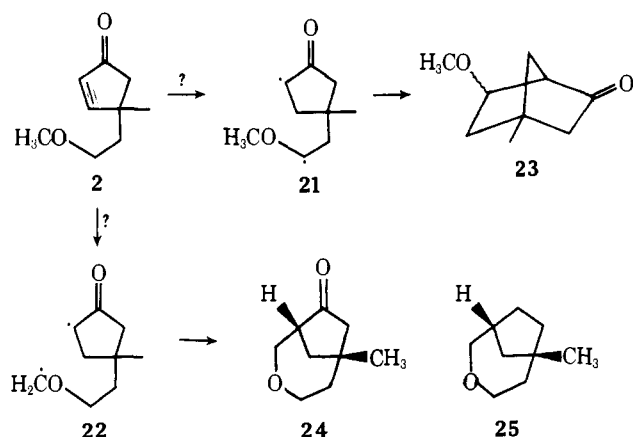
We turn now to the second stereochemical question raised by the photochemistry of **1**, which concerns optimal ring size for hydrogen transfer. Extensive studies of the type II reaction of ketones have shown that, while photochemical 1,5-transfer to carbonyl oxygen is generally favored, larger cyclic transition states are occasionally possible¹⁶ and 1,4-transfer can take place in some special cases.¹⁷ Irradiation of aralkyl thiones, on the other hand, leads to 1,6-hydrogen transfer to the sulfur atom.¹⁸ There are also reports that photolysis of two α -substituted styrenes results in 1,5-transfer of hydrogen to the unsubstituted β -carbon atom in reactions analogous to the type II process.¹⁹ It appeared worthwhile then to determine the extent of specificity associated with these abstractions in which the transfer is to sp² carbon in cyclopentenones.

Formation of **3** should involve the diastereomeric biradicals **11** and **12** (1,5-transfer with formation of a primary alkyl radical), as discussed above, and/or the isomeric biradical **19** resulting from 1,4-transfer of hydrogen and generation of a tertiary radical. The rearrangement of **1** to **3** thus provides an opportunity to look for competition between these two paths. This was done through irradiation of **1d** and comparison of the NMR spectrum of the deuterated cyclopentanone formed with that of undeuterated **3**. At 220 MHz in the presence of the shift reagent Eu(fod)₃²⁰ the α and β protons of the cyclopentanone ring are readily separated and may be integrated. The spectra indicated that no deuterium had been lost in the rearrangement of **1d**, and that the product was labeled only α to the carbonyl group, as shown in **3d**. The biradical intermediate then is **20**, the deuterated isotopic isomer of **11** and **12**, and both hydrogen transfers occurring in the conversion of **1d** to **3d** are 1,5-transfers.

We sought further information on this point through study of the photochemistry of the 2-methoxyethyl-substituted ketone **2**. Here 1,5-transfer to the β -carbon atom is impossible, but both 1,4- and 1,6-transfers are conceivable and would lead to **21** and **22**, respectively. Photolysis of **2** led to slow destruction of starting ketone, with formation of much polymer and a single volatile product in 17% yield.⁷ Under essentially these same conditions related rearrangements involving 1,5-transfer occur rapidly and in much higher yield. The NMR spectrum

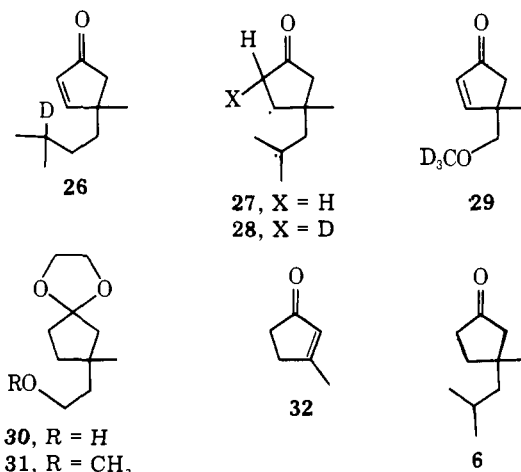


of the photoproduct lacked a methoxy signal, indicating that it could not be **23**. The compound was shown to be **24** by Wolff-Kishner reduction to 6-methyl-3-oxabicyclo[4.2.1]nonane (**25**), which was identical with a sample prepared by



stepwise synthesis.²¹ There is evidence then only for inefficient 1,6-hydrogen transfer in the photochemistry of **2**.²² Judging qualitatively from these observations with **1d** and **2**, we conclude that in these systems 1,5-transfer of hydrogen is strongly favored over 1,6-transfer, and that there is no evidence for 1,4-transfer.

In the above discussion and in previous reports^{1,2} we have suggested that all products formed in these rearrangements of cyclopentenones arise through biradicals formed on initial transfer of side chain hydrogen to the β -carbon atom, as shown in eq 1 and in structures **11** and **12**. The results of labeling experiments with **1d** and with **26**¹ indicate clearly which side chain hydrogen is transferred to which olefinic carbon atom of the enone system, but they do not clarify the order of hydrogen transfer in formation of the olefinic products. Thus these data do not rule out photochemical rearrangement of **1** to biradical **27** through initial hydrogen abstraction by the α -carbon atom, followed by transfer of methyl hydrogen to the β carbon to yield **3**. Since there are known a few examples of photochemical reactions of enones initiated by intramolecular hydrogen transfer to the α carbon,⁶ it is important to consider whether this process plays a role in the rearrangements of cyclopentenones to alkenylcyclopentanones under discussion here. Several observations militate against this possibility. Initial, 1,5-hydrogen transfer to the α -carbon atom would yield a 1,4 biradical (see **27**). One common fate of such species is coupling to form cyclobutanes, but no such products have been found in these reactions, although in all cases investigated there have been bicyclic coupling products indicative of hydrogen abstraction by the β -carbon atom. Secondly, the observed

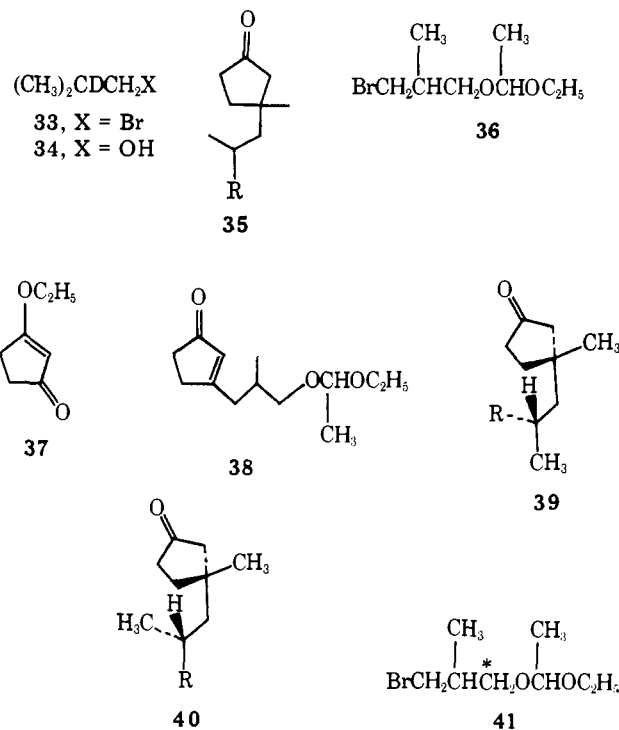


variations in photochemistry with structure of the cyclopentenone side chain are most reasonably and succinctly explained by exclusive initial hydrogen transfer to the β -carbon atom in all cases. Most importantly, a kinetic isotope effect is expected when the initial hydrogen transfer involves deuterium rather than protium, with the labeled species reacting more slowly. In previous investigations involving the deuterated ketones **26** and **29** these isotope effects were qualitatively noted.^{1,2,23} We have now compared the photoisomerization of **1** and **1d** in a merry-go-round apparatus and find essentially no difference ($< \pm 2\%$) in the quantum yields for disappearance of starting ketone in the two series. This is reasonable if initial, rate-controlling abstraction of protium from a methyl group yields **20** from **1d**, but unlikely if deuterium transfer occurs first to form **28**. We conclude from these diverse considerations that the initial hydrogen abstraction in these rearrangements is solely by the β -carbon atom.

Preparative Experiments. Methoxy ketone **2** was prepared from hydroxy ketal **30**.²⁴ Methylation followed by bromination-dehydrobromination^{1,25} of **31** and subsequent deketalization yielded **2**.

The unlabeled ketone **1** was available from 3-methylcyclopentenone (**32**). Conjugate addition^{1,4,26,27} of isobutylmagnesium bromide furnished **6**, and this could be converted to **1** by bromination-dehydrobromination (35%). Alternatively **6** was oxidized to **1** in 70% yield with palladium(II) chloride and hydrochloric acid in acetic acid-dioxane.²⁸ For the deuterated analogue **1d** the labeled Grignard reagent was prepared from 1-bromo-2-methylpropane-2-*d* (**33**), obtained from alcohol **34**¹ with triphenylphosphine and bromine.²⁹

The key intermediate for synthesis of labeled isomers **1e** and **1f** was the diastereomeric mixture of hydroxy ketones **35a**. This material was itself accessible, provided convenient functionality for the separation of diastereomers, and could be easily converted to **1e** and **1f**. Ketone **35a** was prepared through conjugate addition of **36**³⁰⁻³² to 3-methylcyclopentenone (**32**), following a procedure developed for related compounds by Eaton.³² This was satisfactory for the unlabeled **35a** needed



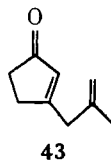
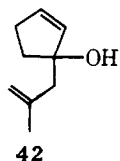
- a, R = CH₂OH
 b, R = CH₂OCONH-(α -naphthyl)
 c, R = C*H₂OH
 d, R = C*H₃

for exploratory work; it was not appropriate for the isotopic series in which the side chain carries a ^{13}C and ^{14}C label, since the conjugate addition leads to loss of half the alkyl halide used.³³ For this reason a procedure making more efficient use of the side chain was also devised. This involved direct addition of the organolithium reagent from **36** to 3-ethoxycyclopentenone (**37**)³⁴ and workup with ammonium chloride to yield **38**. Conjugate addition of lithium dimethylcuprate²⁷ to **38** and subsequent hydrolysis then afforded **35a**. This alternative approach was less convenient, but it improved the yield of **35a** based on **36** from 16 to 38%.

The diastereomers of **35a** were then separated and characterized as the corresponding α -naphthylurethanes **35b**. These urethanes were hydrolyzed to furnish keto alcohols **39a** and **40a**. In the labeled series the carbon bearing the primary hydroxyl group in these keto alcohols will be labeled; the hydroxyl function has now served its purposes of providing the needed distinction between atoms of the side chain and of permitting separation of diastereomers. Its final removal was demonstrated on **35a**. This was ketalized, converted to the tosylate, and reduced with lithium aluminum hydride in the usual way.

We now applied this sequence to preparation of labeled materials. The label for the diastereotopic methyl groups of **1** must fulfill three requirements: (1) it must interfere minimally with the photochemical process under investigation; (2) it must permit simple determination of the origin of **3** from **11** and **12**; and (3) it must provide a means of assigning the stereochemistry of **1e** and **1f**. The first requirement eliminates use of deuterium labeling because of the expected kinetic isotope effects; the second is nicely met by ^{14}C labeling as demonstrated by the experiments with **3e** and **3f** already described; the third requirement appeared to be most easily answered by ^{13}C enrichment, as will be explained shortly. We thus chose to employ a mixture of ^{13}C and ^{14}C as the label. Starting with potassium cyanide containing both K^{13}CN and K^{14}CN and following prior art^{35,36} as well as reactions used for synthesis of unlabeled **36**, we prepared labeled bromide **41**. From this point the synthesis proceeded as outlined above through **39c** and **40c**. Each of these was now converted to the corresponding isomer of labeled 3-isobutyl-3-methylcyclopentanone, **39d** and **40d**, respectively. Oxidation with palladium(II) in acid then gave **1e** and **1f**. Several dilutions with unlabeled materials were made during the synthesis to provide **1e** and **1f** with a suitable level of ^{14}C for counting and with $\sim 5\%$ enrichment in ^{13}C for the NMR experiment described below.

The simplest way to assign the stereochemistry of **1e** and **1f** and their synthetic precursors appeared to be to take advantage of the fate of the labeled methyl group on photochemical isomerization to **4**. As depicted in Scheme II, the label in **4e** must be at C(4), while that in **4f** will appear in the methyl group attached to C(3). The discrimination of **4e** and **4f** by ^{13}C NMR measurements is straightforward, since both off-resonance decoupling and chemical shift differences permit distinction between methyl and methylene signals.³⁷ This was done without difficulty; the sample of labeled **4** carrying excess ^{13}C in the far upfield ($\delta_{\text{Me}_4\text{Si}}$ 26.0 ppm) methyl signal was assigned as **4f**, and that with ^{13}C enrichment in a lower field (37.7 ppm) methylene signal was assigned as **4e**. Thus the photochemical reactions under study themselves led to a rigorous stereochemical assignment for the label in substrates **1e** and **1f**.



Authentic **3** was prepared from **42**, the product formed from cyclopentenone and methallylmagnesium chloride. This underwent allylic rearrangement and oxidation to **43** in acidic chromium trioxide,³⁸ and treatment of **43** with lithium dimethylcuprate²⁷ furnished **3**.

Conclusion

The investigations described here provide new insight into these hydrogen transfer reactions of cyclopentenones. Abstraction by the β -carbon atom through a six-membered intermediate is quite selectively favored, as seemed plausible in advance. Less readily foreseen was the stereoselective rearrangement of **1** by way of biradical **11**. A completely satisfying explanation of this finding is not obvious, and this fact serves as a reminder that there is still little information of this sort available concerning the properties of biradicals. It is a commonplace that prediction of the course of reactions involving these intermediates is difficult; success in surmounting this problem will require an improved understanding of the steric and electronic factors influencing their formation and destruction.

Experimental Section

General. All VPC was carried out on a Varian Aerograph Model A-90-P gas chromatograph using columns prepared from aluminum tubing. The column oven was operated at 145–190 °C and the helium flow rate was 75–120 mL/min. The following columns were used: A, 30% DEGS on 40/60 Chromosorb W, 10 ft \times 0.375 in.; B, 25% QF-1 on 40/60 Chromosorb W, 10 ft \times 0.25 in.; C, 30% Carbowax 1500 on 40/60 Chromosorb W, 10 ft \times 0.375 in.; D, 25% DEGS on 60/80 Chromosorb P, 15 ft \times 0.25 in.; E, 25% PDEAS on 40/60 Chromosorb W, 48 ft \times 0.25 in.

Unless otherwise specified, IR and NMR spectra were obtained for CCl_4 solutions, the former on a Perkin-Elmer Model 237B spectrophotometer and the latter on a Varian T-60A (60 MHz) spectrometer. Varian HR-220 (220 MHz, CW and FT mode) and Bruker HX-90 (22.63 MHz, for ^{13}C spectra in C_6D_6) spectrometers were also used as indicated. A Packard Model 3320 Tri-Carb liquid scintillation spectrometer was used for counting ^{14}C activity of samples in Aquasol-2 (New England Nuclear) liquid scintillation cocktail. Melting points were determined on a Thomas-Hoover apparatus, and are corrected. Reactions involving organometallic compounds were carried out in anhydrous diethyl ether using flame-dried glassware. Solutions were dried over anhydrous MgSO_4 , Na_2SO_4 , or K_2CO_3 . Unless otherwise noted, solvents were removed in vacuo with a rotary evaporator. Unless otherwise noted, pure compounds were obtained as colorless liquids.

Photolysis of 4-Methyl-4-isobutylcyclopentenone (1). A benzene solution of **1** (450 mg, ~ 1 mg/mL) was irradiated through an uranium glass filter as previously described.³⁹ The photolysis was terminated when IR spectroscopy indicated no remaining starting material. Removal of the benzene by distillation and preparative VPC of the residue on column A (145 °C) gave the following compounds (in order of elution).

1, *exo*-3-Dimethylbicyclo[3.2.1]octan-6-one (**5**, 3%): IR 2955 (s), 2930 (m), 2870 (w), 1746 (s), 1452 (m), 1400 (w), 1372 (w), 1248 (w), 1172 (w), 1118 (w), 1077 (w), 1030 cm^{-1} (w); NMR (220 MHz) δ 2.33 (br s, 1 H), 1.98 (dd, $J = 4, 18$ Hz, 1 H), 1.80 (dd, $J = 0.5, 18$ Hz, 1 H), 1.96–1.00 (m, 7 H), 1.12 (s, 3 H), 0.905 (d, $J = 7$ Hz, 3 H); mass spectrum m/e 152.1233 (M^+ , calcd for $\text{C}_{10}\text{H}_{16}\text{O}$, 152.1200).

1, *endo*-3-Dimethylbicyclo[3.2.1]octan-6-one (**4**, 31%): IR 2950 (s), 2860 (w), 1746 (s), 1450 (m), 1400 (m), 1377 (w), 1367 (w), 1162 (w), 1090 (w), 1070 (w), 1045 (w), 895 cm^{-1} (w); NMR (220 MHz) δ 2.29 (m, 1 H), 2.18 (dd, $J = 3, 18$ Hz, 1 H), 2.13–1.36 (m, 7 H), 1.73 (d, $J = 18$ Hz, 1 H), 1.14 (s, 3 H), 1.01 (d, $J = 7$ Hz, 3 H); ^{13}C NMR $\delta_{\text{Me}_4\text{Si}}$ 26.0 (q), 26.8 (d), 29.7 (q), 37.7 (t), 39.0 (s), 43.6 (t), 46.0 (t), 49.0 (d), 53.2 (t), 162.5 (s); mass spectrum m/e 152.1218 (M^+ , calcd for $\text{C}_{10}\text{H}_{16}\text{O}$, 152.1200).

3-Methyl-3-(2-methyl-2-propenyl)cyclopentanone (**3**, 31%): IR 3080 (w), 2955 (s), 2925 (m), 1745 (s), 1640 (w), 1450 (m), 1400 (m), 1372 (m), 1145 (m), 885 cm^{-1} (s); NMR (220 MHz) δ 4.88 (m, 1 H), 4.71 (m, 1 H), 2.24–1.71 (m, 6 H), 2.13 (s, 2 H), 1.77 (m, 3 H), 1.05 (s, 3 H).

Anal. Calcd for C₁₀H₁₆O: C, 78.89; H, 10.59. Found: C, 78.97; H, 10.48.

The photolyses of labeled enones **1e** and **1f** were carried out in the same manner. Compounds **3-5 (e)** and **3-5 (f)** were separated by VPC on column D. ¹³C NMR spectra of products **4e** and **4f** were measured. Comparison with the ¹³C NMR of **4** revealed **4e** to be enriched at the C(4) position and **4f** at the C(3) methyl carbon.

Ozonolysis of 3-Methyl-3-(2-methyl-2-propenyl)cyclopentanone (3). Enone **3** (104 mg, 0.67 mmol) in ethyl acetate (12.5 mL) was subjected to ozonolysis at -78 °C for 30 min. The solvent was evaporated in vacuo, keeping the ozonide at ca. 0 °C. Water (7 mL) and Zn powder (0.27 g) were added to the residue, and the mixture was heated at reflux for 3 h. The solids were filtered off and washed with hot water and pentane. The aqueous layer was continuously extracted with pentane (17 h). The solvent was removed to give a colorless liquid (75 mg, 74%) identified as 3-methyl-3-(2-oxopropyl)cyclopentanone: IR 2940 (m), 2920 (w, sh), 2860 (w), 1740 (s), 1720 (s), 1445 (w), 1400 (m), 1370 (w), 1355 (m), 1255 (w), 1240 (w), 1155 (m), 1130 (w), 1035 (w), 1005 (w), 940 cm⁻¹ (w); NMR (220 MHz) δ 1.14 (s, 3 H), 2.08 and 1.79–2.35 (s and m, respectively, 9 H), 2.526 (s, 2 H). A sample for analysis was purified on column B.

Anal. Calcd for C₉H₁₄O₂: C, 70.10; H, 9.15. Found: C, 69.97; H, 9.14.

A portion (ca. 50%) of the aqueous layer was treated with a solution of dimedone (100 mg) in ethanol (5 mL). The first crop of precipitate was collected, washed, dried (13 mg, white fine needles), and identified as the dimedone derivative of formaldehyde from the following data: mp 191–192 °C, mmp (with authentic sample) 191–192 °C (lit.⁴⁰ mp 191–191.5 °C).

Labeled enones **3e** and **3f** (60–65 mg) were ozonized as above. In each case the dione was purified by VPC, and the formaldehyde derivative was checked by melting point (191–192 °C) determination. The ¹⁴C activity of the pure enone **3 (e or f)**, repurified by VPC on column D) and of the corresponding degradation products was determined for each case (see Table I).

Hydrogenation of 3. Unsaturated cyclopentanone **3** (20 mg) was hydrogenated over 5% Pd/C in methanol at 1 atm for 0.75 h. After filtration and removal of solvent, the IR and NMR spectra of the product were identical with those of **6** described below.

Photolysis of 1d. The photolysis of **1d** and the isolation of the methylcyclopentanone were carried out as described for **1** above. The 220-MHz NMR spectrum of **3d** in the presence of Eu(fod)₃²⁰ was compared with a similarly determined spectrum of **3**. Those signals undergoing the greatest downfield shift were assigned to the protons α to the carbonyl group. The unlabeled ketone exhibited resonances at δ 3.95 (m, 2 H) for C(5) and at 3.79 (d, *J* = 18 Hz, 1 H) and 3.63 (d, *J* = 18 Hz, 1 H) for C(2). For **3d**, the respective protons were located at δ 3.47 (br m, 1.00 H) for C(5) and at 3.32 and 3.16 for the AB quartet of C(2).

Simultaneous irradiation of solutions with identical concentrations of **1** and **1d** was carried out in a merry-go-round apparatus. The rate of disappearance of the enones was measured periodically by VPC analysis of aliquots on column D (170 °C). After photolysis for 1.0 h, 87% of **1** and 89% of **1d** remained, and after 1.5 h the values were 84 and 85%, respectively.

Photolysis of 2. The cyclopentanone **2** was photolyzed as previously described³⁹ to give the bicyclo keto ether **24** in 17% yield. An analytical sample was obtained on column B: IR 2960 (s), 2940 (s), 2885 (s), 1745 (s), 1452 (m), 1422 (w), 1395 (m), 1374 (m), 1352 (m), 1230 (m), 1168 (s), 1140 (m), 1085 (m), 1077 (s), 945 (m), 890 cm⁻¹ (m); NMR (220 MHz) δ 3.75 (ddd, *J* = 4, 4, 12 Hz, 1 H), 3.69 (d, *J* = 4 Hz, 2 H), 2.83 (ddd, *J* = 2, 12, 12 Hz, 1 H), 2.30 (m, 1 H), 2.13 (dd, *J* = 3, 13 Hz, 1 H), 2.07 (d, *J* = 18 Hz, 1 H), 1.97 (dd, *J* = 3, 18 Hz, 1 H), 1.82–1.29 (m, 3 H), 1.23 (s, 3 H).

Anal. Calcd for C₉H₁₄O: C, 70.10; H, 9.15. Found: C, 70.00; H, 9.31.

3-Isobutyl-3-methylcyclopentanone (6). A solution of isobutylmagnesium bromide was prepared from magnesium (5.35 g, 0.22 g-atom) and isobutyl bromide (27.4 g, 0.20 mol) in ether (160 mL). The reaction mixture was cooled to 0 °C and copper iodide (3.81 g, 0.02 mol) and tributylphosphine (4.05 g, 0.02 mol) were added, followed by 3-methylcyclopent-2-enone (15.35 g, 0.16 mol) in ether (75 mL). Upon completion of the addition, the reaction mixture was poured into a saturated ammonium chloride solution with vigorous stirring. Extraction with ether, drying, and removal of solvent yielded 29.8 g. Ketonic material was separated using Girard's Reagent T.

Distillation of the ketonic fraction afforded 10.69 g (43%): bp 99–102 °C (15 mm); IR 2955 (s), 1747 (s), 1460 (m), 1400 (m), 1382 (w), 1375 (w), 1362 (w), 1167 (m), 1130 cm⁻¹ (w); NMR (220 MHz) δ 2.20–2.09 (m, 2 H), 1.95 (s, 2 H), 1.82–1.16 (m, 5 H), 1.04 (s, 3 H), 0.95 (d, *J* = 7 Hz, 3 H), 0.93 (d, *J* = 7 Hz, 3 H).

Anal. Calcd for C₁₀H₁₈O: C, 77.86; H, 11.76. Found: C, 77.84; H, 11.81.

Methyl Methacrylate.³⁵ Concentrated H₂SO₄ (7.40 g, 0.075 mol) and pulverized copper (20 mg) were stirred under nitrogen atmosphere in a three-necked flask fitted with a septum, a thermometer, and a reflux condenser. Acetone cyanhydrin (4.20 g, 0.049 mol), prepared³⁵ from KCN and acetone–bisulfite adduct, was added to the mixture over a period of 10 min, keeping the temperature at ca. 60 °C with external cooling. After the addition the temperature was raised to 130 °C, and the mixture stirred at 135–140 °C for 30 min and cooled back to 60 °C. Hydroquinone (20 mg) and a mixture of methanol (3.20 g, 0.10 mol) and water (3.60 g, 0.20 mol) were introduced into the flask and the resulting mixture refluxed for 3 h and 15 min. The temperature fell from 88 to 83 °C during this time. Hydroquinone (20 mg) was added again and, changing to a downward condenser fitted with a copper spiral, distillate consisting of water, methanol, and methyl methacrylate was collected over a range of 70–97 °C. The crude distillate (7 g) was cooled. The upper layer was separated, washed with two 3-mL portions of 40% aqueous CaCl₂ to remove water and methanol, and dried over CaCl₂ to yield a colorless liquid (2.7 g, 54%). The product had the same IR and NMR spectra as those of authentic methyl methacrylate and appeared to be pure by NMR. (Extraction of the combined aqueous layers with ether afforded 160 mg more of the product.)

Labeled methyl methacrylate was prepared in two batches following the above procedure and using a total of 6.0 g of KCN, 2.0 g of ~90% enriched K¹³CN, and 1.8 mg (250 μCi) of K¹⁴CN (yield 65%).

1-Bromo-2,5-dimethyl-4,6-dioxaoctane (36). Methyl methacrylate (60 g) was treated with hydrogen bromide according to the procedure of Pickard and Lochte³⁶ and the bromo ester was reduced with a 1:1 mixture of lithium aluminum hydride and aluminum chloride at -78 °C following Nystrom.³¹ The crude bromohydrin was then treated with ethyl vinyl ether in the presence of dichloroacetic acid as described for a related case by Eaton.³² The bromo acetal was obtained in 80% overall yield after distillation: bp 55–58 °C (2 mm); IR 2980 (s), 2880 (s), 1452 (m), 1375 (s), 1330 (m), 1225 (m), 1125 (s), 1075 (s), 1050 (s), 995 (m), 937 (m), 920 cm⁻¹ (m); NMR (60 MHz) δ 4.61 (q, *J* = 6 Hz, 1 H), 3.89–3.00 (m, 6 H), 2.00 (m, 1 H), 1.38–0.90 (m, 9 H).

C(1)-Labeled methyl methacrylate was used to prepare labeled **41** in 63% overall yield following the above procedure.

3-[3-(1-Ethoxyethoxy-2-methylpropyl)-2-cyclopentenone (38). Bromoacetal **36** (1.12 g, 0.005 mol) was added dropwise to a mixture of ether (5 mL) and 0.5-cm lengths of lithium wire (ca. 130 mg, 0.019 g-atom) stirred under nitrogen atmosphere. The addition took 45 min at -2 °C and the mixture was stirred for an additional 45 min at -20 °C.

The organolithium reagent was transferred into a second dry three-necked flask fitted with a stopper, a condenser, and a septum and kept at 0 °C under nitrogen while ketone **37** (566 mg, 0.0045 mol)³⁴ in 1.5 mL of ether was added through the septum over a period of 5 min. The mixture was stirred magnetically at room temperature for 1.5 h.

The contents of the flask were poured over a mixture of 5 mL of ice in 5 mL of saturated aqueous NH₄Cl. The layers were separated and the aqueous layer extracted with ether. The combined ether layer was washed with brine and dried. The solvent was removed in vacuo to yield an orange colored oil (1.04 g) containing the desired acetal as the major product (ca. 50% of mixture; IR 1713 (C=O), 1620 cm⁻¹ (C=C); NMR δ 4.57 (q, -OC(CH₃)HO-), 5.83 (m, =CH)). The crude product was treated with dichloroacetic acid (0.065 mL) in ethyl vinyl ether (4 mL) overnight at room temperature to reprotect any acetal hydrolysis products that may have formed in the above workup. The usual workup and removal of solvent gave a yellow oil (1.1 g, 97% crude yield based on **36**, containing excess starting materials and ca. 50% enone **38**).

The labeled product was prepared in the same manner and distilled bulb-to-bulb (>100 °C, 2 mm) to give a colorless oil (ca. 80% of crude product) for use in subsequent reactions.

3-(3-Hydroxy-2-methylpropyl)-3-methylcyclopentanone (35a). Bromo acetal **36** (63.0 g, 0.28 mol) was treated with lithium wire (4.43

g, 0.638 g-atom) forming the organolithium as described for a related case by Eaton.³² This solution was added to copper iodide (26.7 g, 0.14 mol) and tributylphosphine (28.3 g, 0.14 mol) in ether (400 mL) at -65°C under a nitrogen atmosphere. The mixture was allowed to warm to -35°C over a period of 1 h before starting dropwise addition of **32** (13.5 g, 0.14 mol) in ether. Upon completion of the addition, the reaction mixture was maintained at -25°C for 10 h. The mixture was poured into ice plus saturated ammonium chloride, filtered through Celite, and extracted with ether. Removal of solvent in vacuo gave 92 g of crude material; another reaction gave 101 g. The acetal was hydrolyzed from the combined material using aqueous dichloroacetic acid and after purification with Girard's Reagent T and distillation, bp $112\text{--}114^{\circ}\text{C}$ (0.4 mm), ketol **35a** (15.28 g, 32%) was obtained: IR 3650 (w), 3450 (br), 2960 (s), 2940 (s), 2875 (s), 1748 (s), 1455 (m), 1400 (m), 1375 (m), 1025 cm^{-1} (s); NMR δ 0.92 and 0.95 (two overlapping doublets ca. 1:1, $J = 6.5$ Hz, 3 H), 1.10 (s, 3 H), 1.2–2.4 (m, 9 H), 3.32 (overlapping d, $J = 6$ Hz, and br s, 3 H).

Alternative Preparation of 35a from 38. A solution of lithium dimethylcuprate was prepared by the addition of methylolithium (35.3 mol of a 1.7 M solution, 60 mmol) to copper iodide (5.72 g, 30 mmol) in ether cooled to -10°C . The enone **38** (1.40 g, 6.2 mmol) in ether (25 mL) was added dropwise and the reaction mixture was allowed to stir at 0°C overnight. The mixture was worked up as described for **3** prepared from **43**. Generally the IR spectrum indicated a substantial amount of starting material remaining and the crude material was recycled until the enone carbonyl band was barely present. Removal of the acetal then gave ketol **35a**, the NMR and IR spectra of which compared satisfactorily with those of the material prepared above from **32**.

The mixture **35c** of labeled diastereomeric ketols **39c** and **40c** was prepared via this route in 45% crude yield based on labeled **38**.

α -Naphthylurethane Derivatives 39b and 40b. The ketol **35a** (1.00 g, 5.88 mmol) and α -naphthyl isocyanate (1.04 g, 6.16 mmol) in benzene (10 mL) were heated at reflux for 2 h. The oil obtained upon removal of solvent was sufficiently pure for preparative thin layer chromatography.

Labeled naphthyl derivatives were prepared from the mixture **35c** of ketols **39c** and **40c** in nearly quantitative yield following the above procedure.

Separation of Urethanes 39b and 40b. The diastereomeric urethanes were separated by chromatography on 20×20 cm glass plates pre-coated with silica gel (Analtech "Uniplates", 2000 μ thick, with UV-254 zinc silicate phosphor indicator).

The crude brown mixture of urethanes (ca. 200 mg/plate) was dissolved in 0.5–1.0 mL of acetone and applied as a thin band (3–5 mm) 1.5 cm from the bottom of each plate. This band was moved up by four repeated 2-cm elutions with acetone, drying the plates between each elution. The plates were then eluted five times with a freshly prepared mixture of ethyl acetate–hexane–benzene (1:4:2) in a pre-saturated chamber. The plates were dried and the eluent replaced after each run. The separation of the bands was followed by a UV lamp (UVS. 11 Mineralight). The two major bands (ca. 1.2 cm wide each) at ca. 8 and 10 cm from the bottom of the plate were scraped off and the silica gel extracted with ethyl acetate. Removal of the solvent gave two products (ca. 60 mg each.) Recrystallization from diethyl ether–petroleum ether gave each diastereomer as a white solid characterized by the following data.

Band at 10 cm (**40b**): mp $65\text{--}67^{\circ}\text{C}$; IR 3440 (w, free N–H) 3380–3280 (w, bonded N–H), 3050 (w), 2945 (m), 1740 (s, br), 1595 (w), 1575 (w), 1530 (m), 1490 (m), 1400 (w), 1340 (w), 1195 (s), 1175 (w), 1100 (w), 1070 (w), 1005 (w), 860 cm^{-1} (w); NMR (220 MHz, FT) δ 1.01 (d, $J = 6.9$ Hz, 3 H), 1.13 (s, 3 H), 1.20–2.40 (m, 9 H), 3.639 (overlapping dd, $J = 9, 10$ Hz, 1 H), 4.070 (dd, $J = 5, 10$ Hz, 1 H), 7.30–8.22 (m, 8 H).

Anal. Calcd for $\text{C}_{21}\text{H}_{25}\text{NO}_3$: C, 74.31; H, 7.42; N, 4.13. Found: C, 74.13; H, 7.34; N, 4.06.

Band at 8 cm (**39b**): mp $82\text{--}83^{\circ}\text{C}$; IR 3440 cm^{-1} (w, free N–H), no bonded N–H band, all other bands same as above; NMR (220 MHz, FT) δ 0.99 and 1.05 (d, $J = 6.6$ Hz, and s, respectively, 6 H), 1.15–2.32 (m, 9 H), 3.80–4.05 (two dd, $J_{AB} = 10.5, J_{AX}, J_{BX} = 6.9, 6.5$ Hz, 2 H), 7.060 (br s, 1 H), 7.30–7.95 (m, 7 H).

Anal. Found: C, 74.57; H, 7.29; N, 4.09.

Diastereomeric 3-Methyl-3-(3-hydroxy-2-methyl)propylcyclopentan-1-ones (39a,c and 40a,c). Ketourethane **40b** (150 mg, 0.44 mmol) was treated with ethylene glycol (0.12 mL, 2.2 mmol) and *p*-toluenesulfonic acid (10 mg) in refluxing benzene (18 mL) for 3

h with separation of water and removal of the initial azeotrope formed. Formation of the ketal was followed by thin layer chromatography (2.5×10 cm pre-coated slides with 250 μ silica gel; four elutions with 1:4:2 mixture of ethyl acetate–hexane–benzene; final distance from the bottom of the slide: ketourethane, 3.7 cm; ketal urethane, 4.3 cm) and NMR (increase of $-\text{OCH}_2\text{CH}_2\text{O}-$ signal at 3.67). Usual workup afforded the desired ketal (165 mg, 98%).

Labeled diastereomers **39b** and **40b** were ketalized in the same manner using 0.8–1.0 g of the ketone in 60 mL of benzene. The ketals had the following spectral properties: IR virtually same as IR of ketourethanes, 1735 cm^{-1} (C=O) band relatively less intense; NMR (ketal from **40b**) δ 0.93 and 1.02 (d, $J = 6$ Hz, and s, respectively, 6 H), 1.1–2.2 (m, ~ 9 H), 3.67 and 3.87 (s and m, respectively, ~ 6 H), 7.2–8.0 (m, 8 H); (ketal from **39b**) δ 0.93 and 1.02 (d, $J = 4$ Hz, and s, respectively, 6 H), 1.1–2.2 (m, 9 H), 3.67 and 3.7–4.1 (s and m, respectively, 6 H), 7.0–8.0 (m, 8 H).

A solution of ketal urethane (98 mg, 0.26 mmol, from **40b**) in ethanol (6 mL) was added to 10% aqueous NaOH (10 mL), and the mixture was heated at reflux for 3.5 h under nitrogen atmosphere. After concentration on a rotary evaporator, the aqueous phase was saturated with NaCl and extracted with ether. The ether solution was washed twice with cold ($5\text{--}10^{\circ}\text{C}$) aqueous 18% HCl. The acidic layer was further extracted with ether and the extracts combined with the original ether solution, washed with brine, and dried. The solvent was removed to yield keto alcohol **40a** (37 mg, 85% crude yield). Spectral properties: IR 3610 (w), 3450 (br), 2950 (s), 2920 (m), 1740 (s), 1455 (w), 1400 (w), 1375 (w), 1245 (w), 1170 (w), 1030 cm^{-1} (m); NMR (**40a**) δ 0.95 (d, $J = 6.5$ Hz, 3 H), 1.08 (s, 3 H), 1.2–2.4 (m, 9 H), 2.88 (br s, 1 H; variable, exchanged with deuterium), 3.28 (d, $J = 6$ Hz, 2 H); NMR for **39a** same as for **40a**, except upfield doublet at 0.93.

Labeled keto alcohols **39c** and **40c** were prepared following the same procedure (95% from labeled **39b** and **40b**).

3-Isobutyl-3-methylcyclopentanone (6) and Labeled Ketones 39d and 40d from Keto Alcohols 39a,c and 40a,c. Diastereomeric keto alcohols **39a,c** and **40a,c** were ketalized using the procedure for keto urethanes **39b** and **40b**. A trace of starting ketone remained unprotected. Yields of crude ketal were $>93\%$; IR (same for both diastereomers) 3600 (m, sh), 3500 (m, br), 2950 (s), 2925 (m), 2870 (m), 1450 (m), 1370 (w), 1330 (m), 1255 (w), 1100 (s), 1010 (w), 940 (m), 920 cm^{-1} (w); NMR (same for both diastereomers) δ 0.92 and 1.03 (d, $J = 6$ Hz, and s, respectively, 6 H), 1.2–2.2 (m, 9 H), 3.20 and 3.30 (br s, variable, and d, $J = 5$ Hz, respectively, 3 H), 3.77 (s, 4 H). A diastereomeric mixture of ketals from **39a** and **40a** (90 mg, 0.42 mmol) was dissolved in pyridine (2 mL) and treated with *p*-toluenesulfonyl chloride (150 mg, 0.79 mmol) at $0\text{--}4^{\circ}\text{C}$ for 22 h. The resulting mixture was poured over ice water (ca. 3 mL) and the product taken up in ether. The combined ether solution was washed with several portions of saturated aqueous CuSO_4 , to remove pyridine, and dried. The solvent was removed to give the desired tosylate (133 mg, 86%).

Labeled tosylate was prepared on a larger (5–6 times) scale in 93–97% yield. Up to 20% of the ketal was hydrolyzed prior to workup in each case as evidence by the weak C=O band in the IR and integration of the $-\text{OCH}_2\text{CH}_2\text{O}-$ signal in the NMR: IR 2950 (s), 2870 (m), 1745 (w), 1600 (w), 1460 (m), 1370 (s), 1185 (s), 1175 (s), 1100 (m), 960 (m), 940 cm^{-1} (w); NMR δ 0.93 and 0.98 (overlapping d and s, respectively, 6 H), 1.2–2.1 (m, 9 H), 2.45 (s, 3 H) (overlapping m and br s, ca. 5 H), 7.26 and 7.67 (two d, $J_{AB} = 8$ Hz, 4 H). Spectra of the two diastereomers were virtually the same.

A solution of ketal tosylate (133 mg, 0.36 mmol) in 5 mL of ether was added to LiAlH_4 (125 mg, 3.3 mmol) in 10 mL of ether, stirred under nitrogen atmosphere. The mixture was heated at reflux for 6 h under nitrogen, then cooled in an ice bath and hydrolyzed with saturated aqueous Na_2SO_4 (ca. 1.3 mL). The white precipitate was filtered and washed with ether. The combined ether solution was washed with brine and dried. The solvent was removed to give a colorless liquid (50 mg.) IR (3610 and 3550–3250 cm^{-1} (OH) and no C=O) and NMR (3.75 signal for $-\text{OCH}_2\text{CH}_2\text{O}-$ only ca. 70% of expected relative to $-\text{CH}_3$ signals at 0.9–1.1) analysis of the product suggested that part of the ketal had been hydrolyzed and the corresponding ketone reduced to the alcohol. The tosyl group reduction was complete.

Reduction of labeled ketal tosylates (2.1–2.6 mmol, ca. 85% ketalized) resulted in the loss of $>50\%$ of the protective ketal as evidenced by NMR. The crude product in each case was deketalized in

25–30 mL of 5% aqueous HCl solution for 1 h at room temperature. After workup (pentane) and removal of solvent, a mixture of ketone (**39d** or **40d**) and alcohol (no ketal signal in NMR; O–H and C=O bands in IR) was obtained.

The crude mixture was dissolved in acetone (20 mL) and treated with Jones reagent¹¹ at 15 °C for 1 h. Excess reagent was destroyed with isopropyl alcohol. After standard workup the desired ketone (**39d** or **40d**) was obtained (40–44%); spectroscopic properties were essentially identical with those given above for **6**.

4-Methyl-4-isobutylcyclopentenone (1) and Labeled Ketones 1e and 1f. Cyclopentanone **6** was brominated–dehydrobrominated according to the procedure of Garbisch,^{1,25} yielding **1** in 35% yield: IR 2955 (s), 2925 (w), 2905 (w), 2870 (w), 1722 (s), 1588 (w), 1462 (w), 1405 (w), 1380 (w), 1370 (w), 1362 (w), 1190 cm⁻¹ (w).

Labeled cyclopentenones **1e** and **1f** were prepared in ~70% yield from **39d** and **40d** by oxidation with palladium(II) as described elsewhere for oxidation of **6** to **1**.²⁸

1-Bromo-2-methylpropane-2-d (33). The bromide was prepared from **34**¹ in 83% yield according to the method of Wiley:²⁹ IR 2960 (s), 2935 (w), 2870 (w), 2145 (w), 1460 (m), 1425 (s), 1377 (m), 1362 (w), 1240 (m), 1228 (m), 1190 (w), 955 (w), 918 (w), 850 cm⁻¹ (w); NMR (220 MHz) δ 3.24 (t, $J = 1$ Hz, 2 H), 1.04 (t, $J = 1$ Hz, 6 H).

Preparation of 1d. The deuterium-labeled enone was prepared by conjugate addition of the Grignard reagent from **33** to **32** and introduction of the double bond by bromination–dehydrobromination as described above. In the 220-MHz NMR spectrum of **1d**, the dd at δ 1.51 had collapsed to a d, $J = 14$ Hz; the dd at 1.34 was simplified to a d, $J = 14$ Hz (slight additional splitting); and the isobutyl methyl doublets became triplets, $J \approx 1$ Hz.

3-Methyl-3-(2-methoxyethyl)cyclopentanone and Its Ethylene Ketal (31). Methylation of **30**²⁴ (7.37 g) was accomplished (78%) with sodium hydride and iodomethane in dimethyl sulfoxide as described previously for a homologous compound.¹ For characterization, the ketal was removed with 10% hydrochloric acid and the ketone purified by VPC on column C (155 °C): IR 2960 (s), 2938 (s), 2880 (s), 2835 (m), 2810 (m), 1748 (s), 1455 (m), 1400 (m), 1375 (w), 1110 cm⁻¹ (s); NMR (60 MHz) δ 3.47 (t, $J = 6.5$ Hz, 2 H), 3.31 (s, 3 H), 2.43–1.55 (m, 8 H), 1.08 (s, 3 H).

Anal. Calcd for C₉H₁₆O₂: C, 69.19; H, 10.32. Found: C, 69.26; H, 10.39.

4-Methyl-4-(2-methoxyethyl)cyclopentenone (2). The methoxy ketal (6.00 g) was brominated–dehydrobrominated, and hydrolyzed as described above to yield 1.07 g of enone **2**. An analytical sample was obtained on column C (165 °C): IR 2960 (m), 2930 (m), 2885 (m), 2835 (w), 2805 (w), 1723 (s), 1590 (w), 1115 cm⁻¹ (s); NMR (220 MHz) δ 7.31 (d, $J = 6$ Hz, 1 H), 5.88 (d, $J = 6$ Hz, 1 H), 3.40–3.23 (m, 2 H), 3.10 (s, 3 H), 2.30 (d, $J = 18$ Hz, 1 H), 2.00 (d, $J = 18$ Hz, 1 H), 1.85–1.62 (m, 2 H), 1.22 (s, 3 H).

Anal. Calcd for C₉H₁₄O₂: C, 70.10; H, 9.15. Found: C, 70.02; H, 9.27.

Wolff–Kishner Reduction of 24. A mixture of ketone **24** (40.1 mg), 97% hydrazine (0.3 mL), and ethylene glycol (1 mL), to which sodium hydride (31.5 mg) had been added, was sealed in a Carius tube and heated at 190 °C for 12 h.⁴¹ The reaction mixture was cooled before opening, diluted with water, and extracted with pentane. After removal of solvent by distillation, preparative VPC of the residue on column E (158 °C) gave **25** having identical spectra (220-MHz NMR and IR) and VPC retention time with an authentic sample.²¹

3-(2-Methyl-2-propenyl)cyclopent-2-enone (43). A suspension of methylmagnesium chloride was prepared from Mg (2.67 g, 0.11 g-atom) and 3-chloro-2-methylpropene (9.05 g, 0.10 mol) in ether (70 mL). 2-Cyclopentenone (3.87 g, 0.047 mol) in ether (50 mL) was added dropwise at 0 °C. The reaction mixture was poured into saturated ammonium chloride and extracted with ether. After drying and removal of solvent, the residue (3.05 g) was taken up in ether (70 mL) and treated at 0 °C with a solution of chromium trioxide (2.21 g) in 5% sulfuric acid (22 mL). The mixture was diluted with water and extracted with pentane. Solvent was removed by distillation and the residue was bulb-to-bulb distilled (140 °C, 8 mm) to give **43** (1.40 g, 22%): IR 3062 (w), 2960 (w), 2905 (m), 1712 (s), 1620 (s), 1435 (m), 1405 (w), 1177 (m), 890 cm⁻¹ (s); NMR (60 MHz) δ 5.85 (m, 1 H), 4.83 (m, 2 H), 3.07 (s, 2 H), 2.64–2.14 (m, 4 H), 1.73 (m, 3 H).

Anal. Calcd for C₉H₁₂O: C, 79.37; H, 8.88. Found: C, 79.65; H, 8.95.

3-Methyl-3-(2-methylprop-2-enyl)cyclopentanone (3) from Dienone

43. To a solution of lithium dimethylcuprate, prepared at 0 °C from copper iodide (3.92 g, 20.6 mmol) and methylolithium (24.2 ml of a 1.7 M solution, 41.2 mmol) in ether (100 mL), was added dropwise the dienone **43** (1.40 g, 10.3 mmol) in ether (50 mL). The reaction mixture was poured onto ice plus saturated ammonium chloride and extracted with ether. The solvent was removed by distillation and the residue was distilled bulb-to-bulb to give 1.03 g, bp 140 °C (8 mm). VPC analysis on column B (150 °C) indicated two components in the ratio of 3:1. The major, first eluted compound was identified as **3** on the basis of identical NMR and IR spectra; the minor peak was unreacted starting material.

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Indirect Detection of a Reversibly Formed Nonfluorescing Exciplex between Benz[*a*]anthracene and *cis*-1,3-Pentadiene. A General Method for Treating Photochemical Kinetic Data^{1a}

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Abstract: Oxygen enhancement of Stern–Volmer plot slopes for the quenching of benz[*a*]anthracene fluorescence by *cis*-1,3-pentadiene in benzene is shown to reveal the presence of a reversibly formed exciplex in this system. In establishing a relationship between experimental lifetime and quantum yield data and the rather complicated rate laws, an iterative least-squares analysis method has been applied which should find general applicability to problems of fitting photochemical kinetic data. The method is also applied to the system benz[*a*]anthracene-7-*d*/*cis*-1,3-pentadiene.

Exciplexes are thought to arise generally from the interaction of electronically excited aromatic hydrocarbon singlets and 1,3-dienes.² When exciplex fluorescence can be detected readily, measurement of quantum yields and lifetimes of this emission as well as that of the parent hydrocarbon can establish the pertinent rate parameters for the system.^{3,4} In the more usual case of weakly fluorescent⁵ or nonfluorescent² exciplexes, establishment of the presence of the exciplex and derivation of rate parameters associated with its formation and decay can be considerably more difficult.⁶ Recent experience with the effect of oxygen on aromatic hydrocarbon/exciplex decay has suggested that fluorescence lifetimes and quantum yields of the parent hydrocarbon alone can yield definitive proof of the existence of an exciplex provided that its formation is reversible.^{3,5,7,8}

The oxygen quenching method for inferring the presence of a nonfluorescing exciplex is applied to the benz[*a*]anthracene (BA)/ and benz[*a*]anthracene-7-*d* (DBA)/*cis*-1,3-pentadiene (P) systems. A method has been developed for correlating the data to the proposed kinetic scheme.

Results

Relative BA and DBA fluorescence quantum yields were determined as a function of [P] in degassed and air-saturated benzene solutions by measuring the reduction of emission intensity at 388 nm (Table I). Data for air-saturated solutions are reported in Table I relative to I_0 for degassed solutions. No

change in the shape of the fluorescence spectra could be detected with addition of P.

Decay rate constants of BA and DBA fluorescence were obtained by monitoring the emission at 430 nm from degassed and air-saturated benzene solutions with and without added P. First-order rate constants and estimated uncertainties are shown in Table II. These rate constants were obtained from semilogarithmic plots of the decaying side of the emission profiles. Visual inspection of these plots showed excellent adherence to single exponential decay.

Discussion

The mechanism

