Tetrahedron. Vol. 30, pp. 1891 to 1902. Pergamon Press 1974. Printed in Great Britain

A CHAPTER ON KETONE PHOTOCHEMISTRY

KURT SCHAFFNER*
Département de Chimie Organique, Université de Genève, 1211 Genève 4

and

OSCAR JEGER
Organisch-chemisches Laboratorium der Eidg. Technischen Hochschule, 8006 Zürich

(*Received* 3 *April* 1974)

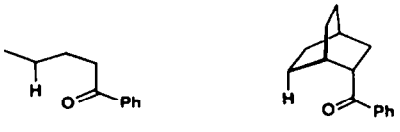
In review articles on Organic Photochemistry the subject is customarily, and appropriately so, introduced in paying tribute to early pioneers, notably the Italian school at the turn of the century, by mentioning the close interdisciplinary relationship with physical and theoretical chemistry, and by comments on the substantial increase in research volume and understanding of excited-state reactivity during the last two decades. (Particular satisfaction can be found in this connection in the tendency of modern chemistry teaching to accept the former "highly specialized field of excited-state chemistry" as an integral part complementing the knowledge of reactions of molecules in their electronic ground state).

However, a comprehensive review, even restricted to the photochemistry of ketones, is beyond the scope of this article. Instead, the authors, having struggled with the subject for the greater part of organic photochemistry's "renaissance" period, intend to scan through some of the research contributions accomplished by themselves and their coworkers. Following the threads of such investigations, mention of a majority of contributions from other laboratories which is legion, shall thus be sacrificed.

Photolytic hydrogen abstraction and cyclization reactions

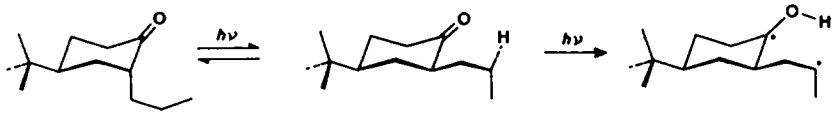
A combination of systematic probing into the photochemical potential of the carbonyl group and of a wide search for selective substitution methods on "non-activated" carbons in the late 1950's led to the discovery by Yang[1] and our group[2] of the photocyclization of saturated ketones to t-cyclobutanols. The reaction is a variation of the Norrish Type II process, initiated by the abstraction of a hydrogen sterically accessible to the half-vacant non-bonding p_y orbital on oxygen of the n, π^* excited carbonyl, followed by cyclization of the biradical intermediate. This steric requirement, which is normally accommodated with a six-membered cyclic transition state placing a γ hydrogen in a lateral position towards the oxygen, was confirmed experimentally. Lewis[3] demonstrated that excited-state reactivity of alkyl phenyl ketones toward γ-hydrogen abstraction is dependent upon molecular conformation reflecting entropic contributions to the transition state (*cf.*, k_γ $1{\cdot}2 \cdot 10^{-8}\,\mathrm{sec}^{-1}$ for **1** and $1{\cdot}0 \cdot 10^{-6}\,\mathrm{sec}^{-1}$ for **2**), and Turro[4] showed that γ-hydrogen abstraction in 2-propyl cyclohexanones occurs selectively in the *cis* isomer with equatorial side chain (**3**), while the *trans* ketone rather epimerizes in a photolytic α-cleavage (Norrish Type I process) and biradical recombination reaction. Furthermore, conformational rigidity in the 1,4-biradical intermediate may distinctly favor closure to cyclobutanols in fused alicyclic systems over cleavage of the central α,β carbon-carbon bond which usually dominates in aliphatic substrates.

Our early observations of t-cyclobutanol forma-



1

2



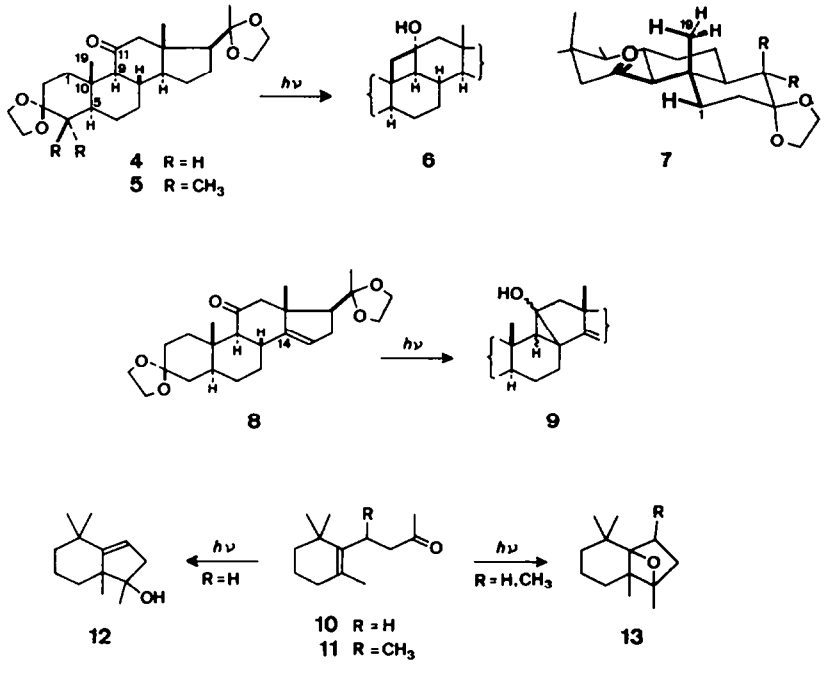
3

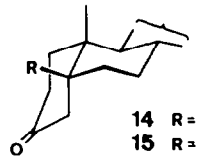
tion from ketosteroids strikingly exemplify these features which provide for a high degree of reaction selectivity and regiospecificity. *E.g.*, the 5α-pregnan-11-one **4** specifically gave the 11β,19-cyclosteroid **6**,[5] and the chemical yield of 47% was raised to 83% upon introduction of a *gem*-dimethyl group at C-4 (**5**).[6] Similar non-bonding steric interactions exerting either favorable or unfavorable effects upon the cyclobutanol formation are manifest in the 5β and Δ^5 analogs of **4**[6-8]. Inspection of ground state models of 11-ketosteroids, *cf.* **7**, reveals that the γ hydrogens at the two positions within reach of the oxygen (CH_3-19 and CH-1β) are above and below the non-bonding orbital. Yet, product formation occurs only through abstraction of a primary hydrogen from the methyl group 19. While cyclization of the 1,11-biradical formed upon an attack at the alternative position C-1 is precluded owing to prohibitive ring strain, the process could have been expected to lead to fragmentation of the 9,10 bond, the more so as the photolyses were carried out in alcoholic solvents known to normally suppress biradical reversion to ground state ketone.[9] This latter effect may be overridden by the practically rigid orthogonal orientation of the biradical orbitals with respect to the 9,10 bond, a geometry which is highly unfavorable for cleavage.[10] An interesting yet still hypothetical factor favoring an attack at CH_3-19 may also be seen in a pyramidal geometry of the excited keto group,† requiring in this case a slight out-of-plane bending of the C–O bond toward a half-axial conformation.

A remarkable change in the photochemical behavior was observed with the Δ^{14}-unsaturated 11-ketosteroid **8** which did not afford a 11,19-cyclobutanol, but rather the cyclopropanol product **9**.[12] Interestingly, a second γ,δ-unsaturated ketone, dihydro-β-ionone (**10**), isomerized to the cyclopentenol **12** in still another photocyclization process in addition to oxetane formation (**13**), whereas the methyl homologue **11** gave only the oxetane product **13**.[13] Mechanistic details on the reactions **8**→**9** and **10**→**12** are not yet known at this writing. Nevertheless, we may note that there is at least a *formal* analogy in the two transformations. In both an allylic β hydrogen is 1,4-transferred to the oxygen with ring closure to either terminal position of the allyl radical moiety. 1,4-Hydrogen transfer also accounts for the products formed on photolysis of some β-aminopropiophenones[14] and aliphatic α,β-unsaturated α-alkyl ketones.[15] The unique situation in **8** is, however, that a direct β-hydrogen abstraction would demand a particularly prohibitive geometric distortion, and a search for an alternative pathway seems appropriate.

A non-planar geometry of the excited ketone, as referred to above, has also been invoked in an attempt to rationalize results on the photoreduction of the steroidal ketones **14** and **15** to sec-alcohols. While they formed about equal amounts of reduc-

†*E.g.*, formaldehyde is known to adopt pyramidal conformations in the thermally equilibrated singlet and triplet excited states.[11]





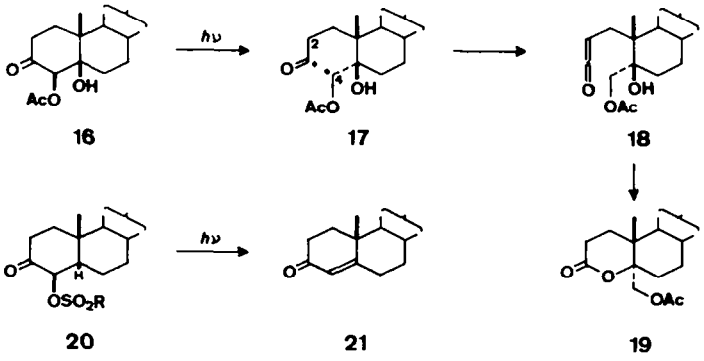
14 R = H
15 R = OH

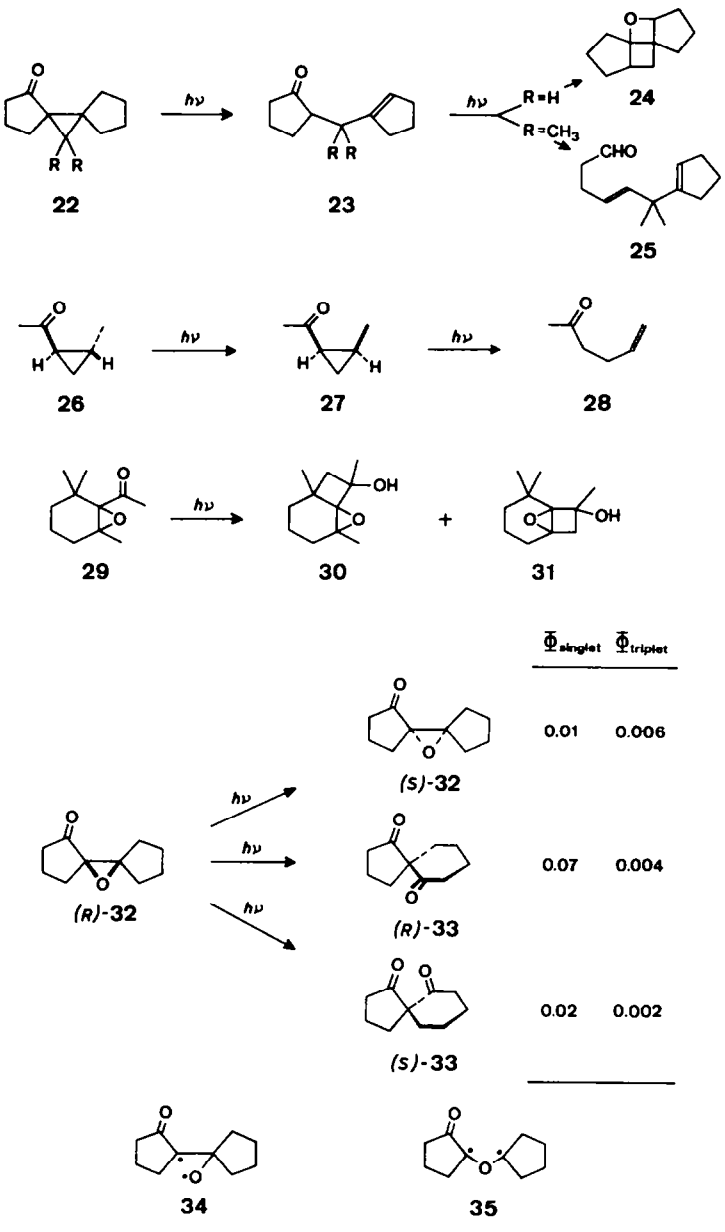
tion products in parallel runs using isopropanol both as solvent and hydrogen donor, the photoreduction with tri-n-butylstannane in benzene proved markedly less efficient for hydroxyketone **15** than for ketone **14**. Apparently the angular hydroxyl group in **15** provides a pathway to reduce the reactivity of the excited carbonyl group in benzene.[16] Taking into account that intramolecular H-bonding of the hydroxyl group to the ketone oxygen is excluded in the ground state for structural reasons whereas intermolecular interaction with the alcoholic solvent is important, it was argued that the nonbonding orbital in one of the two possible orientations of the pyramidal excited ketone could approach the hydroxylic hydrogen. This may suffice for an association providing, without entirely breaking the O–H bond, a pathway for a radiationless transition to the ground state.[17]

Photolytic cleavage of bonds attaching α-substituents

One section of the vast and still rapidly growing array of photorearrangements of ketones on which we have centred some of our efforts, is based on the light-induced cleavage of bonds attaching certain atoms or groups to the α carbon in processes other than the Type II cycloelimination. Such photocleavages are widely documented in the literature for a considerable number of examples $X–C_\alpha–C=O$ with X = mostly electronegative substituents or cyclopropane carbons. Utilization of the simple atomic orbital resonance model the n,π*-excited carbonyl had been assigned the dual capacity of ejecting such substituents as either radicals or anions.[18] The resulting $*C_\alpha–C=O$ group (* = ·or+) could be expected to smoothly initiate skeletal rearrangements in suitable aliphatic and alicyclic compounds. The following examples serve to demonstrate that the competition between different modes of primary photochemical processes may be controlled to a high degree by the nature of α-substituents and eventually be used to conduct highly selective transformations in excellent preparative yields. On irradiation in benzene, the steroidal α-acetoxy-β-hydroxyketone **16** readily isomerized to the acetoxylactone **19** in 88% yield.[19] The molecular mechanism responsible for this transformation is obviously a Norrish Type I α-cleavage to the biradical **17**, followed by an intramolecular hydrogen transfer from C-2 to C-4 and subsequent lactonization of the intermediate hydroxyketene **18**. With α-sulfonyloxy groups, however, photolytic elimination processes predominate to the exclusion of the α-cleavage. Thus, **20** (R=Me or *p*-tolyl) yielded the unsaturated ketone **21** in 80% yield.[19] Analogous results were also obtained with α-bromoketones.

Reaction selectivity cannot always be predicted on the basis of the nature of the α-substituent alone. Other structural features, including stereochemical factors, may occasionally play a decisive role. *E.g.*, ketones **22**,[20] **27**,[21] **29**,[22] and **32**[23] have in common both rigidly fixed γ hydrogens within reach of the oxygen and an α-cyclopropyl or α-epoxy group, yet compounds **22** (R=H or Me), **27** and **29** furnished only products from Type II fragmentation (→**23** and **28**) or cyclization (→**30** and **31**). The γ,δ-unsaturated ketones of type **23** proved too photoreactive themselves to accumulate in the product mixtures, but rather isomerized further to yield quantitatively the oxetane **24** (through a Paternó-Büchi cycloaddition of the carbonyl group to the double bond) and the doubly unsaturated aldehyde **25** (through ketone α-cleavage), respectively. Only the *trans*-cyclopropyl ketone **26**, which lacks suitable hydrogens for abstraction, rearranged to the *cis*-isomer **27**, evidently through a photolytic ring cleavage and recombination process. Similarly, compound **32**, the closest possible epoxy analogue of the cyclopropyl ketone **22** (R=H), appears to react exclusively through epoxide opening. A detailed study of the optically





active (*R*)-**32** showed that its photoisomerizations occur predominantly from the excited singlet state on direct irradiation, but that triplet sensitization can effect, although less efficiently, the same transformations. The quantum yield data exclude, however, that one common intermediate (*cf* **34**†) is involved in the three reaction paths in both the singlet and the triplet reaction. In particular, the racemization of the epoxyketone may be due to the reclosure of either or both biradicals **34** and **35**, and the rate difference between rearrangement and rotation around the central carbon-carbon bond is greater in singlet-generated **34** than in the triplet analogue.

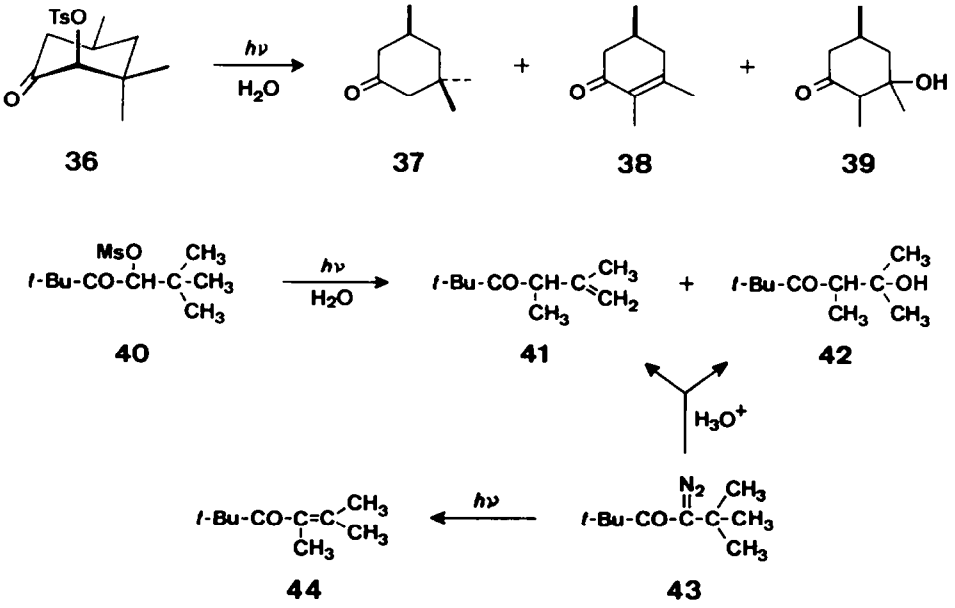
Evidence for the feasibility of a heterolytic photocleavage and formation of a ketocarbenium ion intermediate as well as information pertaining to the importance of steric criteria were obtained with the monocyclic ketone **36** possessing an axial

†A radical cleavage of the C_α–O bond has been favored over a heterolytic process on the basis of ($\beta \rightarrow \alpha$) migratory aptitudes.[24]

α-tosyloxy group and its equatorial isomer, and with the aliphatic sulfonyloxyketones **40** and **45**. On irradiation in dry dioxan, **36** afforded as 1:4 mixture of **37** and **38**, and in aqueous dioxan **38** and **39** were formed in a 5:1 ratio.[25] The mechanism of the reductive removal of the tosyloxy group and formation of the saturated ketone **37** is not resolved. Radical elimination of the α-substituent both directly from the excited ketone and subsequent to hydrogen abstraction by the carbonyl oxygen may account for this result. The formation of the ketones **38/39** and **41/42** (the latter from the photolysis of **40** in wet dioxan), however, demands that at least here the tosyloxy elimination is a direct photolytic process which proceeds in a heterolytic fashion to afford, via $\beta \rightarrow \alpha$ methyl migration, β-ketocarbenium ions. These on hydration are trapped as hydroxy-ketones **39** and **42** at the expense of the unsaturated ketones **38** and **41**, respectively. Independent support for cationic intermediates in the photochemical reaction path to **41** and **42** derives from decompositions of the diazoketone **43** which gave the same products in aqueous acid in the dark, whereas the conjugated ketone **44** was obtained exclusively on photolysis.[26]

Contrary to the relatively rapid photochemical conversion of the axial tosyloxyketone **36**, the equatorial isomer reacted only very slowly in dry dioxan yielding a 1:1 mixture of **37** and **38**. This result conforms with the model of a π^* – assisted cleavage mode[27] which should be sterically optimal when an axial σ bond is broken, and less efficient when an equatorial bond is involved.

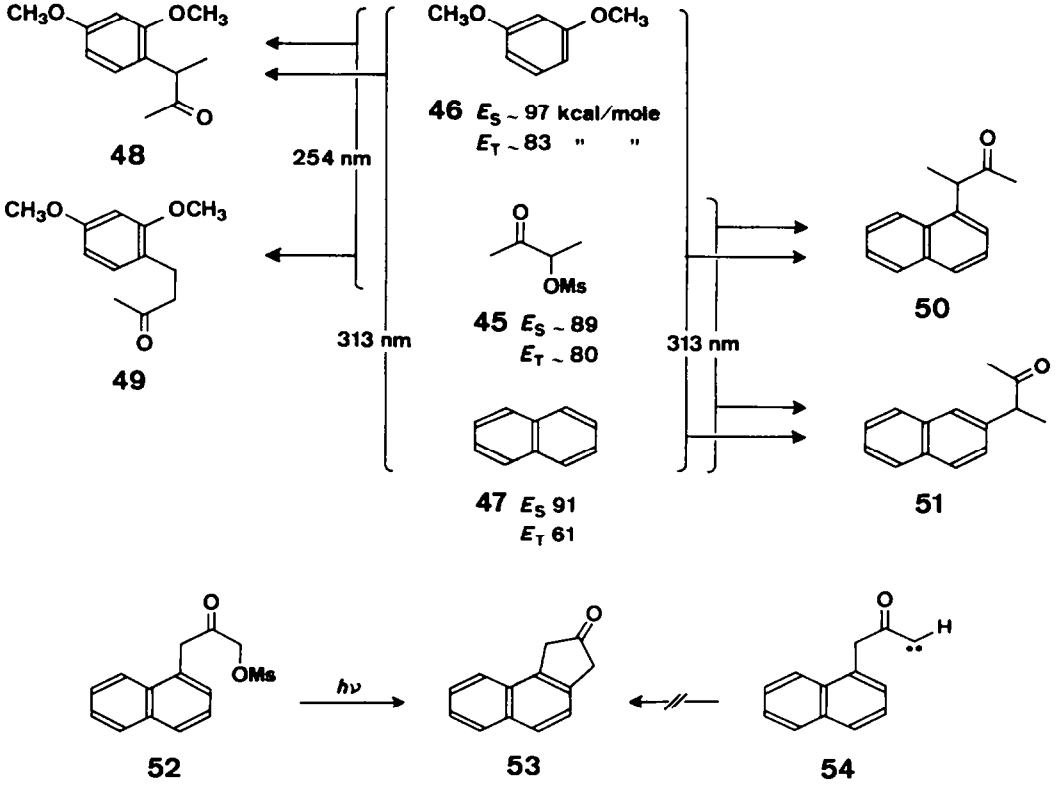
Furthermore, a combination of sensitization and quenching experiments with 2-mesyloxybutan-3-one (**45**) in acetonitrile demonstrated that two different, presumably radical and ionic, photoelimination modes selectively originate from the singlet and triplet excited states, respectively.[26,28,29] 1,3-Dimethoxy-benzene (**46**) which is higher in energy than **45** in both the singlet and triplet excited states, sensitized the mesyloxy elimination and gave the arylbutanones **48** and **49**. Addition of pentadiene as a triplet quencher of **45** and **46** selectively inhibited the formation of the β-substituted ketone (**49**). Naphthalene (**47**) ranks energetically between the singlet levels of compounds **45** and **46**, and much below their triplets. When used as a sensitizer, it afforded exclusively α-substituted butanones (**50** and **51**). Accordingly, selective excitation of naphthalene in a mixture of **45**, **46** and **47** furnished only the α-aryl ketones **48**, **50** and **51**. The direct experimental evidence available for assigning homolytic and heterolytic cleavage modes—both appearing likely events from the results of **36**, **40**, and **43**—to the singlet and triplet reactions of **45**, respectively, is not completely coherent. Acetic acid, when used as a solvent for the photolysis of **45** and **46**, suppressed the formation of the β-aryl ketone **49** and gave 1-acetoxybutan-3-one instead, but it did not interfere with the formation of α-aryl ketone **48**. Also, the α-ketocarbene **54** did not yield benz[*e*] indan-2-one (**53**) which is the major photoproduct of the ketomesylate **52**. Direct photolytic elimination of methanesulfonic acid to form ketocarbene intermediates is consequently ruled out in favor of radical decomposition in the singlet route to α-substitution, but it remains an alternative to a triplet elimination of mesylate anion although the former process has been disproved for

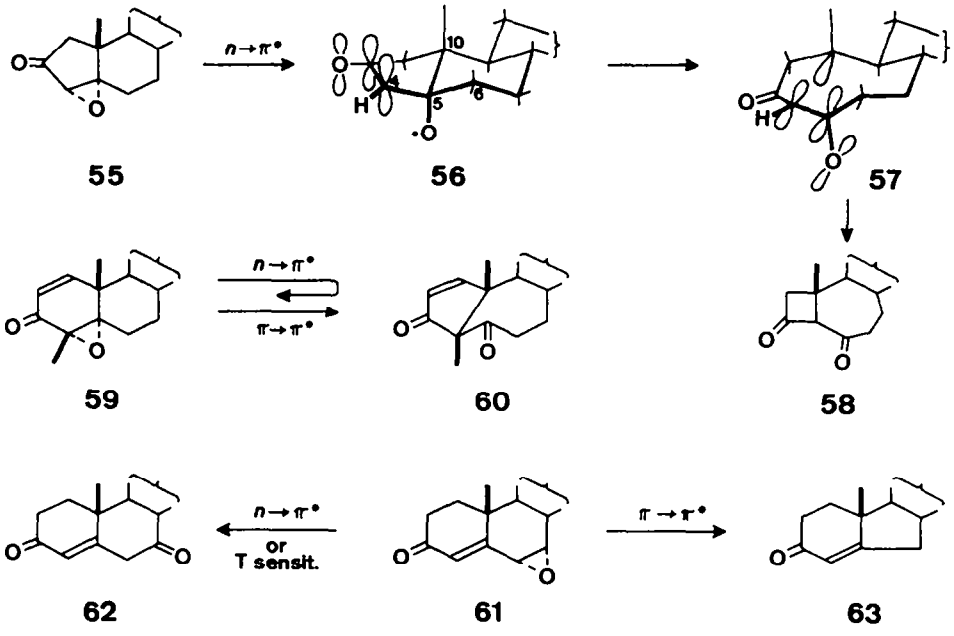


pivaloin mesylate (**40**). Both α-ketocarbene and α-ketocarbenium ion can be expected to give methyl vinyl ketone which may lead to the β-aryl ketone **49** in the acidic solution of the photolysis. We should note again, however, that in sulfonic-acid containing solutions in the dark or with ultraviolet light under otherwise comparable conditions neither hydration of **38**, **41** and **44** nor a deconjugation **44** → **41** were observed.

Despite the relatively complex reaction pattern exhibited by the simple bis-exocyclic α,β-epoxyketone **32**[30] the utilization of the photolytic C_α–O opening proved a successful tool to accomplish stereospecific and regioselective skeletal rearrangements of steroidal epoxyketones. In endocyclic epoxides such as, *e.g.*, **55** the C_α–O bond is properly aligned with the ketone π system for photolytic cleavage whereas the C_α–C_β bond is less favorably oriented. Epoxide epimerization via biradical intermediates corresponding to **35** is therefore less likely, and rotation around the C_α–C_β bond and reclosure— an alternative for the photoracemization of **32**—is not possible in many endocyclic epoxyketones. Furthermore, conformational constraints in fused alicyclic systems can render the stereoelectronics of the rearrangement of the intermediate biradical favorable for such 1,2-alkyl shifts which allow maintainance of continuous orbital overlap and electronic redistribution at the participating centres (*cf* **57**), hence inversion of configuration at the α carbon and retention at the (β → α)-migrating γ carbon. The resulting stereochemical and regional specificities of the epoxyketone rearrangement have been documented with numerous examples in the steroid field.[31,32] The case of the epoxyketone **55** may serve as an illustration where a concerted 10(5 → 4)-migration to form the cyclobutanone derivative **58** is exclusively chosen rather than dissociation of the 5,6 bond in biradical **56** and 4 → 6 cyclization to a much less strained bridged diketone.

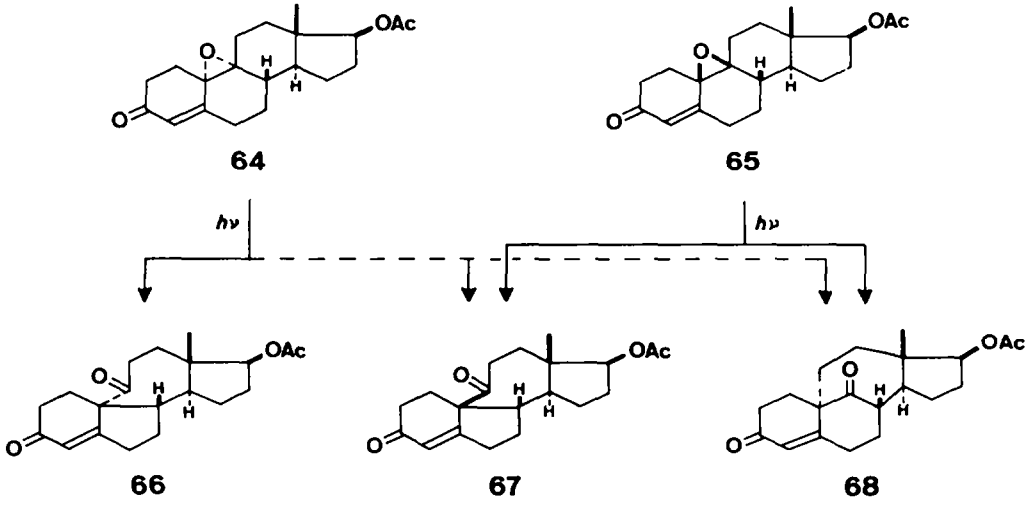
The attempt to subject the α′,β′-unsaturated α,β-epoxyketone **59** to the analogous photorearrangement uncovered a new photochemical property of cycloalkenones. On irradiation in the long-wavelength n-π* absorption band the compound remained unchanged, and the expected rearrangement to the β diketone **60** occurred only when **59** was excited to the second singlet (π,π*) state with 254 nm light.[32] Another example of a specifically π → π*-induced reaction of an enone was found with the α,β-unsaturated γ,δ-epoxyketone **61**.[33] In this case, however, isomerization to **62**—a double-bond homologous extension of the epoxide cleavage and rearrangement (of the δ hydrogen) discussed above for saturated epoxyketones—takes place almost quantitatively from the lowest-energy excited state on irradiation in the n → π* band with light





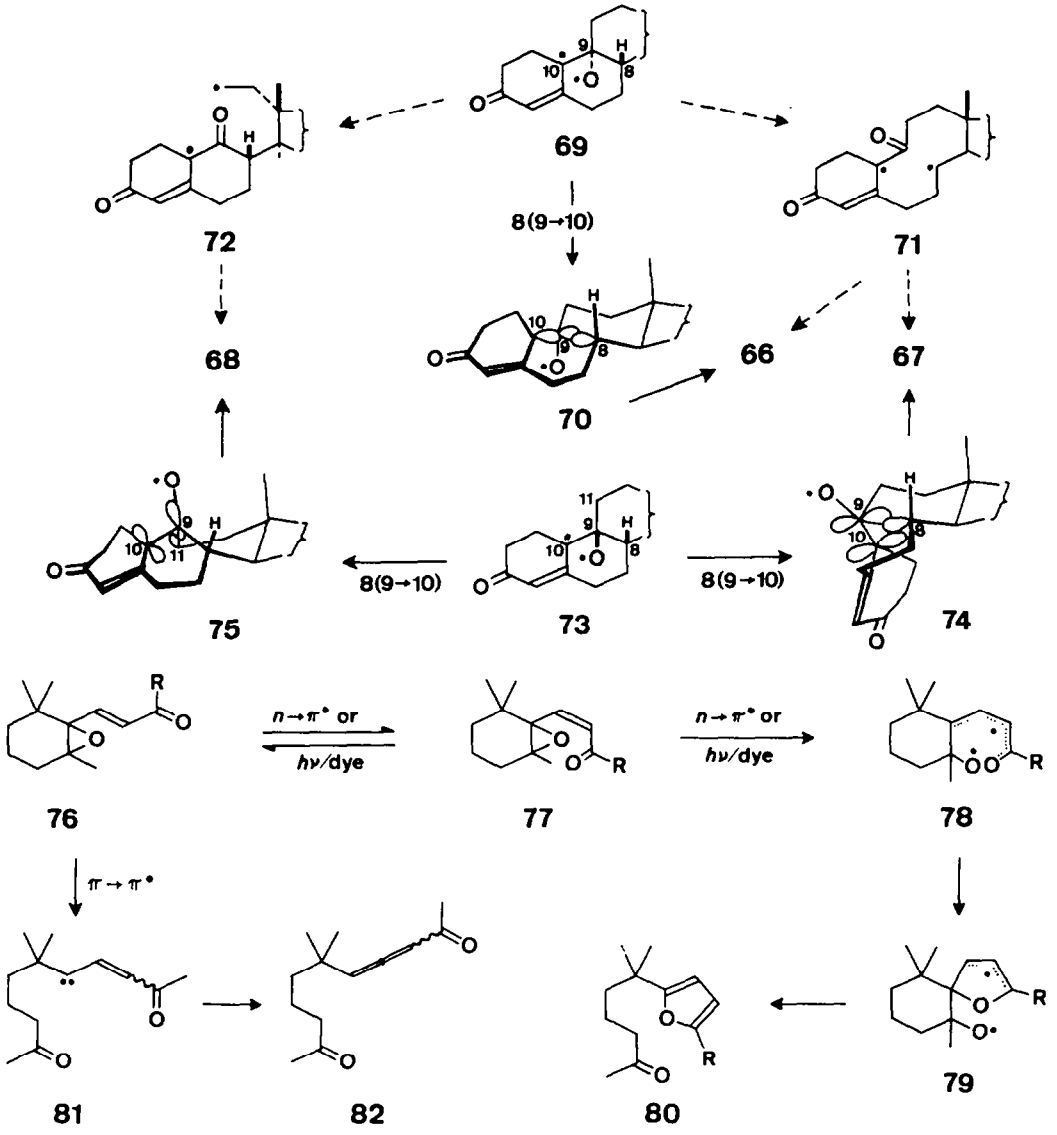
above 310 nm or on triplet sensitization using acetophenone. But an additional product, **63**, is formed here in about 30% yield when the irradiation is carried out with light of 254 nm (see also the following chapter for specifically $\pi \rightarrow \pi^*$-induced reactions of enones).

The photorearrangements of the epimeric compounds **64** and **65** exhibit some intriguing stereochemical aspects. They have been interpreted to illustrate particularly well how and to which extent stereoelectronic control due to conformational constraints in alicyclic systems may provide for selective transformations of such α,β-unsaturated γ,δ-epoxyketones.[34] Irradiation in the $n \rightarrow \pi^*$ absorption band of **64** in ethanol at −65°C exclusively afforded the rearranged ene-dione **66**; whereas at +24°C both under otherwise unchanged conditions and upon triplet sensitization essentially identical mixtures composed of product **66** (1 part), its stereoisomer **67** (*ca* 0·05 parts), and the structural isomer **68** (*ca* 0·1 part) were obtained. Selective $\pi \rightarrow \pi^*$ excitation of **64** at −78°C and +24°C led again to three-component mixtures with an even somewhat higher percentage of **67** and **68**. On the other hand, the epimeric epoxyketone **65** isomerized selectively to **67** and **68** at +24°C with both $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ excitation. Neither the epoxyketones **64** and **65** nor the photoproducts **66–68**



proved photochemically interconvertible. Inspection of the skeletal rearrangements of the intermediates **69** and **73**, which are assumed to result upon photolytic C_{10}–O bond cleavage of the epoxyketone, to **66** and **67/68**, respectively, reveals that in each case the required 1,2-alkyl shifts can smoothly proceed via transition states, *cf* **70**, **74** and **75**, profiting of three-center orbital overlap. Alternately, the loss of product selectivity due to such stereoelectronic control, which is observed for **64** at higher temperature with $n \rightarrow \pi^*$ excitation and with triplet sensitization, is explicable in terms of radical dissociation into **71** and **72** participating increasingly at the thermal transformation of **69**. The similar effect of $\pi \rightarrow \pi^*$ excitation even at low temperature indicates that some of the π,π^*-singlet energy may become available as thermal activation energy. One may further conclude that the smaller steric strain in **67** and **68**, as compared to **66**, is responsible for maintaining selectivity in product formation from **65** also at + 24°C and with $\pi \rightarrow \pi^*$ excitation.

Reaction paths other than $\delta \rightarrow \gamma$ migration become available to the photochemical C_γ–O fragmentation product of α,β-unsaturated γ,δ-epoxyketones when the enone group is aliphatic and thus is geometrically less restrained than within a cyclic frame. The conversion of *trans*-β-ionone epoxide (**76**, R=Me)[35,36] to the furyl ketone **80** suggests that *E*-*Z* isomerization of the double bond (→**77**) and epoxide cleavage (→**78**) is followed by cyclization between the ketone oxygen and the γ



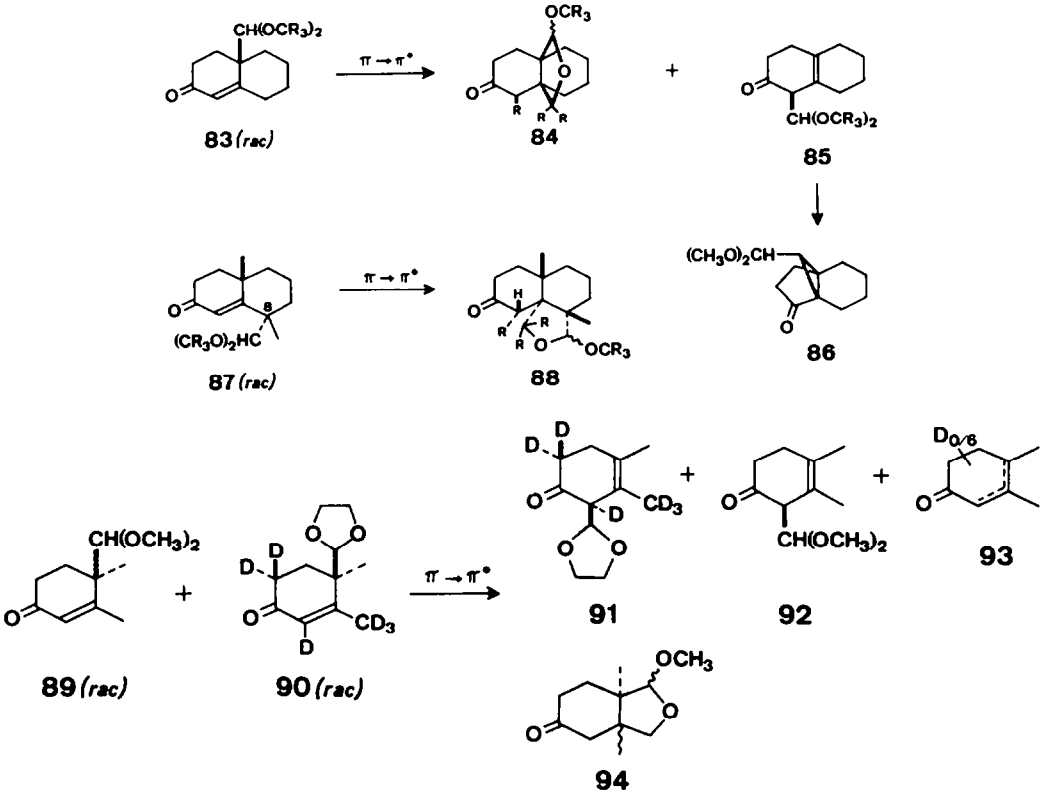
carbon, and 1,4 cleavage of the resulting biradical **79**.[36] The ring closure **78** → **79** occurs essentially to the exclusion of any skeletal rearrangement, and the furyl ketone **80** (R=Me) is formed as the sole product on n → π* irradiation to low conversion.[35] The preparative disadvantage due to the photoinstability of **80** on direct photolysis is overcome by the fact that the transformation **76** → **80** (R=Me) can be achieved in good chemical yield by irradiation in the presence of dyestuffs such as hematoporphyrin and methylene blue.[36] The role of *cis*-β-ionone epoxide (**77**, R=Me) as an intermediate in **76** → **80** is supported by the successful control of the stepwise reaction in the corresponding aldehyde series. Thus **76** (R=H) isomerized with hematoporphyrin selectively to **77**, while both **76** and **77** gave **80** on irradiation with dinaphthylene thiophene.

As in the case of the steroidal enone-epoxide **61**, π → π* excitation of **76** (R=Me) yields still other products, *e.g.* the allene **82**,[35] in addition to the furyl ketone **80**. As a possible route to **82** rupture of both the C_γ–O and C_γ–C_δ bonds to carbene **81** has been suggested.

Specifically π → π induced reactions of α,β-unsaturated ketones: γ → α Shifts and hydrogen abstraction by the α-carbon*

The α,β-unsaturated ketone **83** on irradiation at >313 nm showed the expected triplet reactions:[37] double bond migration to the β,γ-unsaturated isomer—due to intermolecular hydrogen transfer processes—as the predominant reaction in iso-octane solution, and relatively inefficient rearrangement in t-butyl alcohol to the bicyclo[3.1.0]hexanone isomer.[38] On selective excitation in the π → π* band with 254 nm new reactions were observed which efficiently competed with the processes from the low-lying triplet state. Isomerization to **84** and **85** were now the major reaction paths. The β,γ-unsaturated ketone **85** is photochemically quite labile, and, owing to sensitization by triplet-excited molecules of **83** in the photolysis mixture, it rearranged to the cyclopropyl ketone **86**.

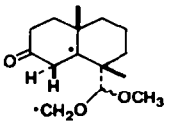
Evidence for the intramolecular nature of the 1,3 (γ → α) dimethoxymethyl shift in **83** → **85** was obtained in the photolysis of a mixture of the monocyclic ketones **89** and **90**.[39] The resulting γ → α rearranged acetals **91** and **92** had retained the isotopic composition of the respective starting compounds and thus showed that no intermolecular exchange of the acetal substituents had occurred. The rearrangement conforms to a sigmatropic 1,3 shift which is photochemically allowed by the orbital symmetry conservation rules of Woodward and Hoffmann, but a dissociation-recombination process involving an intimately associated radical pair



intermediate represents a mechanistic alternative. Indeed, the likewise specifically $\pi \rightarrow \pi^*$ induced formation of Δ^2- and Δ^3-dimethylcyclohexenones **93** may be taken as circumstantial evidence in favor of the latter mechanism.

The cyclizations **83**→**84** and **89**→**94** represent *formally* an addition of a methoxyl C–H bond to the double bond. The photolysis of a 1:1 mixture of **83**, R=H and D, gave a H/D isotope effect of 2·7 for the cyclization. No cross-transfer of methoxyl hydrogen or deuterium was found, and only non-deuteriated (**84**, R=H) and hexadeuteriated compounds (R=D) were formed, hence the hydrogen transfer to the ketonic α position in the final product is intramolecular. Assuming a stepwise reaction, hydrogen abstractions by the ketone oxygen and directly by the α carbon remain to be considered as possible primary photochemical processes. An NMR examination of the hemicyclic acetal (**84**) formed from **83** (R=D) in t-butyl alcohol showed that there is no protic exchange of deuterium as could have been expected to occur in an enolic intermediate resulting from deuterium transfer to the ketone oxygen[40] (thus invalidating an earlier erroneous conclusion). Ketone **87** (R=H,D) was chosen in order to explore the second reaction path. The methoxy groups of this compound are definitely too remote from the ketone oxygen to permit a hydrogen abstraction by the latter in any conceivable ring conformation. Nevertheless, they are equally favorably positioned as in **83** for an eventual direct hydrogen transfer to the α-carbon.

On $n \rightarrow \pi^*$ excitation (>340 nm) **87** (R=H) remained unchanged, but its—photochemically quite unreactive—triplet state was shown to sensitize the dimerization of added 1,3-cyclohexadiene. With $\pi \rightarrow \pi^*$ excitation at 254 nm, however, **87** (R=H and D) furnished the cyclization products **88** in 77% total yield after full photochemical conversion and chromatographic separation of the C-8′ epimers.[40]† Qualitatively identical results were also obtained with **87** (R=D) at 254 nm in t-butyl alcohol, again without any protic exchange of deuterium at position C-1. A product of a sigmatropic 1,3-dimethoxymethyl migration, analogous to **83**→**85**, has not been found in this series. In view of the structural constraints in **87**, this result proves that the photocyclization **87**→**88** involves a direct hydrogen transfer to the α-carbon (C-1) and, barring a concerted $\pi_s^2 + \sigma_s^2$ cycloaddition, the formation of the biradical intermediate **95**.



95

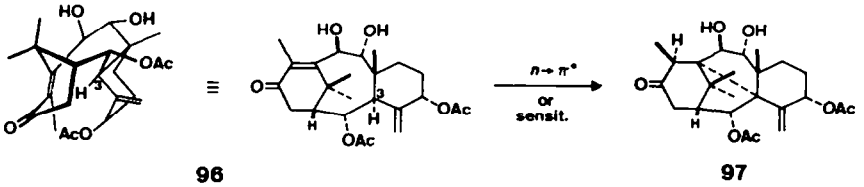
The identification of the reactive excited state in these transformations is still subject to further scrutiny. The quantum yield for both disappearance of starting material and product formation is 0·02 over the entire wavelength region of the $\pi \rightarrow \pi^*$ absorption band of **87**. Together with the fact that $n \rightarrow \pi^*$ excitation is insufficient, one may therefore conclude that either the vibrationally equilibrated $S_2(\pi,\pi^*)$ state is identical with the reactive species or that the latter is accessible only via S_2 but not via the energetically lower-lying S_1 (n,π^*) state.‡

Although we find no literature precedent for hydrogen transfer to the α-carbon of an enone in an upper excited state, the photoisomerization of taxinine and some of its derivatives, *e.g.* **96**, has been shown recently by Nakanishi[42] to follow a structurally similar path (→**97**) from the π,π^* triplet state. In view of the rigid orientation of the allylic C(3)–H bond in closest proximity and proper alignment above the enone double bond, a concerted addition has been envisaged as the most likely mechanism.

These hydrogen transfers to the α carbon supplement the hitherto known photoreductive processes of α,β-unsaturated cyclic ketones. Unless a particular reaction mode is entropically favored over an otherwise prevailing process for special stereotopic factors, n,π^* triplet states add hydrogen on the oxygen, and π,π^* triplet states add hydrogen to the β carbon. A correlation of these regiospecificities of hydrogen addition with excited-state configurations is available, *e.g.*, for the steroidal enone pair **98** and **100**.[41,43] An investigation of the singlet-triplet transition by phosphorescence excitation spectroscopy showed that the lowest-lying triplet state of **98** (6,6-difluoroandrost-4-ene-13,17-dione) is n,π^* in nature and that **100**

†Analogous results were also achieved with the C-8 diastereoisomer of **87**.[40]

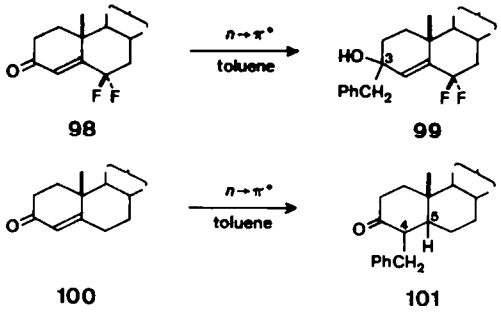
‡Note that in 10-methyl-$\Delta^{1(9)}$-octal-2-one both the n,π^* and $\pi\pi^*$ triplet states are below the n,π^* singlet energy level.[41]



96 **97**

(testosterone acetate) possesses a lowest π,π^* triplet. Irradiation of **98** at 366 nm in toluene solution afforded exclusively the 3-epimeric allyl alcohols **99** (the corresponding secondary allyl alcohols were formed in t-butyl alcohol), whereas **100** under identical conditions abstracted hydrogen with the β carbon and yielded the 4/5-epimeric α-benzyl ketones **101**.†

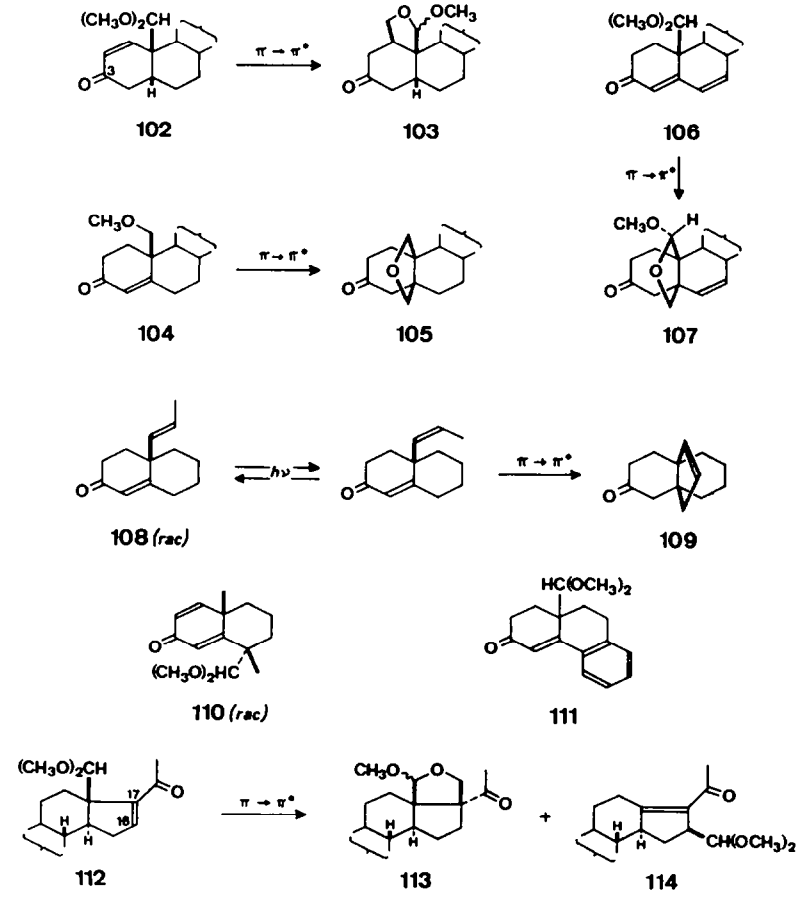
The specifically $\pi \rightarrow \pi^*$ induced cyclization of α,β-unsaturated δ-dimethoxymethyl ketones has been applied to various steroidal 3-ketone derivatives, often with satisfactory preparative yields.[46] *E.g.*, the transformations **102** → **103** and **104** → **105** gave yields of 65% and 30%, respectively, after chromatographic isolation, and the linear dienone **106** afforded 72% of product **107**. Furthermore, a synthetic access to carbocyclic systems, such as the propellane structure **109**, proved feasible with similar photocyclizations.[47] On irradiation of dienone **108** at 254 nm the formation of **109** (> 80%



yield in the presence of base to continuously reverse the bimolecularly controlled triplet double bond shift to the β,γ-unsaturated isomer) efficiently competed with the reversible *E-Z* photoisomerization of the aliphatic double bond which is the only unimolecular reaction on $n \rightarrow \pi^*$ excitation.

Limitations to the structural variability in starting materials were encountered with compounds **110**, **111**,[48] and **112**.[49] The cross-conjugated cyclohexadienone **110** rearranged to phenolic isomers—typical end products of multistep photorearrangements of cross-conjugated cyclohexadienones[50]—at

†For additional examples of hydrogen addition from toluene to the β-carbon, see Ref 44, and for analogous intramolecular hydrogen transfers, see Ref 45.



both >340 nm and 254 nm. While the linearly conjugated bicyclic dienone corresponding to **106** reacts analogously to the latter,[48] the benzohomologue **111** remained unchanged irrespective of the excitation wavelengths used. Finally, $\pi \rightarrow \pi^*$ excitation of the steroid **112** gave rise to a photocyclization (→**113**) which corresponds to hydrogen addition to the β position (C-16) and α alkylation (C-17), although a parallel 1,3 migration of the dimethoxymethyl substituent was observed here as in **83**, **89**, and **90**.

CONCLUSION

One may confidently accept the assumption that most general principles of ketone and aldehyde photoreactions are known today, with the variability being naturally limited. However, we hope to have shown above—and many more convincing examples are available from the literature—that novel features and unexpected variations in photochemical behavior are often introduced as a function of the complexity of molecular structures, and that for this reason continued research in this area is still worthwhile.

REFERENCES

[1]N. C. Yang and D.-D. H. Yang, *J. Am. Chem. Soc.* **80**, 2913, (1958); *Tetrahedron Letters* 10 (1960)

[2]P. Buchschacher, M. Cereghetti, H. Wehrli, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **42**, 2122 (1959); M. Cereghetti, H. Wehrli, K. Schaffner, and O. Jeger, *Ibid.* **43**, 354 (1960); H. Wehrli, M. Cereghetti, K. Schaffner, J. Urech, and E. Vischer, *Ibid.* **44**, 1927 (1961)

[3]F. D. Lewis, R. W. Johnson, and D. R. Kory, *J. Am. Chem. Soc.* **95**, 6470 (1973), and Refs therein

[4]N. J. Turro and D. S. Weiss, *Ibid.* **90**, 2185 (1968); K. Dawes, J. C. Dalton, and N. J. Turro, *Mol. Photochem.* **3**, 71 (1971)

[5]H. Wehrli, M. S. Heller, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **44**, 2162 (1961)

[6]J. Iriarte, K. Schaffner, and O. Jeger, *Ibid.* **46**, 1599 (1963)

[7]M. S. Heller, H. Wehrli, Schaffner, and O. Jeger, *Ibid.* **45**, 1261 (1962)

[8]For a detailed discussion, see O. Jeger and K. Schaffner, *Chem. Weekblad* **60**, 389 (1964)

[9]P. J. Wagner, I. E. Kochevar, and A. E. Kamppainen, *J. Am. Chem. Soc.* **94**, 7489 (1972)

[10]D. S. Weiss, N. J. Turro, and J. C. Dalton, *Mol. Photochem.* **2**, 91 (1970); I. Fleming, A. V. Kemp-Jones, and E. J. Thomas, *Chem. Commun.* 1158 (1971)

[11]E. W. Abrahamson, J. G. F. Littler, and K. -P. Vo, *J. Chem. Phys.* **44**, 4082 (1962), and Refs therein

[12]P. Gull, H. Wehrli, and O. Jeger, *Helv. Chim. Acta* **54**, 2158 (1971)

[13]M. Zink, H. Wolf, and O. Jeger, unpublished results

[14]H. J. Roth and M. H. El-Raïe, *Tetrahedron Letters* 2445 (1970); *Arch. Pharm.* **305**, 213, 229 (1972)

[15]R. A. Cormier, W. L. Schreiber, and W. C. Agosta, *Chem. Commun.* 729 (1972)

[16]P. Keller, G. Eggart, H. Wehrli, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **50**, 2259 (1967)

[17]For a discussion, see also K. Schaffner, *Pure Appl. Chem.* **16**, 75 (1968)

[18]H. E. Zimmermann, *Adv. Photochem.* **1**, 393 (1963)

[19]G. Hüppi, G. Eggart, S. Iwasaki, H. Wehrli, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **49**, 1968 (1966)

[20]H. J. Wüthrich, Doctoral Thesis, ETH Zürich (1972)

[21]W. G. Dauben, L. Schutte, and R. E. Wolf, *J. Org. Chem.* **34**, 1849 (1969)

[22]E. Müller, H. Wolf, and O. Jeger, unpublished results

[23]H. J. Wüthrich, A. Siewinski, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **56**, 239 (1973)

[24]*cf.* C. K. Johnson, B. Dominy, and W. Reusch, *J. Am. Chem. Soc.* **85**, 3894 (1963); H. E. Zimmermann, B. R. Cowley, C.-Y. Tseng, and J. W. Wilson, *Ibid.* **86**, 947 (1964)

[25]S. Iwasaki and K. Schaffner, *Helv. Chim. Acta* **51**, 557 (1968)

[26]A. Tuinman, A. Ghosh, K. Schaffner, and O. Jeger, *Chimia* **24**, 27 (1970); A. Ghosh and K. Schaffner, unpublished results

[27]L. D. Hess, J. L. Jacobson, K. Schaffner, and J. N. Pitts, Jr., *J. Am. Chem. Soc.* **89**, 3684 (1967)

[28]A. Tuinman, S. Iwasaki, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **51**, 1778 (1968); J. Gauthier and K. Schaffner, unpublished results (1971)

[29]A. Tuinman, Doctoral Thesis, ETH Zürich (1970)

[30]Similar results were also reported by Johnson *et al.*[24] for the diastereomeric pulegone oxides

[31]H. Wehrli, C. Lehmann, K. Schaffner, and O. Jeger, *Helv. Chim. Acta* **47**, 1336 (1964); H. Wehrli, C. Lehmann, T. Iizuka, K. Schaffner, and O. Jeger, *Ibid.* **50**, 2403 (1967); J. Pfister, C. Lehmann, and H. Wehrli, *Ibid.* **51**, 1505 (1968)

[32]H. Wehrli, C. Lehmann, P. Keller, J.-J. Bonet, K. Schaffner, and O. Jeger, *Ibid.* **49**, 2218 (1966)

[33]J. A. Saboz, T. Iizuka, H. Wehrli, K. Schaffner, and O. Jeger, *Ibid.* **51**, 1362 (1968)

[34]D. Bauer, T. Iizuka, K. Schaffner, and O. Jeger, *Ibid.* **55**, 852 (1972)

[35]B. R. von Wartburg, H. R. Wolf, and O. Jeger, *Ibid. Ata* **56**, 1948 (1973)

[36]W. Skorianetz and G. Ohloff, *Ibid.* **56**, 2151 (1973)

[37]D. Belluš, D. R. Kearns, and K. Schaffner, *Ibid.* **52**, 971 (1969); P. Margaretha and K. Schaffner, *Ibid.* **56**, 2884 (1973), and Refs therein

[38]J. Gloor, K. Schaffner, and O. Jeger, *Ibid.* **54**, 1864 (1971)

[39]J. Gloor and K. Schaffner, unpublished results; *cf.* K. Schaffner, *Pure Appl. Chem.* **33**, 329 (1973)

[40]J. Gloor, G. Bernardinelli, R. Gerdil, and K. Schaffner, *Helv. Chim. Acta* **56**, 2520 (1973)

[41]*cf.* G. Marsh, D. R. Kearns, and K. Schaffner, *J. Amer. Chem. Soc.* **93**, 3129 (1971), and Refs therein

[42]T. Kobayashi, M. Kurono, H. Sato, and K. Nakanishi, *J. Am. Chem. Soc.* **94**, 2863 (1972)

[43]K. Schaffner, *Pure Appl. Chem., Suppl.* **1**, 405 (1971)

[44]R. Reinfried, D. Belluš, and K. Schaffner, *Helv. Chim. Acta* **54**, 1517 (1971)

[45]S. Wolff, W. L. Schreiber, A. B. Smith, III, and W. C. Agosta, *J. Am. Chem. Soc.* **94**, 7797 (1972)

[46]M. Karvaś, F. Marti, H. Wehrli, K. Schaffner, and O. Jeger, unpublished results

[47]F. Nobs and K. Schaffner, unpublished results; *cf.* J. Gloor, F. Nobs, and K. Schaffner, *Chimia* **28**, 22 (1974)

[48]J. Gloor and K. Schaffner, unpublished results

[49]F. Marti, H. Wehrli, and O. Jeger, *Helv. Chim. Acta* **56**, 2698 (1973)

[50]K. Schaffner, *Adv. Photochem.* **4**, 81 (1966)