Photochemistry of α-Hydroxy-β,γ-unsaturated Ketones. A Photochemical Synthesis of 1,4-Diketones

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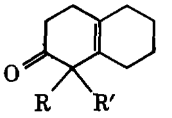
Abstract: The photochemical reactions of 3-hydroxy-3-methylpent-4-en-2-one and 1-acetylcyclohex-2-en-1-ol have been studied to evaluate the mechanistic effects of an α-hydroxy substituent on β,γ-unsaturated ketone photoreactivity and to assess the viability of a photochemical 1,4-diketone synthesis from α-hydroxy-β,γ-unsaturated ketones. Direct irradiation of 3-hydroxy-3-methylpent-4-en-2-one gave 2,5-hexanedione in 33% yield (87% of volatiles) and 1-acetylcyclohex-2-en-1-ol gave 3-acetylcyclohexanone in 22% yield (78% of volatiles). The rearrangement of 1-acetylcyclohex-2-en-1-ol to the 1,4-diketone was accompanied by cyclohexanone, cyclohex-2-en-1-one, acetaldehyde, and biacetyl, suggesting a stepwise α-cleavage mechanism for the 1,3-shift. Surprisingly, xanthone-sensitized irradiation of both α-hydroxy ketones gave essentially the same product distribution as in direct irradiation, albeit with greatly reduced quantum efficiency, suggesting that these two β,γ-unsaturated ketones differ from the norm in undergoing triplet-state 1,3-shifts. The relationship of these findings to other studies is discussed.

Introduction

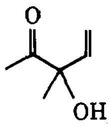
Since Buchi and Burgess reported observing the first 1,3-acyl shift in 1960,[1] β,γ-unsaturated ketones have become one of the most widely investigated photochemical systems. Comprehensive reviews are now available which summarize the complex photochemistry of these molecules.[2-4] This paper directs attention to a more subtle and relatively unexplored aspect of β,γ-unsaturated ketone photochemistry, namely the *mechanistic and synthetic consequences* of α-substitution, particularly the effects of α-oxy groups.[5,6]



1a, R = H, R′ = H
1b, R = H, R′ = CH_3
1c, R = CH_3, R′ = CH_3

Few studies to date have considered the effects of α-substituents on the photochemistry of β,γ-unsaturated ketones. The most notable example is the recent work of Engel et al., who discovered that increasing α-methylation in the $\Delta^{9,10}$-octalone series **1a–c** strongly promoted the 1,3-acyl sigmatropic shift at the expense of the oxadi-π-methane reaction of the lowest triplet.[7]

We have examined the photochemical behavior of two α-hydroxy-β,γ-unsaturated ketones, namely 3-hydroxy-3-methylpent-4-en-2-one (**2**)[5a,c] and 1-acetylcyclohex-2-en-1-ol (**3**).[5a,b] Our interest in the α-hydroxy modification of the simple β,γ-unsaturated ketone bichromophore was twofold. Firstly, we were intrigued by the possibility of transforming the class of molecules **4** to the 1,4-diketones **6** by means of photolysis. Thus, if the n-π* singlet excited state of **4** were to follow the precedent set by numerous other β,γ-unsaturated ketones,[2,3] it would undergo a 1,3-acyl shift giving the intermediate enol **5**. Rapid enol–keto tautomerization would be anticipated, leading to the 1,4-diketone **6** (eq 1). Such a synthetic scheme for γ-diketones could be advantageous because of the inherently mild reaction conditions of photolysis (neutral medium, ambient temperature, etc.).



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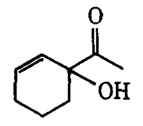

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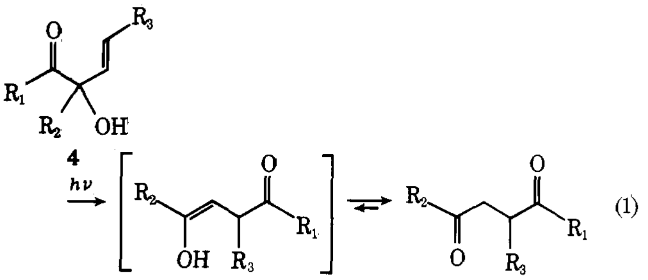
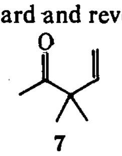


4 **5** **6** (1)

Secondly, but of equal importance in the photochemical study of α-hydroxy-β,γ-unsaturated ketones, we sought to explore the mechanistic effects of the α-hydroxy substituent. In view of recent work of Engel and Schexnayder[7,8] it was not unreasonable to assume that an α-hydroxy substituent could have an equally profound influence on β,γ-unsaturated ketone excited-state behavior, particularly when one considers the high electronegativity of oxygen and its radical-stabilizing characteristics.

To date, only a few investigations of α-oxy-β,γ-unsaturated ketones have been reported. Sasaki et al.,[9,10] McMurry et al.,[11] Carlson and Prabhu,[12] and we[5] have reported the excited-state behavior of some α-hydroxy-β,γ-unsaturated ketones. However, the molecules studied by Sasaki[9,10] and McMurry[11] were rigid polycyclics and, in some cases, also α′,β′-unsaturated. They were, therefore, less than perfect mechanistic models for α-hydroxy-β,γ-unsaturated ketones in general.

3-Hydroxy-3-methylpent-4-en-2-one (**2**) and 1-acetylcyclohex-2-en-1-ol (**3**) were chosen as suitable models whose molecular geometry would not be expected to artificially enhance the 1,3-acyl shift product yield. For example, 3,3-dimethylpent-4-en-2-one (**7**), an acyclic system structurally similar to **2**, gives only 22% of the 1,3-acyl shift product.[13,14] Cyclic systems such as **8**, however, frequently give much higher yields of the 1,3-acyl shift product, presumably because the α-cleavage radicals are held in close proximity by the residual ring bridge. This dramatic difference can be seen in the fact that the reversible 1,3-acyl shift of **8** is very efficient in the sense that side products are negligible and that the quantum yields for the forward and reverse reactions sum to about 0.70.[15]



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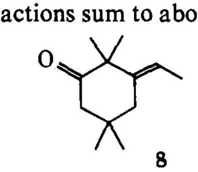

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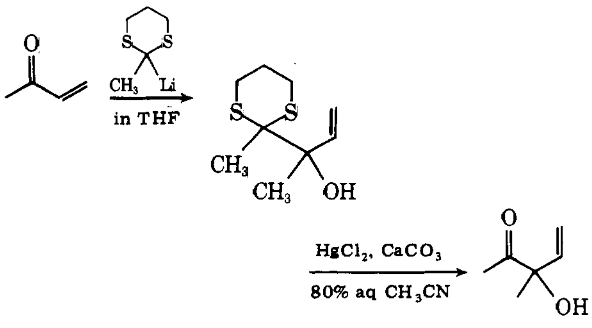
No special effect of this sort was anticipated in **2** or **3**, since the carbonyl is not incorporated into a ring. On the other hand, all α-hydroxy-β,γ-unsaturated ketones differ from their nonhydroxylated counterparts because of the possibility of H bonding between the carbonyl and hydroxyl groups.[9,16] This carbonyl:hydroxyl H bonding in α-hydroxy-β,γ-unsaturated ketones has reportedly been reflected in the electronic absorption spectra as either abnormally small hypsochromic[9] or even bathochromic[16d] shifts of the n-π* band with increasing solvent polarity. Several explanations for the effect have been offered.[9,16]

Results

Synthesis. The α-hydroxy-β,γ-unsaturated ketones **9** and **10** were prepared according to the method of Corey et al.[17] and Seebach.[18] Following addition of 2-lithio-2-methyl-1,3-dithiane to methyl vinyl ketone (for **2**) or 2-cyclohexenone (for **3**), the ketols **2** and **3** were obtained from the dithiane adducts by cleavage with a calcium carbonate buffered solution of mercuric chloride in 80% aqueous acetonitrile. An alternative cleavage procedure using *N*-chlorosuccinimide and silver nitrate in 80% aqueous acetonitrile was less satisfactory. Overall yields of **2** and **3** were 39 and 62%, respectively (eq 2 and 3).



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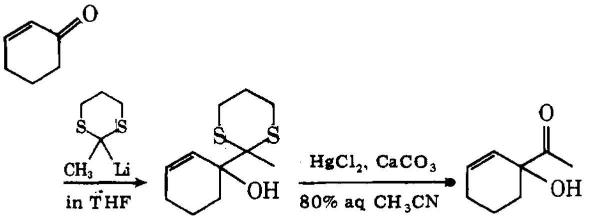

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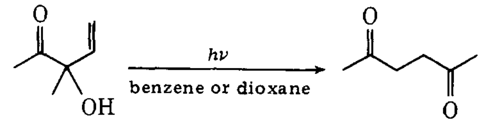
(3)

All spectral parameters recorded (cf. Experimental Section) were consistent with the structures of **2** and **3**. Ultraviolet spectra for the two compounds were recorded in both cyclohexane and acetonitrile. Maxima for the n-π* band of **3** were at 283 nm (ε 73) in the former and at 287 (ε 72) in the latter, corresponding to a pronounced *bathochromic* absorption shift with increasing solvent polarity. A similar result was seen for **2**, with the n-π* maximum at 280 nm (ε 149) in cyclohexane, but bathochromically shifted to 285 nm (ε 124) in acetonitrile.

Direct Photolyses. Typical photolyses were run on degassed 10% (by volume) solutions of **2** or **3** in spectral grade benzene or dioxane. In each case the reaction was monitored by GLC (cf. Experimental Section) and NMR, using hexadecane (for **2**) and nonadecane (for **3**) as internal standards.

Irradiation of **2** for 1 h resulted in more than 60% destruction of the ketol. A new peak was apparent in the GLC trace which was easily separable from the starting ketol (**2**) by preparative GLC. The photoproduct was an isomer of **2**, having the same molecular weight (114) by mass spectral analysis. The infrared, with no hydroxyl group but a strong carbonyl absorption at 1710 cm^{-1}, and the NMR, with two singlets in a ratio of 3:2 at δ 2.12 and 2.58, identified the photoproduct as 2,5-hexanedione (**9**) (Scheme I), an assignment proven conclusively by comparison of spectra and GLC retention times with those of an authentic sample.[19] Three more volatile photoproducts were visible in trace amounts, having GLC retention times less than the solvent. Because they were present only in minute quantities, no attempt was made to ascertain their identities. The yield of **9** was found to be maximized at 33% overall (87% of the volatile fraction) after 11 h of photolysis, by which time 98% of **2** had been destroyed.

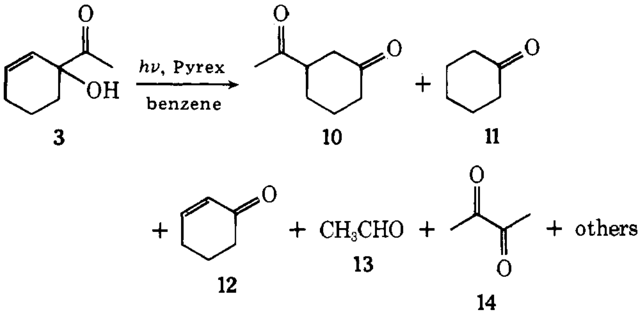
Scheme I. Direct Photolysis of 3-Hydroxy-3-methylpent-4-en-2-one



2 **9**

Photolysis of **3** gave NMR spectra which showed a monotonic increase in the aliphatic:vinyl peak intensity ratio on increasing irradiation time, broadening and eventual disappearance of the originally sharp hydroxyl resonance, and the appearance and steady growth of a sharp spike at δ 1.78. Prolonged irradiation caused the solutions to become pale yellow. GLC analysis revealed the formation of one major primary photoproduct and nine minor products (Scheme II). Monitoring the disappearance of starting material (**3**) and the appearance of the major photoproduct (**10**) vs. irradiation time indicated that the yield of **10** was maximized at about 66–91% reaction of **3**. At 86% reaction, photoproduct **10** accounted for 78% of the volatile components, but only for about 22% of total reaction, suggesting polymerization also occurred. (The minor reaction products are also compatible with this interpretation.) Further reaction of **3** was inefficient due to the internal filtering effect of the yellowing solution, and yields of the major photoproduct diminished on extended irradiation as secondary reactions became dominant.

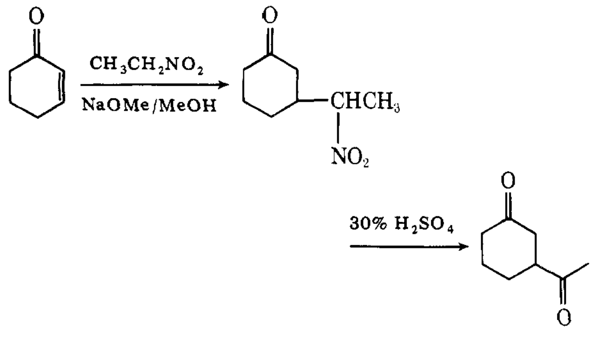
Scheme II. Photochemistry of 1-Acetylcyclohex-2-en-1-ol



The major product (**10**) was collected by preparative gas-liquid chromatography on SE-30 at 147 °C. The mass, IR, and NMR spectra of material isolated from photolysates were identical with those of authentic samples of 3-acetylcyclohexanone synthesized by the methods of McCoubrey[20] (eq 4) and Corey and Crouse[17b] (eq 5).

Among the minor products, four were identified by their GLC retention times on multiple columns (cf. Experimental Section). These were cyclohexanone (**11**, the most abundant by-product, 13% of volatiles), cyclohex-2-en-1-one (**12**, trace), acetaldehyde (**13**, trace), and biacetyl (**14**, trace). At least five other trace products remained unidentified. It was also shown from GLC retention times that 2-acetylcyclohexanone (**15**), cyclohex-2-en-1-ol (**16**), and cyclohexanol (**17**) were definitely not among the photoproducts of **3** on direct irradiation.

A plot of the appearance of the minor photoproducts **11** and **12** vs. irradiation time showed no induction period and indicated both were primary photoproducts of **3**; however, both are also photoproducts of secondary photolysis of **10**.



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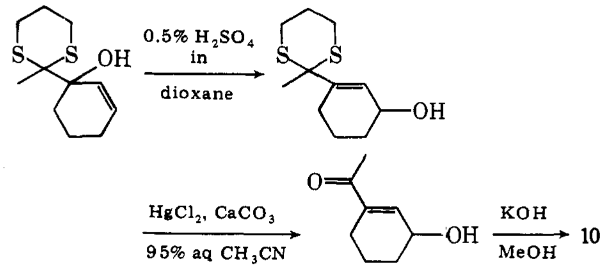

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Multiplicity Studies. Two samples of **2** in *p*-dioxane, one containing 1 M 1,3-cyclohexadiene as an indicating quencher,[21-24] were irradiated in parallel and monitored by GLC periodically for 41 h. Neither singlet nor triplet cyclohexadiene dimers were found,[21-24] nor was the principal singlet quenching product, 1,3,5-hexatriene, observed.[23,24] Furthermore, the ratios of **2**:**9** were continually identical (±3%) in both photolysis tubes, indicating no detectable quenching had occurred.

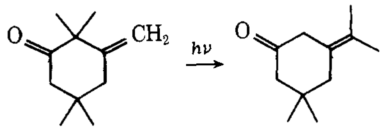
Two 0.05 M solutions of **2** in benzene with nonane as internal standard, one containing 0.18 M xanthone, were irradiated for 16 h using a 1000-W Osram super-pressure mercury arc lamp and Schoeffel GM-250 monochromator at a 23-nm bandwidth centered at 365 nm; samples were monitored by GLC. After 16 h of irradiation none of the ketol **2** in the control sample had disappeared, assuring that no direct reaction occurred under these irradiation conditions. Irradiation of the xanthone-sensitized sample for 16 h, however, led to a 54% disappearance of the starting ketol and the formation of 2,5-hexanedione, characterized by its NMR. The quantum yield for xanthone-sensitized disappearance of **2** at 365 nm was determined to be 0.03 mol/einstein, using piperylene trans-cis isomerization ($\Phi = 0.44$)[25-27] for actinometry. Appearance of **9** had a sensitized quantum efficiency of 0.004.

In a preparative irradiation run on a 5% solution of **2** in xanthone-saturated benzene using a Schoeffel monochromator at a wavelength of 365 nm, a second product was detectable after 84 h in an amount ca. equal to that of **9**. This material had a much longer retention time than either **2** or **9** (19.5 min on a 20-ft SE-30 column at 140 °C vs. 5.0 and 6.8 for **2** and **9**), suggesting that the substance was a dimeric product, possibly resulting from a cycloaddition reaction. This product was not further characterized.

Sensitized irradiations of **2** in xanthone-saturated benzene or *p*-dioxane were also conducted with the broad band irradiation of Rayonet 350-nm lamps, but the results were mechanistically ambiguous. Although their relative extinction coefficients suggested xanthone would absorb *nearly* 100% of the incident 350-nm light, the unsensitized control samples of **2** disappeared at about the same rate (±20%) as the sensitized ones, indicating that direct excitation from stray light was about as efficient as sensitization.[28]

Irradiation of 10% degassed solutions of ketol **3** in benzene containing 0.15 M xanthone (calculated to absorb over 99% of incident light in the 350-nm region) with 350-nm Rayonet lamps to 82% conversion of **3** gave **10** as the major product (82% of volatile products, 21% of the total photolysate). Cyclohexanone (**11**) was again the most abundant by-product (9% of volatile products). Traces of cyclohex-2-en-1-one (**12**), acetaldehyde (**13**), biacetyl (**14**), and ca. five other unidentified substances were also detected by GLC analysis of the photolysate. Thus, the results of photosensitized irradiation closely matched those of the direct irradiation (Scheme II). There were minor differences between direct and xanthone-sensitized runs. The latter yellowed faster; also, the amount of **12** formed in the sensitized irradiation appeared to be ca. three times that formed in direct irradiation, although it was only a trace component in both photolysates. Finally, several of the unidentified substances in the photolysates apparently had different GLC retention times and, thus, different identities in the direct and xanthone-sensitized irradiations. Sensitized irradiations of **3** in acetone as solvent and sensitizer gave comparable results.

The quantum yield for disappearance of **3** sensitized with 0.15 M xanthone at 300 nm was determined as ca. 0.10 at 7% conversion, using the photochemical reaction (eq 6) of 3-methylene-2,2,5,5-tetramethylcyclohexanone (**18**)[15] as actinometer because of the similar absorptivity of **3** and **18** in the n-π^* region. Quantum yields of ca. 0.26 for disappearance of **3** and 0.08 for appearance of **10** were similarly measured at ca. 18% conversion in direct irradiation. Extrapolation of a plot of apparent quantum yields vs. percent reaction gave an approximate quantum yield for disappearance of **3** of 0.40 at zero reaction.



(6)

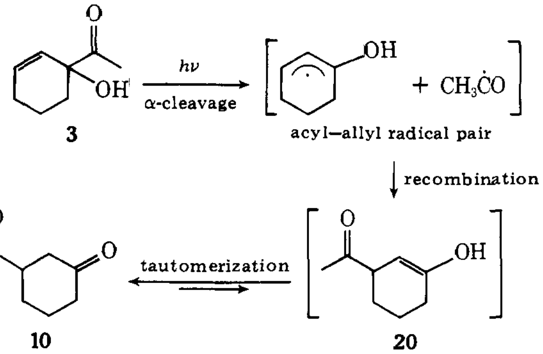
18 **19**

The direct reaction of **3** was partially quenched by added 2 M 1,3-cyclohexadiene; the quantum yield for the disappearance of **3** at 300 nm was approximately halved. The quenched photolysates were analyzed by GLC, revealing the presence of the same three photodimers formed from 1,3-cyclohexadiene under β-acetonaphthone triplet sensitization[21] and none of the 1,3,5-hexatriene which is formed in the direct irradiation of the quencher.

Discussion

Direct Photolysis. Mechanistic Conclusions. Current understanding of the many 1,3-acyl shifts occurring in β,γ-unsaturated ketones[2,3] suggests the most likely mechanism for the **2** → **9** and **3** → **10** transformations is stepwise photochemical α-cleavage, recombination, and enol-keto tautomerization (Scheme III), involving the intermediacy of an

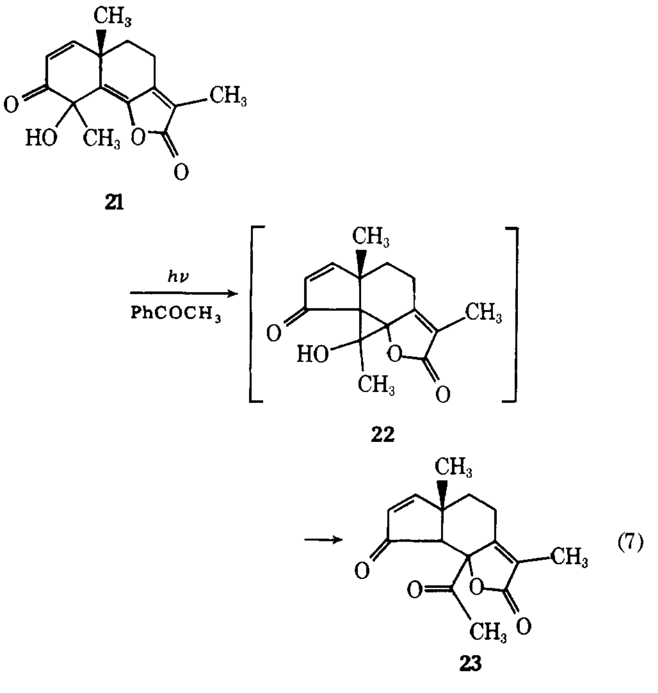
Scheme III. Stepwise Mechanism for the Photochemical 1,3-Acyl Rearrangement of 1-Acetylcyclohex-2-en-1-ol



acyl-allyl radical pair. It is the last stage (**20** → **10**) of the reaction sequence which distinguishes the **3** → **10** type of 1,3-shift from the typical case wherein the 1,3-shift product is an isomeric β,γ-unsaturated ketone existing in photochemical equilibrium with the starting ketone.[2,3] Enol-keto tautomerization has the effect of rendering the 1,3-shift irreversible.

The by-products identified in the photolysis of **3**—cyclohexanone (**11**), cyclohexenone (**12**), acetaldehyde (**13**), and biacetyl (**14**) (Scheme II)—are strong evidence that α-cleavage is the initial step, since all the identified by-products are redox or recombination products of the acetyl and hydroxycyclohexenyl radicals. It is important in this regard that **11** and **12** were shown to be formed from **3** without an induction period. Thus, it cannot be argued these were secondary photoproducts with no bearing on the mechanism of the major isomerization. A similar mechanism seems likely for the **2** → **9** transformation. Of course, the possibility of a concerted 1,3-acyl shift mechanism, [π2s + σ2s] cycloaddition followed by tautomerization, operating parallel to and competing with the stepwise path cannot be ruled out for either **2** or **3**.

The **2** → **9** and **3** → **10** rearrangements could, in principle, be rationalized in other ways as well. McMurry et al. have recently reported the photochemical conversion of the 4α- and 4β-hydroxysantonenes **21** to 1,4-diketone **23** (eq 7).[11] However, **23**, which was one of several products from direct irradiation and the sole product with acetophenone sensitization, is clearly the result of a triplet-state 1,2-acyl shift (oxadi-π-methane reaction) to unstable cyclopropanol **22**, which opens to the diketone **23**.[11]



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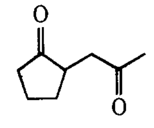
(7)

Were this mechanism operative in the rearrangement of **2**, the observed 1,4-diketone **9** would again be the product; therefore, this pathway has not been unreservedly eliminated as a possible mechanistic route to 2,5-hexanedione. It is an inherent aspect of **2** that the 1,3- and 1,2-acyl shift mechanisms cannot be distinguished by their products if the purported hydroxycyclopropyl ketone rearranges to diketone too rapidly. However, 1-acetylcyclohex-2-en-1-ol (**3**) does enable one to distinguish between these mechanisms on the basis of products alone. Were a sequence similar to that shown in eq 7 operative for **3**, the expected product would have been 2-acetonylcyclopentanone (**24**). Although it is uncertain that **24** was completely missing in photolysates of **3**, it is sure that it was not present as more than a trace component (as one of the unidentified trace products). Thus, the conventional oxadi-π-methane route cannot explain the **3** → **10** rearrangement. On the other hand, a 1,3-acyl shift in **21** followed by prototropy should have given **25** rather than the observed **23**. Since the actual products **10** and **23** are 1,4-diketones, it is clear that both 1,2- and 1,3-acyl shifts of α-hydroxy-β,γ-unsaturated ketones can lead to (albeit different) 1,4-diketones. However, the structural features in α-hydroxy-β,γ-unsaturated ketones which determine whether a 1,2- or a 1,3-shift occurs have not yet been elucidated.



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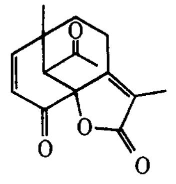

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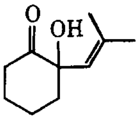
While this study was in progress two additional reports of 1,4-diketone syntheses from the photochemical rearrangement of α-hydroxy-β,γ-unsaturated ketones became available.[9,12] Carlson and Prabhu[12] attempted to exploit this principle to effect ring expansion in 2-hydroxy-2-(2-methyl-1-propenyl)cyclohexanone (**26**) (eq 8). In contrast to our own results, their yield of the diketone product (**27**) was only 15% of the volatile fraction; the aldehyde **28**, presumably arising from a 1,5-hydrogen shift following α-cleavage, was the principal photoproduct. The ring expansion was presumed to proceed via a 1,3-acyl shift and tautomerization but no mechanistic details were given.



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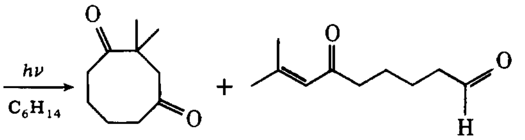

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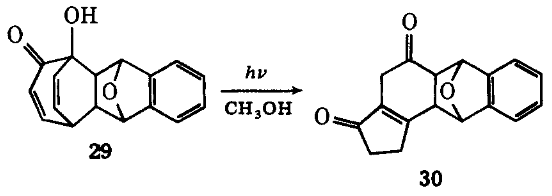
(8)

Carlson's conclusion[12] that an α-hydroxyl may reduce the efficiency of the 1,3-acyl shift in such systems is probably not always applicable. Quantum efficiencies determined for disappearance of **3** and appearance of **10** were 0.26 and 0.08. These are comparable with quantum yields measured for other 1,3-acyl shifts in nonhydroxylated systems. Furthermore, Sasaki et al.[9] have shown that the α-hydroxy-α′,β′,β,γ-unsaturated ketone **29** rearranges to 1,4-diketone **30** in 84% yield (eq 9). The analogy between their work and ours is not perfect, since (a) their study involved a rigid molecule having a conjugated chromophore; (b) α-cleavage would not lead to independent, solvent-separable radicals as is the case for **2** and **3**; and (c) use of methanol as solvent would probably minimize internal hydrogen bonding as a factor in the reactivity of **29**.[16a] Clearly, however, the α-hydroxy-β,γ-unsaturated ketone-to-1,4-diketone conversion can be both efficient and practical under favorable structural circumstances.



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(9)

Reaction Multiplicity. A useful generalization about the dichotomous reactivity pattern of β,γ-unsaturated ketones has been that n-π^* singlet states undergo 1,3-acyl shifts to isomeric β,γ-unsaturated ketones, whereas triplet states (largely π-π^*) reorganize via 1,2-acyl shifts to cyclopropyl ketones. Theoretical rationalizations based on (a) spin density distribution,[29] and (b) CNDO/s molecular orbital calculations[30] have been proposed. However, exceptions to the general pattern are known[5,8,31] and the possibility that the 1,3-acyl shifts arise in a T_2 state (n-π^*) in some molecules has been suggested by both Dalton and Schaffner.[32,33]

Excluding the present study, the few reactions of α-hydroxy-β,γ-unsaturated ketones recently disclosed[9,11,12] appear to follow the usual pattern, although, as with other β,γ-unsaturated systems, the factors governing the singlet-triplet reaction partitioning are still not clear. Thus, **26** → **27**[12] and **29** → **30**[9] are direct irradiation (singlet state) 1,3-acyl shifts which could not be photosensitized. For **26**, at least, this could be a manifestation of the free rotor effect,[4,16,34] invisible in **26** because of the substitution pattern. Also, the **21** → **23** rearrangement[12] is an acetophenone-sensitized (triplet state) 1,2-acyl shift.

That the 1,3-acyl shifts of **2** and **3** could be photosensitized, even with low quantum efficiency, is thus unusual in the photochemistry of β,γ-unsaturated ketones with or without α-hydroxy substituents. Schuster and Engel have suggested[33] that unintended direct excitation of substrate or singlet sensitization may be the cause of some apparently sensitized 1,3-shifts. The narrow band, sensitized irradiation of **2** and the control, however, leave little doubt that for **2** and **3**, the anomalous behavior is not an artifact of stray light. It is thus likely that the *sensitized* conversions of **2** to **9** and **3** to **10** are (rare)[32] examples of triplet-state 1,3-acyl shifts.

Furthermore, since the triplet-sensitized reaction of **3** gives a "fingerprint"[35] of the chemical reactivity of triplet **3**, the nearly identical product distributions of the direct and sensitized irradiations suggest either that the *direct* reaction also occurs in the triplet state (reached by efficient intersystem crossing, unusual in a β,γ-unsaturated ketone), or that the singlet and triplet states have remarkably similar reactivity. The only significant difference in product distribution between the direct and sensitized runs was the threefold larger (but still trace) amount of cyclohex-2-en-1-one (**12**) formed in the latter. This can be attributed to the greater liklihood of secondary reaction of **10** in sensitized irradiations. The lower quantum yield for sensitized conversion of **3** to **10** suggests that part of the direct reaction (ca. two-thirds) must be occurring directly from the singlet state, the remainder via intersystem crossing and reaction in the triplet. The effect of 2 M 1,3-cyclohexadiene, which about halved the direct irradiation quantum yield, leads to a similar conclusion. Seeing triplet 1,3-cyclohexadiene photodimers in the photolysates and seeing no 1,3,5-hexatriene indicate that what quenching was observed was triplet, not singlet quenching.[21-23] Although complications in interpreting sensitization and quenching experiments are well known,[36] the available data thus indicate, in an internally consistent picture, that in direct reaction between half and two-thirds of singlets react directly via a 1,3-acyl shift; the remainder intersystem cross to the triplet, from which a virtually identical reaction ensues.

Seeing no quenching by cyclohexadiene in the photolysis of **2** makes it difficult to assess how much of the direct reaction of **2** occurs via the triplet state. The low quantum yields for sensitized ketol disappearance (0.03) and diketone appearance (0.004) suggest the proportion may be small. The fact that **3** gives a 1,3-shift from the triplet state with an efficiency more than three times greater than **2** may be another manifestation of the free rotor effect.[15,34] Thus, **2** can dissipate its triplet energy by undetectable rotation about the double bond; this option is not available to **3** which has its olefinic portion constrained in a ring.

The configuration of the reactive singlet and triplet states, whether n-π^* or π-π^*, is not clear. Emission spectroscopy was of no help since neither fluorescence nor phosphorescence was detected from **3**. Irradiation was nominally in the n-π^* band, but the bathochromic shift of this band in polar solvents raises a question about the strict correctness of this simple designation. Sasaki et al.[9] interpreted the unusually small hypsochromic effect of polar solvents on the long-wavelength band of **29** as evidence for excited-state carbonyl–hydroxyl H bonding. It would also seem that n orbital involvement in H bonding should raise the energy of the n-π^* transition relative to the higher π-π^* and allow more configuration interaction of the two states. A bathochromic polar solvent shift is consistent with having considerable π-π^* character in the "n-π^*" band. The low molar absorptivity, however, suggests that complete inversion of the levels, with π-π^* lying lowest, has not occurred. No experimental information is available on the configuration of the reactive triplet.

Practicality of the 1,4-Diketone Synthesis. Taken together with recent results from other laboratories, the present work allows a preliminary assessment of the synthetic potential of the synthesis of 1,4-diketones from α-hydroxy-β,γ-unsaturated ketones (**4** → **6**). The optimal conversions of **2** to **9** and **3** to **10** were 33 and 22%, respectively. These two reactions would appear to represent transformations in which *minimum* yields of the 1,3-shift diketone products would be anticipated since, as previously pointed out, the 1,3-shift of β,γ-unsaturated ketones is least efficient in molecules with acyclic carbonyls. Despite this limitation, diketones **9** and **10** constituted 87 and 78%, respectively, of the volatile materials (including starting material), so that isolation of the major product is facile, even though the overall yield is rather low. Thus, even in this relatively rigorous test, it would be fair to state that the combination of mild reaction conditions and ease of isolation would make the mediocre yields acceptable in some instances.

Experimental Section[37]

2-Methyl-2-(1-hydroxy-1-methylprop-2-en-1-yl)-1,3-dithiane. Using procedures developed by Corey and Seebach,[17b,c,18] an oven-dried 2-l. three-neck flask, equipped with a scrupulously dry 500-ml addition funnel, mechanical stirrer, and dry nitrogen inlet, was immersed in an insulated, circulating ethanol cold bath. Tetrahydrofuran (1300 ml, dried by two successive distillations from lithium aluminum hydride) and 70.0 g (0.522 mol) of 2-methyl-1,3-dithiane[17a] were added to the reaction flask which was then cooled to −20 °C. *n*-Butyllithium (386 ml of freshly titrated[38] 1.44 N solution, 0.57 mol) was transferred by nitrogen pressure to an addition funnel and added over a 1-h period; the solution was then stirred for an additional 1.5 h. Freshly distilled methyl vinyl ketone (78.3 g, 1.12 mol) was added dropwise. When addition was complete, the temperature of the cold bath was raised to 0 °C and the mixture was allowed to stir for 48 h. Large amounts of solid, presumably the lithium salt of the dithiane–ketone adduct, formed. The solution was diluted with 1000 ml of water, and this two-phase system was stirred for 0.5 h. The organic layer was washed with water (3 × 1000 ml), brine (1000 ml), dried over anhydrous sodium sulfate, and concentrated in vacuo to give 154 g of a light-yellow liquid. Distillation through a 20-cm vacuum-jacketed Vigreux column gave 9.6 g of unreacted 2-methyl-1,3-dithiane [bp 90 °C, (8.8 mm)] and 68.2 g (64%) of clear, colorless 2-methyl-2-(1-hydroxy-1-methylprop-2-en-1yl)-1,3-dithiane, bp 152 °C (10.2 mm); infrared (neat film) absorptions at 3500 (broad), 3100, 3000, 2950, 2845, 1455, 1420, 1375, 1325, 1280, 1243, 1190, 1105, 1075, 1000, and 930 cm^{-1}; NMR (CCl_4) resonances at δ 1.40 (3 H, singlet, methyl), 1.66 (3 H, singlet, methyl), 1.75–2.16 (2 H, multiplet, C-5 ring methylene), 2.48 (1 H, singlet, hydroxyl), 2.67–3.00 (4 H, multiplet, C-4 and C-6 ring methylenes), 5.12, 5.33, and 6.23 (3 H, ABX pattern, cis terminal H, trans terminal H, and single vinyl H, respectively, $J_{AX} = 17$, $J_{BX} = 10$, $J_{AB} = 2$ Hz).

2-Methyl-2-(cyclohex-2-en-1-ol)-1,3-dithiane. The procedure of Corey and Crouse[17b] was followed using 2-methyl-1,3-dithiane (6.7 g, 50 mmol) and 2-cyclohexenone (4.8 g, 50 mmol), giving a crude product which was crystallized from an ether–petroleum ether mixture. The first crop of crystals, mp 52–55 °C [lit.[17b] 54–55 °C], weighed 3.8 g (33%). The second crop, mp 50–53 °C, weighed 3.5 g for a total yield of 64%. The NMR spectrum coincided well with the literature report.[17b]

3-Hydroxy-3-methylpent-4-en-2-one (2). Using the procedure developed by Corey and Erickson,[17a] a 5-l. three-neck flask with an overhead mechanical stirrer, condenser, nitrogen inlet, and heating mantle was charged with 1.56 l. of 80% aqueous acetonitrile, 87.8 g (0.323 mol) of mercuric chloride, and 36.7 g (0.367 mol) of calcium carbonate (to buffer the solution near pH 7). 2-Methyl-2-(1-hydroxy-1-methylprop-2-en-1-yl)-1,3-dithiane (30.0 g, 0.147 mol) dissolved in 1040 ml of 80% aqueous acetonitrile was added to the reaction mixture dropwise. The reaction mixture was stirred at room temperature for 4 h and then refluxed for 48 h. Within an hour after heating was begun, a tan solid formed which was removed after reflux by suction filtration through a pad of Celite 512 (AW). The filter cake was washed thoroughly with ether; the filtrate was diluted with 1 l. of additional ether, and this solution was washed with 5 M ammonium acetate (2 × 900 ml) and brine (1000 ml). The organic layer was dried over anhydrous sodium sulfate and all but 200 ml of the solution was removed by distillation through a 4-ft vacuum-jacketed fractionating column filled with glass helices. The distillate was monitored for the presence of 3-hydroxy-3-methylpent-4-en-2-one by GLC (20-ft × 0.38-in. 15% SE-30 on Chromosorb P-DMCS, 152 °C, 145 ml/min). Additional solvent was removed by spinning band distillation (Nester-Faust 50-cm Adiabatic Annular Teflon spinning band column), giving 50 ml of light red concentrate. By preparative GLC (3-ft × 0.25-in. 10% BDS on Chromosorb P-DMCS, 70 °C, 200 ml/min) 10.95 g (60%) of colorless 3-hydroxy-3-methylpent-4-en-2-one was isolated. Further purification for spectral and photochemical purposes was achieved by GLC (5-ft × 0.25-in. alkali-treated 10% Carbowax 20M on firebrick, 146 °C, 167 ml/min, retention time 2.3 min). 3-Hydroxy-3-methylpent-4-en-2-one had bp 64 °C (20 mm); infrared (neat film) absorptions at 3462 (broad, hydroxy), 3100 (vinyl), 2995, 2940, 1705 (carbonyl), 1635 (vinyl), 1414, 1357, 1177, 1143, 995 (vinyl), and 931 (vinyl) cm^{-1}; NMR (CCl_4) resonances at δ 1.48 (3 H, singlet, α-methyl), 2.02 (1 H, singlet, hydroxyl), 2.17 (3 H, singlet, acetyl methyl), 5.16, 5.39, 5.94 (3 H, ABX pattern, cis terminal H, trans terminal H, and single vinyl H, respectively; $J_{AX} = 17$, $J_{BX} = 10$, $J_{AB} = 2$ Hz); ultraviolet λ_{max} at 280 nm (ε 149) in cyclohexane, λ_{max} at 285 nm (ε 124) in acetonitrile; significant mass spectral fragmentations (with relative intensities) at *m/e* 114 (1, P), 71 (68), 43, (100), 41 (15), 27 (24), and 15 (25).

Anal. Calcd for $C_6H_{10}O_2$: $M\cdot^+$ 114.0682. Found: 114.0662.

1-Acetylcyclohex-2-en-1-ol (3). Two different procedures reported by Corey and Erickson[17a] were used.

Method A. Using 11.4 g (50.2 mmol) of 2-methyl-2-(cyclohex-2-en-1-ol)-1,3-dithiane in a calcium carbonate buffered solution of mercuric chloride in 80% aqueous acetonitrile, a 97% yield of crude 1-acetylcyclohex-2-en-1-ol was obtained [lit.[17a] 93%]. Pure product was obtained by distillation through a 4-in. Vigreux column: bp 50 °C (0.1 mm) [lit.[17a] 32 °C (0.08 mm)]; NMR (CCl_4) resonances at δ 1.30–2.33 (6 H, multiplet, three methylenes), 2.30 (3 H, singlet, acetyl methyl), 3.81 (1 H, singlet, hydroxyl), 5.24–5.58 (1 H, doublet, $J_1 = 10$ Hz, C-2 vinyl hydrogen), 5.80–6.19 (1 H, doublet of triplets, $J_1 = 10$ Hz, $J_2 = 3$ Hz, C-3 vinyl hydrogen); NMR ($CDCl_3$) resonances at δ 1.43–2.34 (6 H, multiplet, $(CH_2)_3$), 2.18 (3 H, singlet, CH_3), 3.89 (1 H, singlet, OH), 5.32–5.63 (1 H, doublet, $J_1 = 10$ Hz, C-2 vinyl), 5.93–6.28 (1 H, doublet of triplets, $J_1 = 10$ Hz, $J_2 = 3$ Hz, C-3 vinyl); IR ($CHCl_3$) absorptions at 1700 cm^{-1} ($\nu_{C=O}$) and 3400 cm^{-1} (ν_{O-H}); IR (CCl_4) absorptions at 1710 cm^{-1} ($\nu_{C=O}$) and 3476 cm^{-1} (ν_{O-H}).

Method B. 2-Methyl-2-(cyclohex-2-en-1-ol)-1,3-dithiane (2.28 g, 9.90 mmol) was reacted with *N*-chlorosuccinimide and silver nitrate dissolved in 80% aqueous acetonitrile to give 0.62 g (45% yield) [lit.[17a] 71%] of 1-acetylcyclohex-2-en-1-ol.

3-Acetylcyclohexanone (10). Method A. 3-Acetylcyclohexanone was synthesized in three steps according to the method of Corey and Crouse[17b] wherein (step 1) 3.23 g (14 mmol) of 2-methyl-2-(cyclohex-2-en-1-ol)-1,3-dithiane was stirred with a 1:1 solution of dioxane and 1% sulfuric acid to give 3.2 g (14 mmol, 99% crude yield) of 2-methyl-2-(cyclohex-1-en-3-ol)-1,3-dithiane: NMR (CCl_4) resonances at δ 1.55 (3 H, singlet, methyl), 1.32–2.30 (6 H, multiplet, carbocyclic ring methylenes), 2.42–2.93 (6 H, multiplet, dithiane methylenes), 3.60 (1 H, singlet, hydroxyl), 4.05–4.42 (1 H, multiplet, methine), 6.19–6.33 (1 H, multiplet, vinyl) [lit.[17b] δ 1.54 (3 H, singlet), 3.77 (1 H, singlet), 4.13–4.38 (1 H, multiplet), 6.20–6.31 (1 H, multiplet)]; (step 2) 2-methyl-2-(cyclohex-1-en-3-ol)-1,3-dithiane (1.13 g, 4.91 mmol) was reacted with mercuric chloride and cadmium carbonate in aqueous acetonitrile to give 3-acetylcyclohex-2-en-1-ol (0.51 g, 73% crude yield) which had NMR (CCl_4) resonances at δ 2.27 (3 H, singlet, methyl), 1.32–2.47 (6 H, multiplets, three methylenes), 3.09 (1 H, singlet, hydroxyl), 4.17–4.60 (1 H, methine hydrogen next to OH), 6.67–6.88 (1 H, multiplet, vinyl) [lit.[17b] δ 2.14 (3 H, singlet, methyl), 3.97–4.41 (2 H, hydroxyl and adjacent hydrogen), and 6.35–6.46 (1 H, multiplet, vinyl)]; (step 3) 3-acetylcyclohex-2-en-1-ol was refluxed with potassium hydroxide dissolved in methanol and water to give 3-acetylcyclohexanone (crude yield 63%) (lit.[17b] 97%).[39] The product had bp 60–70 °C (0.07 mm) [lit.[17b] 79–81 °C (0.02 mm), lit.[20] bp 140–145 °C (15 mm)]; mp 31.5–38° (lit.[17b] 37.4–38.3 °C, lit.[20] 39 °C); IR (CCl_4) carbonyl absorption at 1700 cm^{-1} (br) [lit.[17b] 5.8–5.9 μ (neat)]; NMR (CCl_4) resonances at δ 1.49–2.53 (8 H, multiplet, methylenes), 2.14 (3 H, singlet, methyl), and 2.53–3.07 (1 H, multiplet, methine) [lit.[17b] (CCl_4) δ 1.45–2.42 (8 H, multiplet), 2.14 (3 H, singlet), and 2.53–3.03 (1 H, multiplet)]; mass spectrum parent peak at *m/e* 140.1 [lit.[17b] 140.0837].

Method B. 3-Acetylcyclohexanone was synthesized in two steps following McCoubrey's procedure[20] wherein (step 1) cyclohex-2-en-1-one (12 g, 0.12 mol) and nitroethane (11 g, 0.15 mol) gave 9.6 g (47% yield) of 3-(1-nitroethyl)cyclohexanone; IR (neat) absorptions at 1700 ($\nu_{C=O}$), 1540 and 1350 (ν_{NO_2}) cm^{-1}; NMR (CCl_4) resonances at δ 1.50–1.60 (3 H, doublet, methyl, $J = 8$ Hz), 0.95–2.67 (9 H, multiplet, ring hydrogens), and 4.30–4.87 [1 H, doublet ($J = 7$ Hz) of quartets ($J = 8$ Hz), methine adjacent to nitro]; semicarbazone derivative of mp 173–175 °C [lit.[20] 179 °C]; (step 2) 3-(1-nitroethyl)cyclohexanone (8.6 g, 50 mmol) was reacted with 30% aqueous sulfuric acid to give 4.1 g (59%) [lit.[20] 65% crude] of 3-acetylcyclohexanone, bp 60–70 °C (0.07 mm). The product solidified after distillation and was recrystallized several times from light petroleum ether (bp 60–80 °C) until pure white crystalline material was obtained, mp 39.0–40.5 °C [lit.[20] 39 °C]. The NMR (CCl_4), IR ($CHCl_3$), and mass spectra were identical with those of 3-acetylcyclohexanone previously prepared by another synthetic route (vide ante).

Photolyses of 3-Hydroxy-3-methylpent-4-en-2-one. Typically, to a polished Pyrex NMR tube were added 49.4 mg (0.433 mmol) of 3-hydroxy-3-methylpent-4-en-2-one, 39.0 mg (0.173 mmol) of hexadecane as internal standard and 500 μl of spectral-grade benzene or dioxane. The tube was capped with a gas-tight septum, degassed (three freeze–pump–thaw cycles), and irradiated with an unfiltered Hanovia 450-W medium-pressure mercury arc lamp. Progress of the photolysis was followed hourly by GLC analysis (5-ft × 0.25-in. alkali-treated 10% Carbowax 20M on firebrick, 148 °C, 167 ml/min). After 11 h of irradiation, the yield of the only significant photoproduct, identified as 2,5-hexanedione by comparison of GLC retention times, infrared, NMR, and mass spectra with those of authentic material,[19,40,41] was maximized at 33% overall (87% of volatiles).

Sensitized irradiations were conducted similarly, but with added 0.17 M recrystallized (ethanol) xanthone, which absorbs ca. 100% of incident 350-nm light according to molar extinction coefficients of 110 and 0 M^{-1} cm^{-1} for xanthone and 3-hydroxy-3-methylpent-4-en-2-one, respectively. Irradiation with Rayonet RUL-3500 lamps produced 2,5-hexanedione as the major photoproduct; no other products could be detected by GLC, although the NMR spectrum of photolyzed solutions showed a broad rise in the baseline in the upfield region. Control samples without xanthone reacted at about the same rate (±20%) as the sensitized ones.

When a 0.1 mmol sample of the ketol and 0.19 M xanthone in benzene was irradiated with a 1000-W Osram super-pressure mercury lamp filtered through a Schoeffel GM-250 monochromator with 7-mm slits, giving a 23-nm band at 365 nm, 52% of the starting ketol had been destroyed and 14% (corrected for GLC response) of the diketone was produced after 16 h. No reaction occurred in an unsensitized control sample.

Using the trans-cis isomerization of piperylene ($\Phi = 0.44$)[25-27] as actinometer, the quantum yields for the sensitized disappearance of 3-hydroxy-3-methylpent-4-en-2-one and for the formation of 2,5-hexanedione were found to be 0.03 and 0.004, respectively.

In an extended photolysis of 100 μl (ca. 0.85 mmol) of 3-hydroxy-3-methylpent-4-en-2-one in 2.0 ml of xanthone-saturated benzene, irradiation for 84 h produced an additional product with a much longer

GLC retention time (19.5 min vs. 5.0 and 6.8 min, respectively, for ketol and diketone). The facts that the product was produced only upon long irradiation and that it had a much longer GLC retention time than the ketol or diketone suggested that this product was a dimer. Its identity was not determined.

When samples of 3-hydroxy-3-methylpent-4-en-2-one (ca. 1 M) in benzene or *p*-dioxane containing ca. 1 M 1,3-cyclohexadiene were irradiated with Rayonet RUL-3000 lamps and analyzed periodically by GLC and NMR for 41 h, there was no indication that 1,3-cyclohexadiene triplet dimers (triplet-state quenching products) were formed nor could any 1,3,5-hexatriene (principal singlet-state quenching product) be detected when the analytical GLC flow rate was decreased to 80 ml/min. After 41 h of irradiation, integration of the 3-hydroxy-3-methylpent-4-en-2-one and 2,5-hexanedione GLC peaks gave a product/ketone ratio which was the same ±3% in samples with or without 1,3-cyclohexadiene.

Direct Irradiations of 1-Acetylcyclohex-2-en-1-ol. Solutions of 1-acetylcyclohex-2-en-1-ol in benzene [ca. 1 M, on scales ranging from 100 mg (0.713 mmol) in 500 μl to 1 g in 10 ml] were degassed, then sealed in Pyrex (quartz for samples larger than 200 mg) tubes under an argon atmosphere, and irradiated for varying time periods with a Pyrex-filtered 450-W medium-pressure mercury arc lamp (Hanovia) or with eight circumferential RUL-3000 lamps (Rayonet). Changes accompanying irradiation were monitored by NMR and GLC. Control experiments verified the absence of any dark reactions occurring under photolysis conditions.

GLC analysis (20-ft × 0.38-in. 15% SE-30 on Chromosorb P-DMCS) revealed the presence of one major photoproduct and at least nine minor ones (vide infra). Irradiations carried out using a Corex-filtered Hanovia lamp were ca. five times faster than those carried out through a Pyrex filter; irradiations with RUL-3500 lamps were about ten times slower than irradiations with RUL-3000 lamps, but the product yields and identities were independent of the light source.

The major photoproduct from direct irradiations of 1-acetylcyclohex-2-en-1-ol was collected by preparative GLC (20-ft × 0.38-in. 15% SE-30 on Chromosorb P-DMCS, 147 °C). Yields of the major photoproduct were maximized at ca. 66–91% conversion of starting material; at 86% reaction, the yield was 22% of the total photolysate, 78% of volatiles. Mass, IR, and ^{1}H NMR spectra of the isolated photoproduct were identical with those of 3-acetylcyclohexanone prepared independently by the methods of Corey and Crouse[17b] and McCoubrey.[20]

The GLC fractions believed from retention times to be unreacted 1-acetylcyclohex-2-en-1-ol were collected and shown by IR, NMR, and mass spectra to be unchanged starting material, which could be rephotolyzed.

Four of the (at least) nine minor products, which totaled to 9% of reacted starting material, were identified by GLC retention times on three different columns: SE-30 at 147 °C, BDS at 122 °C and Carbowax 20M at 145 °C. In general, compounds considered identified had retention times identical with those of the authentic materials on two or, where possible, on all three of these columns. The materials so identified were cyclohexanone (13% of volatiles, 3% yield), cyclohex-2-en-1-one (trace), acetaldehyde (trace), and biacetyl (trace). Five products (all trace) were not identified, but were shown not to be 2-acetylcyclohexanone, cyclohexanol, or cyclohex-2-en-1-ol.

Quantum yields for reaction of 1-acetylcyclohex-2-en-1-ol were measured at 300 nm (a) directly, (b) with 0.15 M xanthone, and (c) with 2.0 M 1,3-cyclohexadiene, all in benzene containing octadecane as internal standard, using 3-methylene-2,2,5,5-tetramethylcyclohexanone ($\Phi = 0.13$)[15] as actinometer.

Disappearance of 1-acetylcyclohex-2-en-1-ol and appearance of 3-acetylcyclohexanone were measured relative to octadecane by GLC on a 5-ft × 0.25-in. alkali-treated Carbowax 20M column. The singlet and triplet photoproducts of 1,3-cyclohexadiene were analyzed by GLC in control experiments using both direct irradiation and sensitization by acetophenone and β-acetonaphthone. Similar analysis of the ketol irradiation in the presence of 2.0 M 1,3-cyclohexadiene showed the reaction efficiency halved and the presence of the known[21-24] triplet cyclohexadiene photodimers.

In other sensitized irradiations, acetone replaced benzene as solvent and irradiations were carried out in quartz tubes with RUL-2537 Å lamps. Product identities and yields were the same except for the yield of cyclohex-2-en-1-one, which was three times larger (but still only 1-2%) in both xanthone- and acetone-sensitized runs than in the direct runs.

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Nitrosation in Organic Chemistry. Nitrosolysis, a Novel Carbon–Carbon Bond Cleavage Effected through Nitrosation. Nitrosolysis of Ketones and Ketone Acetals[1]

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Abstract: Nitrosation of cyclohexanone with nitrosyl chloride in liquid sulfur dioxide in the presence of methanol, ethanol, or isopropyl alcohol and at least 1 equiv of hydrogen chloride provides the corresponding 2-alkoxy-3-oximinocyclohexenes. However, when the reaction was carried out without the added hydrogen chloride, the alkyl 6-oximinohexanoates are obtained. This novel carbon–carbon bond cleavage was extended to several other ketones. The successful outcome of this reaction was attributed to an efficient trapping of the α-nitrosohydroxycarbonium ion intermediates with an alcohol and facile in situ cleavage of the resulting α-nitroso hemiacetal. The mechanism of the reaction changes dramatically by changing the nature of the nucleophile associated with the nitrosating reagent. Thus, in the absence of efficient nucleophiles, the α-nitrosocarbonium ion, resulting from the electrophilic addition of the nitrosonium ion to the double bond of an enol or even an olefin, behaves as a 1,3-dipolar ion that can be intercepted with a carbonyl group as a dipolarophile to provide a novel single-step synthesis of various 3-oxazoline *N*-oxides. In this way a reaction of cyclohexanone with *tert*-butyl nitrite and boron trifluoride etherate gave 2,2-dimethyl-1-oxa-4-azaspiro[4.5]dec-3-en 4-oxide. Similarly, a reaction of cyclohexanone with nitrosyl tetrafluoroborate and 1-methylcyclohexene afforded 4,5,6,7-tetrahydro-7a-methylspiro[benzoxazoline-2,1′-cyclohexene] 3-oxide. The same product was also obtained either from a reaction of 1-methylcyclohexyl nitrite with boron trifluoride etherate and cyclohexanone, or 1-methylcyclohexanol with nitrosyl tetrafluoroborate and cyclohexanone. A reaction of cyclohexanone diethyl acetal with ethyl nitrite in liquid sulfur dioxide in the presence of ethanol and a catalytic amount of an acid gave ethyl 5-cyanopentanoate. The diethyl acetals of various cyclic and open chain ketones undergo similar carbon–carbon bond cleavage. The proposed mechanism for the nitrosolysis of cyclohexanone diethyl acetal involves an acid-catalyzed reversible formation of the enol ether from the ketone acetal; an electrophilic addition of the nitrosonium ion, generated from the ethyl nitrite and the acid catalyst, to the double bond of the enol ether; a reaction of the thus produced 1-alkoxy-2-nitrosocarbonium ion with the alcohol to provide the α-nitroso ketone acetal; an acid-catalyzed carbon–carbon bond cleavage to provide the corresponding ω-oximinodiethoxycarbonium ion; a reversible reaction of the carbonium ion with an excess of the alcohol to give the ω-oximinoorthocaproate; and a reaction of the thus produced ortho ester with the oxime to afford the observed ester nitrile.

Nitrosation, a process for the introduction of a nitroso group or its equivalent into an organic structure by a replacement of an activated α-hydrogen by a nitroso group, was discovered by Victor Meyer in 1873.[2,3] Approximately at the same time, Tilden established that a nitroso group can be introduced into an organic structure through the addition of a nitrosating reagent (nitrosyl chloride) across a carbon–carbon double bond.[4,5]

Perhaps the two most prominent features in the chemistry of a nitroso group are unusually facile dimerization to nitroso dimers[6] and the ready isomerization to the corresponding oximes.[6] Thus, primary and secondary aliphatic nitroso compounds generally exist as the corresponding disubstituted diazene 1,2-dioxides,[7] which, in turn, often exist as a pair of interconvertible geometrical *Z* and *E* isomers. It is now well documented that the dimerization initially provides the *Z* isomer, which under thermodynamic conditions isomerizes to the more stable *E* form.[8] It appears that the dimerization process requires fairly low energies of activation in the order of 6–10 kcal/mol,[8f,9] as compared with 20–30 kcal/mol estimated for the energy of activation for the dissociation of the dimers to monomers.[8f,9b,10] Energies of activation for the dimerization of tertiary nitroso compounds, for steric reasons, are significantly higher and they generally exist in monomeric form.[11,12]

The isomerization of primary and secondary nitroso compounds to the corresponding oximes is not a spontaneous process[6,8c] and in the gas phase requires activation energies in excess of 35 kcal/mol. However, the isomerization of the nitroso compounds in solution is apparently catalyzed both by acids and bases and also appears to be influenced by solvents and heat.[6] Secondary nitroso compounds resulting from an addition of a nitrosating reagent such as nitrosyl chloride or nitrosyl formate across a carbon–carbon double bond dimerize readily and generally exist as the corresponding nitroso dimers.[4,5,12,13] In contrast, nitrosation of ketones usually provides the α-oximino ketones directly. It thus appears that the secondary α-nitroso group in the initially formed α-nitroso ketones, under the condition of the nitrosation reaction undergoes a very facile isomerization to the oxime.[3,5,6]

In addition to its synthetic value as a general method for introducing a nitrogen function into organic molecules, the