in eq 3–6, either step 4 or step 5 will be rate-limiting depending on the relative values of the rate constants k_{-2} and k_3. Both the literature and this work confirm the role of alkyl substitution at the β carbon in determining this ratio. In those cases where this carbon is tertiary ($\Delta^{5(6)}$-3-keto steroids,[3] 3-ethoxycholesta-3,5-diene,[3] and 3-methyl-3-cyclohexen-1-one), protonation of the enol or ether occurs preferentially at the γ carbon. In those cases where the β carbon is secondary (2-hydroxyhexa-2,4-diene[23] and 3-cyclohexen-1-one), protonation at the α carbon dominates.

In the systematic study by Rogers and Sattar,[24] the acid-catalyzed hydrolysis of several conjugated enol ethers showed protonation at the α and/or γ carbon as indicated by the formation of the corresponding β,γ or α,β unsaturated ketone, respectively. Their data clearly indicate that substitution at the β carbon enhances γ over α protonation. On the other hand, substitution at the α or the γ carbon inhibits protonation at that carbon. These results are consistent with the well-known effects[25] of substitution on olefin protonation.

We conclude that in general one may expect the acid-catalyzed isomerization of β,γ unsaturated ketones to α,β unsaturated ketones to occur *via* enol intermediates. The enolization step will be rate-determining if the α carbon is primary, but the protonation of the enol will be rate-limiting if the β carbon is secondary. These two situations will be distinguishable in general by the solvent isotope effect, although intermediate cases[7] may occur.

Registry No.—3-Cyclohexen-1-one, 4096-34-8; 3-methyl-3-cyclohexen-1-one, 31883-98-4; 2-cyclohexen-1-one, 930-68-7; 3-methyl-2-cyclohexen-1-one, 1193-18-6.

[23] H. Morrison and S. R. Kurowsky, *Chem. Commun.*, 1098 (1967).

[24] N. A. J. Rogers and A. Sattar, *Tetrahedron Lett.*, 1471 (1965).

[25] Reference 19, p 43.

The Mechanism of the Acid-Catalyzed Double-Bond Migration in 4-Methyl-4-penten-2-one and 2-Cyclohexen-1-yl Methyl Ketone[1]

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Received July 9, 1971

The solvent–isotope effect (k_{D_2O}/k_{H_2O}) of about 1.4 observed in the acid-catalyzed isomerization of 4-methyl-4-penten-2-one to 4-methyl-3-penten-2-one in aqueous sulfuric acid demonstrates that this reaction occurs through a rate-determining enolization. The isomerization of 2-cyclohexen-1-yl methyl ketone to 1-cyclohexen-1-yl methyl ketone has a solvent–isotope effect of 1.0, and the rate of hydrogen exchange (enolization) at the α carbon is faster than the rate of isomerization; thus this reaction occurs through a rate-limiting protonation of the enol. These results are in agreement with previous results showing the role of substitution at the carbon β to the carbonyl in determining the nature of the rate-limiting step.

The acid-catalyzed isomerization of β,γ- to α,β-unsaturated ketones occurs *via* an enol intermediate. Malhotra and Ringold[3] have shown by the solvent isotope effect (k_{D_2O}/k_{H_2O}) of 1.6 that the isomerization of $\Delta^{5(6)}$- to Δ^4-3-keto steroids occurs *via* a rate-determining formation of the enol. Similarly,[4] we have concluded from the solvent isotope effect (k_{D_2O}/k_{H_2O}) of 1.3 that the isomerization of 3-methyl-3-cyclohexen-1-one to 3-methyl-2-cyclohexen-1-one also occurs by a rate-determining enolization. On the other hand, the isomerization of 3-cyclohexen-1-one to 2-cyclohexen-1-one shows a reversed solvent isotope effect (k_{D_2O}/k_{H_2O}) of 0.2, indicating a rate-limiting protonation of the enol. We concluded that, in general, β,γ unsaturated ketones with a tertiary β carbon will isomerize *via* a rate-determining enolization, while those with a secondary β carbon will isomerize *via* a rate-limiting protonation of the enol.

We describe here the results obtained for the acid-catalyzed isomerizations of 4-methyl-4-penten-2-one and 2-cyclohexen-1-yl methyl ketone. In both cases the rate of appearance of the conjugated isomer shows complex kinetic behavior, as monitored by uv measurements. A complete kinetic analysis has been carried through, and the results are consistent with the above generalization.

Experimental Section

1-(Acetoxyethylidenyl)-2-cyclohexene.—Following the method of House and Trost,[5] 5 ml of 70% perchloric acid was added to a mixture of 500 ml of carbon tetrachloride, 150 g of acetic anhydride, and 25 g of 1-cyclohexen-1-yl methyl ketone under nitrogen. After stirring for 2 hr, the solution was neutralized with a saturated solution of sodium bicarbonate. Two ether extracts of the neutral mixture were combined, washed with a saturated solution of sodium chloride, and dried with magnesium sulfate. The solvent was removed by rotary evaporation after the drying agent was removed by filtration. The 31.2 g of crude material resulting showed 84% conversion to the enol ester by gas chromatography (Carbowax 20M on Chromosorb W). Because distillation [bp 71–72° (1.2 mm)] resulted in large amounts of pot residue, analytical samples were obtained by gas chromatography: ir (CCl_4) 1750, 1670, and 1220 cm^{-1}; nmr (CCl_4) δ 1.5–2.4 (m, 6), 1.8 (s, 3), 2.0 (s, 3), 5.6 (m, 1), and 6.1 ppm (m, 1).

Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.09; H, 8.26.

1-Cyclohexen-1-yl Methyl Ketone.—Prepared by the rearrangement of 1-ethynylcyclohexanol according to the procedure of Newman,[6] a small sample was purified by gas chromatography (Carbowax 20M on Chromosorb W), $\lambda_{max}^{H_2O}$ 239 nm (ϵ 12,000).

2-Cyclohexen-1-yl methyl ketone was prepared by the addition of the conjugated enol acetate, 1-(acetoxyethylidenyl)-2-cyclohexene, to methyllithium according to the method of House and

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[1] Supported in part by grants from the National Science Foundation, GP-1572 and GP-6133X.

[2] National Institutes of Health Predoctoral Fellow, 1966–1968, GM-30, 162.

[3] S. K. Malhotra and H. J. Ringold, *J. Amer. Chem. Soc.*, **87**, 3228 (1965).

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[6] M. S. Newman, *J. Amer. Chem. Soc.*, **75**, 4740 (1953).

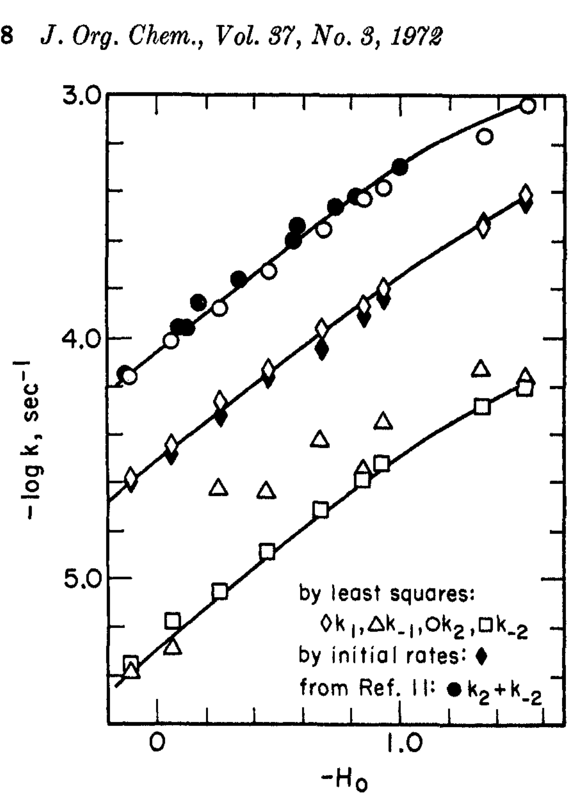


Figure 1.—Rate constants for 4-methyl-4-penten-2-one in aqueous sulfuric acid. Scheme of eq 1.

Trost.[5] Gas chromatography (Carbowax 20M on Chromosorb W) indicated 92% conversion and afforded a pure sample: ir (CCl_4) 1710 cm^{-1}; nmr (CCl_4) δ 1.6–2.1 (m, 6), 2.1 (s, 3), 3.0 (m, 1), and 5.8 ppm (s, 2).

Anal. Calcd for $C_8C_{12}O$: C, 77.37; H, 9.74. Found: C, 77.11; H, 9.99.

2-Cyclohexen-1-yl-1-*d* Methyl Ketone.—This compound was prepared by the same method as its undeuterated counterpart except that the lithium enolate was quenched with a 10% solution of acetic acid-*O-d* in deuterium oxide. The product was purified by preparative gas chromatography, and was shown by mass spectroscopy to contain 93.7% deuterium (at C-1) according to isotopic abundances in the fragments).

4-Methyl-4-penten-2-one.—Distillation (spinning-band column containing about 30 theoretical plates, reflux ratio about 50:1) of commercial 4-methyl-3-penten-2-one (mesityl oxide) plus *p*-toluenesulfonic acid as a catalyst[7] resulted in a mixture containing about 30% 4-methyl-4-penten-2-one. Three refractionations (without catalyst) yielded material which was 96% pure. Small amounts of pure substance were obtained as needed from this mixture by gas chromatography (tricresyl phosphate on Chromosorb P): ir (CCl_4) 1720 cm^{-1}; nmr (CCl_4) δ 1.7 (s, 3), 2.0 (s, 3), 3.0 (m, 2), 4.8 (m, 1), and 4.9 ppm (m, 1).

Kinetic Procedures.—With the exceptions of the nmr and mass spectrometer experiments described below, the results here were obtained from the time-dependent behavior of the uv absorbances of the conjugated isomers. We have described the solutions and the apparatus used in the accompanying paper.[4]

The pseudo-first-order rate constants for the isomerizations of 2-cyclohexen-1-yl methyl ketone in H_2SO_4–H_2O and of 2-cyclohexen-1-yl-1-*d* methyl ketone in D_2SO_4–D_2O were determined by the use of the computer program LSKIN1.[8]

The uv data for 4-methyl-4-penten-2-one and for 2-cyclohexen-1-yl methyl ketone in D_2SO_4–D_2O exhibited non-first-order behavior, and they were treated in terms of eq 1 and 2. The integrated kinetic expressions for the conjugated isomers were obtained from the sets of differential rate equations for these schemes using matrix algebra methods which are described elsewhere.[9] The rate constants were computed from a nonlinear least-squares fit of the data to these expressions using a computer program based on Newton's method.[10]

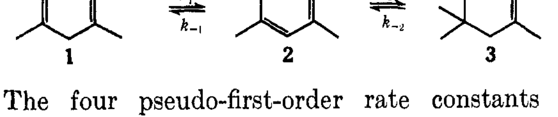
As noted, some rate constants were estimated from the initial rates, *i.e.*, by dividing the limiting slope of the absorbance *vs.* time curve at time zero by the initial concentration of the unconjugated isomer.

In qualitative kinetic experiments with 4-methyl-4-penten-2-one followed by nmr, about 0.2 g of substrate was diluted to 10 ml with 5–10% H_2SO_4. An nmr tube was filled with a portion of the solution and placed in the probe at 30–35°. The concentrations of the three species of this system (4-methyl-4-penten-2-one, 4-methyl-3-penten-2-one, and 4-hydroxy-4-methylpentan-2-one) were monitored by the distinct absorbances due to their C-4 methyl groups.

In the measurement of the rate of exchange of 2-cyclohexen-1-yl methyl ketone in heavy water, about 0.1 g of 2-cylcohexen-1-yl methyl ketone was dissolved in 50 ml of 3% aqueous deuteriosulfuric acid. The solution was placed in a serum-capped flask in a constant-temperature bath at 25.0°. At 5-min intervals 5-ml aliquots were withdrawn by hypodermic syringe and quenched by addition to 50 ml of pentane and 25 ml of water containing about 0.75 equiv of sodium bicarbonate in a separatory funnel. The pentane layer was washed with a saturated aqueous solution of sodium chloride and reduced to about 100 μl with a rotary evaporator. The solution was separated by gas chromatography (SE-30 on Chromosorb W at 120°) and the 2-cyclohexen-1-yl methyl ketone was collected. Low-voltage (30 eV) mass spectral analysis was used to calculate the fraction deuterated from peak heights. Each of the nine points (extending from 8 to 70% reaction) was the average of five or more spectra. High-voltage (70 eV) spectra confirmed that incorporation was in the 1 position: the ratio of the *m/e* 43 to the *m/e* 44 peaks for the acetyl fragment showed natural isotopic abundance, while the ratio of the *m/e* 81 to the *m/e* 82 peaks for the cyclohexenyl fragment was the same as that for the molecular ion.

Results and Discussion

4-Methyl-4-penten-2-one.—The kinetic solutions of 4-methyl-4-penten-2-one (**1**) in aqueous sulfuric acid showed a comparatively rapid initial increase in absorbance due to the formation of 4-methyl-3-penten-2-one (**2**). The absorbance reached a maximum which corresponds to about 20 mol % of the total organic material and then slowly decreased to about 6–7%. By comparing the time-dependent nmr spectra of reacting solutions with the spectra of the known materials, it was apparent that as **2** formed it was hydrated to 4-hydroxy-4-methylpentan-2-one (**3**).[11] Therefore, it was felt that the data should be analyzed in terms of the kinetic scheme in eq 1.



(1)

The four pseudo-first-order rate constants were determined at several acidities from a least-squares fit of the integrated rate equation for **2** to the uv data. The results are listed in Table I and are displayed in Figure 1. The last column of this table lists k_1 as determined from the initial rates of appearance of **2**. The results show a somewhat larger than desirable scatter. Improved results would have been expected by fixing k_2 and k_{-2} as independently determined by Bell, Preston, and Whitney.[11] However, we chose to allow all constants to be determined by the analysis. The concordance of our values for k_2 and for k_{-2} with those of Bell, *et al.*,[11] is gratifying.

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[7] F. H. Stross, J. M. Monger, and H. deV. Finch, *J. Amer. Chem. Soc.*, **69**, 1627 (1947).

[8] D. F. DeTar and C. E. DeTar in "Computer Programs for Chemistry," D. F. DeTar, Ed., W. A. Benjamin, New York, N. Y., 1968, Chapter 6.

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[10] W. E. Wentworth, *J. Chem. Educ.*, **42**, 96 (1965). T. A. Reichert of this department was primarily responsible for the program used.

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TABLE I

RATE CONSTANTS FOR 4-METHYL-4-PENTEN-2-ONE IN AQUEOUS SULFURIC ACID.[a] RATE SCHEME OF EQ 1

H_2SO_4, %	$-H_0$	10^5k,[b] sec^{-1} k_1	k_{-1}	k_2	k_{-2}	10^5k_1,[c] sec^{-1}
4.87	−0.11	2.57	0.404	6.85	0.423	2.53
6.54	0.06	3.57	0.510	9.85	0.645	3.28
8.68	0.24	5.36	2.40	13.3	0.895	4.84
11.21	0.46	7.26	2.34	19.1	1.28	6.84
14.27	0.68	11.0	3.79	28.1	1.95	9.14
16.82	0.85	14.1	2.87	37.7	2.63	12.6
18.02	0.93	16.3	4.43	42.0	2.98	14.9
23.98	1.34	29.0	7.41	68.6	5.25	29.8
26.47	1.52	38.8	6.29	96.4	6.96	36.5

[a] Temperature, 25.0°. [b] Determined by least-squares analysis. [c] Determined from initial rate of isomerization.

Results of similar experiments in D_2SO_4–D_2O media are given in Table II. These results show clearly that the solvent isotope effect (k_{D_2O}/k_{H_2O}) is greater than one (column 8); therefore, the reaction occurs *via* a rate-determining enolization, as is also the case for other β,γ unsaturated ketones with trisubstituted β carbons which have been studied, $\Delta^{5(6)}$-3-keto steroids,[3] and 3-methyl-3-cyclohexen-1-one.[4]

TABLE II

RATE CONSTANTS FOR 4-METHYL-4-PENTEN-2-ONE IN D_2SO_4–D_2O. RATE SCHEME OF EQ 2[a]

D_2SO_4, %	$-D_0$	10^5k,[b] sec^{-1} k_1	k_{-1}	k_2	k_{-2}	10^5k_1,[c] sec^{-1}	$k_1^{D_2O}/k_1^{H_2O}$ [d]
14.5	0.76	19.2	6.94	5.35	0.369	18.0	1.5
16.0	0.87	22.1	8.99	6.46	0.570	23.8	1.7
17.6	0.99	23.8	12.4	7.75	0.535	21.4	1.3
19.1	1.10	30.6	13.8	8.13	0.645	27.7	1.4
20.1	1.17	30.4	17.2	9.27	0.585	26.5	1.2
21.2	1.24	37.2	17.0	9.66	0.740	32.4	1.2

[a] Temperature, 25.0°. [b] Determined from least-squares analysis. [c] From initial rates. [d] $k_1^{D_2O}$ from column 7, this table; $k_1^{H_2O}$ interpolated from column 7, Table I.

2-Cyclohexen-1-yl Methyl Ketone.—The rate of formation of 1-cyclohexen-1-yl methyl ketone (**5**) from 2-cyclohexen-1-yl methyl ketone (**4**) showed first-order behavior; the rate constants are listed in Table III. On the other hand, the formation of **5** from **4** in D_2SO_4–D_2O was monotonic, but not first order. The reason for this became apparent when the rate of exchange of the C-1 hydrogen of **4** was measured to be 3.21×10^{-4} sec^{-1} in 3.01% D_2SO_4 ($D_0 = 0.36$). This is nearly ten times more rapid than the rate of isomerization as determined from the initial rate of formation of **5** (see Table V, column 7). Therefore, the exchanged compound, 2-cyclohexen-1-yl-*1-d* methyl ketone (**6**), must be considered a kinetically significant species. The isomerization rates for the two media are compared in Figure 2. Within experimental error there is no solvent effect for the isomerization reaction.

TABLE III

RATE CONSTANTS FOR FORMATION OF 1-CYCLOHEXEN-1-YL METHYL KETONE FROM 2-CYCLOHEXEN-1-YL METHYL KETONE IN AQUEOUS SULFURIC ACID[a]

H_2SO_4, %	$-H_0$	10^4k, sec^{-1}	H_2SO_4, %	$-H_0$	10^4k, sec^{-1}
1.67	−0.62	0.137	17.3	0.88	3.78
2.96	−0.35	0.234	20.8	1.13	5.84
3.92	−0.23	0.342	21.8	1.18	5.86
4.72	−0.13	0.428	26.6	1.53	10.4
6.51	0.06	0.774	28.9	1.70	13.2
9.25	0.31	1.25	32.4	1.96	19.2
13.13	0.60	2.24			

[a] Temperature, 25.0°.

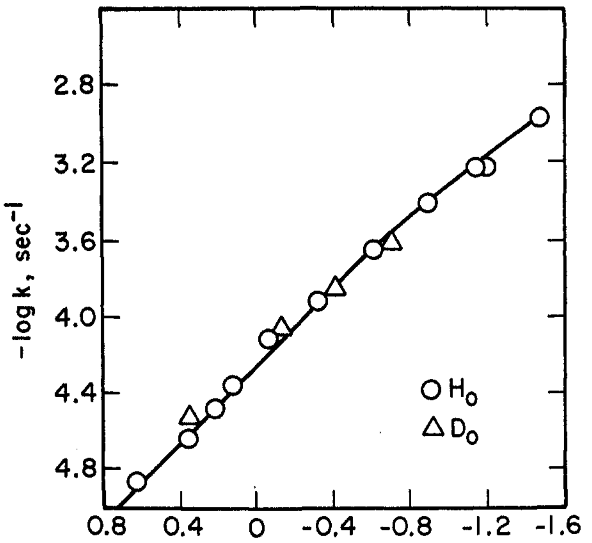


Figure 2.—Solvent isotope effect for formation of 1-cyclohexen-1-yl methyl ketone from 2-cyclohexen-1-yl methyl ketone.

When compound **6** was prepared and then isomerized, first-order behavior was observed; the rate constants are listed in Table IV. By interpolation of these data and comparison with the initial rate data from Table V, an isotope effect ($k_{C\text{-}1\ H}/k_{C\text{-}1\ D}$) of 4.5 was calculated for the isomerization reaction. Thus it was felt that the total behavior of the formation of **5** from **4** in D_2SO_4–D_2O could be accounted for in terms of kinetic scheme 2. Table V lists the rate constants determined for this model by a nonlinear least-squares regression on the uv data for the formation of **5**.

TABLE IV

RATE CONSTANTS FOR FORMATION OF 1-CYCLOHEXEN-1-YL METHYL KETONE FROM 2-CYCLOHEXEN-1-YL-*1-d* METHYL KETONE IN D_2SO_4–D_2O[a]

D_2SO_4, %	$-D_0$	10^5k, sec^{-1}
7.0	0.16	2.02
10.3	0.45	3.49
15.0	0.80	6.62

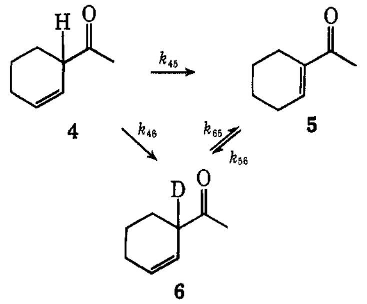
[a] Temperature, 25.0°.

TABLE V

RATE CONSTANTS FOR 2-CYCLOHEXEN-1-YL METHYL KETONE IN D_2SO_4–D_2O. KINETIC SCHEME 2[a]

D_2SO_4, %	$-D_0$	10^5k,[b] sec^{-1} k_{45}	k_{46}	k_{65}	k_{56}	10^5k_{45},[c] sec^{-1}	$k_{C\text{-}1\ H}/k_{C\text{-}1\ D}$ isom[d]
2.94	0.36	2.45	20.4	.383	0.0541	3.04	
6.72	0.13	8.45	66.0	1.27	0.274	8.7	4.5
9.49	0.40	16.8	145	3.00	0.498		
9.75	0.42	18.7	153	3.05	0.518	14.8	4.8
12.9	0.66	37.9	279	6.49	1.21		
13.7	0.71	34.9	301	6.41	1.24	24.2	4.4
17.0	0.94	80.8	692	15.0	3.21		

[a] Temperature, 25.0°. [b] Determined by least-squares analysis. [c] From initial rates. [d] $k_{C\text{-}1\ D}$ interpolated from Table IV.


(2)

In summary, we have found that in D_2SO_4–D_2O 2-cyclohexen-1-yl methyl ketone exchanges the hydrogen at C-1 (*i.e.*, enolizes) about ten times faster than it isomerizes to 1-cyclohexen-1-yl methyl ketone. Since the C-1 D compound isomerizes at a rate which is $^1/_{4.5}$th of that of the C-1 H compound, the former compound accumulates, and the formation of the conjugated isomer shows non-first-order behavior. Because enolization is faster than isomerization, we conclude that protonation of the enol has become rate-limiting in the isomerization process, as we have observed previously for 3-cyclohexen-1-one.[4]

Because the medium can be expected to affect the enolization process and the protonation of the enol to form either the α-deuterated β,γ-unsaturated ketone or the α,β-unsaturated ketone, the observed solvent isotope effect is a complex combination of the effects on these individual processes. For enol formation we expect the usual effect (k_{D_2O}/k_{H_2O}) of about 1.4.[4] If we take the effect which has been observed on the protonation of enol ethers[12] or of acetone's enol[13] as a model, we can expect effects of 0.3–0.4 on the protonations of the enol (at the α carbon to form α-deuterated 2-cyclohexenyl methyl ketone and at the γ carbon to form γ-deuterated cyclohexenyl methyl ketone), contributing to the total observed effects on the rate of isomerization in opposing directions. Apparently in this case these contributions result in the total observed effect of 1.0. This is in contrast to the result for 3-cyclohexen-1-one, where the rate of exchange is so much faster than the rate of isomerization that the enolization process is virtually at equilibrium, which is affected comparatively little by the medium. In that case the medium effect on the protonation of the enol leading to isomerized product clearly dominates the observed solvent isotope effect.

Registry No.—**1**, 3744-02-3; **4**, 29372-98-3; **5**, 932-66-1; 1-(acetoxyethylidenyl)-2-cyclohexene, 32958-83-1.

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Photoreduction of 2,4-Dimethyl-3-oxo-3,5,6,7,8,8a-hexahydro-1,8a-butanonaphthalene, a Nonphotorearranging Cross-Conjugated Cyclohexadienone

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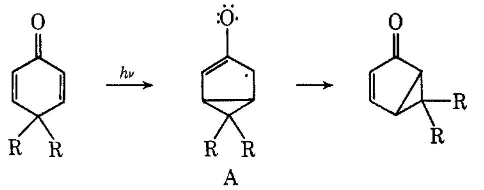
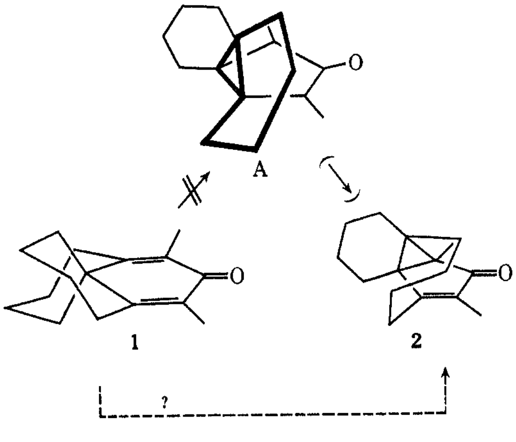
Received June 18, 1971

The title substance (1) was prepared from an (iodobutyl)tetrahydronaphthol by internal displacement. Failure of 1 to undergo type A photorearrangement was observed, and a low quantum efficiency for photodecomposition was noted. In 2-propanol solvent, photoreduction of one of the double bonds of 1 was achieved. Nmr examination of 1 and its di- and tetrahydro derivatives allowed stereochemical structure assignments to be made. The mechanism of photoreduction is considered to be a proton abstraction (radical) from solvent by excited 1, followed by a disproportionation.

Recent reports[1,2] examining the influence of steric factors in the type A photorearrangement of 2,5-cyclohexadienones have prompted us to record the synthesis and limited photochemical reactivity of a novel tricyclic dienone (**1**). Our original intent in preparing the ring system of **1** was to attempt to disprove the mechanistic proposals for the type A photoisomerization of cyclohexadienones advocated by Zimmerman.[3] A key intermediate in the latter scheme involves bridging between β and β′ positions of the conjugated system (A). It will be observed that due to the geometric constraints imposed by the tetramethylene bridges of the spiro ring system of **1** the intermediate (containing as it would a trans-fused norcarane ring—bold face bonds) may not





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