J. Am. Chem. Soc. 1983, 105, 1289–1292 1289

Reactions of Carbenes with Acetone. Reversible Thermal Formation and Fragmentation of Carbonyl Ylides and Their Cycloaddition to Acetone

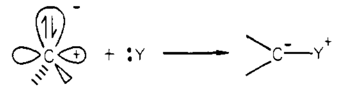
Michel Bêkhazi and John Warkentin*

Contribution from the Department of Chemistry, McMaster University, Hamilton, Ontario, Canada L8S 4M1.

Received June 2, 1982

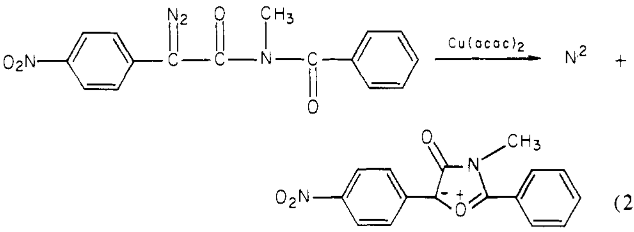
Abstract: 2-Methoxy-2,5,5-trimethyl-Δ3-1,3,4-oxadiazoline (**1**) undergoes thermal decomposition in solution to form a carbonyl ylide intermediate. In acetone-d_6 a portion of the ylide is trapped by cycloaddition but a large fraction undergoes fragmentation, either to methyl acetate and 1-methylethylidene or to acetone and 1-methoxyethylidene. Both carbenes react with acetone-d_6 at the carbonyl oxygen to generate carbonyl ylides and they also insert into C–D bonds of the ketone. The carbonyl ylides themselves react with acetone by a 1,3-cycloaddition processes.

Singlet carbenes can react as Lewis acids by sharing a pair of nonbonding electrons contributed by a Lewis base (eq 1). If Y

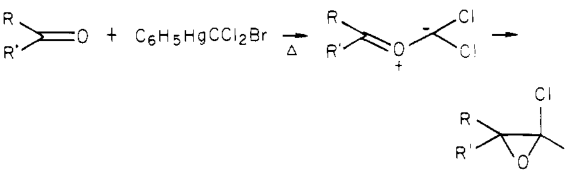


(1)

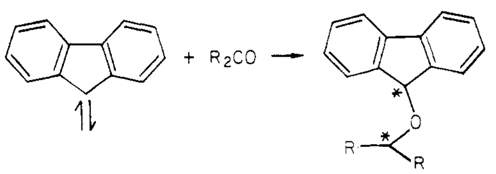
is an uncharged species, the product of such an acid–base reaction is an ylide (eq 1). Nucleophilic species that are known to trap carbenes according to eq 1 include some with sulfur, nitrogen, halogen, and oxygen as the nucleophilic site.[1] Examples in which the nucleophilic site is carbonyl oxygen and the result of trapping is a carbonyl ylide are shown in eq 2[2] and 3.[3,4] Since both examples involve metallic species among the reactants, it is not clear whether the reactive intermediate preceding the ylide was a carbene or a carbenoid. The only examples, to our knowledge, of carbonyl ylide formation by reaction of a free carbene with ketones are those reported recently by Wong, Griller, and Scaiano.[5] They generated singlet fluorenylidene, which was identified spectrophotometrically, and followed its capture by aliphatic ketones to form carbonyl ylides (eq 4). Ethyl acetate apparently failed to react with singlet fluorenylidene in the sense of eq 4, since the expected alkoxy-substituted carbonyl ylide intermediate could not be detected.[5]



(2)

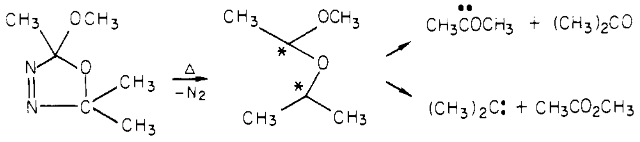


(3)



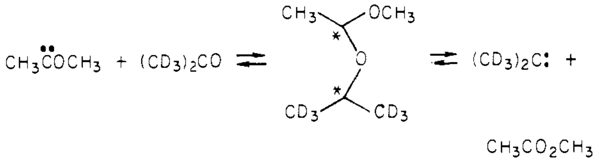
(4)

We recognized that our recently discovered[6] thermal fragmentation of an alkoxy-substituted carbonyl ylide (eq 5) might



(5)

be used to determine whether or not an alkoxy-substituted carbene can react with a ketone. If one or both fragmentations were reversible, some initial products from one sense of fragmentation would be converted to products from the other sense of fragmentation (eq 5). This could be detected through the use of labeled acetone or labeled methyl acetate as solvent. In view of the failure of ethyl acetate to form an ylide with fluorenylidene[5] (see above), acetone-d_6 would be the logical choice, and it would be expected to yield $(CD_3)_2C$: according to eq 6.

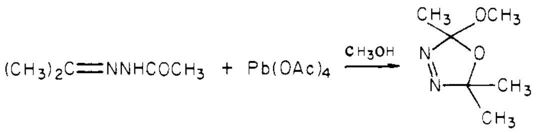


(6)

We wish to report evidence for the capture of 1-methylethylidene and 1-methoxyethylidene by acetone-d_6 to form a tetralkyl carbonyl ylide and an alkoxy trialkyl carbonyl ylide, respectively. Cycloadditions of the carbonyl ylides to the ketone are also reported.

Methods, Results, and Discussion

2-Methoxy-2,5,5-trimethyl-Δ3-1,3,4-oxadiazoline (**1**) was prepared by the route outlined in eq 7. It was decomposed in



1

(7)

---

[1] The subject of ylide formation from carbenes has been reviewed recently. See: Nikolaev, V. A.; Korobitsyna, I. K. *Zh. Vses. Khim. Ova.* **1979**, *24*, 496 and references cited therein.

[2] Hamagushi, M.; Ibata, T. *Tetrahedron Lett.* **1974**, 4475.

[3] (a) Seyferth, D.; Tronich, W. *J. Organometal. Chem.* **1969**, *18*, 8. (b) Seyferth, D.; Smith, W. E. *Ibid.* **1971**, *26*, 655. (c) Seyferth, D.; Hopper, S. P. *Ibid.* **1973**, *51*, 77. (d) Seyferth, D.; Tronich, W.; Smith, W. E.; Hopper, S. P. *Ibid.* **1974**, *67*, 341.

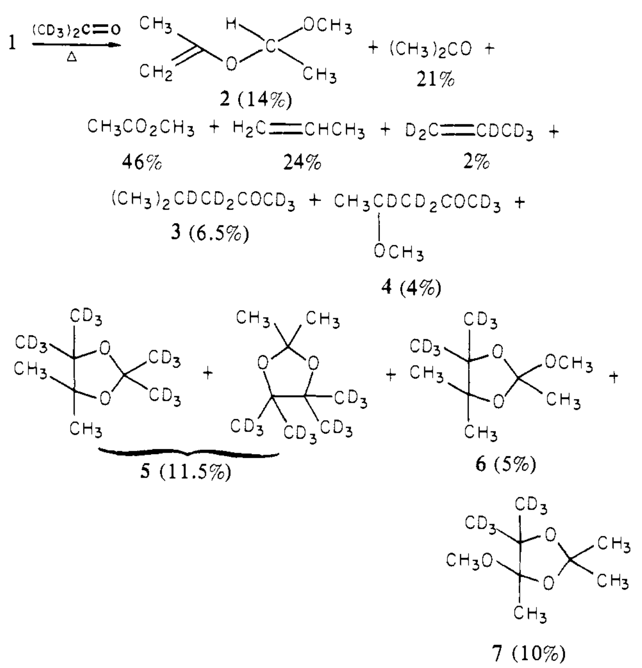
[4] The carbonyl ylides in eq 2 and 3 are written in dipolar form to emphasize the origin of the generic name for the class. It is not clear to what extent such species have dipolar, as opposed to diradical, character.

[5] Wong, P. C.; Griller, D.; Scaiano, J. C. *J. Am. Chem. Soc.* **1982**, *104*, 5106.

[6] Bêkhazi, M.; Warkentin, J. *J. Am. Chem. Soc.* **1981**, *103*, 2473.

0002-7863/83/1505-1289$01.50/0

Scheme I

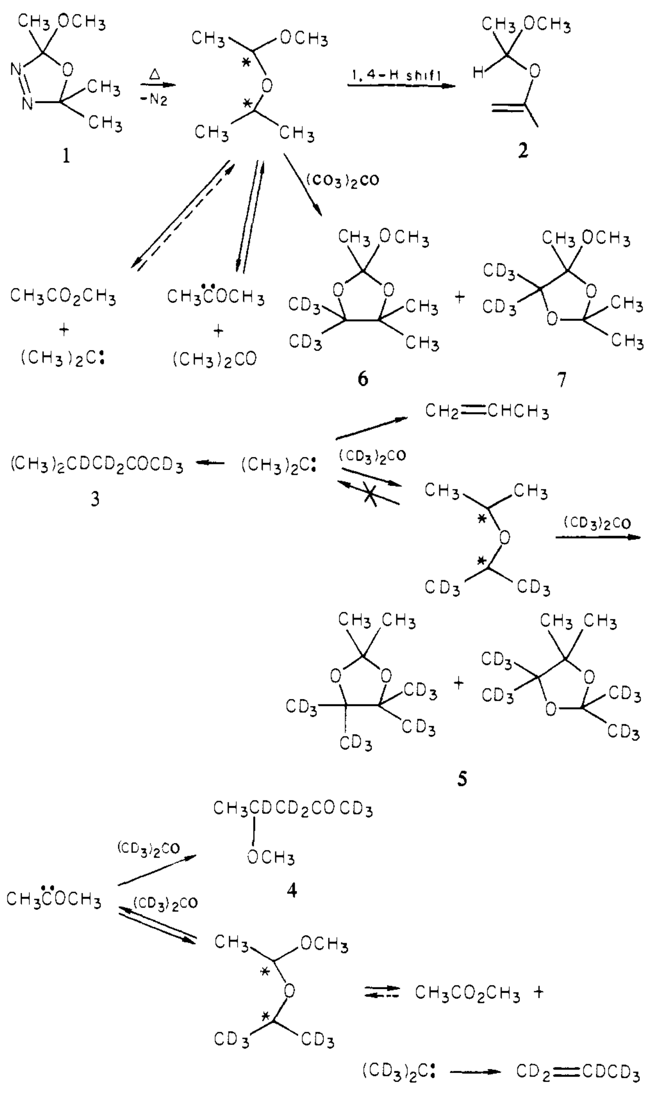


acetone-d_6 at 79.5 °C to afford the products shown in Scheme I.

The identities and yields of products in Scheme I were determined as follows. A sample of **1** was decomposed, in $(CD_3)_2CO$ containing CH_2Cl_2 as internal standard, in a sealed NMR tube. Yields of acetone, methyl acetate, propene, and 1-methoxy-1-[(1-methylethenyl)oxy]ethane (**2**) were determined by averaging integrals of appropriate signals against those of the internal standard.[7] Errors in those yields are ±5% or less of the values reported. The tube was then opened and an aliquot was analyzed by GC–FTIR and GC–MS. Yields of **3**, **4**, and **5** and the combined yields of **6** and **7** were determined from the GC traces, using the GC trace for **2** and its yield (from ^{1}H NMR) for reference. Error in these yields are higher but should not exceed ±20% of the values reported. The molecular weights and fragmentation patterns from the mass spectra gave preliminary information about the identities and deuterium content of compounds **3**–**7**. Those structures were then confirmed through the ^{1}H NMR spectra of their unlabeled analogues, which were separated by GC and collected, after decomposing a large sample of **1** in ordinary acetone. Details necessary for the main mechanistic argument follow in the next paragraphs. Other detail can be found in the Experimental Section.

The presence of propene-d_6 among the products is based on three observations. First, the vapor-phase FTIR spectrum, taken "on the fly" as the propene fraction eluted from the GC column, showed C–D stretching bands at 2295, 2264, and 2217 cm^{-1} in addition to all the bands found in the spectrum of authentic propene. Second, the ^{2}H NMR spectrum of the reaction mixture showed broad singlets, at δ 4.89, 5.06, and 5.71. A high-field signal expected near δ 1.70 could not be resolved from signals of other products. Those chemical shifts correspond closely to the ^{1}H chemical shifts for authentic propene (δ 1.69, 4.91, and 5.79). Finally, bromination of the propene from the reaction mixture followed by separation of the dibromopropane by gas chromatography and analysis by MS gave m/z 127, 129 ($C_3D_6Br^+$); 121, 123 ($C_3H_6Br^+$); 46 ($C_3D_5^+$, rel abundance 2.5); 41 ($C_3H_5^+$, relative abundance 33). Signals at m/z 127, 129, and 46 were absent from the mass spectrum of authentic 1,2-dibromopropane. These results, taken together, leave no doubt that propene-d_6 was present in the propene fraction. From the intensities of the allyl cation signals (m/z 46, 41) the ratio of propene-d_6 to propene was estimated to be 0.08.

Scheme II



Enol ether **2**, a known compound,[8] was readily recognized from its ^{1}H NMR spectrum, as were 4-methyl-2-pentanone[9] and 4-methoxy-2-pentanone[10] (Table I). The last two, when made in acetone-d_6, had the required deuterium content of **3** and **4**. Hexamethyl-1,3-dioxolane has been reported.[10] Our material had ^{1}H NMR and mass spectra consistent with reported values[10] (Table I), and **5**, the d_{12} analogue obtained from decomposition of **1** in acetone-d_6, gave the required mass spectrum (Table I).

The isomeric methoxydioxolanes **6** and **7** (and their unlabeled analogues) could not be separated from each other. Assignment of structure is based on mass spectral evidence (m/z 165, $C_8D_6H_9O_3^+$, M – CH_3, Table I) for the deuterated mixture and on the ^{1}H NMR evidence for the unlabeled mixture. The spectrum of the latter had two methoxy signals at δ 3.30 and 3.35. These were assigned, tentatively, to **7** and **6**, respectively, because the δ 3.35 signal had the same intensity as a δ 1.87 singlet, which could best be assigned to the CH_3CO_3 methyl group of **6**.[11] The ratio (**7**/**6**) was about 2:1.

A mechanism that can account for the products obtained from thermolysis of **1** in acetone-d_6 is shown as Scheme II, which is

---

[7] Yields are expressed in terms of moles of product per mole of reactant, in the usual way. Since **2** is a product formed with 1:1 stoichiometry from the ylide intermediate, whereas the others come from fragmentations with 2:1 stoichiometry, the yields total neither 100% nor 200%.

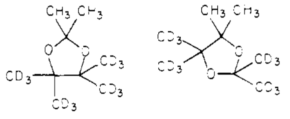
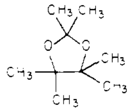
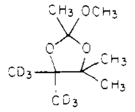
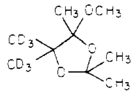
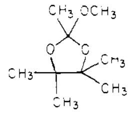
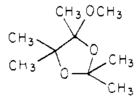
[8] Hitchcock, A. P.; Zweep, S.; Steel, T.; Bêkhazi, M.; Warkentin, J. *Can. J. Chem.* **1982**, *60*, 2914.

[9] Shermer, W. D. Ph.D. Thesis, University of Illinois, 1970.

[10] Kirmse, W.; Englemann, A.; Heese, J. *Chem. Ber.* **1973**, *106*, 3073.

[11] The chemical shift of a similar CH_3 group in a model compound, $CH_3-C(OCH_3)(OCD_3)-O-CD(CH_3)_2$, is δ 1.92 in CD_3OD.[6]

Table I. Spectra of Products

compound[a]	^1H NMR[b]	MS, m/z
$CH_3C(=CH_2)OC(CH_3)HOCH_3$ (2)	1.39 (3 H, d, J = 5.4 Hz); 1.84 (3 H, s); 3.36 (3 H, s); 3.96 (2 H, s); 5.11 (1 H, q, J = 5.4 Hz)	
$(CH_3)_2CDCD_2COCD_3$ (3)		106 ($C_6D_6H_6O^+$); 91 ($C_5D_6H_3O^+$); 88 ($C_5D_3H_6O^+$); 74 ($C_4D_3H_4O^+$); 60 ($C_3D_2H_4O^+$)
$(CH_3)_2CHCH_2COCH_3$	0.93 (6 H, d, J = 7.5 Hz); 2.01 (3 H, s); 1.87-2.40 (3 H, m)	
$CH_3C(OCH_3)DCD_2COCD_3$ (4)		122 ($C_6D_6H_6O_2^+$); 107 ($C_5D_6H_3O_2^+$); 104 ($C_5D_3H_6O_2^+$); 76 ($C_4D_3H_6O^+$)
$CH_3C(OCH_3)HCH_2COCH_3$	1.11 (3 H, d, J = 6.0 Hz); 2.03 (3 H, s); 2.35-2.46 (2 H, m); 3.16 (3 H, s); 3.55-3.70 (1 H, m)	
 5		155 ($C_8D_{12}H_3O_2^+$); 152 ($C_8D_9H_6O_2^+$); 94 ($C_5D_9O^+$); 91 ($C_5D_6H_3O^+$)
	1.25 (12 H, s); 1.44 (6 H, s)	
 		165 ($C_8D_6H_9O_3^+$); 149 ($C_8D_6H_9O_2^+$); 105 ($C_6D_6H_5O^+$); 91 ($C_5D_6H_3O^+$)
 	1.25 (s); 1.28 (s) 1.31 (s); 1.43 (s); 1.87 (s); 3.30 (s); 3.35 (s)[c]	

[a] Where both unlabeled and deuterated analogues are listed, the former were obtained from decomposition of 1 in acetone and the latter came from decomposition of 1 in acetone-d_6. [b] δ values, $CDCl_3$. [c] Some signals in this spectrum were not fully resolved, and determination of relative integrals was difficult. The sum of the integrals of the methoxy signals at δ 3.30 and 3.35 was one-fifth of the sum of the integrals of the methyl signals.

discussed below. Intramolecular H transfer to form **2** is a well-documented reaction of carbonyl ylides[8,12,13] and is the major process when **1** is decomposed in the gas phase.[8] Cycloaddition of tetramethyl carbonyl ylide to acetone to form hexamethyl-1,3-dioxolane (analogue of **5**) has been reported,[9] and similar cycloaddition of a methoxy-substituted carbonyl ylide, leading to **6** and **7** in this case, is not surprising.[14] The preferred sense of cycloaddition, favoring **7** over **6**, is reasonable, since the transition state leading to **7** is expected to have a better alignment (head to tail) of the dipoles of the reactants.

Products **3** and **4** are clearly those of insertion of 1-methylethylidene and 1-methoxyethylidene, respectively, into a C–D bond of acetone-d_6. These products reinforce the previous claim[6] that the carbonyl ylide from **1** fragments thermally to carbonyl compounds and carbenes.

Formation of propene-d_6 is of major importance. Reversible addition of 1-methylethylidene to acetone-d_6 can be ruled out as a likely source of propene-d_6 because of the high calculated barrier to thermal fragmentation of carbonyl ylides that lack a donor substituent.[15] Such thermal fragmentations have never been found to compete with cycloadditions.[16] The only reasonable mechanism for formation of propene-d_6 appears to be that shown at the bottom of Scheme II, with the requirement that 1-methoxyethylidene adds reversibly to acetone-d_6 to form the alkoxy-substituted carbonyl ylide. This is the first demonstration of the reversible thermal fragmentation and re-formation of a carbonyl ylide and only the second example of addition of a carbene to a ketone to form an ylide, in which there is no ambiguity about whether or not the carbene is a free species or a metal-complexed carbenoid. Whether or not 1-methylethylidene attacks methyl acetate to form the same ylide is a question that is left open at this time, as indicated with the dashed arrow in Scheme II.[17]

Experimental Section

Proton NMR spectra were acquired with a Varian EM-390 or with a Bruker WP-80 instrument. Deuterium spectra of propene-d_6 were obtained with a Bruker WM-400 spectrometer. The solvent was $CDCl_3$, and shifts are expressed relative to the chloroform signal at δ 7.27.

Gas-phase infrared spectra were obtained with a Nicolet, Model 799, Fourier transform instrument equipped with a Varian Aerograph Model 920 gas chromatograph. Mass spectra were acquired with a VG 7070 mass spectrometer equipped with a Varian Aerograph Model 920 gas chromatograph and with the VG 2035 data system.

Synthesis of 1. To a yellow solution of lead tetraacetate (44.3 g, 0.10 mol) in absolute methanol (300 mL) at ice temperature was added acetone *N*-acetylhydrazone (11.4 g, 0.10 mol). The solution was stirred during the addition and thereafter until the yellow color was discharged. Potassium hydroxide (pellets, 10 g) was added to destroy the acetoxyoxadiazoline coproduct and the solution was kept at 0 °C, with stirring, for 2 h. Most of the solvent was then removed with a rotary evaporator, water was added to the residue, and the aqueous solution was extracted with CH_2Cl_2. The organic layer was washed several times with water before it was dried over $CaCl_2$. Removal of the solvent with a rotary evaporator and bulb-to-bulb distillation (10^{-2} torr) of the residue from an unheated flask to one cooled with liquid N_2 afforded 8.5 g (60%) of 2-methoxy-2,5,5-trimethyl-$\Delta3$-1,3,4-oxadiazoline: ^1H NMR δ 1.43 (3

---

(12) Shimizu, M.; Bartlett, P. D. *J. Am. Chem. Soc.* **1978**, *100*, 4260.

(13) Bēkhazi, M.; Warkentin, J. *Can. J. Chem.* submitted for publication.

(14) For other examples of 1,3-dipolar cycloadditions to carbonyl and thiocarbonyl compounds see: Huisgen, R.; Sustmann, S. *Heterocycles*, **1976**, *5*, 141.

(15) Houk, K. N.; Rondan, N. G.; Santiago, C.; Gallo, C. J.; Gandour, R. W.; Griffin, G. W. *J. Am. Chem. Soc.* **1980**, *102*, 1504 and references cited therein.

(16) Huisgen, R. *Angew. Chem., Int. Ed. Engl.* **1977**, *17*, 572 and references cited therein.

(17) It is unlikely that this question can be answered readily through the use of labeled methyl acetate as solvent. The fast, 1,2-H shift in 1-methylethylidene, which made the present study possible, is likely to destroy most of the carbene before it can be caught by methyl acetate. That likelihood is high because of the fact that singlet fluorenylidene reacts much more slowly with ethyl acetate than with dialkyl ketones,[5] as mentioned in the introduction.

H, s), 1.55 (6 H, s), 3.06 (3 H, s); ^{13}C NMR δ 23.4, 24.0, 25.1, 50.4 (OCH_3), 119.9 (C-5), and 133.7 (C-2); MS (CI/NH_3), *m/z* 162 (M^+). Anal: ($C_6H_{12}N_2O_2$) C, H, N.

Thermolysis of 1 in $(CD_3)_2CO$. Oxadiazoline **1** (20 mg, 1.39 × 10^{-4} mol) in $(CD_3)_2CO$ (0.5 mL) containing CH_2Cl_2 (internal standard) was sealed into an NMR tube after several freeze–pump–thaw cycles at 10^{-2} torr. The tube was heated at 80 °C for 8 days, at which time the signal from **1** had disappeared. Yields of **2**, acetone, methyl acetate, and propene were determined by NMR at 90 MHz, by using an expanded δ scale and the cut-and-weigh procedure.

Products from analogous thermolysis of **1** (100 mg, 6.9 × 10^{-4} mol) in acetone-d_6 (3.0 mL) in a Pyrex tube were transferred to a bulb-to-bulb still and the most volatile fraction (propene plus some acetone, ester, and some solvent) was distilled over.

The distillate was used to obtain the ^{1}H and ^{2}H NMR spectra of the propene/propene-d_6 mixture and it was injected into the GC-MS system and into the GC-FT/IR system for the mass spectrum and infrared spectrum of the mixture. The remaining distillate was treated with Br_2 in CCl_4 to convert propenes to dibromopropanes, which were collected from a GC column (6 ft × 0.25 in. 20% DEGS, 140 °C, 40 mL min^{-1}) for mass spectrometric analysis.

The distillation residue, containing acetone, methyl acetate, solvent, and high boiling materials, was analyzed by GC (6 ft × 0.25 in. column, 3% OV-17, temperature programmed to 200 °C after 5 min at 35 °C) to determined relative yields, which were converted to absolute yields through correlation with the ^{1}H NMR assay, as described in the text. Mass spectra of each eluent were obtained on the fly. Acetone, methyl acetate, **3**, **2**, **4**, **5**, and **6** plus **7** were eluted in that order.

Thermolysis of 1 in Acetone. The thermolysis was similar to that described above for the large-scale decomposition in acetone-d_6. Much of the volatile material, including solvent, was separated from the less-volatile products by bulb-to-bulb distillation as already described. Both the distillate and the distillation residue were analyzed with a GC column similar to that used for deuterated products (OV-17, but 10%) from which the components eluted in the same order. Components were collected to determine the ^{1}H NMR spectra in Table I.

Acknowledgment. Financial support of this work by the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged. We are indebted to E. Osei-Twum for many of the mass spectra. The high-field NMR spectra were obtained at the Southwestern Ontario NMR Centre funded by a grant from NSERC.

Registry No. 1, 77879-49-3; **2**, 84369-94-8; **3**, 84369-95-9; **4**, 84369-96-0; **5** (isomer 1), 84369-97-1; **5** (isomer 2), 84369-98-2; **6**, 84369-99-3; **7**, 84370-00-3; $(CD_3)_2CO$, 666-52-4; $(CH_3)_2CO$, 67-64-1; $CH_3CO_2CH_3$, 79-20-9; $H_2C{=}CHCH_3$, 115-07-1; $D_2C{=}CDCD_3$, 1517-52-8.

Regiochemical Control in Intramolecular Photochemical Reactions of 1,5-Hexadien-3-ones and 1-Acyl-1,5-hexadienes

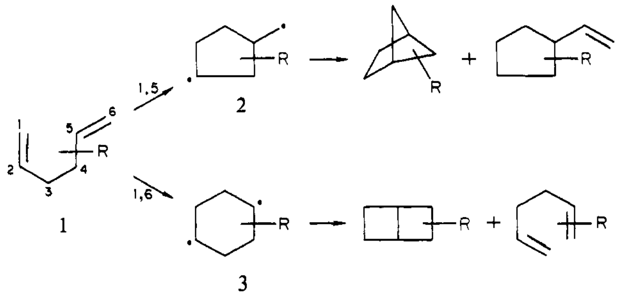
Steven Wolff* and William C. Agosta*

Contribution from the Laboratories of The Rockefeller University, New York, New York 10021.

Received July 21, 1982

Abstract: Both 1,5-hexadien-3-ones (**7**) and 1-acyl-1,5-hexadienes (**8**) generally undergo intramolecular photochemical cyclization by way of 1,5 (crossed) closure (see **2**), as do other derivatives of 1,5-hexadienes (**1**). Through study of the photochemistry of 14 members of series **7** and **8**, summarized in Tables I and II, two effects that modify this regiochemistry and favor a shifting to 1,6 (straight) closure (see **3**) were identified. These are alkyl substitution at C(5) and incorporation of the conjugated double bond in a five- or six-membered ring. These effects are additive, and with both present (as in **4** and **19**) regiospecific 1,6 closure can occur. The sources of these effects and implications of these reactions for the mechanism of the intermolecular [2 + 2] cyclization are discussed.

Over the past 15 years numerous inquiries have supported the generalization[1,2] that ultraviolet irradiation of 1,5-hexadienes (**1**)



leads preferentially to 1,5 (crossed) closure, with formation of a biradical intermediate **2** that then proceeds to products. All indication of the alternative 1,6 (straight) closure leading to **3** is frequently completely absent, and little or no change results from incorporation of the hexadiene double bonds into more complex systems such as trienes,[2] tetraenes,[3] or α,β-unsaturated ketones[4,5] or esters.[6] Typically **2** collapses to a bicyclo[2.1.1]hexane or, with appropriate substitution, it may disproportionate, while **3** either gives a bicyclo[2.2.0]hexane or fragments to an isomeric 1,5-hexadiene. Various authors have called attention to this "rule of five" and its broad validity over the years,[1,2,7,8] and the few exceptions known[9,10] are reasonably understood to result from special structural features.

In contrast to these generalizations Smith noted some 10 years ago that photolysis of ketone **4** in methanol gave only the two isomers of ester **5**, a result requiring 1,6 closure.[11] Further

---

(1) Srinivasan, R.; Carlough, K. H. *J. Am. Chem. Soc.* **1967**, *89*, 4932.

(2) Liu, R. S. H.; Hammond, G. S. *J. Am. Chem. Soc.* **1967**, *89*, 4936.

(3) White, J. D.; Gupta, D. N. *Tetrahedron* **1969**, *25*, 3331.

(4) Bond, F. T.; Jones, H. C.; Scerbo, L. *Tetrahedron Lett.* **1965**, 4685.

(5) Gibson, T. W.; Erman, W. F. *J. Org. Chem.* **1972**, *37*, 1148.

(6) Scheffer, J. R.; Wostradowski, R. A. *J. Org. Chem.* **1972**, *37*, 4317. Crandall, J. K.; Mayer, C. F. *Ibid.* **1970**, *35*, 3049.

(7) Dilling, W. L. *Chem. Rev.* **1966**, *66*, 373. Turro, N. J. "Modern Molecular Photochemistry"; Benjamin/Cummings: Menlo Park, CA, 1978; Chapter 11 and references cited therein.

(8) The most recent discussions known to us are those of (a) Hoye, T. R.; Martin, S. J.; Peck, D. R. *J. Org. Chem.* **1982**, *47*, 331. (b) Oppolzer, W. *Acc. Chem. Res.* **1982**, *15*, 135.

(9) Ward, H. R.; Karafiath, E. *J. Am. Chem. Soc.* **1969**, *91*, 522, 7474 (allylically stabilized radical).

(10) Yoshioka, H.; Mabry, T. J.; Higo, A. *J. Am. Chem. Soc.* **1970**, *92*, 923 (structurally constrained system).

0002-7863/83/1505-1292$01.50/0 © 1983 American Chemical Society