Thermolysis of 2-(3-Butyn-1-oxy)-2-methoxy-5,5-dimethyl-Δ^3-1,3,4-oxadiazoline in Solution. A Remarkable Cascade of Carbene and Other Reactions

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Thermolysis of 2-(3-butyn-1-oxy)-2-methoxy-5,5-dimethyl-Δ^3-1,3,4-oxadiazoline in benzene or in toluene affords (1α,1aα,3aα,6aα,6bα)-methyl 1a-ethenyloctahydro-6a-methoxy-2,2-dimethyl-3,6-dioxacyclobut[*cd*]indene-1-carboxylate in up to 74% yield. A reasonable mechanism involves about ten sequential steps and some novel intermediates including a dioxycarbene, a cyclopropenone ketal, and a vinylogous dioxycarbene. Various steps in the proposed mechanism were inferred from the results of deuterium-labeling experiments and from the incorporation of key intermediates from solution into the final product.

Recently we reported the preparation of 2,2-dialkoxy-Δ^3-1,3,4-oxadiazolines, such as **2**, by oxidation of the (methoxycarbonyl)hydrazone of acetone (**1**) in the presence of an alcohol (Scheme 1).[1,2] Thermolysis of **2** in benzene caused cycloreversion to the corresponding carbonyl ylide **3** and subsequent fragmentation of the ylide afforded a dialkoxycarbene (**4**) and acetone (Scheme 1). Evidence for formation of a dialkoxycarbene intermediate came from the observation that, in general, acetone as well as the (*E*)- and (*Z*)-tetraalkoxyethenes, to be expected from dimerization of **4**, were formed in high yields.[1]

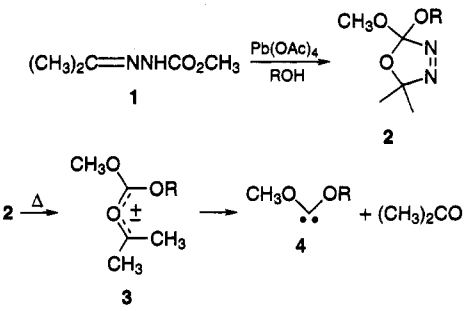
Butynoxymethoxyoxadiazoline (**5**), prepared to investigate intramolecular reactions of the triple bond with the ylide and/or the carbene (Scheme 2), did not afford tetraalkoxyethene on thermolysis.[1] Instead there was obtained a minor product, thought to be **8**, with the same composition as ylide intermediate **6**. It was attributed to intramolecular cycloaddition of the ylide to the triple bond, followed by ring opening and rearrangement.[1] The structure of the major product from **5** was not known, but it was evident from the mass spectrum that it had the composition of one unit of ylide plus one unit of carbene.

We now report that the major product of thermolysis of **5** in benzene or toluene is the tricyclic cyclobutanone ketal **17a** (up to 74%) and that the minor product, previously described as **8**, is actually an isomer (**15**) (Scheme 2). The essential features of a complete mechanism for the formation of **17a** have been worked out, and the mechanism accounts for **15** and for its role in the formation of **17a**.

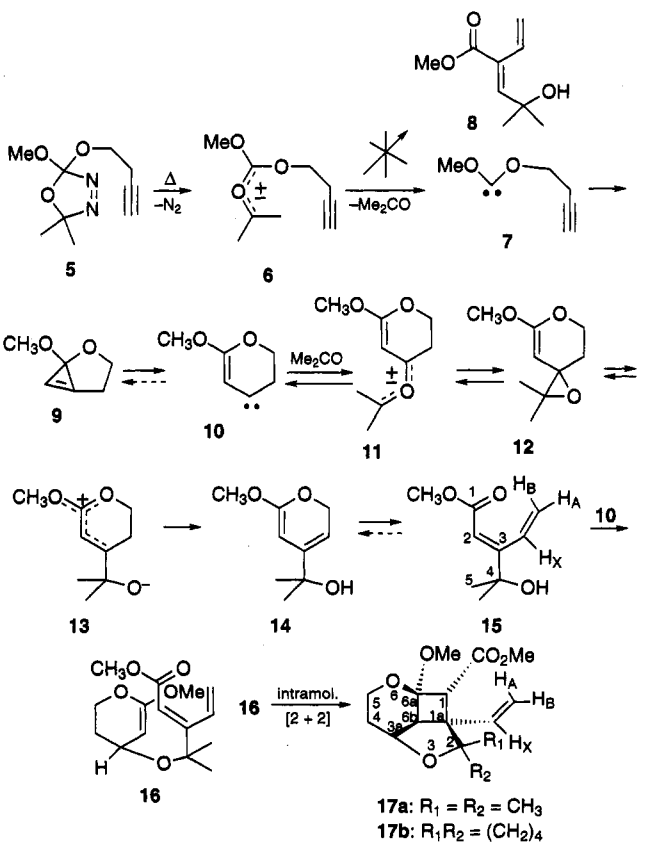
Results and Discussion

The composition of **17a**, $C_{14}H_{22}O_5$, which was indicated by the ^1H and the ^{13}C NMR data, was confirmed by mass spectrometry. The connectivity and stereochemistry of **17a**, although they were also inferred from the exhaustive application of NMR techniques, were not compelling because several other solutions were possible. Therefore, the molecular structure was established by means of single-crystal X-ray diffraction.[3] With the structure and stereochemistry of **17a** firmly established, a mechanistic

Scheme 1



Scheme 2



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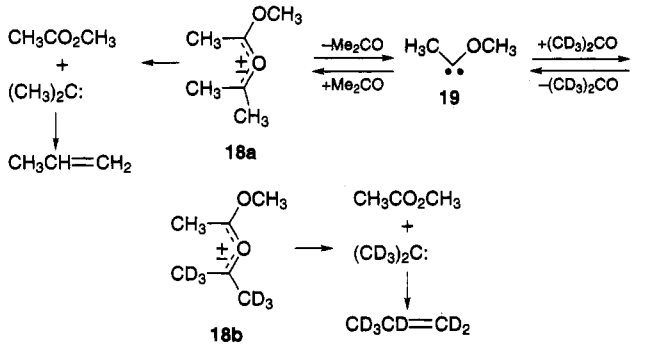
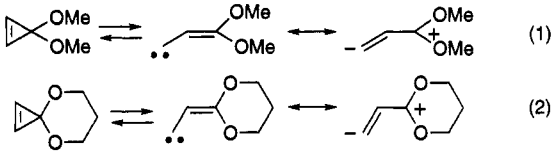
Scheme 3



hypothesis was generated and then tested by means of isotope labeling and by introduction of accessible reaction intermediates. We begin with the mechanism (Scheme 2) and then proceed to discuss the steps and the evidence and/or precedents for them.

The first step, thermal fragmentation of oxadiazoline **5** to N_2 and carbonyl ylide **6**, is well established.[4-7] It is a $[4\pi + 2\pi]$ cycloreversion that is allowed, according to orbital symmetry, to be concerted.[8,9] That step is presumably irreversible, as cycloadditions to N_2 are unknown. The fragmentation of the ylide, to dialkoxycarbene **7** and acetone, is based on analogy to the chemistry of a close analogue. Ylide **18a** fragments reversibly to 1-methoxyethylidene (**19**) as shown by trapping **19** with acetone-d_6[10] (Scheme 3) to afford propene-d_6 via ylide **18b**. Fragmentation of carbonyl ylide **6** to carbene **7** and acetone (Scheme 2) is also implied by the observation that acetone and tetraalkoxyethenes are major products from thermolysis of simple dialkoxyoxadiazolines **2** (Scheme 1, R = Et for example).[1]

Intramolecular addition to an unactivated triple bond, converting **7** to **9** (Scheme 2), appears to be unprecedented for dialkoxycarbenes. Such carbenes are classified as nucleophilic[11] and their reactivity toward unactivated CC multiple bonds is low.[11] We assume that intramolecularlity is the feature that makes that step competitive. There are numerous examples of cyclopropene/vinylcarbene interconversions[12,13] to model the step that converts **9** to **10**. That step is probably reversible, because **10** is a 3,3-dioxyvinylcarbene analogous to those generated by thermolysis by cyclopropenone ketals.[14] In the cases of monocyclic and spirocyclic cyclopropenone ketals, thermal ring opening to vinylcarbenes is reversible[14c] (eqs 1 and 2). The stability of **10** is indicated



strongly by the fact that it seeks out acetone, formed earlier in the decomposition of **5**, to form **11** or **12** or **13**.[15] Dipole **13**, whether derived directly from **10** and acetone or *via* precursors **11** and/or **12**, affords **14** by a proton transfer that is the intramolecular equivalent of the second step of an E1 reaction. Although **13** could go directly to **15** instead, through an E2-like transition state involving OH bond formation concerted with C–H and O–C bond cleavages, the geometry must be well away from the ideal antiperiplanar relationship of the participating bonds. For that reason, two steps are more likely: **13** giving **14**, and **14** forming **15** in an electrocyclic ring opening. There are good models for electrocyclic ring-opening reactions[16] of the type **14** → **15**, which are similar to Claisen rearrangements, to suggest that the process would be facile at 110 °C.[16] In contrast to the dienone ⇌ α-pyran system,[16] where the α-pyran predominates at equilibrium, **15** could be isolated in pure form, free of **14**.

Intermediate **15** does not accumulate under the reaction conditions because, as an alcohol, it reacts rapidly with carbene **10** to afford **16** by overall OH insertion.[11b,17] The fact that carbene **7** is not trapped similarly indicates that **7** evolves to **10** quite rapidly. Compound **16** has the empirical formula of the major product (**17a**) and formation of **17a** involves an intramolecular $[2\pi + 2\pi]$ cycloaddition[18] between the electron-rich enediol diether functional group and the electron-poor α,β-unsaturated ester group. Although the conversion of **16** to **17a** is written

(3) Space group $P2_1/a$. *R* factor 5.1. A manuscript containing details of the molecular and crystal structures has been submitted to *Acta Crystallogr.*

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(15) Which one of these is the primary adduct is unknown. Electrophilic carbenes attack ketones at oxygen, to form carbonyl ylides, but nucleophilic carbenes could be more prone to attack at carbonyl carbon or to form oxirane in a concerted step. Since **13** appears to be required and could arise directly or via the others, we include all three until further information becomes available.

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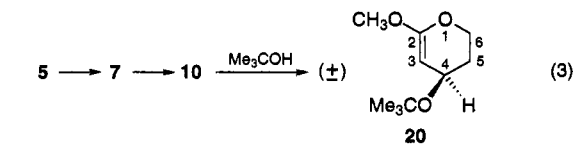
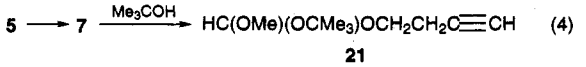
as one step in Scheme 2, a two-step process, with a dipolar intermediate that is short-lived, is believed to apply because a concerted mechanism could operate only in the [2πa + 2πs] mode.[8,9] The likelihood of a fast second step means that the stereochemistry of **17a** probably defines that of precursors **16** and **15**; i.e., the terminal vinyl and the ester group are on the same side of the central double bond of **15** (*E* configuration). A NOE difference experiment performed on **15** (Experimental Section) confirmed that assignment.

Strong support for some of the steps of Scheme 2 came from experiments designed to test the mechanistic hypothesis. First, acetone-d_6, added in 4-fold excess to a solution of **5** in benzene, was incorporated to afford **17a**-d_6, which had the same ^{1}H NMR spectrum as **17a**, except that the methyl group singlets were reduced in intensity. From the ^{1}H NMR spectrum, the ratio **17a**-d_6:**17a** was about 80:20 while the mass spectrum gave that ratio as 87:13. Thus acetone from solution, both acetone-d_6 and acetone from precursor **5**, were incorporated. Further support for that feature of Scheme 2 and evidence that the trapping of carbene **10** is not restricted to acetone came from a thermolysis experiment in which cyclopentanone (12.6 equiv) was introduced. The spirocyclic product **17b** was obtained in 60% yield.

The mechanistic hypothesis was also tested with labeled **5**. Oxadiazoline **5**-d_1 (alkyne labeled) afforded **17a**-d_2, the ^{1}H NMR spectrum of which clearly showed the absence of signals for H-1 and H-6b as well as loss of coupling caused by the latter. Similarly a small sample of **15**, isolated from the mixture of products of thermolysis of **5**, was added to a dilute toluene solution of **5**-d_1 (alkyne labeled) and the latter was thermolyzed. If **15** were an intermediate on the pathway to **17a**, then the product formed by incorporation of **15** from solution would be **17a**-d_1. Additional product, formed from 5-d_1 alone, would be **17a**-d_2. The product isolated from the experiment was analyzed for deuterium content by mass spectrometry and the **17a**-d_1:**17a**-d_2 ratio was found to be 46:54, as judged from the relative intensities of the *m/z* 283 and 284 peaks in the mass spectrum. Fragment ion signals were also appropriately twinned. This result establishes the intermediacy of **15** in the overall mechanism of formation of **17a** because **5**-d_1 alone afforded primarily **17a**-d_2. Finally, **10** was intercepted with an alcohol other than **15**, by adding a little *tert*-butyl alcohol to **5** prior to thermolysis. Similar trapping of vinylogous oxycarbenes with methanol has been reported.[17c,d] A compound with spectroscopic properties expected for **20** (eq 3) was obtained. In particular, the ^{1}H NMR spectrum contained a 1H vinyl multiplet at relatively high field (δ = 3.86) commensurate with the enediol system, a 1H methine signal at δ 3.95, and a pattern for the methylene groups that could be assigned completely to **20** (Experimental Section). Moreover, with a high concentration of added *tert*-butyl alcohol, carbene **7** was trapped in large measure (*ca.* 90%), before it could close to **9**, to afford *tert*-butyl 3-butynyl methyl orthoformate (**21**) (eq 4).

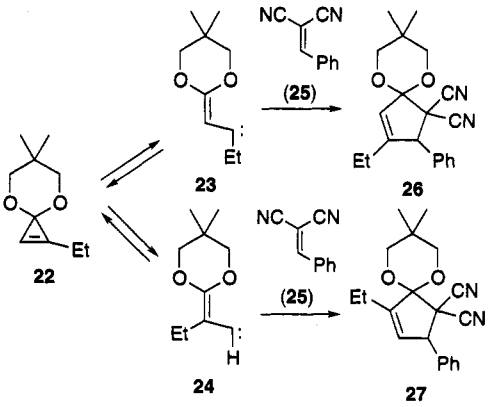


20 (3)



21 (4)

Scheme 4



An important feature of the postulated mechanism is that **10** does not undergo a 1,2-H shift. There is now excellent precedent for slow 1,2-H migration in alkoxycarbenes. Moss and co-workers[19] found that rate constants for the 1,2-H shift in carbenes are very sensitive to the substituents, in keeping with prediction based on theory.[20] The activation energy for a 1,2-H shift increases with increasing electron-donor ability of a carbene substituent,[20] to make that reaction of methoxyneopentylcarbene (for example) too slow at room temperature to be detectable.[19] Carbenes such as **10**, with two oxygen atoms interacting conjugatively with the carbenic carbon, render the p-orbital there nonvacant. As a result the migration, which is related electronically to rearrangement of carbocations,[19,20] is greatly retarded. That the H-shift potentially available to **10** is very slow has been demonstrated with a close model. Nakamura and coworkers[21] reported that vinylcarbenes **23** and **24**, generated by thermal ring-opening of cyclopropenone ketal **22**, reacts with benzylidenemalononitrile (**25**) to afford adducts **26** and **27** in the ratio 29:71 and in 82% overall yield (Scheme 4). Adduct **26** is derived from vinylcarbene **23**, which is a close analog of **10**. In particular **23** has the same option of 1,2-H migration versus an intermolecular reaction and clearly eschews the former.

Precedents for carbonyl addition of vinylcarbenes such as **10** were not found. Acyclic analogs of **10** react with carbonyl compounds by [3 + 2] cycloaddition.[14a,c,h,j;22] It is not surprising to find that **10** does not react that way, for the adduct would be a bicyclo[3.2.1] system with a bridgehead double bond.

In summary, the thermolysis of **5** sets off an unusually rich and remarkably clean cascade of chemical reactions that begin by disassembly of a ring system (**5**), formation of new ring systems (**9** and **10**) through carbene and cyclopropene chemistry, the reincorporation of a fragment extruded initially (acetone), some unimolecular rearrangements, carbene chemistry on the eventual product (**15**) of those rearrangements and, finally, an intramolecular [2π + 2π] cycloaddition. While some details remain to be worked out, it is clear that intramolecular attack of the dialkoxycarbene center on a triple bond can be quite facile and that a 3,3-dioxy vinylcarbene such as **10** has very interesting properties, including slow 1,2-H migration and a strong affinity for the ketonic carbonyl

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group. Experiments are underway in search of other intramolecular and intermolecular chemistry of dioxycarbenes.

Experimental Section

General Methods. NMR spectra were recorded on Bruker AM-500, AC-300, or AC-200 instruments. IR spectra were obtained with a Perkin-Elmer Model 283 spectrometer and UV spectra were recorded on a Perkin-Elmer Lambda 9 instrument. A Rigaku AFC6R diffractometer, with Cu rotating anode, was used to determine the structure of **17a**.

Synthesis of 5. Solid lead tetraacetate (95% purity, 14.0 g, 0.030 mol) was added slowly with stirring to an ice-cooled solution of 3-butyn-1-ol (8.6 g, 0.12 mol) and the (methoxycarbonyl)hydrazone of acetone (**1**), (4.0 g, 0.030 mol) in dichloromethane (100 mL). Increments of oxidant were small enough to keep the solution temperature below 10 °C. After overnight stirring at room temperature, the precipitate was removed by gravity filtration and the organic filtrate was washed with aqueous sodium bicarbonate solution (5%) before it was dried over magnesium sulfate. Evaporation of the solvent left a crude oil that was chromatographed on a silica column (24:1 hexane/ethyl acetate) to afford **5** (2.2 g, 0.011 mol) as a colorless oil in 37% yield. IR (CCl_4) cm^{-1}: 3300 (≡CH), 3030-2840 (C—H), 2110 (C≡C), 1580 (N=N). ^1H NMR (200 MHz, $CDCl_3$) δ: 1.52 (s, 3H), 1.53 (s, 3H), 1.94 (t, ^4J = 2.7 Hz, 1H), 2.49 (dt, ^3J = 7.2 Hz, ^4J = 2.7 Hz, 2H), 3.42 (s, 3H), 3.76 (dt, ^3J = 7.2 Hz, ^2J = −9.3 Hz, 1H), 3.84 (dt, ^3J = 7.2 Hz, ^2J = −9.3 Hz, 1H). ^{13}C NMR (50.3 MHz, $CDCl_3$) δ: 19.9, 24.0, 24.2, 51.9, 62.8, 69.7, 80.4, 119.4, 136.7. MS (*EI*) *m/z* (rel intensity): 167, 129 (100), 111, 97, 73, 59 (molecular ion not observed). MS (high resolution) *m/z*: 129.0685, calcd for $C_5H_9N_2O_2$ 129.0664. MS (CI, NH_3) *m/z*: 216 $(M + NH_4)^+$.

Anal. Calcd for $C_5H_9N_2O_2$: C, 54.52; H, 7.12; N, 14.14. Found: C, 54.32; H, 7.22; N, 13.75.

Thermolysis of 5. A solution of **5** (2.0150 g, 10.177 mmol) in 100 mL of toluene blanketed with dry N_2 was reflued for 30 h. The solvent was removed with a rotary evaporator and the residue was purged further of volatiles, using a sublimation apparatus kept at 65 °C/0.05 Torr. When no more material collected on the cold surface, the brown residue (1.2743 g) was examined by ^1H NMR spectroscopy, which showed that it was primarily **17a**.

Passage of the crude **17a** through a short column of silica (30% ethyl acetate in hexane) gave, after evaporation of the solvent, a colorless oil. Dissolution of the oil in toluene and chilling of the solution in the refrigerator afforded crystalline **17a** (1.0567 g, 3.747 mmol) in 74% yield.

Liquid collected on the cold surface of the sublimation apparatus was subjected to centrifugal chromatography (2-mm silica plate, Chromatotron apparatus, 25% ethyl acetate in hexane) which afforded ester **15** (0.087 g, *ca.* 5%).

Similar thermolyses on a smaller scale were carried out in benzene using the sealed tube method. For example, a solution of **5** (0.3112 g, 1.57 mmol) in benzene (15.6 mL, Reagent Grade) was flame sealed into a glass tube of 100-mL volume, after degassing at 0.1 Torr by the freeze−pump−thaw sequence. The tube was then immersed in an oil bath operating at 110 ± 0.1 °C for 30 h before it was cooled and opened. **Caution**: Pressure from N_2 released in the thermolysis must be taken into account in choosing sample size and vessel volume. Workup as described above for larger scale reactions gave the same results, as judged by ^1H NMR spectroscopy of the crude product.

(1α,1aα,3aα,6aα,6bα)-(±)-Methyl 1a-ethenyloctahydro-6a-methoxy-2,2-dimethyl-3,6-dioxacyclobut[*cd*]indene-1-carboxylate (17a): white solid, mp 85.5 − 87.3 °C. IR (CCl_4) cm^{-1}: 3080 (=C—H), 3040-2800 (C—H), 1740 (C=O), 1637 (C=C). ^1H NMR (500 MHz, C_6D_6) δ: 0.83 (s, 3H), 1.26 (s, 3H), 1.35 (m, $^2J_{4\alpha,4\beta}$ = −14.6 Hz, $^3J_{4\alpha,5\beta}$ = 12.1 Hz, $^3J_{4\alpha,5\alpha}$ = 4.9 Hz, $^3J_{3a,4\alpha}$ = 3.1 Hz, 1H, H-4α), 1.41 (m, $^2J_{4\alpha,4\beta}$ = −14.6 Hz, $^3J_{4\beta,5\beta}$ = 2.5 Hz, $^3J_{4\beta,5\alpha}$ = 2.1 Hz, $^3J_{3a,4\beta}$ = 2.8 Hz, 1H, H-4β), 2.51 (d, $^3J_{3a,6b}$ = 7.2 Hz, 1H, H-6b), 3.14 (s, 3H, ether CH_3), 3.40 (s, 3H, ester), 3.60 (m, $^2J_{5\alpha,5\beta}$ = −12.0 Hz, $^3J_{5\alpha,4\alpha}$ = 4.9 Hz, $^3J_{4\beta,5\alpha}$ = 2.1 Hz, 1H, H-5), 3.88 (m, $^3J_{3a,6b}$ = 7.2 Hz, $^3J_{3a,4\alpha}$ = 3.1 Hz, $^3J_{3a,4\beta}$ = 2.8 Hz, 1H, H-3a), 3.96 (s, 1H, H-1), 3.99 (m, $^3J_{4\alpha,5\beta}$ = 12.1 Hz, $^2J_{5\alpha,5\beta}$ = −12.0 Hz, $^3J_{4\beta,5\beta}$ = 2.5 Hz, 1H, H-5β), 5.02 (dd, $^3J_{AX}$ = 17.3 Hz, $^2J_{AB}$ = −1.7 Hz, 1H, H-A), 5.21 (dd, $^3J_{BX}$ = 10.7 Hz, $^2J_{AB}$ = −1.7 Hz, 1H, H-B), 6.42 (dd, $^3J_{AX}$ = 17.3 Hz, $^3J_{BX}$ = 10.7 Hz, 1H, H-X). ^{13}C NMR (125 MHz, C_6D_6) δ: 21.5 (−) (CH_3), 22.9 (−) (CH_3), 26.8 (+) (C-4), 43.1 (−) (C-6b), 48.8 (−) (OCH_3), 48.9 (−) (C-1), 50.8 (−) (OCH_3), 56.2 (+) (C-1a), 59.0 (+) (C-5), 70.2 (−) (C-3a), 83.1 (+) (C-2), 96.3 (+) (C-6a), 114.9 (+) (CH_2=CH), 135.1 (−)-(CH_2=*C*H), 168.8 (+) (CO). MS (EI) *m/z* (rel intensity): 282 ($M^{+\cdot}$, 12), 251 ($M^+ - OCH_3$, 8), 223 ($M^+ - C_2H_3O_2$, 40), 135 (100), 113 (100). The molecular structure of **17a** was secured by means of single-crystal X-ray diffraction.[3]

(*E*)-Methyl 3-Ethenyl-4-hydroxy-4-methylpent-2-enoate (15). Compound **15** was obtained as an oil. Attempts to grow a crystal failed. UV (EtOH): λ_{max} 271 nm (ϵ = 1900). IR (CCl_4) cm^{-1}: 3610 (br, OH), 3060 − 2820 (CH), 1728 (CO). ^1H NMR (500 MHz, C_6D_6) δ: 0.91 (s, 1H, OH), 1.11 (s, 6H), 3.40 (s, 3H), 5.21 (m, $^2J_{AB}$ = −1.8 Hz, $^3J_{AX}$ = 12.0 Hz, 1H, H-A), 5.44 (m, $^2J_{AB}$ = −1.8 Hz, $^3J_{BX}$ = 18.0 Hz, 1H, H-B), 6.18 (s, 1H, H-2), 7.15 (m, $^3J_{AX}$ = 12.0 Hz, $^3J_{BX}$ = 18.0 Hz, 1H, H-X). ^{13}C NMR (125 MHz, C_6D_6) δ: 29.6 (C-5), 50.8 (C-4), 72.7 (CH_3O), 115.8 (*C*H=CH_2), 120.6 (CH=*C*H$_2$), 132.5 (C-2), 160.6 (C-3), 167.0 (CO). MS (EI) *m/z* (rel intensity): 170 ($M^{+\cdot}$, 12), 155 ($M^+ - CH_3$, 5), 139 ($M^+ - CH_3O$, 13), 111 ($M^+ - C_2H_3O_2$, 17), 59 (100). NOE irradiation at the *gem*-dimethyl frequency caused enhancement of signal intensities at δ = 5.44 (H_B) and δ = 6.18 (H-2).

Thermolysis of 5 in the Presence of Acetone-d_6. The sealed tube/benzene method described above was used, with initial concentrations of 0.1 M **5** and 0.4 M acetone-d_6, 99% labeled. Isolated **17a** showed reduced signal intensities, in the ^1H NMR spectrum, for the methyl singlets suggesting *ca.* 80% incorporation of acetone-d_6 from solution. The mass spectrum showed (*m/z*) 288:282 = 87:13, in satisfactory agreement with the result from NMR spectroscopy.

Thermolysis of 5 in the Presence of Cyclopentanone. A solution of **5** (0.1700 g, 0.8586 mmol) and cyclopentanone (0.850 g, 10.1 mmol) in toluene (10 mL) was refluxed for 30 h. Evaporation of most of the solvent and centrifugal chromatography of the residue (2-mm silica plate, Chromatotron apparatus), using ethyl acetate (30%) in hexanes for elution, afforded **17b** (0.079 g, 60%) as a viscous oil. ^1H NMR (300 MHz, C_6D_6) δ: 1.31−1.47 (m, 8H, 6H, cyclopentyl + H-4α, and H-4β), 1.64−1.71 (m, 2H, cyclopentyl), 2.49 (d, $^3J_{3a,6b}$ = 7.2 Hz, H-6b), 3.14 (s, 3H, ether CH_3), 3.39 (s, 3H, ester CH_3), 3.62 (m, $^2J_{5\alpha,5\beta}$ = −11.6 Hz, $^3J_{5\alpha,4\alpha}$ = 4.7 Hz, $^3J_{5\alpha,4\beta}$ = 2.2 Hz, 1H, H-5α), 3.81 (m, $^3J_{3a,6b}$ = 7.3 Hz, $^3J_{3a,4\alpha}$ = 2.9 Hz, $^3J_{3a,4\beta}$ = 2.9 Hz, 1H, H-3a), 3.95 (s, 1H, H-1), 4.04 (m, $^3J_{4\alpha,5\beta}$ = 11.6 Hz, $^2J_{5\alpha,5\beta}$ = −11.6 Hz, $^3J_{4\beta,5\beta}$ = 3.5 Hz, 1H, H-5β), 5.14 (m, $^3J_{A,X}$ = 17.3 Hz, $^2J_{A,B}$ = −1.8 Hz, 1H, H-A), 5.25 (m, $^3J_{B,X}$ = 10.7 Hz, $^2J_{A,B}$ = −1.8 Hz, 1H, H-B), 6.51 (m, $^3J_{A,X}$ = 17.3 Hz, $^3J_{B,X}$ = 10.7 Hz, 1H, H-X). ^{13}C NMR (75 MHz, C_6D_6) δ: 24.6, 25.8, 26.9, 33.1, 33.2, 43.2 (C-6b), 48.8 (OMe), 50.7 (C-1), 50.8 (OMe), 55.0 (C-1a), 59.1 (C-5), 70.5 (C-3a), 95.4 (C-2), 96.6 (C-6a), 115.0 (C-10), 135.3 (C-9), 169.0 (CO). MS (GCMS, EI) *m/z* (rel intensity): 308 ($M^{+\cdot}$, 15), 277 ($M^+ - OCH_3$, 2), 249 ($M^+ - C_2H_3O_2$, 35), 113 (100).

Preparation of 5-d_1. Oxadiazoline **5** (0.400 g, 2.02 mmol) was added to D_2O (10 mL) together with six pellets (*ca.* 0.6 g) of KOH. The heterogeneous mixture was stirred vigorously for 3 h before dichloromethane (10 mL) was added for extraction. The organic layer was dried with $MgSO_4$ and the solvent was taken off with a rotary evaporator. Oxadiazoline **5**-d_1 was obtained in quantitative yield. The ^1H NMR spectrum was identical to that of **5**, except for a missing triplet at 1.94 ppm and a triplet, instead of a doublet of triplets, at δ 2.49.

Thermolysis of 5-d_1. The sealed tube/benzene method, described above, was used and the isolated major product was examined by ^1H NMR spectroscopy and by mass spectrometry. The ^1H NMR spectrum showed clearly the absence of signals for H-1 and H-6b and the removal of one coupling for the signal from H-3a, with respect to the spectral data for **17a** (above). In the mass spectrum, the molecular ion signal was at *m/z* 284, corresponding to **17a**-d_2.

Thermolysis of 5-d_1 in the Presence of 15. Oxadiazoline **5-d_1** (0.0005 g, 0.003 mmol) was refluxed for 30 h in toluene (0.5 mL) in the presence of **15** (0.0010 g, 0.0051 mmol). The product was not isolated but the crude reaction mixture was analyzed by GC/MS which showed that **17a** had been formed (retention time) and that it consisted of d_1 and d_2 species in the ratio 46:54, as judged from the relative intensities of the signals at *m/z* 283 and 284.

Thermolysis of 5 in the Presence of *tert*-Butyl Alcohol (0.015 M). A solution of oxadiazoline **5** (0.2052 g, 1.036 mmol) and *tert*-butyl alcohol (0.222 g, 3.0 mmol) in toluene (200 mL) was refluxed for 30 h. Removal of most of the solvent, and spectroscopy of the residue (^{1}H and ^{13}C NMR, GCMS), showed that it consisted primarily of **20**. ^{1}H NMR (500 MHz, C_6D_6) δ: 1.11 (s, 9H), 1.47 (m, $^2J_{5\alpha,5\beta} = -13.8$ Hz, $^3J_{6\alpha,5\beta} = 5.2$ Hz, $^3J_{5\beta,4} = 2.9$ Hz, $^3J_{6\beta,5\beta} = 2.4$ Hz, $^4J_{5\beta,3} = 1.2$ Hz, 1H, H-6β), 1.62 (m, $^2J_{5\alpha,5\beta} = -13.8$ Hz, $^3J_{6\beta,5\alpha} = 11.9$ Hz, $^3J_{5\alpha,4} = 4.3$ Hz, $^3J_{6\alpha,5\alpha} = 3.8$ Hz, 1H, H-5α), 3.23 (s, 3H, OCH_3), 3.856 (m, $^3J_{4,3} = 4.9$ Hz, $^4J_{5\beta,3} = 1.2$ Hz, 1H, H-3), 3.862 (m, $^2J_{6\alpha,6\beta} = -10.4$ Hz, $^3J_{6\alpha,5\beta} = 5.2$ Hz, $^3J_{6\alpha,5\alpha} = 3.8$ Hz, $^4J_{6\alpha,4} = 1.0$ Hz, 1H, H-6α), 3.95 (m, $^3J_{4,3} = 4.9$ Hz, $^3J_{5\alpha,4} = 4.3$ Hz, $^3J_{5\beta,4} = 2.9$ Hz, $^4J_{6\alpha,4} = 1.0$ Hz, 1H, H-4), 4.12 (m, $^3J_{6\beta,5\alpha} = 11.9$ Hz, $^2J_{6\alpha,6\beta} = -10.4$ Hz, $^3J_{6\beta,5\beta} = 2.4$ Hz, 1H, H-6β). ^{13}C NMR (75 MHz, C_6D_6) δ: 28.7 (−) (Me_3), 32.2 (+) (C-5), 54.2 (−) (CH_3O), 61.2 (−) (C-4), 63.8 (+) (C-6), 72.7 (+) (CMe_3), 74.2 (−) (C-3), 161.6 (+) (C-2). MS (EI) *m/z* (rel intensity): 186 ($M^{+\bullet}$, 4), 171 ($M^+ - CH_3$, 1), 129 ($M^+ - C_4H_9$, 4), 113 ($M^+ - C_4H_9O$, 100). The compound is very sensitive to moisture and attempts to isolate a pure sample failed.

Thermolysis of 5 in the Presence of *tert*-Butyl Alcohol (0.5 M). A solution of **5** (0.100 g, 0.505 mmol) and *tert*-butyl alcohol (0.40 g, 5.4 mmol) in benzene (10 mL) was heated in a sealed tube at 100 °C for 30 h. Evaporation of the solvent and excess *tert*-butyl alcohol left a residue that was *ca.* 90% **21**, by ^{1}H NMR spectroscopy. ^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.26 (s, 9H), 1.95 (*t*, $^4J = 2.7$ Hz, 1H), 2.46 (dt, $^3J = 6.9$ Hz, $^4J = 2.7$ Hz, 2H), 3.28 (s, 3H), 3.635 (*t*, $^3J = 6.9$ Hz, 1H), 3.643 (*t*, $^3J = 6.9$ Hz, 1H), 5.31 (s, 1H). ^{13}C NMR (500 MHz, $CDCl_3$) δ: 19.78 (CCH_2), 28.61 (($CH_3)_3$), 50.45 (CH_3O), 60.72 (OCH_2), 69.22 ($C(CH_3)_3$), 74.57 (C≡CH), 81.41 (C≡CH), 109.36 (HCO_3). MS (GCMS, EI) *m/z* (rel intensity): 186 ($M^{+\bullet}$, 1), 171 ($M^+ - CH_3$, 1), 155 ($M^+ - OCH_3$, 3), 117 ($M^+ - C_4H_5O$, 3), 113 ($M^+ - C_4H_9O$, 57), 57 ($C_4H_9^+$, 100).

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Supplementary Material Available: Copies of ^{1}H and ^{13}C NMR spectra of **5**, **17b**, **20**, and **21** (9 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.