

(s, axial Me on C-4), 0.790 (d, $J = 6.6$ Hz, Me on C-2); ^1H (irr) \rightarrow ^1H (positive NOE): 5.330 \rightarrow 4.583, 3.286; 5.069 \rightarrow 3.286, 1.217, 0.957, 0.829; 4.583 \rightarrow 5.330, 0.790; 3.286 \rightarrow 5.330, 5.069, 4.583, 1.217; 1.217 \rightarrow 5.069, 3.286; 0.957 \rightarrow 5.069, 4.583, 3.286; 0.829 \rightarrow 5.069, 1.880, 1.217; 0.790 \rightarrow 5.330, 4.583, 1.880.

The slower moving material was purified in a similar manner (1:1 EtOAc-hexane) to give two fractions, each one containing the compounds of gross structure **4**. No attempt was made to fully characterize each isomer; instead the mixture was refluxed for 1 h with 0.5 N HCl. After the solution had cooled, the water was removed (in vacuo) and the hydrolyzate was acetylated with Ac_2O /pyridine (2:1) overnight at room temperature. After removal of the reagents and standard workup, a crude oil was obtained which after HPLC on a silica column (30% EtOAc in hexane) afforded 1 mg of diacetate **5** and 1 mg of lactone **6**. Compound **5** had the following properties: $[\alpha]_{\text{D}}^{25} -18^\circ$ (CH_2Cl_2 , c 0.5); ^1H NMR (CDCl_3) δ 4.958 (m, H on C-3), 4.070 (t, 2 H on C-1), 2.024 (s, OAc on C-1 and C-3), 1.765-1.955 (m, 2 H on C-2), 1.53 (br m, 2 H on C-4), 1.26 (br m, 6 H on C-5, C-6, and C-7), 0.862 (t, 3 H on C-8). Compound **6** had the following properties: CD (MeOH) $[\theta]_{257} = +1150$; ^1H NMR (CDCl_3) δ 6.850 (m, H on C-3), 6.016 (dt, 9.8 and 1.8 Hz, H on C-2), 5.14 (m, C-7 H and C-8 H), 4.459 (m, H on C-5), 2.36 (m, 2 H on C-4), 2.044 (s, OAc), 2.031 (s, OAc), 1.90 (m, 2 H on C-6), 1.213 (d, $J = 6.7$ Hz, 3 H on C-9).

Conversion of 3 to Lactone 9. To a solution of 5 mg of compound **3** in 2 mL of CH_2Cl_2 was added a catalytic amount of *p*-toluenesulfonic acid monohydrate. After 6 h at room temperature the mixture was diluted with CH_2Cl_2 and poured over ice-cold saturated sodium bicarbonate solution. The organic layer was washed with water and saturated sodium chloride solution, dried, and evaporated to give 3 mg of a 1:1 mixture of the α and β hemiacetals (**8**). This material was treated without purification with excess MnO_2 (20 mg) in CH_2Cl_2 at room temperature. After 12 h the mixture was filtered through a small column of silica gel (1 g). Elution with ethyl acetate afforded 2.1 mg of an oil which was purified by HPLC on a silica column (35% EtOAc, 1% EtOH in hexane) to give 1.5 mg (overall yield 36%) of lactone **9**: CD (MeOH) $[\theta]_{227} = -2860$; ^1H NMR (CDCl_3) δ 5.203 (qd, $J = 6.3$ and 3.9 Hz, H on C-6), 4.834 (d, $J = 10.5$ Hz, axial H on C-3), 4.082 (d, $J = 3.9$ Hz, axial H on C-5), 2.573 (dq, $J = 10.5$ and 6.8 Hz, axial H on C-2), 2.143 (s, OAc) 2.058 (OAc), 1.333 (d, $J = 6.3$ Hz, Me on C-6), 1.261 (d, $J = 6.8$, Me on C-2), 0.993 (s, Me on C-4), 0.989 (s, Me on C-4). Hydrolysis of **9** with 0.5 N HCl (reflux) gave the corresponding diol **10**: CD (MeOH) $[\theta]_{224} = -2160$; ^1H NMR (CDCl_3) δ 4.024 (br qd, $J = 6.3$ and 4.3 Hz, H on C-6), 3.311 (br d, $J = 10.2$ Hz, H on C-3).

Synthesis of (S)-(+)-1,3-Diacetoxyoctane. (Z)-2-Octen-1-ol (950 mg) was epoxidized by the Sharpless method¹⁴ employing unnatural (-)-diethyl tartrate as the chiral pool. After 48 h at -20°C , standard workup and HPLC on silica (30% EtOAc in hexane) gave 2(R),3(S)-epoxy-1-octanol. The epoxide (33 mg) was treated with lithium aluminum hydride (19 mg) in tetrahydrofuran (2.5 mL).¹⁵ After 20 min at 0°C , water (0.5 mL) was added followed by 6-8 drops of 2% H_2SO_4 . This mixture was filtered and evaporated to dryness. The residue was taken up in ethanol-water (1:3) and treated with sodium metaperiodate (23 mg) in water (1 mL) at 0°C . After 2.5 h excess NaBH_4 was added followed by 1 M potassium phosphate (pH 7) buffer. The mixture was stirred until it was homogeneous (1 h). The ethanol was evaporated, and the remaining aqueous mixture was lyophilized. The dried residue was treated with Ac_2O /pyridine (2:1) overnight at room temperature. After standard workup and HPLC on Partisil (20% EtOAc in hexane), (S)-1,3-diacetoxyoctane was obtained, $[\alpha]_{\text{D}}^{25} + 15.2^\circ$ (CH_2Cl_2 , c 1.7).

Acknowledgment. This research was supported by PHS Grant CA12623-10, awarded by the National Cancer Institute, Department of Health and Human Services. High-frequency NMR studies at the University of Hawaii were made possible by NSF Grant CHE81-00240. FAB mass spectra were determined at the University of California Bio-organic, Biomedical Mass Spectrometry Resource (A. L. Burlingame, director), supported by NIH Grant RR00719.

Registry No. 1, 93279-26-6; **1** diacetate, 93279-28-8; **2**, 93279-27-7; (S)-**5**, 93222-25-4; (R)-**5**, 93222-26-5; **6**, 93222-27-6; **9**, 93222-28-7; **10**, 93222-29-8; (Z)-2-octen-1-ol, 26001-58-1; (-)-diethyltartrate, 13811-71-7.

Supplementary Material Available: 300-MHz ^1H NMR spectra of **1** and **2** in CDCl_3 (2 pages). Ordering information is given on any current masthead page.

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Preparation of Furanoradialene by the Flash Vacuum Pyrolysis of Diesters of 3,4-Bis(hydroxymethyl)-2,5-dimethylfuran¹

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Contribution from Ames Laboratory and the Department of Chemistry, Iowa State University, Ames, Iowa 50011. Received September 19, 1983. Revised Manuscript Received July 2, 1984

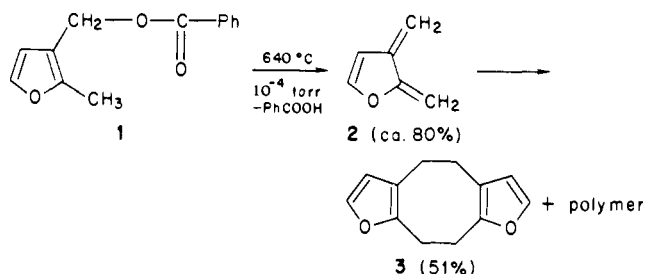
Abstract: Pyrolysis of 3,4-bis(acetoxymethyl)-2,5-dimethylfuran (**8**) gives a 12% yield of a [4 + 2] dimer (**10**) of furanoradialene (**4**). A similar pyrolysis of 3,4-bis(benzoyloxymethyl)-2,5-dimethylfuran (**9**) gives **10** in 69% yield. Low-temperature ^1H and ^{13}C NMR spectral studies show that **4** is the primary pyrolysis product from **8** and **9**, which forms **10** upon warming. Pyrolysis of 3,4-bis[acetoxymethyl]-2,5-dimethylfuran (**8-d₄**) gives [4 + 2] dimer **10-d₈** via the intermediacy of **4-d₄**. A concerted mechanism is proposed for the conversion of furanoradialene (**4**) to **10**.

Recently we reported that the flash vacuum pyrolysis (FVP) of (2-methyl-3-furyl)methyl benzoate (**1**) gives good yields of 2,3-dimethylene-2,3-dihydrofuran (**2**).³ Compound **2** is an air-

sensitive material which readily undergoes dimerization, forming the head-to-head [4 + 4] dimer (**3**). Although **2** has been previously postulated as an intermediate in the liquid-phase pyrolysis

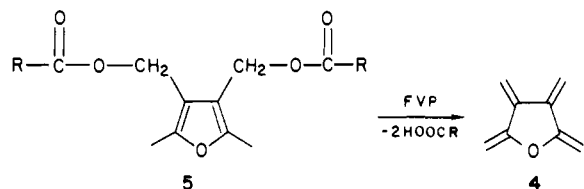
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of (2-methyl-3-furylmethyl)trimethylammonium hydroxide³ and the gas-phase pyrolysis of tetrahydrobenzofuran,⁴ the FVP of methyl-substituted, furylmethyl esters is the best method currently available for generating solutions of dimethylenedihydrofurans.²

In an attempt to develop a route to furanoradialene (**4**) based on this method, a study of the pyrolysis reactions of diester derivatives **5** of 3,4-bis(hydroxymethyl)-2,5-dimethylfuran (**6**) was undertaken. It was anticipated that the pyrolysis of **5** would produce **4** by the independent loss of two molecules of the corresponding carboxylic acid.



Furanoradialene (**4**) is the furan analogue of the radialenes, a class of compounds characterized by having a carbocyclic ring in which each carbon is part of an exocyclic, carbon-carbon double bond.⁵ The parent radialenes which have been synthesized and studied to date are [3]radialene,⁶⁻¹⁹ [4]radialene,²⁰⁻²⁵ [6]radial-

ene,²⁶⁻²⁸ naphtharadialene,⁵ and furanoradialene (**4**).²⁹ Although the parent radialenes are air-sensitive materials which are highly reactive, several stable, substituted radialenes have been reported.³⁰⁻⁴¹

Results

3,4-Bis(hydroxymethyl)-2,5-dimethylfuran (**6**)⁴² was prepared in 92% yield by reducing diethyl 2,5-dimethyl-3,4-furandicarboxylate (**7**)^{43,44} with lithium aluminum hydride.⁴⁵ Diol **6** was converted to diacetate **8** by treatment with acetyl chloride in the presence of triethylamine and to dibenzoate **9** by similar treatment with benzoyl chloride.

Diacetate **8** was pyrolyzed at temperatures ranging from 450 to 650 °C. At temperatures below 500 °C, only the starting ester **8** was recovered. Incomplete conversion of **8** was observed between 500 and 550 °C, and at temperatures above 570 °C, no **8** was recovered. The FVP of **8** at each temperature produced a white band in the liquid-nitrogen-cooled trap. During a pyrolysis, a 1:1 mixture of carbon disulfide (CS₂) and chloroform-*d*₁ (CDCl₃), a convenient low-temperature solvent, was deposited into the trap through a side arm. After the trap contents were liquified by warming the trap to -78 °C, ¹H and ¹³C NMR spectra were recorded at -60 °C. The sample was then warmed to 0 °C, and NMR spectral data were again recorded. The product mixtures kept below -60 °C consisted mainly of acetic acid, furanoradialene (**4**), and polymer, along with trace amounts of one [4 + 2] dimer of **4**, **10**. When the samples were warmed to 0 °C, the product mixtures consisted of acetic acid, polymer, and [4 + 2] dimer **10**. Although there are six possible [4 + 2] and four possible [4 + 4] dimers of **4**, no evidence for any other dimer of **4** was obtained. This conclusion is supported by the observation that 91% of the furanoradialene (**4**) present in the ¹H NMR samples is converted to [4 + 2] dimer **10** upon warming the samples to 0 °C. The low yields of furanoradialene (**4**) obtained from the pyrolyses of **8** were due to the extensive polymerization which occurred.

The structure of **4** was indicated by its spectral properties. The ¹H NMR spectrum included two-proton singlets at δ 5.55 and 5.52 for the exocyclic, methylene hydrogens at the three and four positions and two-proton doublets at δ 4.59 and 4.52 (*J* = 3 Hz) for the exocyclic, methylene hydrogens at the two and five positions. These chemical shifts are consistent with those previously reported for furanoradialene (**4**).²⁹ The ¹³C NMR spectrum of **4** included signals at δ 156.1 for ring carbons two and five, δ 135.8 for ring carbons three and four, δ 106.0 for the exocyclic, meth-

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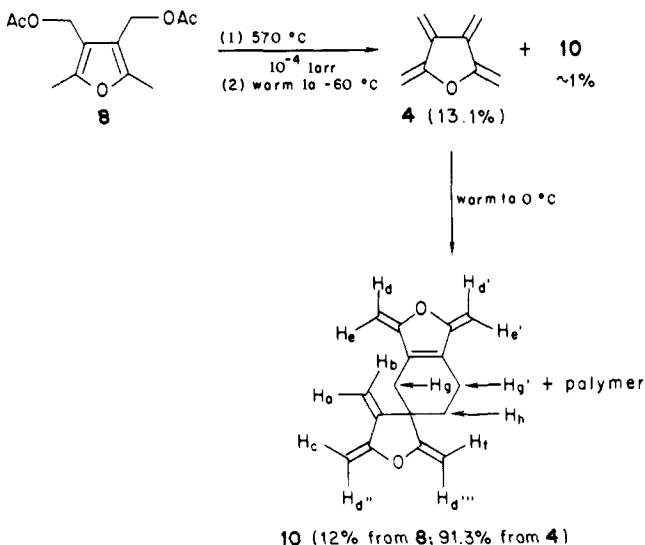
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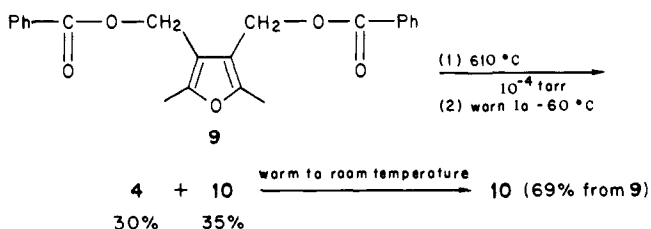
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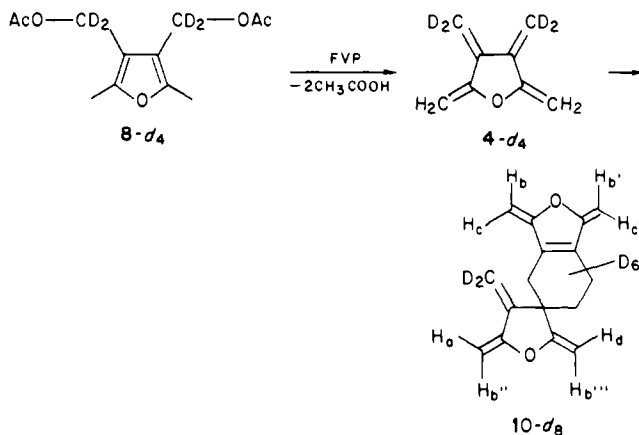
ylene carbons at ring positions three and four, and δ 81.9 for the exocyclic, methylene carbons at ring positions two and five. The ¹³C NMR chemical shifts observed for the ring carbons of 4 are consistent with those observed for ring carbons two and three in 2,3-dimethylene-2,3-dihydrofuran (2) [(1:1 CS₂/CDCl₃, -60 °C) δ 157.62 and 139.63].² These ¹³C NMR chemical shifts differ slightly from those previously reported for 4 which were taken from a ¹³C NMR spectrum of a complex mixture containing 4 as a minor component.²⁹ The chemical shifts were incorrectly assigned to signals at δ 160.5 for ring carbons two and five and δ 156.6 for ring carbons three and four.

The structure of [4 + 2] dimer 10 was also indicated by its spectral properties. The ¹³C NMR spectrum of 10 consisted of 16 peaks, with appropriate chemical shifts, including signals at δ 82.62, 81.48, 81.05, and 80.83 for the four exocyclic, methylene carbons at the two and five positions of the dihydrofuran and tetrahydrofuran rings. The ¹³C NMR spectrum also included a peak at δ 106.72 for an exocyclic, methylene carbon at either the three or the four position of a tetrahydrofuran ring. The only dimer of 4 with structural features consistent with the observed ¹H and ¹³C NMR chemical shifts is [4 + 2] dimer 10. The dimer decomposes readily at room temperature, even in solution, and attempts to isolate it resulted in extensive decomposition.

In order to improve the yield of furanoradialene (4), a study of the pyrolysis chemistry of 3,4-bis(benzoyloxymethyl)-2,5-dimethylfuran (9) was undertaken (furan benzoates, for reasons that are not clear, often give better yields of the reactive products than the corresponding acetates). The pyrolysis of 9 at 610–620 °C and ca. 10⁻⁴ torr was carried out by using the procedure described for the pyrolysis of 8. The product mixtures kept below -60 °C consisted of furanoradialene (4) and [4 + 2] dimer 10, along with benzoic acid and a substantial amount of white polymeric material. After warming the product solution to room temperature, a 69% yield of [4 + 2] dimer 10 was formed from starting dibenzoate 9. The ¹H and ¹³C NMR chemical shifts for 4 and 10 from 9 matched those of samples obtained from 8.



The preparation and pyrolysis of 8-*d*₄ was undertaken in order to assign the ¹H and ¹³C NMR chemical shifts of 4 and 10. A mass-spectral analysis of 8-*d*₄ indicated greater than 96% *d*₄ incorporation. The ¹H and ¹³C NMR spectra of 4-*d*₄ and 10-*d*₈ were recorded at -60 °C and at room temperature, respectively.



The ¹H NMR spectrum of 4-*d*₄ consisted of two proton doublets ($J = 2.5$ Hz) at δ 4.61 and 4.52 for the exocyclic, methylene hydrogens at the two and five positions. The ¹³C NMR spectrum of 4-*d*₄ included signals at δ 156.08 for ring carbons two and five, at δ 135.8 for ring carbons three and four, and at δ 81.8 for the methylene carbons attached to ring positions two and five. Upon warming the sample to room temperature, 4-*d*₄ dimerized, forming 10-*d*₈.

Discussion

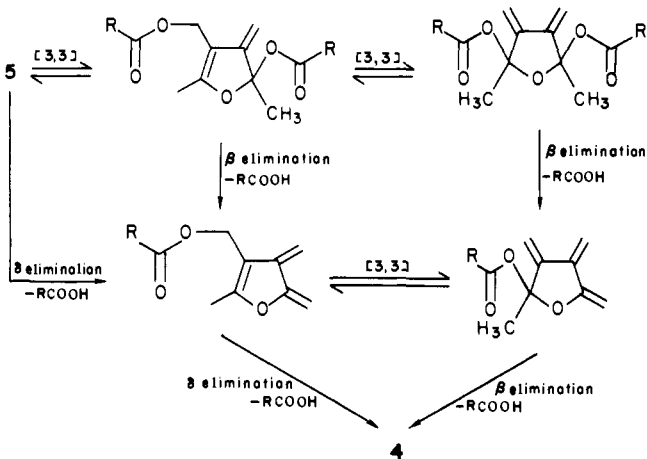
A migration mechanism was previously proposed for the conversion of (2-methyl-3-furyl)methyl benzoate (1) to 2,3-dimethylene-2,3-dihydrofuran (2).² A set of mechanistic pathways which account for the formation of furanoradialene (4) from diesters (5) of 3,4-bis(hydroxymethyl)-2,5-dimethylfuran (6) is presented in Scheme I. Furanoradialene (4) may be formed either from diacetate 8 or dibenzoate 9 by two independent β eliminations of the corresponding carboxylic acid, after a [3,3] shift of the carboxylate group. This type of 1,4 elimination of a carboxylic acid during ester pyrolysis has literature precedent in the pyrolysis of allylic⁴⁶⁻⁵¹ and benzylic⁵²⁻⁵⁴ esters containing δ hydrogens. In the product mixtures from several allylic esters, the initially formed [3,3] shift products have been isolated.^{46,50,55-61}

A less likely explanation for the formation of furanoradialene (4) from 5 involves direct δ eliminations of two molecules of the corresponding carboxylic acid from 5. Although the δ -elimination pathway cannot be ruled out, there are no literature examples of 1,4 eliminations during ester pyrolyses in which the two-step mechanism, involving a [3,3] shift of the carboxylate group, followed by β elimination of the carboxylic acid, cannot explain the experimental results.

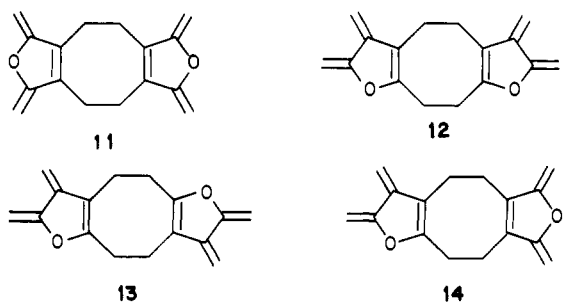
The exclusive formation of [4 + 2] dimer 10 can be explained by a concerted, Diels-Alder dimerization of furanoradialene (4).

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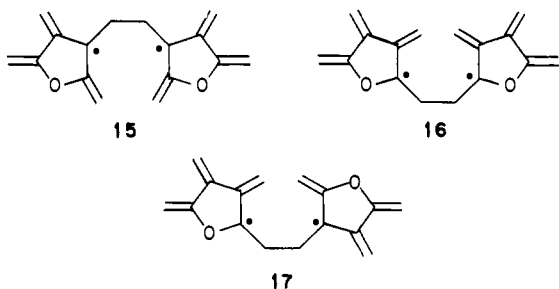
Scheme I



An alternative diradical pathway for the dimerization of **4** should lead to the formation of one or more of [4 + 4] dimers **11–14** in addition to [4 + 2] dimer **10**.

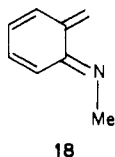


There are three possible diradical intermediates from **4**: **15**, **16**, and **17**. Intermediate **15** is the only diradical intermediate which can form the observed [4 + 2] dimer **10** and would be expected to form one or more of the [4 + 4] dimers (**11**, **12**, or **14**) as minor products. Formation of only [4 + 2] dimer **10** supports the concerted mechanism.



In the analogous dimerization of [4]radialene, the only product isolated was [4 + 4] dimer and a diradical mechanism was proposed for its formation.^{20–22}

The formation of [4 + 2] dimer **10** has literature precedent in the formation of spirodimers from *ortho*-xylylene,⁶² imine **18**,⁶³ and 4,5-dimethylenecyclohepta-2,6-dien-1-one (**22**).⁶⁴

**18**

Experimental Section

Methods and Materials. The pyrolysis apparatus has been previously described (the glassware is now available from Kontes).⁶⁵ Chemical shifts are recorded in parts per million (δ) from tetramethylsilane (Me_4Si). Melting points were determined with a Thomas-Hoover apparatus and are uncorrected. Diethyl 2,5-dimethyl-3,4-furandicarboxylate was prepared from diethyl 2,3-diacetylsuccinate⁶⁶ by using a literature procedure.^{43,44}

3,4-Bis(Acetoxyethyl)-2,5-dimethylfuran (8). To a stirred slurry of 5.23 g (0.138 mol) of lithium aluminum hydride in 250 mL of dry ether (LiAlH_4) at 0 °C was slowly added a solution of 16.14 g (0.0672 mol) of diethyl 2,5-dimethyl-3,4-furandicarboxylate (**7**) in 100 mL of dry ether. After the mixture was stirred for 4 h at room temperature, a standard workup⁴⁵ yielded 10.18 g (0.0651 mol; 97%) of crude 3,4-bis(hydroxymethyl)-2,5-dimethylfuran (**6**).⁴² IR (CHCl_3) 3610, 3395, 1612, 1163, 1095, 996 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.38 (s, 4 H), 3.89 (br s, 2 H), 2.20 (s, 6 H); ^{13}C NMR (CDCl_3) δ 146.67 (s), 118.77 (s), 54.96 (t, $J = 143$ Hz), 11.13 (q, $J = 128$ Hz). A solution of 2.36 g (0.03 mol) of acetyl chloride in 20 mL of dry ether (LiAlH_4) was added dropwise to a stirred solution of 1.21 g (0.0078 mol) of **6** and 1.97 g (0.019 mol) of triethylamine in 50 mL of dry ether. After the mixture was stirred for 8 h at room temperature, 10 mL of water was added and the layers were separated. The aqueous layer was extracted with ether (5×10 mL). The ether layers were combined and washed with 1 M hydrochloric acid (3×10 mL), saturated sodium bicarbonate (3×10 mL), and saturated sodium chloride (3×10 mL). After drying (MgSO_4) and removal of the solvent, the crude product was purified by distillation yielding 1.81 g (0.0076 mol; 97%) of **8**: bp 94 °C (0.05 mm); IR (thin film) 1740, 1606, 1225, 1166, 1015, 954, 762 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.92 (s, 4 H), 2.28 (s, 6 H), 2.06 (s, 6 H); ^{13}C NMR (CDCl_3) δ 170.70 (s), 149.52 (s), 114.80 (s), 56.83 (t, $J = 148$ Hz), 20.86 (q, $J = 129$ Hz), 11.43 (q, $J = 128$ Hz); high-resolution mass spectrum calcd for $\text{C}_{12}\text{H}_{16}\text{O}_5$ 240.09978, measured 240.100439.

3,4-Bis(benzoyloxymethyl)-2,5-dimethylfuran (9). A solution of 30.64 g (0.218 mol) of benzoyl chloride in 50 mL of dry ether (LiAlH_4) was added dropwise to a stirred solution of 15.5 g (0.0991 mol) of **6** and 31.67 g (0.313 mol) of triethylamine in 400 mL of dry ether. After the mixture was stirred for 7 h at room temperature, 50 mL of water was added and the products were isolated by using the method described for preparation of diacetate **8**. The crude product (32.85 g; 0.0901 mol; 91%) was purified by recrystallization from ether yielding 25.94 g (0.0712 mol; 72%) of clear prisms of **9**: mp 97–97.8 °C; IR (CHCl_3) 1720, 1622, 1265, 1170, 1100, 1020, 915, 865, 705 cm^{-1} ; ^1H NMR (CDCl_3) δ 8.14–7.8 (m, 4 H), 7.65–7.03 (m, 6 H), 5.24 (s, 4 H), 2.33 (s, 6 H); high-resolution mass spectrum calcd for $\text{C}_{22}\text{H}_{20}\text{O}_5$ 364.13108, measured 364.13145.

General Pyrolysis Procedure. The pyrolyses were run at temperatures from 450 to 650 °C. A sample of the furylmethyl ester in a Pyrex boat was placed into the sample compartment, and the apparatus was heated to obtain temperatures ranging from 50 to 150 °C. A condenser cooled to ca. –20 °C was inserted between the furnace and the liquid-nitrogen-cooled trap to collect any unreacted starting material and benzoic acid formed as a byproduct in the pyrolyses of dibenzoate **9**. During each pyrolysis, 2 mL of a 1:1 mixture of carbon disulfide (CS_2) and deuteriochloroform (CDCl_3) was deposited into the trap through a side arm. After all of the starting material had distilled out of the sample compartment, nitrogen was introduced into the system and a weighed amount of 1,2-dichloroethane or 1,1,2,2-tetrachloroethane was added for use as an internal standard. The trap was then warmed to –78 °C, and a 1:1 mixture of CS_2 and CDCl_3 (2 mL) was used to rinse the material on the insert of the trap to the bottom. The product solution was mixed by rinsing the walls of the trap with the solution ca. ten times with use of a cold pipet (CS_2 at –78 °C). The product solution was placed into four 5-mm NMR tubes at –78 °C, and NMR spectra were recorded at temperatures below –60 °C for each tube. After the tubes were warmed to 0 °C, NMR spectra were again recorded.

Pyrolysis of 3,4-Bis(acetoxyethyl)-2,5-dimethylfuran (8). A 0.341-g quantity of **8** was pyrolyzed at 570 °C by using the general procedure. After the product solution was placed into the NMR tubes at –78 °C, ^1H and ^{13}C NMR spectra were recorded at temperatures below –70 °C. The tubes were slowly warmed to 0 °C, and NMR spectra were again recorded. The yields of furanoradialene (**4**) and [4 + 2] dimer **10** were determined by quantitative ^1H NMR analysis by using known amounts of dichloroethane as an internal standard. In addition to acetic acid, **4**, and **10**, which were found in the product trap, a large amount of an air-sensitive, cellophane-like polymer was deposited in the area of the

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apparatus from the furnace to the trap. At a pyrolysis temperature of 570 °C, a 13% yield of **4** was detected in the NMR tubes at temperatures below -70 °C, along with ca. 1% of the [4 + 2] dimer **10**. At 0 °C the product solution consisted of [4 + 2] dimer **10** (12% from **8**; 91.3% from **4**) and a small amount of white, insoluble, polymeric material. The products were identified from the following data.

Furanoradialene (4) [2,3,4,5-tetramethylene-2,3,4,5-tetrahydrofuran]: ¹H NMR (1:1 CS₂/CDCl₃; -78 °C) δ 5.55 (s, 2 H), 5.52 (s, 2 H), 4.59 (d, *J* = 3 Hz, 2 H), 4.52 (d, *J* = 3 Hz, 2 H); ¹³C NMR (1:1 CS₂/CDCl₃; -78 °C) δ 156.08 (s), 135.76 (s), 105.97 (t, *J* = 162 Hz), 81.86 (t, *J* = 162 Hz); [lit.²⁹ ¹H NMR (CDCl₃; -50 °C) δ 5.59 (br s, 4 H), 4.61 (AB quartet, *J* = 2.5 Hz, 4 H); ¹³C NMR (CDCl₃; -60 °C) δ 160.5, 156.6, 106.2, 81.8].

[4 + 2] Dimer 10: ¹H NMR (1:1 CS₂/CDCl₃) δ 5.5 (s, 1 H) (H_a), 4.92 (s, 1 H) (H_b), 4.54 (d, *J* = 2.5 Hz, 1 H) (H_c), 4.46 (d, *J* = 2.5 Hz, 4 H) (H_d, H_d, H_d, H_d), 4.09 (m, 2 H) (H_e, H_e), 3.94 (d, *J* = 2.5 Hz, 1 H) (H_f), 2.55-2.27 (m, 4 H) (H_g, H_g), 1.88-1.65 (m, 2 H) (H_h); ¹³C NMR (1:1 CS₂/CDCl₃) δ 165.72, 160.95, 160.79, 156.99, 146.76, 134.79, 133.76, 106.72, 82.62, 81.48, 81.05, 80.83, 45.02, 33.26, 30.23, 18.09.

Pyrolysis of 3,4-Bis(benzoyloxymethyl)-2,5-dimethylfuran (9). A 0.439-g (1.21 mmol) quantity of **9** was pyrolyzed at 610 °C by using the general procedure. ¹H and ¹³C NMR analyses at -70 °C indicated that furanoradialene (**4**) and [4 + 2] dimer **10** were the only major products formed from **9**, aside from benzoic acid and a substantial amount of white, polymeric material. Quantitative ¹H NMR analysis at -78 °C indicated that the product mixture consisted of 0.359 mmol of **4** (30%) and 0.211 mol of **10** (35%). The ¹H and ¹³C NMR spectra of **4** formed from dibenzoate **9** matched the spectra of **4** formed from diacetate **8**. Upon warming the samples above -50 °C, **4** rapidly dimerized forming [4 + 2] dimer **10**. The ¹H and ¹³C NMR of **10** matched the spectra of **10** obtained from diacetate **8**. ¹H NMR analysis using a 1,1,2,2-tetrachloroethane internal standard indicated that a quantitative yield of **10** was formed from **4** (69% yield from dibenzoate **9**).

3,4-Bis[acetoxymethyl]-2,5-dimethylfuran (8-d₄). To a stirred slurry of lithium aluminum deuteride (3.41 g; 81.2 mmol) in 5 mL of dry ether (LiAlH₄) at 0 °C was added dropwise a solution of 5.489 g (22.8 mmol) of diethyl 2,5-dimethyl-3,4-furandicarboxylate (**7**) in 20 mL of dry ether. After the mixture was stirred for 7 h at room temperature, a standard workup⁴⁵ yielded 2.88 g (17.98 mmol; 79%) of **6-d₄**:

IR (CHCl₃) 3605, 3400, 2260-2050, 1612, 1276, 995, 860 cm⁻¹; ¹H NMR (CDCl₃) δ 4.75 (br s, 2 H), 2.18 (s, 6 H). A solution of 1.554 g (19.8 mmol) of acetyl chloride in 10 mL of dry ether was added dropwise over a 15-min period to a stirred solution of 2.88 g (18.0 mmol) of **6-d₄** and 2.517 g (24.9 mmol) of triethylamine in 15 mL of dry ether. After the mixture was stirred for 20 h at room temperature, 10 mL of water was added and the products were isolated by using the method described for preparation of diacetate **8**. The crude product (3.068 g; 12.6 mmol; 70%) was purified by short-path distillation, yielding 2.529 g (10.4 mmol; 58% isolated yield) of **8-d₄**: bp 80-81 °C (0.005 mm); IR (thin film) 2280-2040, 1735, 1610, 1255, 1155, 1045, 1015, 925 cm⁻¹; ¹H NMR (CDCl₃) δ 2.26 (s, 6 H), 2.05 (s, 6 H); ¹³C NMR (CDCl₃) δ 170.92, 149.63, 114.52, 20.97, 11.48; high-resolution mass spectrum calcd for C₁₂H₁₂D₄O₅ 244.12489, measured 244.12465. ¹H NMR spectral analysis of **8-d₄** showed no evidence for any deuterated species other than **8-d₄**.

Pyrolysis of 8-d₄. A 0.422-g quantity of **8-d₄** was pyrolyzed at 600 °C by using the general procedure. The pyrolyzate was collected in 4 mL of 1:1 CS₂/CDCl₃ and NMR spectral data were recorded at low temperature for 3,4-dimethylene-2,5-dimethylene-2,3,4,5-tetrahydrofuran (**4-d₄**): ¹H NMR (1:1 CS₂/CDCl₃; -60 °C) δ 4.61 (d, *J* = 2.5 Hz, 2 H), 4.52 (d, *J* = 2.5 Hz, 2 H); ¹³C NMR (1:1 CS₂/CDCl₃; -60 °C) δ 156.08, 135.60, 81.80. Upon warming the samples to room temperature, **4-d₄** was cleaning converted to [4 + 2] dimer **10-d₈**: ¹H NMR (1:1 CS₂/CDCl₃) δ 4.53 (d, *J* = 2.5 Hz, 1 H) (H_a), 4.45 (d, *J* = 2.5 Hz, 4 H) (H_b, H_b, H_b, H_b), 4.09 (m, 2 H) (H_c, H_c), 3.92 (d, *J* = 2.5 Hz, 1 H) (H_d); ¹³C (1:1 CS₂/CDCl₃) δ 165.42, 160.64, 160.31, 156.57, 146.53, 134.65, 133.58, 82.51, 81.64, 81.21, 80.99, 44.89. The signals for the CD₂ carbons were not observed after 25000 scans (pulse width = 2.0 μs). NMR analysis of the pyrolysis product mixtures formed from **8-d₄** showed no evidence for any deuterated species other than **4-d₄** and **10-d₈**.

Acknowledgment. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Chemical Sciences Division, under contract W-7405-ENG-82.

Registry No. **4**, 75075-85-3; **4-d₄**, 92009-82-0; **6**, 90199-61-4; **6-d₄**, 91994-43-3; **7**, 19434-69-6; **8**, 91994-45-5; **8-d₄**, 91994-44-4; **9**, 91994-46-6; **10**, 91994-47-7; **10-d₈**, 92009-83-1.

Pyrrolizidinone and Indolizidinone Synthesis: Generation and Intramolecular Addition of α-Acylamino Radicals to Olefins and Allenes

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Abstract: α-Acylamino radicals can be generated by treatment of phenylthio, methylthio, or phenylselenenyl lactams of type **7**, **8**, and **17** with tri-*n*-butyltin hydride in the presence of AIBN. The radicals add intramolecularly to olefins and allenes to give indolizidinones and pyrrolizidinones. The product distribution depends on the substitution patterns of the unsaturated moiety and the length of the chain connecting the radical and olefinic centers. Product ratios appear to reflect the kinetic partitioning of the radical between cyclization pathways. These reactions are potentially useful in the area of pyrrolizidine alkaloid synthesis. The conversion of cyclization products **50** and **51** to (±)-supinidine (**1**) serves as an example.

During studies directed toward a synthesis of structures related to the Dendrobatid alkaloid GTX-223AB, we encountered a situation in which a 5-hexenyl radical cyclization was used to provide evidence for a stereochemical assignment.⁴ From a synthetic standpoint, we were struck by the ease with which this

reaction allowed the preparation of a reasonably complicated tricyclic compound. Provided with this stimulus, we decided to embark on studies designed to develop and apply free radical cyclizations to natural product synthesis. A literature survey revealed that although much was known about carbon-carbon bond-forming free radical cyclizations, there had been relatively few attempts to design syntheses which relied on their use.⁵⁻⁸ In

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