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# The Effects of α-Methyl Group Substitution on the Dimerization Products of Furan-Based *o*-Quinodimethanes[1]

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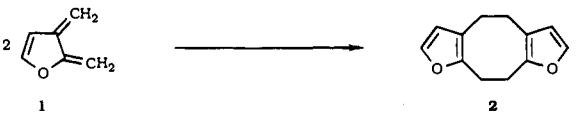
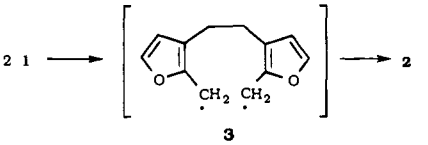
**Abstract:** 3-Ethylidene-2-methylene- (**12**), 2-ethylidene-3-methylene- (**13**), and 2,3-diethylidene- (**14**) 2,3-dihydrofurans were prepared by fluoride-induced 1,4-conjugative elimination of trimethylsilyl acetate from the appropriate precursors. The $^1$H NMR spectra of these furan-based *o*-quinodimethanes were obtained and the dimerization products of each were studied. It was found that a methyl group at the 3-methylene position retards the rate of dimerization which is consistent with the previously proposed dimerization mechanism, the two-step mechanism involving rate-determining formation of a diradical intermediate followed by rapid cyclization of the diradical. Structures were assigned to 6 dimers from **12**, 7 dimers from **13**, and 5 dimers from **14**. Most of these dimers are [4 + 4] and [4 + 2] cyclo dimers, but one, **44**, is an intramolecular disproportionation product derived from the diradical proposed in the dimerization of **13**. Identification of dimer **44** provides additional support for the two-step diradical mechanism. From analysis of the stereochemistry and regiochemistry of the dimers, it is concluded that both cisoid and transoid diradical intermediates are formed by cisoid and transoid encounters of two monomer molecules. Also, from analysis of the products it is concluded that the regiochemistry of the cyclization of the diradical intermediates is controlled mainly by the interaction of the active sites of the furan moieties in the cyclization step; the initial conformation of the intermediate is not important.

## Introduction

2,3-Dimethylene-2,3-dihydrofuran (**1**), the furan-based *o*-quinodimethane (*o*-QDM), has been studied extensively by our research group during the past decade.[2-7] Much of our work has focused on the mechanism of the dimerization of **1** which occurs readily in solution at temperatures above −30 °C. Of special interest is the fact that the dimerization gives almost quantitatively the head-to-head [4 + 4] dimer **2**.[2] On the basis of a secondary deuterium kinetic isotope effect study, it was



concluded that the cyclization involves rate-determining formation of diradical **3**, followed by rapid closure of the diradical to give the dimer.[3,7a] Additional support for this two-step mecha-



[⊗] Abstract published in *Advance ACS Abstracts*, November 15, 1994.

(1) Based on work by M.-k.L. in partial fulfillment of the requirements for the Ph.D. Degree at Iowa State University.

(2) Trahanovsky, W. S.; Cassady, T. J.; Woods, T. L. *J. Am. Chem. Soc.* **1981**, *103*, 6691.

(3) Chou, C.-H.; Trahanovsky, W. S. *J. Am. Chem. Soc.* **1986**, *108*, 4138.

(4) Chou, C.-H.; Trahanovsky, W. S. *J. Org. Chem*, **1986**, *51*, 4208.

(5) Trahanovsky, W. S.; Huang, Y.-c. J.; Leung, M.-k. *J. Org. Chem.* **1994**, *59*, 2594.

(6) Trahanovsky, W. S.; Chou, C.-H.; Cassady, T. J. *J. Org. Chem.* **1994**, *59*, 2613.

(7) (a) Chou. C.-H. Ph.D. Dissertation, Iowa State University, 1986. (b) Huang, Y.-c.J. Ph.D. Dissertation, Iowa State University, 1986. (c) Lee, S. K. Ph.D. Dissertation, Iowa State University, 1987.

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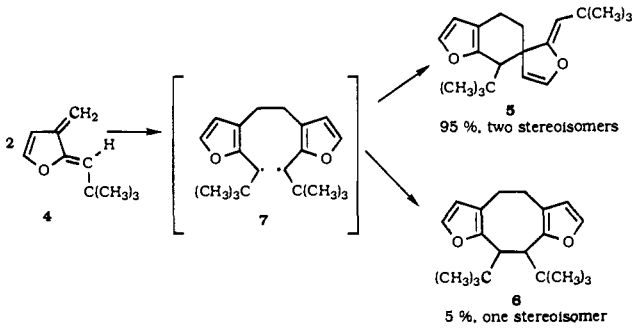
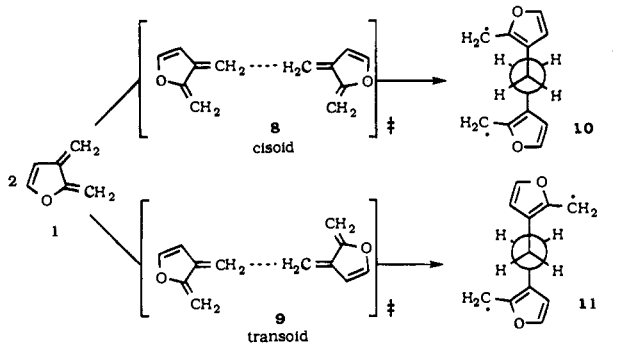
nism was obtained from a study of the effects on the dimerization rates and products of *tert*-butyl group substitution on the 3-methylene and 2-methylene groups.[5,7b]

A question that has not yet been answered is why does the intermediate diradical **3** close to give predominantly the [4 + 4] dimer.[8] Some simple derivatives of **1** give a fair amount of the [4 + 2] dimers expected from closure of the intermediate diradical[7a,b] and many indole-based,[9] thiophene-based,[10] and benzene-based[11] *o*-QDM's give predominantly or exclusively [4 + 2] dimers. For example, the *tert*-butyl derivative **4**[5,7b] gives a high yield of two stereoisomeric [4 + 2] dimers (**5**) and a small amount of [4 + 4] dimer **6**, dimers expected from diradical **7**.

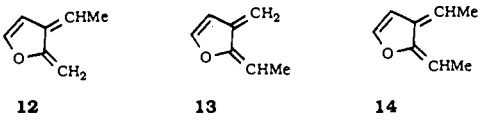



It is conceivable that the mode of cyclization is determined by the relative orientation of the *o*-QDM monomers in the transition state of the first step of dimerization.[12] We have found that the rate of dimerization of both benzene-based[11d] and furan-based[6,7a] *o*-QDM's is not affected by bulky substituents (e.g., a *tert*-butyl group) on ring positions away from the diene moiety. This is consistent with dimerization transition states which have the rings of the two monomers oriented away from each other. The extreme of this "exo" orientation for the furan-based *o*-QDM leads to transition states **8** and **9**. The cisoid transition

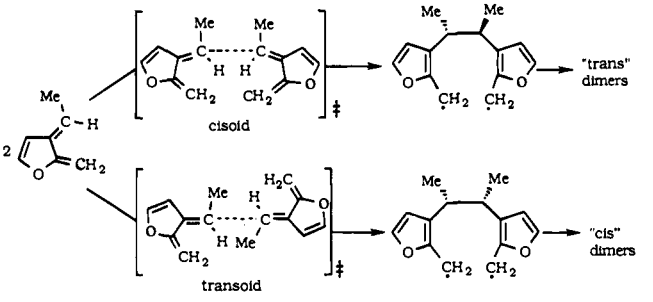



state **8** would produce diradical **10** and the transoid transition state **9** would produce diradical **11** (**10** and **11** are conformational isomers). Diradical **10** could collapse directly to either the [4 + 4] or the [4 + 2] dimer but diradical **11** could not produce the [4 + 4] dimer without converting to another conformation which has the two methylene radical sites on the same side of the molecule. Thus if there are two types of orientations, each might lead to different ratios of [4 + 4] to [4 + 2] dimers or conformational changes of the initially formed diradicals may occur so rapidly that each orientation would produce the same ratio of [4 + 4] to [4 + 2] dimers.[13] This can be expressed as two questions: (a) Are there two types of transition state orientations, the cisoid and the transoid orientations represented by **8** and **9**, respectively? (b) If there are two types of orientations, do they lead to the same or different ratios of [4 + 4] to [4 + 2] dimers?

In an attempt to answer these two questions, we initiated a study of the derivatives of **1** with methyl groups on the termini of the reactive diene unit, *o*-QDM's **12**, **13**, and **14**. We expected that a methyl group on the 3-methylene group would



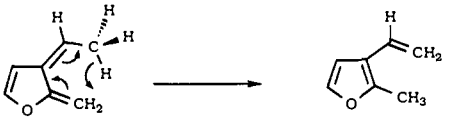

have the *E* configuration which would allow us to probe the relative importance of transition states **8** and **9** by studying the stereochemistry of the final dimers. The cisoid orientation would produce the trans 3-ethano bridge and the transoid orientation would produce the cis 3-ethano bridge (these diradicals are configurational isomers). Analysis of the dimers would show the relative importance of the two initial pathways




and the fate of the initially formed diradical or diradicals produced by one or both pathways. The results of this study are presented and discussed herein.

## Results

Although pyrolysis has been used extensively in the preparation of **1** and its derivatives, it could not be used in the present study. The major problem arising from pyrolysis is the competitive [1,5] hydrogen shift which can occur at high




temperature.[14] To avoid this interference, substituted 2,3-dimethylene-2,3-dihydrofurans **12**, **13**, and **14** were prepared in the solution phase at room temperature by the fluoride-

(8) Chauhan P. M. S.; Crew, A. P. A.; Jenkins, G.; Storr, R. C.; Walker, S. M.; Yelland, M. *Tetrahedron Lett.* **1990**, *31*, 1487.

(9) (a) Marinelli, E. R. *Tetrahedron Lett.* **1982**, *23*, 2745. (b) Vice, S. F.; Nandin de Carvalno, H.; Taylor, N. G.; Dmitrienku, G. I. *Tetrahedron Lett.* **1989**, *30*, 7289. (c) Haber, M.; Pindur, U. *Tetrahedron* **1991**, *47*, 1925.

(10) (a) Huang, Y.-c. J. MS Thesis, Iowa State University, 1984. (b) van den Berg, K. J. Ph.D. Dissertation, Groningen Univeristy, 1990. (c) van den Berg, K. J.; van Leusen, A. M. *Recl. Trav. Chim. Pays-Bas* **1993**, *112*, 7.

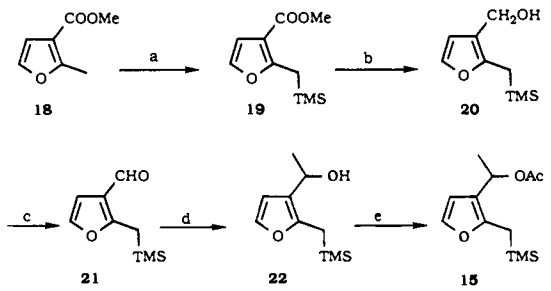
(11) (a) Errede, L. A. *J. Am. Chem. Soc.* **1961**, *83*, 949. (b) Macias, J. R. Ph.D. Dissertation, Iowa State University, 1987. (c) Fischer, D. R. Ph.D. Dissertation, Iowa State University, 1990. (d) Trahanovsky, W. S.; Macias, J. R. *J. Am. Chem. Soc.* **1986**, *108*, 6820. (e) Trahanovsky, W. S.; Chou, C. H.; Fischer, D. R.; Gerstein, B. C. *J. Am. Chem. Soc.* **1988**, *110*, 6579.

(12) Winnik, M. A. *Chem. Rev.* **1981**, *81*, 491; *Acc. Chem. Res.* **1985**, *18*, 73.

(13) See Curtin–Hammett Principle: Carey, F. A.; Sundberg, R. J. *Advanced Organic Chemistry*, Part A, 3rd ed.; Plenum: New York and London, 1990; pp 215–216.

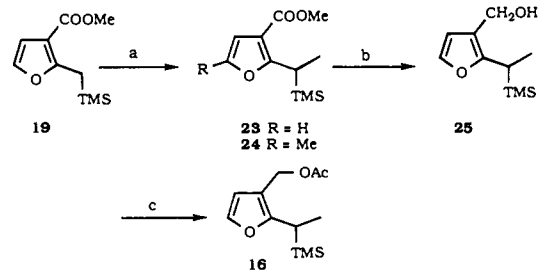
(14) Lee observed significant amounts of [1,5] hydrogen shift products in the gas phase pyrolytic preparation of α-alkenyl furan-based *o*-quinodimethanes.[7c]

**Scheme 1**[a]



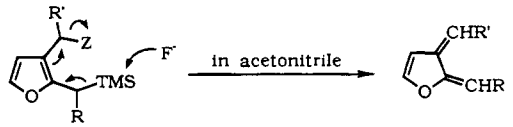

a. 2LDA, TMSCl, -78 °C; b. $LiAlH_4$; c. $CrO_3$• 2Py; d. MeLi; e. AcCl, Py

**Scheme 2**[a]

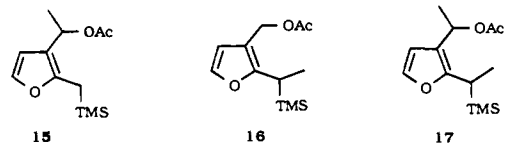



a. LDA, MeI; b. $LiAlH_4$; c. AcCl, Py

induced 1,4-conjugative elimination from the appropriate trimethylsilyl derivative.




For the generation of *o*-QDM's, the trimethylammonium group is the common leaving group[11b-e,15] but because of difficulty in preparation of the appropriate trimethylammonium salt, we switched to the acetate as the leaving group.[16] Precursors **15**, **16**, and **17** were synthesized as follows:




The synthesis of **15** is summarized in Scheme 1. Selective silylation of methyl furancarboxylate **18** at the 2-methyl group was achieved by use of chlorotrimethylsilane and 2 equiv of lithium diisopropylamide at low temperature to give ester **19** without competitive methylation at the 5-position.[17] Direct reduction of ester **19** to alcohol **20** by $LiAlH_4$[18] followed by modified Collins oxidation provided aldehyde **21**.[19] Addition of methyl lithium to aldehyde **21** followed by acetylation of alcohol **22** gave precursor **15**.

(15) (a) Ito, Y.; Nakatsuka, M.; Saegusa, T. *J. Am. Chem. Soc.* **1980**, *102*, 863. (b) Ito, Y.; Nakatsuka, M.; Saegusa, T *J. Am. Chem. Soc.* **1982**, *104*, 7609. (c) Ito, Y.; Nakajo, E.; Sho, K.; Saegusa, T. *Synthesis* **1985**, 698. (d) Chauhan, P. M. S.; Jenkins, G.; Walker, S. M.; Storr, R. C. *Tetrahedron Lett.* **1988**, *29*, 117.

(16) (a) Sieber, P. *Helv. Chim. Acta* **1977**, *60*, 2711. (b) Gerlach, H. *Helv. Chim. Acta* **1977**, *60*, 3039.

(17) (a) Su, H.-W.; Hirose, K.; Shirai, K.; Kumamoto, T. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 2725. (b) Clark, R. D.; Jahangir, *J. Org. Chem.* **1987**, *52*, 5378.

(18) Fieser, L. F.; Fieser, M. *Reagents for Organic Synthesis*; John Wiley and Sons: New York, 1967; Vol. 1, pp 581–595.

(19) Ratcliffe, R.; Rodehorst, R. *J. Org. Chem.* **1970**, *35*, 4000.

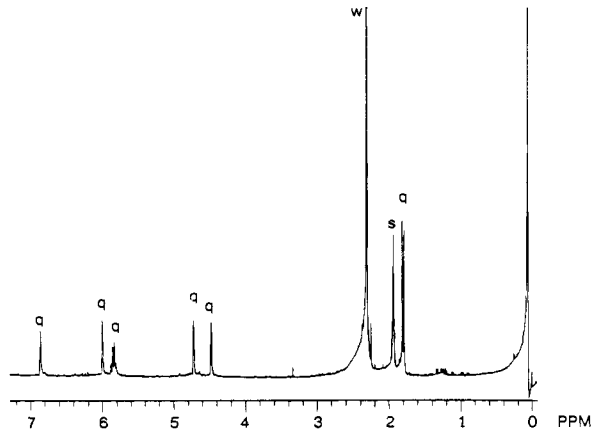
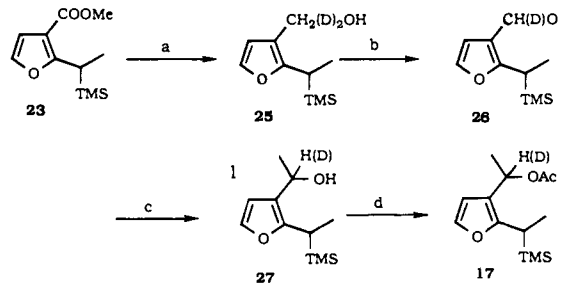



**Figure 1.** $^1H$ NMR spectrum (300 MHz, in $CD_3CN$) of 3-ethylidene-2-methylene-2,3-dihydrofuran (**12**) recorded at room temperature (q, *o*-QDM **12**; w, $H_2O$ from TBAF salt; s, $CHD_2CN$ in acetonitrile-$d_3$).

**Scheme 3**[a]




a. $LiAlH_4$ or $LiAlD_4$; b. $CrO_3$• 2Py; c. MeLi; d. AcCl, Py

The synthesis of **16** is outlined in Scheme 2. On treatment of **19** with LDA, followed by MeI in THF at −78 °C, α-methylation adjacent to the trimethylsilyl group was achieved to afford **23**. However, co-generation of overmethylated product **24** could not be avoided. Purification of **23** from this mixture was necessary since the side products derived from **24** would interfere with the final dimerization product analyses. Purified **23** was then subjected to $LiAlH_4$ reduction followed by acetylation of **25** to provide **16**.

The synthesis of **17** is shown in Scheme 3. Alcohol **25** was oxidized by modified Collins reagent to provide aldehyde **26**. Treatment of aldehyde **26** with methyl lithium followed by acetylation of alcohol **27** led to precursor **17**. Since the regiostructural assignments of the dimerization products cannot be obtained simply from their $^1H$ NMR spectra, the deuterium-labeled dimers were desired. In our study, deuterated **17** was prepared from deuterated alcohol **25** which was derived from the reduction of **23** with $LiAlD_4$.

**Generation and Dimerization of 12.** Fluoride-induced 1,4-conjugative elimination of trimethylsilyl acetate from **15** was carried out in acetonitrile using an excess amount of tetrabutylammonium fluoride (TBAF) to give the reactive 3-ethylidene-2-methylene-2,3-dihydrofuran (**12**). The existence of **12** was first proved by a trapping experiment. In the presence of a large excess of methyl acrylate (10 equiv), **12** was trapped nearly quantitatively to give a mixture of Diels–Alder adducts **28**.[2,7] By GC/MS and $^1H$ NMR analyses, four regio- and stereoisomers were identified. Direct evidence for the existence of **12** was

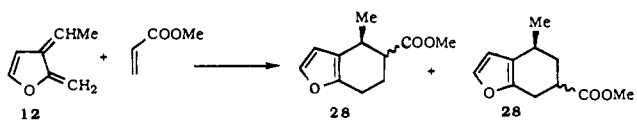
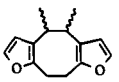
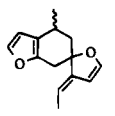
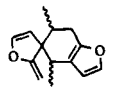
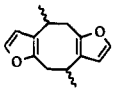
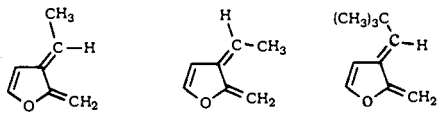


**Table 1.** Dimerization Products of 3-Ethylidene-2-methylene-2,3-dihydrofuran (**12**)

| Dimer | Number of possible diastereomers | Mode of cyclization | Number of isolated dimers | GC retention time, (yield, %) |
|---|---|---|---|---|
|  **30** and **31** | 2 | Head-to-head [4+4] | 2 | 23.27 (32 %)[a] **30** 25.25 (10 %)[a] **31** |
|  **32** | 4 | Head-to-tail [4+2] | 1 | 23.94 (10 %)[a] **32** |
|  **33** and **34** | 4 | Head-to-tail [4+2] | 2 | 21.44 (24 %)[a] **33** 21.57 (18 %)[a] **34** |
|  **35** and **36** | 2 | Head-to-tail [4+4] | 1 | 22.79 (-4 %)[b] **35** |
| **37** | | Unknown | - | 22.61 (-2 %)[c] **37** |

[a] The dimer was isolated and identified by $^1$H NMR spectroscopy. [b] The dimer was identified by the GC/MS and the $^1$H NMR spectrum of the dimer mixture. [c] The dimer was identified by the GC/MS analysis.

obtained by $^1$H NMR spectroscopy. Due to its low molecular weight and high volatility, *o*-QDM **12** was generated and immediately distilled along with the deuterated solvent under vacuum at ambient temperature and the mixture was condensed in a cold trap at −78 °C. After the distillation, the condensate was warmed to room temperature and the $^1$H NMR spectrum was obtained (Figure 1). Interestingly, *o*-QDM **12** is relatively stable and only dimerizes or polymerizes slowly at room temperature. The spectrum of **12** shows that only one stereoisomer was produced. Since both *E* and *Z* isomers of *o*-QDM **12** would give rise to the same $^1$H NMR pattern, the pattern itself does not reveal the stereochemistry of **12**, but some stereochemical conclusions can be drawn from the chemical shifts of **12**. Fortunately, the very unreactive *tert*-butyl derivative *o*-QDM *E*-**29** was prepared by Huang[5,7b] by flash vacuum pyrolysis (FVP). The chemical shifts of the olefinic protons



*E*-12 *Z*-12 29

of *o*-QDM's **12** and *E*-**29** are nearly identical and therefore we assign the *E* configuration to *o*-QDM **12**.

In the absence of a trapping reagent, **12** dimerizes to give a complicated mixture of dimers (~50%) and polymers. A similar yield of dimers was obtained in both a TBAF solution and the distillate, which suggests that polymerization of **12** is not a TBAF-induced reaction.

GC/MS analysis of the product mixture shows that seven dimers were formed in the dimerization of **12** (Table 1). Five of them were readily separated and characterized by $^1$H NMR spectroscopy. Two of these five are head-to-head [4 + 4] adducts **30** and **31** (42%) while the other three are head-to-tail

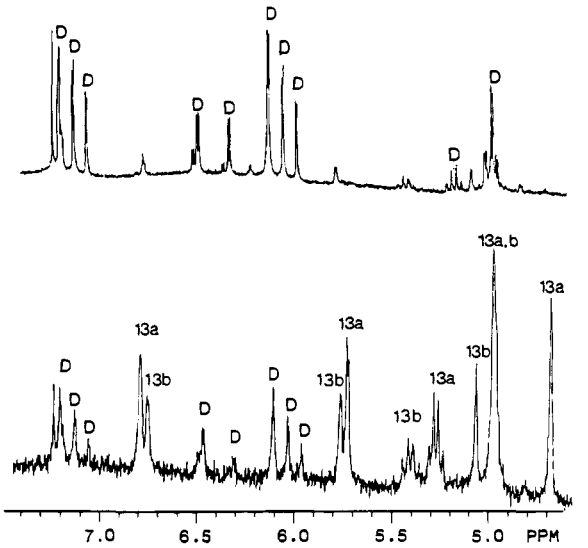
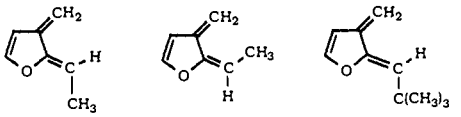



**Figure 2.** $^1$H NMR spectrum (300 MHz, in $CD_3CN$) of 2-ethylidene-3-methylene-2,3-dihydrofuran (**13**): (bottom spectrum) recorded right after the preparation of **13** (13a, 2*Z*-**13**; 13b, 2*E*-**13**; D, dimers); (top spectrum) recorded 24 h later (D, dimer).

[4 + 2] adducts **32**−**34** (52%). The assignments of **30** and **31** were based on the AA′BB′ pattern around $\delta$ 2.5 ppm in both of the $^1$H NMR spectra. The structure of **32** was confirmed by both the characteristic quartet at $\delta$ 4.8 ppm which results from the signal for the *exo*-methine proton adjacent to a methyl group and the typical AB pattern around $\delta$ 3.0−2.2 ppm. The assignments of **33** and **34** were based on the observations of a typical signal for the *exo*-methylene protons with no AB quartet in their $^1$H NMR spectra. In addition, these assignments were further confirmed by decoupling experiments. Dimer **35** could not be isolated and identified successfully until FVP of **34** was carried out. FVP[20] of **34** gave rise to a mixture of **35** and **36** in a 2 to 1 ratio. They were identified by GC/MS and $^1$H NMR analyses. On the basis of the identical retention times, fragmentation patterns in the GC/MS, and chemical shifts in the $^1$H NMR spectra, **35** was identified as a minor product in the dimerization. Dimer **37** could not be isolated and identified, but the GC/MS analyses of **37** show a fragmentation pattern very similar to those of the other dimers.

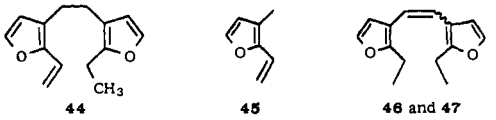
**Generation and Dimerization of *o*-QDM 13.** Fluoride-induced 1,4-conjugative elimination of trimethylsilyl acetate from **16** in acetonitrile led to reactive 2-ethylidene-3-methylene-2,3-dihydrofuran (**13**). By use of the same technique applied to *o*-QDM **12**, the $^1$H NMR spectrum of **13** was obtained (Figure 2, bottom). However, due to its higher reactivity toward dimerization, *o*-QDM **13** dimerized during the $^1$H NMR acquisition process, and therefore small amounts of dimers also showed in the $^1$H NMR spectrum. Interestingly, unlike *o*-QDM **12**, two different sets of olefinic proton signals, labeled **13a** and **13b**, are observed in the spectrum. The signals of the major isomer, **13a**, and the minor isomer, **13b**, disappeared with time, leaving only signals from dimers (Figure 2, top). Because of the nearly identical olefinic proton chemical shifts of **13a** and *Z*-**4**, which was prepared by Huang by FVP,[5,7b] we assign the *Z* configuration to **13a** and the *E* configuration to **13b**.

(20) (a) Trahanovsky, W. S.; Ong, C. C.; Pataky, J. G.; Weitl, F. J.; Mullen, P. W.; Clardy, J. C.; Hansen, R. S. *J. Org. Chem.* **1971**, *36*, 3575. Commercial apparatus is available from Kontes Scientific Glassware, Vineland, NJ 08360. (b) For review, see: Brown, R. F. C. *Pyrolysis Methods in Organic Chemistry*; Academic: New York, 1980; Chapter 2.



*Z*-13 *E*-13 *Z*-4

Dimerization of **13** led to a mixture of seven dimers. Six of these were isolated and identified as head-to-head dimers **38**–**43** (Table 2). Intramolecular disproportionation product **44** could not be identified until FVP[20] of the dimer mixture was performed. The assignments of **38** and **39** were based on both the characteristic AA′BB′ signals of the 3-ethano bridge protons and the quartet which results from the 2-ethano protons adjacent to the methyl group. On the other hand, the assignments of **40**–**43** were supported by the characteristic olefinic quartets resulting from the *exo*-methine protons adjacent to a methyl group and the quartets arising from the methylene bridge protons adjacent to the other methyl group. When the dimer mixture was subjected to FVP at 630 °C, a mixture of six components, **38**, **39**, and **44**–**47**, was obtained. Fragmentation product **45** was distilled along with deuterated solvent introduced after the pyrolysis and identified as the major product, and significant amounts of intramolecular disportionation products **44** (15%) and **46** (10%) were isolated. The assignment of **44** is supported



**44** **45** **46** and **47**

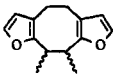
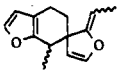
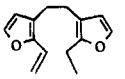
by the observation of the signals of the ethyl group, four ethano bridge protons (AA′BB′ signal) and three vinyl protons at $\delta$ 6.41, 5.55, and 5.07 ppm. Similar results were obtained in the pyrolysis of the mixture of [4 + 2] dimers **40** and **41**. We concluded that **44** is a minor component in the original dimer mixture because the GC retention time and mass spectrum of one of the original products matched those of **44** obtained from the FVP of the dimer mixture. The structural assignment of **46** is based on the observation of the signals for the ethyl group and olefinic protons on the bridge at $\delta$ 6.52 ppm. The structural assignment of **47**, the cis–trans isomer of **46**, is based on a mass spectrum which is very similar to that of **46**.

**Generation and Dimerization of *o*-QDM 14.** Fluoride-induced 1,4-conjugative elimination of trimethylsilyl acetate from **17** in acetonitrile led to the reactive 2,3-ethylidene-2,3-dihydrofuran (**14**). By utilizing the same vacuum distillation technique, the $^1$H NMR spectrum of the reactive intermediates was obtained (Figure 3). Again, two sets of olefinic signals are observed in the spectrum. Since we know that introduction of a methyl substituent at the 3-methylene position leads to a single isomer *E*-**12** while a methyl substituent at the 2-methylene position leads to a pair of cis–trans isomeric *o*-QDM's *E*-**13** and *Z*-**13**, we concluded that **14** is a mixture of *ZE*-**14** and *EE*-**14**.

*ZE*-14 *EE*-14

*o*-QDM's *ZE*-**14** and *EE*-**14**, condensed at low temperature, dimerized slowly at room temperature to give rise to a mixture of four separable major dimers **48**–**51** (Table 3) and fourteen minor dimers, which were detected by GC/MS analyses. Since the head-to-head, head-to-tail, and tail-to-tail [4 + 2] dimers

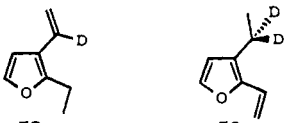
**Table 2.** Dimerization Products of 2-Ethylidene-3-methylene-2,3-dihydrofuran (**13**)

| Dimer | Number of possible diastereomers | Mode of dimerization | Number of isolated dimers | GC retention time, (yield, %) |
|---|---|---|---|---|
|  **38** and **39** | 2 | Head-to-head \|4+4\| | 2 | 16.36 (12 %)[a] **38**<br>17.59 (18 %)[a] **39** |
|  **40-43** | 4 | Head-to-head \|4+2\| | 4 | 15.90 (33 %)[a] **40**<br>16.39 (12 %)[a] **41**<br>17.14 (18 %)[a] **42**<br>17.24 ( 4 %)[a] **43** |
|  **44** | 1 | Head-to-head dispropor-tionation | 1 | 16.04 (~2 %)[b] **44** |

[a] Compound was isolated and identified by $^1$H NMR spectroscopy. [b] Compound was identified by GC/MS analysis.

cannot be distinguished simply by $^1$H NMR spectroscopy, deuterium isotope labeling experiments were performed. Separation of the deuterated dimers **48**–**51** by silica gel liquid chromatography afforded essentially pure dimers which were suitable for $^1$H NMR analyses. The disappearance of the ethano bridge proton signals on the $^1$H NMR spectra of deuterated **49** and **50** strongly supports the head-to-head [4 + 2] assignments. The relative configuration between methyl substitutents on the ethano bridge of **49** was deduced from the spin–spin coupling constant between the methine protons on the bridge. The spin–spin coupling constant with $J_{HCCH}$ = 9.5 Hz indicates that the methine protons on the ethano bridge are in the anti position (with a dihedral angle *ca.* 180°).[21] However, the moderate coupling constant ($J_{HCCH}$ = 6.6 Hz) of **50** does not lead to any definite assignment. In order to establish the stereochemistry of **50**, dimers **49** and **50** were subjected to FVP.

Pyrolysis of deuterated **49** generated a mixture of fragmentation products **52** and **53** along with three [4 + 4] dimers **48**, **54**, and **55**. On the other hand, pyrolysis of deuterated **50** under



**52** **53**

similar conditions led to the same fragmentation products **52** and **53** but totally different [4 + 4] dimers **51**, **56**, and **57**. The structures were assigned on the basis of GC/MS and $^1$H NMR analyses which were based on comparison of the $^1$H NMR spectra (Figure 4) of the pyrolysates. The common proton signals at $\delta$ 6.46 and 6.27 ppm were assigned to the furan ring proton at the 4-position of **52** and **53**, respectively. The down field shift of the signal at $\delta$ 6.46 ppm is due to the effect of the 3-vinyl substituent. The assignments were further confirmed by comparison of the chemical shifts with those of the signals of **45** and **46**. The doublets at $\delta$ 6.24, 6.07, and 6.03 ppm in Figure 4, top trace, and the doublets at $\delta$ 6.22, 6.18, and 6.14 ppm in Figure 4, bottom trace, indicate the existence of two different sets of [4 + 4] dimers, which are also suggested by their GC/MS fragmentation patterns. By chemical shifts and

(21) The vicinal Karplus correlation relationship. See: Silverstein, R. M.; Bassler, G. C.; Morrill, T. C. *Spectrometric Identification of Organic Compounds*, 5th ed.; John Wiley and Sons: New York, 1991; pp 196–197.

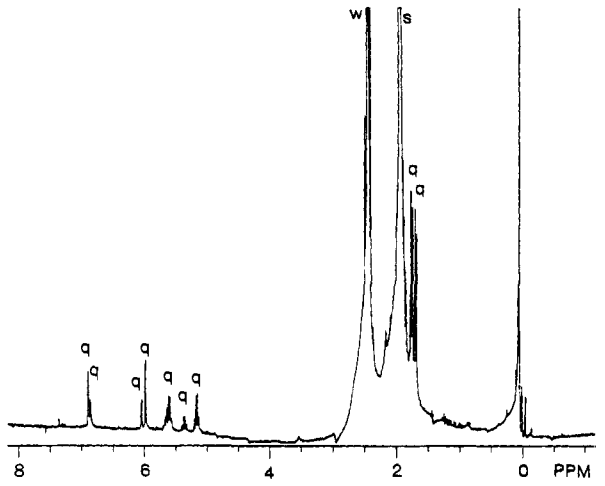
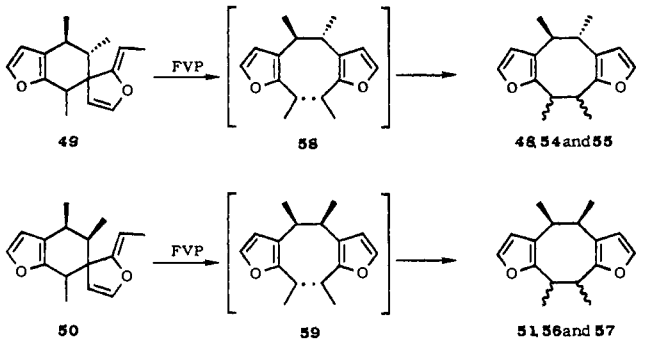



**Figure 3.** $^1$H NMR spectrum (300 MHz, in $CD_3CN$) of 2,3-diethylidene-2,3-dihydrofuran (**14**) recorded at room temperature (q, diastereomeric *o*-QDM 2*Z*,3*E*-**14** and 2*E*,3*E*-**14**; w, $H_2O$ from TBAF salt; s, $CHD_2CN$ in acetonitrile-$d_3$).

GC retention times, [4 + 4] dimer **48** was identified as one of the components in the pyrolysate of **49** while [4 + 4] dimer **51** was assigned as one of the products in the pyrolysate of **50**.

To explain these pyrolysis results, we suggest that the stereochemistries of the ethano bridges of **49** and **50** are different. If both **49** and **50** have the same relative configuration on the ethano bridge, we should have obtained the same [4 + 4] dimers in the pyrolyses. However, if these configurations are different, generation of the stereoisomeric diradical intermediates **58** and **59** is expected. Since the relative configuration

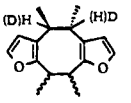
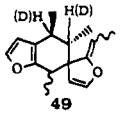
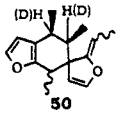
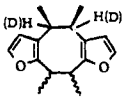



of the ethano bridge is maintained during the diradical formation process, there is no doubt that cyclization of the diradicals **58** and **59** affords two different sets of diastereomeric [4 + 4] dimers. Since the relative configuration of **49** was identified to be anti on the ethano bridge, we assigned the syn configuration to **50**. Also, because we identified **48** and **54** as pyrolysis products of **49** and **51** as one of the pyrolysis products of **50**, their relative configurations of the 3-ethano bridges are determined.

## Discussion

Recent kinetic and product studies are consistent with the proposal that 2,3-dimethylene-2,3-dihydrofuran (**1**) dimerizes by a two-step diradical mechanism which involves rate-determinating formation of a diradical intermediate followed by rapid cyclization of the diradical.[2] On the basis of deuterium kinetic isotope studies, Chou and Trahanovsky concluded that only the 3-methylene carbon is involved in the rate-determinating step while the 2-methylene carbon is involved only in the diradical ring-closure process and attributed these results

**Table 3.** Dimerization Products of 2,3-Diethylidene-2,3-dihydrofuran (**14**)

| Dimer | Mode of cyclization | Retention time, (yield, %) |
|---|---|---|
|  **48** and **54** | Head-to-head \|4+4\| | 52.24 ( 6 %)[a] **48**<br>58.06 ( 2 %)[b] **54** |
|  **49** | Head-to-head \|4+2\| | 54.15 (42 %)[a] |
|  **50** | Head-to-head \|4+2\| | 58.00 (39 %)[a] |
|  **51** | Head-to-head \|4+4\| | 60.43 ( 6 %)[a] |

[a] The dimer was isolated and identified by $^1$H NMR spectroscopy. The structure was further confirmed by the deuterium isotope labeling experiment. [b] The dimer was identified by comparison of the retention time and MS pattern with those of the pyrolysis products of **49**.

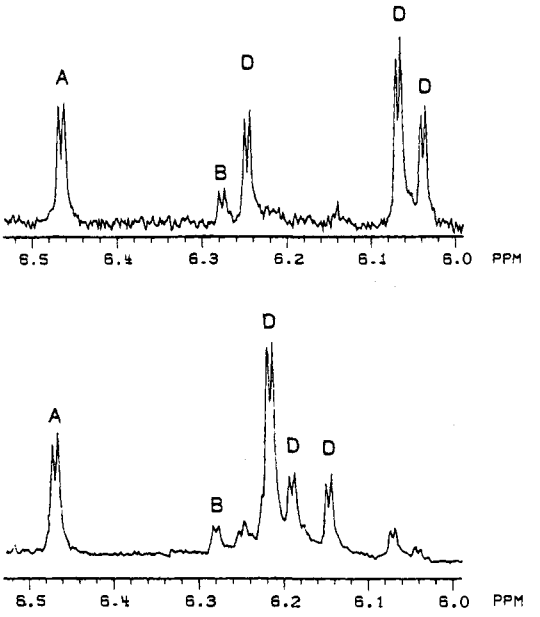



**Figure 4.** (Top) $^1$H NMR spectrum (300 MHz, $CDCl_3$) of the pyrolysate of [4 + 2] dimer **49** (A, 2-ethyl-3-ethylenylfuran (**52**); B, 3-ethyl-2-ethylenylfuran (**53**); D, [4 + 4] dimers **48**, **54**, and **55**). (Bottom) $^1$H NMR spectrum (300 MHz, $CDCl_3$) of the pyrolysate of [4 + 2] dimer **50** (A, 2-ethyl-3-ethylenylfuran (**52**); B, 3-ethyl-2-ethylenylfuran (**53**); D, [4 + 4] dimers **51**, **56**, and **57**).

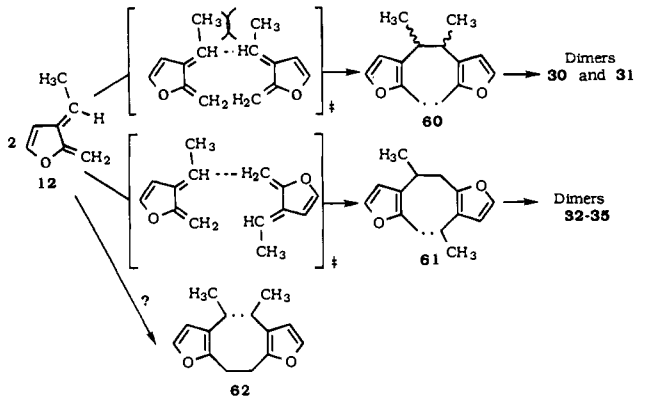
to the relative stability of the furfuryl diradicals.[3,7a] This argument is consistent with the fact that the 2-furfuryl radical is more stable than the 3-furfuryl radical.[22] In the present study introduction of methyl substituents on the reactive diene unit of furan-based *o*-QDM's indeed affects both the diradical formation step and the diradical cyclization step. We now discuss these effects.

On the basis of the proposed diradical mechanism, we expected to see retardation of furan-based *o*-QDM dimerizations

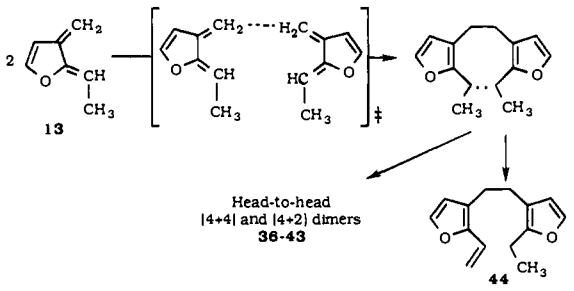
(22) Strom, E. T. P.; Russell, G. A.; Schoeb, J. H. *J. Am. Chem. Soc.* **1966**, *88*, 2004.

by introduction of a bulky substituent on the 3-methylene position. In fact, the trend of the relative reactivity of 2,3-dimethylene-2,3-dihydrofuran (**1**), 3-ethylidene-2-methylene-2,3-dihydrofuran (**12**), and 2-methylene-3-(*tert*-butylmethylene)-2,3-dihydrofuran (**29**) toward dimerization is strongly consistent with this expectation. The parent *o*-QDM **1** is so reactive that it dimerizes at −20 °C, the 3-methyl derivative (**12**) dimerizes slowly within several hours at room temperature, and the 3-*tert*-butyl derivative (**29**) is unreactive at room temperature and no dimer was isolated even after all of the monomer disappeared at higher temperatures.[5,7b]

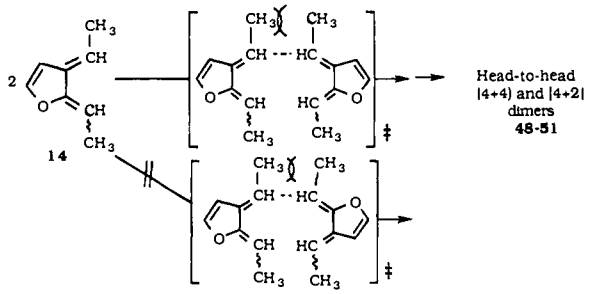
The shielding of the reactive 3-methylene position of *o*-QDM **12** by the methyl substituent apparently retards the head-to-head dimerization process enough to allow the head-to-tail dimerization to become competitive. In the dimerization of **12**, significant amounts of head-to-tail dimers **32**−**35** were isolated along with the head-to-head [4 + 4] dimers **30** and **31**. These results are attributed to the competitive formation of the head-to-tail diradical **61** which further cyclizes to head-to-tail dimers **32**−**35**. The head-to-head [4 + 4] dimers **30** and **31** are the dimers expected from the head-to-head diradical **60**, but it is possible that these dimers arise from tail-to-tail diradical **62**. However, the assumption that the head-to-head diradical **60** is involved is consistent with the fact that head-to-head dimerization of the dimethyl *o*-QDM **14** still occurs even though **14** has a methyl group on the 3-methylene position.



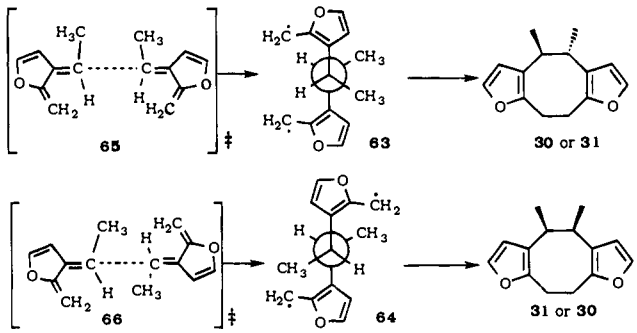

Introduction of a methyl substituent on the 2-methylene carbon, instead of the 3-methylene position, does not retard the head-to-head dimerization. In fact, *o*-QDM **13** dimerizes exclusively in the head-to-head fashion to give rise to [4 + 4] and [4 + 2] dimers **38**−**43**. Importantly, identification of the intramolecular disproportionation product **44** in this case provides additional support for the diradical mechanism. It is conceivable that **44** could be formed by a concerted reaction, but the orientation requirements of the transition state of such a reaction would be high. Intramolecular disproportionation of diradicals has been observed.[23]




In contrast to the dimerization of **12**, *o*-QDM **14** dimerizes mainly in a head-to-head fashion. Introduction of methyl substituents at the 2-methylene and 3-methylene positions indeed enhances steric retardation of both head-to-head and head-to-tail dimerization processes. As the discrepancy of the steric hindrance disappears, electronic influences predominate and, like the parent *o*-QDM **1**, *o*-QDM **14** dimerizes again in the head-to-head fashion.

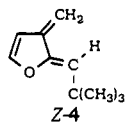



The $^1$H NMR of **12** (Figure 1) indicates that only one stereoisomer (which we assigned the *E* configuration) was formed and therefore formation of both head-to-head [4 + 4] dimers **30** and **31** in the dimerization of **12** indicates the existence of two distinct diradical intermediates, **63** and **64**.[24] However, both diradicals, cisoid **63** and transoid **64**, cyclize in




a [4 + 4] fashion. These results indicate that the second step of the head-to-head dimerization is not influenced by the relative orientation of the monomers in transition states **65** and **66** and that both the cisoid and transoid diradicals derived from these transition states cyclize in the same fashion.

On the other hand, a methyl group on the 2-methylene position changes the preference of cyclization of the diradical. Dimerization of **13** provides the head-to-head [4 + 2] and head-to-head [4 + 4] dimers in a 2.3 to 1 ratio. This observation is consistent with the result of *o*-QDM *Z*-**4** dimerization.[5,7b] *o*-QDM *Z*-**4** was generated by FVP and is reported to dimerize mainly in a head-to-head [4 + 2] fashion.

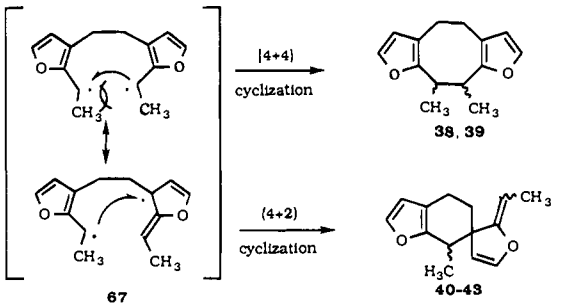



Pyrolysis of the [4 + 2] dimers of *o*-QDM **13** led to a series of thermodynamically stable products. On the basis of this FVP experiment, we conclude that the [4 + 4] dimers are thermodynamically more stable than the [4 + 2] dimers which means that the cyclization of diradical **67** indeed is a kinetically

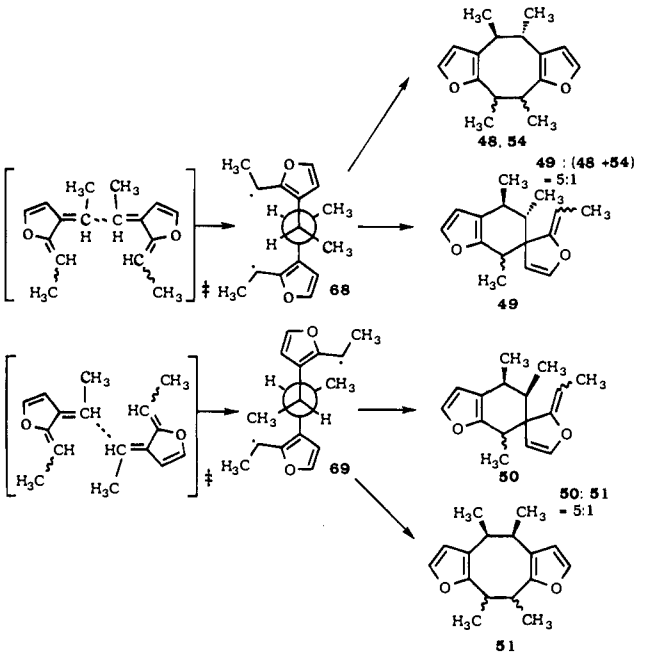
(23) (a) Johnston, L. J.; Scaiano, J. C. *Chem. Rev.* **1989**, *89*, 521. (b) Bergman, R. G. In *Free Radicals*; Kochi, Jay K., Ed.; John Wiley and Sons: New York, 1973; Vol. I, p 231.

(24) No evidence for the other isomer (the *Z* isomer) was obtained under any conditions; the dimerization was followed by $^1$H NMR spectroscopy and as the signals for the dimers increased, the signals for *E*-12 disappeared with the development of no signals that could be attributed to *Z*-12.

controlled process. Increasing steric hindrance at the 2-methylene position by introduction of a substituent appears to retard the [4 + 4] cyclization which allows the [4 + 2] cyclization to become competitive.



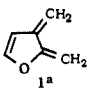
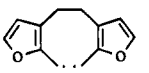
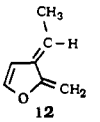
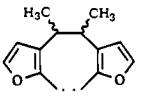
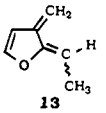
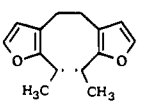
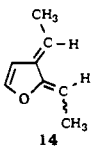
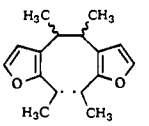

The combined features of the dimerization of *o*-QDM **12** and of *o*-QDM **13** can be seen in the dimerization of *o*-QDM **14**. Similar to *o*-QDM **12**, *o*-QDM **14** dimerized to two series of head-to-head dimers which possess different relative configurations of their 3-ethano bridges. On the basis of our analyses, dimers **48, 49,** and **54** are originally derived from cisoid diradical **68** and dimers **50** and **51** are derived from transoid diradical **69**. These results again implicate the existence of the cisoid




and transoid monomer encounterings in the diradical formation step. On the other hand, the methyl substituents on the 2-furfuryl radical sites of **68** and **69** again make a distinct change in the mode of cyclization. Unlike the head-to-head diradical intermediate of the parent *o*-QDM **1** and those of *o*-QDM **12**, but similar to that of *o*-QDM **13**, diradicals **68** and **69** prefer to cyclize in a [4 + 2] fashion. More interestingly, both **68** and **69** cyclized to give rise to a mixture of [4 + 2] and [4 + 4] dimers in a similar ratio of 5 to 1. This observation suggests that the preference for the cyclization mode of the diradical intermediates in the dimerization is insensitive to the initial conformation of the diradicals or the relative orientation of the monomers in the transition state of the diradical formation step.

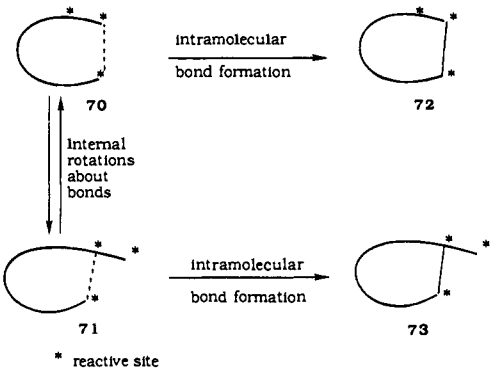
To summarize our studies, a comparison of the dimerization results is shown in Table 4. The cisoid and transoid monomer encounterings in the diradical formation step were successfully labeled by introducing a methyl group at the 3-methylene

**Table 4.** Cyclization Regioselectivity of the Diradical Intermediates in the Dimerization of Furan-Based *o*-Quinodimethanes

| Entry | *o*-QDM | Head-to-head diradical intermediate | Cyclization regioselectivity [4+4] : [4+2] |
|---|---|---|---|
| 1 |  1[a] |  | > 20 |
| 2 |  12 |  | > 20 |
| 3 |  13 |  | < 0.5 |
| 4 |  14 |  | < 0.25 |

[a] See ref 2.

**Scheme 4**




position of the furan-based *o*-QDM's. Once the diradical intermediate is formed, the methyl substituents on the 3-ethano bridge do not show any significant effect on the mode of cyclization of the diradical. On the other hand, the mode of cyclization is strongly affected by a methyl substituent on the 2-methylene position. This result indicates that steric retardation of bond formation between two 2-furfuryl radical sites of the diradical intermediate may slow down the [4 + 4] cyclization and allow the [4 + 2] cyclization to become competitive.

In general, cyclization of a reactive species involves an internal bond rotation step as well as the intramolecular bond formation step between the active sites on the chain.[12] A generalized scheme representing the cyclization reaction is depicted in Scheme 4. Conformational motion of the carbon chain brings the intermediate to reactive conformation **70** or **71** which can further cyclize to form cyclization products **72** and **73**, respectively. In principle, any factor that can affect the internal rotation or the intramolecular bond formation of the intermediate can be crucial in the regioselectivity of the cyclization.[12,25] However, in view of the results of this study of the furan-based *o*-QDM dimerizations, we believed that the

(25) One of the common examples is the exo—endo cyclization regioselectivity of alkenyl radicals. See: Laird, E. R.; Jorgensen, W. L. *J. Org. Chem.* **1990**, *55*, 9 and references cited therein.

**Table 5.** FVP of the Dimer Mixtures of 2-Ethylidene-3-methylene-2,3-dihydrofuran (**13**)

| pyrolysis product | precursor: mixture of **38**–**44**[a] retention time, min (yield, %) | precursor: mixture of **40** and **41**[b] retention time, min (yield, %) |
|---|---|---|
| **45** | 4.05 (5.0) | 4.05 (42.9) |
| **47** | 13.27 (0.5) | 13.32 (3.2) |
| **44** | 13.65 (11.2) | 13.68 (14.6) |
| **38** | 13.86 (41.7) | 13.89 (16.1) |
| **39** | 14.79 (39.8) | 14.82 (12.9) |
| **46** | 15.53 (2.1) | 15.58 (10.3) |

[a] FVP at 614–620 °C under vacuum ($2.1 \times 10^{-5}$ Torr). [b] FVP at 625–638 °C under vacuum ($1.4 \times 10^{-4}$ Torr).

**Table 6.** GC/MS Analyses of the Original Dimers of Deuterated *o*-QDM **14** and the Major Components in the Pyrolysates of the Deuterated [4 + 2] Dimers **49** and **50**

| assigned structure | GC retention time, min (yield %): dimer of *o*-QDM **14** | pyrolysate of **49** | pyrolysate of **50** |
|---|---|---|---|
| fragmentation product **52** | | 4.84 (17) | 4.85 (16) |
| fragmentation product **53** | | 5.18 (4) | 5.19 (4) |
| [4 + 4] dimer +**54** | | 51.46 (15) | *b* |
| [4 + 4] dimer **48** | 52.42 (6.5) | 52.25 (21) | |
| [4 + 2] dimer **49** | 54.15 (38.6) | | |
| [4 + 2] dimer **50** | 58.00 (36.0) | | |
| [4 + 4] dimer **55** | 58.06 (~2) | 58.06 (37) | *b* |
| [4 + 4] dimer **56** and **57** | | *a* | 58.36 (27) |
| [4 + 4] dimer **51** | 60.43 (6.5) | *a* | 60.40 (40) |

[a] The minor components, which are less than 3%, may be generated from the impurity in the pyrolyzed sample of **49**. [b] The minor components, which are less than 4%, may be generated from the impurity in the pyrolyzed sample of **50**.

bond formation step between the active sites of the two furan moieties of the diradical intermediate is the key step in controlling the regioselectivity in the diradical cyclization process. The first insight we obtained from our experiments is the successful labeling of the cisoid and transoid transition states, which led to cisoid and transoid diradicals, in the dimerization. On the basis of these results, we reasonably extrapolate this conclusion to the dimerization of the parent 2,3-dimethylene-2,3-dihydrofuran (**1**) and suggest the co-existence of the conformationally isomeric cisoid and transoid diradicals **10** and **11** in the dimerization. Since both cisoid and transoid diradicals lead to the same kind of cyclization products in all the cases we studied, we believe that the initial conformation of the diradical is unimportant in the regioselectivity of the diradical cyclization and diradical conformations **10** and **11** will lead to the same [4 + 4] dimer. Thus, the answers to the two questions we raised in the Introduction are as follows: (a) Yes, the initial step of the dimerization involves two types of transition state orientations, the cisoid and the transoid and (b) each orientation leads to the same ratio of [4 + 4] to [4 + 2] dimers.

## Experimental Section

**Methods and Materials.** The pyrolysis apparatus has been previously described.[20] $^1$H NMR spectra were obtained on a Nicolet NT-300 spectrometer. Chemical shifts are reported in parts per million ($\delta$) from tetramethylsilane (TMS). Gas chromatographic analyses were performed on a Hewlett-Packard model 5480A gas chromatograph (GC) equipped with a 30 m, DB-1 capillary column from J&W scientific and a flame ionization detector. Combined gas chromatographic/mass spectra (GC/MS) analyses were performed on a Finnigan 4000 GC/MS with Incos data system. High-resolution mass spectra were measured with an Associated Electronics Industries MS-902 instrument or MS 50 mass spectrometer. Infrared spectra (IR) were recorded on a Beckman Acculab II spectrometer. Tetrahydrofuran (THF) was distilled from sodium/benzophenone immediately before use. Acetonitrile was deaerated immediately before use. Diisopropylamine was distilled from calcium hydride ($CaH_2$). Commercial methyl lithium (in ether), *n*-butyl lithium (in hexane), chlorotrimethylsilane, tetrabutylammonium fluoride (TBAF), and methyl 2-[(trimethylsilyl)methyl]-3-furancarboxylate were purchased from Aldrich Chemical Co.

**Methyl 2-[(Trimethylsilyl)methyl]-3-furancarboxylate (19).** To a stirred solution of diisopropylamine (29.6 g, 293 mmol) in THF (200 mL) at −78 °C was added *n*-butyl lithium (115 mL, 288 mmol) under nitrogen. The mixture was stirred for 1 h and a solution of chlorotrimethylsilane (17.0 g, 157 mmol) and methyl 2-methyl-3-furancarboxylate (**18**) (19.0 g, 136 mmol) in THF (200 mL) was added dropwise over 90 min. After addition, the solution was further stirred for 1 h and the reaction was quenched at low temperature by addition of water. The solution was then warmed to room temperature and extracted with 3 × 150 mL of $CH_2Cl_2$. The combined organic phases was treated with 100 mL of brine and dried over anhydrous $Na_2SO_4$. Removal of the solvent left an oil which was distilled under reduced pressure to give essentially pure ester **19** (22.4 g, 78%): bp 105–110 °C (20 mmHg); IR (neat, NaCl) 2850–2980 (C–H), 1720 (C=O), 1250 (Si–$CH_3$) cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 7.14 (d, 1H, $J$ = 1.9 Hz), 6.58 (d, 1H, $J$ = 1.9 Hz), 3.78 (s, 3H), 2.56 (s, 2H), 0.03 (s, 9H); mass spectrum *m/e* (relative intensity) 212 (10), 197 (20), 181 (7), 108 (84), 89 (160), 80 (22), 73 (100), 59 (20), 45 (31); exact mass, *m/e* 212.08727, calcd for $C_{10}H_{16}O_3Si$ 212.08688.

**3-(Hydroxymethyl)-2-[(trimethylsilyl)methyl]furan (20).** To a stirred $LiAlH_4$ suspension (2.0 g, 53 mmol) in anhydrous diethyl ether (30 mL) at 0 °C was added an ethereal solution of carboxylic ester **19** (6.8 g, 32 mmol in 30 mL of anhydrous ether) dropwise over 20 min. After addition of the ester, the mixture was further stirred for 3 h and then worked up as usual[18] to provide the crude alcohol **20**. Distillation of the crude oil under vacuum gave essentially pure alcohol **20** (5.4 g, 29 mmol, 91%): bp 103–105 °C (17 mmHg); IR (neat, NaCl) 3280 (O–H), 2900–2980 (C–H), 1260 (Si–$CH_3$), 1050 (C–OH) cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 7.20 (d, 1H, $J$ = 1.9 Hz), 6.34 (d, 1H, $J$ = 1.9 Hz), 4.41 (d, 2H, $J$ = 4.6 Hz), 2.06 (s, 3H), 1.22 (t, 1H, J=4.6 Hz), 0.03 (s, 9H); mass spectrum *m/e* (relative intensity) 184 (7), 94 (100), 75 (32), 73 (66), 45 (24); exact mass, *m/e* 184.09234, calcd for $C_9H_{16}O_2Si$ 184.09196.

**3-(1-Hydroxyethyl)-2-[(trimethylsilyl)methyl]furan (22).** To a solution of pyridine (12.4 g, 156 mmol) in dichloromethane (200 mL), protected by a drying tube, was added chromium trioxide (7.8 g, 78 mmol). The solution was stirred for 15 min at room temperature and then a solution of alcohol **20** (2.4 g, 13 mmol) in dichloromethane (10 mL) was added in one portion. A tarry, black deposit separated immediately. After an additional 15 min of stirring at room temperature, the solution was decanted from the residue and worked up in the same manner as reported by Ratcliffe[19] to afford the crude aldehyde **21**. Distillation of the crude oil under reduced pressure provided essentially pure aldehyde **21** (1.6 g, 62%): bp 68–70 °C (0.5 mmHg); $^1$H NMR ($CDCl_3$) $\delta$ 9.81 (s, 1H), 7.20 (d, 1H, $J$ = 2.1 Hz), 6.63 (d, 1H, $J$ = 2.1 Hz), 2.45 (s, 2H), 0.06 (s, 9H); mass spectrum *m/e* (relative intensity) 182 (13), 167 (12), 73 (100), 45 (17).

To a stirred solution of aldehyde **21** (1.6 g, 8.8 mmol) in THF (80 mL) was added dropwise an ethereal solution of methyl lithium (6.5 mL, 1.4 M, 9.1 mmol) at −78 °C. After addition, the solution was further stirred for 30 min and was then quenched with water at low temperature. The mixture was extracted with 3 × 100 mL of diethyl ether. The combined organic phases was washed with 100 mL of brine and dried over anhydrous $MgSO_4$. Removal of the solvent left the crude oil which was further distilled under reduced pressure to give essentially pure alcohol **22** (1.4 g, 80%): bp 65–67 °C (0.35 mmHg); IR (neat, NaCl) 3360 (br, O–H), 2900–2980 (C–H), 1250 (Si–$CH_3$) cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 7.18 (d, 1H, $J$ = 1.7 Hz), 6.35 (d, 1H, $J$ = 1.7 Hz), 4.74 (q, 1H, $J$ = 6.5 Hz), 2.06 (s, 2H), 1.53 (br s, 1H), 1.43 (d, 3H, $J$ = 6.5 Hz), 0.04 (s, 9H); mass spectrum *m/e* (relative intensity) 198 (20), 108 (90), 75 (46), 73 (100), 45 (19); exact mass, *m/e* 198.10794, calcd for $C_{10}H_{18}O_2Si$ 198.10761.

**3-(1-Acetoxyethyl)-2-[(trimethylsilyl)methyl]furan (15).** To a stirred solution of acetyl chloride (1.2 g, 15 mmol) in benzene (10

mL), protected by a drying tube, at room temperature was added a solution of pyridine (1.2 g, 15 mmol) in benzene (5 mL). After addition, a white precipitate formed immediately. The solution was stirred for 10 min and a solution of alcohol **22** (1.4 g, 7 mmol) in benzene (5 mL) was added. The mixture was stirred for an additional 2 h and then quenched with water and extracted with 2 × 50 mL of dichloromethane. The combined organic phases was washed with 100 mL of brine, dried over anhydrous $Na_2SO_4$, and concentrated to provide a colorless crude oil. Distillation of the crude oil under reduced pressure afforded essentially pure ester **15** (1.5 g, 88%): bp 81−83 °C (1.4 mmHg); IR (neat, NaCl) 2900−2990 (C−H), 1740 (C=O), 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.18 (d, 1H, $J$ = 1.9 Hz), 6.35 (d, 1H, $J$ = 1.9 Hz), 5.74 (q, 1H, $J$ = 6.5 Hz), 2.11−2.02 (AB q, 2H, $J$ = 14.8 Hz), 2.00 (s, 3H), 1.45 (d, 3H, $J$ = 6.5 Hz), 0.02 (s, 9H); GC/MS (70 eV) *m/e* (relative intensity) 240 (6), 181 (11), 117 (17), 108 (100), 73 (83), 43 (56); exact mass, *m/e* 180.09720, calcd for $C_{10}H_{16}OSi$ (M − $CH_3COOH$) 180.09705.

**Methyl 2-[1-(Trimethylsilyl)ethyl]furan-3-carboxylate (23).** To a solution of diisopropylamine (4.8 g, 47.5 mmol) in THF (40 mL) at −78 °C under nitrogen was added 19 mL of 2.5 M *n*-BuLi solution in hexanes (47.1 mmol). After 2 h at −78 °C, a solution of trimethylsilylated methyl furancarboxylate **19** in THF (5 mL) was added. The reaction mixture was further stirred at −78 °C for 8 h and a solution of MeI (10.0g, 71 mmol) in THF (5 mL) was then added. After being stirred for an additional 30 min, the reaction mixture was quenched by addition of water at low temperature. The quenched solution was warmed to room temperature and extracted twice with diethyl ether. The combined extracts was washed with brine, dried over anhydrous $MgSO_4$, concentrated under reduced pressure, and fractionally distilled under vacuum to provide a mixture of **23** and overmethylated product **24** in a 10:1 ratio. The mixture was further purified with silica gel flash chromatography with a mixture of benzene and hexanes (1:3) as the eluent. The purity of **23** was checked by GC/MS analysis: bp 72−72 °C (0.9 mmHg); IR (neat, NaCl) 2900−3000 (C−H), 1720 (s, C=O) 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.18 (s, 1H), 6.58 (s, 1H), 3.78 (s, 3H), 3.25 (q, $J$ = 7.3 Hz, 1H), 1.32 (d, $J$ = 7.3 Hz, 3H), −0.01 (s, 9H); mass spectrum, *m/e* (relative intensity) 226 ($M^+$, 17), 211 (15), 197 (5), 195 (5), 167 (3), 151 (8), 123 (9), 122 (100), 121 (30), 94 (30), 73 (60); exact mass, *m/e* 226.10266, calcd for $C_{11}H_{18}O_3Si$ 226.10253.

**3-(Hydroxymethyl)-2-[1-(trimethylsilyl)ethyl]furan (25).** To a suspension of $LiAlH_4$ (1 g, 26 mmol) in diethyl ether (50 mL) at 0 °C was added dropwise a solution of ester **23** (1.8 g, 8.0 mmoL). The reaction mixture was stirred overnight at ambient temperature and worked up as usual[18] to provide the crude oil which was subjected to vacuum distillation to provide essentially pure alcohol **25** (1.1 g, 70%): bp 74−75 °C (1 mmHg); IR (neat, NaCl) 3700−3100 (br, O−H), 2880−2960 (C−H), 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.22 (d, $J$ = 1.7 Hz, 1H), 6.33 (d, $J$ = 1.7 Hz, 1H), 4.47−4.38 (AB q, $J$ = 12.1 Hz, 2H), 2.25 (q, $J$ = 7.5 Hz, 1H), 1.54 (br s, 1H), 1.30 (d, $J$ = 7.5 Hz, 3H), −0.14 (s, 9H); mass spectrum, *m/e* (relative intensity) 198 ($M^+$, 5), 183 (4), 167 (5), 124 (5), 109 (13), 108 (100), 107 (18), 79 (22), 75 (50), 73 (89), 45 (33), 43 (20); exact mass, *m/e* 198.10759, calcd for $C_{10}H_{18}O_2Si$ 198.10761.

Deuterated **25** was prepared in the same manner except that $LiAlD_4$ was used as the reducing agent: IR (neat, NaCl) 3700−3000 (br, C−H) 2200, 2120 (C−D), 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.22 (d, $J$ = 1.9 Hz, 1H), 6.34 (d, $J$ = 1.9 Hz, 1H), 2.25 (q, $J$ = 7.5 Hz, 1H), 1.30 (d, $J$ = 7.5 Hz, 3H), 1.19 (s, 1H), −0.07 (s, 9H); mass spectrum, *m/e* (relative intensity) 200 ($M^+$, 4), 185 (3), 167 (6), 110 (100), 81 (11), 75 (33), 73 (73); exact mass, *m/e* 200.12034, calcd for $C_{10}H_{16}D_2O_2Si$ 200.12017.

**3-(Acetoxymethyl)-2-[1-(trimethylsilyl)ethyl]furan (16).** Ester **16** was prepared following the procedure described above used to prepare **15** from a solution of acetyl chloride (0.9 g, 11.5 mmol) in benzene (20 mL), a solution of pyridine (0.9 g, 11.1 mmol) in benzene (5 mL), and a solution of alcohol **25** (1.1 g, 5.6 mmol) in 5 mL of benzene to afford essentially pure **16** (1.1 g, 82%): bp 82−83 °C (0.75 mmHg); IR (neat, NaCl) 2800−2960 (C−H), 1750 (C=O), 1250, 1230 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.22 (d, $J$ = 1.9 Hz, 1H), 6.31 (d, $J$ = 1.9 Hz, 1H), 4.93−4.80 (AB q, $J$ = 12.3 Hz, 2H), 2.28 (q, $J$ = 7.4 Hz, 1H), 2.04 (s, 3H), 1.29 (d, $J$ = 7.4 Hz, 3H), −0.02 (s, 9H); mass spectrum, *m/e* (relative intensity) 240 ($M^+$, 9), 225 (1), 198 (8), 183 (14), 117 (23), 109 (10), 108 (100), 107 (20), 79 (20), 75 (32), 73 (81), 45 (25), 43 (56); exact mass, *m/e* 240.11813, calcd for $C_{12}H_{20}O_3Si$ 240.11818.

**2-[1-(Trimethylsilyl)ethyl]-3-furaldehyde (26).** To a vigorously stirred suspension of $CrO_3$ (0.9 g, 9 mmol) in $P_2O_5$ dried $CH_2Cl_2$ (50 mL) cooled in an ice bath was added 5 g of pyridine slowly. The reaction mixture turned a deep red. After 15 min a solution of alcohol **25** (300 mg, 1.5 mmol) in $CH_2Cl_2$ (10 mL) was added in one portion. A tarry black deposit precipitated immediately. The deep brownish solution was further stirred for 15 min, decanted, and worked up as reported by Ratcliffe[19] to give a crude oil. Distillation of the crude oil under vacuum provided essentially pure aldehyde **26**: IR ($CCl_4$, NaCl) 2800−2970 (C−H), 2740 (O=C−H), 1670 (s, C=O), 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 9.85 (s, 1H), 7.23 (d, $J$ = 2.0 Hz, 1H), 6.64 (d, $J$ = 2.0 Hz, 1H), 2.85 (q, $J$ = 7.3 Hz, 1H), 1.38 (d, $J$ = 7.3 Hz, 3H), 0.01 (s, 9H); mass spectrum, *m/e* (relative intensity) 196 ($m^+$, 88), 181 (9), 167 (11), 151 (13), 147 (21), 138 (5), 124 (12), 107 (11), 95 (5), 75 (45), 73 (100); exact mass, *m/e* 196.09168, calcd for $C_{10}H_{16}O_2Si$ 196.09196.

Deuterated **26** was prepared from deuterated **25** in the same manner. The product was purified on a silica gel column with a mixture of hexanes and ethyl acetate (8:1) as the eluent: IR (neat, NaCl) 2900−2980 (C−H), 2100 (C−D), 1670 (C=O), 1250 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.24 (d, $J$ = 2.0 Hz, 1H), 6.66 (d, $J$ = 2.0 Hz, 1H), 2.86 (q, $J$ = 7.3 Hz, 1H), 1.40 (d, $J$ = 7.3 Hz, 3H), 0.02 (s, 9H); mass spectrum, *m/e* (relative intensity) 197 ($M^+$, 98), 182 (10), 168 (8), 147 (22), 125 (11), 108 (10), 75 (51), 73 (100); exact mass, *m/e* 197.09859, calcd for $C_{10}H_{15}DO_2Si$ 197.09824.

**3-[(Hydroxyethyl)]-2-[1-(trimethylsilyl)ethyl]furan (27).** To a stirred solution of aldehyde **26** (130 mg, 0.67 mmol) in THF (20 mL) was added dropwise an ethereal solution of methyl lithium (0.6 mL, 0.82 mmol) at −78 °C. After addition of the reagent, the solution was further stirred for 30 min and was quenched with water at low temperature and worked up as mentioned previously in the preparation of **22** to give a diastereomeric mixture of alcohols **27** (135 mg, 95%): IR of the diastereomeric mixture ($CCl_4$, neat), 3700−3100 (br, O−H), 2890−2900 (C−H), 1260 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR of the diastereomeric mixture ($CDCl_3$) $\delta$ 7.21 (d, $J$ = 1.9 Hz, 1H), 6.36 (d, $J$ = 1.9 Hz, 1H), 4.82−4.75 (m, 1H), 2.28−2.23 (m, 1H), 1.43 (d, $J$ = 6.4 Hz, 3H), 1.32−1.25 (two d, $J$ = 7.7 Hz, 3H), 0.02 and −0.01 (two s, 9H); GC/MS, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (5 min). Component 1: GC retention time (relative intensity) 9.68 min (65%), mass spectrum, *m/e* (relative intensity) 212 ($M^+$, 2), 197 (3), 194 (3), 167 (5), 123 (10), 122 (52), 121 (5), 108 (3), 107 (41), 105 (3), 75 (35), 73 (100), 45 (29), 43 (33). Component 2: mass spectrum, *m/e* (relative intensity) 212 ($M^+$, 2), 197 (2), 194 (3), 167 (6), 123 (9), 122 (50), 121 (5), 108 (3), 107 (41), 105 (3), 75 (35), 73 (100), 45 (29), 43 (33); exact mass of diastereomeric mixture *m/e* 212.12297, calcd for $C_{11}H_{20}O_2Si$ 212.12326.

Deuterated **27** was prepared from deuterated **26** in the same manner: bp ~100 °C (5.2 mmHg); IR of the diastereomeric mixture (neat, NaCl) 3700−3100 (br, O−H), 2890−2990 (C−H), 2160 (C−D), 1260 (Si−$CH_3$) $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 7.21 (d, 1.9 Hz, 1H), 6.36 (d, $J$ = 1.9 Hz, 1H), 2.24 (m, 1H), 1.43 (s, 3H), 1.32−1.26 (two d, $J$ = 7.5 Hz, 3H), 0.12−0.02 (two s, 9H); GC/MS, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (5 min). Component 1: GC retention time (relative intensity) 9.30 min (62%), mass spectrum, *m/e* (relative intensity), 213 (2), 198 (3), 167 (4), 123 (100), 108 (54), 75 (31), 73 (82), 45 (31), 43 (42). Component 2: GC retention time (relative intensity) 9.86 min (33%), mass spectrum *m/e* (relative intensity) 213 (2), 198 (3), 167 (5), 123 (100), 108 (55), 75 (33), 73 (88), 45 (32), 43 (41); exact mass of diastereomeric mixture *m/e* 213.12925, calcd for $C_{11}H_{19}DO_2Si$ 213.12954.

**3-[1-(Acetoxyethyl)]-2-[1-(trimethylsilyl)ethyl]furan (17).** Acetoxy furan **17** was prepared in the same manner as described in the preparation of **15** from a solution of acetyl chloride (400 mg, 5.12 mmol) and pyridine (400 mg 5.06 mmol) in benzene (10 mL) and a solution of alcohol **27** (130 mg, 0.61 mmol) in benzene (5 mL) to provide a diastereomeric mixture of esters **17** (105 mg, 68%). IR of

the mixture (NaCl, neat) 2860–2980 (O–H), 1740 (C=O), 1250 (Si–$CH_3$) $cm^{-1}$; $^1H$ NMR of the major component (66%) ($CDCl_3$) $\delta$ 7.21 (d, $J$ = 1.9 Hz, 1H), 6.34 (d, $J$ = 1.9 Hz, 1H), 5.83 (q, $J$ = 6.6 Hz, 1H), 2.28 (q, $J$ = 7.5 Hz, 1H), 1.99 (s, 3H), 1.45 (d, $J$ = 6.5 Hz, 3H), 1.24 (d, $J$ = 7.5 Hz, 3H), −0.04 (s, 9H); GC/MS of the major component, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (10 min), retention time 11.21 min; mass spectrum, *m/e* (relative intensity) 254 ($M^+$, 5), 212 (6), 197 (8), 195 (9), 194 (6), 122 (100), 177 (24), 107 (59), 75 (30), 73 (95), 45 (26), 43 (43). $^1H$ NMR spectrum of the minor component (32%) ($CDCl_3$) $\delta$ 7.21 (d, $J$ = 1.9 Hz, 1H), 6.33 (d, $J$ = 1.9 Hz, 1H), 5.76 (q, $J$ = 6.6 Hz, 1H), 2.33 (q, $J$ = 7.4 Hz, 1H), 1.99 (s, 3H), 1.44 (d, $J$ = 6.6 Hz, 3H), 1.26 (d, $J$ = 7.4 Hz, 3H), −0.04 (s, 9H); GC/MS of the minor component, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (10 min), GC retention time 11.35 min; mass spectrum, *m/e* (relative intensity) 254 ($M^+$, 5) 212 (6), 197 (8), 195 (9), 194 (6), 122 (100), 117 (24), 107 (59), 75 (30), 73 (95), 45 (26), 43 (43). Exact mass of diastereomeric mixture, *m/e* 254.13394, calcd for $C_{13}H_{22}O_3Si$ 254.13383.

The diastereomeric deuterated derivatives of **17** were prepared from deuterated alcohol **27** in the same manner: IR (neat, NaCl) 2860–2970 (C–H), 1740 (C=O), 1250 (Si–$CH_3$). The $^1H$ NMR spectra and GC/MS of both diastereomers were obtained from their mixture: $^1H$ NMR of the major component (64%) ($CDCl_3$) $\delta$ 7.21 (d, $J$ = 1.9 Hz, 1H), 6.35 (d, $J$ = 1.9 Hz, 1H), 2.30 (q, $J$ = 7.4 Hz, 1H), 2.01 (s, 3H), 1.46 (s, 3H), 1.29 (d, $J$ = 7.4Hz, 3H), −0.16 (s, 9H); GC/MS of the major component, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (10 min), retention time 11.23 min; mass spectrum, *m/e* (relative intensity) 255 ($M^+$, 4), 213 (4), 198 (8), 196 (8), 123 (100), 108 (47), 75 (29), 73 (85), 45 (30), 43 (56). $^1H$ NMR spectrum of the minor component (36%), ($CDCl_3$) $\delta$ 7.21 (d, $J$ = 1.9 Hz, 1H), 6.34 (d, $J$ = 1.9 Hz, 1H), 2.38 (q, $J$ = 7.4 Hz, 1H), 2.01 (s, 3H), 1.46 (s, 3H), 1.26 (d, $J$ = 7.4 Hz, 3H), −0.16 (s, 9H); GC/MS of the minor component, temperature program, initial temperature (time), rate, final temperature (time), 120 °C (5 min), 10 °C/min, 200 °C (10 min), retention time 11.37 min; mass spectrum 255 ($M^+$, 6), 213 (5), 198 (9), 196 (9), 123 (90.5), 108 (52), 75 (27), 73 (100), 40 (30), 43 (56). Exact mass of diastereomeric mixture, *m/e* 255.13974, calcd for $C_{13}H_{21}DO_3Si$ 255.14011.

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**Supplementary Material Available:** The experimental procedures including spectral data for the preparation, observation, and dimerization of **12**, **13**, and **14**, for the Diels–Alder trapping reaction of **12**, and for the pyrolysis of some of the dimers of **12**, **13**, and **14** (12 pages). This material is contained in many 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.

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