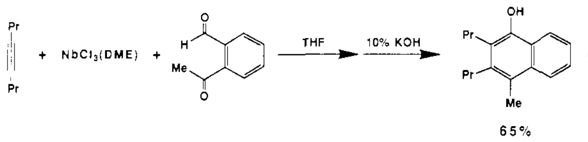
starting materials for the synthesis of more complicated polyaromatic compounds. The origin of the regioselection in these reactions appears to be due, in part, to steric effects (possibly dictated by the coordination environment of the metal) since 3,3-dimethyl-2-butyne gives rise to an analogous regioisomer (entry 5).[12]

Ketones (e.g., acetophenone) do not insert into the metal–carbon bonds of these niobium alkyne complexes. However, the stepwise mechanism in Scheme I suggested that the initial insertion of the formyl function in a 2-formylaryl ketone would lead to an intermediate that might facilitate coordination and insertion of the ketone into the second metal–carbon bond. As shown in eq 2,



(2)

the reaction between 4-octyne, $NbCl_3(DME)$, and 2-formylacetophenone in tetrahydrofuran leads to a good yield of 4-methyl-2,3-di-*n*-propyl-1-naphthol. Unfortunately, using (trimethylsilyl)phenylacetylene in a similar reaction only provided low yields of the desired naphthol along with a variety of other products. This can be rationalized by assuming that the formyl group selectively inserts into the least hindered metal–carbon bond,[13] forcing the keto group to react with the more hindered metal–carbon bond. The second insertion would therefore be slowed down allowing for secondary reactions to occur.

Sterically hindered alkynes such as bis(trimethylsilyl)acetylene fail to provide significant yields of the desired naphthols under the standard conditions, and terminal alkynes are consumed in cyclotrimerization reactions when reacted with $NbCl_3(DME)$.[14] We have also found that trialkylstannylalkynes do not appear to form stable alkyne complexes. Improved yields for all of the reactions discussed are usually obtained when 1.5 equiv of $NbCl_3(DME)$/alkyne are employed. A general experimental for the formation of 1-naphthols via the coupling of alkynes with 1,2-aryldialdehydes promoted by $NbCl_3(DME)$ is provided below. All reactions were carried out under a nitrogen atmosphere.

1-Naphthol Synthesis. A dry 250-mL flask was charged with $NbCl_3(DME)$[15] (2.0 g, 6.9 mmol) and tetrahydrofuran (ca. 100 mL). A tetrahydrofuran solution (ca. 5 mL) of alkyne (6.9 mmol) was then added (via syringe), and the stirred mixture was gently refluxed for 12 h. The reaction mixture was cooled to 0 °C, and a tetrahydrofuran solution (ca. 5 mL) of the dialdehyde (4.6 mmol) was added via syringe. The reaction was stirred for 1.5 h and then poured into a separatory funnel and treated with potassium hydroxide (10% w/v, 100 mL). The mixture was shaken until the aqueous layer was nearly colorless and then extracted with ether (3 × 100 mL). The combined ether layers were dried briefly over $MgSO_4$ and filtered. The ether was removed in vacuo yielding the crude product which was purified by flash chromatography[16] (silica gel, 230–400 mesh, hexane/ethyl acetate).

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Supplementary Material Available: NMR, IR, and mass spectral data and C, H, and N analysis information for all naphthols (5 pages). Ordering information is given on any current masthead page.

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[11] (a) Sibi, M. P.; Shankaran, K.; Alo, B. I.; Hahn, W. R.; Snieckus, V. *Tetrahedron Lett.* **1987**, *28*, 2933. (b) Effenberger, F.; Spiegler, W. *Chem. Ber.* **1985**, *118*, 3900. (c) Trost, B. M.; Yoshida, J. *Tetrahedron Lett.* **1983**, *24*, 4895. (d) Weber, W. P. *Silicon Reagents for Organic Synthesis*; Springer-Verlag: Berlin, 1983; Chapter 8. (e) Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761.

[12] Confirmed by obtaining 2-methyl-1-naphthol after removing the *tert*-butyl group with $AlCl_3$/toluene (Tashiro, M. *Synthesis* **1979**, 921).

[13] We have observed such regioselective insertions when adding 1 equiv of a monoaldehyde to these niobium–alkyne complexes.

[14] Similar results have been obtained with other niobium(III) and tantalum(III) complexes: Cotton, F. A.; Hall, W. T.; Cann, K. J.; Karol, F. J. *Macromolecules* **1981**, *14*, 233.

[15] $NbCl_3(DME)$ was prepared as described in ref 1. Alternatively, it may be purchased from the Aldrich Chemical Company.

[16] Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

Solvent Effects in Intramolecular Diels–Alder Reactions of 2-Furfuryl Methyl Fumarates: Evidence for a Polar Transition State[1]

Michael E. Jung* and Jacquelyn Gervay

Department of Chemistry and Biochemistry
University of California
Los Angeles, California 90024

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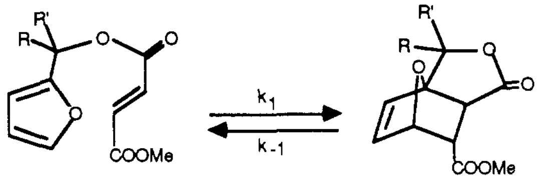
The Diels–Alder reaction proceeds via the concerted but nonsynchronous formation of the two new σ bonds.[2] For this reason, a large degree of charge separation is not developed in the transition state, and such cycloadditions are relatively insensitive to changes in solvent polarity.[2] In fact Berson and co-workers developed a parameter to measure solvent polarity, Ω, which was based on the difference in the endo/exo product ratio of the intermolecular Diels–Alder reaction of methyl acrylate with cyclopentadiene in various solvents.[3] However, the overall rates for the cycloadditions did not differ greatly with solvent polarity.[2,3] We now wish to report significant rate enhancement of the intramolecular Diels–Alder reaction of 2-furfuryl methyl fumarates **1** by the use of polar solvents.

Recently we described experiments which eliminated angle compression (the "Thorpe–Ingold effect") as the major reason for the *gem*-dialkyl effect in the cyclization of 2-furfuryl methyl fumarates.[4] Our results showed that in this reaction in which a three-atom tether leads to the formation of a five-membered ring, namely **2**, conformational changes with dialkyl substitution ("reactive rotamer effect") were more important in causing the large rate acceleration.[4] During these studies, we had occasion to examine the effect of solvent on the intramolecular cycloadditions of the furfuryl fumarates **1a–e**, which proceed at 25 °C to give cleanly the lactone cycloadducts **2a–e** as the sole reaction



1a	R = R' = H	**2a**
1b	R = H R' = Me	**2b**
1c	R , R' = $(CH_2)_2$	**2c**
1d	R , R' = $(CH_2)_3$	**2d**
1e	R = R' = Me	**2e**

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[1] Presented at the 196th National Meeting of the American Chemical Society, Los Angeles, CA, September 1988; paper ORGN 191.

[2] (a) For an excellent review of the mechanistic aspects on the Diels–Alder reaction, including solvent effects, see: Sauer, J.; Sustmann, R. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 779. (b) For earlier work, see: Wassermann, A. *Diels–Alder Reactions*; Elsevier: Amsterdam, 1965.

[3] Berson, J. A.; Hamlet, Z.; Mueller, W. A. *J. Am. Chem. Soc.* **1962**, *84*, 297.

[4] Jung, M. E.; Gervay, J. *Tetrahedron Lett.* **1988**, *29*, 2429.

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Table I. Solvent Effects on Cycloaddition of **1** To Give **2**

			k_1 (s^{-1})		
compd	R	R′	toluene-d_8	CD_3CN	DMSO-d_6
1a	H	H	$\sim 10^{-9\,a}$	2×10^{-7}	3.2×10^{-6}
1b	H	Me	3.0×10^{-8}	1.1×10^{-6}	6.6×10^{-6}
1c	$(CH_2)_2$		2.5×10^{-7}	1.3×10^{-6}	6.5×10^{-6}
1d	$(CH_2)_3$		3.4×10^{-6}	3.6×10^{-5}	1.3×10^{-4}
1e	Me	Me	1.3×10^{-4}	3.4×10^{-4}	$\sim 10^{-3\,b}$

[a] Estimated since K_{eq} too small to determine rate. [b] Estimated since K_{eq} too large to determine rate.

Table II. Relative Rate Constants for the Cycloaddition of **1** To Give **2**

compd	R	R′	$k_{\text{rel toluene}}$	$k_{\text{rel acetonitrile}}$	$k_{\text{rel DMSO}}$
1a	H	H	1	~200	~3200
1b	H	Me	1	36.7	220
1c	$(CH_2)_2$		1	5.2	26
1d	$(CH_2)_3$		1	10.6	38.2
1e	Me	Me	1	2.6	7.7

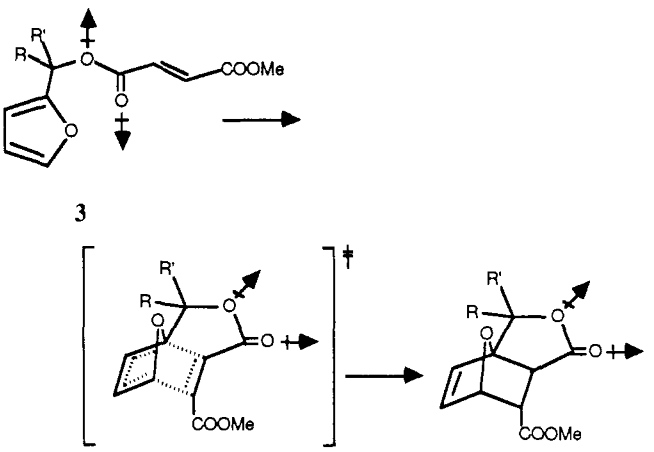
Table III. Rate of Cyclization of **1b** in Relation to Solvent Polarities

solvent	dielectric constant	E_T	k_1 (s^{-1})	k_{-1} (s^{-1})
DMSO-d_6	48.9	45.0	6.6×10^{-6}	7.7×10^{-7}
CD_3CN	37.9	46.0	1.1×10^{-6}	2.0×10^{-7}
acetone-d_6	20.5	42.2	5.5×10^{-7}	1.6×10^{-7}
CD_2Cl_2	8.9	41.1	3.0×10^{-7}	2.7×10^{-7}
$CDCl_3$	4.7	39.1	4.3×10^{-7}	$4.1 \times 10^{-7\,a}$
toluene-d_8	2.38	33.9	3.0×10^{-8}	2.6×10^{-7}

[a] Both the forward and reverse reactions may be larger than expected due to catalysis by trace amounts of HCl in the $CDCl_3$ (even after passage through alumina).

products.[5] As shown in Table I, the rate constants for the Diels–Alder reaction (k_1)[6] increase with increasing alkyl substitution, as we have described previously.[4,9] However, the rates of cyclization are significantly faster in acetonitrile than toluene and faster still in DMSO. A comparison of the relative rate constants is given in Table II. The solvent effect can be quite large in certain cases with k_{rel} being as large as 3200. The cycloaddition of the monomethyl compound **1b** was also examined in several additional solvents, with the results shown in Table III. The increase of the rate constants with increasing solvent polarity agrees better with the dielectric constant of the solvent than with the E_T parameter for solvent polarity.[10] As Table III indicates, the rate of the cycloreversion reaction, k_{-1}, is relatively insensitive to changes in polarity.

This solvent effect and its absence in the corresponding intermolecular reactions[11] is easily explained by looking at the reaction course and the transition state. The starting material should exist primarily in the conformation **3** with the s-trans conformation about the ester bond, in order to minimize dipole effects.[12] In order to cyclize, rotation about this bond to give the s-cis conformer must occur to arrive at the transition state **4**, which, due to the s-cis ester conformation, now has a net dipole moment. It is therefore more polar than the starting material and thus should be stabilized more by polar than non-polar solvents. Since the transition state for the corresponding intermolecular reactions does not require an s-cis ester conformation, it would more resemble the starting material in polarity and thus should experience no major solvent effects. The absence of significant change in k_{-1} as the polarity of the solvent is varied (Table III) lends support for this mechanistic hypothesis since the cycloreversion of **2** would not be expected to involve major changes in polarity in reaching the transition state **4**, since both have similar cisoid ester conformations.

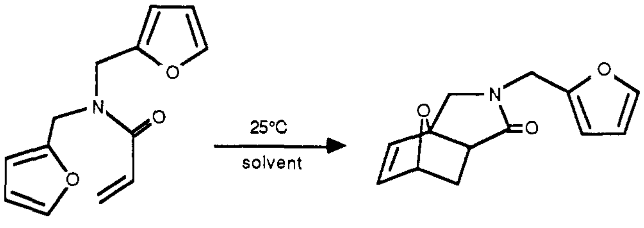


3

4

2

If this argument of a polar transition state due to the s-cis ester conformation is correct, then one would expect a similar intramolecular cycloaddition which lacks this special polar transition state to be relatively insensitive to solvent polarity. For example, cyclization of the corresponding tertiary amide **5** to give the lactam **6** should have a relatively nonpolar transition state (due to the lack of strong dipole effects in tertiary amides) and should not experience similar solvent effects. This is indeed the case. Cyclization of the amide **5** in various solvents—toluene-d_8, CD_2Cl_2, $CDCl_3$, acetone-d_6, CD_3CN, DMSO-d_6—at 25 °C produced the expected lactam **6** at essentially the same rate, irrespective of solvent.



5 **6**

In summary we have discovered an interesting and useful solvent effect on intramolecular cycloadditions of furfuryl fumarates. It is interesting to point out that by combination of solvent and substitution effects, one can achieve an overall rate enhancement of about 10^6 (rate constants of $\sim 10^{-9}$ for **1a** in toluene and $\sim 10^{-3}$ for **1e** in DMSO).

Acknowledgment. We thank the National Institutes of Health (GM-31349) for their generous financial support and Frank Anet, Ken Houk, Mal Nicol, and Larry Levine for helpful discussions and advice.

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(5) The product **2b** of the cycloaddition of the monomethyl compound **1b** is a 1.2:1 mixture of diastereomers at the methyl-bearing secondary center.

(6) All rate constants were calculated by using the kinetic expression for a reversible first-order reaction,[7] i.e., $\ln \{[A] - [A]_\infty/[A]_0 - [A]_\infty\} = -(k_1 + k_{-1})t$ where $[A]$ is the relative concentration of the acyclic precursor determined by ^{1}H NMR integration. The value of $[A]_\infty$ was determined by fitting this equation to the FORTRAN CURFIT program.[8] The approximated values of $[A]_\infty$ were in good agreement with experimentally determined values.

(7) Espenson, J. H. *Chemical Kinetics and Reaction Mechanisms*; McGraw-Hill: New York, 1981; pp 42–45.

(8) Bevington, P. R. *Data Reduction and Error Analysis for the Physical Sciences*; McGraw-Hill: New York, 1969; pp 237–242.

(9) In our earlier paper[5] we stated that the retro-Diels–Alder reaction was not occurring at 25 °C in these solvents. We now have shown that the adducts are undergoing cycloreversion under these conditions and have calculated the rate constants for the retro reaction (k_{-1}). Thus it is more correct to describe these reactions in terms of rate constants for the forward and backward reactions rather than half-lives.

(10) Reichardt, C. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 29.

(11) Generally solvent effects on most simple cycloadditions are relatively small, rarely larger than a factor of 10. For a good discussion, see the section on solvent effects in ref 2a.

(12) (a) Dale, J. *Stereochemistry and Conformational Analysis*; Verlag Chemie: New York, 1978; pp 83–85. (b) Testa, B. *Principles of Organic Stereochemistry*; Marcel Dekker: New York, 1979; p 105. (c) Eliel, E. L.; Allinger, N. L.; Angyal, S. J.; Morrison, G. A. *Conformational Analysis*; Interscience: New York, 1965; p 21.