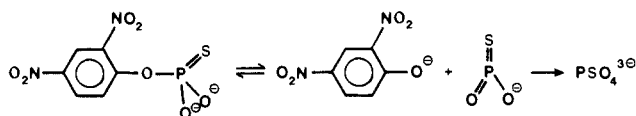


Scheme I



solution. We report here the effects of pressure on the rate of hydrolysis of 2,4-dinitrophenyl thiophosphate dianion that provide strong evidence for a dissociative mechanism involving monomeric thiometaphosphate as an intermediate, in contrast to the corresponding reaction of the phosphate ester.⁴

Although monomeric metaphosphate anion has been widely accepted as an intermediate with finite lifetime in the hydrolysis of phosphate monoesters,⁵ more recent studies are not consistent with a fully dissociative mechanism. For example, the alcoholysis of 2,4-dinitrophenyl [¹⁶O,¹⁷O,¹⁸O]phosphate dianion in aqueous methanol occurs with inversion of configuration which is inconsistent with a symmetrically solvated intermediate.⁶ This observation alone does not however rule out the fleeting existence of a metaphosphate intermediate that does not survive long enough to allow the leaving group to diffuse away or for the species to tumble before being captured. le Noble et al. reported that the volume of activation for the hydrolysis of 2,4-dinitrophenyl phosphate dianion is $-4.8 \text{ cm}^3 \text{ mol}^{-1}$ (i.e., the reaction is accelerated by pressure).⁴ It is argued that the activation volume for a reaction may distinguish dissociative from associative reaction mechanisms,⁷ although the interpretation of small negative volumes of activation in mechanistic terms has been questioned.⁸ In the dissociative pathway bond breakage is complete before bond making thus involving an expansion in the transition state, whereas in the associative mechanism bond making and bond breaking proceed together with bond formation usually dominating, thus involving a shrinkage at the transition state. Typically associative reactions have volumes of activation in the range -5 to $-10 \text{ cm}^3 \text{ mol}^{-1}$, whereas dissociative reactions show activation volumes exceeding $+10 \text{ cm}^3 \text{ mol}^{-1}$.⁷ Our stereochemical studies on the thiophosphoryl-transfer reactions of 4-nitrophenyl thiophosphate have suggested that monomeric thiometaphosphate may be sufficiently kinetically and thermodynamically stable to participate as an intermediate even in reactions in aqueous solution.³ Following the work of le Noble^{4,7} we would predict that thiophosphoryl-transfer reactions in aqueous solution will show a volume of activation with the opposite sign to that recently reported for the corresponding phosphoryl-transfer reaction.

We have investigated the rate of hydrolysis of 2,4-dinitrophenyl thiophosphate dianion (Scheme I) as a function of pressure.⁹ The

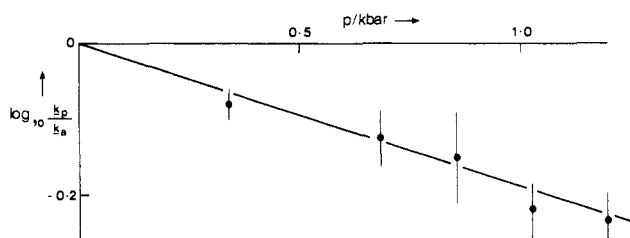


Figure 1. Pseudo-first-order rate constants as a function of pressure for the hydrolysis of 2,4-dinitrophenyl thiophosphate dianion in aqueous solution (pH 12.7, 25 °C).

rate constant for release of 2,4-dinitrophenoxide from the thiophosphate dianion was observed to be reduced by pressure with a volume of activation of $+11 \text{ cm}^3 \text{ mol}^{-1}$ (Figure 1). Although the error bars on the plot are significant, the sign of the volume of activation is clearly positive and differs from that reported by le Noble for the corresponding phosphate ester.⁴ Since in the latter case an associative reaction mechanism has been deduced on the basis of a number of studies,^{2,4} it is likely that the change in sign for the reaction of the corresponding thiophosphate signals a change in mechanism. A dissociative reaction would give rise to an expansion in the transition state which would be expected to be further amplified by the effects of the greater charge delocalization at the transition state (electrostriction effects). The difference in activation volumes for the reactions of 2,4-dinitrophenyl phosphate and the corresponding thiophosphate is large ($16 \text{ cm}^3 \text{ mol}^{-1}$) and lends some support to the claim that this parameter is a good mechanistic indicator.^{3,4,8} These observations are consistent with the conclusions drawn from the stereochemical studies as discussed above and provide further direct evidence for the participation of monomeric thiometaphosphate ion as an intermediate in the hydrolysis of aryl thiophosphate dianion in aqueous solution. Confirmation that thiophosphoryl- and phosphoryl-transfer reactions follow different and distinct mechanistic pathways in aqueous solution may be pertinent to the use of the former to probe enzyme-catalyzed reactions.^{1b,c}

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Remarkably Similar Solution and Solid-State Structures for Two Divergently Reactive Lithium Enolates Derived from Vinylogous Urethanes

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The synthetic utility of the lithium enolate **1** generated from the vinylogous urethane **2** in anti-selective aldol reactions has been demonstrated.¹ An attempt to develop enantioselection for this anti-aldol process led us to generate the lithium enolate **3** from the vinylogous urethane **4**—the anticipation being that these structurally similar enolate species would augment each other in

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(9) 2,4-Dinitrophenyl thiophosphate dianion was generated in situ by addition of 2,4-dinitrophenyl thiophosphoryl dichloride (mp 53–56 °C; δ_p + 54.2 (dioxan); M^+ 316, 318, 320 (9:6:1 as expected for two chlorine)) to aqueous sodium hydroxide (0.05 M) to give a final concentration of 0.08 mM in thiophosphate. Hydrolysis of the dichloride was complete within the first 15 minutes as determined by ³¹P NMR spectroscopy; the resonance at +54.2 ppm for the dichloride was rapidly replaced by a singlet at +50.6 ppm for 2,4-dinitrophenyl thiophosphate dianion. The hydrolysis of 2,4-dinitrophenyl thiophosphate was followed by the release of 2,4-dinitrophenoxide monitored at 400 nm, and good first-order kinetics were observed ($k = 6.9 \times 10^{-4} \text{ s}^{-1}$, (25 °C); $t_{1/2}$ 16.7 min). The products were confirmed as 2,4-dinitrophenoxide and inorganic thiophosphate (+41.1 ppm) by UV and ³¹P NMR spectroscopy, respectively. Rate constants were determined graphically; any residue of the dichloride would have shown up as an initial curvature in the plots, which was not observed. The error bars shown in Figure 1 represent our estimates for the 95% confidence limits, based both our confidence in the best straight lines for the respective high pressure runs and on the reproducibility of the simultaneous atmospheric pressure run in each case. For further details of the method of determining k_p , see: Hallinen, N.; McArdle, P.; Burgess, J.; Guardado, P. *J. Organomet. Chem.* **1987**, *333*, 77.

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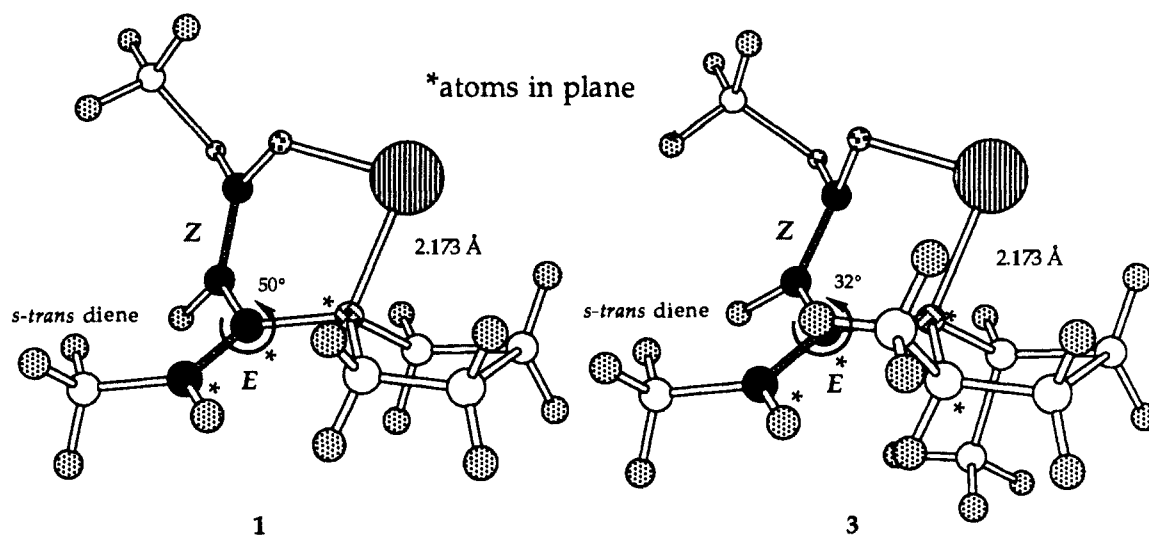
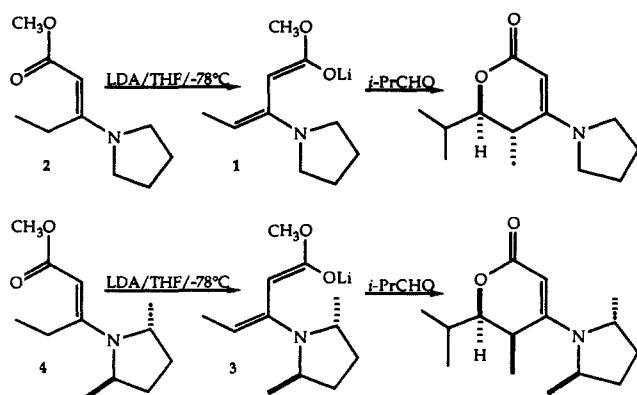
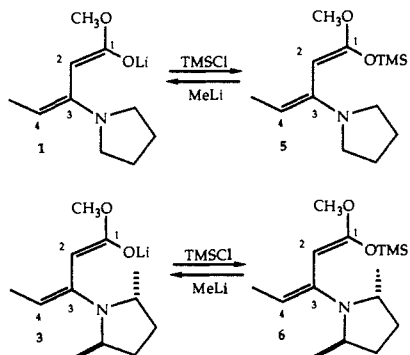


Figure 1. Chem. 3D ball and stick drawings based on the atomic coordinates obtained from enolates **1** and **3** and represented as monomeric species for clarity.

a variety of synthetic problems. **3** underwent smooth aldol additions but, to our surprise, did so only in the syn-stereo-manifold.² Provoked by this unusual result, we examined both the solution and solid-state structures of **1** and **3** with ¹³C NMR and single crystal X-ray.



The ¹³C NMR study was carried out by generating the enolates **1** and **3** in THF solution followed by reaction of these species with trimethylsilyl chloride ($-78\text{ }^{\circ}\text{C}$) to form the keteneacetal enamines **5** and **6**, respectively. Careful low-temperature distillation (20



$^{\circ}\text{C}$, 10^{-6} Torr) gave pure **5** and **6** and their ¹³C NMR spectra were recorded in THF-*d*₈. In addition, THF-*d*₈ solutions of **5** and **6** were treated with methyl lithium ($-40\text{ }^{\circ}\text{C}$) to generate the enolates **1** and **3**, and their ¹³C NMR spectra were also recorded.³ The

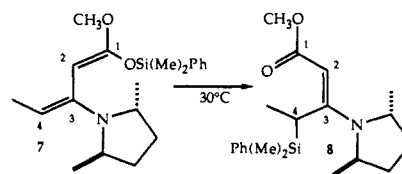
Table I

compd no.	¹³ C NMR chemical shifts (ppm)			
	C-1	C-2	C-3	C-4
5	157.6	75.0	141.6	92.5
1	166.1	63.2	148.4	91.5
6	157.1	74.7	137.4	98.0
3	164.9	64.2	142.9	95.2

chemical shift values obtained in this manner are recorded in Table I.

The C-1–C-2 and C-3–C-4 olefin geometries of **1** and **5** have been described as indicated.³ Further it had been concluded that a significant twist about the C-2–C-3 bond must be present in both **1** and **5**, since little upfield shift occurred at C-4 on going from neutral keteneacetal enamine **5** to the enolate **1**. Initially, we assumed that the same olefin geometries would hold for the enolate **3** and its keteneacetal enamine **6**.

Indeed, it was easily demonstrated that **3** and **6** possess the indicated C-1–C-2 olefin geometry by the observation that a facile first-order silyl migration occurs from oxygen to C-4, a rearrangement most easily seen in the transformation **7** to **8**. The 98.0 ppm chemical shift value for C-4 of **6** is within the normal range reported for (*E*)-enamines.⁴



An interesting aspect of this study was the observation that a greater degree of upfield shift at C-4 was found on going from the neutral keteneacetal enamine **6** to the enolate **3**. This implies less twist about the C-2–C-3 bond in these species than their simple pyrrolidine substituted analogues **5** and **1**. The subtle, but real ¹³C NMR differences between these two enolates coupled with our desire to determine their diene geometries (*s-trans* or *s-cis*), and to examine the possibility of intramolecular lithium–nitrogen bonding in them, convinced us of the need to carry out single-crystal X-ray studies.

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The lithium enolate **1** crystallized as a tetramer from benzene, while the enolate **3** crystallized as a dimer from THF.⁵ In both **1** and **3** the lithium atoms are tetracoordinate and are coordinated to a single pyrrolidine nitrogen atom. Besides the obvious difference in aggregation state, another significant difference between **1** and **3** is the incorporation of THF into the latter aggregate. It is noteworthy that the presence of the coordinating solvent THF leads to a dimer rather than a tetramer.

Comparison of the crystallographically independent lithium enolate residues in **1** and **3** reveals no significant conformational differences among these species.⁶ Thus, a computer generated plot overlaying a single enolate residue from both **1** and **3** is depicted schematically in the Supplementary Material with atom labels inserted. Some average structural parameters for the enolates depicted are given in Table II, also in the Supplementary Material.

For the four crystallographically independent enolate residues in the tetramer **1**, the rms torsion angle corresponding to C(1)-C(2)-C(3)-C(4) is 129.0 (0.6)°; the analogous torsion angle in the dimer **3** is -144.1 (0.5)°. Hence, there is considerable deviation from an anti-periplanar s-trans conformation about the C(2)-C(3) bond in both enolates. In both **1** and **3**, the pyrrolidine nitrogens are pyramidal and are an average of 0.40 Å out of the plane formed by the three covalently attached carbon atoms. This geometry is to be expected since each of the nitrogen atoms are coordinated to a single Li atom.

As typically observed for simple enamines,⁷ one of the C-N bonds of each of the pyrrolidine rings is nearly eclipsed with the C-C π -bond. Thus the rms torsion angle for the four crystallographically independent enolates, corresponding to C(4)-C(3)-N(1)-C(7) in structure **9**, is 5.9 (0.9)° for the tetramer **1** and -2.4 (0.4)° for the dimer **3**. Hence there are no strikingly different structural features between **1** and **3** other than the increased steric hindrance in **3** caused by the 2,5-dimethyl substitution on the pyrrolidine rings.

Both enolates, **1** and **3**, have been found to react in a kinetically controlled manner at C-4 to give anti and syn aldol products, respectively, and to so behave with a wide variety of aldehydes. In view of their close structural similarity, the origin of the stereochemical divergency found for these enolates must arise from different reaction transition states. We are currently attempting to delineate these differences.

Acknowledgment. Financial support from the NIH and the Merck Corp. are gratefully acknowledged. The work at Brown University was partially supported by the NIH through Grant GM-35982.

Supplementary Material Available: Tables of atomic coordinates, bond lengths and angles, and anisotropic thermal parameters along with a computer-generated plot of the dimethylpyrrolidine vinylous urethane enolate and tables of atomic coordinates, bond lengths and angles, anisotropic thermal parameters, and torsion

angles along with a red-green plot of the overlapping major and minor orientations for the pyrrolidine vinylous urethane enolate (19 pages). Ordering information is given on any current masthead page.

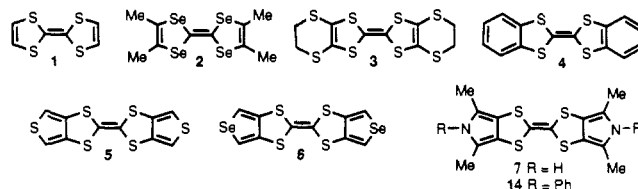
Synthesis of Bis(2,5-dimethylpyrrolo[3,4-d])tetrathiafulvalene, an Annelated TTF Derivative with Good Electron Donor Properties

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Highly conducting lower dimensional organic metals based on the potent one-electron donor TTF (tetrathiafulvalene, **1**) have been studied intensely in the last 15 years.¹ The salts of TMTSF (tetramethyltetraselenafulvalene, **2**) superconduct below about 1 K,² while one salt of ET (bis(ethylenedithiolen)TTF, **3**), namely ET₂Cu(SCN)₂, superconducts below $T_c = 10.4$ K.³ Several annelated derivatives of TTF (DBTTF = **4**, DTTTF = **5**, DSTTF = **6**) have also been studied in the search for other good one-electron donors,⁴⁻⁷ but they had considerably higher solution oxidation potentials than TTF.



For binary complexes of a one-electron donor **D** and a one-electron acceptor **A**, a good rule of thumb is^{8,9} that if the difference $I_D - A_A$ (I_D = ionization potential of **D**, A_A = electron affinity of **A**) is too large, then mixed-stack Mulliken π - π charge-transfer complexes with low degree of charge transfer (π - π mixed stacking $D^0A^0D^0A^0$: electrical insulators) are obtained; if $I_D - A_A$ is small, then ionic salts with high charge transfer result (π - π mixed stacking $D^+A^-D^+A^-$: semiconductors); for intermediate $I_D - A_A$ the desired segregated stacking of TTF TCNQ can be achieved ($D^+D^0D^+/A^-A^0A^-$). For ion-radical salts such as TMTSF₂X or ET₂X (X = inorganic anion) no such rule of thumb has emerged.

While annelated TTF derivatives prepared so far (**3-6**) tend to be weaker electron donors than TTF, we report here the synthesis of BP-TTF (bis(2,5-dimethylpyrrolo[3,4-d])tetrathiafulvalene, **7**) a pyrrolo-annelated TTF which is a stronger donor than TTF. As shown in Scheme 1, the known^{10,11} 3,4-dithiocyanatopyrrole (**9**) was prepared in 82% yield (mp 130-2 °C; lit. 134-6

(5) The pyrrolidine vinylous urethane enolate **1** crystallized in the centrosymmetric, triclinic space group $P\bar{1}$. The unit cell parameters were determined to be $a = 9.902$ (4) Å, $b = 11.463$ (7) Å, $c = 19.853$ (11) Å, $\alpha = 82.49$ (5)°, $\beta = 84.37$ (4)°, and $\gamma = 75.70$ (4)°. This unit cell contained two enolate tetramers of molecular formula $(C_{10}H_{18}NO_2Li)_4$ in a volume of 2159.8 (1.2) Å³ which produces a calculated density of 1.12 g/cm³. A total of 5868 reflections were recorded in the range $3.5^\circ < 2\theta < 45^\circ$. After accounting for some disorder in the crystal the final agreement factors are $R = 0.084$ and $R_w = 0.095$. The dimethylpyrrolidine vinylous urethane enolate **3** crystallized in the centrosymmetric, monoclinic space group $P2_1/n$. The unit cell parameters were determined to be $a = 11.712$ (3) Å, $b = 10.192$ (2) Å, $c = 14.380$ (6) Å, and $\beta = 98.92$ (4)°. This unit cell contained two THF-solvated enolate dimers of molecular formula $[(C_{10}H_{18}NO_2Li) \cdot (C_4H_8O)]_2$ in a volume of 1695.8 (1.2) Å³ which produces a calculated density of 1.12 g/cm³. A total of 1949 reflections were recorded in the range $3.5^\circ < 2\theta < 45^\circ$. The final agreement factors are $R = 0.058$ and $R_w = 0.060$.

(6) A computer-generated plot overlaying a single enolate residue from both **1** and **3** is depicted schematically in the Supplementary Material with atom labels inserted. Some average structural parameters for the enolates depicted are given in Table II of the Supplementary Material.

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