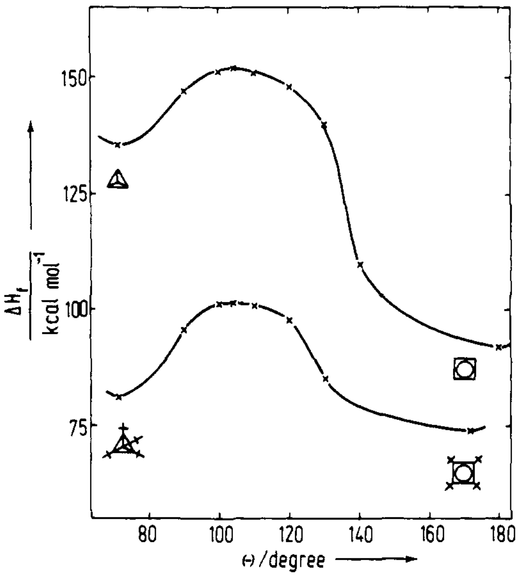


Figure 2. Reaction profiles for the rearrangements **1** → **2** and **3** → **4**. The MNDO-CI$_0$ heat of formation is plotted as function of the angle θ (see text and Figure 1).

biradicaloid with C_{2v} symmetry (see Figure 1); its structure has been completely optimized by minimizing the gradient norm, and its force constant matrix has a single negative eigenvalue.[14] Figure 2 shows the MNDO-CI$_0$ reaction profile for the rearrangement **3** → **4** assuming C_{2v} symmetry. It should be pointed out that no local C_{2v} minimum corresponding to a bicyclobutanediyl biradical is found, contrary to a previous study.[10,15]

For the tetra-*tert*-butyl substituted systems, it is computationally too expensive to carry out complete MNDO-CI$_0$ optimizations and compute a rigorous activation energy for the reaction **1** → **2**. To obtain an estimate of the activation energy, a reaction profile for the rearrangement **1** → **2** was constructed by optimizing the geometries at the MNDO SCF level[16] and then carrying out a single MNDO-CI$_0$ calculation at these geometries. From the resulting curve (see Figure 2), the activation energy is estimated to be 20 kcal/mol,[17] which seems to be compatible with the observed[1] thermal stability of **1**.

Our calculations thus indicate that the activation energy for the thermal decay of the tetrahedrane to the cyclobutadiene system is increased only by ~5 kcal/mol when replacing the four hydrogen atoms by four *tert*-butyl groups. This is probably related to the fact that the transition state comes early on the reaction coordinate (see Figure 2); the *tert*-butyl groups still occupy favorable positions so that the steric effect on the activation energy is fairly small. On the other hand, given the observed thermal stability of tetra-*tert*-butyltetrahedrane, our results strongly suggest that unsubstituted tetrahedrane should be long lived enough to be easily detected if it can be prepared by some mechanism.

Acknowledgment. This work was supported by the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie. The calculations were carried out at the TR 440 computer of the Rechenzentrum der Universität Marburg and the IBM 370/168 computer of the Rechenzentrum der Technischen Hochschule Darmstadt.

References and Notes

(1) Maier, G.; Pfriem, S.; Schäfer, U.; Matusch, R. *Angew. Chem.* **1978**, *90*, 552.
(2) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4899.
(3) Herzberg, G. "Molecular Spectra and Molecular Structure II. Infrared and Raman Spectra of Polyatomic Molecules"; Van Nostrand: Princeton, N.J., 1945; p 9.
(4) Iroff, L. D.; Mislow, K. *J. Am. Chem. Soc.* **1978**, *100*, 2121.
(5) Hounshell, W. D.; Mislow, K. *Tetrahedron Lett.* **1979**, 1205.
(6) Delbaere, L. T. J.; James, M. N. G.; Nakamura, N.; Masamune, S. *J. Am. Chem. Soc.* **1975**, *97*, 1973.
(7) Using empirical force-field calculations, a stabilization of ~43 kcal/mol due to steric effects of *tert*-butyl substitution has been found: K. Mislow, private communication.
(8) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4907.
(9) Dewar, M. J. S. *Pure Appl. Chem.* **1975**, *44*, 767, and private communication.
(10) Böhm, M. C.; Gleiter, R. *Tetrahedron Lett.* **1978**, 1179.
(11) Schulman, J. M.; Venanzi, T. J. *J. Am. Chem. Soc.* **1974**, *96*, 4739.
(12) Hehre, W. J.; Pople, J. A. *J. Am. Chem. Soc.* **1975**, *97*, 6941.
(13) Kollmar, H., private communication.
(14) McIver, J. W., Jr., Komornicki, A. *J. Am. Chem. Soc.* **1972**, *94*, 2625.
(15) The existence of such minima in ref 10 might be due to incomplete geometry optimization.
(16) To reduce the computational effort in the reaction path calculation, all methyl groups were assumed to have equal bond lengths, equal bond angles, and threefold symmetry.
(17) According to test calculations on simple systems, this value is believed to deviate from the rigorous MNDO-CI$_0$ value by <3 kcal/mol.

Armin Schweig,* Walter Thiel
Fachbereich Physikalische Chemie der Universität
Auf den Lahnbergen, D-3550 Marburg, West Germany

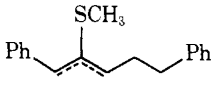
Received January 22, 1979

Enol Thioethers in Synthesis. Regiocontrolled Arylation via Organopalladium Chemistry

Sir:

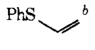
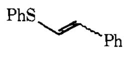
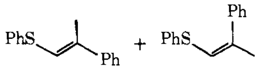
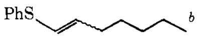
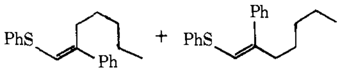
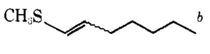
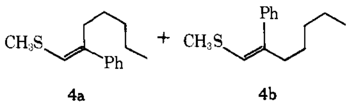
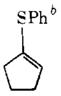
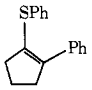
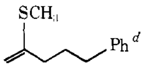
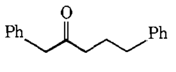
The unusual versatility of sulfur has led to many important developments in organic synthesis. Surprisingly, this versatility remains unrealized for enol thioethers which normally are considered less useful enol derivatives compared with enol ethers, enol esters, enamines, etc. We report here an unusual ambidence in the regioselectivity of arylation of enol thioethers catalyzed by palladium that can provide new avenues for applications of these intermediates for structural elaboration.

The arylation of olefins catalyzed by palladium has been outstandingly developed by Heck and his co-workers who state "double bonds substituted with electron donating substituents tend to produce significant amounts of 2-aryl adducts in addition to the major 1-aryl isomers".[2,3] We find that intermolecular arylations of enol thioethers lead regioselectively to the 2-aryl adducts, whereas intramolecular arylations lead regioselectively to the 1-aryl system. Table I summarizes the intermolecular reactions. The arylations were performed in two ways. In the first, 1 equiv of phenylmercuric chloride was reacted with ~6 mol % of Li$_2$PdCl$_4$ and 1 equiv of cupric chloride in THF at room temperature in the presence of 1 equiv of vinyl sulfide. After 24 h, the reaction was filtered, evaporated, and chromatographed. Enol thioethers from aldehydes (entries 1-4) and ketones (entries 5 and 6) both react. In the last case, the sensitivity of the enol thioether **7** to hydrolysis led to its conversion into the ketone **6** during silica gel chromatography. In each case, only one regioisomer which resulted from β-phenylation was detected. Entry 6 illustrates that the thermodynamically less stable enol thioether reacts without prior equilibration.[6] Thus, the arylation is fully regiocontrolled. When the enol thioethers are a mixture of stereoisomers, the products are also a mixture of stereoisomers although in different ratios. NMR allowed determination of the isomeric ratios by examination of the vinyl proton geminal to the sulfur substituent (**1**, δ 6.84 (E), 6.52 (Z); **2**, δ 6.6 (E), 6.3 (Z); **3**, δ 6.48 (E), 6.2 (Z); **4**, δ 6.04 (E), 5.52 (Z)). In the second ap-



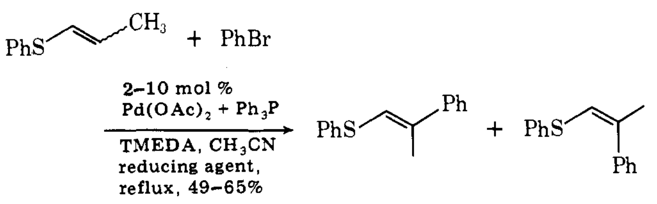
7

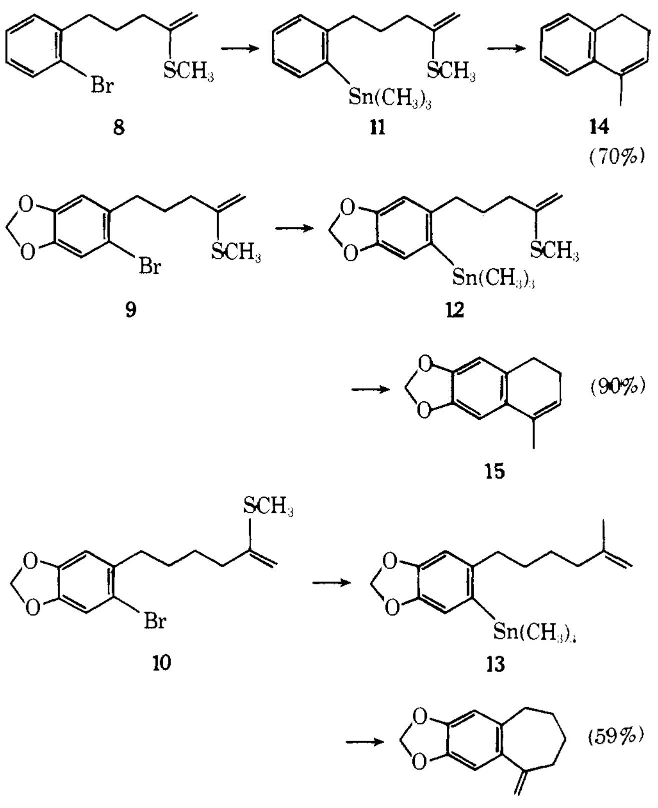
Table I. Phenylation of Enol Thioethers Catalyzed by Palladium

entry	vinyl sulfide	*E*/*Z* ratio	product[a]	*E*/*Z* ratio	% isold yield
1			 1	7:3	68
2		1:1.43	 2a 2b	3:1	65[e]
3		1:1.06	 3a 3b	2.4:1	33
4		1.28:1	 4a 4b	3:1	38
5			 5		40
6			 6		43

[a] New compounds have been characterized by spectral means and elemental composition. [b] Prepared by oxidation of the thioketal followed by pyrolysis.[4] [c] Prepared by base-catalyzed isomerization of allyl phenyl sulfide.[5] [d] Prepared by the oxidative decarboxylation of 2-methyl-2-methylthio-5-phenylpentanoic acid with NCS.[6] [e] This run employed 2 equiv of $CuCl_2$. Use of 1 equiv gave a 48% yield.

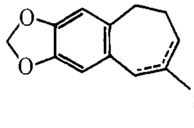
proach, bromobenzene was reacted with a palladium(0) catalyst (2–10 mol %) generated in situ by reduction of palladium acetate with Dibal, $(C_2H_5)_2AlOC_2H_5$, or excess TMEDA, with the latter two being preferred, to form the phenylpalladium species. The sluggishness of the reaction led to reflux times of 3–4 days. The yields are notably higher than the corresponding cases of enol ethers.[3]



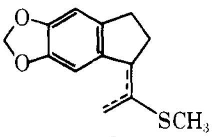


The high regioselectivity for β-phenylation is totally reversed in the intramolecular reaction. Attempts to utilize the aryl bromides **8**–**10** for cyclization via palladium(0) catalysis failed. Conversion of **9** into its mercury derivative proceeded in poor yield and gave no observed cyclization products upon treatment with a catalytic amount of Li_2PdCl_4 in the presence of cupric chloride. On the other hand, the aryltin compounds[7] **11**–**13** are excellent precursors. Metal–halogen exchange of **8**–**10** using t-C_4H_9Li in THF followed by addition of trimethyltin chloride led to the desired tin compounds **11**–**13** in 50–85% yields. Treatment of **12** with a stoichiometric amount of palladium chloride in acetonitrile produced the cyclized product **15** (whose identity is confirmed by comparison with an authentic sample[8]) in 74% yield and not the products **17** or **18** (which would result from prior isomerization of the enol thioether before cyclization) from arylation at the β carbon of the enol thioether. Attempts to effect the reaction with a catalytic amount of palladium chloride required the addition of a thiophilic agent such as mercuric chloride. Indeed, treatment of **12** with 10 mol % palladium chloride and 1 equiv of mercuric chloride in dry acetonitrile for 12 h at room temperature gave **15** in 90% yield. The absence or presence of strong electron-donating groups on the aromatic ring does not affect the cyclization (**11** → **14**, **12** → **15**). Furthermore, even seven-membered rings can form in good yields (**13** → **16**).

A most striking feature of these observations is the orthogonality of the regiochemical results for the inter- and intramolecular processes. Contrasting the high selectivity and good yields to low selectivity and poorer yields in the arylation of enol

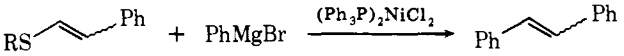


17

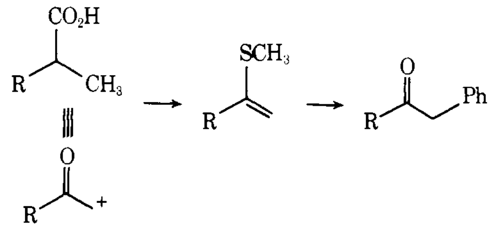


18

acetates and enol ethers also give the reaction special merit. The intermolecular palladium-catalyzed reaction of enol thioethers contrasts with the recent report of the nickel-catalyzed reaction of these compounds where the opposite regiochemistry was observed. Thus, the two methods complement one another.



The utility of these observations is demonstrated by the very mild cyclization conditions and the net arylation α to a carbonyl group.[9,10] The widespread availability of enol thioethers by addition of sulfur-stabilized anions to carbonyl groups,[11] addition of RSX to olefins followed by elimination of HX,[12] reaction of vinyllithium reagents with disulfides,[13] isomerization of allyl sulfides,[5] metalation and alkylation of phenylvinyl sulfide,[14] rearrangement of 1-phenylthio-1-vinylcyclopropanes,[15] oxidative decarboxylation of α-thio acids,[6] etc., allows a whole host of substrates to serve as enolonium equivalents. This is shown explicitly for one case below (see entry 6, Table I). The unique role of sulfur in organometallic reactions appears to be an exciting one for further exploitation.



Acknowledgment. We thank the National Science Foundation for their generous support of our programs.

References and Notes

(1) For some recent papers see: Ziegler, C. B., Jr.; Heck, R. F. *J. Org. Chem.* **1978,** *43*, 2941. Cortese, N. A.; Ziegler, C. B., Jr.; Hrnjez, B. J.; Heck, R. F. *Ibid.* **1978,** *43*, 2952. Patel, B. A.; Ziegler, C. B.; Cortese, N. A.; Plevyak, J. E.; Zebovitz, T. C.; Terpko, ; Heck, R. F. *Ibid.* **1977,** *42*, 3903. For use of organomercury derivatives see: Heck R. F. *J. Am. Chem. Soc.* **1971,** *93*, 6896 and earlier references in that series. For reviews see: Heck, R. F.; *Fortschr. Chem. Forsch.* **1970,** *16*, 221; *Acc. Chem. Res.* **1969,** *2*, 10. Trost, B. M. *Tetrahedron* **1977,** *33*, 2615.

(2) Ziegler, C. B., Jr.; Heck, R. F. *J. Org. Chem.* **1978,** *43*, 2949.

(3) For examples of enol ethers see: Heck, R. F. *J. Am. Chem. Soc.* **1968,** *90*, 5535. Arai, I.; Deves, G. D., Jr. *Ibid.* **1978,** *100*, 286; *J. Org. Chem.* **1978,** *43*, 4110. For reaction of enol thioethers with Grignard reagents catalyzed by nickel complexes see: Okamura, H.; Muira, M.; Takei, H. *Tetrahedron Lett.* **1979,** 43.

(4) Deljai, A.; Stefanac, Z.; Balenovic, K. *Tetrahedron Suppl.* **1966,** No. 8, 33. Genét, J. P.; Tanigawa, Y., unpublished observations in these laboratories.

(5) O'Connor, D. E.; Lyness, W. I. *J. Am. Chem. Soc.* **1964,** 86, 3840. Trost, B. M.; Hiroi, K.; Kurozumi, S. *Ibid.* **1975,** *97, 438.*

(6) Trost, B. M.; Crimmin, M. J.; Butler, D. *J. Org. Chem.* **1978,** 43, 4549.

(7) For transfers from organostannanes to palladium see: Heck, R. F. *J. Am. Chem. Soc.* **1969,** *91*, 6707. Kosugi, M.; Sasazawa, K.; Shimizu, Y.; Migita, T. *Chem. Lett.* **1977,** 301. Kosugi, M.; Shimizu, Y.; Migita, T. *Ibid.* **1977,** 1423. Milstein, D.; Stille, J. K. *J. Am. Chem. Soc.* **1978,** *100*, 3636. It is interesting to note that, in contrast to our observations reported herein, Heck reports very low yields with Ph_4Sn in intermolecular arylations. His low yields may be due to use of a protonic solvent.

(8) Trost, B. M.; Reiffen, M.; Crimmin, M. J. *J. Am. Chem. Soc.* **1979,** 101, 257.

(9) For a totally different approach from enol thioethers see: Trost, B. M.; Tanigawa, Y. *J. Am. Chem. Soc.*, in press.

(10) For an approach based upon α-substituted hydrazones see: Sacks, C. E.; Fuchs, P. L. *J. Am. Chem. Soc.* **1975,** *97*, 7372.

(11) Grayson, J. E.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1977,** 2263. Carey, F. A.; Court, A. S. *J. Org. Chem.* **1972,** *37*, 939. Shahak, I.; Almog, J. *Synthesis* **1969,** 170; **1970,** 145. Mukaiyama, T.; Fukuyama, S.; Kumamoto, T. *Tetrahedorn Lett.* **1968,** 3787. Wittig, G.; Schlosser, M. *Chem. Ber.* **1961,** *94*, 1373.

(12) Hopkins, P. B.; Fuchs, P. L. *J. Org. Chem.* **1978,** *43*, 1208.

(13) Seebach, D.; Neumann, H. *Chem. Ber.* **1974,** *107*, 847.

(14) Oshima, K.; Shimoji, K.; Takahashi, H.; Yamamoto, Y.; Nozaki, H. *J. Am. Chem. Soc.* **1973,** *94*, 2694. Cookson, R. C.; Parsons, P. J. *J. Chem. Soc., Chem. Commun.* **1976,** 990. Harirchian, B.; Magnus, P. *Ibid.* **1977,** 522. Braun, M. *Tetrahedron Lett.* **1978,** 3695. Grobel, B. T.; Seebach, D. *Chem. Ber.* **1977,** *110*, 852, 867.

(15) Trost, B. M.; Keeley, D. E. *J. Am. Chem. Soc.* **1976,** *98*, 248.

Barry M. Trost,* Yoshio Tanigawa
Samuel M. McElvain Laboratories of Organic Chemistry
Department of Chemistry, University of Wisconsin—Madison
Madison, Wisconsin 53706

Received March 12, 1979

Structure and Dynamic Behavior of *n*-Propyllithium from ^{13}C, ^{7}Li, and ^{6}Li NMR

Sir:

Alkyllithium compounds in hydrocarbon solvents exist as tetramers[1] and hexamers[2] and undergo a variety of dynamic processes including fast inversion at carbon[3] and carbon-lithium bond exchange.[3,4]

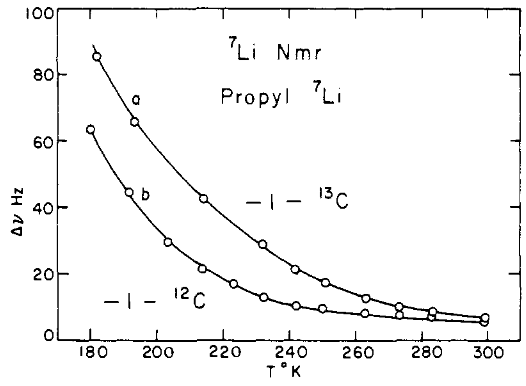


Figure 1. ^{7}Li NMR, 23.37 MHz, line widths for *n*-propyllithium (lower) and *n*-propyllithium-*1*-^{13}C (upper), both 0.6 M in cyclopentane.

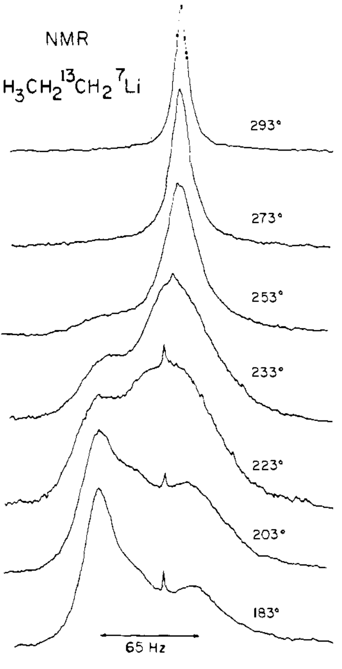


Figure 2. ^{13}C NMR, 22.03 MHz, of C_1 of *n*-propyllithium-*1*-^{13}C, 0.6 M in cyclopentane, different temperatures.