

group of **2** by a (*Z*)-enolate **4** opposite to the bulky sulfonamide group³ and (2) coordination of Zn^{II} with the oxygen atom of the nitroso group trans to the N—C(2) bond.¹¹

An analogous transition state **B**[†] involving (*E*)-enolates suffers repulsion between the C(3) of the bornane skeleton and the enolate C(α) substituent. Indeed, (*E*)-zinc enolates derived from cyclic ketones such as α -tetralone, β -tetralone, or cyclohexanone or from the propionate ester of 2,6-dimethylphenol¹⁰ reacted sluggishly with **2a**. Only partial conversion to complex mixtures was observed.

In conclusion, reagents **2a** and **2b**, which are readily accessible in both antipodal forms,² represent the first chiral [NH₂⁺] equivalents and thus open a new route to diastereo- and enantiomerically pure β -aminols. The synthetic potential of electrophilic nitroso compounds is being further explored in our laboratory.

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Supplementary Material Available: Preparations and analysis data, including mp, IR, ¹H NMR, ¹³C NMR, MS, and [α] values (11 pages). Ordering information is given on any current masthead page.

(11) An X-ray structure analysis of dichlorobis(4-nitroso-*N,N*-dimethyl-aniline)zinc(II) exhibits torsional angles Zn—O—N—C = -171.5° and 176.7°; Hu, S.; Thompson, D. M.; Ikekwere, P. O.; Barton, R. J.; Johnson, K. E.; Robertson, B. E. *Inorg. Chem.* 1989, 28, 4552-4554.

The First Example of Transition-Metal-Catalyzed Addition of Aromatic Thiols to Acetylenes

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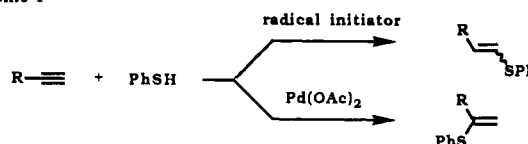
While the properties of the complexes resulting from stoichiometric reactions of thiols with transition-metal complexes have been well-studied,¹ there are few reports of transition-metal-catalyzed synthetic reactions with thiols.² For instance, for transition-metal-catalyzed addition of thiols to carbon-carbon unsaturated compounds, there is only one example of addition to a 1,3-diene to the best of our knowledge.^{2d} Perhaps widespread prejudice that thiols are catalyst poisons has precluded investi-

Table I. Effects of Catalysts on the Addition of PhSH to **1a**^a

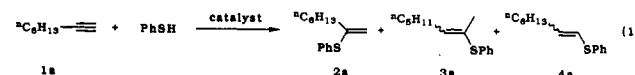
entry	catalyst	condition ^b	yield (%) ^c		
			2a	3a	4a
1	Pd(OAc) ₂	A	85 ^d	<1	<1
2	Pd(OAc) ₂	B	62	14	4
3 ^e	Pd(OAc) ₂	C	67	2	<1
4	none	A	0	0	47
5	AcOH	A	0	0	78
6	Pd(PPh ₃) ₄	B	4	10	2
7	Pd(PPh ₃) ₄	C	1	45	4
8	Pd(PhCN) ₂ Cl ₂	C	2	73	0
9	Pt(PPh ₃) ₄	C	2	80	18
10	Ni(PPh ₃) ₂ Cl ₂	C	1	22	2
11	Rh(PPh ₃) ₃ Cl	C	14	23	52 ^f

^a **1a** (1.0 mmol), catalyst (0.02 mmol), solvent (0.5 mL), and PhSH (1.0 mmol) for 16 h. ^b A: THF, 40 °C. B: THF, 67 °C. C: PhH, 80 °C. ^c Determined by GLC and ¹H NMR spectrometry. ^d Isolated yield. ^e 2,2-Bis(phenylthio)octane (5% based on **1a**) and (PhS)₂ (14%) were also produced. ^f E/Z = 98/2.

Scheme I



gation in this area. In this paper we describe the interesting finding that many transition-metal catalysts indeed catalyze the addition of aromatic thiols to acetylenes to provide vinyl sulfides.³ Table I summarizes the results of the addition of benzenethiol to 1-octyne (**1a**) in the presence of various transition-metal catalysts. Among



the catalysts examined, Pd(OAc)₂ exhibited excellent selectivity to afford the adduct **2a** (eq 1) in good yield (entries 1-3).^{4,5} In the absence of catalyst or presence of AcOH, **2a** was not obtained at all, and only **4a** was produced (entries 4 and 5).⁶ This may indicate that the palladium complex formed in situ also played an important role in suppression of the formation of **4a**.⁷ It has been well-established that the free radical additions of thiols to terminal acetylenes provide anti-Markovnikov adducts,⁸ while the present Pd(OAc)₂-catalyzed addition afforded the Markovnikov adducts successfully. Thus, these methods presented the regio-complementary approach to give vinyl sulfides (Scheme I).⁹ When Pt(PPh₃)₄ was employed as a catalyst, **3a** was produced

(3) For the synthetic utility of vinyl sulfides, see: (a) Trost, B. M.; Lavoie, A. C. *J. Am. Chem. Soc.* 1983, 105, 5075. (b) Magnus, P.; Quagliato, D. J. *Org. Chem.* 1985, 50, 1621.

(4) Procedure (entry 1): In a reaction vessel were placed Pd(OAc)₂ (0.02 mmol), THF (0.5 mL), **1a** (1.0 mmol), and then PhSH (1.0 mmol). After 16 h at 40 °C, the resulting catalyst was removed by filtration through Celite, and then the solvent was evaporated. The crude oil was subjected to MPLC (silica gel) to obtain **2a** (85%). Also isolated in smaller quantities were 2,2-bis(phenylthio)octane (3% based on **1a**) and diphenyl disulfide (6%).

(5) The additions to **1a** of some other thiols such as *n*BuSH, C₆F₅SH, MeOCOCH₂SH, and 2-pyridinethiol were not catalyzed by Pd(OAc)₂ under similar reaction conditions.

(6) The addition proceeded probably via a free radical mechanism by an adventitious amount of oxygen.

(7) It has been reported that Fe(CO)₅ inhibited the radical addition of ArSH to phenylacetylene, see: Kandror, I. I.; Petrova, R. G.; Petrovskii, P. V.; Freidlina, R. Kh. *Izv. Akad. Nauk SSSR, Ser. Khim.* 1969, 7, 1621.

(8) (a) Peach, M. E. In *The Chemistry of the Thiol Group*; Patai, S., Ed.; Wiley: London, 1974; Vol. 2. (b) Ichinose, Y.; Wakamatsu, K.; Nozaki, K.; Birbaum, J. L.; Oshima, K.; Utimoto, K. *Chem. Lett.* 1987, 1647. (c) Griesbaum, K. *Angew. Chem., Int. Ed. Engl.* 1970, 9, 273.

(9) There are few examples of Markovnikov addition of thiols to acetylenes by nucleophilic attack of thiolate anion, but the relatively longer reaction time or more severe conditions are essential; see: (a) Truce, W. E.; Simms, J. A. *J. Am. Chem. Soc.* 1956, 78, 2756. (b) Borisova, A. I.; Filippova, A. K.; Voronov, V. K.; Shostakovskii, M. F. *Izv. Akad. Nauk SSSR, Ser. Khim.* 1969, 2498.

(1) For notable examples, see: (a) Kim, Y. J.; Osakada, K.; Sugita, K.; Yamamoto, T.; Yamamoto, A. *Organometallics* 1988, 7, 2182. (b) Keskinen, A. E.; Senoff, C. V. *J. Organomet. Chem.* 1972, 37, 201. (c) Ugo, R.; La Monica, G.; Cenini, S. *J. Chem. Soc. A* 1971, 522. (d) Nyholm, R. S.; Skinner, J. F.; Stiddard, M. H. B. *J. Chem. Soc. A* 1968, 38. (e) Chatt, J.; Mann, F. G. *J. Chem. Soc.* 1938, 1949. (f) Chatt, J.; Hart, F. A. *J. Chem. Soc.* 1960, 2807. (g) Chatt, J.; Hart, F. A. *J. Chem. Soc.* 1953, 2363. (h) Fenn, R. H.; Segrott, G. R. *J. Chem. Soc., Dalton Trans.* 1972, 330. (i) Fenn, R. H.; Segrott, G. R. *J. Chem. Soc. A* 1970, 3197. (j) Umakoshi, K.; Ichimura, A.; Kinoshita, I.; Ooi, S. *Inorg. Chem.* 1990, 29, 4005. (k) Gaylor, J. R.; Senoff, C. V. *Can. J. Chem.* 1972, 50, 1868. (l) Osakada, K.; Hayashi, H.; Maeda, M.; Yamamoto, T.; Yamamoto, A. *Chem. Lett.* 1986, 597. (m) Gaines, T.; Roundhill, D. M. *Inorg. Chem.* 1974, 13, 2521. (n) Rakowski DuBois, M. *Chem. Rev.* 1989, 89, 1.

(2) (a) Antebi, S.; Alper, H. *Organometallics* 1986, 5, 596. (b) Shim, S. C.; Antebi, S.; Alper, H. *J. Org. Chem.* 1985, 50, 147. (c) Shim, S. C.; Antebi, S.; Alper, H. *Tetrahedron Lett.* 1985, 26, 1935. (d) Dzhemilev, U. M.; Kunakova, R. V.; Gaisin, R. L. *Izv. Akad. Nauk SSSR, Ser. Khim.* 1981, 11, 2655. (e) Talley, J. J.; Colley, A. M. *J. Organomet. Chem.* 1981, 215, C38. (f) McKervey, M. A.; Ratananukul, P. *Tetrahedron Lett.* 1982, 23, 2509. (g) Holmquist, H. E.; Carnahan, J. E. *J. Org. Chem.* 1960, 25, 2240. (h) Iqbal, J.; Pandey, A.; Shukla, A.; Srivastava, R. R.; Tripathi, S. *Tetrahedron* 1990, 46, 6423.

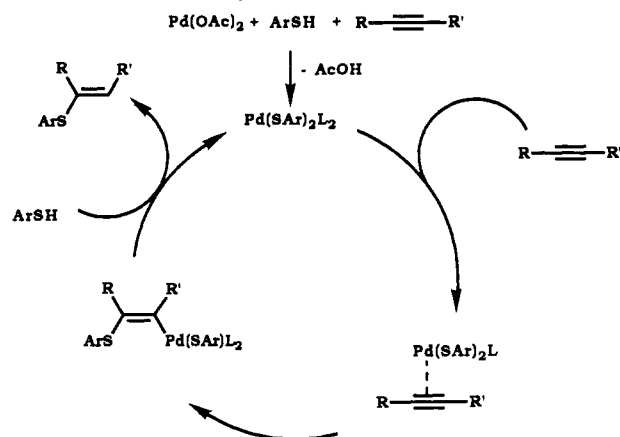
Table II. Pd(OAc)₂-Catalyzed Addition of ArSH to Acetylenes^a

entry	acetylene	ArSH	product and yield (%) ^b	yield of regioisomers (%) ^c
1	R ₁ = R ₂ = Me	PhSH	86	0
2	R ₁ , R ₂ = -(CH ₂) ₄	PhSH	63	0
3	R ₁ = R ₂ = Me		85	0
4	ⁿ C ₈ H ₁₅		55	.4
5 ^e	Me ₃ Si	PhSH	56	5
6 ^f	H ₂ N	PhSH	65 (87) ^g	0
7		PhSH	70	.4
8	ⁿ Pr	PhSH	72 (E/Z = 34/66) ^c (E/Z = 92/8) ^{c,h}	
9	Me	PhSH	53 (E/Z = 63/37) ^c 29 (E/Z = 46/52) ^e	
10	ⁿ C ₈ H ₁₁	PhSH	87 (E/Z = 98/2) ⁱ	2

^a Conditions: acetylene (1.0 mmol), Pd(OAc)₂ (0.02 mmol), and ArSH (1.0–1.3 mmol) in THF (0.5 mL) at 67 °C for 12–16 h. ^b Isolated yield. ^c Determined by ¹H NMR and GLC. ^d A complex mixture was produced as byproduct. ^e Without solvent at 70 °C. ^f 24 h. ^g NMR yield. ^h 10 min. ⁱ See ref 14.

as a major product (entry 9). Considering that PhSH oxidatively adds to Pt(PPh₃)₄ to afford PtH(PPh₃)₂(PhS),^{1b,c} similar species may be generated in this catalytic reaction system.¹⁰ Pd(PPh₃)₄, Pd(PhCN)₂Cl₂, and Ni(PPh₃)₂Cl₂ also exhibited catalytic activity and similar selectivity of the products (entries 6–8 and 10), while the Rh(PPh₃)₃Cl-catalyzed reaction provided (*E*)-4a as a major product with high stereoselectivity (entry 11).

To ascertain the stereochemistry of the Pd(OAc)₂-catalyzed addition to give Markovnikov adduct 2a, the reaction of PhSH with 1-octyne-1-*d* (containing >93% *d*) in THF-*d*₈ was followed by ¹H NMR spectroscopy. The *E/Z* ratio¹¹ of monodeuterated adducts 2a changed from 100/0 (6% conversion) after 15 min to 86/14 (81% conversion) after 8 h. Thus, the *E* isomer can be accepted as the kinetic product, which gradually isomerized to the *Z* isomer.¹² This clearly indicated that *cis* addition of PhSH to 1a proceeded at least at the initial stage. The results of the Pd(OAc)₂-catalyzed addition of some aromatic thiols to acetylenes are shown in Table II. Hydroxy, trimethylsilyl, and amino groups may be present in the acetylenes (entries 1–3, 5, and 6). Among the aromatic thiols examined, 2,6-dichlorobenzene-1-thiol and 2-naphthalene-1-thiol also added to acetylenes (entries 3 and 4).¹³ The acetylene bearing a tethered olefin unit underwent chemoselective addition to the triple bond (entry 7). The addition also proceeded smoothly with internal acetylenes to give a mixture of stereoisomers, although the *cis* adduct (*E* isomer) was also predominantly

Scheme II. Proposed Reaction Path for the Pd(OAc)₂-Catalyzed Addition of ArSH to Acetylenes

formed at the beginning of the reaction (entry 8). The addition to 2-butyne-1-ol gave slight regioselectivity (entry 9). Interestingly, the addition to 2-octynoic acid afforded the adducts with good stereo- and regioselectivity (entry 10).¹⁴

To obtain some insight into the active catalyst of the Pd(OAc)₂-catalyzed addition, the reaction of Pd(OAc)₂ with 3 equiv of PhSH¹⁵ was carried out in THF-*d*₈. The mixture immediately deposited dark brown precipitates,¹⁶ and the formation of ca. 2 equiv of AcOH was confirmed by ¹H NMR spectroscopy. Although the actual reaction pathway of Pd(OAc)₂-catalyzed addition of ArSH to acetylenes is still unknown, a mechanistic proposal includes the following: (1) ligand exchange of AcO ligand with PhS group in the presence of acetylene^{16,17} to give AcOH and an active catalyst; (2) coordination of acetylene to palladium; (3) syn-thiopalladation¹⁸ to acetylene to form *cis*-vinylpalladium (the order of R' preferred: hydrogen > oxygen-containing group > alkyl group); and (4) trapping of the vinyl group by PhSH¹⁹ or AcOH with retention of stereochemistry to give the Markovnikov adduct with regeneration of the catalyst (Scheme II).

Further study is focusing on details of the mechanisms of this addition catalyzed by Pd(OAc)₂ and other catalysts. The present study presages the development of a new class of transition-metal-catalyzed reactions based on thiols.

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Supplementary Material Available: Listings of experimental procedures and analysis data for the compounds in this communication and ¹H NMR spectra for the reaction of 1-octyne-1-*d* with PhSH (7 pages). Ordering information is given on any current masthead page.

(14) The assignment of stereochemistry was confirmed by ¹H NMR spectroscopy. The signal of the *cis* vinyl proton for the PhS group appeared upfield from that of *trans* vinyl proton by ca. 0.3–0.7 ppm. See the supplementary material.

(15) Nyholm et al. have already described that the reaction of Pd(OAc)₂ with PhSH gave a polymeric product; see ref 1d.

(16) This precipitate scarcely exhibited the catalytic activities for the addition of PhSH to 1a. On the other hand, the precipitates prepared in the presence of 1a had a moderate catalytic activity. Detailed results are provided in the supplementary material.

(17) To obtain good yields of Markovnikov adducts in this Pd(OAc)₂-catalyzed addition, acetylenes must be added to Pd(OAc)₂ before the addition of PhSH; see ref 4.

(18) We have already reported the Pd(PPh₃)₄-catalyzed addition of diphenyl disulfide to acetylenes, indicating the facile insertion of acetylene into the Pd–S bond; see: Kuniyasu, H.; Ogawa, A.; Miyazaki, S.; Ryu, I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1991**, *113*, 9796.

(19) For the ability of thiol to cleave the alkyl–metal bond, see: Johnson, A.; Puddephatt, R. J. *J. Chem. Soc., Dalton Trans.* **1975**, 115.

(10) The ratio of a mixture of isolated 2a/3a (82/18) changed to 13/87 in the presence of Pt(PPh₃)₄, PhSH, and acetylene, suggesting that 2a is a precursor of 3a.

(11) The assignment of the vinyl protons was confirmed by an NOE experiment of 2a.

(12) The formation of the product containing two deuteriums was not observed judging from the fragmentation of the mass spectrum of the product. This fact may indicate that the isomerization of *E* to *Z* is promoted by addition and elimination of Pd–SPh (and/or PhS*) to the C–C double bond of 2a.

(13) The substituents on aromatic thiol had drastic effects on the Pd(OAc)₂-catalyzed addition. For example, the addition of 4-chloro- or 4-hydroxybenzenethiol to 1a gave bis-adducts as the main products. On the other hand, the addition of 4-methyl- or 4-methoxybenzenethiol to 1a was scarcely catalyzed by Pd(OAc)₂ under similar reaction conditions. The details are now under investigation.