

respect to the cyclohexane ring, as illustrated in Scheme II. We designate 7 as the syn-anti-syn configuration. This stereochemical course of epoxidation of 6 is indeed surprising since Dreiding models suggest that the syn approach of the mCPBA is sterically less encumbered than the anti approach. It appears that stereoelectronic factors play a role in this unusual epoxidation. On triphenylphosphine deoxygenation of endoperoxide 2b in CHCl_3 at 25 °C the epoxydiene 8 was obtained in 70% yield (mp 81–82 °C, recrystallized from $\text{CH}_2\text{Cl}_2/n\text{-C}_6\text{H}_{14}$ mixture after silica gel chromatography at –15 °C).^{6,12} Finally, on diimide reduction¹¹ of endoperoxide 2b the saturated bicyclic peroxide 9 was obtained in 80% yield (mp 123 °C, recrystallized from $n\text{-C}_6\text{H}_{14}$).^{6,13} Its structure is confirmed by independent synthesis starting from cyclooctatriene.¹⁴

The successful singlet oxygenation of the bicyclic valence isomer of cyclooctatetraene opens up new avenues for its synthetic manipulation and utilization. Preliminary efforts reveal that cyclooctatetraene itself can be oxygen difunctionalized via indirect routes to the potentially valuable endoperoxide 2a.¹⁵

Acknowledgment is made to the donors of the Petroleum Research Fund (11022-AC-1), administered by the American Chemical Society, the National Science Foundation (Grant No. CHE-78-12621), the National Institutes of Health (Grant No. GM-00141-05 and RR-8102-07), and the Universities of Puerto Rico and Würzburg for generous financial support. We thank BASF for a generous sample of cyclooctatetraene, Professor H. Hopf (Universität Braunschweig) for the ¹³C NMR spectra, and Dr. K. Peters for the X-ray determination.

Registry No. 1b, 4011-16-9; 2b, 6841-69-6; 3, 4840-84-0; 5, 54251-47-7; 6, 75266-45-4; 7, 75266-46-5; 8, 75266-47-6; 9, 249-89-8.

(11) Adam, W.; Eggelte, H. J. *J. Org. Chem.* 1977, 42, 3987.

(12) For 8: ¹H NMR (CCl_4 , Me_4Si) δ 2.96–3.37 (m, 4 H), 5.92 (d, 2 H), 6.23 (m, 2 H); IR (CCl_4) 3120, 3080, 3060, 2900, 1580, 1470, 1080, 830 cm^{-1} .

(13) For 9: ¹H NMR (CCl_4 , Me_4Si) δ 2.18 (m, 8 H), 3.03 (m, 2 H), 3.93 (m, 2 H); IR (CCl_4) 2960, 2880, 1475, 1455, 1040, 945 cm^{-1} .

(14) Adam, W.; Erden, I. *Tetrahedron Lett.* 1979, 2781. The physical constants and spectral data reported for the bicyclic peroxide 9 (structure 3b in ref 14) are erroneous. We thank Professor H. D. Martin and Mr. M. Kunze of this Institute for calling our attention to this error and for a sample of 1,3,5-cyclooctatriene. Cf. correction in: *Tetrahedron Lett.*, in press.

(15) In our hands the endoperoxides 2b and 9 were sufficiently stable at room temperature (ca. 20 °C) for routine manipulation; however, in view of the inherent danger of organic peroxides in general, all safety precautions should be taken when working with such compounds.

Supplementary Material Available: Experimental details of these transformations (3 pages). Ordering information is given on any current masthead page.

(16) NIH Career Development Awardee (1975–1980). Send correspondence to the Würzburg address.

Waldemar Adam,*¹⁶ Omar Cueto, Ottorino De Lucchi

Department of Chemistry
University of Puerto Rico
Rio Piedras, Puerto Rico 00931, and
Institute of Organic Chemistry
University of Würzburg
D-8700 Würzburg am Hubland, West Germany
Received June 17, 1980

Palladium-Catalyzed Polyhetero-Claisen Rearrangement

Summary: The S → N allylic rearrangement of S-allylthioimidates is performed efficiently by the catalysis of Pd(II) salt to give N-allylthioamides (71–100% yields).

Sir: The thioamide group has increasingly been recognized as a useful synthon in organic syntheses.¹ Although the transformation of secondary thioamides to tertiary thioamides is sometimes required in a reaction sequence, a general and satisfactory procedure for such transformation is presently lacking.² One apparent possibility is the utilization of the rearrangement of S-allylthioimidates to N-allylthioamides, but this type of S → N rearrangement is one of the least studied polyhetero-Claisen rearrangements,³ probably owing to the many possible side reactions (e.g., double bond isomerization, deallylation, etc.).

We have found that Pd(II) catalyzes nicely the S → N allyl group migration of S-allylthioimidates and we report the very efficient N-allylation reaction of secondary thioamides.

S-Allylthioimidate (1), upon heating in tetralin at 150 °C for 4 h, provided mainly the double bond isomerization product, S-propenylthioimidate (3, 93%), together with a small amount of the desired rearrangement product, N-allyl-N-methylthiobenzamide (2, 7%) (Scheme I). On the other hand, in the presence of 1 mol% Pd(II) 1 was found to rearrange selectively to give 2 (THF, reflux, 2 h).

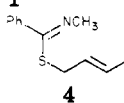
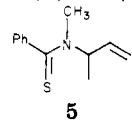
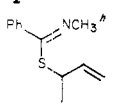
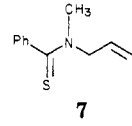







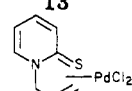
Some preliminary results are summarized in Table I, which reveals the efficiency and some interesting features of the reaction. The efficiency of the Pd(II) salt (as PdCl_2 or $\text{PdCl}_2\text{-(PhCN)}_2$) is evident by a comparison of entries 1 and 3. Under the same conditions except for the absence of Pd(II), no reaction took place and 1 was recovered completely. Triphenylphosphine retards the reaction (entry 2). Neither Pd(0) (as tetrakis(triphenylphosphine)palladium) nor other metal salts (NiCl_2 , CuCl , HgCl_2)⁴ effected the S → N rearrangement. Accompanied by these observations, the regiospecific rearrangements of

(1) (a) Woodward, R. B. *Pure Appl. Chem.* 1968, 17, 519; 1971, 25, 283; 1973, 33, 145. (b) Eichenmoser, A. *Q. Rev., Chem. Soc.* 1970, 24, 366. (c) Takano, S.; Hirama, M.; Araki, T.; Ogasawara, K. *J. Am. Chem. Soc.* 1976, 98, 7087. (d) Tamaru, Y.; Harada, T.; Yoshida, Z. *Ibid.* 1978, 100, 1923; 1979, 101, 1316; 1980, 102, 2392. (e) Tamaru, Y.; Harada, T.; Iwamoto, H.; Yoshida, Z. *Ibid.* 1978, 100, 5221. (f) Tamaru, Y.; Harada, T.; Yoshida, Z. *Tetrahedron Lett.* 1978, 2167; 1979, 3525. (g) Tamaru, Y.; Kagotani, M.; Yoshida, Z. *J. Org. Chem.* 1979, 44, 2816.

(2) (a) Trost, B. M.; Kunz, R. A. *J. Am. Chem. Soc.* 1975, 97, 7152 and references cited therein. (b) Zabicky, J. "The Chemistry of Amide"; Interscience: New York, 1970.

(3) For comprehensive review, see: (a) Rhoads, S. J.; Raulins, N. R. *Org. React.* 1975, 22, 1; (b) Bennet, G. B. *Synthesis* 1977, 589; (c) Ziegler, F. E. *Acc. Chem. Res.* 1977, 10, 227.

Table I. Palladium(II)-Catalyzed Rearrangement of *S*-Allylthioimidates to *N*-Allylthioamides

entry	<i>S</i> -allylthioimide ^a	conditions ^b	conv, % ^c	product ^d	yield, % ^e
1	1 ^f	PdCl ₂ (PhCN) ₂ , THF, reflux, 8 h	82	2	99
2	1 ^f	PdCl ₂ (PPh ₃) ₂ , THF, reflux, 5 h	20	2	
3	1 ^f	tetralin, 150 °C, 4 h	97	2 (7) + 3 (93)	
4		PdCl ₂ (PhCN) ₂ , THF, reflux, 24 h	83		98
5	4	neat, 170 °C	0 ^g	—	
6		PdCl ₂ (PhCN) ₂ , THF, reflux 2 h	100		94
7		PdCl ₂ (PhCN) ₂ , THF, reflux, 24 h	45		71
8		PdCl ₂ (PhCN) ₂ , THF, reflux, 2.5 h	91		93
9		PdCl ₂ (PhCN) ₂ , THF, reflux, 24 h	92		91
10		PdCl ₂ (PhCN) ₂ , ⁱ THF, reflux, 2 h	100		96

^a A syn and anti mixture (1, 1:1; 4, 1:1; 6, 1:1). ^b Generally 1.0–1.1 mol % palladium salt is used. For entry 2, 1.7 mol % PdCl₂(PPh₃)₂ is applied. ^c Conversion is determined by VPC (Silicon DC550). ^d The structures of all new compounds are satisfied by spectral and analytical data. ^e All products (except for 15) were purified by Kugelrohr distillation. Yields refer to the isolated ones based on conversions. ^f The starting thioimide 1 is contaminated with a small amount (<8%) of *S*-propenyl isomer. ^g Complete recovery of starting material. ^h The starting thioimide 6 is contaminated with ~20% *S*-crotyl isomer (4), but a mixture of these isomers is kinetically separated to give 7 selectively, with remaining 4 unchanged. ⁱ An equimolar amount of Pd(II) salt is used.

S-crotyl- and *S*-methallylthioimidates to *N*-methallyl- (entry 4) and *N*-crotylthioamides (entry 6), respectively, speak against the intermediacy of π -allylpalladium species.⁵ The most probable mechanism is illustrated in Scheme II, which involves imino (C-3) palladation (C-2) to form an intermediate B. A similar mechanism has been proposed by Overman for the palladium(II)-catalyzed Cope rearrangement⁶ and allylic rearrangement of allyl acetates.⁷ Very recently Gompper et al. have reported acceleration of the rearrangement of *S*-allylthioimidates by electron-withdrawing substituents at the 2-position of the allyl group, and they isolated an intermediate like B (with a benzoyl or carbethoxy group in place of Pd).⁸ On the other hand, *S*-allylthioimidates with a substituent (CH₃, Ph, or Cl) at the 2-position of the allyl group were found to be unreactive and were recovered completely independent of the presence or absence of Pd(II). This interference of rearrangement by the 2-substituents might be also rationalized by Scheme II on the basis of an unfavorable imino (C-3) palladation (C-2), which now requires Pd–C (tertiary) bond formation.

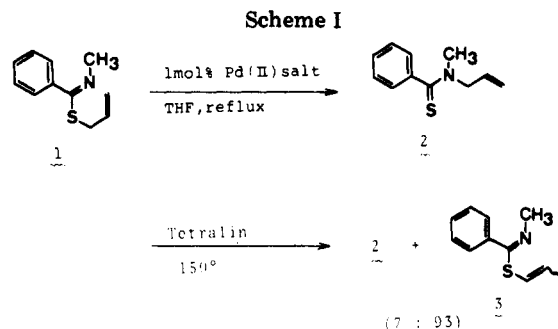
(4) Overman, L. E. *J. Am. Chem. Soc.* 1974, 96, 597; 1976, 98, 2901; *Tetrahedron Lett.* 1975, 1149.

(5) For a comprehensive review, see: Trost, B. M. *Tetrahedron* 1977, 33, 2615.

(6) Overman, L. E. *J. Am. Chem. Soc.* 1980, 102, 865.

(7) (a) Henry, P. M. *J. Am. Chem. Soc.* 1972, 94, 5200. (b) Overman, L. E.; Knoll, F. M. *Tetrahedron Lett.* 1979, 321.

(8) (a) Gompper, R.; Kohl, B. *Tetrahedron Lett.* 1980, 907. (b) See also: Gompper, R.; Ulrich, W.-R. *Angew. Chem.* 1976, 88, 298, 300.

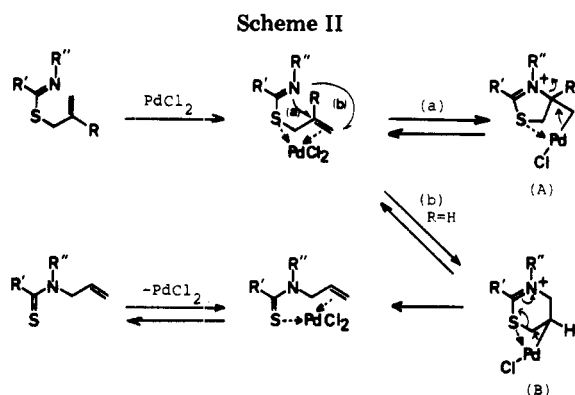


In marked contrast to allyl group migration to the carbon α to the thiocarbonyl group (probably via ketene S,N-acetal) observed for the thermal (~200 °C) rearrangement of five- (8) and seven-membered cyclic *S*-allylthioimidates (10),⁹ palladium(II) catalyzed the selective S \rightarrow N rearrangement of these imidates to provide *N*-allylthiopyrrolidone and *N*-allylthio- ϵ -caprolactam, respectively (entries 7, 8).

The last two examples in Table I (entries 9, 10) deserve some comment. The S \rightarrow N rearrangement of *N*-acetyl-2-(allylthio)imidazole (12) requires a high reaction temperature and prolonged reaction time¹⁰ (145 °C, 72 h),

(9) Black, D. St. C.; Eastwood, F. W.; Okraglik, R.; Poynton, A. J.; Wade, A. M.; Welker, C. H. *Aust. J. Chem.* 1972, 25, 1483.

(10) Kohn, H.; Arceneaux, J. H. *J. Org. Chem.* 1977, 42, 2339.



while in the presence of 1 mol% $\text{PdCl}_2(\text{PhCN})_2$ the rearrangement attains completion by refluxing in THF for 24 h. With 1 equiv of $\text{PdCl}_2(\text{PhCN})_2$ the rearrangement is complete within 1 h at room temperature and gives a precipitate of a 1:1 complex of PdCl_2 and 13. Compound 13 can be isolated by treatment of the complex with excess pyridine. The technique of stabilization of the product by complex formation is successfully applied to the thermodynamically unfavorable rearrangement¹¹ of *S*-allyl-2-mercaptopyridine (14) to 1-allyl-2-thiopyridone (15).^{12,13}

The following example is illustrative of the simplicity and utility of this catalytic reaction (entry 1). A THF (5 mL) solution of *S*-allyl-*N*-methylthiobenzimidate (1 mmol) and $\text{PdCl}_2(\text{PhCN})_2$ (0.01 mmol) is refluxed under argon for 8 h. After evaporation of THF, the residue is subjected directly to a Kugelrohr distillation to give *N*-allyl-*N*-methylthiobenzamide in 81% yield [bp 150 °C (1.5 mmHg)].¹⁴

Acknowledgment. We are grateful for the partial support for this research from the Ministry of Education, the Japanese Government (Grant-in-Aid for Environmental Science No. 403022 and Grant-in-Aid for Scientific Research No. 475663).

Registry No. (*E*)-1, 75311-48-7; (*Z*)-1, 75311-49-8; 2, 75311-50-1; 3, 75311-51-2; (*E*)-4, 75311-52-3; (*Z*)-4, 75311-53-4; 5, 75311-54-5; (*E*)-6, 75311-55-6; (*Z*)-6, 75311-56-7; 7, 75311-57-8; 8, 1558-77-6; 9, 1558-74-3; 10, 1558-78-7; 11, 1558-76-5; 12, 61076-81-1; 13, 62139-89-3; 14, 65063-38-9; 15, 75332-11-5; 16, 75311-58-9; $\text{PdCl}_2(\text{PhCN})_2$, 14220-64-5; $\text{PdCl}_2(\text{PPh}_3)_2$, 13965-03-2.

Yoshinao Tamaru, Masahiro Kagotani
Zen-ichi Yoshida*

Department of Synthetic Chemistry
Kyoto University, Yoshida, Kyoto 606, Japan

Received June 24, 1980

(11) Makisumi, Y.; Sasatani, T. *Tetrahedron Lett.* **1969**, 1975.

(12) For the Pt(II)-catalyzed rearrangement of 2-(allyloxy)pyridine to 1-allyl-2-pyridone, see: Stewart, A. F.; Seibert, R. P. *J. Org. Chem.* **1968**, *33*, 4560.

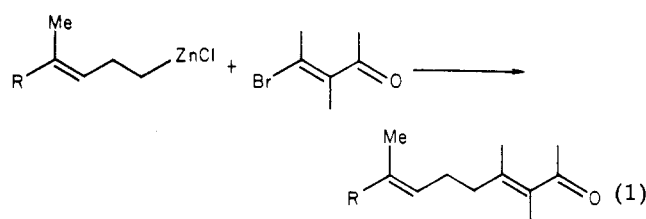
(13) 1-Allyl-2-thiopyridone (16) was freed from PdCl_2 by exposure to an excess pyridine and purified by column chromatography (50% yield). Application of heat to 16 (Kugelrohr distillation, 130 °C (6 mmHg)) caused complete isomerization to 14.

(14) For entries 1-8, the products could be purified by a Kugelrohr distillation because the starting thioimidates showed much lower boiling points. The product 13 was purified by column chromatography on silica gel (benzene-EtOAc gradient).

A Palladium-Catalyzed Stereospecific Substitution Reaction of Homoallylzincs with β -Bromo-Substituted α,β -Unsaturated Carbonyl Derivatives. A Highly Selective Synthesis of Mokupalide¹

Summary: Stereodefined homoallylzinc halides readily participate in a Pd-catalyzed stereospecific ($\geq 98\%$) substitution reaction with β -bromo-substituted α,β -unsaturated carbonyl derivatives, thereby providing a highly stereoselective and efficient route to butenolides and furans of terpenoid origin, such as mokupalide (1) and dendrolasin (2).

Sir: We report that the Pd-catalyzed reaction of alkylzinc derivatives with alkenyl halides reported recently by us² can readily be adapted to effect the "conjugate substitution" reaction³⁻⁵ of stereodefined homoallylzinc derivatives with β -halo- α,β -unsaturated carbonyl derivatives (eq 1). We further report that the reaction is well



suited for the selective synthesis of butenolides and furans of terpenoid origin, such as mokupalide⁶ (1) and dendrolasin⁷ (2).

(1) Selective Carbon-Carbon Bond Formation via Transition Metal Catalysis. 16. Controlled Carbometalation. 7. Part 6: M. Kobayashi, L. F. Valente, E. Negishi, W. Patterson, and A. Silveira, Jr., *Synthesis*, in press.

(2) (a) E. Negishi, L. F. Valente, and M. Kobayashi, *J. Am. Chem. Soc.*, **102**, 3298 (1980). For earlier publications on related reactions, see also the following: (b) S. Baba and E. Negishi, *J. Am. Chem. Soc.*, **98**, 6729 (1976); (c) N. Okukado, D. E. Van Horn, W. L. Klima, and E. Negishi, *Tetrahedron Lett.*, 1027 (1978); (d) E. Negishi, N. Okukado, A. O. King, D. E. Van Horn, and B. I. Spiegel, *J. Am. Chem. Soc.*, **100**, 2254 (1978); (e) A. O. King, N. Okukado, E. Negishi, *J. Chem. Soc., Chem. Commun.*, 683 (1977).

(3) In contrast to the conjugate addition reaction its substitution counterpart, i.e., substitution on the β carbon atom of α,β -unsaturated carbonyl and related derivatives ("conjugate substitution"), has not been well developed for widespread use as a method of carbon-carbon bond formation. The Cu-catalyzed or -promoted cross-coupling reaction of α,β -unsaturated carbonyl derivatives that are β -substituted with O,^{4a-c} S,^{4d,e} and halogen^{4f-i} groups is promising.⁵ Its current scope is, however, essentially limited to those cases where the groups displacing the β substituents are simple alkyl groups such as methyl and *n*-butyl.

(4) (a) C. P. Casey, D. F. Martin, and R. A. Boggs, *Tetrahedron Lett.*, 2071 (1973); (b) C. P. Casey and D. F. Martin, *Synth. Commun.*, **3**, 321 (1973); (c) S. Caechi, A. Caputo, and D. Misiti, *Indian J. Chem.*, **12**, 325 (1974); (d) G. H. Posner and D. J. Brunelle, *J. Chem. Soc., Chem. Commun.*, 907 (1973); (e) S. Kobayashi, H. Takei, and T. Mukaiyama, *Chem. Lett.*, 1097 (1973); (f) L. Decaux and R. Vessiere, *C. R., Hebd. Seances Acad. Sci.*, **267**, 738 (1968); (g) E. Piers and I. Nagakura, *J. Org. Chem.*, **40**, 2694 (1975); (h) E. Piers, I. Nagakura, and H. E. Morton, *ibid.*, **43**, 3630 (1978); (i) K. E. Harding and C. Tseng, *ibid.*, **43**, 3974 (1978).

(5) In addition to the organocopper reactions in ref 4 the following "conjugate substitution" reactions should also be noted. (a) Pd: for a review, see R. F. Heck, *Acc. Chem. Res.*, **12**, 146 (1979). (b) Mg: see, for example, R. Ramage and A. Satter, *J. Chem. Soc. D.*, 173 (1970). (c) B: G. A. Molander and H. C. Brown, *J. Org. Chem.*, **42**, 3106 (1977).

(6) (a) M. B. Yunker and P. J. Scheuer, *J. Am. Chem. Soc.*, **100**, 307 (1978); (b) F. W. Sum and L. Weiler, *ibid.*, **101**, 4401 (1979).

(7) (a) R. Bernardi, C. Cardani, D. Ghiringhelli, A. Selva, A. Baggini, and M. Pavan, *Tetrahedron Lett.*, 3893 (1967); (b) K. A. Parker and W. S. Johnson, *ibid.*, 1329 (1969); (c) A. F. Thomas and M. Ozainne, *J. Chem. Soc. C*, 220 (1970); (d) M. E. Garst and T. A. Spencer, *J. Am. Chem. Soc.*, **95**, 250 (1973); (e) K. Kondo and M. Matsumoto, *Tetrahedron Lett.*, 391 (1976); (f) S. Takahashi, *Synth. Commun.*, **6**, 331 (1976); (g) Y. Kojima, S. Wakita, and N. Kato, *Tetrahedron Lett.*, 4577 (1979).