(0.445 mol) of PCl_3 were placed 75 mL (0.422 mol) of purified $CHCl_3$ and the mixture was refluxed for 7 h. The white solid formed was dissolved in approximately 600 mL of CH_2Cl_2 and cooled to −25 °C with the addition of dry ice. Water was added dropwise, with continuous swirling, while the aluminum products coagulated, leaving a clear liquid. The liquid was decanted, filtered twice, dried over $CaCl_2$, and refiltered. The solvent was removed on a flash evaporator, leaving ≈50 mL of a pale yellow, clear liquid, which was fractionally distilled at 1–2 mm. The fraction distilling at 61–64 °C ($Cl_2CHP(O)Cl_2$) was collected (41.8 g) and added to 100 mL of water with stirring. A large fraction of water was then removed with a flash evaporator and the product dried for 9 days in vacuo over P_2O_5, mp 110–114 °C (lit. 113–116 °C).[56]

All other materials were reagent grade commercial products.

Kinetics. The slow reactions were measured in a temperature-controlled Gilford Model 2000 or a Perkin-Elmer Model 559 spectrophotometer. Cuvettes containing buffer solutions were equilibrated at 25 °C and BMN or malononitrile/benzaldehyde added by injecting a few μL of concentrated stock solution. pH measurements were performed with a Corning Model 110 pH meter thermostated at 25 °C.

The fast reactions were monitored in a Durrum stopped-flow apparatus with computerized data handling. BMN solutions for mixing experiments were prepared in slightly acidic solution, to prevent hydrolysis in the reservoir syringe of the stopped-flow apparatus. pH measurements were performed on mock mixing solutions outside the stopped-flow apparatus.

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Registry No. BMN, 2700-22-3.

Supplementary Material Available: Kinetic data, Tables S1–S4 (6 pages). Ordering information is given on any current masthead page.

Communications to the Editor

Inversion of the Electronic Reactivity of Allyl Acetates Using an Aluminum-Tin Reagent

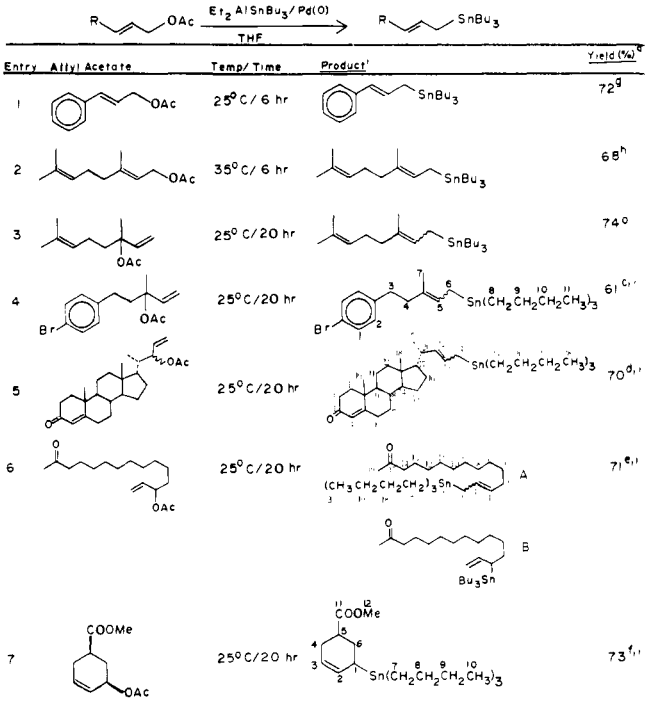
Barry M. Trost* and James W. Herndon

McElvain Laboratories of Organic Chemistry
Department of Chemistry, University of Wisconsin
Madison, Wisconsin 53706

Received June 20, 1984

Recently, allylstannanes have emerged as valuable tools in organic synthesis, coupling with electrophiles such as carbonyl compounds under mild conditions and in a highly chemoselective and regioselective manner.[1,2] Allylstannanes also serve as a very soft source of allyl anion, making them ideal substrates for reaction with allyl[3] and arylpalladium(II) complexes.[4] However, their use in synthesis has been restricted to reactions involving relatively simple allyl systems, since current methods of synthesis of allylstannanes suffer from the often poor chemoselectivity and regioselectivity exhibited by the stannylating reagent.[5-13]

Table I. Conversion of Allyl Acetates to Alkylstannanes



[a] The yields are of chromatographed samples and are homogenous by TLC analysis. [b] The product was obtained as a 1:1 mixture of *E*/*Z* isomers. [c] The product was obtained as a 6:4 mixture of *E*/*Z* isomers. [d] The product was obtained as a 9:1 mixture of trans/cis olefin isomers. [e] The ratio A:B = 82:18. Product B was not isolable, but treatment of the reaction mixture with trifluoroacetic produced an 82:18 mixture of terminal/internal olefin isomers. [f] The product was obtained as a 70:30 mixture of trans/cis isomers. [g] Reference 22. [h] Reference 23. [i] The numbering of carbons corresponds to spectral data for new compounds reported in the supplementary material.

We were prompted to undertake a study of the reaction of an aluminum–tin species with allylic acetates in the presence of a catalyst to overcome existing limitations.[14] Nevertheless, such

(1) Sawyer, A. K. In "Organotin Compounds"; Marcel Dekker: New York, 1971; Vol. III.

(2) Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 555–566.

(3) (a) Trost, B. M.; Keinan, E. *Tetrahedron Lett.* **1980**, *21*, 2595–2598. (b) Godschalx, J.; Stille, J. K. *Tetrahedron Lett.* **1980**, *21*, 2599–2602.

(4) Kosugi, M.; Sasazawa, K.; Shimizu, Y.; Migita, J. *Chem. Lett.* **1977**, 301–302.

(5) For coupling of (trialkylstannyl)lithium reagents with allylic halides, see: Wickham, G.; Young, D.; Kitching, W. *J. Org. Chem.* **1982**, *47*, 4884–4895.

(6) Still, W. C. *J. Am. Chem. Soc.* **1978**, *100*, 1481–1487.

(7) San Filippo, J., Jr.; Silbermann, J.; Fagan, P. J. *J. Am. Chem. Soc.* **1978**, *100*, 4834–4842.

(8) Quintard, J. P.; Hauvette-Fray, S.; Pereyre, M. *Bull. Soc. Chim. Belg.* **1978**, *87*, 505.

(9) For coupling of trialkylstannyl cuprate reagents with allylic acetates, see: Naruta, Y.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1983**, 1264.

(10) Piers, E.; Chong, J. M.; Morton, H. E. *Tetrahedron Lett.* **1981**, *22*, 4905–4908.

(11) For coupling of allyllithium or allyl Grignard reagents with triorganostannyl halides, see: Abel, E. W.; Rowley, R. J. *J. Organomet. Chem.* **1975**, *84*, 199–229.

(12) For coupling of [2-(trimethylstannyl)ethylidene]triphenylphosphorane with aldehydes and ketones, see: Seyferth, D.; Wursthorn, K. R.; Mammarella, R. E. *J. Organomet. Chem.* **1979**, *179*, 25–36.

(13) For hydrostannylation of 1,3-dienes, see: Neumann, W. P.; Sommer, R. *Liebigs Ann. Chem.* **1967**, *701*, 28–39.

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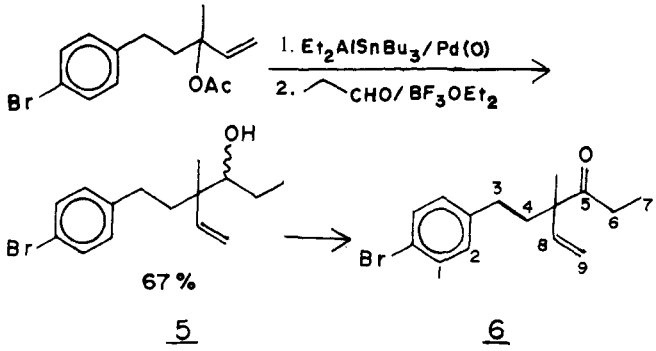
Scheme I. Direct Conversion of Allyl Acetates to Homoallyl Alcohols



a development is complicated by the much higher reactivity of allylstannanes—a reactivity that is also catalyzed by transition metals. For example, allylstannanes couple efficiently with allyl acetates in the presence of palladium(0)[3a] which, at first glance, would seem to preclude their synthesis under similar conditions. The reagent of choice must be reactive enough to couple with an allylpalladium(II) complex[15] under mild conditions and kinetically fast enough so that it reacts much faster with the allylpalladium(II) complex than the resultant allylstannane reacts. We chose (tributylstannyl)diethylaluminum as our stannylating reagent, which is readily available by reaction of (tributylstannyl)lithium with diethylaluminum chloride.[16] The results from the reaction of (tributylstannyl)diethylaluminum with various allyl acetates in the presence of tetrakis(triphenylphosphine)-palladium(0) at 25 °C in THF are summarized in Table I.

From Table I, it can be seen that this reagent reacts with a very high degree of regioselectivity for the less substituted carbon of the allyl system. The reaction also proceeds with a remarkably high degree of chemoselectivity. As seen in entries 5, 6, and 7, enone, ketone, and ester functionalities remain totally intact even in the presence of excess stannylaluminum reagent; this is in sharp contrast to the normal behavior of alkylaluminum reagents[17] and especially the silylaluminum reagent.[14] Aryl bromides are also unaffected (entry 4) under the conditions of the reaction. The yields in the reaction are satisfactory; however, attempted isolation of the products by flash chromatography on silica gel leads to some product loss due to protiodestannylation on the column. Isolation of the allylstannanes to do subsequent reactions may not even be necessary. If the crude reaction mixture from entry 4 (in hexane) was filtered through silica gel and the eluent reacted with propionaldehyde and boron trifluoride etherate in methylene chloride, then compound **5** was obtained in 67% yield (on the basis of allylic acetate) as a mixture of diastereomers (Scheme I). Subsequent oxidation with pyridinium chlorochromate produced a single ketone (compound **6**) for characterization.

The reaction appears to go with inversion of the stereochemical configuration of the allyl acetate carbon (entry 7); this path is in contrast to the mode of addition of stabilized nucleophiles to allyl acetates catalyzed by palladium(0).[15] The stereochemical relationship of the ester and tin groups was assigned on the basis of a 12-Hz ^{13}C–$^{117,119}Sn$ coupling constant between C-5 and tin[18]

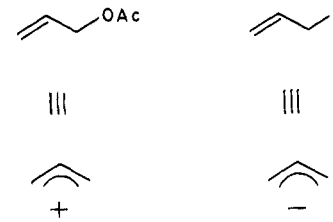
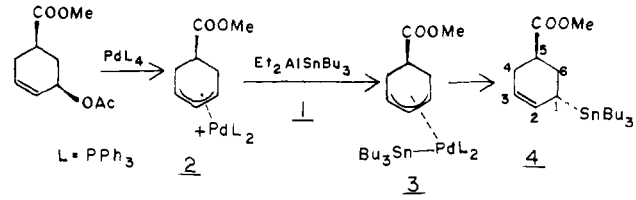


Figure 1. Synthon relationships.

Scheme II. Mechanism of Palladium-Catalyzed Formation of Allylstannanes from Allyl Acetates



in the major isomer and one of 40 Hz in the minor isomer. Because of the stereochemistry observed for the major product **4** in entry 7 (see Table I), we propose the mechanism outlined in Scheme II via intermediates **2** and **3** as being the predominate pathway for the reaction.[15] Under the same conditions and in the absence of a palladium catalyst, compound **4** (trans isomer only) was obtained in only 12% yield.

The regioselectivity of addition is considerably different from that observed in reactions with the corresponding aluminum–silicon reagent,[14] where in the palladium-catalyzed reaction there is a bias to deliver the silicon to the more substituted end. Since allylstannanes are known to isomerize rapidly under mild conditions,[20] the isomer distribution may simply be a reflection of the thermodynamic stability of the allylstannane isomers. The fact that geranyl acetate (entry 2) gives an isomerically pure product whereas linalyl acetate (entry 3) gives a mixture of stereoisomers suggests that no equilibration of the products is taking place.[21]

In a typical procedure, to a 0.1–1.0 M solution of 1.5 equiv of hexabutylditin in THF at 0 °C under nitrogen was added a solution of 1.5 equiv of *n*-butyllithium (in hexane), and the mixture was allowed to stir for 20 min at 0 °C. The solution was then cooled to −78 °C, and a solution of 1.5 equiv of diethylaluminum chloride in toluene was added. The solution was allowed to stir 1 h at −78 °C; then a solution of 0.05 equiv of $Pd(PPh_3)_4$ in THF was added, followed by the addition of a solution of 1.0 equiv of the allyl acetate in THF, warming to room temperature over a

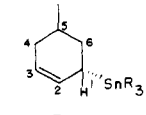
(14) (a) Trost, B. M.; Yoshida, J.-I.; Lautens, M. *J. Am. Chem. Soc.* **1983**, *105*, 4494–4497. (b) For other reactions of this reagent, see: Roesch, L.; Altnau, G.; Otto, W. H. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 581–582 and references therein.

(15) A π-allylpalladium(II) complex has been proposed as the reactive allylating species in the addition of nucleophiles to allyl acetates in the presence of palladium(0). For a review, see: Trost, B. M. *Tetrahedron* **1977**, *33*, 2615–2649.

(16) While this work was in progress, independent work involving the use of this reagent in reaction with acetylenes was reported by Nozaki and coworkers. Hibino, J.-I.; Natsubara, S.; Morizama, Y.; Koichiro, O.; Nozaki, H. *Tetrahedron Lett.* **1984**, *25*, 2151–2154.

(17) For a review of the reaction of various alkylaluminum reagents with carbonyl compounds, see: Eisch, J. J. *Compr. Organomet. Chem.* **1982**, *1*, 555.

(18) In assigning the relative stereochemistry in a related system (compound **7**), the authors[5,19] predicted a ^{13}C–$^{117,119}Sn$ coupling constant (C-5 to



7

tin) of 14 Hz for the trans isomer and 46 Hz for the cis isomer on the basis of Karplus relationships and assuming an equatorial conformation for the methyl group. We have assumed a similar equatorial bias for the carbomethoxy group in compound **4** in making our stereochemical assignments.

(19) Dumartin, G.; Quintard, J.-P.; Pereyre, M. *J. Organomet. Chem.* **1980**, *185*, C34–C36.

(20) Dibutyltin dichloride catalyzes the isomerization of crotyl tributyltin at 30 °C. Since Lewis acids such as diethylaluminum acetate are presumably present in the reaction mixture, it is likely that isomerization is occurring by a similar mechanism. For a recent paper, see: Gambaro, A.; Morton, D.; Tagliavani, G. *J. Organomet. Chem.* **1981**, *210*, 57–62.

(21) For a rationale based on olefin coordination, see: Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1980**, *102*, 4730–4743. For a more thorough discussion of this rationale, see: Verhoeven, T. R. Ph.D. Thesis, University of Wisconsin, Madison, WI, 1979.

(22) Naruta, Y. *J. Am. Chem. Soc.* **1980**, *102*, 3774–3783.

(23) Maruyama, K.; Naruta, Y. *J. Org. Chem.* **1978**, *43*, 3796–3797.

period of 1 h, and stirring at 25 °C (or above) until the allylic acetate had disappeared as diagnosed by TLC. The solution was then cooled to 0 °C and an excess of aqueous ammonia solution was added slowly. After aqueous workup, the final separation was achieved via flash chromatography on silica gel using 1% triethylamine in all eluting solvents.

In summary, what we have presented is a very mild and efficient method for the formation of functionalized allylstannanes in a highly chemoselective and regioselective fashion. This functional group interconversion represents a net conversion of the electronic nature of the allyl acetate from electrophilic to nucleophilic (Figure 1). The ready availability of allyl acetates coupled with the high degree of selectivity exhibited by the aluminum–tin reagent makes this conversion a potentially valuable tool for organic synthesis. We are presently pursuing synthetic strategies revolving around this methodology.

Acknowledgment. We thank the National Institutes of Health (BI 1 F32 CA07473-01) for a fellowship to James W. Herndon and to the National Science Foundation for their generous support of our programs.

Registry No. 1, 92074-24-3; *cis*-**4**, 92097-37-5; *trans*-**4**, 92097-38-6; (*R**,*R**)-**5**, 92097-43-3; (*R**,*S**)-**5**, 92097-39-7; **6**, 92097-40-0; **7**, 60729-55-7; A, 92097-35-3; B, 92097-36-4; CH_3CH_2CHO, 123-38-6; $(Bu_3Sn)_2$, 813-19-4; Et_2AlCl, 96-10-6; (*E*)-$PhCH{=}CHCH_2OAc$, 21040-45-9; (*E*)-$PhCH{=}CHCH_2SnBu_3$, 74785-32-3; (*E*)-$(CH_3)_2C{=}CH(CH_2)C(CH_3){=}CHCH_2OAc$, 105-87-3; $(CH_3)_2C{=}CH(CH_2)_2C(CH_3)(OAc){=}CH_2$, 115-95-7; (*E*)-$(CH_3)_2C{=}CH(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 67883-63-0; (*Z*)-$(CH_3)_2C{=}CH(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-30-8; 4-$BrC_6H_4(CH_2)_2C(CH_3)(OAc){=}CH_2$, 92097-41-1; (*E*)-4-$BrC_6H_4(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-31-9; (*Z*)-4-$BrC_6H_4(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-32-0; $CH_3CO(CH_2)_{10}CH(OAc)CH{=}CH_2$, 92097-42-2; 17α-22-acetoxy-chola-4,23-dien-3-one, 92216-14-3; (17α,22*E*)-24-(tributylstannyl)-chola-4,22-dien-3-one, 92097-33-1; (17α,22*Z*)-24-(tributylstannyl)-chola-4,22-dien-3-one, 92097-34-2.

Supplementary Material Available: Characterization data for organostannanes from Table I, entries 4–7, and for compounds **5** and **6** (3 pages). Ordering information is given on any current masthead page.

On the Regiochemistry of Metal-Catalyzed Allylic Alkylation: A Model

Barry M. Trost* and Ming-Hong Hung

McElvain Laboratories of Organic Chemistry
Department of Chemistry, University of Wisconsin
Madison, Wisconsin 53706

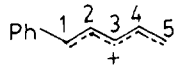
Received June 28, 1984

Allylic alkylation reactions with stabilized anions that proceed on metal templates introduce a new dimension for selectivity that is not necessarily bound by the structure of the substrate.[1-5] Regiocontrol, in particular, appears interesting but somewhat confusing. For example, Pd templates generally lead to reaction at the less hindered terminus of the allyl fragment,[1,6] Mo templates lead to reaction at the more hindered end with malonate as a nucleophile but not with more hindered nucleophiles,[2] and W templates have shown a bias for reaction at the more hindered position regardless of nucleophile.[3] While reaction at the less substituted terminus logically derives from the influence of steric factors, the source and, consequently, predictability of the reaction at the more hindered position is uncertain. We wish to suggest a model that addresses this major concern.

Allylmetal complexes can be viewed as allyl cations bonded to zero-valent metal. In order to generate the simplest possible model, we probed the question of the intrinsic bias for nucleophilic attack on the cation itself in the absence of any steric or metal effects. Lets consider the phenylpentadienyl cation. Table I lists relevant data from MNDO and INDO calculations. On the basis of charge considerations, the order of attack should be C(1) ~ C(3) > C(5). Frontier orbital considerations as revealed by the LUMO coefficients predict exactly the same order.

In order to test these predictions, we must realize that these complexes are η^3 species. Thus, in the absence of any Michael-type addition and assuming equilibration of the two regioisomeric η^3 complexes is slow relative to alkylation, the regiochemistry of alkylation will also depend on which complex is generated as shown in Scheme I. On the basis of charge and frontier orbital considerations, complex A should alkylate at C(3) and complex B almost equally at C(1) and C(3).

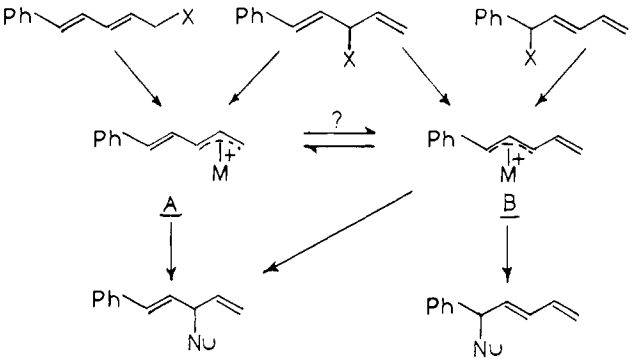
Table I. MO Calculations of Phenylpentadienyl Cation



	C(1)	C(2)	C(3)	C(4)	C(5)
			Total Charge		
MNDO	0.286	−0.226	0.246	−0.203	0.150
INDO	0.246	−0.059	0.239	−0.013	0.139
			p_z Occupancy[a]		
MNDO	0.618	1.141	0.658	1.114	0.722
INDO	0.654	1.087	0.688	1.044	0.791
			p_z Charge[a]		
MNDO	0.382	−0.141	0.342	−0.114	0.278
INDO	0.346	−0.087	0.312	−0.044	0.209
			LUMO Coefficients		
MNDO	−0.600	−0.014	0.556	−0.026	−0.355
INDO	0.571	0.016	−0.539	−0.003	0.392

[a] p_z occupancy and p_z charge refer to the π system orthogonal to the molecular plane.

Scheme I. Predicted Regioselectivity of Alkylation of the Phenylpentadienyl System



(1) For palladium-catalyzed reactions, see: Trost, B. M.; Verhoeven, T. R. *Compr. Organomet. Chem.* **1982**, *8*, 779. Tsuji, J. "Organic Synthesis with Palladium Compounds"; Springer-Verlag: Berlin, 1980. Trost, B. M. *Tetrahedron* **1977**, *33*, 2615.

(2) For molybdenum templates, see: Trost, B. M.; Lautens, M. *Organometallics* **1983**, *2*, 1687; *J. Am. Chem. Soc.* **1983**, *105*, 3343; *J. Am. Chem. Soc.* **1982**, *104*, 5543.

(3) For tungsten templates, see: Trost, B. M.; Hung, M.-H. *J. Am. Chem. Soc.* **1983**, *105*, 7757.

(4) For nickel templates, see: Cuvigny, T.; Julia, M. *J. Organomet. Chem.* **1983**, *250*, C21. Consiglio, G.; Morandini, F.; Piccolo, O. *J. Chem. Soc., Chem. Commun.* **1983**, 112.

(5) For iron and cobalt templates, see: Roustan, J. L.; Merour, J. Y.; Houlihan, F. *Tetrahedron Lett.* **1979**, 3721.

(6) (a) Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1976**, *98*, 630. (b) Akermark, B.; Hansson, S.; Krakenberger, B.; Vitagliano, A.; Zetterberg, K. *Organometallics* **1984**, *3*, 679. (c) Keinan, E.; Sahai, M. *J. Chem. Soc., Chem. Commun.* **1984**, *648*. (d) Curtis, M. D.; Eisenstein, O. *Organometallics* **1984**, *3*, 887. Also see: Davies, S. G.; Green, M. L. H.; Mingos, D. M. P. *Tetrahedron* **1978**, *34*, 3047.

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