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Silylstannanes in Organic Synthesis. Scope and Limitation of Palladium-Catalyzed Reaction with Acetylenes

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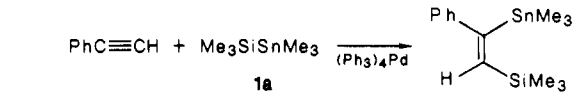
Terminal acetylenes react with silylstannanes in the presence of catalytic amounts of tetrakis(triphenylphosphine)palladium to give highly regio- and stereoselective addition (cis addition with tin always adding to the internal position). The process is general and tolerates a number of functional groups including Cl, OH, OTHP, and CN. With propargyl substitution, however, the reaction is not useful. Several reactions of silyl tin olefins (transmetalation, halogenation, and $AlCl_3$-catalyzed acylation) are described. These reactions allow useful organic fragments (or halogen) to be introduced while generally retaining the silicon moiety available for further manipulation.

Bimetallic reagents are presently emerging as powerful new agents in the arsenal of the synthetic chemist. Species containing the Sn–Cu,[3] Sn–Sn,[4] Sn–Si,[5] Si–Si,[6] Zn–Si,[7] Sn–Al,[8] Sn–Li,[9] and Te–Si[10] bonds, for example, have been recently employed to effect novel reactions. Particularly exciting is the fact that one or both of the metallic components of these reagents are retained in the resulting products, thus providing a convenient handle for further transformation. Along these lines, we have been examining the chemistry of silylstannanes. While they have been known for about 20 years,[11] their chemistry has not been extensively explored.[5] We recently described a new reaction of silylstannanes with acetylenes which is catalyzed by palladium.[12] This process yields olefins with vicinal silicon and tin substitution. Herein we present a study of the scope and limitations of this silylstannylation reaction and briefly survey the chemistry of the silyl tin olefins.

Results and Discussion

Silylstannane Synthesis. Silylstannanes 1 are easily prepared by generating a tin anion (lithium reduction of a distannane[12] or deprotonation of a tin hydride[9,13]) and quenching with a silyl chloride. The clear colorless liquid products are easily purified by distillation.[14] We handle 1 under an inert atmosphere in subdued light although we have not actually checked their photochemical and oxygen sensitivity. The thermal stability of (trimethylsilyl)trimethyltin was tested at 185 °C where it was found to survive for 6 h in a sealed tube with no decomposition.

Reaction with Acetylenes. We began exploring the chemistry of (trimethylsilyl)trimethyltin (**1a**) with phenylacetylene and found that adduct **2a** could be formed



2a

at room temperature in the presence of tetrakis(triphenylphosphine)palladium. In subsequent reactions of

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(1) Summer Du Pont Resident Research Participant 1985.
(2) Contribution No. 4029 from the department.
(3) Piers, E.; Morton, H. E. *J. Chem. Soc., Chem. Commun.* **1978**, 1033–1034.
(4) Killing, H.; Mitchell, T. N. *Organometallics* **1984**, *3*, 1318–1320. Mitchell, T. N.; Amamria, A.; Killing, H.; Rutschow, D. *J. Organomet. Chem.* **1983**, *241*, C45–C47.
(5) Kosugi, M.; Ohya, T.; Migita, T. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 3539–3540. Azizian, H.; Eaborn, C.; Pidcock, A. *J. Organomet. Chem.* **1981**, *215*, 49–58.
(6) Watanabe, H.; Kobayashi, M.; Saito, M.; Nagai, Y. *J. Organomet. Chem.* **1981**, *216*, 149–157. Matsumoto, H.; Nagashima, S.; Yoshihiro, K.; Nagai, Y. *J. Organomet. Chem.* **1975**, *85*, C1–C3. Matsumoto, H.; Nagashima, S.; Kato, T.; Nagai, Y. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 279–280.
(7) Okuda, Y.; Wakamatsu, K.; Tückmantel, W.; Oshima, K.; Nozaki, H. *Tetrahedron Lett.* **1985**, *26*, 4629–4632.
(8) Matsubara, S.; Tsuboniwa, N.; Morizawa, Y. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 3242–3246.
(9) Still, W. C. *J. Am. Chem. Soc.* **1978**, *100*, 1481–1487. Tamborski, C.; Ford, F. E.; Soloski, E. J. *J. Org. Chem.* **1963**, *28*, 237–239.
(10) Sasaki, K.; Aso, Y.; Otsubo, T.; Ogura, F. *Tetrahedron Lett.* **1985**, *26*, 453–456.
(11) Schumann, H.; Ronecker, S. *Z. Naturforsch. B* **1967**, *B22*, 452–453.
(12) Chenard, B. L.; Laganis, E. D.; Davidson, F.; RajanBabu, T. V. *J. Org. Chem.* **1985**, *50*, 3666–3667. Also see: Mitchell, T. N.; Killing, H.; Dicke, R.; Wickenkamp, R. J. *J. Chem. Soc., Chem. Commun.* **1985**, 354–355.
(13) We thank Dr. M. H. Fisch and Argus Chemical Co. for a generous sample of trimethyltin hydride.
(14) For the lower boiling silylstannanes, spinning-band distillation was used to prepare analytically pure material.

0022-3263/86/1951-3561$01.50/0

1a with other less reactive acetylenes,[15] a side reaction complicated the process. With the aid of GC/MS it was shown that **1a** will readily equilibrate with hexamethylditin and hexamethyldisilane in a reaction catalyzed by $(Ph_3P)_4Pd$. Fortunately with higher homologues of **1**, the

$$\mathbf{1a} \rightleftharpoons Me_3SiSiMe_3 + Me_3SnSnMe_3$$

disproportionation was inhibited and in subsequent studies **1a** was avoided.

The reaction of acetylenes and silylstannanes is highly regio- and stereoselective. In most cases the adducts form from cis addition and in all examples examined to date the tin group was attached to the internal olefin carbon atom. Attempts to force the stannyl group into the terminal position by increasing the size of its substituents (methyl to butyl to phenyl) did not alter the regiochemistry. In two examples (acetylene and (trimethylsilyl)acetylene) the reaction gave a mixture of cis and trans products.[16] We believe this to be the result of initial cis addition followed by palladium-catalyzed equilibration of the product. In support of this hypothesis we subsequently found that if the catalyst was not removed prior to purification by distillation, the higher boiling adducts could be partially isomerized. Therefore it was not surprising that the disubstituted adduct from acetylene would isomerize at a lower temperature. Presumably the trisubstituted product from (trimethylsilyl)acetylene is readily isomerized because the length of the Si–C_{sp^2} bond (1.84 Å[17]) is much longer than the C_{sp^3}–C_{sp^2} bond (1.46 Å[17]), rendering the olefin more available to the catalyst than the other trisubstituted products.

The structures of the adducts were easily confirmed by the Sn–H coupling with the lone vinyl proton.[18] Trans constants are generally about 180 Hz, whereas cis and geminal values are about 100 Hz.[4] Our values of 165–230 Hz for these couplings are therefore easily assigned to the trans structures.

The broad scope of this acetylene addition reaction is demonstrated in Table I. However, the process is limited to terminal acetylenes, presumably due to steric considerations. In fact even terminal acetylenes with large substituents (*tert*-butyl) are reluctant to participate.

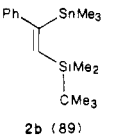
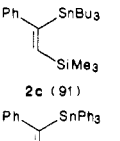
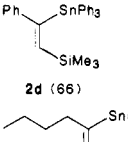
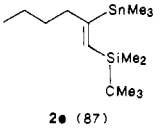
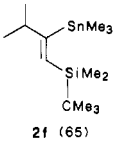
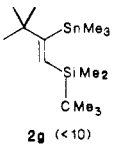
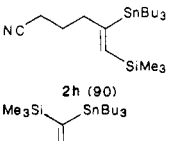
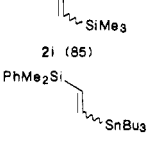
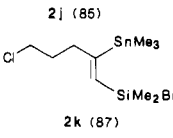
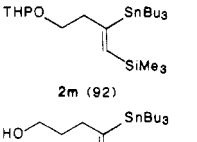
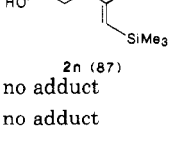
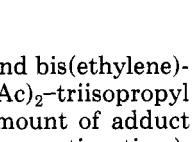
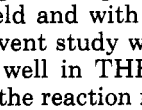
While we have not exhaustively examined all functional groups for compatibility under the reaction conditions [typically 65 °C/8–72 h/THF/1 mol % $(Ph_3P)_4Pd$], a number of substituents were tolerated nicely. For example, Cl, CN, OTHP, OH, and Me_3Si groups had little effect on the yield of adduct when present in the starting acetylene. It was satisfying to learn that the hydroxyl group did not interfere as we were particularly concerned about side reactions in this system.

Substituents proved to be a problem only when located in the propargylic position. For example, propargyl bromide was converted into a multitude of products. A similar result was observed with 2-methyl-3-butyn-2-ol acetate.

Tetrakis(triphenylphosphine)palladium was the catalyst of choice being effective at 1 mol % or less. A number of other catalysts were examined, including $Pd(OAc)_2$, $Pd(OAc)_2$–triisopropyl phosphite, $(CH_3CN)_2PdCl_2$, Pd/C, $Mo(CO)_6$, $(Ph_3P)_3RhCl$, cyphos RhCl dimer, and Rh/Al_2O_3, K_2PdCl_4, K_2PtCl_4, chloroplatinic acid, and bis(ethylene)-rhodium acetoacetate. Only the $Pd(OAc)_2$–triisopropyl phosphite system gave a significant amount of adduct (albeit in lower yield and with a longer reaction time).

An extensive solvent study was not performed as the chemistry worked well in THF and neat. In fact for volatile acetylenes the reaction may be best effected in a sealed tube.

Table I. Reaction of Silylstannanes with Acetylenes

silylstannane	acetylene	product (% isolated yield)
t-$BuMe_2SiSnMe_3$ (**1b**)	PhC≡CH	 **2b** (89)
$Bu_3SnSiMe_3$ (**1c**)	PhC≡CH	 **2c** (91)
$Ph_3SnSiMe_3$ (**1d**)	PhC≡CH	 **2d** (66)
t-$BuMe_2SiSnMe_3$ (**1b**)	1-hexyne	 **2e** (87)
t-$BuMe_2SiSnMe_2$ (**1b**)	*i*-PrC≡CH	 **2f** (65)
t-$BuMe_2SiSnMe_3$ (**1b**)	*t*-BuC≡CH	 **2g** (<10)
$Bu_3SnSiMe_3$ (**1c**)	$NC(CH_2)_3C{\equiv}CH$	 **2h** (90)
$Bu_3SnSiMe_3$ (**1c**)	$Me_3SiC{\equiv}CH$	 **2i** (85)
$PhMe_2SiSnBu_3$ (**1e**)	HC≡CH	 **2j** (85)
n-$BuMe_2SiSnMe_3$ (**1f**)	$Cl(CH_2)_3C{\equiv}CH$	 **2k** (87)
$Bu_3SnSiMe_3$ (**1c**)	$THPOCH_2CH_2C{\equiv}CH$	 **2m** (92)
$Bu_3SnSiMe_3$ (**1c**)	$HOCH_2CH_2CH_2C{\equiv}CH$	 **2n** (87)
$Bu_3SnSiMe_3$ (**1c**)	$BrCH_2C{\equiv}CH$	no adduct
$Bu_3SnSiMe_3$ (**1c**)		no adduct

Reactions of Silyl Tin Olefins. In principle, it should be possible to selectively and sequentially carry out further reactions of both the vinylsilane and vinylstannane units

(15) We believe the less reactive acetylenes are ones which are poor ligands for palladium because of steric bulk.

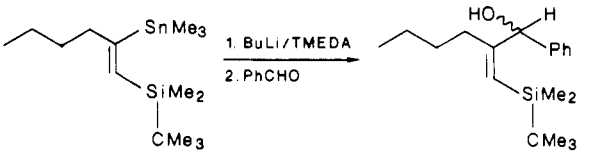
(16) Mitchell has also observed one case where a cis–trans mixture was obtained. See ref 12.

(17) Hine, J. *Structural Effects on Equilibria in Organic Chemistry*, Wiley Interscience: New York, 1975; p 48.

(18) Tin has two NMR active isotopes (117 and 119 amu) each with a spin of $^1/_2$ and present at about 7% natural abundance.

which coexist in **2**. This could ultimately lead to complex molecular structures from simple acetylenic starting materials. We have begun to examine the reactivity of **2**, focusing on the vinylstannane, and present here our observations regarding transmetalation, halogenation, and aluminum chloride catalyzed acylation.

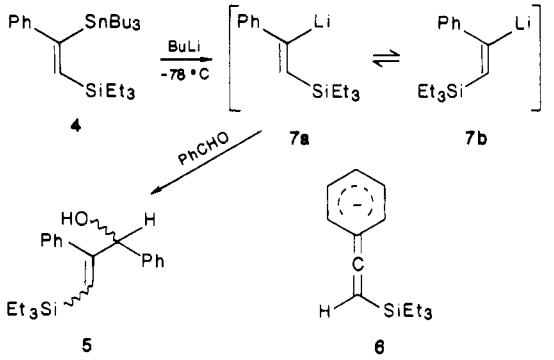
In the literature lithium–tin exchange of vinylstannanes has been shown to be a fickle reaction, excellent in some cases[19] and poor in others.[20] In our hands transmetalation of **2e** proved to be a low efficiency process leading to a 25% yield of product **3** on trapping with benzaldehyde. The reaction can be substantially improved, however (60% isolated yield), by conducting the process in the presence of 1.2 equiv of TMEDA. Surprisingly, styrene derivative



2e **3**, 60%

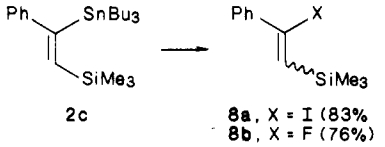
4 did not require TMEDA for efficient transmetalation. Exchange was complete within seconds at −78 °C or lower and the yield of allyl alcohol **5** was comparable.

Normally vinyl anions are configurationally stable; however, lithiated **4** was not. It rapidly equilibrated presumably through **6** resulting in a cis–trans mixture of **5** being formed. Interestingly, the product resulting from **7b** in which the vinyl anion is trans to the silicon atom was the preferred configuration as judged by the product mixture obtained (1:4 cis–trans ratio). The identities of *cis*- and *trans*-**5** were secured by NOE experiments.



4 **7a** **7b** **5** **6**

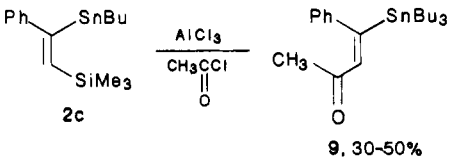
Halogenation of **2** was briefly examined next. Iodine is introduced into **2c** by simply stirring it in a methylene chloride solution with iodine. In this manner **8a** was obtained as a clear oil (83%). While **8a** could be isolated



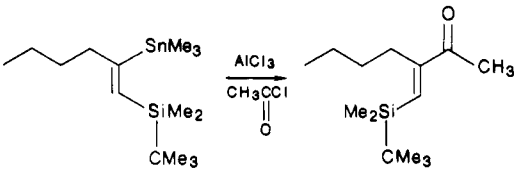
2c **8a**, X = I (83%)
8b, X = F (76%)

by simple flash chromatography and characterized spectroscopically, it was relatively unstable, decomposing to a black resin within 2 days in the dark at ambient temperature. Attempts to introduce fluorine by direct contact of **2c** with elemental fluorine were complicated by overfluorination of both the vinyl and phenyl groups. Fluorination was conveniently effected, however, by transmetalation followed by quenching with an *N*-alkyl-*N*-fluorosulfonamide according to the procedure of Barnette[21] to give **8b** in 76% yield. All of the halogenation products **8** obtained from these reactions were cis–trans mixtures. We also note that desilylation was not observed.

Finally we have examined Lewis acid catalyzed acylation of **2**. This was intriguing because it provided an opportunity to directly compare the succeptability of the vinylsilane and -stannane moieties to this vigorous electrophilic substitution reaction.[22] We find that the substitution is very sensitive to the carbon side chain present in **2**. Thus, **2c** upon treatment with $AlCl_3$ and acetyl chloride in methylene chloride (0 °C, 1 h) gives 30–50% yields of **9** wherein silicon has been replaced preferentially.

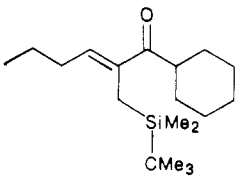


2c **9**, 30-50%



2e **10**, 69%

In contrast, **2e**, when subjected to the same conditions, yields **10** (69%). Again the stereochemistry about the double bond was shown by NOE experiments. Clearly tin is the preferred leaving group for electrophilic substitution and only with the additional carbonium ion stabilizing ability of the phenyl group can silicon compete effectively under these conditions. The acylation reaction is not limited to acetyl chloride. Others such as benzoyl chloride and cyclohexanecarboxylic acid chloride work equally well. It is important to recognize that double-bond migration can be a competing process under these conditions. Indeed, the product obtained from the reaction of **2e** and cyclohexanecarboxylic acid chloride was **11**. This structure was proved by ^{13}C NMR which showed the methylene carbon attached to silicon at 28.50 ppm with a Si–C coupling of 65 Hz.



11

Summary

The reaction of silylstannanes with acetylenes has been extensively studied. In general, any terminal acetylene will react in the presence of a catalytic amount of tetrakis(triphenylphosphine)palladium to give cis silyl tin olefin products in high yield. A number of substituents have been found to tolerate the reaction conditions which greatly enhances the potential utility of the process. Several reactions of adducts **2** were examined, emphasizing conversion of the vinylstannane moiety into some other useful organic fragment. Further efforts in this area will focus on direct manipulation of the vinylsilane unit either

(19) See, for example: Piers, E.; Morton, H. E. *J. Org. Chem.* **1979**, *44*, 3437–3439.
(20) See, for example: Barth, W.; Paquette, L. A. *J. Org. Chem.* **1985**, *50*, 2438–2443.
(21) Barnette, W. E. *J. Am. Chem. Soc.* **1984**, *106*, 452–454.
(22) For an example of acylation of vinylsilanes, see: Mikami, K.; Kishi, N.; Nakai, T. *Tetrahedron Lett.* **1983**, *24*, 795–798, and references cited therein.

prior or subsequent to vinylstannane reaction.

Experimental Section

General Procedures. Melting points were taken with a Thomas-Hoover or a Buchi capillary melting point apparatus and are uncorrected. Infrared spectra were recorded on a Nicolet 7199 FT infrared spectrometer and are reported in reciprocal centimeters. Only strong bands are reported unless otherwise stated. Proton NMR were obtained at either 360 or 300 MHz with Nicolet FT NMR instruments. NMR data are reported in parts per million (δ) downfield from tetramethylsilane in deuteriochloroform. Analyses were determined by either Micro-Analysis, Inc., Wilmington, DE, or Galbraith Laboratories, Inc., Knoxville, TN. GLC analysis was performed on an HP5790 instrument using a 10% SP2100 columm (6 ft × $^1/_8$ in., stainless steel) and the following temperature program: 100 °C for 1 min, increase at 15° per min to 250 °C, hold at 250 °C for 15 min.

(*tert*-Butyldimethylsilyl)trimethylstannane (1b). Method 1. This reaction is run in a three-necked flask with a condenser, magnetic stir bar, and an ultrasonic bath under an argon atmosphere. Hexamethylditin (25 g, 76.3 mmol) was dissolved in THF (100 mL) and lithium metal (1.3 g, 185 mmol) was added in small pieces to the solution (the metal was flattened with a hammer and rinsed briefly in ethanol and then toluene before addition). The ultrasonic bath was turned on and the solution was sonified for 24 h during which time it gently refluxed. The ultrasonic bath was replaced with a magnetic stirrer and the solution was cooled to ambient temperature. *tert*-Butyldimethylsilyl chloride (11.5 g, 76.3 mmol) was added all at once and the mixture was stirred 10 min. A sample showed no hexamethylditin and one new product (t_R 5.04 min). The reaction was filtered under nitrogen through Celite into a flask and the THF was distilled off at 100-mm pressure. The vacuum was lowered to 11 mm and the distillation was continued to give one fraction (bp 69 °C) of 95% pure product. This fraction was spinning-band distilled to give 8.8 g (41%) of (*tert*-butyldimethylsilyl)trimethylstannane as a clear colorless oil: bp 72–73.5 °C/11 mm; NMR ($CDCl_3$, 80 MHz) 0.9 (s, 9 H), 0.12 (s, 6 H), 0.06 (s, 9 H); IR (neat) 2960, 2933, 2900, 2890, 2860, 1472, 1465, 1365, 1255, 1247, 1008, 839, 823, 805, 760, 666, 519, 509.

Anal. Calcd for $C_9H_{24}SiSn$: C, 38.74; H, 8.67. Found: C, 38.72; H, 8.61.

(*tert*-Butyldimethylsilyl)trimethylstannane (1b). Method 2. A three-necked flask with magnetic stirring, septum, and nitrogen inlet was dried under a nitrogen stream and charged with THF (200 mL) and diisopropylamine (25.2 mL, 182 mmol). The solution was chilled to −10 °C and *n*-butyllithium (100 mL, 160 mmol, 1.6 N) was added dropwise via addition funnel (20 min). The solution was stirred for 5 min and then trimethyltin hydride (40 mL, 145.6 mmol, 60% in toluene) was added via syringe over 10 min. The solution was stirred 45 min at 0 °C and then *tert*-butyldimethylsilyl chloride (24.1 g) was added as a solid. The mixture was stirred 30 min and then a GLC trace was taken which showed one new product and a very small amount of starting material left. Gradually, lithium chloride precipitated out of the solution. The volatiles were pumped off at 100 mm, then the mixture was filtered under nitrogen, and the filtrate was spinning-band distilled as above to give 29.54 g (72%) of (*tert*-butyldimethylsilyl)trimethylstannane as a clear oil which was identical with that prepared by method 1.

(Trimethylsilyl)trimethylstannane (1a) was prepared in 31% yield by method 1 and 43% yield by method 2: bp 77 °C/95 mm by spinning-band distillation (lit.[11] bp 144–146 °C/760 mm); IR (neat) 2980, 2950, 2910, 2900, 1248, 855, 839, 766, 695, 620, 519, 508; NMR (80 MHz) 0.25 (s, 9 H with Sn coupling of 32 Hz), 0.1 (s, 9 H with Sn coupling of 47, 46 Hz).

2-(*tert*-Butyldimethylsilyl)-1-phenyl-1-(trimethylstannyl)ethene (2b). The following is a representative synthesis of silyl tin olefins. To a three-necked flask with nitrogen inlet and magnetic stirring were added THF (30 mL), phenylacetylene (2.2 mL, 20 mmol), (*tert*-butyldimethylsilyl)trimethyltin (5.60 g, 20 mmol), and tetrakis(triphenylphosphine)palladium (100 mg). The solution was heated to 70 °C for 3 h. One new product was formed by GLC analysis (t_R 11.7 min). The solution was concentrated; then the residue was dissolved in ether and filtered through Celite. The ether was evaporated to leave a yellow oil which was Kugelrohr distilled to give 430 mg, bp 25–40 °C (0.1 mm), of recovered silyl-tin compound and 6.83 g (89%) of white solid (**2b**): bp 100 °C (0.1 mm); mp 46.5–48 °C; NMR (300 MHz) 7.34–7.26 (m, 2 H), 7.19–7.13 (m, 1 H), 7.06–6.97 (m, 2 H), 6.6 (s, 1 H with Sn–H coupling of 182, 174 Hz), 0.93 (s, 9 H), 0.18 (s, 9 H with Sn–H coupling of 53, 51 Hz), 0.10 (s, 6 H); ^{13}C NMR (Sn–C coupling in parentheses) 166.69 (455, 435), 151.5 (51.5, 49), 145.13 (66.7, 63.6), 127.6 (3), 125.99 (18.7), 125.6 (5.76), 26.58, 16.8, −4.57, −5.7 (338.6, 323.6); IR (KBr) 2945, 2920, 2880, 1482, 1467, 1459, 1250, 1240, 855, 836, 821, 805, 775, 765, 755, 735, 728, 700, 522, 509.

Anal. Calcd for $C_{17}H_{30}SiSn$: C, 53.56; H, 7.93. Found: C, 53.77; H, 7.60.

1-(*tert*-Butyldimethylsilyl)-2-(trimethylstannyl)-1-hexene (2e) was prepared as above (70 °C for 24 h): 87%, Kuglerohr pot temperature 76–83 °C/0.2 mm; IR (neat) 2950, 2925, 2855, 1470, 1462, 1360, 1252, 1246, 838, 822, 803, 767, 521; NMR (360 MHz) 6.36 (s, 1 H with Sn coupling of 198, 189 Hz), 2.4 (dt, J = 1.5, 7 Hz, 2 H with Sn coupling of 52 Hz), 1.3 (m, 4 H), 0.9 (s with a triplet buried under it, 12 H), 0.2 (s, 9 H with Sn coupling of 53, 51 Hz), 0.05 (s, 6 H).

Anal. Calcd for $C_{15}H_{34}SiSn$: C, 49.88; H, 9.49. Found: C, 49.75; H, 9.21.

5-Chloro-1-(butyldimethylsilyl)-2-(trimethylstannyl)-1-pentene (2k) was prepared as above (70 °C/24 h): clear colorless oil, 87% (bp 86–96 °C/0.13 mm); NMR (360 MHz) 6.38 (t, J = 1 Hz, 1 H with Sn–H coupling of 194 and 185 Hz), 3.5 (t, J = 7 Hz, 2 H), 2.47 (dt, J = 1, 7.5 Hz, 2 H with Sn–H coupling of 49 Hz), 1.81 (quintet, J = 7.5 Hz, 2 H), 1.31 (m, 4 H), 0.88 (t, J = 7 Hz, 3 H), 0.58 (m, 2 H), 0.22 (s, 9 H with Sn–H coupling of 53 and 51 Hz), 0.08 (s, 6 H).

Anal. Calcd for $C_{14}H_{31}ClSiSn$: C, 44.06; H, 8.19. Found: C, 43.84; H, 8.15.

1,2-Bis(trimethylsilyl)-1-(tributylstannyl)ethene (2i) was prepared as above (65 °C/48 h) as a mixture of cis/trans isomers: clear pale yellow oil (85%); NMR (360 MHz) [7.48 (s with Sn coupling of 244, 233 Hz), and 7.29 (s with Sn coupling of 175, 167 Hz), 1 H], 1.54–1.41 (m, 6 H), 1.39–1.25 (seven-line multiplet—actually two overlapping sextets, 6 H), 0.99–0.84 (m, 15 H), 0.16, 0.15, 0.13, and 0.06 (four singlets, 18 H); ^{13}C NMR (Sn–C coupling in parantheses) 172.93 (215.5, 206.5 Hz) and 171.17 (269, 257 Hz) quaternary vinyl carbons, 166.19 (41 Hz, Si coupling 62 Hz) and 163.72 (12 Hz, Si coupling 66 Hz) protonated vinyl carbon, 29.28 (19 Hz) and 29.17 (18.5 Hz) CH_2 next to methyl in $SnBu_3$, 27.54 (61 Hz) and 27.39 (55 Hz) CH_2 β to Sn in $SnBu_3$, 13.69 and 13.62 (no Sn coupling) methyls in $SnBu_3$, 12.03 (309, 297 Hz) and 10.96 (306, 293 Hz) CH_2 α to Sn, 1.05 (11 Hz) and 0.74 (no Sn coupling) and −0.31 (no Sn coupling) and −0.43 (4 Hz) trimethylsilyl methyls; IR (neat) 2960, 2930, 2885, 2860, 1245, 855, 835.

Anal. Calcd for $C_{20}H_{46}Si_2Sn$: C, 52.06; H, 10.05. Found: C, 51.88; H, 10.10.

(Trimethylsilyl)tributylstannane (1c) was prepared by method 2 on a 320-mmol scale: 97 g (83%), clear colorless oil; bp 87 °C/0.5 mm; IR (neat) 2960, 2930, 2900, 2888, 2860, 1467, 1460, 1378, 1245, 837, 692; NMR (300 MHz) 1.48 (m, 6 H), 1.3 (sextet, J = 7 Hz, 6 H), 0.95–0.81 (m, 15 H), 0.24 (s, 9 H with Sn coupling of 26 Hz).

3-(Tributylstannyl)-4-(trimethylsilyl)-3-buten-1-ol (2m) THP ether was prepared as above (70 °C/48 h): 92% as a clear yellow oil, bp 150 °C/0.05 mm (Kugelrohr pot temperature); NMR (360 MHz) 6.46 (s with Sn–H coupling of 178, 170 Hz, 1 H), 4.59 (t, J = 3 Hz, 1 H), 3.92–3.82 (m, 1 H), 3.73–3.63 (m, 1 H), 3.55–3.45 (m, 1 H), 3.4–3.28 (m, 1 H), 2.66–2.46 (t, J = 7 Hz, with Sn–H coupling of 42 Hz, 2 H), 1.87–1.25 (m, 18 H), 1.0–0.8 (m, 15 H), 0.09 (s, 9 H); IR (neat) 2948, 1170–1140 (m), 850.

Anal. Calcd for $C_{24}H_{50}O_2SiSn$: C, 55.71; H, 9.74. Found: C, 55.62; H, 10.01.

5-Chloro-2-(tributylstannyl)-1-(trimethylsilyl)-1-pentene was prepared as above (70 °C/72 h): 80%, clear yellow oil, 110–130 °C/0.5 mm (Kugelrohr pot temperature); NMR (360 MHz) 0.11 (s, 9 H), 0.85–4.0 (m, 15 H), 1.26–1.4 (m, 6 H), 1.4–1.55 (m, 6 H), 1.75–1.85 (m, 2 H), 2.3–2.54 (distorted t, J = 12 Hz, J_{Sn-H} = 44 Hz, 2 H), 3.46–3.55 (t, J = 15 Hz, 2 H), 6.4 (long range coupled s, J_{Sn-H} = 180, 176 Hz, 1 H); IR (neat) 2900, 1450, 1250, 860, 838.

Anal. Calcd for $C_{20}H_{43}ClSiSn$: C, 51.57; H, 9.31. Found: C, 51.35; H, 9.11.

4-(Tributylstannyl)-5-(trimethylsilyl)pent-4-en-1-ol (2n) was prepared as above (70 °C/72 h): 88% as a clear oil; bp 120–160 °C/0.5 mm (Kugelrohr pot temperature); NMR (360 MHz) 0.12 (s, 9 H), 0.86–0.98 (m, 15 H), 1.26–1.36 (m, 6 H), 1.4 ppm (s, 1 H, disappears upon D_2O addition), 1.43–1.54 (m, 6 H), 2.25–2.44 (m, J_{Sn-H} = 44, 40 Hz, 2 H), 1.55–1.65 (m, 2 H), 3.58–3.68 (m, 2 H), 6.47 (m, J_{Sn-H} = 180 Hz, 1 H); IR (neat) 3250–3400 (br), 850.

Anal. Calcd for $C_{20}H_{44}OSiSn$: C, 53.70; H, 9.91. Found: C, 53.76; H, 9.89.

3-(Tributylstannyl)-4-(trimethylsilyl)-3-buten-1-ol was prepared as above (70 °C/72 h): 77%, clear yellow oil; bp 100–140 °C/0.5 mm (Kugelrohr pot temperature); NMR (360 MHz) 0.12 (s, 9 H), 0.86–0.98 (m, 15 H), 1.26–1.39 (m, 6 H), 1.43–1.54 (m, 6 H), 1.72 (s, 1 H, disappears upon D_2O addition), 2.45–2.65 (m, J_{Sn-H} = 50 Hz, 2 H), 3.5–3.63 (m, 2 H), 6.47 (m, J_{Sn-H} = 180 Hz, 1 H); IR (neat) 3250–3400 (br), 1555, 850.

Anal. Calcd for $C_{19}H_{42}OSiSn$: C, 52.67; H, 9.77. Found: C, 52.79; H, 9.85.

1-(Phenyldimethylsilyl)-2-(tributylstannyl)ethene (2j). A dry Fisher–Porter tube was charged under nitrogen with THF (20 mL), (tributylstannyl)phenyldimethylsilane (8.5 g, 20 mmol), and tetrakis(triphenylphosphine)palladium (0.18 g). The pressure gauge head was assembled, and the apparatus was chilled to 0 °C and evacuated to about 40 mm of pressure. The tube was charged with acetylene (5 psi) with stirring. The system was evacuated to 40 mm and the charging process was repeated two more times. Finally the charged tube was heated to 55 °C. Gradually the pressure dropped below atmospheric and the system was recharged with more acetylene. The pressure was increased to 10 psi and the charging process was repeated as necessary until acetylene consumption ceased (7 days). GLC at this time indicated no starting material was left and one major and one minor product were formed. The reaction was poured through a plug of neutral alumina with methylene chloride and the filtrate was concentration at reduced pressure. The residue was Kugelrohr distilled at 110–150 °C and 0.1 mm (pot temperature) to give 7.66 g (85%) of a mixture of adducts with the trans adduct being favored (4/1 over the cis product): NMR (360 MHz) of the trans product 7.55 (m, 2 H), 7.35 (m, 3 H), 6.94 (AB q = 138 Hz, J = 22 Hz, 2 H with Sn coupling of 100, 95 Hz), 1.57–1.23 (m, 12 H), 1.05–0.8 (m, 15 H), 0.35 (s, 6 H); IR (neat) 2960, 2930, 2870, 2860, 1248, 1115, 835, 820, 785, 730, 700.

Anal. Calcd for $C_{22}H_{40}SiSn$: C, 58.55; H, 8.93. Found: C, 58.31;, H, 8.89.

Transmetalation of Silyl Tin Olefins. Synthesis of 3. To a dry three-necked flask with magnetic stirrer and nitrogen inlet were added dry THF (4 mL), TMEDA (0.18 mL, 1.2 mmol), and 2-(tributylstannyl)-1-(*tert*-butyldimethylsilyl)-1-hexene (0.36 g, 1 mmol). The solution was chilled to −78 °C and butyllithium (0.75 mL, 1.2 mmol, 1.6 N) was added via syringe. The reaction was stirred for 1 h; then benzaldehyde (0.12 mL, 1.2 mmol) was added. The solution was warmed to ambient temperature and stirred 1 h. The solvent was removed at reduced pressure and the residue was partitioned between ether and water. The phases were separated and the organic layer was washed with brine and dried through a cone of calcium sulfate. Concentration left an oil which was chromatographed on silica gel (2 × 4 in., 3% ether/hexane, 100-mL fractions) to give 100 mL, nil; 700 mL, 240 mg of a mixture of butyltrimethyltin and starting material; 200 mL, nil; 600 mL, 180 mg (59%) of **3** as a clear colorless oil: NMR (300 MHz) 7.42–7.22 (m, 5 H), 5.59 (s, 1 H), 5.56 (d, J = 4 Hz, 1 H), 2.09–1.97 (m, 1 H), 1.84–1.73 (m, 1 H), 1.76 (d, J = 4 Hz, 1 H, exchangeable), 1.44–1.14 (m, 4 H), 0.96 (s, 9 H), 0.81 (t, J = 7 Hz, 3 H), 0.20 (s, 3 H), 0.18 (s, 3 H); IR (neat) 3460, 2955, 2930, 2860, 1612 (m), 1603 (m), 1470, 1463, 1450, 1257, 1250, 1035, 1022, 837, 825, 808, 755, 700.

Anal. Calcd for $C_{19}H_{32}OSi$: C, 74.93; H, 10.59. Found: C, 74.68; H, 10.75.

Preparation of 5. To a dry three-necked flask with magnetic stirrer, septum, and a nitrogen inlet were added 1-phenyl-1-(tributylstannyl)-2-(triethylsilyl)ethlene (5.06 g, 10 mmol) and THF (30 mL). The solution was chilled to −78 °C and butyllithium (7.6 mL, 12 mmol, 1.6 N) was added via syringe. The solution was stirred 10 min at −78 °C and then benzaldehyde (1.22 mL, 12 mmol) was added. The solution was allowed to warm to ambient temperature and stir 1 h. The reaction was concentrated onto silica gel (10 g) and flash chromatographed (3 × 4 in., 100-mL fractions, hexane eluent) to give 200 mL, nil; 1600 mL, 2 g of tetrabutyltin; 100 mL, nil. Continued elution with 5% ether/hexane gave 100 mL, nil; 700 mL, 0.18 g of a mixture of byproducts; 500 mL, 0.34 g of *Z* isomer; 700 mL plus 700 mL of 10% ether/hexane, 1.58 g of the *E* isomer. The *Z* and *E* isomers were each contaminated by their opposite isomer. The combined yield was 1.92 g, 59%: NMR (360 MHz) of the minor isomer (*Z*) 7.5–7.1 (m, 10 H), 6.07 (s, 1 H), 5.85 (d, J = 5 Hz, 1 H), 2.11 (d, J = 5 Hz, 1 H), 1.08 (t, J = 8 Hz, 9 H), 0.8 (q, J = 8 Hz, 6 H); IR (neat) 3630–3300 (br), 2970, 2910, 2875, 1595, 1492, 1450, 1002, 763, 753, 735, 718, 699; NMR (360 MHz) of the major isomer (*E*) 7.43–7.13 (m, 9 H), 6.88 (meta coupled d, J = 8 Hz, 1 H), 6.07 (long range coupled s, 1 H), 5.39 (d, J = 4 Hz, 1 H), 2.12 (d, J = 4 Hz, 1 H), 0.83 (t, J = 8 Hz, 9 H), 0.3 (long range coupled q, J = 8 Hz, 6 H); IR (neat) 3630–3200 (br), 2950, 2910, 2875, 1454, 1015, 1004, 737, 700.

Anal. Calcd for $C_{21}H_{28}OSi$: C, 77.72; H, 8.70. Found: C, 77.62; H, 8.82.

1-Iodo-1-phenyl-2-(trimethylsilyl)ethene (8a). To a three-necked flask equipped with magnetic stirrer, addition funnel, and a nitrogen inlet were added 1-phenyl-1-(tributylstannyl)-2-(trimethylsilyl)ethene (500 mg, 1.07 mmol) and dry methylene chloride (15 mL). The solution was chilled to 0 °C and a solution of iodine (275 mg, 1.07 mmol) in methylene chloride (35 mL) was added dropwise over 15 min. The mixture was allowed to warm to ambient temperature and stirred 3 h. The mixture was diluted with methylene chloride and extracted with water and brine; then it was dried through a cone of calcium sulfate and concentrated onto silica gel. Flash chromatography on silica gel (1 × 6 in., hexane, 100-mL fractions) gave 100 mL, nil, 200 mL, 270 mg, clear oil, 83%; NMR (80 MHz) 7.7–7.3 (m, 5 H), 6.9 (s, 1 H), 0.3 (s, 9 H). The compound decomposed on standing in the dark at ambient temperature for 24 h.

1-Fluoro-1-phenyl-2-(*tert*-butyldimethylsilyl)ethene (8b). To a dry three-necked flask equipped with magnetic stirrer, septum, and a nitrogen inlet were added 1-phenyl-1-(trimethylstannyl)-2-(*tert*-butyldimethylsilyl)ethene (3.8 g, 10 mmol) and THF (30 mL). The solution was chilled to −78 °C and butyllithium (7.6 mL, 12 mmol, 1.6 N) was added via syringe. The solution was stirred 3 min at −78 °C and then *N*-fluoro-*N*-norbornyl-*p*-toluenesulfonamide (2.8 g, 10 mmol) was dissolved in THF (10 mL) and added via syringe. The solution was allowed to warm to ambient temperature and stirred for 2 h. GLC showed a *Z*/*E* mixture of products (t_R 8.35 and 8.87 min). The reaction mixture was concentrated onto silica gel and flash chromatographed (2 × 8 in., hexane, 100-mL fractions) to give 300 mL, nil; 100 mL, 960 mg of a clear oil (butyltrimethyltin); 300 mL, 1.80 g, 76% of a *Z*/*E* mixture of the product: ^{19}F NMR (200 MHz, not proton decoupled) −92.65 (d, J = 62.5 Hz, 1 F), −55.57 (d, J = 37.7 Hz, 1 F).

Anal. Calcd for $C_{14}H_{21}FSi$: C, 71.13; H, 8.95. Found: C, 70.74; H, 8.86.

(*E*)-4-Phenyl-4-(tributylstannyl)but-3-en-2-one (9). To a dry three-necked flask equipped with magnetic stirrer and nitrogen inlet were added 1-phenyl-1-(tributylstannyl)-2-(trimethylsilyl)ethene (0.93 g, 2 mmol) and methylene chloride (1 mL). The solution was chilled to 0 °C and acetyl chloride–aluminum chloride complex (2 mL, 1 mmol, 0.5 M in methylene chloride) was added. The mixture was allowed to warm to ambient temperature for 1 h; then it was poured onto ice (100 g) with stirring and the organics were extracted with methylene chloride (2 × 40 mL). The combined organic layer was washed with brine, dried through a cone of calcium sulfate and concentrated. The residue was flash chromatographed on silica gel (2 × 8 in., 100-mL fractions, hexane eluent) to give 400 mL, nil; 600 mL, 80 mg of an unidentified oil; 1000 mL, nil. Continued elution with 1% ether/hexane gave 1300 mL, nil. Further elution with 5% ether/hexane gave 800 mL, 0.34 g (45%) of product as a clear yellow oil: NMR (360 MHz) 7.37–7.21 (m, 3 H), 7.1–7.04 (m, 2 H), 6.9 (s, 1 H with Sn coupling of 100, 96 Hz), 2.33 (s, 3 H), 1.39 (m, 6 H), 1.24 (sextet, J = 7.5 Hz, 6 H), 0.93 (m, 6 H), 0.84 (t, J = 7.5 Hz, 9 H); HRMS, m/e 379.1078 (M^+ − butyl).

(*E*)-3-Butyl-4-(*tert*-butyldimethylsilyl)but-3-en-2-one (10). To a dry three-necked flask equipped with magnetic stirrer and nitrogen inlet were added methylene chloride (25 mL), aluminum chloride (1.33 g, 10 mmol), and acetyl chloride (0.71 mL, 10 mmol). The mixture was chilled to 0 °C and 1-butyl-1-(trimethylstannyl)-2-(*tert*-butyldimethylsilyl)ethene (3.61 g, 10 mmol) was added via syringe. The mixture was allowed to warm to ambient temperature and stir 30 min; then it was poured onto ice (300 mL) with stirring and the organics were extracted with methylene chloride (3 × 40 mL). The combined organic layer was washed with brine, dried through a cone of calcium sulfate, and concentrated. The residue was flash chromatographed on silica gel (3 × 8 in., 100-mL fractions, hexane eluent) to give 1400 mL, 20 mg unidentified oil. Continued elution with 10% ether/hexane gave 1000 mL, nil. Further elution with 10% ether/hexane (800 mL) and 20% ether/hexane (400 mL) gave 1.67 g (69%) of product as a yellow oil: NMR (360 MHz) 6.38 (s, 1 H), 2.36 (br t, J = 8 Hz, 2 H), 2.0 (s, 3 H), 1.23–1.07 (m, 4 H), 0.71 (partially obscured t, J = 7 Hz, 3 H), 0.69 (s, 9 H), –0.08 (s, 6 H); IR (neat) 2960, 2930, 2859, 1688, 1573, 1470, 1462, 1360 (m), 1350, 1250, 1175, 835, 825, 810, 770. Irradiation of the vinyl proton gave a strong NOE enhancement to the acetyl methyl protons, thus demonstrating that the product had the *E* configuration.

Anal. Calcd for $C_{14}H_{28}OSi$: C, 69.93; H, 11.74. Found: C, 70.28; H, 11.83.

Preparation of 11. To a dry three-necked flask equipped with magnetic stirrer and nitrogen inlet were added methylene chloride (25 mL), aluminum chloride (1.33 g, 10 mmol), and cyclohexanecarboxylic acid chloride (1.34 mL, 10 mmol). After chilling to 0 °C, 1-butyl-1-(trimethylstannyl)-2-(*tert*-butyldimethylsilyl)ethene (3.61 g, 10 mmol) was added via syringe. The mixture was allowed to warm to ambient temperature and stirred 30 min; then it was poured onto ice (300 g) with stirring and the organics were extracted with methylene chloride (3 × 40 mL). The combined organic layer was washed with brine, dried through a cone of calcium sulfate, and concentrated. The residue was flash chromatographed on silica gel (2 × 10 in., 100-mL fractions, hexane eluent) to give 4000 mL, nil. Continued elution with 1.5% ether/hexane gave 900 mL, 0.15 g, of the minor isomer of the product; 500 mL, 0.2 g, of a mixture of both isomers of the product; 700 mL, 1.98 g (64%) of the major isomer of the product: NMR (360 MHz) 6.4 (s, 1 H), 2.53 (t, J = 7.5 Hz, 2 H), 2.36 (m, 1 H), 1.88–1.74 (m, 4 H), 1.71–1.63 (m, 1 H), 1.42–1.19 (m, 9 H), 0.90 (s, with partially obscured t, 12 H), 0.12 (s, 6 H); IR (neat) 2960, 2930, 2860, 1684, 1575 (m), 835, 825; ^{13}C NMR 203.36, 163.04, 134.58, 51.42, 32.86, 32.11, 28.50 (Si coupling of 65 Hz), 26.85, 25.94, 25.78, 23.38, 17.24, 13.89, –6.20. The silicon coupling to a methylene carbon proves that the double bond has migrated. It is not clear if the major product has the *Z* or *E* configuration.

Anal. Calcd for $C_{19}H_{36}OSi$: C, 73.95; H, 11.76. Found: C, 73.94; H, 11.77.

Registry No. **1a**, 16393-88-7; **1b**, 97877-91-3; **1c**, 17955-46-3; **1d**, 103731-39-1; **1e**, 103731-36-8; **1f**, 103731-29-9; **2b**, 97877-94-6; **2c**, 103731-37-9; **2d**, 103731-38-0; **2e**, 97877-95-7; **2f**, 97877-96-8; **2g**, 97877-97-9; **2h**, 103731-40-4; *cis*-**2i**, 103731-26-6; *trans*-**2i**, 103731-27-7; *cis*-**2j**, 103731-34-6; *trans*-**2j**, 103731-35-7; **2k**, 103731-28-8; **2m**, 103731-30-2; **2n**, 103731-32-4; **3**, 103731-41-5; **4**, 103731-42-6; *cis*-**5**, 103731-43-7; *trans*-**5**, 103731-44-8; **8a**, 103731-45-9; *cis*-**8b**, 103731-46-0; *trans*-**8b**, 103731-47-1; **9**, 103731-49-3; **10**, 103731-50-6; *cis*-**11**, 103731-51-7; *trans*-**11**, 103731-52-8; $Cl(CH_2)_3C{\equiv}CH$, 14267-92-6; $THPOCH_2CH_2C{\equiv}CH$, 40365-61-5; $Cl(CH_2)_3(SnBu_3)C{=}CH(SiMe_3)$, 103731-31-3; $HO(CH_2)_3C{\equiv}CH$, 5390-04-5; $HO(CH_2)_2(SnBu_3)C{=}CH(SiMe_3)$, 103731-33-5; $HOCH_2CH_2C{\equiv}CH$, 927-74-2; *i*-$PrC{\equiv}CH$, 598-23-2; *t*-$BuC{\equiv}CH$, 917-92-0; $NC(CH_2)_3C{\equiv}CH$, 14918-21-9; $(CH_3)_2C(OAc)C{\equiv}CH$, 1604-29-1; $Me_3SnSnMe_3$, 661-69-8; *t*-$BuMe_2SiCl$, 18162-48-6; Me_3SnH, 1631-73-8; $PhC{\equiv}CH$, 536-74-3; $(Ph_3P)_4Pd$, 14221-01-3; $Me_3SiC{\equiv}CH$, 1066-54-2; $HC{\equiv}CH$, 74-86-2; $BrCH_2C{\equiv}CH$, 106-96-7; cyclohexanecarboxylic acid chloride, 2719-27-9; benzaldehyde, 100-52-7; 1-hexyne, 693-02-7; *N*-fluoro-*N*-norbornyl-*p*-toluenesulfonamide, 103731-48-2.

Directed Lithiation of Tertiary β-Amino Benzamides

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The directed ortho-lithiation–alkylation of several tertiary β-amino benzamides was studied. The ortho-substituted β-amino benzamides were hydrolyzed directly with 6 N hydrochloric acid, or by a three-step, one-pot reaction involving methylation, elimination, and treatment with aqueous acid. *o*-Toluic acid, 2-*n*-butylbenzoic acid, 2-methoxy-6-methylbenzoic acid, and 4-methoxy-2-methylbenzoic acid were prepared by using this ortho-metalation–hydrolysis methodology. Ortho-lithiation and reaction with benzaldehyde or dimethylformamide followed by hydrolysis with aqueous acid gave lactones in good yield. Methanolysis of *N*-(4-methoxy-2-methylbenzoyl)-*N'*-methylpiperizine with sulfuric acid/methanol gave methyl 4-methoxy-2-methylbenzoate in 71% yield. The conversion of tertiary benzamides into ketones and aldehydes was examined. Treatment of certain tertiary benzamides with alkyllithium reagents gave ketones, while reaction with a modified aluminum hydride reagent gave aldehydes.

Directed metalation reactions of aromatic compounds continue to be of considerable interest.[1] A variety of ortho-directing groups have been utilized on various aromatic rings to direct metalation in the ortho or ortho-benzylic positions. Carboxylic acid derived directing groups[1] include tertiary amides, secondary amides, thioamides, and oxazolines. As was pointed out in a recent review,[1d] the advantages of the tertiary amide include ease of preparation, priority over other directors during the metalation step, utility in polysubstituted aromatic systems, and resistance to nucleophilic attack. The resistance to nucleophilic attack can be a problem if one wishes to convert the tertiary amide group into another functionality. In fact, the main disadvantage of the *N*,*N*-dialkylamide as an ortho-metalation directing group is its resistance to hydrolysis.[1d]

During a recent study involving ortho-metalation directed by α-amino alkoxides,[2] we had the opportunity to investigate an ortho-lithiation–methylation of *N*-[2-(di-

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