JOC*Note*

Palladium Complex Catalyzed Acylation of Allylic Esters with Acylstannanes: Complementary Method to the Acylation with Acylsilanes

Yasushi Obora, Masafumi Nakanishi, Makoto Tokunaga, and Yasushi Tsuji*

Catalysis Research Center and Division of Chemistry, Graduate School of Science, Hokkaido University, Sapporo 060-0811, Japan

tsuji@cat.hokudai.ac.jp

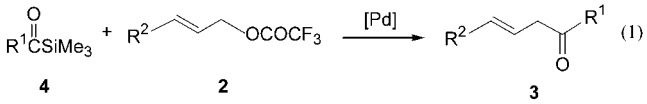
Received April 8, 2002

Abstract: Palladium-catalyzed acylation of allylic trifluoroacetates (**2**) using acylstannanes (**1**) is reported. The reaction serves as a complementary method to the previously reported acylation with acylsilane (**4**). In particular, the reaction is profitable in the acylation of unsubstituted allyl trifluoroacetate (**2a**) and benzoylation of allylic trifluoroacetates to afford synthetically useful β,γ-unsaturated ketones (**3**) in good yields without undesirable isomerizations.

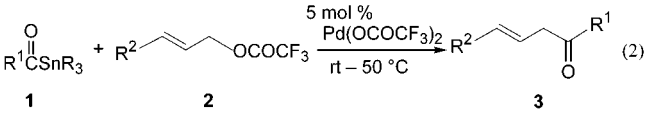
The palladium(0)-catalyzed nucleophilic substitution of allylic esters has been widely applied in organic synthesis, since it is one of the most efficient methods for C−C, C−N, and C−O bond formation.[1] As nucleophiles, stabilized carbanions,[2] enolates,[3] organotin reagents,[4] and nitrogen nucleophiles[5] can be successfully employed in the reaction.

On the other hand, *acylation* of allylic esters must be a potent method for synthetically useful β,γ-unsaturated ketones.[6] However, due to the *electrophilic* nature of the carbonyl functionality, generation of *nucleophilic* acyl species is usually difficult. Therefore, fewer examples of such allylic acylations have been reported.[7,8] For example, acylzirconocene chloride[7a] and chromium carbene complexes[7b] have been employed as acylation reagents in palladium complex catalyzed acylation of allylic acetates or bromides. Unfortunately, these reactions gave acylation products as a mixture of regioisomers.

Recently, we reported the palladium complex catalyzed acylation of allylic trifluoroacetates (**2**) with acylsilanes (**4**) (eq 1).[8] The reaction affords β,γ-unsaturated ketones



(**3**) in good yields. For the acylation reaction, we postulated by DFT calculation that the high-lying HOMO of **4**[9] is crucial as well as the low-lying LUMO of η^3-allylpalladium trifluoroacetate intermediate (**6**).[8] In most cases, **4** functions as a good acylation reagent. In the reaction, however, there are two drawbacks as a synthetic method. First, benzoyl functionality is introduced to allylic positions in only low yields (20−40%). Second, the acylation of unsubstituted allyl trifluoroacetate (**2a**) does not provide the corresponding β,γ-unsaturated ketones selectively: undesirable isomerization to α,β-unsaturated isomers (**5**) inevitably occurs. To overcome these drawbacks, we focused on acylstannane (**1**) as the acylation reagent. So far, **1** has been employed as an acylation reagent for organohalides,[10a] acid chlorides,[10b] and α,β-unsaturated carbonyl compounds.[10c] Furthermore, acylstannylations of alkynes[11a] and dienes[11b,c] with **1** have been reported by Shirakawa and Hiyama et al. In the present paper, we report a palladium-complex catalyzed acylation of **2** with **1** (eq 2), which serves as a complementary method to the acylation with **4**.



First, we carried out DFT calculations (B3LYP/LANL2DZ) on $MeCOSnMe_3$ as a model compound, since molecular orbital calculations on **1** have not been reported. The result is shown in Figure 1. The HOMO of $MeCOSnMe_3$ (Figure 1a) resembles that of $MeCOSiMe_3$ (Figure 1b) very much, which consists of a strong mixing of the M−CO (M = Si or Sn) σ-orbital and the localized oxygen lone pair.[12] Furthermore, it is noteworthy that the DFT calculation indicates the acylstannane has much

(1) (a) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, U.K., 1995. (b) Harrington, P. J. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon: Oxford, U.K., 1995; Vol. 12, pp 797−904. (c) Trost, B. M. *Acc. Chem. Res.* **1996**, *29*, 355 and references therein.

(2) (a) Tsuji, J.; Takahashi, H.; Morikawa, M. *Tetrahedron Lett.* **1965**, *21*, 4387. (b) Trost, B. M.; Verhoeven, T. R. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon: Oxford, U.K., 1982; Vol. 8, Chapter 57, p 799.

(3) (a) Negishi, E.; Matsushita, H.; Chatterjee, S.; John, R. A. *J. Org. Chem.* **1982**, *47*, 3188. (b) Trost, B. M.; Self, C. R. *J. Org. Chem.* **1984**, *49*, 468.

(4) (a) Trost, B. M.; Keinan, E. *Tetrahedron Lett.* **1980**, *21*, 2595. (b) Godschalx, J. P.; Stille, J. K. *Tetrahedron Lett.* **1980**, *21*, 2599. (c) Gollaszweski, A.; Schwartz, J. *Organometallics* **1985**, *4*, 417.

(5) (a) Trost, B. M.; Genet, J. P. *J. Am. Chem. Soc.* **1976**, *98*, 8516. (b) Trost, B. M.; Keinan, E. *J. Org. Chem.* **1979**, *44*, 3451.

(6) (a) Van Der Weerdt, A. J. A.; Cerfontain, H. *Tetrahedron* **1981**, *37*, 2121. (b) Ito, N.; Etoh, T.; Hagiwara, H.; Kato, M. *Synthesis* **1997**, 153. (c) Borecka, B.; Gudmundsdottir, A. D.; Olovsson, G. Ramamurthy, V.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1994**, *116*, 10322. (d) Banerjee, A. K.; Acevedo, J. C.; Gonzalez, R.; Rojas, A. *Tetrahedron* **1991**, *47*, 2081.

(7) (a) Hanzawa, Y.; Tabuchi, N.; Taguchi, T. *Tetrahedron Lett.* **1998**, *39*, 6249. (b) Sakurai, H.; Tanabe, K.; Narasaka, K. *Chem. Lett.* **1999**, 309.

(8) Obora, Y.; Ogawa, Y.; Imai, Y.; Kawamura, T.; Tsuji, Y. *J. Am. Chem. Soc.* **2001**, *123*, 10489.

(9) This characteristic feature of acylsilane has been reported; see (a) Yoshida, J.; Itoh, M.; Matsunaga, S.; Isoe, S. *J. Org. Chem.* **1992**, *57*, 4877. (b) Yoshida J.; Matsunaga, S.; Isoe, S. *Tetrahedron Lett.* **1989**, *30*, 5293.

(10) (a) Kosugi, M.; Naka, H.; Harada, S.; Sano, H.; Migita, T. *Chem. Lett.* **1987**, 1371. (b) Verlhac, J.-B.; Chanson, E.; Jousseaume, B.; Quintard, J.-P. *Tetrahedron Lett.* **1985**, *26*, 6075. (c) Shirakawa, E.; Yamamoto, Y.; Tsuchimoto, T.; Hiyama, T. *Chem. Commun.* **2001**, 1926.

(11) (a) Shirakawa, E.; Yamasaki, K.; Yoshida, H.; Hiyama, T. *J. Am. Chem. Soc.* **1999**, *121*, 10221. (b) Shirakawa, E.; Nakao, Y.; Yoshida, H.; Hiyama, T. *J. Am. Chem. Soc.* **2000**, *122*, 9030. (c) Shirakawa, E.; Nakao, Y.; Hiyama, T. *Chem. Commun.* **2001**, 263.

(12) (a) Bock, H.; Seidl, H. *J. Am. Chem. Soc.* **1969**, *91*, 355. (b) Ramsey, B. G.; Brook, A.; Bassindale, A. R.; Bock, H. *J. Organomet. Chem.* **1974**, *74*, C41.

10.1021/jo0202482 CCC: $22.00 © 2002 American Chemical Society
Published on Web 07/11/2002

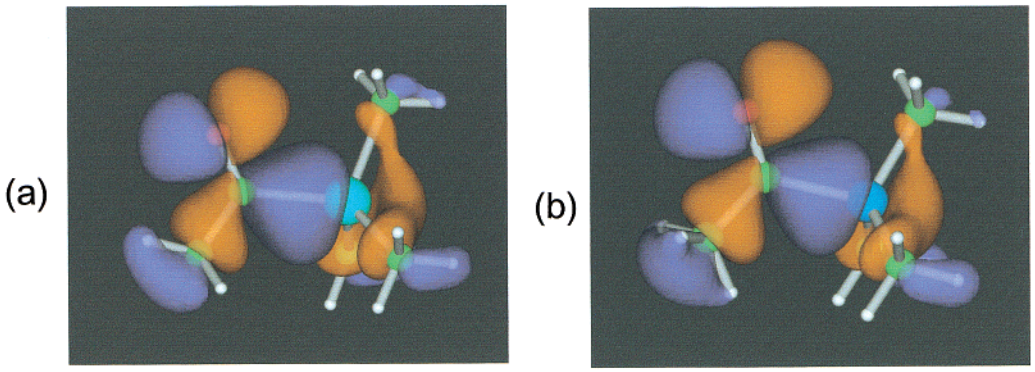
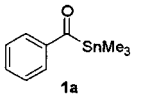
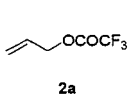
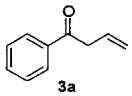
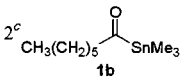
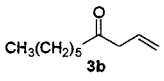
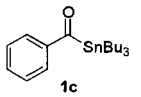
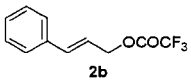
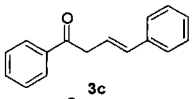
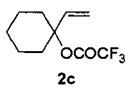
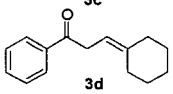


FIGURE 1. HOMOs of optimized (a) $MeCOSnMe_3$ and (b) $MeCOSiMe_3$ by B3LYP/LANL2DZ.

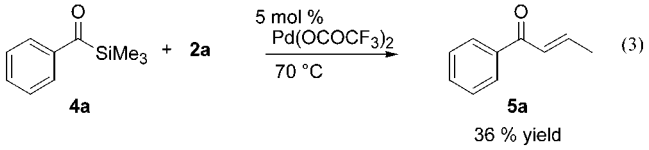
TABLE 1. Palladium Complex Catalyzed Acylation of Allylic Trifluoroactates[a]

entry	1	2	3	yield/%[b]
1	 1a	 2a	 3a	76
2[c]	 1b	2a	 3b	71
3	 1c	2a	3a	64
4	1a	 2b	 3c	50 (63)
5	1a	 2c	 3d	61

[a] Conditons: **1** (0.50 mmol), **2** (0.50 mmol), $Pd(OCOCF_3)_2$ (0.025 mmol), and THF (0.25 mL) at room temperature for 8 h. [b] Isolated yields. The number in parentheses show GLC yield determined by the internal standard method. [c] The reaction was carried out at 50 °C.

higher HOMO energy (−5.950 eV) than the acylsilane (−6.219 eV). Therefore, we expect **1** could be a more promising acylation reagent in the palladium-complex catalyzed allylic acylation.

The acylation of **2** with **1** was carried out in the presence of a catalytic amount (5 mol %) of $Pd(OCOCF_3)_2$ (Table 1). When an equimolar mixture of benzoyl(trimethyl)stannane (**1a**) and unsubstituted allyl trifluoroacetate (**2a**) was subjected to the acylation reaction, the corresponding β,γ-unsaturated ketone (**3a**) was obtained in 76% yield selectively at room temperature (entry 1). As mentioned above, the acylation of **2a** with **4** only afforded α,β-unsaturated ketones (**5**) via undesirable isomerization, and benzoylation with benzoyl(trimethyl)-silane (**4a**) provided products in low yields.[8] Actually, when **4a** was used in place of **1a** in entry 1, almost no reaction occurred at room temperature, while at 70 °C only the corresponding (*E*)-α,β-unsaturated ketone (**5a**) was obtained in 36% yield (eq 3). Furthermore, **2a** successfully reacted with alkanoylstannane (**1b**) and benzoyl(tributyl)stannane (**1c**) to afford **3b** and **3a**, respectively, without the isomerization (entries 2 and 3). As for the benzoylation, unlike **4a**, **1a** reacted with **2b** and **2c** smoothly at room temperature to afford **3c** and **3d** selectively in good yields, respectively (entries 4 and 5). In contrast, when **4a** was used in place of **1a** in entry 4, no reaction occurred at room temperature and at 70 °C **3c** was obtained as a mixture of *E*/*Z* stereoisomers in 26% yield.[8] Thus, as expected, **1** is much more proficient than **4** to realize the acylation at lower temperature, which prevents the undesirable isomerization ($\beta,\gamma/\alpha,\beta$ and *E*/*Z*) to afford the product in higher yield.[13]



In the acylation using **1**, observed catalytic activity of each catalyst precursor and effect of the leaving group of the allylic esters were very similar to the acylation using **4**.[8] In entry 4, $Pd(OCOCF_3)_2$ as the catalyst precursor gave the best yield of **3c** (63% by GLC). Other palladium, platinum, or nickel complexes showed lower catalytic activity under the same reaction conditions as entry 4: the yield of **3c** was 54% with $Pd(DBA)_2$, 48% with $Pd(OCOCH_3)_2$, 33% with $[Pd(\eta^3\text{-}C_6H_5CH{=}CHCH_2)(CF_3COO)]_2$, and trace with $Pt(C_2H_4)(PPh_3)_2$. The catalyst precursors such as $Pd(\eta^3\text{-}C_6H_5CH{=}CHCH_2)(CF_3COO)(PPh_3)$, $Pd(PPh_3)_4$, $PdBr_2(COD)$, and $Ni(COD)_2$ did not provide **3c** at all. As for the leaving group of the allylic esters, the trifluoroacetates gave the best yields, whereas no acylation product was obtained with the corresponding acetates, methyl carbonates, and trichloroacetates. As the solvent, THF gave the best yield, and toluene could be used similarly. All these features observed with **1** are very reminiscent of the acylation with **4**, suggesting reaction mechanism of these two acylation reaction would be very similar having analogous catalytic cycles, which consists of oxidative addition of **2** to palladium(0) species, transmetalation of η^3-allylpalladium trifluoroacetate (**6**) with **1**, and finally reductive elimination of (η^3-allyl)-acylpalladium intermediate to afford **3** and regenerate the catalytic species. By analogy to the acylation with **4**,[8] it might be conceivable that the high-lying HOMO of

(13) When the reaction of **2a** with **1a** was carried out at 70 °C instead of room temperature under otherwise the same reaction conditions as entry 1, all the β,γ-isomer (**3a**) was isomerized to the α,β-isomer (**5a**).

1 (vide supra) facilitates the HOMO−LUMO interaction[14] with the low-lying LUMO of **6**,[8] which would be crucial in the catalytic cycle.

In conclusion, the acylation of **2** with **1** is found to be complementary to the acylation with **4**. In particular, the reaction with **1** is profitable in the acylation of the unsubstituted allyl trifluoroacetate (**2a**) and benzoylation of **2** to afford β,γ-unsaturated ketones in good yields without the isomerization.

Experimental Section

Materials. The reagents and the solvents were dried and purified before use by the usual procedures.[15] The following catalyst precursors and complexes were prepared by the published methods: $Pd(OCOCF_3)_2$,[16a] $Pd(DBA)_2$,[16b−c] $Pd(OCOCH_3)_2$,[16d] $[Pd(\eta^3\text{-}C_6H_5CH{=}CHCH_2)(CF_3COO)]_2$,[16e] $Pd(\eta^3\text{-}C_6H_5CH{=}CHCH_2)(CF_3COO)(PPh_3)$,[16e] $Pd(PPh_3)_4$,[16f] $PdBr_2(COD)$,[16g] $Ni(COD)_2$,[16h] and $Pt(C_2H_4)(PPh_3)_2$.[16i] Acylstannanes **1** were prepared according to the published methods.[17] Allylic trifluoroacetates (**2**) were obtained with the corresponding alcohols.[8] The acylation products (**3a**−**c**[18a−c] and **5a**[18d]) were identified by comparing their spectra with the reported data.

Analytical and Computational Procedures. All manipulations were performed under argon atmosphere in conventional Schlenk-type glasswares on a dual-manifold Schlenk line. NMR spectra were recorded at 400 MHz (^{1}H) and 100 MHz (^{13}C). The GC analysis was made on a chromatograph equipped with an integrator with a column (3 mm i.d. × 3 m) packed with silicon OV-17 (2% on Uniport HP, 60/80 mesh) or Apiezon Grease L (5% on Uniport HP, 60/80 mesh). Elemental analysis was performed at the Center for Instrumental Analysis of Hokkaido University. Molecular orbital calculations were performed with the Gaussian 98[19] package on an HP Exemplar V2500 at the Computing Center of Hokkaido University.

Acylation Procedure. A typical procedure is described for the synthesis of **3c**. A mixture of **1a** (121 mg, 0.50 mmol), **2b** (115 mg, 0.50 mmol), $Pd(OCOCF_3)_2$ (8.0 mg, 0.025 mmol), and THF (0.25 mL) with a magnetic stirring bar was placed under an argon flow in a 20 mL round-bottomed flask. The reaction mixture was stirred for 8 h at room temperature. After the reaction, the whole mixture was passed through a short silica gel column (8 mm i.d. × 50 mm) to afford a clear yellow solution. GLC analysis on the Apiezon Grease L with bibenzyl as an internal standard showed **3c** was formed in 63% yield. The product (**3c**)[18c] was isolated as a white solid in 50% yield by column chromatography (silica gel with hexane/EtOAc = 9/1).

3d: colorless oil; 120 °C (pot)/0.5 mmHg; ^{1}H NMR ($CDCl_3$) δ 1.55−1.57 (m, 6H), 2.14−2.22 (m, 4H), 3.71 (d, J = 7 Hz, 2H), 5.38 (t, J = 7 Hz, 1H), 7.42−7.50 (m, 2H), 7.52−7.58 (m, 1H), 7.95−8.00 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 26.69 (CH_2), 27.49 (CH_2), 28.37 (CH_2), 29.13 (CH_2), 37.06 (CH_2), 37.63 (CH_2), 112.81 (CH), 128.36 (CH), 128.52 (CH), 132.92 (CH), 136.78 (C), 143.41 (C), 198.81 (C); IR (neat, cm^{-1}) 1686 ($\nu_{C=O}$); MS (relative intensity) m/z 214 (M^+, 3), 106 (7), 105 (100), 77 (36); HRMS cacld for $C_{15}H_{18}O$ 214.1358, found 214.1357.

Acknowledgment. We are grateful to Professor K. Hori of Yamaguchi University for useful discussions. This work was supported by a Grant-in Aid for Scientific Research on Priority Area "Molecular Physical Chemistry" (No. 11166202) from the Ministry of Education, Science and Culture, Japan. Financial support from the Asahi Glass Foundation is also gratefully acknowledged.

Supporting Information Available: Cartesian coordinates of optimized $CH_3COSnMe_3$ and $CH_3COSiMe_3$ by B3LYP/LANL2DZ. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0202482

(14) (a) Albright, T. A.; Burdett, J. K.; Whangbo, M. H. *Orbital Interactions in Chemistry*; Wiley: New York, 1985. (b) Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; Wiley: New York, 1976. (c) Rauk, A. *Orbital Interaction Theory of Organic Chemistry*, 2nd ed.; Wiley: New York, 2001.

(15) Armagego, W. L. F.; Perrin, D. D. *Purification of Laboratory Chemicals*, 4th ed.; Butterworth-Heinemann: Oxford, U.K., 1997.

(16) (a) Stephenson, T. A.; Morehouse, S. M.; Powell, A. R.; Heffer, J. P.; Wilkinson, G. *J. Chem. Soc.* **1965**, 3632. (b) Takahashi, Y.; Ito, T.; Sakai, S.; Ishii, Y. *J. Chem. Soc., Chem. Commun.* **1970**, 1065. (c) Rettig, M. F.; Maitlis, P. M. *Inorg. Synth.* **1977**, *17*, 134. (d) Murata, S.; Ido, Y. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 1746. (e) Vitagliano, A.; Åkermark, B.; Hansson, S. *Organometallics* **1991**, *10*, 2592. (f) Coulson, D. R. *Inorg. Synth.* **1972**, *13*, 121. (g) Drew, D.; Doyle, J. R. *Inorg. Synth.* **1972**, *13*, 52. (h) Schunn, R. A. *Inorg. Synth.* **1974**, *15*, 5. (i) Blake, D. M.; Roundhill, D. M. *Inorg. Synth.* **1978**, *19*, 120.

(17) (a) Capperucci, A.; Degl'Innocenti, A.; Faggi, C.; Reginato, G.; Ricci, A. *J. Org. Chem.* **1989**, *54*, 2966. (b) Still, W. C. *J. Am. Chem. Soc.* **1978**, *100*, 1481.

(18) (a) **3a**: Kachinsky, J. L. C.; Salomon, R. G. *J. Org. Chem.* **1986**, *51*, 1393. (b) **3b**: Fujita, T.; Watanabe, S.; Suga, K.; Inaba, T.; Takagawa, T. *J. Appl. Chem. Biotechnol.* **1978**, *28*, 882. (c) **3c**: Galli, C.; Gentili, P.; Rappoport, Z. *J. Org. Chem.* **1994**, *59*, 6786. (d) **5a**: Pitts, M. R.; Harrison, J. R.; Moody, C. J. *J. Chem. Soc., Perkin Trans. 1* **2001**, 955.

(19) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J, M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gompartz, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*; Gaussian: Pittsburgh, PA, 1998.