We report herein β-effect controlled dimerization and trimerization reactions of β-(trihalosilyl)- and β-(dihalomethylsilyl)styrenes that lead to 1,2,3-trifunctionalized indans containing three or four contiguous chiral centers.

In the presence of trifluoromethanesulfonic acid (triflic acid), β-(trichlorosilyl)styrene[7,8] (**1a**) undergoes an oligomerization reaction.[9] By use of the appropriate dilution conditions (2.8 M in $CDCl_3$) and low temperature (−55 °C),[10] it was possible to form mainly the dimer **4a** (Scheme I; **4a**:**6a** = 92:8, yield ca. 55% by ^1H NMR);[11] the remaining products were higher oligomers. In contrast, the reaction of (dichloromethylsilyl)styrene[8] (**1c**) under the same conditions led to a mixture that contained mostly desilylated trimer **9c** contaminated with dimer **6c** (Scheme I; **9c**:**6c** = 7:2, yield ca. 50% by ^1H NMR).[11] The remaining products in these reactions were also higher oligomers.

The formation of dimers **4** and **6** can be rationalized in the manner shown in Scheme I. The leaving-group ability of the trichlorosilyl and dichloromethylsilyl groups is poor. Therefore, after protonation of **1** to form cation **2**, protiodesilylation[12] does not occur and a reaction occurs with the only viable nucleophile in solution, another styrene. Intermediate **3** arises from an *ul*-addition process, whereas **5** arises from a *lk*-addition of another monomer. In either case, the cationic center can then be attacked by the phenyl ring in an intramolecular Friedel–Crafts reaction on the face anti to the silyl group to form **4** or **6**, respectively.

The product arising from *ul*-addition is the kinetic product; warming the reaction of **1a** to 0 °C leads to a 50:50 mixture of **4a**/**6a**.[13] The preference for *ul*-addition under conditions of kinetic control with Lewis acid catalysis has often been observed.[14] With a more electron-rich silyl group ($MeSiCl_2$ compared with $SiCl_3$) and a correspondingly increased β-effect,[15] the stabilized cations **2c**, **3c**, and **5c** can undergo equilibration leading eventually to the thermodynamic product **6**. In the case of the less stabilized cation **3a**, kinetic trapping of the cation occurs in an intramolecular Friedel–Crafts reaction.

The mechanism of formation of **9** is more difficult to rationalize as the key intermediate is presumably **7** in which one of the chiral centers has been lost; it could arise from either **3** or **5**. *lk*-Addition of **2** to **7** would give symmetrical **8**, which can cyclize to **9** in a Friedel–Crafts reaction, again on the least hindered face (Scheme I).

The dimerization of styrenes under acidic conditions, leading to indans, is a well-documented reaction[16] and has been shown to occur to give highly substituted indans in special cases.[17] A stereoselective example with *p*-quinone methides was recently reported by Angle et al.[18] The dimerization reaction reported is of interest not only because of the observed stereocontrol resulting from the substitution on silicon but from the fact that the chlorosilyl groups provide a handle for further synthetic elaboration. We are currently examining related reactions in which other carbon electrophiles annelate onto the silylstyrene to determine the synthetic potential of such a strategy.

Acknowledgment. We gratefully acknowledge the financial support of this work by the Natural Sciences and Engineering Research Council of Canada, the awarding of an exchange scholarship to R.J. from the Deutscher Akademischer Austauschdienst, the awarding of a Sherman Scholarship to C.D. by McMaster University, and the awarding of an Ichikizaki Young Chemists Travel Award to M.A.B.

Supplementary Material Available: Experimental procedures for the preparation of **4**, **6**, and **9**; spectroscopic data (mp; IR; MS; ^1H; ^{13}C, ^{29}Si NMR) for **4e**, **6e**, and **9e**; ORTEP diagrams from the X-ray crystal structure analysis of **4e** and **9e** (4 pages). Ordering information is given on any current masthead page.

(7) The starting materials **1a**,**c** are readily prepared by the H_2PtCl_6-catalyzed hydrosilation of phenylacetylene with $HSiCl_3$ or $HSiMeCl_2$, respectively, in THF. Tamao, K.; Yoshida, J.; Yamamoto, H.; Kakui, T.; Matsumoto, H.; Takahashi, M.; Kurita, A.; Murata, M.; Kumada, M. *Organometallics* **1982**, *1*, 355 and references cited therein. **1b**,**d** are prepared by the fluorination of **1a** and **1c**, respectively, using ZnF_2.

(8) Similarly, (trifluorosilyl)styrene (**1b**) led primarily to **4b** and (difluoromethylsilyl)styrene to a mixture of **6d** and **9d**, respectively. However, reactions with the fluorinated compounds were notoriously difficult to work with and were accompanied by extensive degradation or formation of side products.

(9) Brook, M. A.; Hülser, P.; Sebastian, T. *Macromolecules* **1989**, *22*, 3814.

(10) Changing the concentration of the reaction or the temperature of the reaction only increased the amount of higher oligomers and/or desilylated product.

(11) The structure of the compounds could not be directly assigned. Therefore, they were first converted to the corresponding air-stable trimethylsilyl derivatives by reaction with MeMgBr (0 °C, Et_2O). The structures of **4e**, **6e**, and **9e** (yield after purification from **1**, **4e** 38%, **6e** 7%, **9e** 24%) were determined by NOE measurements and confirmed for **4e** and **9e** by X-ray crystal structure determination. Frampton, C. S.; Brook, M. A.; Jueschke, R.; Sebastian, T. *Acta Crystallogr., Sect. C* submitted for publication.

(12) The normal reaction course with (trimethylsilyl)styrene and acid is protiodesilylation to form styrene: Weber, W. P.; Koenig, K. E. *J. Am. Chem. Soc.* **1973**, *95*, 3416.

(13) One of the reviewers was concerned that the 50:50 mixture of isomers **4a**/**6a** could arise from equilibration of the two at the higher temperature. To discount this possibility, a 90:10 mixture of **4a**/**6a** (prepared at −55 °C) was submitted to triflic acid catalysis at higher temperature (0–25 °C overnight). No change in the ratio of stereoisomers was observed.

(14) Brook, M. A.; Seebach, D. *Can. J. Chem.* **1987**, *65*, 836. Seebach, D.; Goliński, J. *Helv. Chim. Acta* **1981**, *64*, 1413.

(15) Brook, M. A.; Hadi, M.; Neuy, A. *J. Chem. Soc., Chem. Commun.* **1989**, 957. Brook, M. A.; Neuy, A. *J. Org. Chem.* **1990**, *55*, 3609.

(16) Moreau, M.; Matyjaszewski, K.; Sigwalt, P. *Macromolecules* **1987**, *20*, 1456. Higashimura, T.; Hiza, M.; Hasegawa, H. *Macromolecules* **1979**, *12*, 217. *Ibid.* **1979**, *12*, 1058. Kunitake, T.; Takarabe, K. *Ibid.* **1979**, *12*, 1061. Hiza, M.; Hasegawa, H.; Higashimura, T. *Polymer J.* **1980**, *12*, 379. MacMillan, J.; Martin, I. L.; Morris, D. J. *Tetrahedron* **1969**, *25*, 905.

(17) Marcuzzi, F.; Melloni, G. *J. Chem. Res., Miniprint* **1979**, 2287.

(18) Angle, S. R.; Arnaiz, D. O. *J. Org. Chem.* **1990**, *55*, 3708.

Stereocontrolled Oxaspirocyclization of Conjugated Dienes via Palladium Catalysis

Jan-E. Bäckvall* and Pher G. Andersson

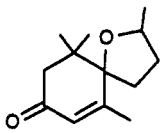
Department of Organic Chemistry, University of Uppsala, Box 531, S-751 21 Uppsala, Sweden

Received December 27, 1990

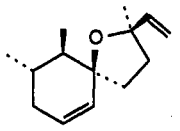
Summary: Mild palladium-catalyzed spirocyclizations of 1-(3-hydroxyalkyl)- and 1-(4-hydroxyalkyl)-1,3-cycloalkadienes (**5a**, **5b**, **5d**, and **5e**) have been developed. The reactions proceed via a spirocyclic π-(allyl)palladium intermediate and result in the 1,4-addition of the hydroxy function and a chloride or an acetate. The stereochemistry of the reactions can be controlled to give either cis or trans 1,4-addition across the double bond.

0022-3263/91/1956-2274$02.50/0

Palladium-catalyzed 1,4-oxidations of 1,3-dienes have become of importance in organic synthesis for the construction of building blocks and key intermediates.[1-4] We recently extended these reactions to an intramolecular variant that allows the preparation of fused heterocyclic systems 2 in a stereocontrolled manner (Scheme I).[4] Our goal was to further extend these intramolecular 1,4-additions to spirocyclizations which may occur if the chain of 1 is situated in the 1-position. If X = O an easy access to spirocyclic ethers would be at hand. Several natural products with such spiroether structures are known, e.g. theaspirone,[5] dihydrotheaspirans,[6] and dactyloxene B.[7] In this paper we report on a stereocontrolled oxaspirocyclization via palladium catalysis.



theaspirone

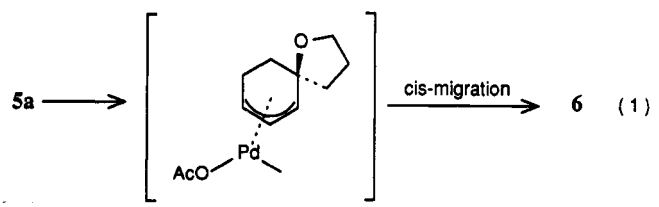


dactyloxene-B

The 1-substituted 1,3-dienes, used as starting materials, were prepared according to a recently developed procedure.[8] Alkylation of the allylic sulfone 3 by a protected halo alcohol afforded compound 4. A highly regioselective 1,4-elimination of benzenesulfinate from 4 and subsequent deprotection afforded the dienylic alcohols 5 in good overall yields from 3 (ca. 70%) (Scheme II).

The palladium-catalyzed oxidation of compounds **5a** and **5b** with benzoquinone as the oxidant was more difficult than for the analogous annulations (Scheme I) because of competing aromatization and Diels–Alder addition of the diene. To depress the Diels–Alder addition with benzoquinone the diene was added slowly to the reaction mixture. This procedure also decreased the aromatization of the starting material to about 5–10%. It was also found that the presence of base (3 equiv of Li_2CO_3) increased the rate of the cyclization. This may be explained by an activation of the nucleophilic hydroxy function.

Palladium-catalyzed reaction of diene **5a** in acetone–acetic acid (4:1) at room temperature in the presence of benzoquinone and Li_2CO_3 afforded spirocyclic ether **6** in 86% yield isolated as a single diastereoisomer (entry 1, Table I). The trans stereochemistry between the oxygen substituents is explained by formation of the π-(allyl)-palladium intermediate shown in eq 1. Attempts to direct



this reaction toward an overall cis addition of the oxygen functions by addition of catalytic amounts (25 mol %) of chloride[1,2b,4] were not successful and gave poor yields of the cis adduct (34% yield, 76% cis). However, a further increase of the chloride concentration (180 mol %) resulted in cis addition product 7 (entry 2) where chloride becomes

Scheme I

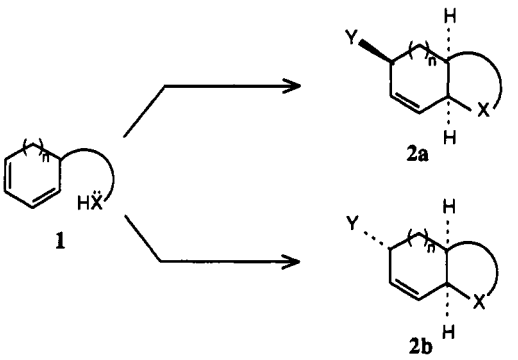
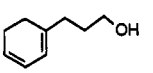
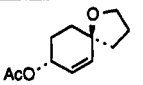
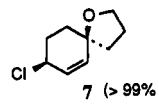
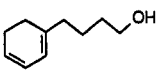
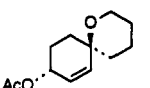
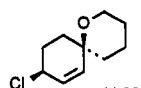
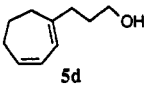
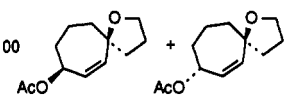
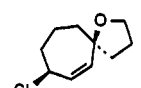
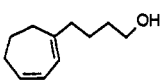
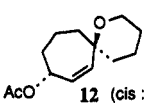
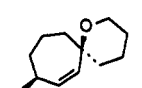


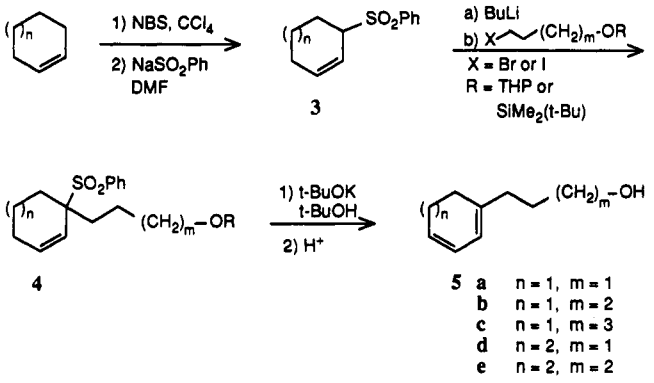
Table I. Palladium-Catalyzed Oxaspirocyclization of Conjugated Dienes[a]

entry	starting material	added salt	reactn time (h)	product	% yield[b]
1	 5a	Li_2CO_3[c]	24	 **6** (> 98% trans)	86
2		LiCl[d]	24	 **7** (> 99% cis)	73
3	 5b	Li_2CO_3[c]	24	 **8** (> 98% trans)	82
4		LiCl[d]	24	 **9** (> 99% cis)	70
5	 5d	-	100	 **10a** : **10b** 12 : 88	60
6		Li_2CO_3[c]	36	**10a** : **10b** 80 : 20	54
7		LiCl[d]	72[e]	 **11** (> 99% cis)	40
8	 5e	-	100	 **12** (cis : trans = 6 : 94)	82
9		LiCl[d]	72[e]	 **13** (>99% cis)	60

[a] Unless otherwise stated the reactions were performed in acetone–acetic acid (4:1) at 20 °C employing 5 mol % $Pd(OAc)_2$ as catalyst and 2 equiv of *p*-benzoquinone as the oxidant. [b] Isolated yield. [c] 3.0 equiv. [d] 1.8 equiv. [e] 35 °C.

(1) Bäckvall, J. E. In *Advances in Metal-Organic Chemistry*; Liebeskind, L. S., Ed.; JAI Press: Greenwich, 1989; Vol. 1, pp 135–175.
(2) (a) Bäckvall, J. E.; Nyström, J. E.; Nordberg, R. E. *J. Am. Chem. Soc.* **1985**, *107*, 3676. (b) Bäckvall, J. E.; Byström, S. E.; Nordberg, R. E. *J. Org. Chem.* **1984**, *49*, 4619. (c) Bäckvall, J. E.; Vågberg, J. O. *J. Org. Chem.* **1988**, *53*, 5695.
(3) (a) Pearson, A. J.; Lai, I.; Lu, W.; Pinkerton, A. A. *J. Org. Chem.* **1989**, *54*, 3882. (b) Opppolzer, W.; Gaudin, J. M.; Birkinshaw, T. N. *Tetrahedron Lett.* **1988**, *29*, 4703. (c) Tanner, D.; Sellén, M.; Bäckvall, J. E. *J. Org. Chem.* **1989**, *54*, 3374.
(4) (a) Bäckvall, J. E.; Andersson, P. G.; Vågberg, J. O. *Tetrahedron Lett.* **1989**, *30*, 137. (b) Bäckvall, J. E.; Andersson, P. G. *J. Am. Chem. Soc.* **1990**, *112*, 3683.
(5) Ina, K.; Sakato, Y.; Fukami, H. *Tetrahedron Lett.* **1968**, 2777.
(6) Kaiser, R.; Kappeler, A.; Lamparsky, D. *Helv. Chim. Acta* **1978**, *61*, 387.
(7) Schmitz, F. J.; McDonald, F. J. *Tetrahedron Lett.* **1974**, 2541.
(8) Bäckvall, J. E.; Sellén, M.; Helquist, P. *J. Org. Chem.* **1991**, *56*, 835.

Scheme II



one of the nucleophiles in accordance with previous results.[1,2b,4] In this reaction it was found that chloride ions had an accelerating effect on the aromatization of the starting material. To prevent this, LiCl was dissolved in acetic acid and added parallel with the diene.

Extending the hydroxyalkyl chain with one carbon led to six-membered oxaspirocycles. Thus, in the same manner as described above **5b** was transformed to **8** and **9** in 82 and 70% yield, respectively (entries 3 and 4, Table I). Applying the same reaction conditions to the diene analogue **5c**, with five carbons in the alkyl chain, did not give the expected seven-membered oxaspirocycle.

Spirocyclization of cycloheptadiene derivatives **5d** and **5e** was slower than for their six-membered analogues. However, in these systems no side products were detected and slow addition of the reagents was no longer needed. Interestingly, for diene **5d** it was now possible to obtain the dual stereocontrol generally associated with palladium-catalyzed 1,4-oxidations.[1,2b,4] In the absence of added salts, **5d** afforded mainly the trans addition product **10b**. Addition of Li_2CO_3 (3 equiv), which is a source for LiOAc and thus favors the external attack, reversed the stereoselectivity and then the cis addition product predominated, **10a**:**10b** being 80:20. The corresponding spiro-oxychlorination of the seven-membered ring derivatives was very slow at 20 °C, after 36 h the conversion of **5d** to **11** was only about 15%. Instead, these reactions (entries 7 and 9) were performed at a slightly elevated temperature (35 °C),[9] and it was then possible to isolate **11** and **13** in 40 and 60% yield, respectively. Spirocyclization of **5e** with a 4-carbon chain afforded **12** in 82% yield.

With the present procedure stereodefined spiro ethers are readily accessible from simple starting materials.[10] They can be further functionalized in a stereospecific manner[1,4] and should provide useful entries to oxaspirocyclic natural products.

General Experimental Procedure: Preparation of 8c-Chloro-2*r*-oxaspiro[4.5]dec-6-ene (7). $Pd(OAc)_2$ (8.1 mg, 0.036 mmol), benzoquinone (160 mg, 2.17 mmol), and Li_2CO_3 (160 mg, 2.17 mmol) were dissolved in acetone/HOAc (2 mL, 4:1). To this solution were then added the dienol **5a** (110 mg, 0.796 mmol, dissolved in 1 mL of acetone) and LiCl (62 mg, 1.45 mmol, dissolved in 1 mL of HOAc) during 16 h with a syringe pump. One hour after the addition was completed, ether (7 mL) was added and the resulting solution was washed with aqueous NaOH (2 × 4 mL, 2 M) and brine (3 mL). The organic phase was then dried ($MgSO_4$), concentrated in vacuo, and distilled in a Kugelrohr apparatus at an oven temperature of 100 °C under reduced pressure (0.01 mmHg) to give **7**[11] (100 mg, 0.579 mmol, 73%).

Acknowledgment. We are grateful to the Swedish Natural Science Research Council for financial support and to Johnson Matthey for a loan of palladium chloride.

(9) Attempts to increase the temperature further resulted in a relative increase of Diels-Alder side products.

(10) For other syntheses of spiro ethers see: (a) Simkins, N. S.; Middleton, D. S. *Tetrahedron* **1990**, *46*, 545. (b) Baxter, J. S.; Green, M.; Lee, T. V. *J. Chem. Soc., Chem. Commun.* **1989**, 1595. (c) Cannone, P.; Belanger, D.; Lemay, G.; Foscolos, G. B. *J. Org. Chem.* **1981**, *46*, 3091. (d) Stanton, S. A.; Felman, S. W.; Parkhurst, C. S.; Godleski, S. A. *J. Am. Chem. Soc.* **1983**, *105*, 1964.

(11) ^1H NMR for **7**: δ 5.81 (dd, J = 3.6, 9.7 Hz, 1 H), 5.70 (d, J = 9.7 Hz, 1 H), 4.52 (m, 1 H), 3.88 (app t, J = 6.6 Hz, 2 H), 2.17-1.92 (m, 5 H), 1.86-1.69 (m, 2 H), 1.62 (m, 1 H).

Enantioselective Chiral Borane-Mediated Aldol Reactions of Silyl Ketene Acetals with Aldehydes. Novel Effect of the Trialkylsilyl Group of the Silyl Ketene Acetal on the Reaction Course

Syun-ichi Kiyooka,* Yuichi Kaneko, Misako Komura, Hidehito Matsuo, and Masahito Nakano

Department of Chemistry, Kochi University, Akebono-cho, Kochi 780, Japan

Received November 19, 1990

Summary: Highly enantioselective aldol reactions of silyl ketene acetals with a variety of aldehydes were achieved by using chiral boranes prepared from the sulfonamides of α-amino acids.

Chiral Lewis acid mediated reactions have been recognized as useful tools for the stereoselective formation of carbon-carbon bonds.[1] However, few examples of the aldol reaction of silyl ketene acetals with aldehydes have been reported.[2] Yamamoto[3a] and Helmchen[3b] independently reported the synthesis of new chiral Lewis acids from borane and the sulfonamides of α-amino acids and applied them to promote asymmetric Diels-Alder reactions. In the course of studies of stereoselective Lewis acid mediated aldol reactions,[4] we examined the ability of such chiral

(1) Bosnich, B. *Asymmetric Catalysis*; Martinus Nijhoff Publishers: Dordrecht, 1986. Noyori, R.; Kitamura, M. In *Modern Synthetic Methods 1989*; Sheffold, S., Ed.; Springer-Verlag: Berlin, 1989; Vol. 5, p 116.

(2) Reetz, M. T.; Kyung, S.-H.; Bolm, C.; Zierke, T. *Chem. Ind.* **1985**, 824. Kobayashi, S.; Sano, T.; Mukaiyama, T. *Chem. Lett.* **1989**, 1319 and references cited therein.

(3) (a) Takasu, M.; Yamamoto, H. *Synlett* **1990**, 194. (b) Sartor, D.; Saffrich, J.; Helmchen, G. *Ibid.* **1990**, 197.

0022-3263/91/1956-2276$02.50/0