Silaborations of Unsaturated Compounds

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Abstract

This thesis deals with the development of transition metal-catalyzed silaborations of 1,3-dienes and 1,6-enynes.

The first part of the thesis describes the development of the enantioselective 1,4-silaboration of 1,3-cyclohexadiene. A number of chiral metal-ligand complexes were evaluated. Up to 82% enantiomeric excess was obtained using a catalyst system derived from $Pt(acac)_2$ and a phosphoramidite ligand. The product formed was employed in allylborations of aldehydes, giving homo-allylic alcohols in good yields with good to moderate diastereoselectivity. In attempts to widen the scope of silaborations to include acyclic, terminally substituted 1,3-dienes, products from H-B exchange with, and H-Si addition to, the dienes were obtained.

The second part describes the development of silaborative carbocyclization of 1,6-enynes. A Pd N-heterocylic carbene complex was found to be effective for the silaborative carbocyclization of unsubstituted enynes, giving the products in good to excellent yields. Employing terminally substituted enynes resulted in low or no yields.

The last part describes investigations into the reaction mechanisms of the processes developed in the first part. It was found that the silylborane undergoes oxidative addition to a Pt(0) complex generated from $Pt(acac)_2$ and DIBALH. After insertion of 1,3-cyclohexadiene into the Pt-B bond a π-allyl complex was observed experimentally. In the addition of silylborane to acyclic, terminally substituted, 1,3-dienes it was shown by deuterium labeling experiments that one diene loses a hydride via H-B exchange and that this hydride is then added to another diene via H-Si addition. A reaction mechanism was proposed for this process.

Keywords: Allylboration, bismetallation, boron, carbocyclization, catalysis, 1,3-diene, enantioselective, 1,6-enyne, interelement, N-heterocyclic carbene, nickel, palladium, phosphine, phosphoramidite, platinum, reaction mechanism, silaboration, silicon, silylborane, stereoselective.

Abbreviations

Abbreviations and acronyms used in agreement with the ACS standards[1] are not listed here.

BINOL	1,1'-bi(2-naphthol)
Cy	cyclohexyl
dba	dibenzylidene acetone
de	diastereomeric excess
DIBALD	diisobutylaluminum deuteride
E	element
ee	enantiomeric excess
etpo	4-ethyl-2,6,7-trioxa-1-phosphabicyclo[2.2.2]octane
H-MOP	2-(diarylphosphino)-1,1'-binaphthyl
M	metal
MTPA-Cl	α-methoxy-α-(trifluoromethyl)phenylacetyl chloride
n.d.	not determined
NHC	N-heterocyclic carbene
pin	pinacol
RCM	ring closing metathesis

[1] http://pubs.acs.org/paragonplus/submission/joceah/joceah_abbreviations.pdf

List of Publications

This thesis is based on the following papers, referred to in the text by their Roman numerals **I-V**:

I. **Enantioselective Platinum-Catalyzed Silicon-Boron Addition to 1,3-Cyclohexadiene**
Martin Gerdin and Christina Moberg
Adv. Synth. Catal. **2005**, *347*, 749-753

II. **Enantioselective Silicon-Boron Additions to Cyclic 1,3-Dienes Catalyzed by the Platinum Group Metal Complexes**
Martin Gerdin, Maël Penhoat, Raivis Zalubovskis, Claire Pétermann and Christina Moberg
J. Organomet. Chem. **2008**, *693*, 3519-3526

III. **Ni-Catalyzed Si-B Addition to 1,3-Dienes: Disproportionation in Lieu of Silaboration**
Martin Gerdin and Christina Moberg
Org. Lett. **2006**, *8*, 2929-2932

IV. **Silaborative Carbocyclizations of 1,6-Enynes**
Martin Gerdin, Christin Worch and Christina Moberg
Preliminary manuscript

V. **Rate and Mechanism of the Oxidative Addition of a Silylborane to Pt^0 Complexes – Mechanism for the Pt-Catalyzed Silaboration of 1,3-Cyclohexadiene**
Guillaume Durieux, Martin Gerdin, Christina Moberg and Anny Jutand
Eur. J. Inorg. Chem. **2008**, 4236-4241

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1. Introduction

Organic chemistry is a continuously evolving discipline, and progress within organic chemistry has a large impact on our lives. It improves our understanding of the world around us, saves lives, and provides access to life enhancing drugs and to novel materials. The devoted effort of skilled chemists has resulted in the development of synthetic routes to a large number of structurally diverse naturally occurring compounds,[2] showing that even molecules with extremely complex structures can be synthesized. But, even if a molecule of interest can be synthesized, its production may require too much waste, chemicals, plant requirements, or working hours to be commercially viable. In order to reduce the cost of producing a molecule it is of utmost importance to minimize the number of steps in the synthetic sequence, as this will influence all the cost drivers mentioned above.[3] Apart from finding short and efficient routes for the synthesis of molecules, the art of organic synthesis is also enhanced by the development of improved purification techniques, parallel synthesis, automation, green-chemistry, and new reagents that are cheaper, less toxic, or easier to handle than the ones previously used for the same transformations.

One approach to reduce the number of steps in a synthetic sequence is to, in a single operation, introduce several functionalities that can be utilized for further transformations, thereby allowing for the formation of structurally complex molecules in a reduced number of steps. In transition metal-catalyzed additions of interelement compounds to unsaturated substrates two reactive functionalities are created in one single transformation.[4] Utilizing the reactivities inherent in the organometallic compounds[5] thus created should allow for the efficient construction of structurally complex molecules.

The addition of silylboranes to unsaturated compounds gives products that contain a silyl and a boryl group which differ in reactivity, thereby allowing for the step-wise utilization of the newly formed functionalities.

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[2] (a) Nicolaou, K. C.; Sorensen, E. J. *Classics in Total Synthesis,* Wiley-VCH, Weinheim, 1996. (b) Nicolaou, K. C.; Snyder, S. A. *Classics in Total Synthesis II*, Wiley-VCH, Weinheim, 2003.

[3] Wender, P. A.; Verma, V. A.; Paxton, T. J.; Pillow, T. H. *Acc. Chem. Res.* **2008**, *41*, 40-49.

[4] (a) Suginome, M.; Ito, Y. *Chem. Rev.* **2000**, *100*, 3221-3256. (b) Beletskaya, I.; Moberg, C. *Chem. Rev.* **2006**, *106*, 2320-2354.

[5] *Comprehensive Organometallic Chemistry*, Abel, E. W.; Stone, F. G. A.; Wilkinson, G., Eds.; Pergamon, Oxford, 1982, Vol. 1-9.

1.1. Aim of this thesis

The aim of this thesis was to create reactive compounds with organometallic functionalities in a stereoselective manner by transition metal-catalyzed additions of silylboranes to unsaturated compounds and to investigate the reactivity of the new adducts. In order to gain further insight into these processes their reaction mechanisms was to be examined.

1.2. Silicon

Silicon

Symbol: Si

Atom number: 14

Molecular weight: 28.0855 kg/mol

Electron configuration: [Ne] $3s^2$ $3p^2$

Electronegativity: 1.90 (Paulings scale)

Selected bond strengths and lengths:[7]

Si-H	350 kJ/mol	1.5 Å
Si-C	300 kJ/mol	1.9 Å
Si-Si	300 kJ/mol	2.4 Å
Si-O	530 kJ/mol	1.6 Å
Si-F	590 kJ/mol	1.6 Å
Si-Cl	400 kJ/mol	2.0 Å

Silicon is the second most abundant element on Earth, surpassed only by oxygen, and makes up 27.7% of its crust. It was first identified as an element and isolated in pure form by Jöns Jacob Berzelius in 1824. In Nature silicon exists mainly as silicon dioxide and as silicates which are the main constituents of the rocks, stones, sands, clays and soils that make out the landscape around us.[6] The first organometallic silicon-containing compound was Et_4Si, which was synthesized by Friedel and Craft in 1863. The silicon-containing organometallics constitute a family of chemically and thermally stable compounds. The chemistry of silicon shows resemblance to that of boron and to its row IV neighbour carbon, with a marked difference in the instability of double bonds to silicon. Nucleophilic substitution is significantly more facile at silicon than at carbon and can be performed using poor leaving groups such as F^-, RO^-, R_3C^- and H^-. The substitution occurs through an associative mechanism, which predominantly proceeds with retention of configuration via pseudorotation, especially when poor leaving groups are employed. Silicon forms markedly strong bonds to electronegative elements such as oxygen and fluorine.[7]

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6 Encyclopedia Brittanica Online – Silicon. http://www.britannica.com/EBchecked/topic/544301/silicon#tab=active~checked%2Citems~checked&title=silicon%20--%20Britannica%20Online%20Encyclopedia

7 Approximate values for homolytic bond dissociation taken from: Armitage, D. A., in *Comprehensive Organometallic Chemistry,* Wilkinson, G.; Stone, F. G. A.; Abel, E. W. (Eds), Pergamon Press, Oxford, **1982**, Volume 2, Chapter 9, pp 1-204.

Silicon has found widespread use in organic chemistry. It is used as protective groups for hydroxyl, ester and alkyne functionalities,[8] as reagents in Peterson olefinations,[9] cross-coupling reactions,[10] allylations,[11] Mukiyama aldol reactions,[12] and hydrosilylations[13] and as a masked hydroxyl functionality.[14] Many of these and other transformations using silicon-containing compounds can be performed in a stereoselective fashion[15] and have, therefore, been used in the synthesis of natural products.[16]

1.3. Boron

Boron[17,18] was first isolated independently, as an impure solid, by Gay-Lussac & Thenard and Davy in 1808. The isolation of pure boron was not realized until 1909 (Weintraub). Boron is much less abundant than silicon and constitutes only about 0.001% of the Earth's mass, mainly as the minerals borax, kernite, and tincalconite.[19]

Boron

Symbol: B

Atom number: 5

Molecular weight: 10.81

Electron configuration: [He] $2s^2$ $2p^1$

Electronegativity: 2.05 (Paulings scale)

Bond strengths[17] and lengths:[18]

B-C	440 kJ/mol	1.6 Å
B-O	780 kJ/mol	1.4 Å
B-B	300 kJ/mol	
B-H	330 kJ/mol	
B-Si	290 kJ/mol	

In the chemistry of boron the vacant p-orbital plays an instrumental role, being responsible for the three center-two electron bond in e.g. diborane

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[8] Wuts, P. G. M.; Greene, T. W. *Greene´s Protective Groups in Organic Synthesis, 4th ed.*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.

[9] Hudrlik, P. F.; Peterson, D. *J. Am. Chem. Soc.* **1975**, *97,* 1464.

[10] Denmark, S. E.; Regens C. S. *Acc. Chem. Res.* **2008**, *41*, ASAP.

[11] Masse, C. E.; Panek, J. S. *Chem. Rev.* **1995**, *95*, 1293-1316, and references cited therein.

[12] Mukiyama, T.; Banno, K.; Narasaka, K. *J. Am. Chem. Soc.* **1974**, *96*, 7503

[13] *Comprehensive Handbook on Hydrosilylation*, Marciniec, B., Ed., Pergamon, Oxford, 1992.

[14] Fleming, I.; Henning, R.; Parker, D. C.; Plaut, H. E.; Sanderson, P. E. J. *J. Chem. Soc. Perkin Trans. 1* **1995**, 317-337.

[15] Fleming, I.; Berbero, A.; Walter, D. *Chem. Rev.* **1997**, *97*, 2063-2192.

[16] Langkopf, E.; Schinzer, D. *Chem. Rev.* **1995**, *95*, 1375-1498.

[17] Approximate values for homolytic bond dissociation, taken from: Darwent, B. deB. *Nat. Stand. Ref. Data. Ser., Nat. Bur. Stand.* **1970**, *31*, 1-52.

[18] Hall, D. G. in *Boronic Acids*, Hall, D. G. (Ed.), WILEY-VCH, Weinheim, **2005**, chapter 1, pp 1-100.

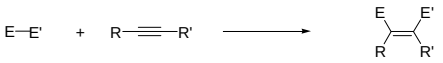
[19] Encyclopedia Brittanica Online – Boron
http://www.britanica.com/EBchecked/topic/74358/boron#tab=active~checked%2Citems~checked&title=boron%20--%20Britannica%20Online%20Encyclopedia

and the Lewis acidity of boron compounds. Boron compounds are in general non-toxic, and recently boron has even found its way into the drug market as the boronic-acid containing drug Velcade®.[18]

In organic chemistry boron holds a prominent place and in many general textbooks the chemistry of boron is, together with elements such as silicon, phosphorous, tin and sulfur, devoted an entire chapter.[20] Among the most important organic transformations involving boron are the Suzuki cross-coupling,[21] hydroboration,[22] and allylboration[23] reactions. Boron functionalities can be oxidized or protodeboronated,[22] further expanding the scope of the chemistry of boron.

1.4. Element-Element Additions

An element-element addition is the addition of a compound containing an interelement linkage[24] across an unsaturated moiety where the interelement bond is being broken and both interelement atoms are incorporated into the product. The interelement linkage is defined as "mutual linkages within the heavy main group elements and linkages between the main group elements and transition metals". The most common interelement linkages in terms of reported crystal structures are, as of 2000, S-S, B-B, P-S and P-P.[24] In terms of the number of reported element-element additions, combinations of Si-, B- and Sn- are the most common. A few extensive reviews covering most of the area have been published.[4]



Scheme 1: Element-Element addition to an alkyne.

Element-element additions are most commonly catalyzed by the Pt group metals, but there are also examples of Rh- and Ru-catalyzed reactions. Phosphine ligands are routinely employed, but ligand-free[25] and isocyanide promoted additions have also been reported.[26] However, highly reactive

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[20] (a) Carey, F. A.; Sundberg, R. J. *Advanced Organic Chemistry, 4th Ed.,* Kluwer Academic / Plenum Publishers, New York, **2001**, Chapter 9, pp 547-594. (b) Norman, R. O. C.; Coxon, J. M. *Principles of Organic Synthesis, 3rd Ed.,* Blackie Academic & Professional, London, **1993**, Chapter 15, pp 458-495.

[21] Miyaura; N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457-2483.

[22] Brown, H. C. *Hydroboration,* 1st Ed., W. A. Benjamin, Inc., New York, 1962.

[23] Kennedy, J. W. J.; Hall, D. G. *Angew. Chem. Int. Ed.* **2003**, *42*, 4732-4739.

[24] Editorial *J. Organomet. Chem.* **2000**, *611*, 3-4.

[25] Meaning that no P or N containing (etc.) compounds are a part of the catalyst system, but not excluding the possibility of dba, acetate or solvent molecules ligated to the metal.

[26] Ito, Y.; Suginome, M.; Murakami, M. *J. Org. Chem.* **1991**, *56*, 1948-1951.

interelement species, such as the unstable B_2Cl_4, undergo uncatalyzed additions to alkenes and alkynes,[27] and diselenides can undergo iodosobenzene promoted additions to methylenecyclopropanes.[28]

Of the substrates employed, alkynes have received most attention,[4,29] probably due to their high reactivity and the usefulness of the products formed. An excellent example of this is the alkyne diboration strategy employed by Brown et al. in the synthesis of Tamoxifen.[30] Other unsaturated moieties that successfully have been used as substrates include alkenes, 1,3-dienes, allenes, conjugated enones, and vinyl- and methylenecyclopropanes. The regio- and stereoselectivity is usually high; alkyne additions are predominantly syn selective, additions to allenes most commonly proceed in a 2,3-fashion, but also 1,2-additions have been reported to occur with high selectivity. In additions to 1,3-dienes dimerized products are often observed along with the, predominantly 1,4-selective, addition product.[4]

Element-element additions are considerably substrate dependent, for example 1,2-dienes are efficiently silaborated using Cp(allyl)Pd/PPh_3 complexes[31] while the addition of the very same silylborane to 1,3-dienes seems to require Ni- or Pt-catalysts.[32] Whereas diborations of alkenes proceed smoothly using Rh-catalysis,[33] the metal of choice for disilylations is most commonly Pd.[4]

The reaction mechanism of the element-element additions is generally presumed to be as follows: first the interelement compound is added to the transition metal catalyst via oxidative addition. The unsaturated substrate then coordinates to the metal and is inserted into one of the metal-element bonds. The final product is then formed via reductive elimination and the active catalyst regenerated (Scheme 2).[4] This reaction mechanism is very general, and does not include the exact nature of the complexes involved. Some conclusions can, however, be drawn from it. For tetracoordinated E-M(II)L_2-E´ complexes to be able to coordinate, and thereby activate, the unsaturated substrates they have loose one of the ligands. This makes bidentate ligands a poor choice for these reactions as the chelate effect would inhibit the formation of a vacant coordination site for the unsaturated moiety. There are accordingly very few

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[27] Irvine, G. J.; Lesley; M. J. G.; Marder, T. B.; Norman, N. C.; Rice, C. R.; Robins, E. G.; Roper, W. R.; Whitell, G. R.; Wright, L. J. *Chem. Rev.* **1998**, *98*, 2658-2722 and references therein.

[28] Shi, M.; Wang, B.-Y.; Li, J. *Eur. J. Org. Chem.* **2005**, 759-765.

[29] Beletskaya, I.; Moberg, C. *Chem. Rev.* **1999**, *99*, 3435-3462.

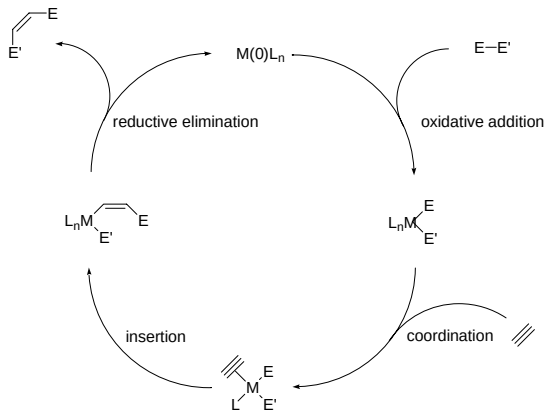
[30] (a) Brown, S. D.; Armstrong, R. W. *J. Am. Chem. Soc.* **1996**, *118*, 6331. (b) Brown. S. D.; Armstrong, R. W. *J. Org. Chem.* **1997**, *62*, 7076.

[31] Suginome, M.; Ohmura, T.; Miyake, Y.; Mitani, S.; Ito, Y.; Murakami, M. *J. Am. Chem. Soc.* **2003**, *125*, 11174-11175.

[32] Suginome, M.; Matsuda, T.; Yoshimoto, T.; Ito, Y. *Org. Lett.* **1999**, *1*, 1567-1569.

[33] Morgan, J. B.; Miller, S. P.; Morken, J. P. *J. Am. Chem. Soc.* **2003**, *125*, 8702-8703.

reported examples where bidentate ligands are employed in Pt and Pd catalyzed element-element additions,[4] the Pd-BINAP catalyzed Si-Si addition to conjugated enones being one of the few.[34] This limitation does not apply to Rh-catalyzed reactions[35] as Rh(III) can accommodate up to six ligands. A survey of the investigations that have been made into the mechanisms of these reactions can be found in Chapter 4.1.



Scheme 2: General mechanism for element-element additions.

In terms of synthetic applications in total synthesis element-element additions have been used in the synthesis of compounds such as (-)-avenaciolide (Si-Si),[36] dl-muscone (Si-Si),[37] 6a-epipretazettine (Si-Sn),[38] and amphidinolide H & G (Si-Sn).[39]

The chemistry of silaborations and silylboranes is more extensively surveyed in Chapter 2.1.

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[34] Hayashi, T.; Matsumoto, Y., Ito, Y. *J. Am. Chem. Soc.* **1988**, *110*, 5579-5581.

[35] One example being Walter, C.; Auer, G.; Oestrich, M. *Angew. Chem. Int. Ed.* **2006**, *45*, 5675-5677.

[36] Niestroj, M.; Neumann, W. P.; Mitchell, T. N. *J. Organomet. Chem.* **1996**, *519*, 45-68.

[37] Suginome, M.; Yamamoto, Y.; Fujii, K.; Ito, Y. *J. Am. Chem. Soc.* **1995**, *117*, 9608-9609.

[38] Overman, L. E.; Wild, H. *Tetrahedron. Lett.* **1989**, *30*, 647-650.

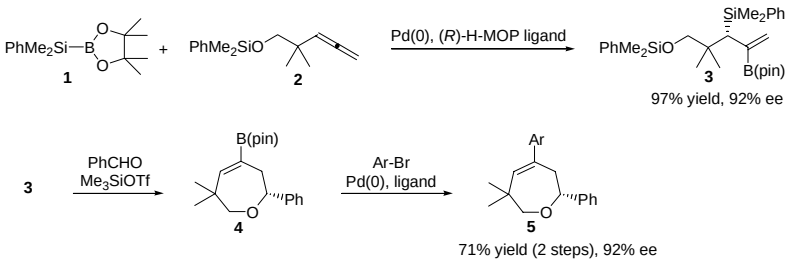
[39] Fürstner, A.; Bouchez, L. C.; Funel, J.-A.; Liepins, V.; Porée, F.-H.; Gilmour, R.; Beaufils, F.; Laurich, D.; Tamiya, M. *Angew. Chem. Int. Ed.* **2007**, *46*, 9265-9270.

2.
Silaboration of 1,3-Dienes

(Papers I-III)

2.1. Introduction

Scheme 3 shows one of the most successful examples of an interelement addition of a silylborane: the enantioselective silaboration of a terminal allene, followed by allylation, ring closure and Suzuki cross-coupling to afford seven-membered ethers (**5**).[40] The silaboration gives rise to allylsilane and vinylboronate moieties and both these functionalities are subsequently utilized in the following steps, in which complete chirality transfer is observed. Overall the sequence has several attractive features: it is enantioselective, the asymmetry is induced using a small amount of a chiral catalyst and all the elements introduced are utilized to construct the complexity found in the final product. This synthetic sequence was performed by M. Suginome and co-workers who, together with Y. Ito, have pioneered the field and successively expanded the scope of silaboration reactions, starting from the silaboration of alkynes in 1996.[41]



Scheme 3: Asymmetric silaboration of allene **2**.

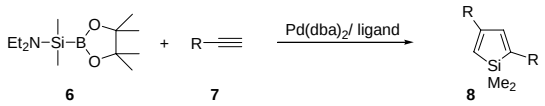
2.1.1. Silaborations

The first process of this kind which was performed was the *Z*-selective Pt- or Pd-catalyzed silaboration of terminal alkynes, which proceeded with excellent regioselectivity, delivering boron to the terminal position.[41] When Ni was used as catalyst for the silaboration of terminal alkynes, mixtures of dimerized

[40] Ohmura, T.; Taniguchi, H.; Suginome, M. *J. Am. Chem. Soc.* **2006**, *128*, 13682-13683.

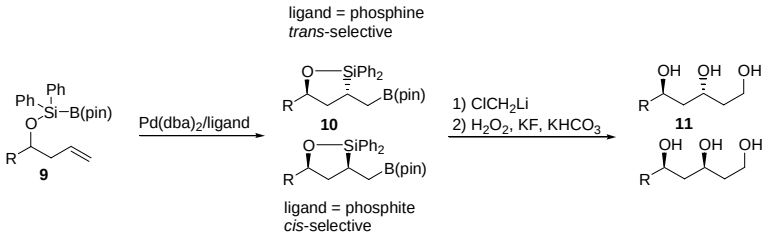
[41] (a) Suginome, M.; Nakamura, H.; Ito, Y. *Chem. Commun.* **1996**, 2777-2778. (b) Suginome, M.; Matsuda, T.; Nakamura, H.; Ito, Y. *Tetrahedron* **1999**, *55*, 8787-8800.

products were obtained.[42] In Pd-catalyzed reactions, changing from silylborane **1** to silylboranes bearing dialkylamino groups on silicon (**6**) resulted in the formation of siloles (**8**) (Scheme 4).[43]



Scheme 4: Syntheis of 2,4-disubstituted siloles via the Pd-catalyzed reaction of silylborane **6** and terminal alkynes.

In the Pt-catalyzed silaboration of terminal alkenes,[44] silicon is delivered to the terminal position, reversing the selectivity compared to that of the silaboration of alkynes. Employing a silylborane tethered to the alkene via oxygen (**9**), the intramolecular version of this reaction was developed (Scheme 5). For steric reasons the silicon was now added to the internal position. The *cis*/*trans* selectivity of the reaction was shown to be dependent on the ligand structure. Via homologation and subsequent oxidation, diastereomeric triols (**11**) were accessed.[45]



Scheme 5: Intramolecular stereoselective silaboration of alkenes, followed by homologation and oxidation to yield triols.

Major efforts were devoted to developing the silaboration of allenes, finally resulting in the reaction sequence shown in Scheme 3, starting with the first reported Pd-catalyzed 2,3-silaborations of terminal allenes.[46] The allylsilane in the 2,3-addition products has been utilized in Lewis acid-promoted allylations of acetals and aldehydes, and Prins-type cyclizations. Products thus prepared were subsequently employed in Pd-catalyzed cross-coupling reactions and Rh-

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[42] Suginome, M.; Matsuda, T.; Ito, Y. *Organometallics* **1998**, *17*, 5233-5235.

[43] Ohmura, T.; Masuda, K.; Suginome, M. *J. Am. Chem. Soc.* **2008**, *130*, 1526-1527.

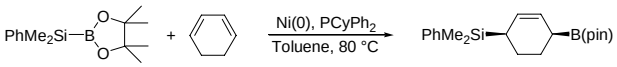
[44] Suginome, M.; Nakamura, H.; Ito, Y. *Angew. Chem. Int. Ed.* **1997**, *36*, 2516-2518.

[45] Ohmura, T.; Furukawa, H.; Suginome, M. *J. Am. Chem. Soc.* **2006**, *128*, 13366-13367.

[46] (a) Suginome, M.; Ohmori, Y.; Ito, Y. *Synlett* **1999**, 1567-1568. (b) Onozawa, S-y.; Hatanaka, Y.; Tanaka, M. *Chem. Commun.* **1999**, 1863-1864. (c) Suginome, M.; Ohmori, Y.; Ito, Y. *J. Organomet. Chem.* **2000**, *611*, 403-413.

catalyzed conjugate additions to enones.[47] When the silaboration of allenes was performed using $Pd(dba)_2$ as catalyst and organic iodides as initiators, 1,2-silaboration of the allene followed, with the boryl group adding to the terminal carbon atom. The allylboronate functionality in the products was employed in allylborations of aldehydes.[48] The asymmetric 2,3-silaboration of allenes was first performed using chiral silylboranes in combination with chiral ligands,[31] the ligand structure was later fine-tuned to give the product in up to 93% ee using silylborane **1**.[40]

The silaboration of acyclic 1,3-dienes can be accomplished by Pt-catalysis, furnishing a 1:1 *E*/*Z* mixture of the 1,4-silaboration products in good yield. When the reaction was performed in the presence of aldehydes a three-component coupling reaction ensued.[49] The 1,4-silaboration of 1,3-dienes was, by the use of Ni-based catalyst systems, extended to include cyclic dienes (cyclohexa- and cycloheptadiene, Scheme 6). The reaction proceeded under $Ni/PCyPh_2$ catalysis to give racemic product with complete *cis*-selectivity. Still, 1,4-disubstituted acyclic dienes did not furnish any product and cyclopenta- and 1,3-cyclooctadiene were also unreactive.[50]



1 **12** **13**

Scheme 6: Stereoselective silaboration of 1,3-cyclohexadiene.

At the outset of our investigations into the chemistry of silaborations we were particularly intrigued by the additions to 1,3-dienes. The products obtained are densely functionalized, containing both allylsilane and allylboronate functionalities that can be utilized for further synthetic transformations. These transformations had not been explored fully, neither had the possibility of forming enantiomerically enriched products. There was also a lack of generality in the substrates that could be employed, an issue that needed to be addressed in order to fully utilize the potential of this approach.

Silaborations are by no means the only asymmetric element-element additions that have been developed: the conjugate addition of Si-Si to enones was reported at an early stage[34] and enantioselective diborations have been

[47] Suginome, M.; Ohmori, Y.; Ito, Y. *J. Am. Chem. Soc.* **2001**, *123*, 4601-4602.

[48] Chang, K.-J.; Rayabarapu, D. K.; Yang, F.-Y.; Cheng, C.-H. *J. Am. Chem. Soc.* **2005**, *127*, 126-131.

[49] Suginome, M.; Nakamura, H.; Matsuda, T.; Ito, Y. *J. Am. Chem. Soc.* **1998**, *120*, 4248-4249.

[50] Suginome, M.; Matsuda, T.; Yoshimoto, T.; Ito, Y. *Org. Lett.* **1999**, *1*, 1567-1569.

performed on alkenes[51] and allenes.[52] Asymmetric Si-Si, B-B and Si-B additions were recently covered in a review.[53]

2.1.2. Silylboranes

Silylboranes are most commonly prepared by the addition of silyllithiums to boron halides. Chlorobis(dialkylamino)boranes are often employed as electrophiles. The resulting bis(dialkylamino)silylborane can then be derivatized to yield catechol and pinacol boronates etc via ligand exchange reactions.[54] Silylborane **1** can be accessed directly via the reaction of phenyldimethylsilyllithium[55] with isopropoxypinacolborane, furnishing the product in good to moderate yield,[56] or it can be purchased from commercial sources. It is air sensitive and needs to be stored under inert atmosphere, but can be handled in air for short periods of time, and it is thermally stable.[57] Compound **1** is in fact one of the most stable silylboranes, much due to the pinacol moiety, and the products obtained from silaborations using **1** are typically stable under standard workup and purification conditions. Chiral, enantiopure analogues (**14**-**18**) of silylborane **1** have been prepared and applied successfully in asymmetric silaborations[31] (vide supra). Quite recently analogues of **1** with heteroatoms replacing the phenyl group on silicon (**19**) have been prepared[58] and shown to exhibit markedly increased reactivities in the silaboration of alkynes, as compared to silylborane **1**.[43]

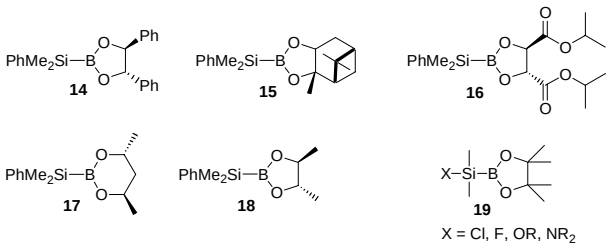


Figure 1: Silylboranes **14**-**19**.

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[51] Morgan, J. B.; Miller, S. P.; Morken, J. P. *J. Am. Chem. Soc.* **2003**, *125*, 8702-8703.

[52] (a) Pelz, N. F.; Woodward, A. R.; Burks, H. E.; Sieber, J. D.; Morken, J. P. *J. Am. Chem. Soc.* **2004**, *126*, 16328-16329. (b) Woodward, A. R.; Burks, H. E.; Chan, L. M.; Morken, J. P. *Org. Lett.* **2005**, *7*, 5505-5507. (c) Pelz, N. F.; Morken, J. P. *Org. Lett.* **2006**, *8*, 4557-4559.

[53] Burks, H. E.; Morken, J. P. *Chem. Commun.* **2007**, 4717-4725.

[54] Hemeon, I.; Singer, R. D. In *Science of Synthesis*, Fleming, I. (Ed.), Georg Thieme Verlag, Stuttgart, **2002**, Vol. 4, Chapter 4.4.8., pp 211-218.

[55] Fleming, I.; Roberts, R. S.; Smith, S. C. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1209-1214.

[56] Suginome, M.; Matsuda, T.; Ito, Y. *Organometallics* **2000**, *19*, 4647-4649.

[57] Suginome, M.; Ito, Y. *J. Organomet. Chem.* **2003**, *680*, 43-50.

[58] Ohmura, T.; Masuda, K.; Furukawa, H.; Suginome, M. *Organometallics* **2007**, *26*, 1291-1294.

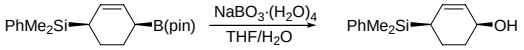
2.1.3. Aim of the study

The aim of our study was to expand the scope of silaborations of 1,3-dienes by developing asymmetric versions of these reactions, finding new catalyst systems that would allow for expansion of the substrate scope, and to explore the utility of the products formed.

2.2. Ni-Catalyzed Enantioselective Silaboration of 1,3-Cyclohexadiene

At the outset of our studies it was known that the 1,4-silaboration of 1,3-cyclohexadiene (**12**) proceeds using catalysts prepared from $Ni(acac)_2$/DIBALH and a number of electron-rich phosphine ligands. The *cis*/*trans* selectivity was shown to depend on the ligand structure and $PCyPh_2$ turned out to perform best in terms of both yield and selectivity (99% yield, >99:1 *cis* selectivity). Under ligand-free or Ni/PPh_3 catalysis no product was obtained, but Ni(0)/$PCyPh_2$ could be replaced by Pt(ethene)(PPh_3), giving the product in low yield.[50] Therefore our efforts aimed at developing an asymmetric version of this reaction started off using Ni-based catalyst systems. We also decided to focus our attention on chiral monodentate phosphine ligands, as bidentate ligands are presumed to inhibit the catalytic cycle.[4,53] This of course limited the choice of ligand structures. Many of the best ligands that have been developed for asymmetric catalysis are bidentate, but there is a growing number of highly efficient monodentate phosphine ligands.[59]

Our first objective was to establish a method to analyze the enantiomeric composition of **13**. As direct analysis by chiral HPLC and GC proved unsuccessful we performed our measurements on a derivative of **13**. Therefore compound **13** was smoothly converted to alcohol **20** with retention of configuration[60] using H_2O_2 or $NaBO_3{\cdot}(H_2O)_4$ as the oxidant. The enantiomers were then readily separated using chiral HPLC (Scheme 7).[61]



13 **20**
63% isolated yield

Scheme 7: Oxidation of compound **1**.

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[59] (a) Feringa, B. L. *Acc. Chem. Res.* **2000**, *33*, 346-353. (b) Mehler, G.; Reetz, M. T. *Angew. Chem. Int. Ed.* **2000**, *39*, 3889-3890. (c) Claver, C.; Fernandez, E.; Gillon, A.; Heslop, K.; Hyett, D. J.; Martorell, A.; Orpen, A. G.; Pringle, P. G. *Chem. Commun.* **2000**, 961-962.

[60] Oxidation of organoboranes to alcohols is a process known to occur with retention of configuration, see: Brown, H. C.; Snyder, C.; Rao, B. C. S.; Zweifel, G. *Tetrahedron* **1986**, *42*, 5505-5510.

[61] CHIRALCEL OD-H, 0.75% iPrOH/hexane, 0.75 ml/min, t_r = 23.5 min (*ent*-**20**), 26.9 min (**20**).

A set of ligands was obtained by means of synthesis, purchase or as generous gifts and evaluated as catalysts in the silaboration of 1,3-cyclohexadiene (Figure 2). The results were rather discouraging: most of the ligands did not catalyze the reaction, and the ones that did produced essentially racemic product.

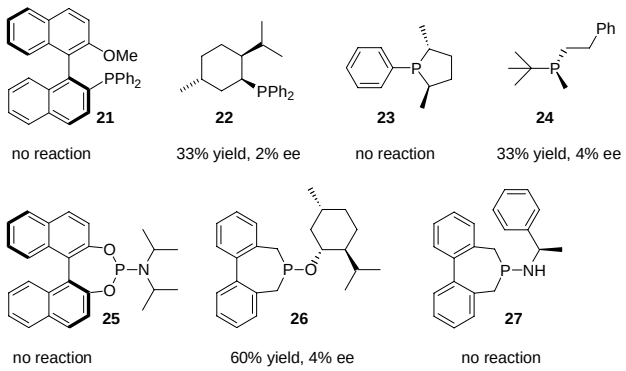


Figure 2: Silaboration of 1,3-cyclohexadiene using chiral Ni complexes. Reactions performed in toluene using 5-10% $Ni(acac)_2$, 10-20% DIBALH, 10-20% ligand, 80 °C, 16-24 h. M/L ratio 1/2. Yields determined by ^1H NMR using 1-methoxynaphthalene as internal standard. Enantiomeric excess determined by chiral HPLC on compound **20**. See reference 61.

BINAP was also tested and, not surprisingly, did not afford any product. Otherwise it should be noted that only electron-rich phosphines, possessing alkyl substituents, seem to catalyze the reaction under these conditions. Increasing the temperature did not improve the yields, instead decomposition of the catalyst (Ni-black) was observed.

2.3. Pt-Catalyzed Enantioselective Silaboration of 1,3-Cyclohexadiene

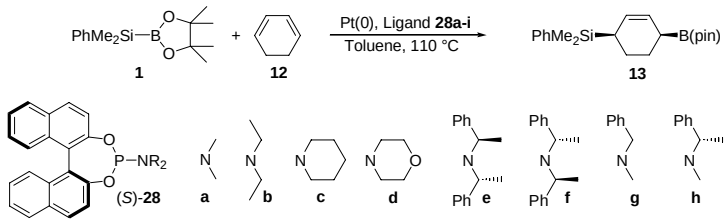
As it seemed that we were severely limited in the choice of ligand, which in turn stopped us from using many of the monodentate ligands that have been utilized successfully in asymmetric catalysis,[59] we decided to take one step back looking for other catalyst systems that would promote the reaction. Thereby we hoped to be able to employ a wider range of ligands, thus enhancing our chances of successfully finding an enantioselective catalyst system. $Pt(ethene)(PPh_3)_2$ had been shown to catalyze the silaboration of 1,3-cyclohexadiene to some extent,[50] showing that Ni is not the only metal of choice for this transformation.

We started our screening by examining a range of Pt and Pd catalyst systems, mainly employing PPh_3 and $PCyPh_2$ as ligands. None of the Pd complexes employed[62] afforded any product. Fortunately Pt turned out to be more efficient and at 110 °C the product was formed in 74% yield using a catalyst system derived from $Pt(acac)_2$/DIBALH and PPh_3. The increased temperature as compared to Ni catalysis was necessary to obtain good yields, as the reaction was sluggish at 80 °C. In fact, PPh_3 was not the only ligand to promote the reaction. Almost any ligand that were combined with Pt at 110 °C afforded the product and even under ligand-free conditions some product (16%) was obtained.

Having established that catalysts prepared from $Pt(acac)_2$ and a wide range of ligands promoted the reaction, we again turned to our principal task of finding a ligand that yields enantiomerically enriched product. First ligands **21**-**25** were employed.[63] Ligands **21**-**24** all gave low too moderate yields and poor enantioselectivities, but the phosphoramidite **25** afforded the product in 61% yield and in 70% ee (Table 1, entry 1). A screening of phosphoramidite ligands was then undertaken. The results from the reactions employing ligands with a standard BINOL backbone are summarized in Table 2. Most notable is ligand **28i** which afforded the product in 84% yield and 77% ee using a comparatively short reaction time (entry 10). It can be noted that the ligands incorporating chiral amines (entries 6-7, 9) did not give improved selectivities, but that there is a match-mismatch effect (entries 6-7).

[62] $Pd(OAc)_2$, $Pd(acac)_2$/DIBALH, $Pd_2(dba)_3$, and allylPdCl were evaluated at 80 °C and 110 °C.
[63] $Pt(acac)_2$ (5 mol %), DIBALH (10 mol %), ligand (10 mol %), toluene, 110 °C.

Table 1: Pt-catalyzed silaboration of 1,3-cyclohexadiene using phosphoramidite ligands.



Entry	Ligand	Time (h)	Yield (%)[a]	ee (%)[b]
1	(*S*)-**19**	41	61	70
2	(*R*)-**28a**	48	23	34
3	(*R*)-**28b**	18	26	69
4	(*R*)-**28c**	48	58	59
5	(*R*)-**28d**	48	80	56
6	(*S*)-**28e**	30	40	28
7	(*S*)-**28f**	48	58	69
8	(*S*)-**28g**	48	84	69
9	(*S*)-**28h**	48	76	24
10	(*S*)-**28i**	24	84	77

Reactions performed in toluene using 5 mol % $Pt(acac)_2$, 10 mol % DIBALH, 10 mol % ligand, 110 °C.
[a] Determined by ^1H NMR using 1-methoxynaphthalene as internal standard.
[b] Determined by chiral HPLC on compound **20**. See reference 61.

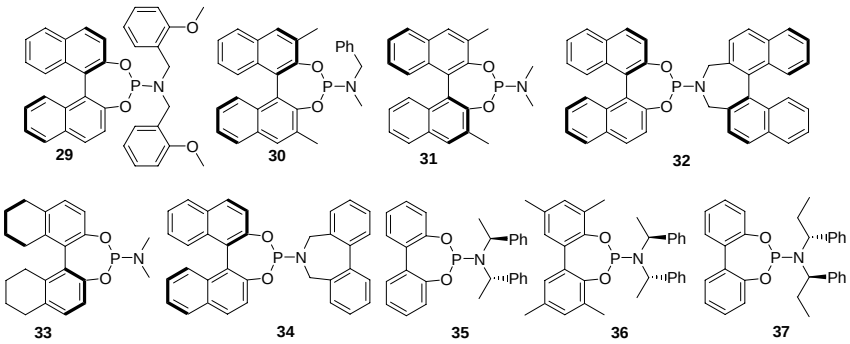
The absolute configuration of compound **13** was determined by transforming allylic alcohol **20** into its corresponding Mosher ester[64] by reaction with (*S*)-MTPA-Cl and analysis according to the rules of Kakizawa and co-workers.[65] The diastereomeric composition of the Mosher esters obtained was in complete agreement with the ee values measured and it was concluded that (*S*)-**28** ligands give (1*R*,4*S*)-**13** as the major product.

The screening for the optimal ligand was continued using phosphoramidite ligands **29**-**37**. These included large structural variations with modified

[64] Dale, J.; Mosher, H. *J. Am. Chem. Soc.* **1973**, *95*, 512-519.
[65] Ohtani, I.; Kusumi, T.; Kashman, H.; Kakisawa, H. *J. Am. Chem. Soc.* **1991**, *113*, 4092-4096.

binaphthol moieties (Table 2, entries 2-3, 5), atropisomeric biphenols (entries 7-9), and binaphthyl amine structures (entry 4). The best results were obtained by introducing methyl groups at the 3-positions in the binaphthol backbone, resulting in slightly increased reactivities but lower selectivities (compare Table 1, entries 2, 8 with Table 2, entries 2-3). Out of the phosphoramidite ligands employed, ligand **28i** is clearly the most efficient, giving 77% ee and 84% yield in 24 hours. This ligand was therefore selected for further studies, aimed at increasing the enantioselectivity. As it furnished the product in high yield in only 24 hours we assumed that there should be room for improving selectivities by lowering of the reaction temperature.

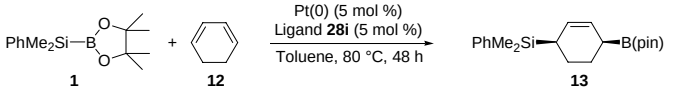
Table 2: Pt-catalyzed silaboration of 1,3-cyclohexadiene using phosphoramidite ligands.



Entry	Ligand	Yield (%)[a]	ee (%)[b]
1	**29**	22	29
2	**30**	92	58
3	**31**	84	57
4	**32**	38	53
5	**33**	51	58
6	**34**	50	27
7	**35**	52	32
8	**36**	26	21
9	**37**	11	13

Reactions performed in toluene using 5 mol % $Pt(acac)_2$, 10 mol % DIBALH, 10 mol % ligand, 110 °C, 48 h.
[a] Determined by ^1H NMR using 1-methoxynaphthalene as internal standard.
[b] Determined by chiral HPLC on compound **20**. See reference 61.

First the optimum metal/ligand ratio was determined. At 110 °C a 1:2 ratio proved most beneficial as a 1:1 ratio resulted in low yields, probably due to catalyst decomposition, and a 1:3 ratio completely suppressed the reaction. The reaction temperature was then decreased to 80 °C, thereby improving the enantioselectivity to 82% ee. At 80 °C a 1:1 metal/ligand ratio proved most efficient in terms of reactivity and this was then used at a 1 mmol scale to furnish compound **13** in 73% isolated yield (Scheme 8).[66]



73% isolated yield, 82% ee

Scheme 8: Pt catalyzed silaboration of 1,3-cyclohexadiene under optimized conditions.

2.4. Allylborations

The enantioenriched product from silaboration of 1,3-cyclohexadiene is of little use in itself, but offers promising reactivities for further synthetic transformations. We decided to explore the use of compound **13** in allylboration reactions. The products from 1,4-silaboration of acyclic 1,3-dienes have previously been employed in allylborations of aldehydes that proceed under mild conditions.[49,50] Incorporating the allylboronate moiety into a cyclohexyl ring might impose altered reactivities, although cyclic allylboronates have also been used successfully in allylboration of aldehydes.[67] Typically the allylboration of aldehydes proceeds with excellent diastereoselectivity, in particular when employing Lewis acid catalysis.[68] Of the Lewis acids employed, $Sc(OTf)_3$ seems to be the most efficient in these transformations.[69]

After some experimentation we found that rather forcing conditions were required for the reaction to proceed efficiently. Under optimized conditions 10 equivalents of benzaldehyde were reacted with compound **13** in a microwave

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[66] Reducing the reaction temperature even further proved unsuccessful as the reaction rate dropped significantly already at 70 °C.

[67] (a) Vaultier, M.; Truchet, F.; Carboni, B. *Tetrahedron. Lett.* **1987**, *28*, 4169-4172. (b) Lallemand, J.-Y.; Six, Y.; Richard, L. *Eur. J. Org. Chem.* **2002**, 503-513. (c) Gao, X.; Hall, D. G.; Deligny, M.; Favre, A.; Carreaux, B.; Carboni, B. *Chem. Eur. J.* **2006**, *12*, 3132-3142. (d) Gao, X.; Hall, D. G.; *J. Am. Chem. Soc.* **2005**, *127*, 1628-1629. (e) Hilt, G.; Hess, W.; Harms, K. *Org. Lett.* **2006**, *8*, 3287-3290.

[68] (a) Kennedy, J. W. J.; Hall, D. G. *Angew. Chem. Int. Ed.* **2003**, *42*, 4732-4739. (b) Yamamoto, Y.; Asao, N.; *Chem. Rev.* **1993**, *93*, 2207-2293.

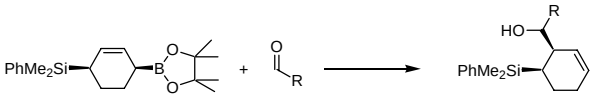
[69] (a) Kennedy, J. W. J.; Hall, D. G. *J. Am. Chem. Soc.* **2002**, *124*, 11586-11587. (b) Kennedy, J. W. J.; Hall, D. G *J. Org. Chem.* **2004**, *69*, 4412-4428.

reactor at 240 °C for 5 hours, giving the allylboration product in 75% isolated yield as a 2:1 mixture of diastereomers.

We began our investigations using benzaldehyde as model substrate. No conversion of the starting materials was observed at room temperature, 80 °C, or 110 °C. Employing Lewis acids such as $Sc(OTf)_3$ or $BF_3{\cdot}OEt_2$ induced decomposition of compound **13**, but no allylboration reaction. It was not until the reaction partners were heated to 180 °C in a microwave reactor that some product formation was observed. This low reactivity is most probably due to the steric hindrance imposed by the dimethylphenylsilyl group.

Compound **13** was then reacted with a range of aldehydes to examine the scope and limitations of this transformation (Table 3). Both aromatic and aliphatic aldehydes can be employed in the reaction, but sterically demanding pivalaldehyde and electron-rich *p*-anisaldehyde failed to react. Overall the diasteroselectivities observed were good to modest, a comparatively poor result compared to other allylborations, which can be attributed to the high temperature needed for the reaction to proceed. The *cis*-relationship between the substituents on the cyclohexyl ring in both isomers of compound **38a** was confirmed by NOESY spectroscopy.

Table 3: Allylborations of aldehydes.



13 **38**

Entry	Aldehyde	Yield[a] (%)	d.r.[b]	Product
1	Benzaldehyde	77	72:28	**38a**
2	Valeraldehyde	88	71:29	**38b**
3	Furfural	76	87:13	**38c**
4	Pivalaldehyde	0	-	**-**
5	*p*-Anisaldehyde	0	-	**-**
6	4-Fluorobenzaldehyde	90	65:35	**38d**
7	Cyclohexanal	72	90:10	**38e**
8	*p*-(Trifluoromethyl)benzaldehyde	64	72:28	**38f**

Reactions performed in 1,2-dichlorobenzene at 240 °C for 2 h in a microwave reactor.
[a] Determined by ^{1}H NMR using 1-methoxynaphthalene as internal standard.
[b] Estimated from crude ^{1}H NMR spectrum.

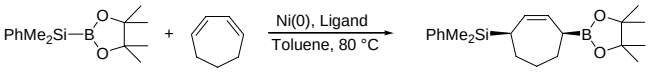
2.5. Enantioselective Silaboration of 1,3-Cycloheptadiene

Having developed conditions for the enantioselective silaboration of 1,3-cyclohexadiene we envisioned that these conditions could also be applied in the silaboration of 1,3-cycloheptadiene (**39**). It has been shown that 1,3-cycloheptadiene can be efficiently silaborated using the same Ni(0)/$PCyPh_2$ catalyst system that was employed in the silaboration of 1,3-cyclohexadiene.[50] We were therefore surprised to find that the Pt-based catalysts that furnished compound **7** in good yields were almost completely inactive in the silaboration of 1,3-cycloheptadiene. Only small amounts of silaboration products whose spectra did not match that of compound **40** were obtained from the Pt-catalyzed reactions. $Pd(acac)_2$ was also employed in combination with PPh_3 and $PCyPh_2$, but did not promote the desired reaction. Finally, we reverted to Ni-catalysis. Fortunately, we could reproduce the reaction using $Ni(acac)_2$/DIBALH/$PCyPh_2$, albeit the recorded yields were somewhat lower than those previously reported.[50] On the other hand, PPh_3 turned out to be an efficient ligand for the reaction, furnishing the product in 97% yield with unaltered >99:1 *cis* selectivity. This observation led us to believe that the Ni-catalyzed silaboration of 1,3-cycloheptadiene might not suffer from the same limitations in terms of only being promoted by electron-rich phosphines, as previously observed in the analogous reaction with 1,3-cyclohexadiene.

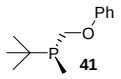
As it turned out, the reaction was promoted by a variety of chiral ligands (Table 4), although the yields were moderate to poor. To assess the enantioselectivities obtained an unusually cumbersome route had to be employed: compound **40** was oxidized to the corresponding alcohol, which was then reacted with (*S*)-MTPA-Cl to yield the Mosher ester.[64] As both the ^1H and ^{19}F NMR signals overlapped for the two diastereomers, the isomeric ratio was analyzed by chiral HPLC.[70] All these efforts were, however, to no avail (Table 4). The enanatioselectivities recorded ranged from 10-22%, with the best results obtained when phosphoramidite ligand **28b** was employed (entry 3). Discouraged by these low selectivities we decided to focus our research efforts elsewhere.

[70] CHIRALCEL OD-H, 0.025% *i*-PrOH/hexane, 1 ml/min.

Table 4: Silaboration of 1,3-cycloheptadiene using chiral Ni complexes.



1 39 40

Entry	Ligand	Yield (%)[a]	ee (%)
1	**25**	-	-
2	**28a**	60	12
3	**28b**	55	22
4	**28f**	8	10
5	**22**	8	n.d.
6	**23**	30	14
7	**24**	17	n.d.
8	 **41**	87	10

Reactions performed in toluene at 80 °C using 5 mol% $Ni(acac)_2$, 2:1 P/Ni ratio, for 24 h.
[a] Determined by ^1H NMR using 1-methoxynaphthalene as internal standard.

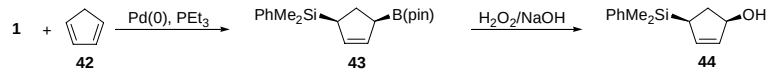
2.6. Silaboration of Cyclopentadiene

Cyclopentadiene has so far not been successfully employed in silaboration reactions,[50] but to the best of our knowledge no concentrated effort on finding suitable reaction conditions for this transformation has been made. We, therefore, undertook a screening of a wide range of catalysts in order to find a set of conditions that would promote the reaction. It turned out that neither complexes based on Ni nor Pt afforded the desired product but, somewhat surprisingly, considering its previous inactivity as a catalyst for silaboration of compounds **12** and **39**, Pd was the metal of choice. When $Pd(acac)_2$ was combined with PEt_3 compound **43** was furnished in 76% yield (Scheme 9).[71] The product was oxidized into allylic alcohol **44** which ^1H NMR spectrum was identical to previously published spectra, and thereby the *cis*-sterochemistry, which was expected in analogy with silaboration of cyclohexa- and cycloheptadiene, was confirmed.[72] Cyclopentadiene was also reacted with

[71] The reaction was performed using $Pd(acac)_2$ (10 mol %), DIBALH (20 mol %), PEt_3 (20 mol %), in toluene at 40 °C for 48 h.

[72] (a) Clive, D. L. J.; Zhang, C.; Zhou, Y.; Tao, Y. *J. Organomet. Chem.* **1995**, *489*, C35-C37. (b) Lipshutz, B. H.; Sclafani, J. A.; Takanami, T. *J. Am. Chem. Soc.* **1998**, *120*, 4021-4022.

chiral silylboranes **14**-**16**, of which **15** turned out to be most selective giving a diastereomeric excess of 53% although the yield was quite modest (43% after 48 h).



Scheme 9: Silaboration of cyclopentadiene.

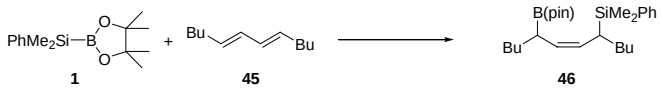
Then, after being successfully repeated over a dozen times, the reaction stopped working. At first this was thought to be due to some rather simple experimental error and the reaction was carefully repeated several times without any trace of product being observed. The reaction parameters were then carefully re-examined.[73] Unfortunately, these efforts were largely unsuccessful. At most 11% of the product was obtained using PMe_2Ph as the ligand.

As improving the quality of the catalyst employed did not solve the problem, it is tempting to speculate that the problem is exactly the opposite – that there was something missing that was present when the reaction was working. This might be a metallic impurity in the $Pd(acac)_2$ or DIBALH used in the reaction. This hypothetic impurity might in some way act as a co-catalyst or activator for the reaction. No proper record on the batches of $Pd(acac)_2$, DIBALH, etc that were employed in the reaction was kept and it is, therefore, difficult to speculate further.

2.7. 1,4-Silaboration of (*E,E*)-5,7-Dodecadiene

Acyclic 1,4-disubstituted 1,3-dienes have never been successfully silaborated. When employing their Ni(0) catalyst system Suginome et al. observed no reaction when silylborane **1** was reacted with 2,4-hexadiene.[50] The products that would arise from this type of reaction would, just as compound **13**, possess two stereocenters as well as allylboronate and allylsilane functionalities (Scheme 10). The $PhMe_2Si$ group would in this type of adducts not be locked in a conformation where it blocks the incoming electrophile and it is reasonable to think that these products would be more reactive in allylboration reactions.

[73] The ligand was distilled prior to use, the order and time of the additions were re-examined, dicyclopentadiene scrupulously dried prior to cracking and the cracked cyclopentadiene dried over molecular sieves, new batches of $Pd(acac)_2$ and DIBALH were employed, the $Pd(acac)_2$ recrystallized, and a number of ligands were re-evaluated.



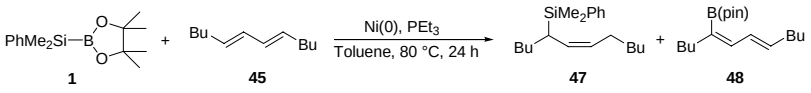
1 45 46

Scheme 10: 1,4-Silaboration of *(E,E)*-5,7-dodecadiene.

Our investigation started by the silaboration of (*E*,*E*)-5,7-dodecadiene using a few different Ni and Pt complexes. Pt showed no activity, but using Ni some interesting results were observed. When Ni(0)/PEt_3 was employed as catalyst using two equivalents of the diene,[74] not one, but two products were obtained in a 1:1 ratio. A complete consumption of both substrates was also observed, which was surprising as an excess of the diene was used. When the reaction was performed using one equivalent of the diene the same two products were obtained in a 1:1 ratio and the diene was completely consumed, while 50% of the silylborane remained. Clearly no 1,4-silaboration was taking place.

2.8. Addition of Silylborane to Acyclic 1,3-Dienes

Instead of a 1,4-silaboration of the diene (**45**), two products were formed in a 1:1 ratio (Scheme 11). Compound **47**, the product of a formal hydrosilylation of the diene, was isolated in 77% yield with high *Z*-selectivity. This product was accompanied by compound **48** that was isolated in 90% yield as a 5:1 mixture of the *E*,*E*- and *Z*,*E*-isomers, with the 5-6 double bond being subject to the *E*/*Z* isomerism. It seemed that the silylborane was split in two parts and that the silyl- and boryl-moieties were added to different dienes. This transformation was accompanied by the loss of a hydride in the diene forming compound **48** and the addition of a hydride to the diene forming compound **47**. It is tempting to speculate that these processes are linked, especially as the two products were formed in a 1:1 ratio (crude ^{1}H NMR).



1 45 47 48

77% yield
> 97:3 *Z*/*E* ratio

90% yield
5:1 *E*,*E*/*Z*,*E* ratio

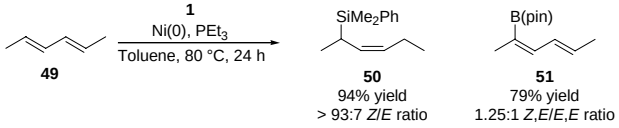
Scheme 11: Addition of silylborane **1** to diene **45**.

In order to gain further insight into this transformation a few other substrates were submitted to the same reaction conditions. When 2,4-hexadiene (**49**)[75] was employed the result was very similar to that obtained with diene **45** (Scheme 12). Two products were again formed in close to 1:1 ratio, one product (**50**) was the result of a formal hydrosilylation of the diene, the other

[74] The reaction was performed using $Ni(acac)_2$ (5 mol %), DIBALH (10 mol %), PEt_3 (10 mol %), in toluene for 24 h at 80 °C.

[75] Technical grade, mixture of isomers.

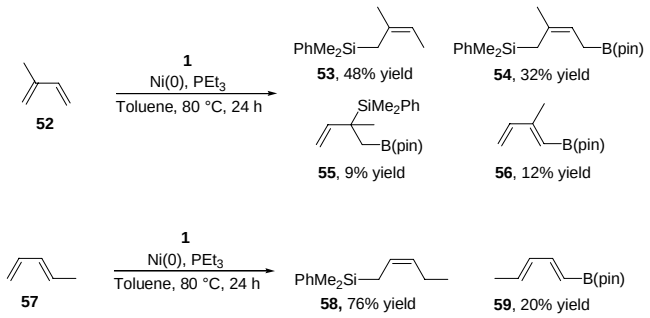
(**51**) from H-B exchange. It should be noted that even though the starting diene consists of a mixture of isomers, the 4-5 double bond in compound **51** has pure *E*-configuration.



Scheme 12: Addition of silylborane **1** to 2,4-hexadiene.

The sterically demanding (*E*,*E*)-2,2,7,7-tetramethyl-3,5-octadiene did not furnish any product when subjected to the standard conditions, most probably as a result of the steric hindrance inherent in the substrate.

Finally, the reactivity of isoprene (**52**) and 1,3-pentadiene (**57**) was examined. Being terminally mono- and unsubstituted, respectively, the reactivity might well differ from that of the terminally disubstituted substrates. Isoprene has, for instance, been shown to react with silylborane **1** under ligand-free Ni(0) catalysis to yield the 1,4-silaboration product as a mixture of isomers.[50] When our Ni(0)/PEt_3 catalyst system was employed a number of products was obtained. From isoprene products of 1,2- and 1,4-silaboration (Scheme 13, **54**-**55**) were accompanied by products of formal hydrosilylation (**53**) and H-B exchange (**56**). 1,3-Pentadiene reacted to give high yields of H-Si addition product (**58**), but this was accompanied by low yields of dienylborane **59**. Along with these two compounds, products of silaboration were also formed.



Scheme 13: Addition of silylborane **1** to isoprene (**52**) and 1,3-pentadiene (**57**).

2.9. Miscellaneous

The chiral silylboranes **14**-**16** were employed in the silaboration of 1,3-cyclohexadiene and 1,3-cycloheptadiene. The highest selectivity in the silaboration of 1,3-cyclohexadiene, 58% de, was obtained using Ni(0)/$PCyPh_2$

as catalyst and silylborane **16**. Efforts to increase the selectivity by combining chiral Pt complexes and the chiral silylboranes resulted in lowered selectivities, as compared to those previously obtained (Table 1 and 2). In the additions to 1,3-cycloheptadiene poor selectivities were obtained.

2.10. Conclusions & Outlook

An asymmetric route to the 1,4-silaboration of 1,3-cyclohexadiene was developed using catalysts prepared from Pt and phosphoramidite ligands. Up to 82% enantiomeric excess was recorded. The product was employed in allylboration reactions giving homoallylic alcohols in good yields and moderate to good selectivities under microwave heated conditions. Our efforts on extending the asymmetric silaboration to include the addition to 1,3-cycloheptadiene were largely unsuccessful as the enanatioselectivities obtained were poor.

In attempts to widen the scope of the silaboration reaction to include acyclic, 1,4-substituted dienes, we discovered a disproportionation reaction. It seemed that the outcome of the addition of silylborane **1** to acyclic 1,3-dienes using $Ni(0)/PEt_3$ catalysis was dependent on the substitution pattern on the diene. 1,4-Disubstituted dienes **45** and **49** only gave products arising from H-B exchange and H-Si addition to the diene, while isoprene and 1,3-pentadiene gave silaboration adducts in addition to the dienylborane and the allylsilane products. Our mechanistic studies on this reaction are discussed in Chapter 4.

Evidently the silaboration of 1,3-dienes is highly substrate dependent. For each substrate combination there seems to be a new metal-ligand combination that is the most efficient. This feature makes developing new methodologies a very time-consuming task.

In order to further optimize the enantioselectivity of the silaboration of 1,3-cyclohexadiene a fine-tuning of the phosphoramidite ligand structure should be undertaken. The most efficient ligand was **28i** with a dibenzylamine moiety. This structure could be modified by introducing different substituents on the phenyl rings and the ligands then assessed in catalysis. In order to rapidly evaluate a large number of phosphoramidite ligands the methods for creating instant ligand libraries developed by de Vries and co-workers could be applied.[76] To fully utilize this approach the bottle-neck of analyzing the enantiomeric composition of the products has to be removed. This could possibly be done by using reverse-phase chiral HPLC, a method unavailable to us at the outset of this project.

[76] (a) Lefort, L.; Boogers, J. A. F.; de Vries, A. H. M.; de Vries J. G. *Org. Lett.* **2004**, *6*, 1733-1735. (b) de Vries, J. G.; Lefort, L. *Chem. Eur. J.* **2006**, *12*, 4722-4734.

3.

Silaborative Carbocyclization of 1,6-Enynes

(Paper IV)

3.1. Introduction

Bismetallation of unsaturated compounds can be combined with cycloisomerizations, providing access to densely functionalized cyclic compounds. However, the reactivity of the compounds formed has not been studied thoroughly, and in most cases only a limited number of substrates has been employed, thereby leaving unanswered questions on the scope and limitations of these processes, as well as the utility of the products formed.

3.1.1. Cycloisomerization of 1,n-Enynes

The metal-catalyzed cycloisomerization of 1,*n*-enynes[77] allows for the efficient and atom economical[78] construction of primarily five- and six-membered rings. One of the first reactions of this kind was the Pd(II)-catalyzed Alder ene reaction developed by Trost and co-workers.[79] The process offers a mild and selective alternative to the thermal Alder ene reaction and allows for the formation of synthetically useful 1,3-dienes that are not accessible by the thermal process.[80] Mechanistically, both Pd(II) and Pd(IV) intermediates have been proposed (Figure 3).[81] This methodology has been extended to include cascade cyclizations of polyenynes,[82] and reductive cyclizations,[83] and has been successfully applied in natural product synthesis.[84] Highly enantioselective versions of the cycloisomerization have also been developed.[85]

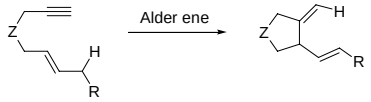


Figure 3: Alder ene reaction.

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[77] Michelet, V.; Toullec, P. Y.; Genêt, J. P. *Angew. Chem. Int. Ed.* **2008**, *47*, 4268-4315 and references therein.

[78] Trost, B. M. *Science* **1991**, *254*, 1471-1477.

[79] Trost, B. M. *Acc. Chem. Res.* **1990**, *23*, 34-42 and references therein.

[80] Trost, B. M.; Tanoury, G. J.; Lautens, M.; Chan, C.; MacPherson, D. T. *J. Am. Chem. Soc.* **1994**, *116*, 4255-4267.

[81] Trost, B. M.; Romero, D. L.; Rise, F. *J. Am. Chem. Soc.* **1994**, *116*, 4268-4278.

[82] Trost B. M.; Shi, Y. *J. Am. Chem. Soc.* **1993**, *115*, 9421-9438.

[83] Trost, B. M.; Rise, F. *J. Am. Chem. Soc.* **1987**, *109*, 3161-3163.

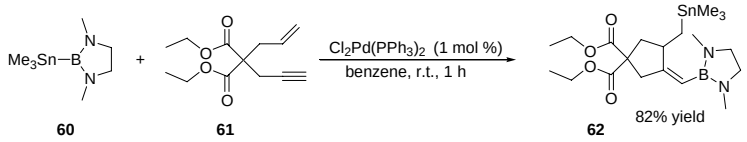
[84] Trost, B. M., Li, Y. *J. Am. Chem. Soc.* **1996**, *118*, 6625-6633.

[85] Hatano, M.; Terada, M.; Mikami, K. *Angew. Chem. Int. Ed.* **2000**, *40*, 249-253.

The cycloisomerization of 1,*n*-enynes has been extended to include concomitant functionalization, such as nucleophilic addition. The nucleophile is believed to undergo addition to an olefin that is activated by Pd(II)[86] or addition to Pd followed by reductive elimination.[87] Another variation of this is the Rh-catalyzed addition of arylboronic acids to 1,6-enynes.[88]

Additions of silanes have been performed in tandem with cycloisomerization reactions. The first silylcarbocyclization was the Rh-catalyzed addition of dimethylphenylsilane to 1,6-enynes discovered by Ojima et al.[89] Highly enantioselective variants of this reaction have been developed.[90] The products formed have successfully been utilized in silicon-based cross-coupling reactions.[91] Hydrostannylative carbocyclizations have also been reported.[92]

Interestingly, the reports on bismetallative carbocyclizations of 1,*n*-enynes are more rare.[77] In a study on the borastannylative carbocyclization of diynes, Tanaka and co-workers also reported the addition to enyne **61** (Scheme 14). The product was formed in high yield as a single diastereo- and regioisomer.[93]



60 **61** **62**

Scheme 14: Borastannylative carbocyclization of enyne **61**.

Mori et al. performed a more detailed study on the silastannylative carbocyclization of 1,6-enynes (Scheme 15).[94] It was shown that, in order to avoid interelement addition over the alkyne, phosphine-free Pd complexes must be employed. The silylstannane added to a number of enynes to give the bismetallated product in good to moderate yields, but the addition to enynes with substituents in the terminal positions met with limited success. The introduction of a methyl group on the alkyne or the olefin moiety resulted in poor yields, while a methyl ester substituent on the olefin proved less

[86] Galland, J.-C.; Dias, S.; Savignac, M.; Genêt, J.-P. *Tetrahedron* **2001**, 57, 5137-5148.

[87] Hanzawa, Y.; Yabe, M.; Oka, Y.; Taguchi, T. *Org. Lett.* **2002**, *4*, 4061-4064.

[88] Miura, T.; Shimada, M.; Murakami, M. *J. Am. Chem. Soc.* **2005**, *127*, 1094-1095.

[89] Ojima, I.; Donovan, R. J.; Shay, W. R. *J. Am. Chem. Soc.* **1992**, *114*, 6580-6582.

[90] (a) Chakrapani, H.; Liu, C.; Widenhoefer, R. *Org. Lett.* **2003**, *5*, 157-159. (b) Widenhoefer, R. A. *Acc. Chem. Res.* **2002**, *35*, 905-913 and references therein.

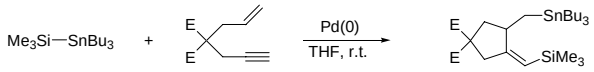
[91] Denmark, S. E.; Liu, J. H.-C. *J. Am. Chem. Soc.* **2007**, *129*, 3737-3744.

[92] Lautens, M.; Mancuso, J. *Org. Lett.* **2000**, *2*, 671-673.

[93] Onozawa, S.-y.; Hatanaka, Y., Choi, N.; Tanaka, M. *Organometallics* **1997**, *16*, 5389-5391.

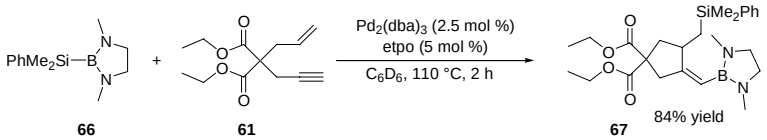
[94] Mori, M.; Hirose, T.; Wakamatsu, H.; Imakuni, N.; Sato, Y. *Organometallics* **2001**, *20*, 1907-1909.

detrimental.[94] Attempts to develop an asymmetric version of this reaction by employing chiral NHC ligands were not successful, as only racemic products were obtained.[95]



Scheme 15: Silastannylative carbocyclization of 1,6-enynes.

The silaborative carbocyclization of enyne **61** has also been reported (Scheme 16).[96] Using silylborane **66** and a Pd(0)/etpo catalyst system the carbocyclization product was obtained in good yield. This reaction was performed as part of a study on diynes and no investigations were made to elucidate the scope and limitations of the methodology with regards to other scaffolds, or the utility of the product formed. In the reactions involving diynes the addition/carbocyclization product was accompanied by silaboration of the alkyne.[96]



Scheme 16: Silaborative carbocyclization of enyne **61**.

Related bismetallative carbocyclization reactions have been reported using bis-dienes,[97] bis-allenes,[98] diynes,[99] and allenynes[100] as substrates.

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[95] Sato, Y.; Imakuni, N.; Mori, M. *Adv. Synth. Catal.* **2003**, *345*, 488-491.

[96] Onosawa, S.-y.; Hatanaka, Y.; Tanaka, M. *Chem. Commun.* **1997**, 1229-1230.

[97] For addition of Sn-Sn, Si-Si, and Si-Sn to bis-dienes, see: Obora, Y.; Tsuji, Y.; Kakehi, T.; Kobayashi, M.; Shinkai, Y.; Ebihara, M.; Kawamura, T. *J. Chem. Soc., Perkin Trans. 1* **1995**, 599-608.

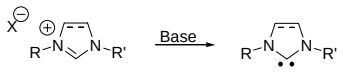
[98] For addition of Ge-Sn to bis-allenes, see: Hong, Y.-T.; Yoon, S.-K.; Kang, S.-K-; Yu, C.-M. *Eur. J. Org. Chem.* **2004**, 4268-4635.

[99] For addition of Si-Sn to diynes, see: (a) Gréau, S.; Radetich, B.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2000**, *122*, 8579-8580. (b) Warren, S.; Chow, A.; Fraenkel, G.; RajanBabu, T. V. *J. Am Chem. Soc.* **2003**, *125*, 15402-15410. For addition of Si-B to diynes, see: (c) Suginome, M.; Matsuda, T.; Ito, Y. *Organometallics* **1998**, *17*, 5233-5235.

[100] For addition of Si-Sn, Sn-B, and Sn-Sn to allenynes, see: Kumareswaran, R.; Shin, S.; Gallou, I.; RajanBabu, T. V. *J. Org. Chem.* **2004**, *69*, 7157-7170.

3.1.2. N-Heterocyclic Carbene Ligands

N-Heterocyclic carbenes constitute a new type of ligands employed in transition metal catalysis. They are typically generated from an imidazolium or imidazolinium salt by deprotonation, yielding a stable, singlet, NHC compound (Scheme 17).[101] The unusual stability of these carbenes is due to the inductive and mesomeric stabilization imposed by the nitrogen atoms. The carbene lone pair (σ) is inductively stabilized by the sigma electron-withdrawing nitrogen atoms, and mesomerically the electron deficiency of the unfilled p_π orbital is reduced by π-donation from the lone pairs on nitrogen.[102]



Scheme 17: N-heterocyclic carbenes.

The NHC ligands are strong electron donors. In a study on Ir-carbonyl complexes Crabtree and co-workers showed that the carbonyl stretching frequencies for complexes containing NHC ligand are even lower than the corresponding complexes of the most Lewis-basic phosphine ligands.[103] Therefore, they bind tightly to metal complexes, and NHC ligands are known to exhibit very low metal dissociation rates.[104] Taking the steric and electronic properties into account it is clear that NHC ligands are not just simply analogues of phosphine ligands, but in many aspects complementary.[105]

NHC ligands have found many applications in catalysis.[101] Among the most noteworthy are the incorporation into Grubbs´ Ru-based olefin metathesis catalysts[106] and the use in Pd-catalyzed cross-coupling reactions,[107] where the Pd-PEPPSI-IPr has proven to be one of the most versatile catalyst systems (Figure 4).[104] N-Heterocyclic carbene ligands have also successfully been employed in the Rh-catalyzed hydrosilylative carbocyclization of 1,6-enynes.[108]

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[101] Hermann, W. A. *Angew. Chem. Int. Ed.* **2002**, *41,* 1290-1309.

[102] Bourissou, D.; Guerret, O.; Gabbaï, F. P.; Bertrande, G. *Chem. Rev.* **2000**, *100*, 39-91.

[103] Chianese, A. R.; Li, X, Janzen, M. C.; Faller, J. W.; Crabtree, R. H. *Organometallics* **2003**, *22*, 1663-1667.

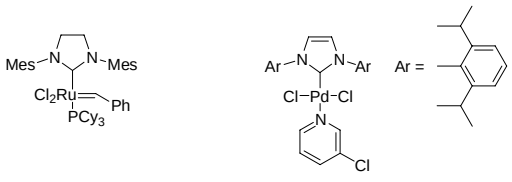
[104] Organ, M. C.; Chass, G. A.; Fang, D.-C.; Hopkinson,. A. C.; Valente, C. *Synthesis* **2008**, 2776-2797.

[105] César, V.; Bellemin-Lapponaz, S.; Gade, L. H. *Chem. Soc. Rev.* **2003**, *33*, 619-636.

[106] Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18-29.

[107] Marion, N.; Nolan, S. P. *Acc. Chem. Res.* **2008**, *41*, ASAP

[108] Park, K. H:; Kim, S. Y.; Son, S. U.; Chung, Y. K. *Eur. J. Org. Chem.* **2003**, 4341-4345.



Grubbs' 2nd Generation Catalyst Pd-PEPPSI-IPr

Figure 4: NHC containing catalysts.

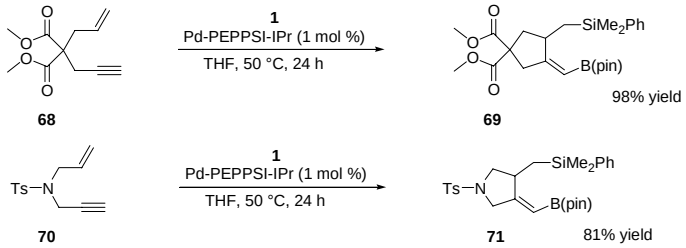
A large number of chiral NHC ligands has been prepared and assessed in asymmetric catalysis.[105] The most successful applications include intramolecular α-arylation of amides,[109] desymmetrization via RCM,[110] and Cu-catalyzed conjugate additions to enones.[111]

3.1.3. Aim of the Study

The aim of our study was to develop a general route for the silaborative carbocyclization of 1,6-enynes using silylborane **1**, allowing for high levels of chiral induction at the newly formed stereocenters. The reactivity of the products formed was to be investigated and efficient methods for further synthetic manipulations developed.

3.2. Silaborative Carbocyclization of 1,6-Enynes

Under optimized conditions the silaborative carbocyclization of enynes **68** and **70**, employing silylborane **1**, proceeded smoothly to furnish the desired product as one single diastereo- and regioisomer in good to excellent yield (Scheme 18). The reaction was performed using low loadings of Pd-PEPPSI-IPr (1 mol %) as the catalyst at elevated temperature (50 °C) employing an excess of the enyne.



Scheme 18: Silaborative carbocyclization of enynes **68** and **70**.

[109] (a) Lee, S, Hartwig, J. F. *J. Org. Chem* **2001**, *66*, 3402-3415. (b) Kündig, E. P.; Seidel, T. M.; Jia, Y.-x.; Bernardinelli, G. *Angew. Chem. Int. Ed.* **2007**, *46*, 8484-8487.

[110] Seiders, T. J.; Ward, D. W.; Grubbs, R. H. *Org. Lett.* **2001**, *3*, 3225-3228.

[111] Martin, D.; Kehrli, S.; d'Augustin, M.; Clavier, H.; Mauduit, M.; Alexakis, A. *J. Am. Chem. Soc.* **2006**, *128*, 8416-8417.

Inspired by the results of Tanaka and co-workers,[96] our efforts leading up to these optimized conditions started by the silaborative carbocyclization of enyne **68** using a number of Pd phosphine and phosphite complexes.[112] At 110 °C the desired product was not formed, instead silaboration of the alkyne predominantly occurred. However, when the N-heterocyclic carbene Pd-PEPPSI-IPr complex, reduced to Pd(0) by MeMgCl, was employed the desired product was obtained, albeit in moderate yield (50%) and as a 5:1 mixture of isomers. Enyne **70** could also be used as substrate, though the yield was low (31%) and the isomeric ratio only 2:1. This result was improved by lowering of the reaction temperature to 50 °C, giving the product in 49% yield as a single diastereomer. As these moderate yields were the result of decomposition of the starting enyne, rather than low reactivity, further optimizations were aimed at suppressing by-product formation and increasing the conversion of the silylborane. This was successfully accomplished by increasing the amount of enyne **70** from 1 to 2 equivalents and decreasing the catalyst loading from 10 to 1 mol %. Thus, compound **71** could be isolated in 81% yield. When the same reaction conditions were applied to substrate **68** the reaction proceeded cleanly to give the desired product in 98% isolated yield.

To investigate the scope of this process a number of enynes with different substituents were employed as substrates (Figure 5). Substituting the methyl ester of **68** for an ethyl ester (**61**) resulted in the desired product being formed in excellent yield. Even though this change was not expected to alter the reactivity in a decisive manner, Mori et al. have shown that the nature of the Z-group in **64** has a clear effect on the rate of silastannylative carbocyclizations.[94]

The introduction of substituents on the alkyne and alkene was explored. The addition of a methyl group (**72-74**) unfortunately inhibited the formation of the desired product. A number of other substituents on the alkene was also evaluated. Running the reaction using compounds **75** and **76**, with methyl ester and phenyl substituents on the alkene, gave some of the desired products, while compounds **77-79** failed to give more than trace amounts. The enynes remained largely intact at 50 °C, but at 80 °C and 110 °C various amounts of decomposition occurred.

[112] Reactions performed in toluene using 5 mol % $Pd_2(dba)_3$ and 10 mol % of PPh_3, $P(OPh_3)$, $P(OEt)_2$, or PMe_2Ph at 110 °C for 18h.

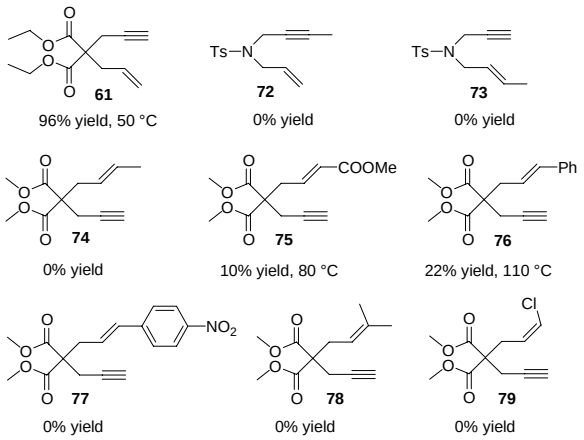


Figure 5: Silaborative carbocyclization of substituted enynes.
Reaction conditions: Si-B 1 (1 equiv.), enyne (1.2 -1.5 equiv.), Pd-PEPPSI-IPr (5 mol %), MeMgCl (10 mol %), THF, 24 h, 50 °C, 80 °C, and 110 °C. Substrates **75** and **79** were not evaluated at 110 °C.

3.3. Attempts at Asymmetric Silaborative Carbocyclization of 1,6-Enynes

In order to try to develop an enantioselective version of this reaction the Pd-PEPPSI-IPr catalyst was replaced by catalyst systems derived from chiral NHC ligands and $Pd_2(dba)_3$ or $Pd(acac)_2$. Deprotonation of the imidazolinium or imidazolium salts was accomplished in situ by base (NaOtBu, DIBALH) or prior to the reaction (**83**, NaH in NH_3/THF[113]). When these catalyst systems were employed in combination with enyne **70** under standard conditions (50 °C, THF) product **71** was obtained in moderate yields as an essentially racemic mixture,[114] an exception being compound **82,** which failed to promote the formation of **71**. By employing imidazolinium salt **80** in diethyl ether, toluene or dichloromethane it was shown that the solvent does not have a critical influence on the enantioselectivity,[115] as the product still was obtained as a racemic mixture.

[113] Arduengo, A. J.; Krafczyk, R.; Scmultzer, R. *Tetrahedron* **1999**, *55*, 14523-14534.
[114] Separation of the enantiomers was accomplished by chiral HPLC: CHIRALCEL OD-H, 12% iPrOH, 0.25 ml/min.
[115] For an example where the choice of solvent is indeed critical, see reference 111.

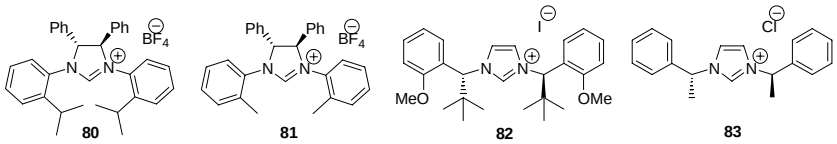


Figure 6: Imidazolinium and imidazolium salts used as NHC precursors.

Having the chiral silylboranes **14**-**16** at hand, these substrates were also employed in the silaborative carbocyclization of enyne **70**. Under standard conditions the desired products were indeed obtained in good yields, but the selectivities were low, not exceeding a 1.1:1 diastereomeric ratio.

Two enynes with chiral auxiliaries (Figure 7) were synthesized and subjected to the standard conditions. This resulted in a smooth formation of the desired product. The yields were excellent, but again the diastereoselectivities obtained were low.[116]

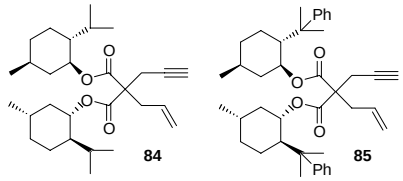
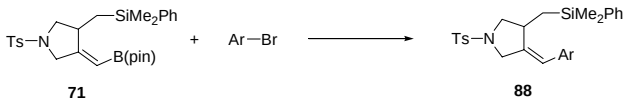


Figure 7: Chiral enynes **84** and **85**.

3.4. Reactivity of the Products Formed

Our investigations on the reactivity of the products formed started by developing conditions for the Suzuki cross coupling reaction employing compound **71** (Scheme 19). We found that by using $Pd(PPh_3)_4$ as catalyst in a mixture of toluene, ethanol, and water the reaction proceeded smoothly at 80 °C with a range of aryl bromides. Both electron-donating and electron-withdrawing substituents were tolerated and the yields were good.



Scheme 19: Suzuki cross-coupling of compound **71**.

[116] 60:40 dr (84), 59:41 dr (85).

3.5. Conclusions & Outlook

A method for performing silaborative carbocyclizations of 1,6-enynes using silylborane **1** was developed. This method reliably gave high yields of the cyclized products when terminally unsubstituted enynes were employed.

The introduction of substituents on the alkyne or alkene part of the enyne inhibits the silaborative carbocyclization. Attempts to overcome this decrease in reactivity simply by an increase in reaction temperature were unsuccessful. A similar observation was made on the silastannylative carbocyclization of enynes where the introduction of a methyl group on either the alkyne or the alkene moiety resulted in low yields of the desired product.[94] This is the only other report on the use of substituted enynes in bismetallative carbocyclization reactions of 1,6-enynes. There are however numerous examples of substituted 1,6-enynes being employed in other cycloisomerization reactions.[77] To overcome this limitation a new catalyst system should be developed, or the reactivity of the system altered, possibly by the use of more reactive silylboranes.[43,58]

Our efforts on developing an asymmetric version of this reaction were unsuccessful. Low levels of induction using chiral NHC ligands were observed.

The products formed were evaluated in Suzuki cross-coupling reactions using a range of aryl bromides. These reactions proceeded in high yield under standard reaction conditions.

Apart from finding conditions to allow for terminally substituted enynes, methods for transforming the silyl group should be developed,[10,14] showing that this does not constitute a “dead end” of the products formed.

4.
Mechanisms

(Papers III and V)

4.1. Introduction

In order to gain insight into, and to increase our understanding of, the silaboration reactions investigated, we decided to study their reaction mechanisms. The reaction mechanism of the Pt-catalyzed silaboration of phenylacetylene has been studied thoroughly, providing a reference point for that of the 1,4-silaboration of 1,3-cyclohexadiene. As the mechanism in both cases is expected to start with the oxidative addition of the silylborane to Pt(0) it is hereby possible to make a direct comparison; to see if the same intermediate is formed, and if there is any effect on this reaction from the DIBALH added, other than to reduce Pt(II) to Pt(0). We also wanted to observe intermediates after insertion of 1,3-cyclohexadiene, expected to occur into the Pt-B bond, and to study the following reductive elimination.

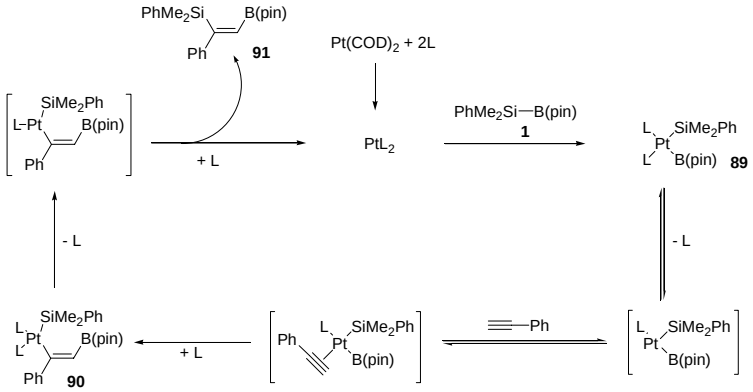
In the addition of silylborane **1** to acyclic 1,3-dienes it seems that while the boron moiety adds to one diene via H-B exchange, the silicon in turn adds to another diene by H-Si addition. This could be due to a disproportionation between two diene molecules where one loses the hydride that is being added to the other. We wanted to test this hypothesis.

4.1.1. Survey of the Field

The general mechanism for interelement additions to unsaturated compounds has been investigated experimentally, both from stoichiometric and catalytic reactions, and by theoretical calculations. Thereby the general mechanism in Scheme 2 has been corroborated.

There are a few detailed studies on the mechanism of silaboration reactions. In a study on the Pt-catalyzed silaboration of phenylacetylene using stoichiometric amounts of Pt complexes, Ozawa and co-workers observed intermediates from oxidative addition of silylborane **1** to Pt(0) (**89**) and intermediates from insertion of the alkyne into the Pt-B bond (**90**). The oxidative addition products were formed simply by mixing silylborane **1**, $Pt(COD)_2$ and 2 equivalents of phosphine ligand (PMe_3, PMe_2Ph, and PEt_3) at room temperature. Using PPh_3 as the ligand no oxidative addition was observed. When phenylacetylene was added to the Si-Pt-B complex at room temperature, insertion of the alkyne into the Pt-B bond followed. The reaction rate showed a negative dependence on phosphine concentration, consistent

with a dissociation of one of the ligands prior to the insertion. Reductive elimination was performed at 60 °C (PMe_2Ph, PMe_3) or room temperature (PEt_3) depending on the steric properties of the ligand. Again a negative dependence of phosphine concentration on the reaction rate was observed, indicating that phosphine dissociation takes place before the reductive elimination. The addition of diphenylacetylene was shown to accelerate the rate of reductive elimination. Taking these observations into account, a reaction mechanism was proposed (Scheme 20).[117]



Scheme 20: Proposed reaction mechanism for silaboration of phenylacetylene.

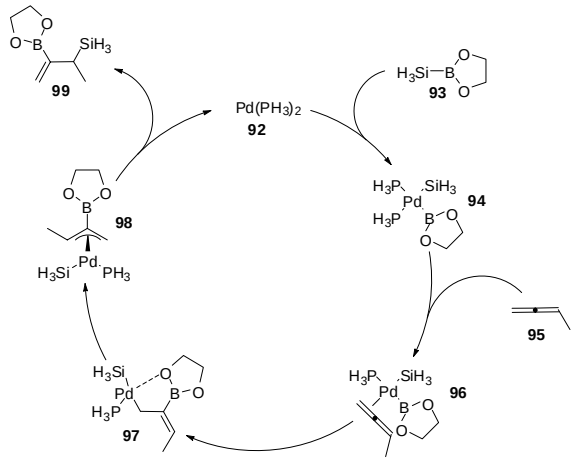
The oxidative addition of $(HO)_2B\text{-}XH_3$ to $M(PH_3)_2$ (X = Si, Ge, Sn or C; M = Pt or Pd) was investigated theoretically.[118] It was found that the addition of B-Si to Pt is exothermic (-33 kcal/mol) and occurs without activation barrier. The addition to Pd was also found to be exothermic (-14 kcal/mol) but with a small activation energy. The additions of B-Sn and B-Ge to both Pd and Pt were calculated to be exothermic as well and to occur with no (Sn) or very small (Ge) activation energy. The unfilled p_π orbital of the boron was shown to be of great importance; in the transition state it participates in a charge transfer interaction that lowers the activation energy and in the B-M complex π-back donation from the metal into the p_π orbital increases the bond strength. Some of the bond energies that were calculated are presented in Table 5.[118]

Table 5: Average bond energies (kJ/mol) calculated by the MP4SDQ method.

	$-B(OH)_2$	$-CH_3$	$-SiH_3$	$-GeH_3$	$-SnH_3$
Pt-	269	177	227	212	194
Pd-	221	123	184	177	168

[117] Sagawa, T.; Asano, Y.; Ozawa, F. *Organometallics* **2002**, *21*, 5879-5886.
[118] Sakakai, S.; Kai, S.; Sugimoto, M. *Organometallics* **1999**, *18*, 4825-4837.

The Pd-catalyzed 2,3-silaboration of terminal allenes[40,48] was investigated by calculations,[119] using a model system similar to that used by Sakaki et al. (Scheme 21).[118] It was shown that the oxidative addition to Pd occurs with no barrier, and that phosphine dissociation takes place prior to insertion of the allene into the Pd-B bond, which also is the rate-determining step. The 1,2-σ-allyl complex (**97**) that is formed after the insertion is converted into a π-allyl complex (**98**). From here reductive elimination takes place to give the 2,3-silaboration product (**99**). The regioselectivity of the reaction is determined at both the insertion and σ-allyl-π-allyl conversion steps, yielding the thermodynamically disfavored (by 18 kJ/mol) 2,3-addition product.[119]



Scheme 21: Proposed mechanism for the Pd-catalyzed silaboration of allene **95**, as supported by DFT calculations.

The oxidative addition to metal complexes has been observed for a number of interelement compounds and the complexes formed have been characterized. Most commonly reported are additions to Pt(0) which take place at room temperature or below with compounds containing interelement B-B,[120] Se-Se,[121] Sn-Sn,[122] Si-Sn,[123] Ge-Sn,[124] and B-Si[117] linkages. Oxidative additions of

[119] Abe, Y.; Kuramoto, K.; Ehara, M.; Nakatsuji, H.; Suginome, M.; Murakami, M.; Ito, Y. *Organometallics* **2008**, *27*, 1736-1742.

[120] (a) Lesley, G.; Nguyen, P.; Taylor, N. J.; Marder, T. B.; Scott, A. J.; Clegg, W.; Norman, N. C. *Organometallics* **1996**, *15*, 5137-5154. (b) Iverson, C. N.; Smith, M. R. I. *Organometallics* **1996**, *15*, 5155-5165.

[121] Ananikov, V. P.; Beletskaya, I. P.; Aleksandrov, G. G.; Ermenko, I. L. *Organometallics* **2003**, *22*, 1414-1421.

[122] Sagawa, T.; Ohtsuki, K.; Ishiyama, T.; Ozawa, F. *Organometallics* **2005**, *24*, 1670-1677.

[123] Sagawa, T.; Sakamoto, Y.; Tanaka, R.; Katayama, H.; Ozawa, F. *Organometallics* **2003**, *22*, 4433-4445.

Si-Sn,[125] Sn-Sn,[126] Si-Si,[127] and Se-Se[121] containing compounds to Pd(0) have also been reported.

The oxidative additions of B-B,[128] Si-Si,[129] and of S-S, Se-Se, and Te-Te[130] to Pd and to Pt have all been studied by calculations. While the oxidative addition of B-B compounds to Pt was shown to be exothermic, the oxidative addition to Pd was calculated to be endothermic and the reverse process to occur with a small or no barrier.[128] In contrast, the oxidative addition of Si-Si was shown to be exothermic to both Pt and Pd, although much less so to Pd than Pt. The activation energy in the addition to Pd was calculated to be significantly smaller than that to Pt. Not all bismetallations are proposed to occur via oxidative addition to a transition metal, in the Pd-catalyzed diboration of alkenes a heterolytic cleavage of the B-B linkage was proposed, avoiding the formation of a B-Pd-B complex.[131]

The insertion of unsaturated compounds into M-E bonds has been studied employing alkynes and $L_2Pt(E,E')$ complexes. An inverse dependence of phosphine concentration on the rate of insertion was consistently reported, showing that a phosphine is displaced by the alkyne during the reaction, either by an associative or dissociative mechanism. These studies were performed on B-Pt-B,[120b] Si-Pt-B,[117] Si-Pt-Si,[132] Sn-Pt-Si,[123] Sn-Pt-Sn,[122] and Sn-Pt-Ge[124] complexes.

To the best of our knowledge the Pt-catalyzed silaboration of alkynes (Scheme 20) is the only element-element addition in which the kinetics of the reductive elimination has been studied. Related studies have been performed on the reductive elimination from Si-Pt-vinyl,[133] -alkynyl[134] and -alkyl[135] complexes and by computational methods on X-Pd-allyl complexes (X = C, Si, Ge, Sn).[136]

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[124] Sagawa, T.; Tanaka, R.; Ozawa, F. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 1287-1295.
[125] Murakami, M.; Yoshida, T.; Kawanami, S.; Ito, Y. *J. Am. Chem. Soc.* **1995**, *117*, 6408-6409.
[126] Tsuji, Y.; Obora, Y. *J. Organomet. Chem.* **2000**, *611*, 343-348 and references therein.
[127] Ozawa, F.; Sugawara, M., Hayashi, T. *Organometallics* **1994**, *13*, 3237-3243.
[128] (a) Cui, Q.; Musaev, D. G.; Morokuma, K. *Organometallics* **1998**, *17*, 742-751. (b) Sakaki, S.; Kikuno, T. *Inorg. Chem.* **1997**, *36*, 226-229.
[129] Sakaki, S.; Ogawa, M.; Kinoshita, M. *J. Phys. Chem.* **1995**, *99*, 9933.
[130] Gonzales, J. M.; Musaev, D. G.; Morokuma, K. *Organometallics* **2005**, *24*, 4908-4914.
[131] Lillo, V.; Mas-Marzá, E.; Segarra, A. M.; Carbó, J. J.; Bo, C.; Peris, E.; Fernandez, E. *Chem. Commun.* **2007**, 3380-3382.
[132] Ozawa, F.; Kamite, J. *Organometallics* **1998**, *17*, 5630-5639.
[133] Ozawa, F., Tani, T.; Katayama, H. *Organometallics* **2005**, *24*, 2511-2515.
[134] Ozawa, F.; Mori, T. *Organometallics* **2003**, *22*, 3593-3599.
[135] Ozawa, F.; Hikida, T.; Hayashi, T. *J. Am. Chem. Soc.* **1994**, *116*, 2844-2849.
[136] Biswas, B.; Sugimoto, M.; Sakaki, S. *Organometallics* **1999**, *18*, 4015-4026.

The addition of silylborane **1** to terminally substituted 1,3-dienes is not the only example of an interelement compound (E-E) reacting by H-E addition and H-E exchange. In the dimerization double-stannation of 1,3-dienes Tsuji et al. also report the 1,4-hydrostannation of the dienes. The hydrogen source was assumed to be excess diene employed, as there was no deuterium incorporation from the solvent (C_6D_6).[137] Yamaguchi and co-workers obtained two products in a 1:1 ratio in the Rh-catalyzed addition of disulfides to allenes, one from the addition of H-S and one from the concomitant S addition/H elimination. A mechanism where, after oxidative addition of S-S to Rh, insertion of the allene into one of the Rh-S bonds is followed by β-hydride elimination and then subsequent H-S addition to a second allene moiety was proposed. No investigations were made to test this hypothesis.[138]

4.1.2. Aim of the Study

The aim of our study was to investigate the reaction mechanism of the Pt-catalyzed silaboration of 1,3-cyclohexadiene and that of the Ni-catalyzed addition of silylborane **1** to acyclic 1,3-dienes. In the silaboration of 1,3-dienes the nature of the active Pt(0) complex was to be investigated, reaction intermediates identified and, if possible, the kinetics of the individual reaction steps monitored. In the disproportionation process we specifically wanted to identify if a hydride is transferred from one diene to another via deuterium labelling experiments.

4.2. 1,3-Cylohexadiene: Cyclic Voltammetry

By cyclic voltammetry in DMF it was shown that after the two electron reduction of $Pt(acac)_2$ to Pt(0) in the presence of phosphine ligands, the Pt coordinate two ligands, forming a neutral complex that was not ligated by acac anions. The Pt phosphine complexes thus formed were shown to be active in the oxidative addition of bromobenzene. The rate of oxidative addition to $Pt(0)(P\textit{n}Bu_3)_2$ was shown to be more than one order of magnitude faster than that to $Pt(0)(PPh_3)_2$. In the oxidative addition of silylborane **1** the addition to the former complex was facile, while that to the latter complex was very slow, the rate difference being more than three orders of magnitude.

4.3. 1,3-Cyclohexadiene: NMR Studies of the Reaction Mechanism

The NMR studies on the reaction mechanism of the 1,4-silaboration of 1,3-cyclohexadiene were performed using stoichiometric amounts of Pt complexes. The toluene used in the catalytic experiments was replaced by C_6D_6, but to

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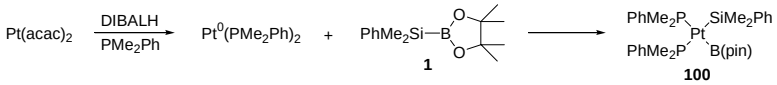
[137] Tsuji, Y.; Kakehi, T. *J. Chem. Soc., Chem. Commun.* **1992**, 1000-1001.

[138] Arisawa, M.; Suwa, A, Fujimoto, K.; Yamaguchi, M. *Adv. Synth. Catal.* **2003**, *345*, 560-563.

increase the solubility of $Pt(acac)_2$, CD_2Cl_2 was also added. Our first objective was to study the oxidative addition of silylborane **1** to Pt(0).



Scheme 22: Oxidative addition of silylborane **1** to Pt(0) yielding complex **100**.

The oxidative addition was studied by pre-forming the Pt(0) complex: at -35 °C DIBALH was added to a mixture of $Pt(acac)_2$ and the ligand, and the resulting mixture was stirred at room temperature for two hours. Silylborane **1** was then added and the reaction mixture transferred to an NMR tube and NMR spectra recorded. Using PMe_2Ph as the ligand resulted in the slow formation of complex **100** (Scheme 22). The complex could be isolated and characterized by ^1H and ^{31}P NMR, proving it to be identical to that obtained from $Pt(COD)_2$, PMe_2Ph, and silylborane **1** by Ozawa and co-workers,[117] although there was a considerable difference in the rate of the reaction. Ozawa and co-workers report the reaction to proceed within one hour,[117] while our system was much slower. A study was performed where the disappearance of silylborane **1** and the formation of complex **100** were monitored. In order to achieve full conversion of the silylborane an excess (2 equiv.) of the Pt complex was employed. The time course of the reaction is shown in Figure 7. From the kinetic data it was estimated that $t_{1/2} \approx 200$ min.

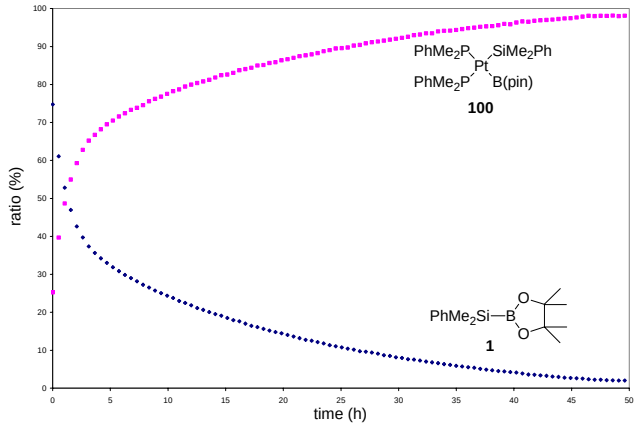
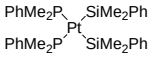


Figure 7: Time course of the oxidative addition of silylborane **1** to Pt(0), yielding complex **100**. The amount of each component at time *t* was determined by ^1H NMR spectroscopy at 30 min intervals. Reaction performed at room temperature in C_6D_6/CD_2Cl_2 (1:1) using a $Pt/PMe_2Ph/$**1** ratio of 2:4:1 at a 0.1 M concentration of Pt.

When PEt_3 was employed as the ligand no product from oxidative addition was observed. The same observation was also made from employing PPh_3, both at room temperature and at elevated temperature (80 °C), and when employing a large excess of Pt/PPh_3 (10 equiv.).

Complex **101** (Figure 8) was also slowly formed under the reaction conditions. The complex could be isolated and was characterized by ^{1}H, ^{13}C and ^{31}P NMR. The identity of the complex was confirmed by comparison with literature data.[132] Around 25 to 50 mol % of complex **101** was typically formed, as compared to the amount of complex **100** that was present. In the Pt-catalyzed silaboration of alkenes,[44] this type of intermediate was proposed to be responsible for the formation of bis-silylated products, but its formation was never observed experimentally. A mechanism involving bis-addition of the silylborane to Pt(0), forming a Pt(IV) complex that then released diborane via reductive elimination, was proposed for the formation of complex **101**.

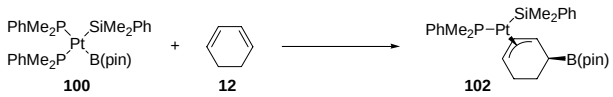


101

Figure 8: Complex **101**.

When 1,3-cyclohexadiene (10 equiv.) was added to a mixture of $Pt(acac)_2$, DIBALH, PMe_2Ph, and silylborane **1** in C_6D_6/CD_2Cl_2 (1:1), a new complex was observed. The ^{1}H and ^{31}P NMR spectra of this complex showed that it contained one phosphine per silyl group, that the methyl groups on silicon were diastereotopic, and that there were no phosphorous *trans* to boron. ^{1}H NMR also revealed a three-spin system[139] consistent with a metal-coordinated π-allyl group. These results were interpreted as the formation of complex **102** (Scheme 23). Its formation was very slow at room temperature, after three days around 17% of silylborane **1** was converted into complex **102**. At 80 °C the formation was more rapid, resulting in up to 50% conversion after a little more than one hour. It was, however, not possible to achieve full conversion in this reaction. Prolonged heating at 80 °C resulted in decomposition and running the reaction for several days at lower temperature[140] gave less than 50% conversion. Numerous attempts, mainly by crystallization techniques, were made to isolate complex **102** in pure form, but they were all futile. The 1,4-silaboration product **7** was not observed in any of the reactions employing PMe_2Ph as the ligand.

[139] δ = 4.92 (d, J =7 Hz, 1H), 4.54 (d, J = 7 Hz, 1 H), 3.6 (m, 1H).
[140] Room temperature, 50 °C, 60 °C.

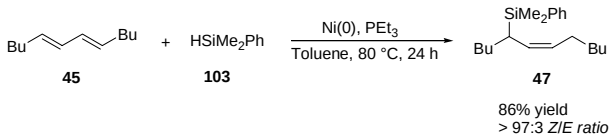


Scheme 23: Formation of π-allyl complex **102**.

Even though we were unable to see any product from oxidative addition of silylborane **1** to Pt using PPh_3 as the ligand, Pt and PPh_3 form an active catalyst for the 1,4-silaboration of 1,3-cyclohexadiene. Clearly a small amount of oxidative addition product was formed, or the reaction proceeds via another pathway. To shed some light on this process the stoichiometric reaction was followed by ^{1}H NMR, employing 1-methoxynaphthalene as internal standard. Heating was gradually increased from 50 to 80 °C, and as expected compound **13** was formed in high yield (96%) after heating at 80 °C overnight. It should be noted that after the same time at 60 °C, 4% of silylborane **1** remained, while a 58% yield of compound **13** was recorded. This leaves 38% of Si and B unaccounted for, proving the reaction does not proceed instantly to product **7** once a catalytically active species has been formed.

4.4. Disproportionation in Lieu of Silaboration

As we proposed that H-Si is added to a diene in a formal hydrosilylation, the Ni catalyst used in the disproportionation reactions was evaluated in the hydrosilylation of dienes **45**, **49**, **52**, and **57**, using dimethylphenylsilane (**103**) as the H-Si source. The addition to diene **45** proceeded smoothly (Scheme 24), furnishing the anticipated product in 86% isolated yield as a single detectable stereoisomer (^{1}H NMR).

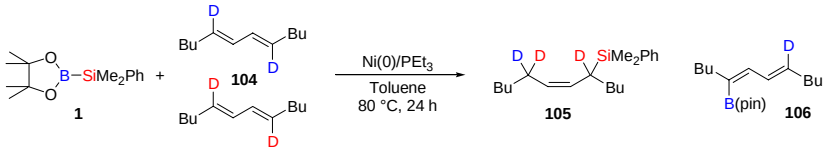


Scheme 24: Ni-catalyzed hydrosilylation of *E*,*E*-5,7-dodecadiene using dimethylphenylsilane.

Dienes **49**, **52**, and **57** also reacted to give the same H-Si addition products as in the disproportionation reactions in good yields, with the same stereoselectivities.

By running the reaction in Scheme 11 using toluene-d_8 as the solvent it was shown that there is no deuterium incorporation from the solvent into product **47**. A bis-deuterated analogue of diene **45**, compound **104**, was synthesized from DIBALD and 1-hexyne. The deuturated diene (**104**) was subjected to the standard reaction conditions, yielding compound **105**, containing three

deuterium atoms, and compound **106**, where one deuterium was replaced by boron. The isotopic purity was high and the impurities that were present could be attributed to isomeric impurities present in diene **104**. Hereby it was shown that the diene acts as the hydrogen source for the formation of product **47** (Scheme 25).

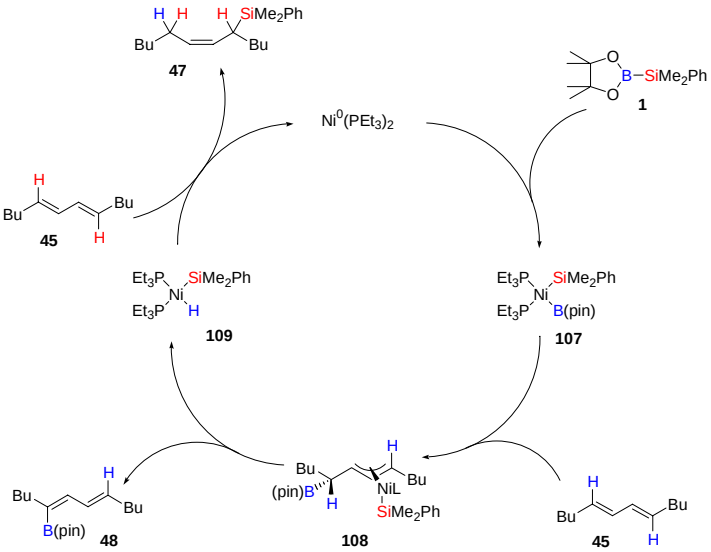


Scheme 25: Deuterium transfer.

When taking into account the larger exothermicity of,[141] and higher reactivity for, insertion into the M-B than M-Si bond,[117] it is reasonable to assume that silaborations proceed via insertion into the M-B rather than the M-Si bond. Further, in the addition of H-Si to acyclic terminally disubstituted dienes the hydride is obtained from another diene in a process that give the same result as hydrosilylations using dimethylphenylsilane as H-Si source. During this process dienylboranes were formed as a mixture of *E*/*Z* isomers, where the *E*/*Z* ratios seem to be dependent on the size of the terminal alkyl substituents.[142] From these observations we propose a reaction mechanism where the initial oxidative addition of Si-B to Ni(0), giving complex **107**, is followed by insertion of the diene into the Ni-B bond, forming a π-allyl complex (**108**). This can then undergo a syn-anti isomerization that would explain the stereochemical outcome of the reaction. From this complex there is a β-hydride elimination yielding compound **48** and complex **109**. Complex **109** then reacts with a second diene to give product **47** and the regenerated active catalyst. The complete catalytic cycle is presented in Scheme 26 and follows the same general mechanism as was proposed for the Rh-catalyzed addition of disulfides to allenes.[138]

[141] Sakaki, S.; Biswas, B.; Musashi, Y.; Sugimoto, M. *J. Organomet. Chem.* **2000**, *611*, 288-298.

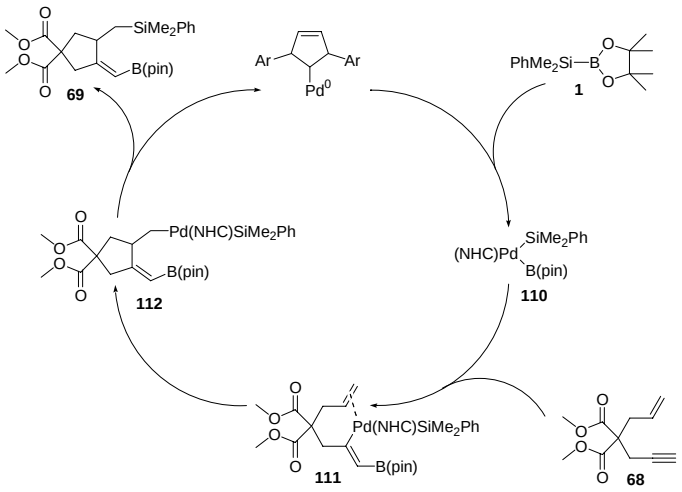
[142] Compare the 5:1 *E*/*Z* ratio in compound **48** with the 1.25:1 *E*/*Z* ratio in compound **51**. It should also be emphasized that the nonfunctionalized olefinic bond has pure E configuration for both compounds.



Scheme 26: Proposed reaction mechanism for the Ni-catalyzed reaction of silylborane **1** and diene **45**.

4.5. Silaborative Carbocyclization of 1,6-Enynes

For the silaborative carbocyclization of 1,6-enynes we propose the reaction mechanism that is depicted in Scheme 27. Oxidative addition of the silylborane is followed by insertion of the alkyne into the Pd-B bond, and subsequent insertion of the olefin into the newly formed Pd-C bond, yielding complex **112**. This process competes with reductive elimination that would give silaboration over the alkyne. From complex **112** reductive elimination gives the silaborative carbocyclization product **69**. This mechanism is consistent with the higher reactivity of M-B bonds compared to M-Si bonds towards insertion (vide supra), with the products of alkyne silaboration that were observed using Pd-phosphine complexes, with the higher reactivity of alkynes than olefins towards interelement additions,[94,4b,117] with the *E* configuration of the olefin in the product, and also with the mechanism proposed for the silastannylative carbocyclization of enynes.[94] We have not yet made any attempts to investigate the mechanism experimentally.



Scheme 27: Proposed mechanism for the silaborative carbocyclization of 1,6-enynes.

4.6. Conclusions

The mechanism of the Pt-catalyzed silaboration of 1,3-cyclohexadiene was investigated. It was found that when silylborane **1** undergoes oxidative addition to a catalyst system prepared from $Pt(acac)_2$, PMe_2Ph, and DIBALH, the same complex is formed as that observed in previous studies employing $Pt(COD)_2$ and PMe_2Ph,[117] suggesting that the reaction proceeds via the same intermediates in $Pt(acac)_2$/DIBALH and $Pt(COD)_2$ catalyzed silaborations. However, as the kinetics of the oxidative addition were much slower using the former catalyst system, there are still details of this process that we do not fully understand.

Upon the addition of 1,3-cyclohexadiene to the product of oxidative addition (**100**) insertion of the diene into the Pt-B bond followed, yielding a π-allyl complex that could not be characterized fully. No product from reductive elimination (**13**) was observed using PMe_2Ph as the ligand.

When PMe_2Ph was replaced by PPh_3 as the ligand no reaction intermediates could be identified, but it was shown that some intermediates must be formed before the final product is released.

In the Ni-catalyzed addition of silylborane **1** to terminally disubstituted 1,3-dienes it was shown that the reaction proceeds to give the two products via hydrogen transfer from one diene moiety to another. A reaction mechanism was proposed based on our observations and previous mechanistic studies on bismetallations using interelement compounds.

5. Concluding Remarks

This thesis deals with the development of silaborations of unsaturated compounds and investigations into the reaction mechanism of these processes.

A method for the enantioselective 1,4-silaboration of 1,3-cyclohexadiene was developed, furnishing the product in good yield and in up to 82% enantiomeric excess. The product obtained was successfully employed in allylborations of aldehydes under microwave heated conditions. The mechanism of the silaboration of 1,3-cyclohexadiene was also investigated.

During attempts to silaborate acyclic, terminally disubstituted, 1,3-dienes, a disproportionation reaction was discovered. The mechanism of this reaction was investigated by deuterium labelling experiments and a reaction mechanism was proposed.

A silaborative carbocyclization of 1,6-enynes employing silylborane **1** was developed. It was found that the reaction proceeded smoothly using unsubstituted enynes, but was inhibited by terminal substituents on the enyne.

In the course of developing new methods for silaborations using silylborane **1** both Ni, Pd, and Pt catalysts have been employed in combination with phosphoramidite-, NHC- and a range of phosphine-ligands. This underlines the importance of finding the appropriate metal-ligand combination for each new substrate employed in silaboration reactions.

There is still much that needs to be done in order to fully realise the potential of silaborations of unsaturated compounds. Especially the reactivity of the functionalities that are created needs to be explored further in order to demonstrate the usefulness of the products formed.

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Appendix A

The following is a description of my contribution to Publications **I** to **V**, as requested by KTH.

Paper **I**: I contributed to the formulation of the research problem, performed the experimental work and wrote parts of the manuscript.

Paper **II**: I contributed to the formulation of the research, performed the majority of the experimental work and supervised diploma worker Claire Pétermann. I wrote the major part of the manuscript.

Paper **III**: I contributed to the formulation of the research problem, performed the experimental work, and wrote the major part of the manuscript.

Paper **IV**: I contributed to the formulation of the research problem, performed the majority of the experimental work and wrote the manuscript.

Paper **V**: I contributed to the formulation of the research problem and performed the NMR spectroscopic investigations.

Appendix B

This appendix contains the experimental procedure for the oxidation of compound **13** into allylic alcohol **20**.

4-(Dimethylphenylsilyl)-cyclohex-2-enol (20)
Compound **13** (58 mg, 0.17 mmol) was dissolved in a THF (4 mL)/H_2O (2 mL) mixture, $NaBO_3 \cdot (H_2O)_4$ (900 mg, 5.8 mmol) was added and the resulting solution was stirred at rt for 2.5 h. Diethyl ether (15 mL) was then added, the water phase was extracted with diethyl ether (7 mL) and the combined organic phases dried over $MgSO_4$, filtered, and concentrated in vacuo. Purification was performed by flash chromatography on SiO_2 using a gradient of 5-10% EtOAc in hexanes, yielding the title compound as a clear oil (25 mg, 0.108 mmol, 64% yield). ^1H spectrum was in accordance with our previously reported data (Paper I).