

Review

Chemistry of Group 13 element-transition metal linkage — the platinum- and palladium-catalyzed reactions of (alkoxo)diborons

Tatsuo Ishiyama, Norio Miyaura *

Division of Molecular Chemistry, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

Received 9 February 2000; accepted 17 March 2000

Abstract

The metal-catalyzed borylation of alkenes, alkynes, and organic electrophiles with B–B compounds was developed for the synthesis of organoboronic esters from simple organic substrates. The platinum(0)-catalyzed addition of bis(pinacolato)diboron to alkenes and alkynes stereoselectively yielded *cis*-bis(boryl)alkanes or *cis*-bis(boryl)alkenes. The addition of diboron to 1,3-dienes with a platinum(0) complex afforded a new access to the *cis*-1,4-bis(boryl)butene derivatives which are a versatile reagent for diastereoselective allylboration of carbonyl compounds. The cross-coupling reaction of diborons with aryl and vinyl halides or triflates, and allyl chlorides or acetates was found to yield aryl-, vinyl-, and allylboronates in high yields in the presence of a base and a palladium catalyst, which provides the first one-step procedure for the synthesis of organoboronic esters from organic electrophiles. The mechanisms and the synthetic applications of these reactions are discussed. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Metal-catalyzed reaction; Diboran(4); Palladium; Platinum; Rhodium; Cross-coupling; Diboration; Organoboron compound

1. Introduction

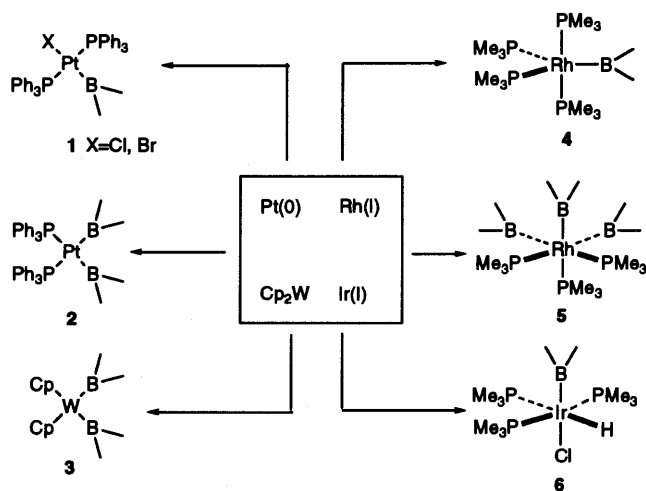
A range of transition metal–boryl compounds have been extensively studied [1–4] since these compounds are key intermediates in various catalytic reactions of Group 13 elements, including the metal-catalyzed hydroboration [5] and diboration [6,7] of alkenes and alkynes. The representative metal-boryl complexes reported in oxidative addition of boron compounds to low-valent transition metals are summarized in Scheme 1. Halocatecholborane ($XBO_2C_6H_4$, $X = Cl, Br$) adds to $Pt(C_2H_4)(PPh_3)_2$ at room temperature giving *trans*-platinum(II) complexes (**1**) [8]. Oxidative addition of diboron (X_2B-BX_2 , $X = \text{halogen, OR}$) to $Pt(PPh_3)_4$ or $Pt(C_2H_4)(PPh_3)_2$ (**2**) [9–11], $Rh(Me)(PMe_3)_4$ (**4** and **5**) [12], and to other low valent metals such as Ir(I) [13], Co(0) [14], and Cp_2W [15] provides a simple and reli-

able method for the synthesis of di- and triboryl-metal complexes. The addition of catecholborane to Ir(I) or Rh(I) affords a key intermediate for catalytic hydroboration (**6**) [16]. The synthesis, characterization, bonding, and reactivity of these catalytically important species have been recently reviewed [1–4]. In addition, extensive theoretical studies of the M–B bond and its role in catalytic cycles have been also studied [17–19].

In this work, particular attention will be given to the synthesis of organoboronic esters via the addition and cross-coupling reactions of diborons catalyzed by a transition metal complex. Much attention has been recently focused on organoboronic acids and their esters due to their practical usefulness for synthetic organic reactions [20,21], molecular recognition such as host-guest compounds [22], and neutron capture therapy in treatment of malignant melanoma and brain tumor [23]; however, there have been very few new developments in methodology for their preparations. The methods now available are based on the reaction of trialkyl borates with Grignard or lithium reagents (transmetalation) or hydroboration of alkenes and

* Corresponding author. Fax: +81-11-7066561.

E-mail address: miyaura@org-mc.eng.hokudai.ac.jp (N. Miyaura).



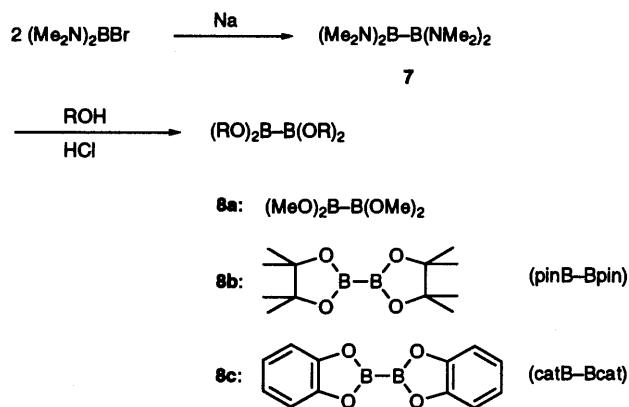
Scheme 1. Synthesis of metal–boryl complexes via oxidative addition.

alkynes with HBX_2 ($X = \text{halogen, alkoxy}$). The addition and cross-coupling reaction of metal-boryl reagents is an alternative and convenient protocol which has been extensively studied for disilanes [24] and distannanes [25], but the related reactions of B–B compounds have not been reported previously. Since (alkoxy)diborons are thermally stable and easily han-

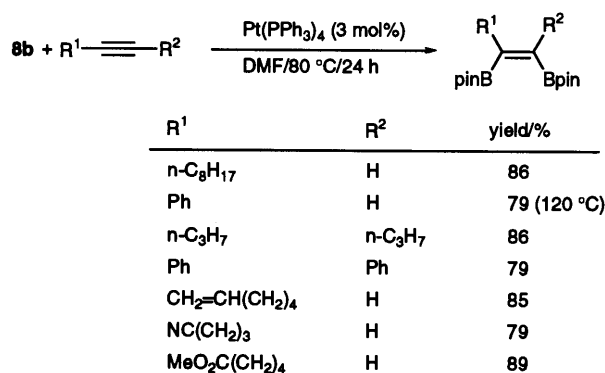
dled in air, the compounds can be useful as a reagent for the boration of alkenes, alkynes, and organic electrophiles.

2. Synthesis of diborons

Diboron tetrachloride ($\text{Cl}_2\text{B}-\text{BCl}_2$) obtained by an electric discharge reduction of boron trichloride ignites in air and undergoes decomposition into boron trichloride and colored solid materials at room temperature [26]. On the other hand, tetra(amido)- and tetra(alkoxy)diboron dramatically enhance the stability of the B–B species at the expense of reactivity. Tetra(dimethylamido)diboron (**7**) is available in large quantity by the Wurtz coupling of bromo- or chloroborane with sodium or potassium in refluxing toluene (Scheme 2) [27]. The treatment of **7** with alcohol or diol provides various alkoxy-derivatives of diboron (**8**) [28–30]. Two diborons, **8b** and **8c**, are now commercially available. Although the reactions of bis(pinacolato)diboron (**8b**) [29] have been extensively studied due to its high stability in air and moisture, and to distillation, similar addition and coupling reactions can be anticipated for other diborons, e.g. tetra(methoxy)diboron (**8a**) [28] and bis(catecholato)diboron (**8c**) [30].



Scheme 2. Synthesis of diboron compounds.



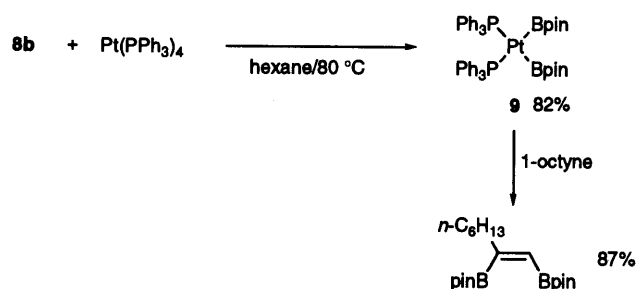
Scheme 3. Diboration of alkynes.

3. Addition reaction of diborons

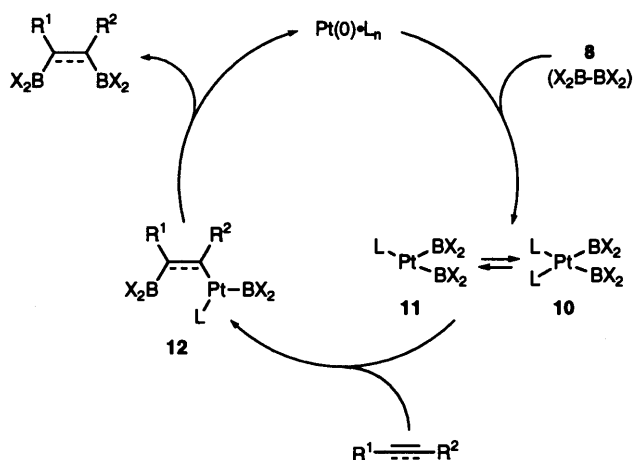
The addition of diboron tetrahalides B_2X_4 ($X = \text{F, Cl, Br}$) to unsaturated hydrocarbons, first discovered by Schlesinger in 1954, is an attractive and straightforward method to introduce boryl groups into organic molecules, but the synthetic use has been severely limited because of the instability and the availability of the reagents [31]. Although the stable amido **7** and alkoxy derivatives of diboron **8a–c** are quite inert to ionic reactions due to the low Lewis acidity of the boron centers conjugated with hetero atoms and a high B–B bond energy [19], the B–B bonds oxidatively add to a low-valent transition metal with the B–B bond cleavage, thus allowing the catalyzed transfer of the B–B bond to unsaturated organic substrates [6,7].

3.1. Diboration of alkynes

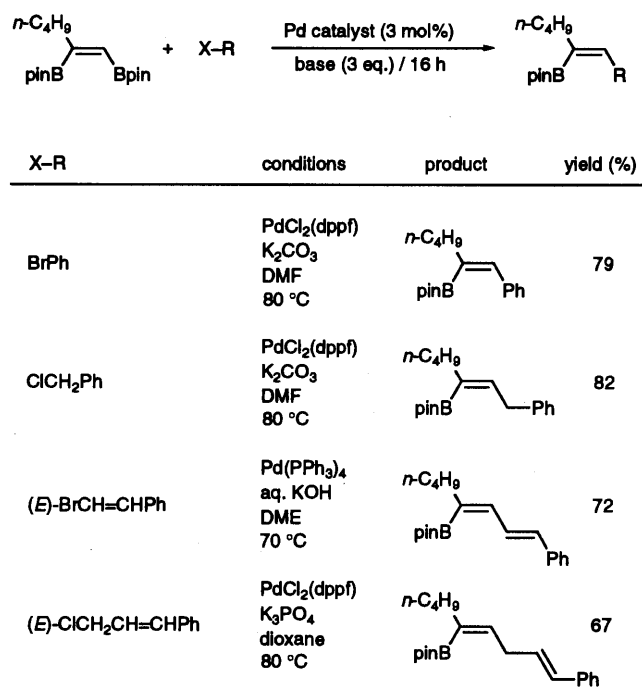
The diboration of alkynes is efficiently catalyzed by a platinum(0) complex such as $\text{Pt}(\text{PPh}_3)_4$, $\text{Pt}(\text{C}_2\text{H}_4)(\text{PPh}_3)_2$ or $\text{Pt}(\text{CO})_2(\text{PPh}_3)_2$ (3 mol%) yielding *cis*-1,2-diborylalkenes in high yields (Scheme 3) [9,32], though $\text{PtCl}_2(\text{PPh}_3)_2$, $\text{Pd}(\text{PPh}_3)_4$, $\text{Pd}(\text{OAc})_2/\text{isocyanide}$, and $\text{RhCl}(\text{PPh}_3)_3$ are ineffective. Platinum(0) complexes similarly catalyze the addition of other (alkoxy)diborons, **8a** [9] and **8c** [10,11], but the reaction of (amido)diborn **7** is very slow even at 120°C. There



Scheme 4. Oxidative addition and insertion of diborons.



Scheme 5. Catalytic cycle for diboration of alkenes and alkynes.

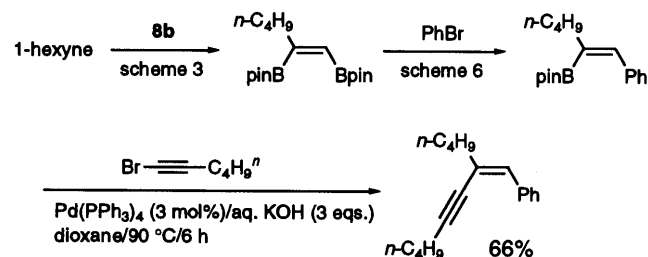
Scheme 6. Synthesis of (*E*)-(1-organo-1-alkenyl)boranes.

are no large differences in the yields and the reaction rates between internal and terminal alkynes and the reaction is available with various functional groups. The carbon–carbon double bond, chloro, epoxy, ester, cyano, and ketone carbonyl groups remain intact during the addition to the carbon–carbon triple bonds.

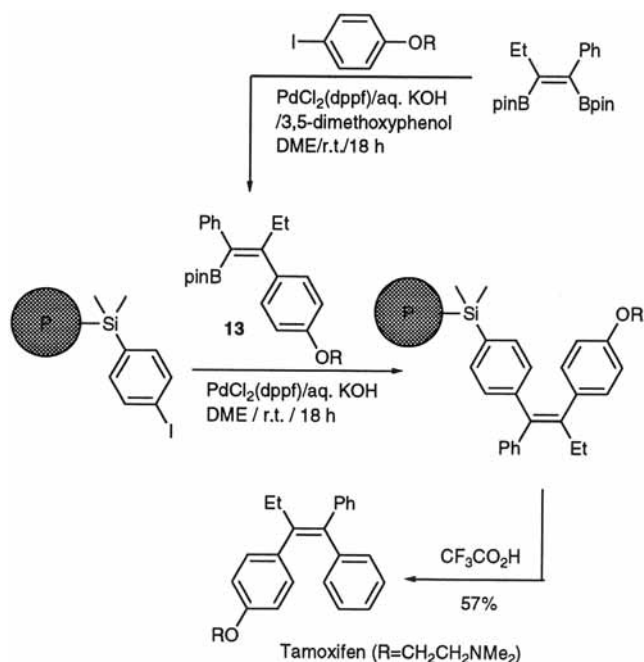
Monitoring of the reaction of **8b** and $\text{Pt}(\text{PPh}_3)_4$ by multinuclear NMR spectroscopy reveals the formation of a new $\text{Pt}(\text{II})$ species which shows reasonable thermal stability to allow isolation and is characteristic of phosphines *cis*-coordinated to a platinum(II) center. A single crystal of **9** consists of a distorted square-planar coordination geometry for the Pt atom containing two *cis* boryl and phosphine ligands where the significant bond angles are $\angle \text{P}(1)\text{-Pt-P}(2)$ (102.65°) and $\angle \text{B}(1)\text{-Pt-B}(2)$ (75.3°) (Scheme 4) [9]. Treatment of **9** with 1-octyne yields 1,2-bis(boryl)octene as the sole product, in consistent with the catalytic cycle shown in Scheme 5 [9–11]. The addition proceeds through (a) oxidative addition of diboron (**8**) to $\text{Pt}(0)$ giving *cis*-B–Pt–B complex (**10**), (b) insertion of alkene or alkyne into the B–Pt bond, and (c) reductive elimination of the product to regenerate the $\text{Pt}(0)$ complex. The catalyst activity significantly decreases in the presence of added PPh_3 , suggesting that phosphine dissociation (**10** → **11**) is a critical step in the catalytic cycle [10b]. A theoretical study based on the B3LYP density functional method also supports the oxidative addition-insertion sequence [17–19].

The transformation of 1,2-bis(boryl)-1-alkenes via a cross-coupling reaction provides a method for regio- and stereoselective synthesis of 1-alkenylboranes because they have potential reactivity difference between two C–B bonds. The regioselective coupling reaction at the terminal C–B bond is shown in Scheme 6 which is synthetically equivalent to carboboration of alkynes [33]. Although the reaction is accompanied with a double-coupling product at both C–B bonds (5–10%), high terminal-selectivity of over 99% is readily achieved. The 1-alkenylboronates thus obtained couple to another organic halide to provide a regio- and stereodefined trisubstituted alkene (Scheme 7) [33].

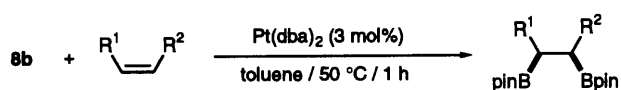
The utility of the stepwise, double-coupling procedure is demonstrated in the parallel synthesis of Tamoxifen and derivatives on solid support (Scheme 8)



Scheme 7. Trisubstituted alkenes via a diboration-coupling sequence.

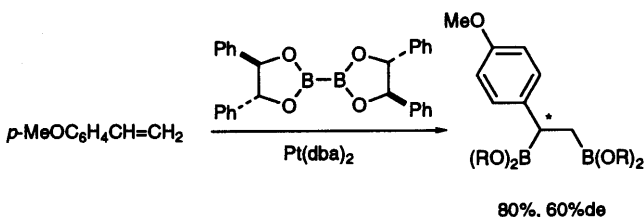


Scheme 8. Solid-phase synthesis of tamoxifen.



alkene	yield (%)
1-decene (1.5 eqs)	82
styrene (1.5 eqs)	86
NCCH ₂ CH=CH ₂ (1.5 eqs)	70
CH ₃ COCH ₂ CH ₂ CH=CH ₂ (3 eqs)	70
cyclopentene (1.5 eqs)	85
cyclohexene (1.5 eqs)	0
norbomene (3 eqs.)	85

Scheme 9. Diboration of alkenes.



Scheme 10. Asymmetric diboration.

[34]. Using this strategy, each position about the ethylene core is modified by the appropriate choice of alkyne, aryl halide, and cleavage conditions.

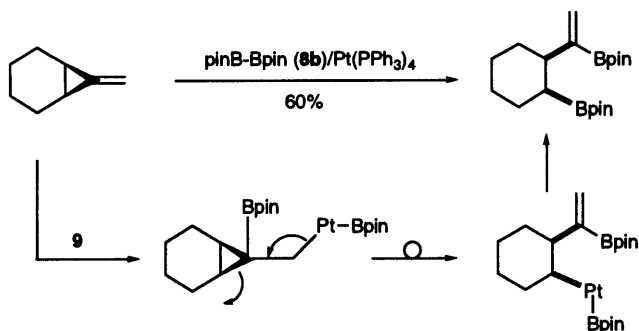
3.2. Diboration of alkenes, 1,3-dienes, and allenes

The phosphine-based platinum(0) catalysts do not catalyze the diboration of alkenes due to the high

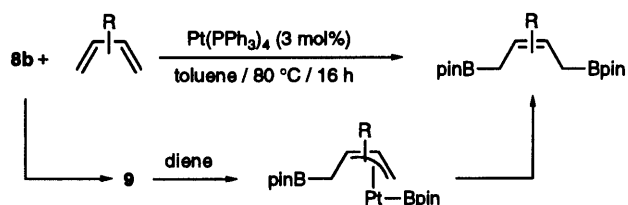
coordination ability of phosphine over the alkene double bond, but platinum(0) complexes without a phosphine ligand such as Pt(dba)₂ [35] and Pt(cod)₂ [36] are an excellent catalyst allowing the alkene insertion into the B–Pt bond under mild conditions. The diboration of aliphatic and aromatic terminal alkenes smoothly takes place at 50°C or even at room temperature. The reaction is significantly slow for disubstituted alkenes and cyclic alkenes, but cyclic alkenes having an internal strain afford the *cis*-diboration products in high yields (Scheme 9) [35].

A phosphine–gold(I) complex [37] and a zwitterionic rhodium(I) complex [38] similarly catalyze the diboration of styrene derivatives. Asymmetric diboration is demonstrated by using chiral diboron compounds (Scheme 10) [35b]. The 1,2-diphenylethanediol derivative achieves 60% d.e. for *p*-methoxystyrene, whereas the tartarate derivative resulted in low diastereoselectivity.

Methylenecyclopropane and its derivatives are of interest as the substrate for the transition metal-catalyzed addition reactions due to their high and unique reactivities originating from the highly strained structure. Palladium-catalyzed silylcyanation, hydrocarbonation, and hydroamination give the products derived from the distal bond cleavage of the cyclopropane ring, whereas the proximal ring-opening products are observed in the palladium-catalyzed hydrostannation and the rhodium-catalyzed hydrosilylation. The platinum-catalyzed reaction of diboron (**8b**) proceeds through the proximal bond cleavage of the cyclopropane ring (Scheme 11) [39]. The catalytic cycle involving the insertion of methylenecyclopropane into the B–Pt bond of **9**, followed by the rearrangement to a homoallylplatinum(II) species gives a ring-opening product. The selective formation of the *cis*-isomers for bicyclic methylenecyclopropane suggests a four-centered cyclic transition state for the ring-opening rearrangement. The results also provide information on the insertion mechanism of **9**;

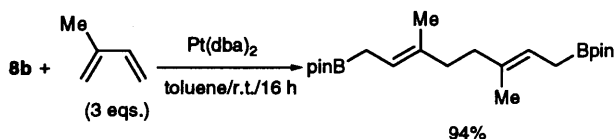


Scheme 11. Diboration of methylenecyclopropanes.

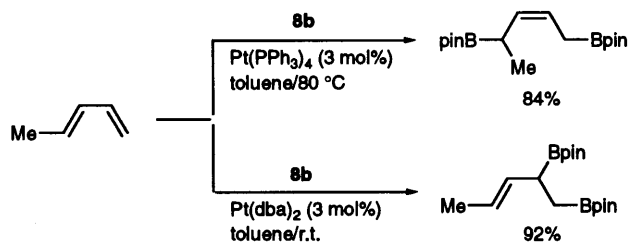


1,3-diene	yield (%)
1,3-butadiene (1.5 eqs)	95
isoprene (1.5 eqs)	93
2,3-dimethyl-1,3-butadiene (1.5 eqs)	91
1,3-pentadiene (4.5 eqs)	84
1,3-cyclohexadiene (1.5 eqs)	91

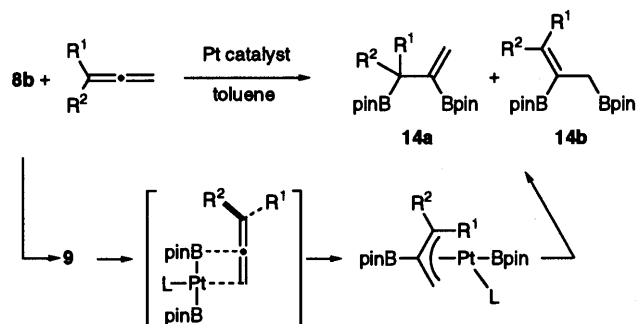
Scheme 12. Diboration of 1,3-dienes.



Scheme 13. 1,8-Diboration of 1,3-dienes.



Scheme 14. 1,2 and 1,4-Diboration of 1,3-dienes.



allene and product		Pt(PPh ₃) ₄ /80 °C		Pt(dba) ₂ -P(Cy) ₃ /50 °C	
R ¹ =	R ² =	yield (%)	14a:14b	yield (%)	14a:14b
H	H	99	—	99	—
<i>n</i> -C ₄ H ₉	H	97	94:6	90	84:16
Me	Me	98	24:76	99	2:98
MeO	H	81	0:100	85	0:100

Scheme 15. Diboration of allenes.

namely, the addition of the Pt–B bond to terminal-alkene gives a primary alkyl-platinum intermediate for both platinum-phosphine and platinum-dba catalysts, which has not been discussed in the catalytic cycle (Scheme 5).

The addition of diboron to 1,3-dienes affords various allylboron compounds which dramatically changes the products and selectivities depending on the ligand of the Pt(0) catalysts. Pt(PPh₃)₄ stereoselectively yields *cis*-1,4-addition products as the sole product for the representative aliphatic and alicyclic dienes (Scheme 12) [40].

The reaction suggests a mechanism involving *S-cis* coordination of diene to **9** by displacing two phosphines, the insertion of the diene to the B–Pt bond giving *anti*- π -allyl(boryl)platinum(II), and the reductive coupling at the less-substituted terminal carbon [40,41].

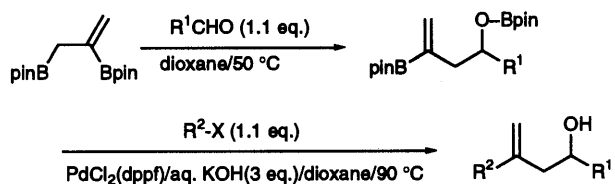
Interestingly, the change of the catalyst to Pt(dba)₂ results in dimerization of the diene before the addition of the diboron (Scheme 13) [40]. Isoprene provides a 1,8-addition product having (*E,E*) configuration and a symmetrical structure derived from the head-to-head coupling. Such dimerization via the stepwise insertion process can be well catalyzed by a phosphine-free platinum complex since the generation of a coordinately unsaturated π -allylplatinum(II) species allows further coordination of the diene and its insertion into the Pt–B bond yielding a di- π -allylplatinum(II) species.

On the other hand, Pt(dba)₂ directs the 1,2-addition to certain conjugated dienes, whereas the 1,4-addition through the π -allylplatinum(II) intermediate is an energetically more favorable process. The 1,4-addition to 1,3-pentadiene with Pt(PPh₃)₄ is consistent with the results shown in Scheme 12, but the same reaction with Pt(dba)₂ exceptionally produces a 1,2-addition product (Scheme 14) [35].

The diboration of allenes giving another series of allylborons is summarized in Scheme 15 [42]. The addition has a strong tendency to occur at the internal double bond, but steric hindrance in both the allenes and the phosphine ligands forces the addition towards the terminal double bond. Thus, the reaction of mono-substituted allenes with a less bulky PPh₃ preferentially produces the internal adducts (**14a**), and the bulky and electron-donating P(Cy)₃ (Cy = cyclohexyl) affords the terminal adducts (**14b**) for 1,1-disubstituted allenes. The *cis*-**14b** is selectively obtained in 1,2-heptadiene (R¹ = C₄H₉, R² = H) by way of addition from the less-hindered side of the terminal double bond.

The diboration of allenes offers a new route to substituted homoallyl alcohols (Scheme 16) [42]. A sequence of allylboronation of aldehydes and the cross-coupling with organic halides provides homoallylic alcohols.

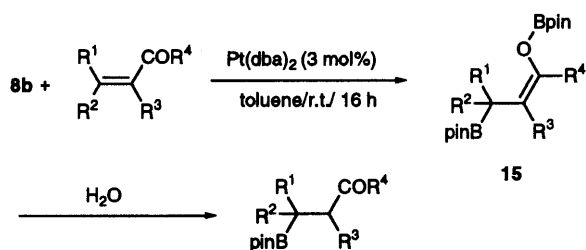
The diboration of enones yields 1,4-addition products (**15**) in the presence of a platinum(0) catalyst such



R ¹ CHO	R ² -X	yield (%)
PhCHO	PhI	75
<i>n</i> -C ₅ H ₁₁ CHO	PhI	62
PhCHO	PhCH ₂ Cl	61
PhCHO	(<i>E</i>)- <i>n</i> -C ₆ H ₁₃ CH=CHI	65

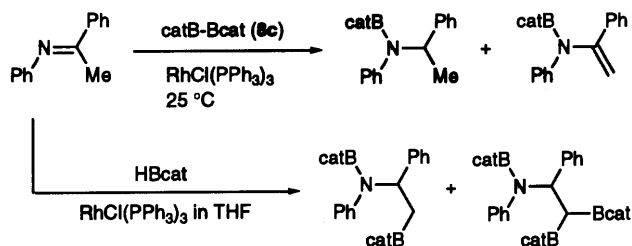
Scheme 16. Synthesis of homoallylic alcohols.

as Pt(C₂H₄)(PPh₃)₂ [43a] at 80 °C or Pt(dba)₂ [43b] at room temperature (Scheme 17). The reaction catalyzed by Pt(C₂H₄)(PPh₃)₂ affords a single isomer which is assumed to be the *Z*-enolate [43a]. The hydrolysis of **15** with water gives β-borylketones in high yields, the conversion of which is synthetically equivalent to the conjugate 1,4-addition of a boryl anion to enones. The diboration of α,β-unsaturated esters and nitriles affords similar products.



R ¹	R ²	R ³	R ⁴	yield/%
H	H	H	CH ₃	88
H	H	CH ₃	CH ₃	64
CH ₃	H	H	CH ₃	72
Ph	H	H	CH ₃	90
2-cyclopentenone				88
2-cyclohexenone				61

Scheme 17. Diboration of α,β-unsaturated ketones.



Scheme 18. Boration of imines.

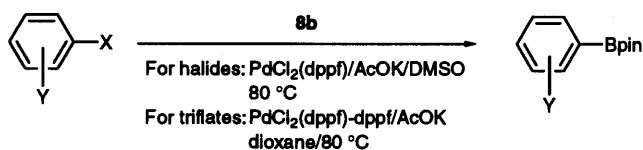
The rhodium-catalyzed addition of diboron (**8c**) to ketimines affords *N*-borylenamines and catecholborane (HBcat) via a sequence of oxidative addition of **8c** to Rh(I), insertion of imine into the Rh–B bond, and finally, β-hydride elimination. An analogously catalyzed reaction of HBcat in THF yields multiple borated products (Scheme 18) [44].

4. Cross-coupling reaction of diborons

The transition metal-catalyzed cross-coupling reaction of disilanes [24] and distannanes [25] is an elegant method for the synthesis of organosilicon and -tin compounds directly from organic electrophiles, but the lack of suitable boron nucleophiles has limited this protocol for boron compounds. However, tetra-(alkoxo)diborons **8** act as the boron-nucleophile in the presence of a base for the palladium-catalyzed cross-coupling reaction of organic electrophiles. More recently, Masuda and Murata found that pinacolborane (Me₄C₂O₂)BH couples to aryl and vinyl electrophiles in the presence of a palladium catalyst and triethylamine [45]. Both reactions provide a simple and direct method for the borylation of organic halides and triflates.

4.1. Aryl and vinyl electrophiles

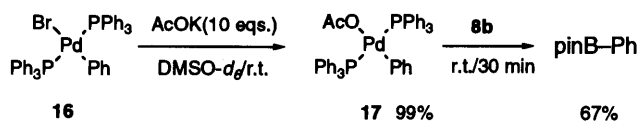
The cross-coupling reaction of diborons with aryl halides and triflates proceeds in the presence of a base and a palladium catalyst (Scheme 19) [46,47]. The use of PdCl₂(dppf) and KOAc in DMSO or DMF is found to be the best conditions for aryl iodides and bromides because a stronger base, such as K₃PO₄ and K₂CO₃,



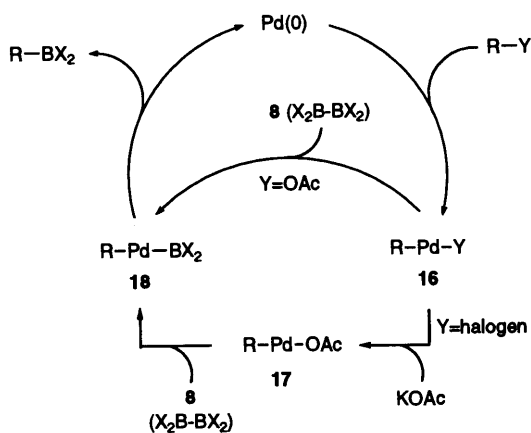
ArX (Ar=)	ArX (X=)	yield/%
<i>p</i> -NCC ₆ H ₄	Br	76
	OTf	75
<i>p</i> -CH ₃ COC ₆ H ₄	Br	80
	OTf	92
<i>p</i> -MeOC ₆ H ₄	I	82
	OTf	93
<i>p</i> -BrC ₆ H ₄	I	86
2,4,6-Me ₃ C ₆ H ₂	I	71
3-bromoquinoline		84
3-iodobenzothiophene		60

Scheme 19. Borylation of aryl electrophiles.

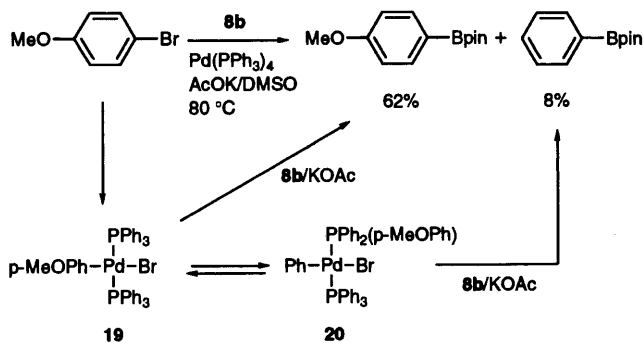
prompts the further coupling of arylboronates with haloarenes, resulting in contamination of a substantial



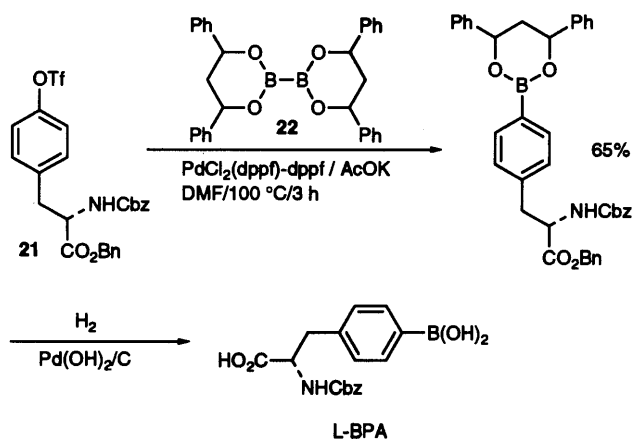
Scheme 20. (Acetoxo)palladium(II) intermediate for transmetalation.



Scheme 21. Catalytic cycle for cross-coupling of diborons.



Scheme 22. Coupling with a phosphine-bound aryls.



Scheme 23. Synthesis of L-BPA.

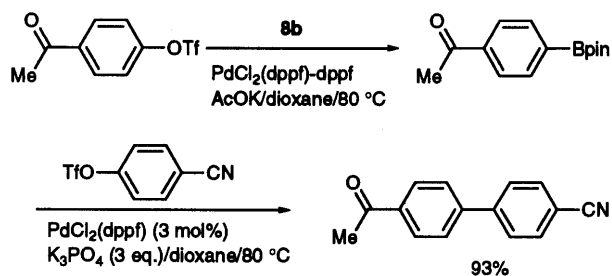
amount of biaryls (36–60% yields) [46]. The coupling of triflates is best carried out in dioxane in the presence of an additional dppf ligand [47]. Arylboronic acid synthesis using Grignard or lithium reagents needs the protection of functional groups sensitive to these reagents, but the coupling reaction is available with various functional groups, e.g. CO_2Me , COMe , NO_2 and CN . Arylboronic acids having an electron-donating group, such as *p*- NMe_2 and *p*- OMe , are synthesized from the corresponding iodides, but aryl bromides or triflates give good results for *p*- CO_2Me , *p*- COMe , *p*- NO_2 , and *p*- CN derivatives because the electron-withdrawing substituents enhance the rate of coupling. However, all attempts at the synthesis of 2-pyridyl-, 2-thiophenyl-, and 2-furylboronate were unsuccessful since such C–B bond adjacent to a hetero atom is highly sensitive to protodeboronation with a base.

The presence of a base such as KOAc is critical for the coupling reaction of diborons, suggesting a transmetalation mechanism occurring from Ar-Pd-OAc generated by displacement of X on Ar-Pd-X with an acetate anion. The quantitative formation of *trans*- $\text{PhPd(OAc)(PPh}_3)_2$ (17) is observed when *trans*- $\text{PhPdBr(PPh}_3)_2$ (16) is treated with excess of KOAc. Although 17 exhibits high reactivity toward diboron 8b, giving a coupling product, no reaction is observed between 8b and 16 (Scheme 20) [46].

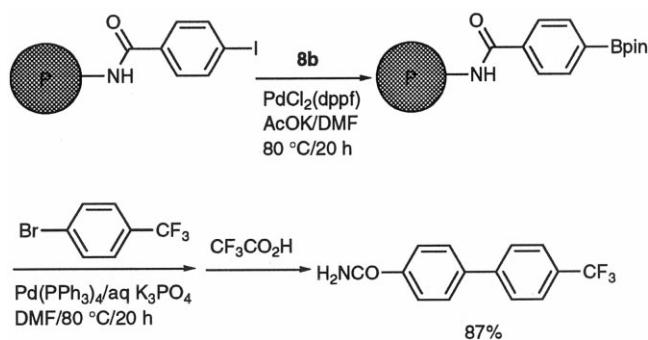
The catalytic cycle based on these observations is outlined in Scheme 21, which involves the formation of (acetoxo)palladium(II) species 17 prior to transmetalation with diboron. The high reactivity of the oxo-palladium complexes for the transmetalation with organoboron compounds can be attributed to both the high reactivity of the Pd–O bond which consists of a soft acid and a hard base combination, and the high oxophilicity of the boron center.

Both $\text{Pd(PPh}_3)_4$ and $\text{PdCl}_2(\text{dppf})$ well catalyze the cross-coupling reaction of diboron, but $\text{Pd(PPh}_3)_4$ often suffers from the formation of phenylboronate derived from the coupling with phosphine-bound aryls (Scheme 22) [46]. The contamination of such unexpected by-products is observed in the reaction of electron-rich haloarenes such as (4-methoxy)- and (4-dimethylamino)bromobenzene, though they are negligibly small amount for electron-deficient haloarenes. The aryl exchange occurs before transmetalation (19 → 20) [48]; thus, the slow transmetalation due to steric and electronic reasons results in enhancing the coupling of phosphine-bound aryls [21b].

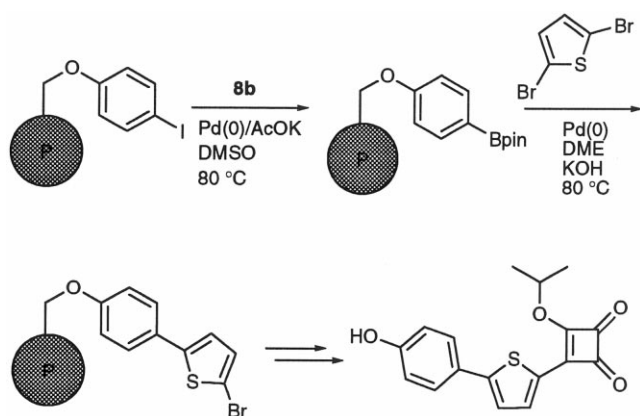
(4-Boronophenyl)alanine (BPA) is a practical boron compound, which is clinically used for the treatment of not only malignant melanoma but also of brain tumors, in neutron capture therapy. The synthesis of L-BPA by this protocol is shown in Scheme 23 [49,50]. Although pinacol esters are very conveniently handled due to their stability in air and moisture, they strongly resist



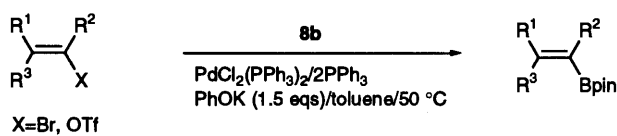
Scheme 24. One-pot synthesis of biaryls.



Scheme 25. Solid-phase synthesis of biaryls.



Scheme 26. Cyclobutenediones on solid support.



R ¹	R ²	R ³	X	yield/%
H	n-C ₈ H ₁₇	H	Br	92
H	Ph	H	Br	88
H	NC(CH ₂) ₃	H	Br	85
H	H	n-C ₈ H ₁₇	Br	74
-(CH ₂) ₄ -		H	Br	99
-(CH ₂) ₄ -		H	OTf	88

Scheme 27. Borylation of vinyl electrophiles.

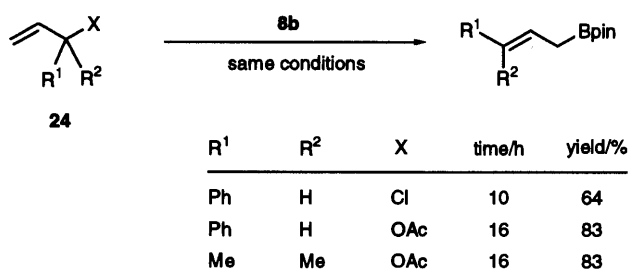
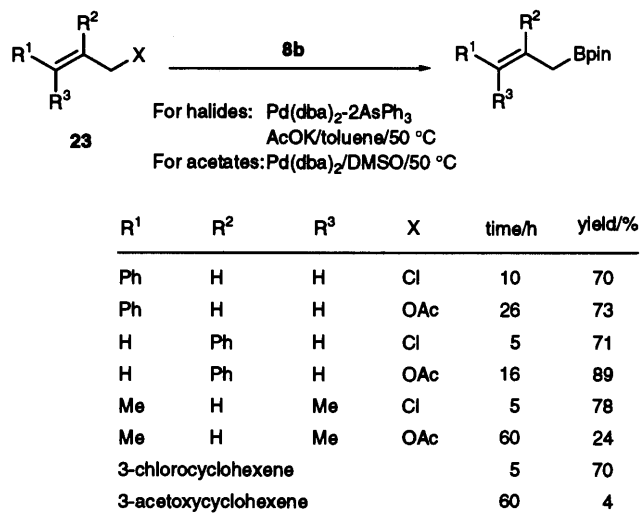
the hydrolysis to arylboronic acids. Alternatively, the 1,3-diphenylpropanediol ester (**22**) is used to deprotect the diol moiety by catalytic hydrogenolysis.

The direct preparation of arylboronic esters from aryl halides or triflates now allows a one-pot, two-step procedure for the synthesis of unsymmetrical biaryls (Scheme 24) [47]. The synthesis of biaryls is readily carried out in the same flask when the first coupling of the triflate with diboron **8b** is followed by the next reaction with another triflate. The protocol also offers a direct and efficient method for the synthesis of the boronic ester in the solid-phase which hitherto met with little success using classical methodology. A solid-phase boronate is quantitatively obtained by treating a polymer-bound iodoarene with the diboron (Schemes 25 and 26) [51]. The next coupling with haloarenes furnishes various biaryls. The robot synthesis or the parallel synthesis on the surface of resin is the topic of further accounts of the research [51c].

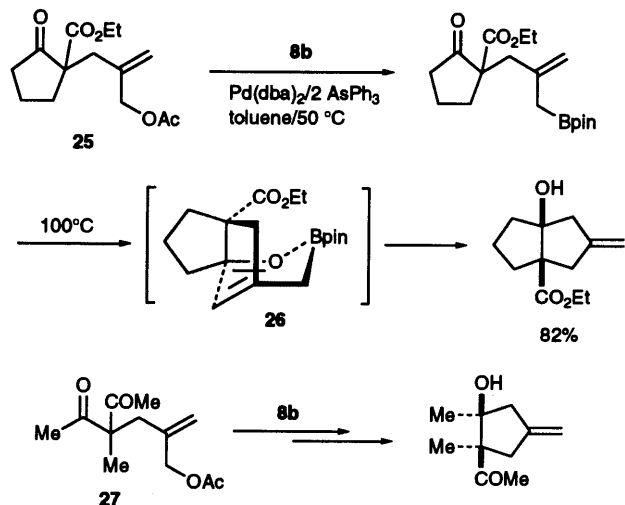
The synthesis of 1-alkenylboronic acids from 1-alkenylmagnesiums or -lithiums suffers from the difficulty of retaining the stereochemistry of 1-alkenyl halides, but the palladium-catalyzed coupling reaction of diboron **8b** and 1-alkenyl halides or triflates directly provides 1-alkenylboronic esters (Scheme 27) [52,53]. Although the reaction conditions applied to the aryl coupling (Scheme 19) resulted in the formation of an inseparable mixture of several products including the Heck coupling, the homocoupling of haloalkenes along with the desired coupling, the selective synthesis of 1-alkenylboronates is achieved in the presence of a palladium-triphenylphosphine complex and solid PhOK in toluene [52]. The reaction conditions can be applied to cyclic and acyclic vinylboronic esters possessing various functional groups, which are not available by conventional hydroboration of alkynes.

4.2. Allyl and benzyl electrophiles

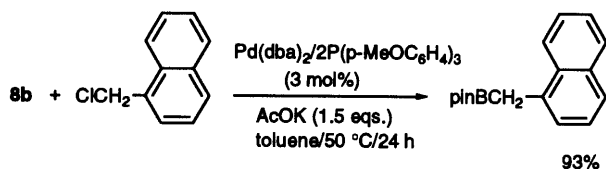
Allylboron compounds are valuable reagents in organic synthesis, addition of which to the carbon–oxygen or the carbon–nitrogen double bond diastereoselectively provides homoallylic alcohols or amines via a chair-like, six-membered cyclic transition state. Allylboron compounds have been synthesized by the transmetalation of allyllithiums or allylmagnesiums to the boron, but the palladium-catalyzed cross-coupling reaction of diboron **8b** with allyl acetates or chlorides regio- and stereoselectively affords the allylboronic esters (Scheme 28) [54,55]. The reaction with allyl acetates [54] occurs under neutral conditions because their oxidative addition directly yields an (acetoxo)palladium(II) species (**17**) (Schemes 20 and 21), but the presence of AcOK is critical in the coupling with allyl chlorides for producing π -allylpalladium acetate intermediate [55].



Scheme 28. Borylation of allylic electrophiles.



Scheme 29. Homoallyl alcohols via intramolecular allylboration.



Scheme 30. Cross-coupling, with benzyl chlorides.

The coupling at the less hindered terminal carbon and the formation of thermally stable (*E*)-allylboronates via the isomerization of *anti*- π -allylpalladium to the more stable *syn*-complex are observed for various allyl electrophiles. Thus, all (*E*)- and (*Z*)-cinnamyl acetate, chloride, and its secondary alcohol derivative afford an (*E*)-cinnamylboronate. The borylation of prenyl acetate results in low yields, but the corresponding tertiary derivative can be used for the same purpose because the boron atom exclusively bonds to its primary carbon.

Intramolecular addition of allylmetal reagents to carbonyl substrates is a powerful tool for the synthesis of cyclic homoallyl alcohols with high regio- and stereoselectivity, but the corresponding reaction of allylboranes has not been well developed mainly due to the lack of a general method for the synthesis of allylboronates having a carbonyl group. The palladium(0)-catalyzed cross-coupling reaction of diboron **8b** provides an efficient and convenient access to variously functionalized allylboranes under neutral conditions (Scheme 29) [56]. A variety of 5-5, 6-5, and 7-5 *cis*-fused exomethylene cyclopentanols are stereoselectively synthesized from β -ketoesters (**25**) or diketone (**27**) via a cross-coupling/intramolecular allylboration sequence.

The coupling with benzyl halides is carried out under similar conditions used for allyl chlorides (Scheme 30) [57]. The selective coupling is achieved by a palladium(0)-tris(*p*-methoxyphenyl)phosphine complex because the slow reaction with Pd(PPh₃)₄ resulted in low yields with accompanying benzyl acetate.

5. Metal-catalyzed reaction of other metal-boryl compounds

The related metal-catalyzed reactions of Si–B [58] and Sn–B [59] compounds have been also extensively studied. However, a part of them have been recently reviewed [7a] and will be further discussed by other members of this research group.

Acknowledgements

We are indebted to our co-workers whose names appear in the references. Financial support from Grant-in-Aid for Scientific Research on Priority Areas (1997–1999) through the Chemistry of Inter-Element Linkage is gratefully acknowledged.

References

- [1] H. Wade, *Angew. Chem. Int. Ed. Engl.* 36 (1997) 2441.
- [2] H. Braunschweig, *Angew. Chem. Int. Ed. Engl.* 37 (1998) 1787.

- [3] G.J. Irvine, M.J. Gerald, T.B. Marder, N.C. Norman, C.R. Rice, E.G. Robins, W.R. Roper, G.R. Whittell, L.J. Wright, *Chem. Rev.* 98 (1998) 2685.
- [4] T.B. Marder, N.C. Norman, *Topics Catal.* 5 (1998) 63.
- [5] For reviews, (a) I. Beleskaya, A. Pelter, *Tetrahedron* 53 (1997) 4957. (b) Z. Delours, M. Srebnic, *Chem. Rev.* 93 (1993) 763. (c) K. Burgess, M.J. Ohlmeyer, *Chem. Rev.* 91 (1991) 1179.
- [6] For review, T. Ishiyama, N. Miyaura, *J. Synthetic Organic Chemistry, Japan* 57 (1999) 503.
- [7] For reviews, (a) L-B. Han, M. Tanaka, *Chem. Commun.* (1999) 395. (b) T.B. Marder, N.C. Norman, *Topics Catal.* 5 (1998) 63.
- [8] W. Clegg, F.J. Lawlor, G. Lesley, T.B. Marder, N.C. Norman, A.G. Orpen, M.J. Quayle, C.R. Rice, A.J. Scott, F.E. Souza, *J. Organomet. Chem.* 550 (1998) 183.
- [9] T. Ishiyama, N. Matsuda, M. Murata, F. Ozawa, A. Suzuki, N. Miyaura, *Organometallics* 15 (1996) 713.
- [10] (a) C.N. Iverson, M.R. Smith III, *J. Am. Chem. Soc.* 117 (1995) 4403. (b) C.N. Iverson, M.R. Smith III, *Organometallics* 15 (1996) 5155.
- [11] G. Lesley, P. Nguyen, N.J. Taylor, T.B. Marder, A.J. Scott, W. Clegg, N.C. Norman, *Organometallics* 15 (1996) 5137.
- [12] C. Dai, G. Stringer, T.B. Marder, A.J. Scott, W. Clegg, N.C. Norman, *Inorg. Chem.* 36 (1997) 272.
- [13] C. Dai, G. Stringer, T.B. Marder, R.T. Baker, A.J. Scott, W. Clegg, N.C. Norman, *Can. J. Chem.* 74 (1996) 2026.
- [14] C. Dai, G. Stringer, J.F. Corrigan, N.J. Taylor, T.B. Marder, N.C. Norman, *J. Organomet. Chem.* 513 (1996) 273.
- [15] (a) J.F. Hartwig, X. He, *Angew. Chem. Int. Ed. Engl.* 35 (1996) 315. (b) J.F. Hartwig, X. He, *Organometallics* 15 (1996) 5350.
- [16] J.R. Knorr, J.S. Merola, *Organometallics* 9 (1990) 3008.
- [17] Q. Cui, D.G. Musaev, K. Morokuma, *Organometallics* 16 (1997) 1355.
- [18] Q. Cui, D.G. Musaev, K. Morokuma, *Organometallics* 17 (1998) 742.
- [19] S. Sakaki, T. Kikuno, *Inorg. Chem.* 36 (1997) 226.
- [20] (a) A. Pelter, K. Smith, H.C. Brown, *Borane Reagents*, Academic, London, 1988. (b) D.S. Matteson, *Stereodirected Synthesis with Organoboranes*, Springer, Berlin, 1995.
- [21] (a) N. Miyaura, A. Suzuki, *Chem. Rev.* 95 (1995) 2457. (b) N. Miyaura, *Synthesis of biaryls via the cross-coupling reaction of arylboronic acids*, in: L.S. Liebeskind (Eds.), *Advances in Metal-Organic Chemistry*, vol. 6, JAI, Stamford, 1998, p. 187. (c) A. Suzuki, 1998. in: F. Diederich, P.J. Stang (Eds.), *Metal-catalyzed Cross-Coupling Reactions*, VCH, Weinheim, 1998, p. 49.
- [22] Si-Si: Y. Hatanaka, T. Hiyama, *Tetrahedron Lett.*, 28 (1997) 4715. J.D. Rich, T.E. Krafft, *Organometallics*, 9 (1990) 2040. H. Matsumoto, K. Shono, Y. Nagai, *J. Organomet. Chem.*, 208 (1981) 145. Sn-Sn H. Azarian, S.S. Dua, C. Eaborn, D.R.M. Walton, A. Pidcock, *J. Organomet. Chem.*, 117 (1976) C55. M. Kosugi, K. Shimizu, A. Ohtani, T. Migita, *Chem. Lett.*, (1981) 829. V. Farina, S.I. Hauk, *J. Org. Chem.* 56 (1991) 4317.
- [23] M.F. Hawthorne, *Angew. Chem. Int. Ed. Engl.*, 32 (1993) 950. A.H. Soloway, *Chem. Rev.*, 98 (1998) 1515.
- [24] K.A. Horn, *Chem. Rev.* 95 (1995) 1317.
- [25] T.N. Mitchell, *Synthesis* (1992) 803.
- [26] G. Urry, T. Wartik, R.E. Moore, H.I. Schlesinger, *J. Am. Chem. Soc.*, 76 (1954) 5293. See also reference 31.
- [27] R.J. Brotherton, A.L. McCloskey, L.L. Petterson, H. Steinberg, *J. Am. Chem. Soc.* 82 (1960) 6242.
- [28] R.J. Brotherton, A.L. McCloskey, J.L. Boone, H.M. Manasevit, *J. Am. Chem. Soc.* 82 (1960) 6245.
- [29] (a) H. Nöth, *Z. Naturforsch.* 39b (1984) 1463. (b) T. Ishiyama, M. Murata, T. Ahiko, N. Miyaura, *Organic Syntheses*, 77 (1999) 176.
- [30] C.N. Welch, S.G. Shore, *Inorg. Chem.* 7 (1968) 225.
- [31] T.D. Coyle, J.J. Ritter, *Advances in Organometallic Chemistry*, vol. 10, Academic, New York, 1972, p. 237.
- [32] T. Ishiyama, N. Matsuda, N. Miyaura, A. Suzuki, *J. Am. Chem. Soc.* 115 (1993) 11018.
- [33] T. Ishiyama, M. Yamamoto, N. Miyaura, *Chem. Lett.* (1996) 1117.
- [34] (a) S.D. Brown, R.W. Armstrong, *J. Am. Chem. Soc.* 118 (1996) 6331. (b) S.D. Brown, R.W. Armstrong, *J. Org. Chem.* 62 (1997) 7076.
- [35] (a) T. Ishiyama, M. Yamamoto, N. Miyaura, *Chem. Commun.* (1997) 689. (b) T.B. Marder, N.C. Norman, C.R. Rice, *Tetrahedron Lett.* 39 (1998) 155.
- [36] C.N. Iverson, M.R. Smith III, *Organometallics* 16 (1997) 2757.
- [37] R.T. Baker, P. Nguyen, T.B. Marder, S.A. Westcott, *Angew. Chem. Int. Ed. Engl.* 34 (1995) 1336.
- [38] C. Dai, E.G. Robins, A.J. Scott, W. Clegg, D.S. Yufit, J.A.K. Howard, T.B. Marder, *Chem. Commun.* (1998) 1983.
- [39] T. Ishiyama, S. Momota, N. Miyaura, *Synlett* (1999) 1790.
- [40] T. Ishiyama, M. Yamamoto, N. Miyaura, *Chem. Commun.* (1996) 2073.
- [41] W. Clegg, T.R.F. Johann, T.B. Marder, N.C. Norman, A.G. Orpen, T.M. Peakman, M.J. Quayle, C.R. Rice, A.J. Scott, *J. Chem. Soc., Dalton Trans.* (1998) 1431.
- [42] T. Ishiyama, T. Kitano, N. Miyaura, *Tetrahedron Lett.* 39 (1998) 2357.
- [43] (a) Y.G. Lawson, M.J.G. Lesley, T.B. Marder, N.C. Norman, C.R. Rice, *Chem. Commun.* (1997) 2051. (b) H. Shima, T. Ishiyama, N. Miyaura, unpublished results.
- [44] T.M. Cameron, R.T. Baker, S.A. Westcott, *Chem. Commun.* (1998) 2395.
- [45] M. Murata, S. Watanabe, Y. Masuda, *J. Org. Chem.*, 62 (1999) 6458. M. Murata, T. Oyama, S. Watanabe, Y. Masuda, *J. Org. Chem.*, 65 (2000) 164.
- [46] T. Ishiyama, M. Murata, N. Miyaura, *J. Org. Chem.* 60 (1995) 7508.
- [47] T. Ishiyama, Y. Itoh, T. Kitano, N. Miyaura, *Tetrahedron Lett.* 38 (1997) 3447.
- [48] (a) K-C. Kong, C-H. Cheng, *J. Am. Chem. Soc.* 113 (1991) 6313. (b) D.K. Morita, J.K. Stille, J.R. Norton, *J. Am. Chem. Soc.* 117 (1995) 8576. (c) reference [21b], pp. 210–216.
- [49] (a) C. Malan, C. Morin, *J. Org. Chem.*, 63 (1998) 8019. (b) H. Nakamura, M. Fujiwara, Y. Yamamoto, *J. Org. Chem.*, 63 (1998) 7529.
- [50] (a) F. Firooznia, C. Gude, K. Chan, N. Marcopulos, Y. Satoh, *Tetrahedron Lett.* 40 (1999) 213. (b) M.E. Jung, T.I. Lazarova, *J. Org. Chem.* 64 (1999) 2976.
- [51] (a) S.R. Piettre, S. Baltzer, *Tetrahedron Lett.*, 38 (1997) 1197. (b) A. Giroux, Y. Han, P. Prasit, *Tetrahedron Lett.* 38 (1997) 3841. (c) P.A. Tempest, R.W. Armstrong, *J. Am. Chem. Soc.* 119 (1997) 7607.
- [52] K. Takahashi, J. Takagi, T. Ishiyama, N. Miyaura, *Chem. Lett.* (1999) 126.
- [53] (a) S.M. Marcuccio, M. Rodopoulos, H. Weigold, 10th International Conference on Boron Chemistry, Durham, England, July 1999, PB-35. (b) M. Murata, T. Oyama, S. Watanabe, and Y. Masuda, 76th Annual Meeting of Chemical Society of Japan, March 1999, 2B712.
- [54] T. Ishiyama, T.-a. Ahiko, N. Miyaura, *Tetrahedron Lett.* 38 (1996) 6889.
- [55] S. Momota, T.-a. Ahiko, N. Miyaura, unpublished results.
- [56] T.-a. Ahiko, T. Ishiyama, N. Miyaura, *Chem. Lett.* (1997) 811.

- [57] Z. Ohohashi, T.-a. Ahiko, T. Ishiyama, N. Miyaura, unpublished results.
- [58] Si-B compounds: M. Suginome, H. Nakamura, Y. Ito, *Chem. Commun.* (1996) 2777. M. Suginome, H. Nakamura, Y. Ito, *Angew. Chem., Int. Ed. Engl.* 36 (1997) 2516. M. Suginome, H. Nakamura, T. Matsuda, Y. Ito, *J. Am. Chem. Soc.*, 120 (1998) 4248. S.-y. Onozawa, Y. Hatanaka, M. Tanaka, *Chem. Commun.* (1997) 1229.
- [59] Sn-B compounds: S.-y. Onozawa, Y. Hatanaka, T. Sakakura, S. Shimada, M. Tanaka, *Organometallics* 15 (1996) 5450. S.-y. Onozawa, Y. Hatanaka, N. Choi, M. Tanaka, *Organometallics* 16 (1997) 5389.