Durham E-Theses

"Rhodium catalysed borylation reactions via direct and indirect c-h activation"

Richard Benjamin Coapes

How to cite:

Coapes, Richard Benjamin (2002) *"Rhodium catalysed borylation reactions via direct and indirect c-h activation"*. Doctoral thesis, Durham University.

"Rhodium Catalysed Borylation Reactions

via Direct and Indirect C-H Activation"
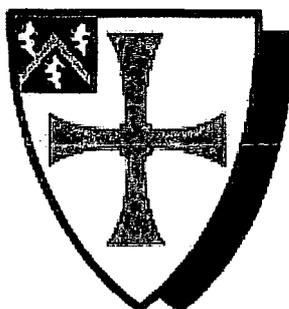
By

Richard Benjamin Coapes

A thesis submitted for the degree of Doctor of

Philosophy

Department of Chemistry

The University of Durham

September 2002

1 8 DEC 2002

Table of Contents

Chapter 5 – Functionalisation of Benzylic and Aryl C—H Bonds by Direct C—H Activation

mol% **1**

Chapter 6 – B-X Adducts of B-Chlorocatecholborane and Phosphines or Amines

toluene-10% C_6D_6

Acknowledgements

Thanks go out to many people and apologies in advance for those who feel left out. If unjustified, I'll buy you a drink.

Firstly, the Marder group past and present. Special thanks go to Rhodri, for help in the early days, Shigeru, for helpful advice and allowing me to 'borrow' reagents, and Jon, for sometimes clearing the sink, and for one of the driest senses of humour there is in Durham. Special thanks goes to Brian for much support and his meticulous care for so many things in the lab, such as the solvent columns and stills, and the glove boxes and vacuum pumps. Particularly, thanks go to Jacquie for friendship, hugs and other moral support in times of need or just if the mood took, and to Chris for a quite amazing sense of humour, and song writing sessions in Klute. Thanks to Prof. Todd Marder, not least for allowing me to try a $[Rh(\mu-Cl)(COE)_2]_2$ prep from $[IrCl_3 \cdot nH_2O]$ and for all he has done for me. I got there in the end!

To the department, the NMR service is worthy of particular note and to Ian McKeag, Catherine Heffernan, and Alan Kenwright I am indebted, most notably Ian for always finding time to try any VT and 2D experiments I needed doing at very short notice. Thanks to Judith Howard, Andes Goeta, Andrei Batsanov, Mike Leech, Dimitrii Yufit for crystal structures and much work for papers. Thanks also to Jaroslava Dostal for elemental analyses and to the glassblowers Malcolm Richardson and Peter Coyne for all they made and repaired.

To friends in the department, most notably Aileen Martin and Stephanie Cornet, I say thanks for tea, chats and proper discussions on almost anything.

Finally, thanks go to my parents for endless support no matter what the circumstances, and to my brother Chris, his wife Bryony and 'little gorgeous' Jessica, for making me an uncle earlier this year.

"Προαιρεισθαι τε δει ασυνατα ειχότα μαλλον η δμ

νατα απιθανα"

"Plausible impossibilities should be preferred to

unconvincing possibilities"

Aristotle, 322-264 B.C.

List of Abbreviations

Å	angstrom
Ar	aromatic group
br	broad (NMR)
Bu^t	*tert*-butyl
cat	catecholato, $(1,2-O_2C_6H_4)$
COD	1,5-cyclooctadiene
COE	*cis*-cyclooctene
Cp	cyclopentadienyl
Cp^*	pentamethylcyclopentadienyl
Cy	cyclohexyl
d	doublet (NMR)
dba	dibenzylideneacetone
dcpe	1,2-bis(dicyclohexylphosphino)ethane
DEPT	distortionless enhancement by polarisation transfer
dppb	1,4-bis(diphenylphosphino)butane
dppm	bis(diphenylphosphino)methane
equiv.	equivalent
Et	ethyl
GC	gas chromatography
h	hour
HSQC	heteronuclear single quantum coherence
IR	infrared
J	coupling constant
L	ligand

M	metal
m	multiplet
Me	methyl
mg	milligram
MHz	megahertz
ml	millilitre
mmol	millimol
MS	mass spectrometry
m/z	mass to charge ratio
nbe	norbornene
neop	neopentylglycolato ($OCH_2CMe_2CH_2O$)
NMR	Nuclear Magnetic Resonance
Ph	phenyl
pin	Pinacolato, ($OCMe_2CMe_2O$)
Pr^i	isopropyl
q	quartet
R	alkyl group
t	triplet
THF	tetrahydrofuran
TMS	trimethylsilyl, tetramethylsilane
tol	tolyl
X	halogen

Abstract for "Rhodium Catalysed Borylation *via* Direct and Indirect C-H Activation"

by R. B. Coapes

This thesis describes both direct and indirect C-H activation borylation processes, catalysed by several Rh-based catalyst precursors.

Chapter One presents an overview of the processes investigated, namely diboration, dehydrogenative borylation, and direct C-H activation of hydrocarbon substrates, which give borylated species that are of interest to synthetic chemists. The uses of such borylated species are also highlighted.

Chapter Two highlights the synthetic procedure for the synthesis of the catalyst precursor $[Rh(acac)(COE)_2]$, which can be used to prepare bis-phosphine catalyst precursors of the form $[Rh(acac)(P_2)]$. Although a procedure appears in the literature, it is not well cited. Also, this new procedure replaces $[Tl(acac)]$ with $[Na(acac)]$ and hence avoids the use of thallium salts.

Chapter Three investigates the reaction of two vinyl(boronate) esters (VBEs) with B_2cat_2, and a wide array of catalyst precursors, which yield, among other species, the tris(boronate) esters $ArCH_2C(Bcat)_3$ and $ArCH(Bcat)CH(Bcat)_2$; the former results from the addition of both borons of the B_2 unit to the **same** carbon atom, and are of interest due to their wide synthetic versatility.

Chapter Four investigates the dehydrogenative borylation of alkenes using both HBpin and B_2pin_2, and several catalyst precursors. Most significantly, this route allows the synthesis of 1,1-disubstituted vinyl(boronate) esters that cannot be made by alkyne hydroboration.

Chapter Five investigates the direct C-H activation of benzylic and aromatic hydrogens using the catalyst precursor $[Rh(Cl)(N_2)(P^iPr_3)_2]$. This allows the functionalisation of hydrocarbon substrates, which are ubiquitous.

Chapter Six investigates the stability of B-chlorocatecholborane to phosphines with the view to a boron analogue of the Heck reaction. In such a reaction, phosphines would likely be employed on the catalyst. An understanding of the stability of the boron reagent under typical reaction conditions is needed, therefore, in order to prevent degradation of B-chlorocatecholborane, a process that is known for catecholborane.

Chapter 1

Introduction

1.1 Classical Diboration

The conventional diboration of alkenes and alkynes has been known for almost 50 years. The reaction was first reported in 1954 by Schlesinger[1] *et al.* who used diboron tetrachloride to diborate ethylene at temperatures as low as −80°C, Eq. 1.1. The reaction yielded $Cl_2BCH_2CH_2BCl_2$ resulting from the sterospecific *syn* addition of the B—B bond to the C=C double bond.
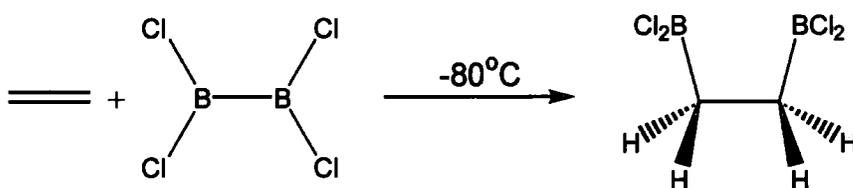
Equation 1.1: Reaction of ethylene with B_2Cl_4

Subsequently, several papers reported the diboration of many alkenes[2,3] as well as the diboration of alkynes,[4] dienes,[2,5] aromatics[2,5] and vinyl organometallics.[6,7]

There has been some debate as to the mechanism for uncatalysed diboration of unsaturated species. The generally accepted mechanism is shown in Scheme 1.1 and involves the interaction of the π-electrons of the double bond and the empty p-orbitals of the two borons, giving a four membered transition state and a concerted cis-addition. However, theoretical calculations on the reaction of B_2H_4 with both $H_2C{=}CH_2$[8] and $HC{\equiv}CH$[9] have shown that the reaction proceeds *via* a three-centred transition state resulting from the donation of the π-electrons of the multiple bond to only one boron atom, which precedes B—B bond cleavage, Scheme 1.2.
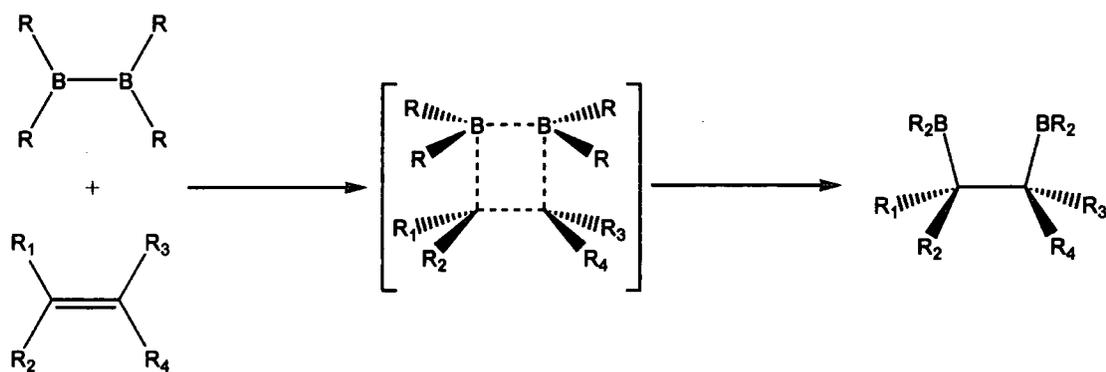
Scheme 1.1: Proposed mechanism for the classical diboration of alkenes with B_2Cl_4
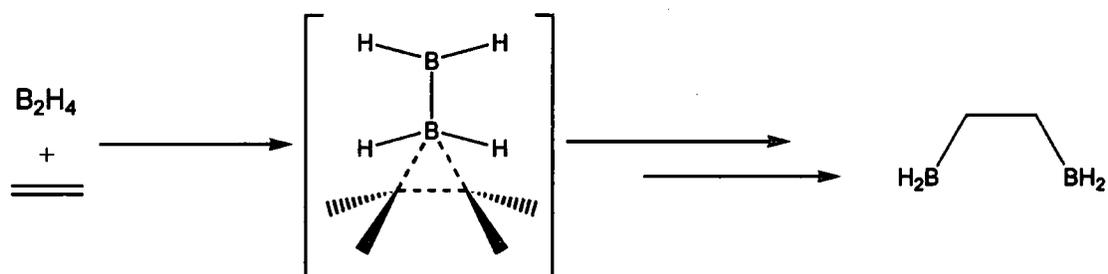
Scheme 1.2: Theoretical intermediate in the diboration of ethylene with B_2H_4

Despite the versatility of the diboron tetrahalides, their widespread use was inhibited

for several reasons. The synthesis of B_2Cl_4 is difficult[1,10] and involves the passage of

eight simultaneous electrical discharges through gaseous BCl_3 or passing BCl_3 over

Cu at 600 °C;[11] the high reactivity makes handling difficult and thermal

disproportionation takes place over a period of time.[12]

More stable B_2X_4 analogues have synthesised, such as $B_2(NMe_2)_4$[13-15] or $B_2(OR)_4$,

[e.g. B_2cat_2[16-19] (cat = 1,2-$O_2C_6H_4$, catecholato), B_2pin_2[15,17,20] (pin =

$O_2CMe_2CMe_2O$, pinacolato), $B_2cat'_2$[21] (cat' = 3,5-$Bu^t_2C_6H_2$) and B_2neop_2[21] (neop =

$OCH_2CMe_2CH_2O$, neopentylglycolato], Figure 1.1, that are considerably more stable

and easier to prepare. However, this increased stability reduces the reactivity and

these analogues fail to react with alkenes or alkynes at all under classical

conditions.[22-24] For these reasons, diboration of unsaturated hydrocarbons was not utilised by synthetic chemists until the early 1990's.
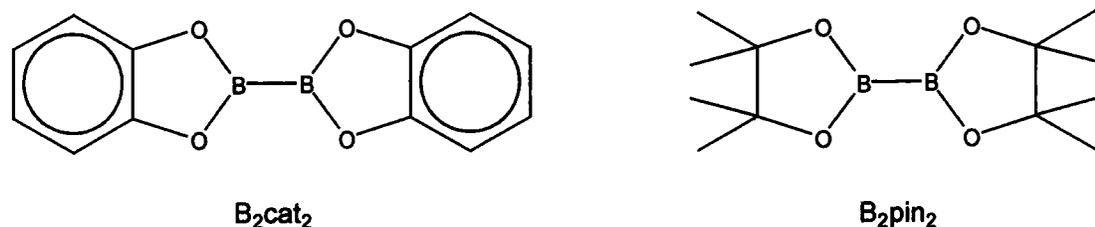
B_2cat_2

B_2pin_2

Figure 1.1: The diboron compounds B_2cat_2 and B_2pin_2

1.2 Metal Catalysed Diboration of Alkynes

The metal catalysed diboration of unsaturated hydrocarbons has grown rapidly over the last ten years and has been reviewed twice.[25,26] The first example of metal catalysed diboration of an alkyne was reported by Miyaura[27] *et al.* in 1993. The Pt(0) complex [Pt(PPh₃)₄] 1 was employed as catalyst precursor for the 1,2-*syn* addition of B_2pin_2 to both internal and terminal alkynes. In general, reactions were conducted at 80°C in DMF for 24 h and 3 mol% catalyst was used. For example, the reaction of dec-1-ene with B_2pin_2 yielded (Z)-CH(Bpin)=C(Bpin)-n-C_8H_{17} which could subsequently be reacted with a Pd(0) catalyst in a Suzuki-Miyaura type cross-coupling.[26] This report also provided spectroscopic evidence for the [Pt(PPh₃)₂(Bpin)₂] species, resulting from oxidative addition of B_2pin_2 to 1, although the NMR data was incorrect.

The following report[28] from Miyaura *et al.* was more comprehensive and investigated additional catalysts, diboron reagents and solvent effects. Wilkinson's catalyst [Rh(Cl)(PPh₃)₃], [Pd(PPh₃)₄], [Pd(OAc)₂] + 15 equiv. ᵗBuCN, [Ni(PPh₃)₄], [Pt(PPh₃)₂Cl₂], [Co(PPh₃)₃Cl] and [CuCN] all showed very little if any activity at all towards diboration. Additionally, the intermediate [Pt(PPh₃)₂(Bpin)₂] was isolated and

characterised by single crystal X-ray diffraction. Reaction of [Pt(PPh$_3$)$_2$(Bpin)$_2$] with 1-octyne yields 1,2-bis(boryl)octene as the sole product. It was also reported that [Pt(PPh$_3$)$_4$] was unreactive in the diboration of alkenes.

In 1996, both Smith[29,30] *et al.* and Marder and Norman[31,32] *et al.* reported the use of *cis*-[Pt(PPh$_3$)$_2$(η-CH$_2$=CH$_2$)$_2$] **2** which adds with stoichiometric B$_2$cat$_2$ to give *cis*-[Pt(PPh$_3$)(Bcat)$_2$] **3**. Smith reported[29] the reaction of **2** with B$_2$cat$_2$ and oct-4-yne to give (Z)-n-Bu-(Bpin)=CH(Bpin)-n-Bu. More importantly, however, the reaction of [Pt(NBE)$_3$] **4** reacted with B$_2$cat$_2$ to give norbornene diboration product; this shows that diboration can take place in the absence of any phosphines and also is the first example of catalytic alkene diboration, even if strained. Similarly, Marder and Norman[31] employed both **2** and **3** as well as *cis*-[Pt(PPh$_3$)$_2$(B-4-Bu^t-cat)$_2$] **5** as catalysts precursors for the diboration of alkynes with the finding that all showed increased reactivity over **1**, whilst *cis*-[Pt(dppb)(Bcat)$_2$] **6**, employing a bis-phosphine, showed only low reactivity, and *cis*-[Pt(dppe)(Bcat)$_2$] **7** showed no reactivity at all; also, addition of PPh$_3$ to **5** considerably reduced its activity. Later Marder[33] *et al.* reported the use of **4** with a variety of phosphines and stoichiometries for the diboration of 4-CF$_3$C$_6$H$_4$C≡CC$_6$H$_4$CF$_3$-4' with B$_2$pin$_2$. Here, a 1:1 ratio of **4**:PPh$_3$ provided an extremely rapid reaction, the catalyst proving so active that total conversion was achieved at room temperature. Activity with no phosphine was considerably reduced and activity with a 1:2 ratio of **4**:PPh$_3$ gave further reduction. Studies on the nature of the phosphine found that PCy$_3$ resulted in very rapid reaction; what was interesting here was the difference between PBu$^t_3$ and PCy$_3$, phosphines with somewhat similar basicity and cone angle; however, the reaction using PBu$^t_3$ proved to be considerably slower indicating the sensitivity of the catalyst to small

changes in either variable. It is clear, therefore, that the most active species is the mono-phosphine complex.

Interestingly, Miyaura[27] *et al.* reported that the reaction with phenyl acetylene, PhC≡CH, was particularly low yielding; Marder and Norman subsequently observed[31] that good yields could be obtained but only with extended reaction times. It was observed, however, that the presence of electron donating *para* substituents, such as MeO, accelerated the reaction whereas electron withdrawing groups, such as CN, decreased the rate especially with the terminal phenylacetylene. In contrast Smith[30] *et al.* found that CF_3 groups at the *para* position in diphenyl acetylenes accelerated the stoichiometric reaction, with MeO giving a slight deactivation. This was later verified in catalytic reactions.[33] There is thus a considerable difference between the internal and terminal phenyl acetylenes.

As for the diboron reagent of choice, both groups noted that B_2pin_2 proved less reactive than B_2cat_2. This is best shown in work by Marder and Norman[31] on the diboration of diynes, Figure 1.2. Here, the reaction of one equiv. of B_2pin_2 with buta-1,3-diynes and using **2** as catalyst precursor gave only the 1,2-diboration product; reaction with two equiv. of B_2pin_2 did yield the tetraborated product but extended reaction times were required, indicating the slow rate of the second diboration step relative to the first. Conversely, the same reaction repeated using 1 equiv. of B_2cat_2 gave a mixture of tetraborated, diborated, and unreacted diyne, indicating that, in this case, the rate for the first and second diboration processes are similar.

The mechanism for alkyne diboration is now well understood,[25,26,28-31,33] and proceeds *via* a $[Pt^0(PR_3)(B(OR)_2)_2]$ active species, Scheme 1.3, generated by oxidative addition of $B_2(OR)_4$ to the catalyst precursor. The alkyne then binds to a vacant site

before insertion into one of the Pt-B bonds. B-C reductive elimination then gives the diborated product, leaving a R_3P-Pt species, to which oxidative addition of $B_2(OR)_4$ regenerates the active species.
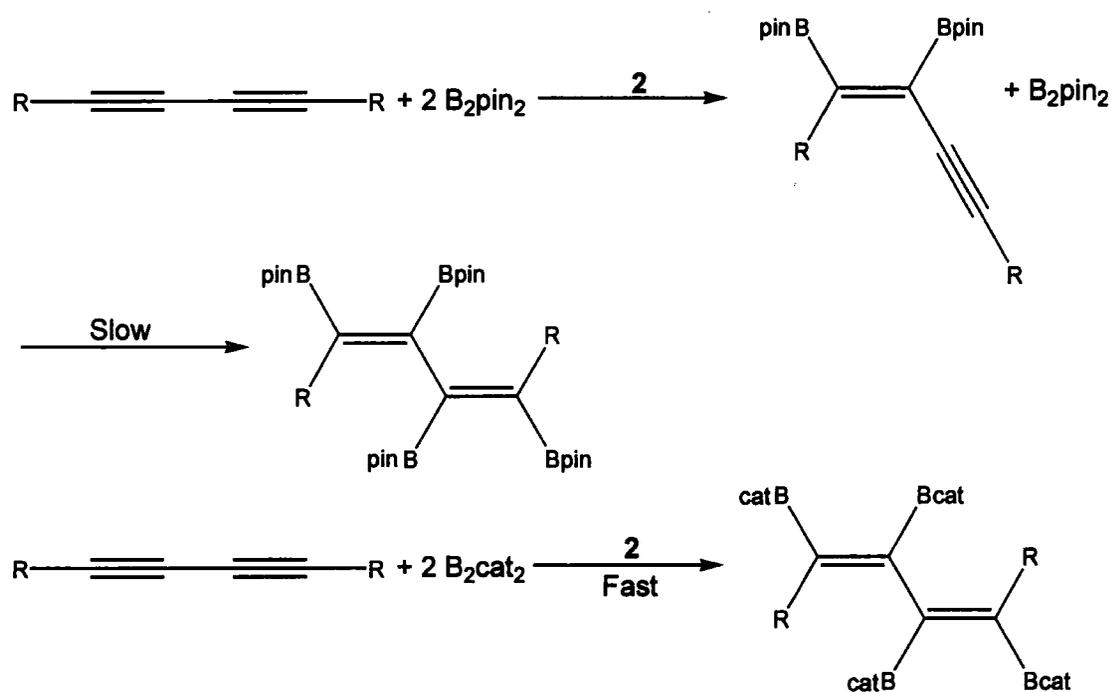
Figure 1.2: Reaction of butadiynes with B_2pin_2 and B_2cat_2
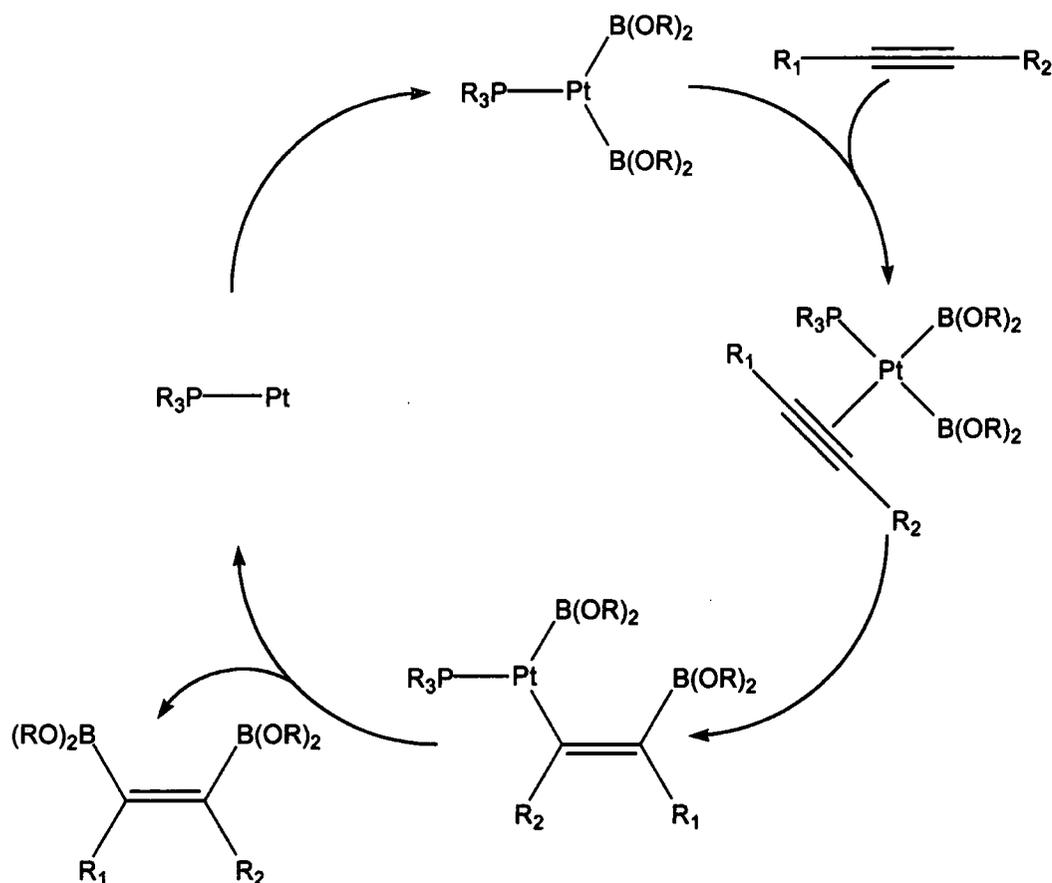
Scheme 1.3: Catalytic cycle for the diboration of alkynes

1.3 Application of metal-catalysed diboration

The *cis*-1,2-bis(boronate) esters produced from alkyne diboration have large number of applications in organic synthesis, and the methodology has quickly been adopted by the synthetic community. An early example is the synthesis of the cedarwood fragrance molecule (Z)-($\pm$)-5,6-dimethylcyclododec-5-en-1-ol which contains a twelve membered ring, the synthesis of which involves a step where an intermediate is diborated using B_2pin_2 and 1 as catalyst.[34] Brown and Armstrong used B_2cat_2 and 2 as catalyst in to diborate an alkyne, the product of which was further reacted in a Suzuki-Miyaura type cross coupling, as one step in a protocol for the general synthesis of the antiestrogenic triphenylethylene derivates, which include the breast cancer treatment Tamoxifen.[35,36] Siebert[37] *et al.* also diborated the unusual alkyne

catBC≡CBcat with B_2cat_2 to give the unusual tetraboronated alkene $(catB)_2C=C(Bcat)_2$ using **2** as catalyst. More general uses of vinyl(boronate) esters will be discussed later.

1.4 Transition metal-catalysed diboration of alkenes

The metal-catalysed diboration of alkenes is less well understood than that of alkynes as it is more complicated because a variety of products are formed due to competing B-C reductive elimination, resulting in alkene diboration, and β-hydride elimination pathways, leading to dehydrogenative borylation, and a possible pathway highlighting this is shown in Scheme 1.4. Dehydrogenative borylation is in itself interesting and will be addressed later. However, problems can arise as the [Rh(H)(B)] species resulting from β-hydride elimination can insert an alkene into either the Rh-H or Rh-B bond, reductive elimination from both gives a mono-boronate ester species, with β-hydride elimination from the latter yielding more vinylboronate and a [Rh(H)₂] species!
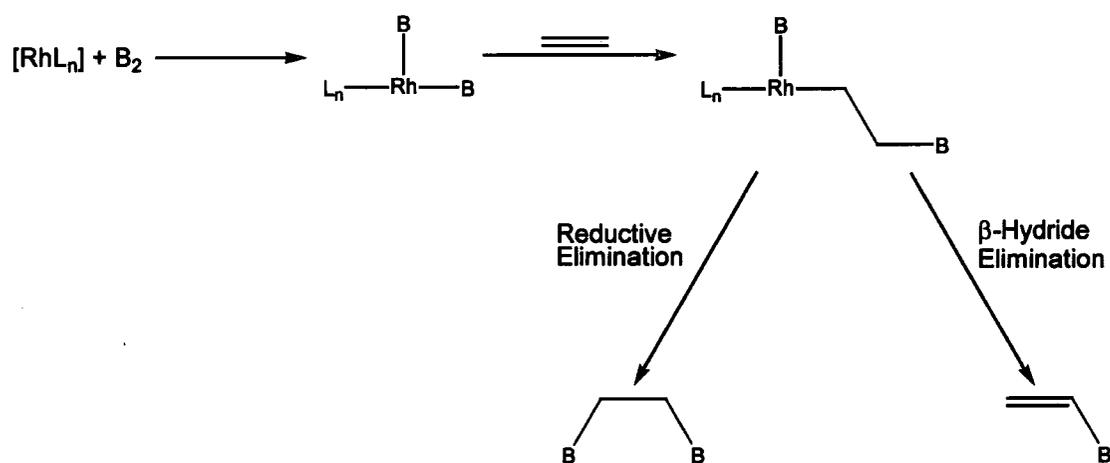
Scheme 1.4: Competing reductive elimination and β-hydride pathways under alkene diboration conditions

8

In 1995, Marder and Baker[38] *et al.* reported the use of a variety of Rh^I catalysts in the reaction of 4-vinyl anisole (**VA**) with B$_2$cat$_2$ and obtained up to nine products, Figure 1.3, due to these competing reductive elimination and β-hydride elimination pathways, and product distributions and catalysts are shown in Table 1.1. Along with the product resulting from diboration, **A**, and that of dehydrogenative borylation, **B**, there is up 28% yield of the unusual tris(boronate) ester **E**, produced from two insertion/β-elimination processes, then a third insertion followed by reductive elimination, when there are no β-hydrogens left. Overall this corresponds to the addition of three boron atoms to the same carbon atom. The use of [Au(Cl)(PEt$_3$)]/dcpe produced only the 1,2-diborated product as the low energy of the d-orbitals in the gold complex would inhibit π-backbonding to the alkene and hence destabilise the alkene-hydride intermediate, leading to β-hydride elimination, relative to the alkyl complex which would lead to reductive elimination. This complex was not very reactive, however, with 1.5 equiv. B$_2$cat$_2$ and a temperature of 80°C for 48 hours being necessary.
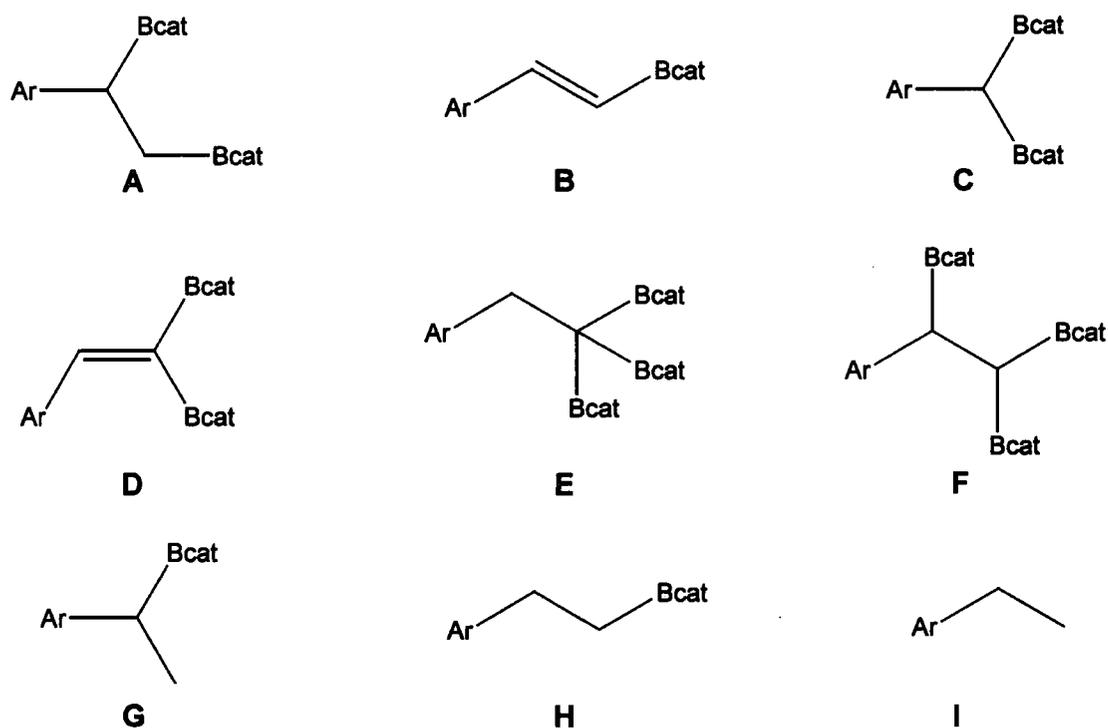
Figure 1.3: Products resulting from the reaction of VA with B$_2$cat$_2$ and Rh^I catalysts

Table 1.1: Products distributions resulting from the reaction of VA with B$_2$cat$_2$

Catalyst	A	B	C	D	E	F	G	H	I
[RuCl$_2$(PPh$_3$)$_4$]		42	13	7			2	25	11
[Ir(μ-Cl)(COE)$_2$]$_2$	21	35	1				14	27	2
[Rh(μ-Cl)(COE)$_2$]$_2$	7	40		2	1	2	43	1	4
[Rh(Cl)(N$_2$)(P^{i}Pr$_3$)$_2$]	8	20	36	5	9		10	12	
[Rh(d^{i}ppe)(η^6-catBcat)]	10	34	31		3		20		2
[Rh(Cl)(PPh$_3$)$_3$]	11	31	1	1	4	1	50	1	1
[Rh(Cl)(PPh$_3$)$_3$]/10 PPh$_3$	13	14	1	3	28	7	30	3	1
[Rh(COD)(dppb)][BF$_4$]	26	35	5				32	1	1
[Rh(dppb)(η^6-catBcat)]	44		10		22		22		2
[Au(Cl)(PEt$_3$)]/dcpe	100								

In an attempt to understand this complicated process, the reaction was repeated using the vinyl(boronate) **B** as the starting alkene, and the results from this study can be found in Chapter 3 of this thesis.

In 1997, Smith *et al.* reported[39] the use of **4** and [Pt(COD)$_2$] for the addition of B$_2$cat$_2$ to terminal alkenes and the strained internal alkenes norbornene and norbornadiene, where diboration occurs exclusively to the *exo*-face. Here, reactions are typically over in 10 minutes at ambient temperature, and the reaction tolerates various functional groups, including esters and alkyl chlorides. However, reaction with other internal alkenes, such as *trans*-3-hexene gives a complex mixture of products including the vinyl(boronate) resulting from β-hydride elimination.

At the same time, Miyaura *et al.* reported[40] the use of [Pt(dba)$_2$] **8** for, again, the diboration of terminal and the strained cyclic alkenes cyclopentene and norbornene with B$_2$pin$_2$ at 50°C for 1 hour; additions to other internal alkenes proved very slow, which cyclooctene providing a low yield of the 1,2-diborated product and with no reaction at all observed with oct-4-ene, stilbene, cyclohexene or 2-methylpropene.

The first example of unstrained internal alkene diboration was reported[41] in 1998 by Marder *et al.* with the use of the zwitterionic catalyst [Rh(dppm)(catBcat)] **9**, which are synthesised *in situ* by reaction of [Rh(acac)(dppm)] with B$_2$cat$_3$. Reaction of B$_2$cat$_2$ and 4 mol% **9** with *cis*- and *trans*-stilbene as well as *trans*-β-methylstyrene in THF gave high yields of the diborated alkene in times no longer than 72 hours. Also, in the diboration of styrene, VA, and 4-chlorostyrene, reaction times indicate that the presence of an electron donating group at the *para* position slightly decrease the rate of reaction relative to that for styrene whereas the presence of electron withdrawing groups slightly enhance the rate.

In the same year, Norman *et al.* reported[42] the diboration of terminal alkenes with the

chiral $B_2(OR)_4$ reagents $B_2(R,R\text{-}OCH(CO_2Me)CH(CO_2Me)O)_2$ **I**,

$B_2(S\text{-}OCH_2CHPhO)_2$ **II** and $B_2(R,R\text{-}OCHPhCHPhO)_2$ **III** and using **8** as catalyst,

achieving up to 80% yield with 60% diastereomeric excess using VA and

$B_2(R,R\text{-}OCHPhCHPhO)_2$.

Most recently, Baker *et al.* reported[43] the use of commercially available

$[Pt(Cl)_2(COD)]$ in THF at ambient temperature for the diboration of the terminal

alkenes VA and 4-chlorostyrene, with yields of 96 and 93 % respectively, and they

also used alkynes and aldimines in their study.

1.5 Metal catalysed diboration of 1,3-dienes

The first example of addition of a diboron compound to 1,3-dienes was reported[44] by

Miyaura *et al.* with a report on the boron analogue of the reactions of disilanes,

digermanes or silylstannanes.[44] The reaction of 3 mol% **1** and 1:1 reaction of

1,3-diene:B_2pin_2 at 80°C in toluene yielded the 1,4-addition product in 93% yield,

Figure 1.3, the rate being slow at room temperature. The use of **8** as catalyst with

isoprene (2,3-dimethyl-1,3-butadiene) resulted in the dimerisation of the diene during

the addition of the diboron reagent, the phosphine-free catalyst giving a rapid rate of

reaction at room temperature, again in toluene, Figure 1.4.

The mechanism of the reaction is shown in Scheme 1.5. Here, oxidative addition of

B_2pin_2 to the Pt^0 centre yields the $[Pt^{II}B_2]$ intermediate, followed by insertion of the

diene into one Pt-B bond forming a π-allyl(boryl)platinum(II) intermediate. Finally,

reductive elimination yields the 1,4-diborate alkene. Although thermal isomerisation

to the thermodynamically more stable (*E*)-isomer might be expected, the reductive

elimination step appears to be faster than isomerisation and so the (Z) isomer is the only product. The mechanism for the dimerisation reaction, however, remains unclear.

R₁ = R₂ = H
R₁ = H, R₂ = Me
R₁ = R₂ = Me
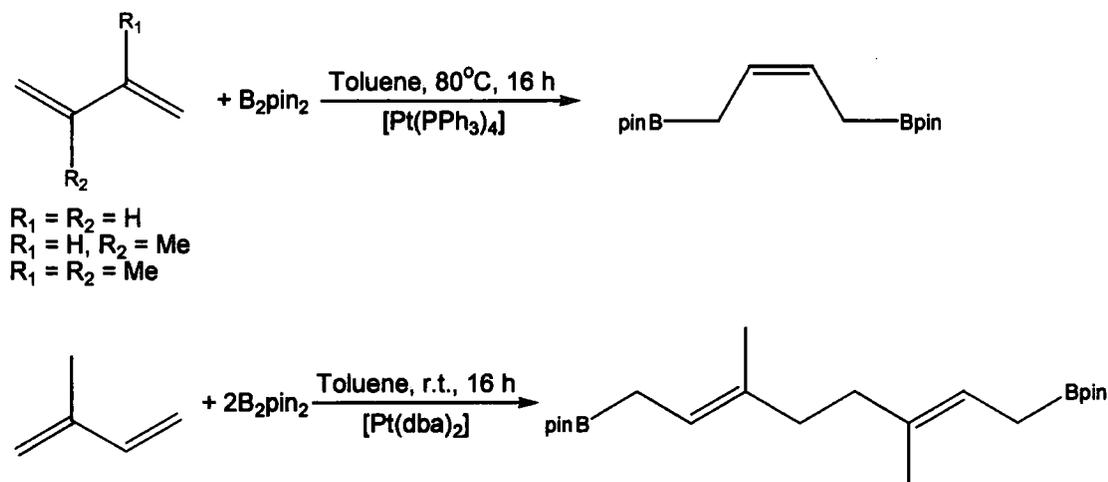
Figure 1.4: 1,4-diboration of 1,3-dienes (top) and the dimerisation reaction (bottom)
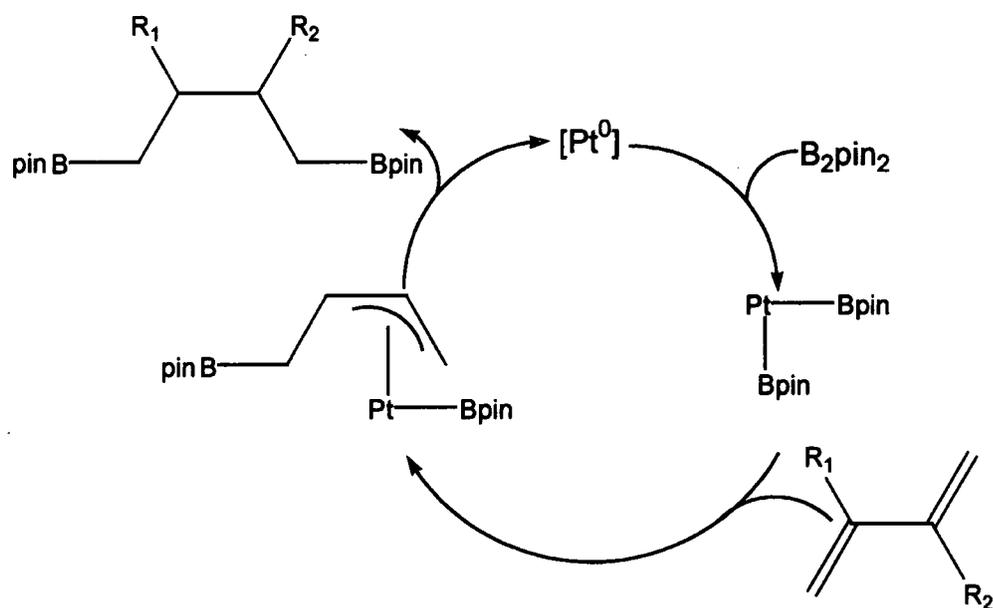
Scheme 1.5: Mechanism for the 1,4-diboration of 1,3-dienes

13

In a subsequent report on the diboration of alkenes, Miyaura *et al.* reported[40] the reaction of both **1** and **8** with penta-1,3-diene and B$_2$pin$_2$, Figure 1.5. Interestingly, the reaction with **8** did not yield the 1,4-diborated product but yielded the 1,2-diborated diene.
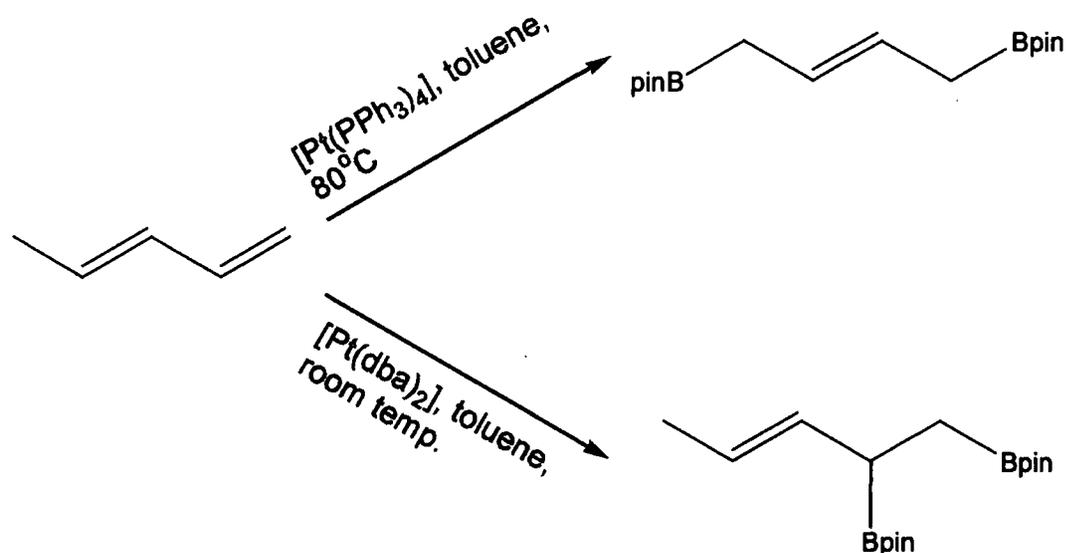
Figure 1.5: The 1,2-diboration of 1,3-pentadiene

In 1998, Norman *et al.* reported[45] use of the chiral diboron reagents **I, II, III**, and B$_2$cat$_2$ in the 1,4-diboration of penta-1,3-diene, hexa-1,3-diene, 2-methyl-penta-1,3-diene and 1,3-cyclohexadiene. Catalyst **2** was used (5 mol%) in toluene at 80°C for 1 day with yields ranging from 55 – 90%. However, the highest diastereomeric excess achieved was 20%, although. Although the use of chiral mono- and bidentate phosphine on the catalyst is a more typical way to control the stereochemistry of the reaction, this was not attempted here.

1.6 Diboration of α,β-unsaturated ketones

Several reports have been published on the diboration of α,β-unsaturated ketones with

B_2cat_2 and B_2pin_2, using several catalysts. The first report[46] was by Marder and

Norman using 5 mol% **2** in toluene at 80°C for 12 hours with both B_2cat_2 and B_2pin_2

and *trans*-4-phenylbut-3-en-2-one and chalcone. With B_2pin_2, the 1,4-diborated

product J was observed and was identified as the (Z)-isomer, Figure 1.6, by NOESY

NMR spectroscopy but reaction with B_2cat_2 showed only the hydrolysis product,

Figure 1.6, further emphasising the sensitivity of Bcat over Bpin. The boronate esters

that results are in contrast to those resulting from hydroboration with HBcat.[47]
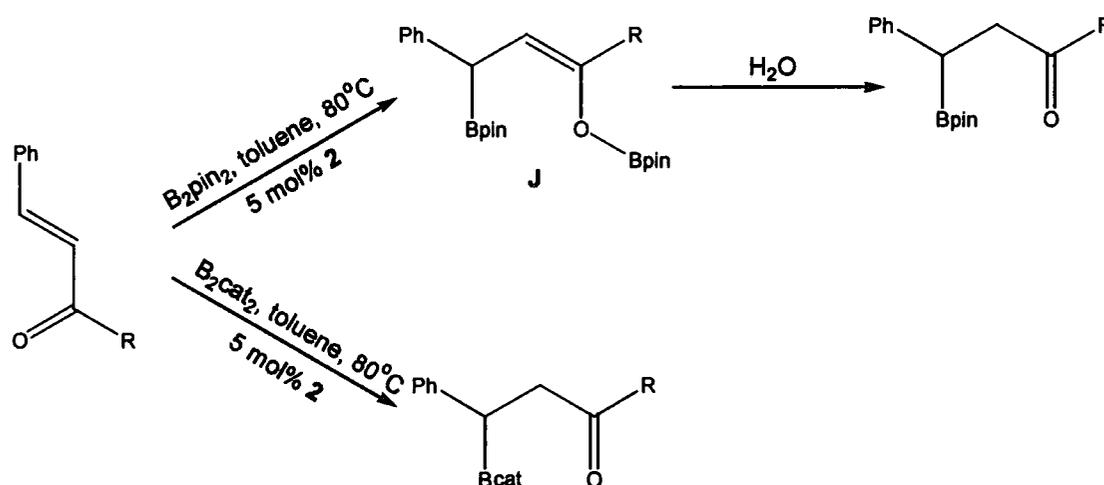
Figure 1.6: Diboration of α,β-unsaturated substrates with B_2pin_2 and B_2cat_2

Miyaura *et al.* reported[48,49] the use of [CuCl] and KOAc as catalyst for the

diboration of several substrates with B_2pin_2 in DMF. In general, stoichiometric

amounts of copper were used but catalytic quantities were used to good effect. The

reactivity of the Cu[I] halides were CuCl > CuI ~ CuBr > CuCN and solvent effects

DMF > DMSO >> toluene > THF. Investigations into the potassium salts showed that

small basic potassium salts increased the yield, as did the addition of LiCl. The

proposed reaction scheme is shown in Equation 1.2, and proceeds by the

transmetalation of B_2pin_2 with CuX to yields a B-Cu species, though this has not been proven.
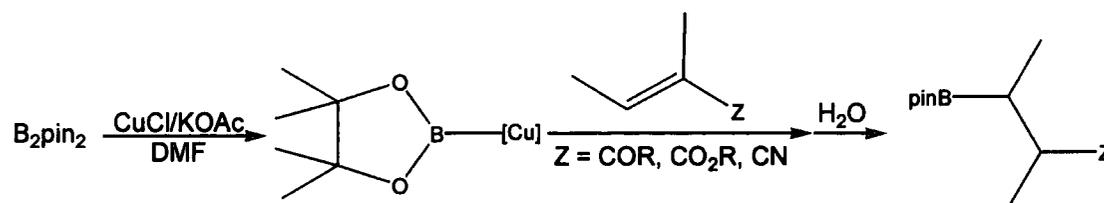
Equation 1.2: The diboration of α,β-unsaturated ketones via transmetalation with

copper

Further work using copper catalysts was undertaken[50] by Hosami *et al.* using a variety of phosphines either in the presence of, predominantly, [Cu(OTf)] **10** but also [CuCl], and also in absence of Cu^I catalyst. Chalcone was used as substrate and DMF as solvent. Reaction at room temperature in the presence of **10** but with no phosphine showed no diboration after 14 hours. Reaction with 1 equiv. of PBu_3 gave a yield of 96% after 10 hours compared to 50% after 24 hours using 1 equiv. PPh_3. Using PBu_3 in the absence of catalysts gave only 7% yield after 24 hours. Reaction with 2 equiv. of PBu^n_3 and **6** reduced the yield to 79% and reaction with the bidentate phoshpine dppp reduced catalytic activity to zero; this was increased to 36% after heating at 60°C for 12 hours. Use of [CuCl] and PBu_3 gave a yield of 83% after 15 hours. Reaction in THF, CH_2Cl_2 and toluene also reduced the yield. Several additional substrates were then investigated using 10 mol% **6** with 1 equiv. of PBu_3, and the results are shown in Figure 1.7. Reactions conducted with B_2cat_2 gave significantly lower yields and were much slower.

Srebnik *et al.*[51] used 5 mol% **1** in toluene at 110 °C for 20 hours using B_2pin_2 and the substrates 4-isopropylcyclohexenone, cycloheptenone, *trans*-cinnemaldehyde and methyl-*trans*-cinnamate; yields of 80%, 86%, 79%, and 68% respectively were obtained. Additions apparently occur *via* the 1,4-addition of B_2pin_2 but only the

hydroborated products were isolated after workup and it is not reported whether the 1,4-diborated compounds were observed.
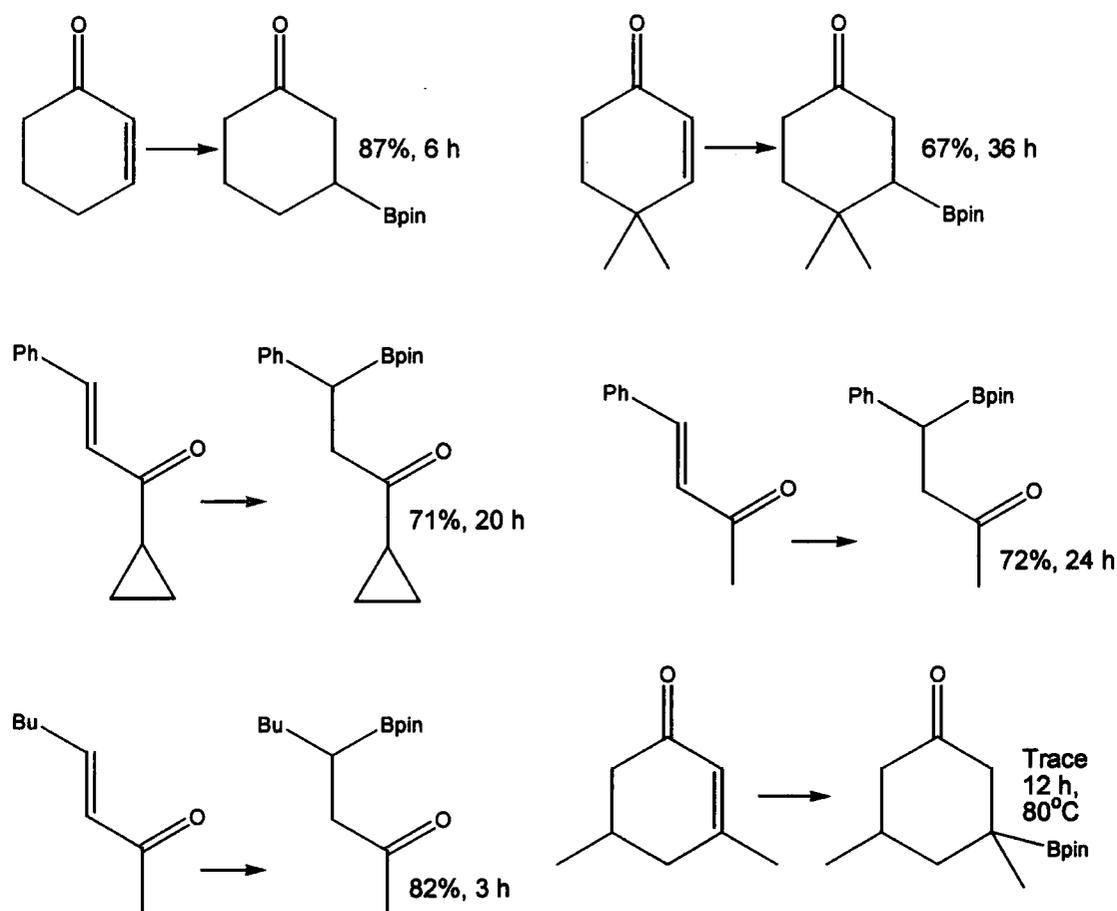
*Figure 1.7: Results obtained from the reaction of 10 mol% **10** with 1 equiv. PBu₃*

Most recently, Kabalka *et al.* reported[52] the use of Wilkinson's catalyst, [Rh(Cl)(PPh₃)₃] **11**, in toluene at 80°C with B₂pin₂ and also with B₂neop₂. Results are comparable between diboron reagents for cyclohexenone. Again, products isolated were the hydroborated product after hydrolysis but no characteristion of the diborated intermediate is reported.

1.7 Dehydrogenative Borylation of alkenes

The dehydrogenative borylation of alkenes is an exciting way to make vinylboronate esters (VBEs) by indirect C-H activation. This reaction does not require alkenyl halides or triflates[26,53] or 1-halo-lithialkenes with extremely low temperatures,[54] and is more general than other routes to VBEs, for example the diboration of methylene cyclopropanes.[55] The most common way to make VBEs is by classical[56,57] or transition-metal catalysed[58-63] hydroboration of alkynes. However, dehydrogenative borylation allows synthesis of 1,1-disubstituted VBEs that cannot be made by alkyne hydroboration. However, in virtually all cases, the hydrogen produced leads to loss of half the alkene substrate to hydrogenation.

Dehydrogenative borylation was first reported in 1983 by Sneddon and co-workers[64] who used 1 mol% [PdBr$_2$] to catalyse the reaction of pentaborane with ethylene, propylene and but-1-ene. The reaction with propylene yielded three isomeric forms of VBE as shown in Equation 1.3. However, 50% of the alkene was lost to hydrogenation although no hydrogen was visibly produced.
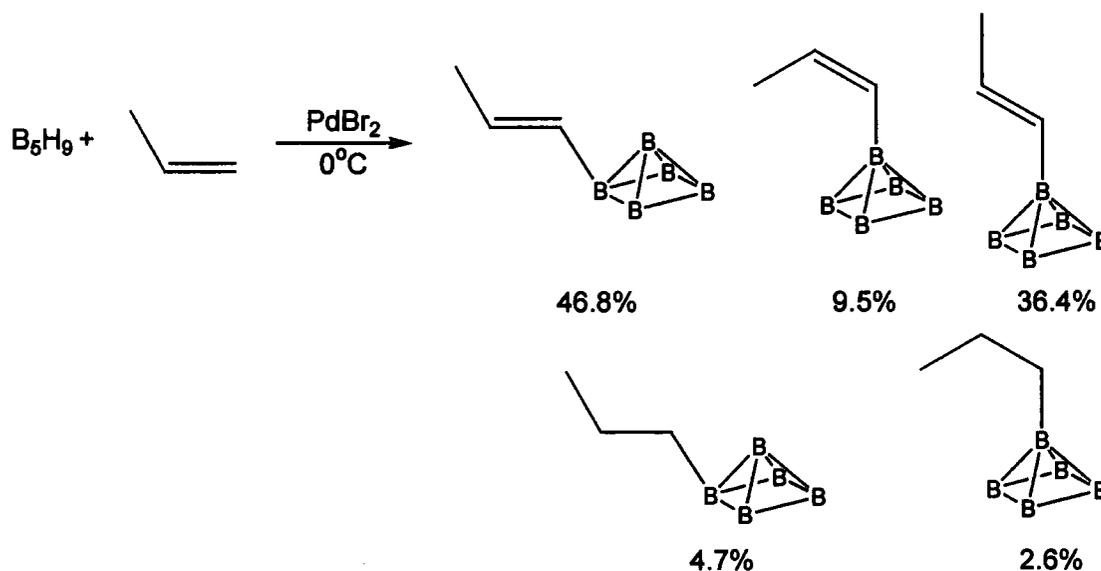
Equation 1.3: The first example of dehydrogenative borylation

Over the last ten years, several papers have reported dehydrogenative borylation processes, the first of which was in a communication by Brown *et al.*[65] who used an oxazaborolidine hydroborating reagents in a reaction with VA. The catalyst used was $[Rh(\mu\text{-}Cl)(\eta\text{-}CH_2CHAr)_2]_2$ where $Ar = 4\text{-}MeO\text{-}C_6H_4$. The reaction yielded a 1:1 mixture of the dehydrogenative borylation product and hydrogenation product, as shown in Equation 1.4.
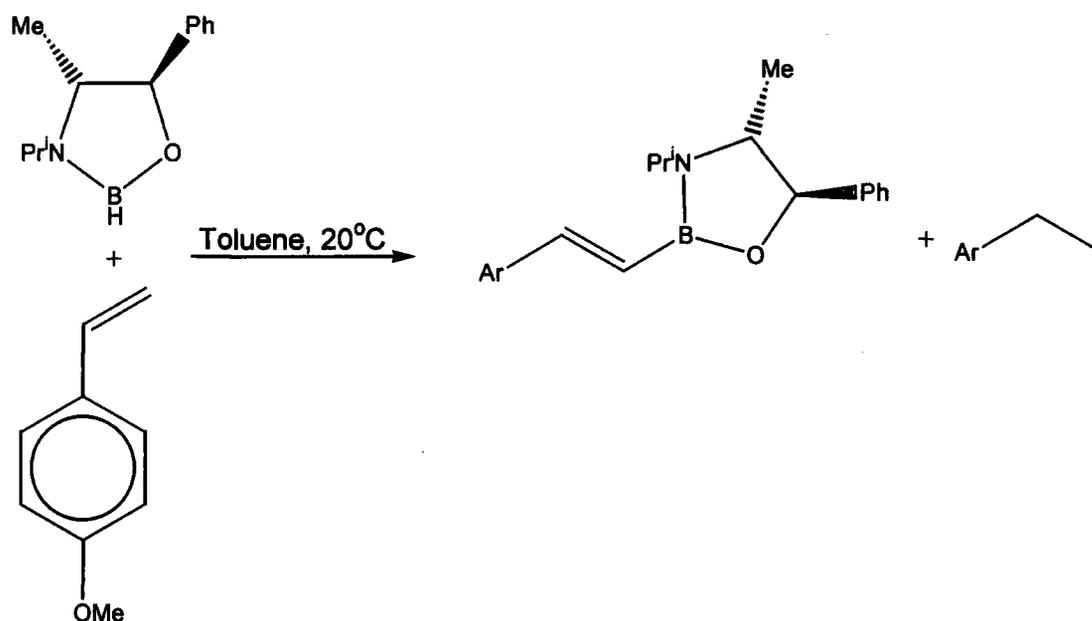
Equation 1.4: Dehydrogenative borylation conducted by Brown et al.

Two years later a full paper[66] gave the additional results which are shown in Equation 1.5, and again the loss of 50% of the alkene to hydrogenation was a problem. Also of significance is the comment that, "The synthetic utility of this reaction appears to be limited to vinylarenes; other alkenes were unreactive or give multiple products." Reactions were also attempted using HBcat as the hydroborating agent. In this case, a rapid reaction occurred, more so than for the oxazaborolidine, but again there was loss of half the alkene substrate to hydrogenation, with no sign of any hydroboration.

19

The catalytic cycle is shown in Scheme 1.6. In this, the equilibrium between bis(alkene) and the benzyl form of one alkene ligand is followed by oxidative addition of HBcat. C-H reductive elimination and binding of a further alkene yields a [Rh(CH$_2$CHAr)$_2$(B(OR)$_2$)] intermediate. Reductive elimination from this intermediate gives B-C bond formation and hence produces the VBE.
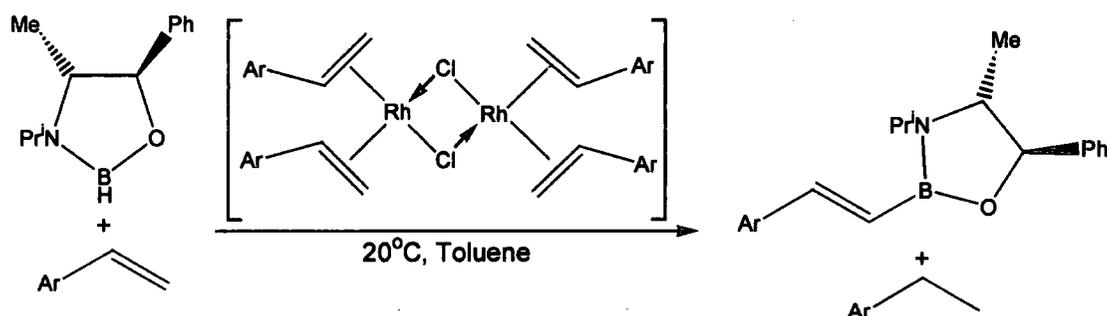
Ar	Yield (%)
4-MeO-C$_6$H$_4$	98
4-Cl-C$_6$H$_4$	99
Ferrocenyl	38

Equation 1.5: Substrates used by Brown et al. in VBE formation
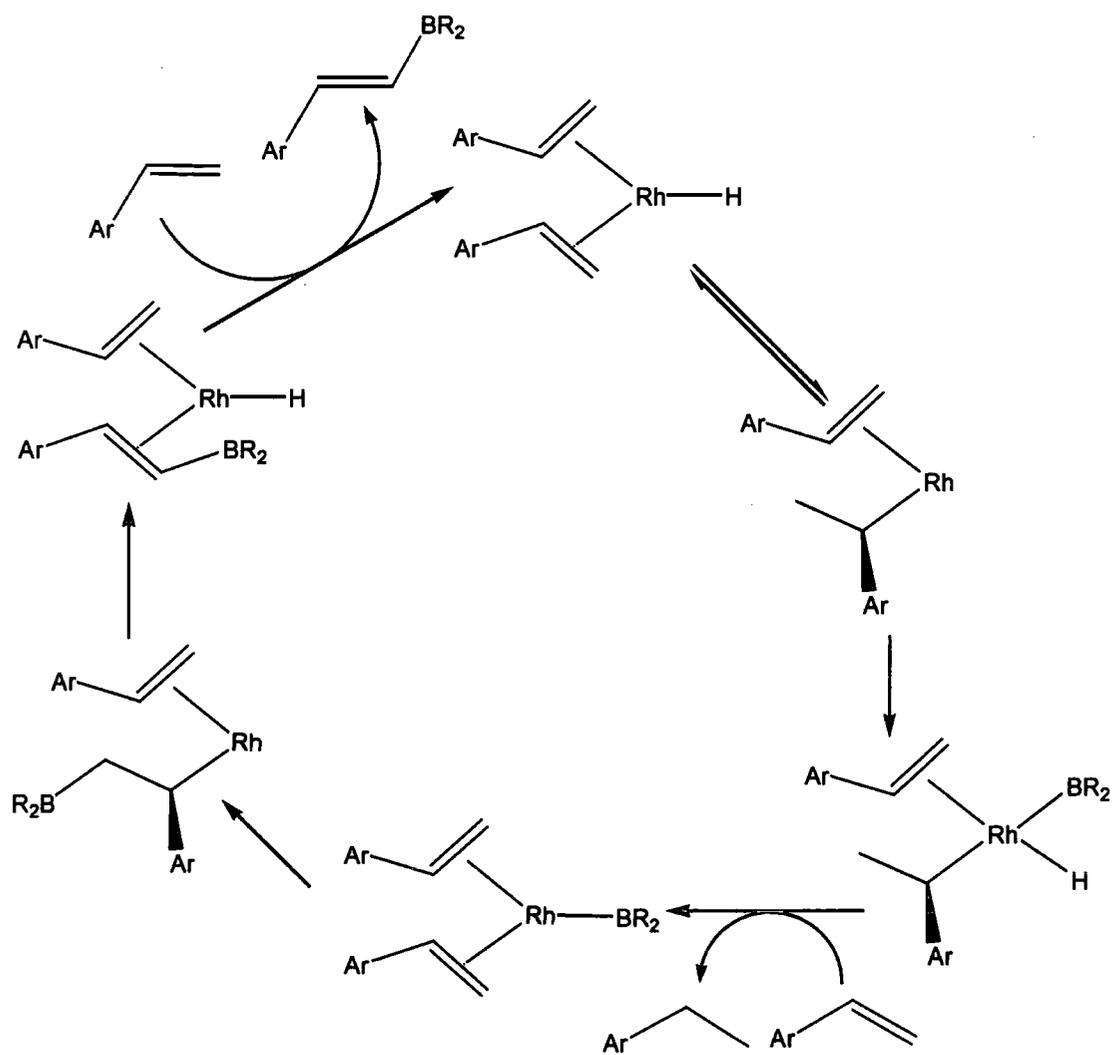
Scheme 1.6: Mechanism of VBE formation

In 1992, Burgess, Marder and Baker *et al.*[59] in their paper on the reaction of HBcat with Wilkinson's catalyst **11** reported that the unsaturated silyl ether 2-methyl-3-[(*tert*-butyldimethylsilyl)oxy]but-1-ene, when using pure **11** yielded, after oxidation, significant amounts of aldehyde resulting from the VBE; the use of partially oxidised catalysts resulted in the alcohol after oxidation. However, yields here are not quoted and no mention is made to the presence of hydrogenated alkene and it is unclear, therefore, whether this reaction is accompanied with significant hydrogenation.

However, in 1993, Marder and Baker *et al.* found[67] that the reaction of α-methylstyrene and HBcat with 2 mol% catalyst at 25°C in THF yielded both the VBE and the saturated alkyl-bis(boronate) ester (BBE), formed from subsequent hydroboration of the VBE. The use of **11** gave a total yield of VBE+BBE of 80% with 17% hydroboration and only 3% hydrogenation, Figure 1.8. Therefore, this represents both the first example of dehydrogenative borylation without significant hydrogenation and the dehydrogenative borylation of a 1,1-disubstituted alkene. This total yield of VBE+BBE can be increased as high as 84% using [Rh(μ-Cl)(PPh₂(*o*-tol))₂]₂ and 88% using **7** + 10 PPh₃, this case giving only 1% hydrogenation. Interestingly, the next highest yield of 86% was achieved using **11** that had been exposed to air for 24 hours, and this also produced only 1% hydrogenation. The regiochemistry can be rationalised by the formation of an η³-benzyl complex, the steric bulk of the Bcat group pointing away from the metal centre and hence in the direction of the methyl group, Scheme 1.7, also the least hindered side of the alkene itself.
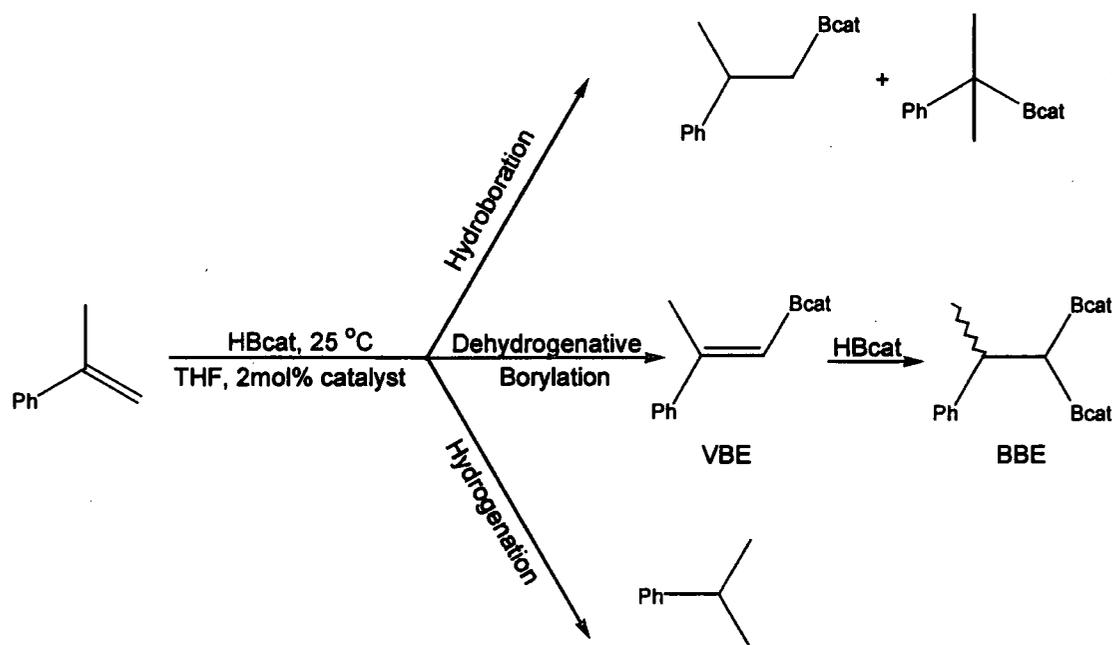
Figure 1.8: Dehydrogenation borylation without significant hydrogenation
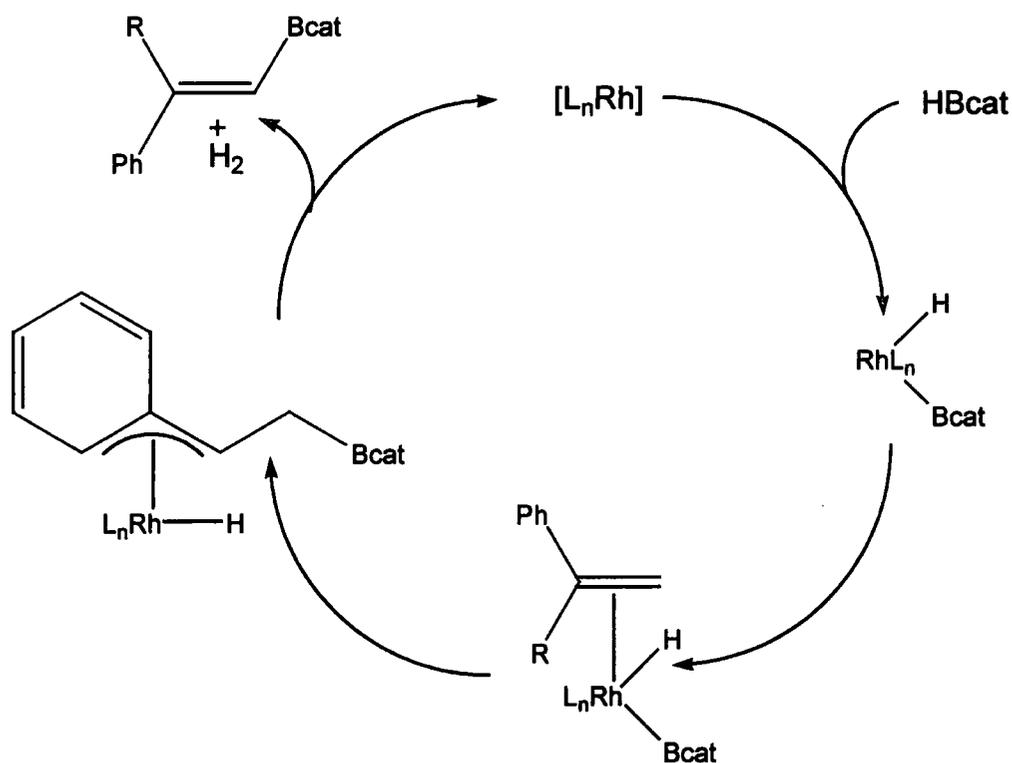
Scheme 1.7: The proposed mechanism for the dehydrogenative borylation of

1,1-disubstituted alkenes

In 1995 Motry and Smith reported[68] the use of the titanium-ethylene complex

$[(Cp^*)_2Ti(\eta^2\text{-}CH_2CH_2)]$ **12** and HBcat or the borane derived from

2,3-dihydroxynaphthalene and BH_3, for stoichiometric dehydrogenative borylation at

-78 °C in toluene, Equation 1.6; again the reaction is accompanied by hydrogenation

of half of the alkene substrate. The catalytic conversion of ethylene to VBE using **12**

was unsuccessful due to the rate of elimination of VBE and subsequent binding of

ethylene being slow and accompanied with the decomposition of **12**. The mechanism,

Scheme 1.8, was determined by the use of deuterium labelled borane, which placed

the deuterium mainly in the ethane evolved (85%) with the remainder incorporated

into the boron-substituted vinylic position of the VBE. Thus, the rate of HD loss is

considerably faster than the rate of the back reaction of the reversible β-elimination

step.
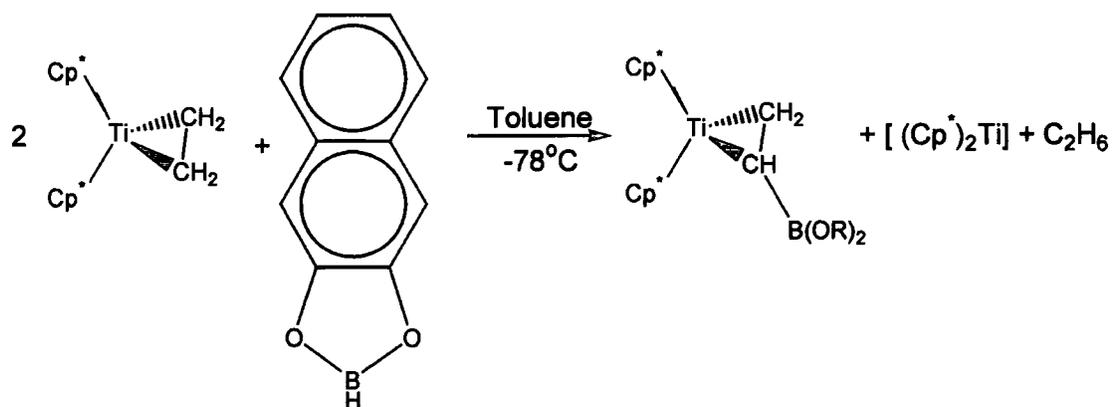
Equation 1.6: Stoichiometric dehydrogenative borylation
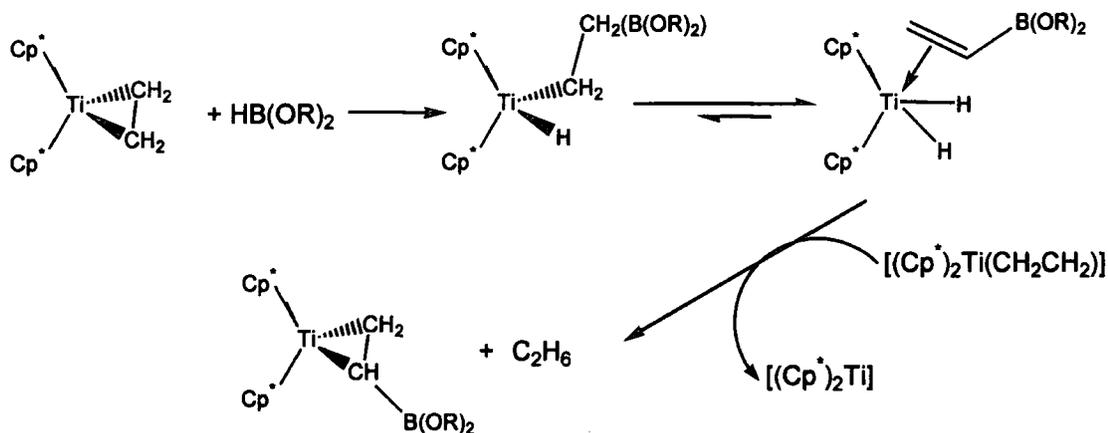
Scheme 1.8: Mechanism for stoichiometric dehydrogenative borylation

Later in 1995, Baker, Marder and co-workers in their publication on the reactions of

organoruthenium phosphine complexes observed[69] dehydrogenative borylation in the

reaction of 9-BBN with [Ru(η^2-C$_2$H$_4$)(PMe$_3$)$_4$], Scheme 1.9. Here, the borane

apparently attacks one of the CH$_2$ groups, forming an borylalkyl intermediate K,

which is in equilibrium with the zwitterionic species L; β-hydride elimination from L

yields a ruthenium di-hydride species and VBE.

24
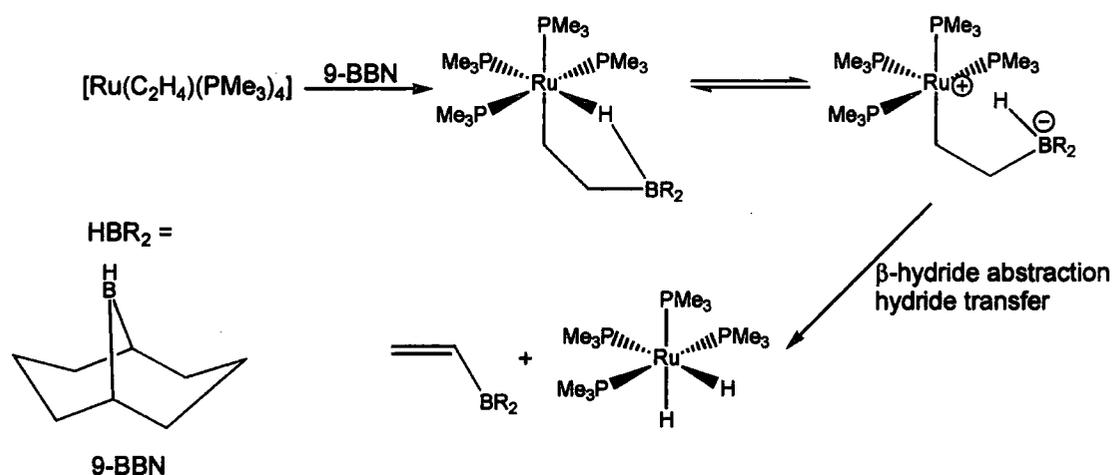
Scheme 1.9: Stoichiometric route to VBE using ruthenium

In 1997 Smith *et al.* reported[70] the titanium catalysed reaction of ethylene with HBOp (benzo-1,3,2-diazaborolane), again using **12** (3 mol%) as catalyst. Once again, half of the ethylene is lost to hydrogenation, Figure 1.9. Catalytic reaction with HBcat yielded no VBE but CH_3CH_2Bcat rather than the VBE, indicating a loss of the selectivity of the stoichiometric reaction.[68] The reaction with HBOp, however, was more successful due to the increased stability of B-N over B-O bonds reducing disproportionation of the borane. Interestingly, the thermodynamics and kinetics for the addition and subsequent elimination processes are inverted, with the displacement of the Bcat VBE being an almost thermoneutral equilibrium, whereas the displacement of the BOp VBE has $\Delta G°_{rxn} < -4.5$ kcal mol^{-1}.

25
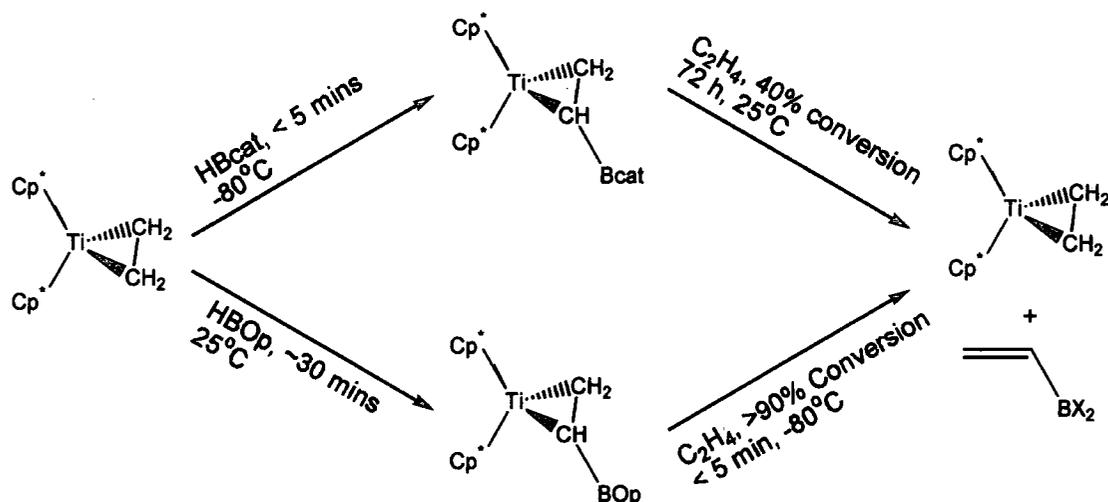
Figure 1.9: Comparison of the reaction of HBcat and HBOp with 12

The next report of dehydrogenative borylation was a communication by Masuda and co-workers[71] on which a full paper has recently been published.[72] The initial report concerns the reaction of 0.5 mol% [Rh(μ-Cl)(COD)]$_2$ 13 with a variety of vinyl arenes including styrene and VA, with HBpin in toluene at room temperature. The distribution of boronated products yields 93-95% VBE, with the remainder being hydroboration products, but, as is typified in the case of styrene, "concurrently, ethylbenzene was generated in 46% yield based on HBpin." Solvent effects were investigated including ClCH$_2$CH$_2$Cl, THF, dioxane and benzene as well as toluene but there was very little difference on yield or product distributions. Additional catalysts [Rh(cod)$_2$][BF$_4$], [Rh$_4$(CO)$_{12}$], [Ir(μ-Cl)(COD)]$_2$, [Ir$_4$(CO)$_{12}$], [Ru$_3$(CO)$_{12}$], and [Ru(Cl)$_2$(cod)]$_n$ were employed but were found to be less effective than 13.

Sneddon et al. reported[73] in 2000 the platinum and palladium catalysed dehydrogenative borylation using [PdBr$_2$] or [(H)$_2$Pt(Cl)$_6$]·6H$_2$O and arachno-6,8-C$_2$B$_7$H$_{13}$ for the dehydrogenative borylation of ethylene, styrene and pent-1-ene at room temperature. The reactions produce mainly dehydrogenative borylation products, with some hydroboration. Although no mention is made of any

hydrogenation products, an excess of alkene is used in each of the reactions suggesting that loss of alkene to hydrogenation is still a problem for this type of system.

Most recently, Westcott et al. reported[74] the use of 5 mol% [Rh(Cl)(PPh$_3$)$_3$] and HBpin in reaction with several alkyl-amino-vinyl ethers at 65°C, Equation 1.7. However, no yields are quoted and the fate of the hydrogen produced is not reported.

$$\text{\raisebox{0pt}{O(CH}_2)_n\text{NR}_2} + \text{HBpin} \xrightarrow[\text{65°C}]{\text{5 mol% [Rh(Cl)(PPh}_3)_3]} \text{pinB} \text{\raisebox{0pt}{O(CH}_2)_n\text{NR}_2} + \text{H}_2$$

n = 3, R = H
n = 3, R = Me
n = 3, R = Et
n = 2, R = Et
n = 3, R = SiMe$_3$
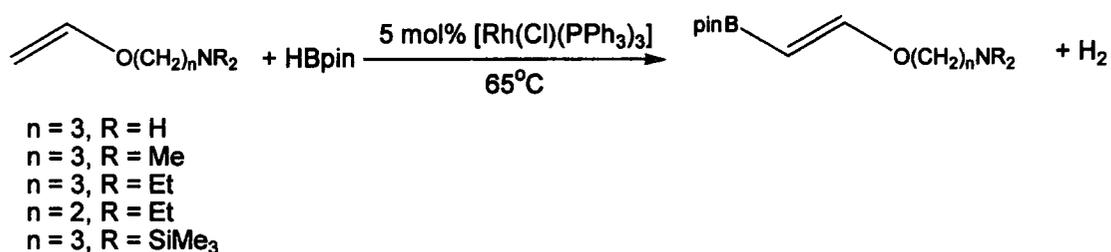
Equation 1.7: The dehydrogenative borylation of alkyl-amino vinyl ethers

1.8 Metal catalysed borylation of alkanes and arenes *via* direct C-H activation

The functionalisation of unreactive C-H bonds in alkanes and arenes has been reviewed several times.[75-80] The area has long been of interest to synthetic chemists, and biochemists; in the case of chemists this interest is mainly due to the significant mechanistic challenges that the field poses,[76,81,82] and for biochemists since several enzymes exist that convert unactivated C-H bonds, normally by hydroxylation. Supplies of hydrocarbons are plentiful but much of the quantity obtained is simply burned as fuel.[83] The field is not only of academic interest. Methane is normally produced in large quantities at remote sites.[81] However, as a gas, methane cannot be transported economically but conversion to a liquid, such as methanol, Equation 1.8, would make remote gas a viable energy source. In this case, however, over oxidation to CO_2 and H_2O is easy and hence the challenge is in achieving partial oxidation. The low reactivity of alkanes, however, means that severe conditions or highly reactive reagents must be used, although the reactions are thermodynamically favoured. Recently, several papers have been published reporting the borylation of alkanes and arenes by direct C-H activation and it is these that will be discussed here.

$$CH_4 + \frac{1}{2}O_2 \rightleftharpoons CH_3OH$$

Equation 1.8: The partial oxidation of methane to methanol

The first report was in 1995 by Hartwig *et al.*[84] who used [Mn(CO)$_5$(Bcat)] **14**, [Re(CO)$_5$(Bcat)] **15**, and [Fe(Cp)(CO)$_2$(Bcat)] **16** for the stoichiometric, photolytic borylation of 1-hexene, benzene and toluene, Figure 1.10. Reaction of **15** with toluene yielded a *meta:para* ratio of 1.6:1, with no *ortho* being produced. Reaction of **15** with hex-1-ene yielded 55% of the *trans* VBE, as well as 20-25% of the hydroboration product. Reaction of **14** and **15** with benzene yielded 45% and 50% PhBcat

28

respectively. Reaction of **16** with toluene gave a *meta:para* ratio of 1.1:1, again with no *ortho* isomer being produced. Reaction with hex-1-ene yielded 90% VBE and 10% hydroboration.
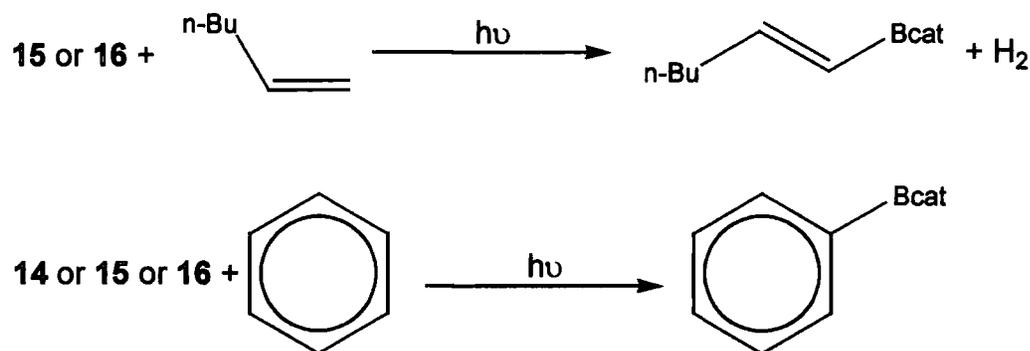
Figure 1.10: Stoichiometric photolytic C-H activation of alkenes and arenes

The following report from the same group reported[85] the first photolytic borylation of alkanes using [W(Cp*)(CO)$_3$(Bcat')] and [M(Cp*)(CO)$_2$(Bcat')] (M = Fe, Ru) (cat' = 1,2-O$_2$C$_6$H$_2$-3,5-Me$_2$). The alkanes used were pentane, ethylbenzene, 2-methyl-butane, and cyclohexane and the results are shown in Figure 1.11. Predominantly borylation at a 1° carbon takes place, although some borylation at a 2° carbon takes place for 2-methyl-butane and borylation at a 2° carbon can only take place with cyclohexane. However, the yields here were considerably lower. The mechanism proposed is shown in Scheme 1.10. Here the reaction either proceeds in a 1-step direct reaction of the catalyst and alkane or *via* the photolytic loss of CO from the metal centre, followed by thermal reaction with R-H to yield the borylated alkane. Several experiments including conducting the reaction under 2 atm of CO, and under 1 atm of ^{13}CO showed no incorporation of ^{13}CO into the catalyst. Hence, the photolytic irreversible dissociation of CO is supported here.

29
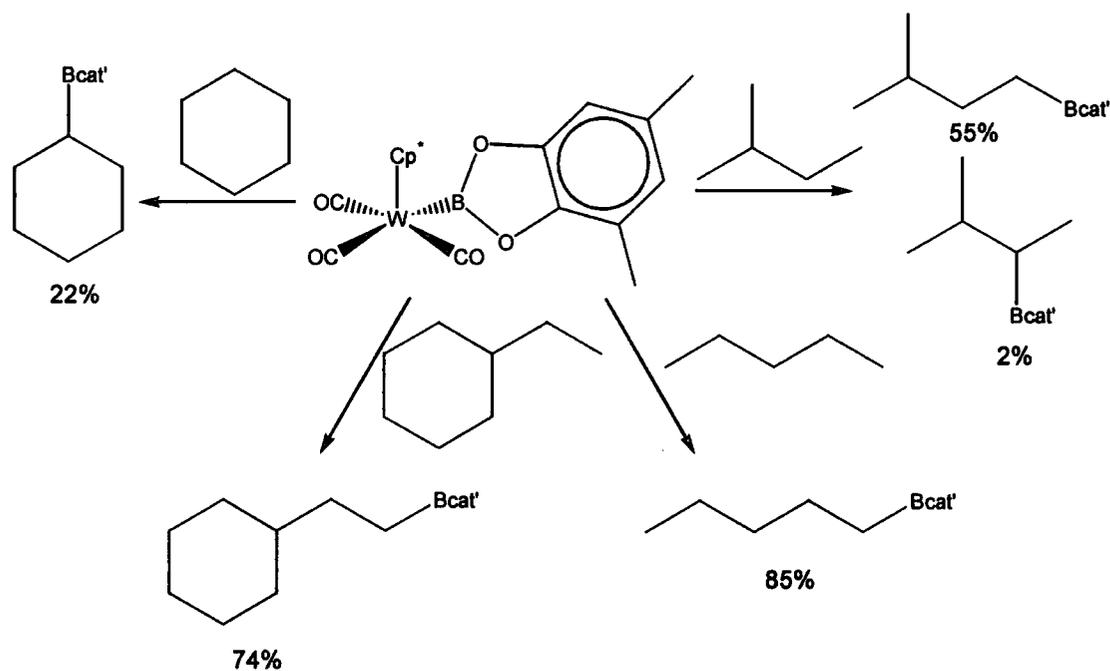
Figure 1.11: Reaction of [W(Cp)(CO)₃(Bcat')] with alkanes*
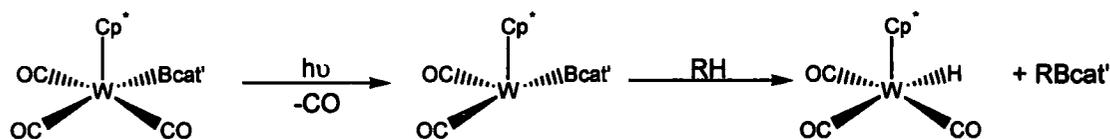
Scheme 1.10: Proposed alkane activation pathway

In 1999 the same group reported[86] further stoichiometric photolytic alkane borylation but also the catalytic photolytic reaction. The reaction of 2.4 – 5 mol% [Re(Cp*)(CO)₃] 17 under 2 atm CO at 25 °C, as shown in Equation 1.9. The percentage conversion of B₂pin₂ ranged from 88% with methylcyclohexane to 100% for di-n-butyl ether and t-butyl ethyl ether. Reaction times were between 36 and 60 hours. It was reported that, "All reactions of B₂pin₂ with alkanes were remarkable in their regiospecificity from the functionalisation of primary sites," and internal isomers, prepared independently, were apparently not observed in the GC/MS of the reaction. Isolation of the complex *trans*-[Re(Cp*)(CO)₂(Bpin)₂] and subsequent

reaction with pentane yielded similar results to those using **17**, suggesting that the reaction proceeds with initial oxidation of B_2pin_2 to the metal centre.

$$R\text{---}H + B_2pin_2 \xrightarrow[\text{h}\upsilon,\ CO,\ 25\ ^\circ C]{2.4 - 5\%\ [Re(Cp^*)(CO)_3]} R\text{---}Bpin + HBpin$$
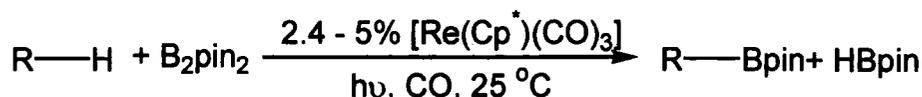
Equation 1.9: Catalytic photolytic C-H activation of alkanes

In the same year the same group reported[87] the photolysis of [Fe(Cp')(CO)(L)(Bcat)] (Cp' = C_5H_5, C_5Me_5; L = CO, PMe_3) and several arenes, Equation 1.10, to give, predominantly, *meta* and *para* isomers, the *ortho* isomer being produced only with anisole. Kinetic isotope effects were investigated for [Fe(Cp)(CO)$_2$(Bcat)] and [M(CO)$_5$(Bcat)] (M = Mn, Re) with benzne/d^6-benzene , which gave k_H/k_D = 3.3, 2.1 and 5.4 respectively, suggesting that the activation process takes place at the metal centre and is not due to a 'free' Bcat radical reacting with free substrate.

X = Me, OMe, Cl, CF₃, NMe₂
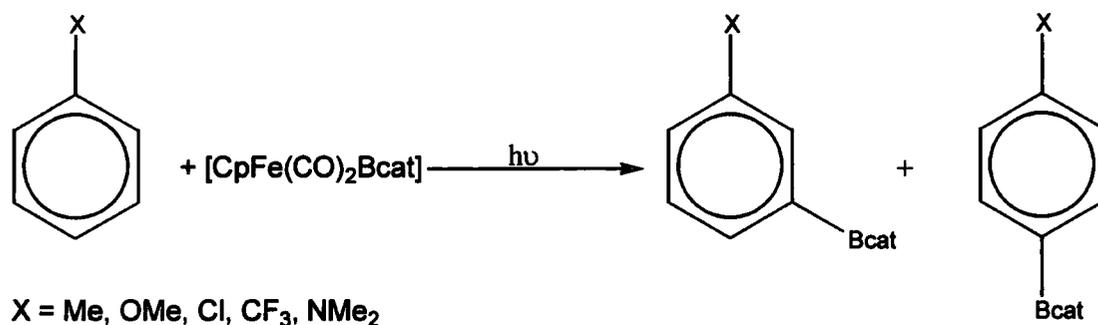
Equation 1.10: Substituted arene functionalisation with [Fe(Cp)(CO)₂(Bcat)]

Also in 1999, Iverson and Smith reported[88] the stoichiometric thermal activation of benzene and cyclohexane using HBcat, HBpin and HB(C_6F_5)$_2$, with [Ir(Cp*)(PMe$_3$)(H)(BR$_2$)], Figure 1.12. Also, the catalytic viability of the reaction was shown in the reaction of 17 mol% [Ir(Cp*)(PMe$_3$)(H)(Ph)] with benzene and HBpin at

150°C for 120 hours, Figure 1.12. This yielded 53% PhBpin, corresponding to approximately 3 turnovers.
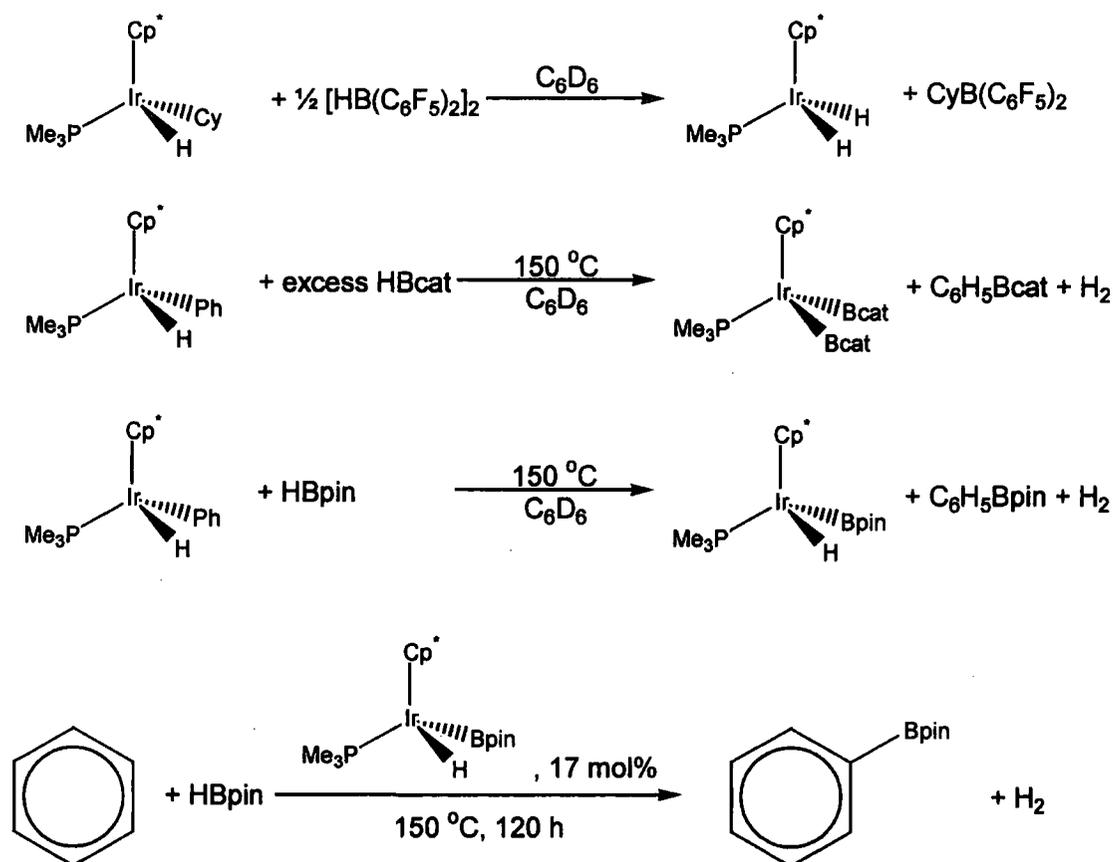
Figure 1.12: Thermal stoichiometric and catalytic C-H activation

In 2000, Harwtig and co-workers reported[89] the reaction of B_2pin_2 and HBpin with n-octane in the presence of 5 mol% $[Rh(Cp^*)(\eta^4\text{-}C_6Me_6)]$ **18** at 150 °C for 25 hours, yielding 88% n-octyl-Bpin, Equation 1.11. The catalyst $[Rh(Cp^*)(\eta^2\text{-}C_2H_4)_2]$ showed higher activity but was less stable over long periods of time. Also, HBpin was found to be less active that B_2pin_2. The stability of **18** over long periods of time is attributed to the C_6Me_6 ligand, which is labile but does not react under the reaction conditions and hence can bind to the "$[(Cp^*)Rh]$" active species before further reaction with B_2pin_2 takes place. Benzene proved very reactive with an 82% yield of PhBpin resulting from 0.5 mol% **18**, corresponding to 328 turnovers.

$$n\text{-}C_8H_{18} + B_2pin_2 \xrightarrow[\text{B}_2\text{pin}_2]{[Rh(Cp^*)(C_6Me_6)]} \text{\scriptsize (n-octyl chain)} Bpin$$

Equation 1.11: Thermal catalytic activation of n-octane

In the same year, Smith *et al.* published[90] a related study, using 2 mol% **18** as well as 20 mol% $[Ir(Cp^*)(PMe_3)(H)(Bpin)]$ **19** or $[Ir(Cp^*)(PMe_3)(H)_2]$ **20** and HBpin at 150 °C. Several aromatic substrates were investigated and isomeric ratios are reported, resulting from steric- and chelate-directing effects of the arene, Table 1.2; no benzylic or alkyl substitution was observed. The results indicate that both **19** and **20** are considerably less reactive than **18**, even at ten times the concentration.

Further photolytic stoichiometric work was published[91] by Waltz and Hartwig using 17 different catalysts of the form $[M(Cp')(L)_n(BR)_2]$, in order to investigate the effect of varying both boryl group and ligand. Reaction with pentane gave a maximum yield of 85%, but the range over all 17 catalysts was 85–0%, indicating many of the catalysts were unreactive in this case.

Also in 2000, a theoretical study on borane C-H activation was reported[92] by Goldfuss and Knochel. This studied the reaction of BH_3 with benzene and substituted aromatics. For benzene, a van der Waals complex is formed with BH_3 before reaction takes place. Investigation into substituents found that the borane attacks the *para* position of mono-substituted aromatics. The lowest activation energies and most exothermic energies of reaction were found for electron donating substituents, such as NMe_2 or MeO. The converse is true for electron withdrawing species, with higher activation energies and less exothermic reactions. This is rationalised by the B-C_{ipso} bond length and C_{ipso} partial charges in the intermediate shown in Figure 1.13. For electron donating versus electron withdrawing substituents, for example NMe_2 vs.

Table 1.2: Products resulting from reaction of 18 and 19 with arenes

Arene	Products	18, % yield, *o:m:p*	19, % yield, *o:m:p*
(benzene)	(Ph–Bpin)	92%	53%
(toluene)	(Me–C₆H₄–Bpin)	72% (1.00:1.93:0.12)	91% (1.00:1.93:0.15)
F₃C–(arene)	F₃C–(arene)–Bpin	84% (1.00:2.00:0)	99% (1.00:2.00:0)
MeO–(arene)	MeO–(arene)–Bpin	65% (1.00:2.63:0.30)	55% (1.00:4.06:0.08)
Me₂N–(arene)	Me₂N–(arene)–Bpin	65% (1.00:1.74:0.04)	n/a
Me₂HC–(arene)	Me₂HC–(arene)–Bpin	67% (1.00:1.99:0.02)	52% (1.00:2.19:0.03)
H–(arene)–F₅	F₅–(arene)–Bpin	41%	81%
F,F,F trisubstituted arene	F,F,F–(arene)–Bpin	46%	n/a
(arene)–C(O)OEt	Bpin–(arene)–C(O)OEt	(1.00, 1.74, 0.29) No yield reported	n/a
(arene)–C(O)NEt₂	Bpin–(arene)–C(O)NEt₂	50% (1.00:1.98:4.17)	n/a
F₃C,F₃C disubstituted arene	F₃C,F₃C–(arene)–Bpin	86%	81%
(dimethyl arene)	(dimethyl arene)–Bpin	73%	60%
(dimethyl pyridine)	(dimethyl pyridine)–Bpin	41%	n/a
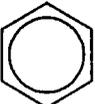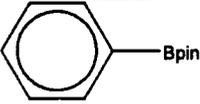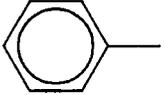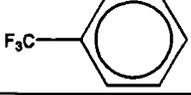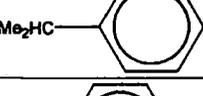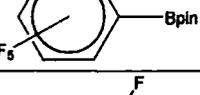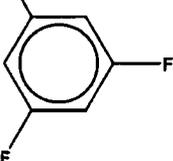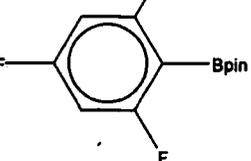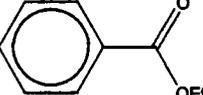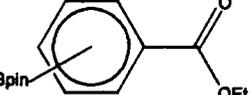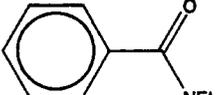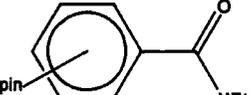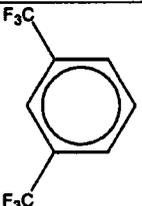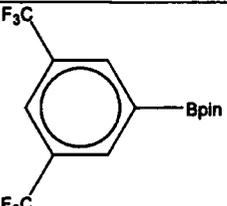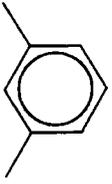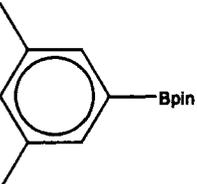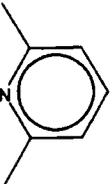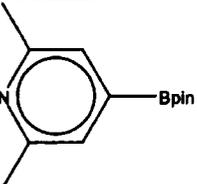
NO$_2$, gives partial charges of –0.34 vs. –0.26, resulting in more stable bonds to the electrophilic boron centre, resulting in shorter B-C$_{ipso}$ bond lengths (1.710Å vs. 1.747Å for NMe$_2$ vs. NO$_2$).
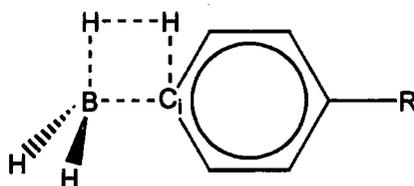
Figure 1.13: Proposed intermediate in the reaction of BH$_3$ with arenes

In 2001, Marder *at al.*[93] used [Rh(Cl)(N$_2$)(P^{i}Pr$_3$)$_2$] **21** as catalysts for arene and benzylic C-H activation of benzene and toluene at 140°C using HBpin. Reaction of benzene, 0.2 M HBpin and 1 mol% **21**, yielded 62% PhBpin after 14 hours (62 turnovers) and 86% after 58 hours; using 0.3 mol% **21**, a 67% yield of PhBpin was produced after 104 hours, corresponding to 222 turnovers. Lower concentrations of HBpin also improved the yield. For example, use of 1.0 M HBpin in benzene gave a 20% yield of PhBpin after 58 hours, whereas a fourfold dilution improved the yield to 35% after the same time. This is attributed to the degradation of HBpin, which was shown in the same paper to be concentration dependent. Toluene yielded very different results. In addition to the three arene activation isomers, the major boron-containing product results from benzylic activation, Figure 1.14. Also, one bis(borylated) product was produced, which was identified as PhCH(Bpin)$_2$. The reaction with both *p*-xylene and mesitylene also yielded predominantly benzylic activation products. This is in contrast to Hartwig's system where only a trace of benzylic activation was observed, with 3-MeC$_6$H$_4$Bpin, the *meta* isomer, produced in the highest yield. Also no alkane activation took place and reaction using B$_2$pin$_2$ was ineffective. Investigations into the reaction mechanism suggested the reaction

proceeds by a homogeneous, rather than a heterogeneous, pathway. Interestingly, [Rh(Cp*)(Cl)$_2$]$_2$ was as an alternative to Hartwig's[89] "[Rh(Cp*)]" system achieving similar results.
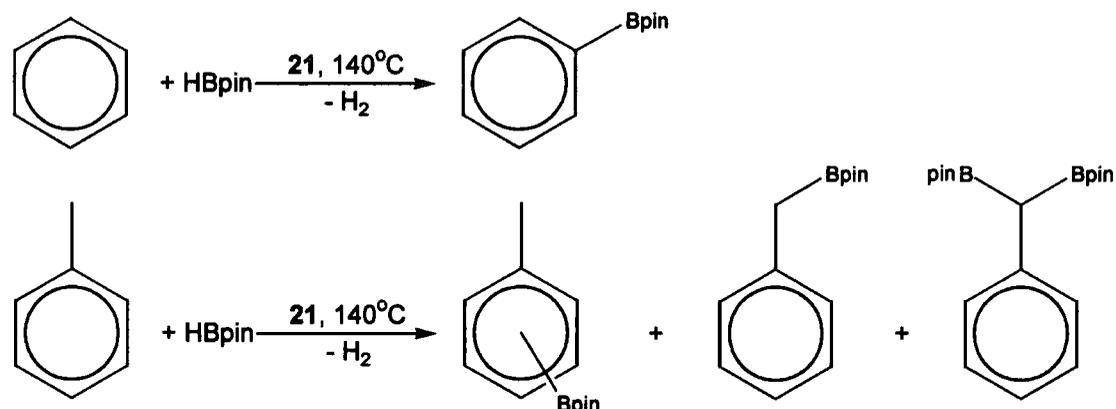
Figure 1.14: Arene and benzylic activation of benzene and toluene

Subsequently, Miyaura *et al.* reported[94] the use of 10% Pd/C as catalyst precursor for the reaction of HBpin or B$_2$pin$_2$ with substituted arenes at 100 °C, to yield benzylic and terminal ethyl activation products only. For ethylbenzene, activation was detected at both the benzylic and terminal positions of the ethyl side chain; for isopropyl benzene, only terminal borylation was seen on the isopropyl side chain, as was the case for 4-isopropyl toluene, with additional benzylic activation at the methyl benzylic position. Yields for significant substrates are shown in Table 1.3.

Later in the same year, Kawamura and Hartwig reported[95] the use of high-valent Ir(V) hydrido boryl species, of the form [Ir(Cp*)(H)$_2$(Bpin)(X)] (X = H, Bpin), the rhodium analogues of which were proposed as intermediates in a previous publication.[89] The stoichiometric reaction with both *n*-octane and benzene both at 200 °C for 2 days yielded 50% and 79% respectively of the borylated products, Figure1.15. With a 1:1 mixture of *n*-C$_8$H$_{18}$:*n*-C$_8$D$_{18}$ gave a kinetic isotope effect of

Table 1.3: Benzylic activation of arenes using 10% Pd/C

Arene	Product	Yield using B_2pin_2	Yield using HBpin
		74	52
		77	-
		79	-
		72	51
		64	45
		39	15
		15	6
		38	13
		39	42
		9	5

37

k_H/k_D = 2.0. No catalytic reactions of Ir(V) catalysts precursors were reported.

$$n\text{-octyl-Bpin} \xleftarrow[\text{200 °C}]{n\text{-C}_8\text{H}_{18}} \overset{\text{Cp}^*}{\underset{\text{H}}{\overset{|}{\underset{}{\text{H}\text{///}\cdots\text{Ir}\cdots\text{\\\\H}}}}}\text{Bpin} \xrightarrow[\text{200 °C}]{\text{C}_6\text{H}_6} \text{C}_6\text{H}_5\text{Bpin}$$
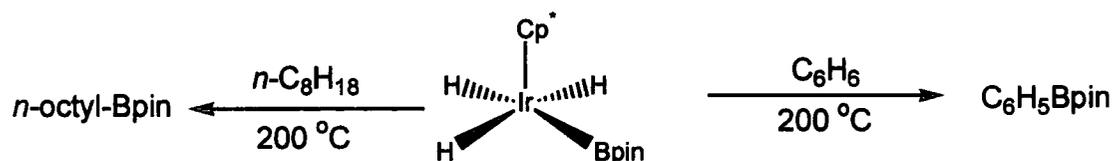
Figure 1.15: Ir(V) stoichiometric C-H activation

In the same year, Smith *et al.* reported[96] that cyclohexane could be used as an inert solvent in the reaction of arenes and HBpin in the presence of 2 mol% **14**. In addition, selective borylation at the 5-position of 1,3-disubstituted arenes was shown over a wider range of substrates than previously reported, Table 1.4[90]

Table 1.4: Further studies of 18 with additional substrates
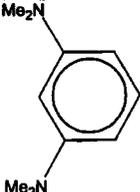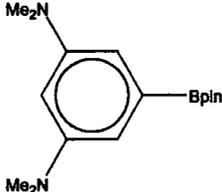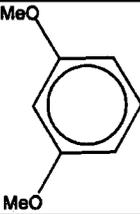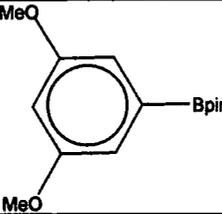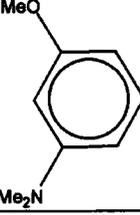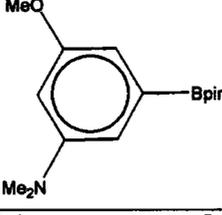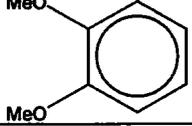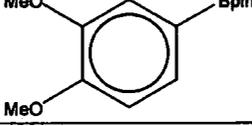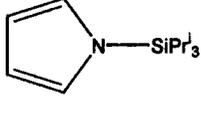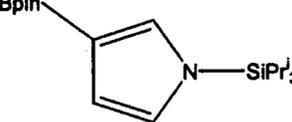
Arene	Product	Yield
Me₂N, Me₂N substituted benzene	Me₂N, Me₂N substituted benzene with Bpin	69%
MeO, MeO substituted benzene	MeO, MeO substituted benzene with Bpin	62%
MeO, Me₂N substituted benzene	MeO, Me₂N substituted benzene with Bpin	75%
MeO, MeO substituted benzene	MeO, MeO substituted benzene with Bpin	82%
pyrrole N—SiPr$^i_3$	Bpin pyrrole N—SiPr$^i_3$	81%

Most recently, both Hartwig and Miyaura *et al*.[97] and Smith *et al*.[98] reported the use

of iridium-based catalysts for arene C-H activation. Hartwig and Miyaura[97] reported

the use of commercially available [Ir(μ-Cl)(COD)]$_2$ **22** with 1 equiv. 2,2'-bipyridine

(bpy) for arene activation with B$_2$pin$_2$ at 80 °C. For benzene, a 95% yield of PhBpin

results after 16 hours, Figure 1.16, Table 1.5. Significantly use of

4,4'-di-*tert*-butyl-2,2'-bipyridine (dtbpy) (Figure 1.16) and 5 mol% **22** catalyses the

reaction with benzene at room temperature, yielding 83% PhBpin after 4.5 hours.
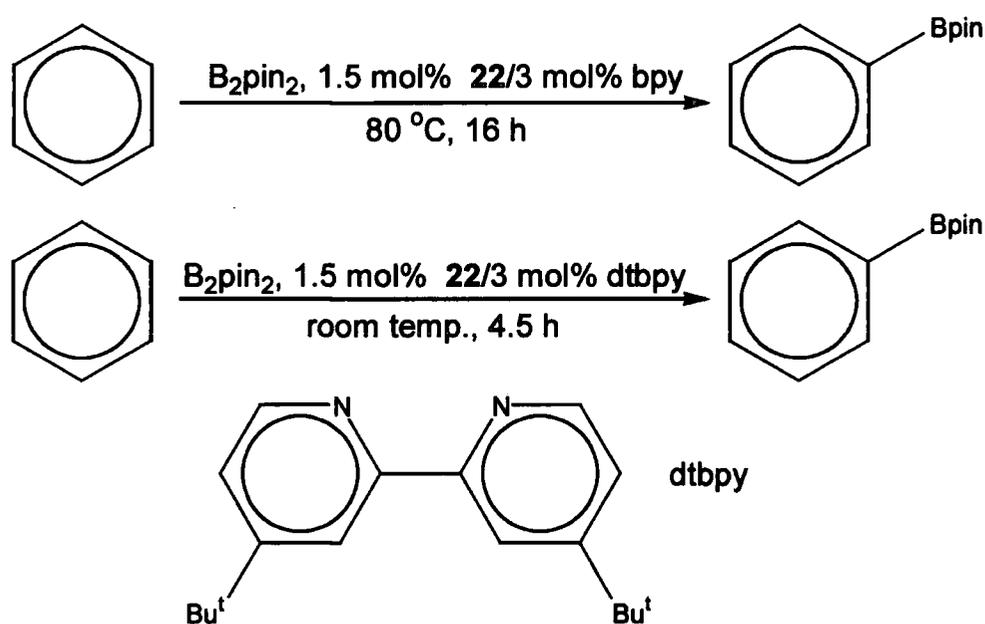
Figure 1.16: Mild iridium-catalysed arene C-H activation

Smith and co-workers[98] used 2 mol% of the iridium catalysts [Ir(MesH)(Bpin)$_3$] **23**

and [Ir(Ind)(COD)] **24** in the presence of the phosphines PMe$_3$, dppe or dmpe, for

arene activiation with B$_2$pin$_2$ at 100-150 °C, Table 1.6. For benzene, the highest yields

were obtained using **23** and PMe$_3$ at 150 °C for 15 hours (98%) and **24** with dppe for

2 hours (95%). Use of **24** with dmpe for 2 hours at 150 °C yielded 84% PhBpin; using

0.02 mol% **24** and dmpe at 150 °C for 61 hours yielded 90% PhBpin, corresponding

to 4500 turnovers. Use of **22** with dmpe at 150 °C yielded 74% PhBpin after 8 hours.

Table 1.5: Reaction of 22 with arenes

Arene	Product	Yield (*o:m:p*)
	Bpin	95%
MeO—	MeO— Bpin	95 (1:74:25)
—	— Bpin	82% (0:69:31)
F₃C—	F₃C— Bpin	80% (0:70:30)
	Bpin	83%
MeO MeO—	MeO MeO— Bpin	86%
Cl Cl—	Cl Cl— Bpin	83%
——	Bpin	58%
	Bpin	86%
—OMe	MeO Bpin	72%
Br —OMe	MeO Bpin Br	73%

41
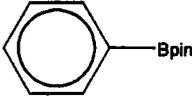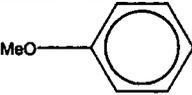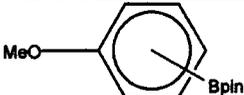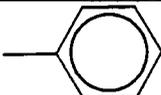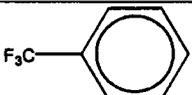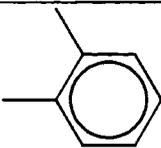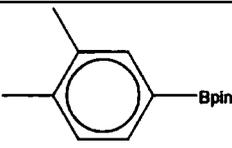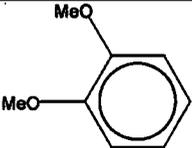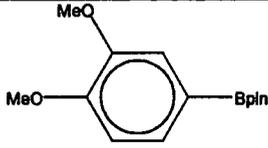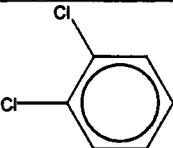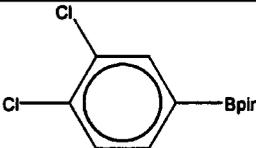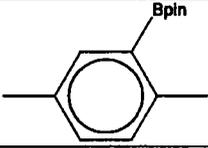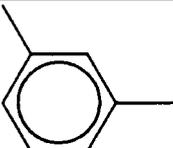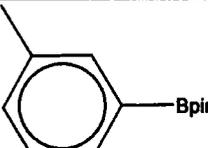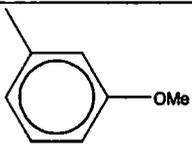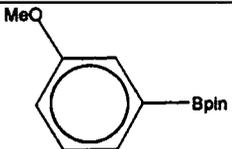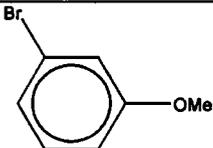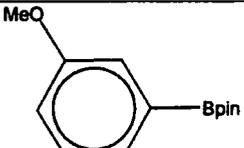
*Table 1.6: Reaction of arenes with **22**, **23**, and **24***

Substrate (S)	Product	S:HBpin	Catalyst	Ligand	Yield(%)
C₆H₆	PhBpin	16:1	**23**	PMe₃	98
C₆H₆	PhBpin	16:1	**24**	PMe₃	88
C₆H₆	PhBpin	16:1	**24**	dppe	95
C₆H₆	PhBpin	16:1	**24**	dmpe	84
C₆H₆	PhBpin	16:1	**24**	dmpe	90
C₆H₆	PhBpin	16:1	**22**	dmpe	74
		4:1	**24**	dmpe	63
		1:5	**24**	dmpe	76
		4:1	**24**	dppe	81[a]
		1:1.5	**24**	dppe	89[a]
		1:1.5	**24**	dppe	92[a]
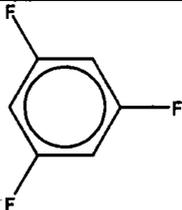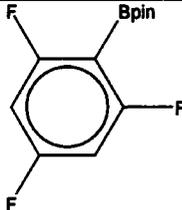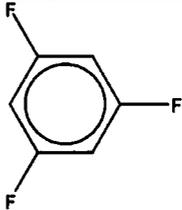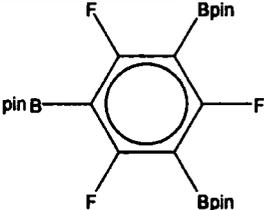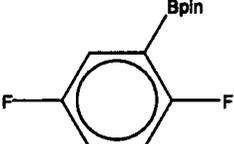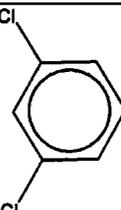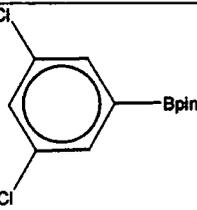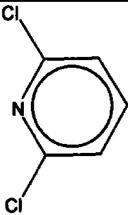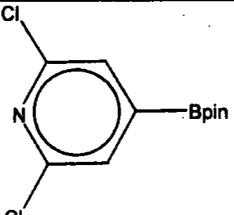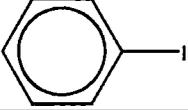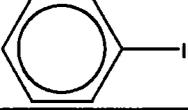
(2,6-dichloropyridine)	(2,6-dichloro-4-Bpin-pyridine)	1:2	**24**	dppe	69[a]
(iodobenzene)	n/a	10:1	**24**	dppe	-[a]
(iodobenzene)	(I-phenyl-Bpin)	10:1	**23**	dppe	77[a]
(Cl, MeO2C benzene)	(Cl, MeO2C, Bpin benzene)	1:2	**24**	dppe	95[a]
(MeO, MeO benzene)	(MeO, MeO, Bpin benzene)	1:3	**24**	dmpe	62

Reactions conducted at 150 °C expect [a] = 100 °C

43

1.9 Uses of boronate esters

Much of the use boron-containing substrates,[99,100] including boronate esters, arises from the reactivity resulting from the empty p-orbital on boron, and, subsequently, the large number of different functionalities into which they can be easily converted. This renders the boron highly susceptible to nucleophilic attack and usually involves the formation of a tetrahedral borate intermediate. If the nucleophile bears a leaving group then a migration of one ligand on boron takes place, resulting in neutral boron and loss of the leaving group. This is exemplified in the oxidation of BR_3 with H_2O_2 and NaOH, Figure 1.17. Oxidation of VBEs with H_2O_2 and NaOH yields the enol which tautomerises to the ketone, Figure 1.17.
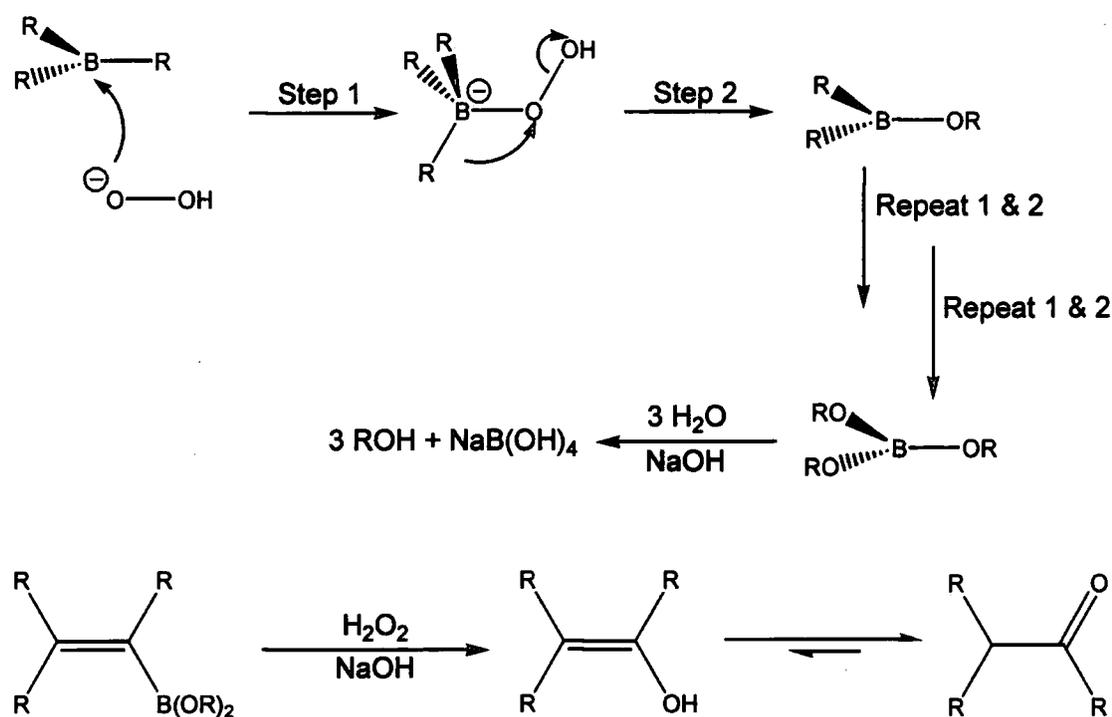
Figure 1.17: Oxidation of BR₃ (top) and VBEs with H₂O₂ and NaOH

Other reactions such as protonolysis, halogenolysis, amination, carbonylation to both aldehydes and ketones, cyanidation, reaction with $HCCl_2OMe$, and reaction with α-halocarbonyl compounds are shown in Figure 1.18.
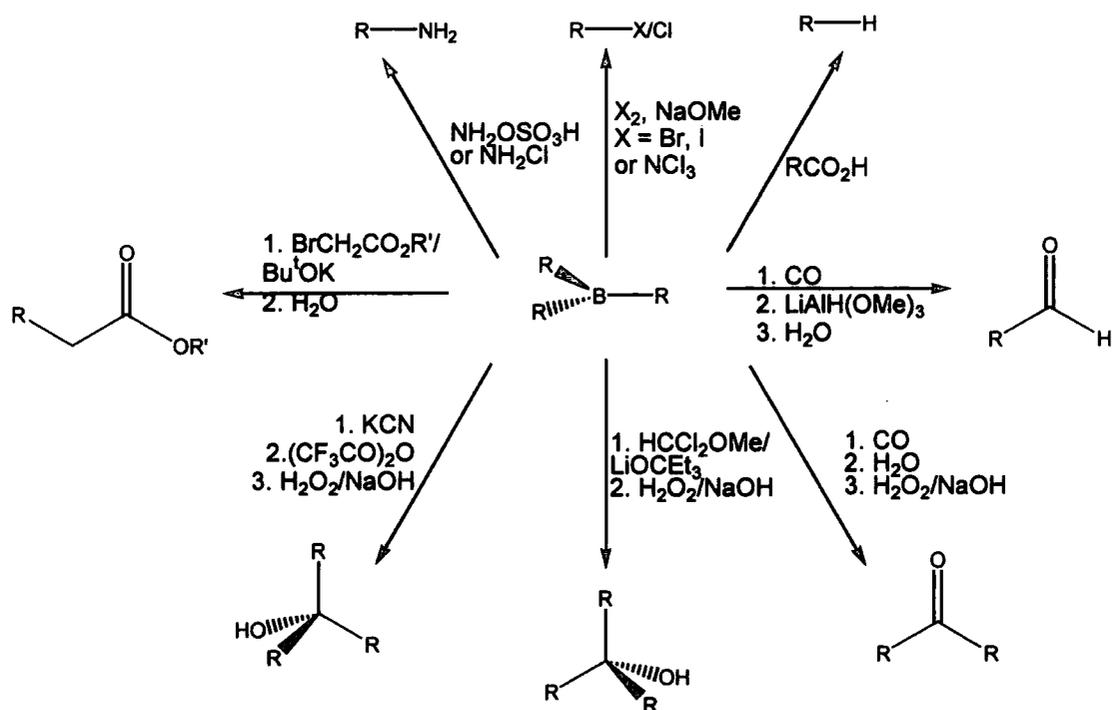
Figure 1.18: Conversion of boranes to other functionalised compounds

Allylboranes have found use in asymmetric synthesis in the reaction with carbonyl compounds, yielding homoallylic alcohols with either one or two chiral centres. For example, the reaction of (+)-α-pinene with $H_3B \cdot SMe_2$, followed by reaction with methanol and then allylmagnesium bromide yields an allylborane; reaction of this allylboronate with benzaldehyde followed by oxidation with H_2O_2 and NaOH gives the alcohol in 96% e.e., Scheme 1.11. The reaction of an aldehyde with an allylboronate which is unsymetrically substituted at the carbon-carbon double bond yields a homoallylic alcohol with two adjacent chiral centres. The (*E*)-allylboranes yield the *threo* diastereomer whilst (*Z*)-allylboranes yield the *erythro* diastereomer, Figure 1.19.
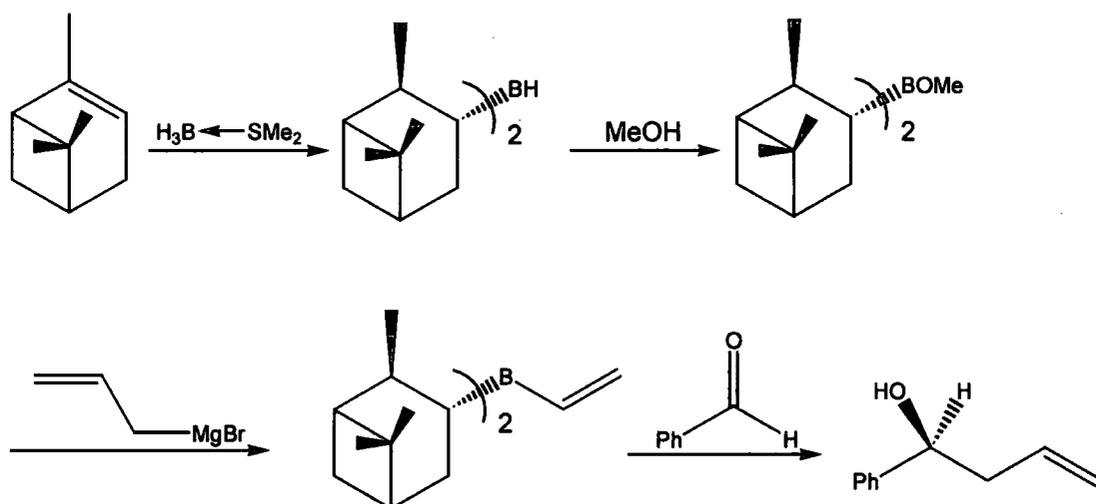
Scheme 1.11: The synthesis of a homoallylic alcohol containing one chiral centre
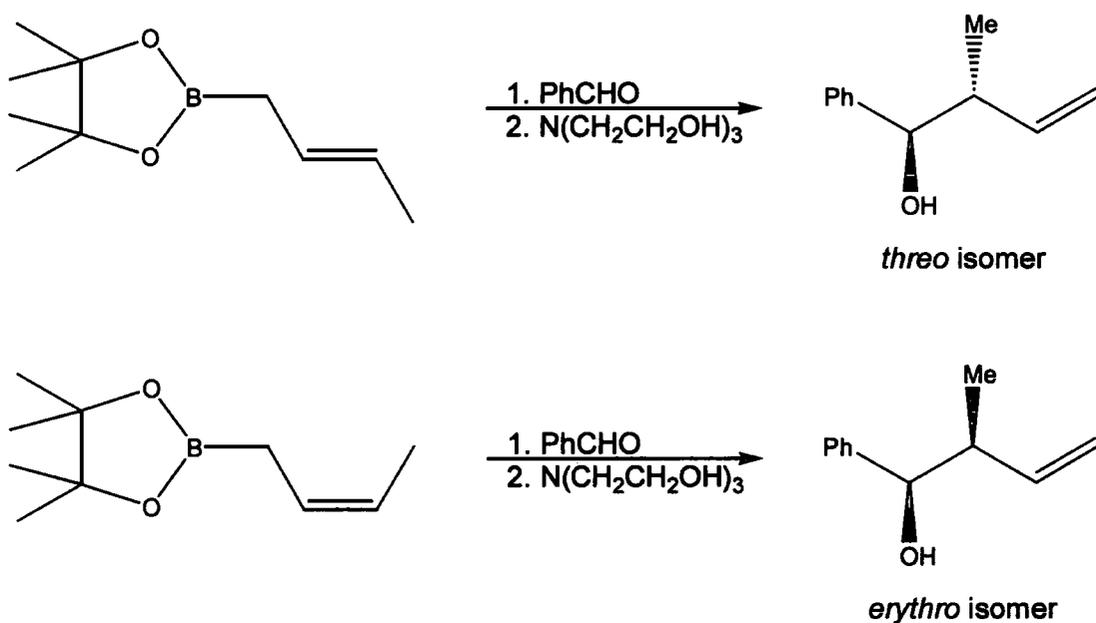
Figure 1.19: The synthesis of a homoallylic alcohol containing two chiral centres

The reaction of boronate esters with dichloromethyllithium, $LiCHCl_2$, results in insertion of the CHCl unit into the C-B bond of the boronate ester, and this reaction is known as the homologation of boronate esters. This reaction is of particular use is chiral alcohols are used as new chiral centres can be formed, as shown in Scheme

1.12. An example of this homologation reaction is in the synthesis of (3S, 4S)-4-methylheptan-3-ol which is a pheromone of the elm bark beetle, Scheme 1.13.
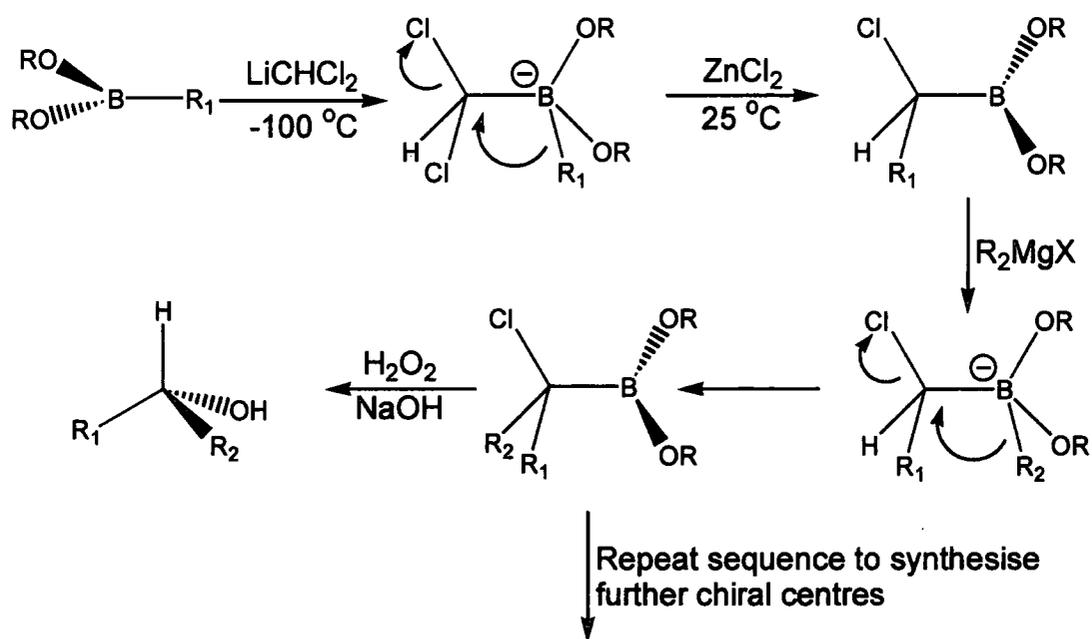
Scheme 1.12: The dichloromethyllithium reaction
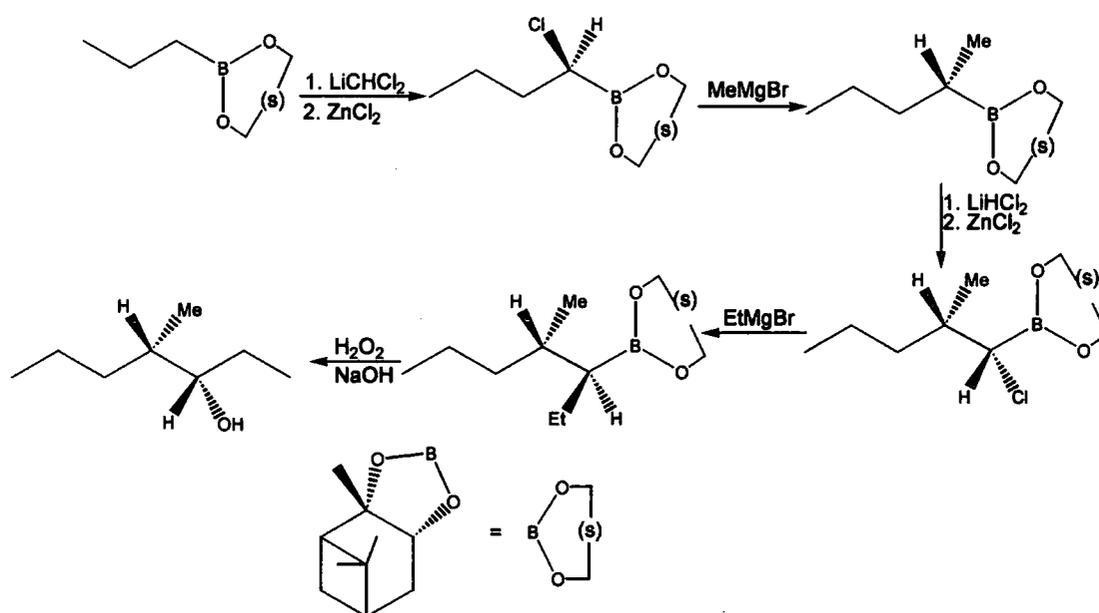
Scheme 1.13: The synthesis of (3S, 4S)-4-methylheptan-3-ol

A major use of vinylboronate esters is in C-C bond formation in Suzuki-Miyaura cross-coupling reactions.[101,102] For example, a pinacolato VBE is reacted with an aryl halide in the presence of a Pd^0 catalyst, yielding a vinyl arene, Scheme 1.14. Significantly, this reaction takes place in aqueous solution and, as the proposed catalytic cycle shows, water is, in fact, required in order to generate the activated boron centre in the hydroxy boronate ester. In part, it is this reaction that encouraged the search for facile syntheses of vinyl- and arylboronate esters as the products are critical in the synthesis of fine chemicals and also to the pharmaceutical industry.
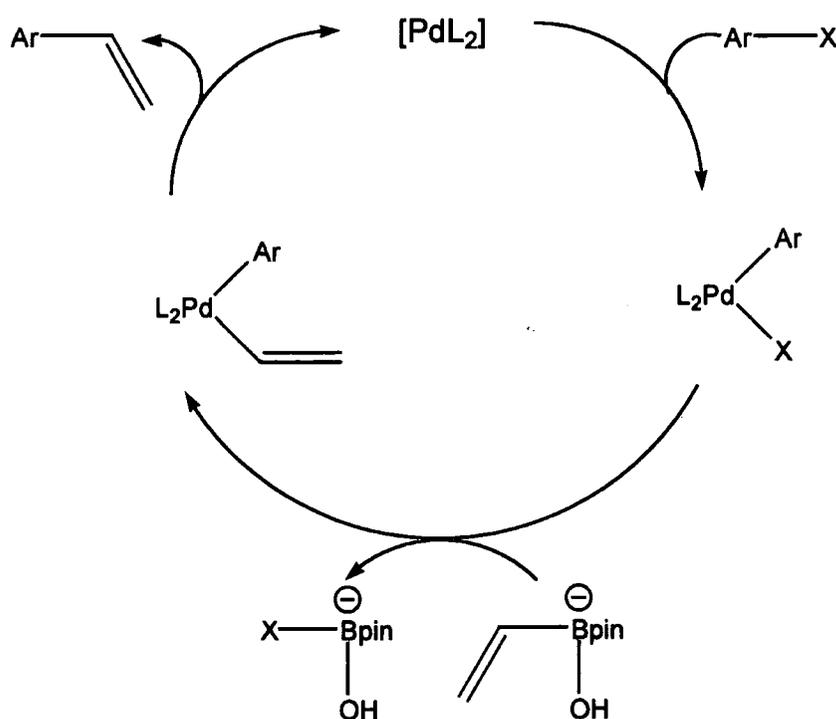
Scheme 1.14: Suzuki-Miyaura cross-coupling reaction

Vinylboronates are also useful in Heck reactions as the formation of the C-C bond can take place without affecting the boronate ester group, and a general example is shown in Equation 1.12.[103] As is clear, the Heck reaction of a VBE followed by a

Suzuki-Miyaura type cross-coupling enables the functionalisation of both ends of the

C=C bond, Equation 1.13.[104,105]
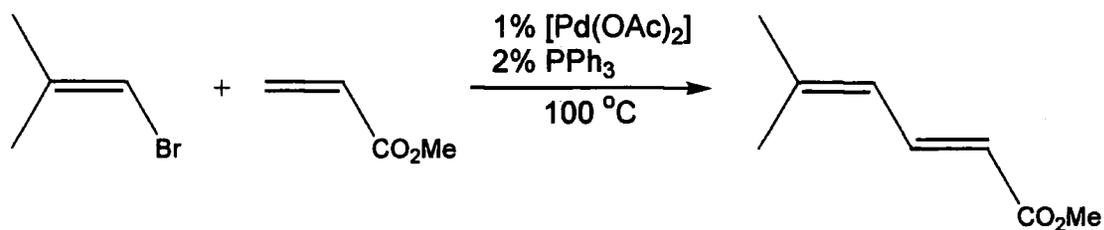
Equation 1.12: Typical Heck Reaction
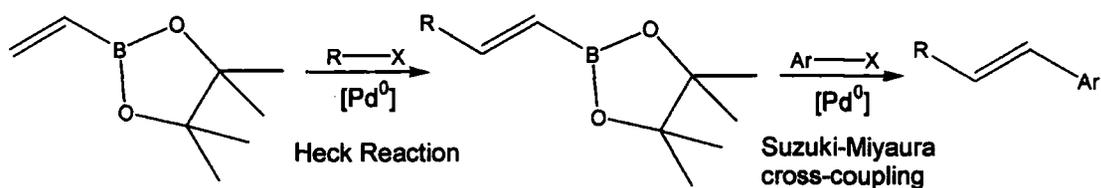
Equation 1.13: Successive Heck and Suzuki-Miyaura cross-coupling reactions

1.10 References

1   G. Urry, J. Kerrigan, T. D. Parsons, and H. I. Schlesinger, *J. Am. Chem. Soc.*, 1954, **76**, 5299.

2   M. Zeldin and T. Wartik, *J. Am. Chem. Soc.*, 1966, **88**, 1336.

3   A. Rosen and M. Zeldin, *J. Organomet. Chem.*, 1971, **31**, 319.

4   C. Chambers, A. K. Holliday, and S. M. Walker, *Proc. Chem. Soc.*, 1964, 286.

5   W. B. Fox and T. Wartik, *J. Am. Chem. Soc.*, 1961, **83**, 498.

6   T. D. Coyle and J. J. Ritter, *J. Organomet. Chem.*, 1968, **12**, 268.

7   J. C. Kotz and E. W. Post, *Inorg. Chem.*, 1970, **9**, 1661.

8   R. Chadha and N. K. Ray, *J. Phys. Chem.*, 1982, **86**, 3293.

9   R. Chadha and N. K. Ray, *Theor. Chim. Acta.*, 1982, **60**, 573.

10   T. Wartik, R. Moore, and H. I. Schlesinger, *J. Am. Chem. Soc.*, 1949, **71**, 3265.

11   P. L. Timms, *Chem. Commun.*, 1968, 1525.

12   J. A. Morrison, *Chem. Rev.*, 1991, **91**, 35.

13   R. J. Brotherton, A. L. McCloskey, L. L. Patterson, and H. Steinberg, *J. Am. Chem. Soc.*, 1960, **82**, 6242.

14   R. J. Brotherton, A. L. McCloskey, J. L. Boone, and H. M. Manasevit, *J. Am. Chem. Soc.*, 1960, **82**, 6245.

15   T. Ishiyama, M. Murata, T.-A. Ahiko, and N. Miyaura, *Org. Synth.*, 1999, **77**, 176.

16   C. N. Welch and S. G. Shore, *Inorg. Chem.*, 1968, **7**, 225.

17   F. J. Lawlor, N. C. Norman, N. L. Pickett, E. G. Robins, P. Nguyen, G. Lesley, T. B. Marder, J. A. Ashmore, and J. C. Green, *Inorg. Chem.*, 1998, **37**, 5282.

18   W. Clegg, M. R. J. Elsegood, F. J. Lawlor, N. C. Norman, N. L. Pickett, E. G. Robins, A. J. Scott, P. Nguyen, N. J. Taylor, and T. B. Marder, *Inorg. Chem.*, 1998, **37**, 5289.

19   M. J. Lesley, N. C. Norman, and C. R. Rice, *Inorg. Synth.*, submitted.

20   D. Manning and H. Nöth, *J. Chem. Soc., Dalton Trans.*, 1985, 1689.

21   P. Nguyen, G. Lesley, N. J. Taylor, T. B. Marder, N. L. Pickett, W. Clegg, M. R. J. Elsegood, and N. C. Norman, *Inorg. Chem.*, 1994, **33**, 4623.

22   R. J. Brotherton, 'Progress in Boron Chemistry', ed. H. Steinberg and A. L. McCloskey, Macmillan, 1964.

23   G. Lesley, T. B. Marder, N. C. Norman, and C. R. Rice, *Main Group Chem. News*, 1997, **5**, 4.

24   W. Clegg, C. Dai, F. J. Lawlor, G. Lesley, T. B. Marder, P. Nguyen, N. C. Norman, N. L. Pickett, C. R. Rice, E. G. Robins, A. J. Scott, and N. J. Taylor, 'Advances in Boron Chemistry', ed. W. Siebert, R. Chem. Soc., 1997.

25   T. B. Marder and N. C. Norman, *Top. Catal.*, 1998, **5**, 63.

26   T. Ishiyama and N. Miyaura, *J. Organomet. Chem.*, 2000, **611**, 392.

27   T. Ishiyama, N. Matsuda, N. Miyaura, and A. Suzuki, *J. Am. Chem. Soc.*, 1993, **115**, 11018.

28   T. Ishiyama, N. Matsuda, M. Murata, F. Ozawa, A. Suzuki, and N. Miyaura, *Organometallics*, 1996, **15**, 713.

29   C. N. Iverson and M. R. Smith, III, *J. Am. Chem. Soc.*, 1995, **117**, 4403.

30   C. N. Iverson and M. R. Smith, III, *Organometallics*, 1996, **15**, 5155.

31   G. Lesley, P. Nguyen, N. J. Taylor, T. B. Marder, A. J. Scott, W. Clegg, and N. C. Norman, *Organometallics*, 1996, **15**, 5137.

32   W. Clegg, A. J. Scott, G. Lesley, T. B. Marder, and N. C. Norman, *Acta. Cryst.*, 1996, **C52**, 1989 and 1991.

33   R. Ll. Thomas, F. E. S. Souza, and T. B. Marder, *J. Chem. Soc., Dalton Trans.*, 2001, 1650.

34   P. Kraft and W. Tochtermann, *Liebigs Ann. Chem.*, 1994, 827.

35   S. D. Brown and R. W. Armstrong, *J. Am. Chem. Soc.*, 1996, **118**, 6331.

36   S. D. Brown and R. W. Armstrong, *J. Org. Chem.*, 1997, **62**, 7076.

37   A. Maderna, H. Pritzkow, and W. Siebert, *Angew. Chem. Int. Ed. Engl.*, 1995, **35**, 1501.

38   R. T. Baker, P. Nguyen, T. B. Marder, and S. A. Westcott, *Angew. Chem. Int. Ed. Engl.*, 1995, **34**, 1336.

39   C. N. Iverson and M. R. Smith, III, *Organometallics*, 1997, **16**, 2757.

40   T. Ishiyama, M. Yamamoto, and N. Miyaura, *Chem. Commun.*, 1997, 689.

41   C. Dai, E. G. Robins, A. J. Scott, W. Clegg, D. S. Yufit, J. A. K. Howard, and T. B. Marder, *Chem. Commun.*, 1998, 1983.

42   T. B. Marder, N. C. Norman, and C. R. Rice, *Tetrahedron Lett.*, 1998, **39**, 155.

43   G. Mann, K. D. John, and R. T. Baker, *Org. Lettl*, 2000, **2**, 2105.

44   T. Ishiyama, M. Yamamoto, and N. Miyaura, *Chem. Commun.*, 1996, 2073.

45   W. Clegg, T. R. F. Johann, T. B. Marder, N. C. Norman, A. G. Orpen, T. M. Peakman, M. J. Quayle, C. R. Rice, and A. J. Scott, *J. Chem. Soc., Dalton Trans.*, 1998, 1431.

46   Y. G. Lawson, M. J. G. Lesley, T. B. Marder, N. C. Norman, and C. R. Rice, *Chem. Commun.*, 1997, 2051.

47   D. A. Evans and G. C. Fu, *J. Org. Chem.*, 1990, **55**, 5678.

48   K. Takahashi, T. Ishiyama, and N. Miyaura, *Chem. Lett.*, 2000, 982.

49   K. Takahashi, T. Ishiyama, and N. Miyaura, *J. Organomet. Chem.*, 2001, **625**, 47.

50   H. Ito, H. Yamanaka, J.-i. Tateiwa, and A. Hosomi, *Tetrahedron Lett.*, 2000, **41**, 6821.

51   H. A. Ali, I. Goldberg, and M. Srebnik, *Organometallics*, 2001, **20**, 3962.

52   G. W. Kabalka, B. C. Das, and S. Das, *Tetrahedron Lett.*, 2002, **43**, 2323.

53   K. Takahashi, J. Takagi, T. Ishiyama, and N. Miyaura, *Chem. Lett.*, 2000, 126.

54   T. Hata, H. Kitagawa, H. Masai, T. Kurahashi, M. Shimizu, and T. Hiyama, *Angew. Chem. Int. Ed. Engl.*, 2001, **40**, 790.

55   T. Ishiyama, S. Momato, and N. Miyaura, *Synlett*, 1999, **11**, 1790.

56   H. C. Brown and S. K. Gupta, *J. Am. Chem. Soc.*, 1975, **97**, 5249.

57   C. F. Lane and G. W. Kabalka, *Tetrahedron*, 1976, **32**, 981.

58   K. Burgess and M. J. Ohlmeyer, *Chem. Rev.*, 1991, 1179.

59   K. Burgess, W. A. van der Donk, S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *J. Am. Chem. Soc.*, 1992, **114**, 9350.

60   S. Pereira and M. Srebnik, *Organometallics*, 1995, **14**, 3127.

61   X. He and J. F. Hartwig, *J. Am. Chem. Soc.*, 1996, **118**, 1696.

62   I. Beletskaya and A. Pelter, *Tetrahedron*, 1997, **53**, 4957.

63   T. Ohmura, Y. Yamamoto, and N. Miyaura, *J. Am. Chem. Soc.*, 2000, **122**, 4990.

64   T. Davan, E. W. Corcoran, Jr., and L. G. Sneddon, *Organometallics*, 1983, **2**, 1693.

65   J. M. Brown and G. C. Lloyd-Jones, *Chem. Commun.*, 1992, 710.

66   J. M. Brown and G. C. Lloyd-Jones, *J. Am. Chem. Soc.*, 1994, **166**, 866.

67   S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

68   D. H. Motry and M. R. Smith, III, *J. Am. Chem. Soc.*, 1995, **117**, 6615.

69   R. T. Baker, J. C. Calabrese, S. A. Westcott, and T. B. Marder, *J. Am. Chem. Soc.*, 1995, **117**, 8777.

70   D. H. Motry, A. G. Brazil, and M. R. Smith, III, *J. Am. Chem. Soc.*, 1997, **119**, 2743.

71   M. Murata, S. Watanabe, and Y. Masuda, *Tetrahedron Lett.*, 1999, **40**, 2585.

72   M. Murata, K. Kawakita, T. Asana, S. Watanabe, and Y. Masuda, *J. Bull. Chem. Soc. Jpn.*, 2002, **75**, 825.

73   D. E. Kadlecek, P. J. Carroll, and L. G. Sneddon, *J. Am. Chem. Soc.*, 2000, **122**, 10868.

74   C. M. Vogels, P. G. Hayes, M. P. Shaver, and S. A. Westcott, *Chem. Commun.*, 2000, 51.

75   R. H. Crabtree, *Chem. Rev.*, 1985, **85**, 245.

76   R. H. Crabtree, *Chem. Rev.*, 1995, **95**, 987.

77   A. E. Shilov and G. B. Shul'pin, *Chem. Rev.*, 1997, **97**, 2879.

78   C. M. Jensen, *Chem. Commun.*, 1999, 2443.

79   S. Niu and M. B. Hall, *Chem. Rev.*, 2000, **100**, 353.

80   M. Torrent, M. Sola, and G. Frenkin, *Chem. Rev.*, 2000, **100**, 439.

81   R. H. Crabtree, *J. Chem. Soc., Dalton Trans.*, 2001, 2437.

82   W. D. Jones and F. J. Feher, *J. Acc. Chem. Res.*, 1989, **22**, 91.

83   W. D. Jones, *Science*, 2000, **287**, 1942.

84   K. M. Waltz, X. He, C. Muhoro, and J. F. Hartwig, *J. Am. Chem. Soc.*, 1995, **117**, 11357.

85   K. M. Waltz and J. F. Hartwig, *Science*, 1997, **277**, 211.

86   H. Chen and J. F. Hartwig, *Angew. Chem. Int. Ed. Engl.*, 1999, **38**, 3391.

87   K. M. Waltz, C. N. Muhoro, and J. F. Hartwig, *Organometallics*, 1999, **18**, 3383.

88   C. N. Iverson and M. R. Smith, III, *J. Am. Chem. Soc.*, 1999, **121**, 7696.

89   H. Chen, S. Schlecht, T. C. Semple, and J. F. Hartwig, *Science*, 2000, **287**, 1995.

90   J.-Y. Cho, C. N. Iverson, and M. R. Smith, III, *J. Am. Chem. Soc.*, 2000, **122**, 12868.

91   K. M. Waltz and J. F. Hartwig, *J. Am. Chem. Soc.*, 2000, **122**, 11358.

92   B. Goldfuss, P. Knochel, L. O. Bromm, and K. Knapp, *Angew. Chem. Int. Ed. Engl.*, 2000, **39**, 4136.

93   S. Shimada, A. S. Batsanov, J. A. K. Howard, and T. B. Marder, *Angew. Chem. Int. Ed. Engl.*, 2001, **40**, 2168.

94   T. Ishiyama, K. Ishida, J. Takagi, and N. Miyaura, *Chem. Lett.*, 2001, 1082.

95   K. Kawamura and J. F. Hartwig, *J. Am. Chem. Soc.*, 2001, **123**, 8422.

96   M. K. Tse, J.-Y. Cho, and M. R. Smith, *Org. Lett.*, 2001, **3**, 2831.

97   T. Ishiyama, J. Takagi, K. Ishida, N. Miyaura, N. R. Anastasi, and J. F. Hartwig, *J. Am. Chem. Soc.*, 2002, **124**, 390.

98   J.-Y. Cho, M. K. Tse, D. Holmes, R. E. Maleczka, Jr., and M. R. Smith, III, *Science*, 2002, **295**, 305.

99   H. C. Brown, E. Negishi, and M. Zaidlewicz, in 'Organoboronate compounds in organic synthesis', ed. G. Wilkinson, F. G. A. Stone, and E. W. Abel, Oxford University Press, Oxford, 1982.

100   S. E. Thomas, in 'Organic synthesis: The roles of boron and silicon', ed. S. G. Davies, Oxford University Press, Oxford, 1991.

101   N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 49.

102   A. Suzuki, *J. Organomet. Chem.*, 1999, **576**, 147.

103   J. March, 'Advanced Organic Chemistry', Wiley Interscience, New York, 1992.

104   S. K. Stewart and A. Whiting, *Tetrahedron Lett.*, 1995, **36**, 3929.

105   N. Hénaff and A. Whiting, *Tetrahedron*, 2000, **56**, 5193.

Chapter 2

Synthesis and Characterisation of [Rh(COE)$_2$(acac)]

2.1 Introduction

Complexes of the form [Rh(β-diketonate)L$_2$], where L = alkene, phosphine, or phosphite and β-diketonate = acetylacetonate (acac), trifluoroacetylacetonate (tfacac) and hexafluoroacetylacetonate (hfacac), have received considerable attention as catalyst precursors[†] or starting materials for the synthesis of catalyst precursors for a variety of reactions including, for example, alkene hydroboration[1,2] and diboration,[3-5] CO$_2$ hydrogenation,[6-8] hydroformylation,[9] and the addition of arylboronic acids to aldehydes,[10] or in stoichiometric and structural studies.[11,12] Often, the [Rh(CO)$_2$(acac)][9,11-13] or [Rh(η^4-COD)(β-diketonate)] (COD = 1,5-cyclooctadiene, C$_8$H$_{12}$)[14,15] complexes are used as precursors to the [Rh(R$_3$P)$_2$(β-diketonate)] reagents, and formation of [Rh(R$_3$P)$_4$]$^+$ [(β-diketonate)]$^-$ can be a significant side reaction with the latter. One of the problems stems from the competing lability of the bidentate COD and β-diketonate ligands. With [Rh(CO)$_2$(acac)] the limited lability of the second CO ligand can cause problems.

For some time the Marder group has employed [Rh(η^2-COE)$_2$(acac)] (1) (COE = cyclooctene = C$_8$H$_{14}$) both as a catalyst precursor in its own right[2] and as an extremely efficient means by which to prepare [Rh(PR$_3$)$_2$(acac)] systems which have been shown to be converted cleanly to zwitterionic [Rh(PR$_3$)$_2$(η^6-catBcat)] (cat = 1,2-O$_2$C$_6$H$_4$) catalyst systems by treatment with B$_2$cat$_3$ or excess HBcat.[1-5, 16]

[†] A 'catalyst precursor' is the compound added to a reaction mixture that forms the 'active catalyst' under the reaction conditions.

Quite recently, Ueda and Miyaura demonstrated[10] the efficiency of a catalyst for the addition of ArB(OH)$_2$ to RCHO, which was prepared *in situ* by addition of one equivalent of ^{t}Bu$_3$P to **1**.

Addition of excess phosphine inhibits the reaction, and thus the active species is presumably a mono-phosphine rhodium complex suggesting the importance of having monodentate labile ligands such as COE, in contrast to COD.

In 1985, Bennett and Mitchell reported[17] the use of **1** in a reaction with a secondary phosphite yet in this paper they reported only an outline of the synthesis and provided no characterisation of **1** itself. In 1996, Esteruelas *et al.*[13] used **1** synthesised by the published procedure[18] for [Ir(η^2-COE)$_2$(acac)], which uses [Ir(COE)$_2$(μ-Cl)]$_2$ and Tl(acac), and yet again no details were provided. In fact, a procedure[19] for synthesising **1** using Tl(acac) was reported by Bennet and Patmore in 1971, along with some characterisation data. It would appear, however, that this original report is not widely known, and an alternative procedure avoiding the use of thallium salts would certainly be desirable for pharmaceutical applications. Indeed our group received several requests for information on our synthetic protocol for **1**. This prompted us to report herein a detailed and reliable procedure for preparing **1** without the use of thallium salts, along with its full spectroscopic and structural characterisation.

2.2 Results and Discussion

Complex **1** was obtained in high yield by the reaction of Na(acac) and [Rh(η^2-COE)$_2$(μ-Cl)]$_2$ (**2**) in toluene with gentle heating at 40°C for 3 h. Shorter times can result in incomplete reaction, whereas extending the reaction period often results in dark precipitates due to some decomposition of **2**, but these are easily

removed by filtration through Celite®. Extraction into hexane followed by the removal of solvent yields **1** as a yellow-orange powder. The compound is stable in the solid state at ambient temperature but there is evidence of decomposition after 24 h when in solution. Assignment of the ^{13}C{^{1}H} NMR spectrum was aided by a DEPT[20] experiment which showed singlets at δ 185.3 due to the C=O carbons on the acac group, a singlet at δ 99.1 due to the central carbon of the acac group, a doublet at δ 78.3 ($^1J_{C-Rh}$ = 13 Hz) due to the olefin carbons of the COE ligands, singlets at δ 30.5, 28.2 and 27.0 due to aliphatic COE carbons, and a singlet at δ 27.3 for the acac methyl groups. The proton NMR spectrum shows a sharp peak at δ 5.04 due to the methyne proton on the acac group, but broad resonances at δ 2.51, 2.47, 2.42, 1.69, 1.56 and 1.41 due to the aliphatic and coordinated olefin COE and acac-CH$_3$ protons. A ^{1}H-^{13}C HSQC[21] experiment (Figure 1) showed that the ^{1}H resonance at δ 5.04 is connected to the ^{13}C resonance at δ 99.1, for the central acac carbon atom, and the ^{1}H resonance at δ 2.51 is due to the coordinated olefin moiety, as it is connected to the ^{13}C doublet at δ 78.3, from the olefinic carbons. The ^{1}H resonances at δ 2.47 and 2.42 are both connected to the ^{13}C resonance at δ 28.2, due to two sets of inequivalent (axial and equatorial) aliphatic COE protons. Next, the ^{1}H resonance at δ 1.69, integrating for a total of 10 protons, is connected to ^{13}C resonances at δ 30.5 (4 methylene COE protons) and δ 27.3 (6 acac CH$_3$ protons). Finally, the ^{1}H resonance at δ 1.56 (4 protons) is connected to the methylene ^{13}C resonance at δ 27.0, and the ^{1}H resonance at δ 1.41 (8 protons) is connected to methylene ^{13}C resonances at δ 30.5 and δ 27.0. The complicated nature of the ^{1}H NMR spectrum is a result of coincidental overlap of various relatively broad resonances.
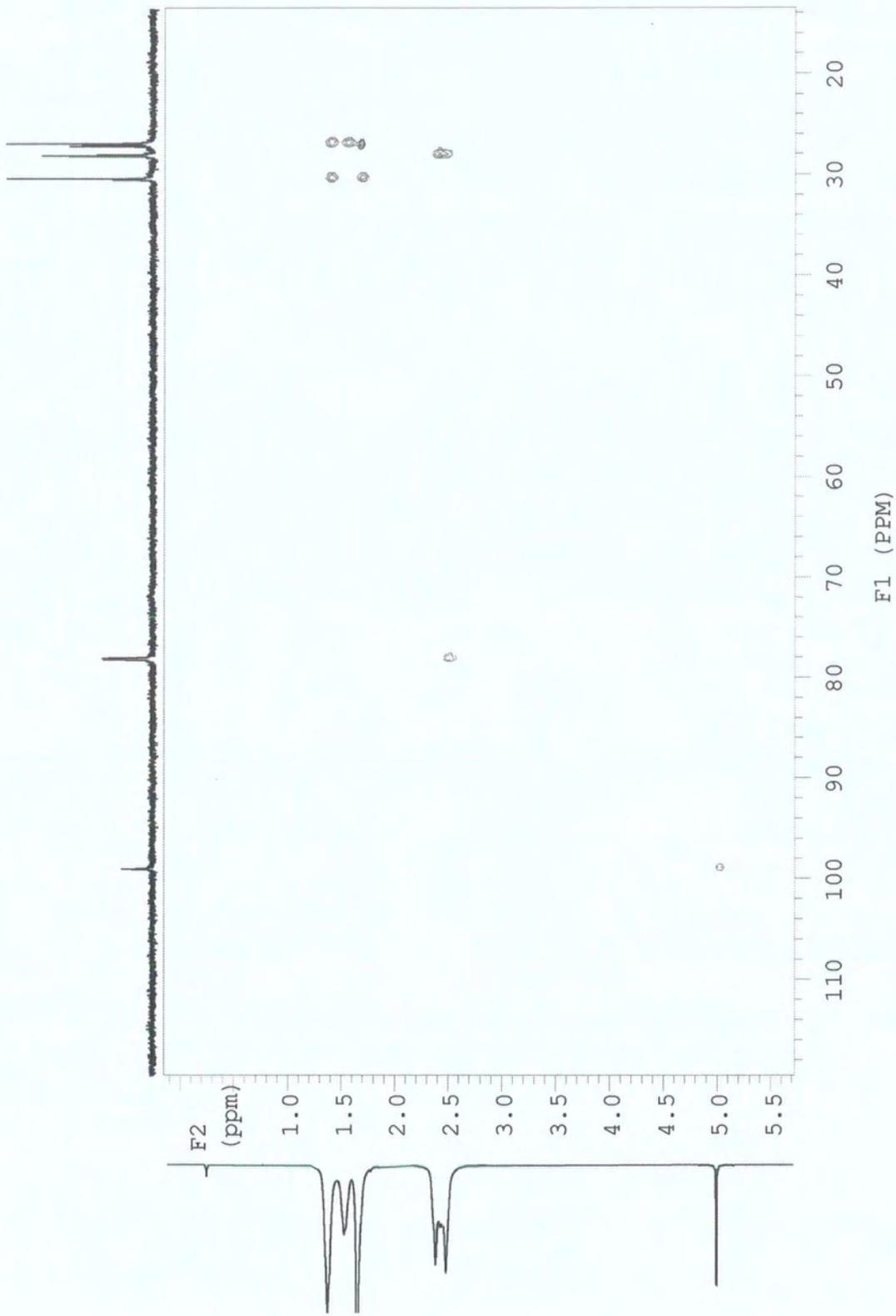
Figure 2.1: The ^1H-^{13}C HSQC spectrum of **1**
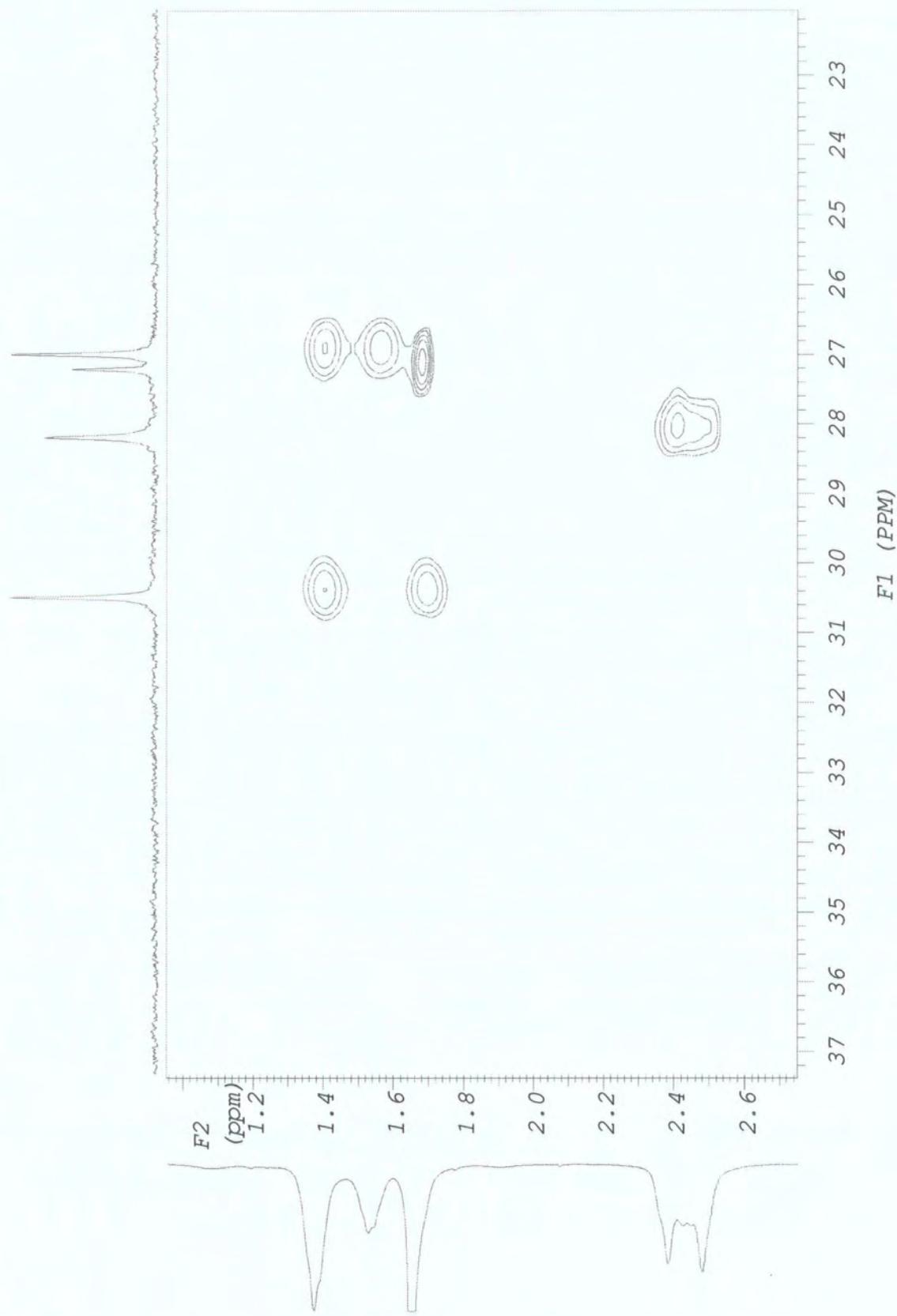
Figure 2.2: An expansion of the aliphatic region of the ^{1}H-^{13}C HSQC spectrum of 1

61

Compound **1** crystallises in the orthorhombic space group Pbca. The eight molecules in the unit cell are arranged in pairs related by an inversion centre, placing the bulky cyclooctene groups as far away from each other as possible.

The geometry around rhodium is approximately square planar (Figure 2.3), with angles (Table 2.1) X(1A)-Rh(1)-X(1B) = 93.6°, X(1A)-Rh(1)-O(2) = 89.4°, X(1B)-Rh-O(1) = 90.2° and O(1)-Rh-O(2) = 87.69(9)° (X(1A) = mid-point of C(1)-C(8), X(1B) = mid-point of C(9)-C(16), C(1), C(8), C(9), and C(16) being the olefinic carbons of the COE ligands). The planes defined by O(1)-Rh(1)-O(2) and X(1A)-Rh(1)-X(1B) are at an angle of 10.6° to each other. The distances from the rhodium atom to the centre of the C-C double bonds are 2.015 Å (Rh-X(1A)) and 2.017 Å (Rh-X(1B)). The deviations of the atoms from the plane defined by Rh(1), O(1), O(2), X(1A) and X(1B) are Rh(1): –0.0054 Å; O(1): 0.1342 Å; O(2): –0.1376 Å; X(1A): 0.1312 Å; X(1B): –0.1332 Å. The olefinic C=C bonds of the COE moieties are nearly perpendicular to this 'square plane': C(1)=C(8) is at 91.2° and C(9)=C(16) is at 91.1°.

Table 2.1: Selected bond lengths (Å) and angles (°) for (1).

	Bond Length (Å) and Angles (°)
C(1)—Rh(1)	2.1417(18)
C(8)—Rh(1)	2.1347(19)
C(9)—Rh(1)	2.1298(19)
C(16)—Rh(1)	2.1417(18)
X(1A)—Rh(1)[a]	2.005(13)
X(1B)—Rh(1)[a]	2.009(14)
O(1)—Rh(1)	2.0624(14)
O(2)—Rh(1)	2.0652(13)
X(1A)—Rh(1)—X(1B)[a]	93.4(6)
X(1A)—Rh(1)—O(1)[a]	171.1(4)
X(1B)—Rh(1)—O(1)[a]	90.1(4)
X(1A)—Rh(1)—O(2)[a]	90.0(4)
X(1B)—Rh(1)—O(2)[a]	171.7(4)
O(1)—Rh(1)—O(2)	87.69(9)

[a] – X(1A) = mid-point of C(1) and C(8); X(1B) = mid-point of C(9) and C(16).
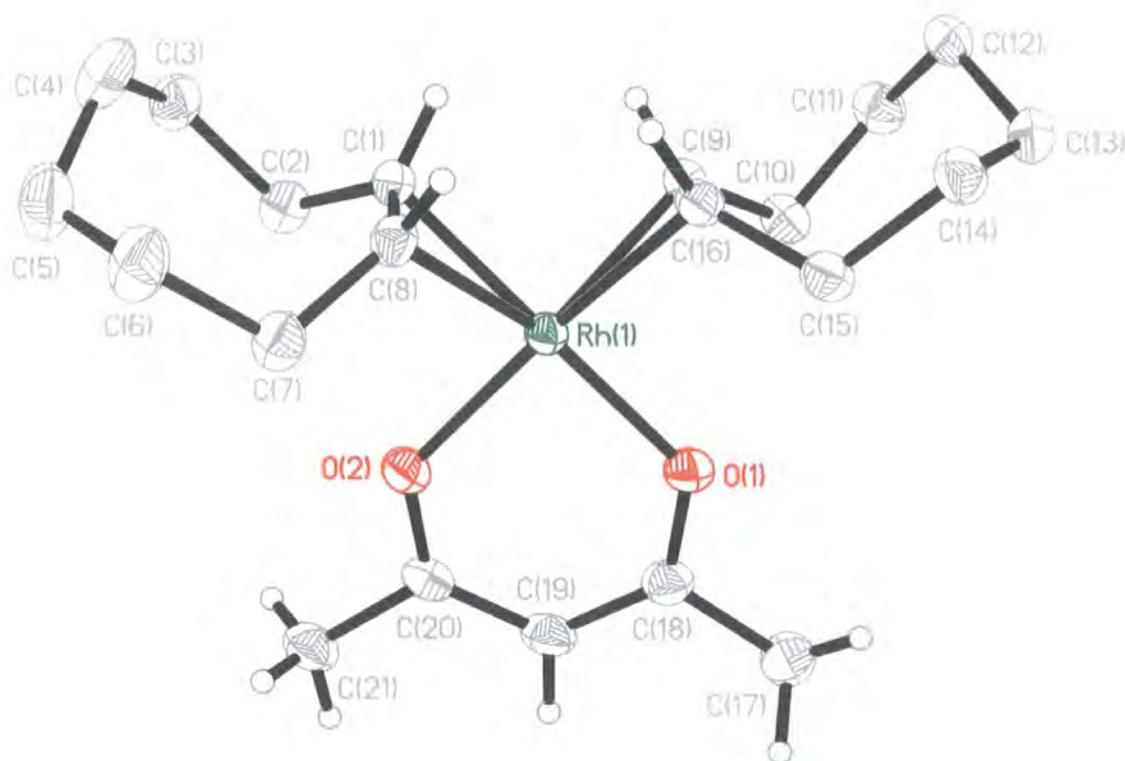
Figure 2.3: Molecular structure of 1

A search of the Cambridge Structural Database[22] revealed that although there are 419

known examples with $Rh-C_8$-rings, only eleven of these are Rh-COE compounds. Of

these, only nine[23-31] contain simple, unsubstituted COE ligands. The only bis(COE)

compound,[27] $[Rh(COE)_2(\eta^5$-N-methylpiperidin-4-yl-Cp)]$, has an X-Rh-X angle of

92.7°, with Rh-(C=C)-centroid distances of 2.013 Å and 2.023 Å, all of which are

similar to compound (1). The Rh-(C=C)-centroid distances for the other Rh-COE

compounds range from 1.959 Å[28] to 2.069 Å.[24]

2.3 Conclusion

This chapter provides full details of the synthesis and characterisation of 1 which are

expected to increase the availability of this useful compound for synthetic and

catalytic applications.

2.4 Experimental Section

All reactions were carried out in a nitrogen atmosphere using Schlenk techniques or an Innovative Technology, Inc. System 1 glove box. Glassware was oven dried before transfer into the glove box. NMR spectra were recorded on Varian Inova 500 (^{1}H, HSQC) and Varian VXR 400 (^{13}C, DEPT) instruments. Proton and ^{13}C NMR spectra were referenced to external SiMe$_4$ *via* residual protons in the deuterated solvents or solvent resonances respectively. Elemental analyses were conducted in the Department of Chemistry at the University of Durham using an Exeter Analytical Inc. CE-440 Elemental Analyzer. The [Rh(COE)$_2$(μ-Cl)]$_2$ was prepared using a published procedure,[32] whereas the NaH (60% dispersion in mineral oil), and acetylacetone were used as purchased from Lancaster Synthesis and Aldrich Chemical Company respectively. Toluene was dried and deoxygenated by passage through columns of activated alumina and BASF-R311 catalyst under argon pressure using a locally modified version of the Innovative Technology, Inc. SPS-400 solvent purification system.[33] C$_6$D$_6$ and hexane were dried over potassium and sodium respectively, and were distilled under nitrogen before use.

2.4.1 Synthesis of Na(acac)

A suspension of NaH, 60% in mineral oil, (1.63 g, 0.041 mol) was degassed and then added to hexane (150 ml) and cooled to -78°C with stirring. A solution of acetylacetone (4.10 g, 0.041 mol) in hexane (50 ml) was added dropwise over a period of 10 min, to allow for the evolution of H$_2$, giving a white precipitate. The reaction mixture was then allowed to warm to room temperature and was stirred for 1 h after which the reaction mixture was filtered, washed with hexane, and the precipitate then dried *in vacuo* to yield 4.98 g (99.6%) of Na(acac) as a fine white powder. ^{1}H NMR

(CD$_3$CN): δ 4.99 (1H, CH), 1.69 (6H, CH$_3$). IR (Nujol, cm^{-1}): ν(acac) 1582, 1518. Found: C = 48.97, H = 5.94%. C$_5$H$_7$O$_2$Na requires C = 49.18, H = 5.78%. N.B. This simple procedure yields rigorously dry Na(acac). Although hydrated Na(acac) is commercially available, and may be suitable for use in the preparation of **1**, a source of any moisture is undesirable for many catalytic reactions.

2.4.2 Synthesis of [Rh(η^2-COE)$_2$(acac)] (1)

To a mixture of [Rh(COE)$_2$(μ-Cl)]$_2$ (0.276 g, 0.385 mmol) and Na(acac) (0.094 g, 0.770 mmol) was added toluene (20 ml) and the reaction was warmed to 40°C with stirring under N$_2$ for 3 h. The reaction mixture was filtered *via* filter cannula, to remove NaCl, and the toluene removed *in vacuo*. The product was extracted into hexane, filtered through a thin pad of Celite®, and isolated by removal of the hexane *in vacuo*, yielding 0.263 g (81%) of **1** as a yellow powder. Single crystals suitable for X-ray diffraction were grown from hexane at –30°C. ^{1}H NMR (C$_6$D$_6$): δ 5.04 (s, acac CH), 2.51 (4H, olefin COE), 2.47 (4H, COE), 2.42 (4H, COE), 1.69 (6H, acac CH$_3$ + 4H, COE), 1.56 (4H, COE), 1.41 (8H, COE); ^{13}C{^{1}H}: δ 185.3 (s, acac C=O), 99.1 (s, acac CH), 78.3 (d, J$_{C-Rh}$ = 13 Hz, olefinic COE), 30.5 (s, COE), 28.2 (s, COE), 27.3 (s, acac CH$_3$), 27.0 (s, COE). IR (Nujol, cm^{-1}): ν(acac) 1620, 1510. Found: C = 59.10, H = 8.34%. RhC$_{21}$H$_{35}$O$_2$ requires C = 59.71, H = 8.35%.

2.4.3 Crystal Structure Determination

C$_{21}$H$_{35}$O$_2$Rh, *M* = 442.40, orthorhombic, *a* = 17.736(3), *b* = 11.041(2), *c* = 20.520(3) Å, *V* = 4018(1) Å^3, *T* = 150K, space group Pbca (N° 61), *Z* = 8, μ (Mo-Kα) = 0.860 mm^{-1}, 28186 reflections measured, 5767 unique (*R$_{int}$* = 0.0219) which were used in all

calculations with 4801 having I ≥ 2σ(I). A yellow crystal of dimensions 0.38 x 0.32 x 0.20 mm^3 was used for the single crystal structure determination of **1**. Data were collected using graphite monochromated Mo-Kα radiation (λ = 0.71073) on a Bruker SMART-CCD 1K detector diffractometer equipped with a Cryostream N$_2$ flow cooling device.[34] Series of narrow ω-scans (0.3°) were performed at several φ-settings in such a way as to cover a hemisphere of data to a maximum resolution of 0.70Å. Cell parameters were determined and refined using the SMART software[35] from the centroid values of 946 reflections with 2θ values between 27° and 46°. Raw frame data were integrated using the SAINT program.[36] The structure was solved using Direct Methods and refined by full-matrix least squares on F^2 using SHELXTL.[37] The reflection intensities were corrected by numerical integration based on measurements and indexing of the crystal faces, T$_{max}$ = 0.851, T$_{min}$ = 0.770. All non-hydrogen atoms were refined with anisotropic atomic displacement parameters (adps). Hydrogen atoms were geometrically placed and allowed to ride on their parent C atom with U$_{iso}$ (H) = 1.5 U$_{eq}$(C) for methyl hydrogens and U$_{iso}$ (H) = 1.2 U$_{eq}$(C) for all others. Idealized C-H distances were fixed at 0.95Å for the aromatic C-H, 0.98Å for methyl groups, 0.99Å for secondary -CH$_2$- groups and at 1.00Å for tertiary C-H groups. The final *R(F)* was 0.0295 (I > 2 σ(I) data) and the *wR(F^2)* was 0.0745 (all data). Crystallographic data for the structural analysis have been deposited with the Cambridge Crystallographic Data Centre, CCDC No. 170713.

2.5 References

1   S. A. Westcott, H. P. Blom, T. B. Marder, and R. T. Baker, *J. Am. Chem. Soc*, 1992, **114**, 8863.

2   S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

3   R. T. Baker, P. Nguyen, T. B. Marder, and S. A. Westcott, *Angew. Chem. Int. Ed. Eng.*, 1995, **34**, 1336.

4   C. Dai, E. G. Robins, A. J. Scott, W. Clegg, D. S. Yufit, J. A. K. Howard, and T. B. Marder, *Chem. Commun.*, 1998, 1983.

5   T. B. Marder and N. C. Norman, *Top. Catal.*, 1998, **5**, 63.

6   K. Angermund, W. Baumann, E. Dinjus, R. Fornika, H. Görls, M. Kessler, C. Krüger, W. Leitner, and F. Lutz, *Chem. Eur. J.*, 1997, **3**, 755.

7   R. Fornica, H. Görls, B. Seemann, and W. Leitner, *Chem. Commun.*, 1995, 1479.

8   F. Hutschka, A. Dedieu, M. Eichberger, R. Fornica, and W. Leitner, *J. Am. Chem. Soc.*, 1997, **119**, 4432.

9   A. van Rooy, P. C. J. Kamer, P. W. N. M. v. Leeuwen, K. Goubitz, J. Fraanje, N. Veldman, and A. L. Spek, *Organometallics*, 1996, **15**, 835.

10   M. Ueda and N. Miyaura, *J. Org. Chem.*, 2000, **65**, 4450.

11   W. Simanko, K. Mereiter, R. Schmid, K. Kirchner, A. M. Trzeciak, and J. J. Ziolkowski, *J. Organomet. Chem.*, 2000, **602**, 59.

12   J. G. Leipoldt, G. J. Lamprecht, and G. J. V. Zyl, *Inorg. Chim. Acta*, 1985, **96**, L31.

13   M. A. Esteruelas, F. J. Lahoz, E. Oñate, L. A. Oro, L. Rodríguez, P. Steinert, and H. Werner, *Organometallics*, 1996, **15**, 3436.

14   P. J. Fennis, P. H. M. Budzelaar, J. H. G. Frijns, and A. G. Orpen, *J. Organomet. Chem.*, 1990, **393**, 287.

15   Z. B. Duan, M. J. Hampden-Smith, E. N. Duesler, and A. L. Rheingold, *Polyhedron*, 1994, **13**, 609.

16   S. A. Westcott, N. J. Taylor, T. B. Marder, R. T. Baker, N. J. Jones, and J. C. Calabrese, *Chem. Commun.*, 1991, 304.

17   M. A. Bennett and T. R. B. Mitchell, *J. Organomet. Chem.*, 1985, **295**, 223.

18   P. Diversi, G. Ingrosso, A. Immirzi, W. Porzio, and M. Zocchi, *J. Organomet. Chem.*, 1977, **125**, 253.

19   M. A. Bennett and D. J. Patmore, *Inorg. Chem.*, 1971, **10**, 2387.

20   M. R. Bendall, D. M. Doddrell, and D. T. Pegg, *J. Am. Chem. Soc.*, 1981, **103**, 4603.

21   L. E. Kay, P. Keifer, and T. Saarinen, *J. Am. Chem. Soc.*, 1992, **114**, 10663.

22   F. H. Allen and O. Kennard, *Chemical Design Automation News*, 1993, **8**, 1 & 31.

23   J. H. Barlow, G. R. Clark, M. G. Curl, M. E. Howden, R. D. W. Kemmitt, and D. R. Russell, *J. Organomet. Chem.*, 1978, **144**, C47.

24   J. H. Barlow, M. G. Curl, D. R. Russell, and G. R. Clark, *J. Organomet. Chem.*, 1982, **235**, 231.

25   B. D. Murray, H. Hope, J. Hvoslef, and P. P. Power, *Organometallics*, 1984, **3**, 657.

26   S. M. Hawkins, P. B. Hitchcock, and M. F. Lappert, *Chem. Commun.*, 1985, 1592.

27   P. C. McGowan, C. E. Hart, B. Donnadieu, and R. Poilblanc, *J. Organomet. Chem.*, 1997, **528**, 191.

28   H. Werner, M. Bosch, M. E. Schneider, C. Hahn, F. Kukla, M. Manger, B. Windmuller, B. Weberndorfer, and M. Laubender, *J. Chem. Soc., Dalton Trans.*, 1998, 3549.

29   P. H. M. Budzelaar, R. de Gelder, and A. W. Gal, *Organometallics*, 1998, **17**, 4121.

30   J. Huang, C. M. Haar, S. P. Nolan, W. J. Marshall, and K. G. Moloy, *J. Am. Chem. Soc.*, 1998, **120**, 7806.

31   L. Lefort, T. W. Crane, M. D. Farwell, D. M. Baruch, J. A. Kaeuper, R. J. Lachicotte, and W. D. Jones, *Organometallics*, 1998, **17**, 3889.

32   A. van der Ent and A. L. Onderdelinden, *Inorg. Synth.*, 1973, **14**, 92.

33   A. B. Pangborn, M. A. Giardello, R. H. Grubbs, R. K. Rosen, and F. J. Timers, *Organometallics*, 1996, **15**, 1518.

34   J. Cosier and A. M. Glazer, *J. Appl. Cryst.*, 1986, **19**, 105.

35   Bruker, in 'SMART-NT. Data Collection Software. Version 5.0. Bruker Analytical X-ray Instruments Inc., Madison, Wisconsin, USA', 1998.

36   Bruker, in 'SAINT-NT. Data Reduction Software. Version 5.0. Bruker Analytical X-ray Instruments Inc., Madison, Wisconsin, USA', 1998.

37   Bruker, in 'SHELXTL. Version 5.1. Bruker Analytical X-ray Instruments Inc., Madison, Wisconsin, USA', 1998.

Chapter 3

Rhodium Catalysed Diboration of (E)-Styrylboronate Esters

3.1 Introduction

Transition metal catalysed diboration[1,2] of unsaturated organic compounds is a new tool in the arsenal of synthetic chemists. Platinum-catalysed alkyne diboration is now a well understood[3-10] process which involves a mono-phosphine[5,6,10] complex as the active species. The reactions provide the syn-addition product exclusively and new high-efficiency catalysts have been reported.[10] In contrast, the 1,2-addition[11-15] of diborane compounds B_2cat_2 or B_2pin_2 (cat = $1,2-O_2C_6H_4$; pin = $OCMe_2CMe_2O$) to alkenes remains a challenge, with clean reactions being observed for terminal and strained internal alkenes only using phosphine-free Pt-catalyst precursors,[12,13] and for the unstrained internal alkenes cis- and trans-stilbene and trans-β-methylstyrene using an *in situ* prepared zwitterionic rhodium complex[16] [Rh(dppm)(η^6-catBcat)]. The difficulty with alkene diborations arises from competing β-hydride elimination and reductive elimination processes which can occur subsequent to alkene insertion into an M—$B(OR)_2$ bond. The β-hydride elimination leads to accompanying dehydrogenative borylation[17-27] and hydroboration[28-30] processes. For example, we have observed[1,11] up to nine products arising from the metal-catalysed addition of B_2cat_2 to 4-vinylanisole, with yields of up to ca. 25% of the unusual tris(boronate) ester $4-MeO-C_6H_4CH_2C(Bcat)_3$ (2,2,2-TBE). Compounds such as (2,2,2-TBE), containing three or even four boronate groups on a single carbon atom,[31-33] are relatively rare but are very interesting due to their documented reactivity arising from the stabilisation of a carbanion centre by the α-boronate ester moieties. Previous

routes to these compounds, developed[31-33] by Matteson and co-workers, required

reactions of $RCCl_3$ with $ClB(OR')_2$ and lithium metal, Scheme 1, and these could

prove difficult to control. More recently, Siebert et al. reported[34] the syntheses of

tris(boronate) esters via hydroboration of alkynylboronates using $HBCl_2$, Scheme 1.

This chapter indicates a catalytic route to the tris(boronate)esters in good yield under

mild conditions and in a single step from readily accessible vinylboronates, (VBEs).

Matteson:

$$CCl_4 + 8\ Li + 4\ (MeO)_2BCl \xrightarrow{THF} \text{[structure: C(B(OMe)_2)_4]} + 8\ LiCl$$

Siebert:

$$\equiv\!\!-\!\!Bcat \xrightarrow[\text{2. Catechol}]{\text{1. 2 }HBCl_2} \text{[structure: MeC(Bcat)_2(catB)]}$$

Our route:

$$\text{Ar-CH=CH-Bcat} + B_2cat_2 \xrightarrow{\text{Rh catalyst}} \text{[structure: Ar-CH_2-C(Bcat)_3]}$$
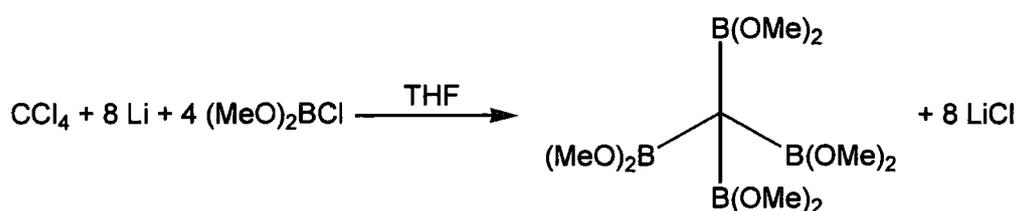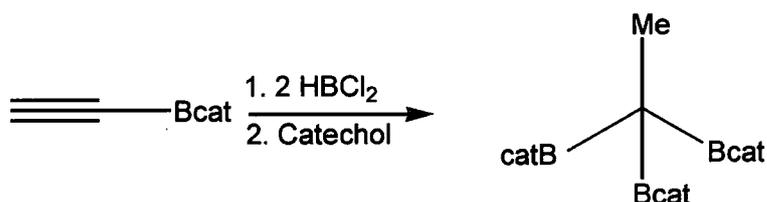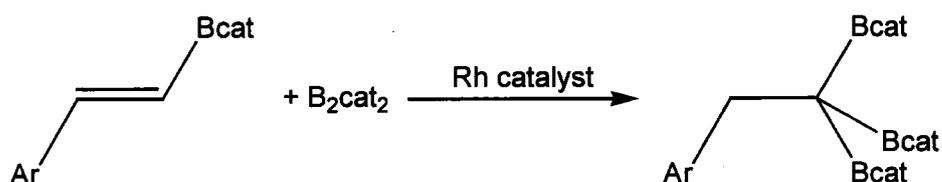
Scheme 3.1: Published routes to tetra- and tris-boronate esters

3.2 Results and Discussion

The styrylboronate esters (VBE's) were prepared in high yields via conventional

hydroboration[35,36] of the corresponding ethynylbenzenes with HBcat, Equation 1.

While this reaction would typically[35,36] require a temperature of ca. 80°C, the use of

HBcat containing a small amount of "BH$_3$" impurity, resulting from the redistribution[37-39] of HBcat to B$_2$cat$_3$ and BH$_3$, allowed the reaction to proceed rapidly at ambient temperature in the absence of solvent.[40-43]

$$Ar\text{—}\!\!\equiv\!\!\text{—}H + HBcat \xrightarrow[\substack{\text{Room}\\\text{Temperature}\\\text{Neat}}]{\text{"BH}_3\text{" promoter}} \begin{array}{c} Ar \\ \diagdown \\ \diagup\diagdown \\ \qquad Bcat \end{array}$$

1a - Ar = Ph
1b - Ar = 4-MeO-C$_6$H$_4$
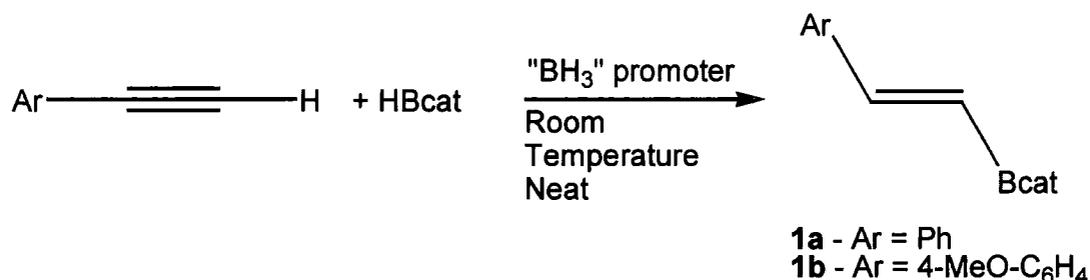
Equation 3.1: 'BH$_3$' promoted hydroboration of ethynylarenes

Compounds **1a** and **1b** were subsequently reacted with B$_2$cat$_2$ in the presence of 1 mol% catalyst and heated to 58°C for 12 hours using THF as solvent. Preliminary studies on this system were carried out[44] by P. Nguyen. This chapter reports a detailed re-examination of this early work along with experiments on new catalysts, and additional mechanistic studies. The products obtained are shown in Scheme 3.2, and product distributions, determined by high-field ^{1}H NMR spectroscopy, are given Table 3.1. In general, there is a similarity in the product distributions resulting from the diboration of either **1a** or **1b**. The catalyst precursor [Rh(PPh$_3$)$_3$Cl] (**7**), gave the highest yield of **2**, 75% and 71% for **1a** and **1b** respectively, Figures 3.1 − 3.6, with the reactions essentially going to completion. Yields of **3**, **4** and **5** were between 5 and 15%. The use of **7** in the presence of 10 equivalents of PPh$_3$ again gave predominantly **2**, but proved slightly less selective than **7** alone, giving 62% and 70% yields with **1a** and **1b** respectively. The zwitterionic catalysts [Rh(dppb)(η^6-catBcat)] (**8**) and [Rh(dppm)(η^6-catBcat)] (**9**), formed as shown in Equation 3.2, also yielded **2**

*Table 3.1: Product distributions for the diboration of **1a** and **1b** with different rhodium catalysts*

Catalyst	Substrate	ArCH₂C(Bcat)₃ (2)	ArCH(Bcat)CH(Bcat)₂ (3)	ArCH(Bcat)CH₂(Bcat) (4)	ArCH₂CH(Bcat)₂ (5)	ArCH=C(Bcat)₂ (6)	Completion[a]
[Rh(PPh₃)₃Cl] (**7**)	1a	75	9	6	5	4	91
	1b	71	15	7	6	1	96
[Rh(PPh₃)₃Cl] (**7**) + 10PPh₃	1a	62	13	10	9	7	93
	1b	70	17	2	3	7	91
[Rh(dppb)(η⁶-catBcat)] (**8**)[b]	1a	63	6	14	10	7	87
	1b	67	5	15	8	5	94
[Rh(dppm)(η⁶-catBcat)] (**9**)[b]	1a	66	17	5	5	8	79
	1b	74	15	Trace	3	8	67
[Rh(COE)₂(μ-Cl)]₂ (**10**) + 2P(o-tol)₃	1a	3	50	0	32	15	96
	1b	11	49	0	35	5	99
[Rh(COE)₂(μ-Cl)]₂ (**10**) + 4P(o-tol)₃	1a	1	47	0	31	21	98
	1b	8	48	0	33	11	98
[Rh(COE)₂(μ-Cl)]₂ (**10**) + 2PPh₂(o-tol)	1a	49	7	8	23	14	77
	1b	47	7	9	22	16	76
[Rh(COE)₂(μ-Cl)]₂ (**10**) + 2 PCy₃	1a	30	45	5	15	4	84
	1b	38	37	4	16	6	87
[Rh(dppb)(η⁶-catBcat)] (**8**) + excess B₂cat₂[c]	1a	70	6	11	7	6	100
	1b	73	8	11	6	2	100
[Rh(COE)₂(μ-Cl)]₂ (**10**) + 4P(o-tol)₃ + excess B₂cat₂[c]	1a	3	53	0	35	9	98
	1b	7	51	0	36	7	100

[a] – Completion was calculated as the percentage of boron-containing products relative to the sum of products plus any unreacted (**1**).

[b] – Generated *in situ* as shown in Equation 3.2.

[c] – A threefold excess of B₂cat₂ relative to **1** was used.

Equation 3.2: Formation of [RhL₂(η⁶-catBcat)]
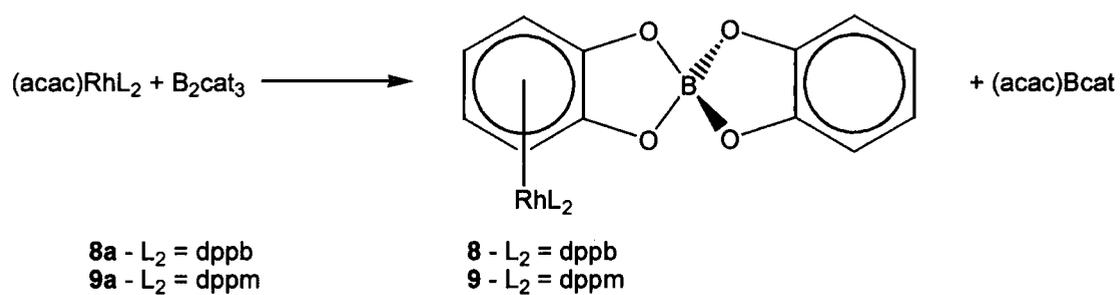
Note: Equation caption rendered as italic: *Equation 3.2: Formation of [RhL$_2$(η^6-catBcat)]*
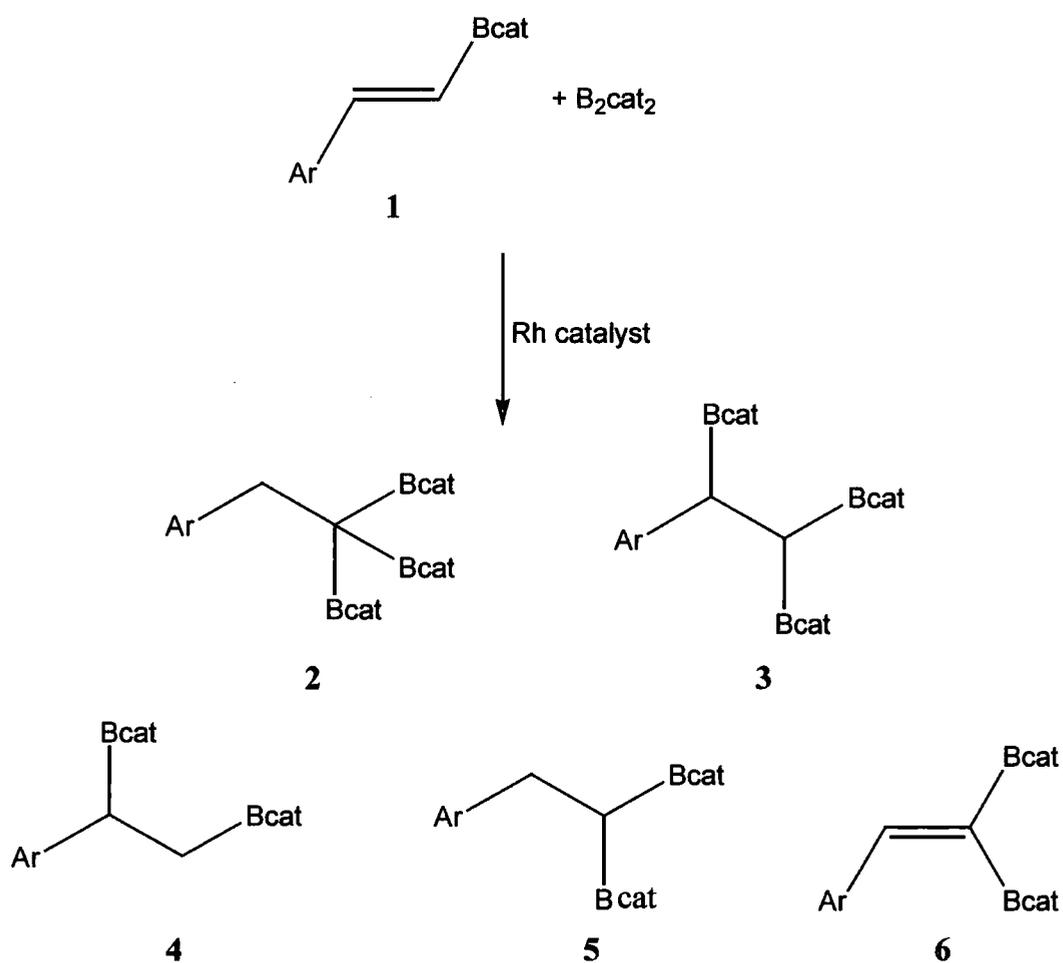
Ar = Ph (a), 4-MeO-C$_6$H$_4$- (b)

Scheme 3.2: Products resulting from the diboration of 1

predominantly (63 and 67% for **8**, 66 and 74% for **9**, for **1a** and **1b** respectively).

Reactions with **8** were 87-94% complete in 12 hours but reaction with **9** only achieved

67-79% completion in this time. The 74% yield of **2b** using **9**, however, was the

highest obtained for this substrate.

The use of [Rh(COE)$_2$(μ-Cl)]$_2$ (**10**) in the presence of 2 equivalents of P(o-tol)$_3$ (1

equivalent per Rh) as shown in Equation 3.3, gave the highest yields of **3** of 50 and

49% for **1a** and **1b** respectively, with completions of at least 96%. The use of four

equivalents of P(o-tol)$_3$ (2 equivalents per Rh) gave very similar product distributions

and hence it would appear that only one P(o-tol)$_3$ binds to Rh. This was confirmed by

the reaction of [Rh(COE)$_2$(μ-Cl)]$_2$ with 1 equivalent P(o-tol)$_3$ per Rh which gave rise

to one doublet at δ 50.7 (J_{P-Rh} = 190 Hz) in the ^{31}P$\{^1$H$\}$ NMR spectrum, Figure 3.x;

addition of 2 equivalents per Rh resulted in the same doublet and also a singlet at δ -

28.7 due to free P(o-tol)$_3$, Figure 3.7. Using **10** in combination with two equivalents

of the less bulky phosphines PPh$_2$(o-tol) or PCy$_3$ (*i.e.* P:Rh = 1:1), gave yields of **3**

which were lower than those found for P(o-tol)$_3$. Thus, PPh$_2$(o-tol) gave mainly **2**

(~50%), whereas PCy$_3$ gave a nearly even split in distributions of both **2** and **3**. It is

clear, therefore, that cone angle, and possibly basicity, of the phosphine are important

factors in the product distributions obtained.
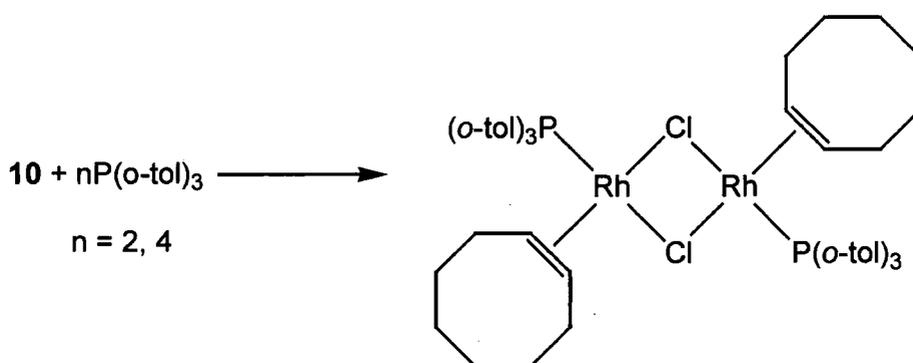
Equation 3.3: Reaction of [Rh(COE)$_2$(μ-Cl)]$_2$ with P(o-tol)$_3$
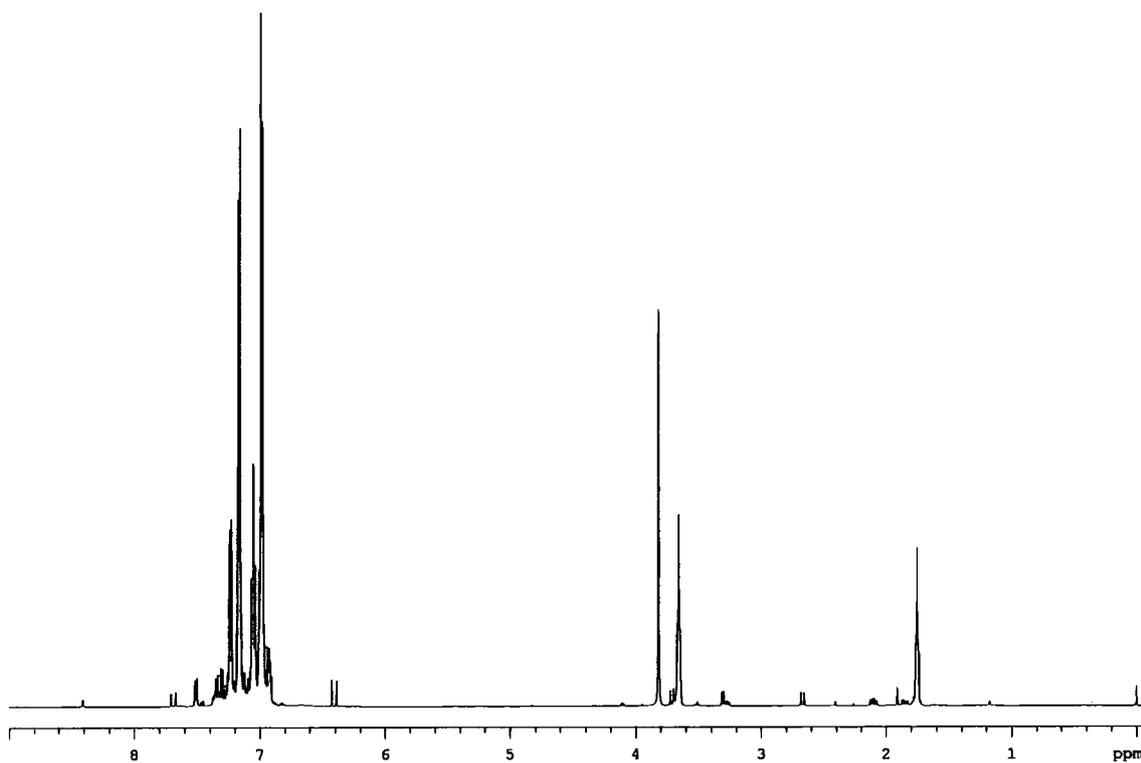
*Figure 3.1: NMR spectrum of the reaction of **1a** and [Rh(Cl)(PPh₃)₃]*
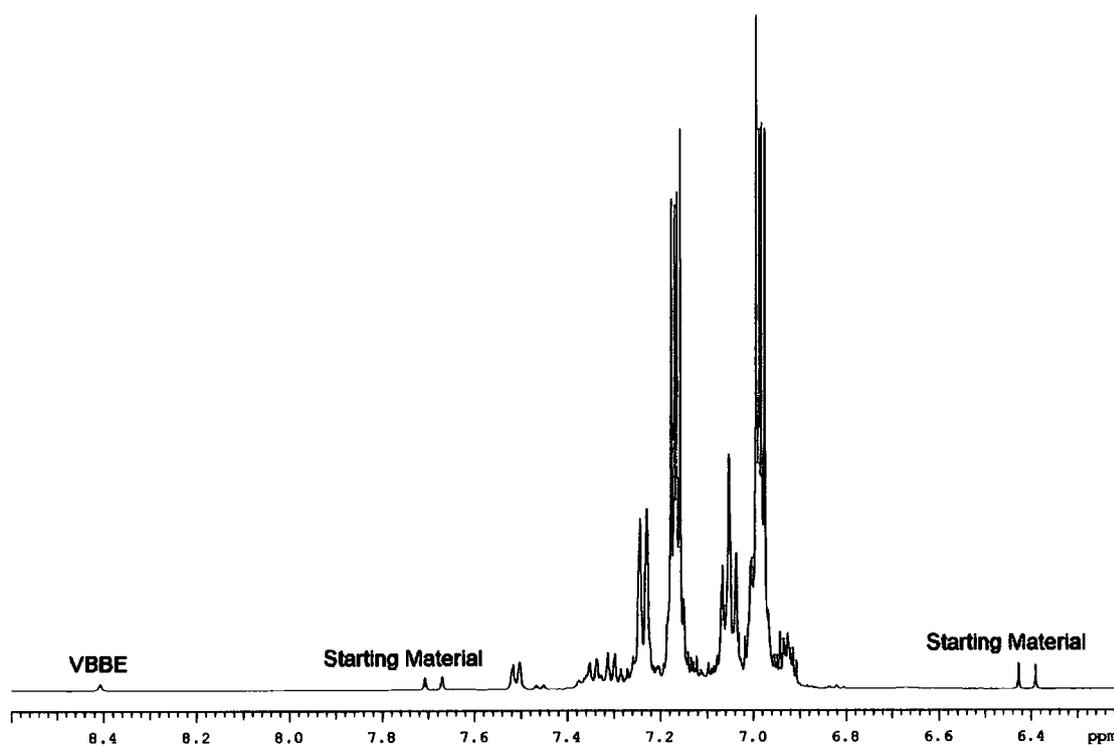
Figure 3.2: Expansion of the aromatic region of the NMR spectrum of the reaction of
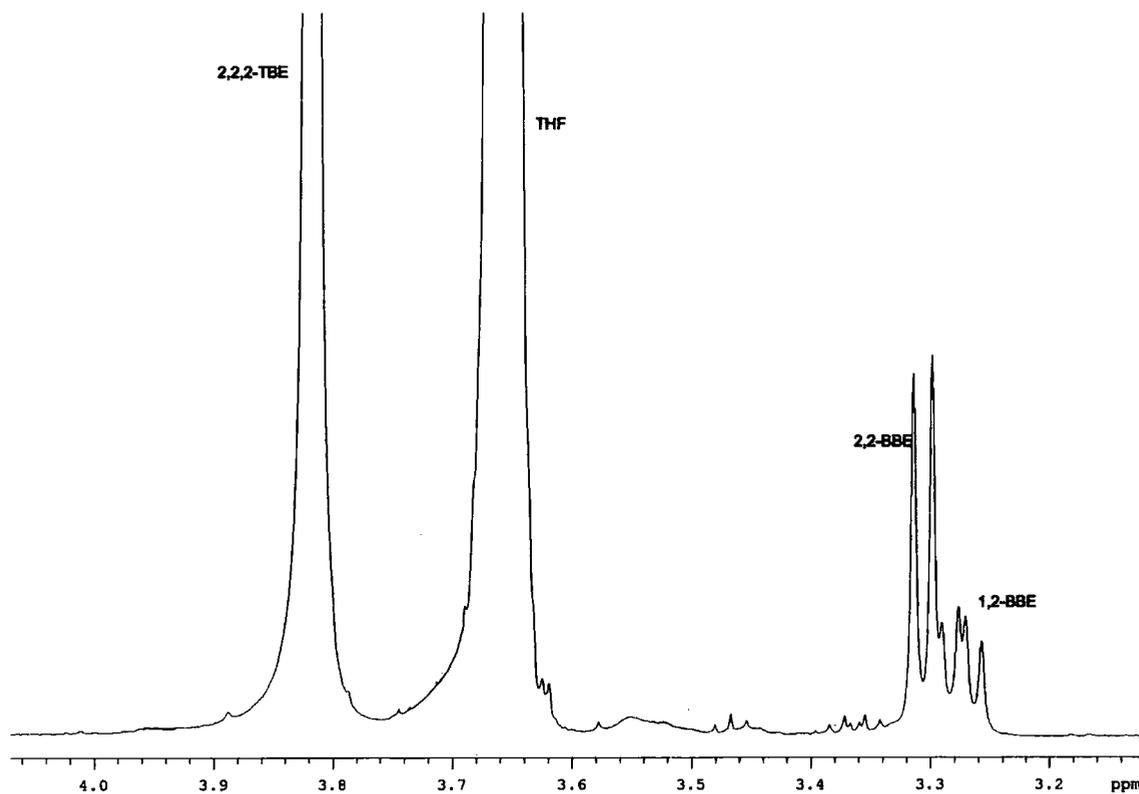
***1a** and [Rh(Cl)(PPh₃)₃]*

Figure 3.3: Expansion of the aliphatic region of the NMR spectrum of the reaction of
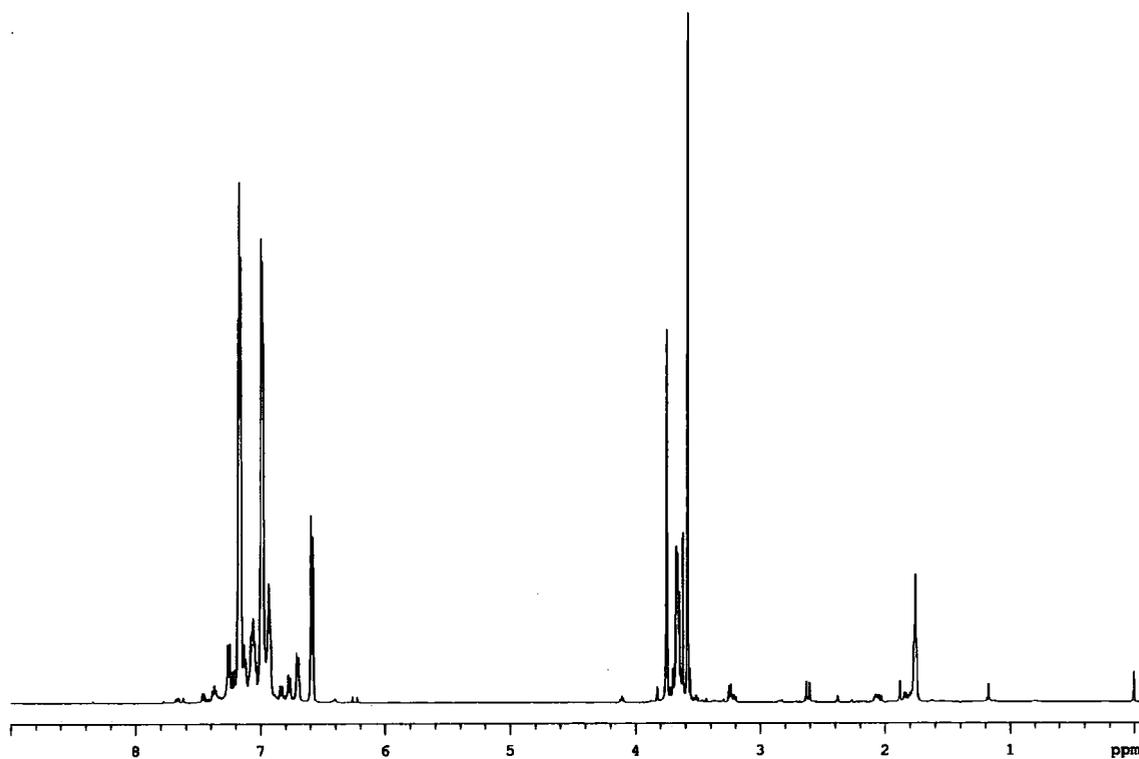
1a and [Rh(Cl)(PPh₃)₃]

Figure 3.4: NMR spectrum of the reaction of 1b and [Rh(Cl)(PPh₃)₃]

77
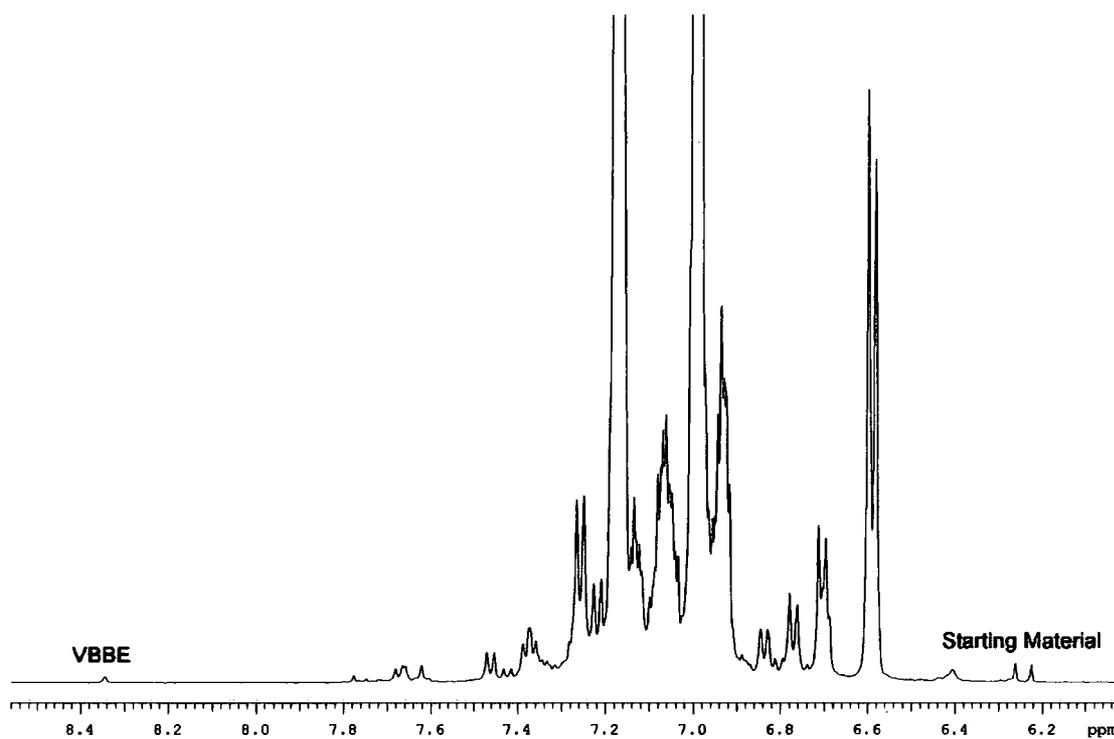
Figure 3.5: Expansion of the aromatic region of the NMR spectrum of the reaction of
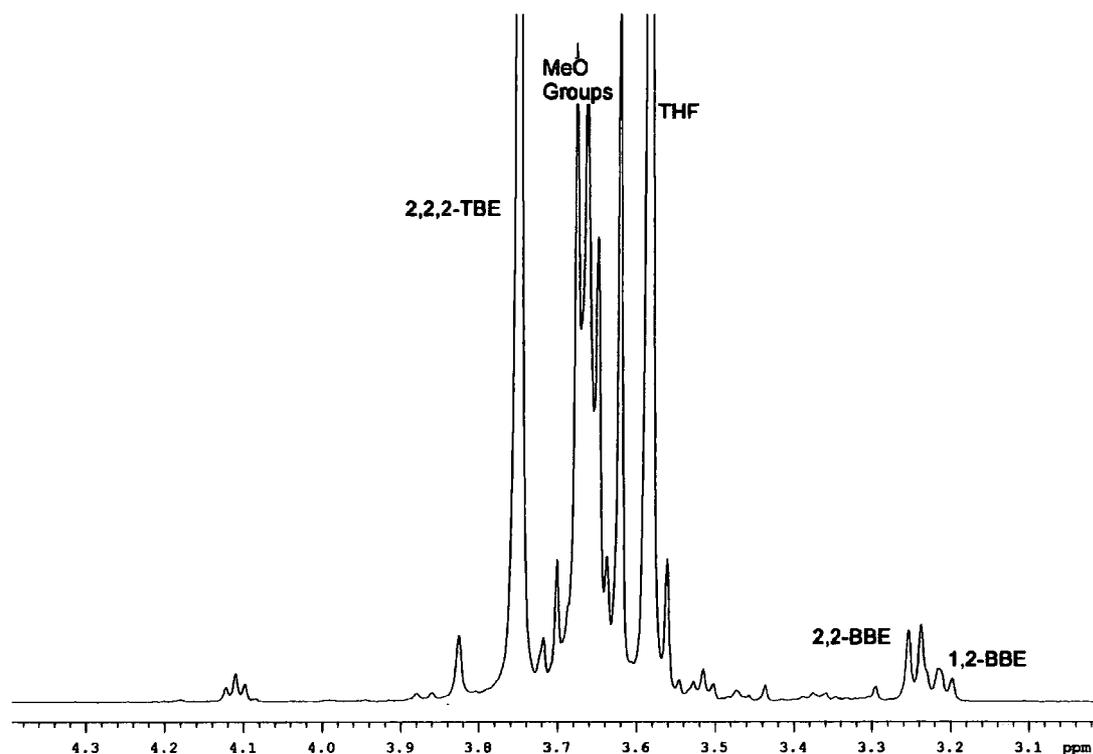
1b and [Rh(Cl)(PPh₃)₃]

Figure 3.6: Expansion of the aliphatic region of the NMR spectrum of the reaction of

1a and [Rh(Cl)(PPh₃)₃]
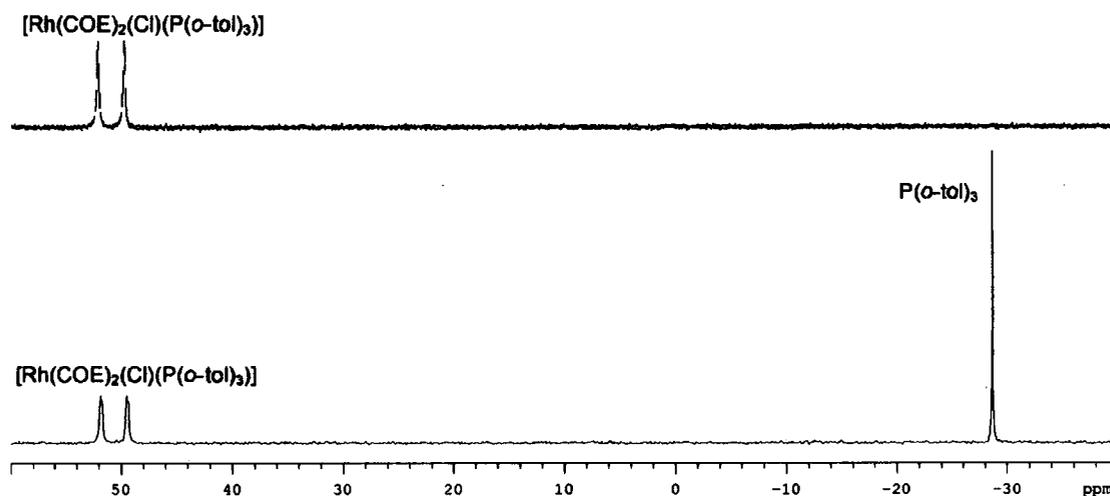
Figure 3.7: $^{31}P\{^1H\}$ NMR spectrum of the reaction between [Rh(COE)$_2$(μ-Cl)]$_2$ and 1 equiv. (top) and 2 equiv. P(o-tol)$_3$

Commercially available [Pt(COD)Cl$_2$], which has been shown to diborate alkenes,[15] failed to diborate **1a** and **1b** but considerable reaction with the THF solvent was observed. Repeating the reaction in benzene showed no diboration to have taken place.

Two reactions were conducted using a threefold excess of B$_2$cat$_2$, relative to **1**, with catalyst **8**, which had given predominantly **2**, and catalyst **10** + 4P(o-tol)$_3$, which had given predominantly **3**. In both cases, the product distributions were similar to those obtained in reactions employing 1 equivalent of B$_2$cat$_2$. In the former case, a small increase in the yield of **2** was observed whereas in the latter case, the yield of **3** was slightly increased. In both cases the reactions went to completion indicating some rate dependence on B$_2$cat$_2$ concentration.

A plausible schematic catalytic cycle is shown in Scheme 3.3. In this, oxidative addition of B$_2$cat$_2$ to the Rh centre forms an unsaturated bis-boryl complex, of which RhCl(Bcat)$_2$(PPh$_3$)$_2$] is representative.[45,46] Coordination of **1** is followed by insertion
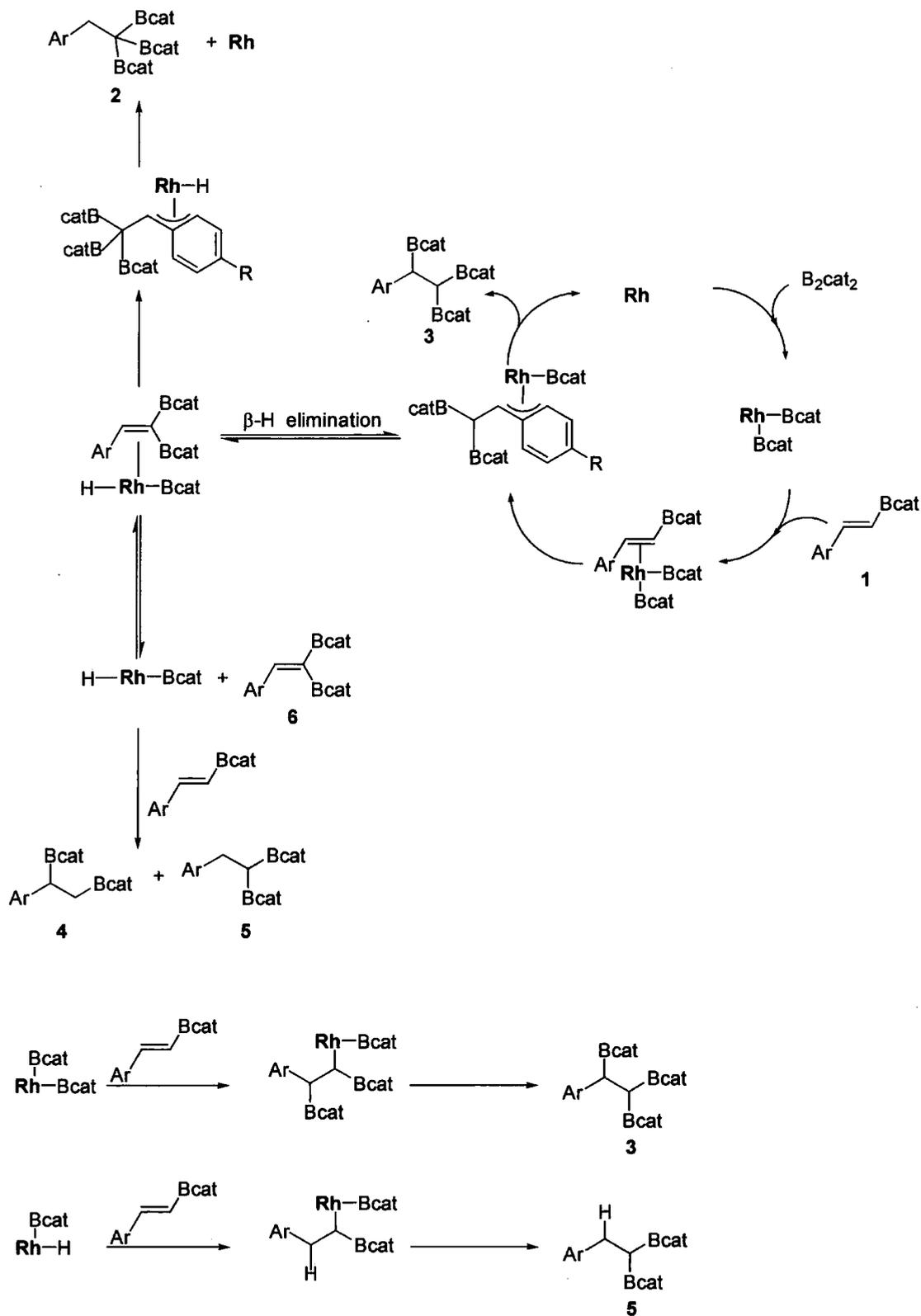
Scheme 3.3: Plausible schematic catalytic cycle for the diboration of 1

Rh^I—Bcat

Bcat

Ar

Ar   Bcat

Rh^I Bcat

B_2cat_2

Bcat

Ar   Bcat

6

+Rh^I—H

Bcat

Rh^{III}—Bcat

Ar   Bcat

Bcat

Bcat

Ar   Bcat + Rh^I—Bcat

Bcat

3
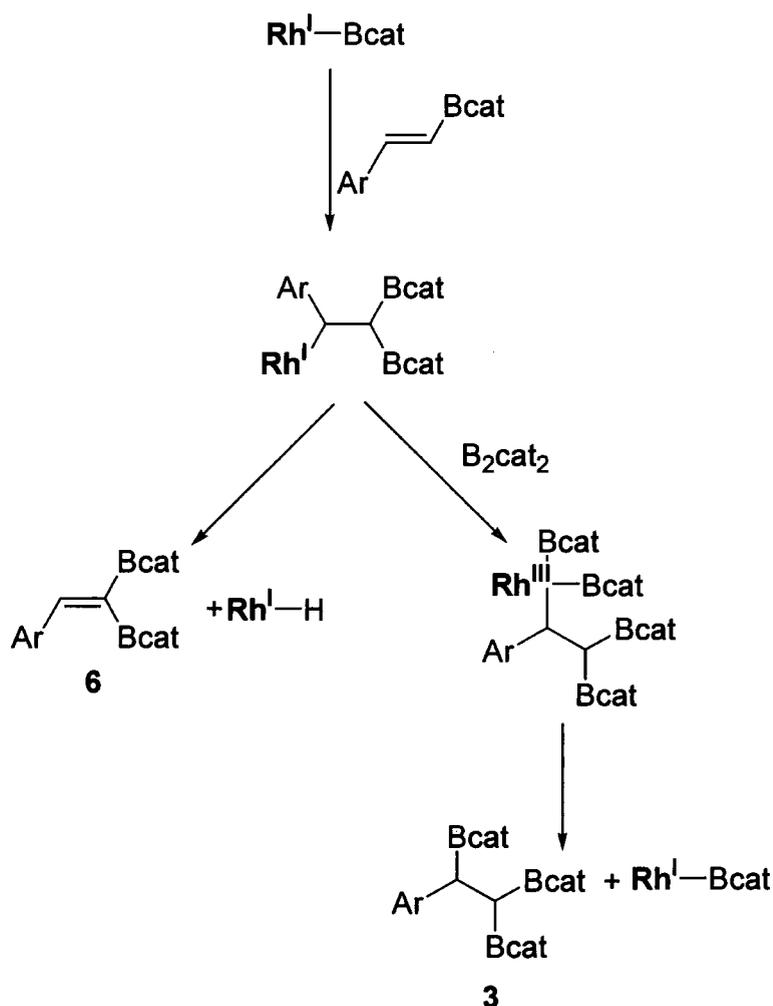
Scheme 3.4: Alternative mechanism of diboration not thought to be operating here

of the alkene linkage into a Rh—B bond. Reductive elimination of the B—C bond

yields **3**. Alternatively, β-hydride elimination gives **6**, and a [Rh(H)(Bcat)]   species.

Subsequent addition of HBcat, via this complex, to **1** gives **4** or **5**, and addition to **6**

yields **2**.

As discussed previously,[18,47] the regiochemistry of compound **2** is consistent with

insertion of the styryl C=C unit into a Rh—B bond, in such a fashion as to give an

η^3-benzyl intermediate. The presence of two Bcat groups on the terminal carbon of

the η^3-benzyl intermediate enhances the rate of β-hydride elimination leading to **6**.

This then reinserts into the Rh—B bond of the [Rh(H)(Bcat)] intermediate with the same regiochemistry to give a 2,2,2-trisboronate-η^3-benzyl complex, with no remaining β-hydrogen, and hence C—H reductive elimination leads to **2**. Thus, the overall catalytic process involves both diboration and a 1,2-hydrogen shift. The high yield of **2** in particular is a result of the tendency of alkyl-Rh complexes with β-boryl groups to undergo rapid β-hydride elimination. If **6** were to insert into the Rh—B bond of a [Rh(Bcat)$_2$] intermediate, this would lead to a tetra(boronate) product which we have not yet identified, *vide infra*.

It is clear from Table 3.1 that the presence of bulkier phosphines in the catalyst precursor produces significantly larger quantities of **5** in relation to **4** and, with P(*o*-tol)$_3$, no **4** is produced at all. This phosphine also provides the highest yield of **3**. Thus, with the bulkiest phosphine, our results suggest that insertion of C=C(Bcat) into the Rh—B bond in a [Rh(Bcat)$_2$] intermediate may take place with either of the two possible regiochemistries. If it inserts as discussed above to give the η^3-benzyl intermediate, β-hydride elimination again gives **6** + [Rh(H)(Bcat)] whereas reductive elimination would give **3**. However, if it inserts the other way around giving [Rh(Bcat)(CH(Bcat)CH(Bcat)Ar)] (Scheme 3.3 – bottom), which should be favoured on steric grounds, reductive elimination of the B—C bond yielding **3** is rapid compared with β-hydride elimination. Likewise, insertion of VBE into the Rh—H bond of any [Rh(H)(Bcat)] present would likely lead to [Rh(Bcat)(CH(Bcat)CH$_2$Ar)], again on steric grounds, giving **5** after B—C reductive elimination.

The significance of the experiments conducted in the presence of excess B$_2$cat$_2$ are as follows. If the mechanism involved a Rh(I) mono-boryl [Rh(Bcat)] (Scheme 3.4) species which inserts C=C(Bcat) to give e.g. [Rh^I(CHArCH(Bcat)$_2$)], we could envisage reaction of this species with B$_2$cat$_2$ to give [Rh^{III}(Bcat)$_2$(CHArCH(Bcat)$_2$)]

82

which would yield **3** by reductive elimination regenerating [Rh^I(Bcat)]. This would compete with β-hydride elimination to give [Rh^I(H)] + **6**. One would have expected this partitioning to be strongly dependent on the concentration of B$_2$cat$_2$. In fact, we see only a small rise in the formation of **2** with catalyst **8** for which **2** already predominated, and a rise in formation of **3** with catalyst (**10** + 4 P(o-tol)$_3$) for which **3** already predominated. Thus, our results do not support a Rh(I) boryl pathway to be operating here.

Clearly, the reaction is rather complex and a detailed mechanistic interpretation is not yet possible although some of the basic features have been identified.

As discussed above, products **2** and **3** result from the diboration of **1** by B$_2$cat$_2$. The formation of **6** generates HBcat, which reacts with **1** to give **4** and **5**. The fact that the total amount of **4** and **5** is always greater than the amount of **6**, however, indicates that there is either an excess of hydrogen or a deficiency of boron in the observed product mixture. One possibility is that small amounts of highly boronated organic species are present, such as ArCH(Bcat)C(Bcat)$_3$ (**11**) or ArC(Bcat)=C(Bcat)$_2$ (**12**), which result from the diboration and dehydrogenative borylation of **6** respectively. Both would be virtually undetectable by NMR spectroscopy in the complex product mixtures, for Ar = Ph, and very difficult to assign unambiguously for Ar = MeOC$_6$H$_4$. Thus **11** would give only a weak singlet in the region δ 3-4, probably obscured by **2**, and an MeO singlet for **11b**. Complex **12a** would contain only aromatic hydrogens and **12b** an additional MeO singlet. Both **11** and **12** would also be undetectable by GC/MS under conditions we typically employ. It is also possible that some B$_2$cat$_3$ is being formed as a decomposition product. Although rigorous techniques are employed to avoid the presence of any water, the possibility of small amounts of surface –OH on glass vessels cannot be ignored as source of H in these small scale reactions. Additionally,

there is evidence for the formation of THF-oligomers in reactions using [Rh(COE)$_2$(μ-Cl)]$_2$ / nPR$_3$ catalyst precursors, and it is possible that these could be partially boronated in some way.

The molecular structures of **1b** is shown in Figure 3.1, and important bond lengths and angles are listed in Table 3.2. In the solid state, **1b** is essentially planar with a slight twist (*ca.* 10°) of the phenyl ring out of the plane of the molecule. This twist is due presumably to a packing effect, resulting from an intermolecular π-interaction between catecholate and adjacent phenyl groups in an asymmetric manner. The sum of the angles around the boron atom is 360.0(1)°. Bond lengths and angles are comparable to the literature values for **1a**.[48]
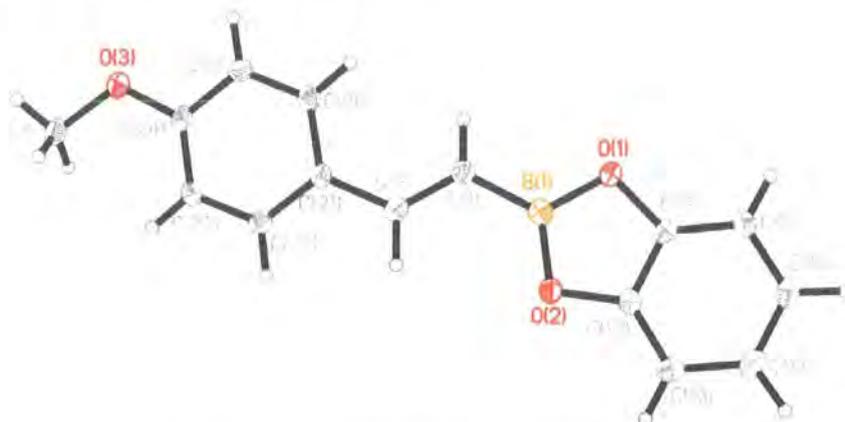
Figure 3.8: Molecular structure of 1b

*Table3. 2: Selected bond lengths (Å) and angles (°) for **1b***

	1b
C(1)—C(2)	1.340(2)
C(1)—B(1)	1.532(2)
B(1)—O(1)	1.3954(19)
B(1)—O(2)	1.3937(19)
C(11)—O(1)	1.3848(17)
C(2)—C(21)	1.470(2)
O(1)—B(1)—O(2)	111.32(13)
O(1)—B(1)—C(1)	123.98(14)
O(2)—B(1)—C(1)	124.70(14)

3.3 Conclusion

The catalysed diboration of styrylboronate esters provides a novel route to **2** and **3** under mild conditions using readily available boron reagents, with selectivity between the two isomeric products depending on the catalyst used. Whilst **3** represents 1,2-addition of the two borons to the C=C double bond, formation of **2** involves a 1,2-hydrogen shift and addition of both borons to a single carbon centre.

3.4 Experimental

All reactions were carried out under a dry nitrogen atmosphere using standard Schlenk techniques or an Innovative Technology, Inc. System 1 glove box. Glassware was oven dried before transfer into the glove box. THF was dried over sodium/benzophenone and $CDCl_3$ was dried over calcium hydride; both were distilled under nitrogen. B_2cat_2 was prepared by established procedures (see, for example, refs.[49-51] and checked for purity by NMR spectroscopy and GC/MS techniques. The catalyst precursors $[Rh(PPh_3)_3Cl]$,[52,53] $[Rh(COE)_2(\mu-Cl)]_2$,[54] $[Rh(dppb)(acac)]$[55] and $[Rh(dppm)(acac)]$[16,55] were prepared using published procedures and checked for purity by NMR spectroscopy. Phosphines were purchased from Aldrich or Strem and were checked for purity by ^1H and $^{31}P\{^1H\}$ NMR spectroscopy before use. ^1H NMR experiments were performed on Varian Inova 500 and Varian C 500 spectrometers and were referenced to residual protio-solvent resonances. $^{31}P\{^1H\}$ NMR experiments were performed on either Varian Unity 200 or Varian VXR-400 instruments and were referenced to external 85% H_3PO_4. Coupling constants are reported in Hertz (Hz).

3.4.1 Synthesis of (E)-*p*-R-C_6H_4-CH=CH-Bcat

The compounds phenyl acetylene or 4-methoxyphenylacetylene (0.0196 mol) and HBcat containing 'BH$_3$' impurity (2.35g, 0.0196 mol) in a round-bottom flask were stirred at ambient temperature for 1 h, after which an orange solid resulted. Successive recrystallisations from Et_2O/hexane (50:50) at −30 °C gave pure **1** as a white solid (~83% yield). For spectroscopic data see refs.[21,45,48]

3.4.2 General Procedure for the Catalysed Diboration of Styrylboronate Esters

A solution of B_2cat_2 (54 mg, 0.23 mmol), styrylboronate ester (0.23 mmol) and catalyst precursor (0.0023 mmol Rh) in THF (1.5 ml) was heated to 58°C under N_2 in a *ca.* 10 ml tube sealed with a Young's tap. After 12 h, the solution was allowed to cool to room temperature and the solvent removed *in vacuo*. The crude reaction mixture was then dissolved in $CDCl_3$ and analysed by high field ^1H NMR spectroscopy.

Selected NMR data ($CDCl_3$) and elemental analyses for boron containing products (see also refs):[21]

2a: δ 3.83 (s, 2H, $CH_2C(Bcat)_3$), 7.02-7.41 (ov. m, 17H, catecholate + phenyl H); $^{11}B\{^1H\}$ δ 35.3; $^{13}C\{^1H\}$ δ 33.6, 112.7, 122.9, 126.4, 128.7, 128.9, 141.4, 148.4. The $C(Bcat)_3$ resonance was not observed due to severe quadrupolar broadening. $C_{26}H_{19}B_3O_6$ requires C = 67.91, H = 4.16%. Found C = 68.09, H = 4.37%.

2b:[21] δ 3.67 (s, 3H, OCH_3), 3.83 (s, 2H, $CH_2C(Bcat)_3$), 6.66 (m, 2H, p-C_6H_4), 7.05-7.10 (ov. m, 8H, catecholate + p-C_6H_4), 7.25 (m, 6H, catecholate H); $^{11}B\{^1H\}$ δ 37.2; $^{13}C\{^1H\}$ 32.9, 55.2, 112.7, 113.9, 122.9, 129.8, 133.6, 148.4, 158.4. The $C(Bcat)_3$ resonance was not observed due to severe quadrupolar broadening.

3a: δ 2.75 (d, J_{H-H} = 11.7, 1H, $CH(Bcat)_2$), 3.69 (d, J_{H-H} = 11.7, 1H, $CHBcat$).

3b: δ 2.68 (d, J_{H-H} = 11.5, 1H, $CH(Bcat)_2$), 3.69-3.74 (ov. m, 4H, $CHBcat$ + OCH_3), 6.78 (m, 2H, p-C_6H_4), 7.01 (m, 2H, catecholate H), 7.14 (m, 2H, catecholate H), 7.33 (m, 2H, p-C_6H_4); $^{11}B\{^1H\}$ δ 23.8; $^{13}C\{^1H\}$ 13.6, 27.0, 55.2, 112.5, 112.6, 114.4, 122.7, 122.8, 129.0, 129.3, 140.0, 148.3, 158.1.

4a: δ 1.93 (2nd order dd, 1H, CH_2Bcat), 2.19 (2nd order dd, 1H, CH_2Bcat), 3.36 (2nd order dd, 1H, $CH(Bcat)$, 7.00-7.08 (m, 4H, catecholate H), 7.13-7.20 (m, 4H,

catecholate H), 7.27-7.41 (m, 5H, phenyl H); ^{11}B{^{1}H} δ 36.8. $C_{20}H_{16}B_2O_4$ requires C = 70.25, H = 4.72%; Found C = 70.12, H = 4.70%.

4b:[21, 45] δ 1.88(2nd order dd, 1H, CH_2Bcat), 2.12 (2nd order dd, 1H, CH_2Bcat), 3.28 (2nd order dd, 1H, CHBcat), 3.76 (s, 3H, OCH_3), 6.85 (m, 2H, p-C_6H_4), 7.00-7.18 (ov. m, 8H, catecholate H), 7.33 (m, 2H, p-C_6H_4); ^{11}B{^{1}H} δ 37.1.

5a: δ 2.12 (t, J_{H-H} = 7.8, 1H, CH(Bcat)$_2$), 3.69 (d, J_{H-H} = 7.8, 2H, CH_2).

5b: δ 2.12 (t, J_{H-H} = 7.8, 1H, CH(Bcat)$_2$), 3.66 (d, J_{H-H} = 7.8, 2H, CH_2).

6a[56] and **6b**: δ 8.40 (s, 1H, CH=C(Bcat)$_2$).

3.4.3 Crystallography

A colourless crystal of **1b** dimensions 0.30 x 0.15 x 0.05 mm^3 was used for the single crystal structure determination. Data were collected by Jacquie Burke using graphite monochromated Mo-Kα radiation (λ = 0.71073) on a Bruker SMART-CCD 1K detector diffractometer equipped with a Cryostream N_2 flow cooling device.[57] Series of narrow ω-scans (0.3°) were performed at several ϕ-settings in such a way as to cover a sphere of data to a maximum resolution of 0.77Å. Cell parameters were determined and refined using the SMART software[58] from the centroid values of 5356 reflections with 2θ values between 5° and 55°. Raw frame data were integrated using the SAINT program.[59] The structure was solved using Direct Methods and refined by full-matrix least squares on F^2 using SHELXTL.[60] The reflection intensities were corrected for absorption and other effects by the multi-scan method[61] based on multiple scans of identical and Laue equivalent reflections, T_{max} = 0.995, T_{min} = 0.973. All non-hydrogen atoms were refined with anisotropic atomic displacement parameters (adps). Hydrogen atoms were located from Difference

Fourier maps and their coordinates and isotropic adps refined. Crystallographic data for the structural analysis have been deposited with the Cambridge Crystallographic Data Centre, CCDC No. 172402.

Table 3.3: Crystal data and processing parameters for 1b

	1b
Empirical Formula	$C_{15}H_{13}BO_3$
Formula Weight	252.1
Temperature / K	105(2)
Diffractometer	Bruker SMART-CCD 1K
Wavelength / Å	0.71073
Crystal System	Monoclinic
Space Group	P2(1)/n
a / Å	6.8374(8)
b / Å	24.170(3)
c / Å	7.4719(8)
α / °	90
β / °	94.102(2)
γ / °	90
V / Å^3	1231.2(2)
D_{calc} / Mg m^{-3}	1.360
Z	4
μ (MoK$_\alpha$)/ mm^{-1}	0.093
F(000)	528

Theta Range for Data Collected / °	1.69 to 27.49
Reflections Collected	12831
Independent Reflections	2822
Refinement Method	Full-matrix least squares on F^2
Goodness-of-fit on F^2	1.066
Final R indices [I>2σ (I)]	$R_1 = 0.0425$,[b]
	$wR_2 = 0.0906$[b]
R indices (all data)	$R_1 = 0.0577$,
	$wR_2 = 0.0971$
Largest diff. peak and hole (e Å^{-3})	0.268 and −0.241

[a] – $GoF = [\Sigma_w \, (\, |F_o| \, - \, |F_c| \,)^2 \, / \, (NO - NV)]^{\frac{1}{2}}$

[b] – $I > 2\sigma(I)$

3.5 References

1   T. B. Marder and N. C. Norman, *Top. Catal.*, 1998, **5**, 63.

2   T. Ishiyama and N. Miyaura, *J. Organomet. Chem.*, 2000, **611**, 392.

3   T. Ishiyama, N. Matsuda, N. Miyaura, and A. Suzuki, *J. Am. Chem. Soc.*, 1993, **115**, 11018.

4   T. Ishiyama, N. Matsuda, M. Murata, F. Ozawa, A. Suzuki, and N. Miyaura, *Organometallics*, 1996, **15**, 713.

5   G. Lesley, P. Nguyen, N. J. Taylor, T. B. Marder, A. J. Scott, W. Clegg, and N. C. Norman, *Organometallics*, 1996, **15**, 5137.

6   C. N. Iverson and M. R. Smith, III, *Organometallics*, 1996, **15**, 5155.

7   Q. Cui, D. G. Musaev, and K. Morokuma, *Organometallics*, 1997, **16**, 1355.

8   Q. Cui, D. G. Musaev, and K. Morokuma, *Organometallics*, 1998, **17**, 742.

9   Q. Cui, D. G. Musaev, and K. Morokuma, *Organometallics*, 1998, **17**, 1383.

10   R. Ll. Thomas, F. E. S. Souza, and T. B. Marder, *J. Chem. Soc., Dalton Trans.*, 2001, 1650.

11   R. T. Baker, P. Nguyen, T. B. Marder, and S. A. Westcott, *Angew. Chem. Int. Ed. Engl.*, 1995, **34**, 1336.

12   T. Ishiyama, M. Yamamoto, and N. Miyaura, *Chem. Commun.*, 1997, 689.

13   C. N. Iverson and M. R. Smith, III, *Organometallics*, 1997, **16**, 2757.

14   T. B. Marder, N. C. Norman, and C. R. Rice, *Tetrahedron Lett.*, 1998, **39**, 155.

15   G. Mann, K. D. John, and R. T. Baker, *Org. Lett.*, 2000, **2**, 2105.

16   C. Y. Dai, E. G. Robins, A. J. Scott, W. Clegg, D. S. Yufit, J. A. K. Howard, and T. B. Marder, *Chem. Commun.*, 1998, 1983.

17 J. M. Brown and G. C. Lloyd-Jones, *Chem. Commun.*, 1992, 710.

18 K. Burgess, W. A. van der Donk, S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *J. Am. Chem. Soc.*, 1992, **114**, 9350.

19 S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

20 J. M. Brown and G. C. Lloyd-Jones, *J. Am. Chem. Soc.*, 1994, **116**, 866.

21 R. T. Baker, J. C. Calabrese, S. A. Westcott, and T. B. Marder, *J. Am. Chem. Soc.*, 1995, **117**, 8777.

22 D. H. Motry and M. R. Smith, III, *J. Am. Chem. Soc.*, 1995, **117**, 6615.

23 D. R. Lantero, D. L. Ward, and M. R. Smith, III, *J. Am. Chem. Soc.*, 1997, **119**, 9699.

24 D. H. Motry, A. G. Brazil, and M. R. Smith, III, *J. Am. Chem. Soc.*, 1997, **119**, 2743.

25 T. M. Cameron, R. T. Baker, and S. A. Westcott, *Chem. Commun.*, 1998, 2395.

26 M. Murata, S. Watanabe, and Y. Masuda, *Tetrahedron Lett.*, 1999, **40**, 2585.

27 C. M. Vogels, P. G. Hayes, M. P. Shaver, and S. A. Westcott, *Chem. Commun.*, 2000, 51.

28 K. Burgess and M. J. Ohlmeyer, *Chem. Rev.*, 1991, **91**, 1179.

29 A. H. Hoveyda, D. A. Evans, and G. C. Fu, *Chem. Rev.*, 1993, **93**, 1307.

30 I. Beletskaya and A. Pelter, *Tetrahedron*, 1997, **53**, 4957.

31 R. B. Castle and D. S. Matteson, *J. Am. Chem. Soc.*, 1968, **90**, 2194.

32 R. B. Castle and D. S. Matteson, *J. Organomet. Chem.*, 1969, **20**, 19.

33   D. S. Matteson, *Synthesis*, 1975, 147.

34   Y. Gu, H. Pritzkow, and W. Siebert, *Eur. J. Inorg. Chem.*, 2001, 373.

35   C. F. Lane and G. W. Kabalka, *Tetrahedron*, 1976, **32**, 981.

36   H. C. Brown and S. K. Gupta, *J. Am. Chem. Soc.*, 1972, **94**, 4370.

37   D. Männig and H. Nöth, *J. Chem. Soc., Dalton Trans.*, 1985, 1689.

38   S. A. Westcott, H. P. Blom, T. B. Marder, R. T. Baker, and J. C. Calabrese, *Inorg. Chem.*, 1993, **32**, 2175.

39   K. Burgess and M. Jaspars, *Organometallics*, 1993, **12**, 4197.

40   A. Arase, Y. Nunokawa, Y. Masuda, and M. Hoshi, *Chem. Commun.*, 1991, 205.

41   A. Arase, Y. Nunokowa, Y. Masuda, and M. Hoshi, *Chem. Commun.*, 1992, 51.

42   A. Arase, M. Hoshi, A. Mijin, and K. Nishi, *Synth. Commun.*, 1995, **25**, 1957.

43   C. E. Garrett and G. C. Fu, *J. Org. Chem.*, 1996, **61**, 3224.

44   P. Nguyen, PhD Thesis, University of Waterloo, Ontario, Canada, 1995.

45   R. T. Baker, J. C. Calabrese, S. A. Westcott, P. Nguyen, and T. B. Marder, *J. Am. Chem. Soc.*, 1993, **155**, 4367.

46   P. Nguyen, G. Lesley, N. J. Taylor, T. B. Marder, N. L. Pickett, W. Clegg, M. R. J. Elsegood, and N. C. Norman, *Inorg. Chem.*, 1994, **33**, 4623.

47   T. Hayashi, Y. Matsumoto, and Y. Ito, *J. Am. Chem. Soc.*, 1989, **111**, 3426.

48   W. Clegg, T. B. Marder, A. J. Scott, C. Wiesauer, and W. Weissensteiner, *Acta. Cryst.*, 2001, **E57**, o63.

49   F. J. Lawlor, N. C. Norman, N. L. Pickett, E. G. Robins, P. Nguyen, G. Lesley, T. B. Marder, J. A. Ashmore, and J. C. Green, *Inorg. Chem.*, 1998, **37**, 5282.

50   W. Clegg, M. R. J. Elsegood, F. J. Lawlor, N. C. Norman, N. L. Pickett, E. G. Robins, A. J. Scott, P. Nguyen, N. J. Taylor, and T. B. Marder, *Inorg. Chem.*, 1998, **37**, 5289.

51   M. J. Lesley, N. C. Norman, and C. R. Rice, *Inorg. Synth.*, submitted.

52   J. A. Osborn, G. Wilkinson, and J. J. Mrowca, *Inorg. Synth.*, 1972, **10**, 67.

53   J. A. Osborn and G. Wilkinson, *Inorg. Synth.*, 1990, **28**, 77.

54   A. van der Ent and A. Onderdelinden, *Inorg. Synth.*, 1973, **14**, 92.

55   P. J. Fennis, P. H. M. Budzelaar, J. H. G. Frijns, and A. G. Orpen, *J. Organomet. Chem.*, 1990, **393**, 287.

56   D. S. Matteson and P. B. Tripathy, *J. Organomet. Chem.*, 1974, **69**, 53.

57   J. Cosier and A. M. Glazer, *J. Appl. Cryst.*, 1986, **19**, 105.

58   Bruker, SMART-NT. Data Collection Software. Version 5.0. Bruker Analytical X-ray Instruments Inc., WI, 1998.

59   Bruker, SAINT-NT. Data Reduction Software. Version 5.0. Bruker Analytical X-ray Instruments Inc., WI, 1998.

60   Bruker, SHELXTL-NT. Version 5.1. Bruker Analytical X-ray Instruments Inc., Wisconsin, 1998.

61   G. M. Sheldrick, SADABS. Empirical Absorption Correction Program. University of Göttingen, Germany, 1998.

Chapter 4

Rhodium Catalysed Dehydrogenative Borylation of 1,1-Disubstituted

Alkenes

4.1 Introduction

Vinylboronate esters (VBEs) are particularly useful synthetic intermediates in many reactions, including C—C bond formation *via* Pd-catalysed Suzuki-Miyaura cross-coupling reactions.[1,2] Vinylboronates are also important for homologation to prepare chiral allylboronates,[3] in Diels-Alder reactions,[4,5] in multicomponent chiral amine synthesis,[6,7] in the preparation of chiral cyclopropanones,[8] and in Heck reactions.[9] VBEs can be prepared by uncatalysed[10,11] or transition-metal catalysed[12-17] hydroboration of alkynes, Eq. (1). More recently, however, VBEs have been synthesised by Pd-catalysed cross-coupling of alkenyl halides or triflates with B_2pin_2 (pin = $OCMe_2CMe_2O$) at 50-80°C,[18,19] Eq. (2), by reaction of 1-halo-1-lithioalkenes and pinacolborane at -110°C,[20] Eq. (3), by Pt-catalysed 1,2-diboration of alkynes,[21-25] Eq. (4), by Pd-catalysed diboration of methylenecyclopropanes,[26] Eq. (5) and by Pd-catalysed borylsilylation or borylstannylation of 1,2-dienes,[27] Eq. (6). An exciting alternative is the catalytic dehydrogenative borylation of alkenes,[13,28-37] Eq. (7), which would allow the direct synthesis of 1,1-disubstituted VBEs that cannot be made by hydroboration of alkynes. However, conditions must be found wherein the H_2 produced is **not** consumed *via* hydrogenation of half of the alkene substrate. Thus, in 1992, Brown *et al.*[28,30] showed that reaction of 4-vinyl anisole with *N*-isopropyl oxazaborolidine in the presence of an $[(\eta^2\text{-alkene})_2RhCl]_2$ complex gave the *trans*-VBE and ethyl anisole in a 1:1 ratio. Several reports then followed using Rh,[13,29,34,35,37] Ti,[31,33] Ru,[32,37] Pd[36] and

Pt[36] based catalysts, but only in one case[29] was the VBE produced in the absence of significant hydrogenation, and a 1,1-disubstituted alkene was employed. We present herein a high yield, highly selective catalytic synthesis of VBEs, including 1,1-disubstituted VBEs, from alkenes without significant hydrogenation or hydroboration using the simple catalyst [RhCl(CO)(PPh$_3$)$_2$] (1) and the diboron reagents B$_2$pin$_2$ or B$_2$neop$_2$ (neop = neopentylglycolato, OCH$_2$CMe$_2$CH$_2$O) all of which are commercially available. Preliminary studies on this system were carries out by F. E. S. Souza.[38] This chapter presents a more detailed re-examination of this system, along with new substrates, catalysts and more extensive mechanistic studies.

$$R_1 \underrel{\equiv}{} R_2 \xrightarrow[\substack{80^\circ C \text{ neat or} \\ R.T. \text{ w/catalyst}}]{H-B(OR)_2} \underset{R_1 \quad R_2}{\overset{B(OR)_2}{\diagdown}} \qquad \textbf{Equation 1}$$

$$\underset{R_2 \quad X}{\overset{R_1 \quad R_3}{\diagdown}} \xrightarrow[\text{PdCl}_2(\text{PR}_3)_2, \text{ base}]{B_2\text{pin}_2} \underset{R_2 \quad Bpin}{\overset{R_1 \quad R_3}{\diagdown}} \qquad \textbf{Equation 2}$$

X = Br, I, OTf

$$\underset{R_2 \quad X_2}{\overset{R_1 \quad X_1}{\diagdown}} \xrightarrow[\text{-110}^\circ C, \text{ THF/Et}_2O]{\substack{1. \text{ BuLi} \\ 2. \text{ B}_2\text{pin}_2}} \underset{R_2 \quad Bpin}{\overset{R_1 \quad Bpin}{\diagdown}} \qquad \textbf{Equation 3}$$

X$_1$ = halogen, X$_2$ = X$_1$ or H

R_1—≡—R_2 $\xrightarrow[\text{R.T.}]{\text{B}_2(\text{OR})_4 \text{ / PR}_3 \text{ / Pt(NBE)}_3}$ (RO)$_2$B, B(OR)$_2$ ... R_1, R_2 Equation 4

$\xrightarrow[\text{toluene}]{\text{B}_2\text{pin}_2 \text{ / Pt(0), 90°C}}$ Bpin ... Bpin Equation 5

R_1 / R_2 =•= $\xrightarrow[\text{80°C, THF}]{\text{PhMe}_2\text{Si—Bpin}}$ R_1, Bpin / R_2—SiMe$_2$Ph + Bpin / R_1—SiMe$_2$Ph / R_2 Equation 6

R_1 R_3 / R_2 H $\xrightarrow{\text{HB(OR)}_2 \text{ or B}_2(\text{OR})_4}$ R_1 R_3 / R_2 Bpin Equation 7

Equations 1-7: Routes to VBE's

4.2 Results and Discussion

In the course of our studies on alkene diboration,[39-41] we examined the reaction of vinyl anisole (VA) with B$_2$pin$_2$ catalysed by 1 in a variety of solvents. Toluene, THF and 1,4-dioxane all gave complicated mixtures containing dehydrogenative borylation, diboration (giving the bis(boronate) ester or BBE), hydroboration and hydrogenation products and, in some cases, vinyl-bis(boronate) esters (VBBEs). In contrast, reaction in CH$_3$CN was very clean giving 93% VBE but the rate was much slower than that in e.g. toluene. We therefore examined the reaction in 3:1 toluene:acetonitrile (3:1 T:A) which proved an excellent compromise between selectivity and rate, giving an 88% selectivity towards VBE, with 12%

hydroboration and 100% conversion in 2 days (Table 1, Entry 1), Figure 4.1. Styrene (Table 1, Entry 8) and 4-chlorostyrene (Entry 9) also produced predominantly VBE with 70 and 79% selectivity respectively. Hydroboration is again the main side product but both give small quantities of the VBBE as well as a trace of diboration product in the case of 4-chlorostyrene, and hydrogenation product in the case of styrene. Both reactions went to 100% conversion, styrene in 5 days and 4-chlorostyrene in 1 day.

The reaction of allyl anisole with 0.67 equiv. B_2pin_2 and 3 mol% **1** int 3:1 T:A yielded several isomers of VBEs (51%, 46% major isomer, 5 isomers in total) and VBBEs (49%, 19% major isomer, 4 isomers) with 66% conversion in 5 days (Entry 10). The large number of isomers produced made identification of individual isomers difficult and also indicates that allyl anisole is unsuitable with this system.

The reaction of 1-octene with 0.67 equiv. B_2pin_2 and 3 mol% **1** in 1 ml of 3:1 T:A (Entry 11) gave 62% selectivity for VBBEs, 43% being the $C_6H_{13}CH=C(Bpin)_2$ isomer, with 38% dehydrogenative borylation. The large number of isomers is most likely due to isomerisation of the double bond along the octene chain. Repeating the reaction in 2 ml of 3:1 T:A (Entry 12) showed a near 1:1 ratio of VBEs:VBBEs, indicating that concentration effects are important in this reaction.

Reaction of VA with 2 equiv. of B_2pin_2 and 5 mol% **1** in both 3:1 TA (Entry 2) and gave 85% selectivity for VBBE, 14% VBE and 1% hydroboration. Thus, in each of the above reactions, both H's of the $=CH_2$ group were replaced by Bpin in a single catalytic reaction.

The 1,2-disubstituted alkene, indene, and the 1,1,2-trisubstituted alkenes 2-methyl-2-butene and 3,4,4-trimethyl-2-pentene proved rather unreactive. Indene showed 90% selectivity for VBE, with 10% hydroboration, but only 20% conversion over 6 days was observed (Entry 13). No reaction at all was observed with either tri-substituted alkenes (Entries 14 and 15).

Therefore, this system is generally unsuitable for dehydrogenative borylation of 1,2-disubstituted alkenes.
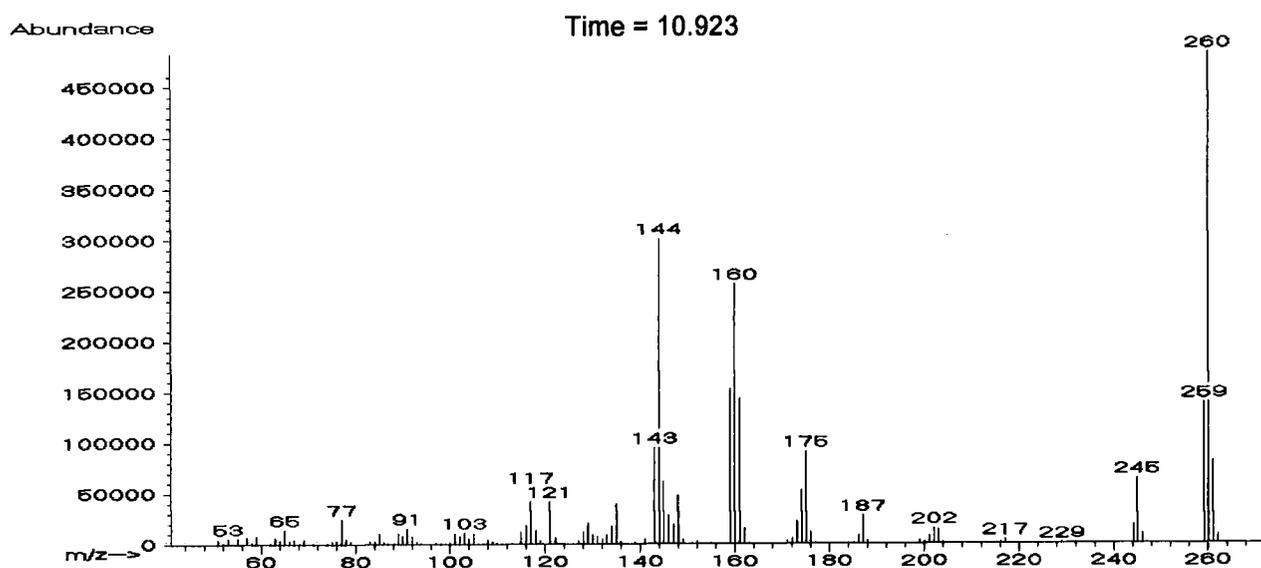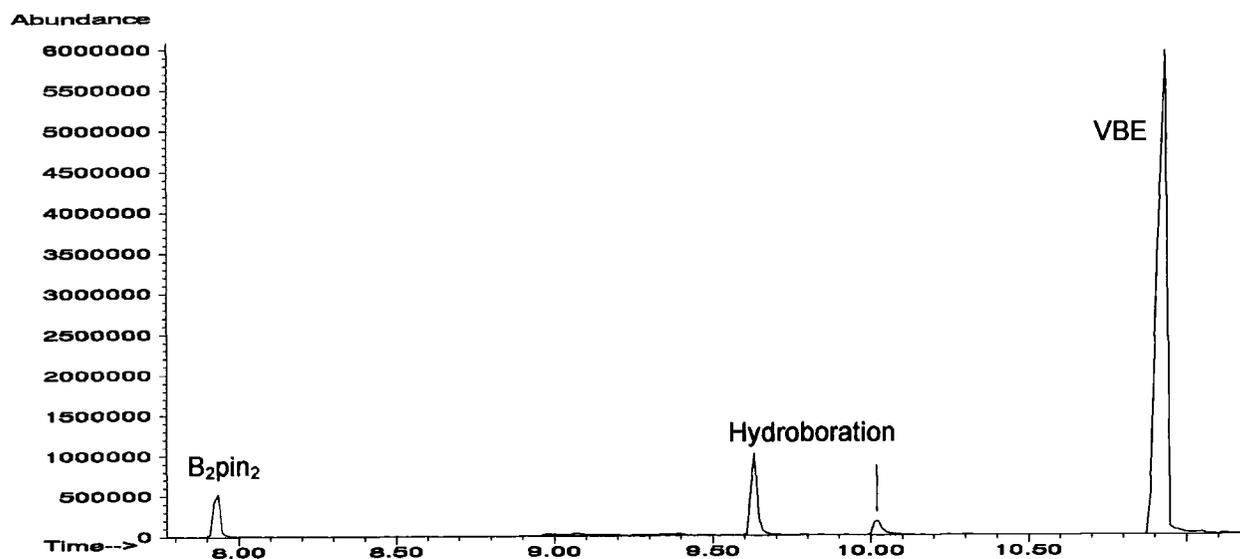
Figure 4.1: Top: GC of reaction of vinyl anisole with B₂pin₂. Bottom: Mass spectrum of

4-MeO-C₆H₄-CH=CHBpin

Table 1: Product distributions for the dehydrogenative borylation of alkenes with B_2pin_2, HBpin and B_2neop_2

Entry	Substrate	Boron Reagent / Catalyst[a]	Hydrogenation	Hydroboration	BBE	Total VBE (maj. isomer)	VBBE (maj. isomer)	Time /days	Solvent[b]	% Conversion
1	vinyl anisole	A/1	Trace	12		88		2	3:1 T:A	100
2	vinyl anisole[c]	A/1		1		14	85 (83)	5	3:1 T:A	100
3	vinyl anisole	A/2	8	16		76		3	3:1 T:A	100
4	vinyl anisole	A/3	4	25		69	2	3	3:1 T:A	95
5	vinyl anisole	A/4	5	39		56		1	3:1 T:A	76
6	vinyl anisole	A/5	2	36	18	44		1	3:1 T:A	83
7	vinyl anisole	C/1	19	6		75		1	3:1 T:A	81
8	styrene	A/1	5	17		71	7	5	3:1 T:A	100
9	4-chlorostyrene	A/1		19	1	79	1	1	3:1 T:A	100
10	allyl anisole	A/1				51(46)	49(19)	5	3:1 T:A	66
11	octene[d]	A/1				43(31)	67(46)	3	3:1 T:A	100[e]
12	octene	A/1				49(39)	51(39)	3	3:1 T:A	100[e]
13	indene	A/1		10		90		6	3:1 T:A	20
14	2-methyl-2-butene	A/1						3	3:1 T:A	0
15	3,4,4-trimethyl-2-pentene	A/1						3	3:1 T:A	0
16	α-methyl styrene	A/1		1		99 (97)		4	3:1 T:A	68
17	α-methyl styrene[f]	A/1		Trace		100 (98)		10 mins	3: T:A	43
18	α-methyl styrene	A/1		9	4	87 (74)		2	T	72
19	α-methyl styrene	A/1		Trace		100 (98)		6	A	70
20	α-methyl styrene[g]	A/1				100 (97)		3	3:1 T:A	90
21	α-methyl styrene[h]	A/1				100 (98)		2	3:1 T:A	100
22	α-methyl styrene	B/1		12		88 (86)		2	3:1 T:A	79

100

23	α-methyl styrene	B/1		3		98 (95)	4	A	72
24	α-methyl styrene	A/2	5			95 (89)	3	3:1 T:A	93
25	α-methyl styrene	A/3	7	2		91 (85)	3	3:1 T:A	91
26	α-methyl styrene	A/4		38		62 + Trace	1	3:1 T:A	27
27	α-methyl styrene	A/5		2	Trace	98 + Trace	2	3:1 T:A	43
28	α-methyl styrene	C/1		9		91 + Trace	1	3:1 T:A	49
29	α-methyl styrene[i]	C/1	6	10		84 + Trace	3	3:1 T:A	49
30	1,1-diphenylethylene	A/1		2		98	4	3:1 T:A	48
31	1,1-diphenylethylene	A/1				100	10 mins	3:1 T:A	58
32	1,1-diphenylethylene	A/1				100	20 mins	3:1 T:A	58
33	1,1-diphenylethylene	A/1		8	4	88	1	T	53
34	1,1-diphenylethylene	A/1		Trace		100	4	A	42
35	1,1-diphenylethylene[g]	A/1		1		99	3	3:1 T:A	76
36	1,1-diphenylethylene[h]	A/1		1		99	3	3:1 T:A	100
37	1,1-diphenylethylene	B/1		16		84	2	3:1 T:A	58
38	1,1-diphenylethylene	B/1		4		96	3	A	66
39	1,1-diphenylethylene	C/1		5		95	2	3:1 T:A	20
40	1,1-diphenylethylene[i]	C/1		9	1	90	3	3:1 T:A	41
41	methylene cyclopentane	A/1				100 (92, 4, 4), 3 iso	3	3:1 T:A	100[e]
42	methylene cyclohexane	A/1		8		92	5	3:1 T:A	80[e]

[a] A = B_2pin_2. B = HBpin. C = B_2neop_2. 1 = *trans*-[Rh(Cl)(CO)(PPh$_3$)$_2$]. 2 = [Rh(Cl)(PPh$_3$)$_3$]. 3 = [Rh(μ-Cl)(PPh$_3$)$_2$]$_2$ 4 = [Rh(acac)(dppm)]. 5 = [Rh(acac)(dppb)]. [b] T = toluene; A = acetonitrile. [c] 2 equiv. B_2pin_2 and 5 mol% catalyst used. [d] 1ml solvent used. [e] Completion determined by ^{1}H NMR spectroscopy. [f] Reactions conducted in a microwave reactor. [g] 5 mol% catalyst was used [h] 1 equiv. B_2pin_2 was used. [i] 1 equiv. B_2neop_2 used.

101

In contrast, reaction of 0.67 equiv. B_2pin_2 with α-methylstyrene, a 1,1-disubstituted alkene, in the presence of 3 mol% of **1** in 3:1 T:A at 80°C gave 97% (E)-Ph(Me)C=CH(Bpin) (**E-VBE**), the configuration of which was determined by NOESY NMR spectroscopy, 2% (Z)-Ph(Me)C=CH(Bpin) (**Z-VBE**) and 1% Ph(Me)(H)C-CH$_2$Bpin, with the reaction proceeding to 68% completion in 4 days (Entry 16), Figure 4.2. Under the same reaction conditions, 1,1-diphenylethylene proved less reactive than α-methylstyrene, most likely due to increased steric bulk, giving 89% VBE with 48% conversion in 4 days (Entry 30), Figure 4.3. Methylenecyclopentane gave 3 isomeric VBEs with 100% conversion after 3 days (Entry 41). Methylenecyclohexane gives 98% of VBE in a reaction that provides 80% conversion after 5 days (Entry 42).

The reaction with α-methylstyrene was repeated using a microwave reactor with heating at 150°C for 20 minutes. These conditions proved too mild, however, and resulted in a conversion of only 43% (Entry 17). The reaction with 1,1-diphenylethylene was also repeated using a microwave reactor, at 200°C for 10 minutes. In this case, product distributions were similar but conversion was increased to 58% (Entry 31). Increasing the reaction time to 20 minutes (Entry 32), however, did not further increase conversion again showing catalysts deactivation and the lower reactivity of 1,1-disubstituted alkenes relative to mono-substituted alkenes.

One possible pathway to the products observed is shown in Scheme 4.1. Oxidative addition of B_2 to the Rh centre gives a Rh(III) bis-boryl. Subsequent alkene insertion and β-hydride elimination yields VBE and a Rh(III) hydrido-boryl species. This can then insert alkene reversibly into the Rh—H bond or into the Rh—B bond, the former potentially leading to hydroboration after reductive elimination, whereas the latter could lead to more VBE by

Figure 4.2: The GC of a typical reaction between α-methylstyrene and B_2pin_2 (top) and the

mass spectrum of the VBE (bottom)

Figure 4.3: The GC of a typical reaction between 1,1-diphenylethylene and B_2pin_2 (top) and the mass spectrum of the VBE (bottom)

β-hydride elimination, leaving a Rh(H)$_2$ species. What is remarkable is the lack of significant

hydroboration or hydrogenation products.

Scheme 4.1: Possible pathway to observed products.

Investigation of solvent effects with α-methylstyrene and 1,1-diphenylethylene using neat

toluene (Entries 18 and 33) or acetonitrile (Entries 19 and 34) showed similar results to those

with VA, with the reactions proving more selective but slower in acetonitrile, Figures 4.4 and

4.5. It is clear, therefore, that acetonitrile shuts down pathways that result in products other

than VBEs. Thus, reductive elimination subsequent to insertion of alkene into one Rh—B

bond is inhibited by CH$_3$CN, allowing β-hydride elimination to predominate. Theoretical

Figure 4.4: The GC of the reaction of α-methylstyrene with B₂pin₂ in toluene (top) and acetonitrile (bottom)

106
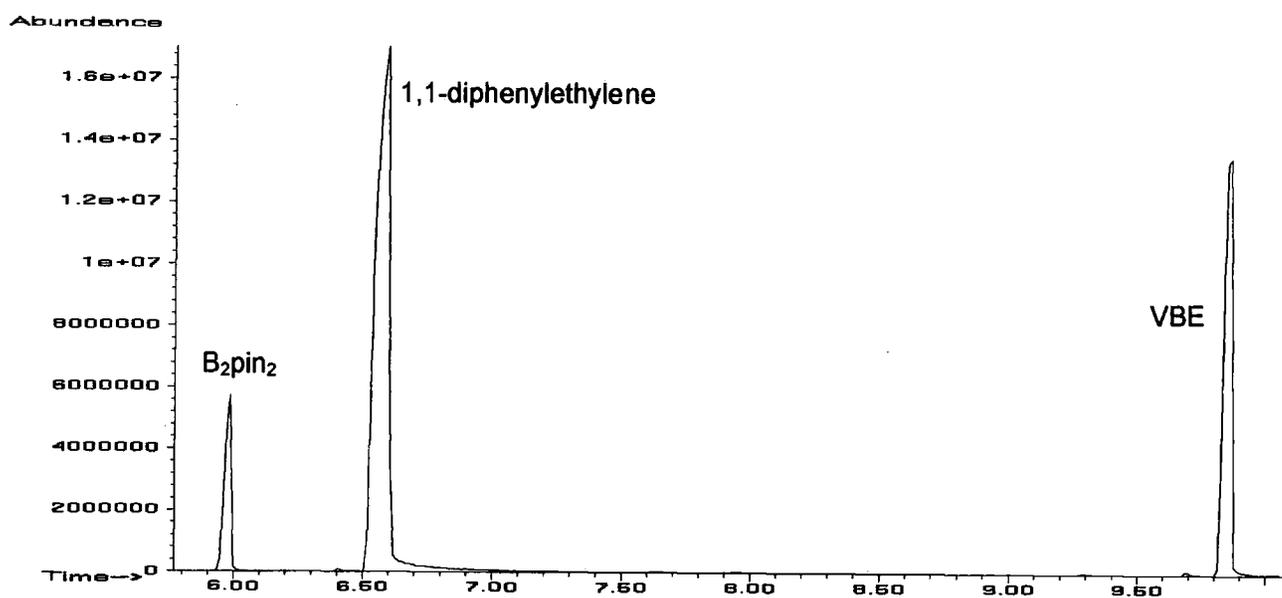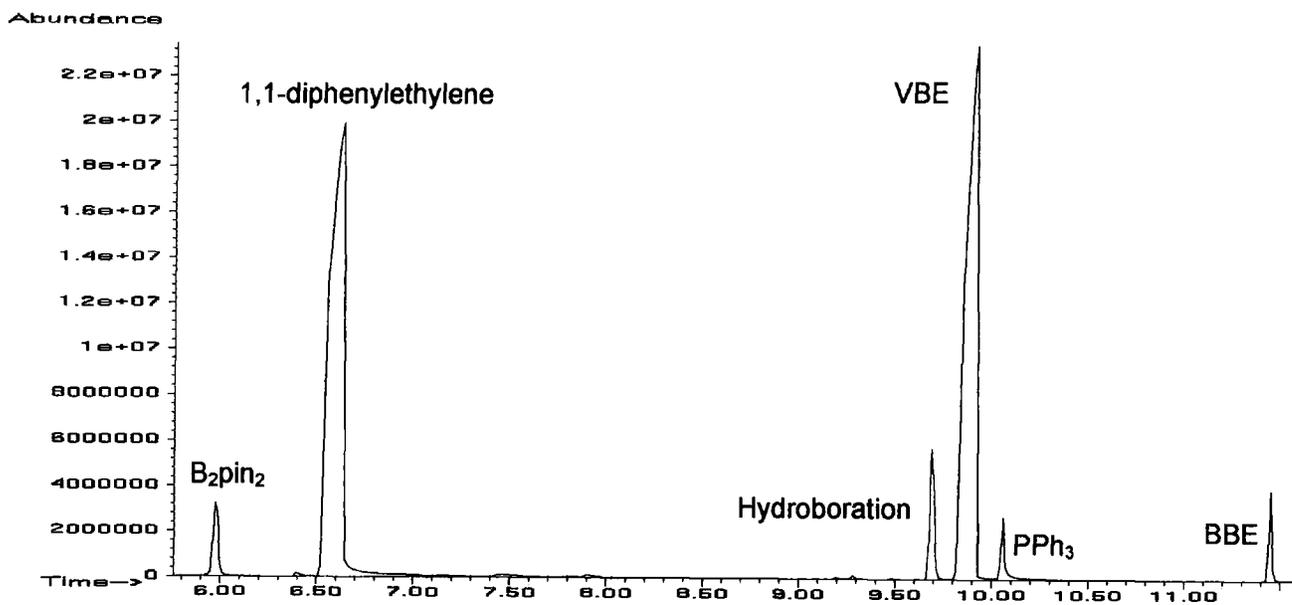
Figure 4.5: The GC of the reaction of 1,1-diphenylethylene with B₂pin₂ in toluene (top) and acetonitrile (bottom)

studies have suggested[42] that intramolecular interaction of a $B(OH)_2$ oxygen with Rh in the model intermediate **4a**, Scheme 4.2, yields a configuration from which C—H reductive elimination is enhanced. However, the presence of a strongly coordinating solvent such as acetonitrile could inhibit the intramolecular coordination of the β-$B(OH)_2$ oxygen, **4b** in Scheme 4.2, leading instead to β-hydride elimination and the VBE product. Additionally, if the acetonitrile is binding to an active site on the catalyst, this could account for the observed lower reactivity of the system in this solvent.
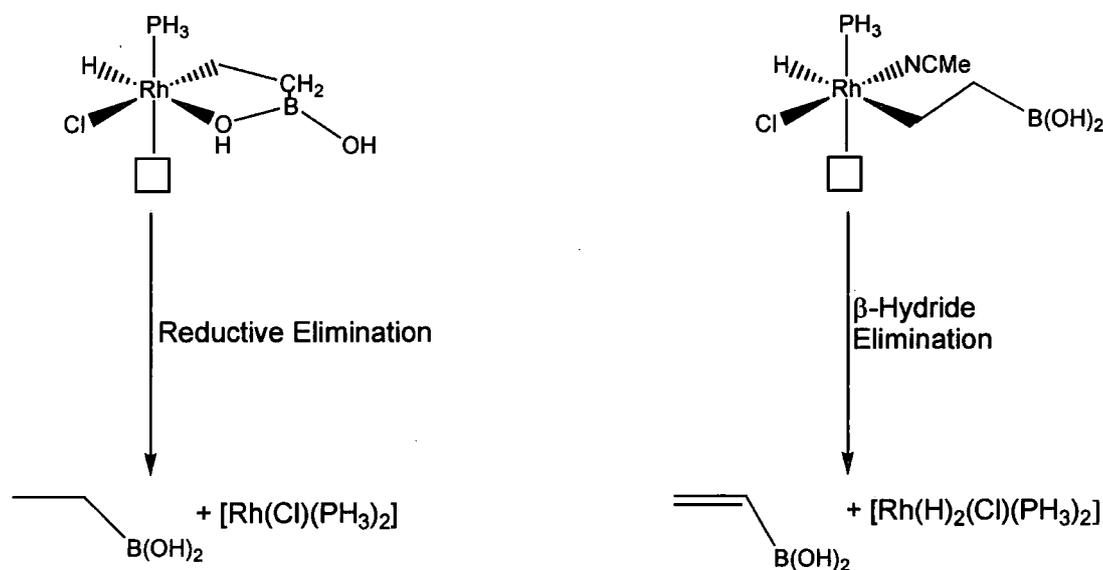
Scheme 4.2: Effect of coordinating solvent on proposed intermediate

Of the 1,1-disubstituted alkenes used, only methylenecyclopentane reached 100% conversion before catalytic activity ceased. In the case of the α-methylstyrene, 68% conversion corresponds to consumption of ~50% of B_2pin_2 suggesting that catalytic activity diminishes after one of the 2 borons is consumed. With 1,1-diphenylethylene 48% conversion represents ~30% consumption of B_2pin_2. Reactions were run, therefore, using 0.67 equiv. B_2pin_2 with 5 mol% **1** or 1 equiv. of B_2pin_2 with 3 mol% **1**. Reactions with 5 mol% catalyst did lead to

higher conversions of 90% for α-methylstyrene (Entry 20) and 70% for 1,1-diphenylethylene (Entry 35) with similar product distributions to Entries 16 and 30. The former indicates some consumption of the second boron of B_2pin_2 with this substrate. The reactions with 1 equiv. of B_2pin_2 both went to 100% completion (Entries 21 and 36) with 100% and 99% yields of VBEs respectively. The implication here is that the RhB_2 species is more reactive than the proposed [Rh(H)(B)] species which would apparently result from consumption of the first boron. The $^1H\{^{11}B\}$ and ^{11}B NMR spectra of a typical reaction mixture showed peaks consistent with the presence of HBpin, the former showing a singlet at δ 4.10, the latter a doublet at δ 28.5 with $J_{B-H} = 178$ Hz.

To investigate the behaviour of the proposed [Rh(H)(B)] intermediate, both α-methylstyrene and 1,1-diphenylethylene were reacted with 1.37 equiv. of HBpin in place of 0.67 equiv. of B_2pin_2. Both gave predominantly VBEs but with significantly more hydroboration. Reaction with α-methylstyrene gave 86% E-VBE, 2% Z-VBE and 12% hydroboration, with 79% conversion in 2 days (Entry 22), Figure 4.6; reaction with 1,1-diphenylethylene gave 84% VBE and 16% hydroboration, with 58% conversion in 2 days (Entry 37), Figure 4.7. It is not clear why the activity of the Rh(H)(Bpin) species is higher when HBpin rather than B_2pin_2 is used as the source of boron. In all cases, however, the colour of the solution changes from clear yellow to clear green over a period of 24-48h, with no precipitate being observed. However, the $^{31}P\{^1H\}$ NMR spectrum of the final solution shows only a doublet due to 1. It is possible that a small amount metal deposition is occurring which is responsible for the green colour.
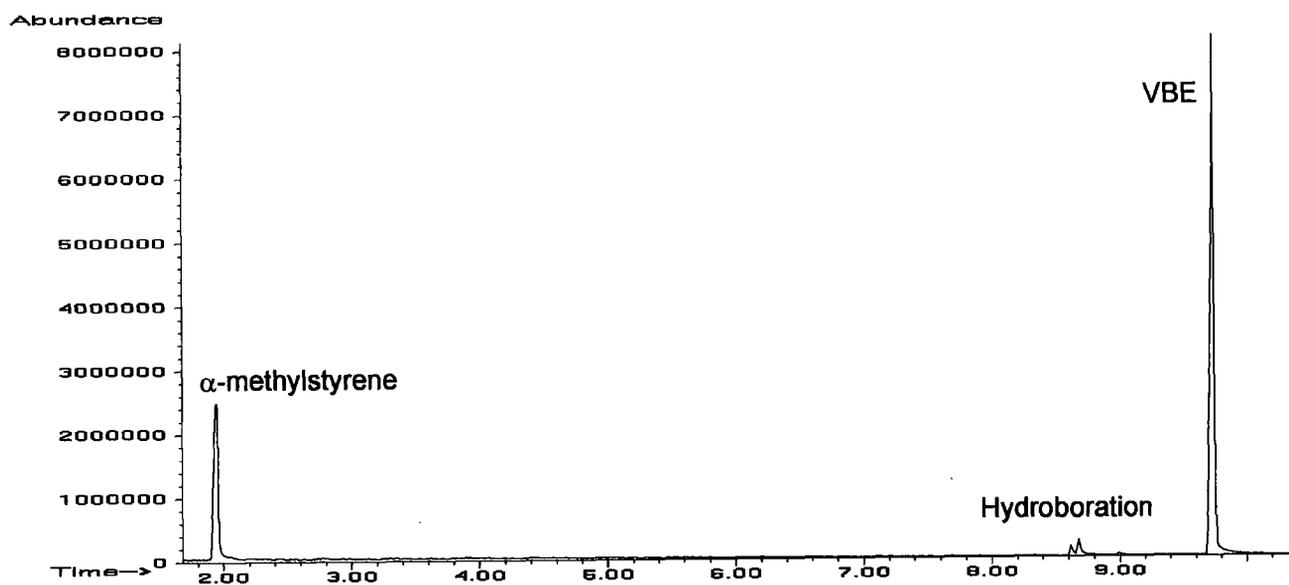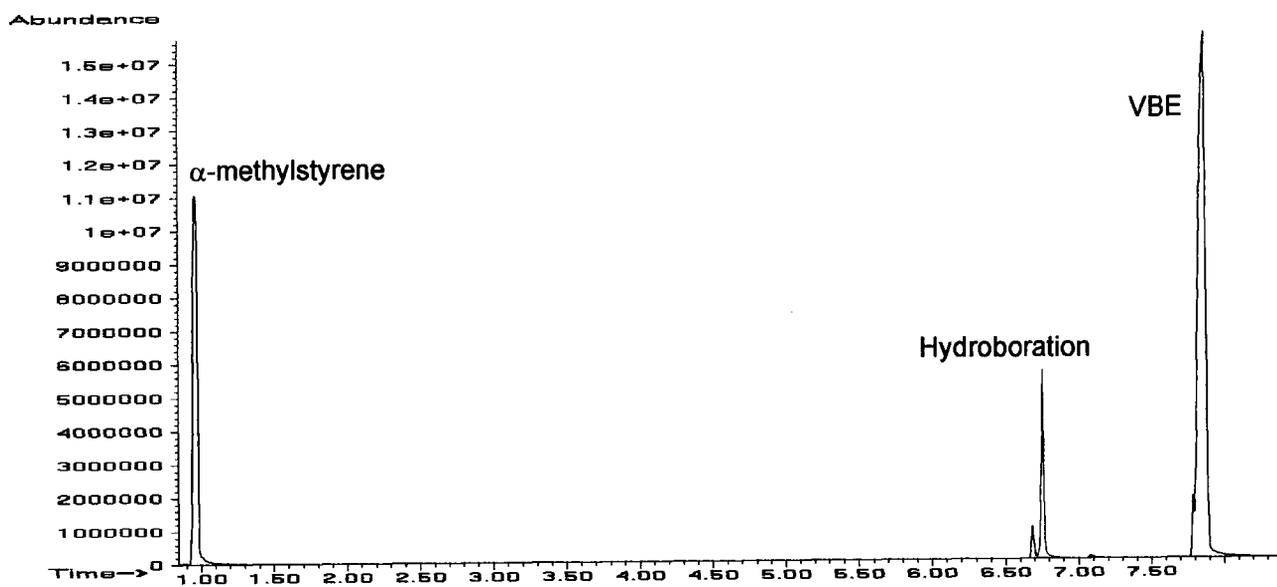
Figure 4.6: The GC of the reaction of α-methylstyrene with B₂pin₂ in 3:1 toluene:acetonitrile (top) and acetonitrile (bottom)

110
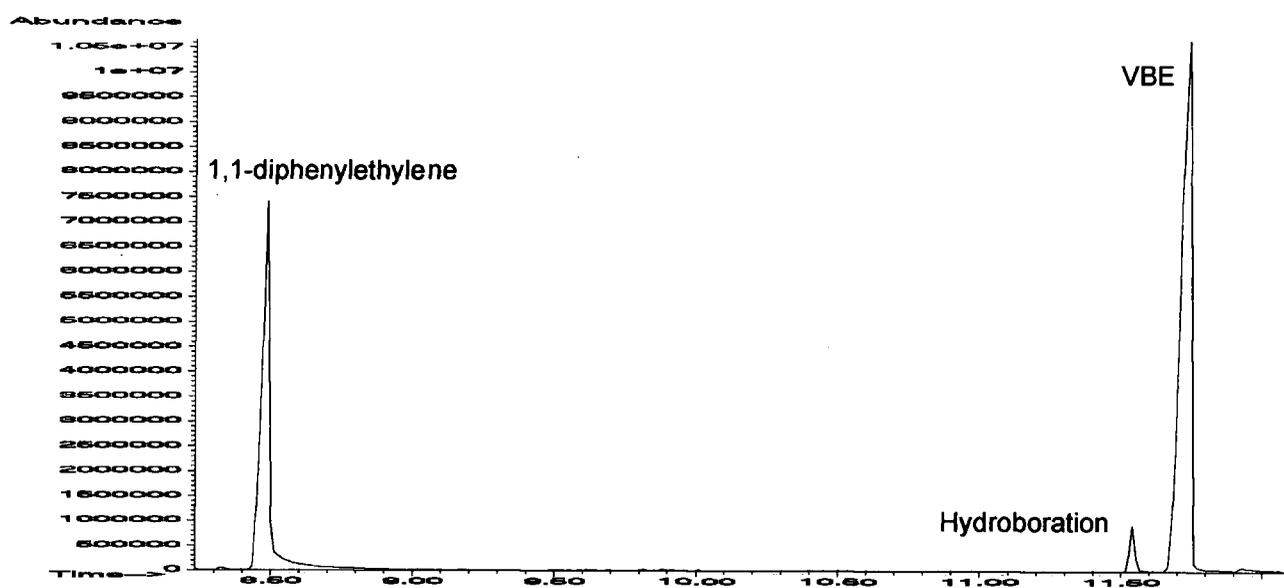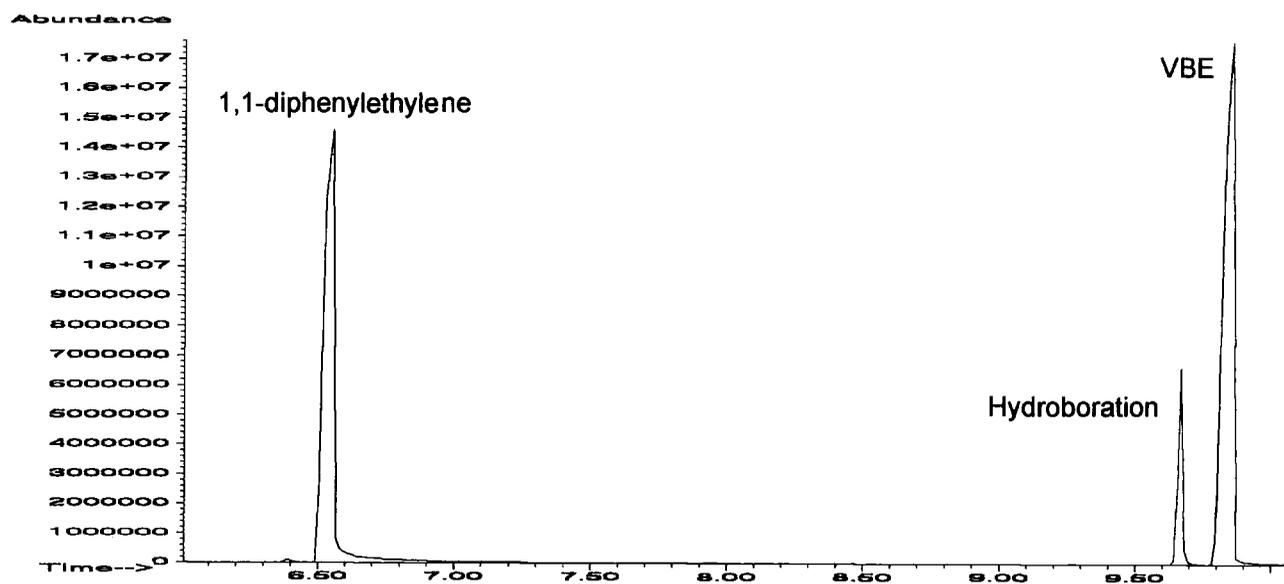
Figure 4.7: The GC of the reaction of 1,1-diphenylethylene with B_2pin_2 in 3:1 toluene:acetonitrile (top) and acetonitrile (bottom)

Since HBpin proved more reactive than B$_2$pin$_2$, the reaction of both α-methylstyrene and 1,1-diphenylethyelene were conducted in neat acetonitrile as solvent. The reaction with α-methylstyrene yielded 98% VBE (95% major isomer) and only 3% hydroboration with a conversion of 72% after 4 days (Entry 23), Figure 4.6. The reaction with 1,1-diphenylethylene gave 96% VBE and 4% hydroboration with 66% conversion in 4 days (Entry 38), Figure 4.7. Both reactions show a considerable increase in selectivity for VBEs compared to the analogous reactions in 3:1 T:A, with conversions of a similar level albeit over a longer period of time.

It should be noted that if the catalytic process involved a Rh(I) mono-boryl intermediate, e.g. formed by B—Cl reductive elimination from [RhL$_n$(Bpin)$_2$Cl], then one would expect the product distributions would be strongly dependent on the concentration of B$_2$pin$_2$, Scheme 4.3. As product distributions for Entries 16 and 30 are almost identical to Entries 21 and 36, a Rh(I) mono-boryl system is not supported.

In order to investigate the effect of catalyst, reactions were conducted using Wilkinson's Catalyst [Rh(Cl)(PPh$_3$)$_3$] (2) and Wilkinson's Dimer [Rh(μ-Cl)(PPh$_3$)$_2$]$_2$ (3) with vinyl anisole and α-methylstyrene in 3:1 T:A. Reaction of vinyl anisole with 2 showed a slightly lower selectivity for VBE than 1, resulting in 76% VBE, 16% hydroboration and 8% hydrogenation with a conversion of 100% in 3 days (Entry 3). A slightly reduced selectivity for VBEs was also observed with α-methylstyrene, with 95% VBE (89% major isomer) and 5% hydrogenation resulting after 3 days (Entry 24). The conversion was increased, however, to 93% showing the higher reactivity of 2 compared to 1. Reaction of 3 with vinyl anisole showed a further reduction in selectivity for VBE compared to 2, with 69% VBE, 25% hydroboration, 4% hydrogenation, 2% VBBE and a conversion of 95% in 3 days (Entry 4). Similarly for α-methylstyrene, selectivity was further reduced compared to 2 with 91% VBE
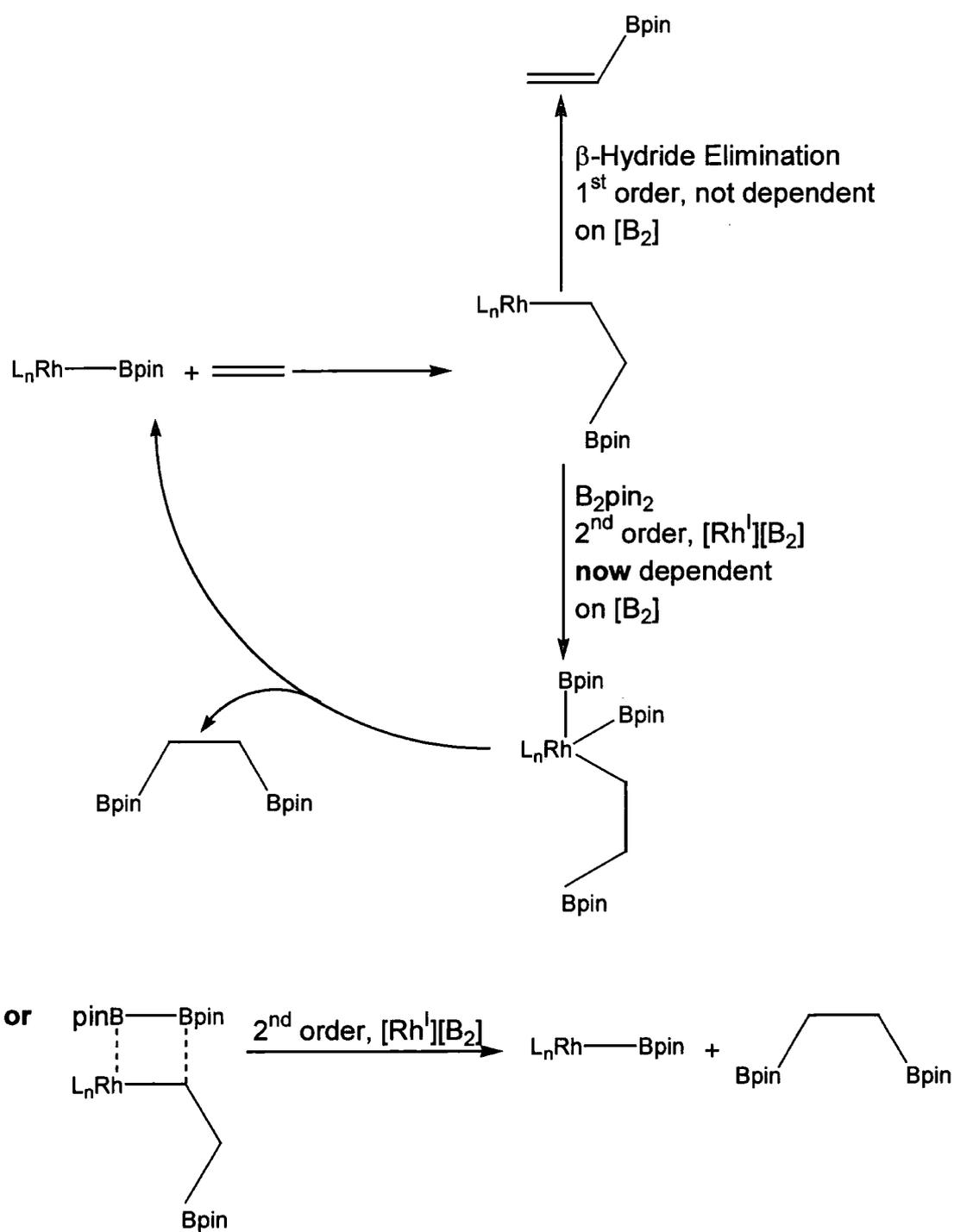
Scheme 4.3: Scheme showing the proposed product dependence on concentration of B_2pin_2

(85% major isomer), 2% hydroboration, 7% hydrogenation and 91% conversion in 3 days (Entry 25). Interestingly, all four reactions using catalysts **2** and **3** produced small quantities of hydrogenation products, whilst hydrogenation products using catalyst **1** were observed only for styrene, with a trace amount observed with vinyl anisole. The use of both **2** and **3** in alkene hydrogenation are well documented[43] and it seems likely that both of these catalysts 'scavenge' the hydrogen produced more effectively than **1** under these reaction conditions. There would also appear to be little difference in the reactivity of both **2** and **3**.

The use of the catalysts [Rh(acac)(dppm)] (**4**) and [Rh(acac)(dppb)] (**5**), whose use as hydroboration agents is well known,[29, 44] were used in reactions again with vinyl anisole and α-methylstyrene. In general, all show very different reactivity and product distributions than the other catalysts employed. Reaction with vinyl anisole and **4** produced only 56% VBE along with 39% hydroboration and 5% hydrogenation, with 76% conversion after 1 day (Entry 5); the reaction between vinyl anisole and **5** proved less selective still for VBE, with 44% VBE, 18% of the bis(boronate) ester (BBE), 36% hydroboration and 2% hydrogenation, but had increased conversion of 83% again in 1 day (Entry 6). It would appear that dehydrogenative borylation only takes place until significant quantities of the "R(H)(Bpin)" intermediate are produced, after which hydroboration predominates. This is also seen in the reaction with α-methylstyrene and **4**, which gives 62% of essentially 1 VBE isomer, 38% hydroboration but with only 27% conversion in 1 day (Entry 26). The reaction between α-methylstyrene using **5** as catalyst, however, gave very different results. In this case 98% of only 1 VBE isomer was produced along with 2% hydroboration, with a conversion of only 43% (Entry 27). It is not clear why very little hydroboration is produced in this case. It is obvious that catalysts **4** and **5** are not suitable in this system due either to low VBE yield, low catalytic activity, or both.

The reactivity of the diboron reagent B_2neop_2, Figure 4.8, was investigated using 3mol% **1** and vinyl anisole, α-methylstyrene, or 1,1-diphenylethylene. Vinyl anisole produced predominantly dehydrogenative borylation, with 75% VBE, 6% hydroboration, 19% hydrogenation, and a conversion of 81%, showing a reduced selectivity for VBE and a lower activity than B_2pin_2 with **1** (Entry 7), Figure 4.9. This was also observed in the reactions with the 1,1-disubstituted with α-methylstyrene giving 91% of 1 VBE isomer, 9% hydroboration and a conversion of 49% in 1 day (Entry 28), Figure 4.10, and 1,1-diphenylethylene giving 95% VBE, 5% hydroboration and a conversion of 20% in 2 days (Entry 39), Figure 4.11. The reactions with α-methylstyrene and 1,1-diphenylethylene were repeated using 1 equiv. of B_2neop_2 which although showing increased conversion were still incomplete (Entries 29 and 40). It is clear that B_2pin_2 is more reactive in this system than B_2neop_2 but this system has not been optimised for B_2neop_2.
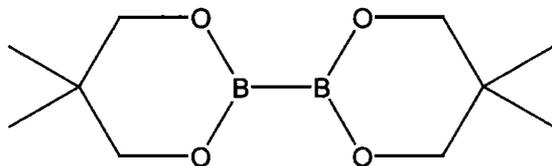
Figure 4.8: The boron reagent B_2neop_2

4.3 Conclusion

Mono- and 1,1-disubstituted alkenes can be converted directly into useful vinylboronates or even vinyl bis(boronate) esters in high yield and with high electivity by catalytic dehydrogenative borylation, a C-H activation process, employing commercially available catalyst and boron reagents. Catalysts **2** and **3** show a greater reactivity at the expense of selectivity for VBE, suggesting that although loss of CO from **1** would produced the same intermediate as loss of PPh_3 from **2** or monomer of **3**, **1** does not proceed though the same intermediate as **2** or **3** in this reaction.
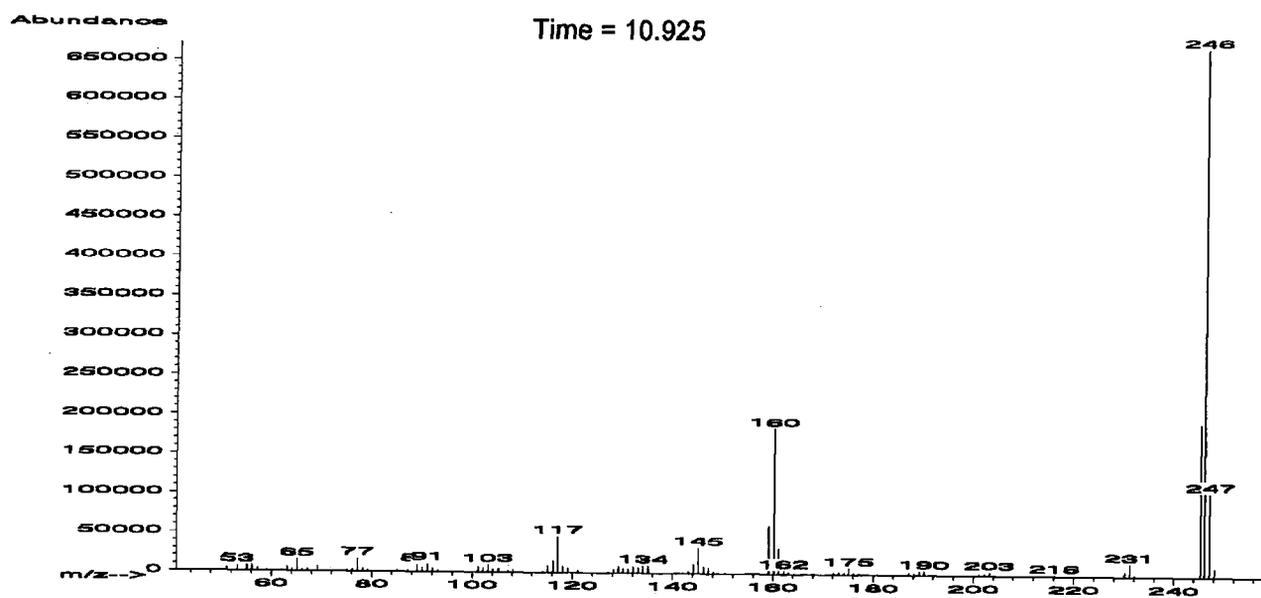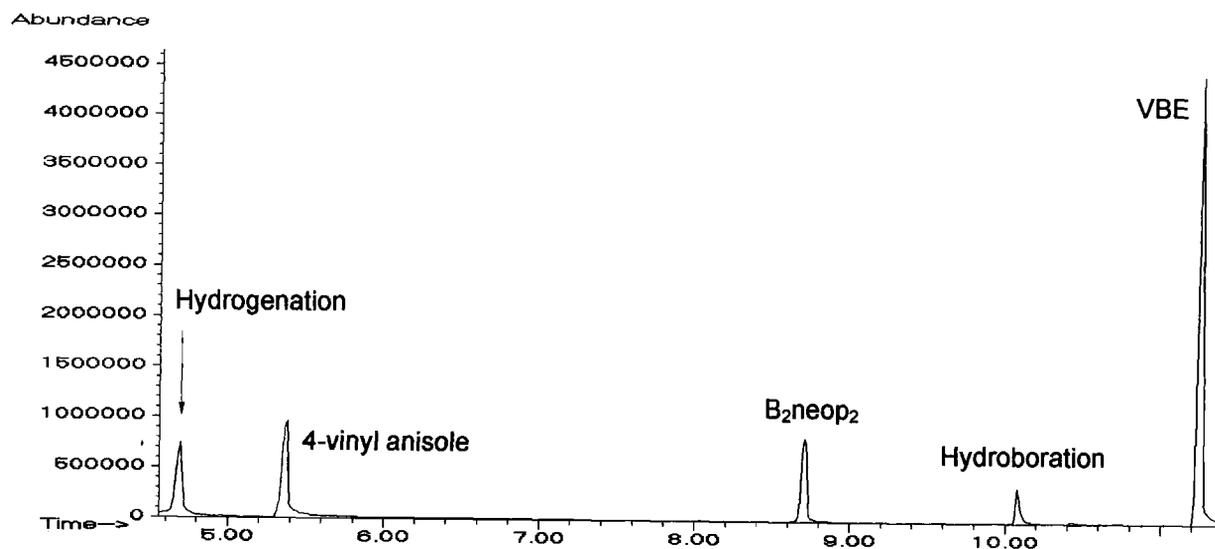
Figure 4.9: The GC of a typical reaction between 4-vinyl anisole and B₂neop₂ (top) and the
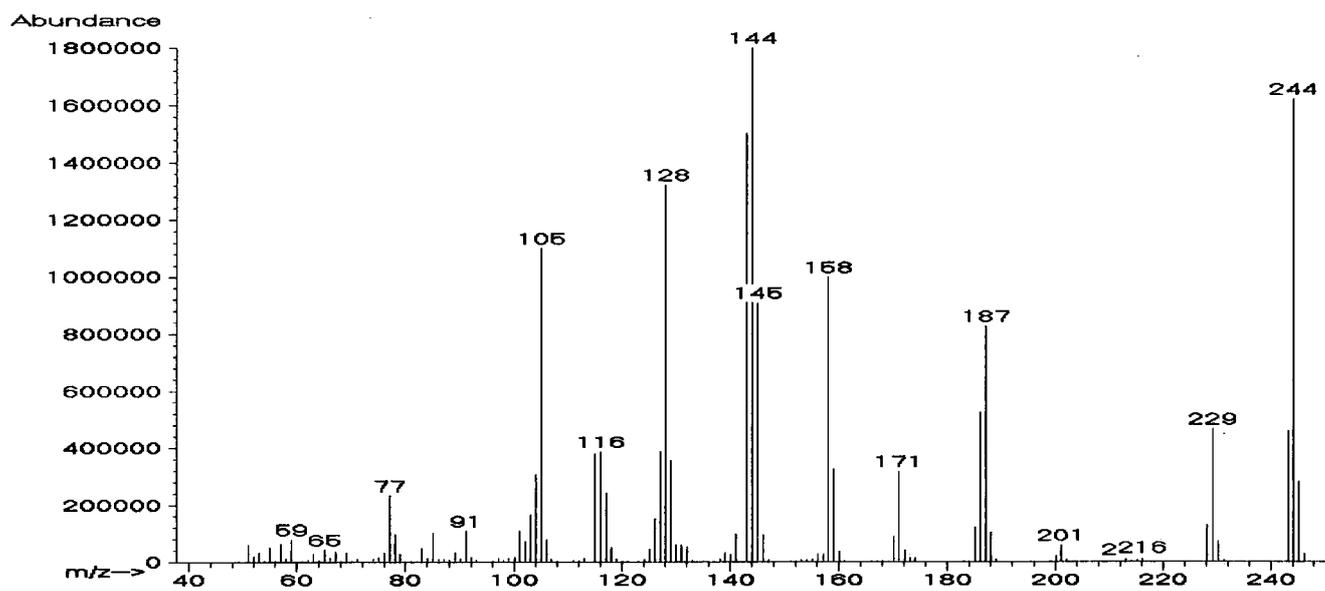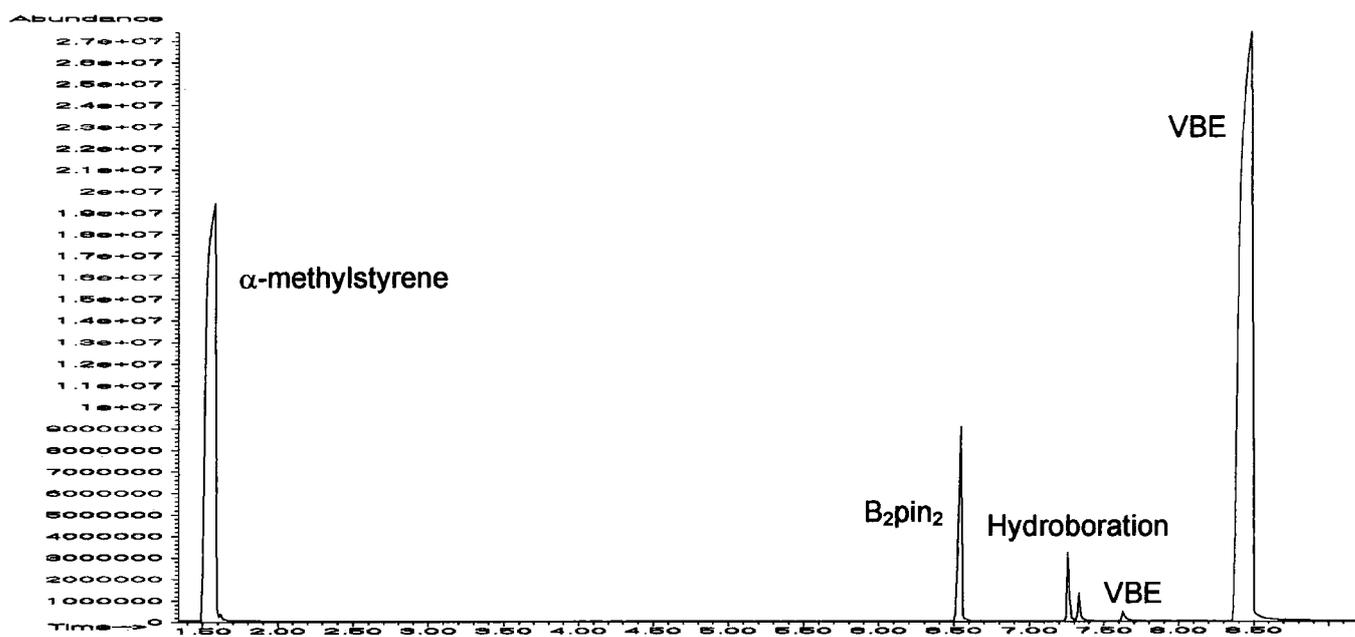
mass spectrum of the VBE (bottom)
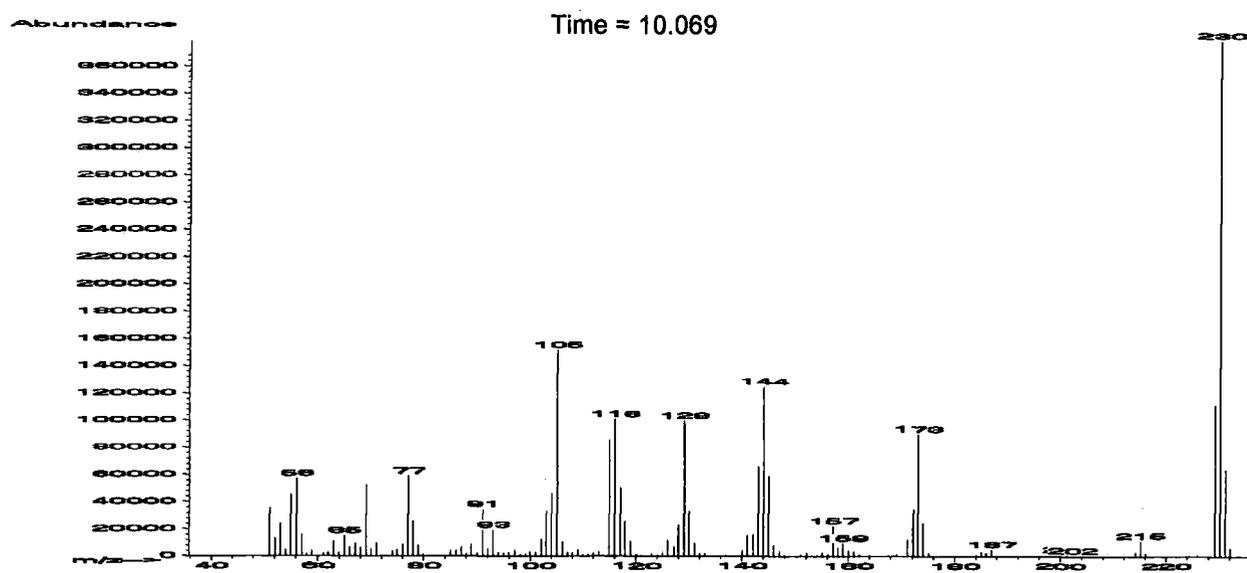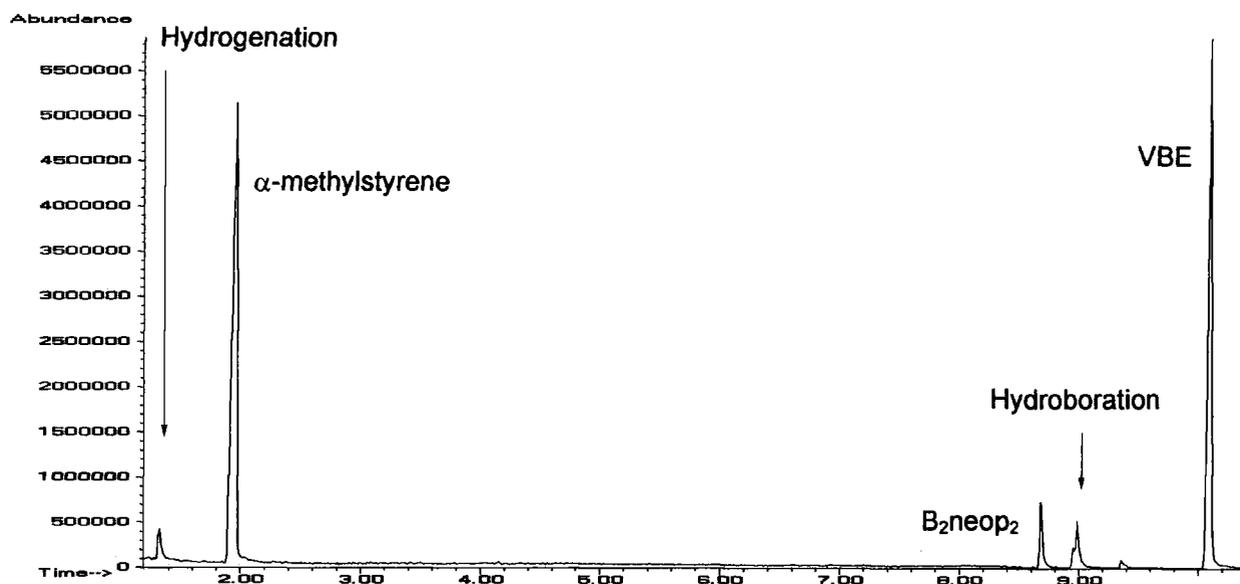
Figure 4.10: The GC of a typical reaction between α-methylstyrene and B₂neop₂ (top) and
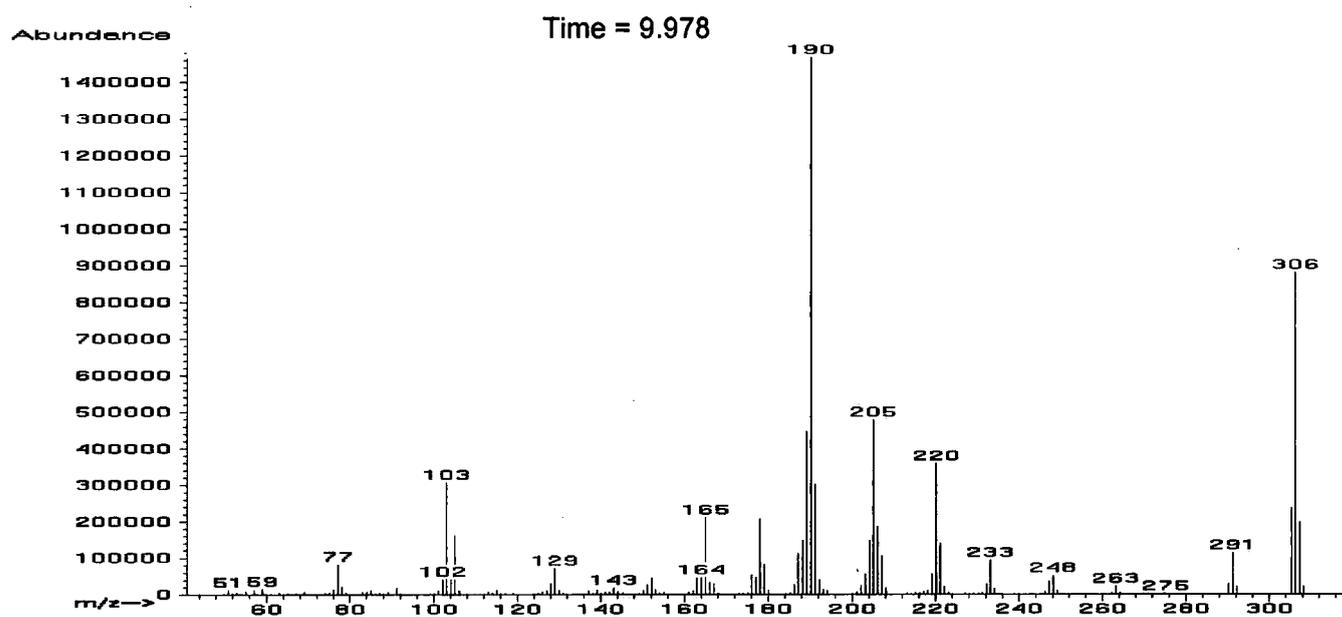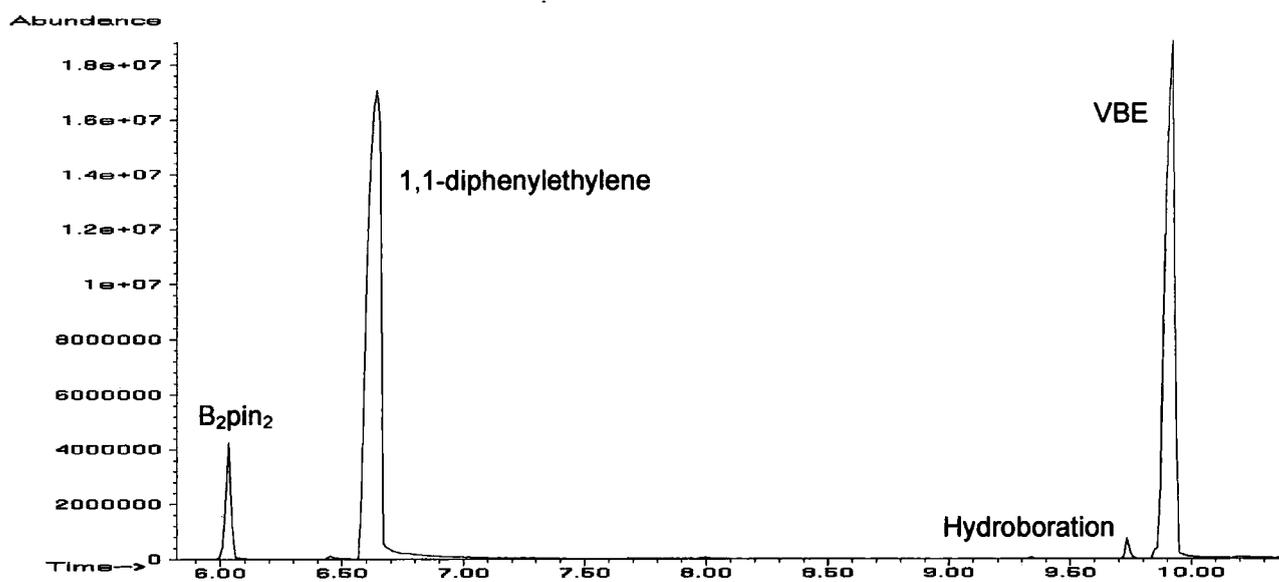
the mass spectrum of the VBE (bottom)
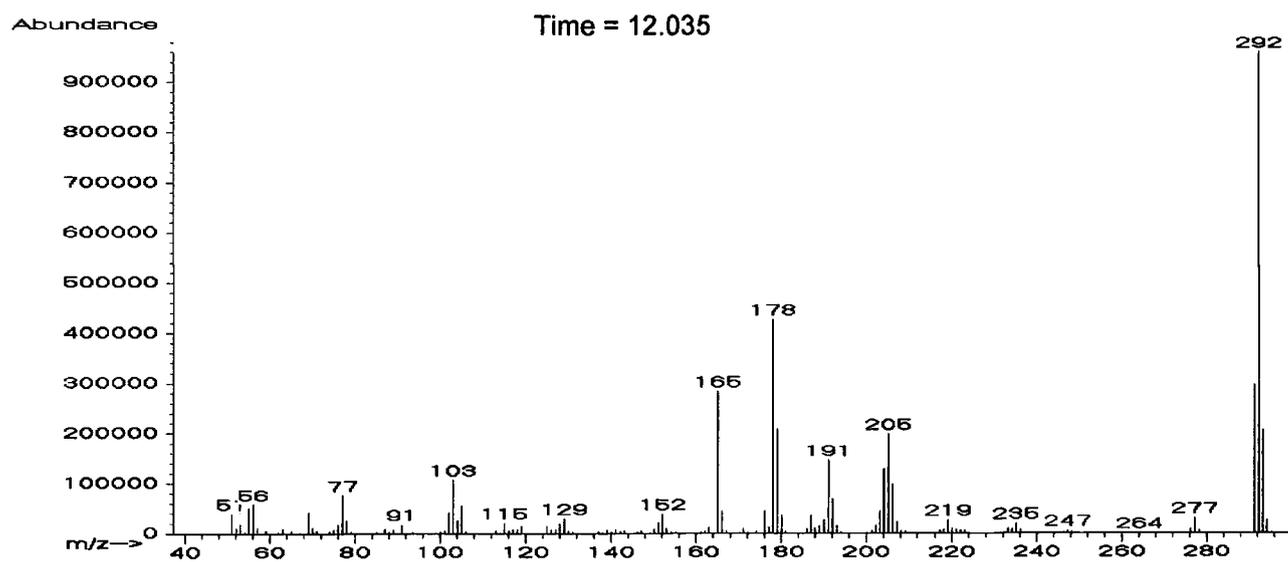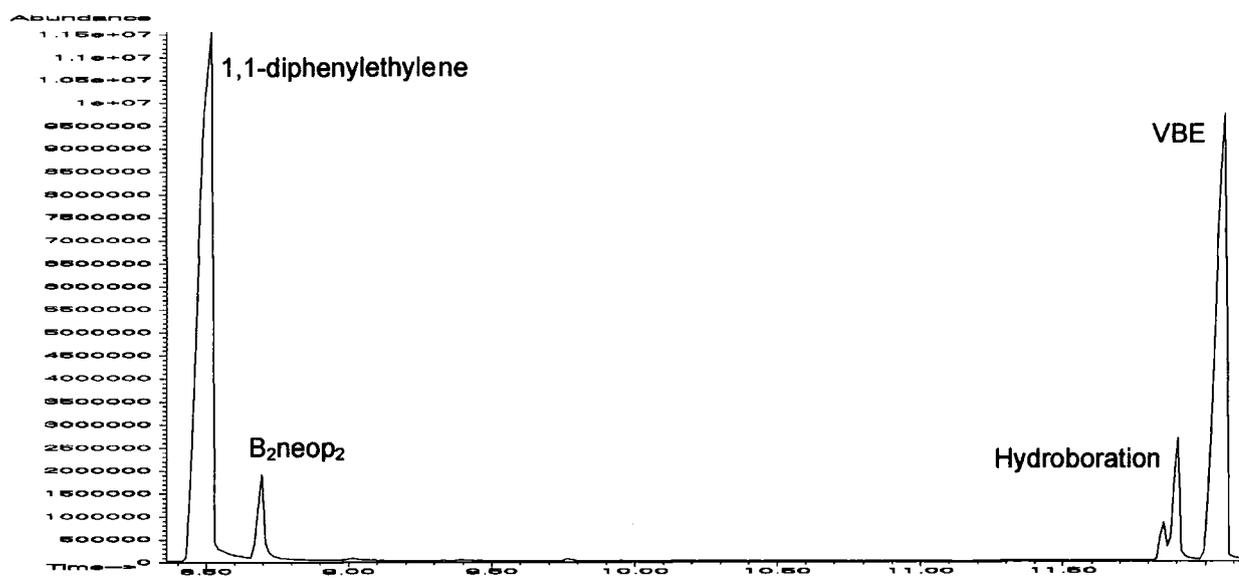
Figure 4.11: The GC of a typical reaction between 1,1-diphenylethylene and B₂neop₂ (top)

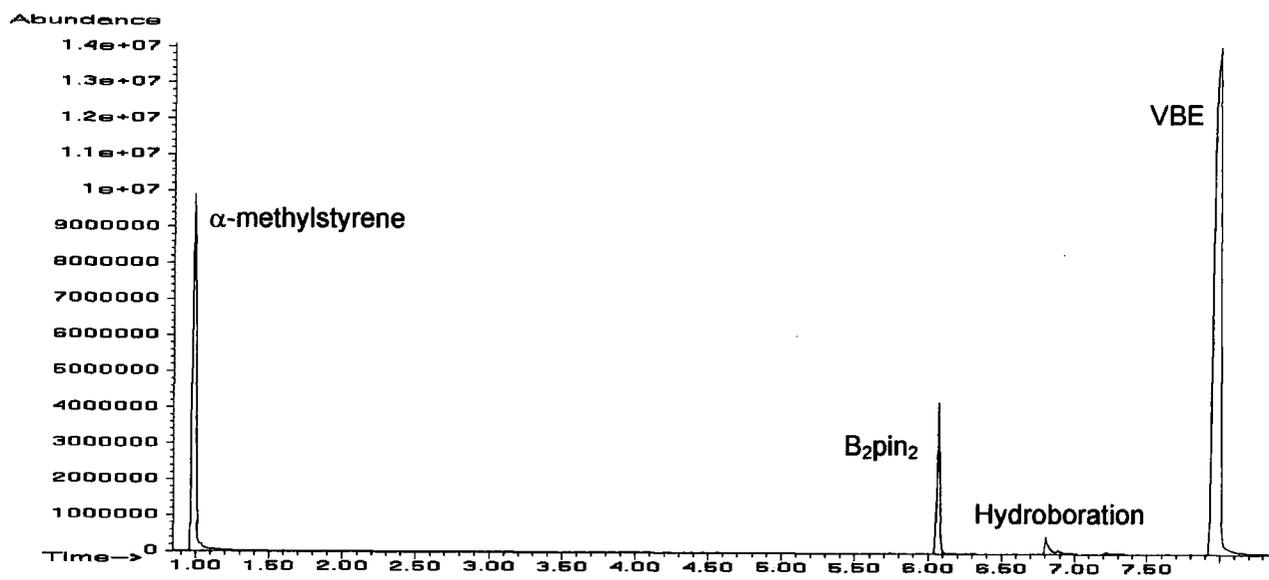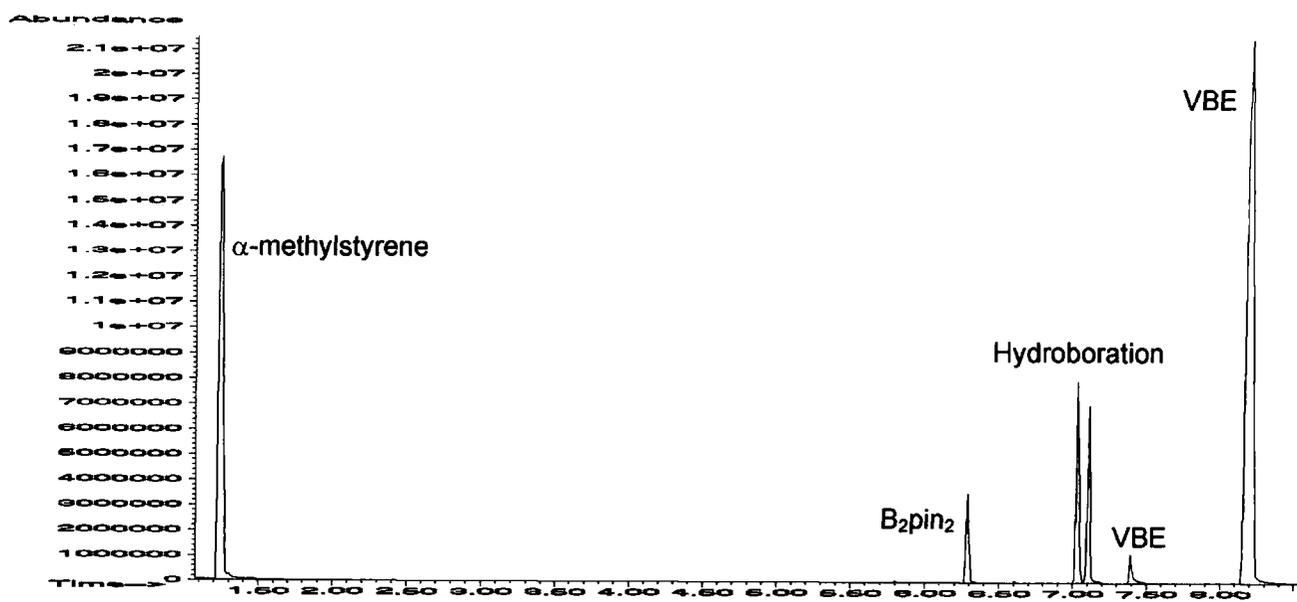*and the mass spectrum of the VBE (bottom)*

4.4 Experimental Section

All reactions were carried out under a dry nitrogen atmosphere using standard Schlenk techniques or an Innovative Technology, Inc. System 1 glove box. Glassware was oven dried before transfer into the glove box. Toluene was dried and deoxygenated by passage through columns of activated alumina and BASF-R311 catalyst under Ar pressure using a locally modified version of the Innovative Technology, Inc. SPS-400 solvent purification system. The solvents CH_3CN, CD_3CN, C_6D_6 and $CDCl_3$ were dried over calcium hydride, and 1,4-dioxane, THF and C_7D_8 were dried over sodium/benzophenone; all were distilled under nitrogen. Alkenes were purchased from Aldrich Chemical Company, Lancaster Synthesis or Avocado Research Chemicals, and were checked for purity by NMR and GC/MS techniques and distilled from calcium hydride under nitrogen. The boron reagents B_2pin_2[45-47] and B_2neop_2[48] were generously donated by Frontier Scientific Inc. and were checked for purity by NMR and GC/MS techniques. The catalyst precursors $[Rh(CO)(Cl)(PPh_3)_2]$,[49,50] $[Rh(Cl)(PPh_3)_3]$,[51,52] $[Rh(\mu-Cl)(PPh_3)_2]_2$,[53] $[Rh(acac)(dppm)]$[54] and $[Rh(acac)(dppb)]$[41,54] were prepared using published procedures and checked for purity by NMR spectroscopy. NMR spectra were recorded on Varian Inova 500 (^1H, $^{13}C\{^1H\}$, HSQC, $^{11}B\{^1H\}$), Varian C 500 (^1H, $^{13}C\{^1H\}$, HSQC), Varian Unity 300 (^{11}B and $^{11}B\{^1H\}$) and Varian Mercury 200 (^1H) instruments. Proton and carbon spectra were referenced to external $SiMe_4$ via residual protons in the deuterated solvents or solvent resonances respectively and ^{11}B chemical shifts were referenced to external $BF_3 \cdot OEt_3$. Elemental analyses were conducted in the Department of Chemistry at the University of Durham using an Exeter Analytical Inc. CE-440 Elemental Analyzer. GC/MS analyses were performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a 5971A mass selective detector and a 7673

autosampler. A fused silica capillary column (10 – 12 m cross-linked 5% phenylmethylsilicone) was used, and the oven temperature was ramped from 50°C or 70°C to 280°C at a rate of 20°C/min. UHP grade helium was used as the carrier gas. The screw-cap autosampler vials used were supplied by Thermoquest Inc. and were fitted with teflon/silicone/teflon septa and 0.2 ml micro inserts.

4.4.1 Typical Reaction Conditions for the Dehydrogenative Borylation of Alkenes

To a solution of catalyst (3 mol%) in 1 ml solvent was added a mixture of boron reagent (0.4 mmol total boron) and alkene (0.3 mmol) in 1 ml solvent (2 ml total solvent volume). The mixture was shaken vigorously to ensure complete mixing, transferred to ampoules sealed with a teflon Young's tap and then heated to 80°C. The reactions were monitored by either GC-MS or a combination of GC-MS and NMR spectroscopy. For the latter, deuterated solvents were employed for the reactions.

4.4.2 (E)-$(CH_3OC_6H_4)CH$=$CHBpin$: ^1H NMR (500 MHz, C_6D_6): δ 1.14 (s, 12H, Bpin), 3.23 (s, 3H, CH_3O), 6.34 (d, $^2J_{H-H}$ = 18 Hz, 1H, =CHBpin), 6.62 (m, 2H, C_6H_4), 7.28 (d, 2H, C_6H_4), 7.76 (d, $^2J_{H-H}$ = 18 Hz, 1H, ArCH=); $^{13}C\{^1H\}$ NMR (126 MHz, C_6D_6): δ 24.8 (s, $BO_2C_2(CH_3)_4$), 54.6 (s, CH_3O), 83.0 (s, $BO_2C_2(CH_3)_4$), 114.2 (s, br, =CHBpin), 116.0 (s, C_6H_4), 128.7 (s, C_6H_4), 130.8 (s, C_6H_4), 145.1 (s, ArCH=), 160.7 (s, C_6H_4); $^{11}B\{^1H\}$ NMR (64 MHz, C_6D_6) 30.9 (s, br); MS (EI): m/z (rel. int.): 260 (100) [M$^+$], 245 (16) [M$^+$ - Me].

4.4.3 (E)-$(Ph)CH$=$CH(Bpin)$: ^1H NMR (500 MHz, C_6D_6): δ 1.12 (s, 12H, Bpin), 6.44 (d, $^2J_{H-H}$ = 18 Hz, 1H, =CHBpin), 7.00 (m, 3H, C_6H_5), 7.24 (m, 2H, C_6H_5), 7.75 (d, $^2J_{H-H}$ = 18 Hz, 1H, ArCH=); $^{13}C\{^1H\}$ NMR (126 MHz, C_6D_6): 24.8 (s, $BO_2C_2(CH_3)_4$), 83.3 (s,

BO$_2$C$_2$(CH$_3$)$_4$), 116.9 (s, br, =CHBpin) 127.4, 128.8, 129.0, 137.9 (s, C$_6$H$_5$), 150.4 (s, ArCH=); ^{11}B{^{1}H} NMR (96 MHz, C$_6$D$_6$): 30.4 (s, br); MS (EI) *m/z* (rel. int.): 230 (52) [M$^+$], 215 (23) [M$^+$ - Me].

4.4.4 (*E*)-(4-ClC$_6$H$_4$)CH=CHBpin: ^{1}H NMR (500 MHz, CDCl$_3$): δ 1.24 (s, 12H, Bpin), 6.13 (d, ^{2}J$_{H-H}$ = 18 Hz, 1H, =CH(Bpin)), 7.17 (m, 4H, C$_6$H$_4$), 7.41 (d, br, ^{2}J$_{H-H}$ = 18 Hz, 1H, ArCH=); ^{13}C{^{1}H} NMR (126 MHz, CDCl$_3$): δ 23.5 (s, BO$_2$C$_2$(CH$_3$)$_4$), 82.5 (s, BO$_2$C$_2$(CH$_3$)$_4$), 126.5, 126.8, 127.0, 127.2, (s, C$_6$H$_4$), 152.5 (s, ArCH=) the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (160 MHz, CDCl$_3$): δ 31.4 (s, br); MS (EI): *m/z* (rel. int.): 264 (66) [M$^+$], 249 (28) [M$^+$ - Me].

4.4.5 4-MeO-C$_6$H$_4$CH=C(Bpin)$_2$: ^{1}H NMR (300 MHz, CDCl$_3$): δ 1.24 (s, 24H, (Bpin)$_2$), 3.79 (s, 3H, CH$_3$O), 6.81 (m, 2H, C$_6$H$_4$), 7.43 (m, 2H, C$_6$H$_4$), 7.64 (s, 1H, ArCH=); ^{11}B{^{1}H} NMR (96 MHz, CDCl$_3$): 30.7 (s, br); MS (EI): *m/z* (rel. int.): 386 (33) [M$^+$], 371 (3) [M$^+$ - Me].

4.4.6 CH$_3$(CH$_2$)$_5$CH=C(Bpin)$_2$: ^{1}H NMR (300 MHz, CDCl$_3$): δ 0.87 (t, 3H, CH$_3$), 1.15-1.45 (m, 32H, (Bpin)$_2$ + (CH$_2$)$_4$), 2.25 (q, ^{3}J$_{H-H}$ = 6 Hz, 2H, =CHCH$_2$CH$_2$), 6.93 (t, ^{3}J$_{H-H}$ = 6H Hz, 1H, =CHCH$_2$); ^{11}B{^{1}H} NMR (96 MHz, CDCl$_3$): 30.7 (s, br); MS (EI): *m/z* (rel. int.): 364 (1) [M$^+$], 349 (2) [M$^+$ - Me].

4.4.7 (*E*)-PhC(Me)=CH(Bpin): ^{1}H NMR (300 MHz, CDCl$_3$) δ 1.3 (s, 12H; Bpin), 2.41 (d, ^{3}J$_{H-H}$ = 1 Hz, 3H, CH$_3$PhC=), 5.77 (q, ^{3}J$_{H-H}$ = 1 Hz, 1H; =CHBpin), 7.31 (m, 2H, C$_6$H$_5$), 7.48 (m, 3H C$_6$H$_5$); ^{13}C{^{1}H} NMR (126 MHz, CDCl$_3$) δ 20.1 (s, CH$_3$PhC=), 24.8 (s,

$BO_2C_2(CH_3)_4$), 82.9 (s, $BO_2C_2(CH_3)_4$), 115.5 (s, br, =CHBpin), 125.8 (s, C_6H_5), 128.0 (s, C_6H_5), 128.2 (s, C_6H_5), 143.8 (s, C_6H_5), 157.8 (MePhC=); ^{11}B{^{1}H} NMR (96 MHz, CDCl$_3$) δ 29.0 (s, br); Elemental analysis calcd. (%) for $C_{15}H_{21}O_2B$: C 73.79, H 8.67; found C 73.21, H 8.67; MS (EI): m/z (rel. int.): 244 (89) [M$^+$], 229 (24) [M$^+$ - Me].

4.4.8 Ph₂C=CHBpin: ^{1}H NMR (300 MHz, CDCl$_3$): δ 1.08 (s, 12H, Bpin), 5.92 (s, 1H, =CHBpin), 7.2-7.3 (m, 10H, Ph); ^{13}C{^{1}H} NMR (100 MHz, CDCl$_3$): δ 24.8 (s, $BO_2C_2(CH_3)_4$), 83.4 (s, $BO_2C_2(CH_3)_4$), 118.0 (s, br, =CHBpin), 127.8, 127.9, 128.0, 128.3, 143.3 (s, Ph), 160.0 (Ph₂C=); ^{11}B{^{1}H} NMR (96 MHz, CDCl$_3$): δ 30.3 (s, br); MS (EI) m/z (rel. int.): 306 (50) [M$^+$], 291 (7) [M$^+$ - Me].

4.4.9 C₆H₁₀=CHBpin: ^{1}H NMR (500 MHz, C$_6$D$_6$): δ 1.08 (s, 12H, Bpin), 1.37 (m, 2H, CH$_2$), 1.47 (m, 2H, CH$_2$), 1.54 (m, 2H, CH$_2$), 2.11 (t, $^3J_{H-H}$ = 6 Hz, 2H, CH$_2$), 2.70 (t, ^{3}J(H,H) = 6 Hz, 2H, CH$_2$), 5.30 (s, 1H, =CHBpin); ^{13}C{^{1}H} NMR (126 MHz, C$_6$D$_6$): δ 25.0 (s, $BO_2C_2(CH_3)_4$), 26.8 (s, CH$_2$), 28.9 (s, CH$_2$), 29.1 (s, CH$_2$), 33.5 (s, CH$_2$), 40.5 (s, CH$_2$), 82.4 (s, $BO_2C_2(CH_3)_4$), 122.0 (s, br, =CH(Bpin)), 166.5 (s, C=CH(Bpin)); ^{11}B{^{1}H} NMR (160 MHz, C$_6$D$_6$): δ 30.1 (s, br); MS (EI): m/z (rel. int.): 222 (6) [M$^+$], 207 (11) [M$^+$ - Me].

4.4.10 (E)-(CH₃OC₆H₄)CH=CHBneop: ^{1}H NMR (500 MHz, C$_6$D$_6$): δ 0.63 (s, 6H, neop-CH_3), 3.23 (s, 4H, neop-CH_2), 3.40 (s, 3H, CH_3O), 6.41 (d, $^2J_{H-H}$ = 18 Hz, 1H, =CHBneop), 7.01 (m, 2H, C$_6H_4$), 7.37 (m, 2H, C$_6H_4$), 7.79 (d, $^2J_{H-H}$ = 18 Hz, 1H, ArCH=); ^{13}C{^{1}H} NMR (126 MHz, C$_6$D$_6$): δ 21.5 (s, Bneop-CH$_3$), 30.1 (s, neop-CMe$_2$), 70.6 (s, Bneop-CH$_2$), 71.9 (s, CH$_3$O), 115.9 (s, C_6H_4), 119.0 (s, br, =CHBneop), 128.8 (s, C_6H_4), 131.3 (s, C_6H_4), 147.6 (s,

ArCH=), 160.5 (s, C_6H$_4$); ^{11}B{^{1}H} NMR (96 MHz, C$_6$D$_6$): δ 27.1 (s, br); MS (EI) m/z (rel. int.): 256 (100) [M$^+$], 231 (3) [M$^+$ - Me].

4.4.11 (E)-PhC(Me)=CH(Bneop): ^{1}H NMR (500 MHz, C$_6$D$_6$): δ 0.60 (s, 6H, neop-CH_3), 2.50 (d, ^{3}J$_{H-H}$ = 1Hz, 3H, CH_3PhC=), 3.38 (s, 4H, Bneop-CH_2), 6.06 (q, ^{3}H$_{H-H}$ = 1 Hz, 1H, =CHBneop), 7.14 (m, 2H, C$_6$$H_5$), 7.31 (m, 3H, C$_6$$H_5$); ^{13}C{^{1}H} NMR (126 MHz, CDCl$_3$): δ 21.8 (s, CH$_3$PhC=), 21.9 (s, neop-CH$_3$), 31.6 (s, neop-CMe$_2$), 72.1 (s, neop-CH$_2$), 119.8 (s, br, =CHBpin), 126.5 (s, C_6H$_5$), 128.1 (s, C_6H$_5$), 128.5 (s, C_6H$_5$), 143.5 (s, C_6H$_5$), 155.4 (s, MePhC=); ^{11}B{^{1}H} NMR (96 MHz, C$_6$D$_6$): δ 26.7 (s, br); MS (EI) m/z (rel. int.): 230 (100) [M$^+$], 215 (3) [M$^+$ - Me].

4.4.12 Ph$_2$C=CHBneop: ^{1}H NMR (500 MHz, C$_6$D$_6$): δ 0.58 (s, 6H, neop-CH_3), 3.21 (s, 4H, neop-CH_2), 6.24 (s, 1H, =CHBneop), 7.11 (m, 2H, Ph), 7.27 (m, 3H, Ph); ^{13}C{^{1}H} NMR (126 MHz, C$_6$D$_6$): 21.5 (s, neop-CH$_3$), 31.4 (s, neop-CMe$_2$), 71.7 (s, neop-CH$_2$), 123.0 (s, br, =CHBneop), 127.9, 128.1, 128.4, 130.1, (s, Ph) 158.2 (s, Ph$_2$$C$=); ^{11}B{^{1}H} NMR (96 MHz, C$_6$D$_6$): 26.7 (s, br); MS (EI) m/z (rel. int.): 292 (100) [M$^+$], 277 (3) [M$^+$ - Me].

4.5 References

1   N. Miyaura and A. Suzuki, *J. Organomet. Chem.*, 1995, **95**, 49.

2   A. Suzuki, *J. Organomet. Chem.*, 1999, **576**, 147.

3   R. W. Hoffman and B. Landman, *Chem. Ber.*, 1986, **119**, 2013.

4   P.-Y. Reynard, Y. Six, and J.-Y. Lallemand, *Tetrahedron*, 1997, **38**, 6589.

5   A. Zhang, Y. Kan, and B. Jiang, *Tetrahedron*, 2001, **57**, 2305.

6   R. A. Batey and D. B. MacKay, *J. Am. Chem. Soc.*, 1999, **121**, 5075.

7   N. A. Petasis and S. Boral, *Tetrahedron*, 2001, **42**, 539.

8   J. E. A. Luithle and J. Pietruszka, *Liebigs Ann.*, 1997, 2297.

9   N. Hénaff and A. Whiting, *Tetrahedron*, 2000, **56**, 5193.

10 H. C. Brown and S. K. Gupta, *J. Am. Chem. Soc.*, 1975, **97**, 5249.

11 C. F. Lane and G. W. Kabalka, *Tetrahedron*, 1976, **32**, 981.

12 K. Burgess and M. J. Ohlmeyer, *Chem. Rev.*, 1991, 1179.

13 K. Burgess, W. A. van der Donk, S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *J. Am. Chem. Soc.*, 1992, **114**, 9350.

14 S. Pereira and M. Srebnik, *Organometallics*, 1995, **14**, 3127.

15 X. He and J. F. Hartwig, *J. Am. Chem. Soc.*, 1996, **118**, 1696.

16 I. Beletskaya and A. Pelter, *Tetrahedron*, 1997, **53**, 4957.

17 T. Ohmura, Y. Yamamoto, and N. Miyaura, *J. Am. Chem. Soc.*, 2000, **122**, 4990.

18 K. Takahashi, J. Takagi, T. Ishiyama, and N. Miyaura, *Chem. Lett.*, 2000, 126.

19 T. Ishiyama and N. Miyaura, *J. Organomet. Chem.*, 2000, **611**, 392.

20   T. Hata, H. Kitagawa, H. Masai, T. Kurahashi, M. Shimizu, and T. Hiyama, *Angew. Chem. Int. Ed. Engl.*, 2001, **40**, 790.

21   T. Ishiyama, N. Matsuda, N. Miyaura, and A. Suzuki, *J. Am. Chem. Soc.*, 1993, **115**, 11018.

22   T. Ishiyama, N. Matsuda, M. Murata, F. Onazawa, A. Suzuki, and N. Miyaura, *Organometallics*, 1996, **15**, 713.

23   G. Lesley, P. Nguyen, N. J. Taylor, T. B. Marder, A. J. Scott, W. Clegg, and N. C. Norman, *Organometallics*, 1996, **15**, 5137.

24   C. N. Iverson and M. R. Smith, III, *Organometallics*, 1996, **15**, 5155.

25   R. L. Thomas, F. E. S. Souza, and T. B. Marder, *J. Chem. Soc., Dalton Trans.*, 2001, 1650.

26   T. Ishiyama, S. Momato, and N. Miyaura, *Synlett*, 1999, **11**, 1790.

27   S.-Y. Onozawa, Y. Hatanaka, and M. Tanaka, *Chem. Commun.*, 1999, 1863.

28   J. M. Brown and G. C. Lloyd-Jones, *Chem. Commun.*, 1992, 710.

29   S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

30   J. M. Brown and G. C. Lloyd-Jones, *J. Am. Chem. Soc.*, 1994, **116**, 866.

31   D. H. Motry and M. R. Smith, III, *J. Am. Chem. Soc.*, 1995, **117**, 6615.

32   R. T. Baker, J. C. Calabrese, S. A. Westcott, and T. B. Marder, *J. Am. Chem. Soc.*, 1995, **117**, 8777.

33   D. H. Motry, A. G. Brazil, and M. R. Smith, III, *J. Am. Chem. Soc.*, 1997, **119**, 2743.

34   M. Murata, S. Watanabe, and Y. Masuda, *Tetrahedron Lett.*, 1999, **40**, 2585.

35   C. M. Vogels, P. G. Hayes, M. P. Shaver, and S. A. Westcott, *Chem. Commun.*, 2000, 51.

36   D. E. Kadlecek, P. J. Carroll, and L. G. Sneddon, *J. Am. Chem. Soc.*, 2000, **122**, 10868.

37   M. Murata, K. Kawakita, T. Asana, S. Watanabe, and Y. Masuda, *J. Bull. Chem. Soc. Jpn.*, 2002, **75**, 825.

38   F. E. S. Souza, M.Sc. Thesis, University of Waterloo, Canada, 1997.

39   R. T. Baker, P. Nguyen, T. B. Marder, and S. A. Westcott, *Angew. Chem. Int. Ed. Engl.*, 1995, **34**, 1336.

40   T. B. Marder, N. C. Norman, and C. R. Rice, *Tetrahedron Lett.*, 1998, **39**, 155.

41   C. Y. Dai, E. G. Robins, A. J. Scott, W. Clegg, D. S. Yufit, J. A. K. Howard, and T. B. Marder, *Chem. Commun.*, 1998, 1983.

42   C. Widauer, H. Grützmacher, and T. Ziegler, *Organometallics*, 2000, **19**, 2097.

43   F. A. Cotton, C. Murillo, G. Wilkinson, and M. Bochmann, 'Advanced Inorganic Chemistry', 6th Edition, Wiley Interscience, New York, 1999.

44   S. A. Westcott, H. P. Blom, T. B. Marder, and R. T. Baker, *J. Am. Chem. Soc.*, 1992, **114**, 8863.

45   D. Manning and H. Nöth, *J. Chem. Soc., Dalton Trans.*, 1985, 1689.

46   F. J. Lawlor, N. C. Norman, N. L. Pickett, E. G. Robins, P. Nguyen, G. Lesley, T. B. Marder, J. A. Ashmore, and J. C. Green, *Inorg. Chem.*, 1998, **37**.

47   T. Ishiyama, M. Murata, T.-A. Ahiko, and N. Miyaura, *Org. Synth.*, 1999, **77**, 176.

48   P. Nguyen, G. Lesley, N. J. Taylor, T. B. Marder, N. L. Pickett, W. Clegg, M. R. J. Elsegood, and N. C. Norman, *Inorg. Chem.*, 1994, **33**, 4623.

49   D. Evans, J. A. Osborn, and G. Wilkinson, *Inorg. Synth.*, 1966, **8**, 215.

50   J. A. McLeverty and G. Wilkinson, *Inorg. Synth.*, 1968, **11**, 99.

51   J. A. Osborn, G. Wilkinson, and J. J. Mrowca, *Inorg. Synth.*, 1972, **10**, 67.

52   J. A. Osborn and G. Wilkinson, *Inorg. Synth.*, 1990, **28**, 77.

53   A. van der Ent and A. Onderdelinden, *Inorg. Synth.*, 1973, **14**, 92.

54   P. J. Fennis, P. H. M. Budzelaar, J. H. G. Frijns, and A. G. Orpen, *J. Organomet. Chem.*, 1990, **393**, 287.

Chapter 5

Functionalisation of Benzylic and Aryl C—H Bonds by Direct C—H Activation

5.1 Introduction

The functionalisation of unreactive C—H bonds has long been of major interest and still poses significant challenges.[1-6] Metal-boryl systems have been employed in the stoichiometric[7-10] (Eq. 1), and photocatalytic[11] (Eq. 2) functionalisation of alkane or arene C—H bonds. In 1999 Smith *et al.* reported[12] the use of [IrCp*(H)(Bpin)(PMe$_3$)] in the thermal catalytic C—H activation benzene, giving approximately 3 turnovers at 150°C. More recently, Hartwig *et al.* reported[13] the use of [RhCp*(η^6-C$_6$Me$_6$)] in the thermal C—H activation of both alkanes and arenes at 150°C, with the finding that B$_2$pin$_2$ was more reactive than HBpin (Eq. 3), on which Smith *et al.* subsequently published[14] a related study.

In the course of studies in the Marder group on the reactivity of B—H bonds with both rhodium and iridium complexes,[15-19] the action of the catalyst [RhCl(N$_2$)(P^{i}Pr$_3$)$_2$] (1) was investigated[20] in reaction with benzene and toluene (Eq. 4). Reaction of benzene with 0.2 M HBpin and 0.3 mol% 1 at 140°C gave 222 turnovers after 104 h, yielding 67% PhBPin. Toluene, although proving less reactive than benzene, yielded PhCH$_2$Bpin, which results from benzylic C—H activation, in contrast to the systems of Hartwig[13] and Smith,[14] and also contained up to 7% of the diborylated product PhCH(Bpin)$_2$. Subsequently, Miyaura *et al.* reported[21] the use of B$_2$pin$_2$ or HBpin with several alkyl substituted arenes in the presence of catalytic quantities of 10% Pd/C at 100°C to give high yields of the benzylic C—H activation product for toluenes, both benzylic and terminal activation for species such as

129

ethylbenzene, and, in the case of cumene, only terminal activation of the side chain is observed (Eq. 5).

More recently, Smith *et al.*[22] reported the use of [Ir(Ind)(COD)] and [Ir(η^6-MesH)(Bpin)$_3$] (MesH = mesitylene) in the presence of mono- and bidentate phosphine ligands with HBpin using the arene as solvent. Reaction conditions varied from 100°C to 150°C and reaction times from 2 – 61 h, giving yields of up to 98% for benzene (Eq. 6). Hartwig[23] and Miyaura[23] have reported the use of [Ir(COD)(μ-Cl)]$_2$ and 2,2-bipyridine as catalyst precursor for arene C—H activation at 80°C for 16 hours, again using the arene as solvent (Eq. 7). The yield for benzene activation was 83%. This chapter examines the reaction of a variety of substrates with **1** for both benzylic and aromatic C—H activation.

$$Cp^* (OC)_n M-B(OR)_2 \xrightarrow{h\upsilon} \text{---}B(OR)_2 \qquad \text{Eq. 1}$$

M = Fe, W, Ru

$$\text{---} + B_2pin_2 \xrightarrow[\text{h}\upsilon,\ CO,\ 25°C]{[MCp'(CO)_3]} \text{---}Bpin + HBpin \qquad \text{Eq. 2}$$

M = Mn, Re

$$n\text{-}C_8H_{18} \xrightarrow[B_2pin_2]{Cp^*Rh(\eta^6\text{-}C_6Me_6)} \text{---}Bpin \qquad \text{Eq. 3}$$

Equations 1-3: C—H activation processes involving metal boryl species

Equations 4-7: C—H activation processes involving metal boryl species

5.2 Results and Discussion

The reaction of toluene with 0.40 mmol HBpin in the presence of 1 mol% **1** at 140°C gave PhCH$_2$Bpin as the major product with *o*-, *m*- and *p*-tolylBpin in the ratio 81:3:12:4 after 58 h.[20] In addition, the diborylated product PhCH(Bpin)$_2$ was observed in a yield of up to 7%. This yield is much higher than would be expected from the toluene:HBpin molar ratio and indicates an activation of the remaining benzylic C—H bonds by the Bpin group in PhCH$_2$Bpin.[20] The reaction was repeated using 1:1 toluene:d$_8$-toluene which gave k$_H$/k$_D$ ~ 3.7 for the first benzylic activation step and k$_H$/k$_D$ ~ 3.5 for the second benzylic activation. This compares to k$_H$/k$_D$ ~ 2.7 for the first arene C-H activation step in 1:1 C$_6$H$_6$:C$_6$D$_6$.

Reaction with ethylbenzene showed a lower selectivity for benzylic over C—H activation. Interestingly, C—H borylation took place at every possible position, Figure 5.1, with 38% PhCH(Bpin)CH$_3$, 39% 3-Et-C$_6$H$_4$(Bpin), 15% 4-Et-C$_6$H$_4$(Bpin), Figure 5.2, 5% 2-Et-C$_6$H$_4$(Bpin) and also, interestingly, 3% PhCH$_2$CH$_2$(Bpin), corresponding to borylation of the terminal carbon of the ethyl side chain, after 72 h, and a conversion of 46%, based on HBpin, Figure 5.3. However, no borylation of n-dodecane, present as an internal standard for GC analysis, was observed, indicating that the system is unsuitable for alkane C—H activation. All isomers were independently synthesised by classical hydroboration,[24] metal-catalysed hydroboration[25,26] or by a Masuda type coupling[27] (Figure 5.1). The classical hydroboration of styrene with HBcat followed by pinacolation yielded PhCH$_2$CH$_2$Bpin; the reaction of styrene and HBcat in THF using 2 mol% [Rh(acac)(dppb)] followed by pinacolation yielded Ph$_2$CH(Bpin)CH$_3$, whereas the reaction of 2- 3- and 4-Br-C$_6$H$_4$Me with HBpin, [Pd(Cl)$_2$(PPh$_3$)$_2$] and Et$_3$N in dioxane yielded the aromatic substituted products. It was noted that both in this case and in the

reaction with toluene, the major isomer resulting from arene borylation is the *meta* isomer, *m:p:o* = 39:15:5 for ethylbenzene and *m:p:o* = 12:4:3 for toluene. Conventionally, alkyl substituents have a positive inductive effect and hence one would expect an *ortho:para* directing effect. The predominance of the *meta* isomer is, therefore, an important result.

The molecular structure of 4-Et-C₆H₄(Bpin) was determined by single crystal X-ray diffraction. Here, the ethyl side chain is approximately perpendicular to the plane of the benzene ring. Also the thermal ellipsoids on the pinacol group, particularly C2 and C4 show that considerable motion is occurring even at 120 K. All bond lengths and angles show no significant deviation from those expected.

Figure 5.1: Products resulting from C—H activation of ethylbenzene and routes to isomers for independent synthesis

Figure 5.2: Molecular structure of 4-Et-C$_6$H$_4$Bpin

Table 5.1: Selected bond lengths (Å) and angles (°) for 4-Et-C$_6$H$_4$Bpin

B-O(2)	1.3671(16)
B-O(1)	1.3675(17)
B-C(7)	1.5579(17)
O(1)-C(1)	1.4711(17)
O(2)-C(2)	1.4646(15)
O(2)-B-O(1)	113.38(11)
O(2)-B-C(7)	123.51(11)
O(1)-B-C(7)	123.11(11)
B-O(1)-C(1)	106.69(10)
B-O(2)-C(2)	106.86(9)
O(1)-C(1)-C(2)	102.16(10)
O(2)-C(2)-C(1)	102.12(9)

Figure 5.3: GC of the reaction between ethylbenzene and HBpin with 2 mol% 1

Reaction with cumene (isopropylbenzene) showed predominantly arene functionalisation after 72 h at 140°C, with 3% PhC(Bpin)Me$_2$, 8% PhCH(Me)CH$_2$Bpin and 89% arene C—H activation, of which 24% is 4-(Bpin)-C$_6$H$_4$CHMe$_2$, and with 52% conversion, Figures 5.4, 5.5. It is likely, therefore, that the major arene activation product is the *meta*-isomer, although this has not yet been independently synthesised. In this case the yield of benzylic C—H activation product is lower even than that of the borylated product resulting from activation of the terminal C—H on the isopropyl group, similar to that observed by Miyaura *et al.* using 10% Pd/C.[21] The extremely low yield of the benzylic activation product is most likely caused by the steric hindrance of two methyl groups on the same carbon atom, the yield of the terminal product being higher due to there being six H's on the methyl groups compared to only one benzylic H. Therefore in this case arene C—H activation predominates. There are also trace amounts of three bis-borylated species. The classical hydroboration of α-methylstyrene with HBcat

135

followed by pinacolation yielded PhCH(Me)CH$_2$Bpin, whereas reaction α-methylstyrene in THF with 2 mol% [Rh(acac)(dppb)] yielded PhCMe$_2$Bpin. Only 4-(Bpin)-C$_6$H$_4$CHMe$_2$ of the arene activation products has been synthesised independently independently synthesised by the Masuda coupling of 4-Br-C$_6$H$_4$CHMe$_2$ with HBpin.

Figure 5.4: Products resulting from the C—H activation of cumene

Figure 5.5: GC of the reaction between cumene and HBpin with 2 mol% 1

The reaction with 4-methyl anisole yielded three peaks corresponding to benzylic activation 54%, giving one product, and arene activation, giving two products 44% total *ortho* and *meta*, with 46% conversion, Figures 5.6, 5.7. No activation of the MeO

136

group was observed but trace amounts (2%) of a bis-borylated species were observed. It is likely, therefore, that the terminal activation seen with ethylbenzene and cumene is a result of rearrangement of the intermediate resulting from benzylic C—H activation. Although neither of the arene activation products have been independently synthesised, the product distributions were determined based on the MeO group being a stronger electron donating group than the methyl group and hence the major arene activation product is *meta* to the MeO group.

Figure 5.6: Products resulting from the C—H activation of 4-methylanisole

Figure 5.7: GC of the reaction between 4-methylanisole and HBpin with 2 mol% 1

137

Interestingly, the independent synthesis of the isomer 4-MeO-C$_6$H$_4$CH$_2$Bpin was achieved by a Masuda-type reaction using 4-MeO-C$_6$H$_4$CH$_2$Cl and HBpin with [Pd(Cl)$_2$(PPh$_3$)$_2$] and Et$_3$N in dioxane. This yielded only 4-MeO-C$_6$H$_4$CH$_2$Cl and is a procedure that has not been reported elsewhere.

The reaction of indane with HBpin and 1 gave a very clean reaction and proved highly selective for benzylic activation, 83%, with 60% conversion, Figures 5.8, 5.9. In contrast to the other reactions, the major product after the benzylic activation product, it is a bis(boronate) species, 9%, with the very small quantities of mono-boryl species resulting from activation of the remaining H's.

+ 9% bis(boronate)

Figure 5.8: Products resulting from the reaction of indane with HBpin and 2 mol% 1

after 72 Hrs

Figure 5.9: GC of the reaction between indane and HBpin with 2 mol% 1

It should be noted that the major product here is chiral and hence the use of a chiral borane would allow asymmetric synthesis. The reaction was repeated, therefore, using ephedrine borane, Figure 1.12, in place of HBpin and the GC of the reaction is shown in Figure 5.10. In contrast to HBpin, the ephedrine borane yields two major indane borylation products, 34% and 32%, with 16% other isomers. As is clear from the GC, however, there are several peaks other than the major two only two of which can correspond to arene C—H borylation products, showing that the reaction is less clean with this hydroborating reagent. Two isomers, 6% and 12%, of bis(borylated) species were also observed, and conversion was 37%, based directly on ephedrine borane with no internal standard. Reaction of ephedrine borane[28] with indene in the presence of 3 mol% [Rh(Cl)(PPh$_3$)$_3$] in THF at room temperature showed the same two major peaks indicating the major products from the C—H activation reaction to be the benzylic and 'terminal' borylated products and not aryl boronate products, Figure 5.11.

Figure 5.10: GC of the reaction between ephedrine borane and indane with 2 mol% 1

139

Figure 5.11: GC of the reaction of indene with ephedrine borane and 3 mol%

[Rh(Cl)(PPh₃)₃]

Figure 5.12: Ephedrine borane

A possible mechanism for the C—H activation process is shown in Scheme 5.1 and shows a possible pathway leading to benzylic C—H activation. In this mechanism, dissociation of N_2 and then reductive elimination of ClBpin yields **2**, several forms of which have been reported.[29] Oxidative addition of a benzylic C—H bond in toluene followed by reductive elimination of H_2 would yield the known[30] 16-electron η3–benzyl rhodium complex **3** which subsequently oxidatively adds HBpin giving **4,** from which reductive elimination of $PhCH_2Bpin$ regenerates **2**. Alternatively, oxidative addition of HBpin by **2** followed by reductive elimination of H_2 would give

140

the highly unsaturated Rh-boryl species **5** which then inserts into the benzylic C—H

bond of toluene to give **4**. Reductive elimination of PhCH$_2$Bpin as before gives **2**.

Detailed experimental and theoretical studies on the structure, bonding and reactivity

of [(^{i}Pr$_3$P)$_2$Rh(Cl)(H)(Bpin)], **1** and **3** are in progress to provide support for the

proposed mechanism.

[RhCl(N$_2$)] + HBpin
1

→ N$_2$

[Rh(Cl)(H)(Bpin)]

→ ClBpin

Arene

H$_2$

Rh [R$_1$, R$_2$]
3

HBpin

[Rh(H)]
2

ArCHR$_1$Bpin

HBpin

→ H$_2$

[Rh(Bpin)]
5

Arene

Bpin
Rh H [R$_1$, R$_2$]
4

Rh = Rh(P^{i}Pr$_3$)$_2$

Scheme 5.1: Proposed catalytic pathway for the benzylic and C—H activation process

As the benzylic activation with indane proved so selective, reactions were conducted

with the related substrates acenaphthene, fluorene, 9,10-dihydrophenanthrene and

1,2,3,4-tetrahydronaphthalene, shown in Figure 5.11. As these reagents are solid, an

inert solvent was required that could be heated to 140°C. A blank reaction using

cyclooctane showed small quantities of several cyclooctane-bis(boryl) isomers, Figure

141

5.12. Careful GC-MS analysis showed trace quantities of cyclooctene and this is almost certainly the cause of the bis(boryl) species. There was also a very small quantity of B_2pin_2 formed in the reaction. A blank reaction with n-dodecane produced no C—H activation and no B_2pin_2.

Acenaphthene

Fluorene

9,10-dihydrophenanthrene

1,2,3,4-tetrahydronaphthalene

Figure 5.11: Substrates related to indane used

Figure 5.12: Reaction of cyclooctane containing a trace amount of cyclooctene with

HBpin and 1 at 140 °C

142

The reaction of acenaphthene with HBpin and **1** in n-dodecane produced, predominantly, a mono-borylated species, 74%, with trace amounts of two other mono-boryl species, 2 and 1%, two bis-borylated species, 12 and 11%, and a conversion of 70% after 72 h, Figure 5.13. Conversions for these substrates are measured directly to HBpin as the reaction is run in n-dodecane and are less reliable.

Figure 5.13: GC of the reaction of acenaphthene with HBpin and 1 after 72 hours

The reaction of fluorene with HBpin and **1** yielded one major mono-boryl species, 78%, with 3 other minor mono-borylated species, 1% 2% and 1% respectively, one isomer of a bis-borylated species, 18%, and a conversion of 69% after 72 hours, Figure 5.14.

Figure 5.14: GC of the reaction of fluorene with HBpin and 1 after 72 hours

The reaction with 1,2,3,4-tetrahydronaphthalene produced three mono-borylation products only, 7%, 25% and 68% respectively, but the reaction is not as complete as the above two, with a conversion of 37% after 72 hours, Figure 5.15.

Figure 5.15: GC of the reaction of 1,2,3,4-tetrahydronaphthalene with HBpin and 1 after 72 hours

Conversely, reaction with 9,10-dihydrophenanthrene and HBpin produced only traces of borylation product after 72 hours, with essentially no reaction having taken place. Clearly, however, the C-H activation for this type of substrate is producing predominantly one mono-borylated species and, for acenaphthene and fluorene, in relatively high yield after only 72 hours.

5.3 Conclusion

The benzylic activation of alkyl arenes is readily achieved using **1** as catalyst, with selectivity highest for benzylic hydrogens on fused ring systems. For benzylic H's on ethyl and substituted ethyl side chains, activation at the terminal position is seen, probably due to a rearrangement of the benzylic activation product. This is indicated as the C-H acitivation product of the MeO group in 4-methyl anisole is not observed, and no C-H activation of n-dodecane was seen. Activation of all aryl hydrogens takes place, with the meta isomer predominating. This is consistent with published theoretical studies[31] on uncatalysed systems using $H_3B \cdot THF$ although the principles will clearly be very different in both cases.

5.4 Experimental

All reactions were carried out under a dry nitrogen atmosphere using standard Schlenk techniques or an Innovative Technology, Inc. System 1 glove box. Glassware was oven dried before transfer into the glove box. Toluene was dried and deoxygenated by passage through columns of activated alumina and BASF-R311 catalyst under Ar pressure using a locally modified version of the Innovative Technology, Inc. SPS-400 solvent purification system.[32] Ethyl benzene, cumene, 4-methyl anisole, indane, acenaphthene, fluorene, 1,2,3,4-tetrahydronaphthalene and 9,10-dihydrophenanthrene were purchased from Lancaster Chemicals, Aldrich Chemical Company, or Avocado Research Chemicals and checked for purity before use. Ethyl benzene, cumene, 4-methyl anisole, and indane were dried over calcium hydride before use. THF was dried over sodium/benzophenone, C_6D_6 was dried over potassium and $CDCl_3$ was dried over calcium hydride. All were distilled under nitrogen. HBpin was made using published procedures[33] and was checked for purity by NMR spectroscopy before use. Ephedrine borane was generously donated by Dr. J. M. Brown and was checked for purity by NMR spectroscopy before use. NMR spectra were recorded on Varian Inova 500 (^{1}H, ^{13}C{^{1}H}, HSQC, ^{11}B{^{1}H}), Varian C 500 (^{1}H, ^{13}C{^{1}H}, HSQC) and Varian Unity 300 (^{1}H, ^{11}B and ^{11}B{^{1}H}) instruments. Proton and carbon spectra were referenced to external $SiMe_4$ via residual protons in the deuterated solvents or solvent resonances respectively. ^{11}B chemical shifts were referenced to external $BF_3 \cdot OEt_3$. Elemental analyses were conducted in the Department of Chemistry at the University of Durham using an Exeter Analytical Inc. CE-440 Elemental Analyzer. GC/MS analyses were performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a 5971A mass selective detector and a 7673 autosampler. A fused silica capillary column (12m cross-linked 5%

phenylmethylsilicone) was used, and the oven temperature was ramped from 70°C to 280°C at a rate of 20°C/min. UHP grade helium was used as the carrier gas. The screw-cap autosampler vials used were supplied by Thermoquest Inc. and were fitted with teflon/silicone/teflon septa and 0.2 ml micro inserts.

5.4.1 Typical procedure for the C—H activation reactions with liquid substrates

To a solution of 0.7 mol% 1 in 1ml of substrate was added HBpin (66 mg, 0.52 mmol) in 1ml substrate. The mixture was shaken vigorously to ensure complete mixing, transferred to 20 ml ampoules, to allow for H_2 produced, sealed with a Teflon Young's tap and then heated to 140°C. The reactions were monitored by GC-MS spectrometry.

5.4.2 Typical procedure for the C-H activation reactions with solid substrates

To a solution of 0.7 mol% 1 in 1 ml n-dodecane was added HBpin (66mg, 0.52 mmol) and substrate (1.04 mmol). The mixture was shaken vigorously to ensure complete mixing, transferred to 20 ml ampoules, to allow for H_2 produced, sealed with a Teflon Young's tap and then heated to 140°C. The reactions were monitored by GC-MS spectrometry.

5.4.3 Procedure for the synthesis of 4-MeO-C$_6$H$_4$CH$_2$Bpin

To a solution of [Pd(Cl)$_2$(PPh$_3$)$_2$] (22 mg, 0.03 mmol) in dioxane (4 ml) was added 4-MeO-C$_6$H$_4$CH$_2$Cl (154 mg, 0.98 mmol), Et$_3$N (0.42 ml, 3.0 mmol), and pinacolborane (0.22 ml, 1.5 mmol). The mixture was stirred at 100 °C for 16 hours, after which the mixture was extracted with hexane, washed with water and dried over

MgSO$_4$. The mixture was then filtered and passed down a column of silica and the solvent removed *in vacuo*.

5.4.4 4-Et-C$_6$H$_4$Bpin

^{1}H NMR (CD$_2$Cl$_2$, 300 MHz): δ 1.23 (t, $^2J_{H-H}$ = 8 Hz, 3H, ArCH$_2$CH_3), 1.33 (s, 12H, Bpin), 2.67 (q, $^2J_{H-H}$ = 8 Hz, 2H, ArCH_2CH$_3$), 7.11 (m, 2H, C$_6$$H_4$), 7.63 (m, 2H, C$_6$$H_4$); ^{13}C{^{1}H} NMR (CD$_2Cl_2$, 126 MHz): δ 15.6 (s, ArCH$_2$$CH_3$), 25.0 (s, BO$_2$$C_2$(CH$_3$)$_4$), 29.4 (s, Ar$CH_2CH_3$), 83.9 (s, BO$_2$$C_2$(CH$_3$)$_4$), 127.6 (s, C$_6H_4$), 135.0 (s, C$_6H_4$), 148.1 (s, C$_6H_4$), the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (CD$_2$Cl$_2$, 96 MHz): δ 30.9; MS (EI) *m/z* (rel. int.): 232 (32) [M$^+$], 217 (50) [M$^+$ - Me]; Elemental Analysis Found: 72.10 % C, 9.24 % H; Calcd: 72.43 % C, 9.11 % H.

5.4.5 3-Et-C$_6$H$_4$Bpin

^{1}H NMR (CD$_2$Cl$_2$, 300 MHz): δ 1.30 (t, $^2J_{H-H}$ = 8 Hz, 3H, ArCH$_2$CH_3), 1.38 (s, 12H, Bpin), 2.70 (q, $^2J_{H-H}$ = 8 Hz, 2H, ArCH_2CH$_3$), 7.34 (m, 3H, C$_6$$H_4$), 7.64 (m, 1H, C$_6$$H_4$); ^{13}C{^{1}H} NMR (CDCl$_3$, 126 MHz): δ 21.9 (s, CH$_2$$CH_3$), 25.5 (s, BO$_2$$C_2$($CH_3$)$_4$), 29.7 (s, CH$_2CH_3$), 83.9 (s, BO$_2$$C_2Me_4$), 129.3, 130.3, 132.1, 137.1, 151.1 (s, C$_6$H$_4$), the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (96 MHz, CDCl$_3$): δ 30.9; MS (EI) *m/z* (rel. int.): 232 (12) [M$^+$], 217 (73) [M$^+$ - Me].

5.4.6 2-Et-C$_6$H$_4$Bpin

^{1}NMR (CDCl$_3$, 300 MHz): δ 1.19 (t, $^2J_{H-H}$ = 7 Hz, 3H, ArCH$_2$CH_3), 1.34 (s, 12H, Bpin), 2.90 (q, $^2J_{H-H}$ = 7 Hz, 2H, ArCH_2CH$_3$), 7.17 (m, 2H, C$_6$H$_4$), 7.35 (m, 2H,

C_6H_4); $^{13}C\{^1H\}$ NMR (CDCl$_3$, 126 MHz): δ 22.4 (s, CH$_2$CH$_3$), 25.8 (s, BO$_2$C$_2$(CH$_3$)$_4$), 29.8 (s, CH$_2$CH$_3$), 84.3 (s, BO$_2$C$_2$Me$_4$), 129.2, 130.0, 131.9, 137.0, 152.4 (s, C_6H_4), the resonance of the carbon attached to boron was not observed; $^{11}B\{^1H\}$ NMR (96 MHz, CDCl$_3$): 31.5; MS (EI) m/z (rel. int.): 232 (31) [M$^+$], 217 (41) [M$^+$ - Me].

5.4.7 PhCH$_2$CH$_2$Bpin

^1H NMR (CD$_2$Cl$_2$, 500 MHz): δ 1.12 (t, $^2J_{H-H}$ = 8 Hz, 2H, CH$_2$Bpin), 1.23 (s, 12H, Bpin), 2.75 (t, $^2J_{H-H}$ = 8 Hz, 2H, CH$_2$CH$_2$Bpin), 7.17 (m, 2H, C$_6H_5$), 7.27 (m, 3H, C$_6H_5$); $^{13}C\{^1H\}$ NMR (CD$_2$Cl$_2$, 126 MHz): δ 13.4 (s, br, CH$_2$Bpin), 25.0 (s, BO$_2$C$_2$(CH$_3$)$_4$), 30.4 (s, CH$_2$CH$_2$Bpin), 83.4 (s, BO$_2$C$_2$Me$_4$), 125.9 (s, C$_6H_5$), 128.4 (s, C$_6H_5$), 128.6 (s, C$_6H_5$), 145.1 (s, C$_6H_5$), the resonance of the carbon attached to boron was not observed; $^{11}B\{^1H\}$ NMR (CD$_2$Cl$_2$, 160 MHz): δ 33.9; MS (EI) m/z (rel. int.): 232 (12) [M$^+$], 217 (11) [M$^+$ - Me].

5.4.8 PhCH(Bpin)CH$_3$

^1H NMR (CD$_2$Cl$_2$, 500 MHz): δ 1.14 (s, 12H, Bpin), 1.58 (d, $^2J_{H-H}$ = 8 Hz, 3H, CH$_3$), 2.24 (q, $^2J_{H-H}$ = 8 Hz, 1H, CH), 7.0-7.1 (m, 5H, Ph); $^{13}C\{^1H\}$ NMR (CD$_2$Cl$_2$, 126 MHz): 21.8 (s, br, CBpin), 24.5 (s, BO$_2$C$_2$(CH$_3$)$_4$), 27.4 (s, CH$_3$), 83.9 (s, BO$_2$C$_2$Me$_4$), 123.5 (s, C$_6H_5$), 125.9 (s, C$_6H_5$), 127.8 (s, C$_6H_5$), 145.8 (s, C$_6H_5$); $^{11}B\{^1H\}$ NMR (CD$_2$Cl$_2$, 160 MHz); 34.2; MS (EI) m/z (rel. int.): 232 (52) [M$^+$], 217 (26) [M$^+$ - Me].

5.4.9 4-Bpin-C$_6$H$_4$-CHMe$_2$

^1H NMR (500 MHz, CD$_2$Cl$_2$): δ 1.24 (d, $^2J_{H-H}$ = 7 Hz, 6H, CH(CH$_3$)$_2$), 1.32 (s, 12H, Bpin), 2.91 (sext, $^2J_{H-H}$ = 7 Hz, 1H, CHMe$_2$), 7.24 (m, 2H, C$_6H_4$), 7.67 (m, 2H, C$_6H_4$);

^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): δ 23.9 (s, CH(*C*H$_3$)$_2$), 25.0 (s, BO$_2$C$_2$(*C*H$_3$)$_4$), 34.7 (s, *C*HMe$_2$), 83.9 (s, BO$_2$*C$_2$*Me$_4$), 126.2 (s, *C$_6$*H$_4$), 135.1 (s, *C$_6$*H$_4$), 152.7 (s, *C$_6$*H$_4$); ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): δ 30.9; MS (EI) *m/z* (rel. int.) 246 (68) [M$^+$], 231 (100) [M$^+$ - Me].

5.4.10 PhC(Bpin)Me$_2$

^{1}H NMR (500 MHz, CD$_2$Cl$_2$): δ 1.18 (s, 12H, Bpin), 1.68 (s, 6H, C*H$_3$*), 7.0-7.1 (m, 5H, C$_6$*H$_5$*); ^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): δ 21.4 (s, br, *C*Bpin), 24.1 (s, BO$_2$C$_2$(*C*H$_3$)$_4$), 26.8 (s, *C*H$_3$), 84.2 (s, BO$_2$*C$_2$*Me$_4$), 122.8 (s, *C$_6$*H$_5$), 126.5 (s, *C$_6$*H$_5$), 127.5 (s, *C$_6$*H$_5$), 144.5 (s, *C$_6$*H$_5$); ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): 33.6; MS (EI) *m/z* (rel. int.): 246 (96) [M$^+$], 231 (100) [M$^+$ - Me].

5.4.11 PhCH(Me)CH$_2$Bpin

^{1}H NMR (500 MHz, CD$_2$Cl$_2$): 1.19 (s, 12H, Bpin), 1.31 (d, ^{2}J$_{H-H}$ = 7 Hz, 3H, CH(C*H$_3$*)CH$_2$Bpin, 1.71 (t, ^{2}J$_{H-H}$ = 7 Hz, 2H, CH(Me)C*H$_2$*Bpin), 3.06 (sext, ^{2}J$_{H-H}$ = 7 Hz, 1H, C*H*(Me)CH$_2$Bpin), 7.18 (m, 2H, C$_6$*H$_5$*), 7.29 (m, 3H, C$_6$*H$_5$*); ^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): 25.2 (s, BO$_2$C$_2$(*C*H$_3$)$_4$), 25.4 (s, CH(*C*H$_3$)CH$_2$Bpin), 36.3 (s, *C*HMeCH$_2$Bpin), 83.7 (s, BO$_2$*C$_2$*Me$_4$), 127.2 (s, *C$_6$*H$_5$), 127.9 (s, *C$_6$*H$_5$), 128.7 (s, *C$_6$*H$_5$), 149.8 (s, *C$_6$*H$_5$), the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): 34.6; MS (EI) *m/z* (rel. int.): 246 (8) [M$^+$], 231 (14) [M$^+$ - Me].

5.4.12 2-Indanyl-Bpin

^{1}H NMR (500 MHz, CD$_2$Cl$_2$): δ 1.15 (s, 12H, Bpin), 2.81 (d, ^{2}J$_{H-H}$ = 8 Hz, 2H, C*H$_2$*), 3.13 (d, ^{2}J$_{H-H}$ = 8 Hz, 2H, C*H$_2$*), 3.32 (pent., ^{2}J$_{H-H}$ = 8 Hz, 1H, C*H*), 7.03 – 7.11 (m,

2H, C$_6$H$_4$), 7.19 – 7.25 (m, 2H, C$_6$H$_4$); ^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): δ 24.8 (s, BO$_2$C$_2$(CH$_3$)$_4$), 36.1 (s, CH$_2$), 36.5 (s, CH$_2$), 83.8 (s, BO$_2$C$_2$(CH$_3$)$_2$), 124.2 (s, CH), 126.1 (s, CH), 144.3 (s, C), the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): 34.4; MS (EI) m/z (rel. int.): 244 (47) [M$^+$], 229 (20) [M$^+$ - Me].

5.4.13 1-Indanyl-Bpin

^{1}H NMR (500 MHz, CD$_2$Cl$_2$): δ 1.18 (s, 12H, Bpin), 2.41 (m, 2H, CH$_2$), 2.98 (m, 2H, CH$_2$), 3.28 (m, 1H, CH), 7.17 – 7.22 (m, 3H, C$_6$H$_4$), 7.35 – 7.38 (m, 1H, C$_6$H$_4$); ^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): 24.0 (s, Bpin), 28.4 (s, CH$_2$), 32.8 (s, CH$_2$), 83.5 (s, BO$_2$C$_2$(CH$_3$)$_4$), 124.8 (s, CH), 125.2 (s, CH), 128.7 (s, CH), 128.9 (s, CH), 144.1 (s, C), 144.4 (s, C), the resonance of the carbon attached to boron was not observed; ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): 34.1; MS (EI) m/z (rel. int.): 244 (92) [M$^+$], 229 (6) [M$^+$ - Me].

5.4.14 4-MeO-C$_6$H$_4$-CH$_2$Bpin

^{1}H NMR (500 MHz, CD$_2$Cl$_2$): δ 1.24 (s, 12H, Bpin), 2.21 (s, 2H, CH$_2$Bpin), 3.77 (s, 3H, CH$_3$O), 6.80 (m, 2H, C$_6$H$_4$), 7.079 (m, 2H, C$_6$H$_4$); ^{13}C{^{1}H} NMR (126 MHz, CD$_2$Cl$_2$): δ 20.5 (s, br, CH$_2$Bpin), 24.9 (BO$_2$C$_2$(CH$_3$)$_4$), 55.5 (s, CH$_3$O), 83.7 (s, BO$_2$C$_2$Me$_4$), 114.1 (s, C$_6$H$_4$), 130.1 (s, C$_6$H$_4$), 130.5 (s, C$_6$H$_4$), 157.6 (s, C$_6$H$_4$); ^{11}B{^{1}H} NMR (160 MHz, CD$_2$Cl$_2$): 33.7; MS (EI) m/z (rel. int.): 248 (78) [M$^+$], 233 (17) [M$^+$ - Me].

Table 5.2: Crystal data and processing parameters for 4-Et-C₆H₄Bpin

	4-Et-C$_6$H$_4$Bpin
Formula	C$_{14}$H$_{21}$BO$_2$
M	232.12
T/K	120(2)
Crystal System	Monoclinic
Space Group	C2/c
a/Å	22.331(8)
b/Å	10.537(5)
c/Å	12.083(6)
β/°	98.59(2)
U/Å^3	2811(2)
Z	8
μ/mm^{-1}	0.070
Reflections measured	11686
Unique Reflections	3716
R_{int}	0.0346
wR$_2$ (all data, on F_2)	0.1130
R[data with $F^2 > 2\sigma(F_2)$]	0.1272

5.5 References

1   W. D. Jones and F. J. Feher, *Acc. Chem. Res.*, 1989, **22**, 91.

2   R. H. Crabtree, *J. Chem. Soc., Dalton Trans.*, 2001, 2437.

3   W. D. Jones, *Science*, 2000, **287**, 1942.

4   S. S. Stahl, J. A. Labinger, and J. E. Bercaw, *Angew. Chem. Int. Ed. Engl.*, 1998, **37**, 2180.

5   R. H. Crabtree, *Chem. Rev.*, 1995, **95**, 987.

6   B. A. Arndsten, R. G. Bergman, T. A. Mobley, and T. H. Peterson, *Acc. Chem. Res.*, 1995, **28**, 154.

7   K. Waltz, X. He, C. N. Muhoro, and J. F. Hartwig, *J. Am. Chem. Soc.*, 1995, **117**, 11357.

8   K. M. Waltz and J. F. Hartwig, *Science*, 1997, **277**, 211.

9   K. M. Waltz, C. N. Muhoro, and J. F. Hartwig, *Organometallics*, 1999, **18**, 3383.

10   K. M. Waltz and J. F. Hartwig, *J. Am. Chem. Soc.*, 2000, **122**, 11358.

11   H. Chen and J. F. Hartwig, *Angew. Chem. Int. Ed. Engl.*, 1999, **38**, 3391.

12   C. N. Iverson and M. R. Smith, III, *J. Am. Chem. Soc.*, 1999, **121**, 7697.

13   H. Chen, S. Schlecht, T. C. Semple, and J. F. Hartwig, *Science*, 2000, **287**, 1995.

14   J.-Y. Cho, C. N. Iverson and M. R. Smith, III, *J. Am. Chem. Soc.*, 2000, **122**, 12868.

15   S. A. Westcott, N. J. Taylor, T. B. Marder, R. T. Baker, N. J. Jones, and J. C. Calabrese, *Chem. Commun.*, 1991, 304.

16   K. Burgess, W. A. van der Donk, S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *J. Am. Chem. Soc.*, 1992, **114**, 9350.

17   S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *Can. J. Chem.*, 1993, **71**, 930.

18   P. Nguyen, H. P. Blom, S. A. Westcott, N. J. Taylor, and T. B. Marder, *J. Am. Chem. Soc.*, 1993, **115**, 9329.

19   G. J. Irvine, M. J. G. Lesley, T. B. Marder, N. C. Norman, C. R. Rice, E. G. Robins, W. R. Roper, G. R. Whittell, and L. J. Wright, *Chem. Rev.*, 1998, **98**, 2685.

20   S. Shimada, A. S. Batsanov, J. A. K. Howard, and T. B. Marder, *Angew. Chem. Int. Ed. Engl.*, 2001, **40**, 2168.

21   T. Ishiyama, K. Ishida, J. Takagi, and N. Miyaura, *Chem. Lett.*, 2001, 1082.

22   J.-Y. Cho, M. T. Tse, D. Holmes, R. E. Maleczka, and M. R. Smith, III, *Science*, 2002, **295**, 305.

23   T. Ishiyama, J. Takagi, K. Ishida, N. Miyaura, N. R. Anastasi, and J. F. Hartwig, *J. Am. Chem. Soc.*, 2002, **124**, 390.

24   H. C. Brown and S. K. Gupta, *J. Am. Chem. Soc.*, 1975, **97**, 5249.

25   S. A. Westcott, H. P. Blom, T. B. Marder, and R. T. Baker, *J. Am. Chem. Soc.*, 1992, **114**, 8863.

26   S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

27   M. Murata, S. Watanabe, and Y. Masuda, *J. Org. Chem.*, 1997, **62**, 6458.

28   J. M. Brown and G. C. Lloyd-Jones, *Tetrahedron: Asymmetry*, 1990, **1**, 869.

29   T. Yoshida, D. L. Thorn, T. Okano, J. A. Ibers, and S. Otsuka, *J. Am. Chem. Soc.*, 1979, **101**, 4212.

30   H. Werner, M. Schafer, O. Nurnberg, and J. Wolf, *Chem. Ber.*, 1994, **127**, 27.

31   B. Goldfuss, P. Knochel, L. O. Bromm, and K. Knapp, *Angew. Chem. Int. Ed. Engl.*, 2000, **39**, 4136.

32   A. B. Pangborn, M. A. Giardello, R. H. Grubbs, R. K. Rosen, and F. J. Timers, *Organometallics*, 1996, **15**, 1518.

33   C. E. Tucker, J. Davidson, and P. Knochel, *J. Org. Chem.*, 1992, **57**, 3482.

Chapter 6

B-X Adducts of B-Chlorocatecholborane and Phosphines or Amines

6.1 Introduction

There are now many examples of the transition metal catalysed addition of boron compounds to various unsaturated substrates, in reactions such as hydroboration,[1-3] diboration,[4,5] dehydrogenative borylation of alkenes,[6-18] silylboration,[19,20] thioboration,[21-23] stannylboration,[24,25] reactions of aryl or vinyl halides or triflates with $B_2(OR)_4$ or $HB(OR)_2$,[26-36] and direct activation of C—H bonds in alkanes and arenes.[37-43] These reactions all involve an EBcat or EBpin species (E = H, Bcat, Bpin, SR, SiR_3, SnR_3, cat = $1,2-O_2C_6H_4$, pin = $OCMe_2CMe_2O$), and several reviews highlight studies of the intermediate metal-boryl species.[44-47] Whilst dehydrogenative borylation of alkenes to vinylboronate esters using $HB(OR)_2$ or $B_2(OR)_4$ is known,[6-16] a more attractive and less expensive variant would be the use of a commercially available $ClB(OR)_2$ reagent, such as ClBcat, and base in a boron analogue of the Heck reaction (Scheme 6.1). Such a reaction would likely entail the oxidative addition of ClBcat to a metal centre,[48] the use of tertiary amines as base, and the use of phosphine ligands on a late transition metal catalyst. Hence, there is a need to ascertain what, if any, reactivity there is between ClBcat and R_3P or R_3N, as it is known that nucleophiles,[49-51] including phosphines,[51] can promote the degradation of HBcat, and it has been suggested[51] that PMe_3 can promote degradation of ClBcat.

We have discussed elsewhere[52] the adducts between BCl_3 and phosphines. In this chapter, we present studies of the reaction of ClBcat with a variety of phosphines,

Et₃N, and pyridines in order to assess the stability of any adducts that form, and the nature and occurrence of boron substituent redistribution processes.

Several of the compounds in this chapter have appeared in the thesis of Fabio E. S. Souza.[53] It was important, however, to reproduce much of this work in order to obtain full characterisation of the adducts, and in order to understand the product distributions and time dependence of the redistribution process.

Dehydrogenative Borylation

R-CH=CH₂ + HB(OR')₂ →[Catalyst] R-CH=CH-B(OR')₂ + H₂

R-CH=CH₂ + (R'O)₂B-B(OR')₂ →[Catalyst] R-CH=CH-B(OR')₂ + HB(OR')₂

Cross-Coupling

R₁R₂C=CR₃X + (R'O)₂B-B(OR')₂ →[Catalyst] R₁R₂C=CR₃B(OR')₂ + XB(OR')₂

Proposed Boron Analogue of Heck Reaction

R-CH=CH₂ + Cl-Bcat →[Catalyst, R'₃N] R-CH=CH-Bcat + [HNR'₃]⁺ Cl⁻

Scheme 6.1: Possible routes to vinylboronate esters

6.2 Results and discussion

Single crystal structures of ClBcat (**1**) (Figure 6.1) and BrBcat (**2**) (Figure 6.2) have been obtained and the relevant bond distance and angles are listed in Table 6.1. Crystals of **1** and **2** are isomorphous and in each case the molecule is located on a

Figure 6.1: Molecular structure of ClBcat

Figure 6.2: Molecular structure of BrBcat

Table 6.1: Selected bond lengths (Å) and bond angles (°) for ClBcat, BrBcat, and the R$_3$P and Et$_3$N adducts of ClBcat.

	ClBcat (1)[a]	BrBcat (2)[a]	Me$_3$P·ClBcat (3a)[b] Molecule A	Molecule B	Et$_3$P·ClBcat (3b)	Bu$^t_3$P·ClBcat (3d)	Cy$_3$P·ClBcat (3e)	Et$_3$N·ClBcat (3h)
B—X (X=Cl, Br)	1.744(3)	1.898(3)	1.9178(17)	1.9105(17)	1.9254(18)	1.914(2)	1.9946(17)	1.8758(10)
B—O(1)	1.381(2)	1.381(2)	1.4631(19)	1.4565(18)	1.459(2)	1.459(2)	1.4721(18)	1.4527(11)
B—O(2)	1.381(2)	1.381(2)	1.4559(18)	1.4578(18)	1.463(2)	1.470(2)	1.4083(16)	1.4576(13)
B—E (E=N, P)			1.9691(17)	1.9646(17)	2.0079(18)	2.048(2)	1.9905(16)	1.6433(13)
C(1)—O(1)	1.395(2)	1.395(2)	1.3725(17)	1.3706(17)	1.3817(18)	1.372(2)	1.3646(16)	1.3717(10)
C(2)—O(2)	1.395(2)	1.395(2)	1.3699(17)	1.3719(17)	1.3776(19)	1.372(2)	1.3971(17)	1.3748(10)
C(1)—C(2)	1.394(3)	1.396(3)	1.396(2)	1.393(2)	1.394(2)	1.398(2)	1.567(2)	1.3905(13)
C(2)—C(3)	1.381(2)	1.402(3)	1.377(2)	1.375(2)	1.387(2)	1.383(2)	1.379(2)	1.3785(13)
C(3)—C(4)	1.400(3)	1.379(2)	1.404(2)	1.405(2)	1.405(3)	1.402(2)	1.346(2)	1.4114(15)
C(4)—C(5)	1.400(3)	1.402(3)	1.387(2)	1.380(3)	1.391(3)	1.382(2)	1.421(2)	1.3829(17)
C(5)—C(6)	1.400(2)	1.398(3)	1.402(2)	1.402(2)	1.410(3)	1.405(2)	1.3519(19)	1.4065(15)
C(1)—C(6)	1.381(2)	1.379(2)	1.378(2)	1.377(2)	1.381(2)	1.380(2)	1.3539(18)	1.3821(12)
E—C(10)			1.799(16)	1.7991(16)	1.8210(18)	1.900(2)	1.8835(14)	1.5120(12)
E—C(20)			1.7931(15)	1.7917(16)	1.8215(17)	1.903(2)	1.7680(13)	1.5261(13)
E—C(30)			1.7928(16)	1.8007(16)	1.8247(18)	1.908(2)	1.8698(19)	1.5198(13)
B—Plane[c]			0.2006	0.1539	0.1435	0.1123	0.2537	0.0363
O(1)—B—O(2)	114.0(2)	113.9(2)	107.25(12)	107.74(11)	107.82(13)	107.10(11)	105.04(11)	107.32(7)
O(1)—B—X	123.00(10)	123.1(1)	110.24(10)	111.86(10)	109.58(11)	109.19(9)	108.69(6)	111.16(7)
O(2)—B—X	123.00(10)	123.1(1)	110.71(10)	110.79(10)	110.90(11)	108.98(9)	110.64(6)	111.43(6)
O(1)—B—E			113.75(10)	109.77(10)	109.69(11)	111.40(9)	107.79(6)	109.73(7)
O(2)—B—E			110.29(10)	112.05(10)	111.67(11)	110.51(9)	113.34(6)	110.35(7)
Cl—B—E			104.64(8)	104.68(8)	107.17(8)	109.59(7)	110.01(6)	106.86(6)

C(10)—E—C(20)			107.40(8)	108.07(8)	105.98(9)	110.95(6)	106.31(6)	110.97(7)
C(20)—E—C(30)			109.44(8)	107.81(8)	107.11(8)	110.30(6)	108.69(6)	105.01(8)
C(10)—E—C(30)			107.71(8)	108.17(8)	107.99(8)	110.23(6)	110.64(6)	110.26(8)
C(10)—E—B			109.93(8)	110.68(7)	115.37(8)	110.75(6)	107.79(6)	106.72(7)
C(20)—E—B			112.35(8)	113.05(7)	110.05(8)	107.74(6)	113.34(6)	111.20(8)
C(30)—E—B			109.87(8)	108.91(7)	109.97(8)	106.75(6)	110.01(6)	112.76(7)
B—O(1)—C(1)	103.71(13)	103.9(1)	105.28(11)	104.94(11)	105.13(12)	105.71(10)	107.52(10)	106.10(7)
B—O(2)—C(2)	103.70(13)	103.9(1)	104.97(11)	105.21(11)	105.10(12)	105.39(10)	105.33(10)	105.94(7)

a – Symmetry related data included for ease of comparison. Atom numbering is as follows: C(4) = C(3A), C(5) = C(2A), C(6) = C(1A), O(2) = O(1A).

b – Compound 3a contains two independent molecules in asymmetric unit. Molecule A: C(10) = C(7), C(20) = C(8), C(30) = C(9); Molecule B: E = P(2), B = B(2), C(1) to C(6) = C(11) to C(16); C(10) = C(17), C(20) = C(18), C(30) = C(19)

c – Distance from B(1) to least-squares plane defined by O(1), C(1), C(6), C(5), C(4), C(3), C(2), O(2).

twofold axis in space group C2/c, passing through the halogen and boron atoms. The boron atom exhibits trigonal planar geometry with the sum of the angles around B being $360.0(2)°$ for **1** and $360.1(2)°$ for **2**. The B—O bond lengths, of $1.381(2)$ Å in both cases, are unaffected by the change of halogen, showing that the halogens contribute equally, and hence probably minimally, to any π-bonding to the boron atom. An $^{11}B\{^{1}H\}$ NMR study of ClBcat in dry $CDCl_3$ solution at room temperature showed no evidence of decomposition over a period of at least 8 weeks.

The reaction of **1** with 1.0 equivalent of each of the phosphines PMe_3, PEt_3, PMe_2Ph, and PBu^t_3, yielded the $R_3P \cdot ClBcat$ adducts **3a**, **3b**, **3c**, and **3d** respectively. The ambient temperature $^{31}P\{^{1}H\}$ NMR spectra of the adducts each displays a broad peak, at a frequency considerably shifted from the position of that of free phosphine (higher frequency for **3a**, **3b**, and **3c**, lower for **3d**), with no evidence of any coupling to boron (Table 6.2). The absence of observed coupling, and the width of the peak,

Table 6.2: Ambient and low temperature ($-40°C$) ^{31}P and ^{11}B date for 1 and 3a-e

Compound	^{31}P shift (ppm) at ambient temperature	^{31}P shift (ppm) at $-40°C$	^{31}P shift (ppm) of free phosphine	^{11}B shift (ppm) at ambient temperature	^{11}B shift (ppm) at $-40°C$
1				28.4	
3a	-27.9	-24.9	-61.4	11.1	11.0
3b	1.4	6.8	-19.9	11.4	11.3
3c	-29.8	-22.8	-45.4	11.8	11.6
3d	25.5	15.3	61.8	15.8	12.1
3e	-3.3	-6.6	10.9	12.2	11.8

compared to the sharp signals displayed by the free phosphines, both point to the adduct being in equilibrium with free ClBcat and phosphine at this temperature (Scheme 6.2).

$$PR_3 : 3a = PMe_3$$
$$3b = PEt_3$$
$$3c = PMe_2Ph$$
$$3d = PBu^t_3$$
$$3e = PCy_3$$
$$3f = PPh_2Me$$
$$3g = PPh_3$$
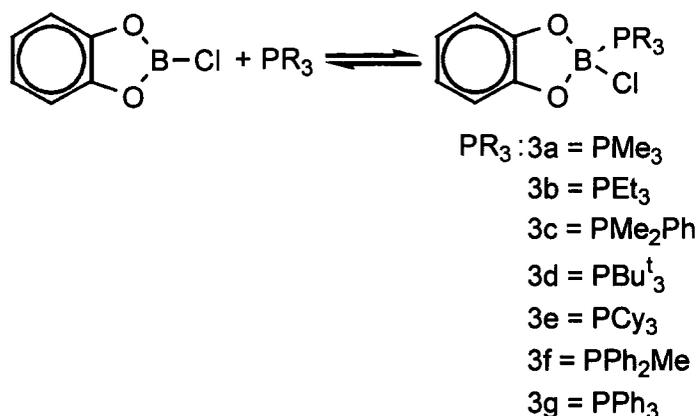
Scheme 6.2: Adduct formation from reaction of ClBcat and PR₃

The low temperature $^{31}P\{^1H\}$ NMR spectra of **3a**, **3b**, and **3c**, all show a further shift to higher frequency and evidence of P—B coupling, at $-20°C$, and display an approximate 1:1:1:1 quartet at $-40°C$, as expected for coupling to ^{11}B (I = 3/2), with J_{B-P} = 175, 169, and 166 Hz for **3a**, **3b**, and **3c** respectively (Figure 6.3). Coupling to ^{10}B is not observed. Adduct **3d**, however, shows no P—B coupling at $-20°C$, but shifts further to lower frequency and shows coupling at $-40°C$ and below, with J_{B-P} = 160 Hz, and with a splitting pattern which is, approximately, a 1:2:2:1 quartet (Figure 6.4). This, it seems likely, is due to the partial thermal decoupling of the boron quadrupole which results in the quartet collapsing towards a singlet, with the two outside peaks decreasing in size, and the two central peaks growing in intensity. The spectrum taken at $-60°C$ shows a more exaggerated distortion from 1:1:1:1 and is consistent with the thermal decoupling of ^{11}B.
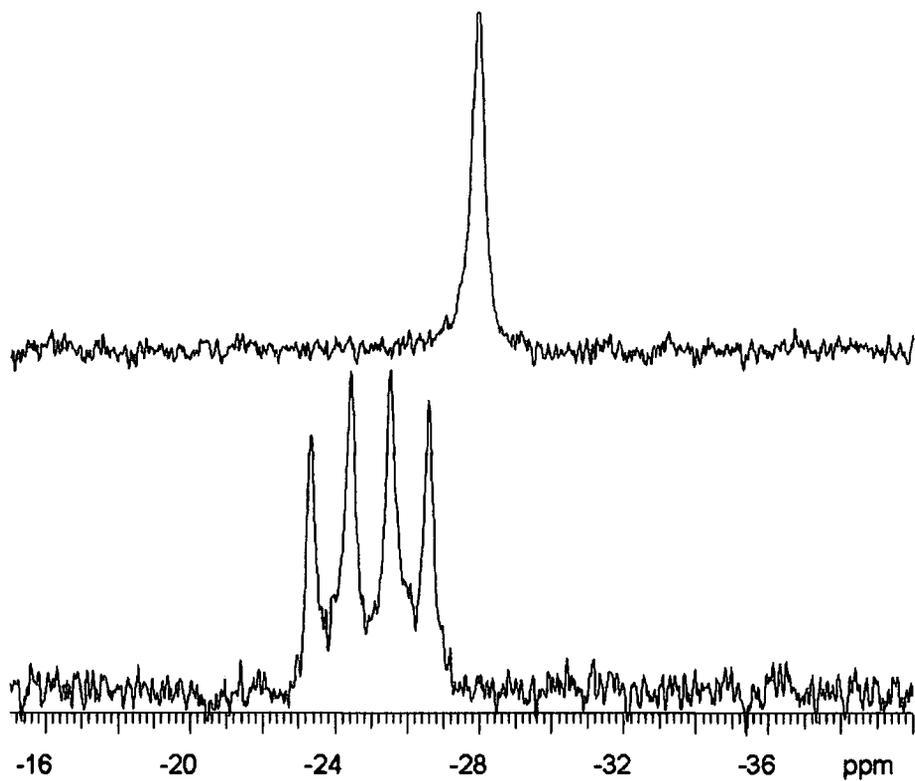
*Figure 6.3: $^{31}P\{^{1}H\}$ NMR spectra of **3a** in toluene-10% C_6D_6 at ambient temperature*

(top) and at -40°C (bottom)
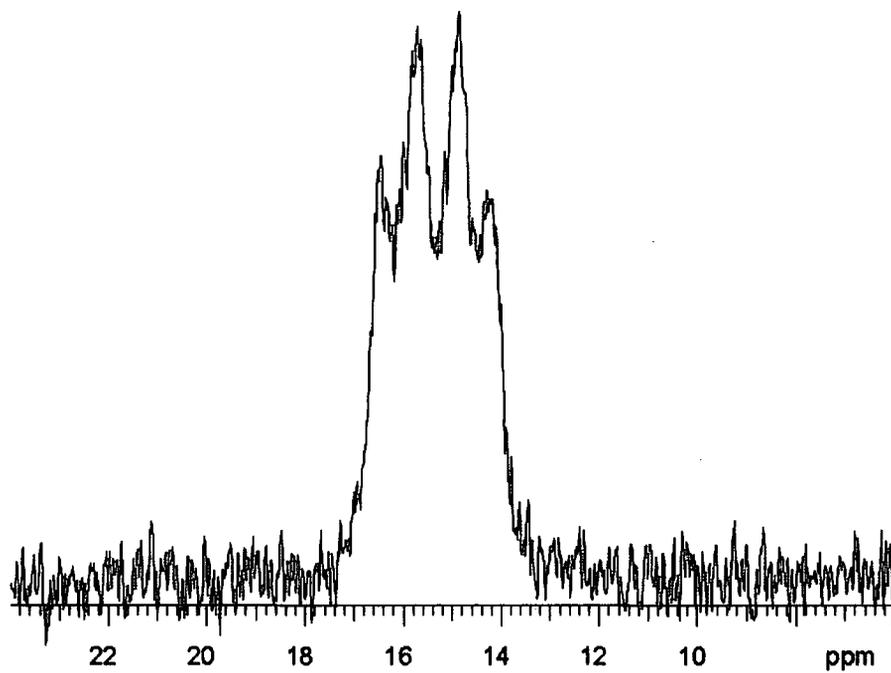
*Figure 6.4: $^{31}P\{^{1}H\}$ NMR spectrum of **3d** in toluene-10% C_6D_6 at -40°C*

163

The ambient temperature ^{11}B$\{^1$H$\}$ NMR spectra of **3a**, **3b**, **3c**, and **3d** all display a peak considerably shifted to lower frequency (Table 6.2) from the position of free ClBcat (δ 28.4) with, as expected, no evidence of coupling to ^{31}P. The low temperature ^{11}B$\{^1$H$\}$ NMR spectra at –40°C, however, all show broad doublets at a frequency shifted slightly further away from free ClBcat (Figure 6.5) and give B—P coupling constants of 178, 167, 166, and 158 Hz for **3a**, **3b**, **3c**, and **3d** respectively.
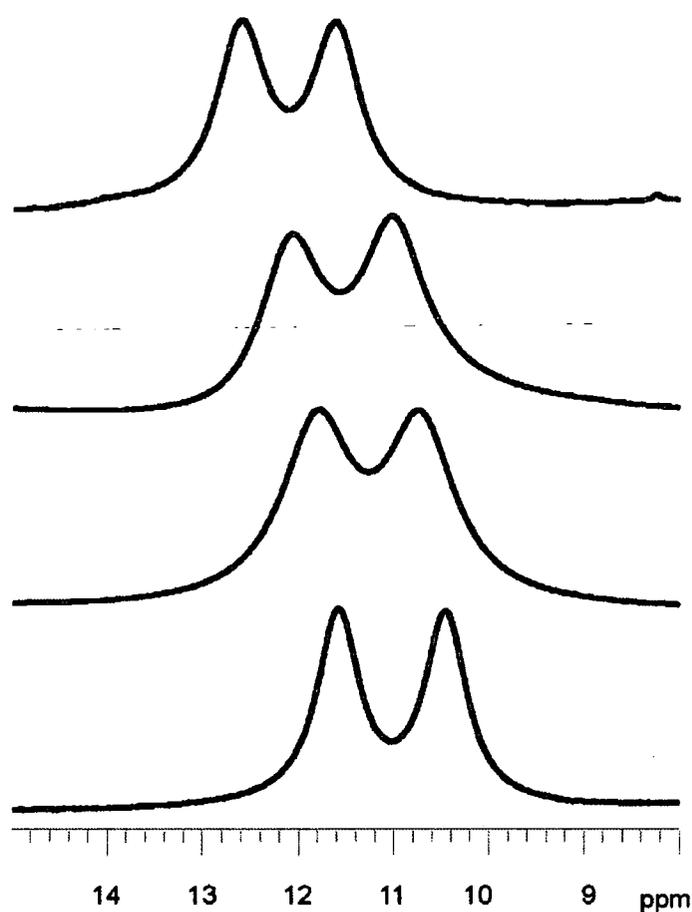
Figure 6.5: ^{11}B$\{^1$H$\}$ NMR spectra of 3a (bottom), 3b, 3c and 3d (top) in toluene-10% C₆D₆

It is clear from the temperature dependence of the ^{31}P and ^{11}B shifts in Table 6.2, that the adducts **3a-e** are mostly bound in solution at ambient temperature. However, **3d** shows substantial shifts in both ^{31}P and ^{11}B resonances as a function of temperature suggesting more dissociation than the others, consistent with PBu$^t_3$ having a particularly large cone angle (*vide infra*).

It was noticed that the $^3J_{H-P}$ coupling constant in **3b** was 16 Hz whereas that for **3d** was 11 Hz. A low temperature ^{1}H NMR spectrum of **3d** at –40°C, however, gave $^3J_{H-P}$ = 15 Hz, with the peak shifted by ~ 0.1 ppm to δ 1.65, further indicating that the adducts are undergoing rapid exchange at room temperature. There is also a change in coupling constant from that in the free phosphine ($^3J_{H-P}$ = 10 Hz), indicating that the increase in coupling constant gives a measure of the association between the phosphine and **1**.

The single crystal structures of **3a**, **3b**, and **3d** have been determined by X-ray diffraction; molecular structures are shown in Figures 6.6-6.8, with bond distances and angles provided in Table 6.1. The B—P bond lengths **3a**, **3b**, and **3d** are 1.966(2) (average for the two independent molecules), 2.008(2), and 2.048(2) Å respectively.

The increase in B—P bond lengths correlates with the decrease in B—P coupling constants and the apparent stability of the adducts. These trends are probably due to a compromise between basicity,[54] measured as the acidity of the conjugate acid [HPR$_3$]$^+$, and cone angle[55] of the phosphine. For example, the pK$_a$ of PBu$^t_3$ is 11.4 versus 8.65 for PMe$_3$. The cone angle of PBu$^t_3$, however, is 182° versus 118° for PMe$_3$, and so Me$_3$P·ClBcat contains the stronger B—P interaction. Similarly, PEt$_3$ has a pK$_a$ of 8.69, very close to that of PMe$_3$, but a cone angle of 132° and so forms a weaker adduct than PMe$_3$. Although purely empirical, this does provide a good guide to explaining the adduct stabilities, structural and spectroscopic parameters.
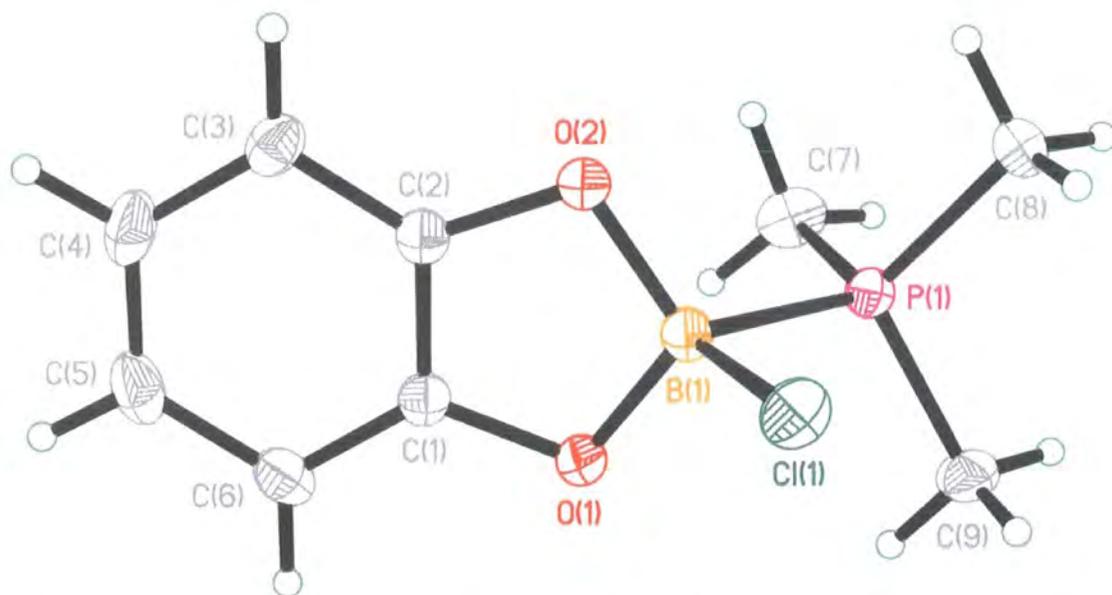
Figure 6.6: Molecular structure of one of the two crystallographically independent

molecules of Me₃P·ClBcat, 3a
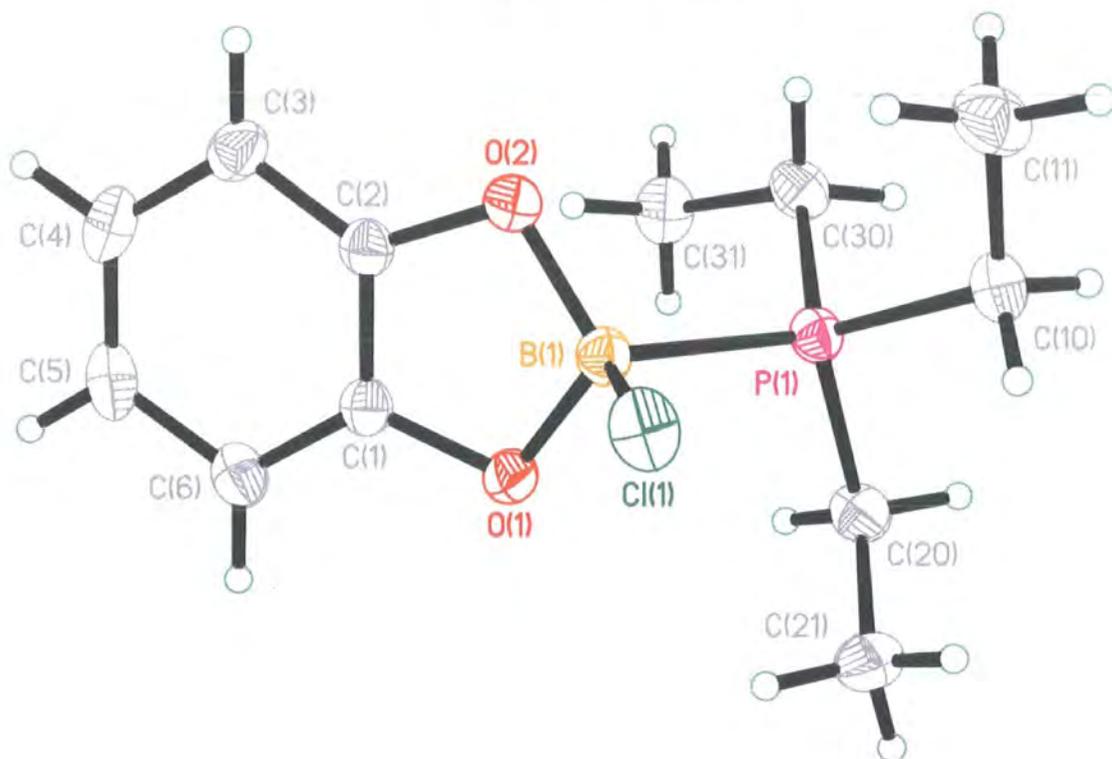
Figure 6.7: Molecular structure of Et₃P·ClBcat, 3b
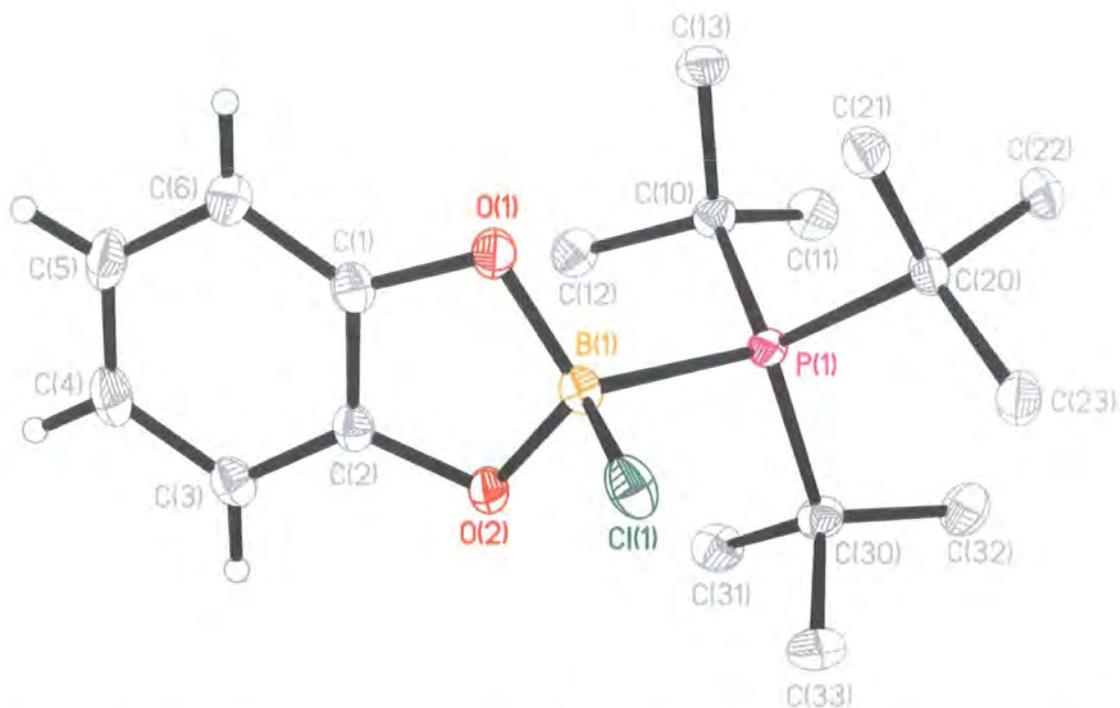
*Figure 6.8: Structure of Bu$^t_3$P·ClBcat, **3d**. Hydrogens on ^{t}Bu groups are omitted for*

clarity

Figure 6.9 shows a plot of the basicity vs. cone angle of the phosphines used. The plot

represents the use of a range of small and large basic and less basic phosphines but

there is no apparent trend. The plot of B-P bond length vs. basicity, Figure 6.10,

appears to show a straight line for **3a**, **3c** and **3d** with **3b** appearing as an anomalous

outlying point, suggesting that the bond length is longer than anticipated. This is

probably the result of intramolecular forces of repulsion due the proximity of the ethyl

groups to the chlorine atom.

As expected, the increase in coordination number at boron from three to four with

change in hybridisation from sp^2 to sp^3, and the concomitant increase in steric

repulsion, cause a lengthening of the B—Cl and B—O bonds from those in **1**. The

B—Cl bonds lengthen by ~10% from 1.744(3) Å in **1** to 1.911(2), 1.925(2), and

1.914(2) Å in **3a**, **3b**, and **3d** respectively, and the B—O bonds lengthen by ~6% an

average of 1.461(2) Å. Note also that O—B(p$_z$) π-bonding should be minimal in the

four coordinate adducts as $B(p_z)$ is now tied up in σ-bonding to P. The boron atom is also 'tipped' out of the plane of the catechol ring, by between ~0.11 Å and 0.20 Å (Table 6.1). The B—P bond lengths in Table 6.1 are comparable with those in the analogous $R_3P \cdot BCl_3$ adducts; for example the B—P bond lengths in $Me_3P \cdot BCl_3$, $Et_3P \cdot BCl_3$, and $Bu^t_3P \cdot ClBcat$ are 1.957(5), 1.981(3), and 2.055(2) Å respectively.[52]
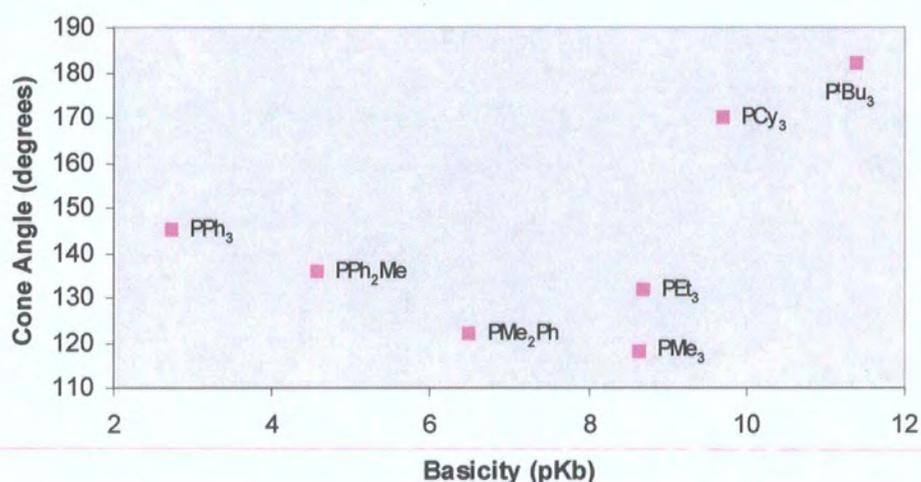
Figure 6.9: Plot of cone angle (^{o}) vs. basicity (pK_b) of the phosphines used
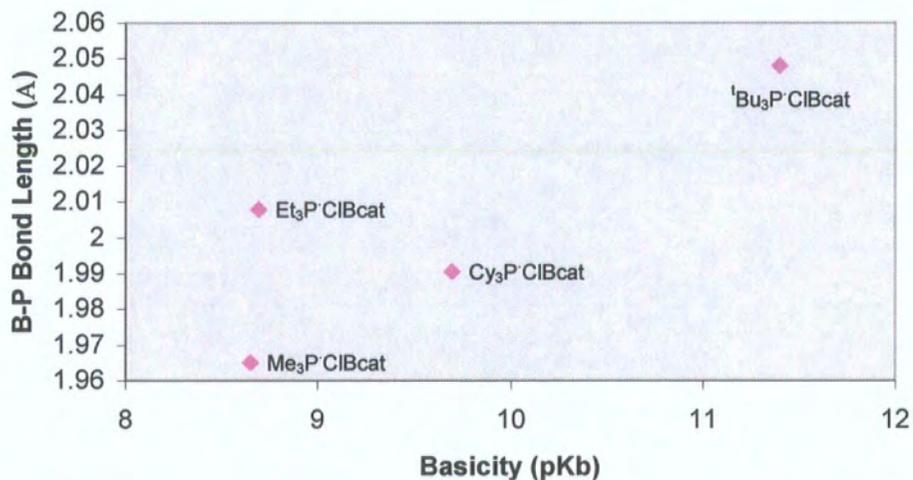
*Figure 6.10: Plot showing B-P bond length (Å) vs. basicity (pK_b) of **3a-3d***

168

The 1:1 reaction of ClBcat with PCy_3 yielded a mixture of products, as indicated by $^{11}B\{^1H\}$ NMR spectroscopy, including $Cy_3P\cdot ClBcat$ (**3e**, δ 12.1), the redistribution products $Cy_3P\cdot BCl_3$ (δ 3.7, d, J_{B-P} = 147 Hz) and B_2cat_3 (δ 23.4), and additional peaks at δ 21.9 and δ 11.1. In contrast, the $^{31}P\{^1H\}$ NMR spectrum showed only a broad peak due to **3e** at δ -3.3 which presumably obscures the signal due to the $Cy_3P\cdot BCl_3$ adduct (δ 3.2, q, J_{P-B} = 147 Hz).[52] A 1.1:1 reaction of PCy_3 and ClBcat (**1**) gave a small amount of a white precipitate of **3e**, recrystallisation of which yielded single crystals. The $^{11}B\{^1H\}$ NMR spectrum showed that the crystals were **3e**, but an additional peak was observed at δ 22.2. The level of this impurity changes, however, depending on concentration of the sample and on the time in solution, so the formation of the impurity would seem to take place in solution. The low temperature $^{31}P\{^1H\}$ NMR spectrum of **3e** showed some coupling at -20 °C, and, at -40°C, displayed a broad 1:2:2:1 quartet, similar to **3d**, at δ -6.6, with J_{P-B} = 159 Hz. The low temperature $^{11}B\{^1H\}$ NMR spectrum at -40 °C showed a doublet at δ 11.8 with J_{B-P} = 160 Hz.

The molecular structure of **3e** has been obtained (Figure 6.11) and comparison of the structures of the four adducts **3a**, **3b**, **3d**, and **3e**, determined by X-ray crystallography, reveals that of **3e** to be quite different from the others. Compared to the analogous bond distances found in **3a**, **3b**, and **3d**, the most obvious differences in the geometry of **3e** are the B—O(2) bond, shortened by 0.05 Å to 1.408(2) Å, the B-Cl bond, lengthened by 0.06 Å to 1.995(2) Å, and the P—B bond length of 1.991(2) Å being shorter than all but that in **3a**. Additionally, P—C(20), at 1.768(2) Å, is over 0.1 Å shorter than P—C(10), 1.884(2) Å, and P—C(30), 1.870(2) Å. There is also further distortion throughout the catechol group, most significantly C(2)—O(2), and C(1)—

C(2) when compared to values obtained from the other adducts, and the boron is further 'tipped' out of the plane of the catechol group by 0.25 Å.
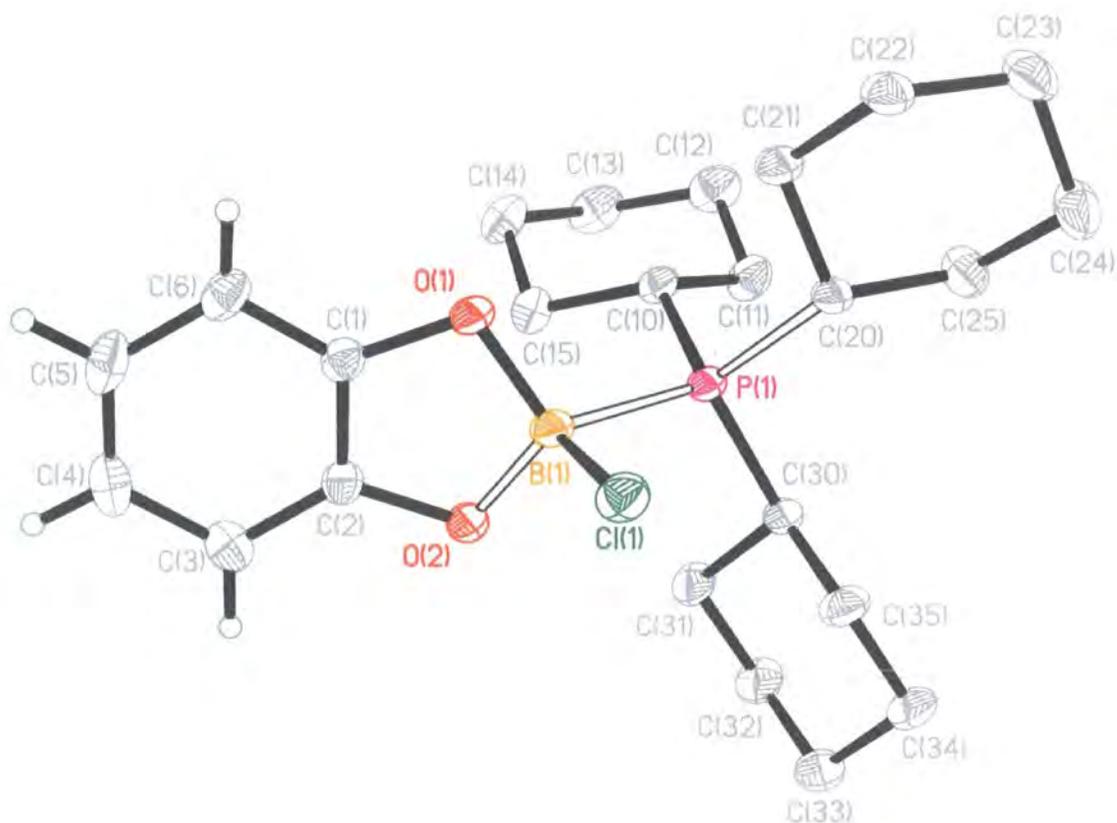
*Figure 6.11: Molecular structure of Cy₃P·ClBcat, **3e**. Hydrogens on the Cy rings are omitted for clarity. Hollow bonds highlight distances which deviate significantly from those in other adducts*

In an attempt to understand why **3e** has a distorted molecular structure in the solid state relative to the other adducts, geometry optimisations (at the HF/6-31G* level with GAUSSIAN94) from the X-ray structural data of all four adducts were carried out by Dr. Mark Fox. Table 6.3 contains selected bond lengths of experimental and optimised 'gas-phase' geometries for these adducts, and these values show very good agreement in all cases except **3e**. Energy differences between experimental (with their hydrogens optimised as they are not located accurately by X-ray crystallography) and

optimised geometries in these adducts reveal a relatively large value of 87 kJmol^{-1} for

3e compared with much smaller values of ca. 10-17 kJmol^{-1} for **3a**, **3b**, and **3d**. Even

allowing for the fact that the total energy of **3e** is larger than those of the other

adducts, the energy difference for **3e** is substantial. We find no obvious intramolecular

reasons for the distortions observed for **3e** in the solid state.

Table 6.3: Comparison of selected bond lengths (Å) and energies between

experimental and optimised (HF/6-31G*) geometries of R$_3$P·ClBcat adducts

R		B-O	B-Cl	B-P	P-C	E (hartrees)	ΔE (kJ mol^{-1})[a]
Me	expt	1.46, 1.46	1.91	1.97	1.80, 1.80, 1.79	-1323.14176	10.0 (7.5)
	theo	1.44, 1.44	1.89	2.03	1.82, 1.82, 1.82	-1323.14556	
Et	expt	1.46, 1.46	1.93	2.01	1.82, 1.82, 1.82	-1440.23448	16.7 (11.3)
	theo	1.44, 1.44	1.89	2.04	1.84, 1.83, 1.84	-1440.24085	
^{t}Bu	expt	1.46, 1.47	1.91	2.05	1.90, 1.90, 1.91	-1674.38484	11.7 (6.7)
	theo	1.44, 1.44	1.91	2.08	1.92, 1.92, 1.93	-1674.38936	
Cy	expt	1.47, 1.41	1.99	1.99	1.77, 1.87, 1.88	-1905.12893	87.4 (46.0)
	theo	1.44, 1.44	1.91	2.05	1.86, 1.86, 1.87	-1905.16231	

[a] – Values (x10^{-3}) in parentheses are generated by ΔE/E(theory) for a more realistic

comparison

Crystal packing forces must therefore account for a large part of the distortion and the associated energy difference computed theoretically between the optimised and observed geometries. Examination of the crystal structure of **3e** revealed close Cl···H intermolecular distances of 2.9 Å involving cyclohexyl hydrogens. A Cambridge Structural Database Search[56] for B—Cl···H—C interactions gave an average distance of 3.4 Å from 166 compounds, very few being shorter than 2.9 Å. Thus, intermolecular packing forces appear to be responsible for the observed differences in the molecular structure in the crystal of the PCy_3 adduct compared to its optimised 'gas-phase' geometry. The experimental solid-state structures of the other adducts are largely unaffected by packing forces, as they correspond very well with their optimised 'gas-phase' geometries, obtained from the *ab initio* molecular orbital calculations.

The 1:1 reactions of **1** with the phosphines PPh_2Me and PPh_3 both yielded the redistribution products B_2cat_3 and $R_3P \cdot BCl_3$ (**5f** and **5g**) as shown in Scheme 6.3. The reactions were not instantaneous, however, and the $^{11}B\{^{1}H\}$ NMR spectrum of each, when taken after one hour, showed B_2cat_3, a doublet due to **5f** or **5g**, and another peak due to unreacted **1** (Figures 6.12 and 6.13). This peak was shifted by ~0.5 ppm to lower frequency from the expected position of free **1**, most likely indicating a very weak interaction between phosphine and **1**. When left for 24 hours, the $^{11}B\{^{1}H\}$ NMR spectra showed only peaks due to B_2cat_3 (**4**) and **5f** or **5g** (Figures 6.12 and 6.13). In these two cases, it seems likely that $R_3P \cdot ClBcat$ adducts do form but that the interactions are very weak due predominantly to low phosphine basicity (PPh_2Me, $pK_a = 4.57$, PPh_3, $pK_a = 2.73$), and the large cone angle ($PPh_2Me = 136°$, $PPh_3 = 145°$).
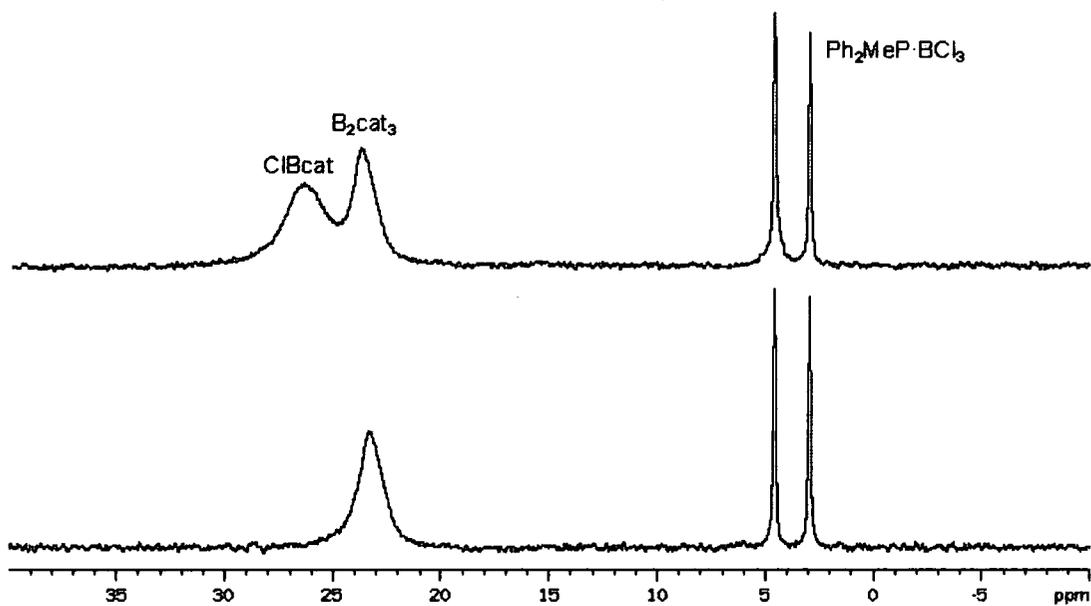
Figure 6.12: The $^{11}B\{^1H\}$ NMR spectrum of the 1:1 reaction of 1 with PPh₂Me in

C₆D₆ after 1 hour (top) and 24 hours

Figure 6.13: The $^{11}B\{^1H\}$ NMR spectrum of the 1:1 reaction of 1 with PPh₃ in C₆D₆

after 1 hour (top) and 24 hours (bottom)

Interestingly, even for those $R_3P \cdot ClBcat$ adducts that were isolated, boron substituent redistribution took place over a period of several weeks in the solid state at $-30^{\circ}C$. It is clear, therefore, that the thermodynamic products are **4** and $R_3P \cdot BCl_3$, with the phosphine adducts of **1** being only kinetically stable. The mechanism, shown in Scheme 6.3, is proposed for the redistribution reaction. In this mechanism, a molecule of **1** with coordinated phosphine reacts with an uncoordinated molecule of **1**, first forming an intermediate, **6**, which then reacts with a further uncoordinated molecule of **1** to form **4** and the $R_3P \cdot BCl_3$ adduct **5**.

This mechanism is based on the fact that once a phosphine is bound to ClBcat, the oxygen atoms, having lost the ability to π-bond to boron, become nucleophilic. Attack at the electrophilic boron of an uncoordinated ClBcat leads to ring opening of the original BO_2 moiety and subsequent transfer of a Cl^- between the two boron centres. Note that the electrophilic attack of ClBcat on an oxygen of the $R_3P \cdot ClBcat$ adduct with ring opening is analogous to the known ability of ClBcat to cleave C—O bonds in ethers.[57]

As the mechanism depends on there being an excess of **1** with respect to PR_3, we presumed that the reaction of all of the phosphines with an excess of **1** would cause the redistribution to take place. In order to investigate this, each of the phosphines was reacted with a five-fold excess of **1**. The reactions were monitored by *in situ* $^{11}B\{^1H\}$ NMR spectroscopy and all showed peaks due to **1**, **4**, and doublets due to **5a-g**. Additionally, one hour after treatment of ClBcat with PMe_3 and PEt_3, doublets were observed at δ 4.0 (J_{B-P} = 183 Hz) and δ 4.1 (J_{B-P} = 175 Hz) respectively (Figures 6.14 and 6.15). We believe that these additional low frequency resonances, which disappear after 24 hours, may be due to the 4-coordinate boron intermediates **6a** and

6b, shown in Scheme 3. The resonance for the 3-coordinate boron is likely to be superimposed on that for B₂cat₃.

Scheme 6.3: Equation and proposed mechanism for boron substituent redistribution

of R₃P·ClBcat in the presence of an excess of ClBcat
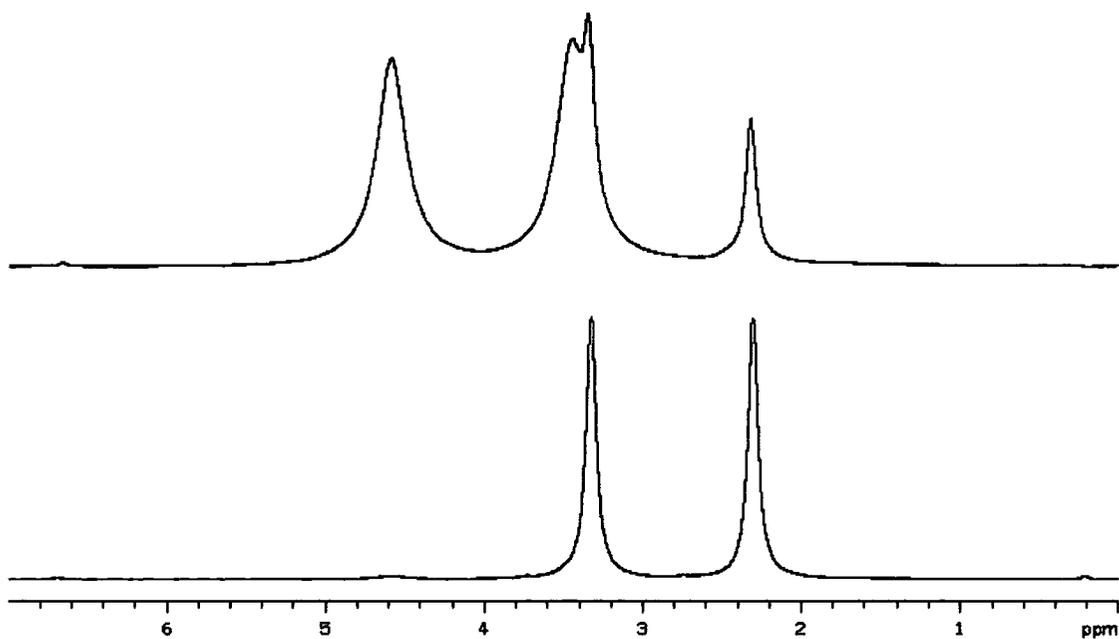
Figure 6.14: The $^{11}B\{^{1}H\}$ NMR spectrum of the 5:1 reaction of 1 with PMe$_3$ in C$_6$D$_6$ after 1 hour (top) and 24 hours (bottom)
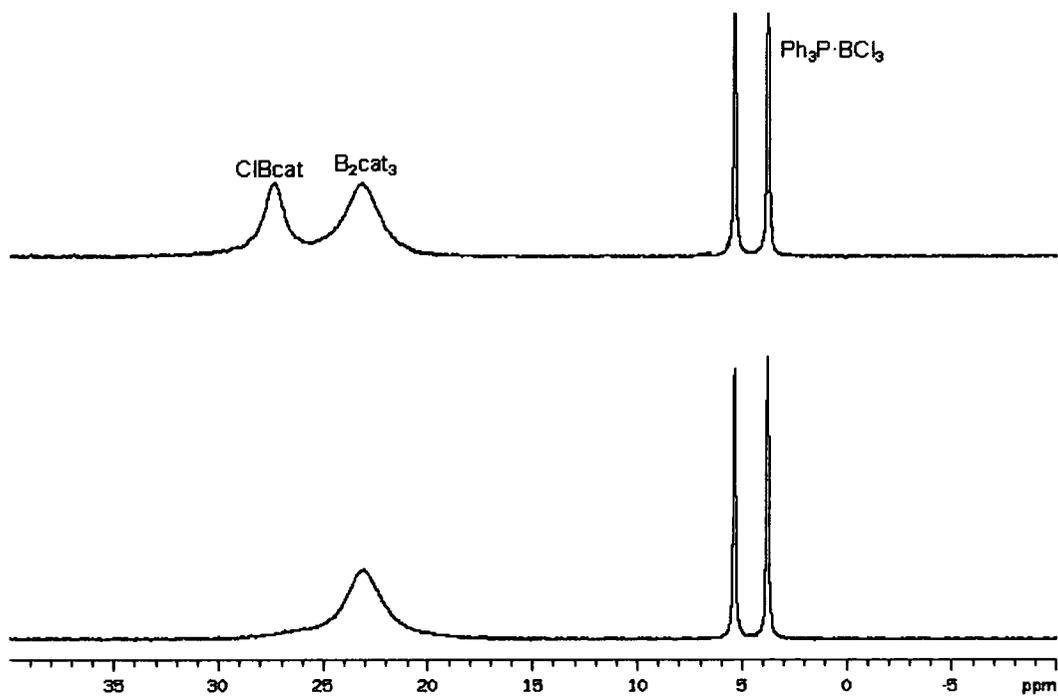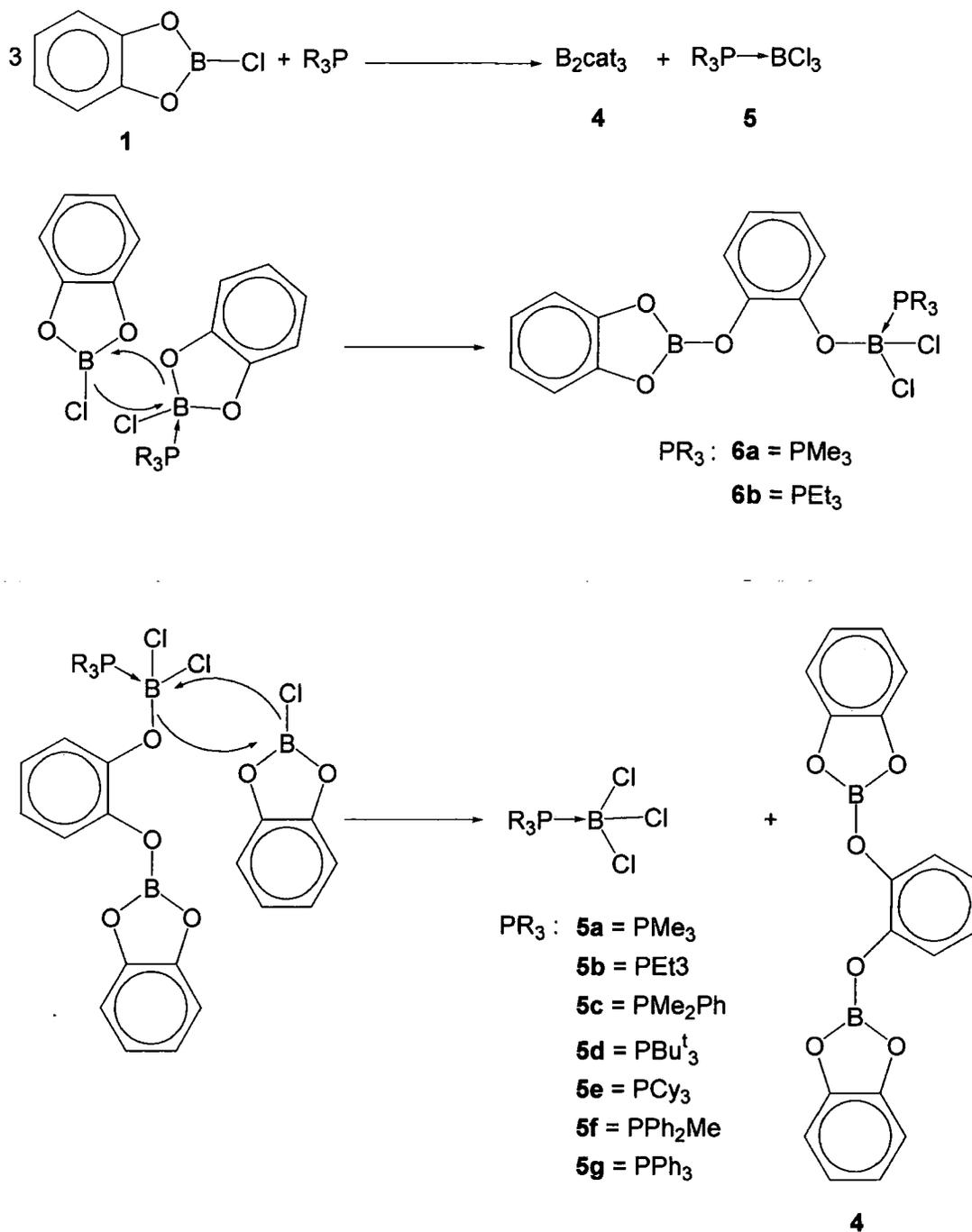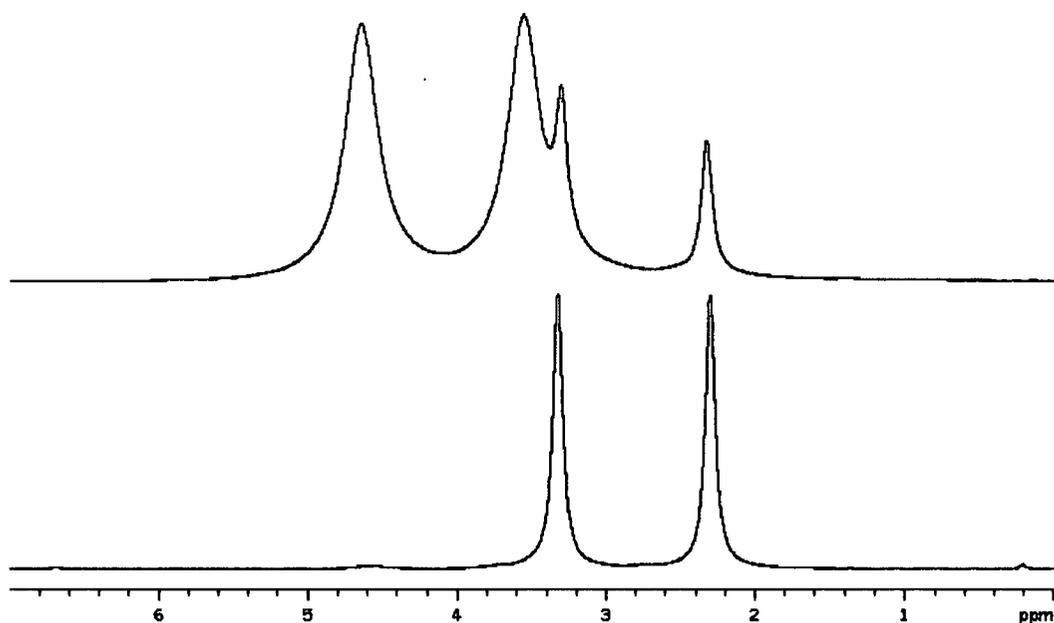

Figure 6.15: The $^{11}B\{^{1}H\}$ NMR spectrum of the 5:1 reaction of 1 with PEt$_3$ in C$_6$D$_6$ after 1 hour (top) and 24 hours (bottom)

The enhanced stability for such a species as an intermediate for PMe$_3$ and PEt$_3$ may be due to the smaller size of these phosphines.

Since the boron substituent redistribution yields B$_2$cat$_3$, we postulated that the complicated ^{11}B{^{1}H} NMR spectrum obtained for the reaction of **1** with PCy$_3$ was the result of some interaction between PCy$_3$ and B$_2$cat$_3$ (**4**). Six reactions were conducted between B$_2$cat$_3$ and 0.1, 1, and 2 equivalents of either PEt$_3$ or PCy$_3$. The *in situ* ^{11}B{^{1}H} NMR spectra (Figure 6.16) of the reactions using PEt$_3$ showed a shift of approximately 2 ppm to lower frequency from the expected position of free **4**, indicating that some interaction between PEt$_3$ and **4** is taking place. This is confirmed by the ^{31}P{^{1}H} NMR spectra, which show broad singlets shifted by approximately 20 ppm to higher frequency from the position of free PEt$_3$. The NMR spectra of the reactions with PCy$_3$, however, clearly show that a reaction is taking place. The ^{11}B{^{1}H} NMR spectra (Figure 6.17) show the formation of a sharp peak at δ 15.0, consistent with the [Bcat$_2$]$^-$ anion, a sharp peak at δ -14.8, and also other as yet unassigned peaks which are consistent with those observed for the reaction between PCy$_3$ and **4**. Removal of the solvent from the 2:1 PCy$_3$:B$_2$cat$_3$ reaction followed by recrystallisation yielded single crystals, the X-ray diffraction analysis of which, though there was disorder, clearly showed the [Bcat$_2$]$^-$ anion and the [HPCy$_3$]$^+$ phosphonium cation.[58] No other products were isolated from any of the reactions with PCy$_3$. The behaviour of PCy$_3$ is unique both in terms of reactivity and structure of the ClBcat adduct; the reasons for this are still elusive. However, it would appear that PCy$_3$ is sufficiently nucleophilic to displace [Bcat$_2$]$^-$ from B$_2$cat$_3$.
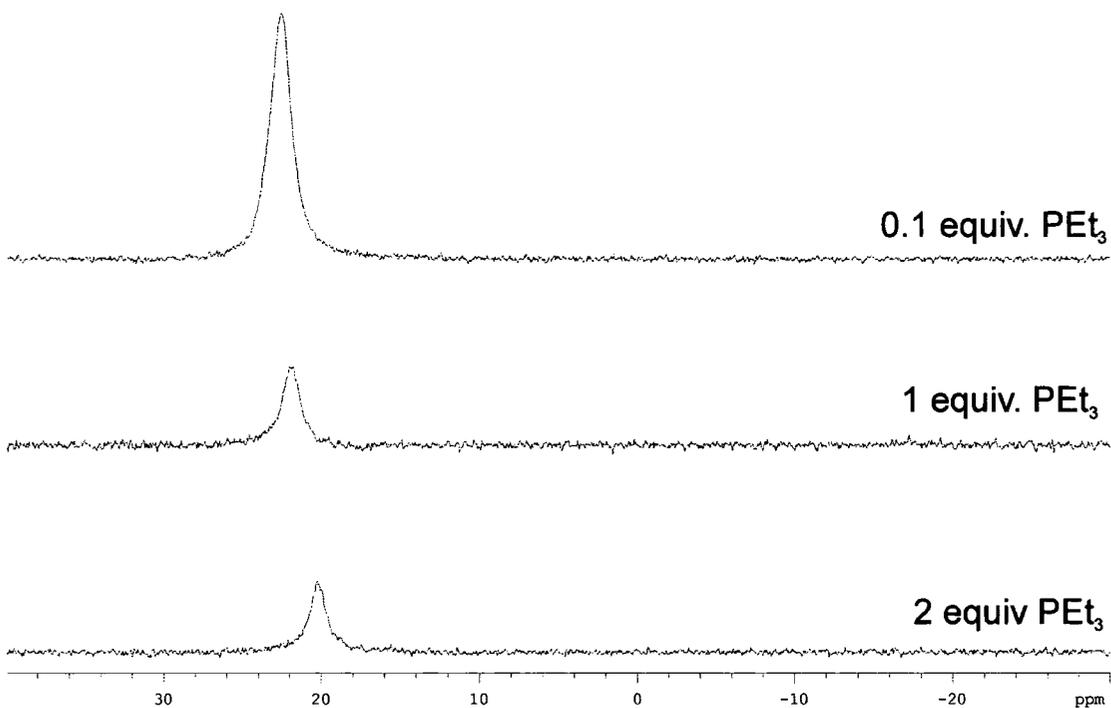
Figure 6.16: $^{11}B\{^1H\}$ NMR spectra of the reaction between 0.1, 1, and 2 equiv. PEt₃
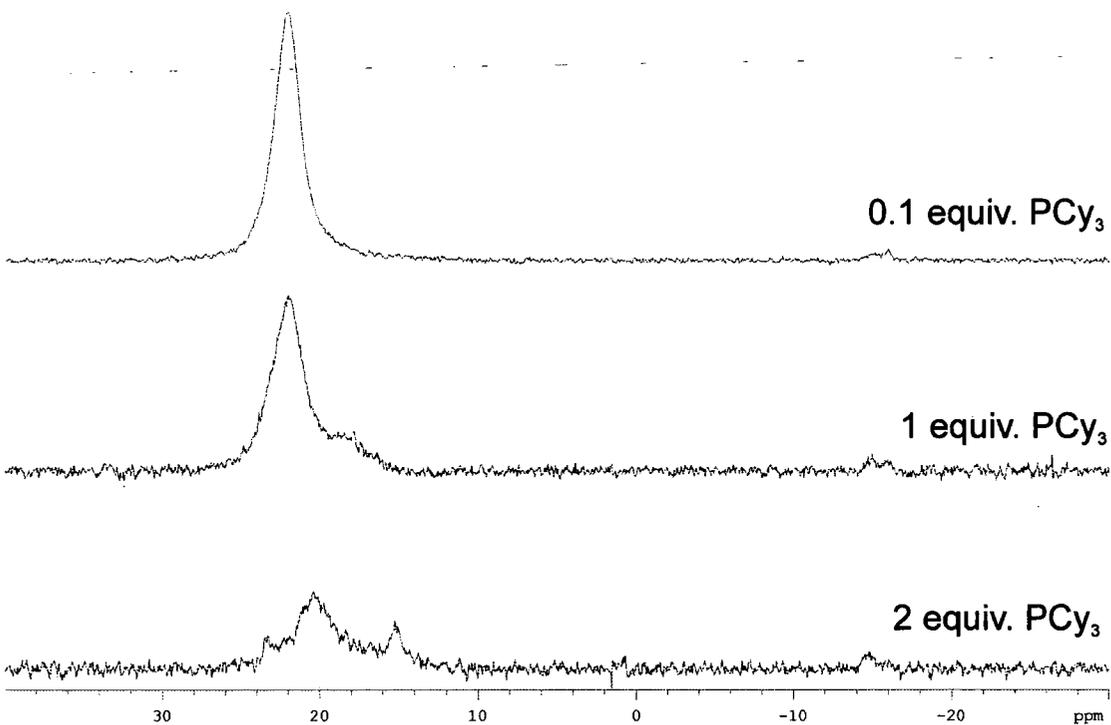
Figure 6.17: $^{11}B\{^1H\}$ NMR spectra of the reaction between 0.1, 1, and 2 equiv. PCy₃

To investigate the effect of nitrogen σ-donors, reactions of **1** with triethylamine, pyridine, 2-picoline, and 4-picoline were carried out (Scheme 6.4). The *in situ* $^{11}B\{^{1}H\}$ NMR spectra all showed broad peaks, shifted to lower frequency from the position of free **1**. The reactions all proceed cleanly, and no evidence of any decomposition was observed. Isolation of the pyridine and picoline adducts as solids proved difficult, as they tend to form oils, but removal of the solvent from the reaction with triethylamine and recrystallisation yielded single crystals of $Et_3N\cdot ClBcat$ (**3h**) suitable for X-ray structural analysis.

3h

3i : $R_1=R_2=H$

3j: $R_1=H$, $R_2=Me$

3k: $R_1=Me$, $R_2=H$
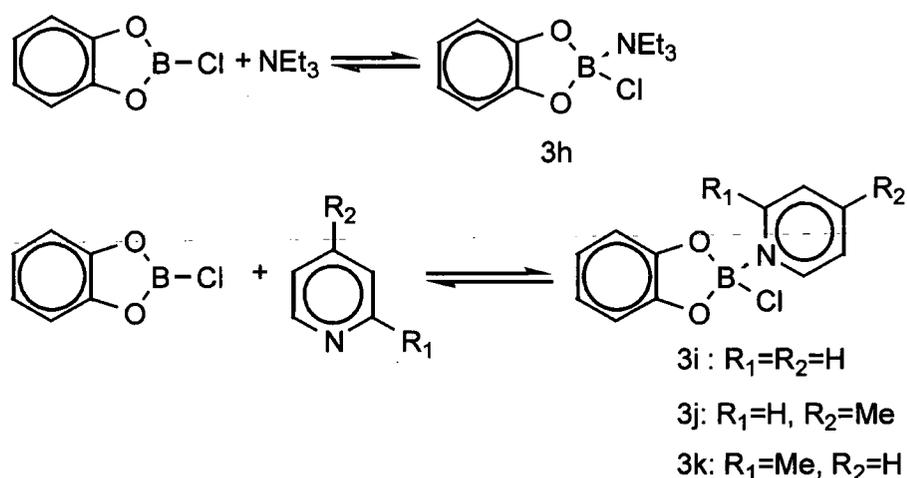
Scheme 6.4: Adduct formation from reaction of ClBcat and Et₃N, pyridine or

picolines

The molecular structure of **3h** (Figure 6.18) shows a B—Cl bond length of 1.876(2) Å which is shorter than the B—Cl bond lengths in any of the phosphine adducts, the shortest of which is 1.911(2) Å in **3a**. This is most probably due to a combination of the smaller size of nitrogen versus phosphorus, reducing steric interactions, and the larger electronegativity of nitrogen. The B—N bond of 1.643(2) Å is considerably

shorter than the B—P bond lengths in any of the adducts, as expected, again due to the smaller size of nitrogen.

In the case of **3h**, NMR analysis of the adduct kept both in solution and in the solid state showed no redistribution to $Et_3N \cdot BCl_3$ and **4**, so this adduct appears to be thermally stable.
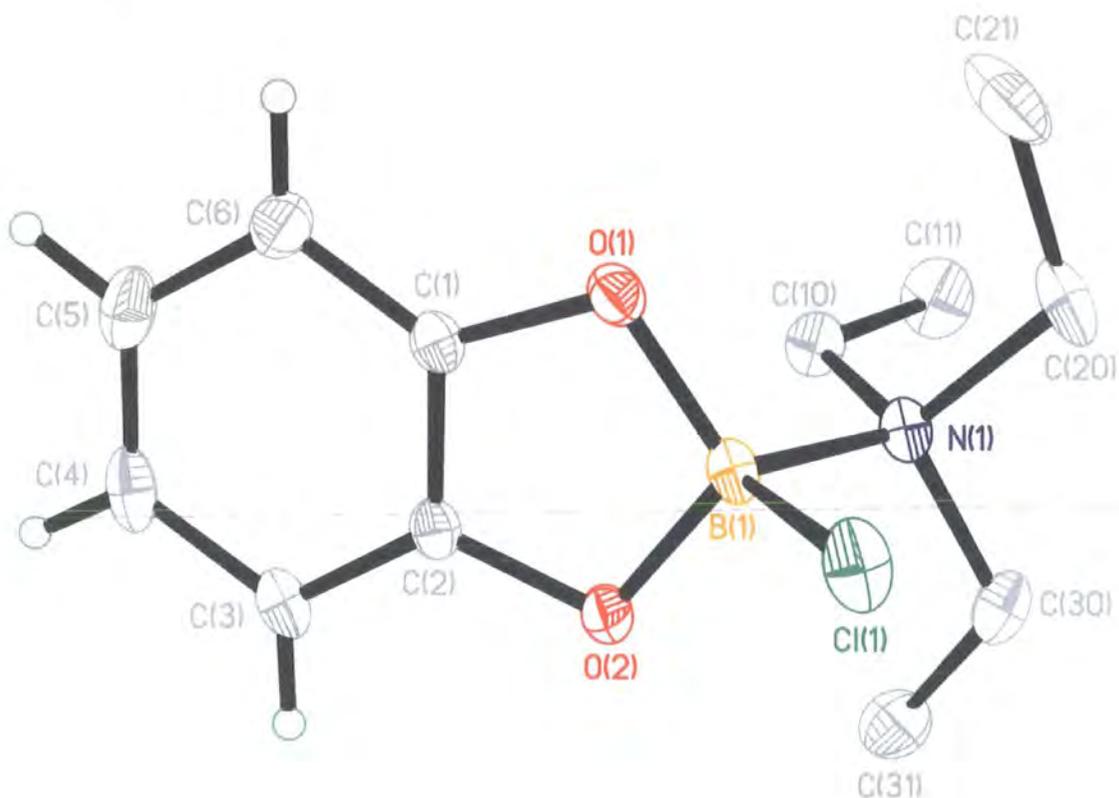
*Figure 6.18: Structure of Et₃N·ClBcat, **3h**. Hydrogens on the Et groups omitted for clarity*

6.3 Conclusion

Phosphine adducts of ClBcat can be isolated only if the phosphine is of sufficient basicity, the less basic phosphines used causing the rapid redistribution of ClBcat to B_2cat_3 and the $R_3P{\cdot}BCl_3$ adduct. The redistribution depends on there being free **1** in solution. The less associated adducts derived from the less basic phosphines provide larger concentration of **1** through dissociation leading to more rapid redistribution. Even those phosphine adducts that were observed or isolated were only kinetically stable, as redistribution took place slowly even in the solid state at $-30°C$. In the case of PCy_3, the phosphine reacts with the B_2cat_3 formed by the redistribution reaction. The presence of an excess of ClBcat relative to any of the phosphines causes the rapid boron substituent redistribution.

The nitrogen σ-donors formed stable adducts with ClBcat with no redistribution observed, either in the solid-state or in solution, over an extended period of time.

Oxidative addition of ClBcat to low-valent, late transition metal phosphine complexes is known.[48] However, if labile phosphine ligands are employed in a catalytic process, reaction according to Scheme 6.3 is to be expected. This may, in fact, be valuable, in so far as it would inhibit re-coordination of the phosphine to the metal centre, with BCl_3 serving as an *in situ* phosphine sponge. It will be important to show that B_2cat_3 and $R_3P{\cdot}BCl_3$ will not otherwise interfere with any catalytic process.

Strong binding of amine bases to ClBcat may serve to inhibit phosphine-promoted redistribution reactions. Examination of the oxidative addition of the B—Cl bond in amine adducts such as **3h** to low-valent late transition metals will be the basis for subsequent studies.

181

6.4 Experimental

Air-sensitive compounds were manipulated in a nitrogen atmosphere using Schlenk techniques or in Innovative Technology, Inc. System 1 glove boxes. NMR spectra were recorded on Bruker AC 200 (^{13}C), Varian Mercury 200 (^{1}H, ^{31}P), Varian Unity 300 (^{1}H, ^{11}B), and Varian Unity Inova 500 (^{11}B and VT ^{11}B) instruments. Variable temperature ^{31}P NMR experiments were conducted on a Varian VXR-400 instrument. Proton and ^{13}C NMR spectra were referenced to external SiMe$_4$ via residual protons in the deuterated solvents or solvent resonances respectively; ^{11}B and ^{31}P shifts were referenced to external BF$_3$·OEt$_2$ and 85% H$_3$PO$_4$ respectively. Elemental analyses were conducted in the Department of Chemistry at the University of Durham using an Exeter Analytical Inc. CE-440 Elemental Analyzer. Toluene was dried and deoxygenated by passage through columns of activated alumina and BASF-R311 catalyst under argon pressure using a modified version of the Innovative Technology Inc. SPS-400 solvent purification system.[59] Chloroform and CDCl$_3$ were dried over calcium hydride, C$_6$D$_6$ was dried over potassium metal, and all were distilled under nitrogen. The B-chlorocatechol borane (Aldrich) was sublimed under vacuum before use. Phosphines were purchased from Aldrich or Strem Chemicals Inc. and were checked for purity by ^{1}H and ^{31}P{^{1}H} NMR spectroscopy before use. Triethylamine, pyridine, and 2- and 4-picoline were purchased from Lancaster and were distilled from calcium hydride.

6.4.1 Preparation of Me$_3$P·ClBcat (3a)

A solution of PMe$_3$ (0.030 g, 0.389 mmol) in toluene (1 cm^3) was added to a solution of ClBcat (0.061 g, 0.389 mmol) in toluene (1 cm^3) and the mixture was stirred for 1 h. The solvent was removed *in vacuo* to yield 0.081 g of a white powder. The product

was recrystallised from a minimum amount of toluene to yield 0.078 g (87%) of a white, crystalline solid. ^{1}H NMR (CDCl$_3$): δ 6.79 (m, 4H, 1,2-O$_2$C$_6$$H_4$), 1.51 (d, 9H, P(C$H_3$)$_3$, J$_{H-P}$ = 11 Hz); ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 11.1 (s); (at -40°C): δ 11.0 (d, J$_{B-P}$ = 178 Hz); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ -27.9 (s); (at -40°C): δ -24.9 (q, J$_{P-B}$ = 175 Hz); ^{13}C-{^{1}H} NMR (CDCl$_3$): δ 150.5 (s, 1,2-O$_2$$C_6H_4$), 119.9 (s, 1,2-O$_2$$C_6H_4$), 110.3 (s, 1,2-O$_2$$C_6H_4$), 9.4 (s, br, P(CH$_3$)$_3$); (Found: C, 46.89; H, 5.78. C$_9$H$_{13}$O$_2$ClBP requires C, 46.91; H, 5.69%).

6.4.2 Preparation of Et$_3$P·ClBcat (3b)

As for (3a) using PEt$_3$ (0.038 g, 0.324 mmol) and ClBcat (0.050 g, 0.324 mmol). Yield 0.068 g (78%). ^{1}H NMR (CDCl$_3$): δ 6.78 (m, 4H, 1,2-O$_2$C$_6$$H_4$), 1.89 (dq, 6H, P(C$H_2CH_3$)$_3$, J$_{H-P}$ = 11 Hz, J$_{H-H}$ = 8 Hz,), 1.22 (dt, 9H, P(CH$_2$CH_3)$_3$, J$_{H-P}$ = 16 Hz, J$_{H-H}$ = 8 Hz); ^{11}B-{^{1}H} (PhMe/10% C$_6$D$_6$) δ 11.4 (s); (at -40°C): δ 11.3 (d, J$_{B-P}$ = 167 Hz); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 1.4 (s); (at -40°C) δ 6.8 (q, J$_{P-B}$ = 169 Hz); ^{13}C-{^{1}H} NMR (CDCl$_3$): δ 150.2 (s, 1,2-O$_2$$C_6H_4$), 119.8 (s, 1,2-$C_6H_4$), 110.3 (s, 1,2-O$_2$$C_6H_4$), 10.5 (d, P(C$H_2CH_3$)$_3$, J$_{C-P}$ = 34 Hz), 6.4 (d, P(CH$_2$CH$_3$)$_3$, J$_{C-P}$ = 5 Hz). (Found: C, 52.60; H, 7.09. C$_{12}$H$_{19}$O$_2$ClBP requires C, 52.89, H, 7.03%).

6.4.3 Preparation of Me$_2$PhP·ClBcat (3c)

As for (3a) using PMe$_2$Ph (0.045 g, 0.324 mmol) and ClBcat (0.050 g, 0.324 mmol). Yield 0.075 g (79%). ^{1}H NMR (CDCl$_3$): δ 7.65 (m, 6H, PMe$_2$(C$_6$$H_5$)), 7.46 (m, 3H, PMe$_2$(C$_6$$H_5$)), 6.83 (m, 2H, 1,2-O$_2C_6$$H_4$), δ 6.74 (m, 2H, 1,2-O$_2C_6H_4$) δ 1.51 (d, 6H, P(C$H_3$)$_2Ph, J_{P-H}$ = 9 Hz); ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 11.8 (s); (at -40°C): δ 11.6 (d, J$_{B-P}$ = 166 Hz); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$) δ -29.8 (s), (at -40°C): δ

-22.8 (q, J_{P-B} = 166 Hz); ^{13}C-{^{1}H} NMR (CDCl$_3$): δ 150.5 (s, 1,2-O$_2$C$_6$H$_5$), 131.5 (s, P(CH$_3$)$_2$Ph), 131.1 (d, P(CH$_3$)$_2$(C$_6$H$_5$)), 129.1 (d, P(CH$_3$)$_2$(C$_6$H$_5$), J_{C-P} = 11 Hz), 120.0 (s, 1,2-O$_2$C$_6$H$_4$), 110.4 (s, 1,2-O$_2$C$_6$H$_4$), 7.9 (d, P(CH$_3$)$_2$Ph), the resonances for the *ipso* carbon of P(CH$_3$)$_2$(C$_6$H$_5$) were not observed. (Found: C, 57.27; H, 5.39. C$_{14}$H$_{15}$O$_2$ClBP requires C, 57.49; H, 5.17%).

6.4.4 Preparation of Bu$^t_3$P·ClBcat (3d)

As for (3a) using PBu$^t_3$ (0.066 g, 0.324 mmol) and ClBcat (0.050 g, 0.324 mmol). The product was recrystallised from toluene layered with hexane to yield 0.095 g (82%) of a crystalline white solid. ^{1}H NMR (C$_6$D$_6$): δ 6.87 (m, 4H, 1,2-O$_2$C$_6$H$_4$), 1.29 (d, 27H, P(C(CH$_3$)$_3$), J_{H-P} = 11 Hz); (at –40°C): δ 1.65 (d, J_{H-P} = 15 Hz); ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 15.8 (s); (at -40°C): δ 12.1 (d, J_{B-P} = 158 Hz); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 25.5 (s); (at -40°C): δ 15.3 (q, J_{P-B} = 160 Hz); ^{13}C-{^{1}H} NMR (CDCl$_3$): δ 120.3 (s, 1,2-O$_2$C$_6$H$_4$), 110.8 (s, 1,2-O$_2$C$_6$H$_4$), 36.9 (d, P(C(CH$_3$)$_3$)$_3$, J_{C-P} = 27 Hz), 30.1 (s, P(C(CH$_3$)$_3$)$_3$), the resonances for C1 and C2 of 1,2-O$_2$C$_6$H$_4$ was not observed); (Found: C, 60.34; H, 8.78. C$_{18}$H$_{31}$O$_2$ClBP requires C, 60.61; H, 8.76%).

6.4.5 Reaction of ClBcat with PCy$_3$

A solution of PCy$_3$ (0.091 g, 0.321 mmol) in toluene (1 cm^3) was added to a solution of ClBcat (0.050 g, 0.321 mmol) in toluene (1 cm^3) and the mixture was stirred for 1 h, by which time a white precipitate had formed. The precipitate was collected by filtration and was recrystallised from toluene layered with hexane to yield a white solid (0.129 g). ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 23.4 (B$_2$cat$_3$), 21.4, 12.1 (Cy$_3$P·ClBcat), 11.1, 3.7 (d, J_{B-P} = 147 Hz, Cy$_3$P·BCl$_3$); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ -3.3 (Cy$_3$P·ClBcat).

6.4.6 Synthesis of Cy₃P·ClBcat (3e)

A 2 mol% excess of PCy$_3$ (0.093 g, 0.330 mmol) in toluene (1 cm^3) was added to a solution of ClBcat (0.050 g, 0.324 mmol) in toluene (1 cm^3), giving a white precipitate which was collected by filtration and recrystallised from toluene layered with hexane, yielding white crystals (0.038 g) from which the single crystal for X-ray analysis was obtained. ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 22.2 (impurity), 12.2 (Cy$_3$P·Cl*B*cat); (at -40°C) δ 11.8 (d, J$_{B-P}$ = 160 Hz); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ -3.3 (Cy$_3$*P*·ClBcat); (at -40°C): δ -6.6, (q, J$_{P-B}$ = 159 Hz); ^{13}C-{^{1}H} NMR (C$_6$D$_6$): δ 149.8 (s, 1,2-O$_2$C$_6$H$_4$), 119.8 (s, 1,2-O$_2$C$_6$H$_4$), 110.4 (s, 1,2-O$_2$C$_6$H$_4$), 30.1 (d, P(C$_6$H$_{11}$)$_3$, J$_{C-P}$ = 26 Hz), 28.0 (s, P(C$_6$H$_{11}$)$_3$), 27.2 (d, P(C$_6$H$_{11}$)$_3$), 25.8 (s, P(C$_6$H$_{11}$)$_3$).

6.4.7 Reaction of ClBcat with PPh₂Me

A solution of ClBcat (0.050 g, 0.324 mmol) in toluene (1 cm^3) was added to a solution of PPh$_2$Me (0.065 g, 0.324 mmol) in toluene (1 cm^3) which was then stirred for 1 h. Removal of solvent yielded a white precipitate (0.094 g). ^{11}B-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ 27.9 (Ph$_2$MeP·Cl*B*cat), 23.2 (*B*$_2$cat$_3$), 4.3 (d, J$_{B-P}$ = 153 Hz, Ph$_2$MeP·*B*Cl$_3$); ^{31}P-{^{1}H} NMR (PhMe/10% C$_6$D$_6$): δ -7.3 (q, J$_{P-B}$ = 155 Hz, Ph$_2$Me*P*·BCl$_3$).

6.4.8 Reaction of ClBcat with PPh₃

A solution of ClBcat (0.050 g, 0.324 mmol) in toluene (1 cm^3) was added to a solution of PPh$_3$ (0.084 g, 0.324 mmol) in toluene (1 cm^3) which was then stirred for 1 h. Removal of solvent yielded a white precipitate (0.118 g). ^{11}B-{^{1}H} NMR

(PhMe/10% C_6D_6): δ 27.9 (s, $Ph_3P\cdot ClB$cat), 23.1 (br, s, B_2cat_3), 4.4 (d, J_{B-P} = 152 Hz,

$Ph_3P\cdot BCl_3$); ^{31}P-{^{1}H} NMR (PhMe/10% C_6D_6): δ 2.0 (q, J_{P-B} = 152 Hz, $Ph_3P\cdot BCl_3$).

6.4.9 Preparation of Et$_3$N·ClBcat (3h)

A solution of NEt_3 (0.033 g, 0.324 mmol) in $CHCl_3$ (1 cm^3) was reacted with ClBcat

(0.050 g, 0.324 mmol) in $CHCl_3$ (1 cm^3) and the mixture was stirred for 1 h. The

solvent was removed *in vacuo* leaving a white powder which was recrystallised from

a minimum amount of $CHCl_3$ to yield 0.072 g (87%) of a crystalline white solid. ^{1}H

NMR ($CDCl_3$): δ 6.89 (m, 4H, $1,2-O_2C_6H_4$), 2.56 (q, 6H, N(CH_2CH$_3$)$_3$, J_{H-H} = 8 Hz), δ

0.71 (t, 9H, N(CH$_2$CH_3)$_3$, J_{H-H} = 8 Hz); ^{11}B-{^{1}H) NMR ($CDCl_3$): δ 13.3 (s); (Found:

C, 56.69; H, 7.59; N, 5.56. $C_{12}H_{19}BClNO_2$ requires C, 56.40; H 7.49; N, 5.48%).

6.4.10 Preparation of C$_5$H$_5$N·ClBcat

A solution of C_6H_5N (0.025 g, 0.324 mmol) in $CHCl_3$ (1 cm^3) was reacted with

ClBcat (0.050 g, 0.324 mmol) in $CHCl_3$ (1 cm^3) and the mixture was stirred for 1 h.

^{11}B-{^{1}H} NMR (*in situ* $CHCl_3$/$CDCl_3$): δ 11.8 ($C_5H_5N\cdot ClB$cat).

6.4.11 Preparation of 2-CH$_3$C$_5$H$_4$N·ClBcat

As for $C_5H_5N\cdot ClBcat$ using $2-CH_3C_5H_4N$ (0.030 g, 0.324 mmol) in $CHCl_3$ (1 cm^3).

^{11}B-{^{1}H} NMR (*in situ* $CHCl_3$/$CDCl_3$): δ 11.7 ($2-CH_3C_5H_4N\cdot ClBcat$).

6.4.12 Preparation of 4-CH$_3$C$_5$H$_4$N·ClBcat

As for $C_5H_5N\cdot ClBcat$ using $4-CH_3C_5H_4N$ (0.030 g, 0.324 mmol) in $CHCl_3$ (1 cm^3).

^{11}B-{^{1}H} NMR (*in situ* $CHCl_3$/$CDCl_3$): δ 11.7 ($4-CH_3C_5H_4N\cdot ClBcat$).

6.4.13 Computational study

Ab initio computations on $R_3P \cdot ClBcat$ adducts were carried out by Dr. Mark Fox using the Gaussian 94 package.[60] The experimental geometries were fully optimised initially at the HF/3-21G level and then at the HF/6-31G* level with no symmetry constraints. Frequency calculations were computed on these optimised geometries at the HF/6-31G* level and no imaginary frequencies were found. For single point energies of the experimental geometries in Table 3, the hydrogens were first optimised at the HF/6-31G* level.

6.4.14 Crystallography

X-ray diffraction experiments were carried out by Mr. Andrew Scott, Dr. Dimitrii Yufit, Dr. Mike Leach, Dr. Andrei Batsanov and Dr. Andres Goeta on a Bruker SMART 3-circle diffractometer with a 1K CCD area detector, using graphite-monochromated Mo-Kα radiation ($\bar{\lambda}$ =0.71073 Å) and a Cryostream (Oxford Cryosystems) open-flow N_2 gas cryostat. At least a hemisphere of data was collected in each case. Semi-empirical absorption corrections, by comparison of Laue equivalents, were applied (except for **3b**) using SADABS or XPREP programs.[61,62] The structures were solved by direct methods and refined by full-matrix least squares against F^2 of all data, using SHELXTL software.[62] All non-H atoms were refined in anisotropic, H atoms in isotropic approximation. Compound **3a** crystallised with two independent molecules in the asymmetric unit which differ little in their geometries. Crystal data and experimental details are summarised in Table 6.4, and full structural information has been deposited with the Cambridge Crystallographic Data Centre as supplementary publications no. CCDC-154920-154926.

Table 4: Crystal data and structure refinement for ClBcat, BrBcat and the R_3P and Et_3N adducts of ClBcat

	ClBcat (1)	BrBCat (2)	Me₃P·ClBcat (3a)	Et₃P·ClBcat (3b)	Bu$^t_3$P·ClBcat (3d)	Cy₃P·ClBcat (3e)	Et₃N·ClBcat (3h)
Formula	$C_6H_4BClO_2$	$C_6H_4BBrO_2$	$C_9H_{13}BClO_2P$	$C_{12}H_{19}BClO_2P$	$C_{18}H_{31}BClO_2P$	$C_{24}H_{37}BClO_2P$	$C_{12}H_{19}BClO_2N$
M	154.35	198.81	230.42	272.50	356.66	434.77	255.54
T/K	120(2)	120(2)	160(2)	200(2)	120(2)	150(2)	100(2)
Crystal System	Monoclinic	Monoclinic	Monoclinic	Orthorhombic	Orthorhombic	Monoclinic	Orthorhombic
Space Group	C2/c	C2/c	P2₁/c	Pbca	Pna2₁	P2₁/n	P2₁2₁2₁
a/Å	10.5584(8)	10.7250(4)	12.2244(10)	13.4416(12)	16.664(1)	11.541(2)	6.6037(3)
b/Å	9.8180(8)	10.0682(4)	16.3667(14)	14.0419(12)	13.455(5)	13.426(3)	13.3458(7)
c/Å	7.1370(5)	7.2078(3)	12.7944(11)	14.6040(12)	8.546(1)	15.070(3)	15.0557(7)
α/°	90	90	90	90	90	90	90
β/°	118.75(1)	119.53(1)	117.195(2)	90	90	92.226(3)	90
γ/°	90	90	90	90	90	90	90
U/Å³	648.62(9)	677.2(2)	2276.8(3)	2756(4)	1916.1(8)	2333.3(8)	1326.88(11)
Z	4	4	8	8	4	4	4
μ/mm⁻¹	0.506	5.992	0.447	0.380	0.289	0.250	0.277
Reflections Measured	2888	3032	14114	27702	14595	28034	15865
Unique Reflections	753	914	5258	3169	4570	6574	3762
R_{int}	0.0319	0.0250	0.0349	0.1318	0.0242	0.0403	0.0152
wR_2 (all data, on F^2)	0.0950	0.0637	0.0842	0.1059	0.0598	0.1055	0.0640
R [data with $F^2>2\sigma(F^2)$]	0.0345	0.0243	0.0317	0.0393	0.0257	0.0395	0.0234

6.5 References

1   K. Burgess and M. J. Ohlmeyer, *Chem. Rev.*, 1991, **91**, 1179.

2   A. H. Hoveyda, D. A. Evans, and G. C. Fu, *Chem. Rev.*, 1993, **93**, 1307.

3   I. Beletskaya and A. Pelter, *Tetrahedron*, 1997, **53**, 4957.

4   T. Ishiyama and N. Miyaura, *J. Organomet. Chem.*, 2000, **611**, 392.

5   T. B. Marder and N. C. Norman, *Top. Catal.*, 1998, **5**, 63.

6   J. M. Brown and G. C. Lloyd-Jones, *Chem. Commun.*, 1992, 710.

7   K. Burgess, W. A. van der Donk, S. A. Westcott, T. B. Marder, R. T. Baker, and J. C. Calabrese, *J. Am. Chem. Soc.*, 1992, **114**, 9350.

8   S. A. Westcott, T. B. Marder, and R. T. Baker, *Organometallics*, 1993, **12**, 975.

9   J. M. Brown and G. C. Lloyd-Jones, *J. Am. Chem. Soc.*, 1994, **116**, 866.

10   R. T. Baker, J. C. Calabrese, S. A. Westcott, and T. B. Marder, *J. Am. Chem. Soc.*, 1995, **117**, 8777.

11   D. H. Motry and M. R. Smith, *J. Am. Chem. Soc.*, 1995, **117**, 6615.

12   D. R. Lantero, D. L. Ward, and M. R. Smith, III, *J. Am. Chem. Soc.*, 1997, **119**, 9699.

13   D. H. Motry, A. G. Brazil, and M. R. Smith, III, *J. Am. Chem. Soc*, 1997, **119**, 2743.

14   T. M. Cameron, R. T. Baker, and S. A. Westcott, *Chem. Commun.*, 1998, 2395.

15   M. Murata, S. Watanabe, and Y. Masuda, *Tetrahedron Lett.*, 1999, **40**, 2585.

16   C. M. Vogels, P. G. Hayes, M. P. Shaver, and S. A. Westcott, *Chem. Commun.*, 2000, 51.

17 M. Murata, K. Kawakita, T. Asana, S. Watanabe, and Y. Masuda, *J. Bull. Chem. Soc. Jpn.*, 2002, **75**, 825.

18 R. B. Coapes, F. E. S. Souza, R. L. Thomas, J. J. Hall, and T. B. Marder, *Angew. Chem. Int. Ed. Engl.*, 2002, submitted.

19 M. Suiginome, H. Nakamura, and Y. Ito, *Chem. Commun.*, 1996, 2777.

20 S.-Y. Onozowa, Y. Hatanaka, and M. Tanaka, *Chem. Commun.*, 1997, 1229.

21 T. Ishiyama, K. Nishijima, N. Miyaura, and A. Suzuki, *J. Am. Chem. Soc.*, 1993, **115**, 7219.

22 Q. Cui, D. G. Musaev, and K. Morokuma, *Organometallics*, 1998, **17**, 1383.

23 I. Beletskaya and C. Moberg, *Chem. Rev.*, 1999, **99**, 3435.

24 S.-Y. Onozawa, Y. Hatanaka, T. Sakakura, S. Shimada, and M. Tanaka, *Organometallics*, 1996, **15**, 5450.

25 S.-Y. Onozowa, Y. Hatanaka, N. Choi, and M. Tanaka, *Organometallics*, 1997, **16**, 5389.

26 N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457.

27 T. Ishiyama, M. Murata, and N. Miyaura, *J. Org. Chem.*, 1995, **60**, 7508.

28 M. Murata, S. Watanabe, and Y. Masuda, *J. Org. Chem.*, 1997, **62**, 6458.

29 S. R. Piettre and S. Baltzer, *Tetrahefron Lett.*, 1997, **38**, 1197.

30 T. Ishiyama, Y. Itoh, T. Kitamo, and N. Miyaura, *Tetrahedron Lett.*, 1997, **38**, 3447.

31 A. Suzuki, *J. Organomet. Chem.*, 1999, **576**, 147.

32 T. Ishiyama and N. Miyaura, *J. Synthetic Organic Chemistry, Japan*, 1999, **57**, 395.

33   T. Ishiyama and N. Miyaura, *Chem. Lett.*, 2000, 126.

34   M. Murata, S. Watanabe, and Y. Masuda, *Tetrahedron Lett.*, 2000, **41**, 5877.

35   M. Murata, T. Oyama, S. Watanabe, and Y. Masuda, *J. Org. Chem.*, 2000, **65**, 164.

36   H. Nakamura, M. Fujiwara, and Y. Yamamoto, *Bull Chem. Soc. Jap.*, 2000, **73**, 231.

37   K. M. Waltz, X. He, C. Muhoro, and J. F. Hartwig, *J. Am. Chem. Soc.*, 1995, **117**, 11357.

38   K. M. Waltz and J. F. Hartwig, *Science*, 1997, **277**, 211.

39   C. N. Iverson and M. R. Smith, III, *J. Am. Chem. Soc.*, 1999, **121**, 7696.

40   K. M. Waltz, C. N. Muhuro, and J. F. Hartwig, *Organometallics*, 1999, **18**, 3383.

41   H. Chen and J. F. Hartwig, *Angew. Chem. Int. Ed. Engl.*, 1999, **38**, 3391.

42   H. Chen, S. Scheldt, T. C. Semple, and J. F. Hartwig, *Science*, 2000, **287**, 1995.

43   S. Shimada, A. S. Batsanov, J. A. K. Howard, and T. B. Marder, *Angew. Chem. Int. Ed. Engl.*, 2001, **40**, 2168.

44   H. Wadepohl, *Angew. Chem. Int. Ed. Engl.*, 1997, **36**, 2441.

45   H. Braunschweig, *Angew. Chem. Int. Ed.*, 1998, **37**, 1786.

46   G. J. Irvine, M. J. G. Lesley, T. B. Marder, N. C. Norman, C. R. Rice, E. G. Robins, W. R. Roper, G. R. Whittell, and L. J. Wright, *Chem. Rev.*, 1998, **98**, 2685.

47   M. R. Smith, III, *Prog. Inorg. Chem.*, 1999, **48**, 505.

48   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, and F. E. S. Souza, *J. Organomet. Chem.*, 1998, **550**, 183.

49   D. Männig and H. Nöth, *J. Chem. Soc. Dalton Trans.*, 1985, 1689.

50   C. Einertshofer, PhD Thesis, Luwig-Maximilians University, Munich, 1992.

51   S. A. Westcott, H. P. Blom, T. B. Marder, R. T. Baker, and J. C. Calabrese, *Inorg. Chem.*, 1993, **32**, 4367.

52   J. M. Burke, F. E. S. Souza, A. S. Batsanov, C. Wilson, D. S. Yufit, J. A. K. Howard, L. Horsburgh, W. Clegg, and T. B. Marder, *J. Chem. Soc. Dalton. Trans.*, in preparation.

53   F. E. S. Souza, MSc Thesis, University of Waterloo, Ontario, Canada,1997.

54   M. M. Rahman, H.-Y. Liu, K. Eriks, A. Prock, and W. P. Gierling, *Organometallics*, 1989, **8**, 1.

55   C. A. Tolman, *Chem. Rev.*, 1977, **77**, 313.

56   F. H. Allen and O. Kennard, , 1993, **8**, 1 & 31.

57   R. K. Boeckman and J. C. Potenza, *Tetrahedron Lett.*, 1985, **26**, 1411.

58   For related structures of $[HPMe_3]^+[Bcat_2]^-$ see: W. Clegg, A. J. Scott, F. J. Lawlor, N. C. Norman, T. B. Marder, C. Dai, and P. Nguyen, *Acta. Crystallogr.*, 1998, **C54**, 1518.

59   A. B. Pangborn, M. A. Giardello, R. H. Grubbs, R. K. Rosen, and F. J. Timers, *Organometallics*, 1996, **15**, 1518.

60   M. J. Frisch, G. W. Trucks, H. B. Schlegel, P. M. W. Gill, B. G. Johnson, M. A. Robb, J. R. Cheeseman, T. Kieth, G. A. Petersson, J. A. Montgomery, K. Raghavachari, M. A. Al-Laham, V. G. Zakrzewski, J. V. Ortiz, J. B.

Foresman, J. Cioslowski, B. B. Stefanov, A. Nanayakkara, M. Challacombe, C. Y. Peng, P. Y. Ayala, W. Chen, M. W. Wong, J. L. Andres, E. S. Replogle, R. Gomperts, R. L. Martin, D. J. Fox, J. S. Binkley, D. J. Defrees, J. Baker, J. P. Stewart, M. Head-Gordon, C. Gonzalez, and J. A. Pople, Gaussian Inc., Pittsburgh PA, 1995.

61   G. M. Sheldrick, SADABS: Program for scaling and correction of area detecotr data, University of Göttigen, Germany, 1996.

62   SHELXTL, An integrated system for solving, refining and displaying crystal structures from diffraction data, Ver. 5.10, Bruker Analytical X-ray Systems, Madison, Wisconsin, U.S.A., 1997.

Summary

This thesis highlights the viability of several different C-H activation processes for the borylation of a variety of hydrocarbon species.

Chapter Two gives the synthetic protocol for the species [Rh(acac)(COE)$_2$], which can be used as a catalyst precursor in its own right or can be used for the synthesis of further catalyst precursors. This protocol precludes the need for [Tl(acac)], necessary in the original but seemingly unknown publication of this species, and so is much more attractive for use in the pharmaceutical industry.

Chapter Three reports the first high-yield catalytic route to the 2,2,2-tris(boronate) esters ArCH$_2$C(Bcat)$_3$ (Ar = Ph, 4-MeO-C$_6$H$_4$), which have a wide range of synthetic applications due to the stabilisation of a carbanion centre by the α-boronate ester groups. Highest yields were achieved using the commercially available catalyst precursor [Rh(Cl)(PPh$_3$)$_3$] and the zwitterionic species [Rh(catBcat)(dppb)]. The tris(boronate) ester ArCH(Bcat)CH(Bcat)$_2$ can be made in moderate yields using [Rh(μ-Cl)(COE)$_2$]$_2$ with 2 or 4 equiv. P(o-tol)$_3$ as catalyst precursor.

Chapter Four reports the synthesis of vinyl(boronate) esters by dehydrogenative borylation of alkenes with B$_2$pin$_2$ or HBpin, using several Rh-based catalyst precursors. With vinyl anisole (VA), B$_2$pin$_2$, and $trans$-[Rh(CO)(Cl)(PPh$_3$)$_2$] both the vinyl(boronate) and vinyl-bis(boronate) esters can be formed readily. Most significantly, however, α-methylstyrene, 1,1-diphenylethylene, methylenecyclohexane and methylenecyclopentane, all 1,1-disubstituted alkenes, all yielded vinyl(boronate) esters which cannot be made by alkyne hydroboration. The reaction is strongly solvent dependent; toluene gives a rapid reaction but with several borylated species being produced, whereas acetonitrile produces a very clean reaction but with a slow rate of reaction. Therefore, 3:1 toluene:acetonitrile was used in order

to provide the best compromise. Reactions with HBpin were more rapid but resulted in higher levels of the hydroboration side product. The catalyst precursor [Rh(Cl)(PPh$_3$)$_3$] resulted in a more complete reaction than use of *trans*-[Rh(CO)(Cl)(PPh$_3$)$_2$], but was less selective for VBEs.

Chapter Five highlights the use of [Rh(Cl)(N$_2$)(P^{i}Pr$_3$)$_2$] as catalyst precursor for the direct C-H activation of benzylic and aromatic hydrogens. Reactions with ethylbenzene, cumene and 4-methyl anisole all yielded aromatic and benzylic borylation products. Selectivity is highest for benzylic and, significantly, *meta*-substituted arenes, in contrast to classical organic chemistry where electron-donating substituents are *ortho* and *para* directing. Indane proved very selective for benzylic activation and also yields a chiral borylated product. Several other substrates similar to indane proved very selective for benzylic activation, the main minor product invariably being a bis(boronate) species.

Chapter Six investigates the interaction of B-chlorocatecholborane (ClBcat) with a variety of phosphines, with the view to a boron analogue of the Heck reaction. The results here show that stability is dependent on a combination of basicity and cone angle of the phosphine, with small highly basic phosphines giving the most stable adducts. The use of an excess of ClBcat with any of the phosphines, however, yielded the redistribution products of the phosphine adduct of BCl$_3$ and B$_2$cat$_3$. The use of Et$_3$N, necessary in a Heck reaction, pyridine, and 2- and 4-picoline all provided adducts that were stable.

Conferences Attended

- IMEBORON X, University of Durham, July 11th-15th, 1999.

- 16th International Symposium – Fluorine Chemistry, University of Durham, 16th – 21st July, 2000.

- Intraboron 2000, University of Bath, August 21st-23rd

- Euroboron 2001, Manoir de la Vicomté, Dinard (France), September 2nd-6th.

Presentations

- 'Synthesis and Stability of Phosphine and Triethylamine Adducts of B-Chlorocatechol Borane,' presented at Intraboron 2000.

- 'The Rhodium Catalysed Borylation of Arenes via C—H Activation' North-East Postgraduate Industry Tour, 2001.

- 'Rhodium Catalysed Borylation via C-H Bond Activation: Direct Synthesis of Aryl- and Benzylboronate Esters' Euroboron 2001.

- 'Rhodium (I) Catalysed Diboration of (E)-Styrylboronate Esters,' Euroboron 2001.

Schools

- North-East Postgraduate Industry Tour 25th – 27th March, 2001.

- 7th BCA/CCG Intensive Course in X-ray Structure Analysis, Trevelyan College, Durham, 30th March – 6th April 2001.

Publications

- Phosphine promoted substituent redistribution reactions of B-chlorocatechol borane: molecular structures of ClBcat, BrBcat, and L·ClBcat (cat = 1,2-$O_2C_6H_4$; L= PMe$_3$, PEt$_3$, PBu$^t_3$, PCy$_3$, NEt$_3$). **R. B. Coapes**, F. E. S. Souza, M. A. Fox *et al.*, *J. Chem. Soc., Dalton Trans.*, 2001, 1201.

- Synthesis, characterisation and molecular structure of [Rh(COE)$_2$(acac)] (COE = cyclooctene, η^2-C_8H_{14}), an important starting material for the preparation of rhodium catalyst precursors J. M. Burke, **R. B. Coapes**, A. E. Goeta *et al.*, *J. Organomet. Chem.*, 2002, **649**, 199.

- Rhodium (I) Catalysed Diboration of (E)-Styrylboronate Esters: Molecular Structures of (E)-*p*-MeO-C_6H_4-CH=CH-B(1,2-$O_2C_6H_4$) and *p*-MeO-C_6H_4-CH$_2$C{B(1,2-$O_2C_6H_4$)}$_3$, P. Nguyen, **R. B. Coapes**, A. D. Woodward *et al.*, *J. Organomet. Chem.*, 2002, **652**, 77.