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Activation of diborylalkenes with Cu (I) catalyst towards C-C coupling

BACHELOR'S THESIS

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Dept. Química Física i Inorgànica

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I would like to dedicate this work to my father, who I know that from wherever he is, he always gives to me the strength to fight and achieve all my goals.

1.ABSTRACT

ENGLISH:

The present research work is aimed to get experience in catalytic organoboron chemistry, through the main habits: literature search, design of experiments, development of catalytic reactions and purification of products, characterization of the new organoboron compounds and analysis of the results.

We have observed that both 1,2-diborylalkenes and 1,1-diborylakenes have been functionalized selectively through copper catalyzed C-B bond activation and reaction with allylbromide.

This work opens the perspective towards new electrophilic trapping in the next steps.

CATALÀ:

Aquest treball de fi de grau esta enfocat a guanyar experiència en la química catalítica organoborada, d'acord amb els següents hàbits: recerca de literatura, disseny d'experiments, desenvolupament de reaccions catalítiques i purificació de productes, caracterització dels nous compostos organoborats i anàlisi dels resultats.

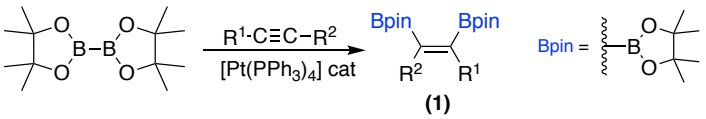
Hem pogut observar que els 1,2-diborilalquens i els 1,1-diborilalquens han estat funcionalizats de forma selectiva mitjançant l'activació de l'enllaç C-B per catàlisi amb coure i reacció amb bromur d'al·lil.

Aquest treball obre la perspectiva a noves reaccions amb electròfils en les següents etapes.

The present Bachelor's thesis has been developed at the Inorganic Chemistry Area in Dept. Química Física i Inorgànica of the University Rovira i Virgili, in the group of Catalytic Organoboron Chemistry (http://www.quimica.urv.es/organoborane/index.php).

2.1. Functionalization of alkenyl 1,2-bis(boronates)

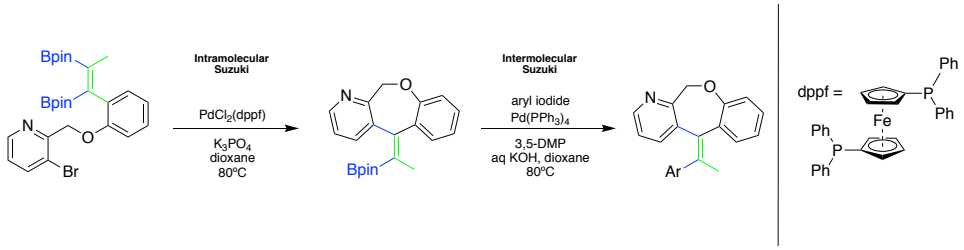
Alkenyl boronates have attracted much attention as versatile building blocks in organic synthesis because these compounds enable further multiple C-C bond formations via Pd-catalyzed cross-coupling reactions, leading to facile stereoselective construction of π-conjugated materials and biologically active compounds.[1] Among this class of versatile intermediates, alkenyl-1,2-bis(boronates) have been relatively less studied. In 1993, an efficient *cis*-selective route to alkenyl-1,2-bis(boronates) (**1**) was discovered by Miyaura, Suzuki and wo-workers.[2] It was reported the addition of tetraalkoxy- and tetraaryl- oxydiboranes, $(RO)_2B\text{-}B(OR)_2$, to terminal and internal alkynes in the presence of $[Pt(PPh_3)_4]$ (Scheme 1). The success of this catalytic transformation could be related to easy oxidative addition of the diboron reagent to the low-valent transition metal complexes. The inhibited β-hydride elimination within the Pt-alkenyl borane intermediates throughout the catalytic cycle, is another advantage in this protocol.



(1)

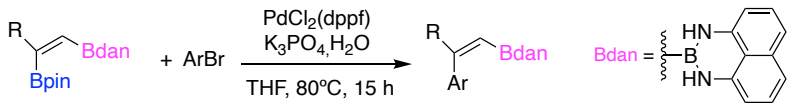
Scheme 1. Platinum-catalyzed diboration of alkynes for the synthesis of alkenyl-1,2-bis(boronates).

Most of the work related to these compounds has been focused on their functionalization through metal-catalyzed cross-coupling reactions. In 2008, Coghlan and co-workers, illustrated a regioselective sequential intra/intermolecular palladium Suzuki cross coupling by subsequent internal C-B functionalization, followed by external C-B functionalization to afford unsymmetrical tetrasubstituted alkenes (Scheme 2).[3]



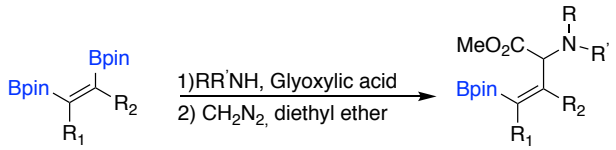
Scheme 2. Sequential intra/intermolecular palladium Suzuki cross coupling to alkenyl-1,2-bis(boronates).

Alternatively, in 2010 Iwadate and Suginome proved to use a differently protected diboron reagent instead of the classical bis(pinacolato) diboron ($B_2(pin)_2$).[4] They observed that the unsymmetrical diboron Bpin-Bdan had higher reactivity in the presence of Pd catalyst, thus allowing internal selective cross coupling (Scheme 3).



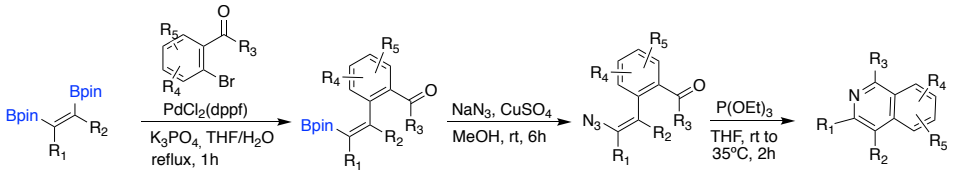
Scheme 3. Internal-selective Suzuki-Miyaura coupling of alkenyl 1,2-bis(boronates) with unsymmetrical Bpin-Bdan.

In 2014, Carboni and co-workers carried out the boron-Mannich reaction with alkenyl 1,2-bis(boronates) as substrates, which proceeded regioselectively at the terminal C-B bond to afford (*E*)-γ-boronated unsaturated amino esters in good yields (Scheme 4).[5] In a similar way, the same group performed an efficient and straightforward synthesis of 1-amino-1H-indines from 1,2-bis (boronates) via a sequential Suzuki-Miyaura coupling/Petasis cyclization reaction.[6]



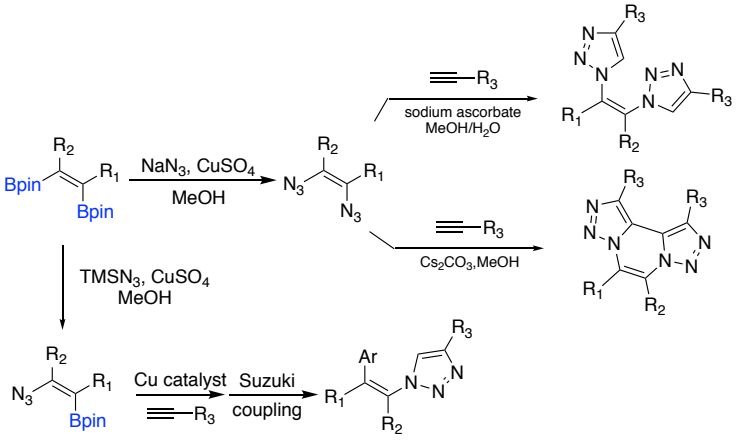
Scheme 4. Boron-Mannich route towards γ-boronated unsaturated amino esters.

In 2017, an efficient and straightforward synthesis of isoquinolines was reported from internal alkenyl 1,2-bis(boronates), easily prepared from the corresponding 1,2-bis(boronates), *via* a sequential copper-catalyzed azidation/aza-Wittig condensation (Scheme 5).[7]



Scheme 5. Synthesis of isoquinolines from alkenyl 1,2-bis(boronates).

More recently, Mali and co-workers demonstrated a stereoselective and convenient route to access (*Z*)-1,2-diazido alkenes from the corresponding alkenyl 1,2-bis(boronates) *via* a copper-mediated reaction with sodium azide. Alternately, mono-functionalization was regioselectively carried out with trimethylsilyl azide as an azidation reactant. The *in-situ* conversion of bis-azides to the corresponding bis-triazoles can be readily achieved in the presence of copper sulfate and sodium ascorbate, while the modification of the catalytic system opened a new convenient route to bis-triazolo-pyrazines, a new class of fused heterocycles (Scheme 6).[8]

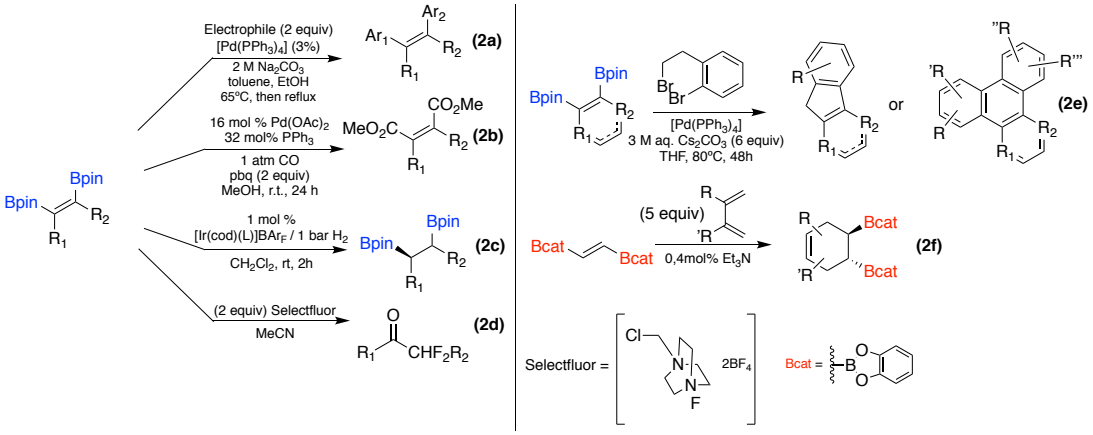


Scheme 6. Synthesis of (*Z*)-1,2-diazido alkenes, (*Z*)-di-(1,2,3-triazolyl)-alkenes and fused bis-triazolo-pyrazines from alkenyl 1,2-bis(boronates).

Other authors have studied convincing examples of the interest of these compounds which can be seen in Scheme 7, such as double Suzuki-Miyaura coupling with 2 equivalents of the same electrophile in a toluene/ethanol system, in the presence of an Na_2CO_3 aqueous solution and $[Pd(PPh_3)_4]$ as the catalyst (**2a**).[9] Further annulation reactions, with aromatic dihalides, can take

place in the presence of [$Pd(PPh_3)_4$] as a catalyst and 3M aqueous Cs_2CO_3 as the base, in THF at 80ºC (**2e**).[10]

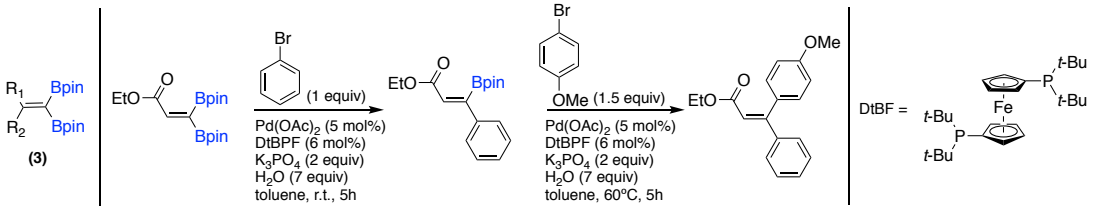
Double functionalization has also been accomplished by double carbomethoxylation in the presence of the catalytic system palladium (II) acetate/triphenylphospine [$Pd(OAc)_2/PPh_3$], with p-benzoquinone as a stoichiometric oxidant in methanol at ambient temperature (**2b**).[11] Enantioselective hydrogenation of alkene 1,2-bis(boronates) using, [Ir(cod)(L)Bar_F] catalyst precursors (**2c**) is another useful strategy.[12] Fluorocarbomethoxylation via electrophilic fluorination with Selectfluor (**2d**) provides access to valuable functionalized ketones.[13] Diels-Alder cycloaddition of 1,2-bis(catecholboryl)ethylene and simple acyclic dienes at 100ºC, in presence of triethylamine, were recently described to synthesize difunctionalized cycles (**2f**).[14]



Scheme 7. Alternative examples about functionalization of alkenyl 1,2-bis(boronates).

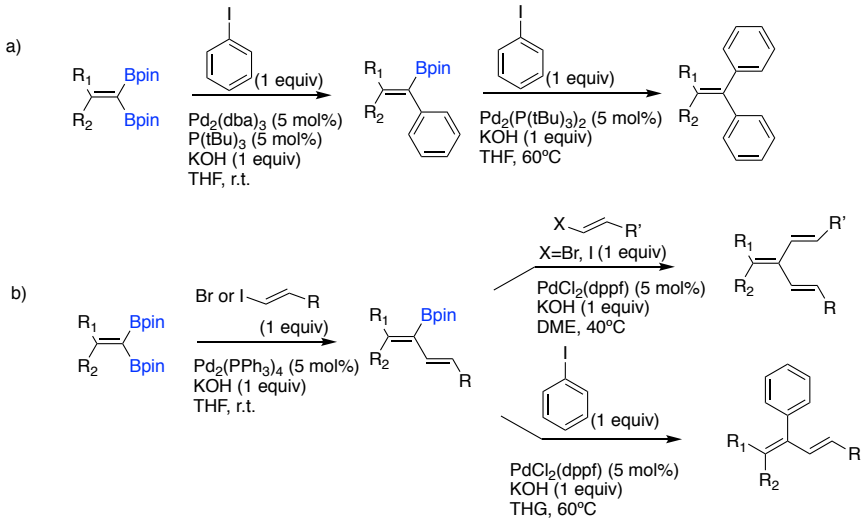
2.2. Functionalization of alkenyl 1,1-bis(boronates)

In the same way as alkenyl 1,2-bis(boronates), alkenyl 1,1-bis(boronates) (**3**) (Scheme 8) are particularly attractive compounds because they are intermediates on route to π-conjugated molecules when subsequent Pd-catalyzed multiple carbon bond formation takes place on the same carbon.[15] Particularly important is the fact that the two geminal boryl substituents of the 1,1-diborylalkenes can be differentiated and transformed in a step-wise manner.[16] In 2015, Sawamura[17] and co-workers performed a Suzuki-Miyaura coupling between β,β-diborylacrylate and bromobenzene in the presence of a $Pd(OAc)_2$ catalyst precursor modified with DtBPF (1,1'-bis(di-*tert*-butylphosphanyl)ferrocene], and demonstrated that the cross-coupling occurs selectively at the boron site *trans* to the ester group to give the corresponding alkenylboronate (with *E*/*Z* > 99:1) in high yield (Scheme 8). This stereoselectivity is probably due to the steric character of the ester group. Additionally, a second cross-coupling with 4-bromoanisole can be performed to give an isomerically pure trisubstituted alkene in good yield (*Z*/*E* > 99:1).



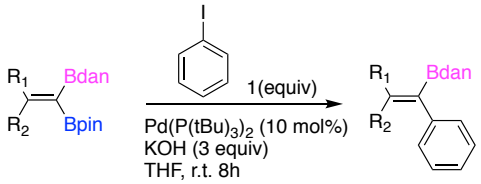
Scheme 8. Pd-catalyzed consecutive carbon-carbon formation with a β,β-diborylacrylate.

In general, 1,1-diborylalkenes can undergo stereoselective cross-coupling with aryl iodides to afford the corresponding (*E*)-alkenylboronates as single isomers.[18-22] Subsequent coupling provides a completely stereocontrolled access to triarylated alkenes. Applying this concept, Hiyama and co-workers[23] developed a stereocontrolled approach to 1,1,2-triaryl-1-alkenes based on sequential cross-coupling of 1,1-diborylalkenes (Scheme 9(a)). Furthermore, these authors extended this stereocontrolled coupling between 1,1-diborylalkenes and alkenyl iodides or bromides to obtain 3-borylated 1,3-dienes in good yields and with high *E*-selectivity also performing a successive Pd-catalyzed coupling with alkenyl or aryl iodides[24] (Scheme 9 (b)).



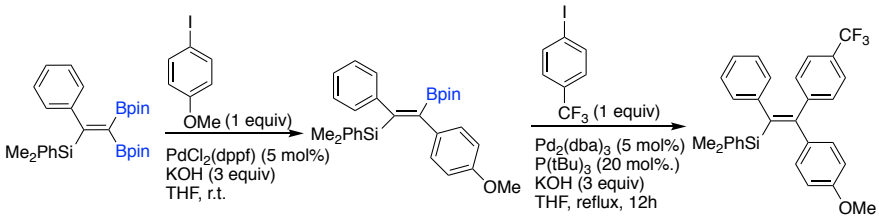
Scheme 9. Stereoselective cross-coupling of 1,1-diborylalkenes to afford triarylated alkenes or triarylated 1,3-dienes.

In 2017, Chirik and co-workers[25] demonstrated that the difference in reactivity of different boryl moieties in 1,1-diborylalkenes, such as Bpin and Bdan, allows a selective Suzuki-Miyaura cross-coupling at the Bpin moiety (Scheme 10).



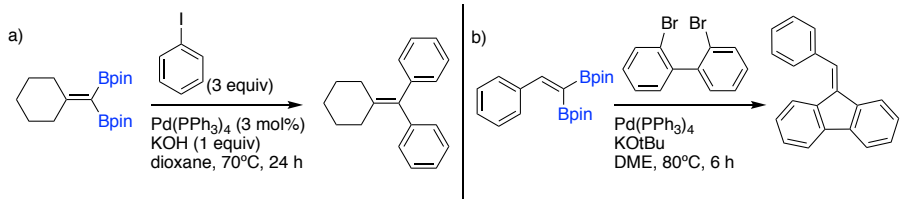
Scheme 10. Pd-catalyzed selective Suzuki-Miyaura cross-coupling at the Bpin moiety.

Nishihara and co-workers[26,27] developed a method for highly chemoselective arylation through Suzuki-Miyaura coupling. They identified $PdCl_2$ (dppf) as a catalyst for the selective arylation, at room temperature, with the *Z* stereoisomer being the major triarylated product. Subsequent Suzuki-Miyaura coupling of the remaining boryl moiety provides access to triarylated compounds (Scheme 11).



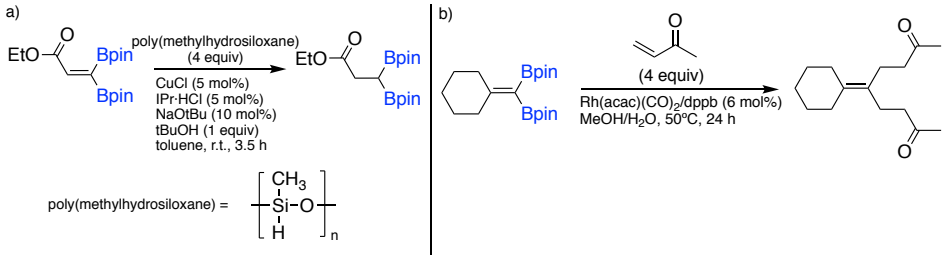
Scheme 11. Chemoselective arylation through Suzuki-Miyaura coupling of 1-phenyl-1-silyl-2,2-diborylethenes.

Double-cross coupling of 1,1-diborylalkenes has also been developed, with the goal of efficient conversion of both C-B bonds into C-C bonds. Hence, Shimizu, Hiyama and co-workers[28] developed a convenient [$Pd(PPh_3)_4$] catalyzed double arylation of 1,1-diborylmethylenecyclohexane (Scheme 12 (a)). Similarly, Jin and co-workers[29] demonstrated the synthetic usefulness of 1,1-diborylalkenes by means of double annulative Suzuki-Miyaura coupling (Scheme 12 (b)).



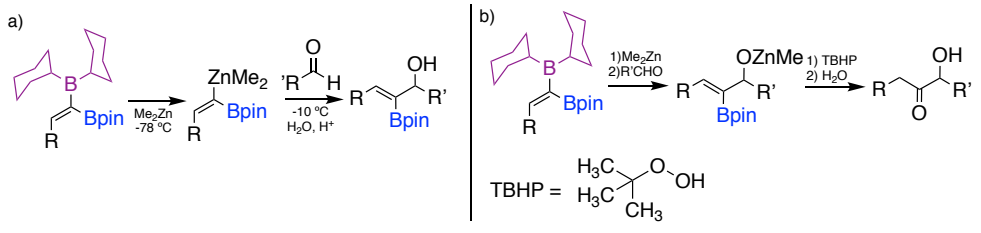
Scheme 12. Pd-catalyzed double cross-coupling of 1,1-diborylalkenes.

Sawamura and co-workers[17] found that β,β-diborylacrylate compounds can be efficiently transformed into the corresponding geminal diborylalkanes through copper-catalyzed conjugate reduction with poly(methylhydrosiloxane) (Scheme 13 (a)). Rh-catalyzed Michael-type double addition[30] also proceeded smoothy to give the corresponding diketone (Scheme 13 (b)).



Scheme 13. (a) Cu-catalyzed selective reduction of β,β-diborylacrylate compounds. (b) Rh-catalyzed Michael addition of a 1,1-diborylmethylene-cyclohexane.

Walsh and co-workers[31] demonstrated that 1,1-diborylalkene compounds containing a Bpin and a dicyclohexylboryl moiety can be transmetallated with organozinc reagents leaving the Bpin moiety untouched. The authors also demonstrated that the resulting boron/zinc heterobimetallic reagent can react with aldehydes, providing Bpin-substituted (*E*)-allylic alcohols (Scheme 14 (a)). Additionally, they illustrated that this kind of compounds can be converted into hydroxy ketones through one-pot four-step transformation (Scheme 14 (b)).



Scheme 14. One-pot generation of B(pin)-substituted allylic alcohols and hydroxy ketones.

In the course of our studies of the development of new catalytic borylation reactions, we became interested in replacing palladium by copper for the catalyzed cross-coupling reactions of alkenyl 1,2- and 1,1-bis(boronates), as it is a more economical and ecofriendly alternative catalyst.

3. OBJECTIVES

The present Bachelor's Thesis is focused on the initiation of innovative research in catalytic organoboron chemistry.

Towards this end, we have planned the following objectives:

1. Acquire the habit to read manuscripts, papers and reviews, related to the subject on the Bachelor's Thesis.
2. Find out the work hypothesis of the planned work, based on scientific rationalization and previous related work performed in the research group, Catalytic Organoboron Chemistry (http://www.quimica.urv.es/organoborane/index.php).
3. Synthesis of alkenyl bis(boronates) with pinacolboryl moieties.
4. Development of copper catalyzed functionalization of alkenyl 1,2-bis(boronates) and alkenyl 1,1-bis(boronates) with allyl bromides.
5. Analysis of the catalytic reactions, with a special emphasis on conversion and regioselectivity, in order to determine the factors that influence the efficiency of the catalytic reactions.
6. Characterization of the new organoboron compounds, by NMR and MS analysis.
7. Determine the main conclusion of this copper catalyzed functionalization of alkenyl 1,2-bis(boronates) and alkenyl 1,1-bis(boronates) with allyl bromides.
8. Predict a future line of work to complete the study conducted through the present research work.

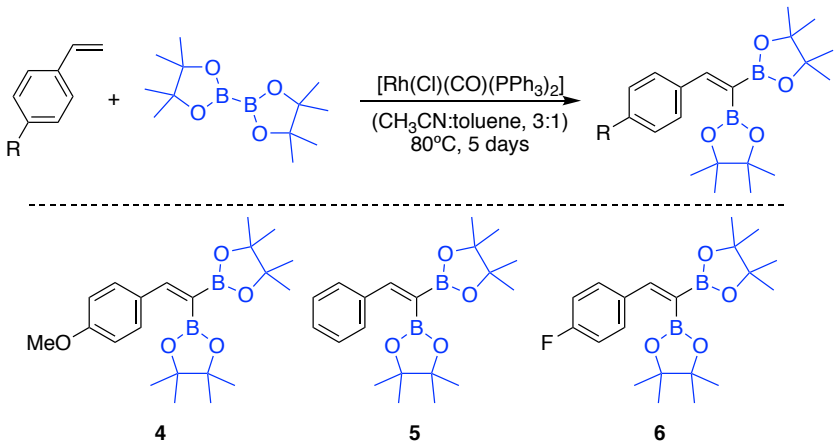
Inspired by these literature precedents, we initiated our studies by synthesizing a series of 1,1-diborylalkenes to further study their functionalization. 1,2-Diborylalkenes were not prepared in this work, as the reagent (*E*)-2,2'-(1-phenylethene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) ester is a commercially available compound.

For the synthesis of 1,1-diborylalkenes, the protocol of rhodium-catalyzed double dehydrogenative borylation of alkenes, was selected for simplicity.

4.1. Rhodium-catalyzed double dehydrogenative borylation of alkenes

In 2003, Marder and co-workers were pioneers in the rhodium-catalyzed transformation of 4-vinylanisole into vinyl-bis(boronic) esters.[32] The catalyst used was *trans*-[RhCl(CO)(PPh_3)$_2$] (5 mol %), known as Wilkinson catalyst, which activated 2 equivalents of B_2pin_2 to afford an 85% yield of the 1,1-diborylalkene. Presumably, the excess of B_2pin_2 favored the double replacement of the terminal H atoms of the 4-vinyl-anisole by two Bpin moieties, in a single catalytic reaction, at 80ºC. Although the detailed mechanism of the dehydrogenative borylation of alkenes remains unknown, it most likely involves insertion of the alkene into a Rh-B bond, followed by β-hydride elimination to give a mono-vinylboronate that undergoes a second dehydrogenative borylation process.

Following the methodology proposed by these authors, we have prepared in this work three 1,1-diborylalkenes, by using different vinylarenes, under the optimized conditions reported in the literature for the synthesis of 4-vinylanisole (Scheme 15).[32]



Scheme 15. Substrate scope of 1,1-diborylalkenes.

Compound **5** had been previously synthesized by other protocols in our research group, that resulted less efficient. Therefore, we have focused our attention mainly on the synthesis and subsequent purification of product **5**, in order to find the optimal conditions. Compounds **4** and **6** were also synthesized to prove that this methodology worked with vinylarenes that are characteristic of different electronic properties. On one hand, 4-vinylanisole (**4**) had the methoxide group which acts as an electron donating group, while on the other hand 1-fluoro-4-vinylbenzene (**6**) contains F^- which acts as electron withdrawing group. From the GC-MS results

obtained, the reaction seemed to work more efficiently for more electron withdrawing substrates, observing a trend that follows as: product formation **4**>**5**>**6**.

4.2. Functionalization of alkenyl 1,1-bis(boronates)

In the research group where I have performed this Bachelor's Thesis, the activation of 1,1-bis(boronates) with Cu (I) catalyst towards C-C coupling was previously studied. The following table (Table 2) corresponds to the results they obtained by using different conditions when studying the functionalization of product **5** with allyl bromide. In particular, the copper activation of compound **5** followed by electrophilic trapping with allyl bromide was deeply optimized.

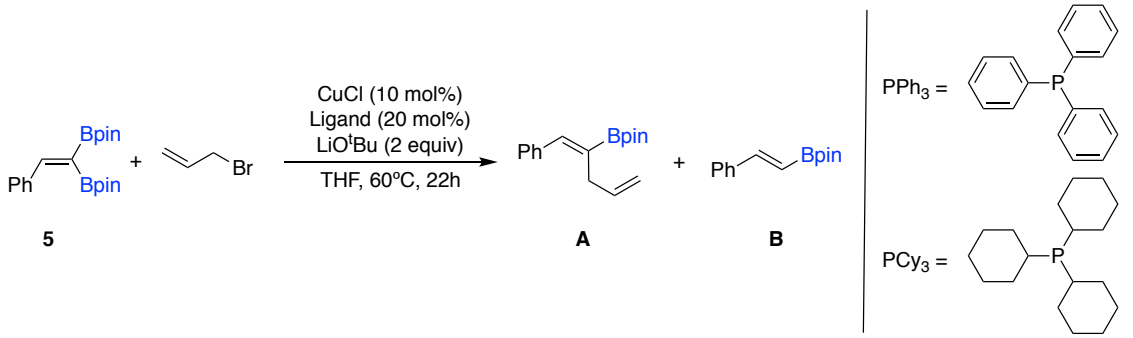


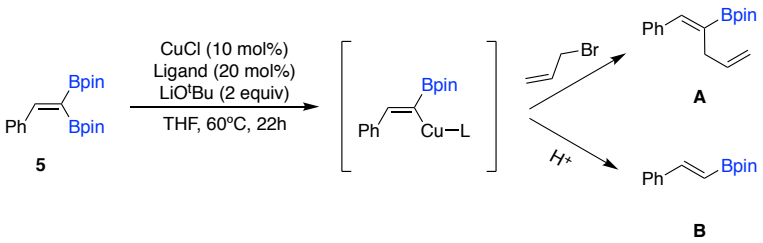
Table 1. Study on the functionalization of product **5** by using different phosphine ligands.[a]

Entry	Ligand	Conv. (%)	A:B ratio	Z/E (%)	Yield A (%)
1	PPh_3	98	91:9	93:7	60
2	PCy_3	91	90:10	96:4	41

[a]Conditions: 0.2 mmol of **5** and 1.5 equivalents of allyl bromide.

The best conditions for high conversion and good selectivity were achieved when 10 mol% CuCl was used as catalyst, 20 mol% of PPh_3 or PCy_3 were used as ligands, with 2 equivalents of Li^{t}OBu acting as base and at 60ºC for 22 hours in THF as solvent. In that content, I performed the reaction at 30ºC in order to study the influence of the temperature. The crude of the reaction was analyzed by GC-MS and NMR. Further purification by flash chromatography in order to separate compound **A** from **B** was performed.

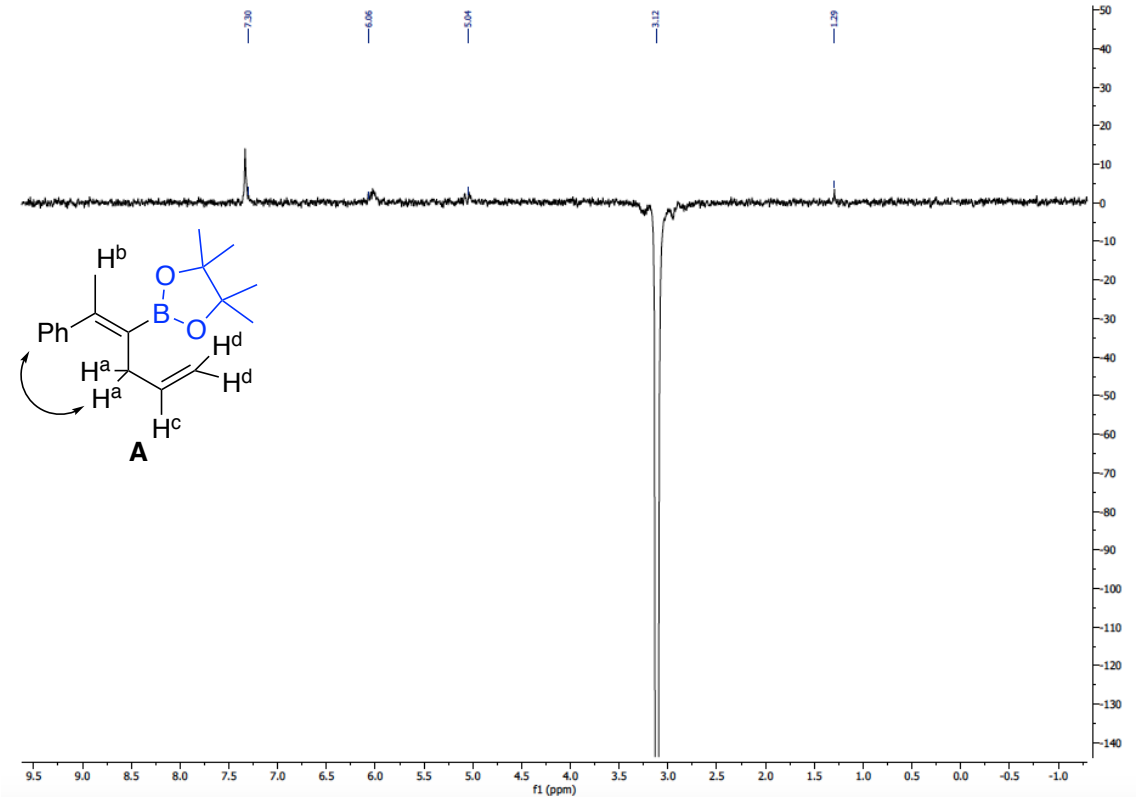
Product **A** seems to be synthetized from the selective activation of the C-Bpin bond in *cis* disposition to C-Ph (Scheme 17). In addition, the electrophilic trapping with the allyl bromide takes place efficiently. Alternatively, product **B** is formed by competition of protonation of the C-Cu bond with H^+ present in the reaction media or in the work up (Scheme 17).



Scheme 16. Selectivity associated to the electrophilic trapping.

Considering the most characteristic signals from the NMR of the crude of the starting material and products **A** and **B**, the conversion has been calculated and it has been found to be 72%. Also from the crude, the ratio between product **A** and **B** has been calculated, A/B=96/4. The *Z*/*E* ratio was calculated by NMR from the characteristic signals of each stereoisomer.

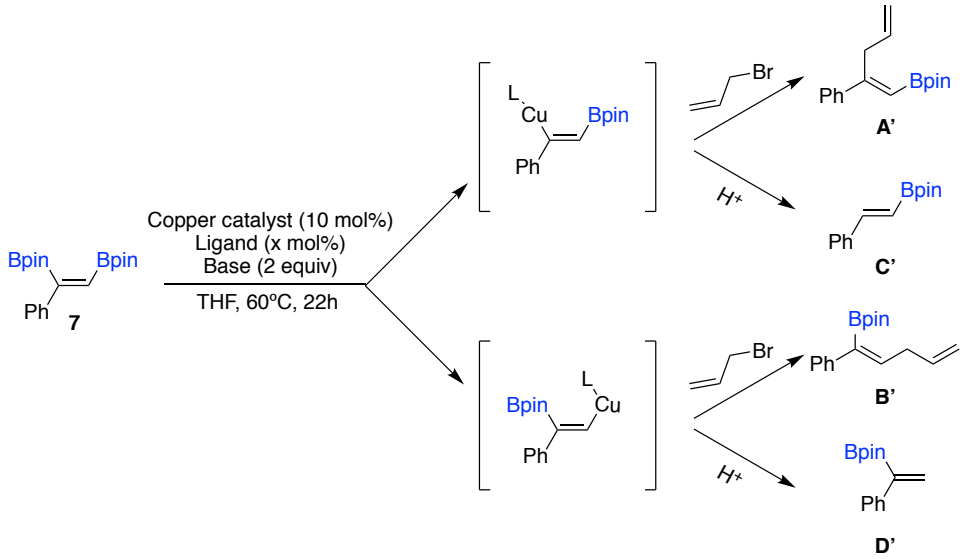
In order to determine if the major product was in *E* or *Z* disposition, nuclear overhauser effect (NOE) technique was used. In this technique a characteristic proton is irradiated in order to see which signals of the other protons observes or not. In this case (Figure 1), the irradiated proton was H^a which from the NOE obtained can be seen that the signal which observes is the one corresponding to the phenylic hydrogens instead of the one corresponding to H^b. This is the main signal which makes clear to differentiate that the major product is in *Z* disposition.



4.3. Functionalization of alkenyl 1,2-bis(boronates)

The main goal of this Bachelor's Thesis is the development of copper catalyzed functionalization of alkenyl 1,2-bis(boronates), because from the best of our knowledge it would be a new attempt to functionalize diborated products in a selective manner. Towards this end, different functionalization conditions have been performed and, the effect of the base, the ligand and the catalyst on the conversion and selectivity have been studied in order to determine the factors that influence the efficiency of these catalytic reactions (Scheme 18).

The selectivity of this functionalization can be explained as activation of internal C-Bpin bond to generate product **A'** after electrophilic trapping with allyl bromide. Alternatively, product **B'** can be obtained when activation of terminal C-Bpin bond is followed by electrophilic trapping with allyl bromide. Eventually, product **C'** is also generated when activation of internal C-B bond is followed by protonation in the work up. In a similar way happens with product **D'** but when the terminal C-B bond is activated (Scheme 18). It has to be note that the formation of product **D'** hadn't been observed.



Scheme 17. Copper catalyzed functionalization of product **7** with allyl bromide.

4.3.1. Effect of the base

We explored first the variation of the cation of the base by using three different kinds of bases LiO^tBu, KO^tBu and NaO^tBu. From the results obtained (Table 3), it can be seen that the cation of the base plays an important role in the activation of 1,2-bis(boronates). The best results regarding to selectivity were achieved when LiO^tBu was involved in the reaction. The plausible coordination of lithium with the oxygen of the Bpin moieties might influence this selectivity. When using KO^tBu and NaO^tBu higher conversions were achieved although with poor selectivity.

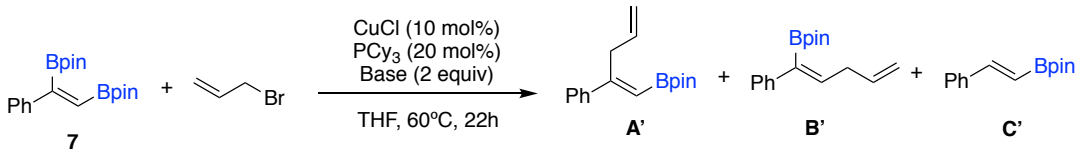


Table 2. Results for the study of the cation of the base on the functionalization of substrate **7**.[a]

Base	Conv. (%)	A':B':C' ratio
LiO^{t}Bu	80	68:26:7
KO^{t}Bu	>99	36:51:13
NaO^{t}Bu	>99	34:40:26

[a]Conditions: 0.2 mmol of **7** and 1.5 equivalents of allyl bromide.

After the study of the influence of the base, we studied also the behavior of two different bases which have lithium as cation, lithium *tert*-butoxide and lithium methoxide. The results obtained (Table 4) show that even though conversion is higher for lithium methoxide, the selectivity is better when lithium *tert*-butoxide is used as base.

Table 3. Results for the study of two different bases on the functionalization of substrate **7**.[a]

Base	Conv. (%)	A':B':C' ratio
LiO^{t}Bu	80	68:26:7
$LiOCH_3$	>99	56:34:10

[a]Conditions: 0.2 mmol of **7** and 1.5 equivalents of allyl bromide.

With the overall results obtained for the study of the effect of the base on the functionalization of 1,2-bis(boronates), the best conditions were stablished when 2 equivalents of lithium *tert*-butoxide are used as base.

4.3.2. Effect of the ligand

For the study of the influence of the ligand on the functionalization of substrate **7**, the monodentate ligands, triphenylphosphine (PPh_3) and tricyclohexylphosphine (PCy_3), were studied and compared with the bidentate ligand xantphos. The complex chloro[1,3-bis(2,6-diisopropylphenyl)imidazole-2-ylidene]copper (I) (CuiPr) was also studied as alternative catalytic system since, the carbene ligands provide more electron enriched Cu (I) species. From the results obtained (Table 5) the lower selectivity was obtained when triphenylphosphine was used as ligand. Similar results were obtained when using tricyclohexylphosphine, xantphos and the carbene. Ligands were involved with conversion from 63% to 80%.

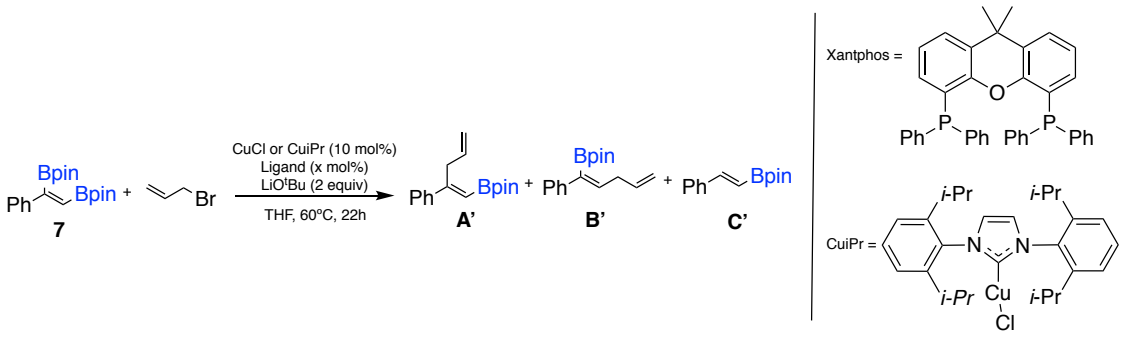


Table 4. Results for the study of the effect of the ligand on the functionalization of substrate **7**.[a]

Catalyst	Ligand	Ligand (mol%)	Conv. (%)	A':B':C' ratio
CuCl	PCy_3	20	80	68:26:7
CuCl	PPh_3	20	>99	38:34:27
CuCl	Xantphos	10	77	62:29:9
CuiPr	-	-	63	69:27:4

[a]Conditions: 0.2 mmol of **7** and 1.5 equivalents of allyl bromide.

Considering both selectivity and conversion the best results were achieved when 20 mol% of tricyclohexylphosphine ligand was used.

4.3.3. Effect of the catalyst

The source of copper (I) has also been considered as one of the main factors that can affect the efficiency of these catalytic reactions. For this study, two different copper sources have been used, copper (I) chloride and tetrakis(acetonitrile)copper (I) hexafluorophosphate. From the results obtained under optimized conditions (Table 6), it can be said that despite the selectivity is quite similar, the conversion diminishes when tetrakis(acetonitrile)copper (I) hexafluorophosphate is used as catalyst.

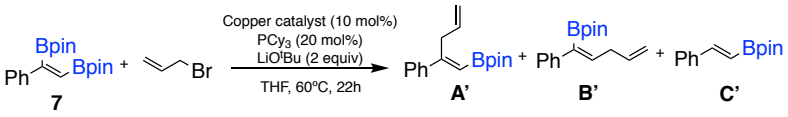
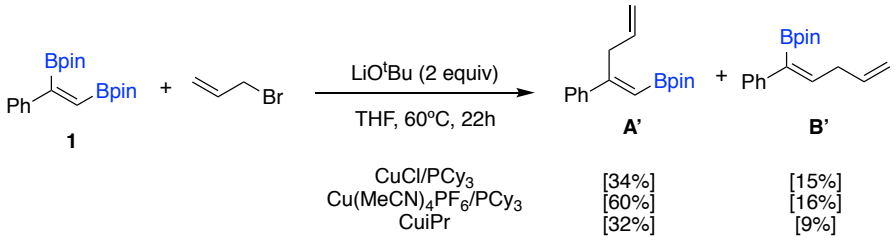


Table 5. Results for the study of the effect of the catalyst on the functionalization of substrate **7**.[a]

Catalyst	Conv. (%)	A':B':C' ratio
CuCl	80	68:26:7
$[Cu(MeCN)_4]PF_6$	68	65:18:17

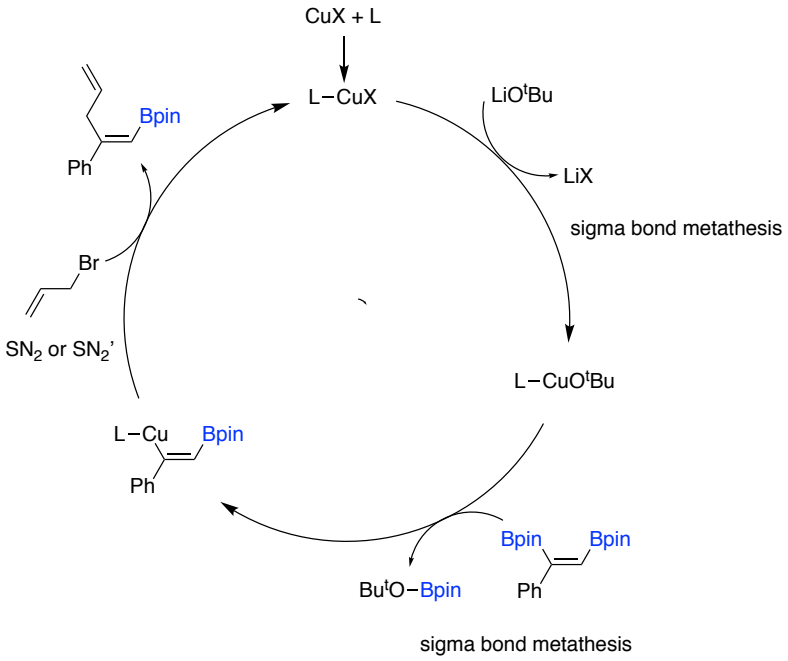
[a]Conditions: 0.2 mmol of **7** and 1.5 equivalents of allyl bromide.

For simplicity, only some of the catalysis were purified by flash chromatography and the yield of product **A'** and **B'** was calculated, **C'** was not calculated because is a byproduct formed in low yield (Scheme 19).



Scheme 18. Isolated Yields of product **A'** and **B'**.

The mechanism we suggest for the catalysis we have studied is:

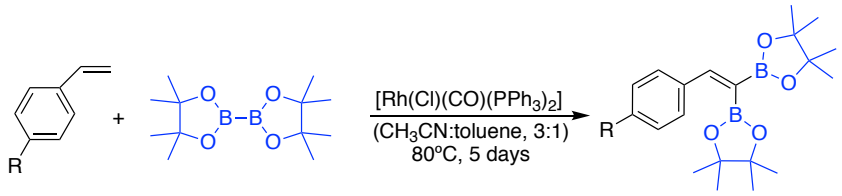


5.1. Materials and Methods

Solvents and reagents: Solvents and reagents were obtained from commercial suppliers and dried and/or purified (if needed) by standard procedures. Tetrahydrofuran and toluene were used from MBRAUN ® MB-SPS 800 Solvent Purifier System and stored under nitrogen and acetonitrile from Alfa Aesar. Ethyl propiolate, styrene and lithium *tert*-butoxide were purchased from Sigma Aldrich. Bis(pincolato)diboron was purchased from Ally Chem, triphenylphosphine from Cymit, tricyclohexylphosphine from Fluorochem and tris(triphenylphosphine)rhodium (I) chloride from Acros Organics. All reactions were conducted in oven and flame-dried glassware under an inert atmosphere of argon, using Schlenk-type techniques. Flash chromatography was performed on standard silica gel (Merck Kieselgel 60 F254 400-630 mesh). Thin layer chromatography was performed on Merck Kieselgel 60 F254 which was developed using standard visualizing agents: UV fluorescence (254 and 366 nm) or potassium permanganate/Δ. NMR spectra were recorded at a Varian Goku 400 or a Varian Mercury 400 spectrometer. ^{1}H NMR and $^{13}C\{^{1}H\}$ NMR chemical shifts (δ) are reported in ppm with the solvent resonance as the internal standard ($CHCl_3$: 7.26 ppm (^{1}H)) and ($CDCl_3$: 77.16 ppm (^{13}C). $^{11}B\{^{1}H\}$ NMR chemical shifts (δ) are reported in ppm relative to $(CH_3)_2O\cdots BF_3$. Data are reported as follows: chemical shifts, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, hept = heptuplet, br = broad, m = multiplet), coupling constants (Hz) and integration. High resolution mass spectra (HRMS) were recorded using a 6210 Time of Flight (TOF) mass spectrometer from Agilent Technologies (Waldbronn, Germnay) with an ESI interface and it was performed at the Servei de Recursos Científics i Tècnics (Universitat Rovira i Virgili, Tarragona). GC-MS analyses were performed on a HP6890 gas chromatograph and an Agilent Technologies 5973 Mass selective detector (Waldbronn, Germany) equipped with an achiral capillary column HP-5 (30m, 0.25mm i. d., 0.25µm thickness) using He as the carrier gas.

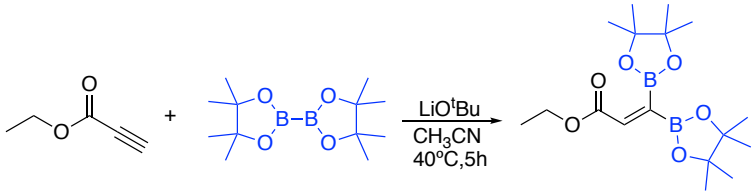
5.2. General procedures

5.2.1 General procedure for the synthesis of 1,1-diborylalkenes by rhodium-catalyzed double dehydrogenative borylation of alkenes



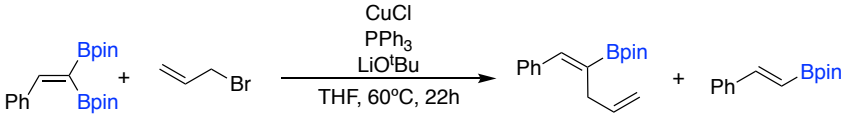
We follow the protocol described in the literature[32] but with some modifications. A 100mL Shlenck flask equipped with a magnetic stir bar was charged with bis(pinacolato) diboron (2 mmol, 2 equiv) and a dry system of (acetonitrile:toluene; 3:1) as solvent (3 mL). Next, the vinylarene (1 mmol, 1 equiv) was added. While the mixture was stirred, a (acetonitrile:toluene; 3:1) solution (3 mL) of Wilkinson catalyst (5 mol%) was introduced into the reaction mixture. The reaction was stirred during 5 days at 80ºC. The solvent was gently concentrated at the rotatory evaporator. The crude residue was purified with silica gel flash chromatography to afford the desired product.

5.2.2 General procedure for the preparation of ethyl 3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate through base-catalyzed 1,1-diboration of activated terminal alkynes



The procedure has been reported in the literature. [17] A 100mL Shlenck flask equipped with a magnetic stir bar was charged with bis(pinacolato) diboron (5 mmol, 1 equiv) and lithium *tert*-butoxide (LiO^{t}Bu) (0.5 mmol, 0.1 equiv) in dry acetonitrile (CH_3CN) as solvent (15 mL). Then, ethyl propiolate (5 mmol, 1 equiv) was added. The reaction was stirred during 5 hours at 40ºC. The solvent was gently concentrated at the rotatory evaporator. The crude residue was purified by sublimation at 90ºC.

5.2.3. General procedure for functionalization of 2,2'-(2-phenylethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) with allyl bromide

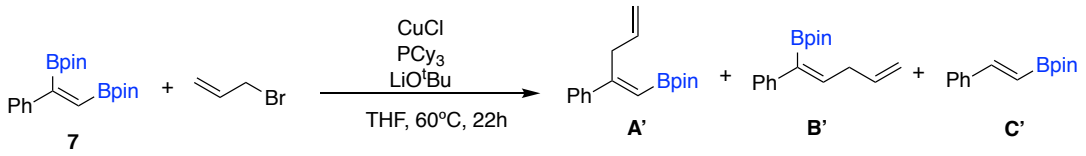


5 **A** **B**

In a flamed Schlenk-tube equipped with a magnetic stir bar, 1,1-diborylakene (0.2 mmol, 1 equiv), CuCl (0.02 mmol, 10 mmol %), PPh_3 (0.04 mmol, 20 mol%) and LiO^{t}Bu (0.4 mmol, 2 equiv) were added in THF (4 mL) under argon atmosphere. The reaction mixture was stirred at 60 °C for 10 min and then, allyl bromide (0.3 mmol, 1.5 equiv) was introduced into the reaction

mixture. After being stirred at 60 °C for 22h, the reaction was concentrated under vacuum and the crude was purified by flash chromatography to afford the desired products.

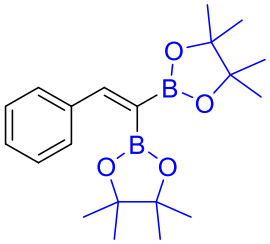
5.2.4. General procedure for functionalization of (E)-2,2'-(1-phenylethene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) with allyl bromide



In a flamed Schlenk-tube equipped with a magnetic stir bar, 1,2-diborylakene (0.2 mmol, 1 equiv), CuCl (0.02 mmol, 10 mmol %), PCy_3 (0.04 mmol, 20 mol%) and LiO^tBu (0.4 mmol, 2 equiv) were added in THF (4 mL) under argon atmosphere. The reaction mixture was stirred at 60 °C for 10 min and then, allyl bromide (0.3 mmol, 1.5 equiv) was introduced into the reaction mixture. After being stirred at 60 °C for 22h, the reaction was concentrated under vacuum and the crude was purified by flash chromatography to afford the desired products.

5.3. Spectral data for alkenyl boranes.

2,2'-(2-phenylethene-1,1-diyl) bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5).



Purified by flash column chromatography (petroleum ether: ethyl acetate = 300:10) yielded **5** (48%, 172.3 mg), as a colourless oil.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.71 (s, 1H), 7.50 – 7.47 (m, 2H), 7.32 – 7.26 (m, 3H), 1.31 (s, 12H), 1.28 (s, 12H).

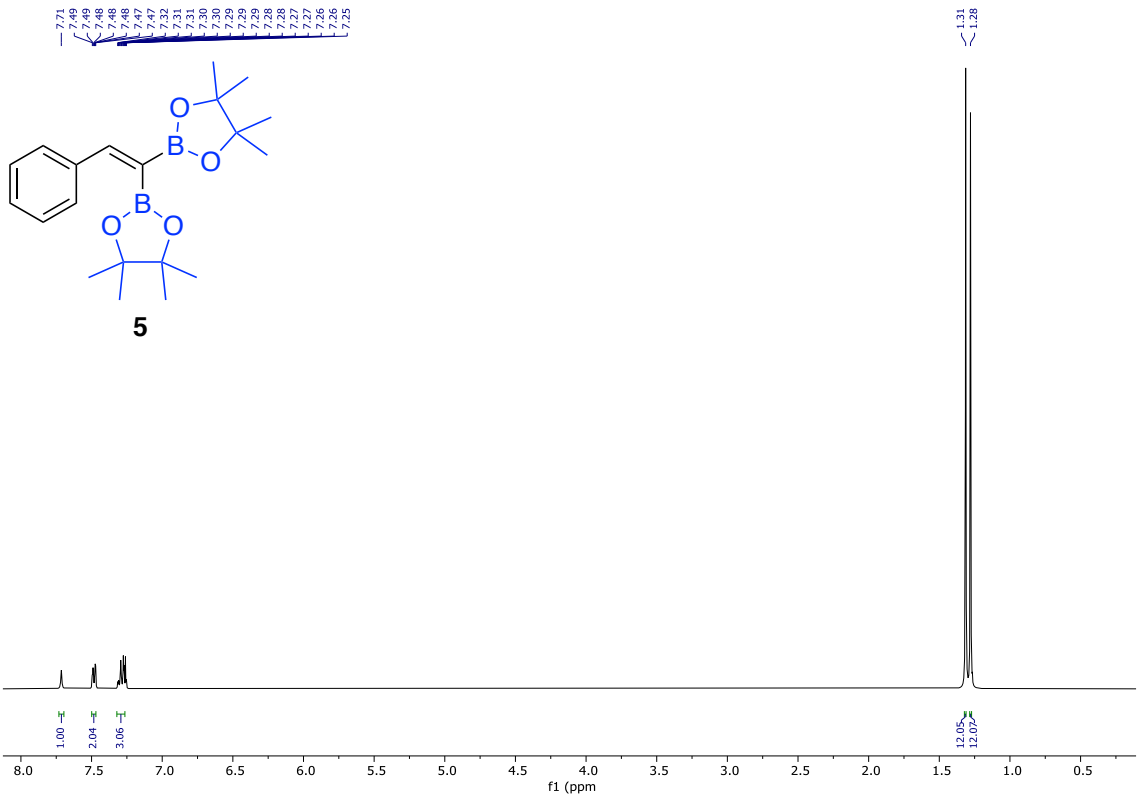
^{13}C NMR ($CDCl_3$, 100 MHz) δ 155.29, 139.75, 128.56, 128.30, 128.24, 83.74, 83.34, 25.01, 24.79.

^{11}B NMR ($CDCl_3$, 128.3 MHz) δ 31.74, 32.53.

These data are in agreement with those reported in the literature.[33]

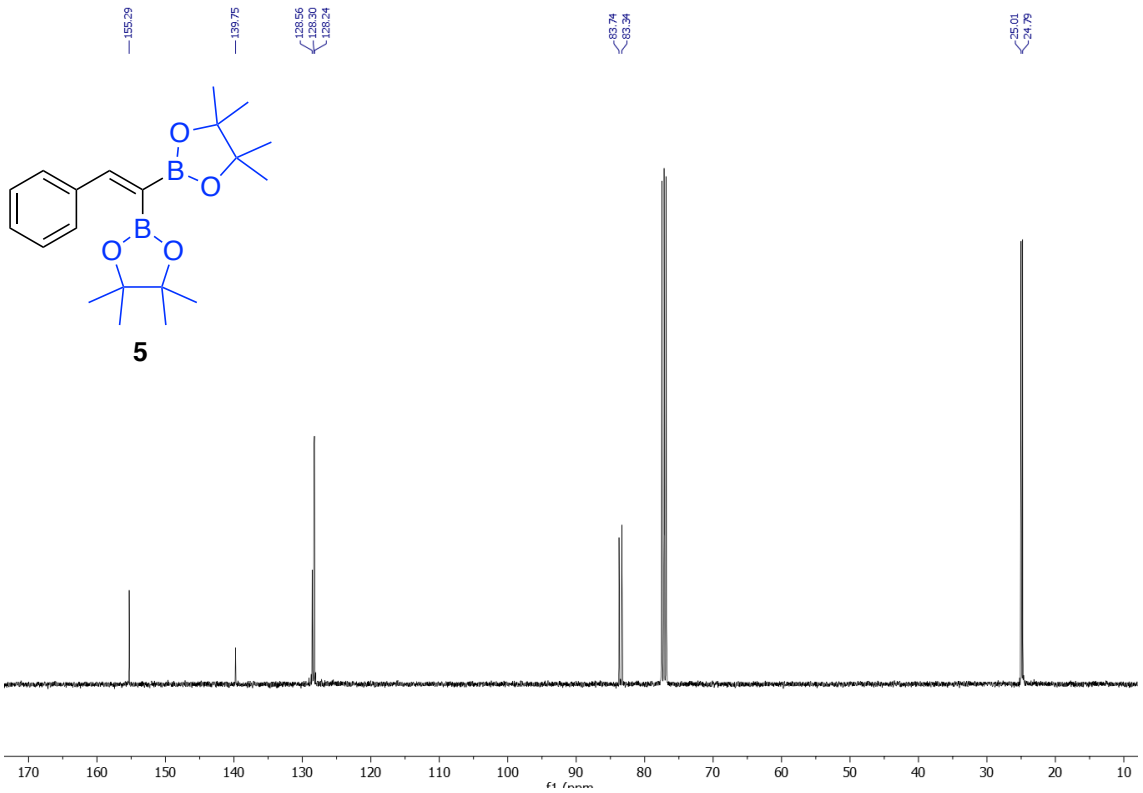
HRMS (ESI) for **$C_{20}H_{34}NB_2O_4$ [M+NH_4^+]$^+$**: calculated 374.2673; found: 374.2681.

^{1}H NMR Spectrum of 2,2'-(2-phenylethene-1,1-diyl) bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5).

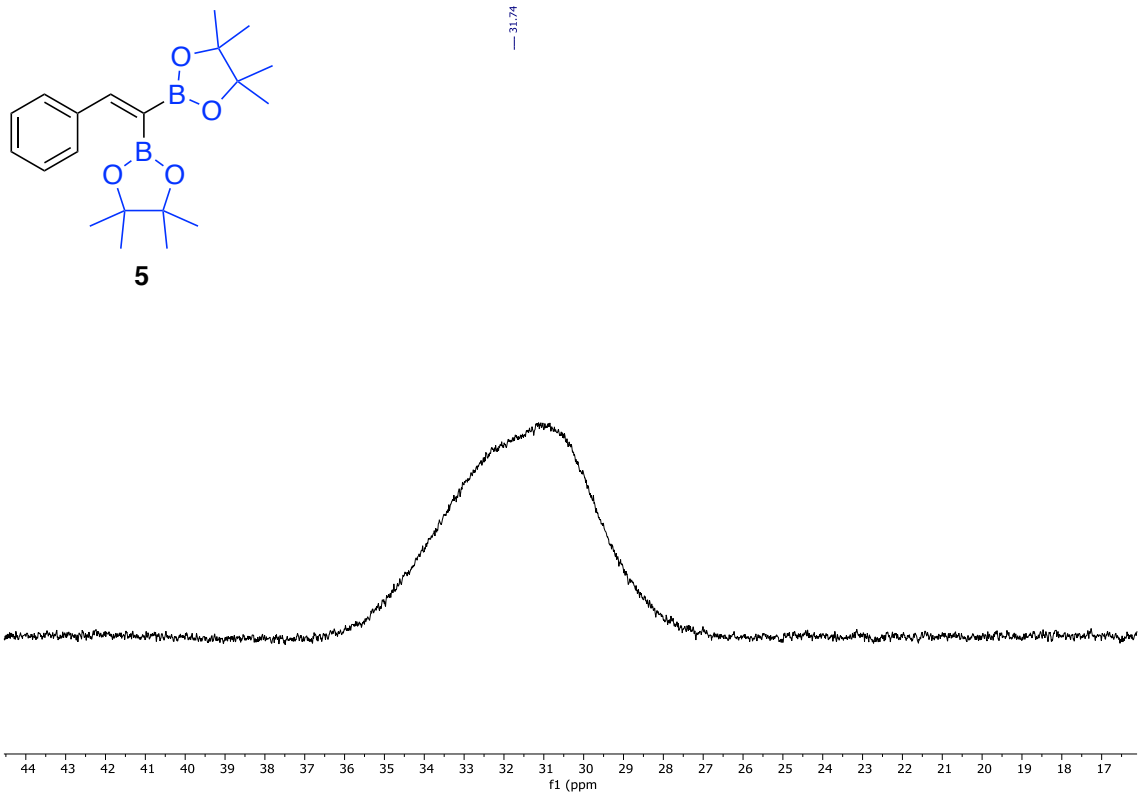


5

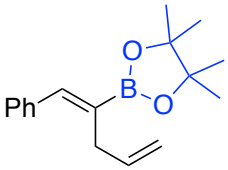
^{13}C NMR Spectrum of 2,2'-(2-phenylethene-1,1-diyl) bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5).



^{11}B NMR Spectrum of 2,2'-(2-phenylethene-1,1-diyl) bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5).



(*Z*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-2-yl)-1,3,2-dioxaborolane (A)



Purified by flash column chromatography (pentane: diethyl ether = 100:1) yielded **A** (60%, 32.4 mg) as a pale yellowish oil.

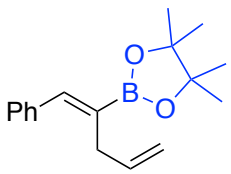
^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.37 – 7.30 (m, 5H), 7.26 (s, 1H), 6.12 – 5.95 (m, 1H), 5.05 (t, J = 12.1 Hz, 2H), 3.12 (d, J = 4.9 Hz, 2H), 1.30 (s, 12H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 143.3, 137.7, 137.6, 129.1, 128.2, 127.5, 114.9, 83.7, 77.36 33.7, 24.9.

^{11}B NMR ($CDCl_3$, 128.3 MHz) δ 30.91.

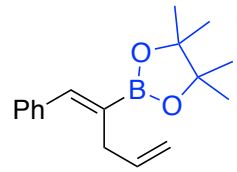
HRMS (ESI) for **$C_{17}H_{27}NBO_2$ [M+NH_4^+]$^+$:** calculated: 288.2129; found: 288.2135.

^{1}H NMR Spectrum of (*Z*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-2-yl)-1,3,2-dioxaborolane (A).



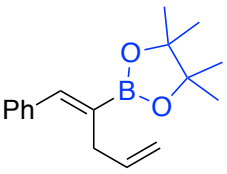
A

^{13}C NMR Spectrum of (*Z*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-2-yl)-1,3,2-dioxaborolane (A).



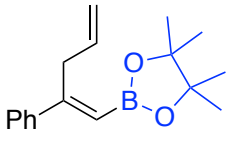
A

^{11}B NMR Spectrum of (*Z*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-2-yl)-1,3,2-dioxaborolane (A).



A

***(E)*-4,4,5,5-tetramethyl-2-(2-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (A').**



Purified by flash column chromatography (pentane: diethyl ether = 250:1) yielded **A'** (60%, 22mg) as a colourless oil.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.50-7.45 (m, 2H), 7.34-7.27 (m, 3H), 5.91-5.78 (m, 1H), 5.76 (s, 1H), 5.08 (dq, J = 17.1, 1.7 Hz, 1H), 4.95 (dq, J = 10.0, 1.5 Hz, 1H), 3.68 (dt, J = 6.5, 1.6 Hz, 2H), 1.31 (s, 12H).

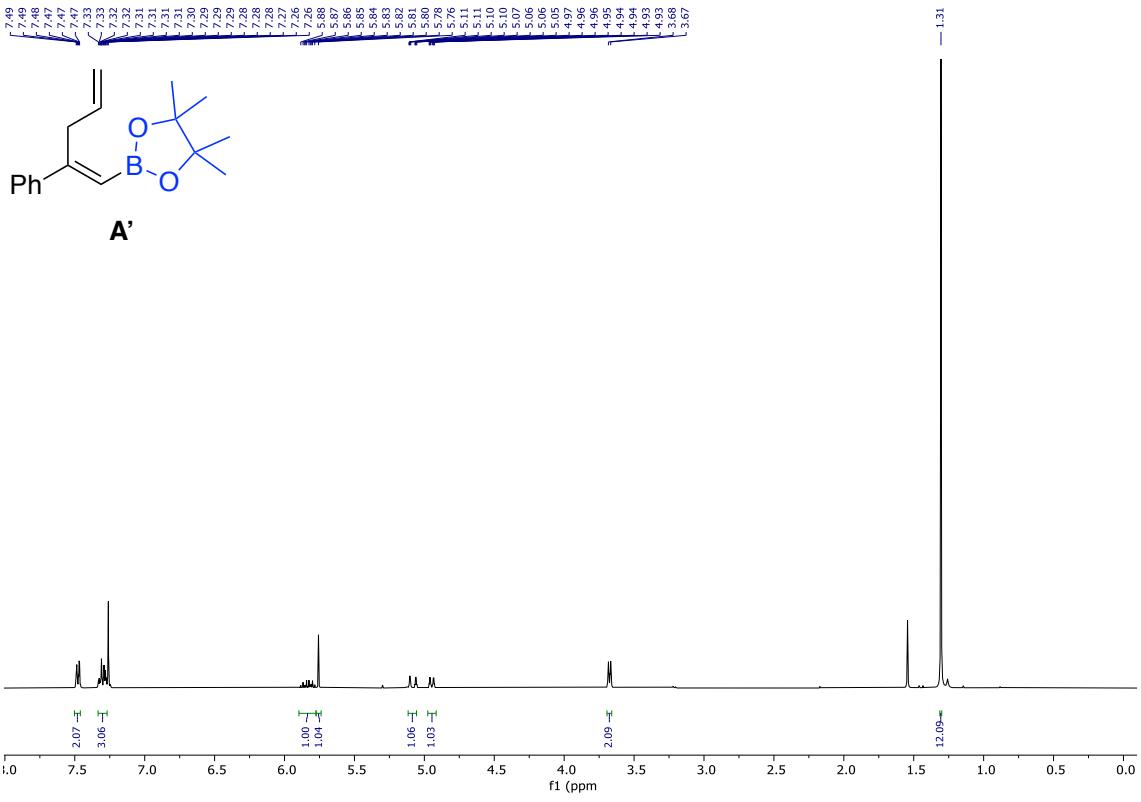
^{13}C NMR ($CDCl_3$, 100 MHz) δ 160.09, 143.05, 137.47, 128.30, 128.04, 126.59, 115.62, 83.16, 38.03, 25.01.

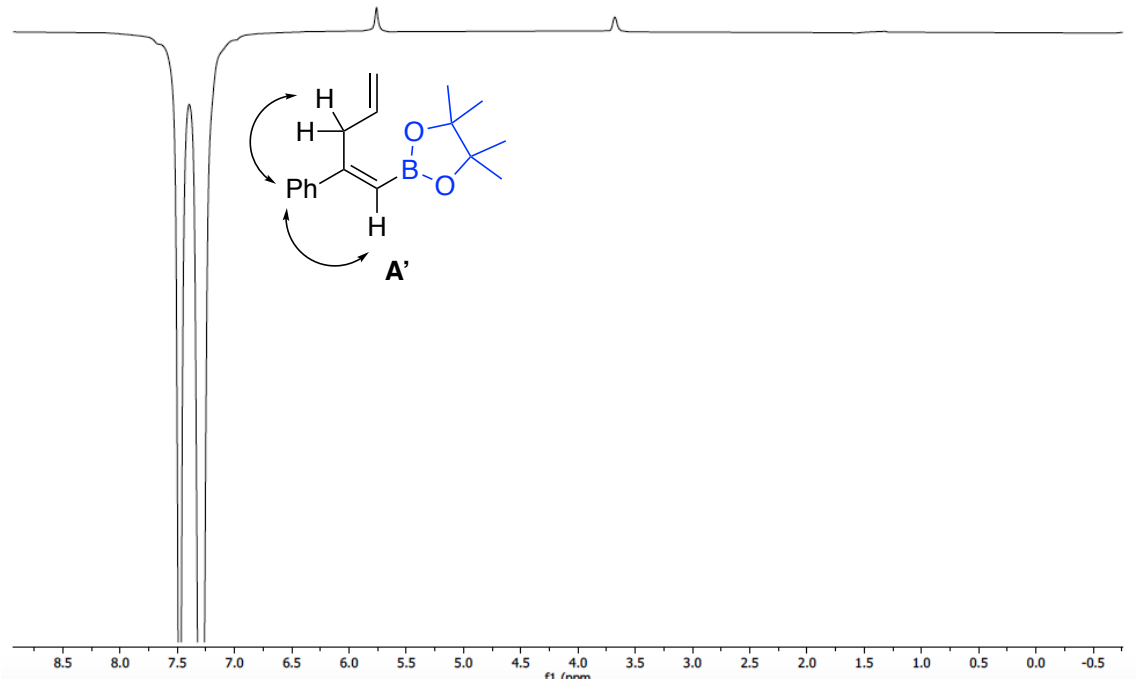
^{11}B NMR ($CDCl_3$, 128.3 MHz) δ 30.19.

These data are in agreement with those reported in the literature.[34]

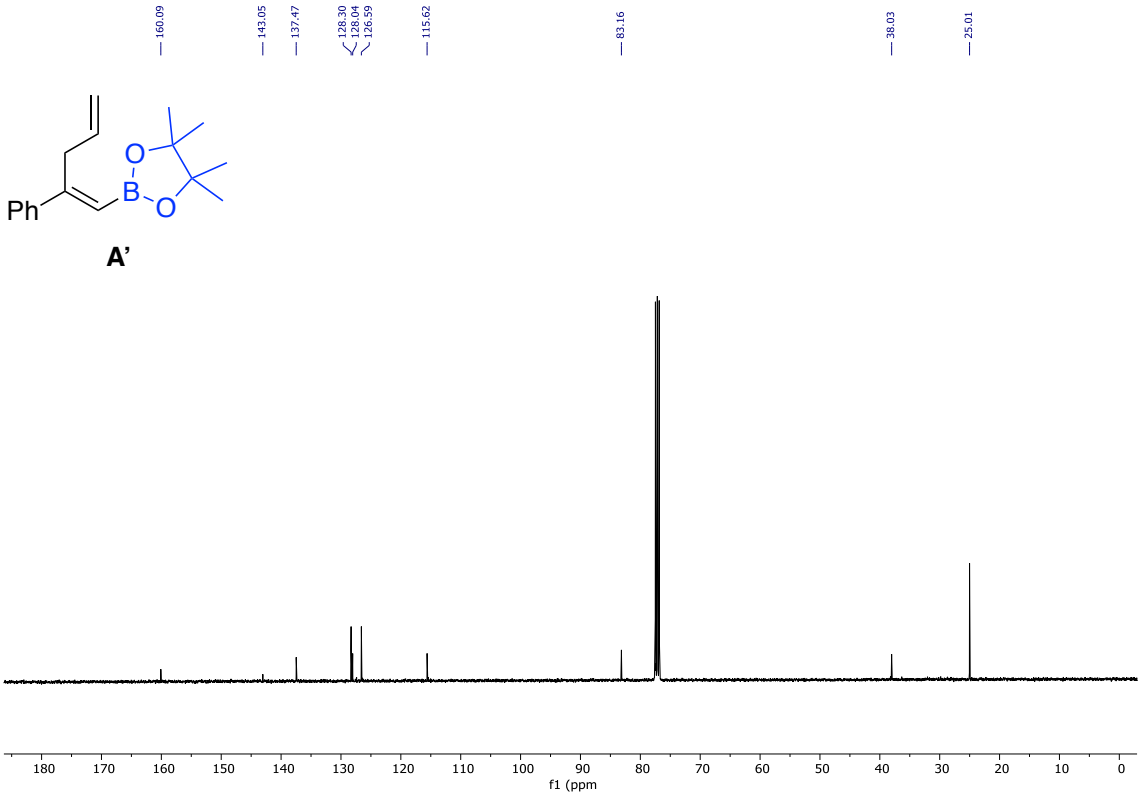
HRMS (ESI) for **$C_{17}H_{27}NBO_2$ [M+NH_4^+]$^+$**: calculated 288.2135; found: 288.2136.

^{1}H NMR Spectrum of *(E)*-4,4,5,5-tetramethyl-2-(2-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (A').

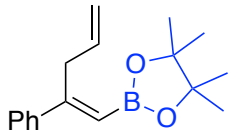




^{13}C NMR Spectrum of *(E)*-4,4,5,5-tetramethyl-2-(2-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (A').

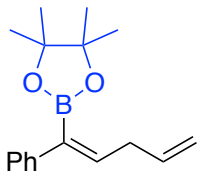


^{11}B NMR Spectrum of *(E)*-4,4,5,5-tetramethyl-2-(2-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (A').



A'

(*E*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (B').



Purified by flash column chromatography (pentane: diethyl ether = 250:1) yielded **B'** (16%, 6mg) as a colourless oil.

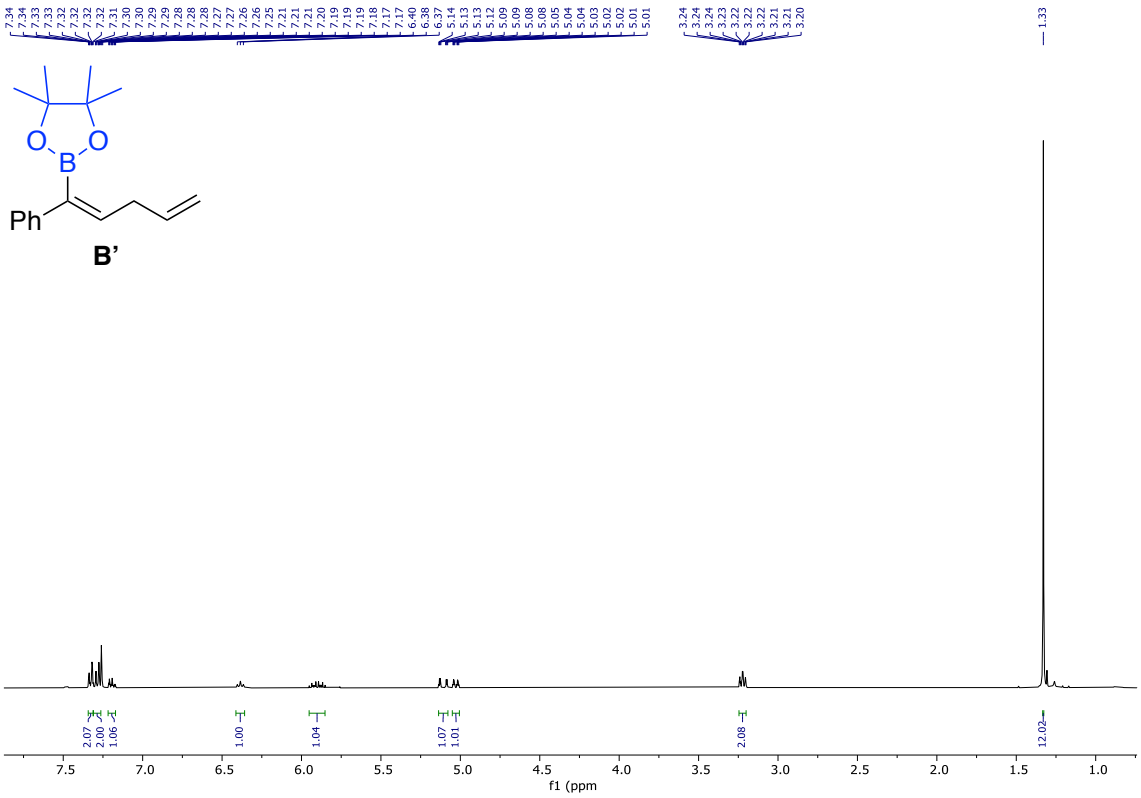
^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.34 – 7.31 (m, 2H), 7.31 – 7.26 (m, 2H), 7.22 – 7.17 (m, 1H), 6.38 (t, J = 7.7 Hz, 1H), 5.95 – 5.85 (m, 1H), 5.11 (dq, J = 17.1, 1.7 Hz, 1H), 5.03 (dq, J = 10.1, 1.5 Hz, 1H), 3.22 (ddt, J = 7.8, 6.4, 1.5 Hz, 2H), 1.33 (s, 12H).

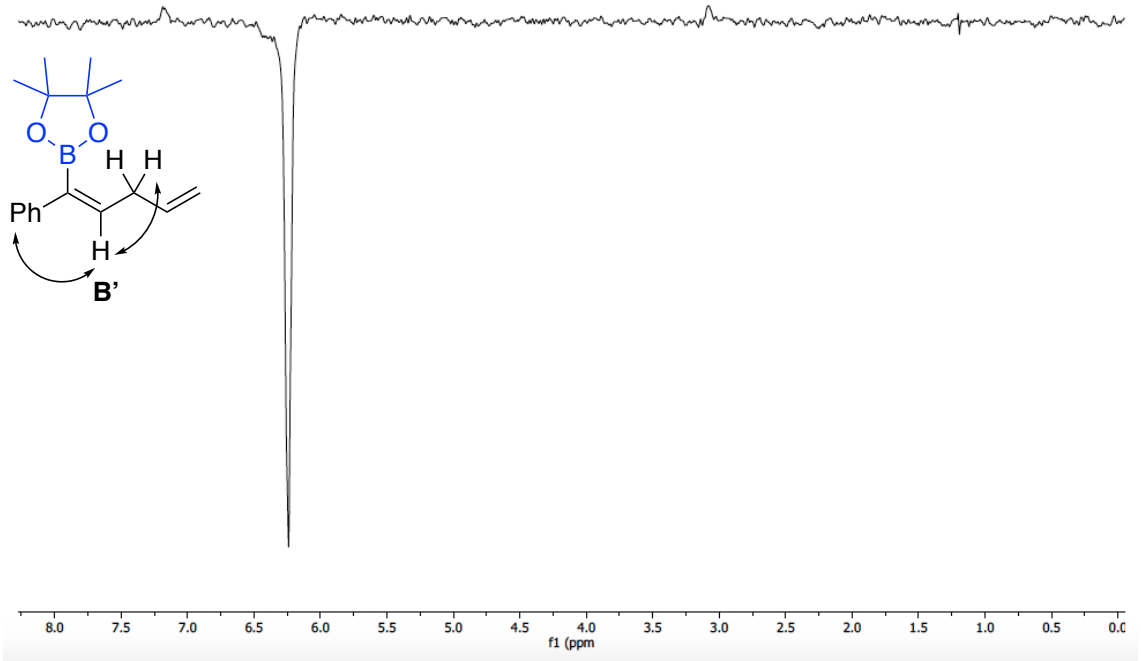
^{13}C NMR ($CDCl_3$, 100 MHz) δ 144.51, 143.15, 137.06, 128.24, 127.38, 126.42, 115.41, 83.70, 36.33, 24.99.

^{11}B NMR ($CDCl_3$, 128.3 MHz) δ 30.83.

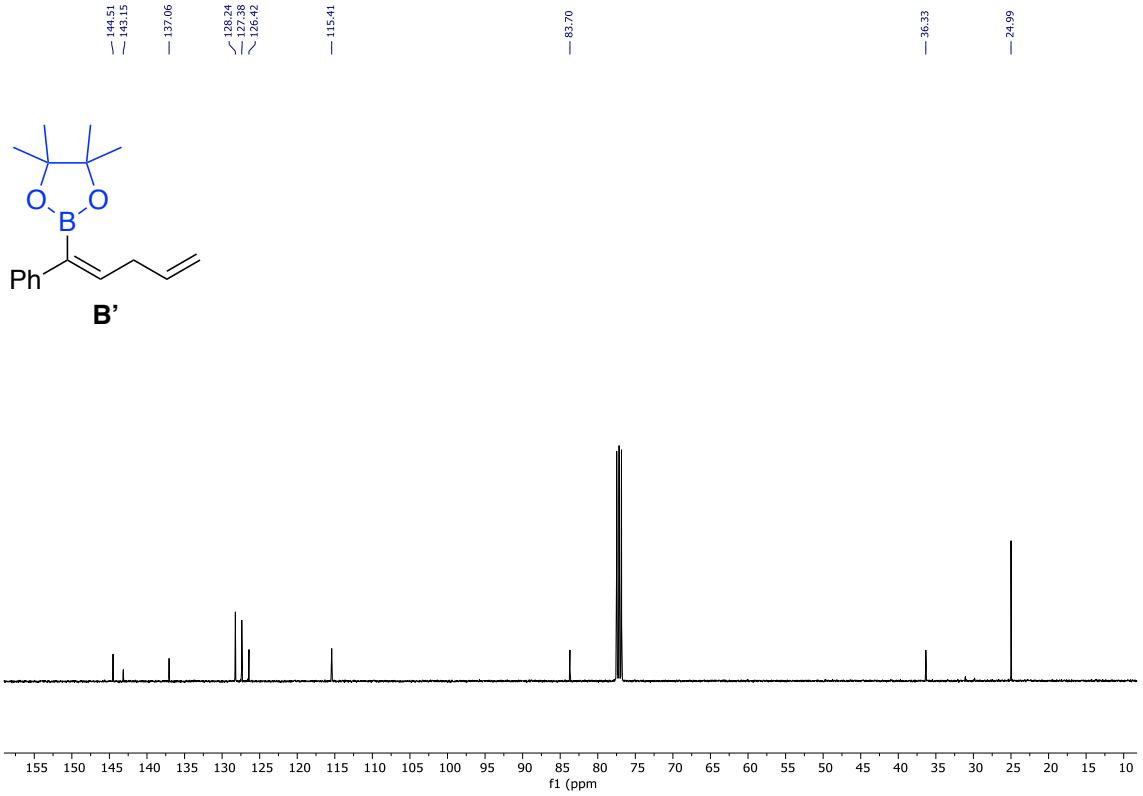
HRMS (ESI) for **$C_{17}H_{27}NBO_2$ [M+NH_4^+]$^+$**: calculated 288.2135; found: 288.2130.

^{1}H NMR Spectrum of (*E*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (B').



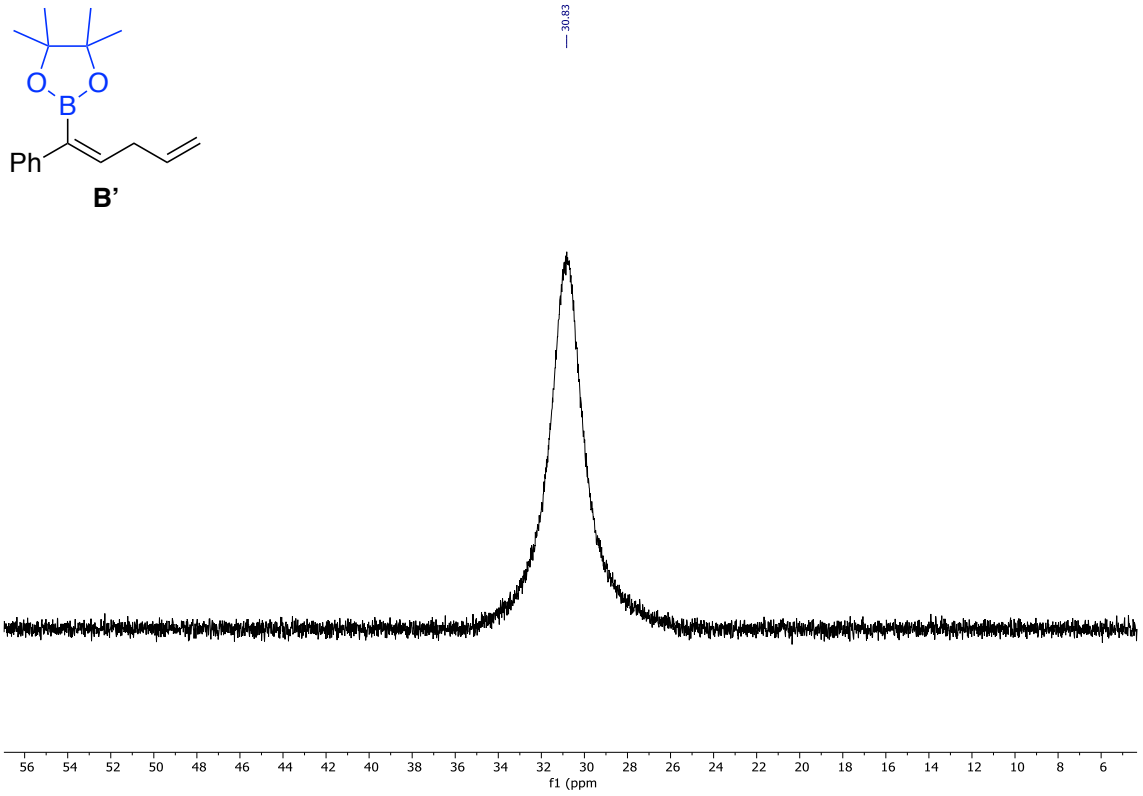


^{13}C NMR Spectrum of (*E*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (B').



B'

^{11}B NMR Spectrum of (*E*)-4,4,5,5-tetramethyl-2-(1-phenylpenta-1,4-dien-1-yl)-1,3,2-dioxaborolane (B').



B'

6. CONCLUSIONS

ENGLISH:

The present Bachelor's Thesis was aimed towards the initiation of an innovative research in the catalytic organoboron chemistry field. It is important to mention that the objectives planned for this work have been accomplished, and the main conclusions are as follow:

1. The habit to read and search information related to my topic has been acquired.
2. We designed the synthetic protocols and the catalysis according to the materials and techniques provided by the research group.
3. The experimental procedures were carried out with rigor and systematic concern about the risks in the laboratory.
4. Copper catalyst can mediate the selective C-B bond of alkenyl diboronates towards *in situ* functionalization with allyl bromide.
5. The new organoboron compounds were fully characterized by NMR and MS analysis.
6. The main conclusion of this copper catalyzed functionalization of alkenyl 1,2-bis(boronates) and alkenyl 1,1-bis(boronates) with allyl bromide is that a more economical and ecofriendly alternative for the catalyzed cross-coupling reactions of alkenyl 1,2- and 1,1-bis(boronates) has been found.
7. A future line of work to complete the study conducted through the present research work would be to study the effect of different electrophiles in the functionalization of alkenyl 1,2-bis(boronates) and alkenyl 1,1-bis(boronates).

CATALÀ:

El present treball de fi de grau estava enfocat en l'inici d'una recerca innovadora en el camp de la química de catàlisis organoborada. Cal esmentar, que els objectius que s'havien planejat per aquest treball han estat assolits, i les conclusions són les següents:

1. L'hàbit de llegir i cercar informació relacionada amb el meu tema ha estat assolit.
2. Hem dissenyat els protocols de síntesis i de catàlisis tenint en compte els materials i tècniques que disposa el grup de recerca.
3. Els procediments experimentals s'han dut a terme rigorosament i tenint en compte els riscs al laboratori.
4. La catàlisis amb coure pot intervenir selectivament en l'enllaç C-B dels alquenil diboronats mitjançant la funcionalització *in situ* amb bromur d'al·lil.
5. Els nous compostos organoborats han estat caracteritzats per RMN i MS anàlisis.
6. La conclusió més rellevant d'aquesta funcionalització per catàlisi amb coure dels alquenil 1,2-bis(boronats) i els alquenil 1,1-bis(boronats) amb bromur d'al·lil es que s'ha pogut trobar una alternativa més econòmica i ecològica per a les reaccions catalitzades d'acoblament creuat dels alquenil 1,2 i 1,1-bis(boronats).
7. Una futura línia de treball per completa l'estudi que s'ha realitzat en el present treball seria estudiar l'efecte de diferents electròfils en la funcionalització dels alquenil 1,2-bis(boronats) i alquenil 1,1-bis(boronats).

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