Reactions of organosilicon compounds catalyzed by triaryl borane Lewis acids

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THESES OF PHD DISSERTATION

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1. Introduction

The society of the 21st century has become heavily dependent on the chemical industry, which fulfills the majority of the society’s needs. Due to this strong engagement, the urge to develop the industrial processes and the supporting disciplines, such as organic chemistry, is constantly increasing. By all means, catalytic processes are the most effective tools of organic chemistry society to fulfill this urge and the increasing needs of the modern civilization. However, nowadays’ catalytic processes should overcome serious expectations. While the continuous increase in effectiveness is an obvious goal during method development, there is high social pressure towards the newly developed methods to be sustainable and environmentally friendly, while maintaining or even increasing their activity.

Therefore, besides organometallic catalysis that had a prominent role in the last 50 years, the organocatalytic methods that use organic molecules as catalysts have at least similar importance in present-day chemistry processes.

To further increase the opportunities of organocatalytic processes, discovering and applying new catalytical methods is ubiquitous. Besides, developing catalysts that are usable in different reaction types, even in consecutive reaction steps, with well-defined selectivity and efficiency is indispensable for the further improvement of this discipline.
2. Aim

On the field of catalysis with borane Lewis acids the archetype of triaryl-borane Lewis acids, tris(pentafluorophenyl)borane is a widely applied and frequently used catalyst. However, due to its instability and high reactivity towards several functional groups, there is an urging need to develop more selective variants. Although several differently substituted triarylboranes have been developed on the field of Frustrated Lewis Pair hydrogenation, their application in other reactions is very limited.

During my PhD research, our aim was to extend the catalytic application of our research group’s previously developed triaryl boranes to selective hydrosilylation reactions and further transformations of organosilicon compounds, thus enhance the scope of catalysts and reactions on the field of borane catalysis.

During our work, our goal was to utilize the enhanced steric hindrance around the catalysts to partially reduce esters to aldehydes selectively. Our further aim was to examine the hydrosilylation of α,β-unsaturated oxo compounds. Our goal was to obtain selective 1,4-addition and form silyl enol ethers that could be transformed in further reactions. While numerous transformations of silyl enol ethers require Lewis acid catalysis, just as our planned hydrosilylation step, the successful 1,4-addition would establish the opportunity of one-pot domino transformations, such as Mukaiyama-aldol reaction.

We also planned to extend the 1,4-addition on allylic acrylates. The resulting silyl ketene acetals would undergo Ireland-Claisen rearrangement in a one-pot manner.

Our further goal was to utilize our catalysts in Diels-Alder reactions. While sterically congested systems tend to react in an exo-selective manner, we planned to perform Diels-Alder reaction with Danishefsky-type dienes and α,β-unsaturated oxo compounds.
3. Results

The results of my PhD research are summarized in the next points:

1. We successfully activated silanes with mesityl bis(pentafluorophenyl)borane (MesB(C₆F₅)₂). The MesB(C₆F₅)₂/Et₃SiH system was capable of reducing oxo compounds under inert circumstances. We performed the reduction of esters to the appropriate silyl acetalts, which were hydrolyzed to obtain the appropriate aldehydes.

   \[
   \begin{align*}
   \text{O} & \quad \text{O} \\
   R & \quad 5\% \text{MesB(C₆F₅)₂} \\
   1\text{a-1} \quad & \quad \text{HSIEt₃ (1eq.)} \\
   \text{toluene, RT} \quad & \quad \text{R} \quad \text{OSIEt₃} \\
   \text{HCl(µC)} \quad & \quad \text{R} \quad \text{H}
   \end{align*}
   \]

2. Due to the sterically hindered MesB(C₆F₅)₂ catalyst, we successfully reduced certain ester functions in the presence of sterically more demanded esters. The selective reduction was confirmed with \(^1\text{H}-\text{NMR}\) spectroscopy measurements in competitive reactions.

   \[
   \text{O} \quad + \quad \text{O} \\
   + \quad \text{HSIEt₃} \quad \text{MesB(C₆F₅)₂} \\
   \text{C₆D₆, 25°C} \quad \text{O} \quad \text{+ Et₃Si-O-O} \\
   \]

3. Hydroisilylation of \(\alpha,\beta\)-unsaturated oxo compounds was performed with the MesB(C₆F₅)₂/Et₃SiH system. We have shown, that in the case of \(\alpha,\beta\)-unsaturated aldehydes 1,2-addition takes place (reduction of the C-O double bond), while \(\alpha,\beta\)-unsaturated ketones undergo conjugated 1,4-addition resulting silyl enol ethers. The reaction of benzylidene-acetophenones showed high Z-selectivity on the formed enol double bond.

   \[
   \begin{align*}
   \text{Ar₁} & \quad \text{O} \quad \text{Ar₂} \\
   \text{Ar₁-} & \quad \text{5% MesB(C₆F₅)₂} \\
   \text{HSIEt₃ (1eq.) CH₂Cl₂, RT} \quad & \quad \text{Ar₂} \quad \text{OSIEt₃}
   \end{align*}
   \]

4. We recognized the importance of selective 1,4-addition and the opportunity of direct transformation of the formed silyl enol ethers in a possible domino reaction cascade. We successfully reacted the silyl enol ether of trans-benzylidene acetophenone with aromatic aldehydes in Mukaiyama-aldol addition with our MesB(C₆F₅)₂ catalyst. The reaction cascade could be performed in a one-pot manner.

   \[
   \begin{align*}
   \text{Ph} & \quad \text{O} \quad \text{Ph} \\
   \text{Ph} \quad & \quad \text{5% MesB(C₆F₅)₂} \\
   \text{HSIEt₃ (1eq.) CH₂Cl₂, RT} \quad & \quad \text{Ph} \quad \text{OSIEt₃}
   \end{align*}
   \]

   \[
   \begin{align*}
   \text{O} & \quad \text{R} \\
   \text{R} \quad & \quad \text{CH₂Cl₂, RT} \\
   \text{O} \quad & \quad \text{Ph} \quad \text{OSIEt₃}
   \end{align*}
   \]
5. The borane catalyzed selective 1,4-hydrosilylation was extended to allylic acrylates. The formed silyl ketene acetals readily underwent [3,3]-sigmatropic rearrangement, therefore a tandem hydrosilylation/Ireland-Claisen reaction cascade was performed in one-pot. We optimized the reaction conditions, mainly focusing on the catalyst, which revealed that the reaction does not require inert conditions.

6. In certain cases, the reaction cascade resulted in products with a different structure than the expected. Examining the phenomenon revealed a possible 1,3-allylic rearrangement of our starting materials in the presence of the 2,3,6-trichlorophenyl-bis(2,3,5,6-tetrafluorophenyl)borane catalyst. The resulting acrylates were also suitable to undergo the hydrosilylation/[3,3]-sigmatropic rearrangement cascade. We examined the scope and the limitation of the allylic rearrangement.

7. After optimizing the reaction parameters of the 1,3-allylic migration/hydrosilylation/Ireland-Claisen rearrangement domino reaction cascade, we extended the scope of the reaction. We made efforts to control the selectivity of the reaction cascade by suppressing the 1,3-allylic rearrangement, however, these efforts remained fruitless.

8. We examined the borane-catalyzed reactions of Danishefsky-type silyloxy-dienes and ethyl acrylate. The observed exo-selective Diels-Alder reaction was extended to silyloxy-dienes generated from benzylidene-acetones.
9. The scope of dienophiles in the borane-catalyzed Diels-Alder reaction was extended to \( \alpha,\beta \)-unsaturated aldehydes, these reactions resulted in substituted cyclohexanone compounds with three vicinal stereocenters diastereoselectively.

![Chemical structure](image)

10. In cooperation with Spanish theoretical chemists, we performed theoretical calculations to explain the stereochemical outcome of the reaction. Calculations showed that the transition state on the reaction pathway to the \textit{exo} selective Diels-Alder product is stabilized by non-covalent interactions between the diene’s C-H bonds and the \textit{ortho}-chlorine substituents of the catalyst (2,6-dichlorophenylbis(pentafluorophenyl)borane).
Papers Forming the Basis of Dissertation:

„Janus Face of the Steric Effect in a Lewis Acid Catalyst with Size-Exclusion Design: Steric Repulsion and Steric Attraction in the Catalytic Exo-Selective Diels–Alder Reaction”


„Size-Exclusion Borane Catalyzed Domino 1,3-Allylic/Reductive Ireland-Claisen Rearrangements. Impact of the Electronic and Structural Parameters on the 1,3-Allylic Shift Aptitude”


„Borane Lewis acid catalyst with Size-Exclusion Design for Selective and Partial Hydrosilylation of Ester and Unsaturated Carbonyls”

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