1-1-2018

Novel Formaldimine Precursor for Use in a Hosomi-Sakurai Reaction for the Formation Of Phenyl-Substituted Homoallylamines And A New Modular Approach For The Synthesis Of Half-Sandwich Ruthenium Complexes

Jonathan Baine

Novel formaldimine precursor for use in a Hosomi-Sakurai reaction for the formation of phenyl-substituted homoallylamines and a new modular approach for the synthesis of half-sandwich ruthenium complexes

By

Jonathan Baine

Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Chemistry
in the Department of Chemistry

Mississippi State, Mississippi

August 2018

Novel formaldimine precursor for use in a Hosomi-Sakurai reaction for the formation of phenyl-substituted homoallylamines and a new modular approach for the synthesis of half-sandwich ruthenium complexes

By

Jonathan Baine

Approved:

Xin Cui
(Major Professor)

Colleen Scott
(Committee Member)

Joseph Emerson
(Committee Member and Graduate Coordinator)

Rick Travis
Dean
College of Arts & Sciences

Name: Jonathan Baine

Date of Degree: August 10, 2018

Institution: Mississippi State University

Major Field: Chemistry

Major Professor: Xin Cui

Title of Study: Novel formaldimine precursor for use in a Hosomi-Sakurai reaction for the formation of phenyl-substituted homoallylamines and a new modular approach for the synthesis of half-sandwich ruthenium complexes

Pages in Study 174

Candidate for Degree of Master of Science

Organometallic allylation for the formation of C-C bonds has been a widely developed area over the past several decades for the formation of homoallylic alcohols and amines. One such pathway, the eponymous Hosomi-Sakurai reaction involves the Lewis acid-catalyzed addition of an allylic silane to an acetal, carbonyl, or imine. This work demonstrates an example of a Hosomi-Sakurai reaction using 1,2-ditosyl diazetidine as a slow release formaldimine precursor with good yield and high selectivity.

Another less classical field, C-H activation, has also been around for several decades, but has recently exploded in new innovations. Through C-H activation chemists are able to bypass the need for functional groups that are substituted out, but instead utilizes the C-H bond as a synthon for further functionalization. This work will also demonstrate a modular approach for the synthesis of several ruthenium complexes with the potential to catalyze C-H activation.

DEDICATION

I would like to dedicate this thesis to my amazing parents John and Patricia Hamshar. You guys helped me out so much to get to school and then get through it! Thank you so much for your wonderful examples as a kid and your very, very patient love!

ACKNOWLEDGEMENTS

I would like to thank my professor Dr. Xin Cui for all his help and guidance. Additionally, I would like to thank my wonderful fiancée Mingjie Li for all her encouragement and advice. Lastly, I would like to thank Arvest Greggs, my pastor from Home Fellowship Church, for believing in me even when I didn't. Your encouragement was invaluable.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

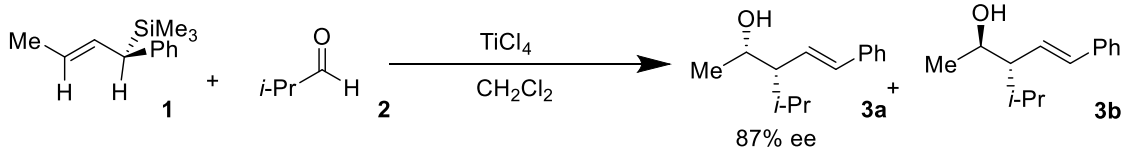
LIST OF SCHEMES

CHAPTER I

INTRODUCTION

1.1 Novel formaldimine precursor for use in a Hosomi-Sakurai reaction for the formation of phenyl-substituted homoallylamines

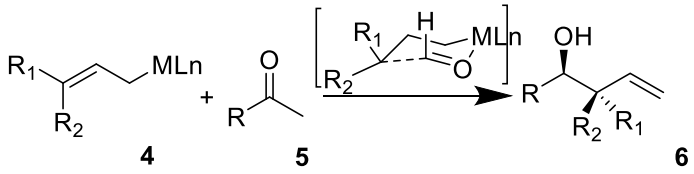
Allylation and aminomethylation are two very effective methods for C-C bond construction involving both a nucleophile and an electron deficient carbonyl or imine bond. Both of these types of reactions have been reviewed extensively with numerous examples containing good to excellent yields and high stereoselectivity.[1-3] For most of these reactions the electron deficient carbonyl or imine needs to be activated by a Lewis acid, or alternatively the nucleophile can be activated by a Lewis base. These activating species can also significantly affect factors such as diastereoselectivity and regioselectivity. In addition to Lewis acid activation, the choice of imine substrate is also an immense factor governing reactivity and/or selectivity. A highly hindered substrate can strongly affect the approach of the nucleophile while a less hindered substrate may increase reactivity. As an extension of this, we report herein a method to utilize 1,2-ditosyl diazetidine, a four membered heterocycle that our group previously produced,[4] to generate the electron deficient formaldimine *in situ* to be used in an allylation reaction, namely a Hosomi-Sakurai reaction.[5,6]



Scheme 1.1 Formation of homoallylic alcohols via organometallic allylation[7]

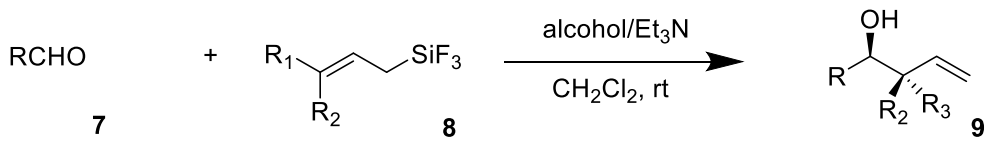
Organometallic allylations have had a long tradition in organic chemistry and typically involve a nucleophile consisting of an allylic olefin (**1**) attacking an electrophilic carbonyl (**2**) or imine substrate. While this topic has been widely studied and reviewed I will present the notable features related to the nucleophiles and substrates used herein. Very often these allylic nucleophiles contain an activating species in a terminal position (Sn, Si, B, etc.). The choice of end-group plays an immense factor in nucleophile activity, intermediate stability, and enantioselectivity and these attributes have been reviewed extensively.[1,2] These reactions have been developed over the past century to demonstrate both effective yields and high enantioselectivity. End-group silanes increase the effectiveness of nucleophilic addition through the stabilizing β-silicon effect.[8] Additionally, stannic species, which have also been utilized very commonly, demonstrate a stabilization through both steric and electronic effects. The nucleophilic olefin attacks generating an acyclic synclinal transition state to minimize steric interactions while at the same time demonstrating a stabilizing interaction between the allylic HOMO and the aldehydic LUMO.[7,9] As a result of the transition state arrangement, the stereochemistry is

strongly affected. Through the variation of the metal at the end of the allylic species scientists have demonstrated strongly *syn* enantioselectivity with Si, Sn, and B species, while Cr, Zn, and In show strong *anti*-selectivity. However, activating chiral Lewis acids and Lewis bases can override these preferences.[10,11] Through organometallic allylation scientists have been able to form an array of homoallylic alcohols and amines.



Scheme 1.2 Organometallic allylation with a closed transition state[1]

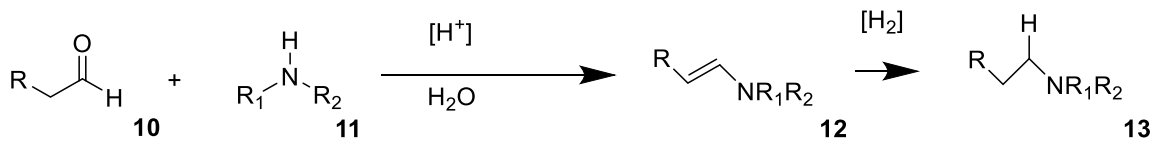
One specific type of organometallic allylation that has been popular over the past few decades is the Hosomi-Sakurai reaction. Demonstrated initially by Hideki Sakurai[6] in 1976, this reaction uses an allylic silane (**8**) to react with a Lewis acid activated carbonyl (**7**), imine or acetal in a stepwise fashion. After the initial addition of the allylic nucleophile, the compound forms a cationic transition state, which is stabilized by a hyperconjugative beta-silicon effect.[8] Next the silyl species is cleaved resulting in a homoallylic alcohol (**9**) or amine. The reaction pathway is able to proceed through either a closed or open transition state depending on which activating Lewis acid used. Observed stereoselectivity is significantly higher for reactions proceeding through the closed transition state due to the rigid conformation.[7,9,12]



Scheme 1.3 Hosomi-Sakurai reaction[6]

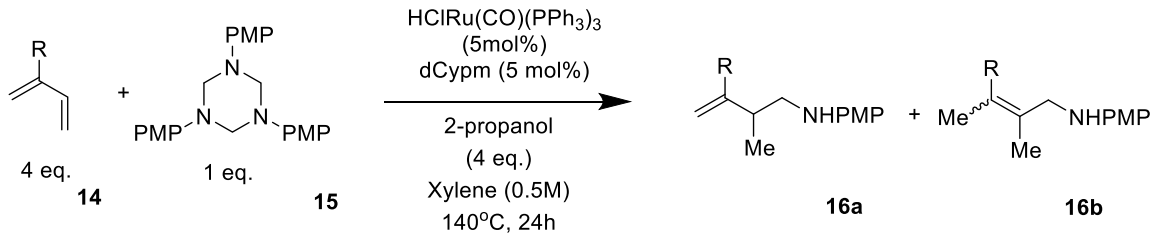
Though several examples of Hosomi-Sakurai reactions exist throughout literature, fewer have utilized a catalytic amount of Lewis acid with imines.[5,13] Indeed there are several variations on the Hosomi-Sakurai reaction that involve various silanes, Lewis acids, and choices of substrate. While most Hosomi-Sakurai reactions involve the use of aldehydes as the substrate, there are numerous examples where both acetals and imines are used.[6,14] These imine substrates react in a similar manner as aldehydes, however nitrogen can be a limiting factor in some cases as it often interferes with Lewis acid catalyzed pathways due to its basic nature.[15] This obstacle in organometallic allylation, however, has been overcome and Lewis acid catalyzed Hosomi-Sakurai reactions with imine substrates remain a very viable route to homoallylamines.

Another reaction pathway very similar to an imine Hosomi-Sakurai reaction is hydroaminomethylation. Hydroaminomethylation involves the addition of a hydrogen, amine, and methyl to a substrate species.[16,17] There are several pathways for



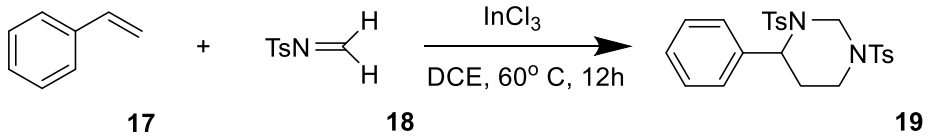
Scheme 1.4 An example of hydroaminomethylation through a reductive pathway[17]

hydroaminomethylation including reductive amination, allylation, and Mannich type reactions, to name a few.[17,18] In effect a Hosomi-Sakurai reaction with an imine substrate is also an example of hydroaminoalkylation. To this end, the use of formaldimine as the substrate would invariably result in a hydroaminomethylation since formaldimine's alkyl species contains only one carbon. Such a reaction is not without precedent. In the 1940s, initial work utilizing $Fe(CO)_5$ as a catalyst for hydroaminomethylation was carried out.[19] Since then significantly more work has been accomplished and has been well reviewed.[17,20,21] In a recent publication in 2016, Michael Krische published a ruthenium-catalyzed addition of dienes to formaldimine.[22] In this work Krische uses a novel triazine precursor (**15**) to generate formaldimine *in situ* (Scheme 1.5). This precursor, as it turns out, was very useful for carrying out hydroaminomethylation as it bypassed selectivity issues due to the high reactivity of formaldimine. Another example of the use of a formaldimine precursor was carried out in 1986 by Hiroshi Kotake.[23]

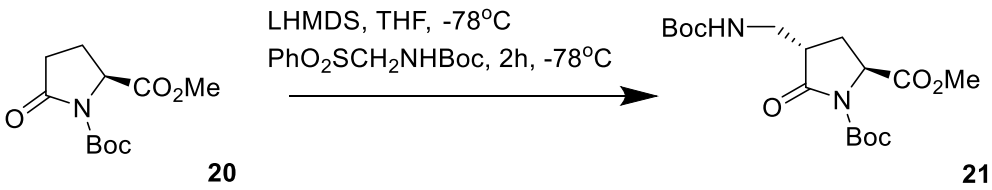


Scheme 1.5 Use of 1,3,5-tris(aryl)-hexahydro-1,3,5-triazine for regiospecific hydroaminomethylation[22]

Kotake used $TsCH_2NHTs$ to generate formaldimine through base cleavage and demonstrated its utility by aminomethylating several nucleophiles including pyrroldines, ester-stabilized carbanions, and sulfone carbanions showing moderate to good yields. This method was again used by Zhou *et al.* and Sikriwal *et al.*[24, 25] in a [2+2+2] catalytic formation of hexahydropyrimidines and in a synthesis of three epimers of penmacric acid respectively (Schemes1.6 and 1.7).



Scheme 1.6 Synthesis of Hexahydropyrimidine[24]



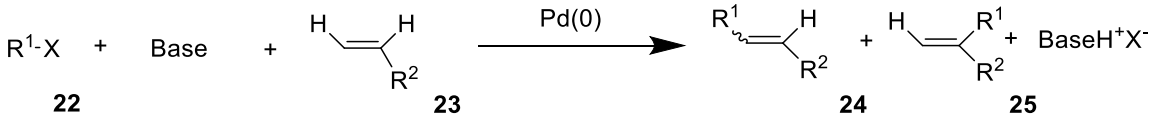
Scheme 1.7 Synthesis of penmacric acid epimer[25]

Formaldimine, however, does suffer from an inherent propensity for instability and decreased selectivity due to its unhindered structure and highly electrophilic center. In an effort to create a source of formaldimine with higher selectivity, our group developed a method to utilize 1,2-ditosyl diazetidine as a slow release formaldimine precursor with high selectivity and reactivity. 1,2-ditosyl diazetidine is a four membered heterocyclic ring containing two nitrogens and two carbons. This variation in chemical bonds (C-N, N-N, C-C) also presents the possibility of additional reactivity. Indeed, nitrogenous heterocycles comprise the majority of pharmaceutical compounds,[26] which gives rise to the possibility that 1,2-ditosyl diazetidine being either in its original form or as a derivation could also be synthetically useful in the development of new medicines. Similar structures include both β-lactams and diazetidinones, which also hold medicinal value where heterocyclic ring systems are found in biologically important agents including antiobiotics.[27]

Herein we demonstrate the utilization of 1,2-ditosyl diazetidine as a selective formaldimine precursor to carry out a Hosomi-Sakurai reaction.

1.2 New modular approach for the synthesis of half-sandwich ruthenium complexes

Throughout the past several decades the world of chemistry has exploded with new ideas as well as new challenges. In the late twentieth century a new approach to linking two molecules together, palladium cross coupling (Scheme 1.8), emerged as an innovative leap forward in technology that replaced several classical methods with a method that is more gentle, selective, and facile.[28] Indeed, the 2010 Nobel prize in chemistry was awarded to Richard Heck, Ei-Ichi Negishi, and Akira Suzuki for their remarkable accomplishments in this area.[29]

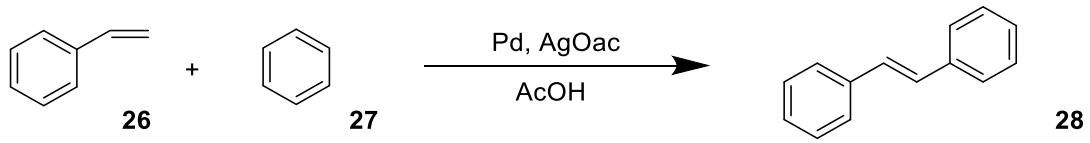


Scheme 1.8 An example Heck reaction for palladium cross coupling[28]

More recently a new area has been growing that promises to likewise replace several classical methods with improved pathways of reactivity. This area, termed C-H activation, involves the cleavage of a C-H bond followed by the highly selective, subsequent, substitution for a functional group at the same position (Scheme 1.9).[30] This pathway utilizes high atom economy and high selectivity with catalytic amounts of a metal catalyst. This type of reactivity offers the promise of replacing the need for functional

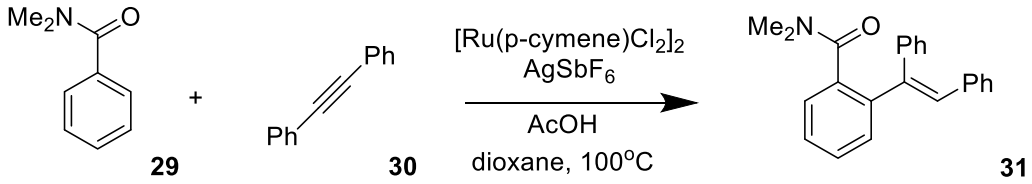
groups in organic substitutions, thereby opening up a very large scope of potential reactivities. This area, however, also encounters significant difficulties.[31] The C-H bond is very nonpolar and also very thermodynamically stable. As a result, utilizing it as a synthon can be very challenging and often requires toxic metals and/or harsh conditions. On the other hand, however, C-H activation removes the usage of a functional group as a reaction partner and thereby removes biproducts which allows for the removal of other potential waste streams.

C-H activation generally employs two types of reactivity: the functionalization of previously unfunctionalized molecules (Scheme 1.9) and the functionalization of a substrate employing some sort of directing group (Scheme 1.10).[32] To accomplish these functionalizations several different transition metal species have been employed including Rh, Pd, Ni, Co, Ir, as well as Ru. In addition, several different directing groups been used with impressive selectivity and good yields.[32,33,34] These directing groups most typically employ either a phosphorous, nitrogen, or a sulfur species due to the high σ-donation as well as the π-accepting ability. As a result of the directing influence, most of the substitutions occur at positions *ortho* to the directing group (Scheme 1.10),[35] however some cases have been shown that demonstrate meta substitution.[36] In metal catalyzed C-H activation of arenes it is the steric factors that guide the substitution. After initial



26 27 28

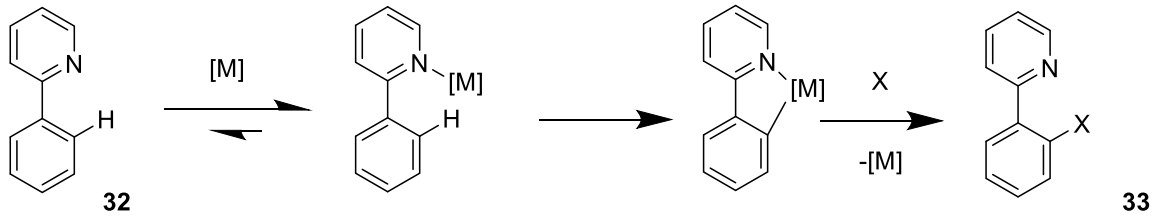
Scheme 1.9 C-H activation on an unfunctionalized benzene[32]



29 30 31

Scheme 1.10 C-H activation to install vinyl groups ortho to an amide directing group on a phenyl ring[36]

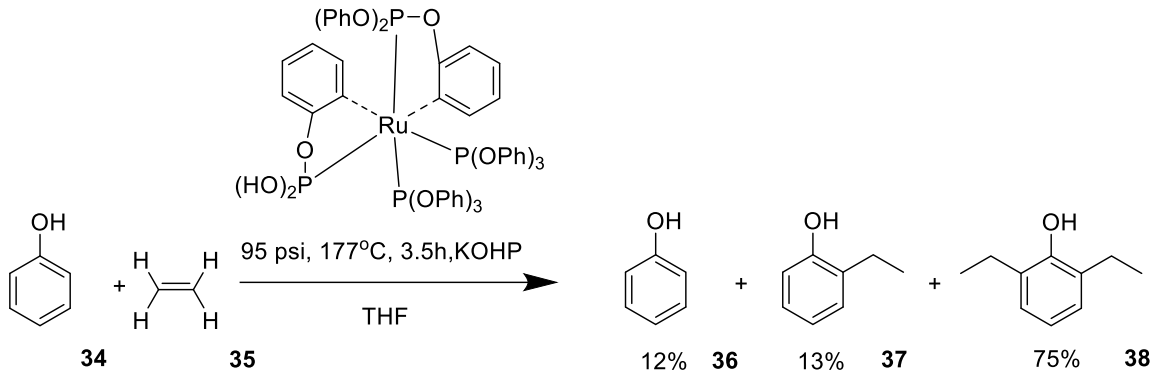
coordination to the directing group the metal forms the most stable metallocycle possible, which typically consists of a five or six membered ring and typically results in *ortho* substitution as a result of the metallocycle (Schemes 1.10 & 1.11).[36]



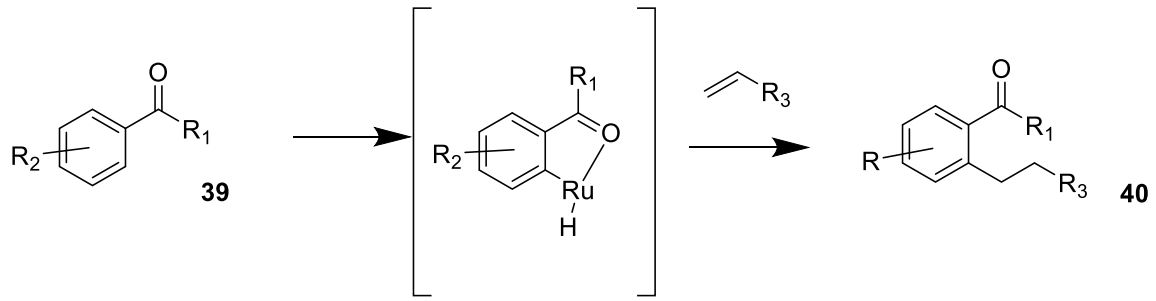
32 33

Scheme 1.11 Directed C-H activation at a meta position arene[36]

Several different transition metals have been used with varying results. Huw Davies has made a very effective use of rhodium carbenes in several syntheses, including one example substituting various groups onto unactivated alkanes.[37] Additionally, Jin-Quan Yu has made a very effective use of palladium catalyzed C-H activation in functionalizing amido cyclopropanes using amino acid ligands to enhance stereoselectivity.[38] Palladium has also been widely and effectively used in the area of C-H activation due to its weak coordinative properties and is one of the most common metals used in this area of chemistry.[32,34] Ruthenium's use as a catalyst in C-H activation has been growing as of late. In 1986 Larry Lewis demonstrated a very early example of ruthenium dependent C-H activation by arylating ethylene and propylene species with varying regioselectivities (Scheme 1.12).[39] Later, a very significant work by Shinji Murai detailed the coupling of several different olefins with various aryl ketones (Scheme 1.13)[40] demonstrating the very significant potential for this pathway to catalyze a very large range of reactions. Indeed, several additions to ruthenium catalyzed C-H activation have been forthcoming over the past twenty years[33,41] and most likely many more will ensue.



Scheme 1.12 Ruthenium catalyzed ortho directed C-H activation arylation of ethylene[39]



Scheme 1.13 Highly regioselective ortho coupling of olefins and aryl ketone species[42]

Herein we demonstrate a new modular approach to the construction of a series of ruthenium complexes with the potential to participate in C-H activation reactions.

1.3 References

(1) Denmark, S. E.; Fu, J. Catalytic Enantioselective Addition of Allylic Organometallic Reagents to Aldehydes and Ketones. *Chemical Reviews* **2003**, *103* (8), 2763.

(2) Yus, M.; González-Gómez, J. C.; Foubelo, F. Diastereoselective Allylation of Carbonyl Compounds and Imines: Application to the Synthesis of Natural Products. *Chemical Reviews* **2013**, *113* (7), 5595.

(3) Yus, M.; González-Gómez, J. C.; Foubelo, F. Catalytic Enantioselective Allylation of Carbonyl Compounds and Imines. *Chemical Reviews* **2011**, *111* (12), 7774.

(4) Lakmal, H. H. C.; Xu, J. X.; Xu, X.; Ahmed, B.; Fong, C.; Szalda, D. J.; Ramig, K.; Sygula, A.; Webster, C. E.; Zhang, D.; Cui, X. Synthesis of C-unsubstituted 1,2-Diazetidines and their Ring-opening Reactions via Selective N─N Bond Cleavage. *The Journal of Organic Chemistry* **2018**.

(5) Lee, P. H.; Lee, K.; Sung, S.-Y.; Chang, S. The Catalytic Sakurai Reaction. *The Journal of Organic Chemistry* 2001, 66 (25), 8646.

(6) Hosomi, A.; Endo, M.; Sakurai, H. Allylsilanes as Synthetic Intermediates. II. Syntheses of Homoallyl Ethers from Allylsilanes and Acetals Promoted by Titanium Tetrachloride. *Chemistry Letters* **1976**, *5* (9), 941.

(7) Denmark, S. E.; Weber, E. J.; Almstead, N. G.; Wolf, L. M. On the Stereochemical Course of the Addition of Allylsilanes to Aldehydes. *Tetrahedron* 2012, 68 (37), 7701.

(8) S.E. Denmark (Ed.), Topics in Stereochemistry, Wiley, New York (1999), pp. 137-200

(9) Denmark, S. E.; Weber, E. J.; Wilson, T. M.; Willson, T. M. Stereochemical and Spectroscopic Studies on the Reaction of Allylstannanes with Aldehydes. *Tetrahedron* 1989, 45 (4), 1053.

(10) Furuta, K.; Mouri, M.; Yamamoto, H. Chiral (Acyloxy)borane Catalyzed Asymmetric Allylation of Aldehydes. *Synlett* 1991, 1991 (08), 561.

(11) Aoki, S.; Mikami, K.; Terada, M.; Nakai, T. Enantio- and Diastereoselective Catalysis of Addition reaction of Allylic Silanes and Stannanes to Glyoxylates by Binaphthol-Derived Titanium Complex. *Tetrahedron* 1993, 49 (9), 1783.

(12) Hollis, T. K.; Bosnich, B. Homogeneous Catalysis. Mechanisms of the Catalytic Mukaiyama Aldol and Sakurai Allylation Reactions. *Journal of the American Chemical Society* **1995**, *117* (16), 4570.

(13) Nakamura, H.; Nakamura, K.; Yamamoto, Y. Catalytic Asymmetric Allylation of Imines via Chiral Bis-π-allylpalladium Complexes. *Journal of the American Chemical Society* **1998**, *120* (17), 4242.

(14) Wang, D.-K.; Zhou, Y.-G.; Tang, Y.; Hou, X.-L.; Dai, L.-X. Allylation of Imines with Allyltrimethylsilane and Experimental Evidences for a Fluoride-Triggered Autocatalysis Mechanism of the Sakurai−Hosomi Reaction. *The Journal of Organic Chemistry* **1999**, *64* (12), 4233.

(15) Kobayashi, S.; Ishitani, H. Catalytic Enantioselective Addition to Imines. *Chemical Reviews* **1999**, *99* (5), 1069.

(16) Eilbracht, P.; Bärfacker, L.; Buss, C.; Hollmann, C.; Kitsos-Rzychon, B. E.; Kranemann, C. L.; Rische, T.; Roggenbuck, R.; Schmidt, A. Tandem Reaction Sequences under Hydroformylation Conditions: New Synthetic Applications of Transition Metal Catalysis. *Chemical Reviews* **1999**, *99* (11), 3329.

(17) Raoufmoghaddam, S. Recent advances in catalytic C–N bond formation: a comparison of cascade hydroaminomethylation and reductive amination reactions with the corresponding hydroamidomethylation and reductive amidation reactions. *Organic & Biomolecular Chemistry* **2014**, *12* (37), 7179.

(18) Arend, M.; Westermann, B.; Risch, N. Modern Variants of the Mannich Reaction. *Angewandte Chemie International Edition* **1998**, *37* (8), 1044.

(19) Reppe, W. Neuere Entwicklungen auf dem Gebiete der Chemie des Acetylens und Kohlenoxyds. *Experientia* **1949**, *5* (3), 93.

(20) Oda, S.; Sam, B.; Krische, M. J. Hydroaminomethylation Beyond Carbonylation:Allene–Imine ReductiveCoupling by Ruthenium-Catalyzed Transfer Hydrogenation. *Angewandte Chemie* **2015**, 127 (29), 8645.

(21) Numajiri, Y.; Pritchett, B. P.; Chiyoda, K.; Stoltz, B. M. Enantioselective Synthesis of α-Quaternary Mannich Adducts by Palladium-Catalyzed Allylic Alkylation: Total Synthesis of (+)-Sibirinine. *Journal of the American Chemical Society* **2015**, *137* (3), 1040.

(22) Oda, S.; Franke, J.; Krische, M. J. Diene hydroaminomethylation via ruthenium-catalyzed C–C bond forming transfer hydrogenation: beyond carbonylation. *Chemical Science* **2016**, *7* (1), 136.

(23) Kinoshita, H.; Inomata, K.; Hayashi, M.; Kondoh, T.; Kotake, H. A New and Effective Aminomethylation by the Use of N-(p-toluenesulfonyl)-p-toluenesulfonamide as an Equivalent of Methanimine. a Convenient Preparation of Pyrrole Compounds. *Chemistry Letters* **1986**, *15* (6), 1033.

(24) Zhou, H.; Lakmal, H. H. C.; Baine, J. M.; Valle, H. U.; Xu, X.; Cui, X. Catalytic [2 + 2 + 2] Cycloaddition with Indium(III)-Activated Formaldimines: a Practical and Selective Access to Hexahydropyrimidines and 1,3-diamines from Alkenes. *Chemical Science* **2017**, *8* (9), 6520.

(25) Sikriwal, D.; Kant, R.; Maulik, P. R.; Dikshit, D. K. A Short Formal Synthesis of Three Epimers of Penmacric Acid. *Tetrahedron* **2010**, *66* (32), 6167.

(26) Vitaku, E.; Smith, D. T.; Njardarson, J. T. Analysis of the Structural Diversity, Substitution Patterns, and Frequency of Nitrogen Heterocycles

among U.S. FDA Approved Pharmaceuticals. *Journal of Medicinal Chemistry* **2014**, *57* (24), 10257.

(27) Worthington, R. J.; Melander, C. Overcoming Resistance to β-Lactam Antibiotics. *The Journal of Organic Chemistry* **2013**, *78* (9), 4207.

(28) Cartney, D. M.; Guiry, P. J. The Asymmetric Heck and Related Reactions. *Chemical Society Reviews* **2011**, *40* (10), 5122.

(29) Halford, B. AWARDS: Three Chemists Share Prize for Palladium-Catalyzed Cross-Couplings. *Chemical & Engineering News* **2010**, *88* (41), 7.

(30) Gutekunst, W. R.; Baran, P. S. C–H Functionalization Logic in Total Synthesis. *Chemical Society Reviews* **2011**, *40* (4), 1976.

(31) Mcmurray, L.; Ohara, F.; Gaunt, M. J. Recent Developments in Natural Product Synthesis Using Metal-Catalysed C–H Bond Functionalisation. *Chemical Society Reviews* **2011**, *40* (4), 1885.

(32) Engle, K. M.; Mei, T.-S.; Wasa, M.; Yu, J.-Q. Weak Coordination as a Powerful Means for Developing Broadly Useful C-H Functionalization Reactions. *Accounts of Chemical Research* **2011**, *45* (6), 788.

(33) Arockiam, P. B.; Bruneau, C.; Dixneuf, P. H. Ruthenium(II)-Catalyzed C−H Bond Activation and Functionalization. *Chemical Reviews* **2012**, *112* (11), 5879.

(34) He, J.; Wasa, M.; Chan, S. L. K.; Shao, Q.; and Yu, J.-Q Palladium-Catalyzed Transformations of Alkyl C−H Bonds. *Chemical Reviews* **2017**, 117 (13), 8754.

(35) Hashimoto, Y.; Hirano, K.; Satoh, T.; Kakiuchi, F.; Miura, M. Ruthenium(II)-Catalyzed Regio- and Stereoselective Hydroarylation of Alkynes via Directed C-H Functionalization. *Organic Letters* **2012**, *14* (8), 2058.

(36) Hartwig, J. F. Regioselectivity of the Borylation of Alkanes and Arenes. *Chemical Society Reviews* **2011**, *40* (4), 1992.

(37) Davies, H. M. L.; Morton, D. Guiding Principles for Site Selective and Stereoselective Intermolecular C–H Functionalization by Donor/Acceptor Rhodium Carbenes. *Chemical Society Reviews* **2011**, *40* (4), 1857.

(38) Wasa, M.; Engle, K. M.; Lin, D. W.; Yoo, E. J.; Yu, J.-Q. Pd(II)-Catalyzed Enantioselective C–H Activation of Cyclopropanes. *Journal of the American Chemical Society* **2011**, *133* (49), 19598.

(39) Lewis, L. N.; Smith, J. F. Catalytic C-C Bond Formation via Ortho-Metalated Complexes. *Journal of the American Chemical Society* **1986**, *108* (10), 2728.

(40) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N. Efficient Catalytic Addition of Aromatic Carbon-Hydrogen Bonds to Olefins. *Nature* **1993**, *366* (6455), 529.

(41) Mihai, M. T.; Genov, G. R.; Phipps, R. J. Access to the Meta Position of Arenes through Transition Metal Catalysed C–H Bond Functionalisation: a Focus on Metals other than Palladium. *Chemical Society Reviews* **2018**, *47* (1), 149.

(42) Padala, K.; Jeganmohan, M. Ruthenium-Catalyzed Ortho-Alkenylation of Aromatic Ketones with Alkenes by C-H Bond Activation. *Organic Letters* **2011**, *13* (23), 6144.

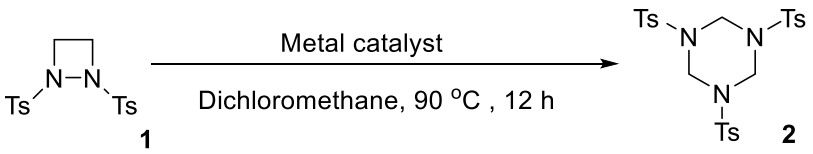
CHAPTER II

RESULTS & DISCUSSION FOR:

NOVEL FORMALDIMINE PRECURSOR FOR USE IN A HOSOMI-SAKURAI REACTION FOR THE FORMATION OF PHENYL-SUBSTITUTED HOMOALLYLAMINES

2.1 Results & discussion

Our project began by first determining a metal catalyzed method for the opening of the ditosyl diazetidine ring **1** that our lab had previously developed.[1] To accomplish this, we set up a series of reactions containing only ditosyl diazetidine, solvent, and a metal lewis acid (Scheme 2.1). After several hours at 100°C the reaction mixture was first tested by thin layer chromatography (TLC) to indicate whether ditosyl diazetidine was consumed and whether or not a new compound appeared, which would indicate ring opening reactions. Secondly, the mixture was analyzed by ^{1}HNMR spectroscopy to verify any preliminary observations as well as to determine what product could have been formed from the retro [2+2] addition reaction. From this information we were able to prove that $FeBr_2$ was the only Lewis acid to open the ditosyl diazetidine ring forming a trimer **2**. While the trimer was not a desirable end-product, it indicated that formaldimine was present and just simply underwent a [2+2+2] reaction with itself in the absence of other possible reactants.



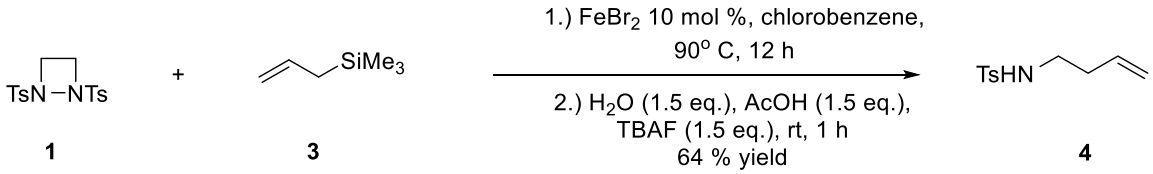
Scheme 2.1 Ring opening and subsequent trimerization

Table 2.1 Metal catalysts for ditosyl diazetidine **1** ring opening to form a trimer **2**

Metal catalyst	Yield of trimer
$CoCl_2$	No reaction
$CuBr_2$	No reaction
$InCl_3$	No reaction
$FeBr_2$	Fully converted
$Sc(OTf)_3$	No reaction
$RuCl_3$	No reaction
$AlCl_3$	No reaction
$MnCl_2$	No reaction

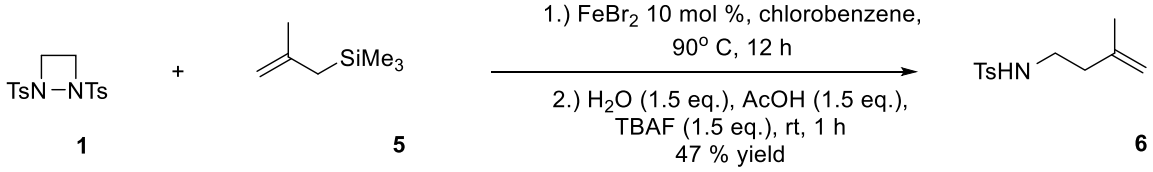
Once we demonstrated a method for the ring opening of ditosyl diazetidine, we then demonstrated its utility in a Hosomi-Sakurai reaction using allyltrimethyl silane and formaldimine from the ditosyl diazetidine. Fortunately, we found that $FeBr_2$ was able to double, not only as the Lewis acid for ring opening, but also as the Lewis acid for the activation of the formaldimine in the Hosomi-Sakurai reaction. Initial attempts at the

reaction proved effective, however ^{1}HNMR still indicated the presence of a trimethyl silyl group around 0 ppm. In order to mediate this problem, we included tetrabutylammonium fluoride as a fluoride ion source to remove the trimethylsilyl group as well as acetic acid as a proton source for the amine. This solved the problem and resulted in moderate yields for both the simple allyltrimethylsilane and also a methyl-substituted allyltrimethylsilane (Schemes 2.2 and 2.3 respectively).



1 **3** **4**

Scheme 2.2 Hosomi-Sakurai reaction using formaldimine precursor **1** and allyltrimethylsilane **3**

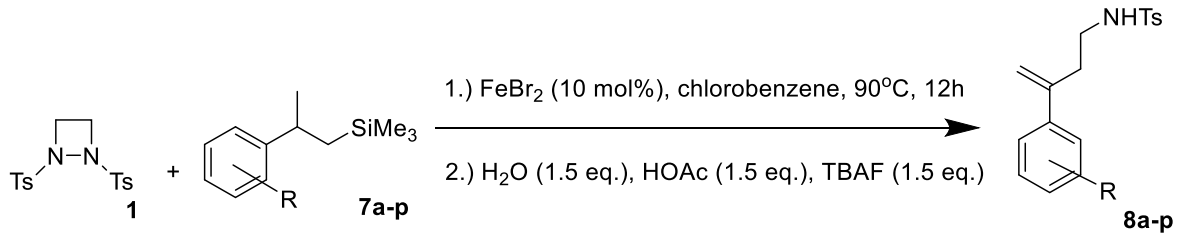


1 **5** **6**

Scheme 2.3 Hosomi-Sakurai reaction using methyl-substituted allyltrimethylsilane **5**

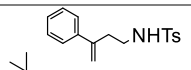
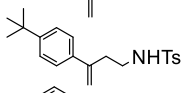
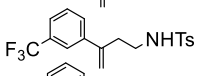
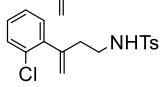
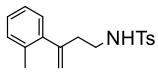
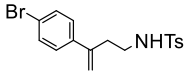
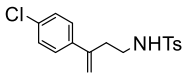
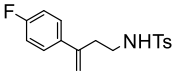
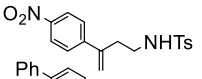
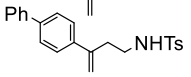
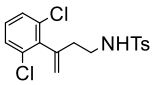
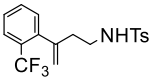
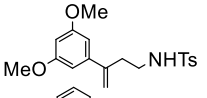
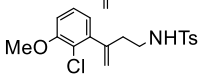
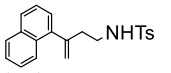
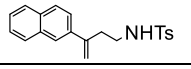
Following our success, we then tested several different phenyl-substituted substrates **7a-p** demonstrating low to excellent yields (Scheme 2.4 and Table 2.2). Phenyl-substituted homoallylamines have thus far required either harsh conditions or a toxic metal catalyst for their synthesis.[2,3,4] In this work we were able to demonstrate a range of phenyl-

substituted homoallylamines that used low-toxicity $FeBr_2$, while at the same time requiring only mild conditions. These phenyl substituents mostly demonstrated yields from 50-80 %. A few substrates demonstrated yields considerably outside this range, however. Of the two substrates with low yields one substrate **7l** carried a trifluoromethyl group at the *ortho* position and the other **7m** carried two methoxy groups at the *meta* positions on the phenyl ring with yields of 36 %. Initially we had anticipated that electron rich substrates would result in increased yield, however **7m** proves otherwise. It is also clear that it is not a matter of the substrate being electron poor either as **7l** shows. When compared to Hammett parameters it becomes very clear that neither electron donating substrates (**7b** and **7e**) nor electron withdrawing (**7i**, **7c**, and **7l**) substrates dominate. Additionally, from comparing unsubstituted (**7a**) to very substituted substrates (**7l**), a minor pattern emerges where the more substituted substrate suffered low yield. However, considering the gap in yield between **7a** and some higher yield substrates (**7d** and **7n)** it is also clear that *ortho* substitution, as would be expected, does not control the extent of the reaction. These results indicate that the substituent factors affecting yield are likely a combination of steric and electronic factors. The two substrates **7d** and **7n** that were converted with very high yields both carried a chlorine atom at the *ortho* position. Truly, it is very interesting that the substituent **7k** with two chlorine atoms in *ortho* positions did not show this high yield.



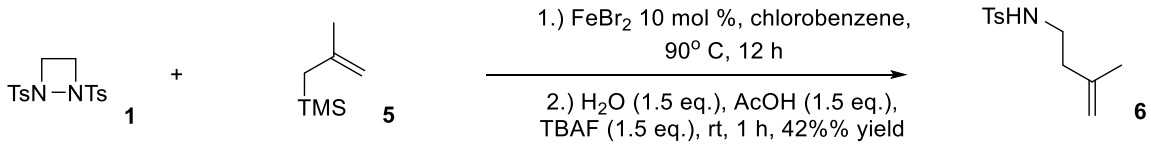
Scheme 2.4 Substrate scope

Table 2.2 Phenyl-substituted allyltrimethylsilane substrates **7a-p**

entry	product		R	yield (%)[b]
1		**7a**	H	78 %
2		**7b**	4-t-Bu	54 %
3		**7c**	3-CF_3	66 %
4		**7d**	2-Cl	90 %
5		**7e**	2-Me	75 %
6		**7f**	4-Br	71 %
7		**7g**	4-Cl	68 %
8		**7h**	4-F	60 %
9		**7i**	4-NO_2	70 %
10		**7j**	4-Ph	53 %
11		**7k**	2,5-Cl	64 %
12		**7l**	2-CF_3	36 %
13		**7m**	3,5-OMe	36 %
14		**7n**	2-Cl, 3-OMe	94 %
15		**7o**	1-naphthyl	69 %
16		**7p**	2-naphthyl	71 %

After completing our substrate scope, we then attempted our reaction at a higher scale (1/2 gram) with similar results for both the allyltrimethyl silane and the methyl-

substituted allyltrimethylsilane. This shows that such a method would conceivably also be useful at a large scale for industrial usage.



Scheme 2.5 ½ gram scale Hosomi-Sakurai reaction using formaldimine precursor **1**

2.2 Conclusion and future Work

In this work we have demonstrated the utility of 1,2-distosyl diazetidine as a formaldimine precursor through a Hosomi-Sakurai reaction. In this work formaldimine was generated in a slow-release manner that resulted in high selectivity and good yields for the synthesis of phenyl-substituted homoallylamines.

2.3 References

1.) Lakmal, H. H. C.; Xu, J. X.; Xu, X.; Ahmed, B.; Fong, C.; Szalda, D. J.; Ramig, K.; Sygula, A.; Webster, C. E.; Zhang, D.; Cui, X. Synthesis of C-Unsubstituted 1,2-Diazetidines and their Ring-opening Reactions via Selective N─N Bond Cleavage. *The Journal of Organic Chemistry* **2018**

2.) Gan, P.; Smith, M. W.; Braffman, N. R.; Snyder, S. A. Pyrone Diels–Alder Routes to Indolines and Hydroindolines: Syntheses of Gracilamine, Mesembrine, and D 7-Mesembrenone. *Angewandte Chemie International Edition* **2016**, *55* (11), 3625.

3.) Yamanaka, M.; Nishida, A.; Nakagawa, M. Ytterbium(III) Triflate/TMSCl: Efficient Catalyst for Imino Ene Reaction. *Organic Letters* 2000, 2 (2), 159.

4.) Pandey, M. K.; Bisai, A.; Pandey, A.; Singh, V. K. Imino-ene Reaction of N-Tosyl Arylaldimines with α-methylstyrene: Application in the Synthesis of Important Amines. *Tetrahedron Letters* **2005**, *46* (30), 5039.

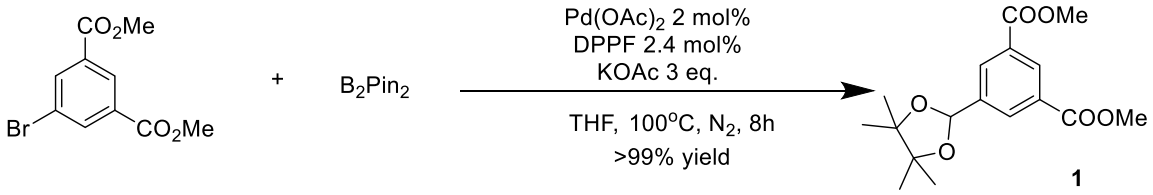
CHAPTER III

RESULTS & DISCUSSION FOR:

A NEW MODULAR APPROACH FOR THE SYNTHESIS OF HALF-SANDWICH RUTHENIUM COMPLEXES

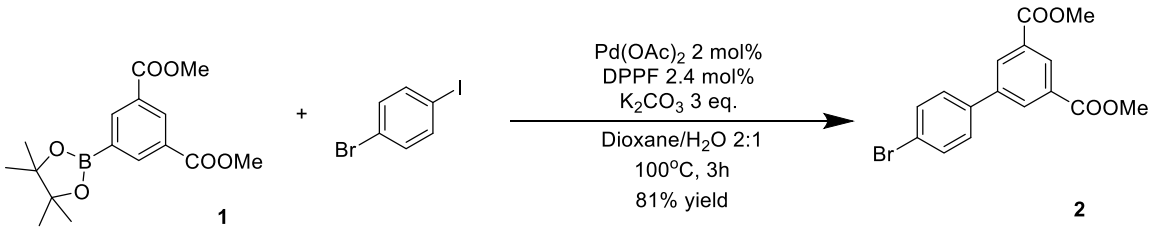
3.1 Synthesis of para-substituted complexes

To begin the synthesis of the complex ligand backbone, the bromide of dimethyl 5-bromoisophthalate was converted to a BPin functional group by a Suzuki cross coupling reaction with bis(pinacolato)diboron. The reaction yielde d **1** quantitatively and numerous examples of a similar nature are extant in literature.[1,2,3] While initial attempts were carried out using only a simple silica gel pad to filter out inorganic media, replacing the need for an aqueous workup, it was later determined that a silica gel column was a superior approach as the residual BPinBr had a similar polarity to **3** and would elute into the product mixture with only a silica pad.



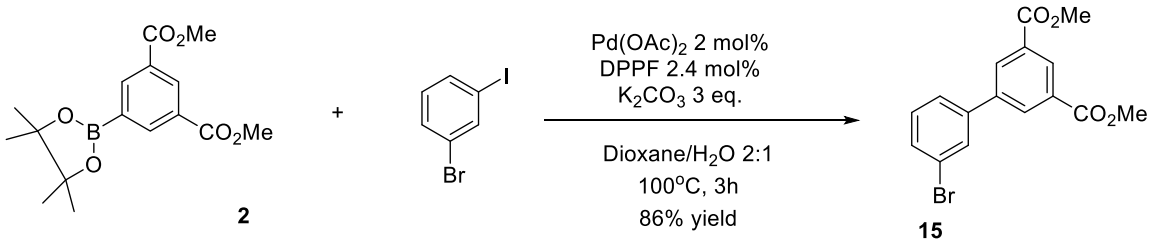
Scheme 3.1 Synthesis of dimethyl 5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl) isophthalate (**1**)

1, in turn, was then used in another Suzuki cross coupling reaction to add a second phenyl ring. For this reaction we found that the effect of the solvent was very important getting substantially lower yield in our initial attempt with toluene/methanol/water 1:1:0.1 (26% yield). We later screened various conditions for similar reactions (Table 1) and settled on a dioxane/water mix for the meta-substituted ligand (Scheme 5.3 & Table 5.1), which we then also began using in the *para*-substituted ligand. When tested in this scheme we observed very good yield (>80%). Later we also investigated altering the base and catalyst trying CsF and $Pd(Ph_3)_4$ resulting in a very slight increase in yield. In addition, we found that shortening the time for the reaction to 3 hours also improved the yield presumably due to decreased product homo-coupling (**2**).



Scheme 3.2 Synthesis of dimethyl 4'-bromo-[1,1'-biphenyl]-3,5-dicarboxylate **2**

For the synthesis of *meta*-substituted ligands this step was altered using 1,3-bromoiodobenzene instead of 1,4-bromoiodobenzene. This then resulted in a different shape **5** that was intended to create a different cavity size for the Ru metal and other potential substituents. This different cavity size could potentially affect the selectivity of our complexes in whichever potential reactivity they are later employed. The remainder of the steps for both *para* and *meta*-substituted ligands used the same conditions and had very similar results.

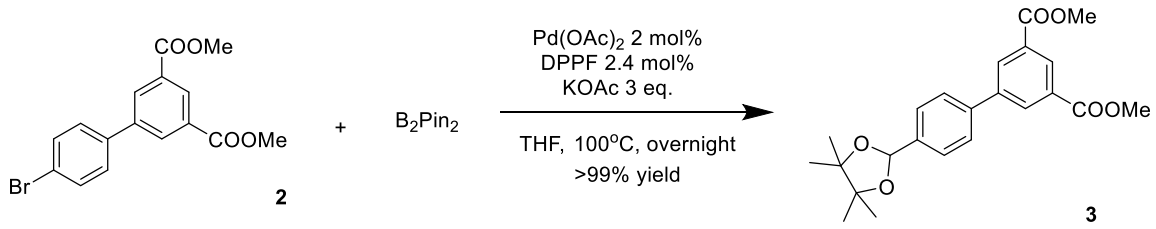


Scheme 3.3 Synthesis of dimethyl 3'-bromo-[1,1'-biphenyl]-3,5-dicarboxylate **15**

Table 3.1 Screening conditions for Scheme 3.3

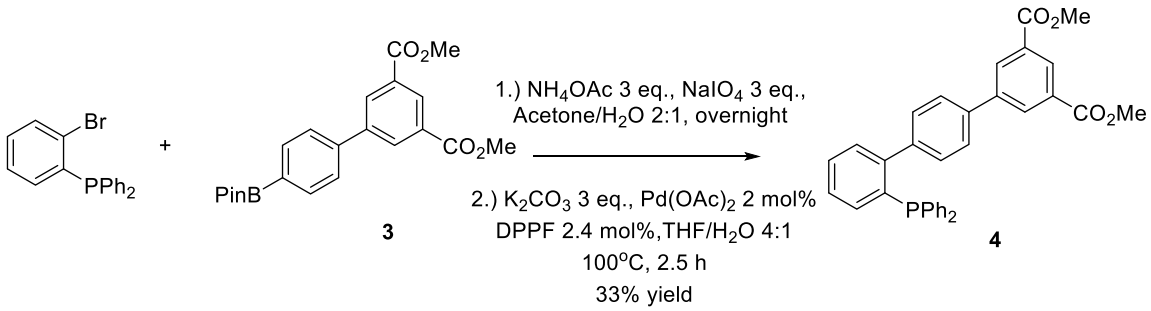
Catalyst	Base	Solvent	Yield
$Pd(OAc)_2$, DPPF	CsF	Dioxane/H_2O 2:1	82%
$Pd(Ph3)_4$	CsF	Dioxane/H_2O 2:1	81%
$Pd(OAc)_2$, DPPF	K_2CO_3	Dioxane/H_2O 2:1	86%

Following the addition of a second phenyl ring another bromide group was also replaced with a BPin under the same conditions as in Scheme 5.1 also demonstrating quantitative yield.



Scheme 3.4 Synthesis of dimethyl 4'-(4,4,5,5-tetramethyl-1,3-dioxolan-2-yl)-[1,1'-biphenyl]-3,5-dicarboxylate (**3**)

We attempted to react **3** in another Suzuki cross coupling to extend the aryl chain and add a phosphine moiety that would act as an anchor for the ruthenium metal due to its strong σ-donating and π-accepting abilites.[4] However, we found that the BPin group was not reactive enough. As a result of this decreased reactivity we then converted the BPin group into a boronic acid group using NH_4OAc and $NaIO_4$ before carrying out another Suzuki cross coupling to yield **4**. Unfortunately, this step suffered from lowered yield as a result of side product formation. After reaction screening, we discovered that the reaction time was very important and at least 2.5 hours were needed, where longer time lengths resulting in no desired product remaining at the end of the reaction. In addition, we tested multiple solvent mixes (Table 5.2) ultimately settling on a THF/H_2O mixture.



Scheme 3.5 Synthesis of (3',5'-bis(methoxycarbonyl)-[1,1'-biphenyl]-4-yl)boronic acid (**5**)

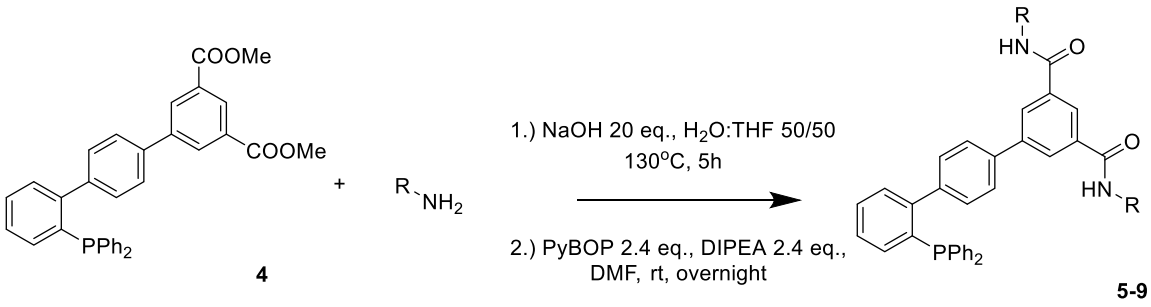
Table 3.2 Screening conditions for step two of figure 3.5

Catalyst	Base	Solvent	Yield
$Pd(OAc)_2$, DPPF	K_2CO_3	THF/H_2O 4:1	38%
$Pd(OAc)_2$, DPPF	K_2CO_3	$Dioxane/H_2O$ 4:1	39%
$Pd(OAc)_2$, DPPF	K_2CO_3	$Toluene/MeOH/H_2O$ 1.0:0.8/0.2	No reaction

Following this reaction, we converted the diester groups into amide functionalities through a two-step process to yield the final ligand (**5-9**). The purpose of the amide was to provide a directing group that can potentially interact with targeted substrates for increased selectivity in future reactions.[5] The first step of this installation involved the hydrolysis of the diester into a dicarboxylic acid using high temperature and strongly basic conditions (20 equivalents NaOH). This step required a significant amount of solvent (240 mL/g diester) to achieve solubility of all species but otherwise ran smoothly. Toward the closure of this work, however, our group began encountering the oxidation of the phosphine after the hydrolysis. This was presumably due to the high temperatures and/or some minor unnoticed alteration in procedure. It was important to circumvent this problem, however, since the phosphine oxides were unable to bind to the ruthenium metal center. The oxidized

phosphines were again reduced using 32 eq. of $SiCl_3$ in toluene at reflux for 6 hours for a quantitative yield.[5]

The next step involved the use of PyBOP and DIPEA for the conversion of the dicarboxylic acid intermediate into the final amide. This step was run effectively in DMF as is commonly described in literature, however, ethyl acetate also proved similarly useful for many amines and did not require the removal of DMF by several water washes. The only limitation to using ethyl acetate was solubility, where the solution would begin as heterogenous and slowly become homogenous as time went on.



Scheme 3.6 Synthesis of amide ligands **5-9**

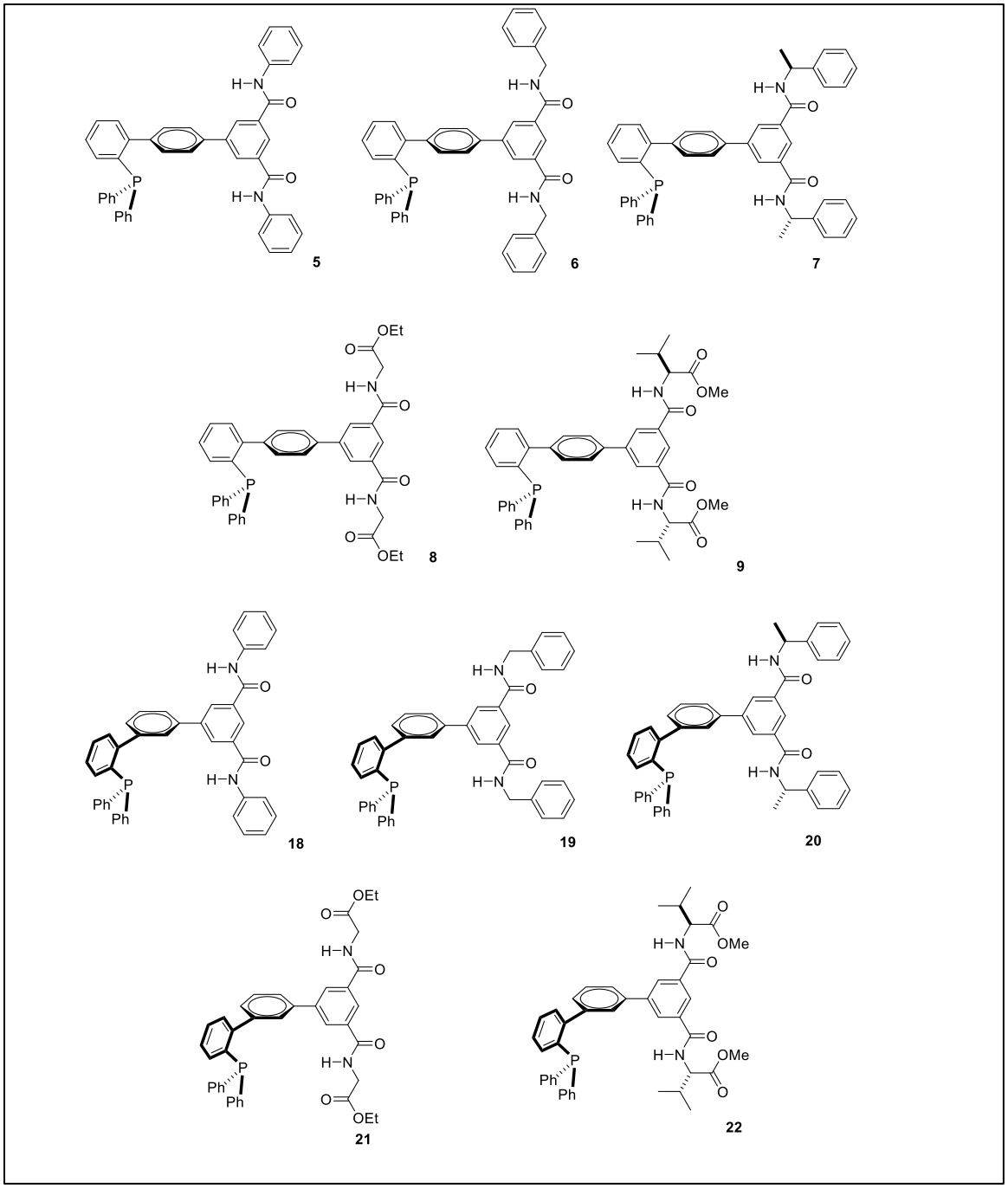
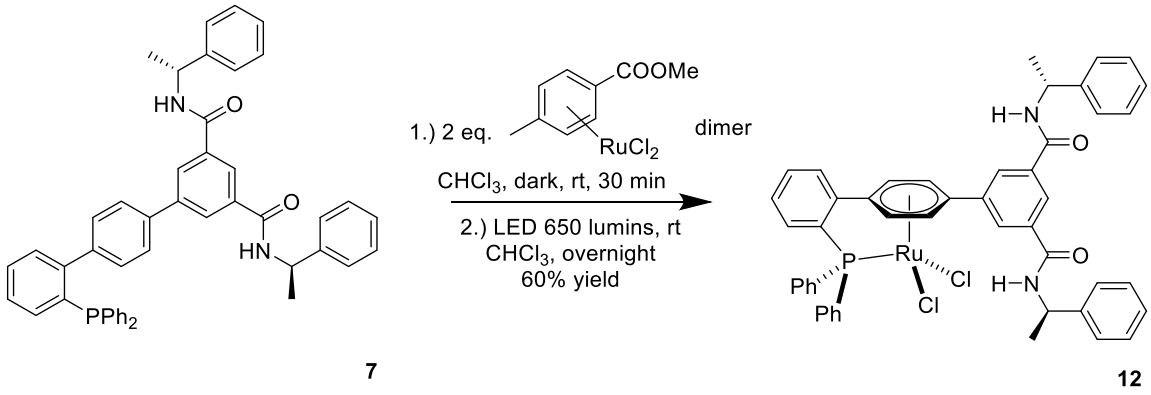


Figure 3.1 Ligands **5-9** and **18-22**

Once the ligand was synthesized, we then used it to coordinate $RuCl_3$ xH_2O in another two-step process. For the first step we simply mixed the ligand with a ruthenium-

coordinated arene in the absence of light, which added the Ru metal onto the phosphine but not onto the aryl ring. After separation of the intermediate from the rest of the reaction media by silica gel column chromatography, 650 lumin light from a desk lamp was shone onto the intermediate which caused the Ru metal to finally add to the aryl species as well. Successful metalation was evident through both ^{1}HNMR, ^{13}CNMR, and ^{31}PNMR spectroscopy as the chemical shifts for the aryl hydrogens moved upfield with the additional electron density from the Ru metal. Conversely, the phosphorous chemical shift moved downfield to 50 ppm from -13 ppm indicating an electron withdrawing effect from the Ru metal. After metalation it was observed that after a variable amount of time the complexes tended to develop a problem with serious insolubility in most solvents. It seems likely that these complexes were dimerizing when this occurs. Interestingly though, these complexes were still able to catalyze preliminary screening reactions becoming homogenous over the course of the reaction. It was discovered that these complexes would dissolve in a $CHCl_3$/MeOH mix. Whenever several (~5-6) drops of MeOH were added to the $CHCl_3$ the complex would begin to dissolve. Once the complexes were redissolved we discovered that they would again become soluble in $CHCl_3$ for a time (usually a matter of days or several hours). This finding seems to support the idea that the complexes dimerize and evinces that the MeOH is able to break up the dimers. This solvent system was also carried into our NMR solutions in order to fully dissolve the entire sample.



Scheme 3.7 Synthesis of metalated complex **12**

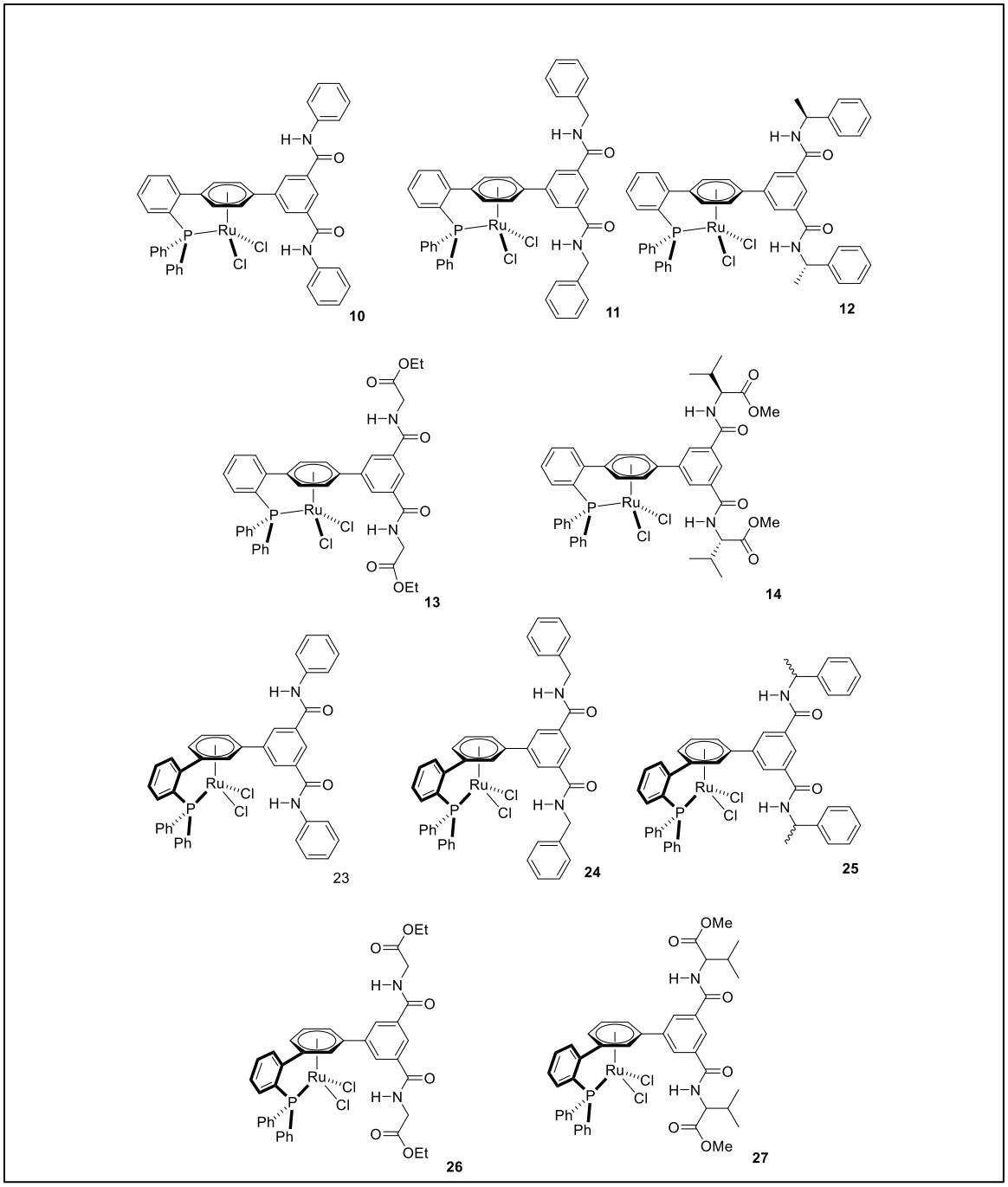


Figure 3.2 Metal complexes **10-14** and **23-24**

Following synthesis these complexes both **25** and **27** demonstrated diastereomers. In **25** these diastereomers were very readily isolabile from each other by silica gel

chromatography, however, the diastereomers of **27** proved nearly identical on silaca gel. Unfortunately, as a result of the high difficulty of separation, **27** was not separated into its isomeric forms. However, it does demonstrate further evidence that chirality can be controlled in these metal complexes.

Upon inspection of the complexes **10-14** and **23-27** one can observe several different functionalities which are intended to provide the potential for various reactivities. The amide groups on each complex are intended to interact via hydrogen bonding or by dipole-dipole interactions with functional groups on the potential substrate thus linking the two species for the formation of a metallocycle intermediate and subsequent C-H activation. For complexes **26** and **13** the nearby ester groups would increase the N-H acidity possibly rendering them to higher selectivity with hydrogen bond acceptors. The diastereotopic complexes of **25** also present the possibility of asymmetric reactivity in the future. One other factor that would affect potential C-H activation is the steric bulk and shape resulting from the amide group and the linear vs. curved shape of the aryl backbone. These steric factors could direct the approach and the coordination of the potential substrate species thus leading to various forms of selectivity (e.g. interact with one functional group over another, *meta* vs. *ortho* substitution, etc.). Indeed, while hopeful, these ideas are very preliminary as further testing remains to be done.

3.2 Conclusion and future work

Our group has demonstrated the synthesis of a range of ruthenium complexes with the potential for C-H activation. Each complex required 6 with high yields in each step except for the 5th step. Future work will be carried out in the utilization of these complexes as potential catalysts.

3.3 References

1.) Cartney, D. M.; Guiry, P. J. The Asymmetric Heck and Related Reactions *Chemical Society Reviews* **2011**, *40* (10), 5122.

2.) Jhang, Y.-Y.; Fan-Chiang, T.-T.; Huang, J.-M.; Hsieh, J.-C. Copper-Catalyzed Annulation: A Method for the Systematic Synthesis of Phenanthridinium Bromide. *Organic Letters* **2016**, *18* (5), 1154.

3.) Negishi, E.; Wang, G. Computational Studies of Versatile Heterogeneous PalladiumCatalyzed Suzuki, Heck, and Sonogashira Coupling Reactions. *1,3-Dienes* **2009**, 1.

4.) Danjo, H.; Kidena, Y.; Kawahata, M.; Sato, H.; Katagiri, K.; Miyazawa, T.; Yamaguchi, K. Multilayered Inclusion Nanocycles of Anionic Spiroborates *Organic Letters* **2015**, *17* (10), 2466.

5.) Engle, K. M.; Mei, T.-S.; Wasa, M.; Yu, J.-Q. Weak Coordination as a Powerful Means for Developing Broadly Useful C-H Functionalization Reactions. *Accounts of Chemical Research* **2011**, *45* (6), 788.

6.) Zhang, H.; Ma, Y.; Sun, X.-L. Chemically-Selective Surface Glyco-Functionalization of Liposomes through Staudinger Ligation *Chemical Communications* **2009**, No. 21, 3032.

CHAPTER IV

EXPERIMENTAL PROCEDURES FOR HOSOMI-SAKURAI

4.1 General considerations:

4.1.1 General experimental methods:

Unless otherwise noted, all solvents were dried with sodium benzophenone and distilled before use. All reactions were set up under argon atmosphere, utilizing glassware that was flame-dried and cooled under vacuum. All non-aqueous manipulations were using standard Schlenk techniques. Reactions were monitored using thin-layer chromatography (TLC) on Silica Gel plates. Visualization of the developed plates was performed under UV light (254 nm) or $KMnO_4$ stain. Silica-gel flash column chromatography was performed on SiliCycle Inc. 40-63 μm silica gel.

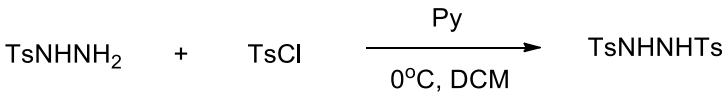
4.1.2 Materials:

Unless otherwise indicated, starting catalysts and materials were obtained from Sigma Aldrich, Oakwood, Strem, or Acros Co. Ltd. Moreover, commercially available reagents were used without additional purification.

4.1.3 Instrumentation:

All NMR spectra were run at 500 MHz (^{13}CNMR) in $CDCl_3$ solution. ^{1}H NMR spectra were internally referenced to TMS. ^{13}C NMR spectra were internally referenced to the residual solvent signal. Data for ^{1}H NMR are reported as follows: chemical shift (δ ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m= multiplet, br = broad), coupling constants (*J*) were reported in Hz. High resolution mass spectra (HRMS) were recorded on Bruker MicrOTOF-QII mass instrument (ESI & EI). Gas Chromatograph Mass Spectrometry analysis were done on Shimdzu GCMS- QP2010 and ESI was the ionization method.

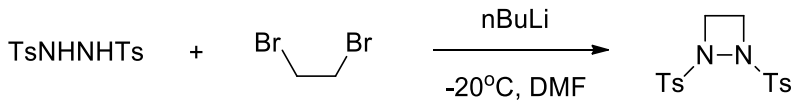
4.2 General procedure for the preparation of 1,2-ditosyl-1,2-diazetidine



Scheme 4.1 Formation of ditosylhydrazine

Tosyl chloride (174 mmol) was added to tosylhydrdazine (139 mmol) in dichloromethane (242 mL) in an ice bath. Pyridine (14.1 mL) was added dropwise in a temperature range of 0-10 ^{0}C. TLC analysis was done to monitor the reaction. A mixture of water (250 mL) and hexane (250 mL) was added to the solution and stirred vigorously for 30 minutes. The solution was then suction filtered and washed with a 1:1 ratio of acetone and water (100 ml). The crystals were then added to acetone (320 mL) and boiled at 80 ^{0}C. Water (150 mL) was added while stirring, and the solution was placed in an ice

bath for an hour. The solution was then suction filtered and washed with a small amount of cold diethyl ether.



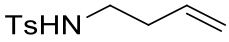
Scheme 4.2 Ring formation of 1,2-ditosyl diazetidine

Under nitrogen atmosphere, butyl lithium (2.5 M in hexanes, 11.2 mL, 28 mmol) solution was added drop wise to a solution of 1,2-ditosylhydrazine (12.9 mmol) in anhydrous dimethylformamide (50 mL) at -20^{0}C via gas tight syringe, and let it stir for 15 minutes. 1,2-Dibromoethane (1.33 mL, 15 mmol) was then added dropwise to the solution at -20 ^{0}C over 10 minutes. The solution was then stirred overnight at -20 ^{0}C. This solution was then allowed to warm to room temperature. The reaction mixture was then added to a mixture of water (240 mL) and ammonium chloride (4.8g, ~90 mmol) in a beaker. The solution was then vacuum filtered and washed with water (3 x 50 mL), and then washed with ethanol (3 x 50 mL). Then the solid were washed with dichloromethane (50 mL) into a clean filter flask, and the filtrate was collected as a yellow liquid. 25 mL of the dichloromethane was then evaporated from the solution. Ethanol (60 mL) was then added to the solution and the dichloromethane was completely evaporated from the solution. The solution containing the solid was then suction filtered and washed with ethanol (2 x 30 mL) and then washed with hexane (20 mL). 1,2-Ditosyl-1,2-diazetidine was produced in 70 % yield. **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.93 (d, *J* = 8.3 Hz), 7.44 (d, *J* = 8.1 Hz), 3.69 (s),

2.51 (s). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 145.70, 130.35, 129.76, 129.30, 47.81, 21.84. **HRMS** (ESI) [M+Na] Clacd for $C_{16}H_{18}N_2O_4S_2$:389.0600, found 389.0600.

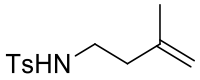
4.3 Catalytic synthesis of homoallylic amines with 1,2-Ditosyl-1,2-diazetidine and different types of styrene derivatives.

N-(but-3-en-1-yl)-4-methylbenzenesulfonamide[1]



An oven dried Schlenk tube was charged with catalyst $FeBr_2$ (2.2 mg, 10 mol %) and 1,2-ditosyl-1,2-diazetadine (36.6 mg, 0.1 mmol). The Schlenk tube was vacuumed to remove air and filled with nitrogen. The Teflon screw cap was replaced with a rubber septum and allyl trimethylsilane (0.3 mmol) and 1 mL of chlorobenzene were added and the Schlenk tube was then purged with nitrogen for 1 minute and the rubber septum was replaced with a Teflon screw cap. 1.5 equivalence H_2O, 1.5 equivalence of acetic acid and 1.5 equivalence of tetrabutylammonium fluoride were added to the reacton mixture and stirred for 1 hour. The reaction mixture was purified by flash chromatography with 5:1 hexane and ethyl acetate as mobile phase (14.5 mg, 64% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.75 (d, J = 8.3 Hz, 1H), 7.31 (d, J = 8.2 Hz, 1H), 5.63 (ddt, J = 17.1, 10.2, 6.9 Hz, 1H), 5.28 – 4.88 (m, 1H), 4.59 (t, J = 5.6 Hz, 1H), 3.02 (q, J = 6.6 Hz, 1H), 2.44 (d, J = 7.6 Hz, 2H), 2.20 (q, J = 6.7 Hz, 1H).**^{13}CNMR** (125 MHz, $CDCl_3$) δ 143.44, 136.96, 134.18, 129.72, 127.13, 118.14, 42.09, 33.60, 21.53.

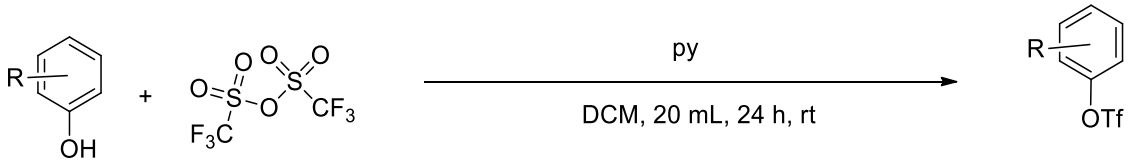
4-Methyl-*N*-(3-methylbut-3-en-1-yl)benzenesulfonamide[2]



Compound was formed using the previous method (22.6 mg, 47% yield).[1] **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.75 (d, *J* = 8.2 Hz, 2 H), 7.31 (d, *J* = 8.0 Hz, 2H), 4.72 (d, *J* = 75.4 Hz, 1H), 4.52 (t, *J* = 5.5 Hz, 1H), 3.05 (dd, *J* = 12.8, 6.6 Hz, 2H), 2.43 (s, 3H), 2.15 (t, *J* = 6.7 Hz, 2H), 1.60 (s, 3H). **^{13}CNMR** (125 MHz, $CDCl_3$) δ 143.43, 141.48, 136.87, 129.71, 127.14, 113.21, 40.52, 37.18, 21.74, 21.53

General procedure for the synthesis of trimethyl(2-arylallyl)silane derivatives.

Aryl triflates.

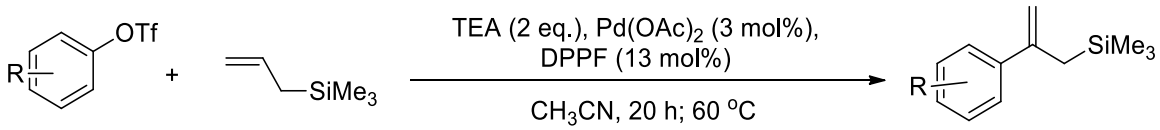


Scheme 4.3 Synthesis of aryl triflates

Phenyl triflate and its derivatives (R = H **1a**, t-Bu **1b**, 3-CF_3 **1c**, 2-Cl **1d**, 2-Me **1e**, 4-Ph **1h**, 2-Cl, 4-OMe **1i**, 3-5-OMe **1j**, 4-NO_2 **1k**, 4-F **1l**, 2,6-Cl **1m**, 2-CF_3 **1n**, 4-Cl **1o**, 4-Br **1p**) were prepared according to the literature method for low to excellent yields.[1] Naphthyl

and 2-Naphthyl substituents were also prepared using this method in moderate to good yields.[3]

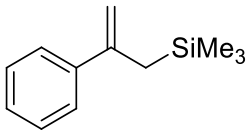
Trimethyl(2-arylallyl)silane derivatives.



Scheme 4.4 Synthesis of phenyl-substituted allylsilanes

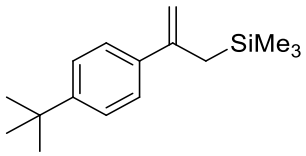
Various trimethyl(2-arylallyl)silane derivatives were synthesized by Heck reaction with aryl triflate **1a-e,** (1.25 mmol), allyltrimethylsilane (6.1 mmol), TEA (2 eq.), Pd(OAc.) (3 mol%), and DPPF (13 mol%) in acetonitrile at 60°C for 20 hours according to the general literature method.[4]

Trimethyl(2-phenylallyl)silane (2a).[4]



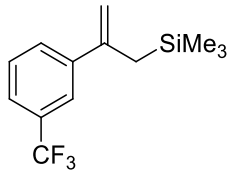
Compound **2a** was prepared according to the general literature method. **^{1}HNMR** (300 MHz, $CDCl_3$) δ 7.38 – 7.32 (m, 2H), 7.29 – 7.16 (m, 3H), 5.08 (d, J = 1.6 Hz, 1H), 4.82 (s, 1H), 1.97 (s, 2H), -0.15 (s, 9H).

(2-(4-(tert-butyl)phenyl)allyl)trimethylsilane (2b).[4]



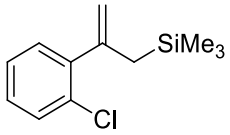
Compound **2b** was prepared from **1b** (2.70 g, 9.57 mmol) and allyl trimethylsilane (7.42 mL, 46.7 mmol) forming a yellow liquid (1.62 g, 69%). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 7.36-7.35 (m, 4H), 5.17 (d, *J* = 1.74 Hz, 1H), 4.86 (d, *J* = 1.56 Hz, 1H), 2.04 (d, *J* = 0.90 Hz, 2H), 1.35 (s, 9H), -0.05 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 150.16, 146.23, 139.70, 128.09, 126.35, 125.92, 125.20, 125.15, 109.33, 34.48, 31.38, 25.96, -1.33. **HRMS (ESI):** Found: m/z 247.1877. Calcd for $C_{16}H_{27}Si$: (M+H) 247.1877.

Trimethyl(2-(3-(trifluoromethyl)phenyl)allyl)silane (2c).[5]



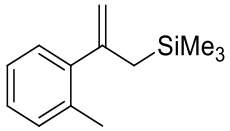
Compound **2c** was prepared from **1c** (368 mg, 1.25 mmol) and allyl trimethylsilane (870 µL, 5.47 mmol) forming a yellow liquid (96.5 mg, 30% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.66 (s, 1H), 7.61 (d, *J* = 7.79 Hz, 1H), 7.53 (d, *J* = 7.76 Hz, 1H), 7.44 (t, *J* = 7.76 Hz, 1H), 5.21 (s, 1H), 4.98 (s, 1H), 2.06 (s, 2H), -0.07 (s, 9H) **^{13}CNMR** (126 MHz, $CDCl_3$) δ 145.38 , 143.51, 130.52 (q, *J* = 32.06 Hz), 129.55, 128.84, 128.59, 124.25 (q, *J* = 272.79 Hz), 123.89 (q, *J* = 3.82 Hz), 123.05 (q, *J* = 3.80 Hz), 111.60, 26.07, -1.46. **HRMS (ESI):** Found: m/z 259.1120. Calcd for $C_{13}H_{18}F_3Si$: (M+H) 259.1124.

(2-(2-chlorophenyl)allyl)trimethylsilane (2d).



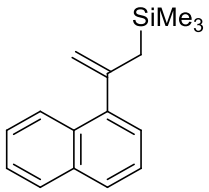
Compound **2d** was prepared from **1d** (326 mg, 1.25 mmol) and allyl trimethylsilane (970 µL, 6.1 mmol) forming a yellow liquid (176.5 mg, 63% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.39-7.34 (m, 1H), 7.27-7.17 (m, 3H), 5.08 (s, 1H), 4.91 (s, 1H), 2.07 (s, 2H), -0.07 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.21, 143.17, 131.90, 130.34, 129.75, 128.10, 126.47, 113.93, 27.99, -1.45. **HRMS (ESI):** Found: 225.0860. Calcd. for $C_{12}H_{18}ClSi$: (M+H) 225.0861.

Trimethyl(2-(o-tolyl)allyl)silane (2e).[6]



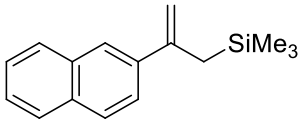
Compound **2e** was prepared from **1e** (300 mg, 1.25 mmol) and allyl trimethylsilane (970 µL, 6.1 mmol) forming a yellow liquid (120.1 mg, 47% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.18-7.15 (m, 4H), 5.04 (s, 1H), 4.80 (s, 1H), 2.38 (s, 3H), 1.94 (s, 2H), -0.06 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 147.80, 144.39, 134.49, 130.21, 128.41, 126.68, 125.35, 112.42, 28.78, 20.18, -1.32. **HRMS (ESI):** Found: m/z 243.0965. Calcd for $C_{13}H_{20}SiK$: (M+K) 243.0965.

Trimethyl(2-(naphthalen-1-yl)allyl)silane



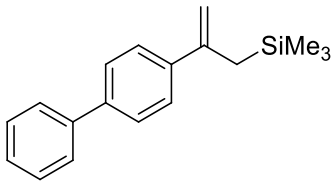
Compound **2f** was prepared from **1f** (345 mg, 1.25 mmol) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (257.8 mg, 86% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.20 (d, *J* = 7.8 Hz, 1H), 7.93 – 7.84 (m, 1H), 7.79 (d, *J* = 8.2 Hz, 1H), 7.59 – 7.48 (m, 2H), 7.48 – 7.43 (m, 1H), 7.38 (d, *J* = 7.0 Hz, 1H), 5.27 (d, *J* = 1.0 Hz, 1H), 5.07 (d, *J* = 1.1 Hz, 2H), 2.19, -0.06 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.79, 142.95, 133.96, 131.00, 128.49, 127.34, 126.23, 125.70, 125.64, 125.30, 125.18, 113.73, 29.86, -1.22.[5]

Trimethyl(2-(naphthalen-2-yl)allyl)silane[6]



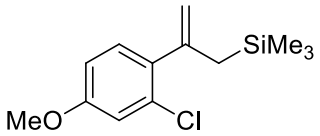
Compound **2g** was prepared from **1g** (345 mg, 1.25 mmol) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (170.9 mg, 57% yield).[3] **^{1}HNMR** (300 MHz, $CDCl_3$) δ 7.94 – 7.81 (m, 3H), 7.66 (d, *J* = 8.6 Hz, 1H), 7.57 – 7.44 (m, 3H), 5.36 (s, 1H), 5.05 (s, 1H), 2.21 (s, 2H), -0.00 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.36, 139.93, 133.34, 132.79, 128.19, 127.64, 127.54, 126.04, 125.71, 124.94, 110.75, 26.10, -1.27.

(2-(biphenyl-4-yl)allyl)trimethylsilane[7]



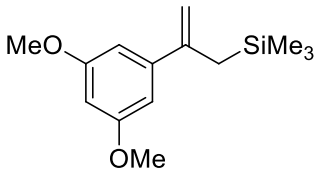
Compound **2h** was prepared from **1h** (378 mg, 1.25 mmol) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (177.7 mg, 53% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.65 (d, *J* = 7.3 Hz, 2H), 7.61 – 7.56 (m, 2H), 7.52 (d, *J* = 8.1 Hz, 2H), 7.50 – 7.45 (m, 2H), 7.40 – 7.34 (m, 1H), 5.25 (d, *J* = 1.1 Hz, 1H), 4.94 (s, 1H), 2.09 (s, 2H), -0.02 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.08, 141.65, 140.79, 139.93, 128.80, 128.77, 127.29, 127.23, 127.20, 127.02, 126.96, 126.76, 126.71, 125.93, 110.11, 26.01, -1.30.

(2-(2-chloro-4-methoxyphenyl)allyl)trimethylsilane



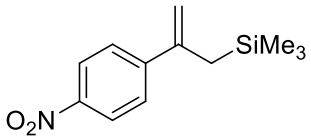
Compound **2i** was formed from **1i** (363 mg, 1.25 mmol) and allyl trimethylsilane (970µL, 6.1 mmol) forming a dark orange liquid (181mg, 57% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.15 (d, *J* = 8.5 Hz, 1H), 6.92 (s, 1H), 6.77 (d, *J* = 8.5 Hz, 1H), 5.05 (s, 1H), 4.88 (s, 1H), 3.82 (s, 3H), 2.05 (s, 2H), -0.07 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 158.95, 145.74, 135.50, 132.41, 130.88, 114.93, 113.73, 112.55, 55.49, 28.22, -1.43.

(2-(3,5-dimethoxyphenyl)allyl)trimethylsilane



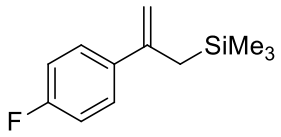
Compound **2j** was formed from **1j** (358 mg, 1.25 mmol) and allyl trimethylsilane (970µL, 6.1 mmol) forming a dark orange liquid (228.6 mg, 91% yield). **H^{1}NMR** (500 MHz, $CDCl_3$) δ 6.58 (s, 2H), 6.40 (s, 1H), 5.15 (s, 1H), 4.88 (s, 1H), 3.83 (s, 6H), 2.00 (s, 2H), -0.05 (s, 9H). **C^{13}NMR** (126 MHz, $CDCl_3$) δ 160.42, 146.60, 145.10, 110.23, 104.82, 99.05, 55.30, 31.58, 26.21, 22.65, 14.11, -1.41. **HRMS (ESI):** Found m/z 273.1281. Calcd. for $C_{14}H_{22}O_2SiNa$: (M+Na) 273.1281.

trimethyl(2-(4-nitrophenyl)allyl)silane



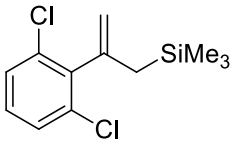
Compound **2k** was formed from **1k** (1.25 mmol, 339 mg) and allyl trimethyl silane (970µL, 6.1 mmol) forming a dark orange liquid (178.8 mg, 61% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.19 (d, J = 8.8 Hz, 2H), 7.56 (d, J = 8.9 Hz, 2H), 5.28 (d, J = 1.0 Hz, 1H), 5.07 (d, J = 1.0 Hz, 1H), 2.07 (d, J = 0.9 Hz, 2H), -0.07 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 149.45, 145.01, 134.59, 129.32, 127.03, 126.25, 123.54, 123.52, 113.64, 25.98, -1.43. **HRMS (ESI):** Found m/z 258.0931. Calcd. for $C_{12}H_{17}NO_2SiNa$: (M+Na) 258.0921.

trimethyl(2-(4-nitrophenyl)allyl)silane[7]



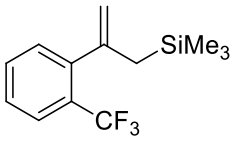
Compound **2l** was formed from **1l** (1.25 mmol, 305 mg) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (165 mg, 54% yield). **H[1]NMR** (500 MHz, $CDCl_3$) δ 7.39 (dd, *J* = 8.7, 5.5 Hz, 2H), 7.01 (t, *J* = 8.7 Hz, 2H), 5.10 (s, 1H), 4.88 (s, 1H), 2.02 (s, 2H), -0.07 (s, 9H). **[13]CNMR** (126 MHz, $CDCl_3$) δ 162.18 (d, *J* = 245.7 Hz), 145.64, (d, *J* = 3.3 Hz), 127.88 (d, *J* = 7.9 -Hz), 114.96, 114.79, 110.04, 26.37, -1.41.

(2-(2,6-dichlorophenyl)allyl)trimethylsilane



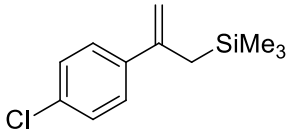
Compound **2m** was formed from **1m** (1.25 mmol, 369 mg) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (137.8 mg, 43% yield). **[1]HNMR** (500 MHz, $CDCl_3$) δ 7.32 (d, *J* = 8.0 Hz, 2H), 7.12 (t, *J* = 8.0 Hz, 1H), 5.29 (d, *J* = 1.2 Hz, 1H), 4.94 (s, 1H), 1.98 (d, *J* = 0.6 Hz, 2H), 0.04, (s, 9H). **[13]CNMR** (126 MHz, $CDCl_3$) δ 142.34, 133.73, 130.50, 128.77, 128.23, 128.13, 126.93, 116.27, 27.77, -1.25.

trimethyl(2-(2-(trifluoromethyl)phenyl)allyl)silane[5]



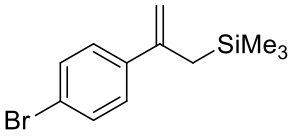
Compound **2n** was formed from **1n** (1.25 mmol, 368 mg) and allyl trimethylsilane (970µL, 6.1 mmol) forming a colorless liquid (44.2 mg, 14% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.65 (d, *J* = 7.9 Hz, 1H), 7.48 (t, *J* = 7.5 Hz, 1H), 7.37 (t, *J* = 7.6 Hz, 1H), 7.29 (d, *J* = 6.5 Hz, 1H), 5.07 (s, 1H), 4.87 (s, 1H), 1.98 (s, 2H), -0.03 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.11, 143.98 (q, *J* = 2.1 Hz), 143.97, 131.29, 130.56, 127.50 (q, *J* = 30.2 Hz), 126.92, (q, *J* = 5.2 Hz), 124.43 (q, *J* = 274.7 Hz), 123.34, 121.16, 113.79, 29.09, -1.31.

(2-(4-chlorophenyl)allyl)trimethylsilane[8]



Compound **2o** was formed from **1o** (1.25 mmol, 326 mg) and allyl trimethylsilane (970µL, 6.1 mmol) forming a colorless liquid (157.4 mg, 56% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.36 (d, *J* = 8.7 Hz, 2H), 7.29 (d, *J* = 8.6 Hz, 2H), 5.14 (d, *J* = 1.4 Hz, 1H), 4.90 (d, *J* = 1.1 Hz, 1H), 2.02 (d, *J* = 0.8 Hz, 2H), -0.07 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 145.51, 141.24, 132.94, 128.23, 127.62, 110.62, 26.10, -1.39.

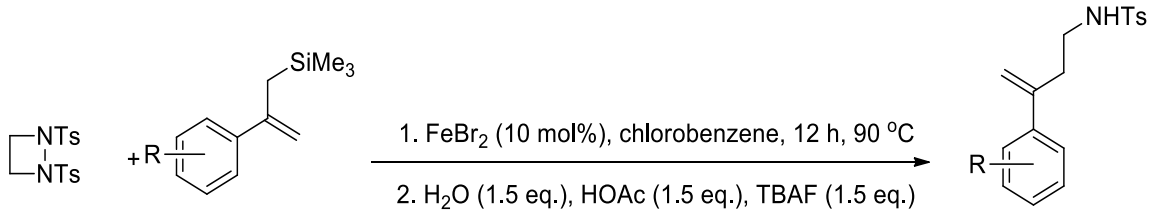
(2-(4-bromophenyl)allyl)trimethylsilane[9]



Compound **2p** was formed from **1p** (1.25 mmol, 337 mg) and allyl trimethylsilane (970µL, 6.1 mmol) forming a yellow liquid (79.9 mg, 30% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.44 (d, *J* = 8.5 Hz, 2H), 7.29 (d, *J* = 8.0 Hz, 2H), 5.14 (d, *J* = 1.3 Hz, 1H), 4.90 (d, *J* = 1.0

Hz, 1H), 2.01 (s, 2H), -0.07 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 145.56, 141.71, 131.19, 127.98, 121.09, 110.69, 26.03, -1.39.

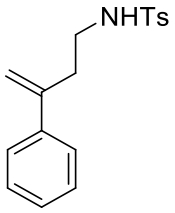
General procedures for the synthesis of homoallylamines



Scheme 4.5 Synthesis of substituted homoallylamines

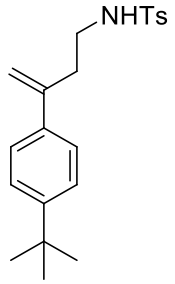
An oven dried Schlenk tube was charged with catalyst $FeBr_2$ (10 mol %) and 1,2-ditosyl-1,2-diazetadine(0.05 mmol). The Schlenk tube was then vacuumed to remove air followed by refilling with nitrogen. The Teflon screw cap was replaced with a rubber septum and chlorobenzene (1mL) and silane (0.15 mmol) were added to the Schlenk tube. The Schlenk tube was then purged with nitrogen for 1 minute and the rubber septum was replaced with a Teflon screw cap. The reaction mixture was then stirred at 90 °C for 12 h. After the 12 hours H_2O (1.5 eq.), acetic acid (1.5 eq.), and tetrabutylammonium fluoride (1.5 eq) were added and the mixture was allowed to stir at room temperature for 1 hour. This was then separated by silica gel chromatography (5:1 ratio of hexane: ethyl acetate).

4-methyl-N-(3-phenylbut-3-en-1-yl)benzenesulfonamide (3a).



Compound **3a** was prepared from diazetidine (18.3 mg, 0.05 mmol) and **2a** (28.6 mg, 0.15 mmol) forming a yellow gel (23.6 mg, 78% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.66 (d, *J* = 8.25 Hz, 2H), 7.31-7.23 (m, 7H), 5.34 (s, 1H), 5.03 (d, *J* = 1.05 Hz, 1H), 4.39 (br, 1H), 3.05 (dt, *J* = 6.60 Hz, 2H), 2.66 (t, *J* = 6.76, 2H), 2.40 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 144.41, 143.37, 139.52, 136.86, 129.68, 128.53, 127.87, 127.06, 126.03, 115.17, 41.30, 35.27, 21.54. **HRMS (ESI):** Found: m/z 324.1027. Calcd. for $C_{17}H_{19}NO_2SNa$: (M+Na) 324.1029.

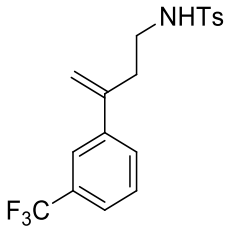
N-(3-(4-(tert-butyl)phenyl)but-3-en-1-yl)-4-methylbenzenesulfonamide (3b).



Compound **3b** was prepared from diazetidine (18.3 mg, 0.05 mmol) and **2b** (37.0 mg, 0.15 mmol) forming a yellow gel (19.2 mg, 54% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.69-7.66 (d, 2H), 7.32-7.29 (m, 1H), 7.27-7.23 (m, 3H), 7.23-7.19 (m, 1H), 5.33 (d, *J* = 0.99 Hz, 1H), 4.98 (d, *J* = 1.05 Hz, 1H), 4.47 (t, *J* = 6.01 Hz, 1H), 3.06 (dt, *J* = 6.01 Hz, 2H), 2.65 (t, *J* = 6.64 Hz, 2H), 2.40 (s, 3H), 1.31 (s, 9H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 151.01,

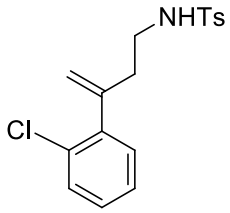
144.05, 143.32, 136.97, 136.46, 129.66, 127.09, 125.67, 125.43, 114.45, 41.34, 35.21, 34.55, 31.30, 21.55. **HRMS (ESI):** Found: m/z 396.1391. Calcd. for $C_{21}H_{27}NO_2SK$: (M+K) 396.1394.

4-methyl-N-(3-(3-(trifluoromethyl)phenyl)but-3-en-1-yl)benzenesulfonamide (3c).



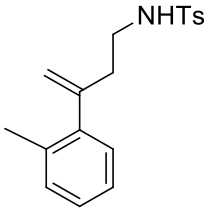
Compound **3c** was prepared from diazetidine (18.3 mg, 0.05 mmol) and **2c** (38.8 mg, 0.15 mmol) forming a yellow gel (24.3 mg, 66 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.68 (d, *J* = 8.16 Hz, 2H), 7.51 (d, *J* = 8.90 Hz, 2H), 7.45 (d, *J* = 7.81 Hz, 1H), 7.41 (t, *J* = 7.61 Hz, 1H), 7.27-7.23 (m, 2H), 5.40 (s, 1H), 5.14 (s, 1H), 4.57 (t, *J* = 5.91 Hz, 1H), 3.05 (dt, *J* = 6.63 Hz, 5.91 Hz, 2H), 2.69 (t, *J* = 6.84 Hz, 2H), 2.40 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) ppm **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.54, 143.23, 140.50, 136.72, 130.90 (q, *J* = 31.94 Hz), 129.71, 129.34, 129.05, 127.04, 124.52 (q, *J* = 3.65 Hz), 124.02 (q, *J* = 273.42 Hz), 122.73 (q, *J* = 3.78 Hz), 116.634, 41.18, 35.12, 21.49. **HRMS (ESI):** Found: m/z 408.0644. Calcd. for $C_{18}H_{18}F_3NO_2SK$: (M+K) 408.0644.

N-(3-(2-chlorophenyl)but-3-en-1-yl)-4-methylbenzenesulfonamide (3d).



Compound **3d** was prepared from diazetidine (18.3 mg, 0.05 mmol) and **2d** (38.8 mg, 0.15 mmol) forming a yellow gel (30.1 mg, 90% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.15 Hz, 2H), 7.32 (d, *J* = 7.76 Hz, 1H), 7.30-7.25 (m, 2H), 7.21-7.13 (m, 2H), 7.02 (dd, *J* = 7.38, 1.35 Hz, 1H), 5.22 (s, 1H), 5.08 (s, 1H), 4.49 (br, 1H), 2.97 (dt, *J* = 6.35, Hz, 2H), 2.59 (t, *J* = 6.50 Hz, 2H), 2.42 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 144.07, 143.42, 140.06, 136.89, 131.99, 130.15, 129.73, 129.71, 128.74, 127.12, 126.80, 118.79, 40.87, 36.64, 21.56. **HRMS (ESI):** Found: m/z 374.0378. Calcd. for $C_{17}H_{18}ClNO_2SK$: (M+K) 374.0378.

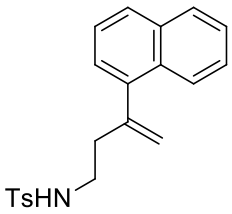
4-methyl-N-(3-(o-tolyl)but-3-en-1-yl)benzenesulfonamide (3e).



Compound **3e** was prepared from diazetidine (18.3 mg, 0.05 mmol) and **2e** (30.7 mg, 0.15 mmol) forming a yellow gel (23.6 mg, 75% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.69 (d, *J* = 8.24 Hz, 2H), 7.28 (d, *J* = 8.02 Hz, 2H), 7.17-7.11 (m, 2H), 7.05 (dt, *J* = 6.99, 6.59, 2.29 Hz, 1H), 6.84 (d, *J* = 7.50 Hz, 1H), 5.15 (d, *J* = 1.39 Hz, 1H), 4.95 (d, *J* = 1.37 Hz, 1H), 4.44-4.35 (br, 1H), 2.98 (dt, *J* = 6.54, Hz, 2H), 2.48 (t, *J* = 6.59 Hz, 2H), 2.43 (s, 3H),

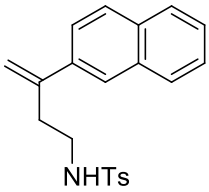
2.20 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 146.12, 143.45, 141.10, 136.85, 134.75, 130.36, 129.73, 128.21, 127.35, 127.11, 125.63, 116.88, 40.98, 37.30, 21.56, 19.76. **HRMS (ESI):** Found: m/z 354.0927. Calcd. for $C_{18}H_{21}NO_2SK$: (M+K) 354.0927.

4-methyl-N-(3-(naphthalen-1-yl)but-3-enyl)benzenesulfonamide



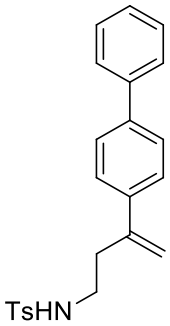
Compound **3f** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2f** (0.15 mmol, 50.5 mg) forming a white solid (23.3 mg, 69% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.86 (dd, *J* = 15.6, 8.0 Hz, 2H), 7.75 (d, *J* = 8.2 Hz, 1H), 7.62 (d, *J* = 8.1 Hz, 2H), 7.50 – 7.42 (m, 2H), 7.35 – 7.30 (m, 1H), 7.21 (d, *J* = 8.0 Hz, 2H), 7.05 (d, *J* = 6.9 Hz, 1H), 5.39 (s, 1H), 5.18 (s, 1H), 4.43 – 4.34 (br, 1H), 2.97 (dt, *J* = 6.4, 6.4 Hz, 2H), 2.66 (t, *J* = 6.6 Hz, 2H), 2.40 (, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 144.93, 143.38, 139.20, 136.75, 133.74, 130.88, 129.67, 128.50, 127.77, 127.04, 126.18, 125.89, 125.17, 118.49, 41.25, 38.04, 21.54. **HRMS (ESI):** Found m/z 374.88. Calcd. for $C_{21}H_{21}NO_2S$: (M+Na) 374.1185.

4-methyl-N-(3-(naphthalen-2-yl)but-3-enyl)benzenesulfonamide



Compound **3g** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2g** (0.15 mmol, 50.5 mg) forming a white solid (24.1 mg, 71% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.82 – 7.73 (m, 3H), 7.67 (s, 1H), 7.60 (d, *J* = 8.2 Hz, 2H), 7.49 – 7.45 (m, 2H), 7.42 (dd, *J* = 8.6, 1.8 Hz, 1H), 7.11 (d, *J* = 8.0 Hz, 2H), 5.50 (s, 1H), 5.15 (s, 1H), 4.44 (t, *J* = 5.8 Hz, (s, 1H), 3.12 – 3.05 (m, 2H), 2.79 (t, *J* = 6.7 Hz, 2H), 2.29 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 144.15, 143.33, 136.57, 133.28, 132.95, 129.57, 128.17, 127.56, 126.99, 126.38, 126.19, 124.87, 124.20, 115.86, 41.29, 35.20. **HRMS (ESI):** Found m/z 374.1184. Calcd. for $C_{21}H_{21}NO_2SNa$: (M+Na) 374.1184.

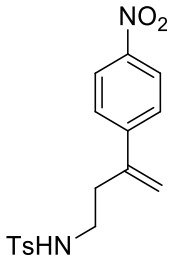
N-(3-(biphenyl-4-yl)but-3-enyl)-4-methylbenzenesulfonamide



Compound **3h** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2h** (0.15 mmol, 56.6 mg) forming a white solid (20.1 mg, 53% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.67 (d, *J* = 7.4 Hz, 2H), 7.58 (d, *J* = 7.7 Hz, 2H), 7.51 (d, *J* = 7.7 Hz, 2H), 7.47 – 7.42 (m, 2H), 7.35 (t, *J* = 8.4 Hz, 3H), 7.27 – 7.20 (m, 2H), 5.41 (s, 1H), 5.06 (s, 1H), 4.52 (s, 1H), 3.08

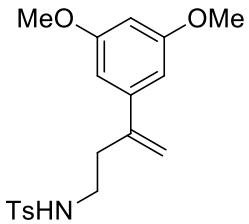
(dt, J = 6.4, Hz, 2H), 2.70 (t, J = 6.7 Hz, 2H), 2.34 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.84, 143.40, 140.69, 140.46, 138.29, 136.82, 129.68, 128.87, 127.51, 127.17, 127.08, 126.96, 126.44, 115.19, 41.34, 35.19, 21.50. **HRMS (ESI):** Found m/z 374.1184. Calcd. for $C_{21}H_{21}NO_2SNa$: (M+Na) 374.1185.

4-methyl-N-(3-(4-nitrophenyl)but-3-enyl)benzenesulfonamide



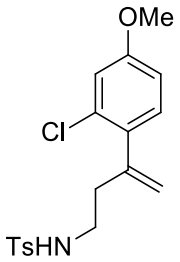
Compound **3i** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2i** (0.15 mmol, 35.3 mg) forming a yellow solid (23.2 mg, 70% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.14 (d, J = 8.3 Hz, 2H), 7.67 (d, J = 8.1 Hz, 2H), 7.42 (d, J = 8.6 Hz, 2H), 7.26 (d, J = 4.8 Hz, 2H), 5.49 (s, 1H), 5.25 (s, 1H), 4.45 (br, 1H), 3.06 (dt, J = 6.6, 6.6 Hz, 2H), 2.73 (t, J = 6.8 Hz, 2H), 2.41 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 147.28, 146.20, 143.69, 142.82, 136.71, 129.74, 127.06, 126.86, 123.82, 118.51, 41.18, 35.17, 21.52. **HRMS (ESI):** Found m/z 347.1061. Calcd. for $C_{17}H_{19}N_2O_4S$: (M+H) 347.1060.

N-(3-(3,5-dimethoxyphenyl)but-3-enyl)-4-methylbenzenesulfonamide



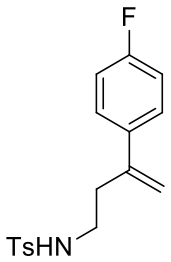
Compound **3j** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2j** (0.15 mmol, 37.6 mg) forming an orange gel (12.6 mg, 36% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.67 (d, *J* = 8.1 Hz, 2H), 7.25 (d, *J* = 9.2 Hz, 4H), 6.42 – 6.36 (m, 3H), 5.34 (s, 1H), 5.02 (s, 1H), 4.37 (s, 1H), 3.78, (s, 6H), 3.05 (dt, *J* = 6.5 Hz, 2H), 2.62 (t, *J* = 6.7 Hz, 2H), 2.41 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 160.82, 144.49, 143.39, 141.77, 136.86, 129.67, 127.04, 115.49, 104.50, 99.63, 55.38, 41.34, 35.48, 21.53. **HRMS (ESI):** Found m/z 384.1237. Calcd. for $C_{19}H_{24}NO_4S$: (M+H) 384.1240.

N-(3-(2-chloro-4-methoxyphenyl)but-3-enyl)-4-methylbenzenesulfonamide



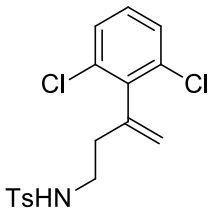
Compound **3k** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2k** (0.15 mmol, 38.2 mg) forming a yellow gel (32.9 mg, 94% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.1 Hz, 2H), 7.28 (d, *J* = 8.1 Hz, 2H), 6.92 (d, *J* = 8.5 Hz, 1H), 6.86 (d, *J* = 2.3 Hz, 1H), 6.69 (dd, *J* = 8.5, 2.4 Hz, 1H), 5.19 (s, 1H), 5.05 (s, 1H), 4.45 – 4.39 (m, 1H), 3.78 (s, 3H), 2.95 (dt, *J* = 6.3 Hz, 2H), 2.56 (t, *J* = 6.4 Hz, 2H), 2.43 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 159.40, 143.64, 143.39, 136.89, 132.56, 132.12, 130.66, 129.69, 127.12, 118.86, 115.02, 112.85, 55.56, 40.87, 36.82, 21.55. **HRMS (ESI):** Found m/z 366.0925. Calcd. for $C_{18}H_{21}ClNO_3S$: (M+H) 366.0925.

N-(3-(4-fluorophenyl)but-3-enyl)-4-methylbenzenesulfonamide



Compound **3l** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2l** (31.3 mg, 0.15 mmol) forming a yellow gel (19.2 mg, 60% yield). **H^1NMR** (500 MHz, $CDCl_3$) δ 7.66 (d, *J* = 8.2 Hz, 2H), 7.29 – 7.20 (m, 4H), 6.96 (t, *J* = 8.7 Hz, 2H), 5.29(s, 1H), 5.02 (s, 1H), 4.41 (d, *J* = 3.7 Hz, 1H), 3.08 – 2.99 (m, 2H), 2.64 (t, *J* = 6.7 Hz, 2H), 2.41 (s, 3H). **C^{13}NMR** (126 MHz, $CDCl_3$) δ 162.29 (d, *J* = 248.2 Hz), 161.30, 143.23 (d, *J* = 14.2 Hz), 136.54, 135.32 (d, *J* = 3.3 Hz), 129.48, 127.52, 127.45, 126.86, 115.26, 115.09, 40.96, 35.15, 21.32. **HRMS (ESI):** Found m/z 320.1114. Calcd. for $C_{17}H_{19}FNO_2S$: (M+H) 320.1115.

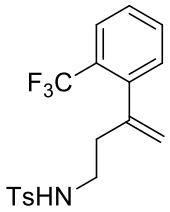
N-(3-(2,6-dichlorophenyl)but-3-enyl)-4-methylbenzenesulfonamide



Compound **3m** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2m** (38.9 mg, 0.15 mmol) forming a yellow gel (23.8 mg, 64% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.73 (d, *J* = 8.2 Hz, 2H), 7.32 – 7.25 (m, 4H), 7.16 – 7.11 (m, 1H), 5.36 (s, 1H), 5.08 (s, 1H), 4.68 (t, *J* = 5.9 Hz, 1H), 3.07 (dt, *J* = 6.4, 5.9 Hz, 2H), 2.53 (t, *J* = 6.4 Hz, 2H), 2.43 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.43, 140.99, 139.01, 137.02, 133.98, 129.73, 128.97,

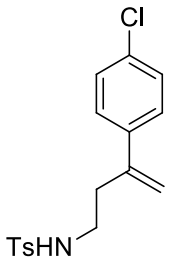
128.17, 127.13, 120.05, 40.82, 36.26, 21.56. **HRMS (ESI):** Found m/z 392.0245. Calcd. for $C_{17}H_{17}Cl_2NO_2SNa$: (M+Na) 392.0249.

4-methyl-N-(3-(2-(trifluoromethyl)phenyl)but-3-enyl)benzenesulfonamide



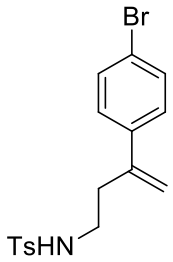
Compound **3n** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2n** (38.8 mg, 0.15 mmol) forming a yellow gel (18.1 mg, 49% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.73 (d, *J* = 8.3 Hz, 2H), 7.62 (d, *J* = 7.8 Hz, 1H), 7.43 (t, *J* = 7.5 Hz, 1H), 7.37 (t, *J* = 7.6 Hz, 1H), 7.30 (d, *J* = 8.0 Hz, 2H), 7.07 (d, *J* = 7.6 Hz, 1H), 5.18 (d, *J* = 0.8 Hz, 1H), 5.03 (s, 1H), 4.48 (br, 1H), 3.09 – 3.02 (m, 2H), 2.52 (t, *J* = 6.7 Hz, 2H), 2.43 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.50 (q, *J* = 7.4 Hz), 140.75, 136.82, 131.51, 130.29, 129.76, 127.88 (q, *J* = 29.9 Hz), 127.44, 127.13, 126.34 (q, *J* = 5.3 Hz), 124.43 (q, J=274.7 Hz), 117.85, 117.86, 40.69, 37.76, 21.55. **HRMS (ESI):** Found m/z 408.0640. Calcd. for $C_{18}H_{18}F_3NO_2SK$: (M+K) 408.0642.

N-(3-(4-chlorophenyl)but-3-enyl)-4-methylbenzenesulfonamide



Compound **3o** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2o** (33.7 mg, 0.15 mmol) forming a yellow gel (22.9 mg, 68% yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 7.65 (d, *J* = 7.9 Hz, 2H), 7.24 (d, *J* = 9.8 Hz, 4H), 7.18 (d, *J* = 8.4 Hz, 2H), 5.33 (s, 1H), 5.06 (s, 1H), 4.48 – 4.39 (m, 1H), 3.02 (dt, *J* = 6.5, 6.5 Hz, 2H), 2.64 (t, *J* = 6.7 Hz, 2H), 2.42 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.52, 143.27, 137.88, 136.68, 133.73, 129.68, 128.65, 127.34, 127.04, 115.73, 41.14, 35.14, 21.55. **HRMS (ESI):** Found m/z 374.0376. Calcd. for $C_{17}H_{18}ClNO_2SK$: (M+K) 374.0378.

N-(3-(4-bromophenyl)but-3-enyl)-4-methylbenzenesulfonamide



Compound **3p** was formed from diazetidine (18.3 mg, 0.05 mmol) and **2p** (0.15 mmol, 57 mg) forming a yellow gel (27.1 mg, 71% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 7.65 (d, *J* = 8.2 Hz, 2H), 7.39 (d, *J* = 8.5 Hz, 2H), 7.27 – 7.23 (m, 2H), 7.12 (d, *J* = 8.5 Hz, 2H), 5.34 (s, 1H), 5.06 (s, 1H), 4.47 – 4.40 (m, 1H), 3.05 – 2.99 (m, 2H), 2.64 (t, *J* = 6.7 Hz, 2H), 2.42 (s, 3H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 143.53, 143.33, 138.36, 136.67, 131.61, 129.69, 127.67, 127.04, 121.88, 115.81, 41.14, 35.09, 21.57. **HRMS (ESI):** Found m/z 380.0313. Calcd. for $C_{17}H_{19}BrNO_2S$: (M+H) 380.0314.

4.4 References

1.) Chintalapudi, V.; Galvin, E. A.; Greenaway, R. L.; Anderson, E. A. Combining Cycloisomerization with Trienamine Catalysis: a Regiochemically Flexible Enantio- and Diastereoselective Synthesis of Hexahydroindoles. *Chemical Communications* **2016**, 52 (4), 693.

2.) Dobbs, A. P.; Guesné, S. J. J.; Parker, R. J.; Skidmore, J.; Stephenson, R. A.; Hursthouse, M. B. A Detailed Investigation of the Aza-Prins Reaction. *Organic & Biomolecular Chemistry* **2010**, *8* (5), 1064.

3.) Qin, L.; Ren, X.; Lu, Y.; Li, Y.; Zhou, J. Intermolecular Mizoroki–Heck Reaction of Aliphatic Olefins with High Selectivity for Substitution at the Internal Position. *Angewandte Chemie International Edition* **2012** *51*, 5915-5919.

4.) Olofsson, K.; Larhed, M.; Hallberg, A. Highly Regioselective Palladium-Catalyzed Internal Arylation of Allyltrimethylsilane with Aryl Triflates. *The Journal of Organic Chemistry* **1998**, *63*, 5076-5079.

5.) Oneill, P. M.; Pugh, M.; Stachulski, A. V.; Ward, S. A.; Davies, J.; Park, B. K. Optimisation of the Allylsilane Approach to C-10 Deoxo Carba Analogues of Dihydroartemisinin: Synthesis and in Vitro Antimalarial Activity of New, Metabolically Stable C-10 Analogues. *Journal of the Chemical Society, Perkin Transactions 1* **2001**, No. 20, 2682.

6.) Guo, L.; Leiendecker, M.; Hsiao, C.-C.; Baumann, C.; Rueping, M. Nickel Catalyzed Dealkoxylative C_{sp2}–C_{sp3} Cross Coupling Reactions – Stereospecific Synthesis of Allylsilanes from Enol Ethers. *Chemical Communications* **2015**, *51* (10), 1937.

7.) Mizuta, S.; Galicia-López, O.; Engle, K. M.; Verhoog, S.; Wheelhouse, K.; Rassias, G.; Gouverneur, V. Trifluoromethylation of Allylsilanes under Copper Catalysis. *Chemistry - A European Journal* **2012**, *18* (28), 8583.

8.) Liu, J.; Chu, L.; Qing, F.-L. Electrophilic Trifluoromethylthiolation of Allylsilanes with Trifluoromethanesulfanamide. *Organic Letters* **2013**, *15* (4), 894.

9.) Saulnier, M. G.; Kadow, J. F.; Tun, M. M.; Langley, D. R.; Vyas, D. M. Chemoselective Synthesis of Allyltrimethylsilanes by Cross-Coupling of Vinyl Triflates with Tris((trimethylsilyl)methyl)aluminum Catalyzed by Palladium(0). *Journal of the American Chemical Society* **1989**, 111 (21), 8320.

CHAPTER V

EXPERIMENTAL PROCEDURES FOR RUTHENIUM COMPLEXES

5.1 General considerations:

5.1.1 General experimental methods:

Unless otherwise noted, all solvents were dried with sodium benzophenone and distilled before use. All reactions were set up under argon atmosphere, utilizing glassware that was flame-dried and cooled under vacuum. All non-aqueous manipulations were using standard Schlenk techniques. Reactions were monitored using thin-layer chromatography (TLC) on Silica Gel plates. Visualization of the developed plates was performed under UV light (254 nm) or $KMnO_4$ stain. Silica-gel flash column chromatography was performed on SiliCycle Inc. 40-63 μm silica gel.

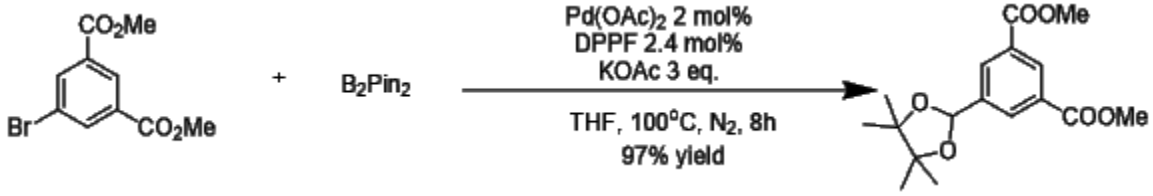
5.1.2 Materials:

Unless otherwise indicated, starting catalysts and materials were obtained from Sigma Aldrich, Oakwood, Strem, or Acros Co. Ltd. Moreover, commercially available reagents were used without additional purification.

5.1.3 Instrumentation:

All NMR spectra were run at 500 MHz or 300 MHz in $CDCl_3$ solution. ^{1}HNMR spectra were internally referenced to TMS. ^{13}CNMR spectra were internally referenced to the residual solvent signal. Data for ^{1}HNMR are reported as follows: chemical shift (δ ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m= multiplet, br = broad), coupling constants (*J*) were reported in Hz. High resolution mass spectra (HRMS) were recorded on Bruker MicrOTOF-QII mass instrument (ESI & EI). Gas Chromatograph Mass Spectrometry analysis were done on Shimdzu GCMS- QP2010 and ESI was the ionization method.

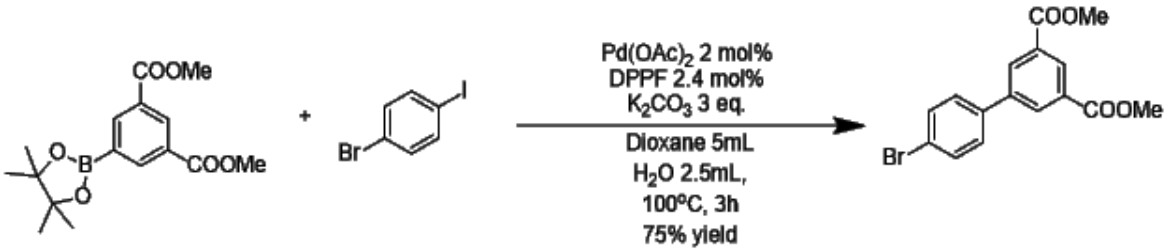
5.2 Synthesis of para substituted complexes



Scheme 5.1 Synthesis of dimethyl 5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl) isophthalate (**1**)[1]

Solid starting materials, aryl bromide (5.46 g, 20 mmol), B2Pin2 (5.33 g, 21 mmol), DPPF (266.0 mg 0.48 mmol), palladium acetate (90.0 mg, 0.4 mmol), and potassium acetate (5.88 g, 60 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, THF (40 mL) were then added through a septum and the reaction was stirred at 100°C overnight. The reaction was then diluted with hexane

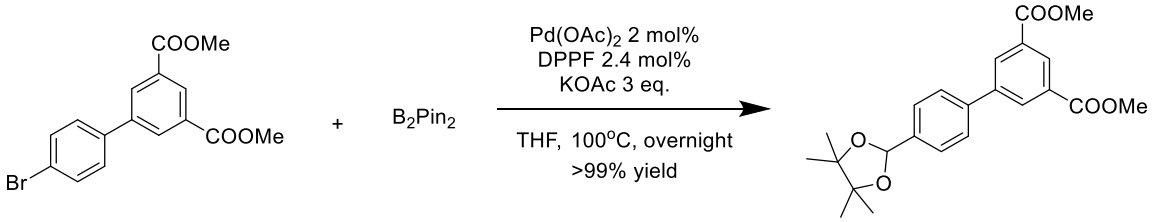
and run through a silica pad (pure ethyl acetate) to remove inorganic materials. Next, the mixture was run through a silica gel column (5:1 hexane:ethyl acetate) to yield a white solid. (6.2251 g, 97 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.77 (t, *J* = 1.8 Hz, 1H), 8.64 (d, *J* = 1.7 Hz, 2H), 3.95 (s, 6H), 1.37 (s, 12H).



Scheme 5.2 Synthesis of dimethyl 4'-bromo-[1,1'-biphenyl]-3,5-dicarboxylate (**2**)

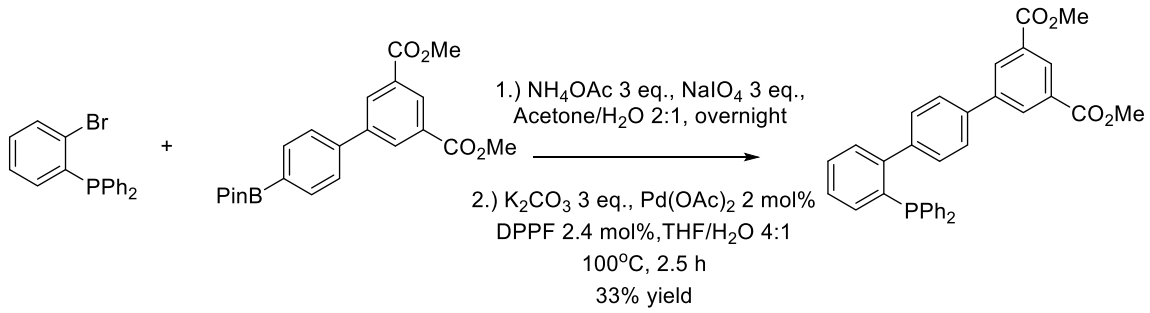
Solid starting materials, diester (1.0 g, 3.16 mmol), bromoiodobenzene (1.34 g, 4.74 mmol), palladium acetate (14.2 mg, 0.06 mmol), DPPF (42.1 mg, 0.076 mmol), potassium carbonate (1.31 g, 9.99 mmol were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, dioxane (5 mL), H_2O (2.5 mL) were then added through a septum and the reaction was stirred at 100°C for 3h. Dioxane was next evaporated out of the mixture and then the reaction was washed with water. The resulting aqueous phase was extracted with ethyl acetate (3x). The combined organic phases were then dried and evaporated and then separated using silica gel chromatography (hexane: ethyl acetate: DCM 8:1:1) to yield a solid product (829.3 mg, 75% yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 8.67 (t, *J* = 1.4 Hz, 1H), 8.42 (d, *J* = 1.4 Hz, 2H), 7.62 (d, *J* = 8.5 Hz, 2H), 7.53 (d, *J* = 8.6 Hz, 2H), 3.98 (s, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.07,

140.73, 137.93, 132.19, 132.03, 131.34, 129.64, 128.75, 122.68, 52.53. **HRMS (ESI):** Found m/z 370.9889. Calcd. for $C_{16}H_{13}BrO_4Na$: (M+Na) 370.9889



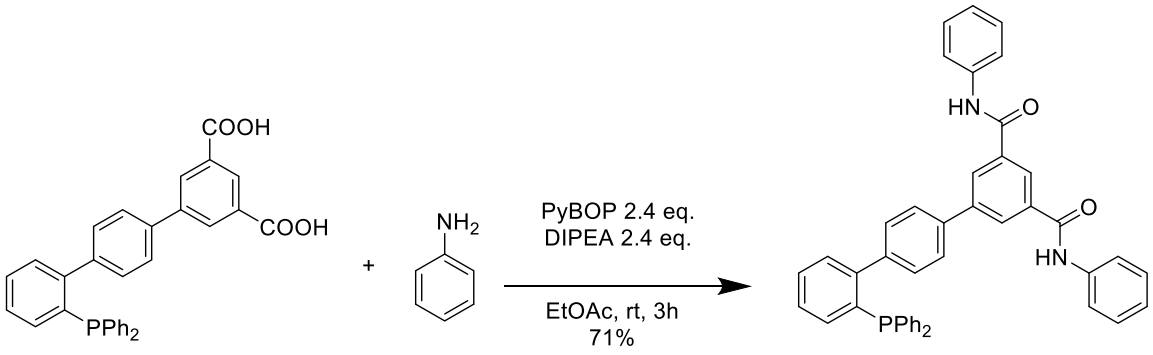
Scheme 5.3 Synthesis of dimethyl 4'-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-[1,1'-biphenyl]-3,5-dicarboxylate (**3**)

Solid starting materials, diester (1.16 g, 3.32 mmol), B_2Pin_2 (917 mg, 3.49 mmol), palladium acetate (15.5 mg, 0.066 mmol), DPPF (45.8 mg, 0.080 mmol), potassium carbonate (1.012 g, 9.96 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, THF (8 mL) were then added through a septum and the reaction was stirred at 100°C overnight. The inorganic media was next filtered out of the mixture by using a silica pad (ethyl acetate). The resultant solution was then evaporated and separated using silica gel chromatography (hexane: ethyl acetate 5:1) to yield a solid product (839.7 mg, 64 % yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 8.66, 8.48 (d, J = 1.5 Hz), 7.92 (d, J = 8.1 Hz), 7.67 (d, J = 8.2 Hz), 3.98, 1.38. **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.20, 141.72, 141.52, 135.48, 132.32, 131.19, 129.58, 126.41, 83.96, 83.49, 52.47, 25.03, 24.89. **HRMS (ESI):** Found m/z 419.32. Calcd. for $C_{22}H_{25}BO_6Na$: (M+Na) 419.1636.



Scheme 5.4 Synthesis of dimethyl 2''-(diphenylphosphaneyl)-[1,1':4',1''-terphenyl]-3,5-dicarboxylate (**4**)

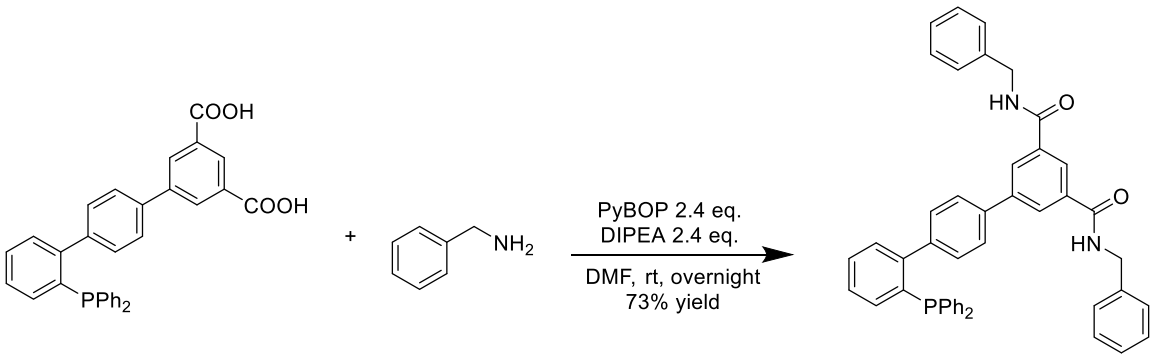
Solid starting materials, boronic acid (314 mg,1.0 mmol), phosphine (376 mg,1.1 mmol), K_2CO_3 (420 mg, 3.0 mmol), palladium tetrakis triphenylphosphine (23 mg, 0.02 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components dioxane (4 mL) and water (1 mL) were then added through a septum and the reaction was stirred at 100°C for 30 min. The reaction was then washed with water. The resulting aqueous phase was then extracted three times with ethyl acetate. The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography to yield a solid product (199.0mg, 38% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.65 (s, 1H), 8.48 (2H), 7.57 (d, J = 7.9 Hz, 2H), 7.43 (t, J = 7.4 Hz, 1H), 7.39 – 7.36 (m, 8H), 7.32, 7.27 – 7.22 (m, 5H), 7.11 – 7.07 (m, 1H), 3.98 (s, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.26, 147.48 (d, J=28.4 Hz), 141.78 (d=28.4 Hz), 141.57, 137.58 (d, J=19.9 Hz), 137.41, 135.89 (d, J= 14.3 Hz), 134.24, 133.92 (d, J=19.8 Hz), 132.21, 131.12, 130.42 (d, J=4.0 Hz), 130.08 (d, 4.9 Hz), 129.28, 128.81, 128.56, 128.43 (d, J=6.8 Hz), 127.61, 126.33, 52.45. **^{31}PNMR** (121 MHz, $CDCl_3$) δ -13.45. **HRMS (ESI):** Found m/z 565.1327. Calcd. for $C_{34}H_{27}O_4PCl$: (M+Cl) 565.1330



Scheme 5.5 Synthesis of 2"-(diphenylphosphaneyl)-N3, N5-diphenyl-[1,1':4',1"-terphenyl]-3,5-dicarboxamide (**5**)

Solid starting materials, phosphine (50 mg, 0.1 mmol), PyBOP (124.9 mg, 0.24 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, aniline (22 µL, 0.24 mmol), DIPEA (42 µL, 0.24 mmol), ethyl acetate (1 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then washed with aqueous ammonium chloride to quench the reaction and the aqueous phase was extracted with ethyl acetate (3x). The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (6:1:1 hexane:ethyl acetate:DCM) to yield a solid product (46.6. mg, 71 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.30 (s, 1H), 8.25 (s, 2H), 8.09 (s, 2H), 7.68 (d, *J* = 7.9 Hz, 3H), 7.57 (d, *J* = 7.5 Hz, 2H), 7.47 – 7.35 (m, 6H), 7.35 – 7.29 (m, 7H), 7.28 – 7.22 (m, 7H), 7.19 (t, *J* = 7.4 Hz, 2H), 7.12 – 7.08 (m, 1H). **^{13}CNMR** (126 MHz, Acetone) δ 165.62, 148.61 (d, 28.9 Hz), 142.70 (d, 6.0 Hz), 141.93, 140.29, 139.09, 138.64 (d, 12.9), 137.35, 137.32, 136.51 (d, J=15.4 Hz), 135.16, 134.50 (d, J=20.0 Hz), 131.39 (d, 4.1 Hz), 131.08 (d, J=4.9 Hz), 129.99, 129.55, 129.49, 129.42 (d, J=4.5 Hz), 128.60, 127.24,

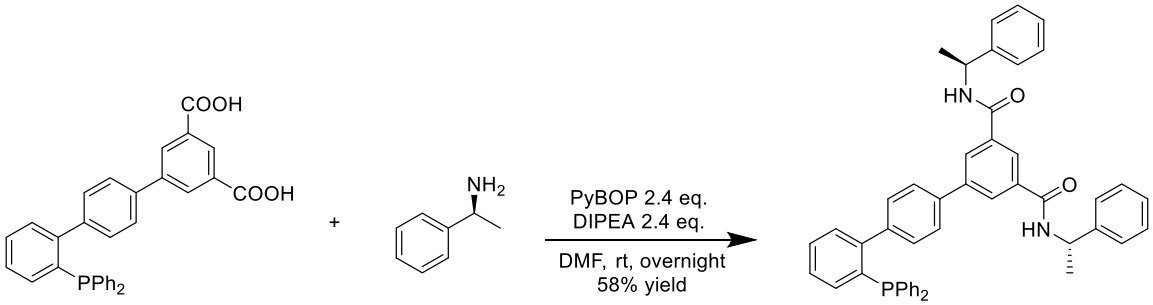
126.71, 124.75, 121.15, 121.09, 121.00. **^{31}PNMR** (202 MHz, Acetone) δ -14.02. **HRMS (ESI):** Found m/z 651.2190. Calcd. for $C_{44}H_{32}N_2O_2P$: (M-H) 651.2196



Scheme 5.6 Synthesis of N3,N5-dibenzyl-2"-(diphenylphosphaneyl)-[1,1':4',1"-terphenyl]-3,5-dicarboxamide (**6**)

Solid starting materials, phosphine (50 mg, 0.1 mmol), PyBOP (124.9 mg, 0.24 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, amine (26 µL, 0.24 mmol), DIPEA (42 µL, 0.24 mmol), ethyl acetate (1 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then washed with aqueous ammonium chloride to quench the reaction and the aqueous phase was extracted with ethyl acetate (3x). The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (2:1 hexane:ethyl acetate) to yield a solid product (49.4 mg, 73 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.15 (d, *J* = 4.3 Hz, 2H), 7.48 (d, *J* = 6.8 Hz, 2H), 7.44 – 7.37 (m, 2H), 7.36 – 7.18 (m, 24H), 7.13 – 7.06 (m, 1H), 6.87 – 6.77 (m, 2H), 4.60 (s, 4H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.54, 147.44 (d, J=28.6 Hz), 141.83, 141.71 (d, J=6.3 Hz), 138.13, 137.82, 137.43 (d, J=11.5 Hz), 135.80 (d, J=14.2 Hz), 135.13, 134.26,

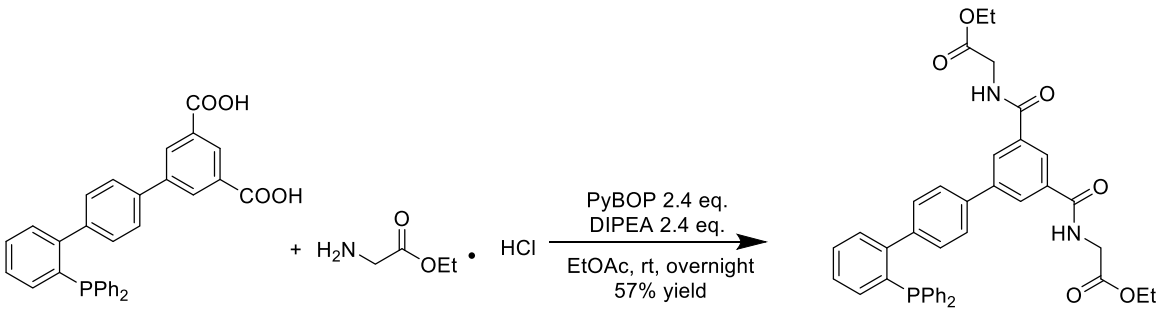
133.85 (d, J=19.7 Hz), 131.65, 130.37 (d, J=3.9 Hz), 130.08 (d, J=5.0 Hz), 128.82, 128.73, 128.70, 128.63, 128.54, 128.42 (d, J=6.8 Hz), 127.87, 127.60, 127.42, 126.33, 125.99, 123.94, 44.21, 29.25. **HRMS (ESI):** Found m/z 659.2504. Calcd. for $C_{46}H_{36}N_2O_2P$: (M-H) 679.2509



Scheme 5.7 Synthesis of 2"-(diphenylphosphaneyl)-N3,N5-bis(1-phenylethyl)-[1,1':4',1"-terphenyl]-3,5-dicarboxamide (**7**)

Solid starting materials, phosphine (100 mg, 0.2 mmol), PyBOP (250 mg, 0.48 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, amine (60 µL, 0.48 mmol), DIPEA (90 µL, 0.48 mmol), dimethyl formamide (2 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then diluted with DCM (15 mL) washed with water (4 x 15 mL). The organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (2:1 hexane:ethyl acetate) to yield a solid product (82mg, 58 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.10 (s, 1H), 8.08 (s, 2H), 7.45 (d, *J* = 7.7 Hz, 2H), 7.41 (s, 1H), 7.35 (d, *J* = 7.3 Hz, 5H), 7.30 (t, *J* = 6.8 Hz, 10H), 7.26 – 7.19 (m, 9H), 7.10 – 7.06 (m, 1H), 6.72 (d, *J* = 7.6 Hz, 2H), 5.34 – 5.26 (m, 2H), 1.57 (d, *J* = 6.8 Hz,

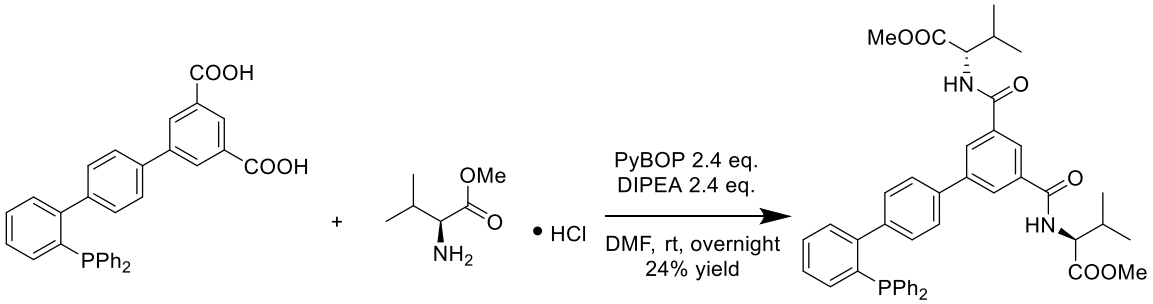
6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 165.77, 147.47 (d, J=28.7 Hz), 142.87, 141.84, 141.71 (d, J=6.2 Hz), 137.91, 137.45 (d, J=11.4 Hz), 135.75 (d, J=14.1 Hz), 135.32, 134.27, 133.86 (d, J=19.8 Hz), 130.37 (d, J=3.8 Hz), 130.07 (d, J=4.9 Hz), 128.82, 128.73, 128.55, 128.42 (d, J=6.8 Hz), 127.61, 127.49, 126.36, 126.31, 126.26, 123.92, 77.28, 77.03, 76.77, 49.57, 21.70 **^{31}PNMR** (202 MHz, $CDCl_3$) δ -13.57. **HRMS (ESI):** Found m/z 708.2900. Calcd. for $C_{48}H_{41}N_2O_2P$: (M) 708.2900



Scheme 5.8 Synthesis of diethyl 2,2'-((2"-(diphenylphosphaneyl)-[1,1':4',1"-terphenyl]-3,5-dicarbonyl)bis(azanediyl))diacetate (**8**)

Solid starting materials, phosphine (200 mg, 0.4 mmol), PyBOP (500 mg, 0.96 mmol) and glycine ester (134.4 mg, 0.96 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, DIPEA (180 µL, 0.96 mmol), DMF (4 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then diluted with DCM (50 mL) washed with water (6 x 50 mL). The organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography to yield a solid product (154.5 mg, 57 % yield).**^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.15 (s, 1H), 8.09 (d, *J* = 1.3 Hz, 2H),

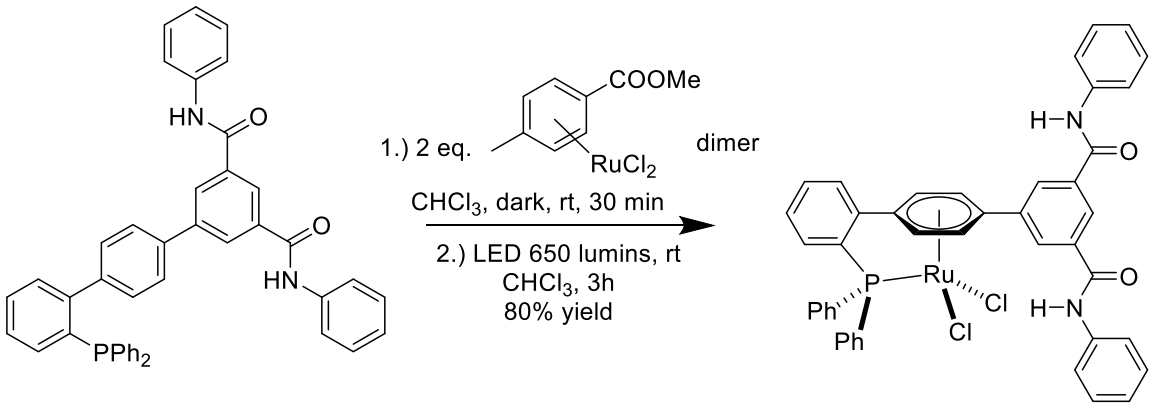
7.45 – 7.39 (m, 3H), 7.37 – 7.32 (m, 2H), 7.32 – 7.27 (m, 6H), 7.25 – 7.20 (m, 6H), 7.09 (dd, *J* = 7.3, 3.7 Hz, 1H), 4.29 – 4.21 (m, 8H), 1.31 (t, *J* = 7.1 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 170.10, 166.98, 166.85, 147.56 (d, J=28.5 Hz), 141.60 (d, J=8.3 Hz), 140.26, 137.86, 137.69, 137.48 (d, J=11.5 Hz), 135.83 (d, J=14.1 Hz), 134.56, 134.44, 134.41, 134.24, 134.05, 133.87 (d, J=19.7 Hz), 133.38, 132.55, 132.02, 131.92, 131.69, 131.62, 130.42, 130.34 (d, J=3.7 Hz), 130.11 (d, J=5.0 Hz), 129.03, 128.83 (d, J=9.1 Hz), 128.54, 128.46, 128.41, 128.31, 127.55, 126.86, 126.77, 126.32, 125.95, 124.48, 124.14, 77.28, 77.03, 76.77, 61.62, 61.60, 61.55, 61.53, 41.97, 29.70, 14.17. **^{31}PNMR** (202 MHz, $CDCl_3$) δ -13.69. **HRMS (ESI):** Found m/z 671.2306. Calcd. for $C_{40}H_{36}N_2O_6P$: (M-H) 671.2306



Scheme 5.9 Synthesis of dimethyl 2,2'-((2"-(diphenylphosphaneyl)-[1,1':4',1"-terphenyl]-3,5-dicarbonyl)bis(azanediyl))bis(3-methylbutanoate) (**9**)

Solid starting materials, phosphine (58.3 mg, 0.12 mmol), PyBOP (143.5 mg, 0.29 mmol) and valine ester (46.7 mg, 0.29 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, DIPEA (51.6 µL, 0.29 mmol), DMF (1 mL) were then added through a septum and the reaction was stirred at room temperature

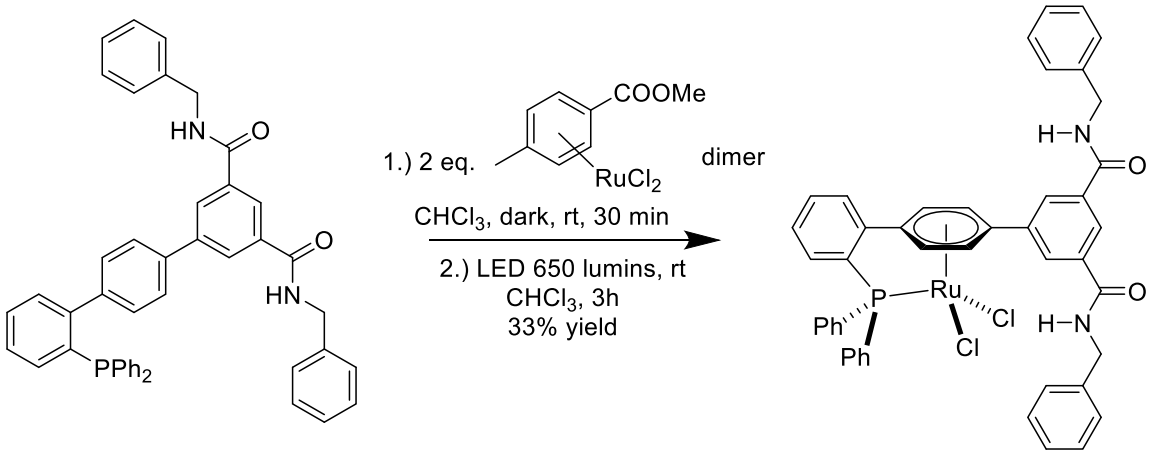
overnight. The reaction was then diluted with DCM (15 mL) washed with water (6 x 15 mL). The organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (2:1 hexane:ethyl acetate) to yield a solid product (21.1 mg, 24 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.20 (s, 1H), 8.17 (s, 2H), 7.55 (d, *J* = 8.1 Hz, 2H), 7.43 (t, *J* = 7.4 Hz, 1H), 7.39 – 7.36 (m, 1H), 7.36 – 7.28 (m, 9H), 7.28 – 7.22 (m, 6H), 7.10 (dd, *J* = 7.5, 3.7 Hz, 1H), 6.75 (d, *J* = 8.6 Hz, 2H), 4.82 (dd, *J* = 8.6, 5.1 Hz, 2H), 3.80 (s, 6H), 1.03 (dd, *J* = 9.9, 6.9 Hz, 12H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 172.38, 166.40, 147.45 (d, J=28.8 Hz), 142.19, 141.88 (d, J=6.1 Hz), 137.89, 137.42 (d, J=11.2), 135.90 (d, J=14.1 Hz), 135.16, 134.22, 133.93 (d, J=19.8 Hz), 130.45 (d, J=3.9 Hz), 130.09 (d, J=4.9 Hz), 128.87, 128.81, 128.58, 128.44 (d, J=6.9 Hz), 127.63, 126.49, 124.21, 57.73, 52.35, 31.66, 19.07, 18.11. **^{31}PNMR** (202 MHz, $CDCl_3$) δ -13.49. **HRMS (ESI):** Found m/z727.2932. Calcd. for $C_{44}H_{44}N_2O_6P$: (M-H) 727.2932



Scheme 5.10 Synthesis of aniline amide Ru complex (**10**)

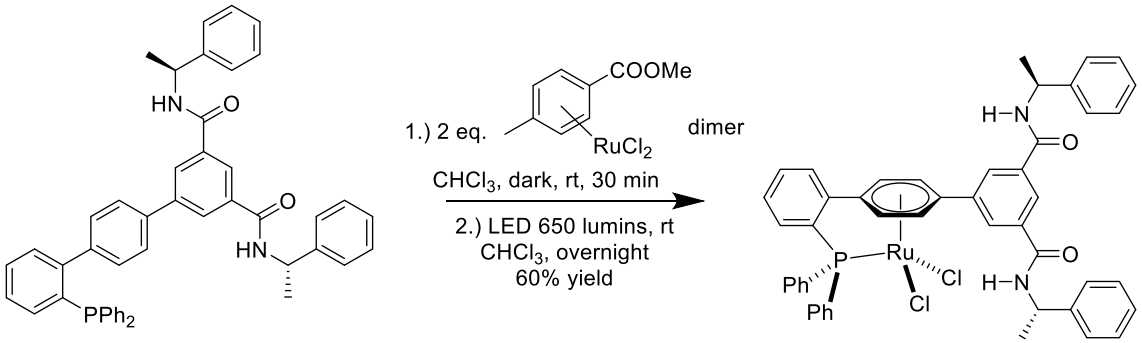
Phosphine ligand (38.5 mg, 0.059 mmol), Ru starting material (75.5 mg, 0.12 mmol), and $CHCl_3$ (3 mL) were added to a small glass vial and stirred under dark conditions for 30

min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) for 3h. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (38.7 mg, 80 % yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 9.82 (s, 1H), 8.58 (s, 2H), 8.46 (s, 1H), 7.73 (d, *J* = 7.4 Hz, 5H), 7.66 – 7.45 (m, 8H), 7.45 – 7.28 (m, 10H), 7.17 – 7.06 (m, 2H), 6.45 (d, *J* = 5.7 Hz, 2H), 5.42 (d, *J* = 5.8 Hz, 2H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 165.56, 144.41, 144.02, 143.47 (d, 22.1 Hz), 138.36, 138.27, 136.67, 136.63, 135.63, 133.80 (d, J=9.9 Hz), 133.18, 131.67, 131.11 (d, J=2.8 Hz), 130.32 (d, J=6.5 Hz), 130.15, 129.65, 129.25, 128.99, 128.93, 128.31 (d, J=11.1 Hz), 127.54 (d, J=12.6 Hz), 127.34, 124.61, 120.84, 120.74, 109.75, 104.60 (d, 15.4 Hz), 96.94, 80.66, 29.73. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.91. **HRMS (ESI):** Found m/z 789.0996. Calcd. for $C_{44}H_{33}ClN_2O_2PRu$: (M-Cl) 789.1006



Scheme 5.11 Synthesis of benzylamine Ru complex (**11**)

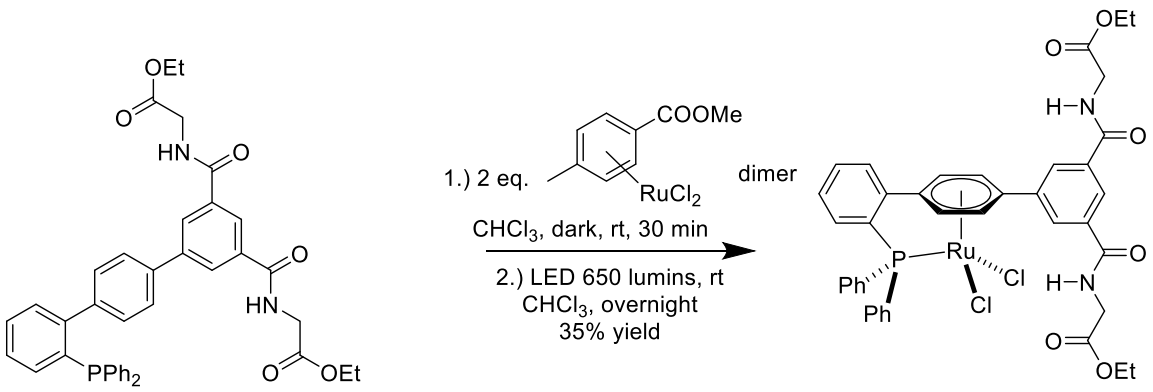
Phosphine ligand (39 mg, 0.057 mmol), Ru starting material (73.8 mg, 0.11 mmol), and $CHCl_3$ (3 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) for 3h. This mixture was then separated by silica gel chromatography (1:1:0.05 $CHCl_3$:EtOAc:MeOH) to yield a yellow product (15.8 mg, 33 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.48 (d, *J* = 1.9 Hz, 2H), 8.32 (d, *J* = 1.7 Hz, 1H), 7.73 (dd, *J* = 7.5, 2.5 Hz, 1H), 7.66 – 7.62 (m, 1H), 7.62 – 7.58 (m, 2H), 7.52 (ddd, *J* = 11.5, 5.5, 3.6 Hz, 4H), 7.48 – 7.42 (m, 2H), 7.39 (dd, *J* = 10.4, 7.8 Hz, 8H), 7.35 – 7.28 (m, 6H), 7.28 – 7.22 (m, 2H), 6.41 (d, *J* = 5.8 Hz, 2H), 5.43 (d, *J* = 5.7 Hz, 2H), 4.62 (s, 4H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 167.08, 144.49, 144.09, 143.59 (d, J=22.3 Hz), 138.27, 135.93, 135.90, 135.51, 133.81 (d, J=9.9 Hz), 133.19, 131.67 (d, J=2.2 Hz), 131.10 (d, J=2.9 Hz), 130.30 (d, J=6.8 Hz), 130.05, 129.81, 129.41, 128.61, 128.31 (d, J=11.0 Hz), 127.83, 127.64, 127.54, 127.32, 126.95, 109.39 (d, J=3.4 Hz), 105.47 (d, J=15.1 Hz), 96.64, 81.00, 44.18, 44.05, 29.75. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.76. **HRMS (ESI):** Found m/z 817.1323. Calcd. for $C_{46}H_{37}ClN_2O_2PRu$: (M-Cl) 817.1319



Scheme 5.12 Synthesis of phenylethylamide Ru complex (12)

Phosphine ligand (50 mg, 0.070 mmol), Ru starting material (80.9 mg, 0.141 mmol), and $CHCl_3$ (5 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) overnight. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (37.2 mg, 60 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.64 (s,2H), 8.25 (s, 1H), 7.71 (1H), 7.69 – 7.51 (m, 8H), 7.51 – 7.35 (m, 10H), 7.35 – 7.18 (m, 9H), 7.05 (d, J = 7.5 Hz, 2H), 6.37 (d, J = 5.8 Hz, 1H), 6.29 (d, J = 5.9 Hz, 1H), 5.37 (dd, J = 8.2, 6.1 Hz, 2H), 5.32 – 5.21 (m, 2H), 1.58 (d, J = 6.9 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 165.34, 144.70, 144.31, 143.59 (d, J=22.1 Hz), 143.20, 135.87, 135.65, 133.90, 133.84 (dd, J=9.8, 5.5 Hz), 133.78, 133.14, 131.51, 131.00 (d, J=2.8 Hz), 130.18, 130.08, 129.76, 129.68, 129.36, 128.79, 128.65, 128.43-127.97 (m), 127.56, 127.46, 127.26, 126.30, 126.14, 108.92 (d, J=3.1 Hz), 105.04 (d, J=14.1 Hz), 97.23, 96.53, 81.07 (d, J=14.0 Hz),

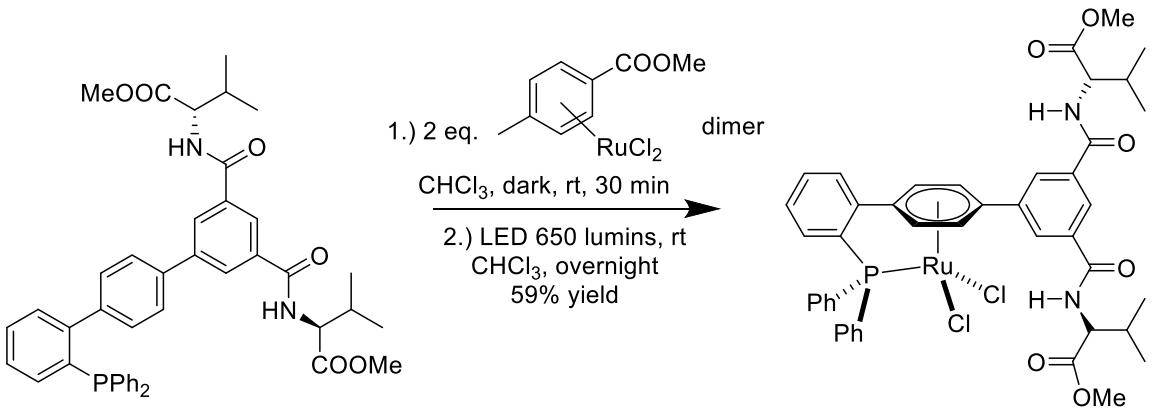
49.85, 22.22. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.91. **HRMS (ESI):** Found m/z 845.1637. Calcd. for $C_{48}H_{41}Cl_1N_2O_2PRu$: (M-Cl) 845.1632



Scheme 5.13 Synthesis of glycine Ru complex (**13**)

Phosphine ligand (50 mg, 0.074 mmol), Ru starting material (95.7 mg, 0.15 mmol), and $CHCl_3$ (5 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) overnight. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (22 mg, 35 % yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 8.53 (s, 2H), 8.33 (s, 1H), 7.73 (d, J = 5.0 Hz, 1H), 7.69 – 7.48 (m, 9H), 7.48 – 7.31 (m, 6H), 6.46 (d, J = 5.2 Hz, 2H), 5.41 – 5.33 (m, 2H), 4.19 (m, 8H), 1.30 – 1.20 (m, 6H) **^{13}CNMR** (126 MHz, $CDCl_3$) δ 169.85, 169.83, 167.18, 167.12, 144.49, 144.09, 143.63 (d, J=22.0 Hz), 135.57, 135.23 (d, J=3.8 Hz), 133.81 (d, J=9.8 Hz), 133.12, 131.61, 131.03 (d, J=2.9 Hz), 130.32, 130.22 (d, J=6.6 Hz), 129.86, 129.46, 128.27 (d, J=10.9 Hz), 127.66, 127.56, 127.16, 109.29 (d, J=3.0 Hz), 105.24 (d,

J=15.1 Hz), 96.70 (d, J=2.6 Hz), 81.00, 61.42, 42.09, 41.98, 14.18. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 54.08. **HRMS (ESI):** Found m/z 809.1116. Calcd. for $C_{40}H_{37}Cl_1N_2O_6PRu$: (M-Cl) 809.1116

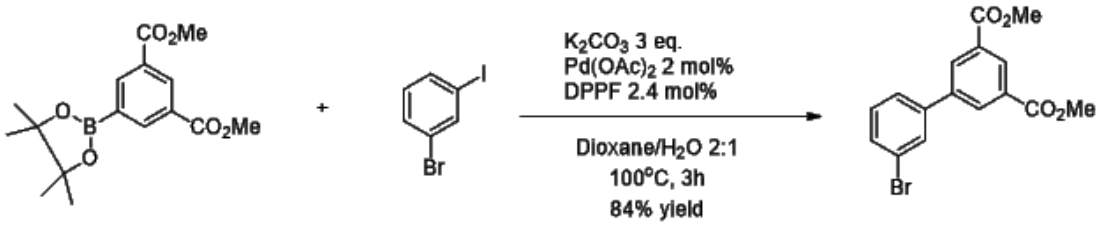


Scheme 5.14 Synthesis of Valine Ru Complex (**14**)

Phosphine ligand (10 mg, 0.014 mmol), Ru starting material (10 mg, 0.014 mmol), and $CHCl_3$ (1 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (2:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) overnight. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (7.4 mg, 59 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.55 (s, 2H), 8.32 (s, 1H), 7.84 (d, *J* = 8.4 Hz, 1H), 7.73 (d, *J* = 7.7 Hz, 1H), 7.64 (t, *J* = 7.0 Hz, 1H), 7.61 – 7.48 (m, 6H), 7.48 – 7.43 (m, 2H), 7.43 – 7.36 (m, 3H), 6.47 – 6.41 (m, 2H), 5.40 (d, *J* = 5.8 Hz, 1H), 4.70 – 4.63 (m, 2H), 3.77 (s, 6H), 1.04 (td, *J* = 6.9, 1.5 Hz, 12H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 172.32, 167.16, 144.59, 143.43, 135.59, 133.88, 133.82 (dd, J=9.6, 5.7 Hz), 133.81, 133.76, 133.22, 131.58, 131.02 (d, J=4.6 Hz), 130.29, 128.31, 128.26 (dd, 11.2, 2.7 Hz), 128.22, 128.20,

127.49, 127.39, 126.84, 97.61, 96.75, 80.39, 58.66, 58.56, 52.19, 31.04, 19.20, 18.45. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.33. **HRMS (ESI):** Found m/z 865.1744. Calcd. for $C_{44}H_{45}ClN_2O_6PRu$: (M-Cl) 865.1742

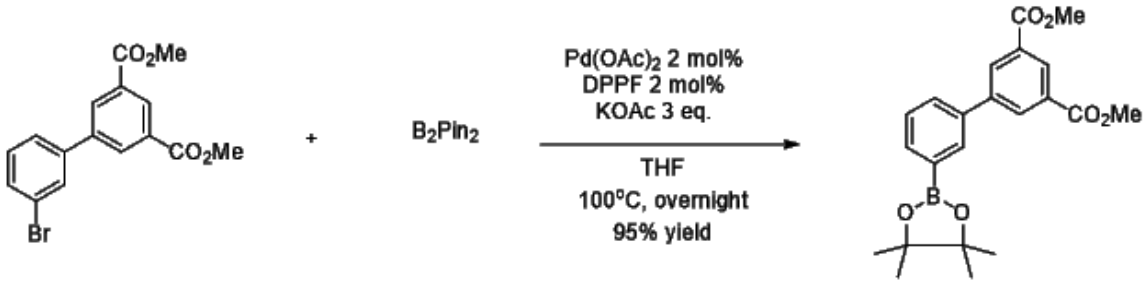
5.3 Synthesis of meta-substituted complexes



Scheme 5.15 Synthesis of dimethyl 3'-bromo-[1,1'-biphenyl]-3,5-dicarboxylate (**15**)

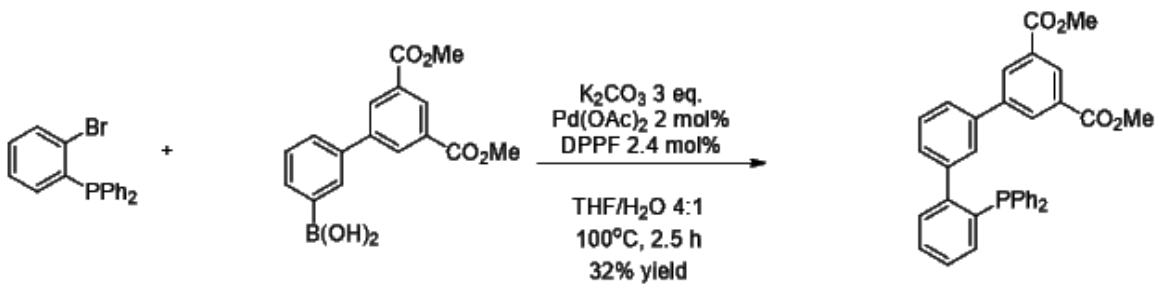
Solid starting materials, diester (1.0 g, 3.16 mmol), 1,3-bromoiodobenzene (600 µL, 4.74 mmol), palladium acetate (14.2 mg, 0.06 mmol), DPPF (42.1 mg, 0.076 mmol), potassium carbonate (1.34 g, 9.48 mmol were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, dioxane (5 mL), H_2O (2.5 mL) were then added through a septum and the reaction was stirred at 100°C for 3h. Dioxane was next evaporated out of the mixture and then the reaction was washed with water. The resulting aqueous phase was extracted with ethyl acetate (3x). The combined organic phases were then dried and evaporated and then separated using silica gel chromatography (hexane: ethyl acetate: DCM 8:1:1) to yield a white solid product (941.6 mg, 85 % yield). **^{1}HNMR** (300 MHz, $CDCl_3$) δ 8.68 (t, J = 1.5 Hz, 1H), 8.42 (d, J = 1.5 Hz, 2H), 7.80 (t, J = 1.7 Hz, 1H), 7.62 – 7.52 (m, 2H), 7.36 (t, J = 7.9 Hz, 1H), 3.99 (s, 6H). **^{13}CNMR** (126 MHz,

$CDCl_3$) δ 166.04, 141.12, 140.45, 132.23, 131.36, 131.22, 130.55, 130.24, 129.89, 125.84, 123.17, 52.54. **HRMS (ESI):** Found m/z 349.0070. Calcd. for $C_{16}H_{14}BrO_4$: (M+H) 349.0070



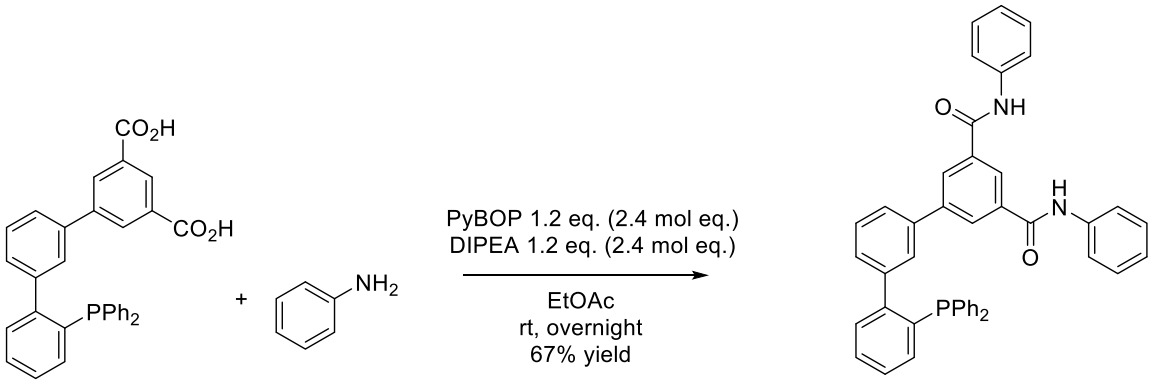
Scheme 5.16 Synthesis of dimethyl 3'-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-[1,1'-biphenyl]-3,5-dicarboxylate (**16**)

Solid starting materials, diester (1. 2 g, 3.44 mmol), B_2Pin_2 (917 mg, 3.61 mmol), palladium acetate (15.5 mg, 0.066 mmol), DPPF (45.8 mg, 0.080 mmol), potassium carbonate (1.012 g, 9.96 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, THF (8 mL) were then added through a septum and the reaction was stirred at 100°C overnight. The inorganic media was next filtered out of the mixture by using a silica pad (ethyl acetate). The resultant solution was then evaporated and separated using silica gel chromatography (hexane: ethyl acetate 5:1) to yield a solid product (1.299 g, 95 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.65 (s, 1H), 8.48 (s, 2H), 8.08 (s, 1H), 7.85 (d, J = 7.3 Hz, 1H), 7.74 (d, J = 7.7 Hz, 1H), 7.49 (t, J = 7.5 Hz, 1H), 3.98 (s, 6H), 1.38 (s, 12H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.30, 142.02, 138.44, 134.64, 133.42, 132.45, 131.08, 130.06, 129.28, 128.42, 84.04, 52.44, 24.90. **HRMS (ESI):** Found m/z 397.1817. Calcd. for $C_{22}H_{26}BO_6$: (M+H) 397.1817



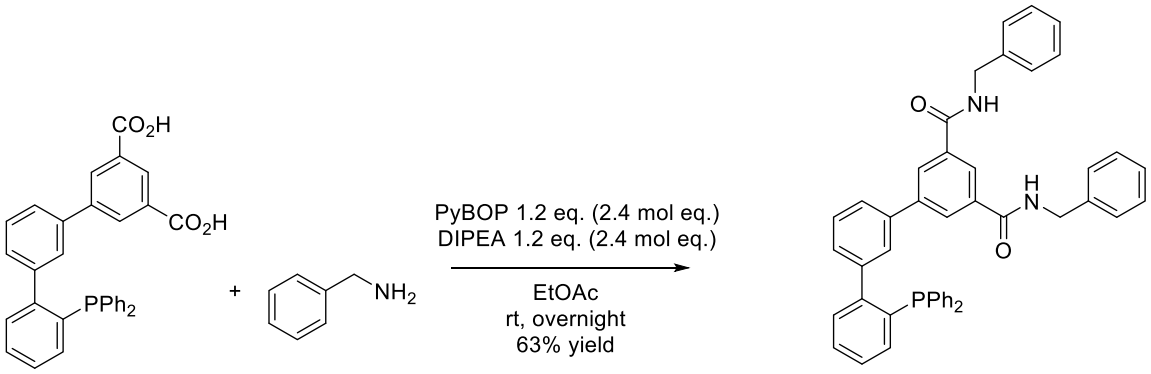
Scheme 5.17 Synthesis of dimethyl 2''-(diphenylphosphaneyl)-[1,1':3',1''-terphenyl]-3,5-dicarboxylate (**17**)

Solid starting materials, phosphine (376 mg, 110 mmol), boronic acid (314 mg, 1.0 mmol), potassium carbonate (420 mg, 3 mmol), palladium acetate (4.5 mg, 0.02 mmol), DPPF (13 mg, 0.024 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, THF (4 mL), H_2O (1 mL) were then added through a septum and the reaction was stirred at 100°C for 2.5h. The reaction was then washed with water. The resulting aqueous phase was then extracted three times with ethyl acetate. The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (10:1 hexane: ethyl acetate) to yield a solid product (170.8 mg, 32 % yield). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.63 (d, *J* = 1.6 Hz, 1H), 8.30 (d, *J* = 1.6 Hz, 2H), 7.56 (d, *J* = 7.8 Hz, 1H), 7.46 – 7.33 (m, 5H), 7.34 – 7.19 (m, 11H), 7.07 (dd, *J* = 7.9, 3.8 Hz, 1H), 3.98 (d, *J* = 1.3 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.24, 147.35 (d, J=27.1 Hz), 142.37 (d, J=5.7 Hz), 141.72, 138.24, 137.17 (d, J= 12.6 Hz), 134.05 (d, J=20.2 Hz), 133.80, 132.27, 131.01, 130.03 (d, J=4.1 Hz), 129.51 (d, J=4.0 Hz), 129.27, 129.03, 128.80 (d, J=3.4 Hz), 128.71, 128.58, 128.41, 128.35, 128.27, 127.61, 125.84, 52.41, 29.71. **^{31}P NMR** (121 MHz, $CDCl_3$) δ -12.57. **HRMS (ESI):** Found m/z 529.1563. Calcd. for $C_{34}H_{26}O_4P$: (M-H) 529.1563



Scheme 5.18 Synthesis of 2''-(diphenylphosphaneyl)-N3,N5-diphenyl-[1,1':3',1''-terphenyl]-3,5-dicarboxamide (**18**)

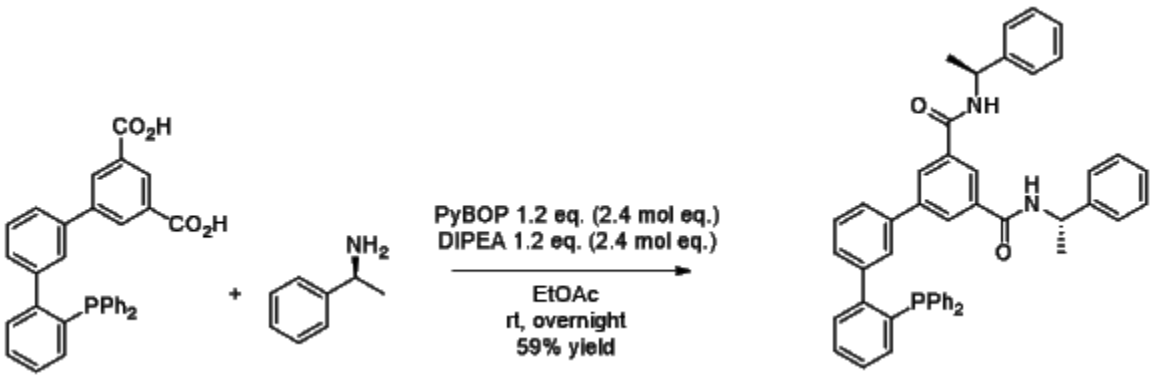
Solid starting materials, phosphine (50 mg, 0.10 mmol), PyBOP (124.9 mg, 0.24 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, amine (22 µL, 0.24 mmol), DIPEA (42 µL, 0.24 mmol), EtOAc (1 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then washed with water and extracted with ethyl acetate (3x). The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (6:1:1 hexane: ethyl acetate:DCM) to yield a solid white product (43.9 mg, 67 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.19 (s, 2H), 8.16 (s, 1H), 7.95 (s, 2H), 7.65 (d, *J* = 8.0 Hz, 4H), 7.50 (d, *J* = 7.6 Hz, 1H), 7.43 – 7.32 (m, 8H), 7.32 – 7.13 (m, 14H), 7.06 (dd, *J* = 7.6, 3.8 Hz, 1H). **^{13}CNMR** (126 MHz, Acetone) δ 165.08, 147.28 (d, J=27.9 Hz), 142.47 (d, J=5.9 Hz), 142.24, 137.92, 137.67, 137.24 (d, J=10.9 Hz), 136.01, 135.89 (d, J=14.2 Hz), 133.89 (d, J=20.0 Hz), 130.07 (d, J=4.8 Hz), 129.65 (d, J=3.3 Hz), 129.13, 128.86, 128.71, 128.68, 128.64, 128.61, 128.56, 128.42 (d, J=6.9 Hz), 127.68, 125.86, 124.88, 123.99, 120.39. **^{31}PNMR** (202 MHz, Acetone) δ -13.34. **HRMS (ESI):** Found m/z 651.2196. Calcd. for $C_{44}H_{32}N_2O_2P$: (M-H) 651.2196.



Scheme 5.19 Synthesis of N3,N5-dibenzyl-2"-(diphenylphosphaneyl)-[1,1':3',1"-terphenyl]-3,5-dicarboxamide (**19**)

Solid starting materials, phosphine (50 mg, 0.10 mmol), PyBOP (124.9 mg, 0.24 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, amine (26 µL, 0.24 mmol), DIPEA (42 µL, 0.24 mmol), EtOAc (1 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then washed with water and extracted with ethyl acetate (3x). The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (2:1 hexane: ethyl acetate) to yield a solid white product (43.1 mg, 59 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.07 (s, 1H), 7.87 (s, 2H), 7.43 (d, *J* = 7.6 Hz, 1H), 7.32 (d, *J* = 7.5 Hz, 2H), 7.27 (d, *J* = 5.6 Hz, 12H), 7.23 – 7.17 (m, 6H), 7.17 – 7.07 (m, 11 H), 6.98 (dd, *J* = 7.3, 3.4 Hz, 1H), 6.52 (t, *J* = 5.0 Hz, 2H), 4.56 (d, *J* = 5.5 Hz, 4H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 166.37, 147.30 (d, J=27.6 Hz), 142.33 (d, J=5.9 Hz), 142.13, 138.36, 137.80, 137.24 (d, J=11.4 Hz), 136.15, 136.03, 135.17, 134.71, 133.99 (d, J=20.0 Hz), 133.86, 131.05, 130.02 (d, J=4.5 Hz), 129.51 (d, J=3.7 Hz), 128.83, 128.76, 128.72, 128.63, 128.54, 128.39, 128.36 (d, J=7.0 Hz), 128.16, 128.00, 127.94,

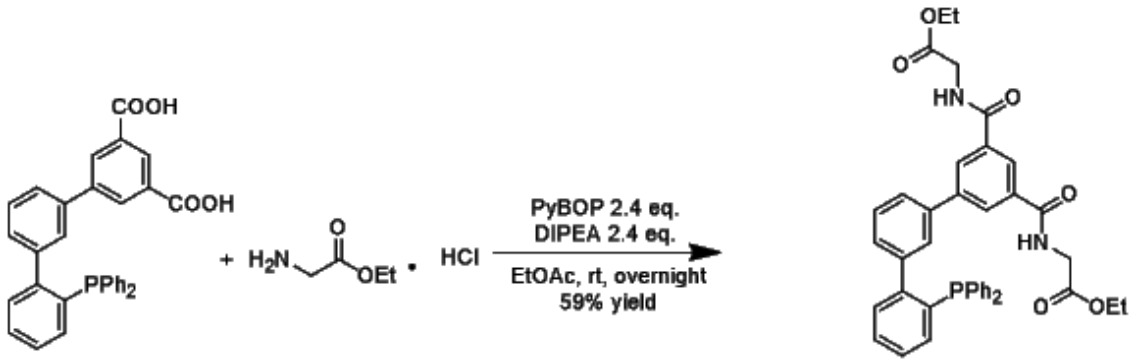
127.75, 127.64, 127.40, 125.97, 124.12, 44.32. **^{31}PNMR** (202 MHz, $CDCl_3$) δ -12.73. **HRMS (ESI):** Found m/z679.2499. Calcd. for $C_{46}H_{36}N_2O_2P$: (M-H) 679.2509.



Scheme 5.20 Synthesis of 2"-(diphenylphosphaneyl)-N3,N5-bis(1-phenylethyl)-[1,1':3',1"-terphenyl]-3,5-dicarboxamide (**20**)

Solid starting materials, phosphine (50 mg, 0.10 mmol), PyBOP (124.9 mg, 0.24 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, amine (30 µL, 0.24 mmol), DIPEA (42 µL, 0.24 mmol), EtOAc (1 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then washed with water and extracted with ethyl acetate (3x). The combined organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography (2:1 hexane: ethyl acetate) to yield a solid product (42.1 mg, 59 % yield) **^{1}HNMR** (300 MHz, $CDCl_3$) δ 8.12 (s, 1H), 7.94 (s, 2H), 7.46 (d, J = 7.4 Hz, 2H), 7.42 – 7.12 (m, 25H), 7.06 (dd, J = 7.2, 3.6 Hz, 1H), 6.60 (d, J = 7.6 Hz, 2H), 5.41 – 5.24 (quint, 2.11), 1.58 (d, J = 6.8 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 165.67, 147.23 (d, J=27.3 Hz), 142.84, 142.29 (d, J=5.9 Hz), 142.09, 138.49, 137.20, 137.13 (dd,

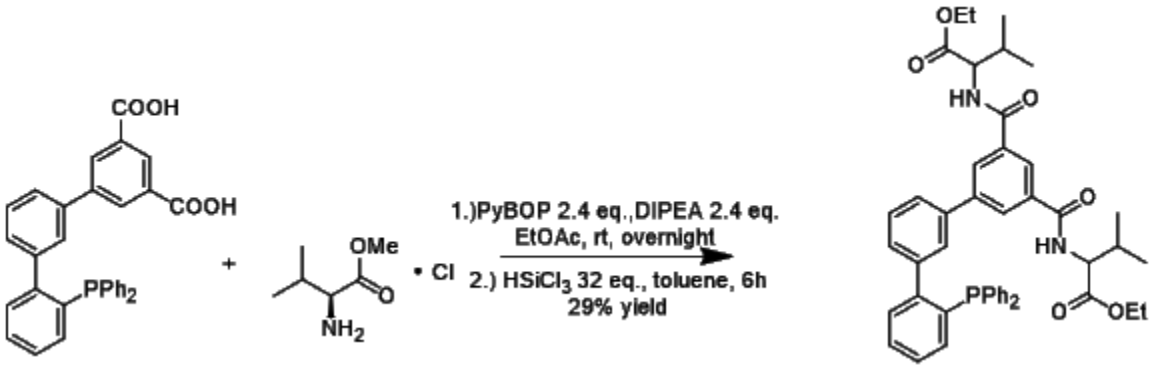
J=11.3 Hz), 137.06, 136.16 (d, J=14.7 Hz), 135.27, 134.05, 133.90, 133.86, 130.04 (d, J=4.6 Hz), 129.50 (d, J=3.8 Hz), 128.75, 128.57 (d, J=2.8 Hz), 128.39, 128.34, 128.30, 127.61, 127.52, 126.27, 125.95, 124.01, 49.54, 21.69. **^{31}PNMR** (121 MHz, $CDCl_3$) δ -12.48. **HRMS (ESI):** Found m/z 707.2820. Calcd. for $C_{48}H_{40}N_2O_2P$: (M-H) 707.2822



Scheme 5.21 Synthesis of diethyl 2,2'-((2"-(diphenylphosphaneyl)-[1,1':3',1"-terphenyl]-3,5-dicarbonyl)bis(azanediyl))diacetate (**21**)

Solid starting materials, phosphine (296.3 mg, 0.6 mmol), PyBOP (740.8 mg, 1.44 mmol) and glycine ester (200 mg, 1.44 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, DIPEA (270µL, 1.44 mmol), DMF (6 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then diluted with DCM (50 mL) washed with water (6 x 50 mL). The organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography to yield a solid product (239.4 mg, 59 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.16 (s, 1H), 7.98 (s, 2H), 7.59 – 7.53 (m, 1H), 7.48 (d, *J* = 5.1 Hz, 1H), 7.46 – 7.38 (m, 2H), 7.38 – 7.31 (m, 3H), 7.31 – 7.24 (m, 8H), 7.23 – 7.19 (m, 3H), 7.06 (dd, *J* = 7.4, 3.6 Hz, 1H), 7.03 – 6.97 (m, 1H), 4.29 – 4.22 (m, 8H), 1.31 (t, *J* = 7.1

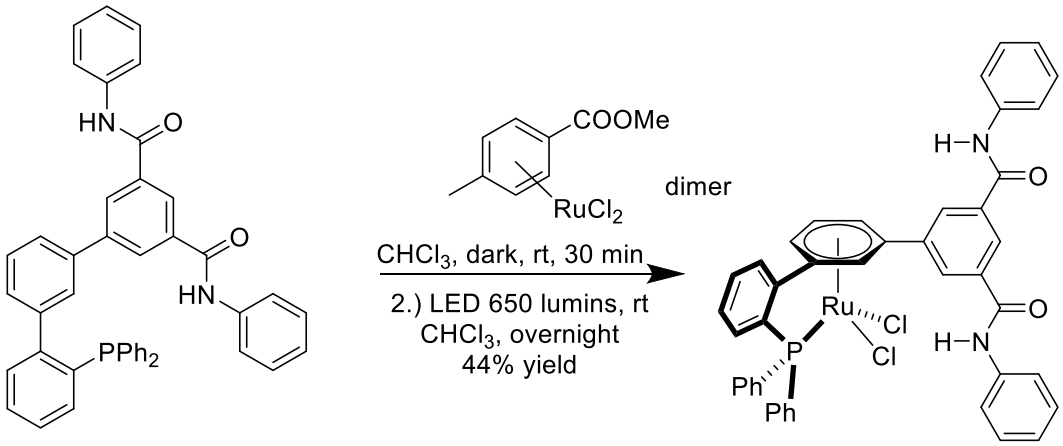
Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 170.14, 170.03, 170.00, 166.67, 147.33 (d, J=27.6 Hz), 142.34 (d, J=6.2 Hz), 142.03, 138.27, 137.24 (d, J=11.2 Hz), 136.15 (d, J=14.3 Hz), 134.58, 134.56, 134.04 (d, J=20.0 Hz), 133.81, 130.09 (d, J=4.5 Hz), 129.55 (d, J=4.0 Hz), 129.09, 128.97, 128.93, 128.74, 128.69, 128.56, 128.38 (d, J=6.9 Hz), 128.27, 128.21, 127.59, 127.19, 125.91, 124.17, 124.01, 61.72, 41.99, 14.18. **^{31}PNMR** (202 MHz, $CDCl_3$) δ -12.65. **HRMS (ESI):** Found m/z 673.2462. Calcd. for $C_{40}H_{38}N_2O_6P$: (M+H) 673.2462



Scheme 5.22 Synthesis of dimethyl 2,2'-((2"-(diphenylphosphaneyl)-[1,1':3',1"-terphenyl]-3,5-dicarbonyl)bis(azanediyl))bis(3-methylbutanoate) (**22**)

Solid starting materials, phosphine (385 mg, 0.82 mmol), PyBOP (1.02 g, 1.94 mmol) and valine ester (331.9 mg, 1.94 mmol) were added to a schlenk tube followed by vacuum addition of nitrogen atmosphere. Liquid components, DIPEA (270 µL, 1.44 mmol), DMF (6 mL) were then added through a septum and the reaction was stirred at room temperature overnight. The reaction was then diluted with DCM (50 mL) washed with water (6 x 50 mL). The organic layer was then dried and evaporated. Finally, the mixture was separated using silica gel chromatography to yield a solid oxide intermediate (348.6 mg, 57 % yield) for the first step. Next the 100 mg of the intermediate was added into a Schlenk tube

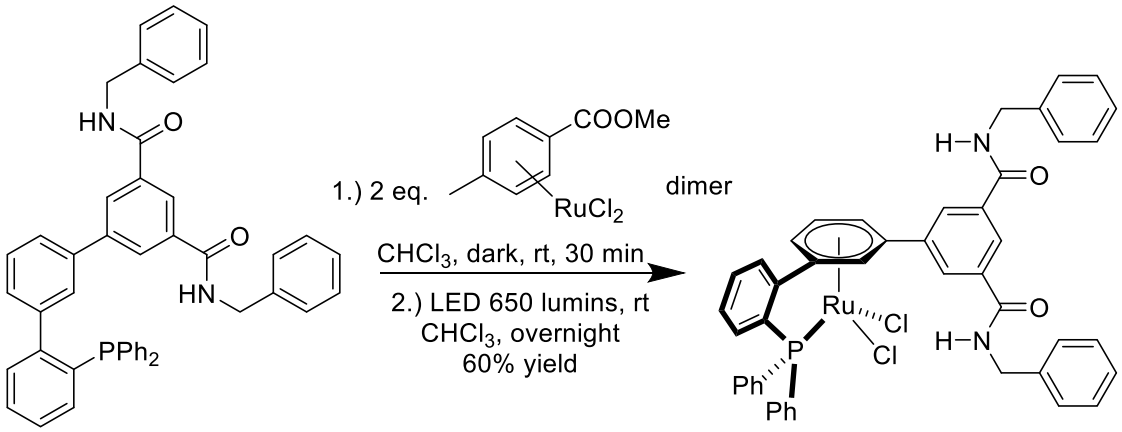
followed by vacuum addition of nitrogen atmosphere. Liquid components, trichlorosilane (440 µL, 4.3 mmol), toluene (6 mL) were then added to through a septum and the reaction was stirred at reflux for 6h. The resulting mixture was then allowed to cool to room temperature. Next the mixture was neutralized by sodium bicarbonate (1 mL saturated aqueous solution) and stirred for 5min at room temperature before washing the mixture with water (15 mL) and extracting with ethyl acetate (3x15 mL). The combined organic phases were then dried and evaporated to yield a white solid (50.7 mg, 30% yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.20 (s, 1H), 8.03 (s, 2H), 7.52 (d, *J* = 7.7 Hz, 1H), 7.44 – 7.40 (m, 2H), 7.39 – 7.33 (m, 2H), 7.31 – 7.19 (m, 14H), 7.06 (dd, *J* = 7.5, 3.8 Hz, 1H), 6.83 (d, *J* = 7.1 Hz, 2H), 4.81 (dd, *J* = 8.5, 5.2 Hz, 2H), 3.78 (s, 6H), 2.35 – 2.25 (m, 2H), 1.03 (dd, *J* = 10.7, 6.9 Hz, 12H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 172.42, 166.51, 147.18 (d, J=26.9 Hz), 142.39 (d, J=5.9 Hz), 138.49, 137.15, 137.09 (dd, J=11.3, 3.5 Hz), 137.03, 136.27 (d, J=14.6 Hz), 135.05, 134.05 (d, J=20.1 Hz), 133.97, 133.74, 130.08 (d, J=4.5 Hz), 129.62 (d, J=4.1 Hz), 128.96, 128.84 (d, J=3.6 Hz), 128.75, 128.59, 128.40, 128.35, 128.29, 127.60, 125.99, 124.23, 57.79, 52.32, 31.61, 19.07, 18.17. **^{31}PNMR** (202 MHz, $CDCl_3$) δ -12.23. **HRMS (ESI):** Found m/z 727.2930. Calcd. for $C_{44}H_{44}N_2O_6P$: (M-H) 727.2932



Scheme 5.23 Synthesis of meta-substituted aniline Ru complex (**23**)

Phosphine ligand (12.7 mg, 0.020 mmol), Ru starting material (15.0 mg, 0.020 mmol), and $CHCl_3$ (3 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (3:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) for 4h. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (7.2 mg, 44 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.61 (s, 1H), 8.51 (d, J = 1.4 Hz, 2H), 7.76 (dd, J = 7.6, 1.8 Hz, 1H), 7.72 (d, J = 7.8 Hz, 4H), 7.69 – 7.63 (m, 3H), 7.63 – 7.56 (m, 2H), 7.51 – 7.45 (m, 1H), 7.45 – 7.40 (m, 2H), 7.37 – 7.30 (m, 7H), 7.28 – 7.22 (m, 2H), 7.15 (t, J = 7.4 Hz, 2H), 6.80 (d, J = 6.2 Hz, 1H), 6.27 (t, J = 5.8 Hz, 1H), 5.56 (s, 1H), 5.50 (d, J = 5.6 Hz, 1H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 164.89, 144.61, 144.21, 143.86, 143.68, 138.16, 138.07, 135.93, 134.30, 134.28, 134.03, 133.95, 133.64, 133.56, 133.05, 131.66, 131.40, 131.19, 131.17, 130.93, 130.91, 130.41, 130.36, 130.30, 130.01, 129.30, 128.91, 128.47, 128.38, 128.32, 128.17, 128.08, 127.77, 127.67, 124.76, 121.10, 121.00, 120.98, 112.31,

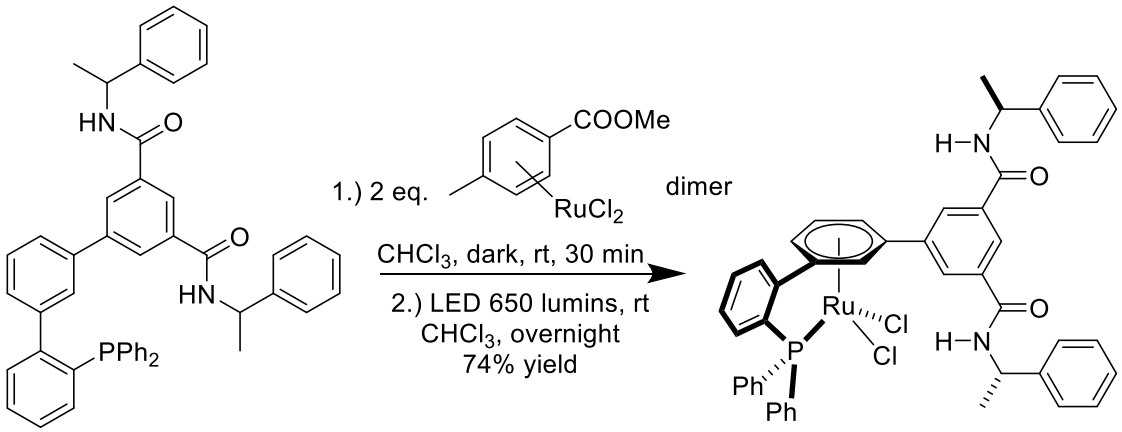
110.40, 110.38, 95.40, 90.75, 90.63, 80.75, 78.98. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.19. **HRMS (ESI):** Found m/z 789.1014. Calcd. for $C_{44}H_{33}ClN_2O_2PRu$: (M-Cl) 789.1006



Scheme 5.24 Synthesis of meta-substituted benzylamine Ru complex (**24**)

Phosphine ligand (16.7 mg, 0.024 mmol), Ru starting material (15.8 mg, 0.024 mmol), and $CHCl_3$ (3 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) for 4h. This mixture was then separated by silica gel chromatography (1:1:0.05 $CHCl_3$:EtOAc:MeOH) to yield a yellow product (12.8 mg, 60 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.44 (s, 1H), 8.41 (s, 2H), 7.76 (d, J = 7.3 Hz, 1H), 7.71 – 7.63 (m, 3H), 7.60 – 7.55 (m, 2H), 7.47 (d, J = 6.8 Hz, 1H), 7.45 – 7.40 (m, 2H), 7.37 – 7.28 (m, 12 H), 7.28 – 7.22 (m, 5H), 6.68 (d, J = 5.8 Hz, 1H), 6.19 – 6.14 (m, 1H), 5.54 – 5.48 (m, 2H), 4.68 – 4.61 (m, 2H), 4.59 (m, 2H). **^{13}CNMR** (126 MHz,

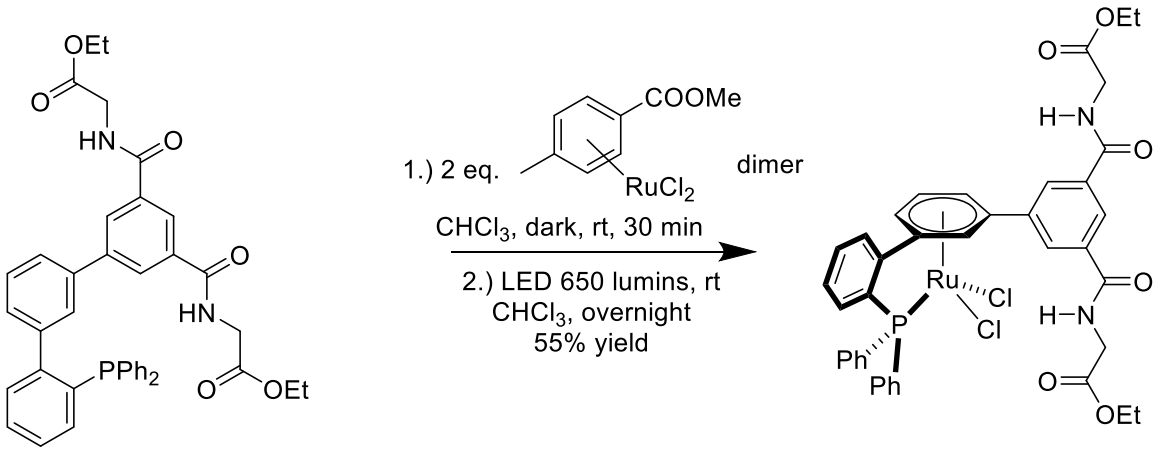
$CDCl_3$) δ 166.35, 144.60, 144.20, 143.76 (d, J=22.2Hz), 138.26, 135.19, 134.17, 134.01 (d, J=9.9 Hz), 133.58 (d, J=9.8 Hz), 133.03, 131.63, 131.19, 130.83, 130.35, 130.30, 128.99, 128.62, 128.45 (d, J=10.9 Hz), 128.10, 128.01, 127.81, 127.74, 127.63, 127.35, 113.69, 110.52 (d, J=2.8 Hz), 94.58, 90.46, 90.35, 80.86, 78.57, 44.08. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.32. **HRMS (ESI):** Found m/z 817.1320. Calcd. for $C_{46}H_{37}ClN_2O_2PRu$: (M-Cl) 817.1319



Scheme 5.25 Synthesis of meta-substituted phenylethylamine Ru complex (**25**)

Phosphine ligand (24 mg, 0.034 mmol), Ru starting material (21.9 mg, 0.034 mmol), and $CHCl_3$ (2 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) for 4h. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow mixture of diastereomers (10.6 mg and 11.8 mg, total=22.4 mg, 74 % yield). Diastereomer 1 (lower spot on TLC)

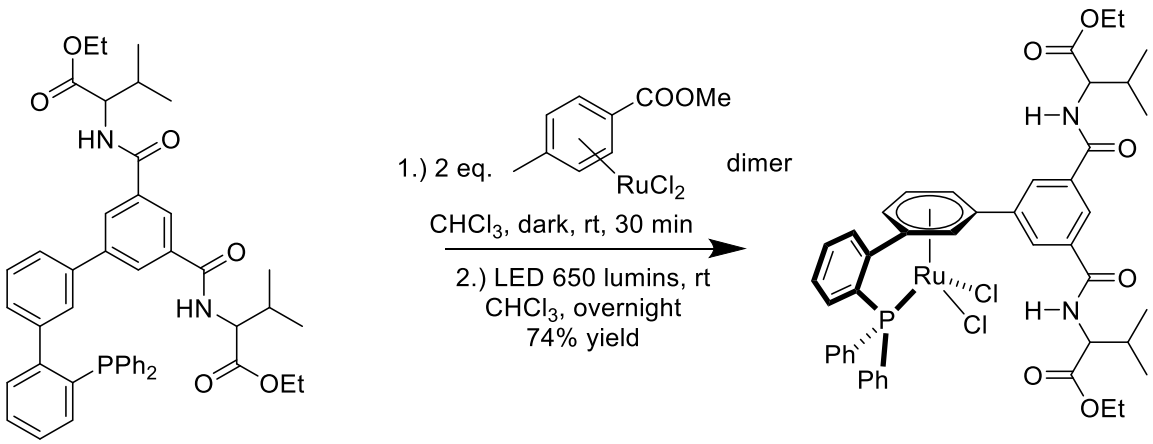
^{1}HNMR (500 MHz, $CDCl_3$) δ 8.45 (s, 2H), 8.28 (s, 1H), 7.73 – 7.68 (m, 1H), 7.68 – 7.60 (m, 3H), 7.60 – 7.55 (m, 2H), 7.49 – 7.43 (m, 1H), 7.43 – 7.38 (m, 2H), 7.34 (d, *J* = 7.5 Hz, 4H), 7.32 – 7.25 (m, 9H), 7.24 – 7.15 (m, 6H), 6.66 (d, *J* = 6.1 Hz, 1H), 6.20 (t, *J* = 5.8 Hz, 1H), 5.47 (d, *J* = 5.6 Hz, 1H), 5.44 (s, 1H), 5.31 – 5.23 (m, 2H), 1.57 (d, *J* = 7.0 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 165.09, 145.06, 144.65, 143.79 (d, J=21.6 Hz), 143.12, 135.30, 134.58, 134.57, 134.01, 133.93, 133.72 (d, J=10.2 Hz), 132.97, 131.48, 131.14, 131.03, 130.76 (d, J=2.9 Hz), 130.15 (d, J=6.8 Hz), 128.65, 128.29 (d, J=10.9 Hz), 128.04, 127.96, 127.65, 127.56, 127.28, 126.94, 126.25, 109.62, 91.28, 81.26, 49.87, 22.12. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 52.72. **HRMS (ESI):** Found m/z 845.1622. Calcd. for $C_{48}H_{41}ClN_2O_2PRu$: (M-Cl) 845.1632. Diastereomer 2 (higher spot on TLC) **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.33 (s, 3H), 7.69 (d, *J* = 6.2 Hz, 1H), 7.60 (dd, *J* = 11.8, 7.2 Hz, 4H), 7.57 – 7.52 (m, 2H), 7.49 – 7.38 (m, 6H), 7.35 (d, *J* = 7.5 Hz, 5H), 7.34 – 7.28 (m, 7H), 7.22 (t, *J* = 7.3 Hz, 2H), 6.99 (d, *J* = 4.8 Hz, 1H), 6.69 (s, 1H), 5.52 (s, 1H), 5.36 (d, *J* = 5.6 Hz, 1H), 5.26 (p, *J* = 6.9 Hz, 2H), 1.54 (d, *J* = 7.0 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 164.96, 144.63, 144.24, 143.81 (d, J=22.0 Hz), 143.42, 134.97, 134.24, 133.87 (d, J=,9.6 Hz) 133.71, 133.63, 133.02, 131.44, 131.12, 130.92-130.87 (m), 130.74 (d, J=2.9 Hz), 130.18, 130.13, 129.95, 129.64, 129.54, 129.25, 128.62, 128.28, 128.22 (dd, J=10.9, 5.4 Hz), 128.15, 127.66, 127.53, 127.43, 127.21, 126.26, 111.83, 111.82, 110.61, 97.74, 89.87, 79.07, 50.02, 22.05. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 53.47. **HRMS (ESI):** Found m/z 845.1636. Calcd. for $C_{48}H_{41}ClN_2O_2PRu$: (M-Cl) 845.1632.



Scheme 5.26 Synthesis of glycine Ru complex (**26**)

Phosphine ligand (50 mg, 0.074 mmol), Ru starting material (95.7 mg, 0.148 mmol), and $CHCl_3$ (5 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) overnight. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (34.3 mg, 55 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.44 (s, 1H), 8.41 (s, 2H), 7.74 (s, 1H), 7.69 (dd, *J* = 11.0, 7.7 Hz, 2H), 7.66 – 7.62 (m, 1H), 7.62 – 7.55 (m, 2H), 7.46 (d, *J* = 6.2 Hz, 1H), 7.43 (d, *J* = 6.2 Hz, 2H), 7.35 (s, 1H), 7.32 – 7.23 (m, 6H), 6.69 (d, *J* = 5.1 Hz, 1H), 6.17 (t, *J* = 5.3 Hz, 1H), 5.52 (d, *J* = 5.3 Hz, 1H), 5.47 (s, 1H), 4.26 – 4.06 (m, 8H), 1.29 (t, *J* = 7.1 Hz, 6H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 169.78, 166.49, 144.66, 143.78 (d, J=21.8 Hz), 134.63, 134.24, 134.07, 133.99, 133.57 (d, J=9.6 Hz), 132.98, 131.54, 131.15, 130.88, 130.79, 130.48, 130.24 (d, J=6.8 Hz), 128.43 (d, J=10.8 Hz), 128.07, 127.98, 127.73, 127.64, 113.41, 110.26, 94.58, 90.60 (d, J=14.5 Hz), 80.97, 78.82, 61.46, 41.96, 14.18.

^{31}PNMR (202 MHz, $CDCl_3$) δ 53.35. **HRMS (ESI):** Found m/z 809.1116. Calcd. for $C_{40}H_{37}N_2Cl_1O_6PRu$:(M-Cl) 809.1116



Scheme 5.27 Synthesis of meta-substituted valine Ru complex (**27**)

Phosphine ligand (50 mg, 0.069 mmol), Ru starting material (44 mg, 0.069 mmol), and $CHCl_3$ (5 mL) were added to a small glass vial and stirred under dark conditions for 30 min. Following this, components were separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc). The resulting red intermediate complex was then added to a small glass vial and stirred under a desk lamp (650 lumin) overnight. This mixture was then separated by silica gel chromatography (1:1 $CHCl_3$:EtOAc) to yield a yellow product (48.1 mg, 74 % yield). **^{1}HNMR** (500 MHz, $CDCl_3$) δ 8.49 (s, 2H), 8.35 (d, J = 19.9 Hz, 1H), 7.71 (d, J = 6.9 Hz, 1H), 7.67 – 7.55 (m, 4H), 7.46 – 7.28 (m, 5H), 7.25 – 7.16 (m, 2H), 7.09 (d, J = 8.2 Hz, 1H), 7.02 (d, J = 8.2 Hz, 1H), 6.68 (dd, J = 15.5, 5.6 Hz, 1H), 6.23 (dt, J = 19.3, 5.6 Hz, 1H), 5.50 – 5.45 (m, 2H), 4.70 – 4.65 (m, 2H), 3.75 (d, J = 7.7 Hz, 6H), 2.30 – 2.21 (m, 2H), 1.01 – 0.96 (m, 12H). **^{13}CNMR** (126 MHz, $CDCl_3$) δ 172.00, 166.14, 165.95,

145.19, 144.79, 143.89 (d, J=21.6 Hz), 134.94, 134.82, 134.80, 134.04, 133.99 (dd, J=9.9, 2.4 Hz), 133.95, 133.88, 133.80, 132.99, 132.94, 131.54, 131.45 (d, J=4.8 Hz), 130.99, 130.96, 130.94, 130.70, 130.46, 130.16, 130.12, 130.07, 129.76, 129.67, 129.36, 128.30, 128.24 (dd, J=10.9, 4.5 Hz), 128.18, 128.04, 127.99 (dd, J=11.0, 2.4 Hz), 127.94, 127.71, 127.64 (dd, J=12.6, 4.6 Hz), 127.07, 126.94, 111.08 (d, J=4.4 Hz), 110.19, 109.39 (t, J=2.7 Hz), 96.05, 95.39, 91.62, 91.54 (dd, J=14.3, 6.2 Hz), 81.57 (d, J=10.8 Hz), 79.96 (d, J=28.8 Hz), 58.33, 58.28, 52.29, 52.21, 31.16, 31.12, 19.15, 19.14, 18.33, 18.26. **^{31}PNMR** (202 MHz, $CDCl_3$) δ 52.63, 52.23. **HRMS (ESI):** Found m/z 865.1747. Calcd. for $C_{44}H_{45}ClN_2O_6PRu$: (M-Cl) 865.1742.

APPENDIX A

SPECTRA FOR HOSOMI-SAKURA

A.1 ^{1}HNMR spectra

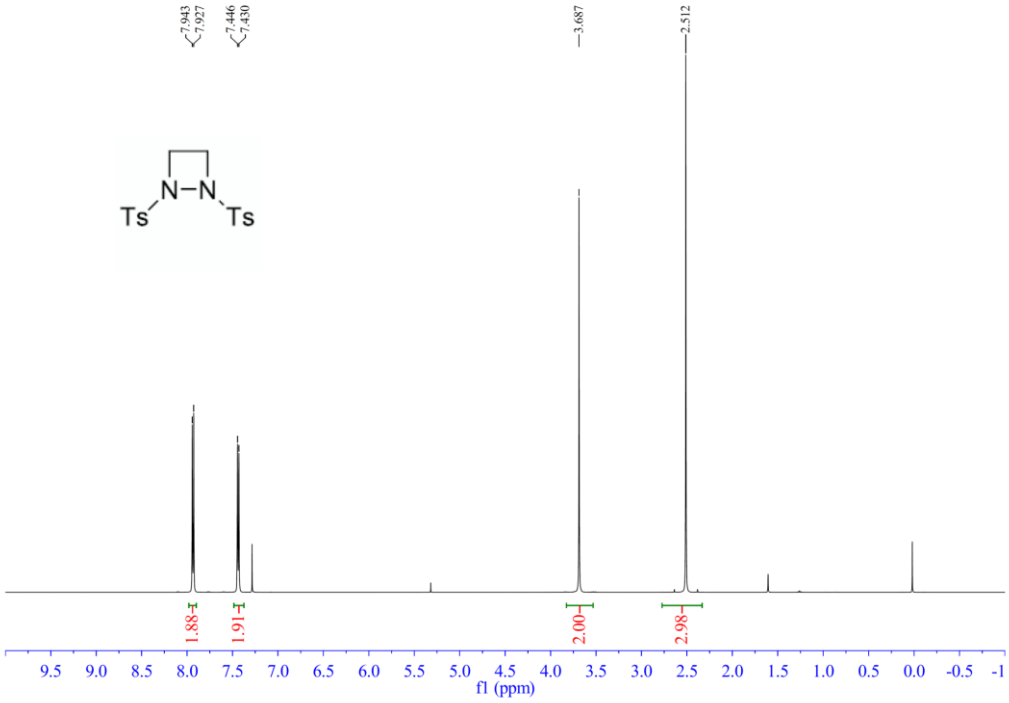


Figure A.1 Diazetidine **1**

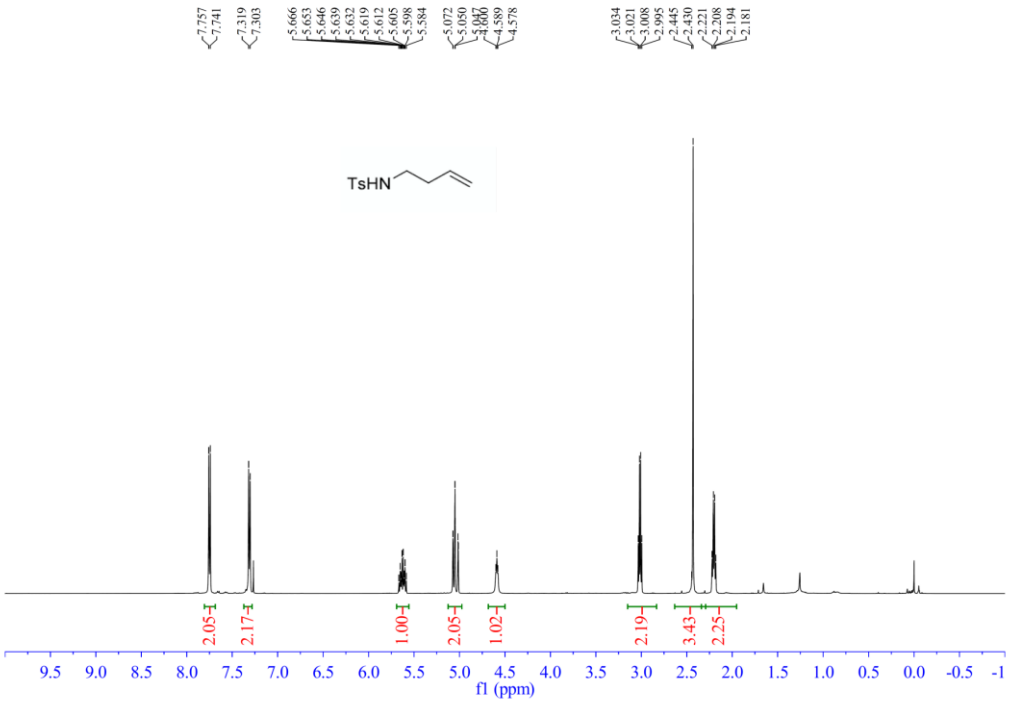


Figure A.2 Amine **4**

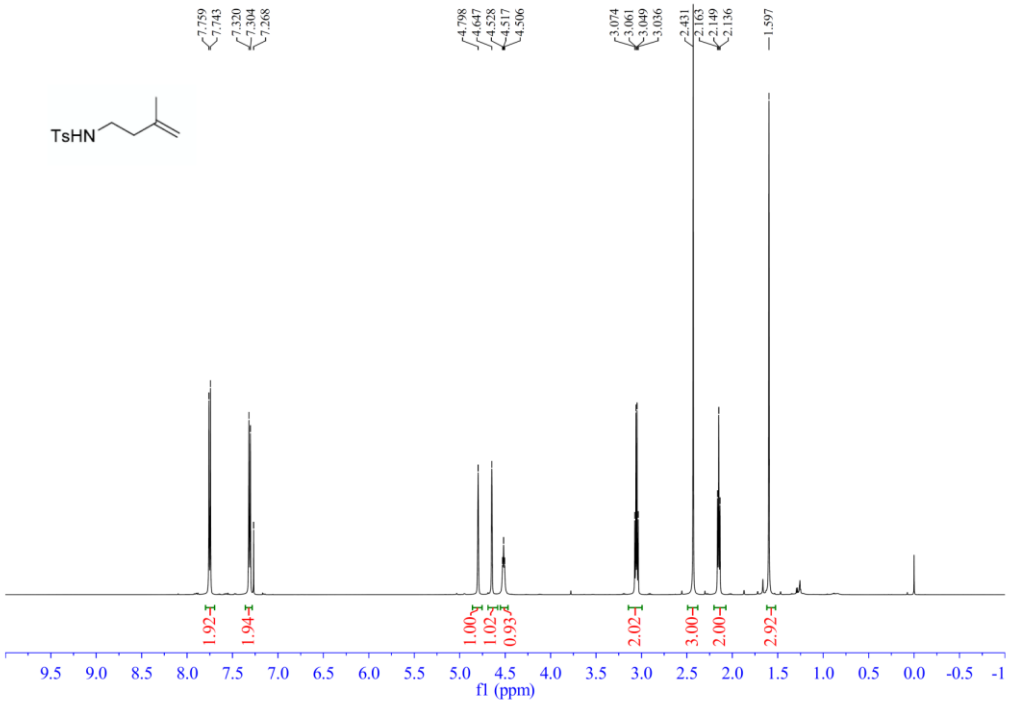


Figure A.3 Amine **6**

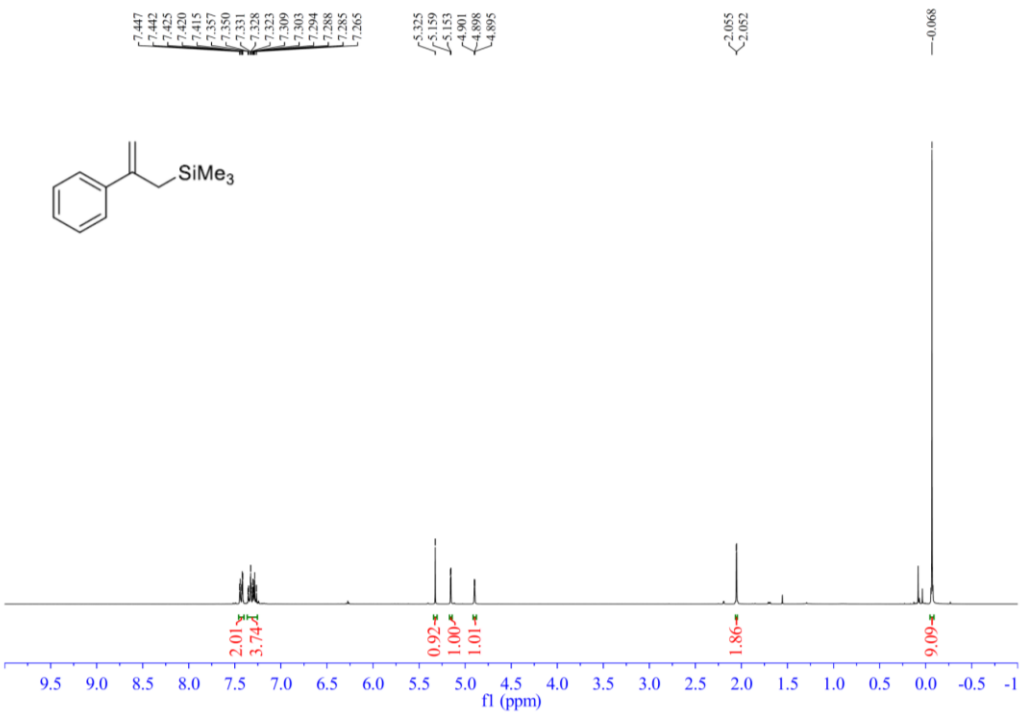


Figure A.4 Silane **7a**

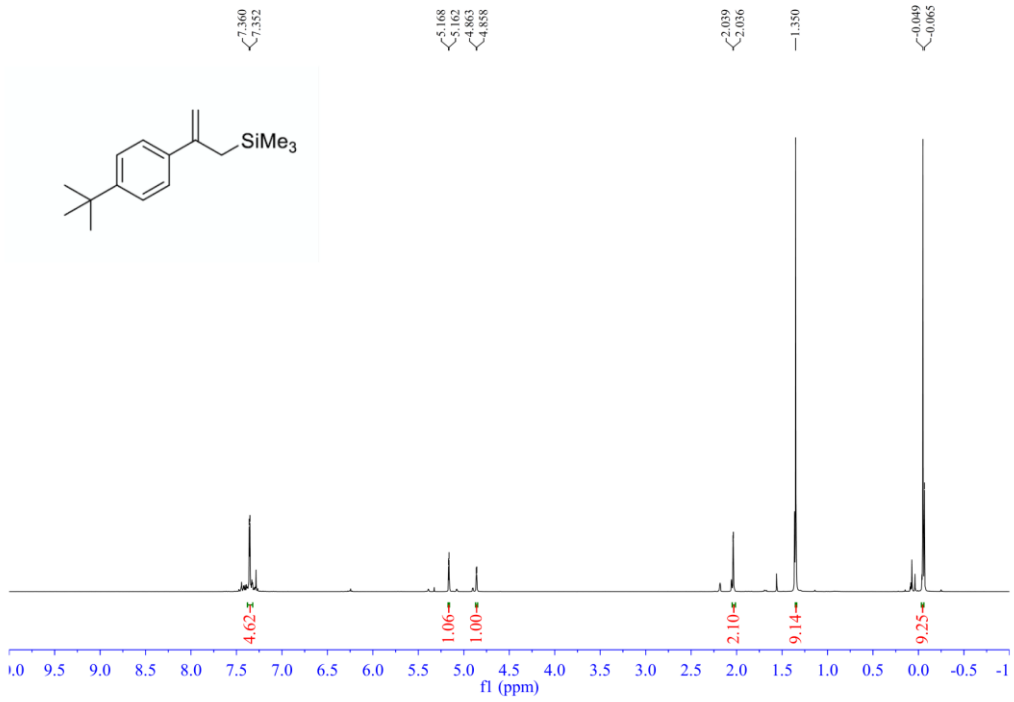


Figure A.5 Silane **7b**

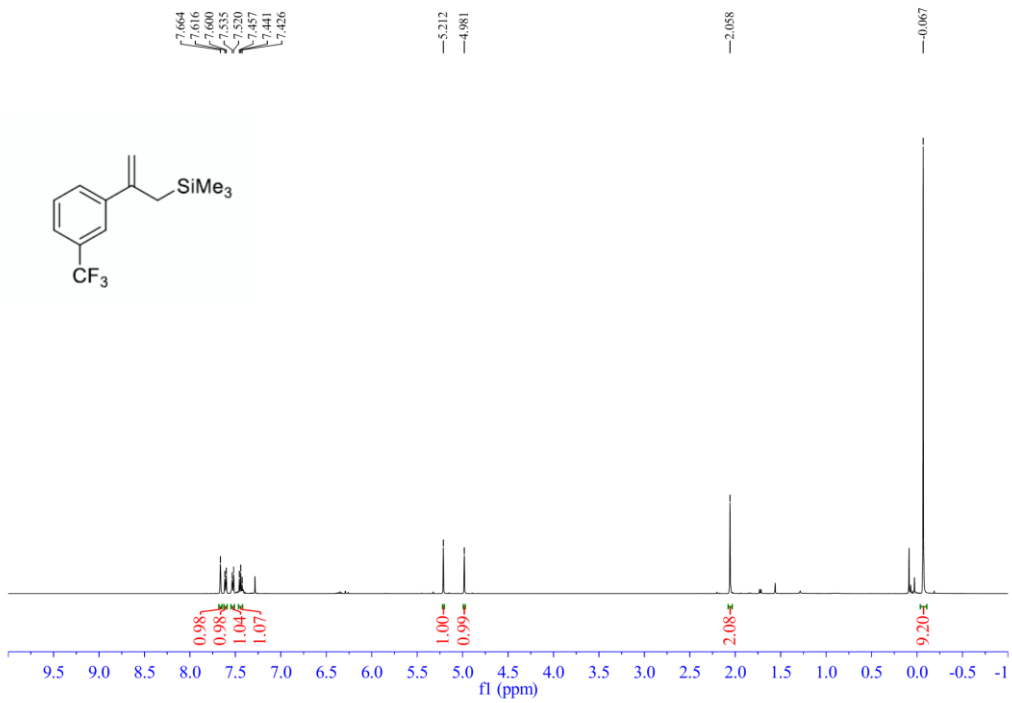


Figure A.6 Silane **7c**

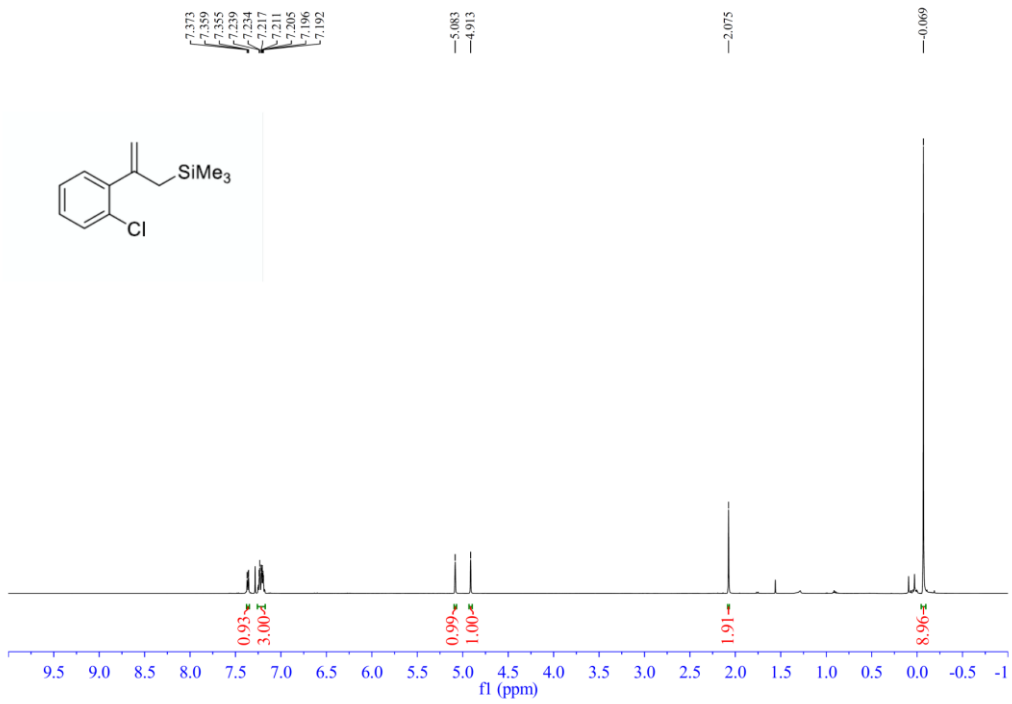


Figure A.7 Silane **7d**

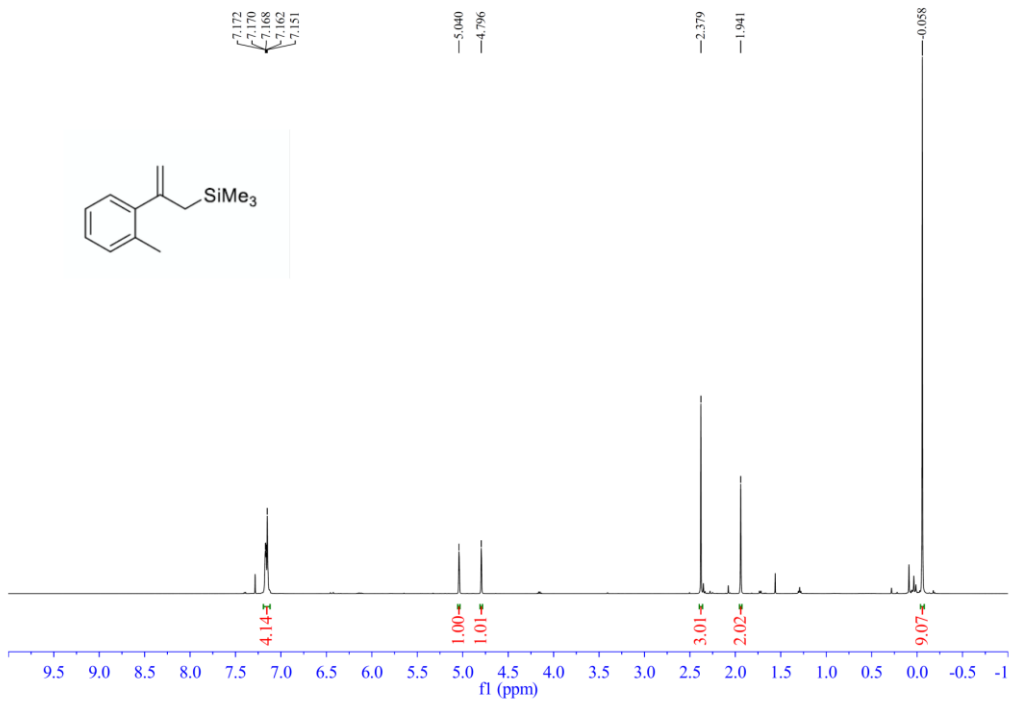


Figure A.8 Silane **7e**

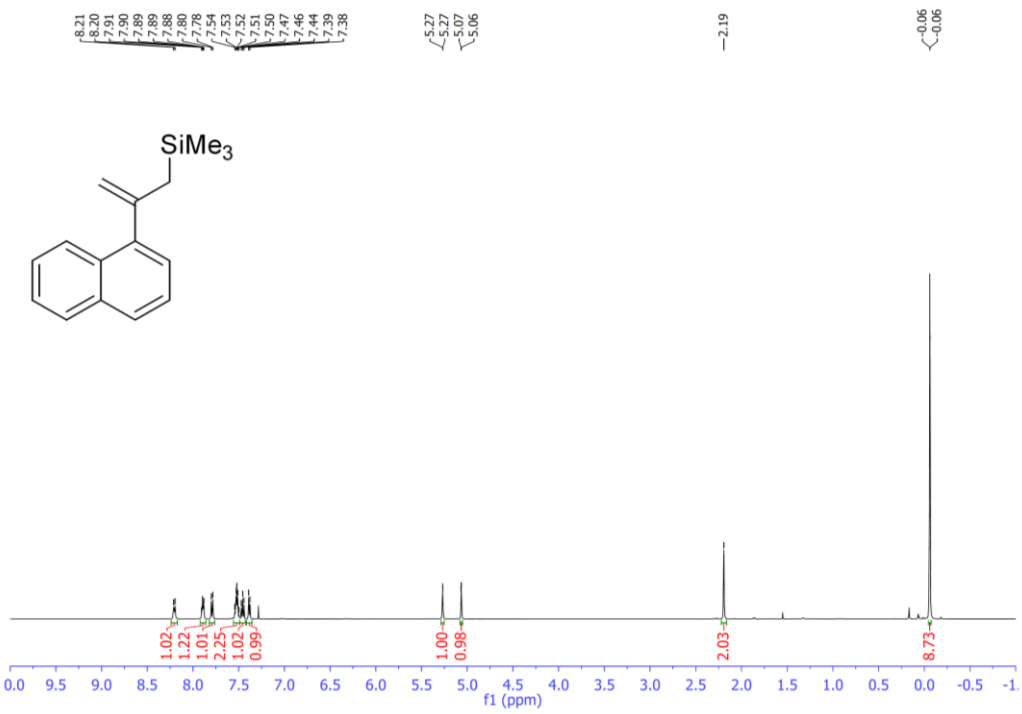


Figure A.9 Silane **7f**

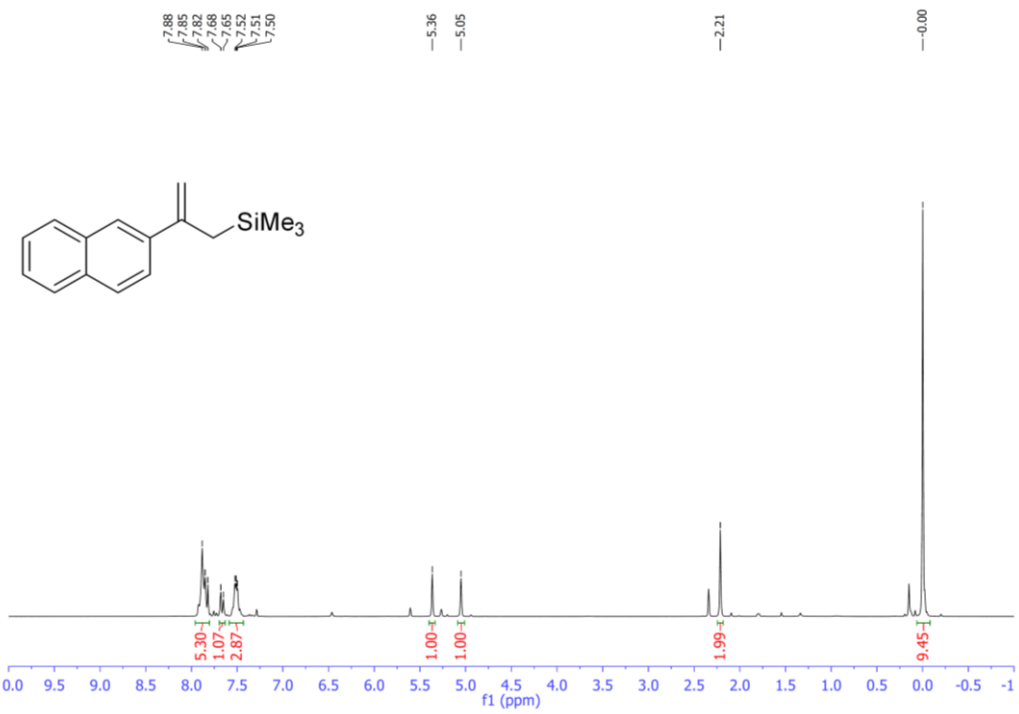


Figure A.10 Silane **7g**

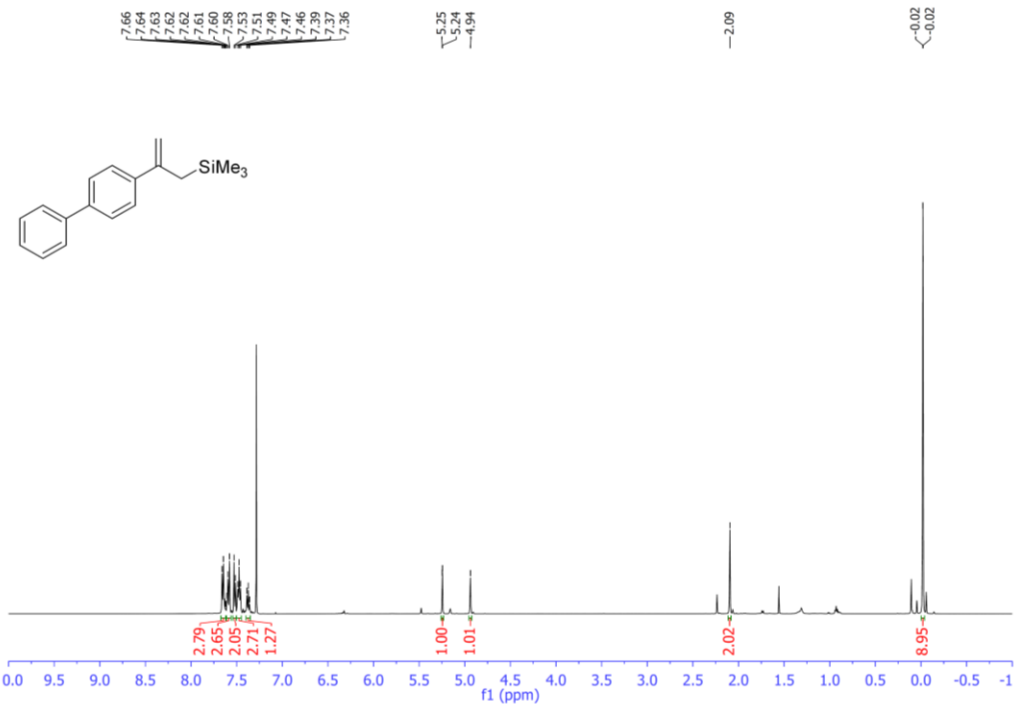


Figure A.11 Silane **7h**

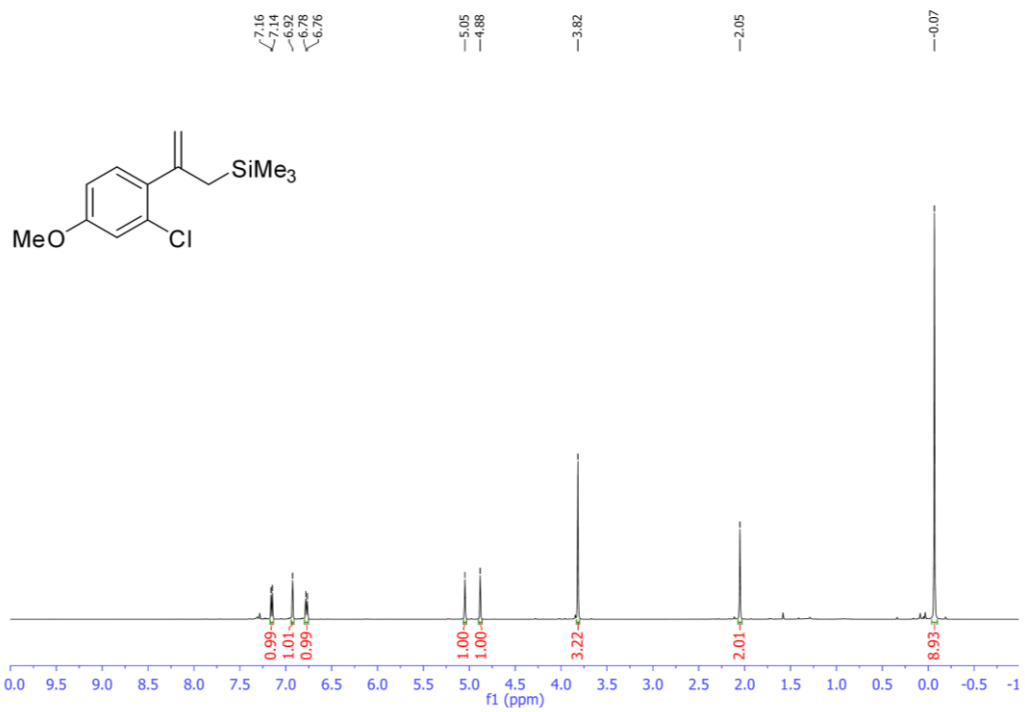


Figure A.12 Silane **7i**

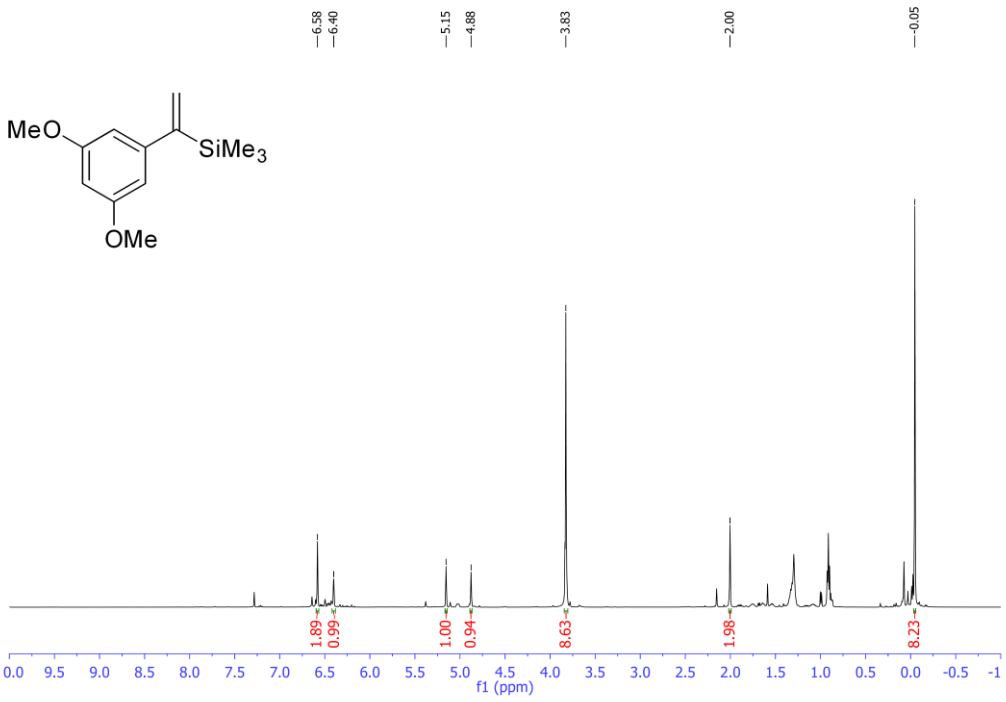


Figure A.13 Silane **7j**

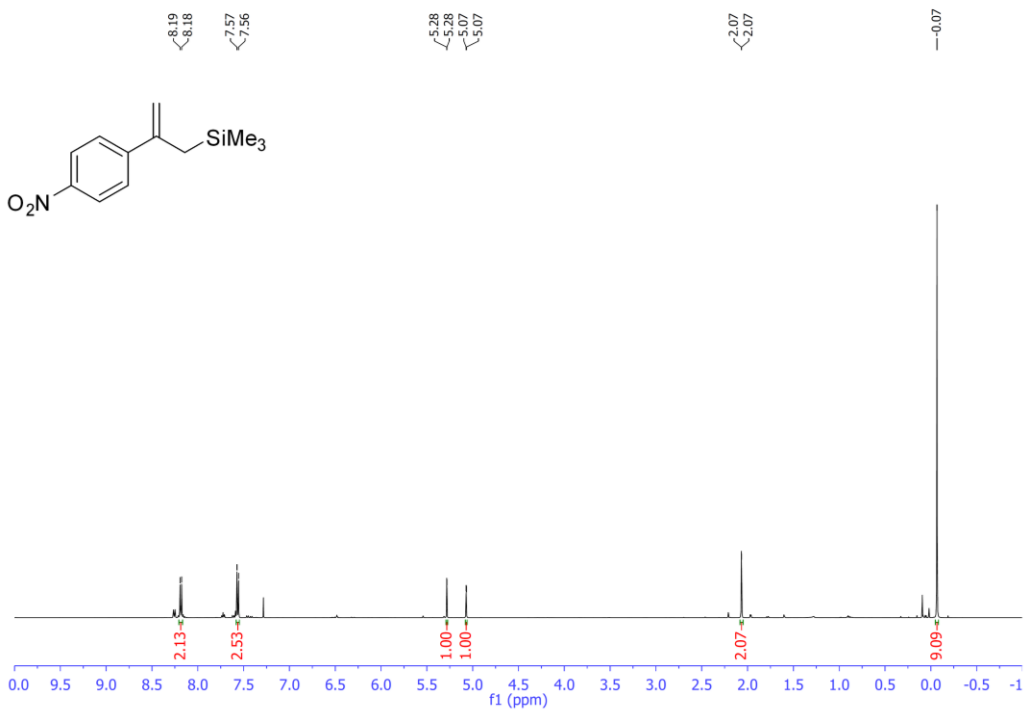


Figure A.14 Silane **7k**

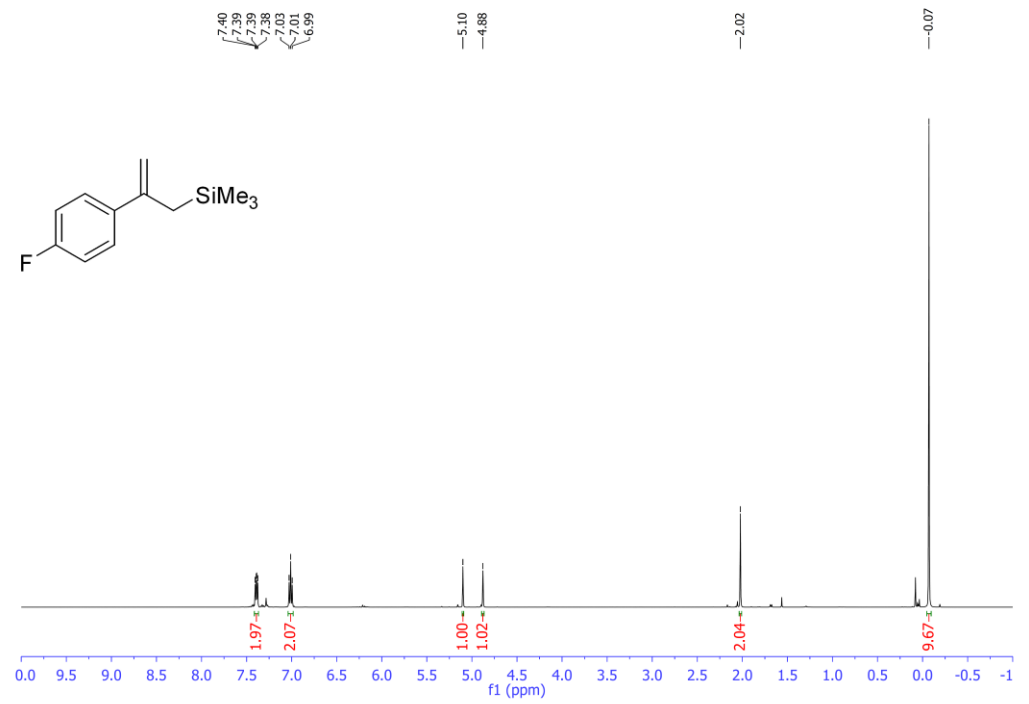


Figure A.15 Silane **7l**

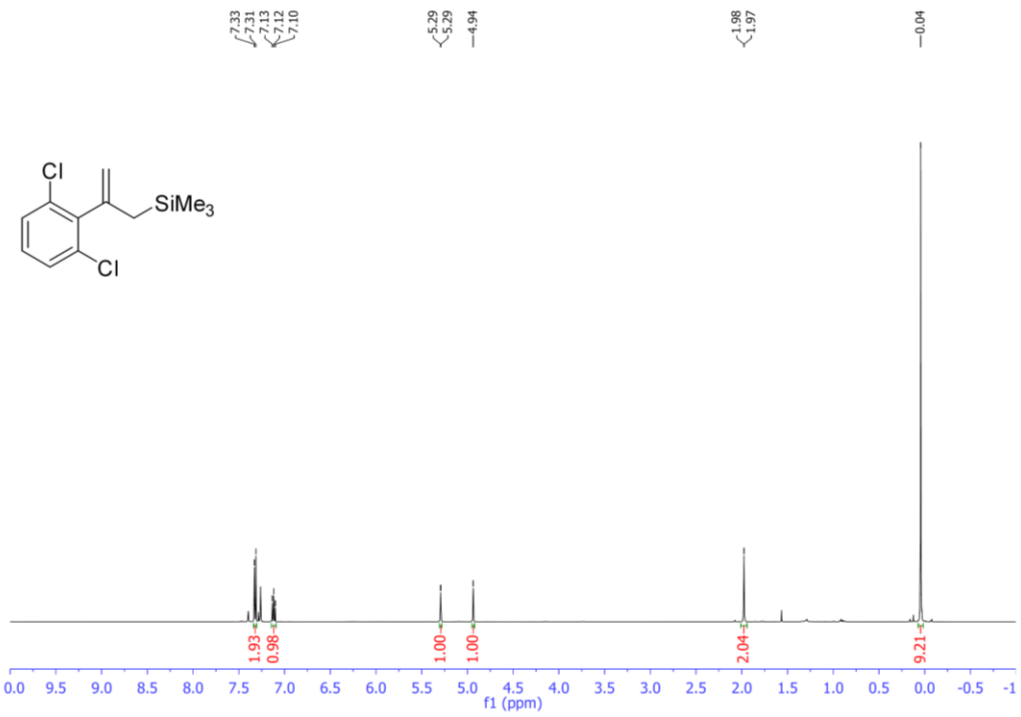


Figure A.16 Silane **7m**

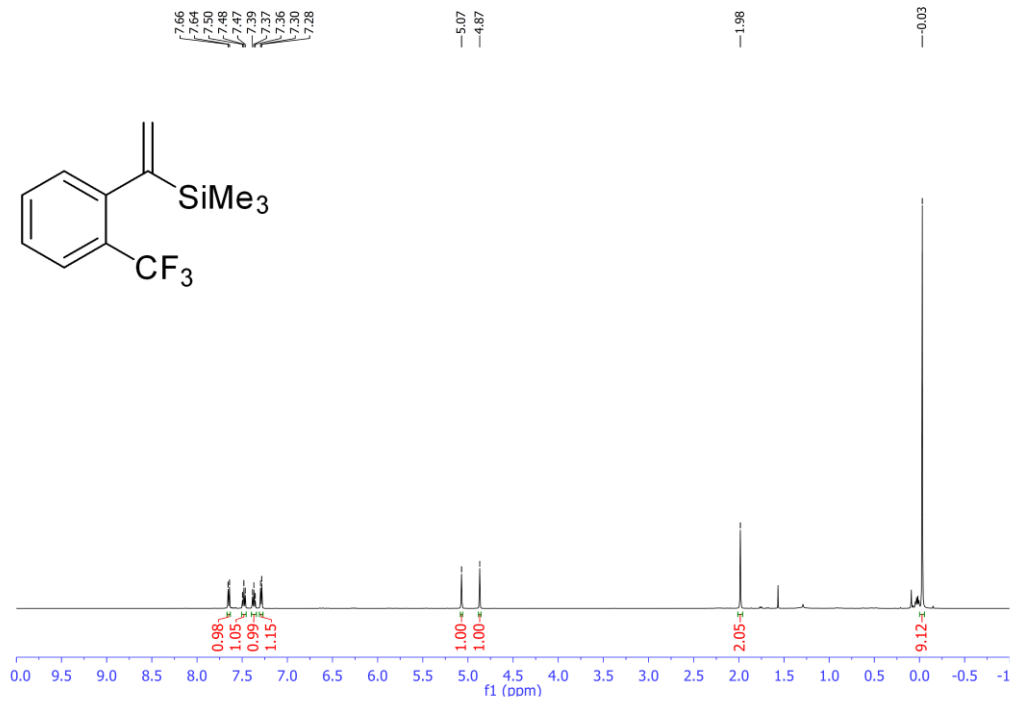


Figure A.17 Silane **7n**

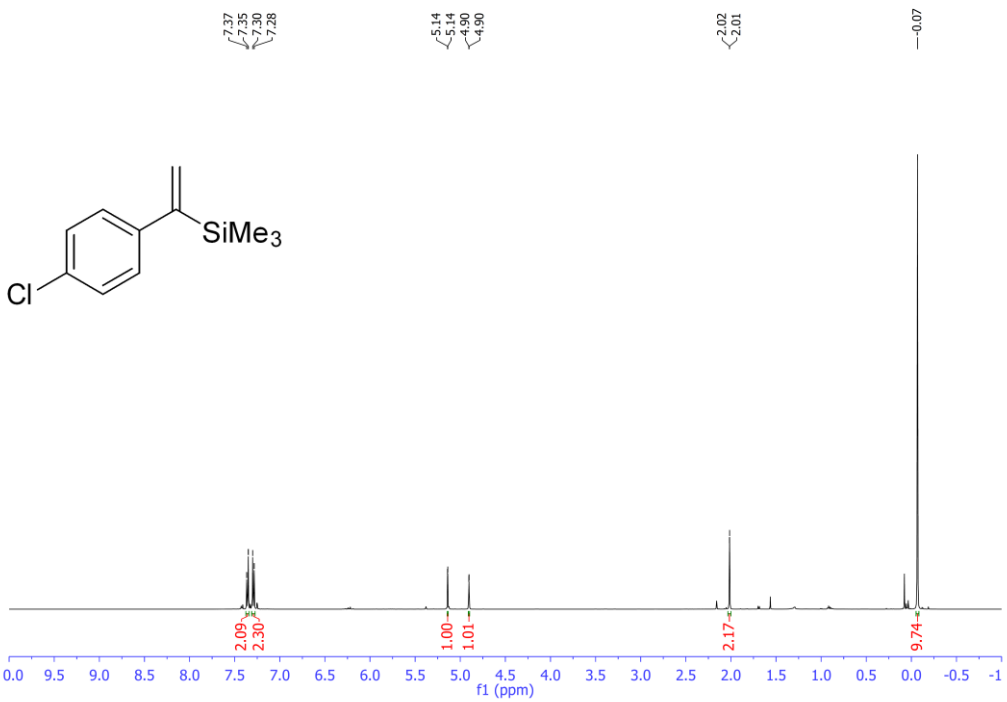


Figure A.18 Silane **7o**

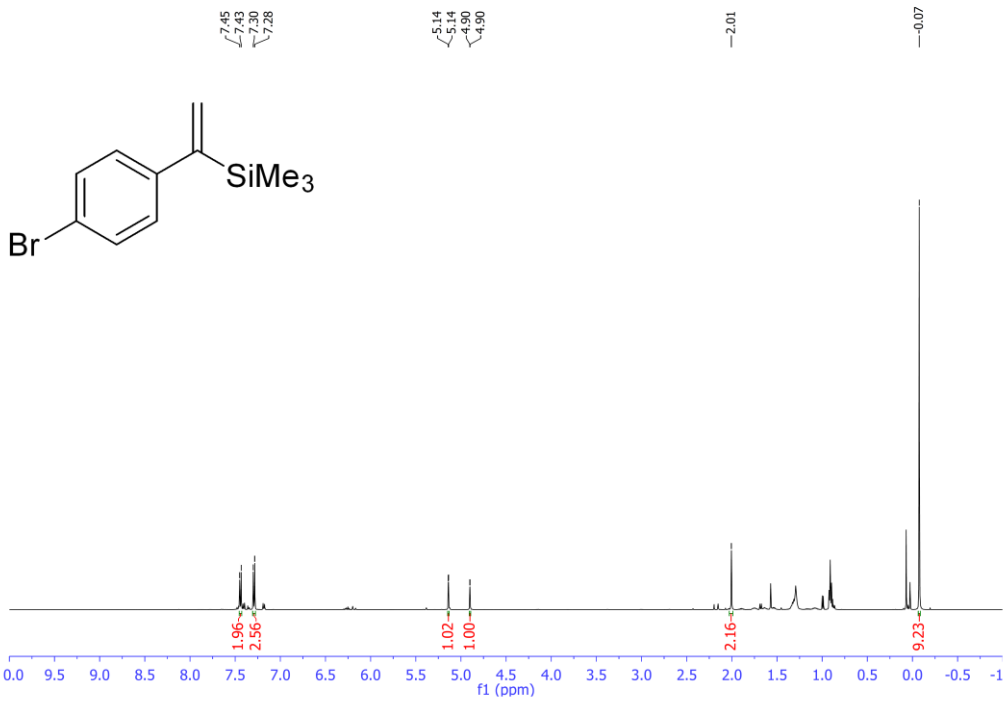


Figure A.19 Silane **7p**

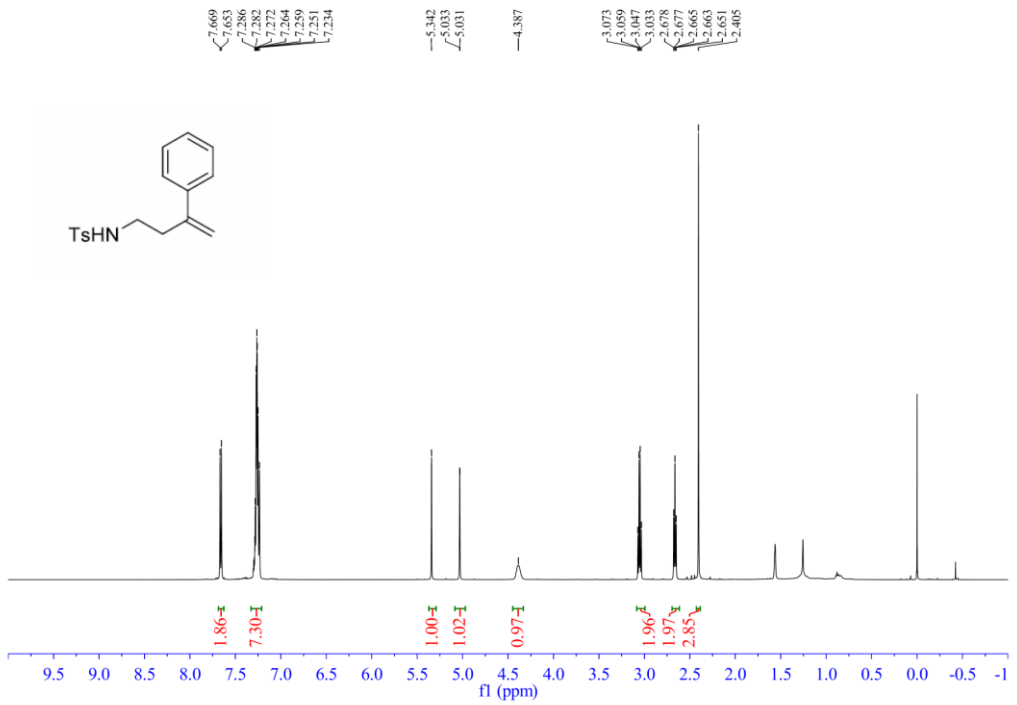


Figure A.20 Amine **8a**

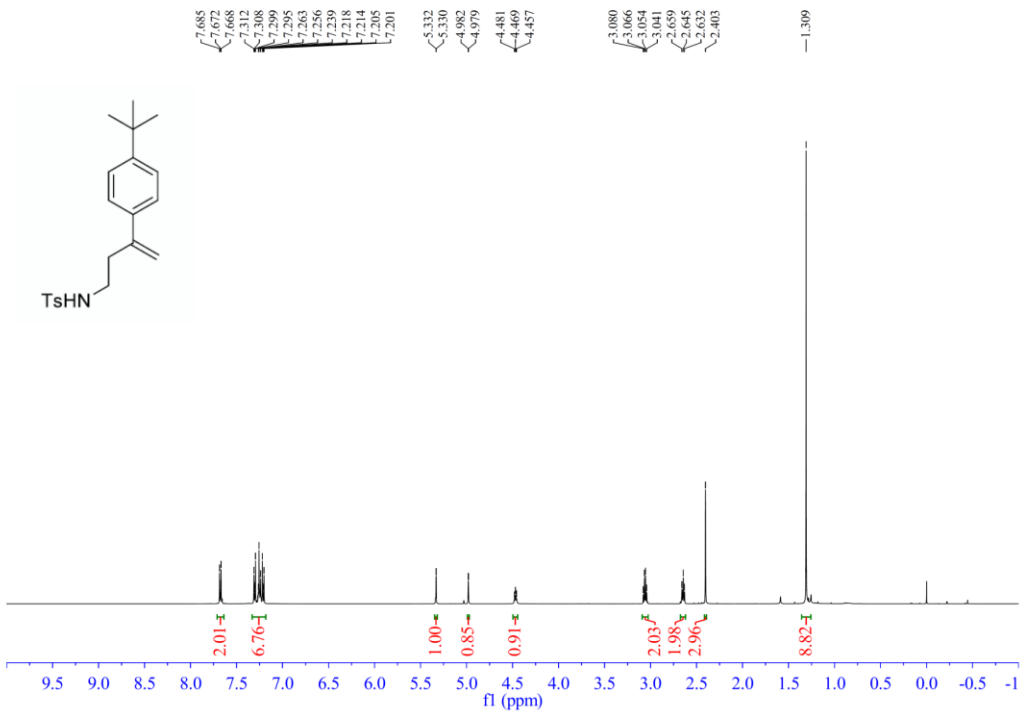


Figure A.21 Amine **8b**

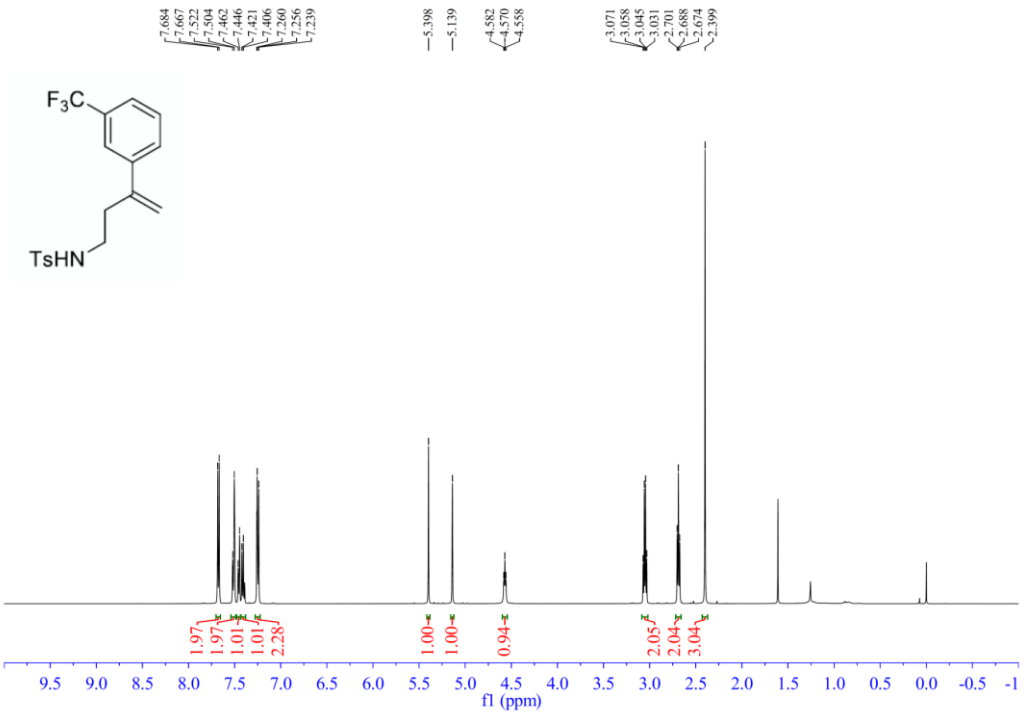


Figure A.22 Amine **8c**

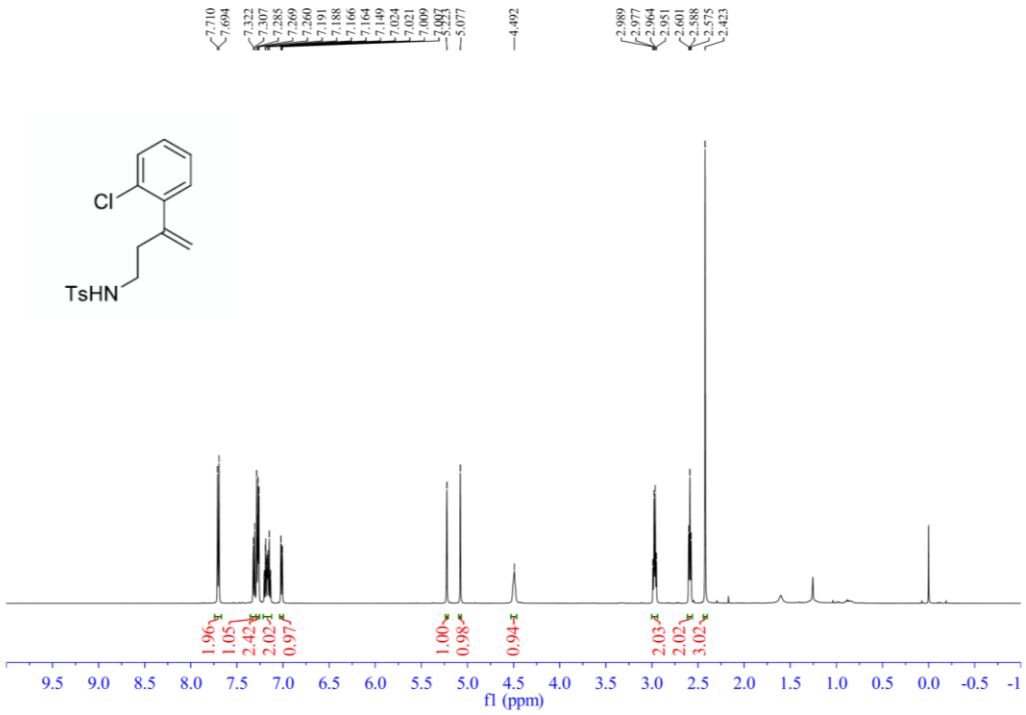


Figure A.23 Amine **8d**

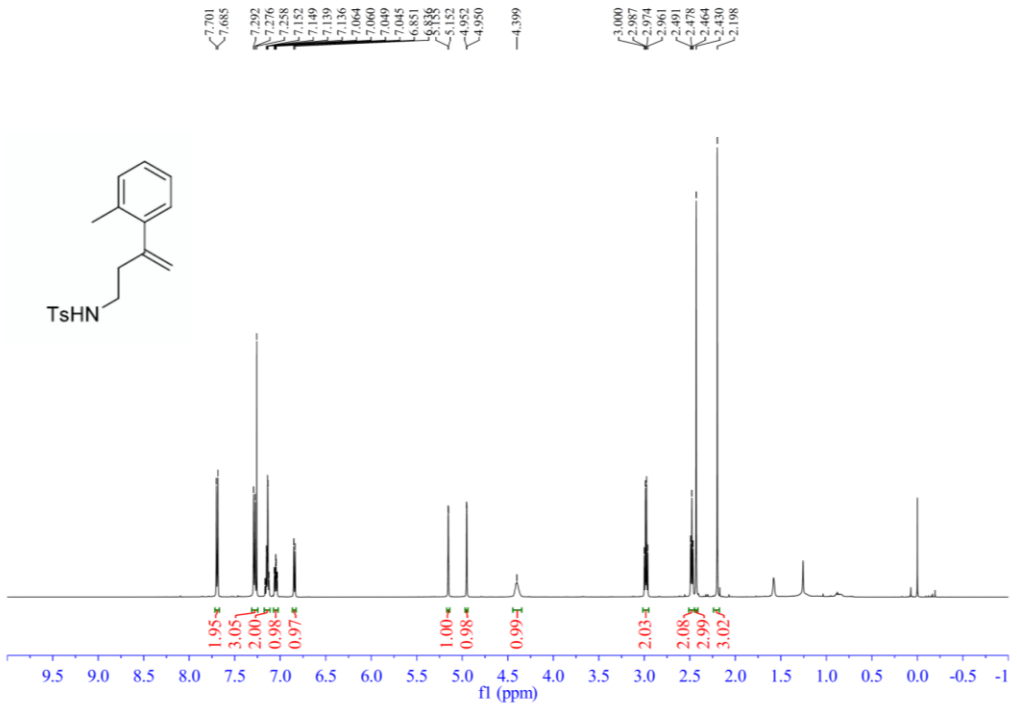


Figure A.24 Amine **8e**

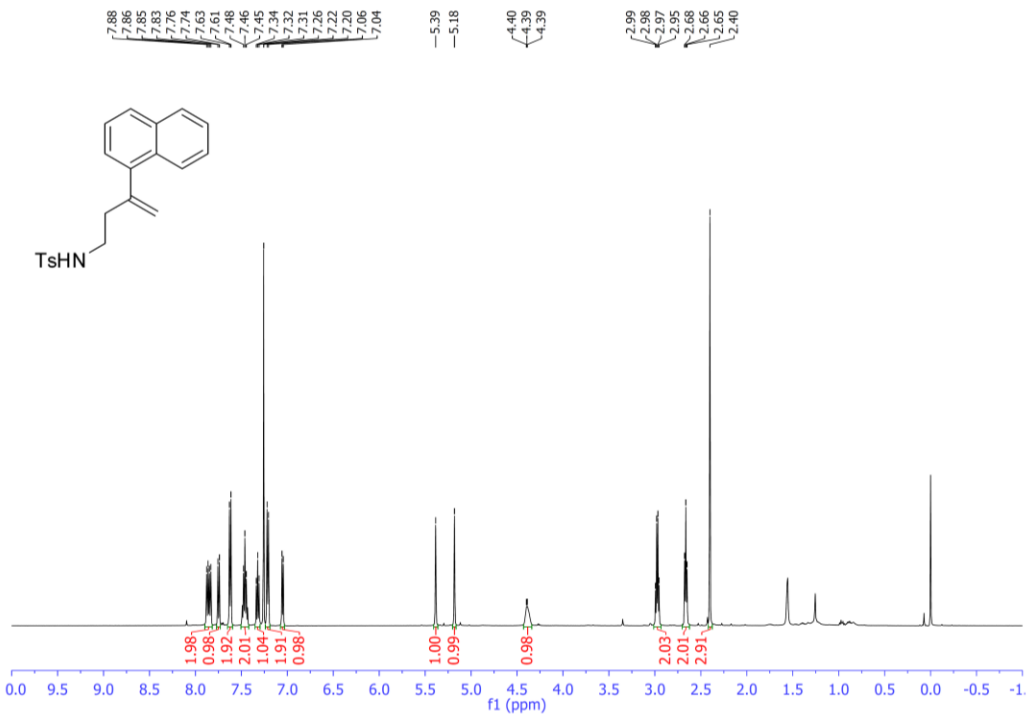


Figure A.25 Amine **8f**

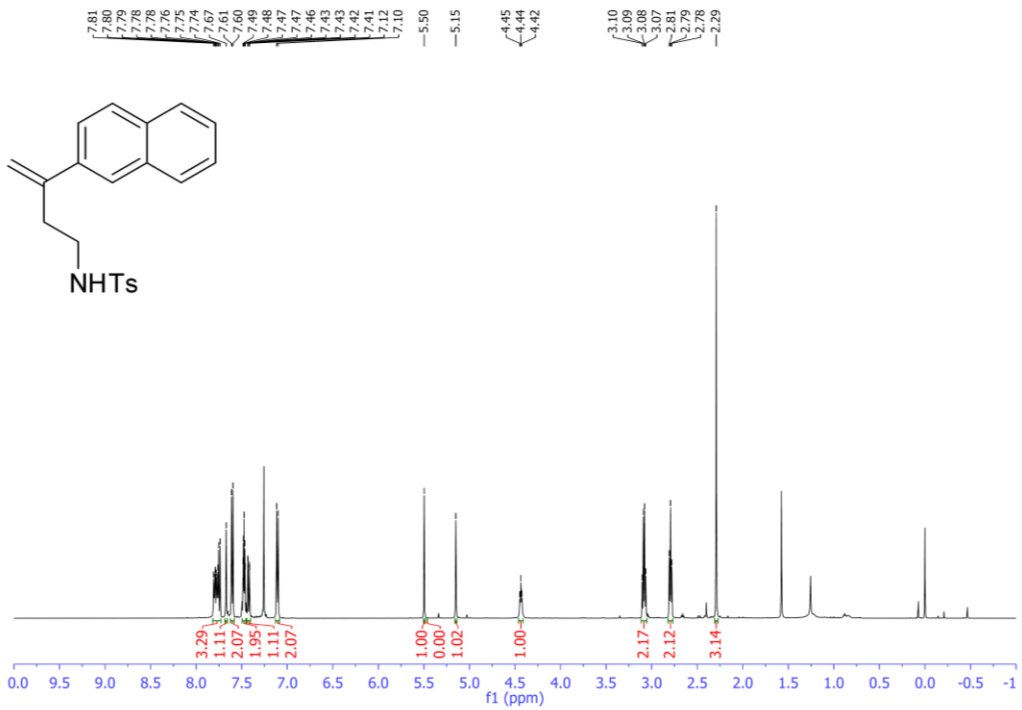


Figure A.26 Amine **8g**

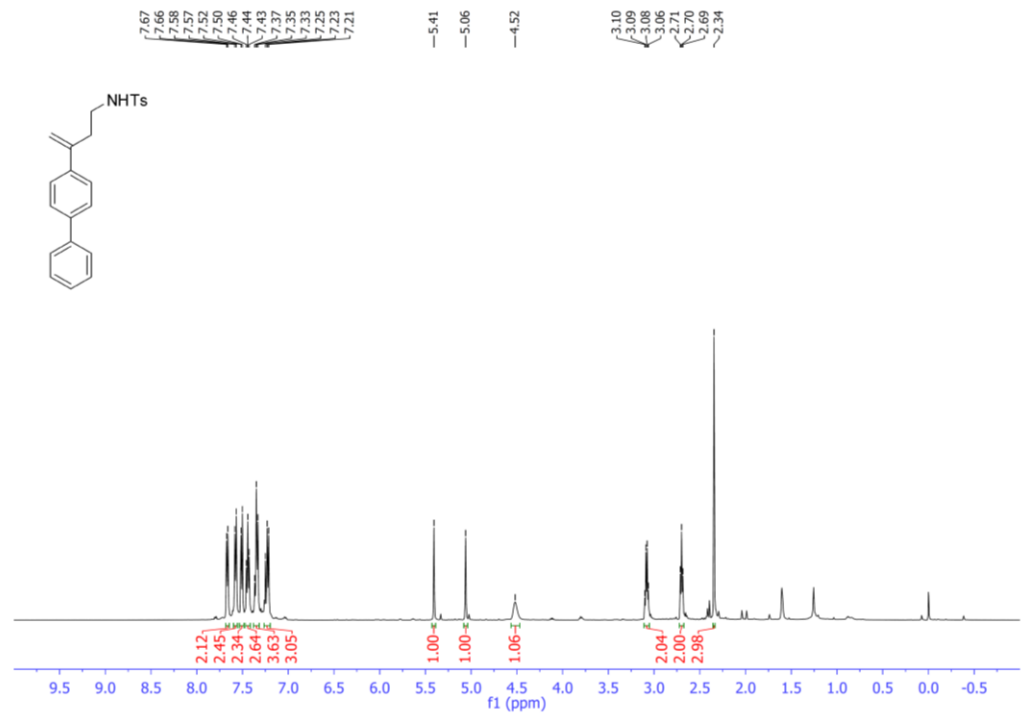


Figure A.27 Amine **8h**

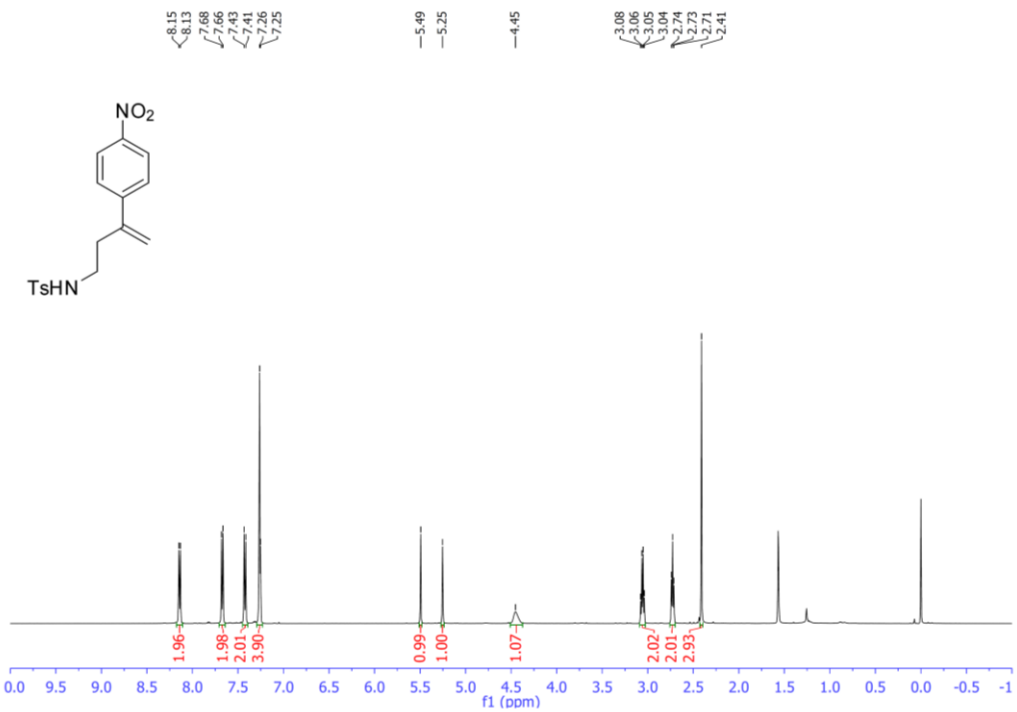


Figure A.28 Amine **8i**

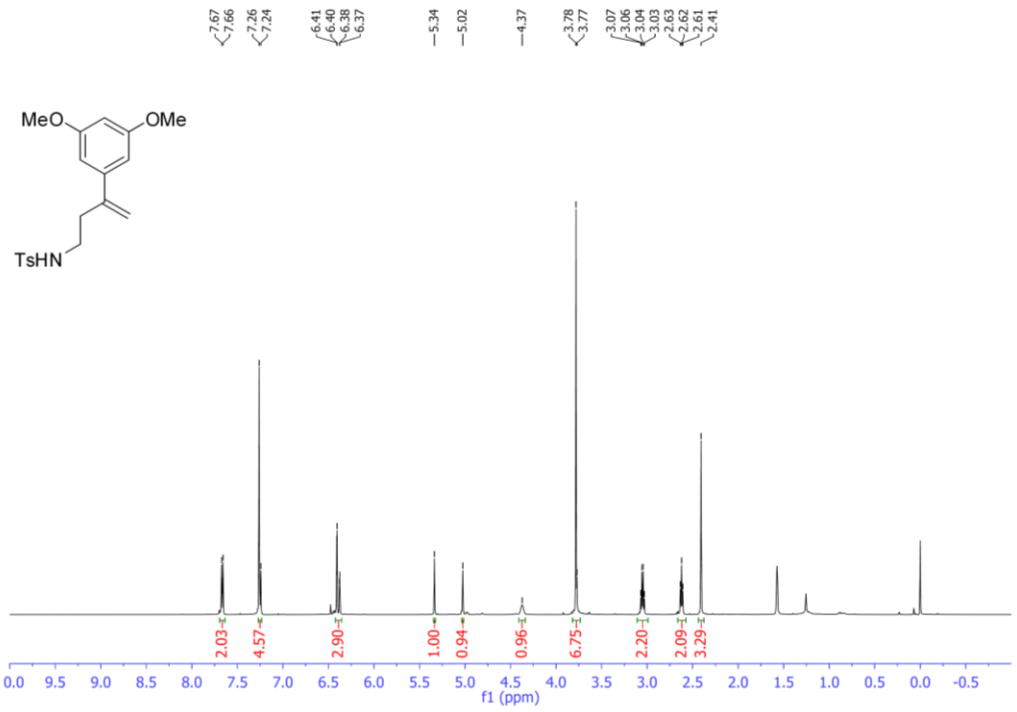


Figure A.29 Amine **8j**

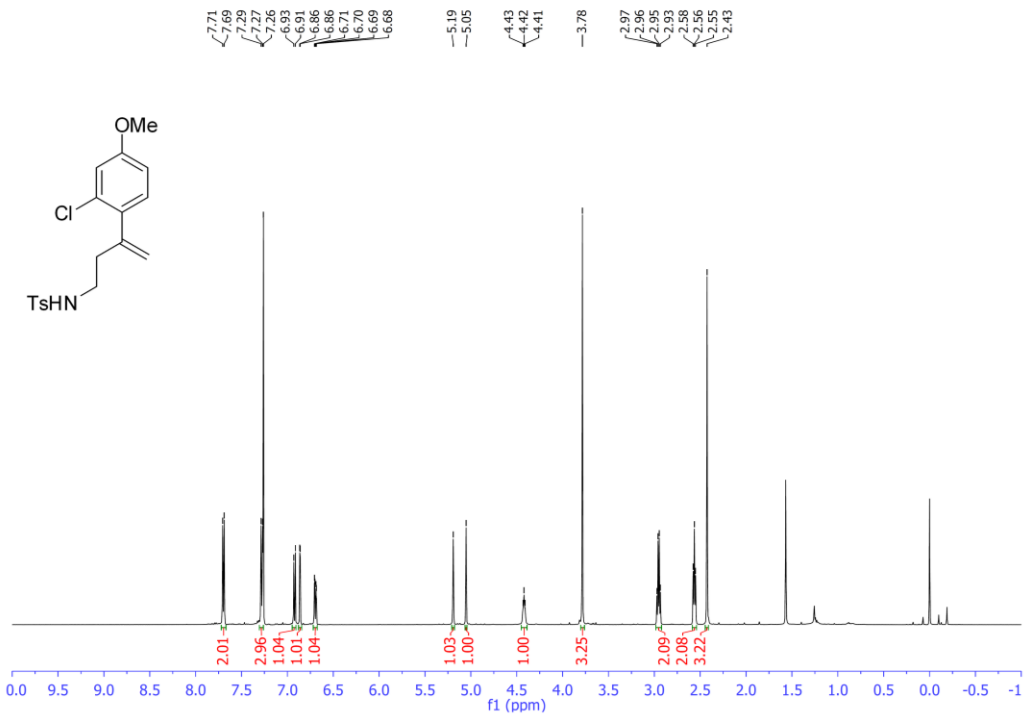


Figure A.30 Amine **8k**

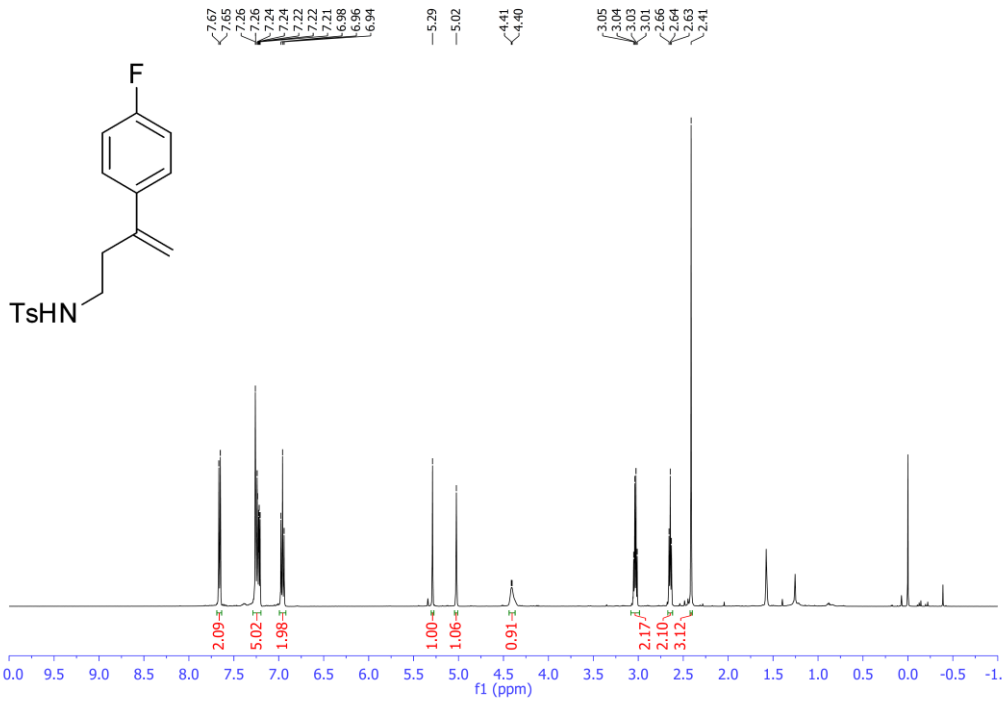


Figure A.31 Amine **8l**

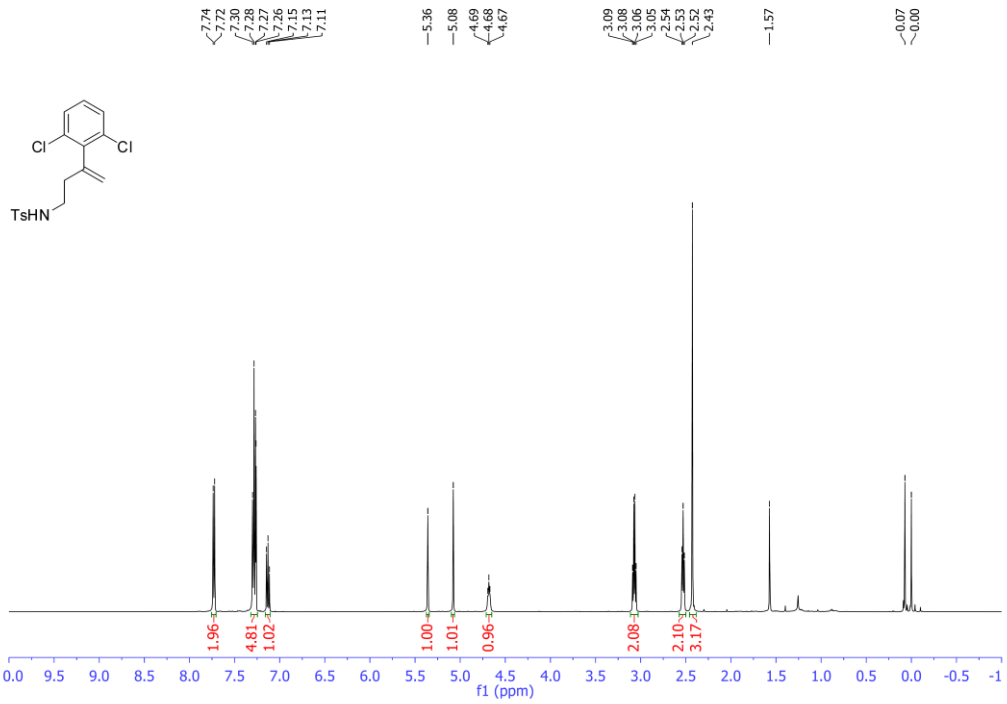


Figure A.32 Amine **8m**

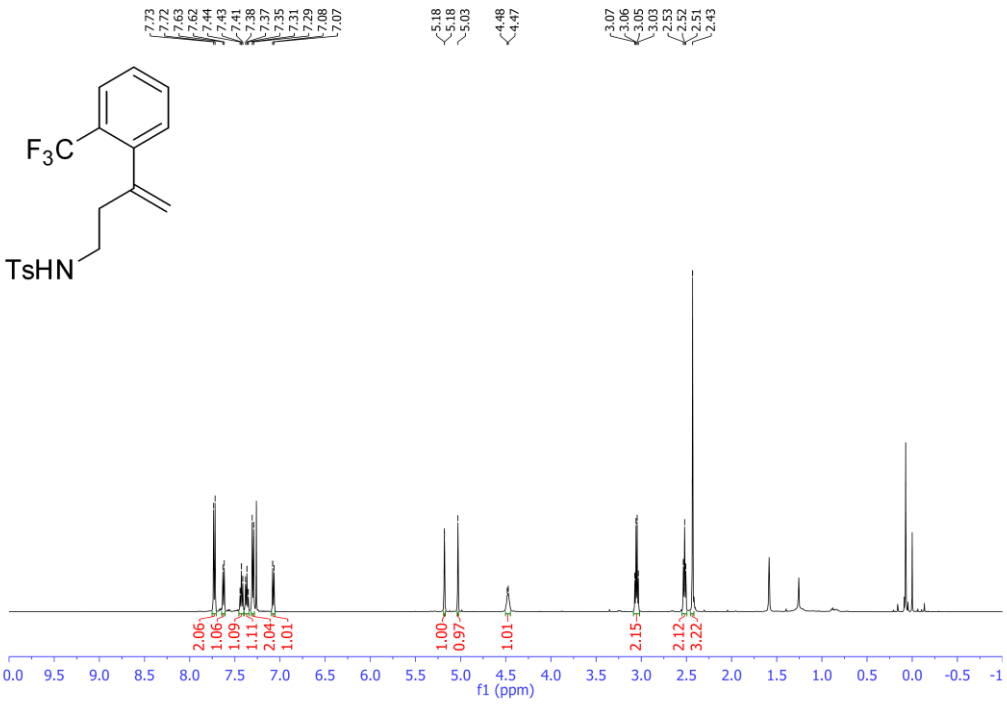


Figure A.33 Amine **8n**

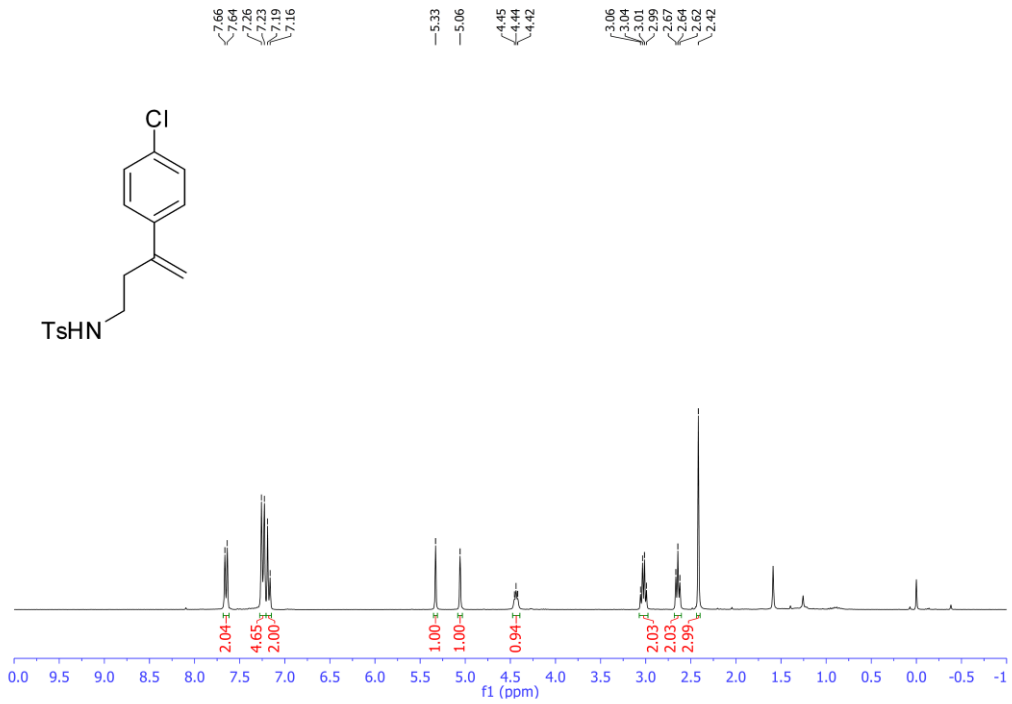


Figure A.34 Amine **8o**

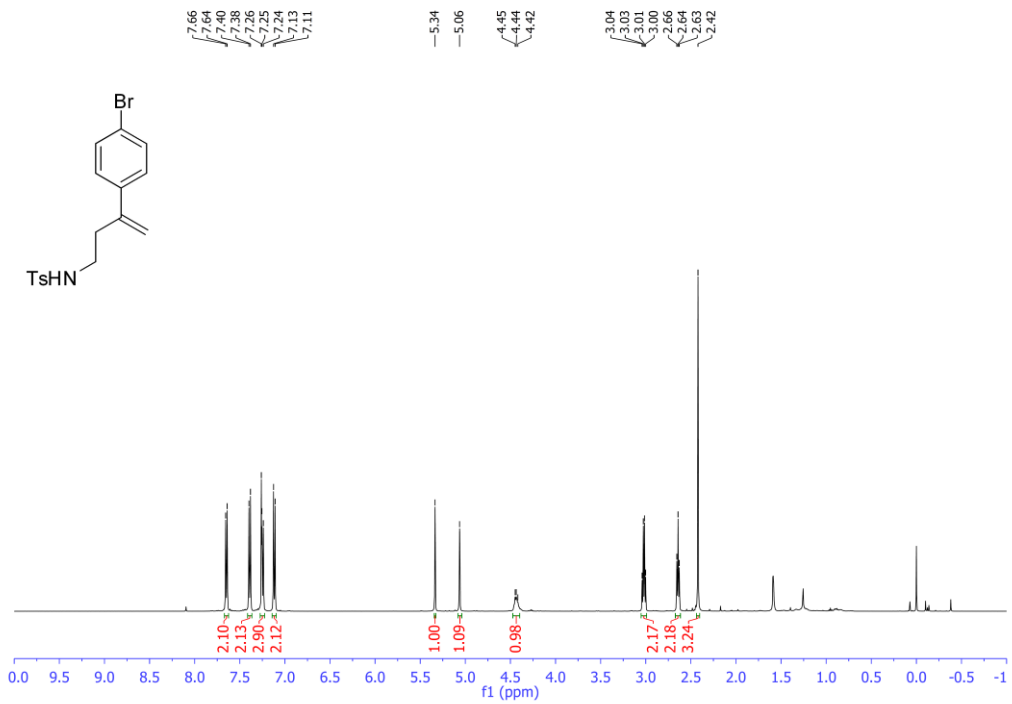


Figure A.35 Amine **8p**

A.2 ^{13}CNMR spectra

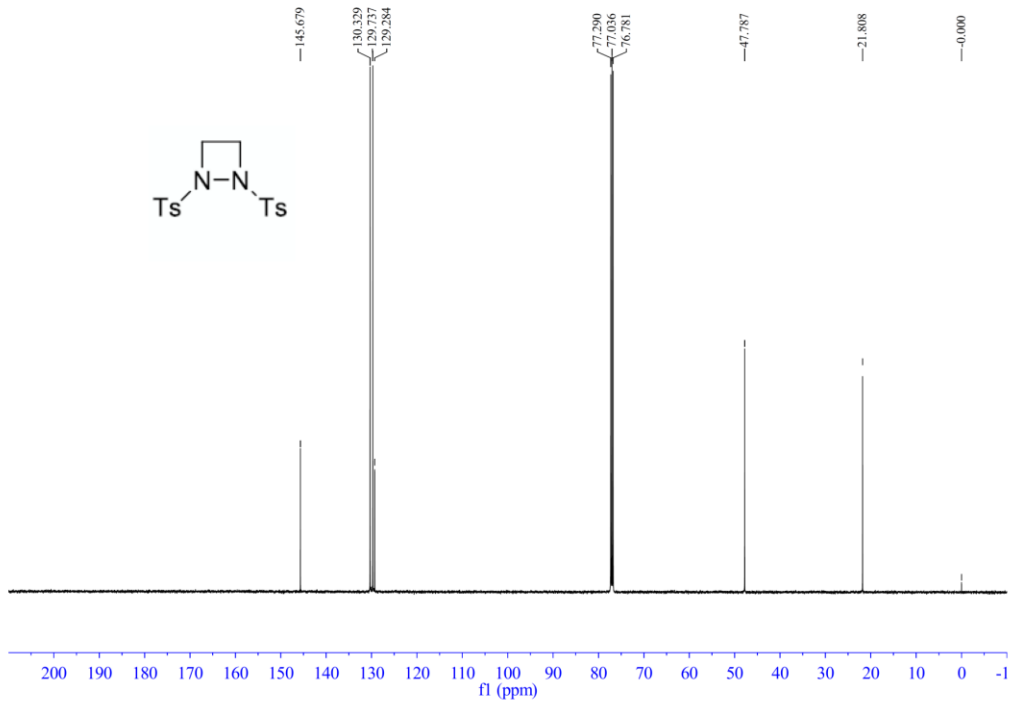


Figure A.36 Diazetidine **1**

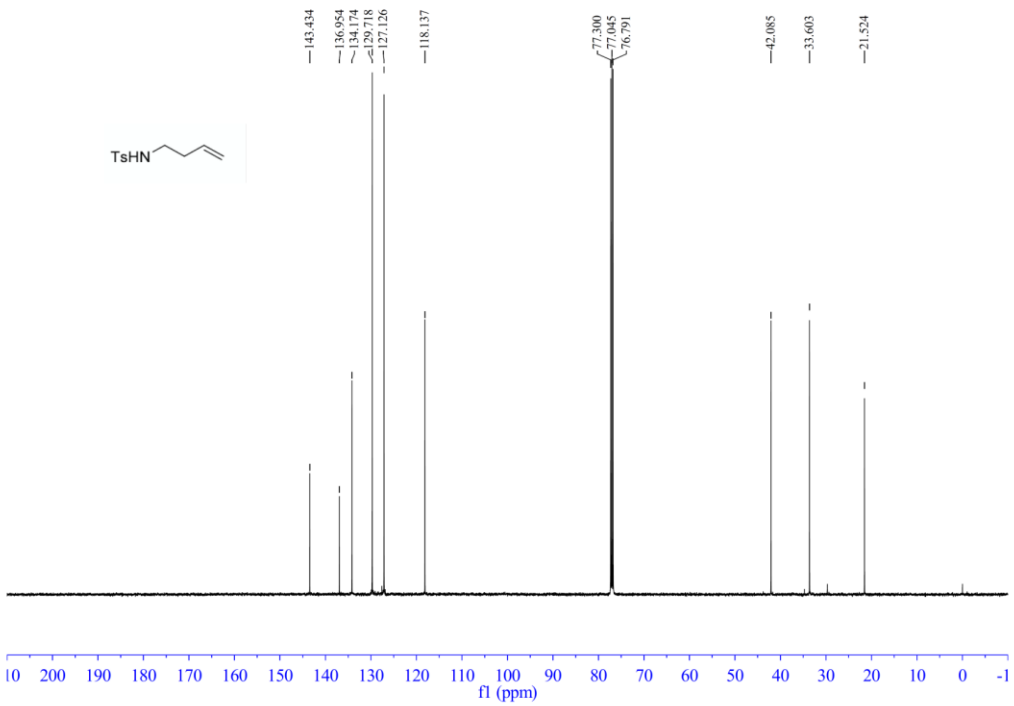


Figure A.37 Amine **4**

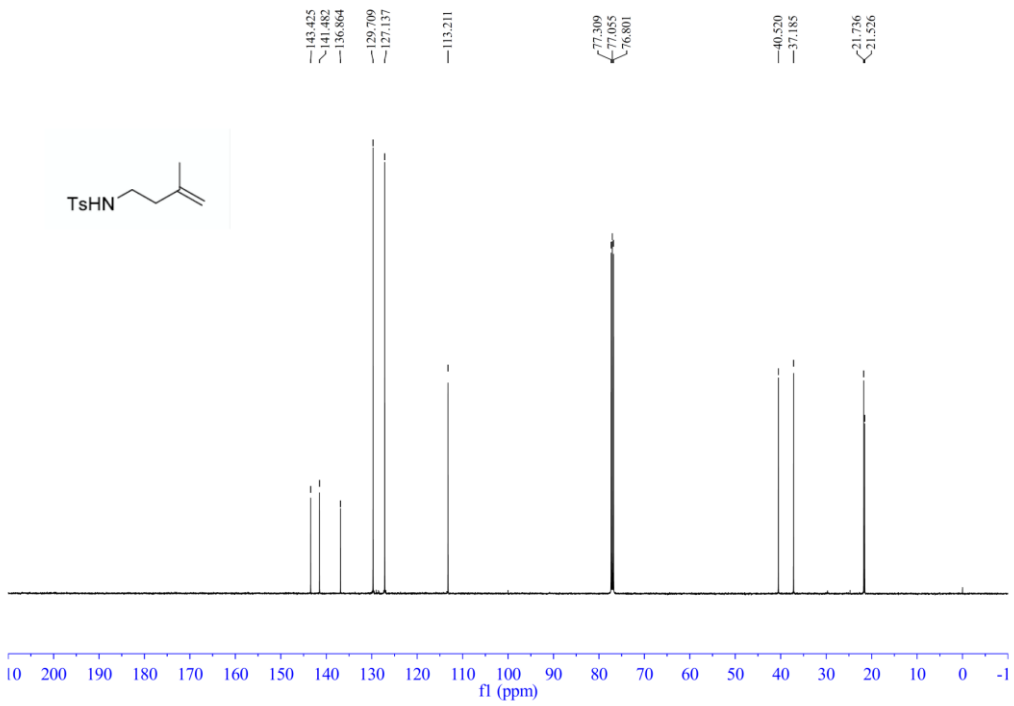


Figure A.38 Amine **6**

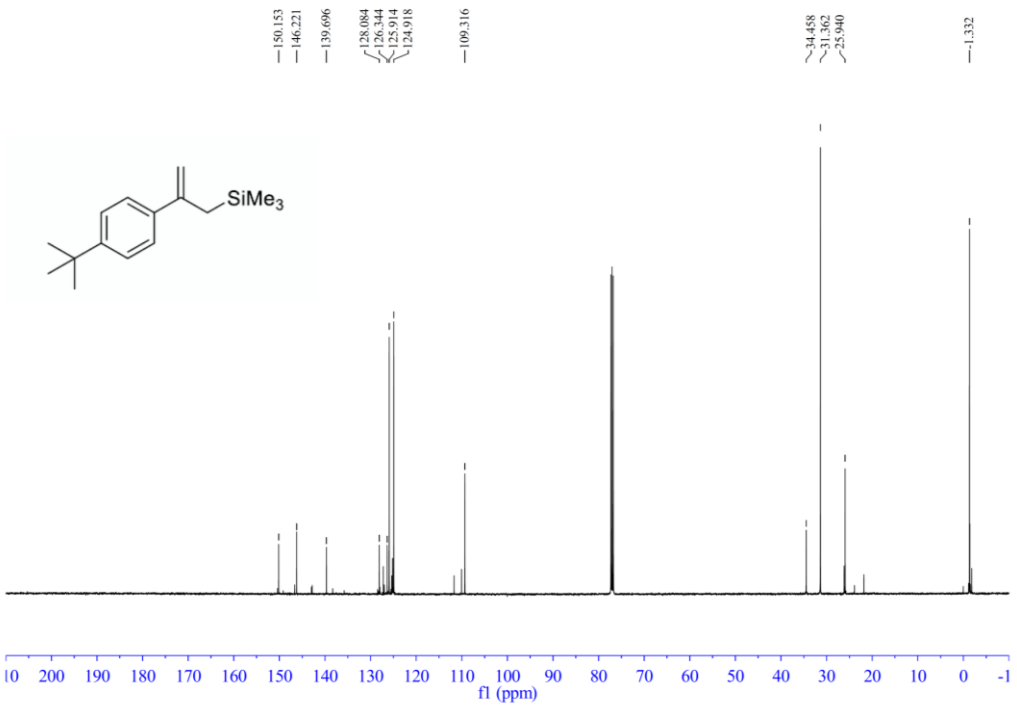


Figure A.39 Amine **8b**

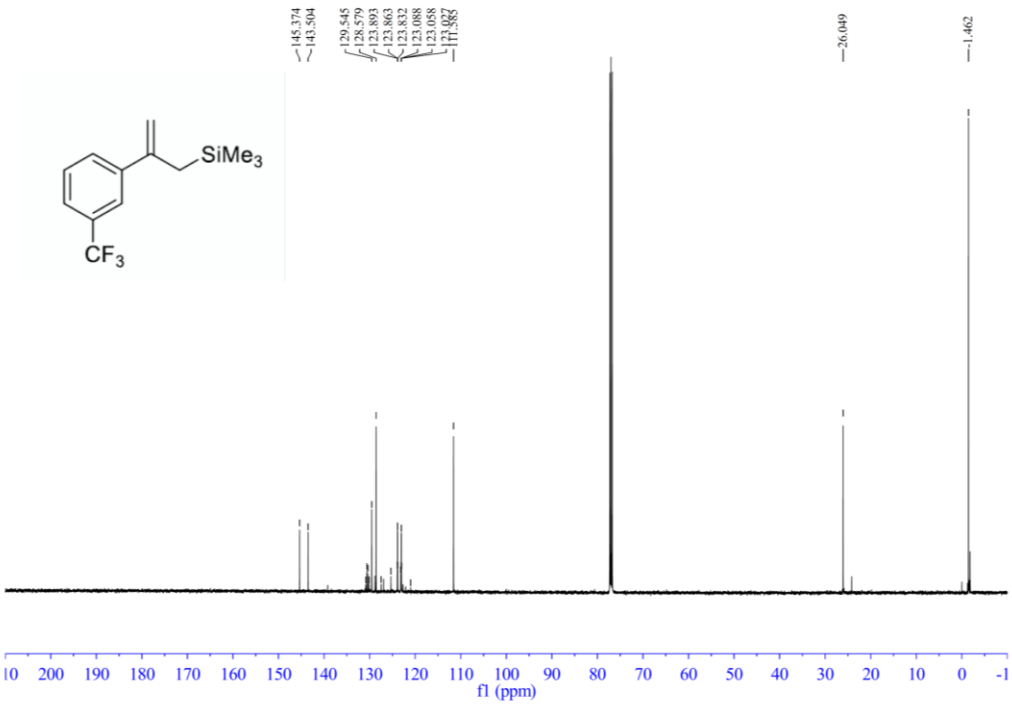


Figure A.40 Silane **7c**

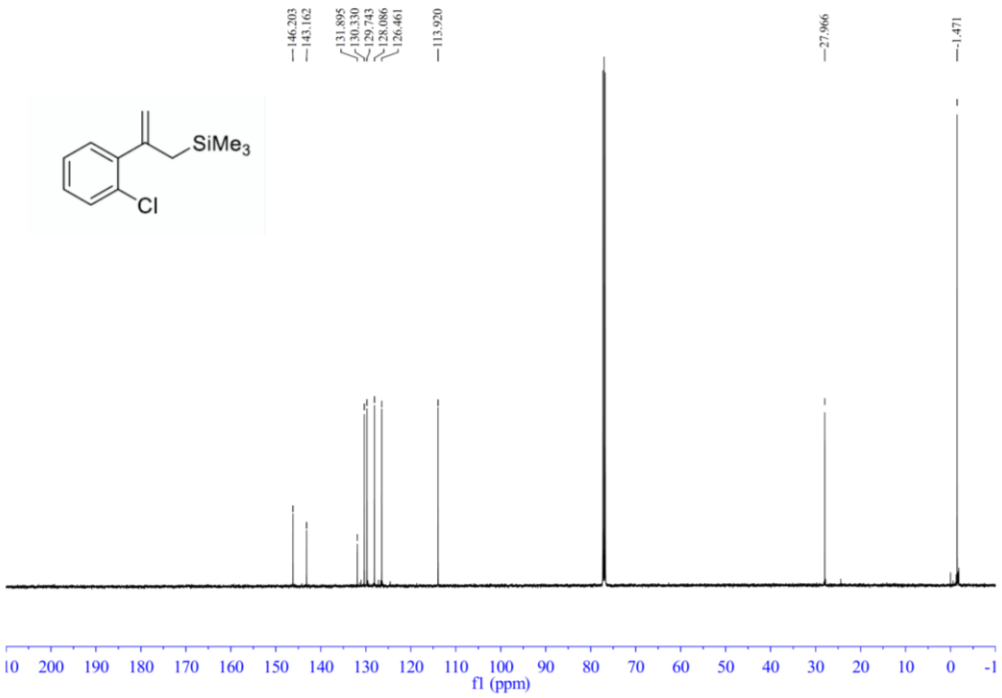


Figure A.41 Silane **7d**

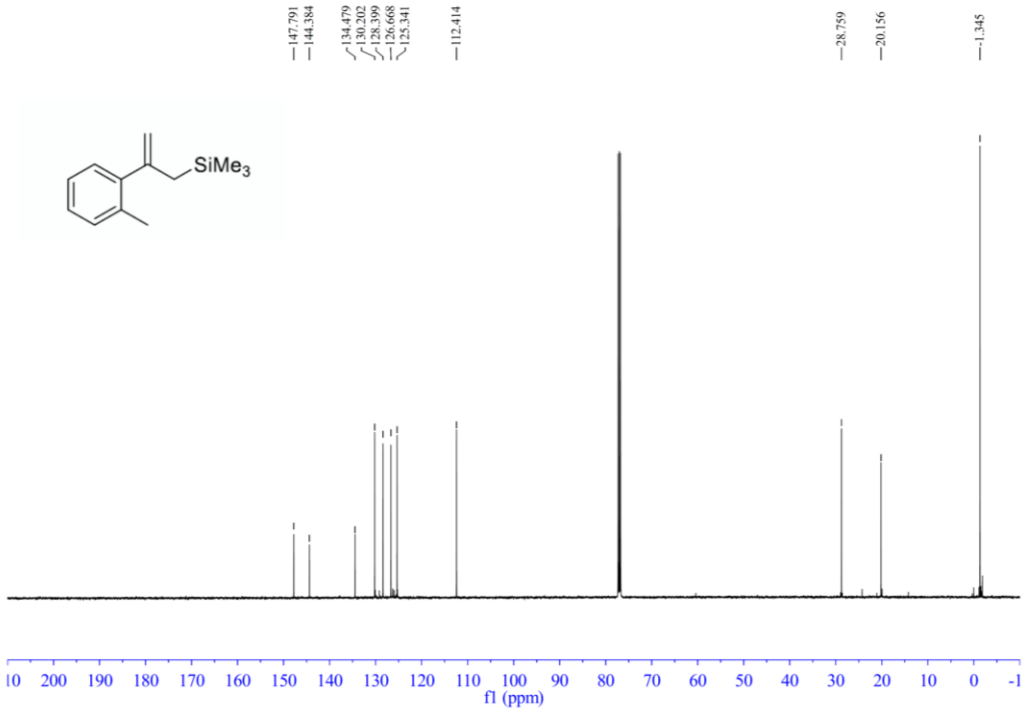


Figure A.42 Silane **7e**

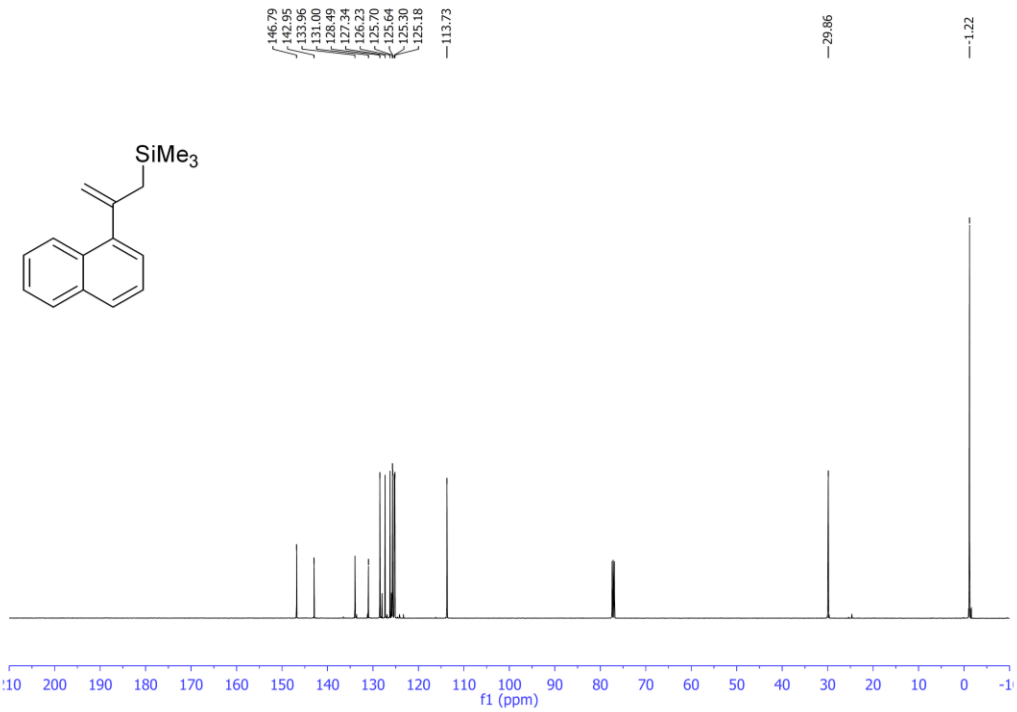


Figure A.43 Silane **7f**

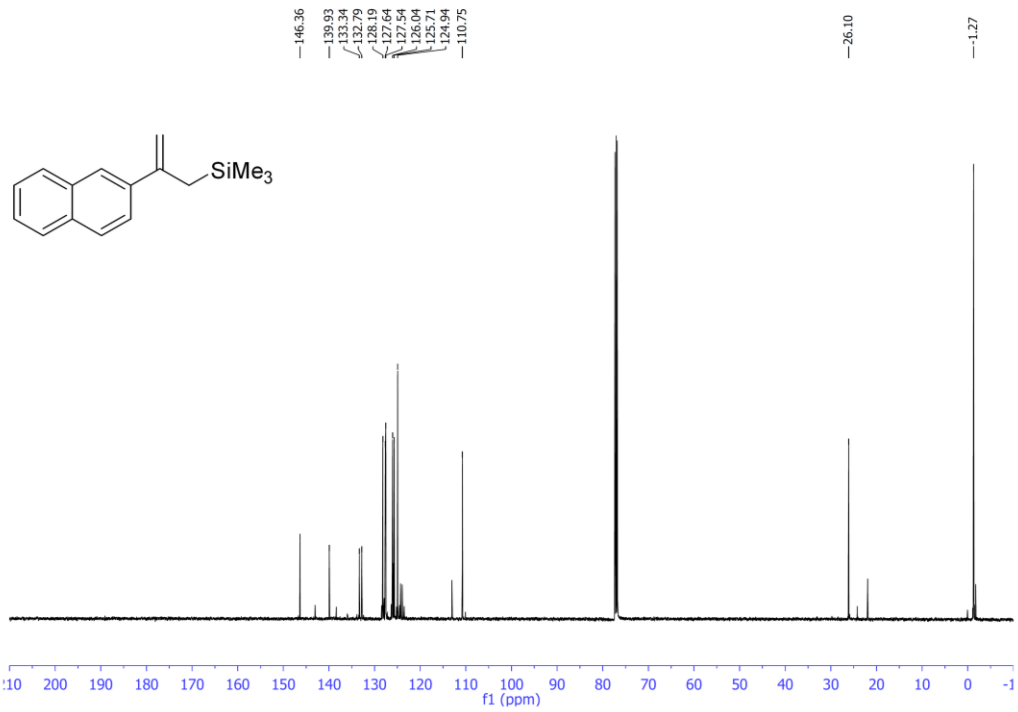


Figure A.44 Silane **7g**

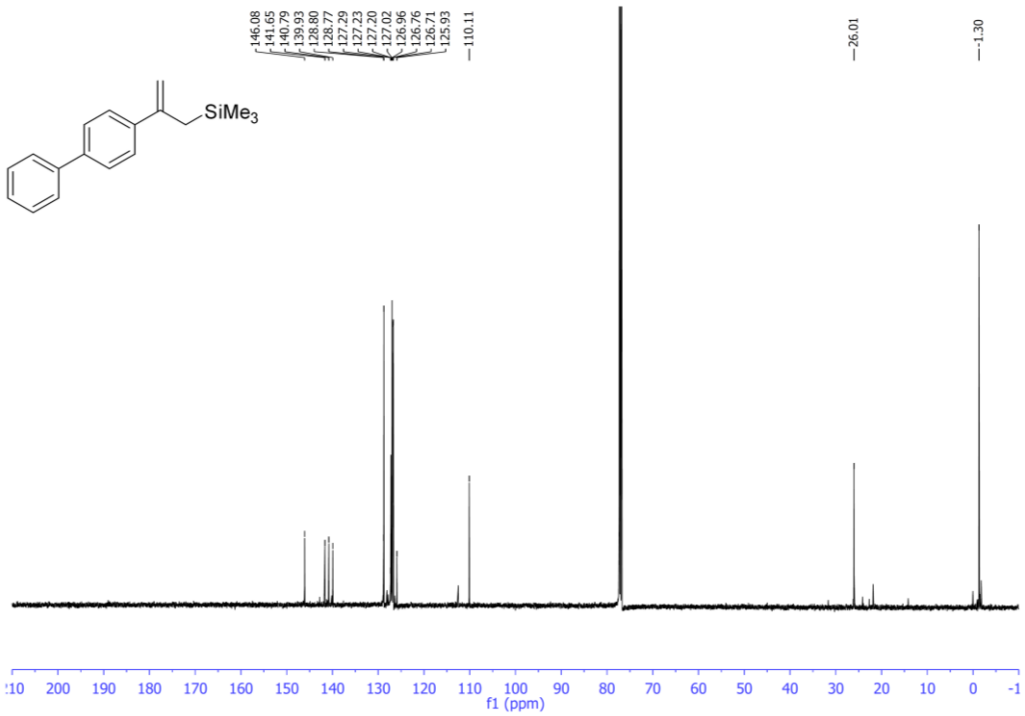


Figure A.45 Silane **7h**

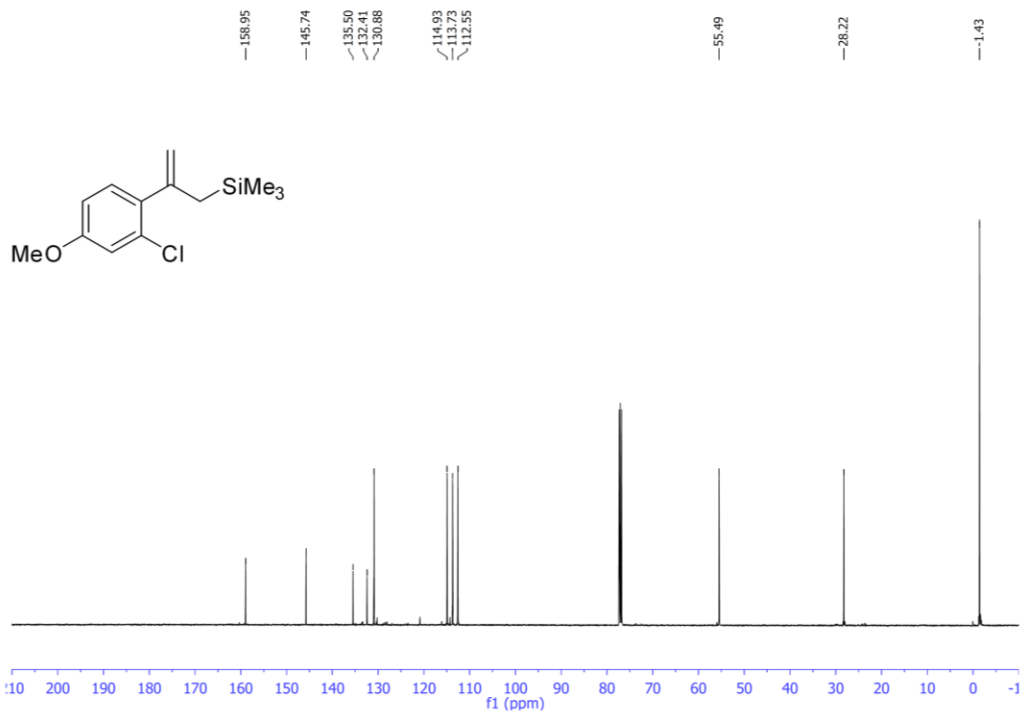


Figure A.46 Silane **7i**

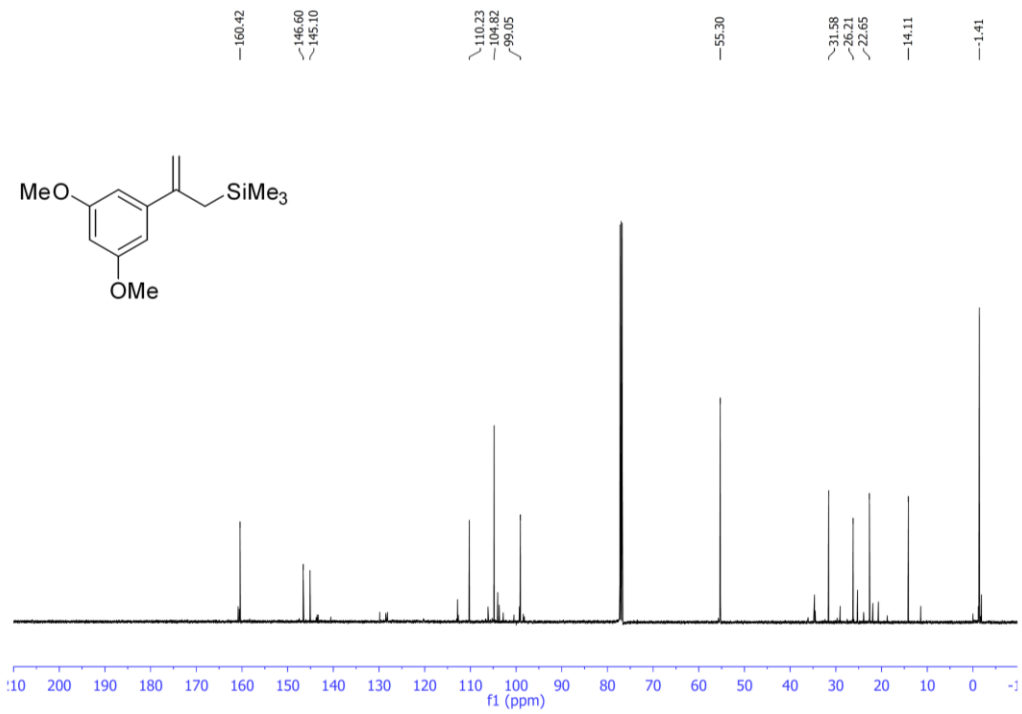


Figure A.47 Silane **7j**

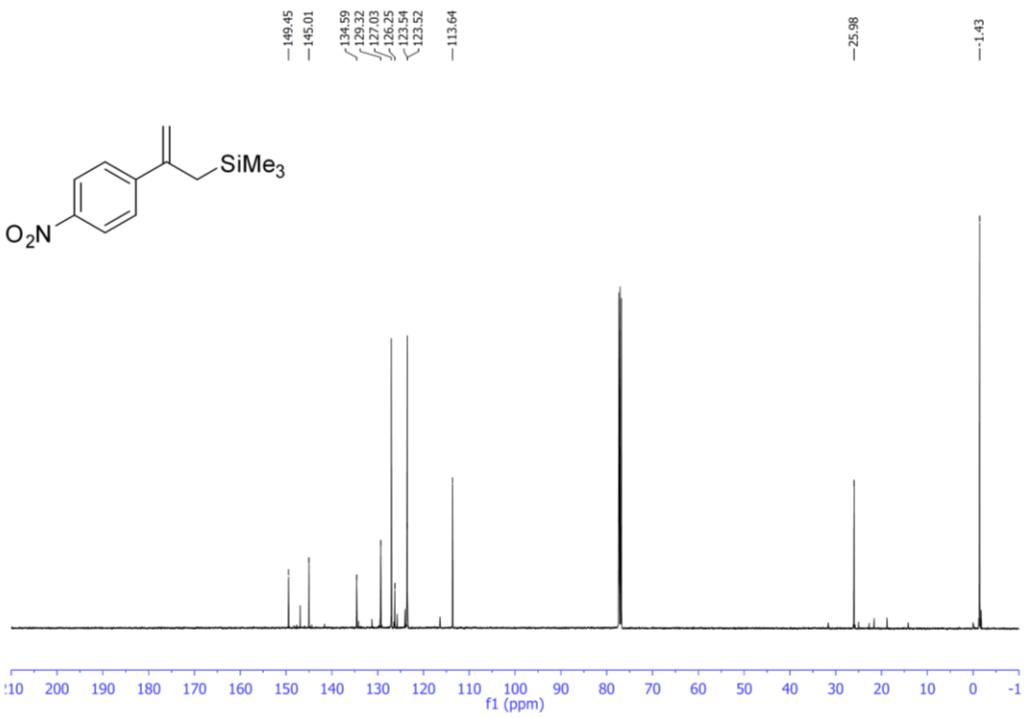


Figure A.48 Silane **7k**

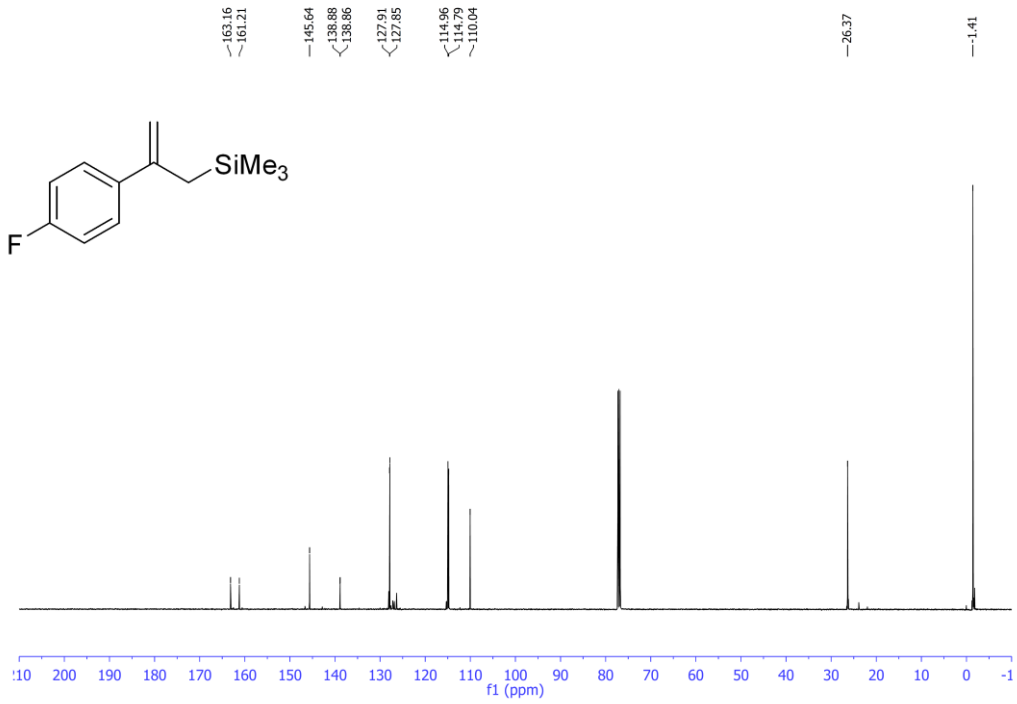


Figure A.49 Silane **7l**

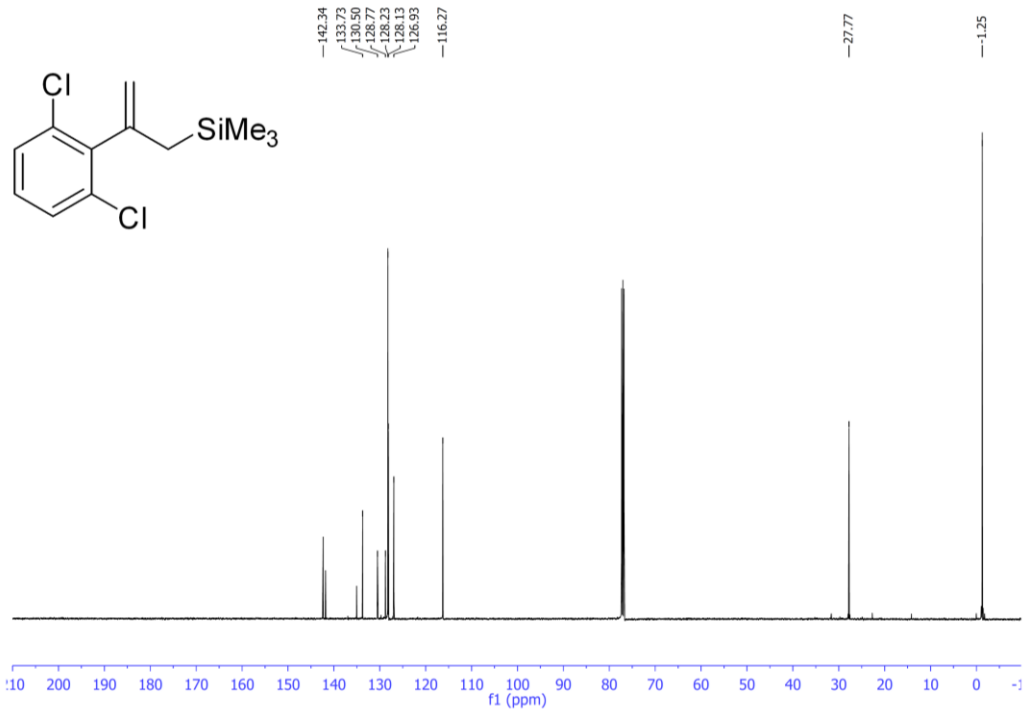


Figure A.50 Silane **7m**

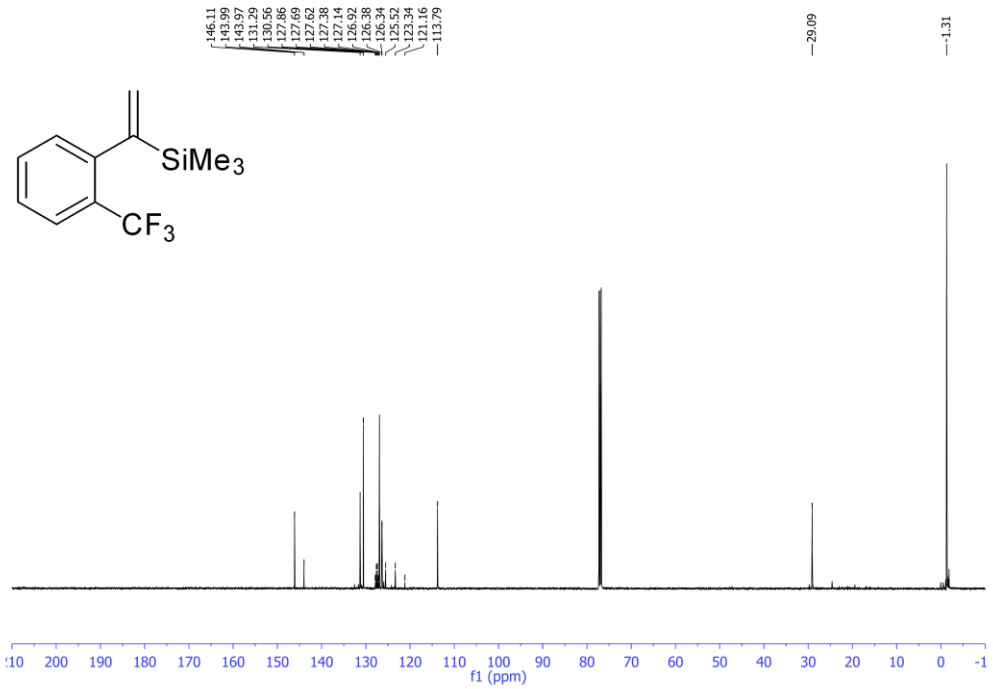


Figure A.51 Silane **7n**

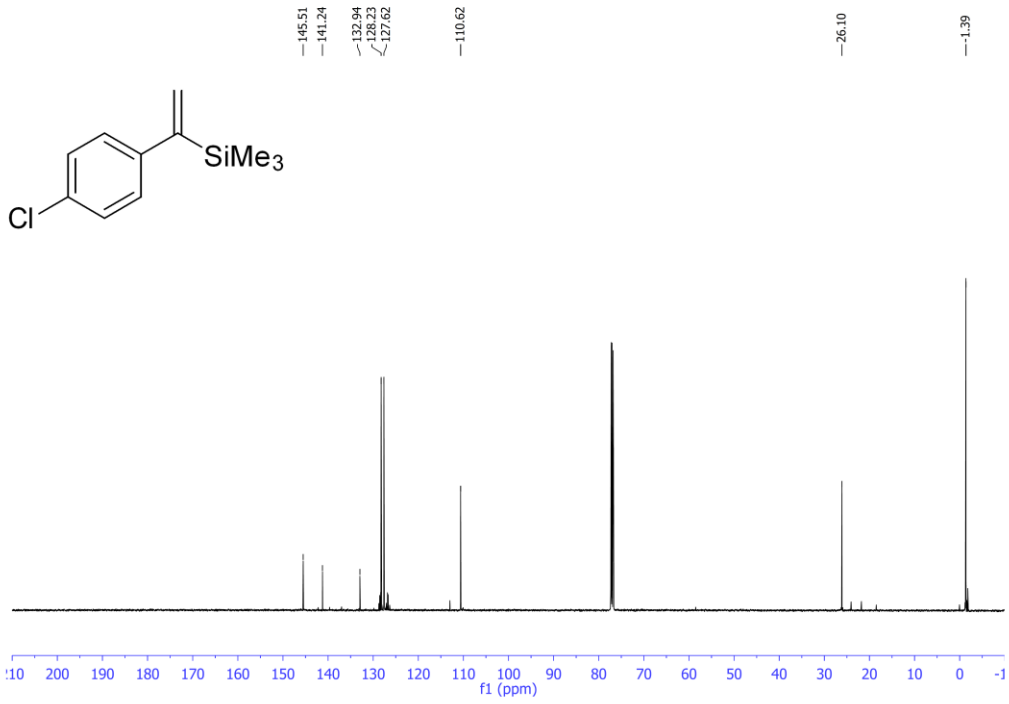


Figure A.52 Silane **7o**

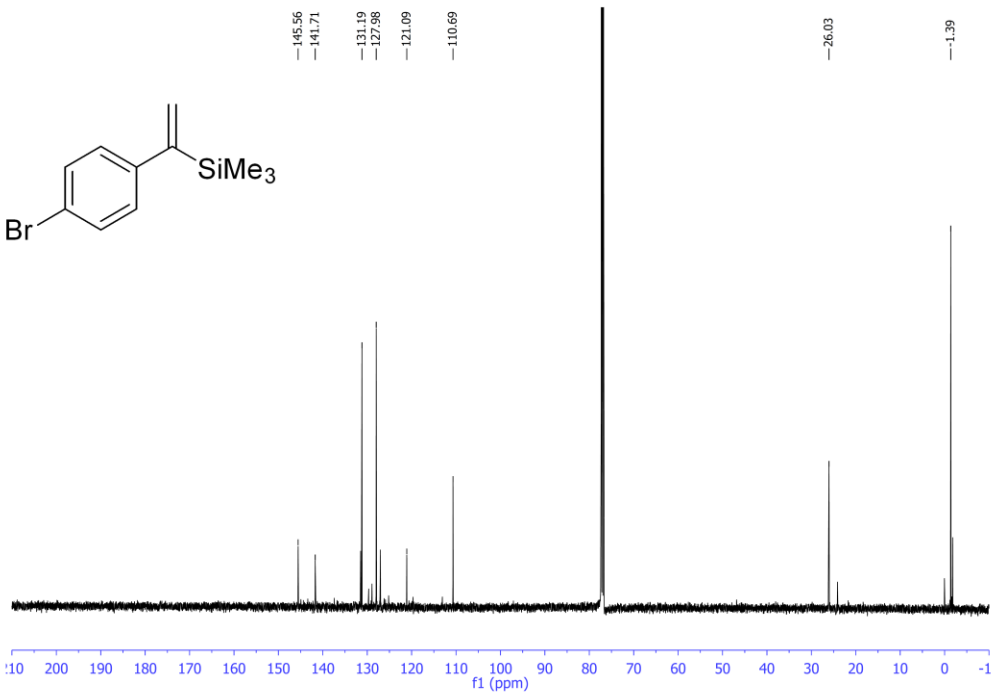


Figure A.53 Silane **7p**

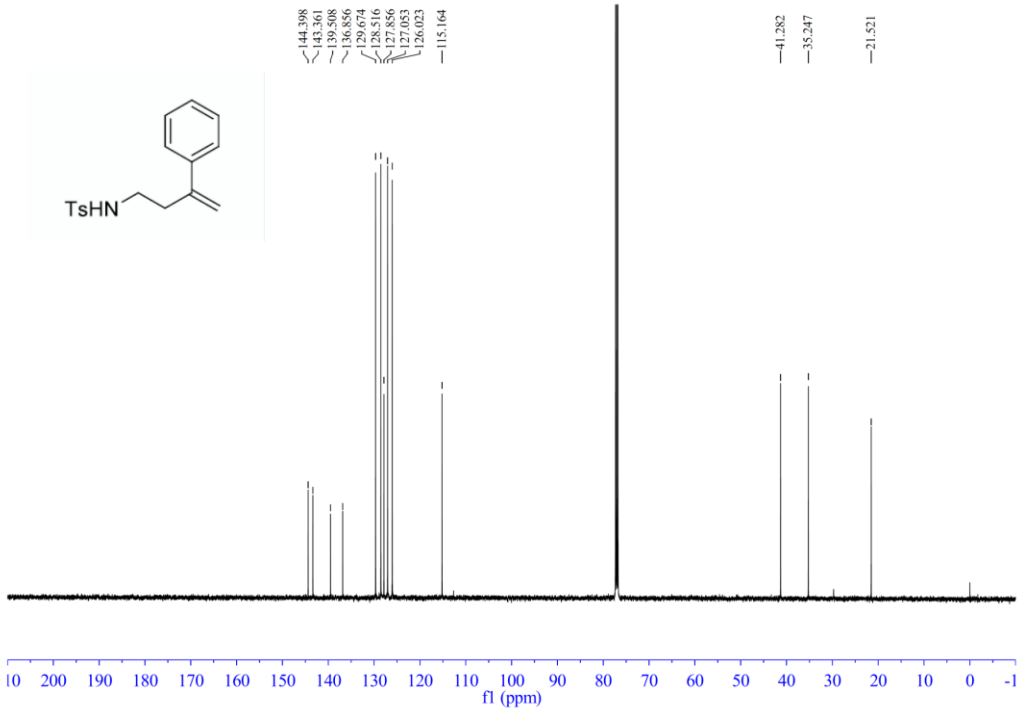


Figure A.54 Amine **8a**

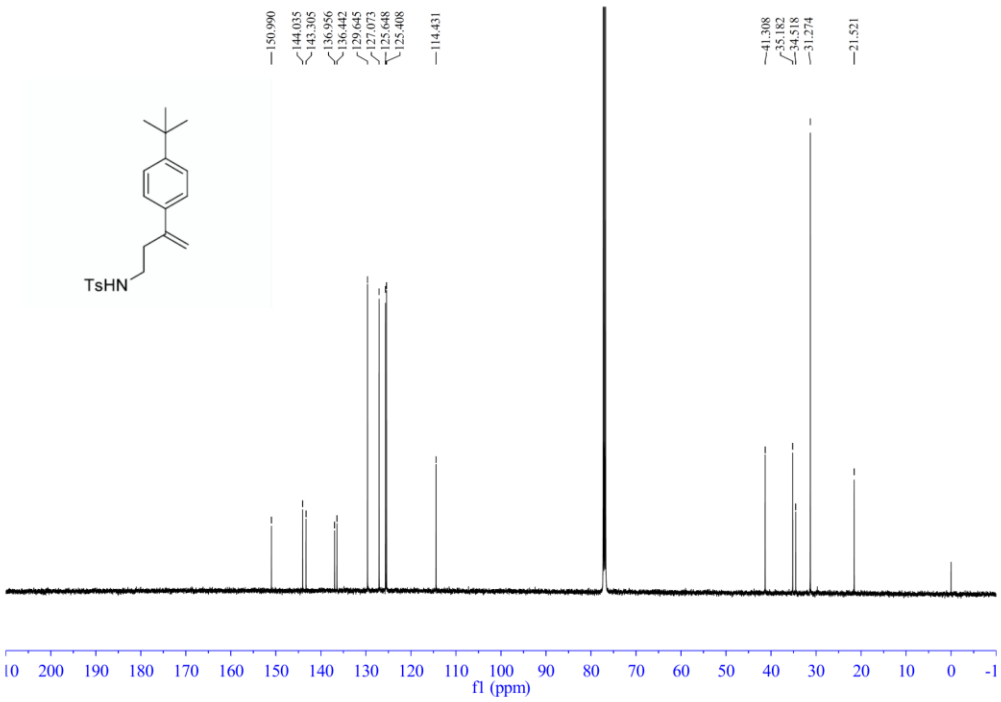


Figure A.55 Amine **8b**

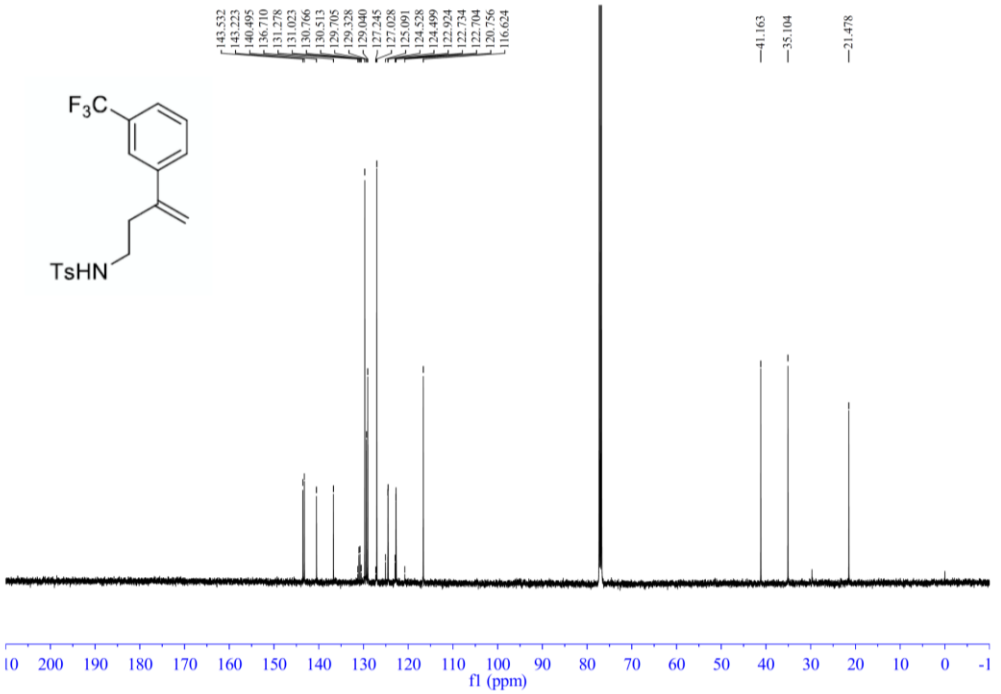


Figure A.56 Amine **8c**

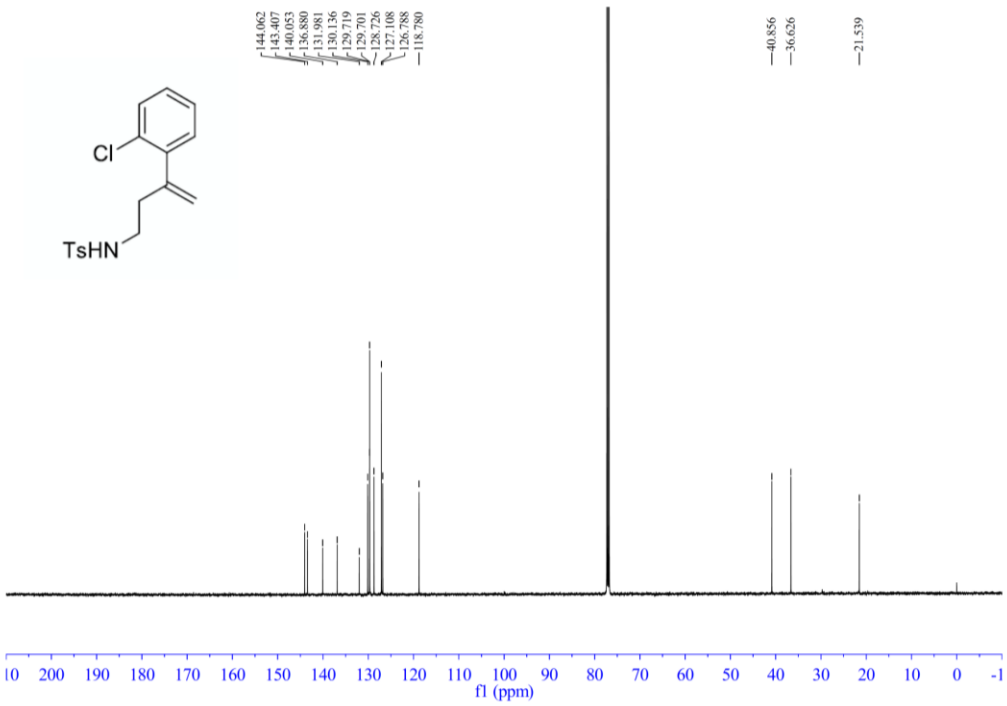


Figure A.57 Amine **8d**

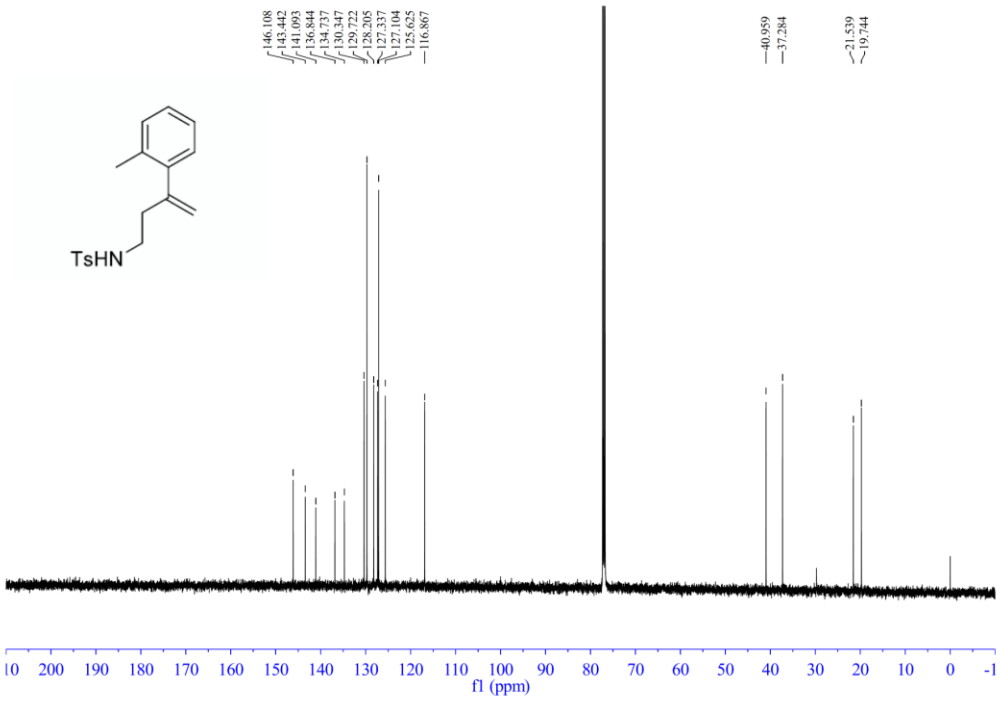


Figure A.58 Amine **8e**

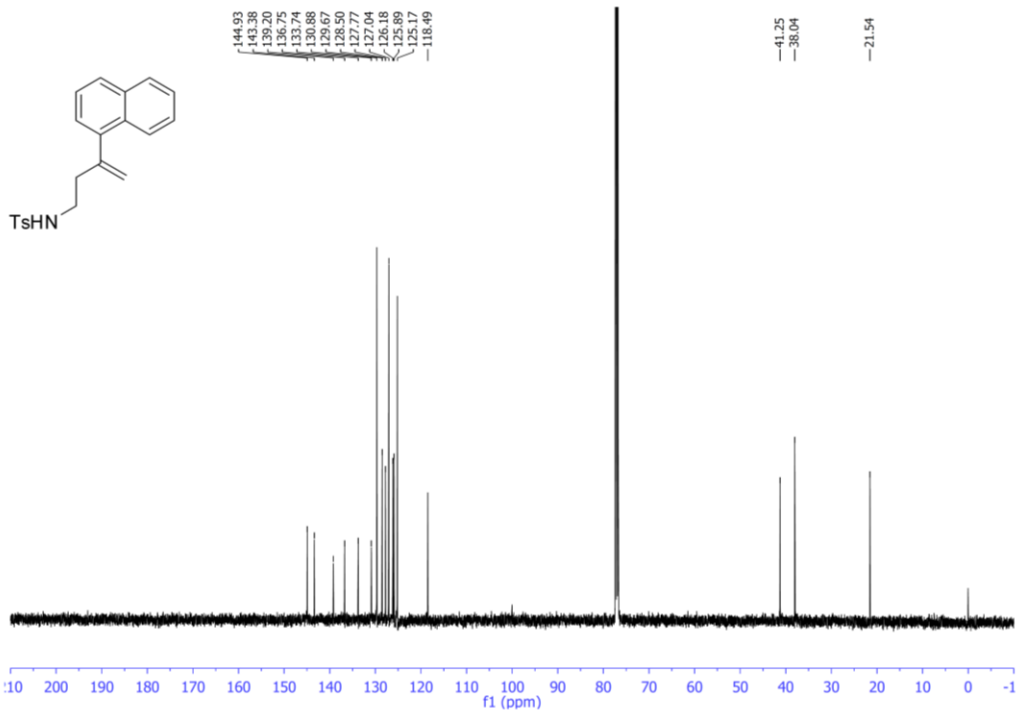


Figure A.59 Amine **8f**

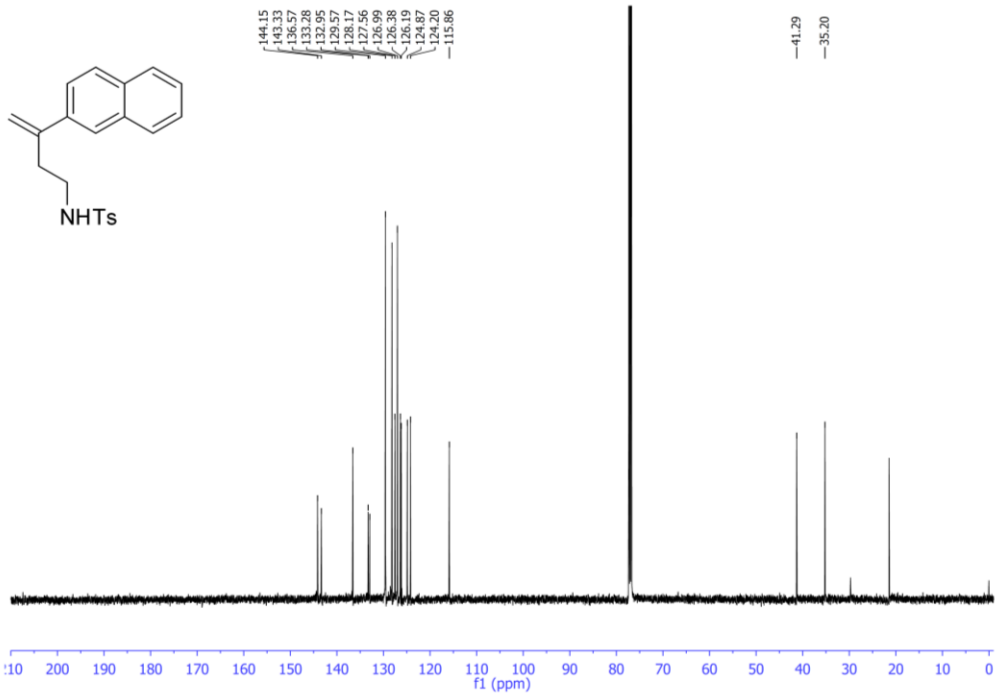


Figure A.60 Amine **8g**

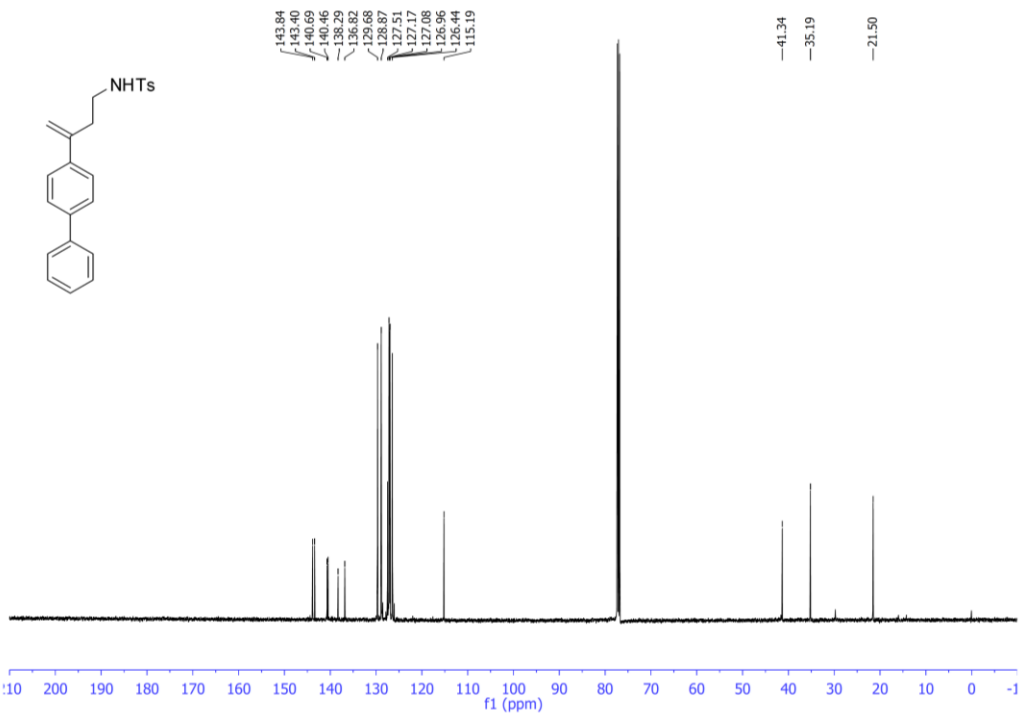


Figure A.61 Amine **8h**

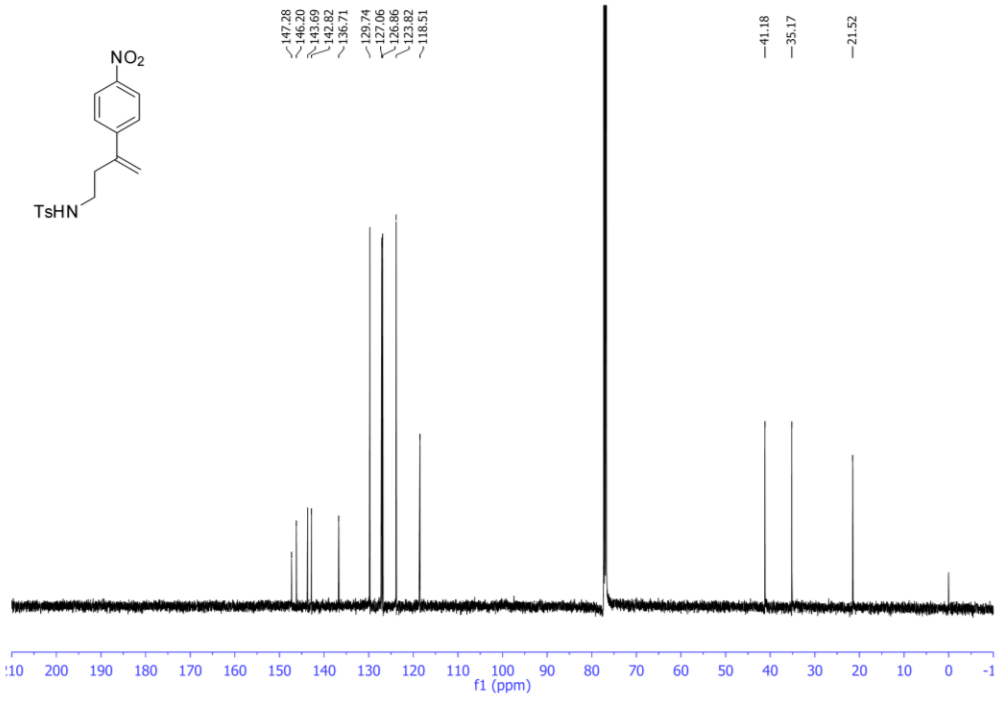


Figure A.62 Amine **8i**

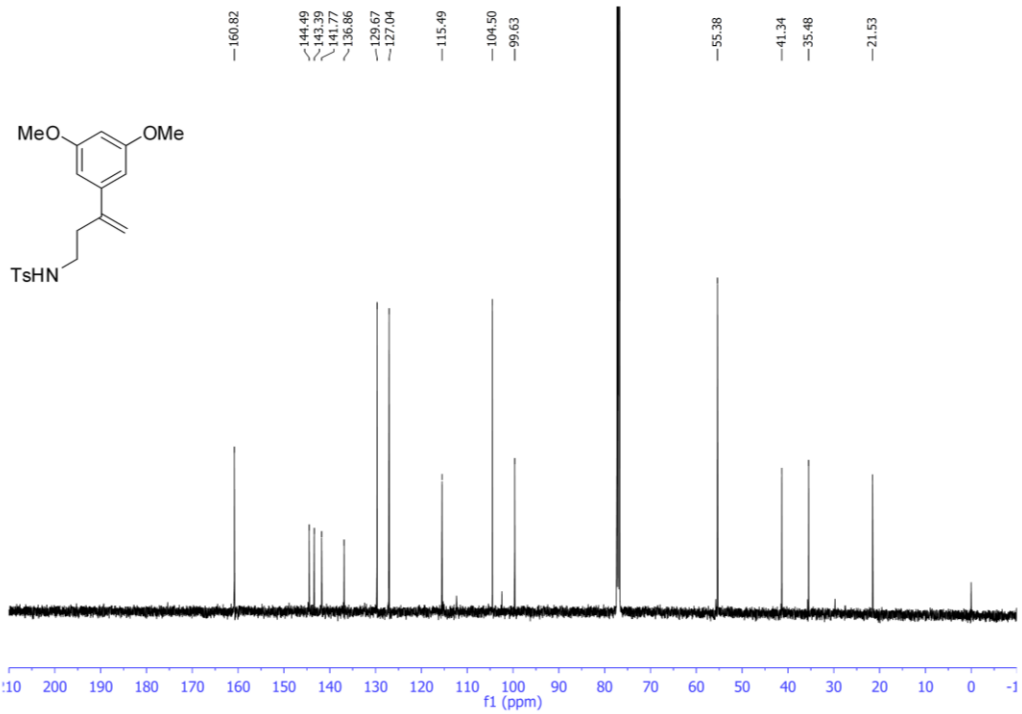


Figure A.63 Amine **8j**

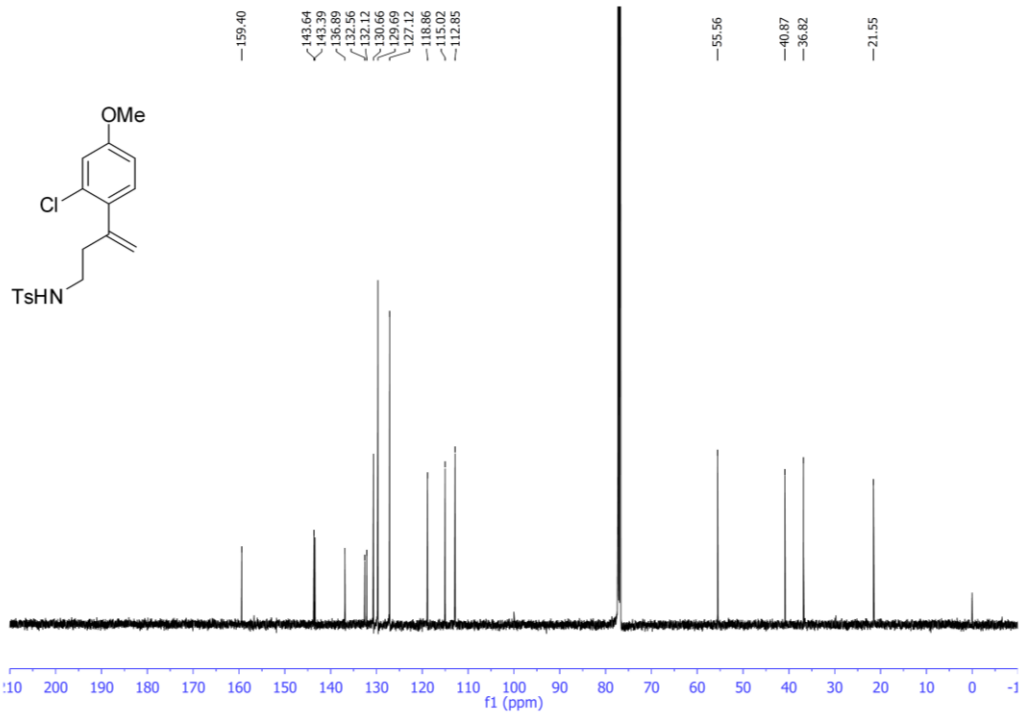


Figure A.64 Amine **8k**

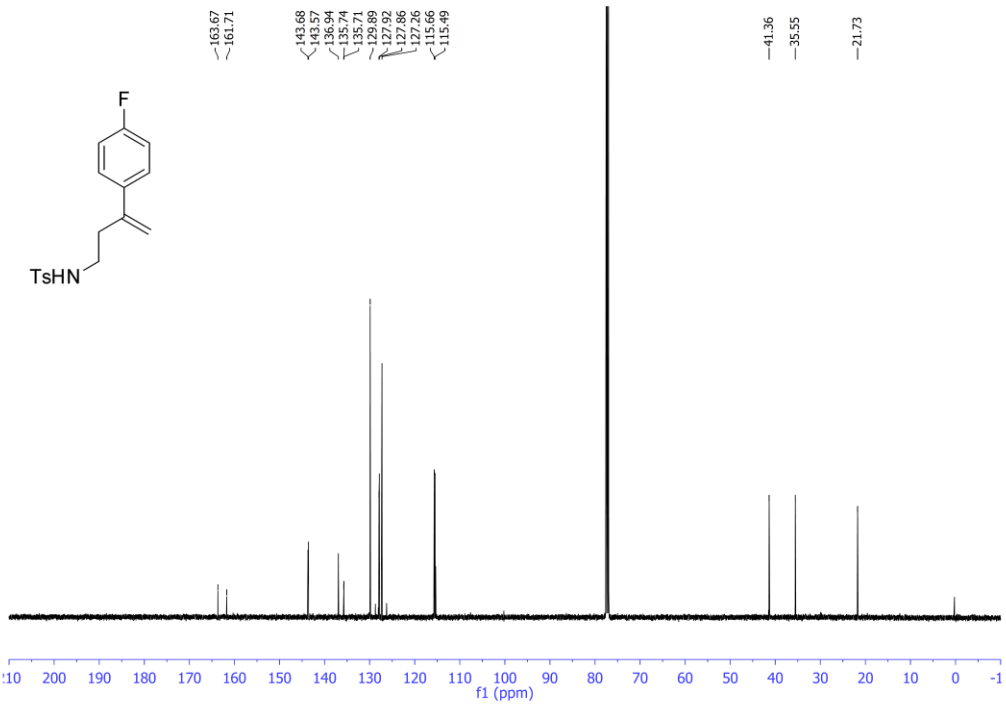


Figure A.65 Amine **8l**

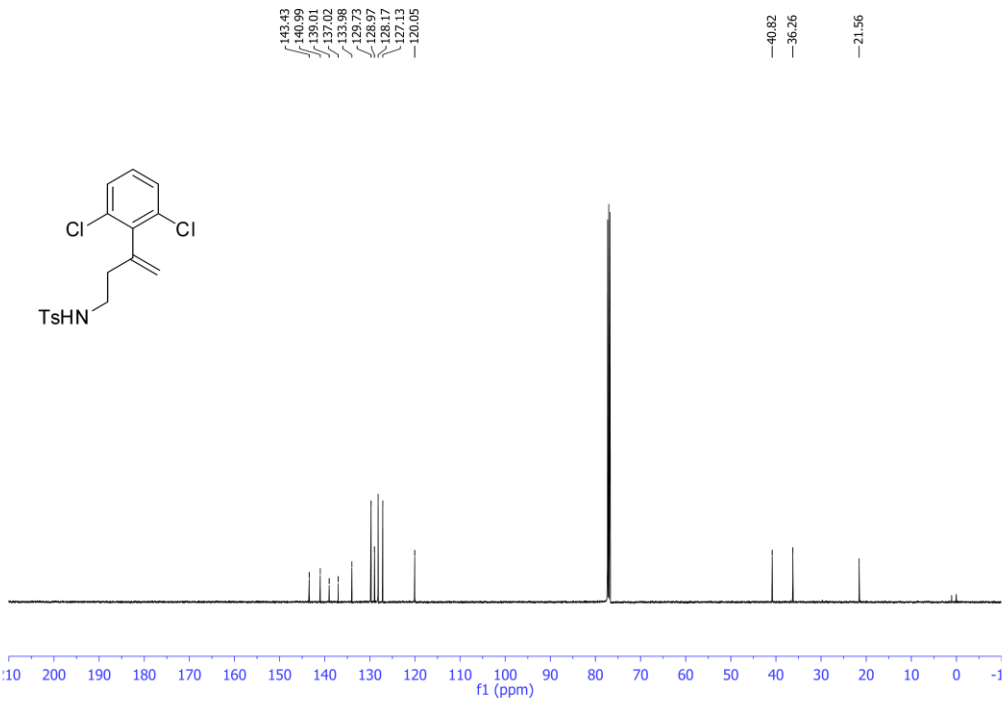


Figure A.66 Amine **8m**

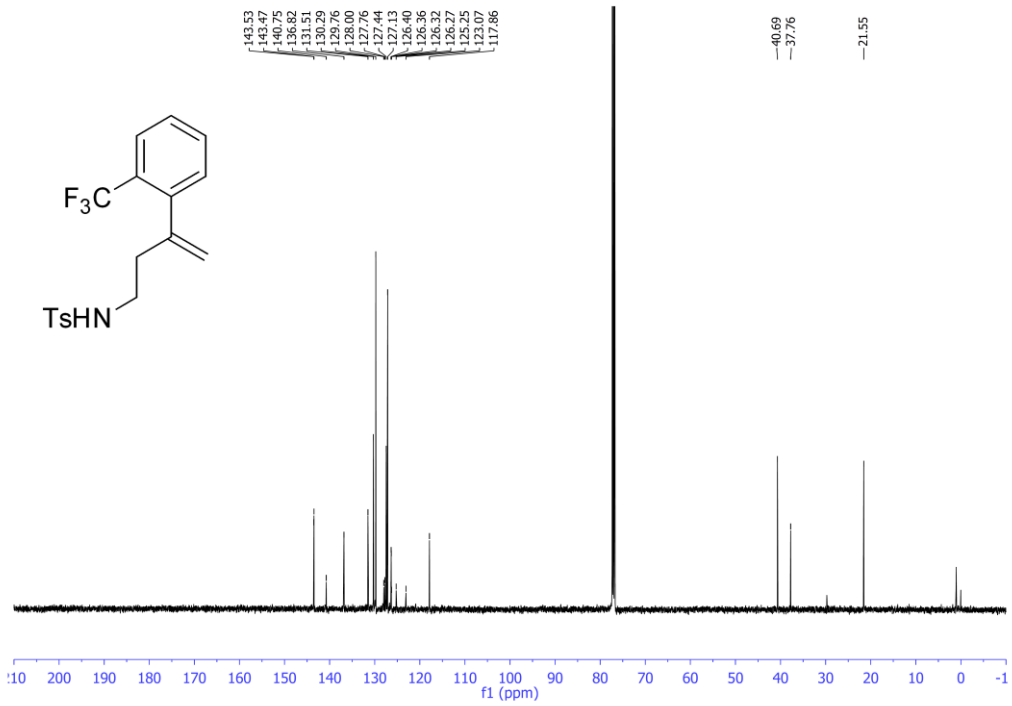


Figure A.67 Amine **8n**

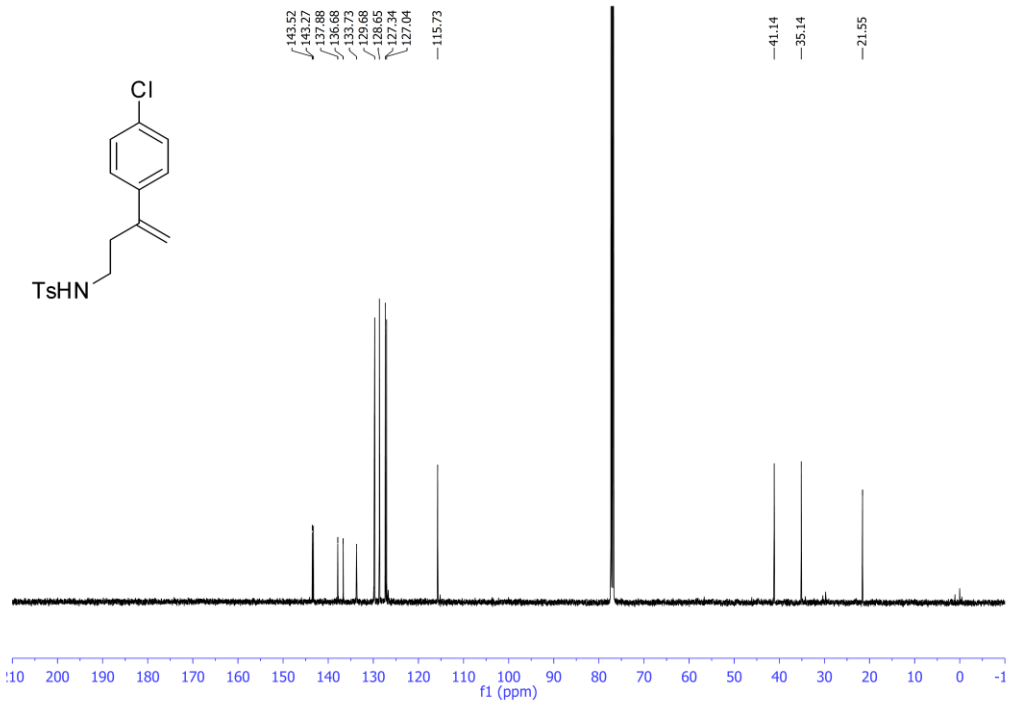


Figure A.68 Amine **8o**

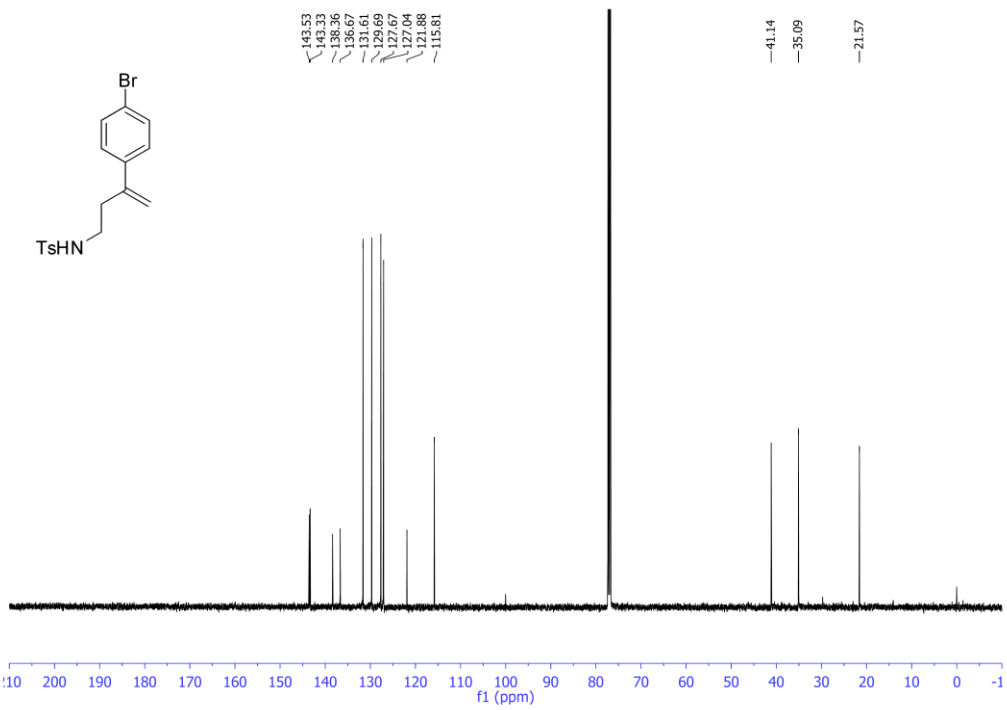


Figure A.69 Amine **8p**

APPENDIX B

SPECTRA FOR RUTHENIUM COMPLEXES

B.1 1HNMR spectra

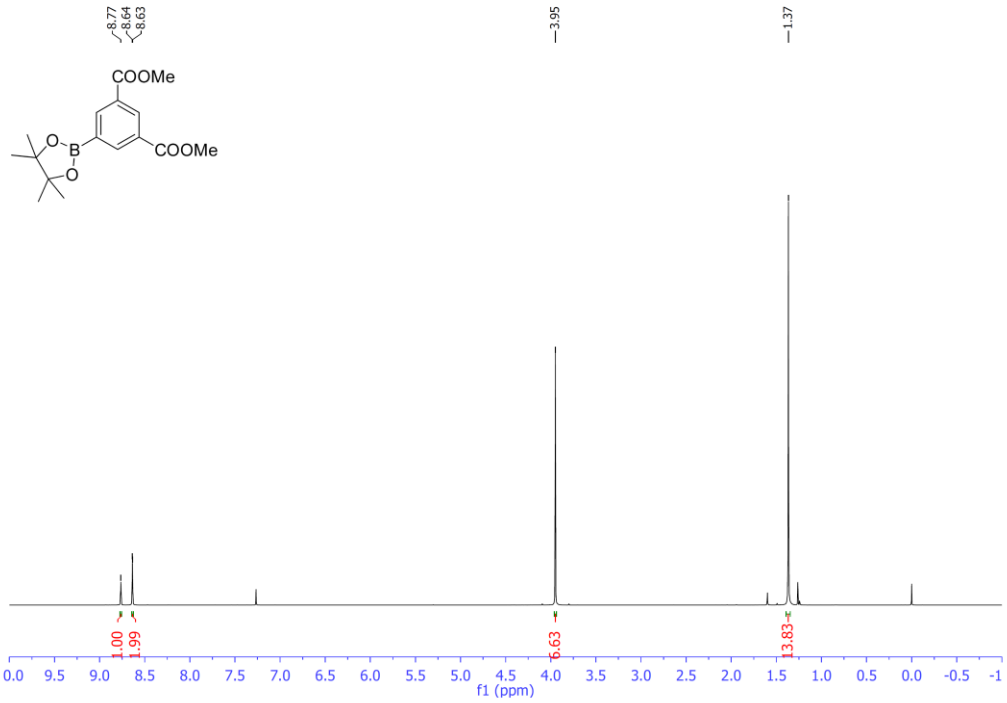


Figure B.1 Intermediate **1**

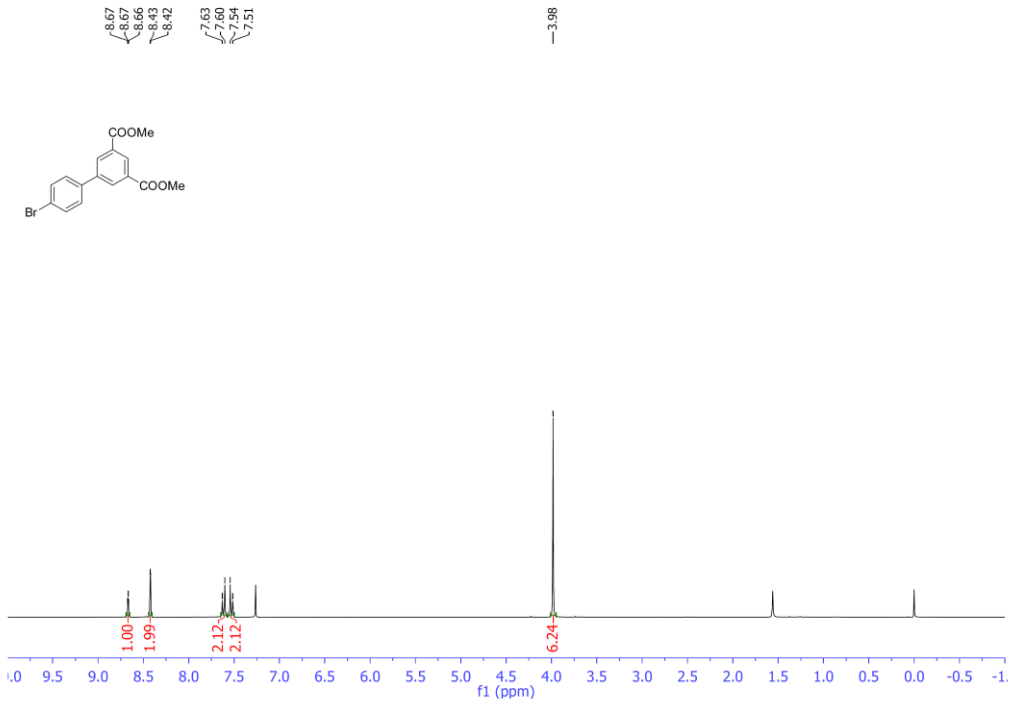


Figure B.2 Intermediate **2**

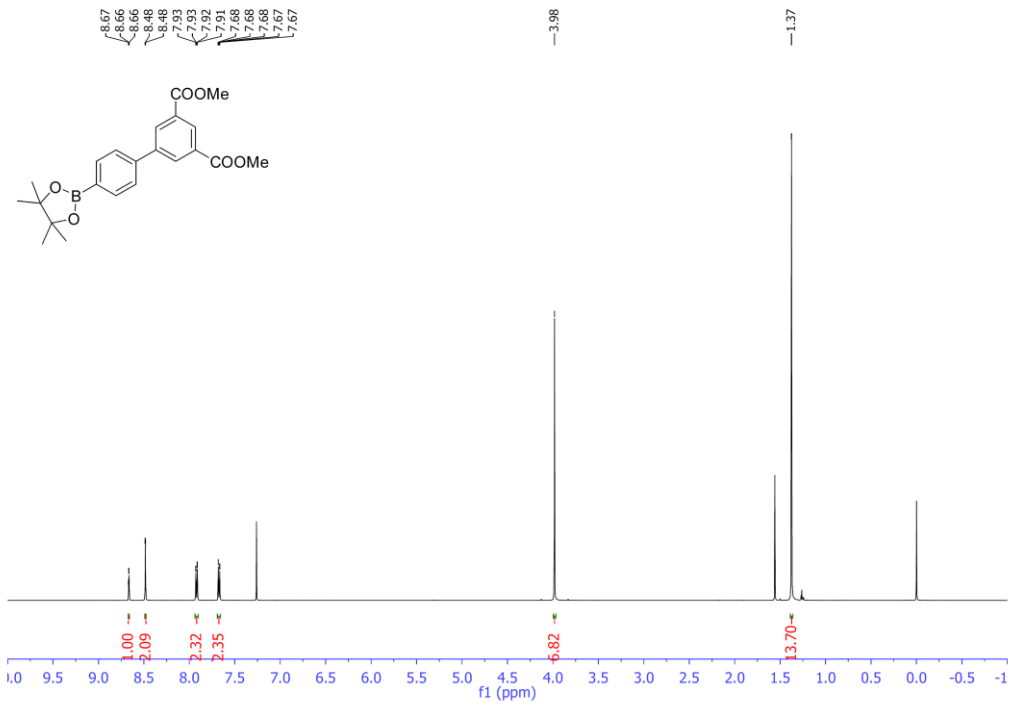


Figure B.3 Intermediate **3**

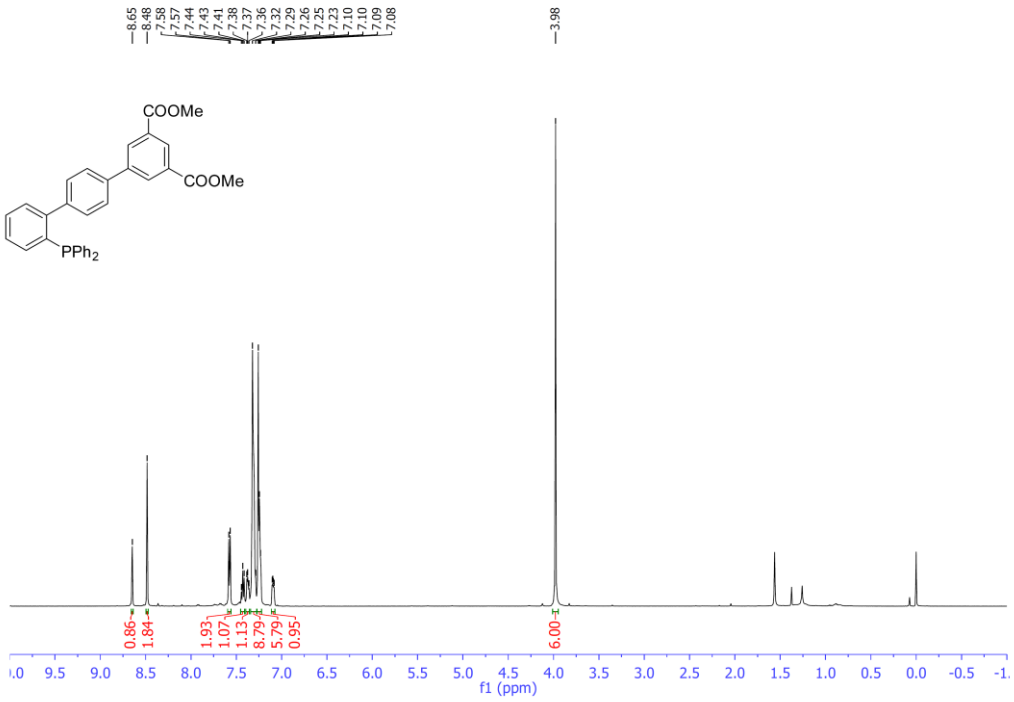


Figure B.4 Intermediate **4**

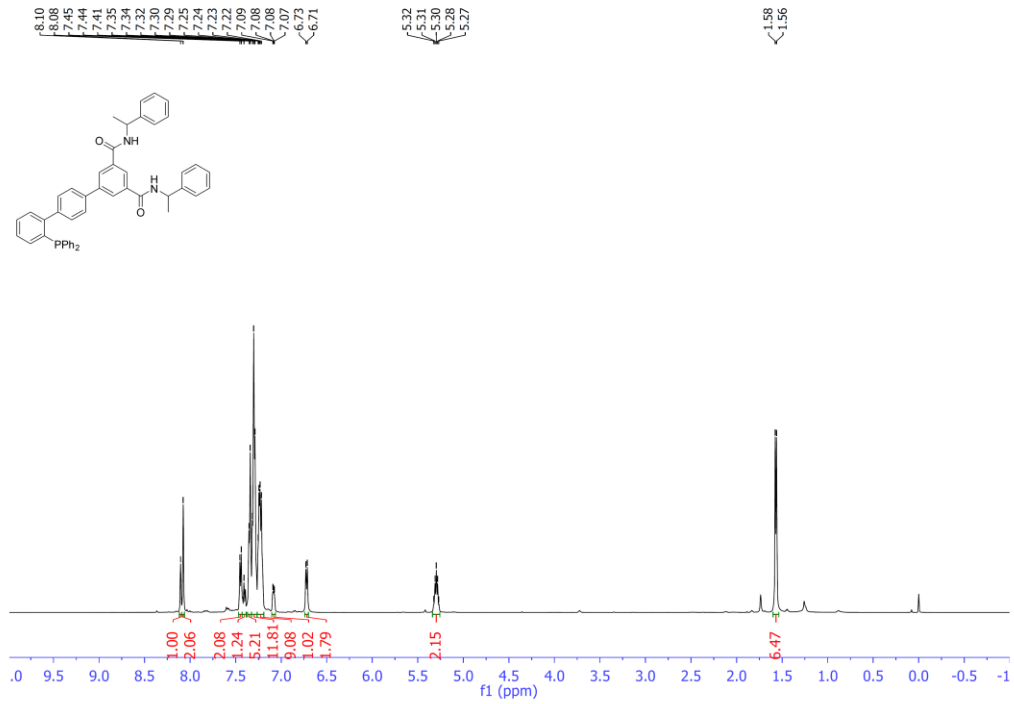


Figure B.5 Ligand **7**

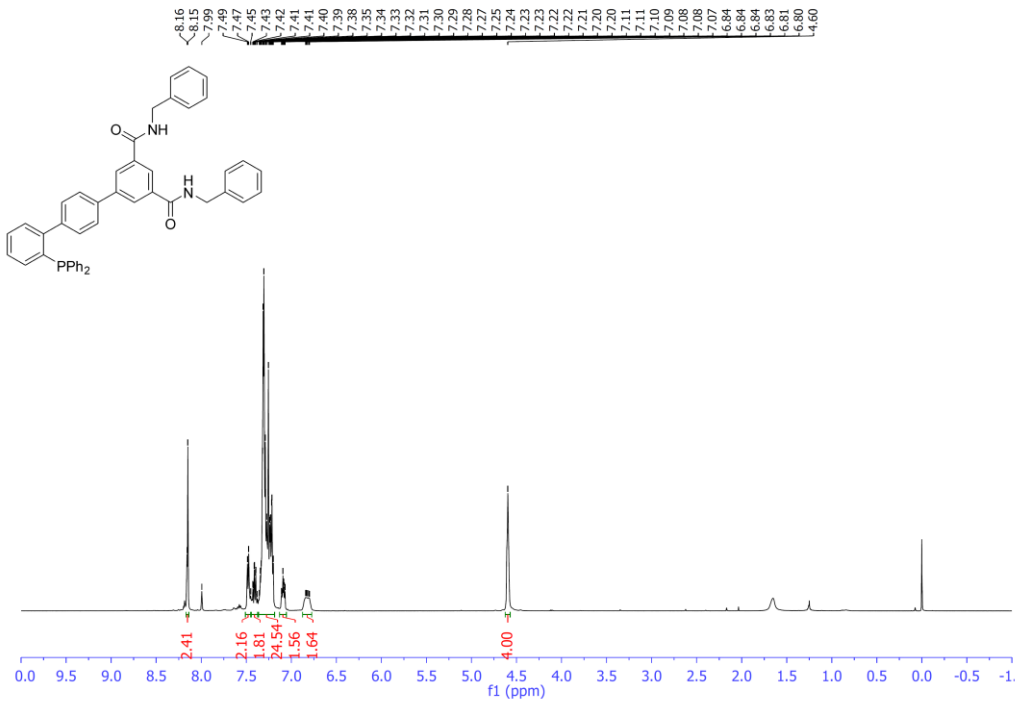


Figure B.6 Ligand **6**

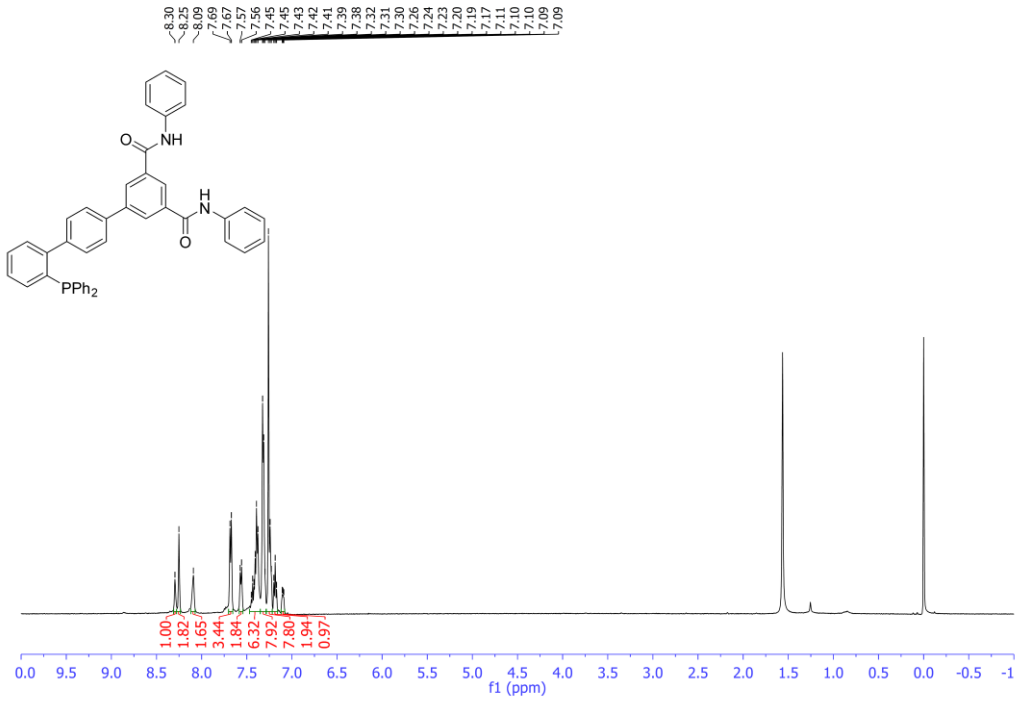


Figure B.7 Ligand **5**

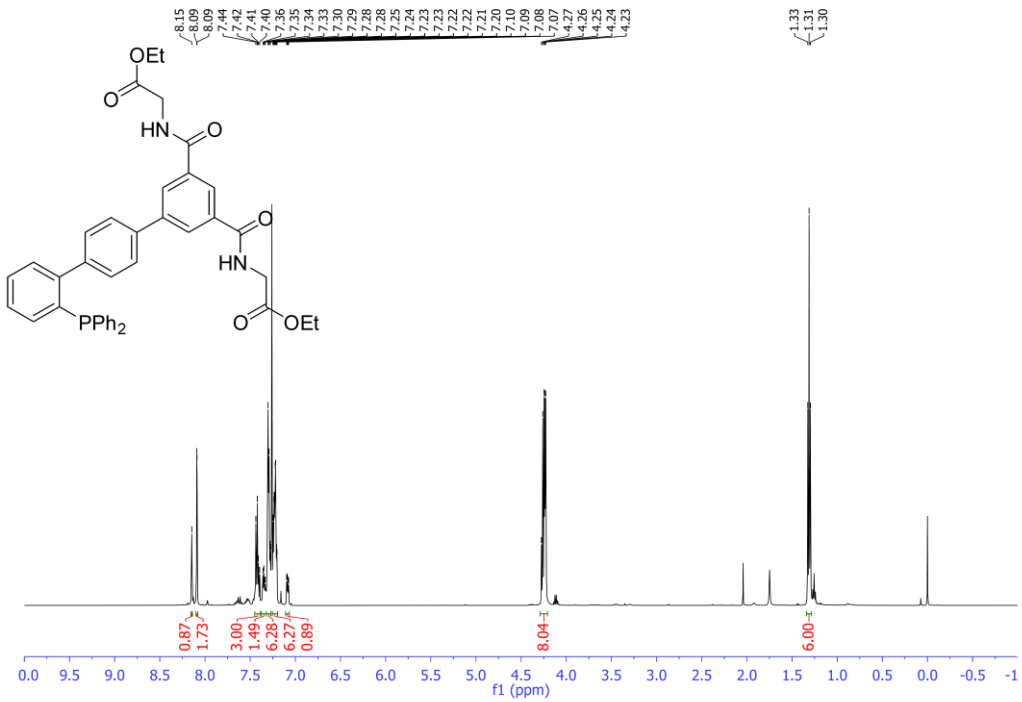


Figure B.8 Ligand **8**

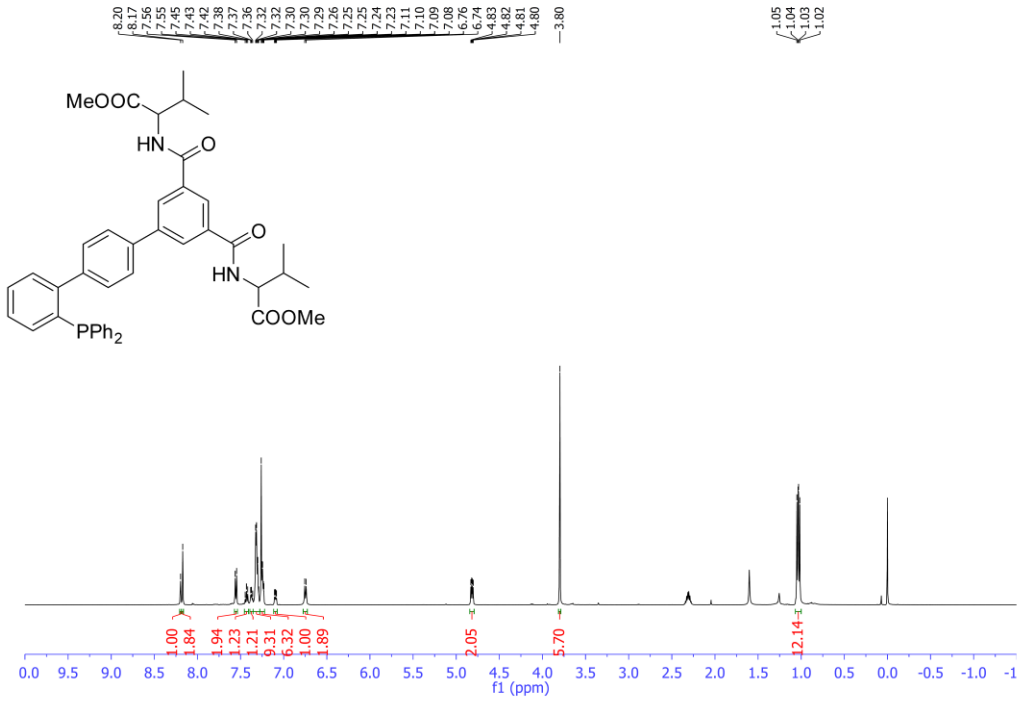


Figure B.9 Ligand **9**

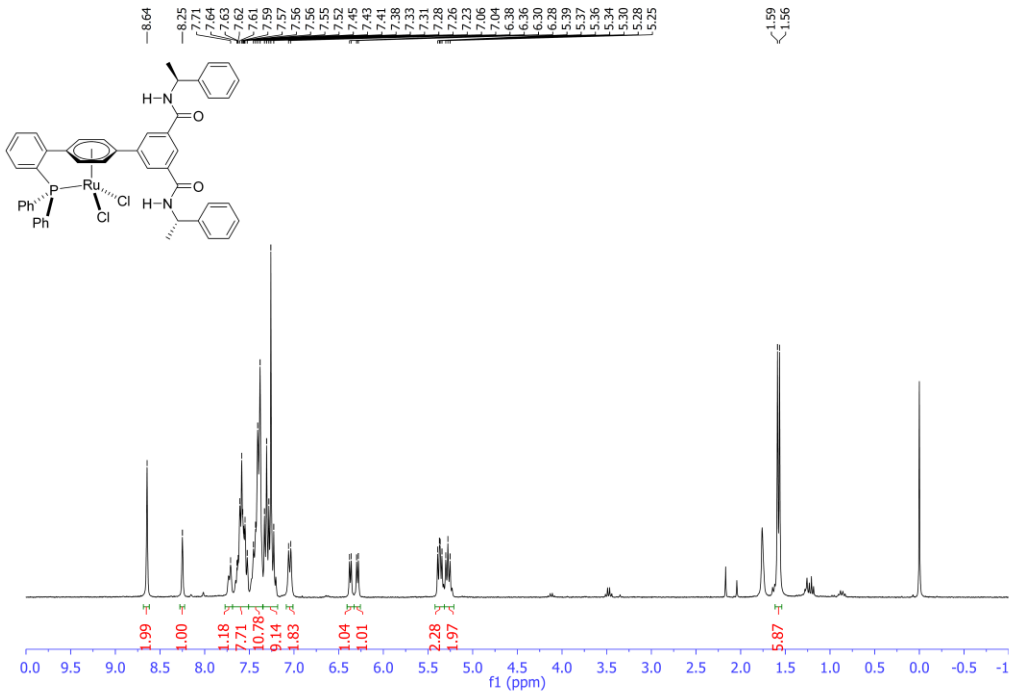


Figure B.10 Ruthenium complex **12**

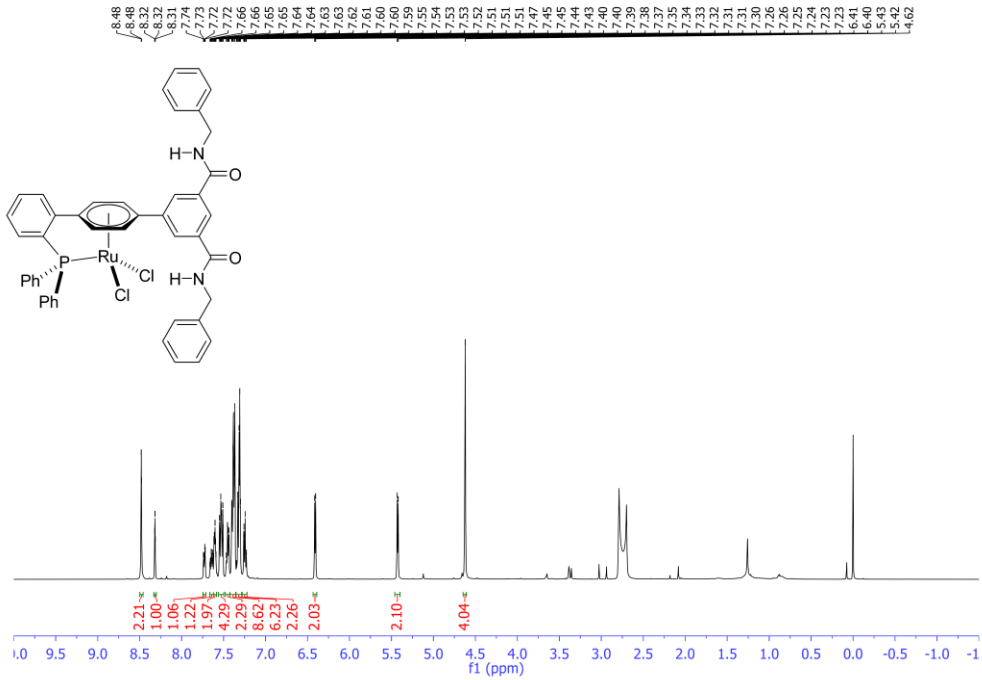


Figure B.11 Ruthenium complex **11**

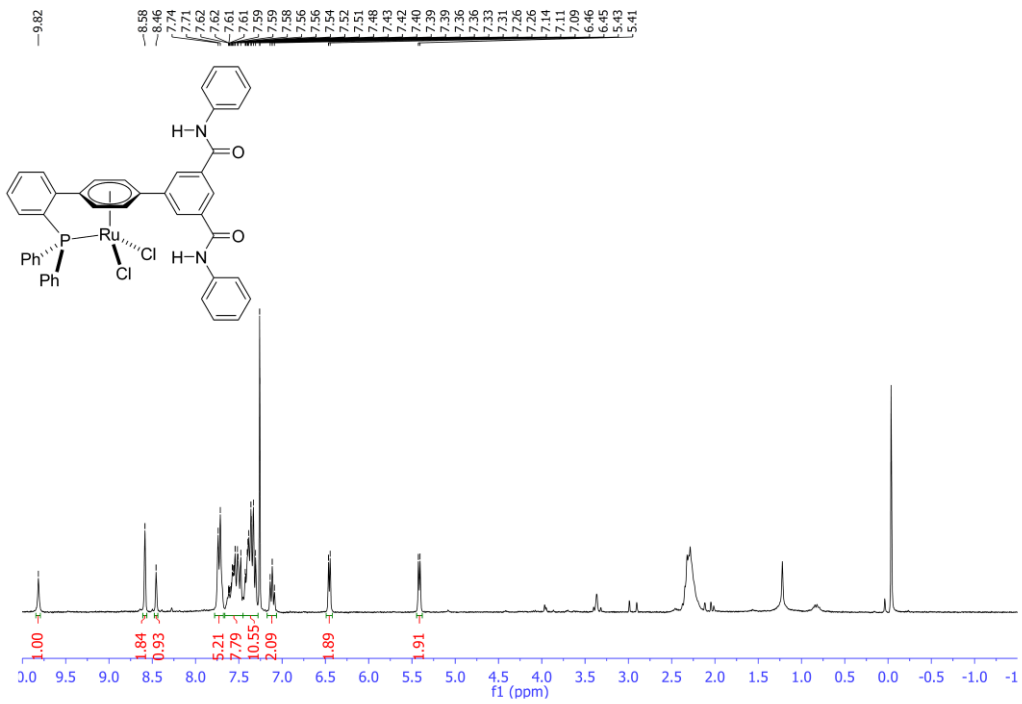


Figure B.12 Ruthenium complex **10**

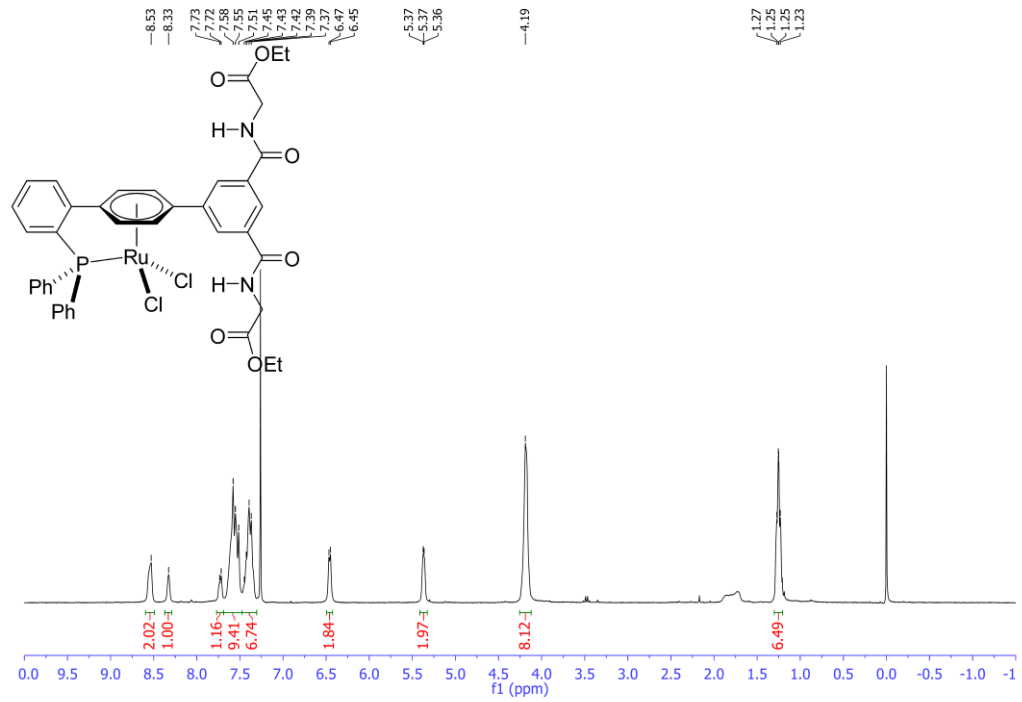


Figure B.13 Ruthenium complex **13**

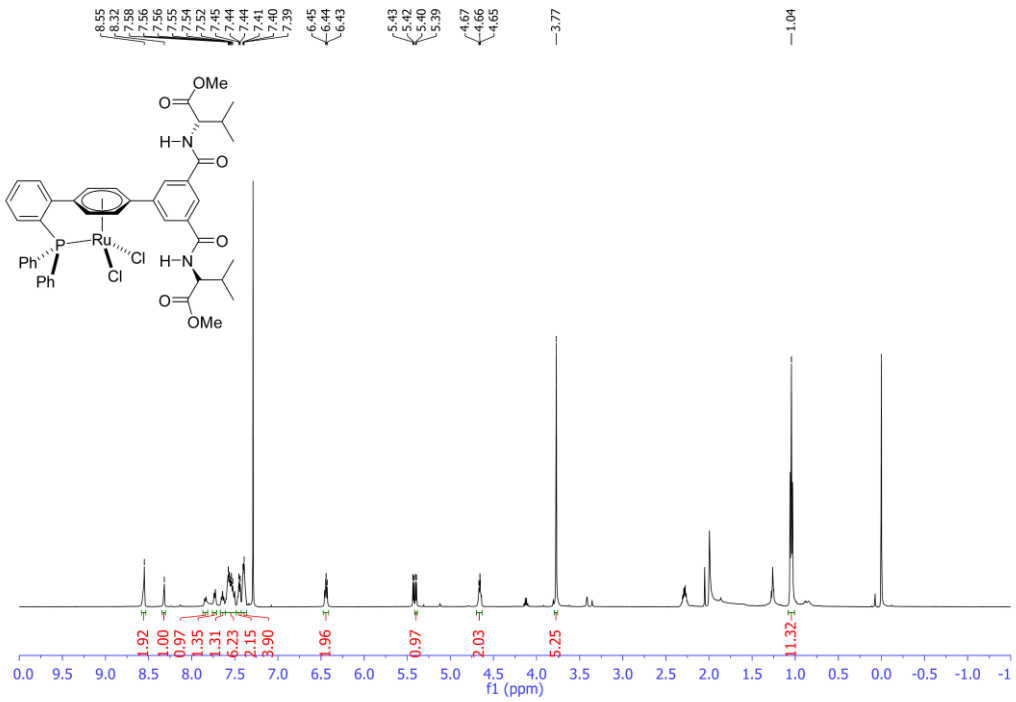


Figure B.14 Ruthenium complex **14**

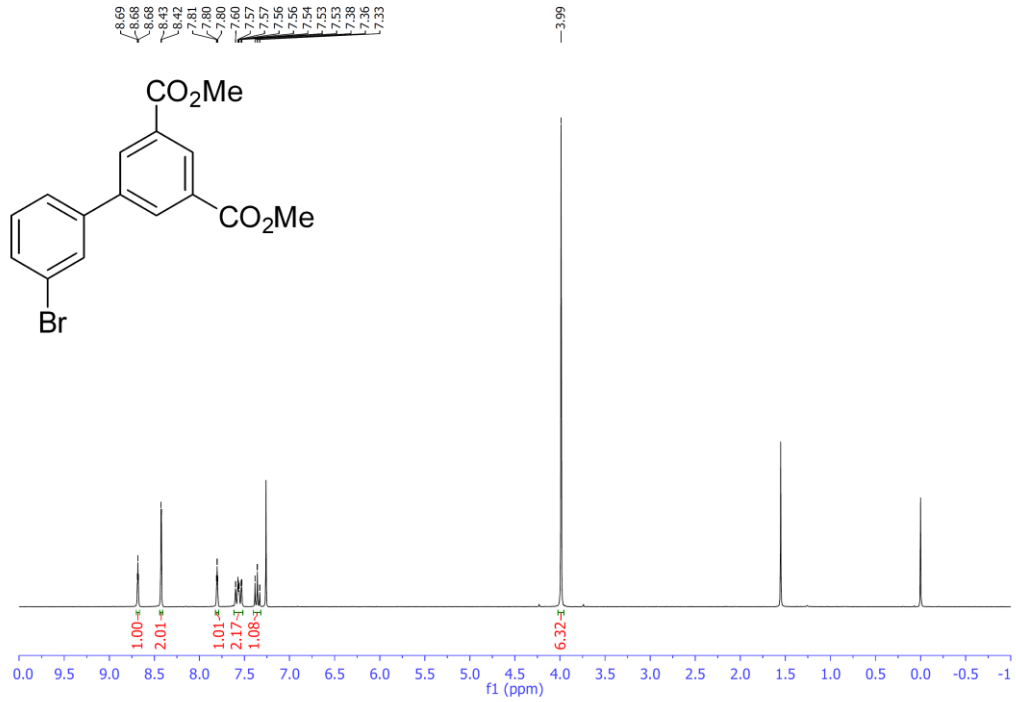


Figure B.15 Intermediate **15**

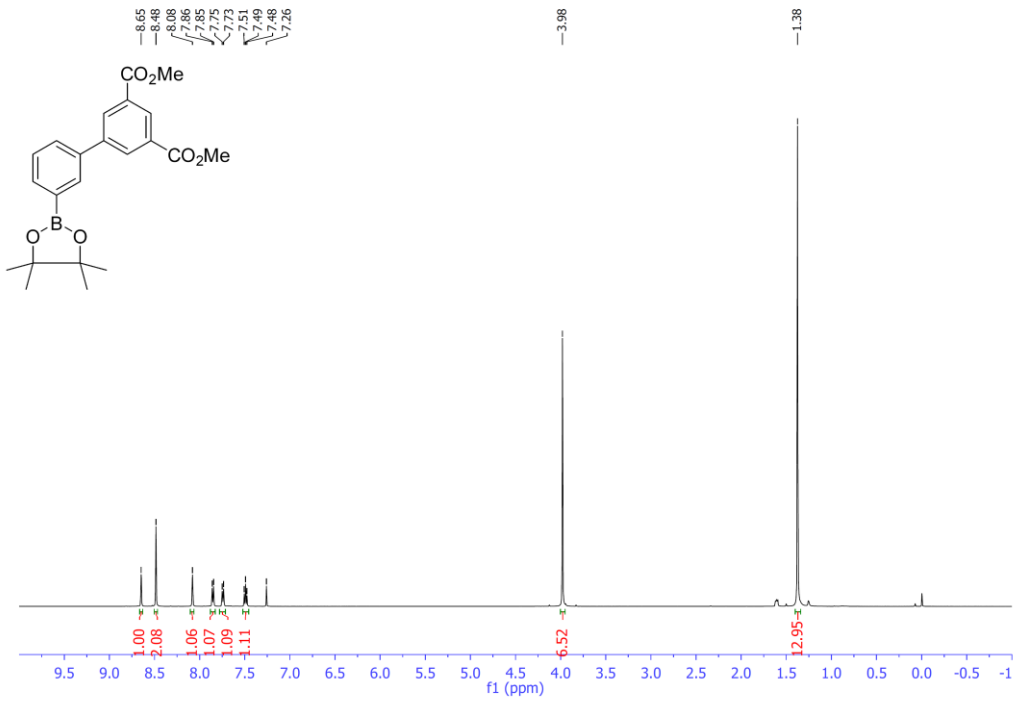


Figure B.16 Intermediate **16**

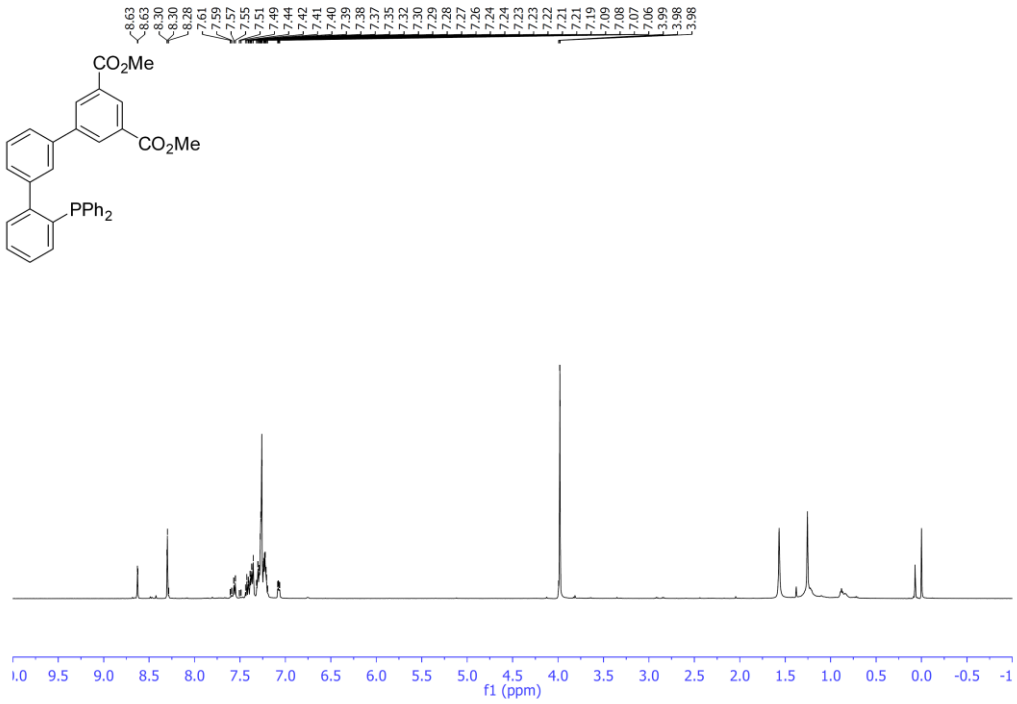


Figure B.17 Intermediate **17**

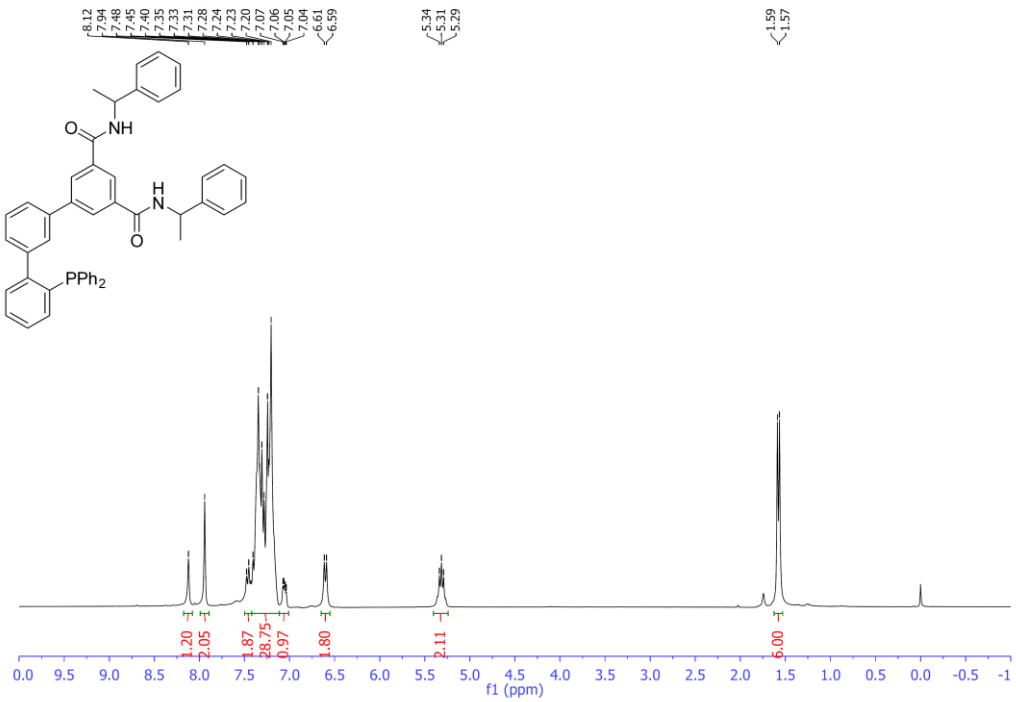


Figure B.18 Ligand **20**

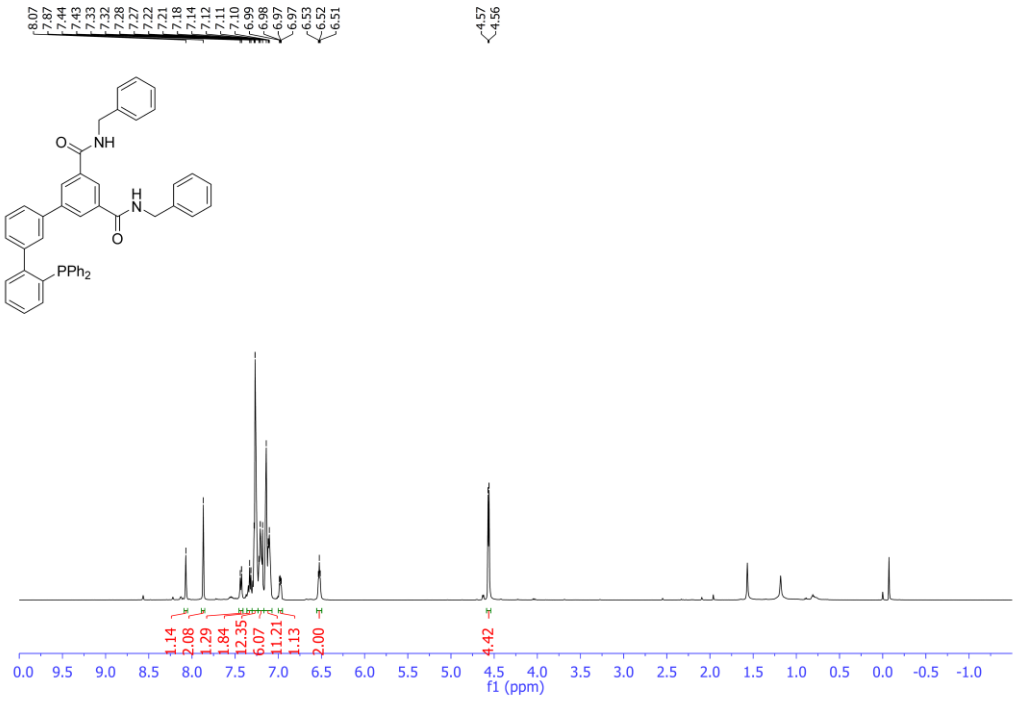


Figure B.19 Ligand **19**

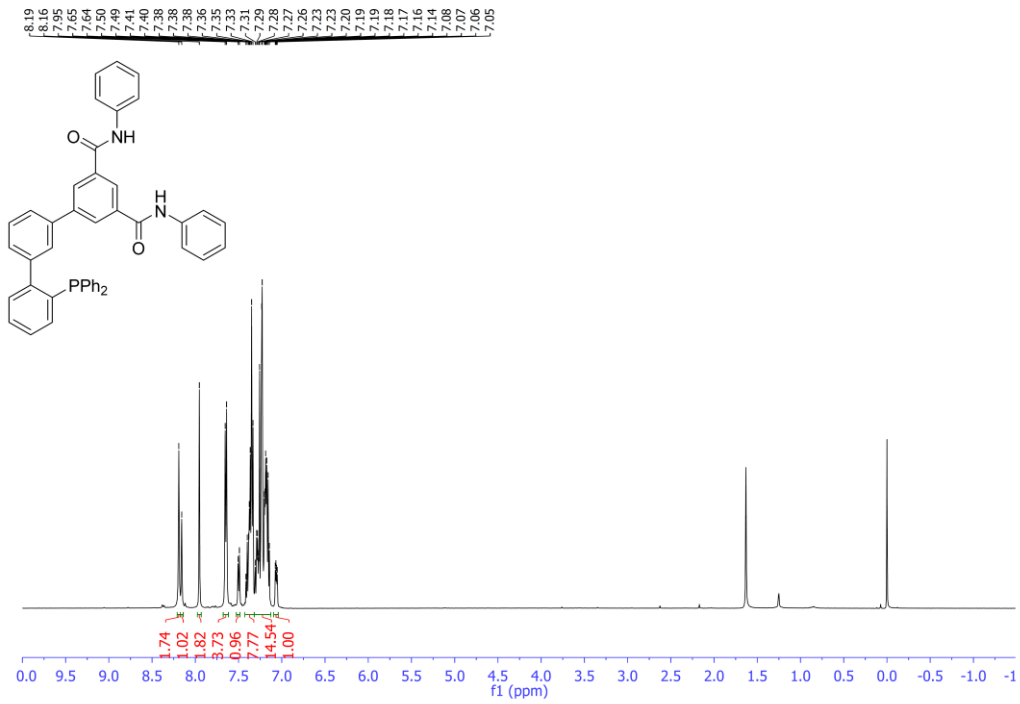


Figure B.20 Ligand **18**

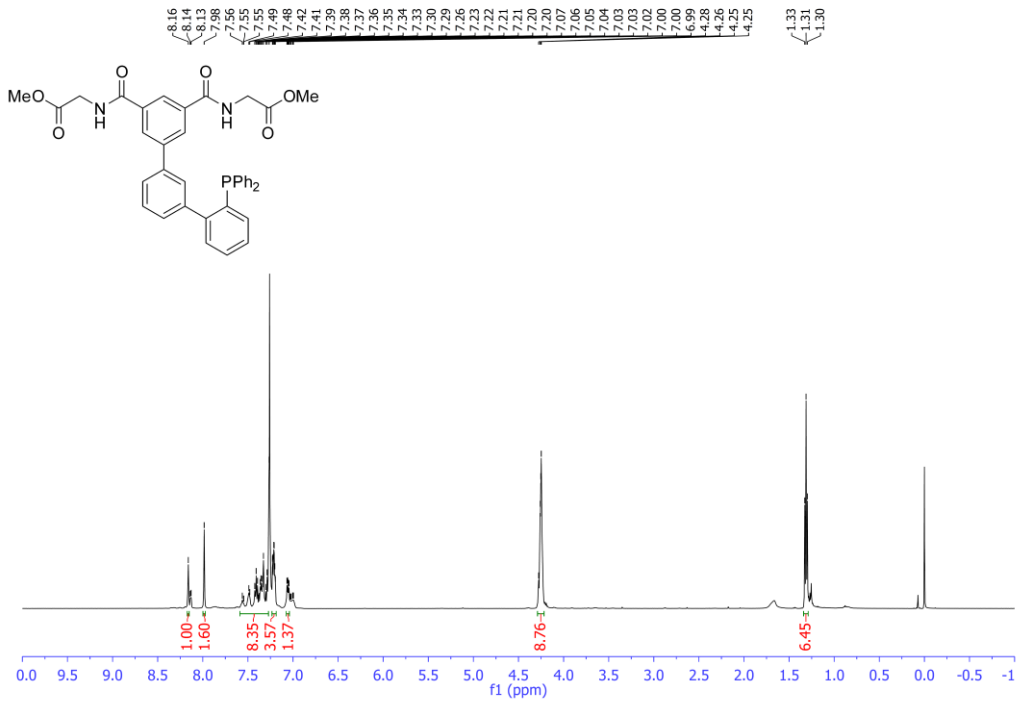


Figure B.21 Ligand **21**

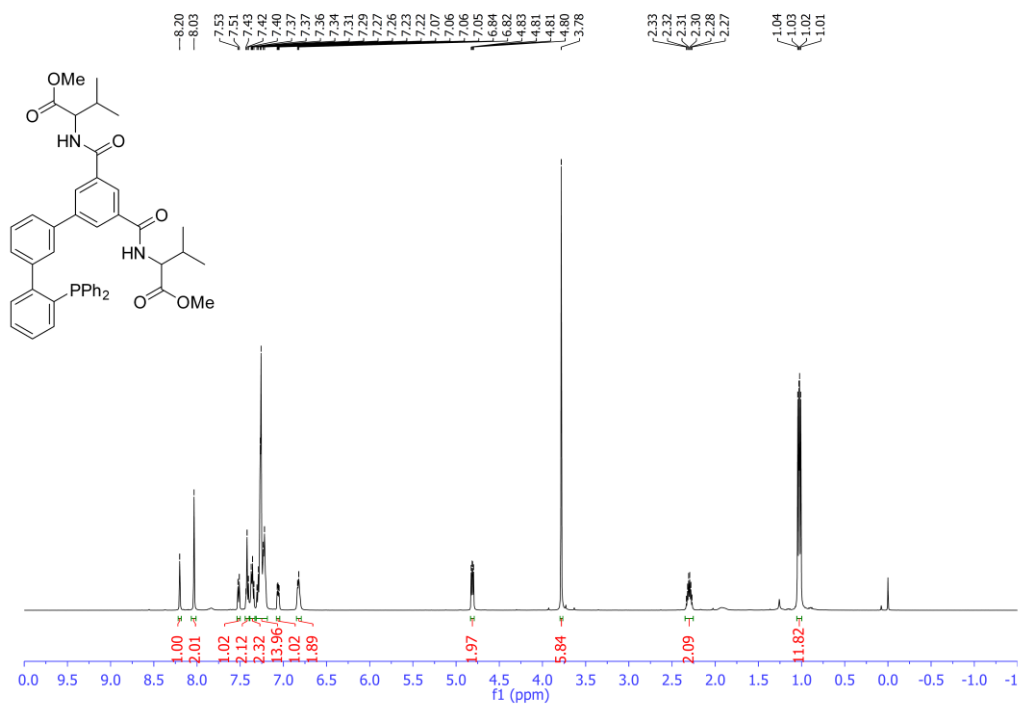


Figure B.22 Ligand **22**

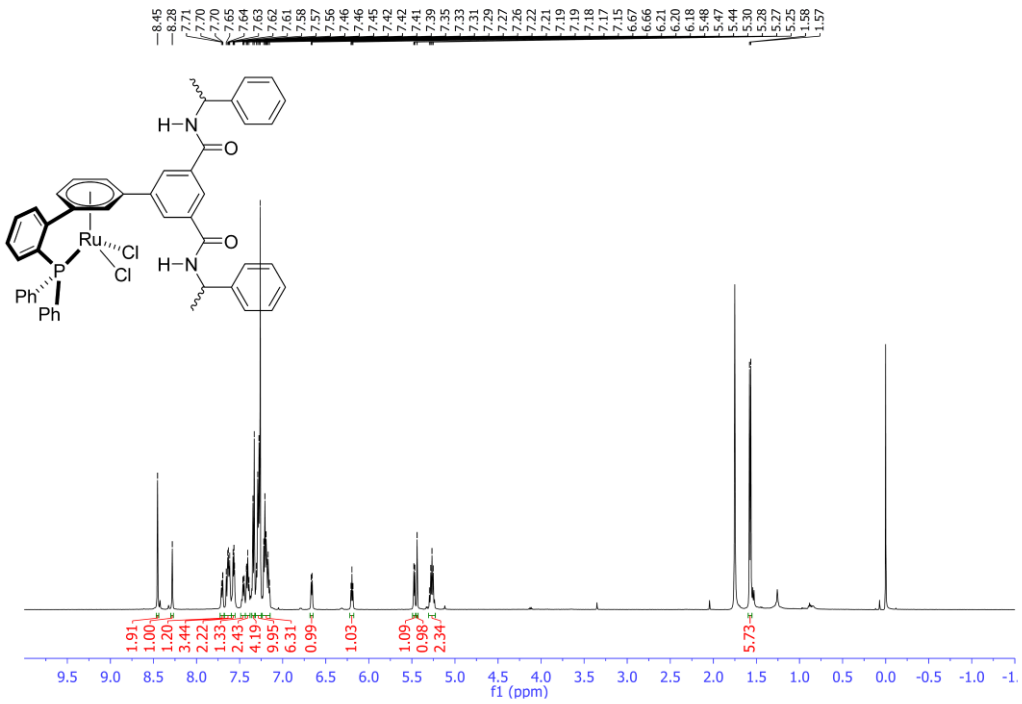


Figure B.23 Ruthenium complex **25**/Diastereomer 1

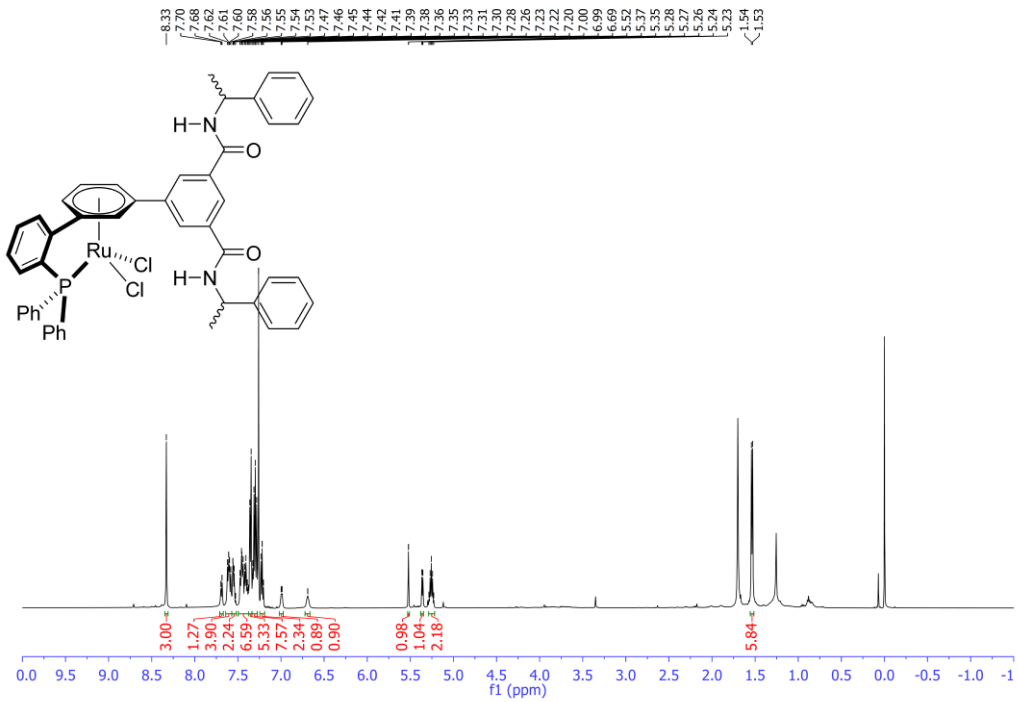


Figure B.24 Ruthenium complex **25**/Diastereomer 2

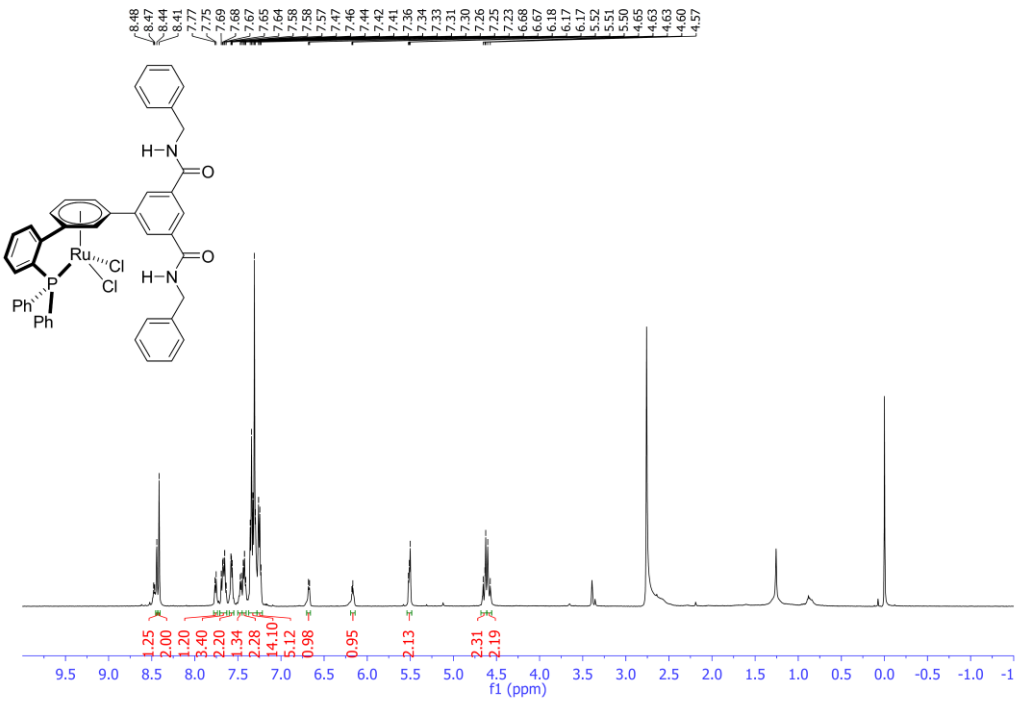


Figure B.25 Ruthenium complex **24**

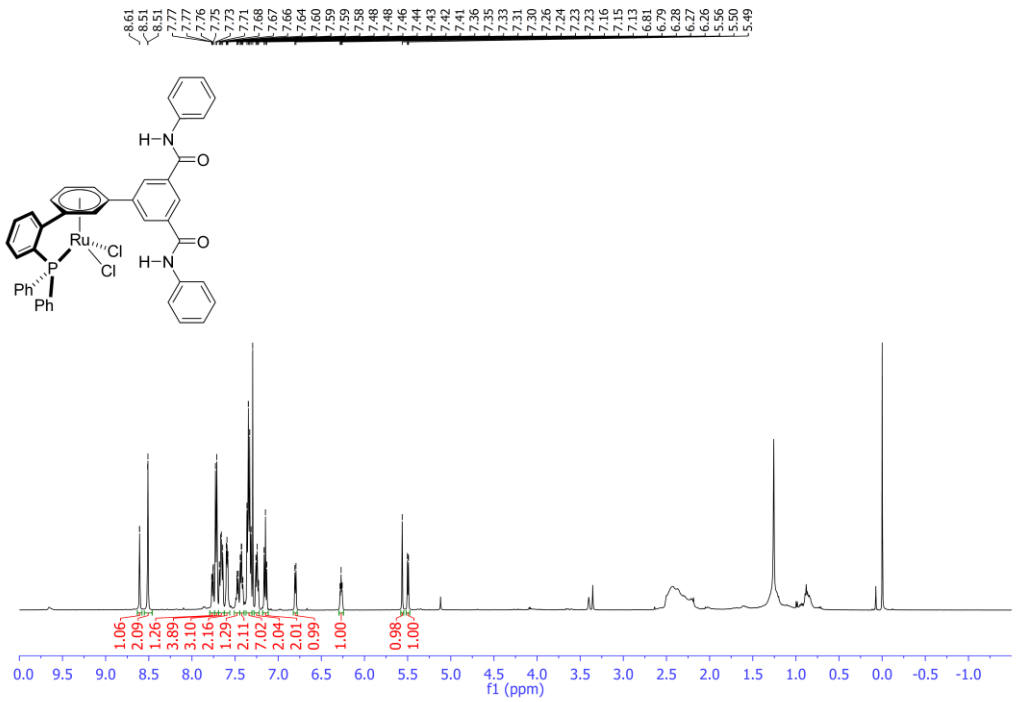


Figure B.26 Ruthenium complex **23**

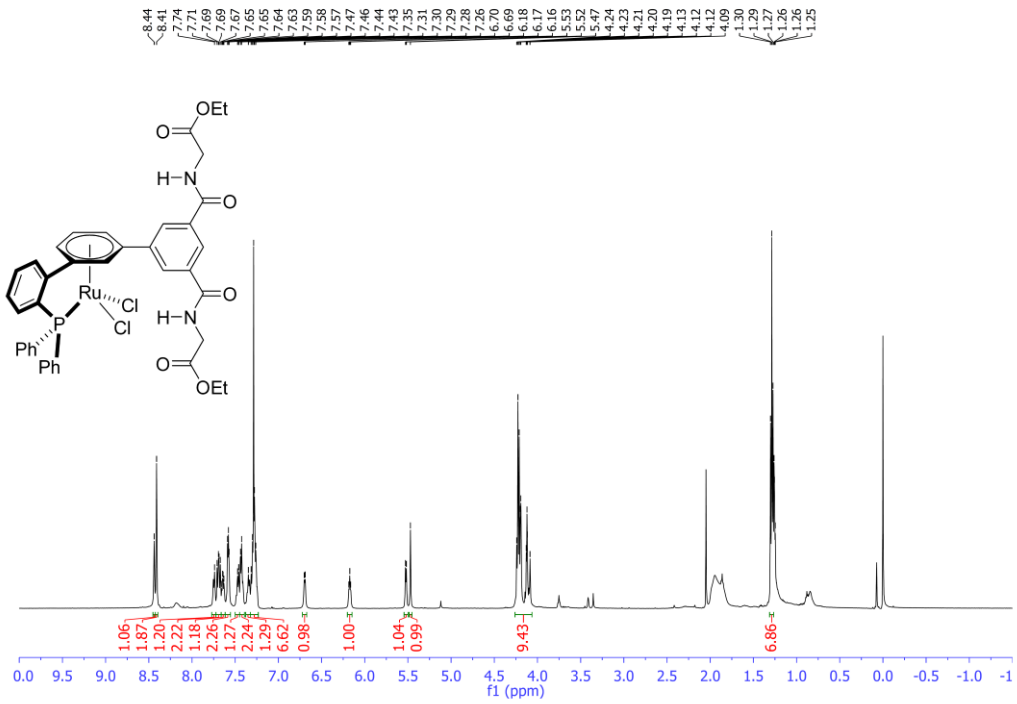


Figure B.27 Ruthenium complex **26**

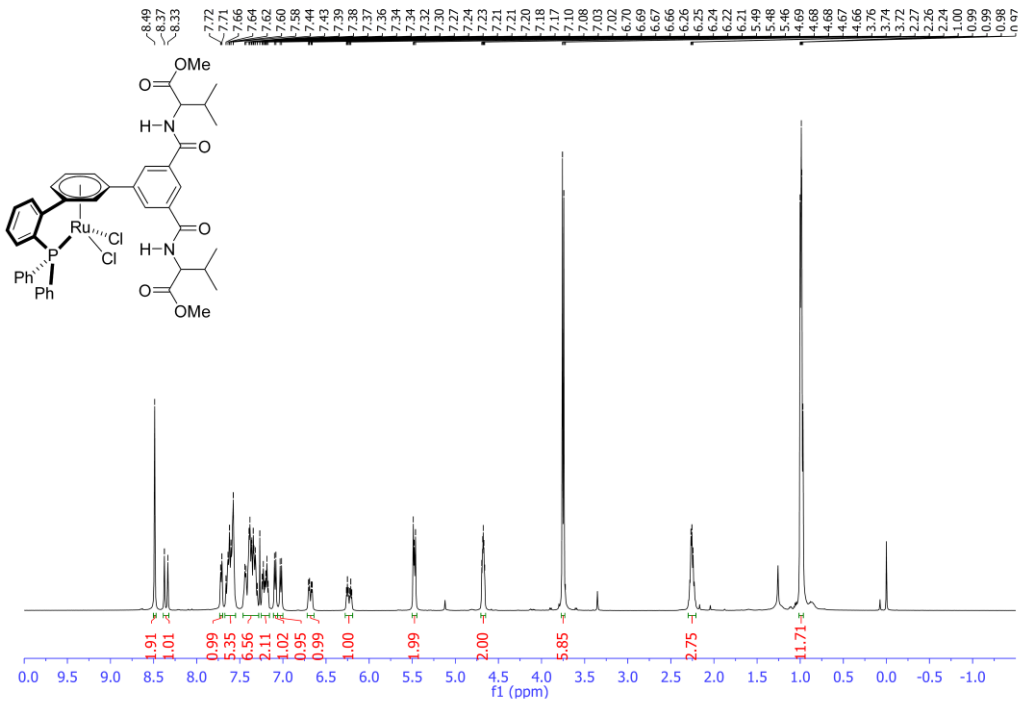


Figure B.28 Ruthenium complex **27**

B.2 ^{13}CNMR spectra

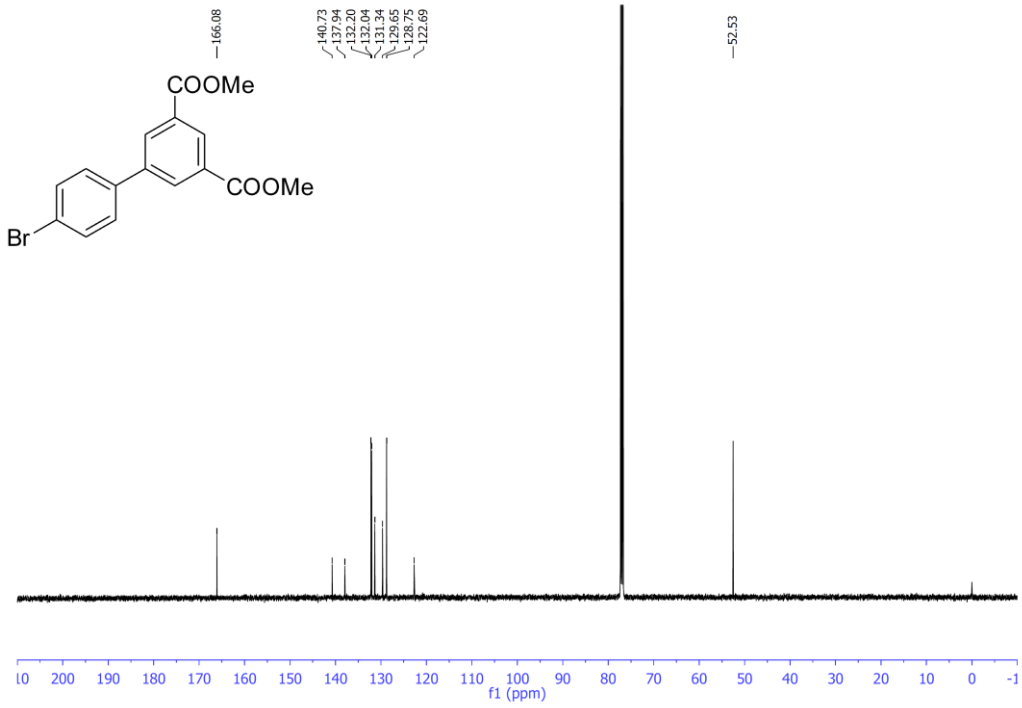


Figure B.29 Intermediate **2**

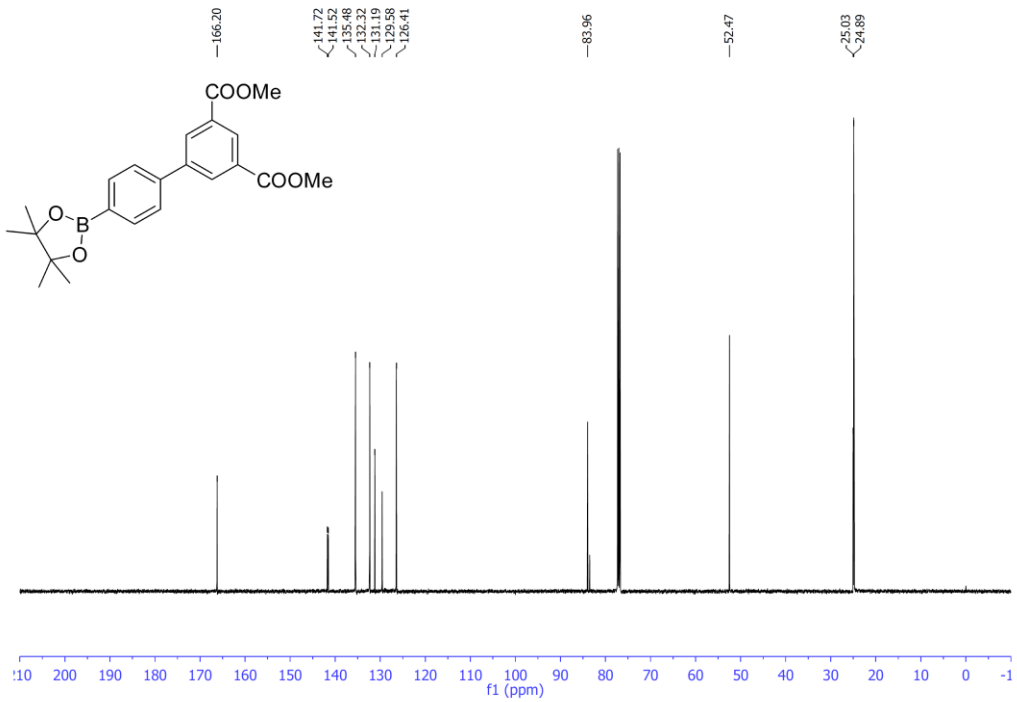


Figure B.30 Intermediate **3**

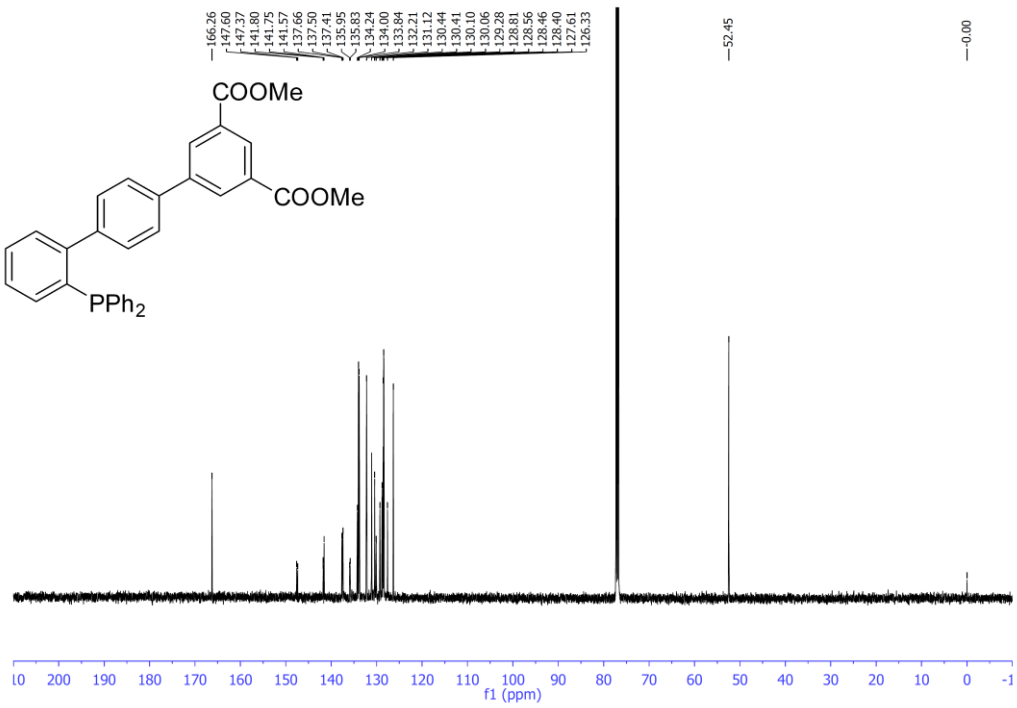


Figure B.31 Intermediate **4**

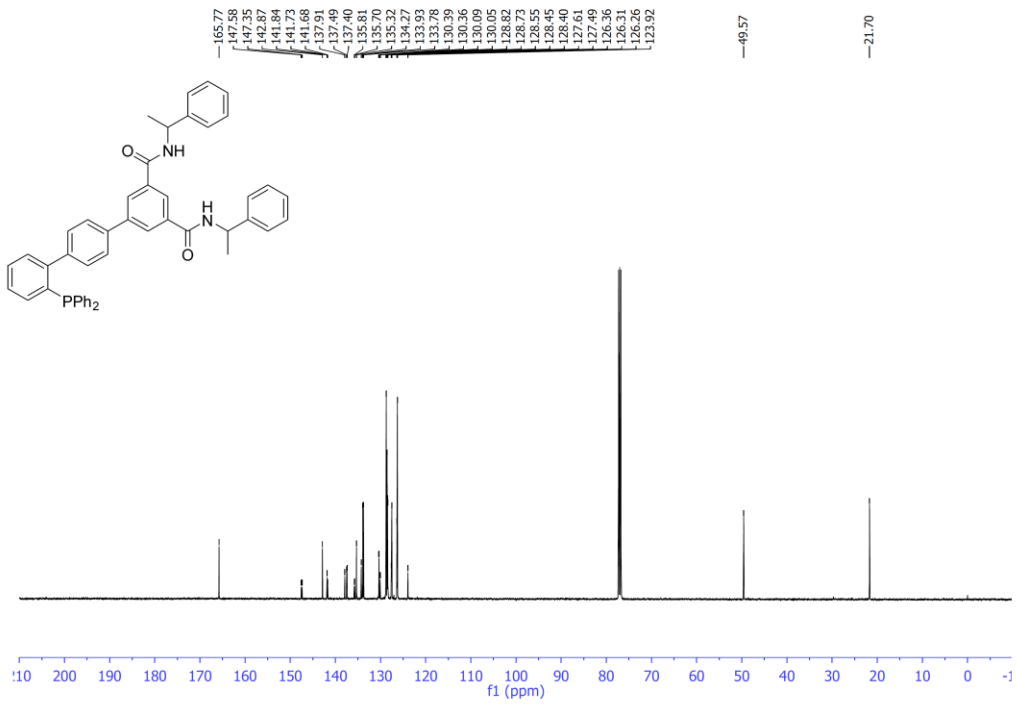


Figure B.32 Ligand **7**

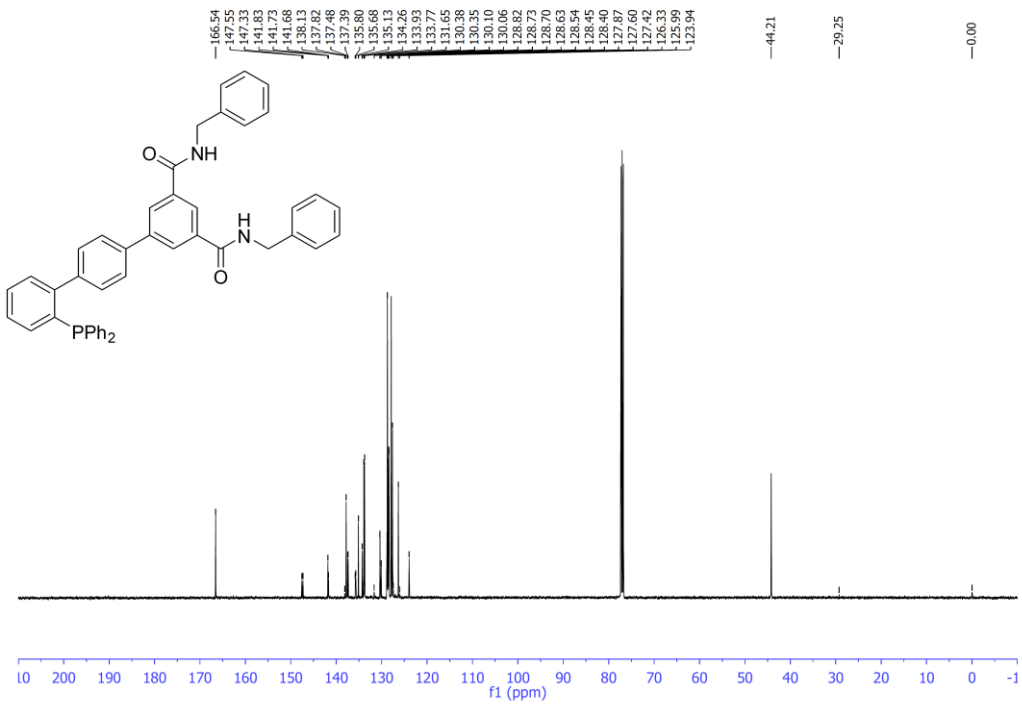


Figure B.33 Ligand **6**

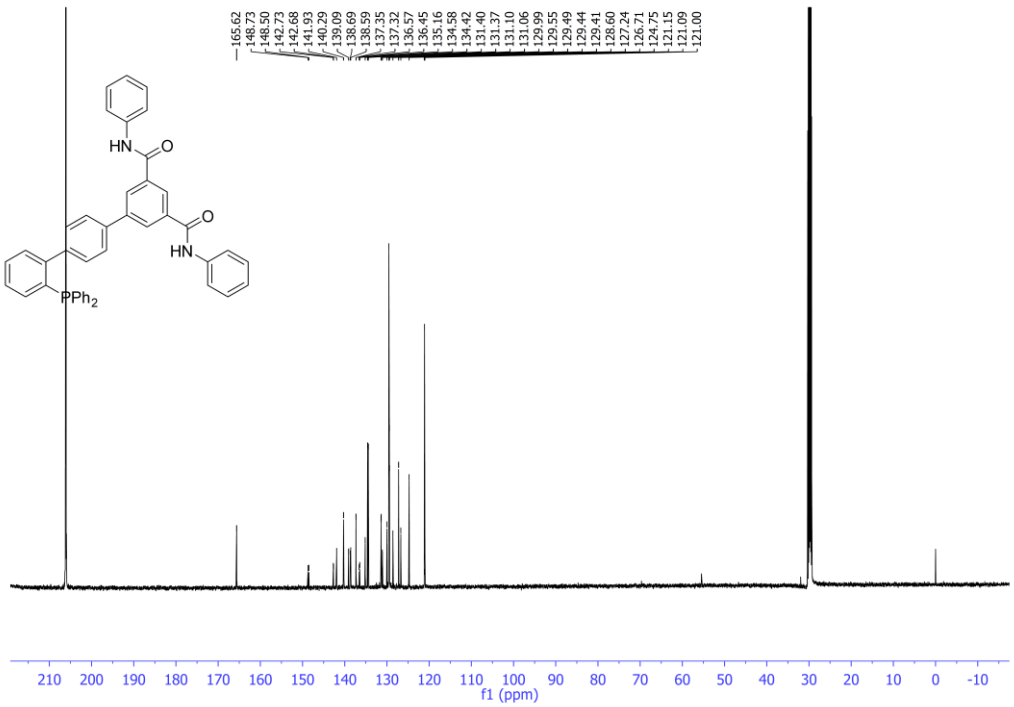


Figure B.34 Ligand **5**

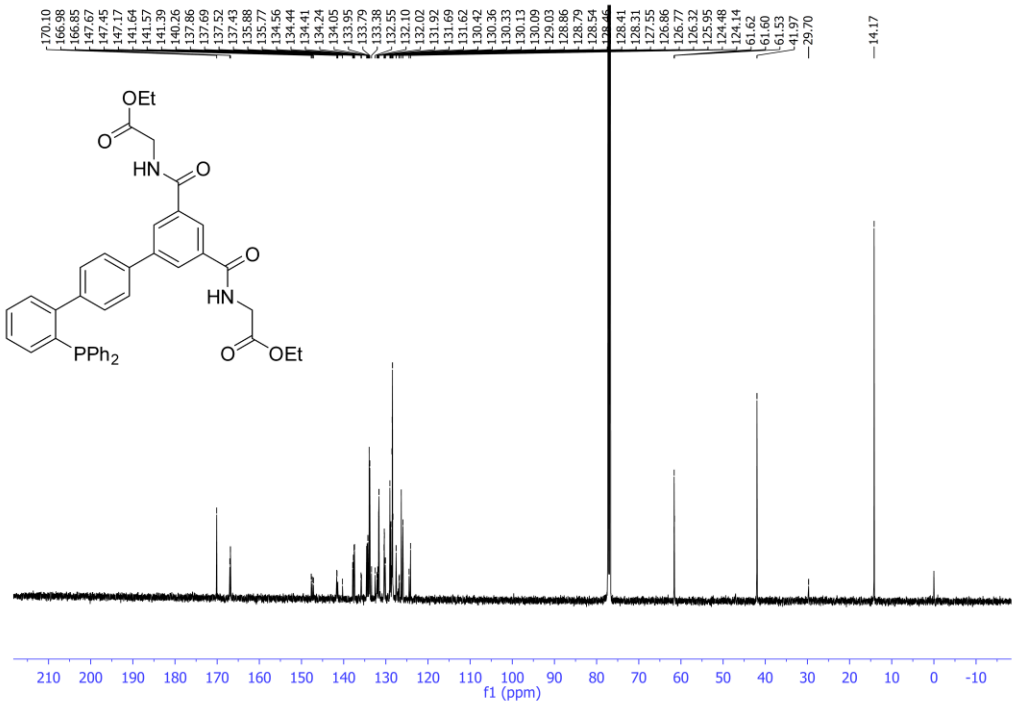


Figure B.35 Ligand **8**

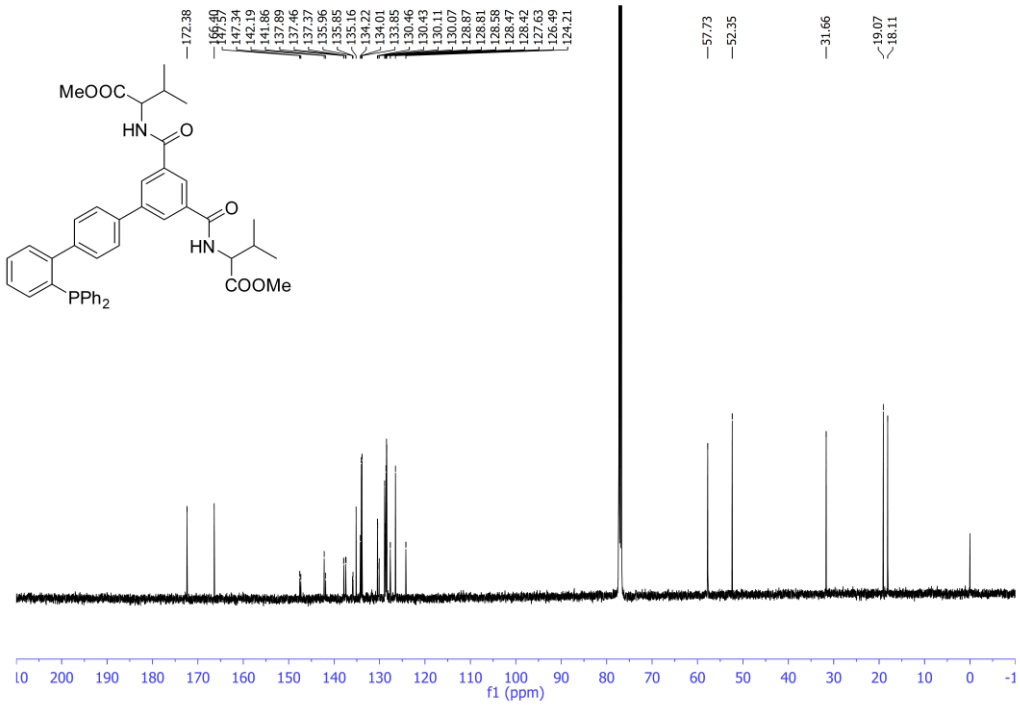


Figure B.36 Ligand **9**

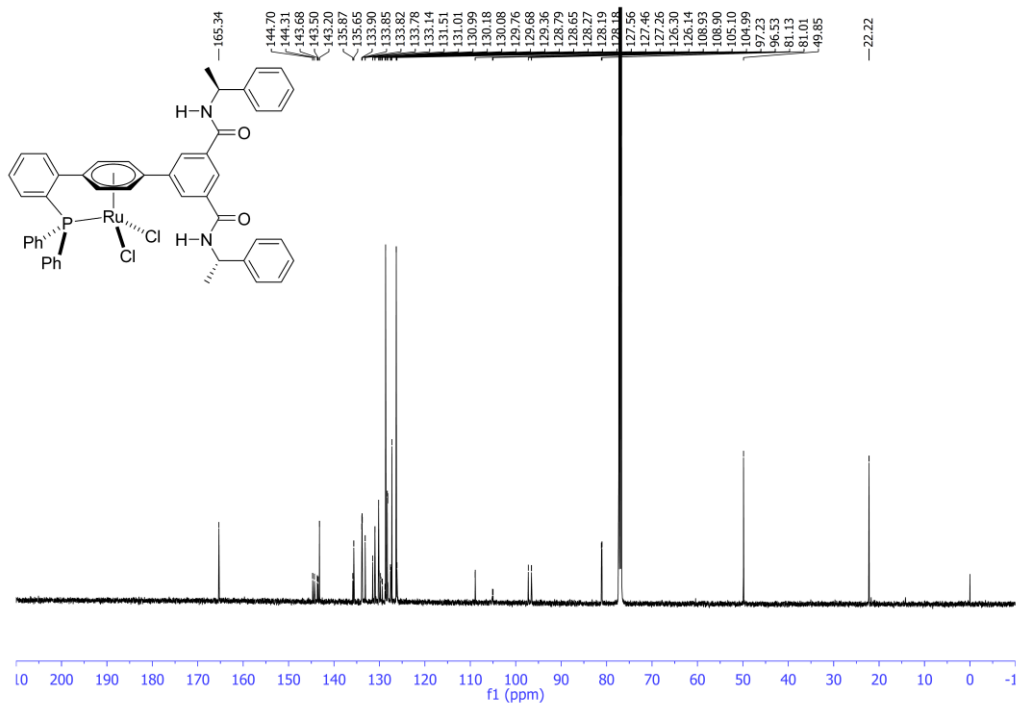


Figure B.37 Ruthenium complex **12**

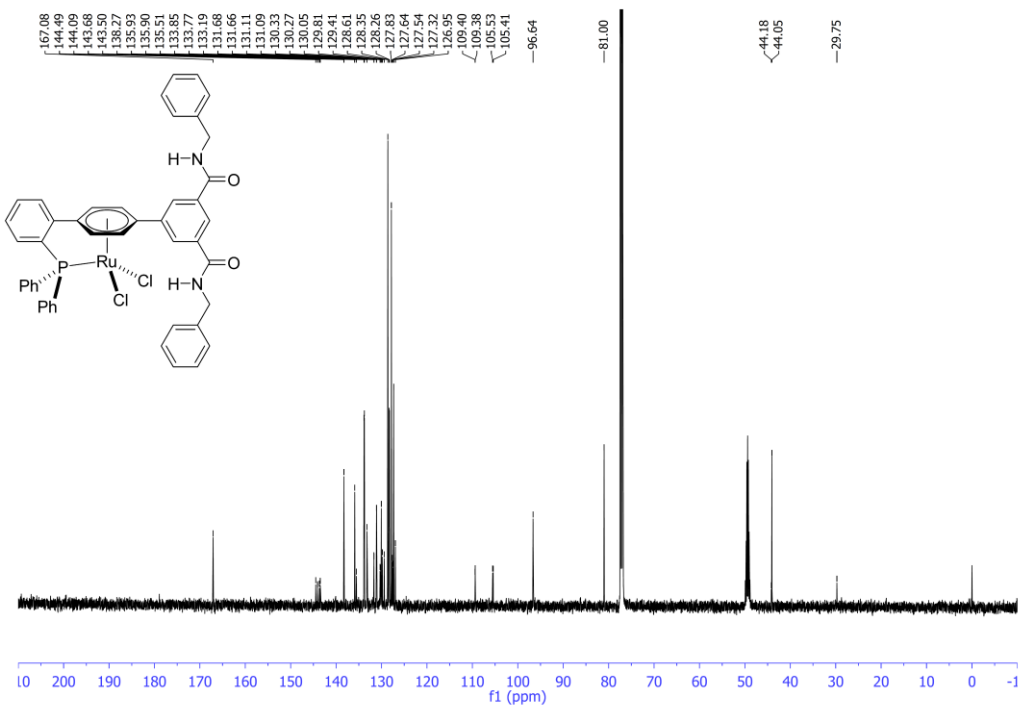


Figure B.38 Ruthenium complex **11**

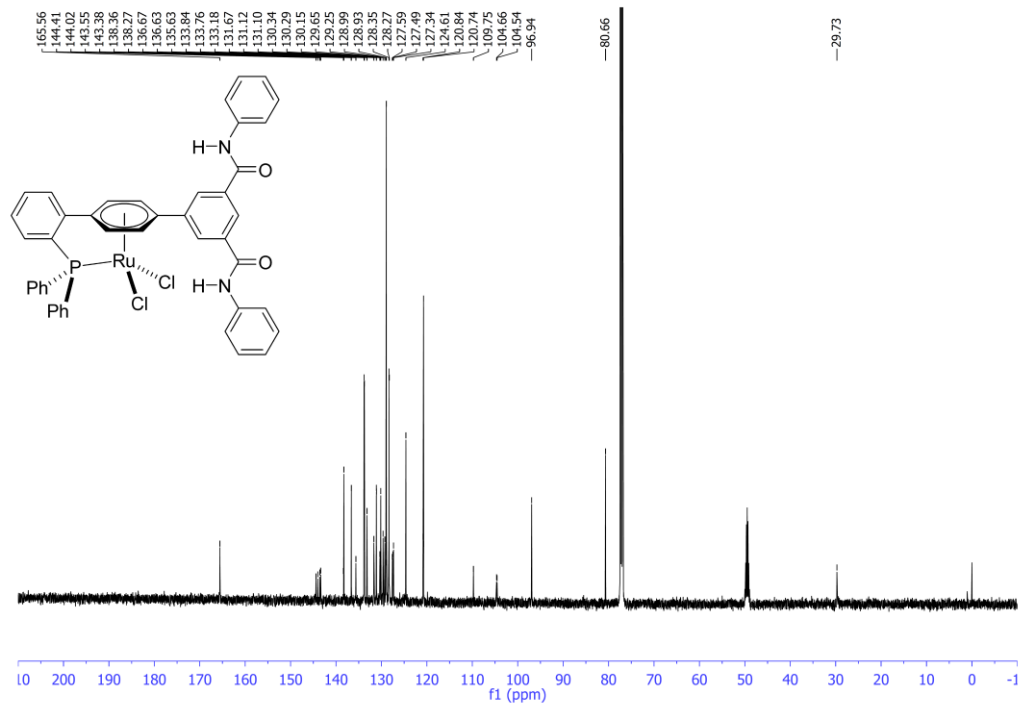


Figure B.39 Ruthenium complex **10**

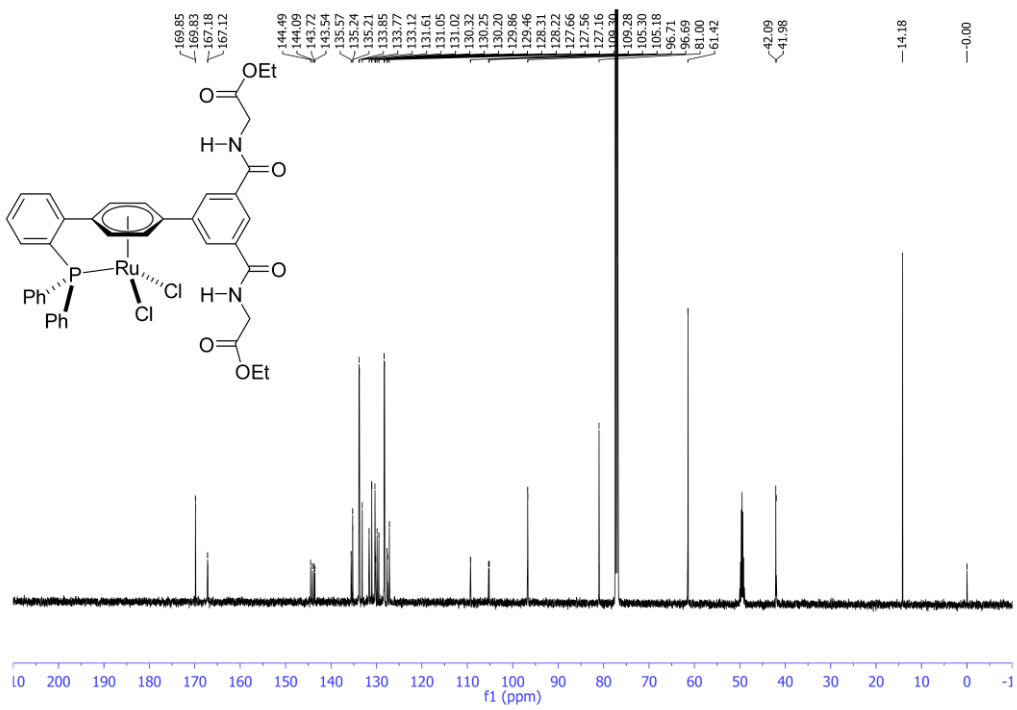


Figure B.40 Ruthenium complex **13**

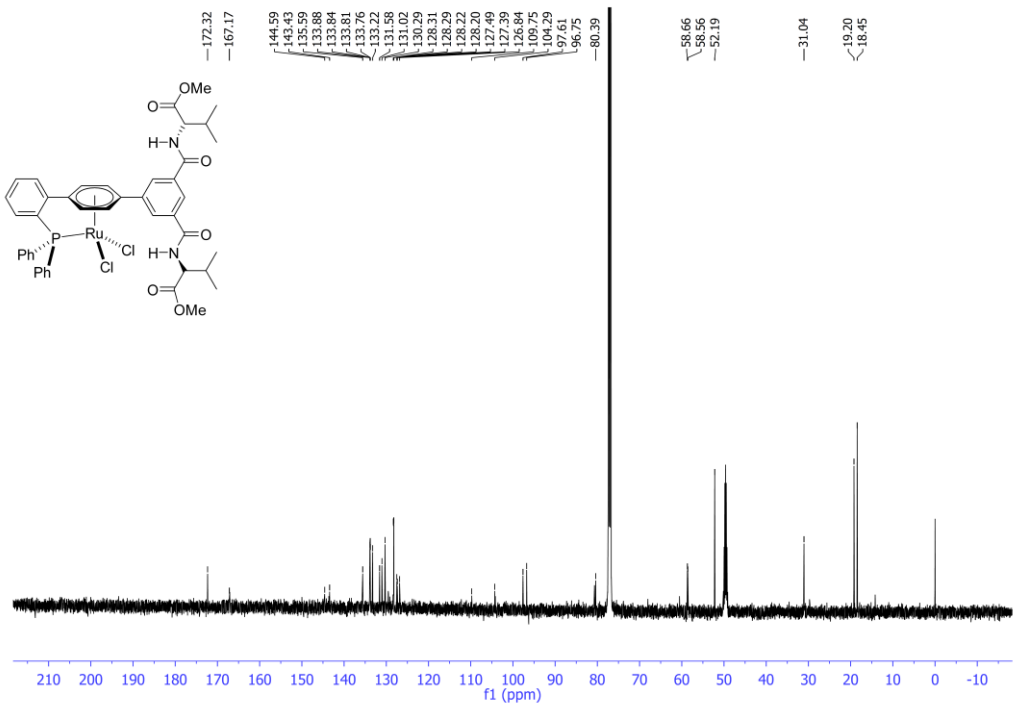


Figure B.41 Ruthenium complex **14**

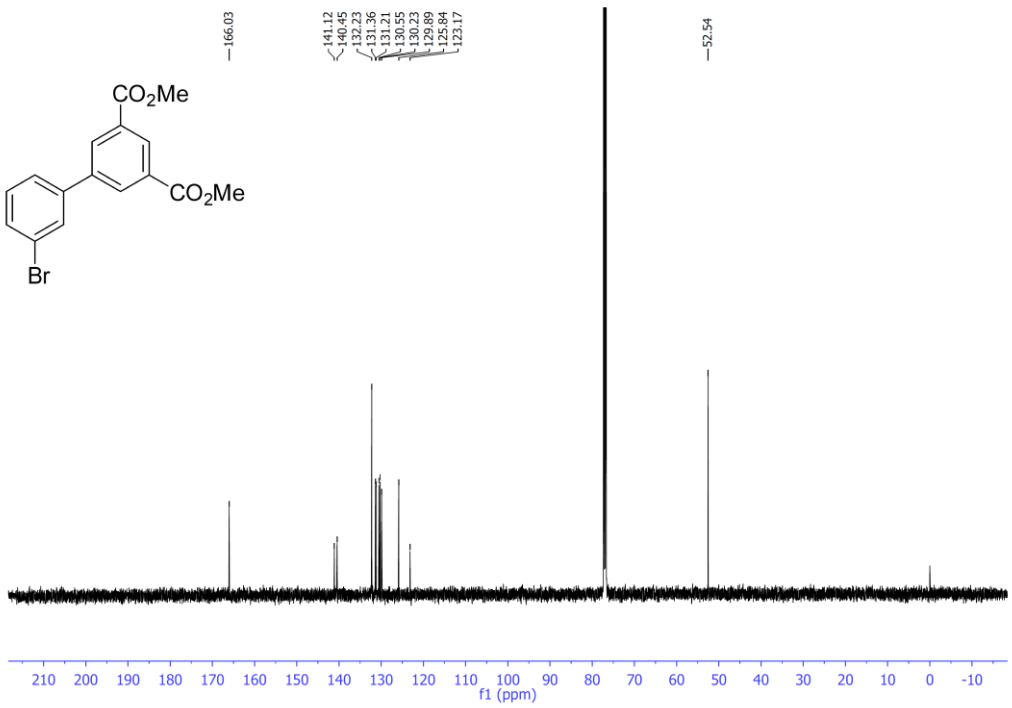


Figure B.42 Intermediate **15**

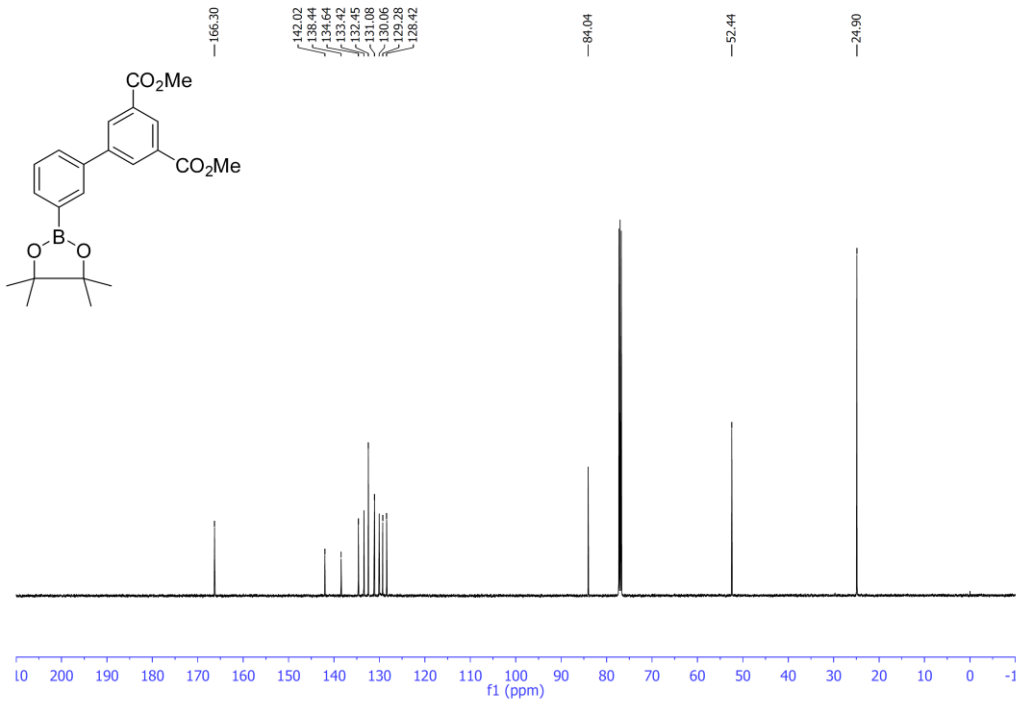


Figure B.43 Intermediate **16**

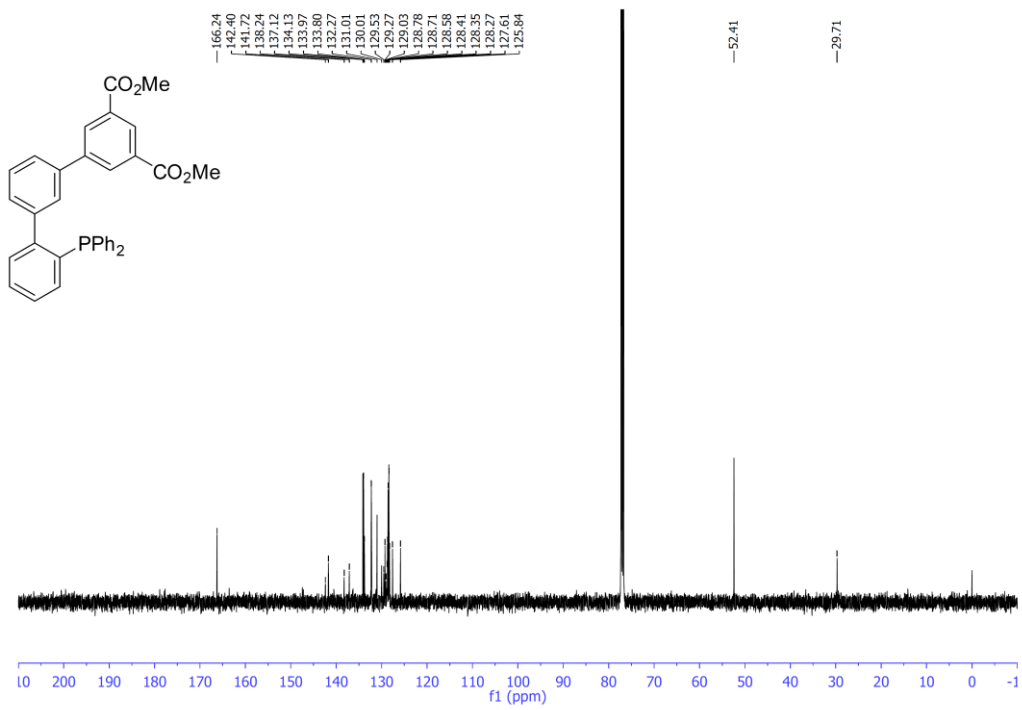


Figure B.44 Intermediate **17**

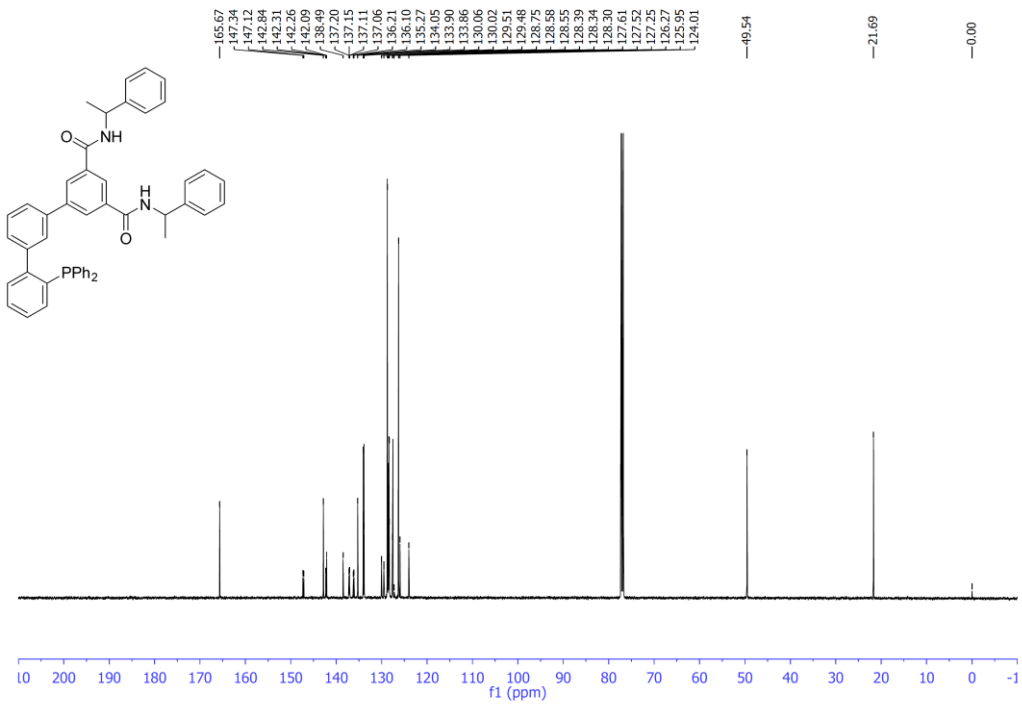


Figure B.45 Ligand **20**

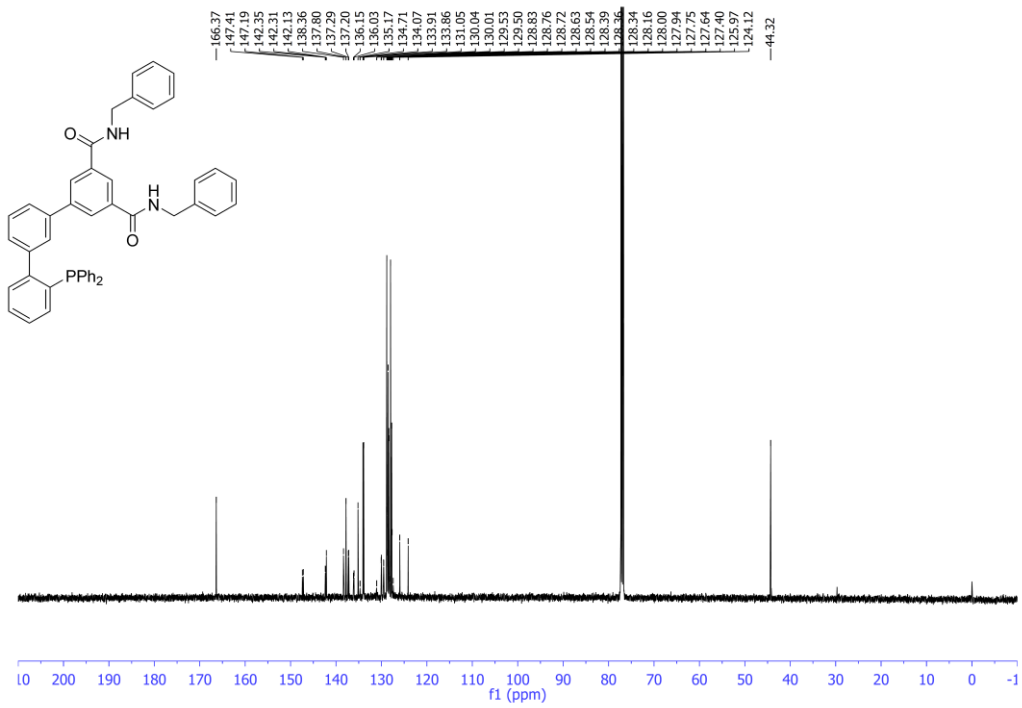


Figure B.46 Ligand **19**

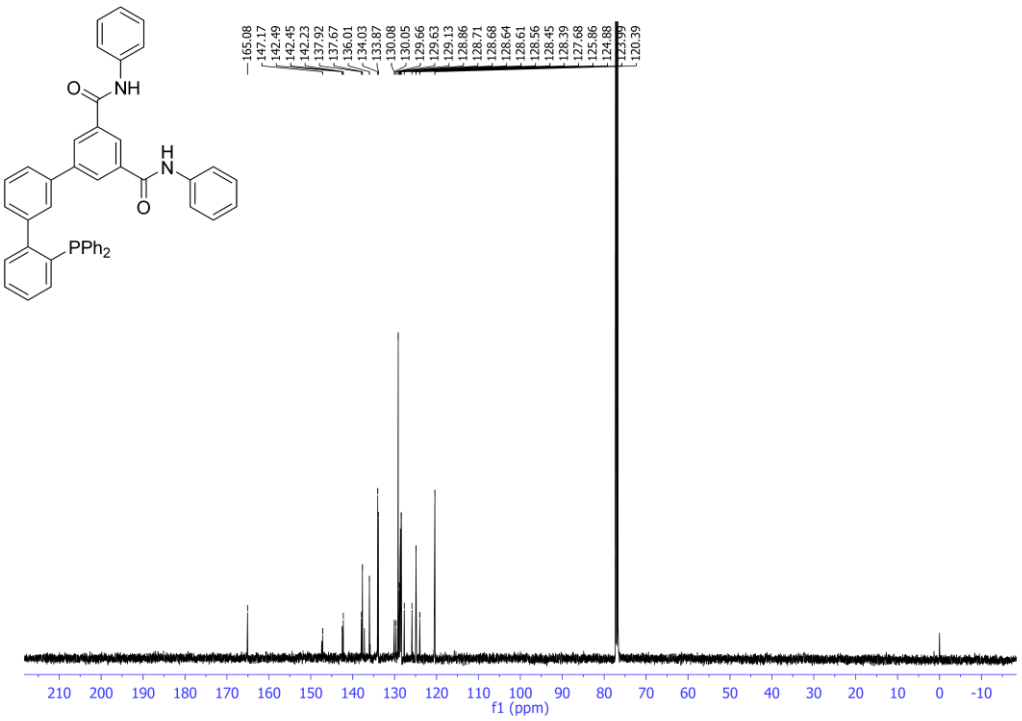


Figure B.47 Ligand **18**

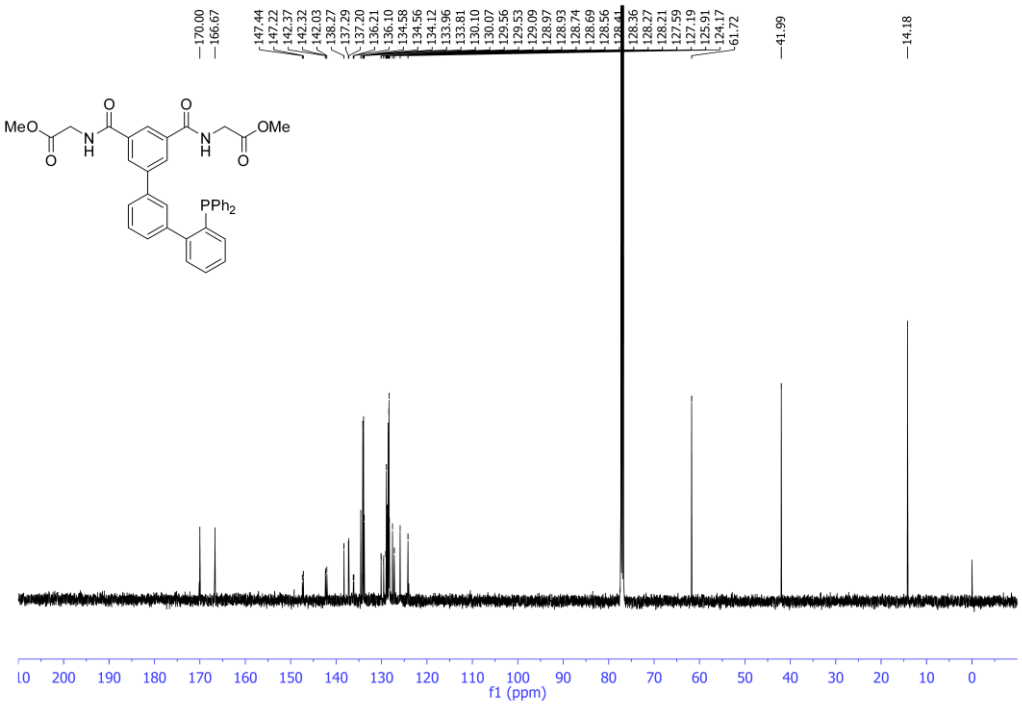


Figure B.48 Ligand **21**

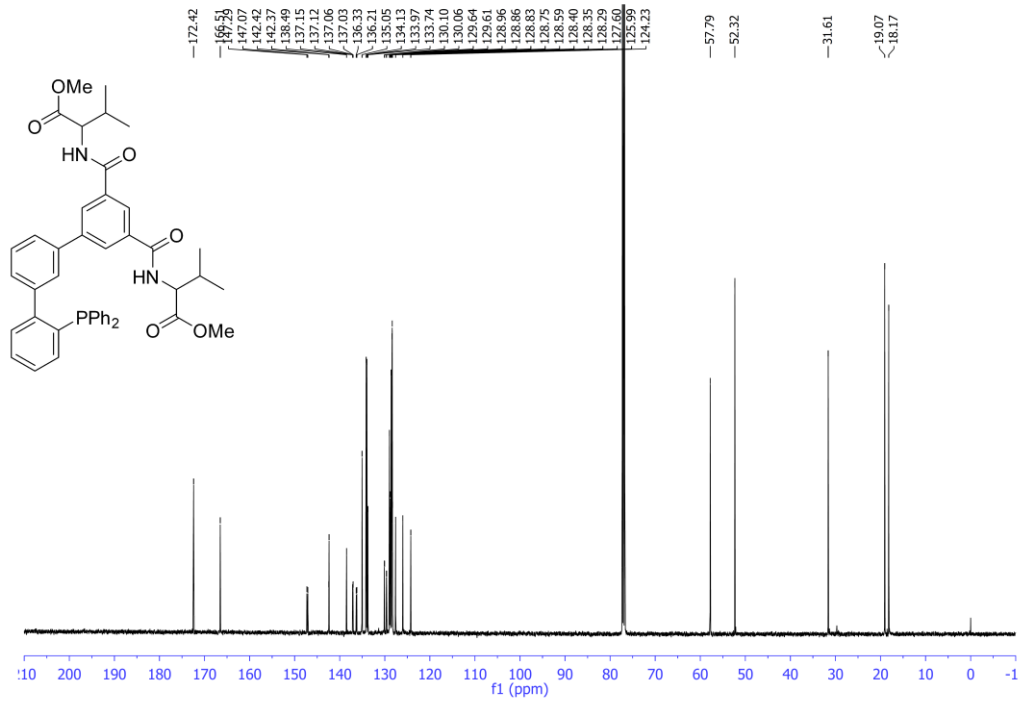


Figure B.49 Ligand **22**

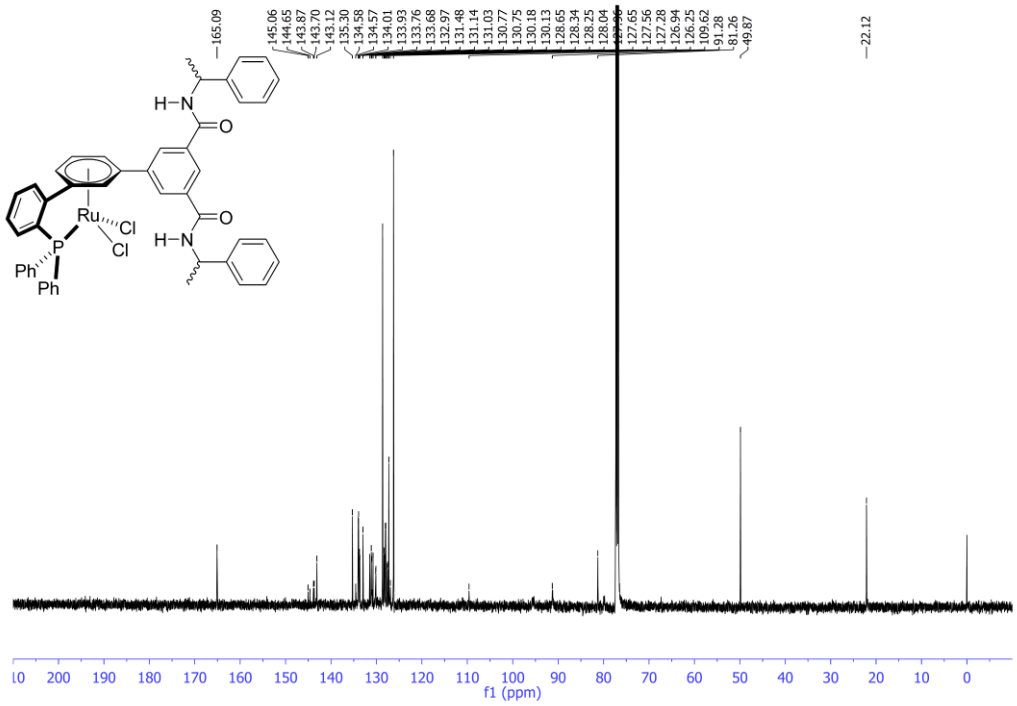


Figure B.50 Ruthenium complex **25**/Diastereomer 1

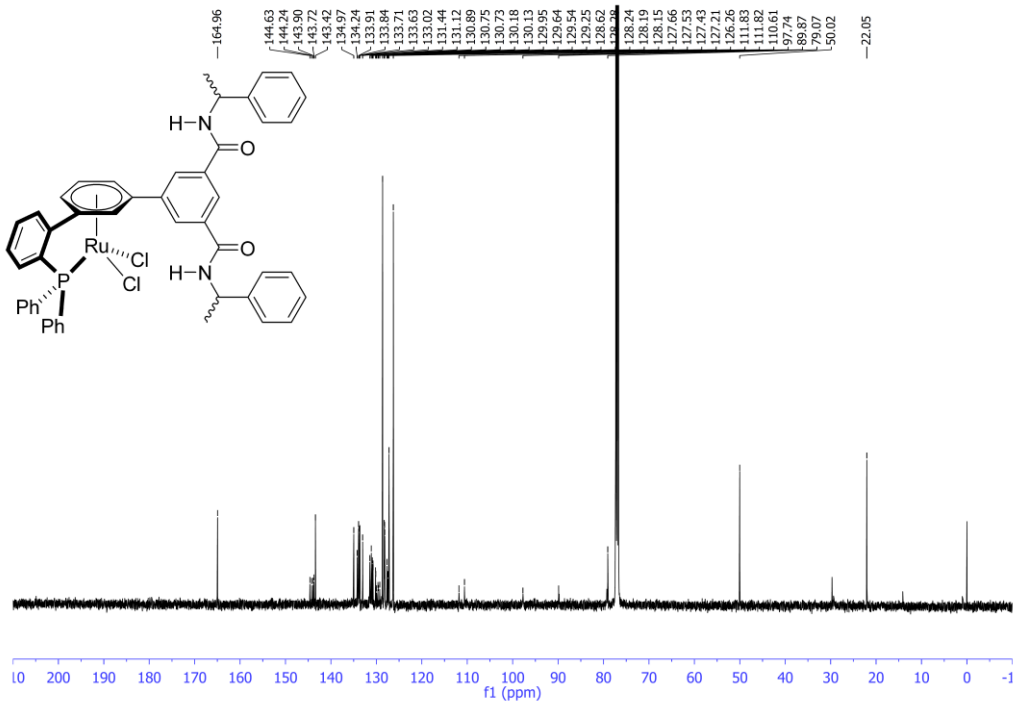


Figure B.51 Ruthenium complex **25**/Diastereomer 2

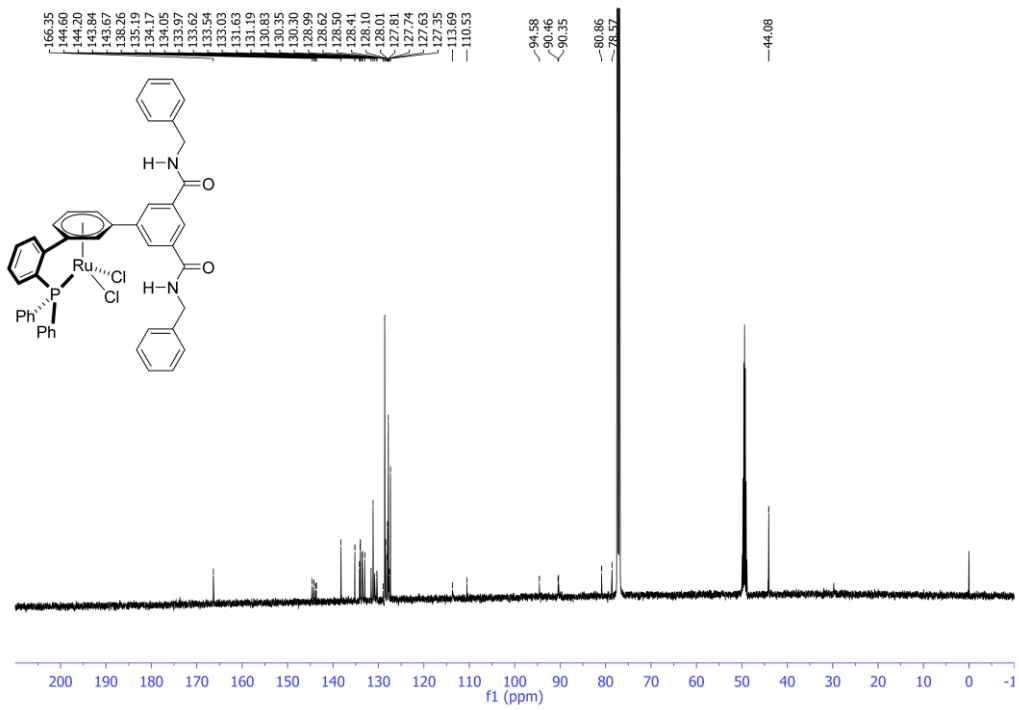


Figure B.52 Ruthenium complex **24**

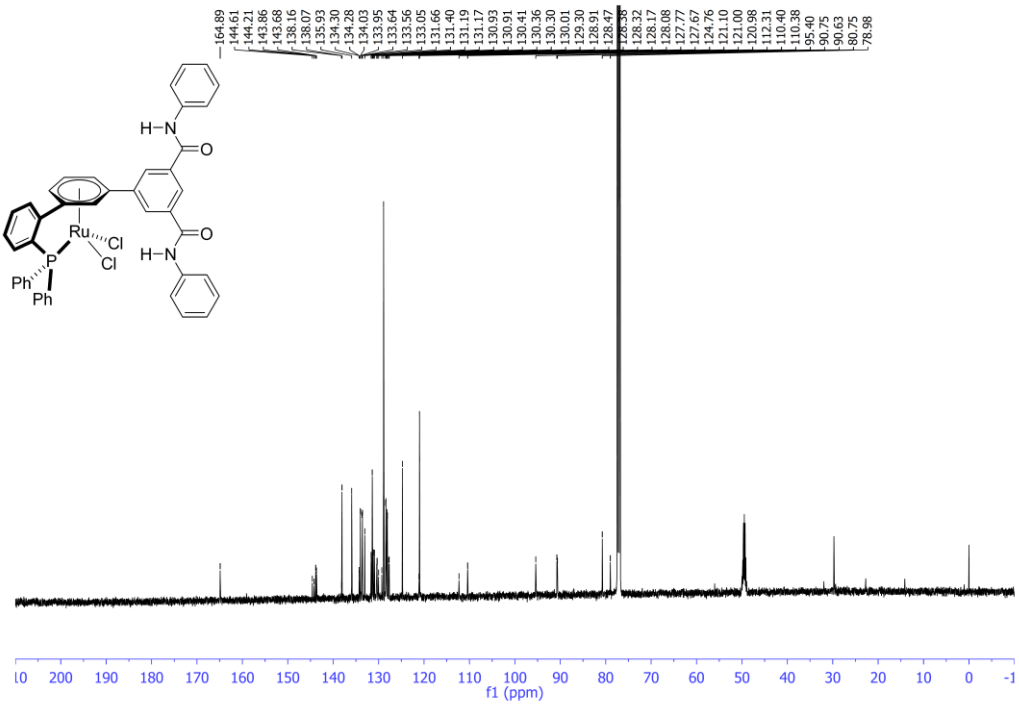


Figure B.53 Ruthenium complex **23**

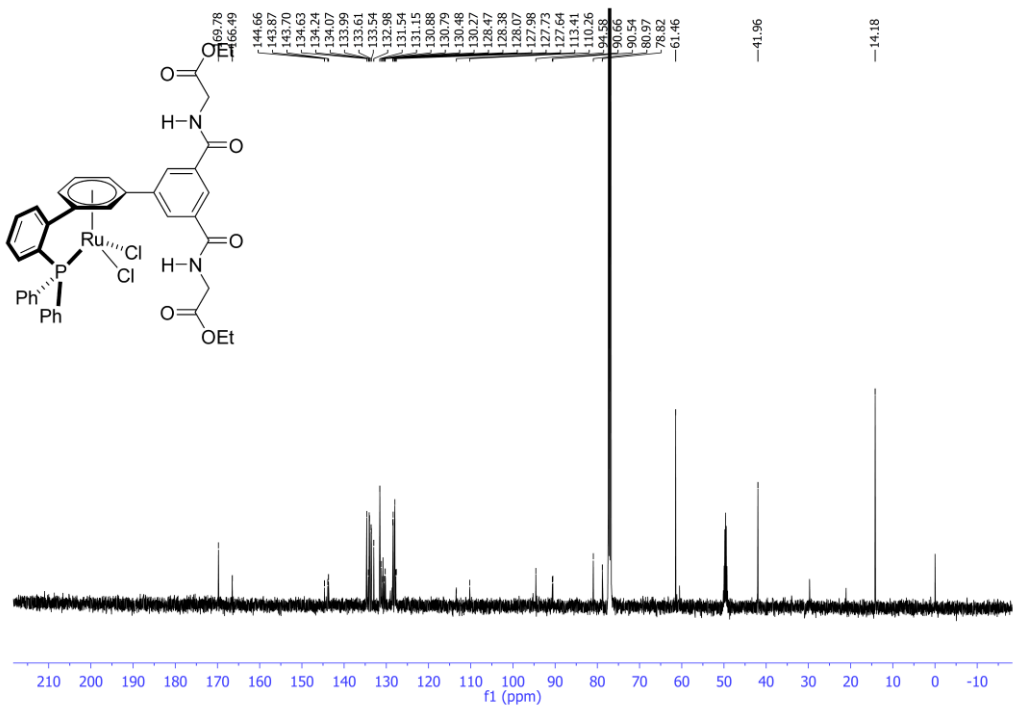


Figure B.54 Ruthenium complex **26**

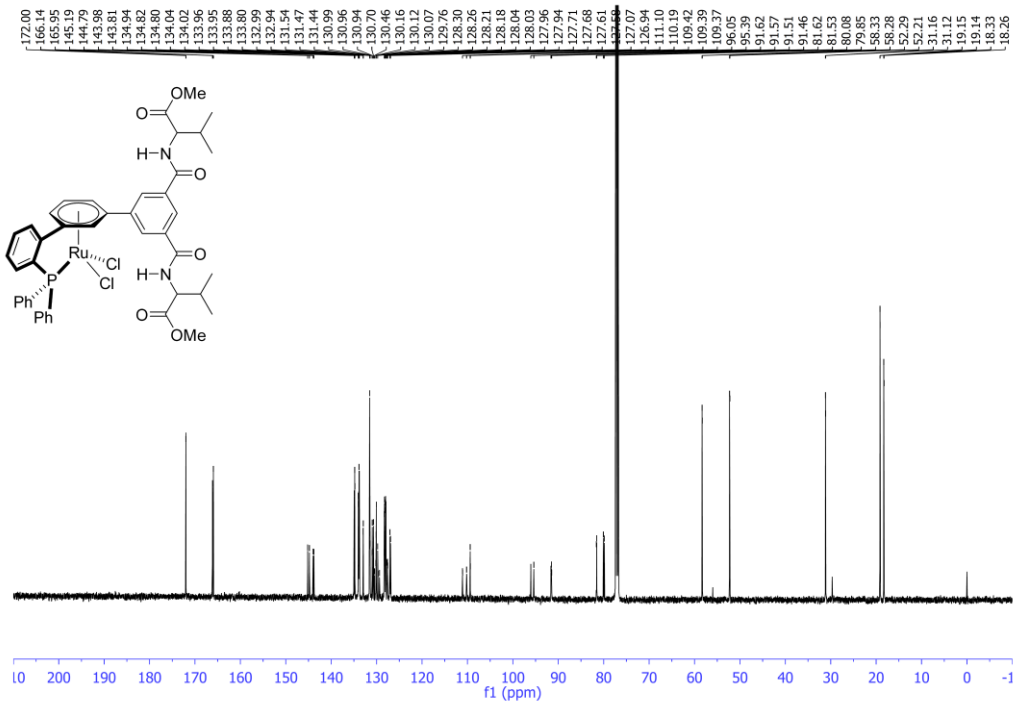


Figure B.55 Ruthenium complex **27**

B.3 ^{31}PNMR spectra

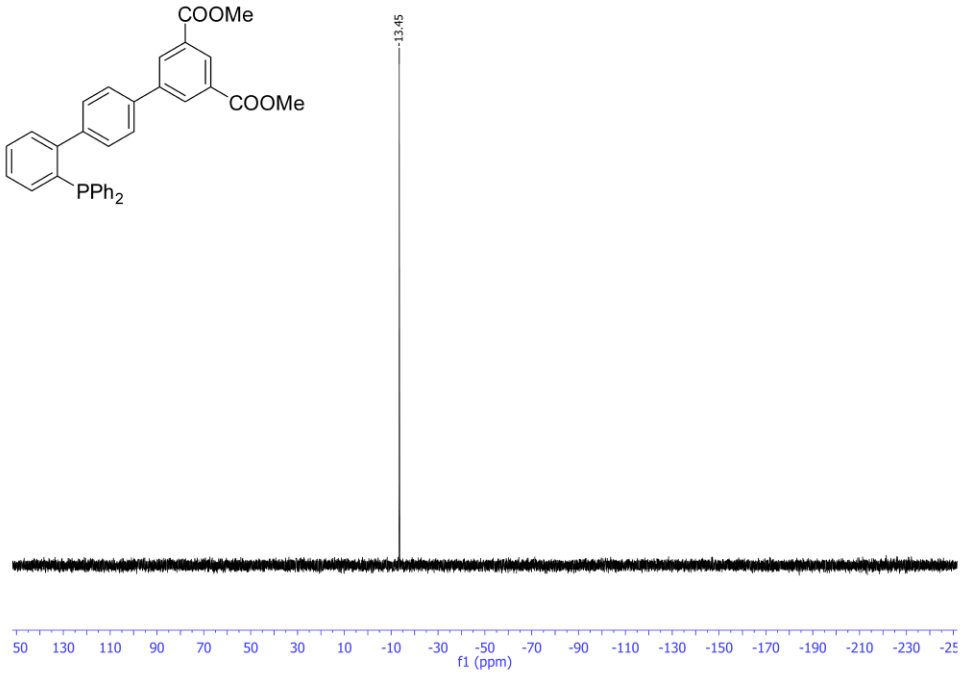


Figure B.56 Intermediate **4**

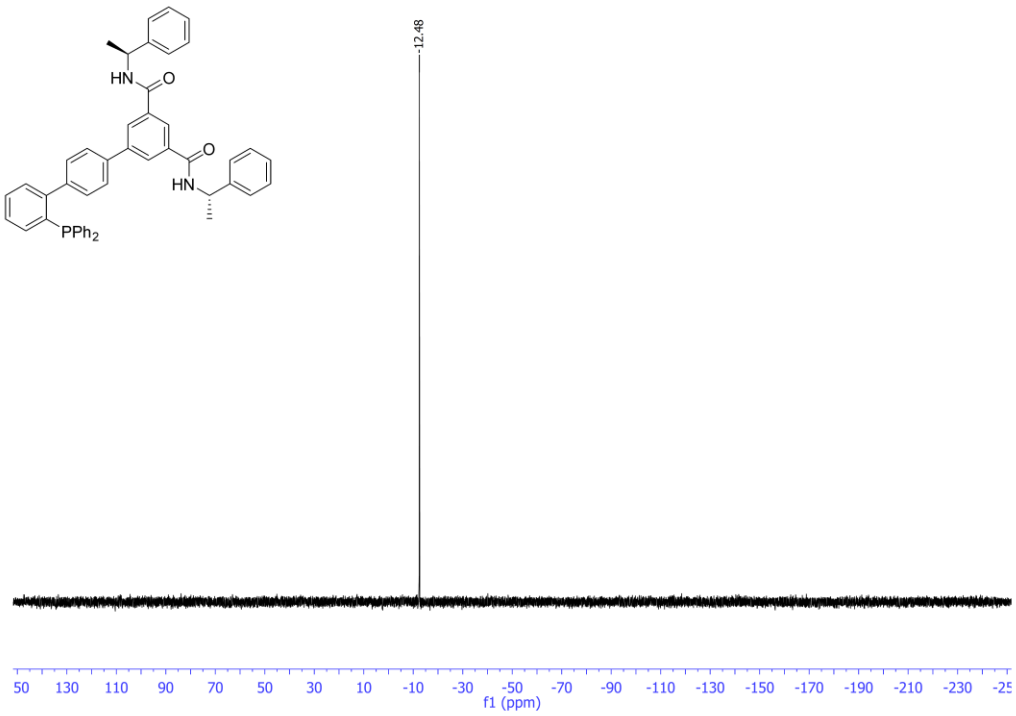


Figure B.57 Ligand **7**

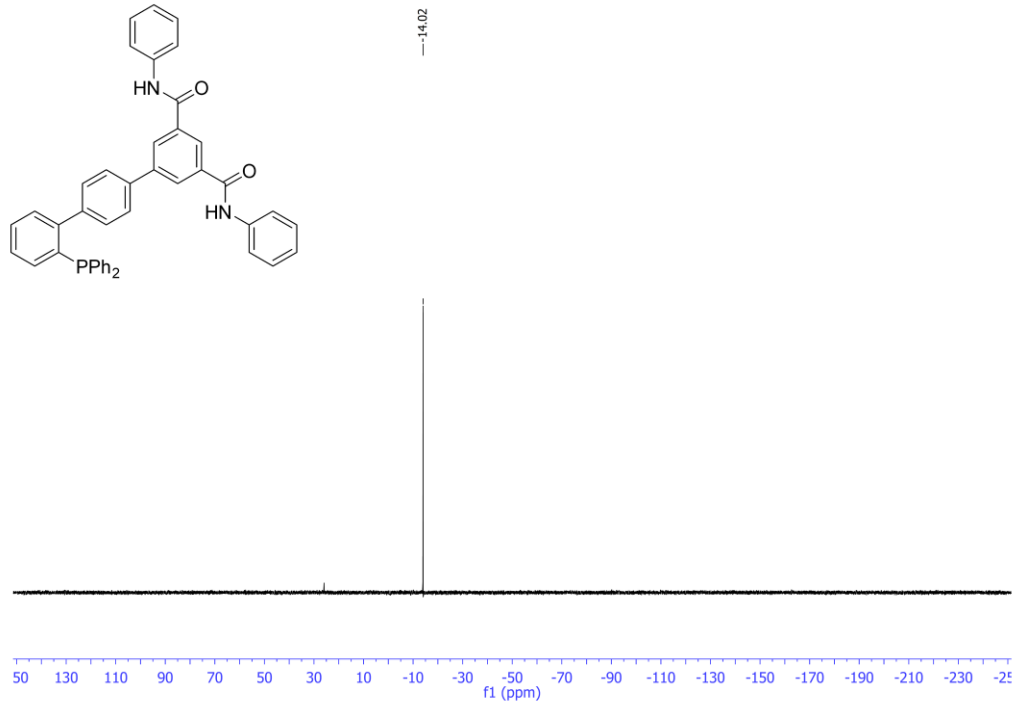


Figure B.58 Ligand **5**

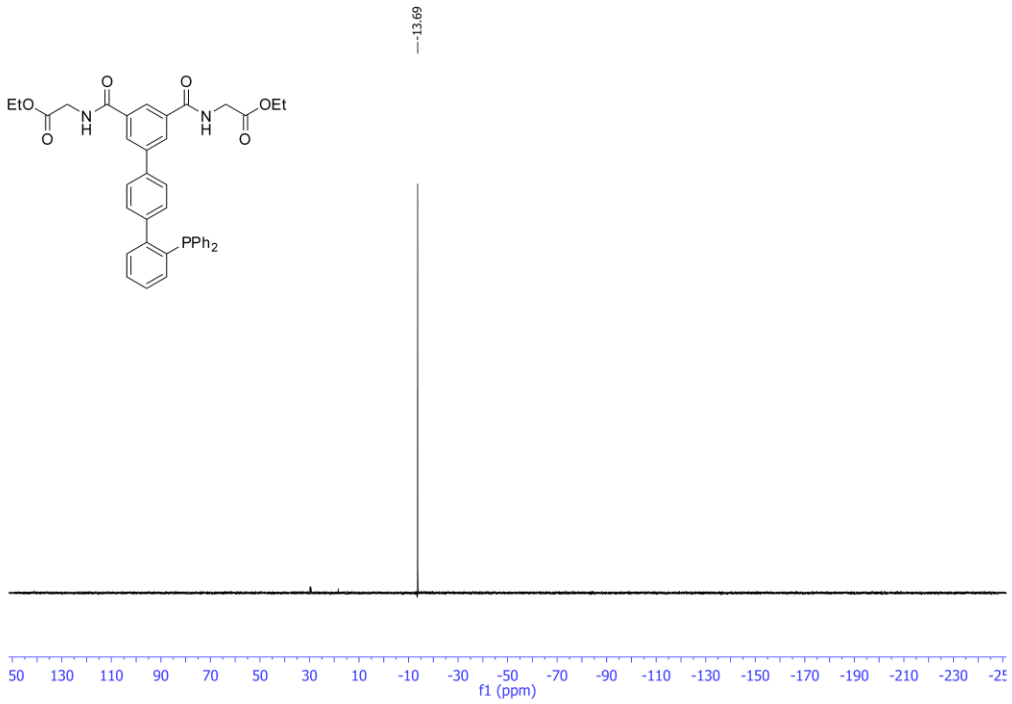


Figure B.59 Ligand **8**

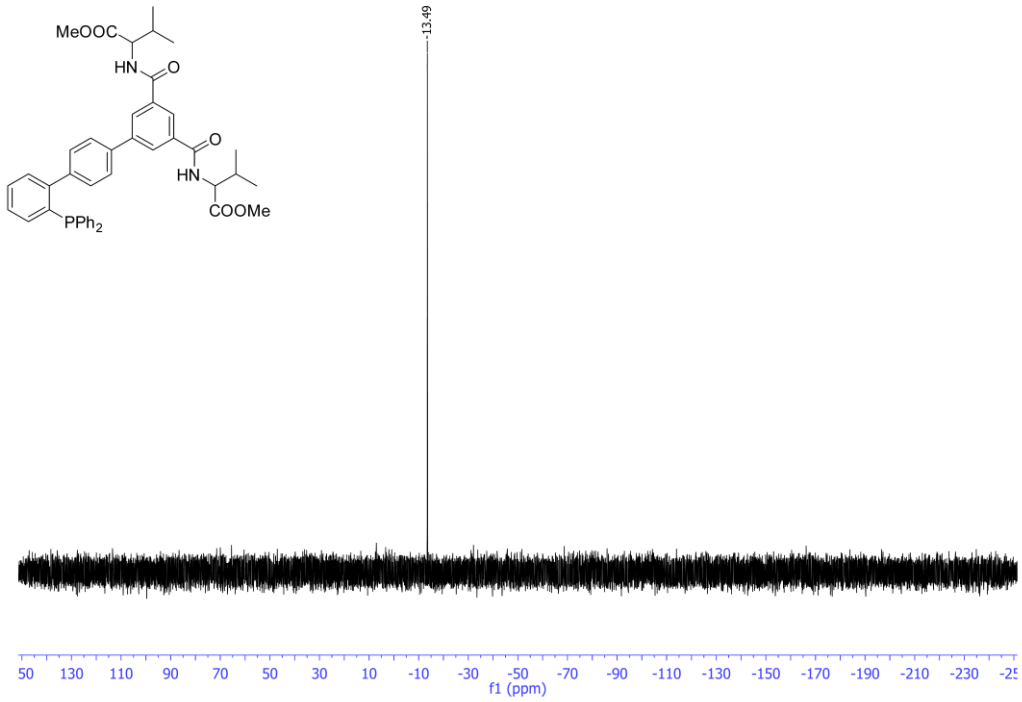


Figure B.60 Ligand **9**

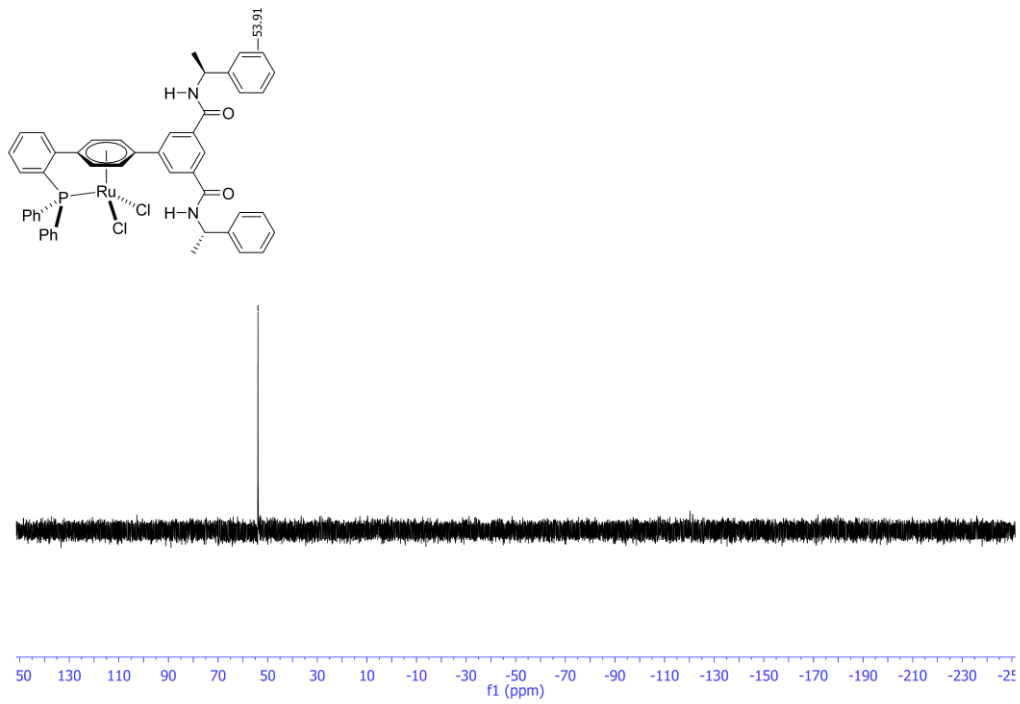


Figure B.61 Ruthenium complex **12**

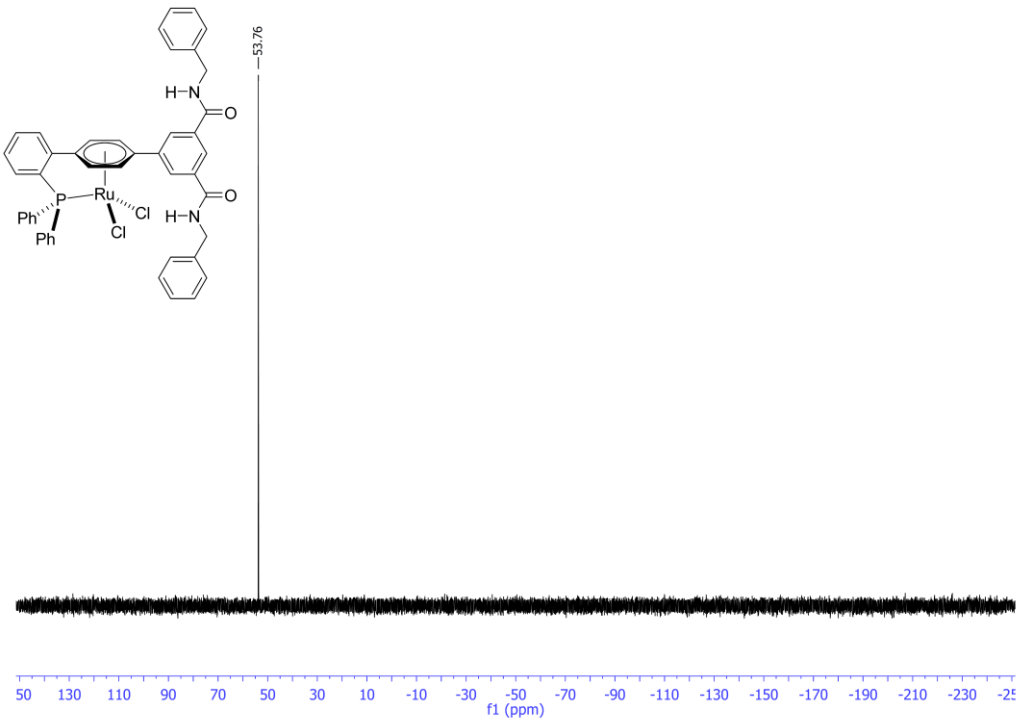


Figure B.62 Ruthenium complex **11**

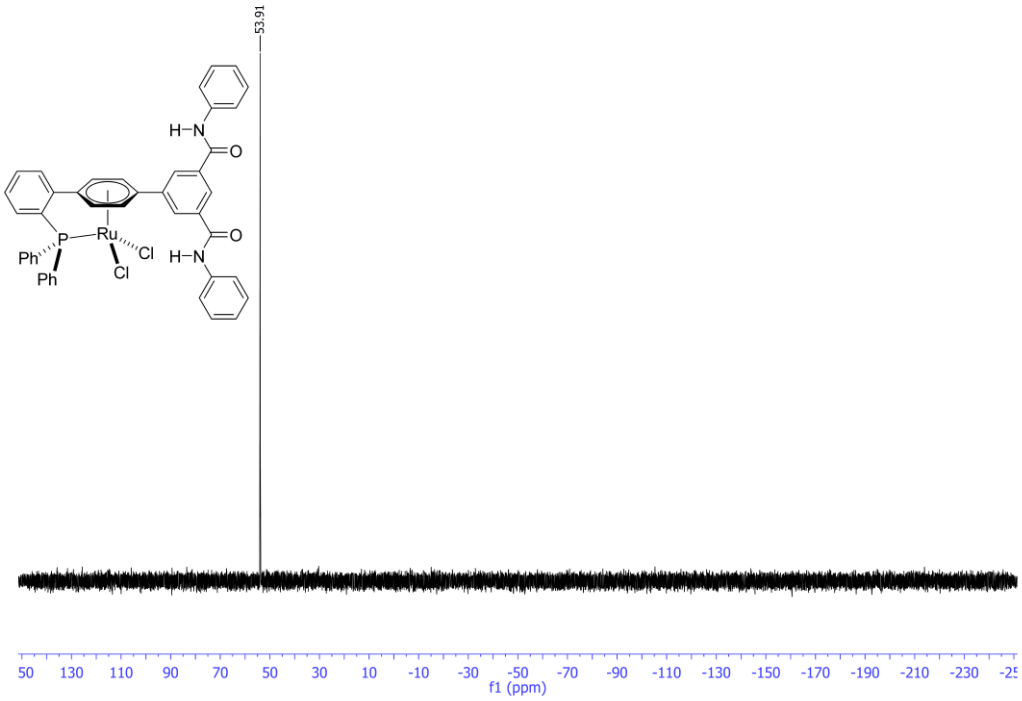


Figure B.63 Ruthenium complex **10**

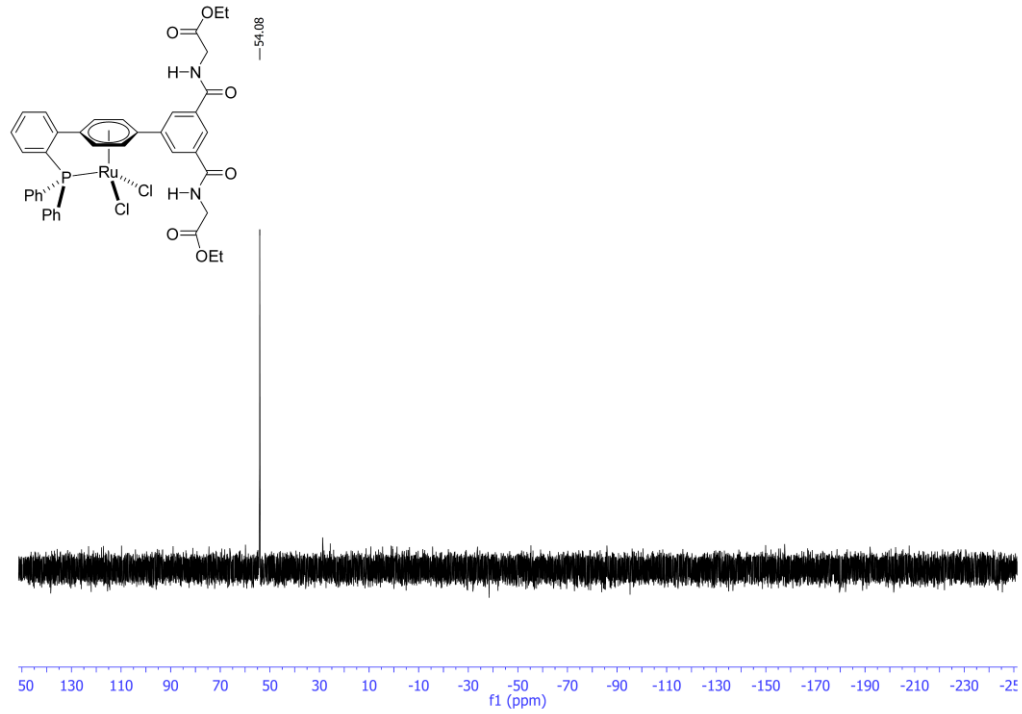


Figure B.64 Ruthenium complex **13**

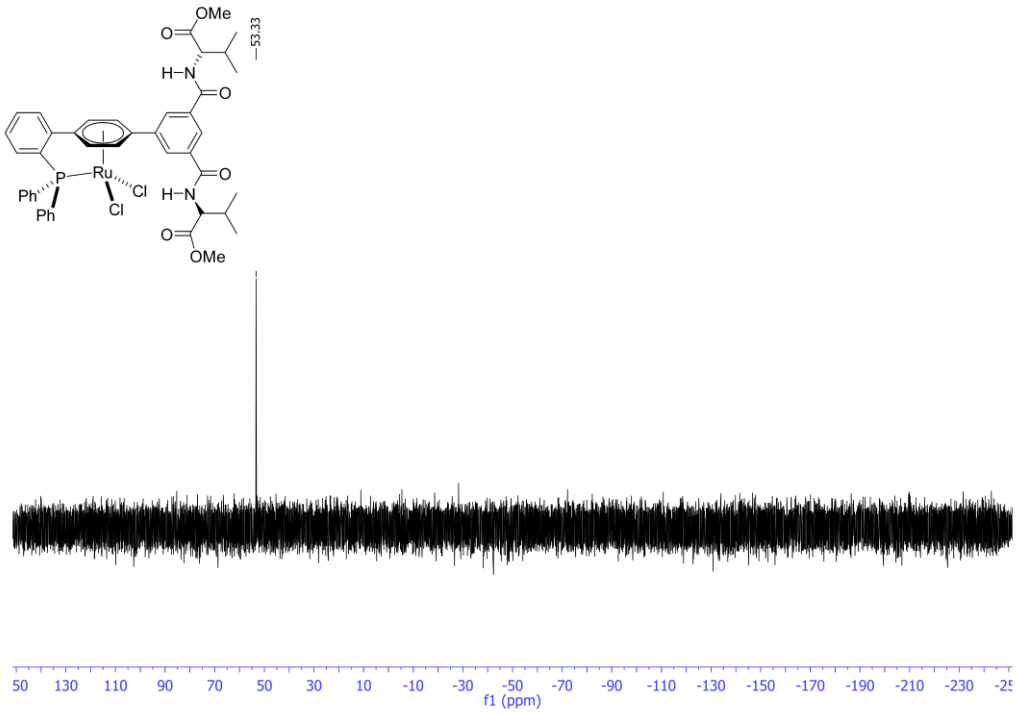


Figure B.65 Ruthenium complex **14**

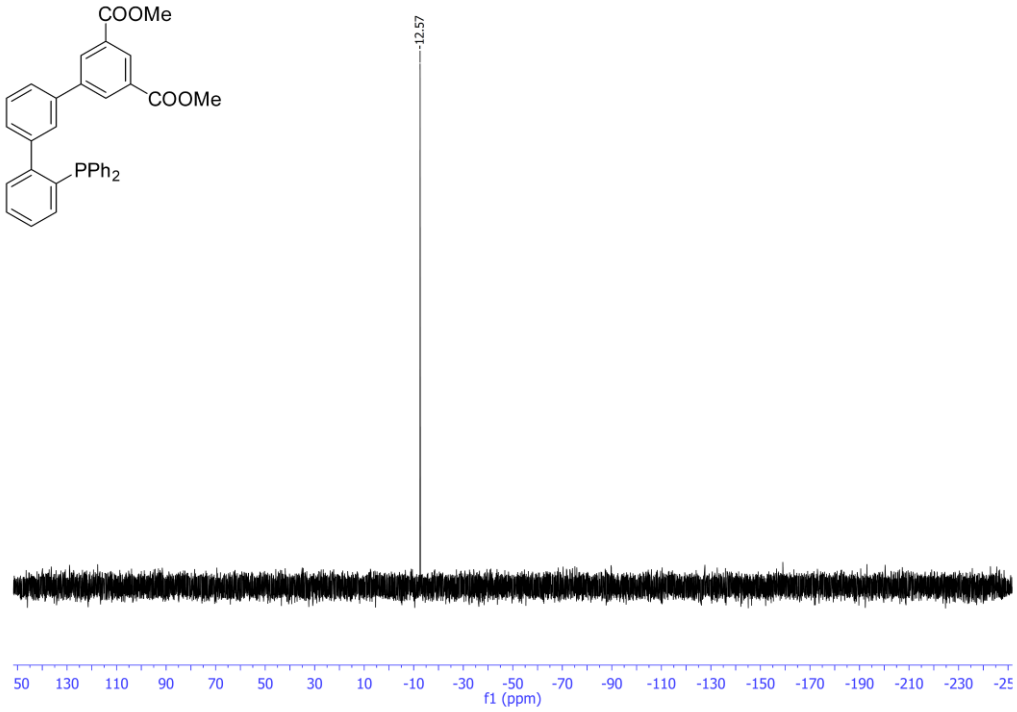


Figure B.66 Intermediate **17**

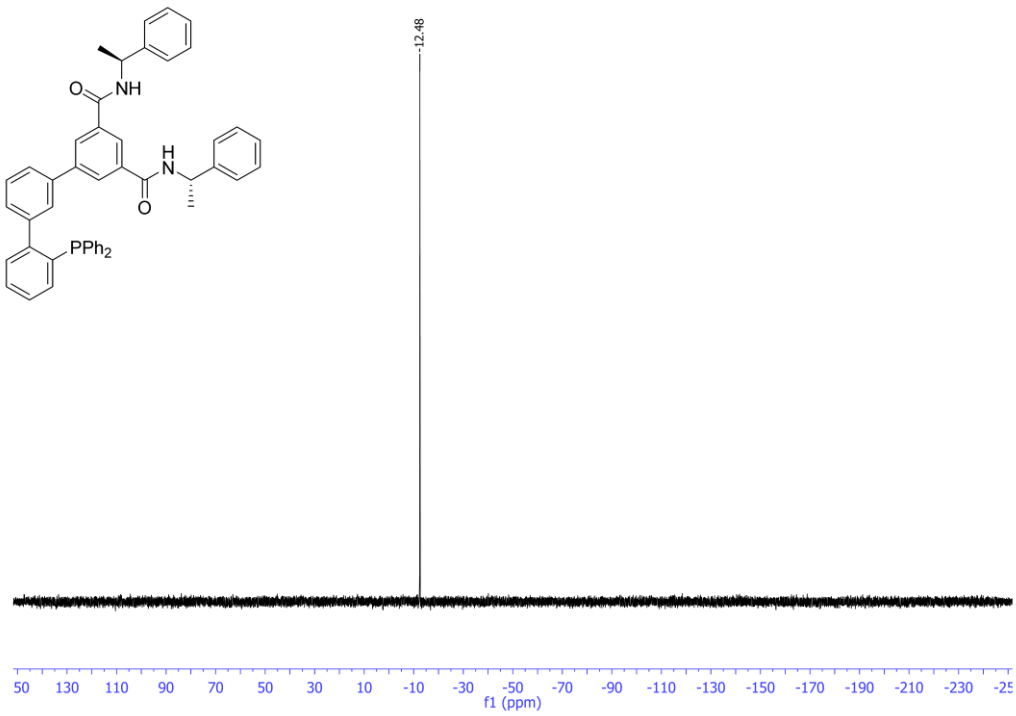


Figure B.67 Ligand **20**

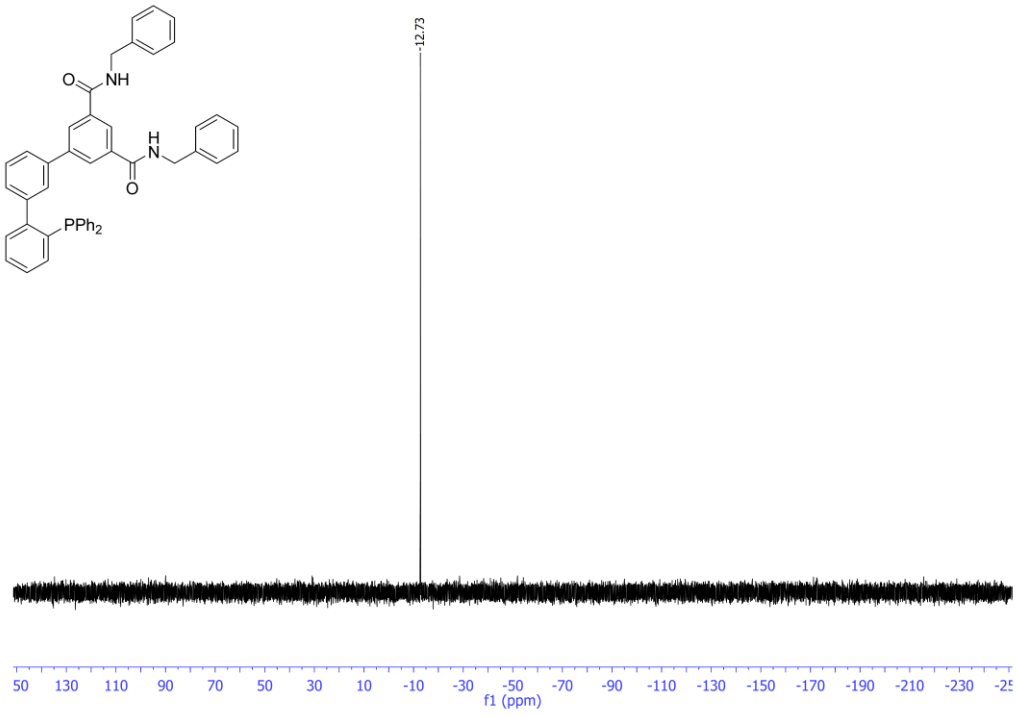


Figure B.68 Ligand **19**

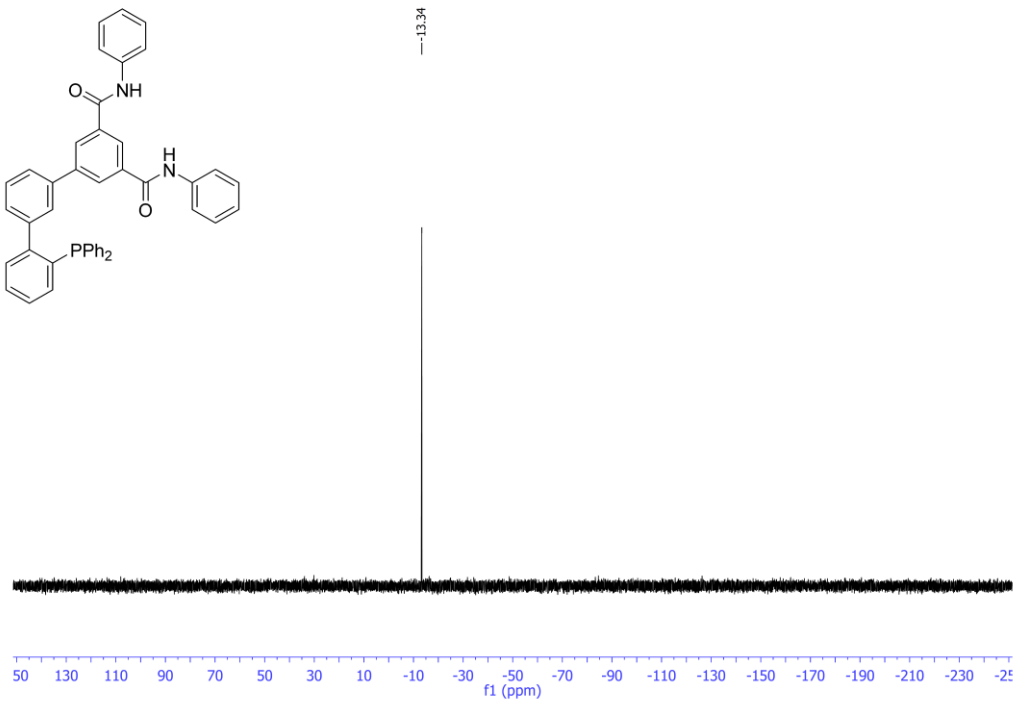


Figure B.69 Ligand **18**

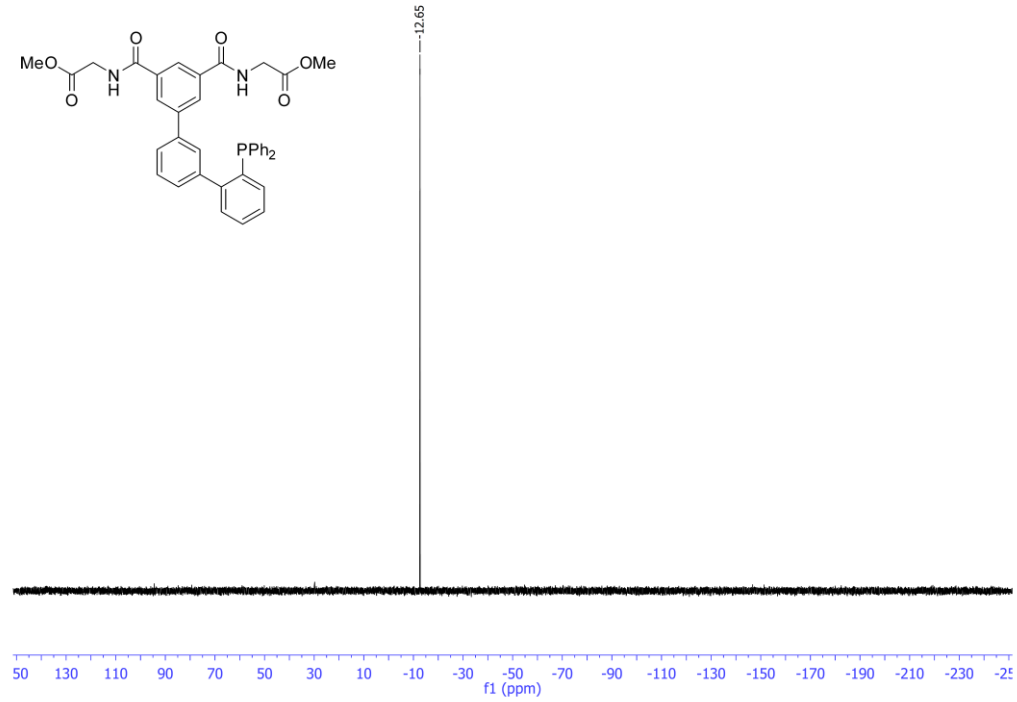


Figure B.70 Ligand **21**

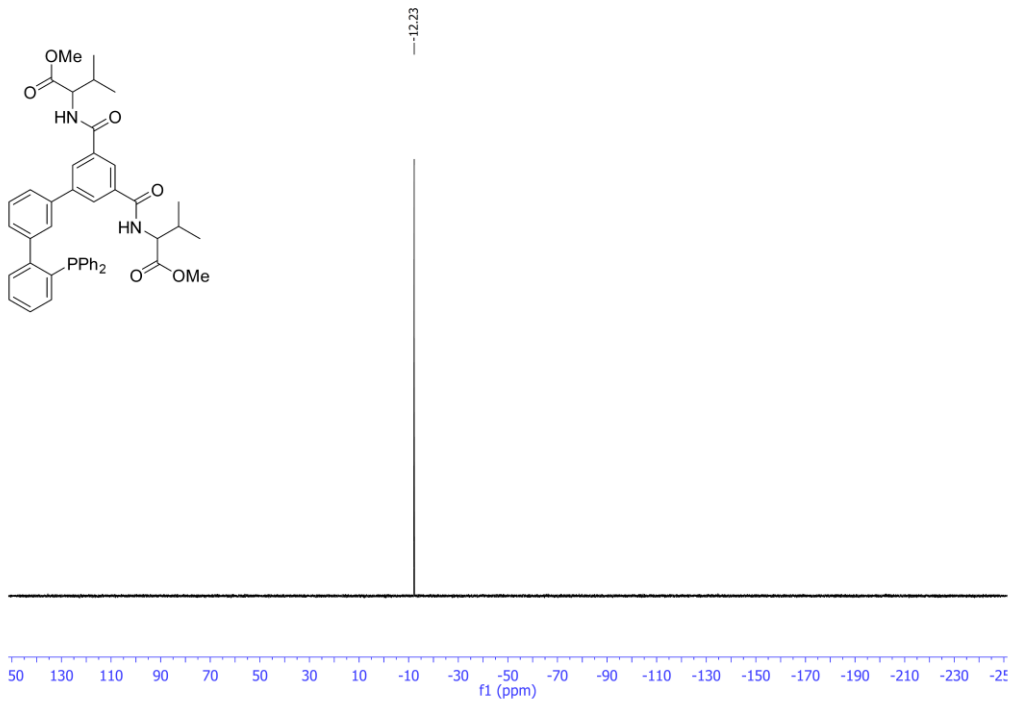


Figure B.71 Ligand **22**

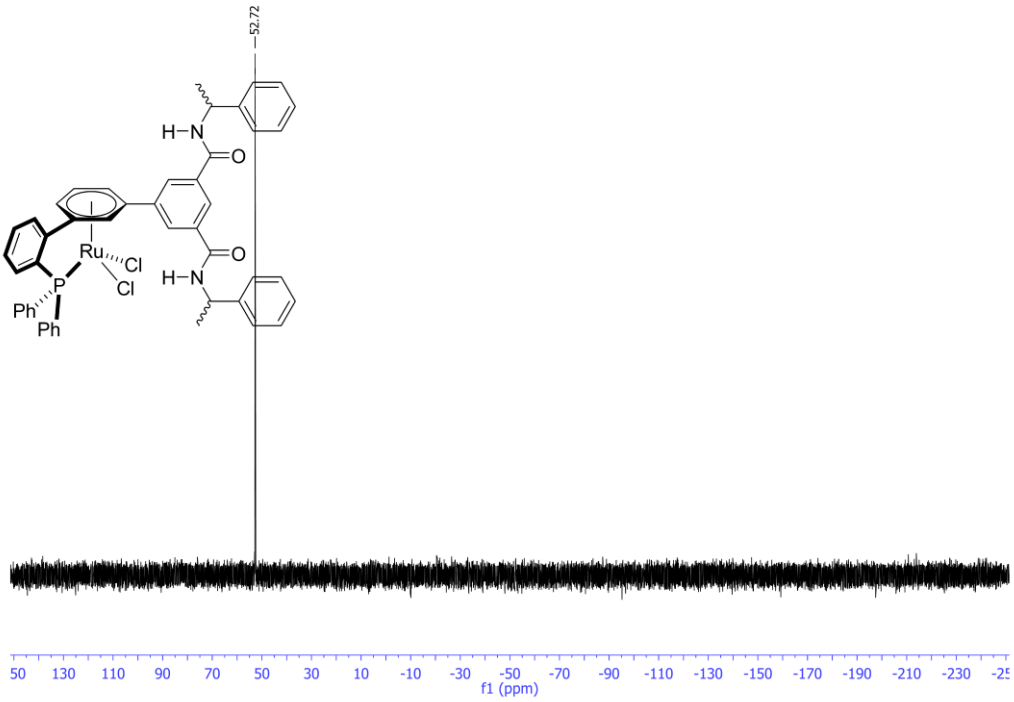


Figure B.72 Ruthenium complex **25**/Diastereomer 1

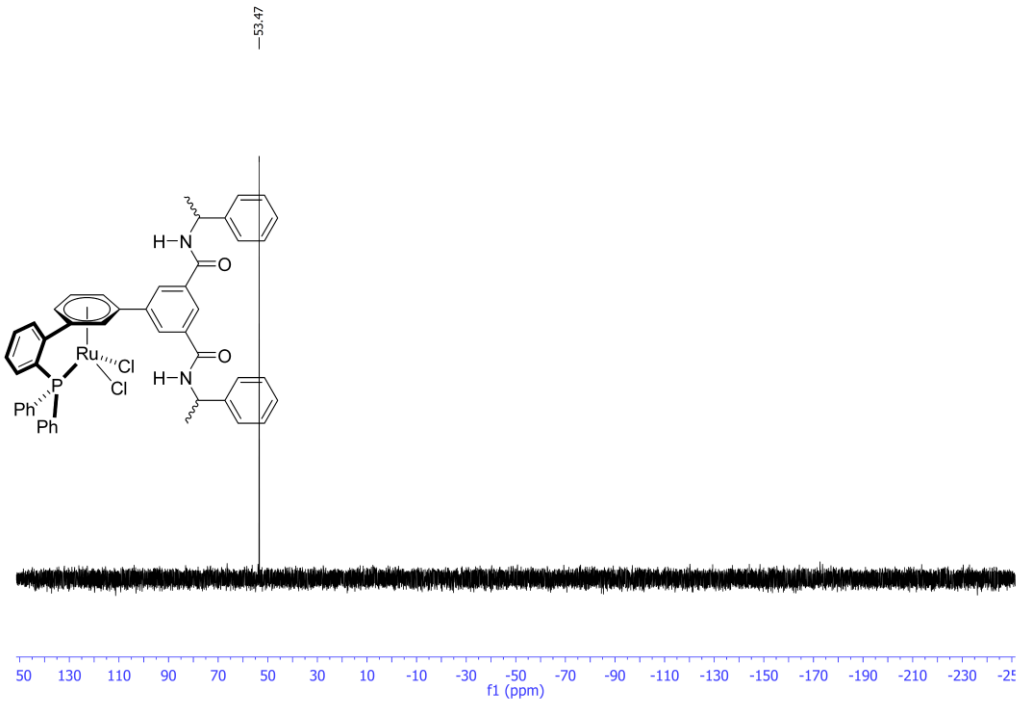


Figure B.73 Ruthenium complex **25**/Diastereomer 2

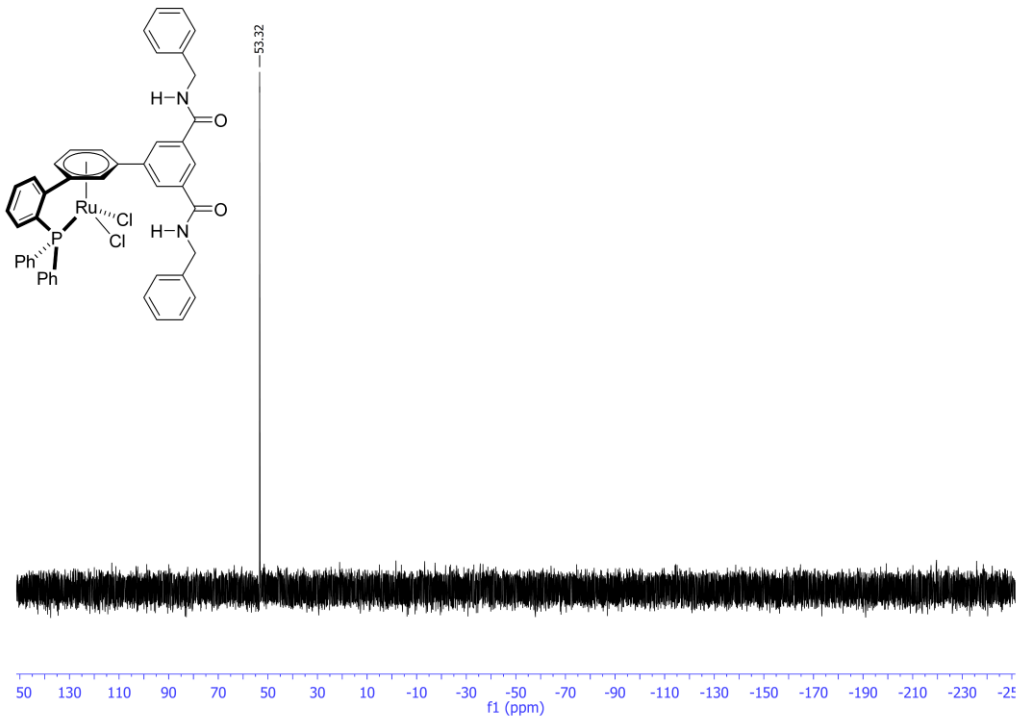


Figure B.74 Ruthenium complex **24**

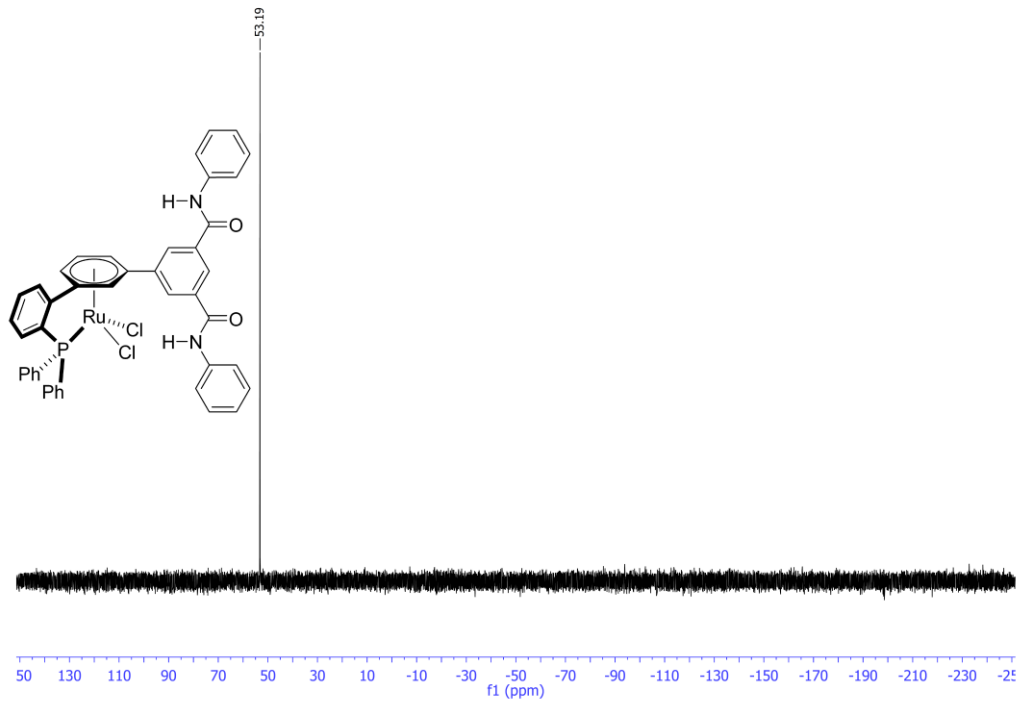


Figure B.75 Ruthenium complex **23**

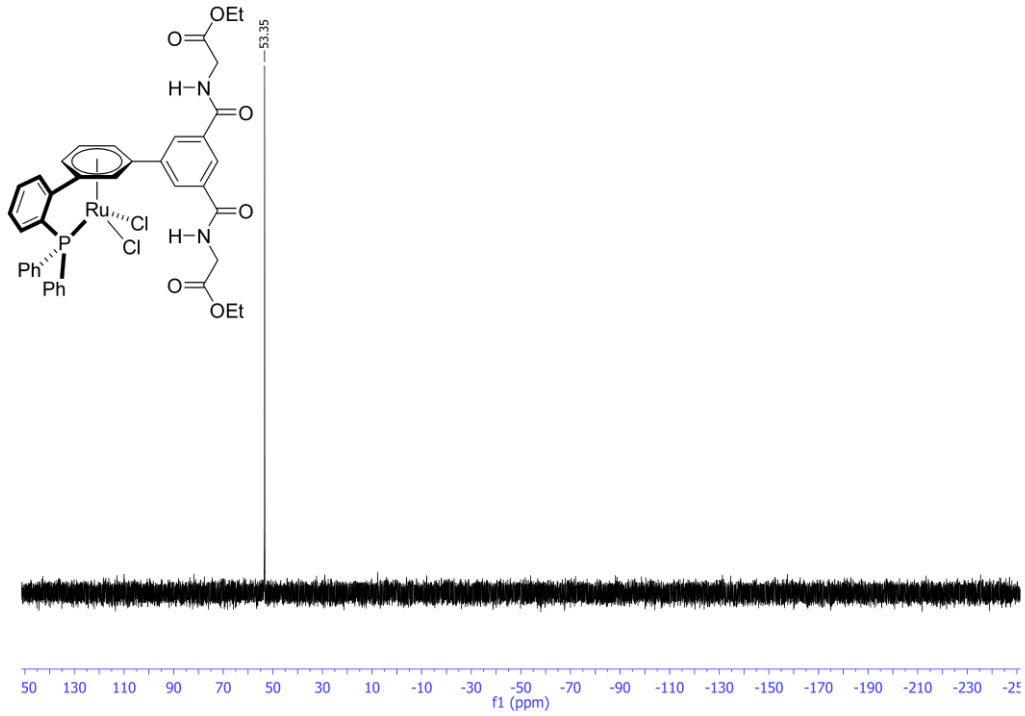


Figure B.76 Ruthenium complex **26**

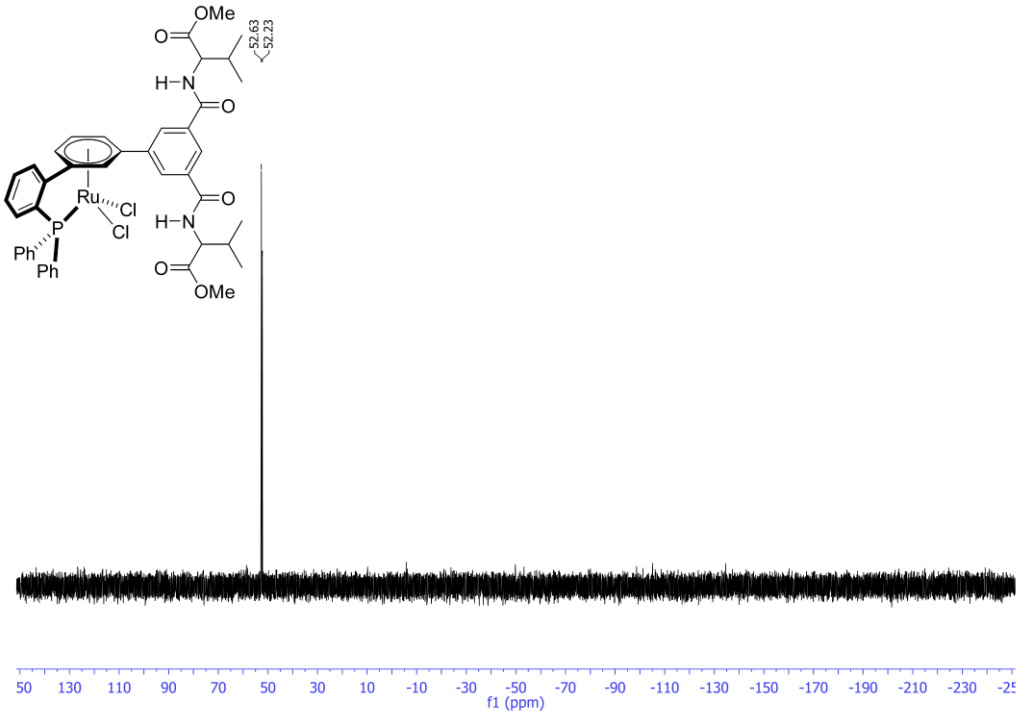


Figure B.77 Ruthenium complex **27**