ABSTRACT

Synthesis and Application of C_2 Asymmetric Phosphinines
via Their Pyrylium Salt Precursors.

Jason R. Bell, Ph.D.

Mentor: Charles M. Garner, Ph.D.

The development of new chiral ligands for asymmetric catalysis is an increasingly important area of research. Though many ligands are phosphorus based, one class of phosphorus ligands, phosphinines (phosphabenzenes), have been little studied. Most studies of chiral phosphinines, especially for those used in asymmetric catalysis have involved essentially attaching achiral phosphinines to chiral auxiliaries.

The synthesis of the first C_2 chiral phosphinine was accomplished by converting (+)-camphor to the corresponding pyrylium salt, and then converting the pyrylium to the phosphinine. Though several initial attempts failed at forming the necessary pyrylium salt using simpler synthetic methods, an effective route for forming the pyrylium was chosen utilizing the preformed 3-ene-1,5-dione precursor. The camphor-based phosphinine was fully characterized and applied to two asymmetric catalytic test reactions, asymmetric hydrosilylation and asymmetric hydrogenation.

Though (+)-camphor provided a convenient, cost-effective, and enantiomerically pure starting material, nature provides few compounds fitting all the necessary

requirements for the starting materials. Therefore, derivatized cyclohexanones were also synthesized. Specifically, pyryliums salts based on 2-methyl-2-phenylcyclohexanone were synthesized, albeit in low yield. Attempts to use the improved synthetic method developed for the camphor-based pyryliums failed at the chlorination stage. Attempts to convert the (+)-camphor chlorobenzylidene intermediate into C_1 chiral pyryliums also failed. The C_2 asymmetric phosphinine based on camphor did react with benzyne to yield a new chiral phosphabarrelene.

Synthesis and Application of C_2 Asymmetric Phosphinines
via Their Pyrylium Salt Precursors.

by

Jason R. Bell, B.S., M.S.

A Dissertation

Approved by the Department of Chemistry and Biochemistry

_____
Patrick J. Farmer, Ph.D., Chairperson

Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree
of
Doctor of Philosophy

Approved by the Dissertation Committee

_____
Charles M. Garner, Ph.D., Chairperson

_____
Kevin G. Pinney, Ph.D.

_____
Robert R. Kane, Ph.D.

_____
Darrin J. Bellert, Ph.D.

_____
Stephen I. Dworkin, Ph.D.

Accepted by the Graduate School
May 2010

_____
J. Larry Lyon, Ph.D., Dean

Page bearing signatures is kept on file in the Graduate School.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SCHEMES

LIST OF ABBREVIATIONS

Å	angstroms
Ac	acetyl
AIBN	azobisisobutyronitrile
BCT	biscamphortoluene
n-Bu	normal butyl
t-Bu	tertiary butyl
cat.	catalytic
1,2-DCE	1,2-dichloroethane
DME	dimethoxyethane
DMF	dimethylformamide
ee	enantiomeric excess
equiv	equivalents
Et	ethyl
Et_2O	diethyl ether
EtOAc	ethyl acetate
FID	flame ionization detector
g	grams
GC	gas chromatography
GC-MS	gas chromatography-mass spectrometry
h	hours
L	liters

M	molarity
min	minute
mL	milliliter
Me	methyl
m.p.	melting point
MS	mass spectrometry
NBS	*N*-bromosuccinimide
NCS	*N*-chlorosuccinimide
NMR	nuclear magnetic resonance
ppm	parts per million
Ph	phenyl
TBAF	tetrabutylammonium fluoride
THF	tetrahydrofuran
TMS	trimethylsilyl

ACKNOWLEDGMENTS

Foremost, I would like to acknowledge and thank my advisor, Dr. Charles Garner, for his support, his enthusiasm, his patience, and for the freedom to explore the project in my own ways. His guidance has allowed me grow from the unsure, inexperienced, graduate student; to an independent, critically thinking, research scientist. I am also thankful to the members of my committee, Drs. Steve Dworkin, Bob Kane, Darrin Bellert, and Kevin Pinney for their time and ideas during this project.

I would like to thank the Donors of the American Chemical Society Petroleum Research Fund for support of this research (grant #47942-AC1). Also, I would like to thank the Robert A. Welch Foundation (grant #AA-1395) for partial support of this work.

I am indebted to my colleagues who have provided continual support, motivation, ideas, and camaraderie throughout this process; Nathan Duncan, Nelson Van Der Velde, Eric Bauch, Sheree Allen, and Tiffany Turner. Also, I am grateful to the members of Baylor University that have contributed to the project as well, including Dr. Andreas Franken and Dr. Kevin Klausmeyer for their work with X-ray crystallography of compounds reported here.

I would like to thank Dr. Paul Primrose for encouraging me to not only return to graduate school, but to come to Baylor University to accomplish my doctorate work. I would like to thank the entire Primrose family for making my family and me feel at home in Texas.

I am deeply thankful for my wife, Julie, and my boys; Jack, Nolan, and Eli, for the love, support and encouragement they have given me during this time, and for the

sacrifices they have made for me to accomplish this goal. I am thankful to my parents and brothers who have supported and encouraged me through all of my studies.

I would also like to thank those people who have somehow encouraged either a love of science or a love of learning in general, which I have carried with me since childhood. I am grateful for my 5th grade teacher Docia Thaxton, for making science real and exciting. I am thankful to Joan Griffin, my 8th grade literature teacher for her excitement and encouragement of making learning a lifelong experience. Finally, to Mrs. Rae Smith, my 12th grade literature teacher and lifelong friend, who always encouraged me to never stop learning, or living, to the fullest.

CHAPTER ONE

Introduction

Background

Chirality is a central link between the chemical and biological sciences. Many of the most important biological molecules, such as amino acids and sugars, are chiral. These chiral molecules then make up the backbones of enormous macrobiomolecules, such as DNA and proteins, causing nearly every biological process to involve chiral interactions. Nature has however chosen to use only one of the possible enantiomers for each molecule, making the chiral interactions of biological processes specific. This means that chemists must be careful when interacting with nature in a stereospecific way, as was seen in the thalidomide tragedy of the late 1950's. Thalidomide was a drug given as a racemic mixture to women to ease morning sickness during pregnancy. Not until four years later was the drug pulled from the market after it was linked to an epidemic of birth defects, most including malformed limbs. It was later discovered that (*S*)-thalidomide was the teratogenic culprit, while (*R*)-thalidomide exhibited the desired pharmacological effect. [1]

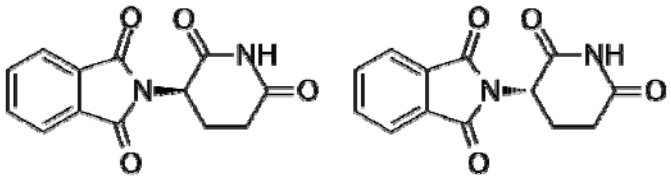


Figure 1.1. Structures of (*R*)-thalidomide and (*S*)-thalidomide.

As seen in the thalidomide example, enantiomers of a drug can have widely varying biological activity. In order to take full advantage of the possibilities of chiral drugs, it must be possible to isolate drugs in an enantiomerically pure fashion. In fact, the FDA now requires separate testing of each enantiomer of any chiral drug. This can be done by separation of the racemic mixture, or by producing only one enantiomer in an asymmetric reaction.

Chiral Resolution

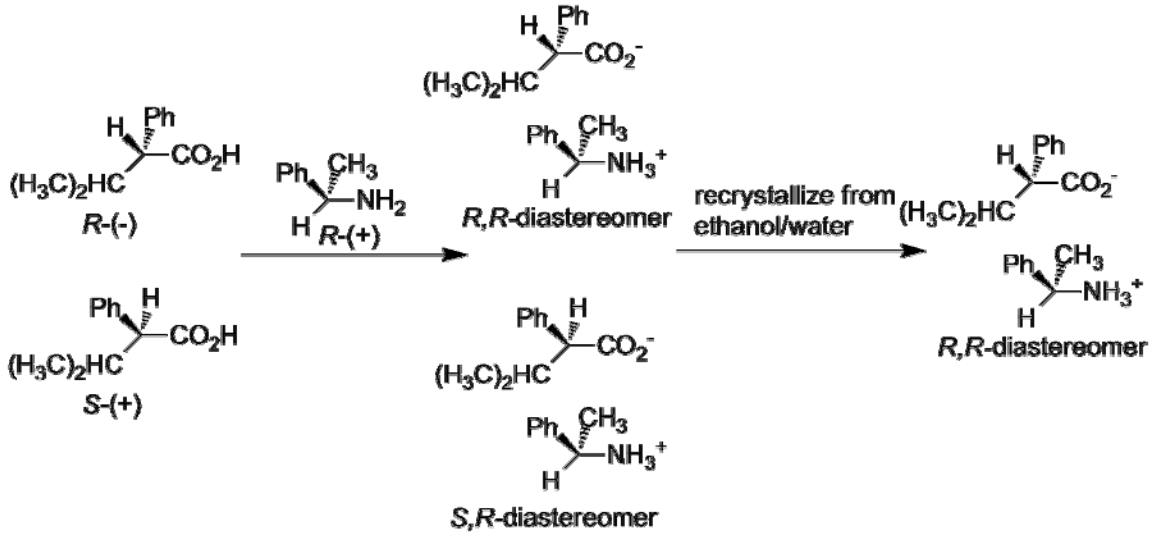
Chiral resolution is performed on both the analytical and preparative scale, and the techniques used for each are typically quite different. The most common method of chiral separation for analytical techniques is chiral chromatography. Chiral chromatography (either gas or liquid chromatography) involves passing enantiomers over a stationary phase which has incorporated into it some chiral component. As the analyte mixture passes over the chiral stationary phase, intermolecular interactions occur, and because of the chiral nature of the stationary phase, stronger interactions occur with one enantiomer. This allows the analytical separation of the enantiomers, which can then be detected separately and quantified.

The first chiral resolution was performed by Louis Pasteur in 1848. When crystallizing sodium ammonium tartrate, a salt of the chiral tartaric acid, Pasteur discovered that non-superimposable crystals were formed. He was able to manually separate the dextrorotatory and levorotatory crystals, and found that though the initial racemic mixture showed no optical rotation, both sets of crystals were optically active and rotated light in opposite directions.[2] However, this method is not generally useful because compounds for which enantiomers crystallize separately (called conglomerates)

are quite rare, and the conditions for this to occur, even for sodium ammonium tartrate, are quite specific. It is much more typical that racemic mixtures form racemic crystals, i.e. where equal amounts of each enantiomer are present in each unit cell.

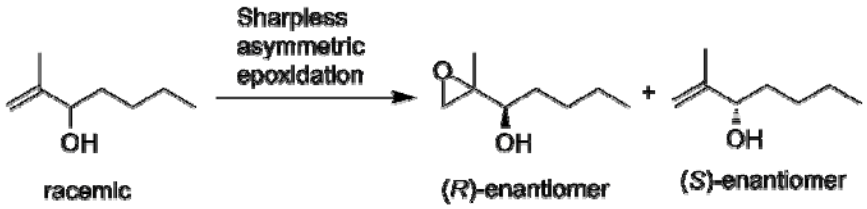
The most common method of preparatively separating enantiomers is by the formation and separation of diastereomers. This involves the desired molecules forming either covalent or ionic bonds with another enantiomerically pure chiral compound. This produces diastereomers that can then be separated by conventional means, typically by fractional crystallization, but sometimes by chromatography. For example, a racemic alcohol might react with a chiral, enantiomerically pure carboxylic acid derivative to form a mixture of diastereomeric esters which can be separated by column chromatography. An example of an ionic interaction would include the reaction of a racemic acid with an enantiomerically pure amine. This acid-base interaction will often result in a diastereomeric complex that can be recrystallized to isolate only one diastereomer, from which an enantiomerically pure acid can be recovered. This is one of the most common methods for chiral resolution, and when the resolution reagent can be recovered it is the most economical of chiral resolution methods.[2]

Kinetic resolution is another technique which can be used to obtain enantiomerically enriched products. This technique takes advantage of the different rates of reaction an enantiomerically pure reagent has with each enantiomer of a racemic reactant. Under the best conditions, the kinetic resolution reagent reacts with one enantiomer at a rate much greater than the other enantiomer, producing in high yield only the product of the faster reacting enantiomer. The solution can then be separated by normal means (recrystallization, chromatography, distillation, etc) to separate the



Scheme 1.1. Example of chiral resolution of a racemic acid using an optically pure amine.

components and recover either the unreacted enantiomer or the product formed, both being enantiomerically enriched.[2]



Scheme 1.2. Example of kinetic resolution using Sharpless asymmetric epoxidation to resolve a racemic alkene.

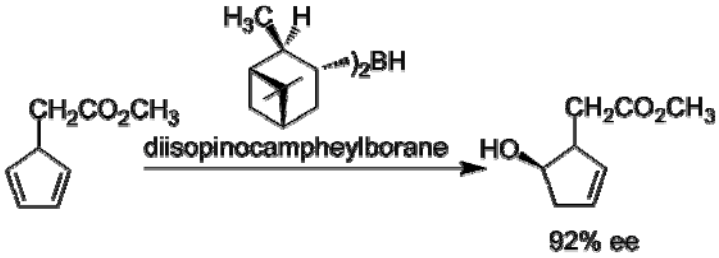
Asymmetric Synthesis

Stoichiometric Asymmetric Synthesis

Even besides the labor involved, one of the greatest disadvantages to chiral resolution techniques is the loss of a minimum of 50% of the starting material in the form of the unwanted enantiomer. It would be quite advantageous if a desired compound

could be directly formed in an enantiomerically enriched or pure form. This would reduce the amount of time, labor and wasted material involved. This approach is referred to as asymmetric synthesis. For these reasons, chemists have been developing asymmetric synthetic reactions for over 30 years.

Stoichiometric asymmetric synthesis can be performed using a prochiral substrate with chiral reagents. A classical example of a chiral reagent is Brown's diisopinocampheylborane reagent. It is derived from borane and α-pinene and has proven to be excellent at asymmetric hydroboration of a wide variety of substrates.[3] The disadvantages to this are the large amounts of chiral materials required to perform the reaction, and separation upon workup.



Scheme 1.3. Example chiral borane used as a stoichiometric chiral reagent.

Catalytic Asymmetric Synthesis

Despite all of the methods discussed concerning chiral resolution and stoichiometric asymmetric synthesis, catalytic asymmetric synthesis is by far the most efficient method of creating enantioenriched compounds. Asymmetric catalysis is so effective because it is possible to transfer chiral information from a very small amount of chiral catalyst to a relatively large amount of substrate. The importance of asymmetric

catalysis was emphasized with the awarding of the Nobel Prize for Chemistry in 2001 to, Noyori, Knowles, and Sharpless for their pioneering work in the area.

The first discovery of asymmetric metal catalysis was by Ryoji Noyori in 1966. Noyori was investigating the nature of carbenes, in particular carbenes that performed highly selective cyclopropanations. These carbenes were produced by a copper catalyzed decomposition of α-diazo ketones. There was debate as to what phenomena caused the selectivity of the carbenes: was there a carbene-Cu covalent bond as a reactive intermediate as Noyori thought, or did the paramagnetic field of the heavy metal influence the carbene as was postulated by Hammond? In order to answer this question Noyori used chiral ligands (a chiral Schiff base) on a Cu(II) complex, and used 1 mol % of this catalyst for the reaction of styrene with ethyl diazoacetate. The results were a 10% enantioselectivity in the copper catalyzed cyclopropanation reaction. This supported Noyori's theory that the carbene was covalently bound to the copper, and the chiral copper environment influenced the carbene's approach to the olefin.[4,5]

Noyori's impact on the field of asymmetric catalysis continued beyond its discovery. In 1980 Noyori's group reported BINAP, one of the most widely used ligands in the history of asymmetric catalysis.[5,6] BINAP has been investigated mostly as a ligand for ruthenium catalyzed hydrogenation. The variety of functionalities that are hydrogenated, the functional group tolerance exhibited, and generally high enantioselectivities yielded, have made BINAP an indispensable ligand.

William Knowles was awarded the Nobel Prize for his work on the asymmetric hydrogenation of cinnamic acid derivatives at Monsanto. By modifying Wilkinsons's catalyst Knowles was able to use cationic rhodium complexes with chiral diphosphine

ligands (DIPAMP) to develop an asymmetric hydrogenation catalyst. The process has been developed so that it is used industrially for the production of the pharmaceutical L-dopa.[7]

The most widely used catalytic asymmetric oxidation reaction is the Katsuki-Sharpless asymmetric epoxidation. The reaction used a Ti(IV) metal center with tartrate esters as the chiral ligands. The stoichiometric oxidant is *t*-butyl hydroperoxide. Though the reaction is limited to allylic alcohols, the convenience of the reaction has made its use widespread. Both enantiomers of the ligands are readily available, so that synthesis of the desired product enantiomer is simply a matter of ligand choice. The reagents are relatively cheap, and the reaction gives high enantioselectivities for a wide range of allylic alcohol substrates.[7,8]

Phosphorus Based Ligands

Many of the most important catalysts use phosphorus-based ligands, especially those containing late transition metals, such as platinum, palladium and rhodium. Two of the three 2001 Nobel Prize recipients' chemistry involved phosphorus based ligands. The significance of these catalysts in asymmetric synthesis prompted extensive efforts over the past few decades to develop new ligands. The vast majority of these ligands are useful for asymmetric hydrogenation,[6,9] while a few have been applied to other reaction types such as hydroformylation,[10] allylic alkylations,[11,12] hydrosilylation,[13] cycloadditions,[14] hydroboration,[15] and Heck reactions.[16] The existence of so many phosphorus ligands can be attributed to the fact that catalysts are often very sensitive to reaction conditions and substrates, sometimes giving widely different results for what

might seem like minor changes in conditions or substrate structure. However, the catalyst is also sensitive to the electronic and steric nature of the ligand, allowing the fine tuning of catalyst behavior and activity by modifying these ligand properties. This allows optimization of results for specific reaction conditions.

Phosphines

The chiral phosphorus ligands that have been studied to date generally belong to one of three types. The phosphines (R_3P, R = alkyl or aryl) were the earliest ligands, and some of the best current catalysts are comprised of this type (e.g., BINAP,[6] DIPAMP,[7] DUPHOS[9] and diazaphospholane **4**[17]). Phosphines can be susceptible to oxidation, but they are generally very stable to various reaction conditions. Alkyl phosphines are generally strong σ-donors, weak π-acceptors.

Phosphites

The phosphites ($P(OR)_3$) are the second largest class of phosphorus ligands, with Chiraphite[10] and BINAPHOS[18] being notable examples. Bulky phosphites have been shown to be extremely active ligands for hydrogenation and hydroformylation. Phosphites are more stable to oxidation than phosphites, but are susceptible to hydrolysis. Phosphites are easier to synthesize than phosphines, and allow a greater diversity in structure and properties.

Phosphoramidites

A closely related group, the phosphoramidites ($(RO)_2PNR_2$), are also well-represented (e.g., **7**).[19] Like phosphites, phosphoramidites are relatively stable to

oxidation, however can be hydrolyzed. Phosphoramidites offer even great synthetic utility, with an extra linkage to modify steric and electronic properties. Though not nearly as common as phosphine or phosphite ligands, the occurrence of phosphoramidites in the literature is steadily growing. There are also a few examples of several other ligand types, almost every possible variation of $R_xP(OR)_y(NR_2)_z$, where x + y + z = 3. These are often specialized for a particular application, or not well studied so will not be presented here.

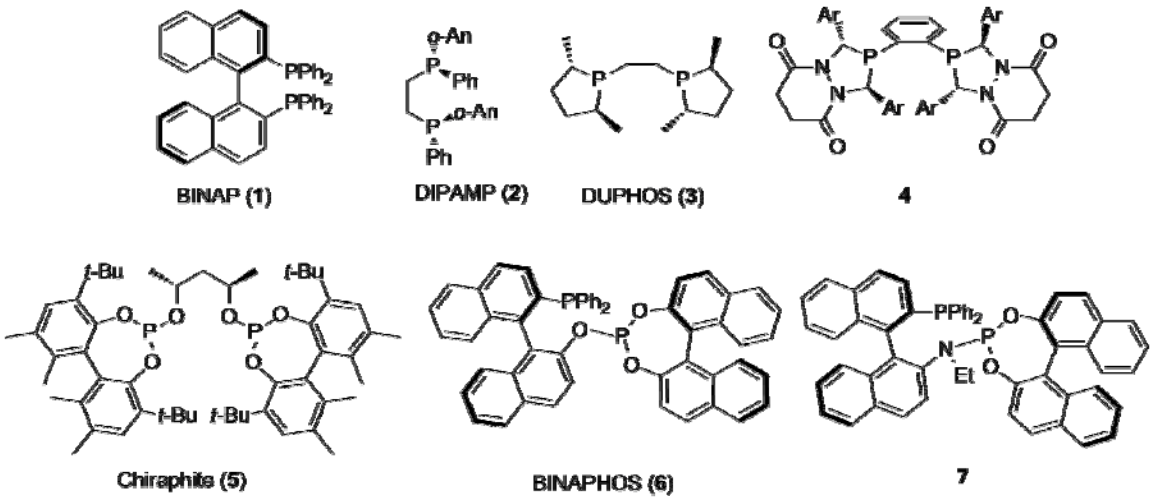


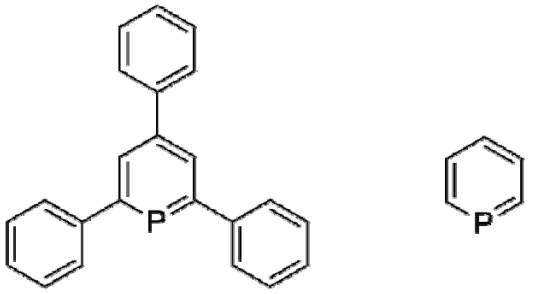
Figure 1.2. Selected representative phosphorus ligands.

Phosphinines

Background

The first λ^3-phosphinine (phosphabenzene, phosphorin) derivative was 2,4,6-triphenylphosphinine (**8**) synthesized in 1966 by Gottfried Märkl.[20] The parent phosphinine (**9**) was not reported until 1971 by Arthur Ashe.[21] Phosphinines are stable to air and water, and have been calculated to have 97% of the aromaticity of benzene.[22,23] This is supported by the chemical shifts of the protons bonded to the phosphinine ring being further downfield than benzene in ^{1}H NMR spectroscopy. For example, in 2,4,6-

triphenylphosphine, a doublet ($^3J_{H,P}$ = 6.0 Hz) for 2H occurs at 8.21 ppm representing the two *meta* protons. This can be attributed to the diamagnetic ring current which occurs with aromatic systems. The aromaticity is also supported by X-ray crystallographic studies of triarylphosphinines. The phosphinine ring is planar, with all C-C bond lengths being equivalent. The size of the phosphorus atom does distort the ring and the length of the P-C bonds. [24]



8 **9**

Figure 1.3. Structures of 2,4,6-triphenylphosphinine and phosphinine.

Though phosphinines are the P-analog of pyridines, they have quite different electronic structures. The HOMO of pyridine contains the lone pair electrons on the N atom, making pyridine a relatively good σ-donor. The orbital containing the lone pair for P in phosphinine however is the HOMO^{-2} level. This causes the P lone pair to be more diffuse, and less directional than its N counterpart, making phosphinines very weak σ-donors. The frontier orbital that has the most effect on phosphinine coordination and chemistry is the LUMO, which is significantly lower in energy than the pyridine LUMO. This low lying π^* orbital readily accepts electron density from any filled metal d-orbital that it overlaps during metal ion coordination, creating a strong π-backbonding ligand system. Due to this effect, phosphinines show the highest affinity, to the electron rich late

transition metals, such as nickel, palladium, platinum, and rhodium, especially for an η^1 binding mode.[25]

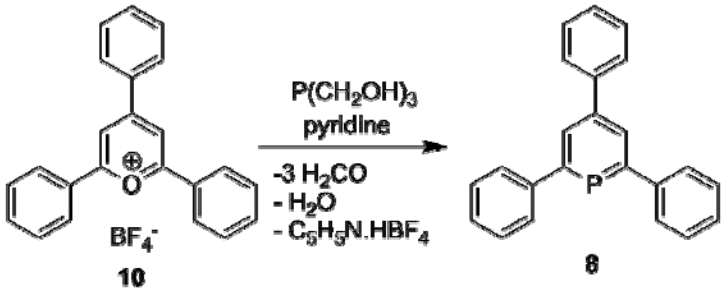
Tolman χ values are used to quantify electronic properties of ligands. The values are usually obtained as the difference of the IR stretching frequency of the *trans* carbonyl of $LNi(CO)_3$ vs the L = $P(t\text{-}Bu)_3$ complex. Large χ values indicate a strong π-acceptor ligand, pulling electron density away from the carbonyls, causing a higher stretching frequency. Low Tolman values indicate strong σ-donor. Due to the toxicity and difficulty of working with $LNi(CO)_3$ complexes, correlations are now made between the Ni derived values and χ values derived from other metal carbonyl species. A comparison of phosphinines with classical phosphine and phosphite ligands suggests that phosphinines are strong π-acceptors similar to phosphites.

Table 1.1 Selected Tolman χ-values of phosphorus ligands.

Ligand	χ	$\nu_{CO(Ni)}$ /cm^{-1}	$\nu_{CO(Rh)}$ /cm^{-1}
2,4,6-triphenyl-phosphinine	24[25]	__	1999
PPh_3	12.9	2069	1979
P(*t*-Bu)$_3$	0	2056	__
PEt_3	5.6	2062	1958
$P(OPh)_3$	29.1	2085	2016
$P(OMe)_3$	23.3	2076	2006
$P[O(2\text{-}t\text{-}BuC_6H_4)]_3$	30	2086	2013

Synthesis

Pyrylium Method. The first synthesis of phosphinines by Märkl involved a ring transformation reaction where a phosphorus nucleophile, in this case tris(hydroxymethylene)phosphine attacks C_α to open the pyrylium ring.[20] Loss of the formaldehyde leaving group regenerates a nucleophilic lone pair, allowing attack to occur again, eventually leading to loss of H_2O, H^+, and a total of 3 equivalents of formaldehyde.

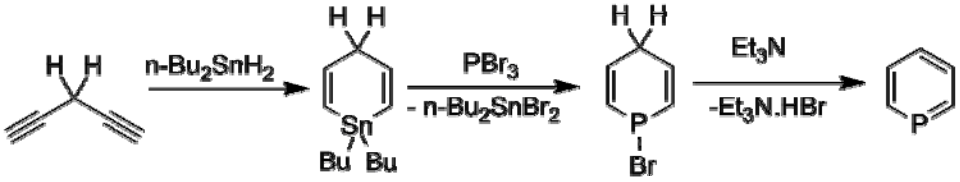


Scheme 1.4. Synthesis of 2,4,6-triphenylphosphinine from the precursor pyrylium.

Other reagents have been used in place of $P(CH_2OH)_3$. The most commonly used reagent is the commercially available tris(trimethylsilyl)phosphine in refluxing acetonitrile.[26] This leads to the formal loss of $O(TMS)_2$ and TMS-F (assuming an F-containing anion). Yields are considerably better using $P(TMS)_3$. Other alternatives include PH_3 gas and PH_4I. [27] Of all the reagents described, PH_3 gives the highest yields by far, though its use is limited by the fact that it is a highly toxic, odorous, and pyrophoric gas. PH_4I is not commercially available, and the synthesis requires dangerous and toxic reagents as well, such as white phosphorus. It is important to note that other nucleophilic reagents can be used to convert pyrylium salts into a variety of other

aromatic compounds. [28] The use of ammonia or mono-alkylamines will form pyridines or pyridiniums salts, respectively. Arsine can be used to form arsinines, hydrogen sulfide can be used to form thiopyryliums, and even carbon nucleophiles, such as Grignards, can be used to form substituted benzenes.

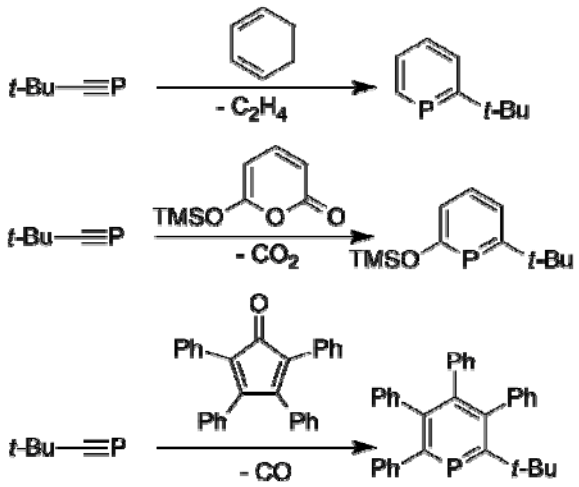
Stannacyclohexadiene Method. The synthesis of the first unsubstituted phosphinine (**9**) by Ashe in 1971 did not utilize the pyrylium route due to the instability of the unsubstituted pyrylium cation. Instead, a dialkyne was reacted with dibutylstannane to form the stannacyclohexadiene intermediate.[21] This compound was subjected to an Sn/P exchange, to lose dibutyltin bromide. After elimination with base, aromatic phosphinine is formed. Unlike the pyrylium route, which has found use to form phosphinines with varying substituents, Ashe's route is only appropriate for an unsubstituted phosphinine.



Scheme 1.5. Synthesis of parent phosphinine *via* stannacyclohexadiene.

Phosphaalkyne Method. Phosphaalkynes can be a versatile precursor to substituted phosphinines. The *t*-butylphosphaalkyne, which can be isolated as a kinetically stable molecule, undergoes a cycloaddition reaction with an appropriate 1,3-diene, such as cyclohexadienes, pyrones, and activated cyclopentadienones to give phosphinines in fair to good yield. In each case the elimination of an organic fragment (C_2H_4, CO_2, or CO) follows the cycloaddition reaction. Though phosphinines of varying

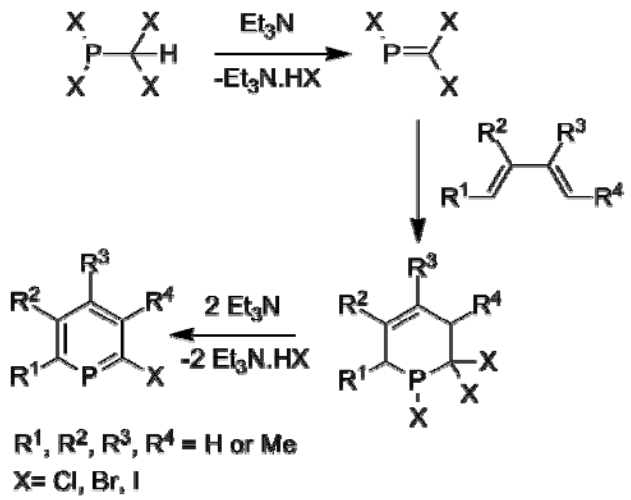
substitution patterns can be formed with this method, it is limited by the necessity of the product to have one *ortho* *t*-butyl group as only *t*-butylphosphaalkyne has proven efficient in this reaction.[29,30]



Scheme 1.6. Examples of reactions utilizing *t*-butylphosphalkyne to form phosphinines.

Phosphaalkenes Method. Analogous to the phosphalkyne method, the halogenated phosphaalkene undergoes a cycloaddition reaction with a methyl substituted 1,3-diene, in this case yielding a tetrahydrophosphinine. This intermediate is then is subjected to basic conditions to allow elimination to the aromatic *o*-halogenated phosphinine. Though the reaction is limited to H or Me substituents, Francois Mathey has utilized this method to investigate the coordination chemistry of the phosphinine ring carbons by halogen/metal exchange of the *ortho* halogen substituent with various transition metals, and to synthesize the biphosphinine analog to bipyridyl ligand (bipy). [30]

Other Methods. There are several other methods of synthesizing phosphinines, most involving the rearrangement of P containing heterocycles upon cycloaddition with alkynes. Examples of this include the ring expansion of 1,2-dihydrophosphetes and phospholes, and rearrangement of azaphosphinines and diazaphosphinines. These



Scheme 1.7. Method utilizing phosphaalkenes for the synthesis of phosphinines with *ortho* halogen substituents.

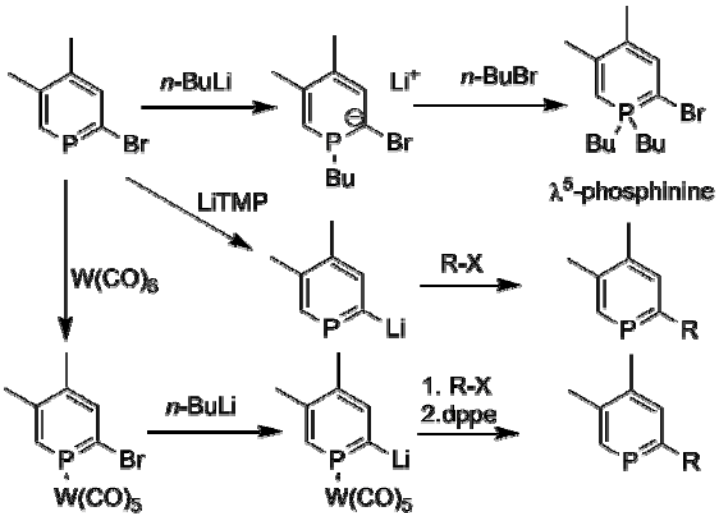
methods give either very specialized products or limited substitution patterns, and so are of limited use.[29,30]

Chemistry

Due to the unique electronic nature of phosphinines, this class of compounds has a limited but intriguing chemistry. This is mainly due to the low energy phosphinine LUMO which is centered on the P atom, and the fact that the P lone pair is contained in a diffuse low energy HOMO^{-2} orbital, rendering the lone pair essentially unreactive. One result of this is that, unlike pyridine, phosphinine is essentially non-basic. The pKa of the conjugate acid of phosphinine ($C_5H_6P^+$) is -16.1.[31] Therefore unlike most other phosphines, phosphinines are also non-nucleophilic.

Due to the low energy LUMO, phosphinines are actually quite susceptible to nucleophilic attack at the P atom. Attempts at deprotonating or performing halogen/metal exchange with common alkyllithium bases such as *n*-butyllithium lead to phosphacyclohexadienyl anions. The further reaction of these anions can be complicated.

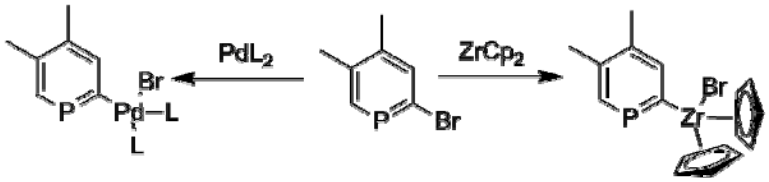
If reacting with an alkyl halide, reaction occurs at the phosphorus, yielding the λ^5-phosphinine as shown in Scheme 1.8. When H^+ is used as the electrophile, addition occurs at C_α to yield the 1,2-dihydrophosphinine. For strong electrophiles such as benzoyl chloride reaction occurs at C_γ to give the 1,4-dihydrophosphinine.[30] The use of bulky lithium amide bases, however, such as lithium tetramethylpiperidine, circumvent this issue due to the bulkiness of the TMP anion which is unable to add to the phosphinine.[32] Protection of the phosphorus atom, with subsequent activation of the P-C bond, is another option. Reaction of the phosphinine with tungsten hexacarbonyl yields the phosphinine/pentacarbonyltungsten coordination complex. Upon reaction with *n*-butyllithium, metal/halogen exchange occurs. Subsequent chemistry can be performed, and the tungsten protecting group can be removed by coordination with a strong phosphine ligand such as 1,2-bis(diphenylphosphino)ethane (dppe).[33]



Scheme 1.8. Representative reactions of phosphinines with alkyllithium bases.

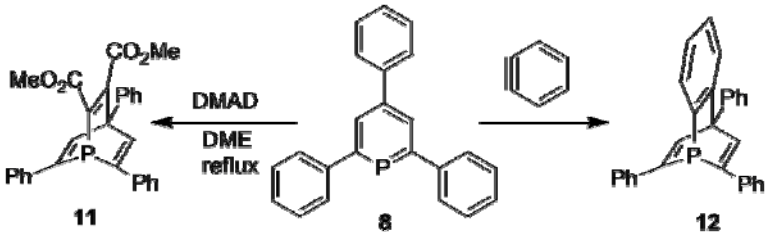
The C-X bond is able to form some organometallic complexes directly. 2-Halophosphinines are able to insert $[PdL_2]$ and $[ZrCp_2]$ into the C-X bonds forming

organometallic derivatives that are capable of diverse functionalization.[33]



Scheme 1.9. Reaction of 2-halophosphinine with PdL_2 or $ZrCp_2$ to form organometallic complex.

Phosphinines readily undergo Diels-Alder reactions with benzyne or activated alkynes. The tricyclic products, known as phosphabarrelenes, are produced in fair to moderate yields. For the benzyne derivatives, benzyne is generated *in situ*, typically from 1-iodo-2-fluorobenzene and Mg^0 in refluxing THF or DME.[34] Activated alkynes that have been used include dimethylacetylene dicarboxylate (DMAD) and hexafluorobutyne.[30]



Scheme 1.10. Conversion of 2,4,6-triphenylphosphinine to phosphabarrelenes.

Coordination Chemistry

Phosphinines exhibit two major modes of coordination, η^1 and η^6. η^1 coordination occurs as a σ complex, end on through the phosphorus atom, and is the most common mode of coordination. It is through this mode of coordination that the strong π-acceptor properties of the phosphinine are dominant. The first homoleptic phosphinine complex

was tetrakis(phosphinine) Ni(0) (**13**). It was formed by the simple displacement reaction of $Ni(COD)_2$ with phosphinine in methylcyclohexane at room temperature. Other homoleptic metal complexes have been synthesized, including those of chromium (**14)**, molybdenum (**15**), tungsten (**16**), and iron (**17**). Substituted phosphinines have been shown to complex many other metals, especially late transition metals, such as rhodium (**18**), iridium and platinum. [33]

π-complexes of phosphinines are much less common than the σ-complexes. This is partly due to the difficult preparation. Most η^1 phosphinine complexes are synthesized by standard displacement reactions, using regular glassware and synthetic techniques, while almost all η^6 complexes require metal vapor deposition techniques. Despite this drawback, several π-complexes exist with various metals. The only homoleptic complexes are the [V(η^6-phosphinine)$_2$] sandwich complex (**19**), as well as the tri-*t*-butylphosphinine sandwich complex with both Ti(0) (**20)** and Cr(0) (**21**). Other heteroleptic π-complexes have been formed with Mo(0), W(0), Fe(0), Ru(I), Rh(I),and Ir(I). Though other complexation modes certainly exist, they are typically quite specialized or occur under severe conditions and are beyond the scope of this work.[33]

Use as Ligand for Catalysis

Remarkably, though phosphinines have existed since 1966, it was not until 1996 that they were studied as potential ligands for metal catalyzed reactions.[35] Since then they have been studied as ligands for a variety of metal catalyzed reactions, including hydroformylation,[35] hydrogenation,[36] cycloadditions,[25] and isomerizations.[37] The most

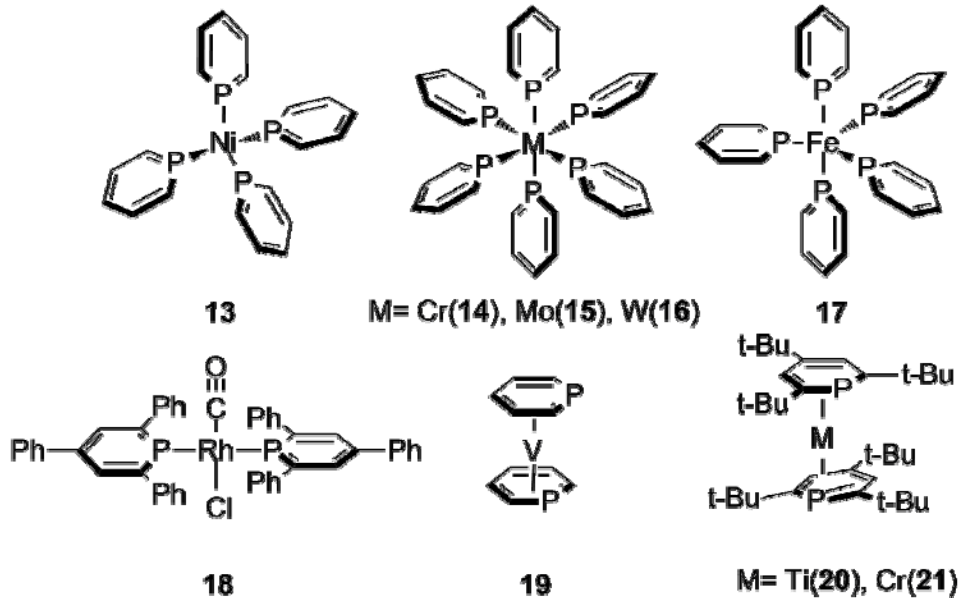


Figure 1.4 Coordination complexes of phosphinines.

significant of these is the work of Bernhard Breit on the use of phosphinines, especially triarylphosphinines as ligand for Rh(I) catalyzed hydroformylation.[35d] Breit found that phosphinines were extremely active catalysts with high turnover frequencies (45370 h^{-1} for 1-octene, four times higher than the industrial Rh/triphenylphosphine system), and could hydroformylate hindered substrates such as α-pinene and tetramethylethylene, something no other catalyst had been able to accomplish up to that point. The phosphinines were also very stable to the reaction conditions showing no loss in activity after at least three runs. Reetz used a rhodium-triphenylphosphinine catalyst for the isomerization of allylic alcohols into carbonyl compounds, obtaining 100% conversion in anywhere from 0.5 to 16 hours depending on the substrate.[37] Koslowski used triphenylphosphinine as the ligand for a nickel mediated [4+2] cycloaddition of a dienyne,[25] a method originally developed by Wender[38] using an air-sensitive phosphite catalyst. The air- and water-stable phosphinine, however, gave results similar to those of

the phosphite with greater ease of handling and purification. Most recently, Müller et al. reported an achiral phosphinine modified with a BINOL-phosphite to form a bidentate ligand (**26**) that was studied in rhodium-catalyzed asymmetric hydrogenation. The catalyst was quite active, with turnover frequencies of up to 5300 h^{-1}, though the enantioselectivity was modest (68% ee).[36]

Novel C_2 Chiral Phosphinine Ligands for Asymmetric Catalysis

The development of asymmetric phosphinine ligands is in its infancy, with only five examples reported to date. None of these possess C_2 symmetry, a feature generally associated with improved performance.[39] In four of the five ligands, chirality is based solely on a chiral auxiliary that is attached to an achiral phosphinine. The last example is an atropisomer (**25**). Of the ligands, the three presented by Breit (**22**, **23**, and **24)** showed no enantioselectivity at all for hydroformylation.[35a] As stated earlier, the phosphinine/phosphite (**26**) by Müller showed modest enantioselectivity for hydrogenation. [36] The atropisomer **25** has yet to be used in any asymmetric reactions.[40]

One goal of this research project is to synthesize chiral phosphinine ligands possessing C_2-symmetry, and evaluate them in several catalytic asymmetric processes described below. The ligands are typified by structures **27** and **28** below, and would represent the first C_2-asymmetric phosphinines. We found that ligand **27** could be derived readily from (+)-camphor (discussed in Chapter 3), but nature provides only a few such materials, so structural variations are quite limited. The benefits of (+)-camphor is its ready availability in an enantiomerically pure form and low cost. Ligand **28**, on the other hand, requires asymmetric synthesis or resolution techniques, but allows for a wide range of structural variations in the phenyl groups, including possible replacement with

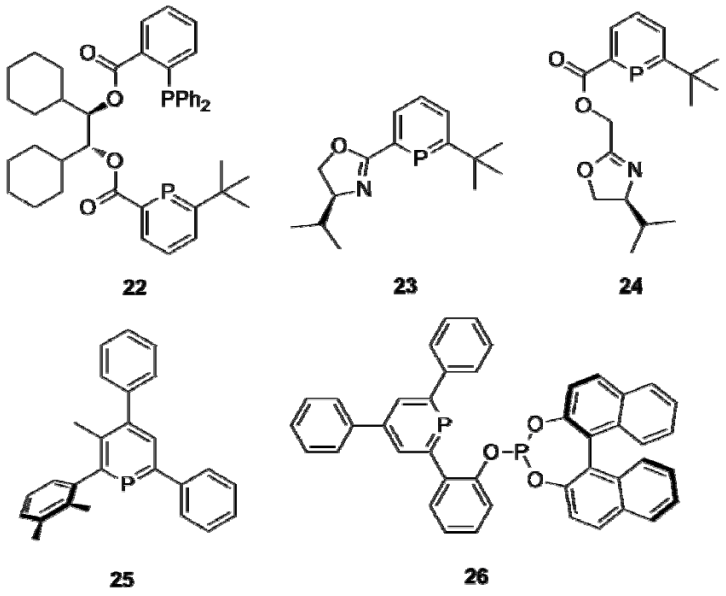


Figure 1.5. The five chiral phosphinines in the literature.

bulky alkyl groups. In both cases, however, both the rigidity and the C_2-nature of the ligand are likely to benefit the asymmetric induction observed in catalytic reactions.

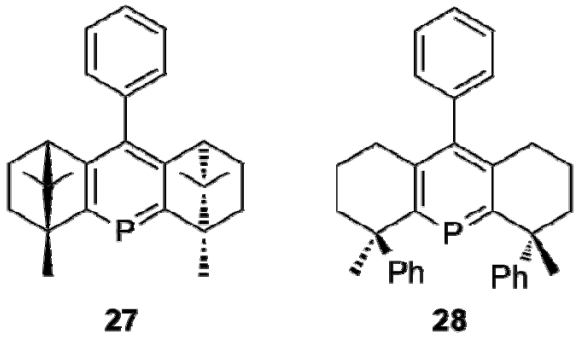


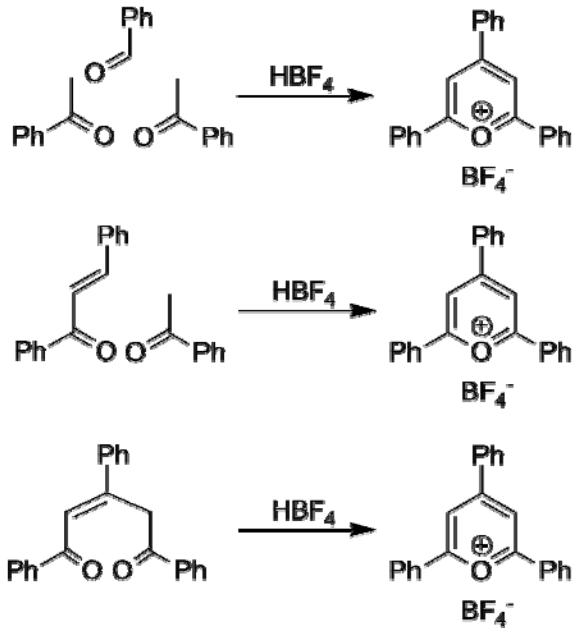
Figure 1.6. Proposed chiral phosphinines that are the focus of this work.

CHAPTER TWO

Initial Attempts

Introduction

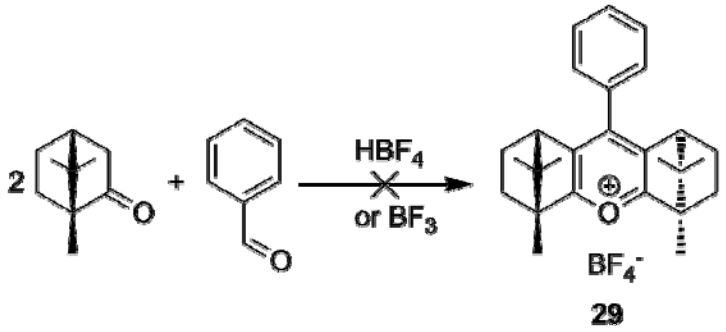
Triarylpyryliums are by far the most common type of pyrylium salts, with simple trialkyl substituted pyrylium salts making up the bulk of other known pyrylium salts. Fused ring systems which contain aliphatic instead of aromatic rings fused to the pyrylium core are quite rare.[28] Therefore initial attempts at synthesizing a chiral pyrylium were based on the methods for synthesizing trimethylpyrylium and triarylpyrylium salts. These reactions can utilize three, two, or one synthetic components, thus requiring the reactants to undergo two, one, or no carbon-carbon bond formations, respectively, in the process of the reaction.



Scheme 2.1. Variations in synthesis of triphenylpyrylium tetrafluoroborate.

Initial Attempts at Synthesis of a Biscamphorpyrylium Salt.

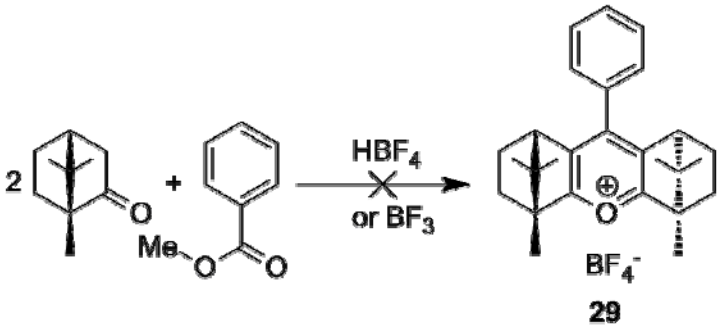
The first attempts at synthesizing a chiral pyrylium salt utilizing (+)-camphor, was a three-component reaction. Two equivalents of camphor were reacted with one equivalent of benzaldehyde under strongly acidic conditions (BF_3 or HBF_4), which would form 3-benzylidenecamphor *in situ*, and would theoretically continue to react with the second equivalent of camphor to ultimately cyclize and dehydrate to form the pyrylium salt **29**. The reactions resulted, however, in only a dark residue that no products could be extracted from, nor were any downfield aromatic resonances indicative of the pyrylium seen in the ^{13}C NMR spectra of the residues.



Scheme 2.2. Attempted one pot synthesis of biscamphorpyrylium **29**.

This reaction requires the formal loss of H^-, presumably in the form of H_2 gas under the acidic conditions. We postulated that the loss of H^- was a major difficulty, and that by incorporating a better leaving group, the reaction would proceed to pyrylium rather than presumably polymeric tars. Therefore, benzaldehyde was replaced with methyl benzoate, which should form a 3-hydroxy-1,5-diketone, which under strongly acidic conditions would provide an excellent leaving group. However, the reaction still produced only a dark residue, from which only methyl benzoate could be isolated. It is

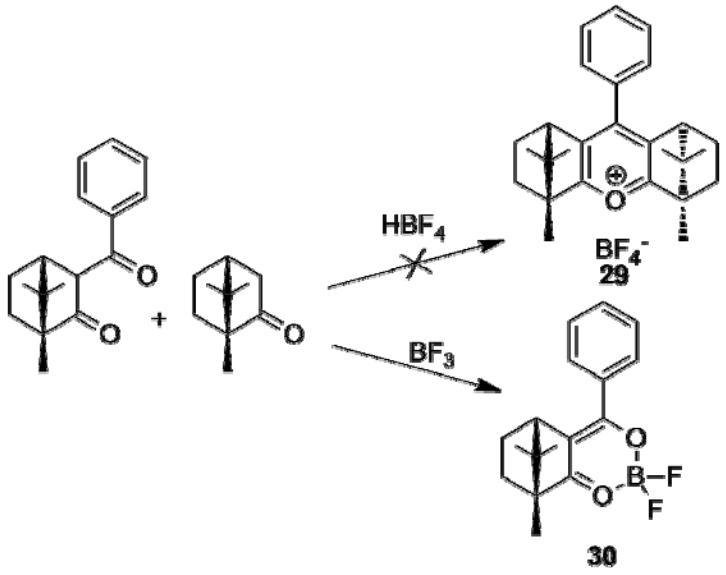
presumed that the dark residue comes from the ring opening decomposition of camphor known to occur under acidic conditions.



Scheme 2.3. Attempted synthesis of biscamphorpyrylium **29** from (+)-camphor and methyl benzoate.

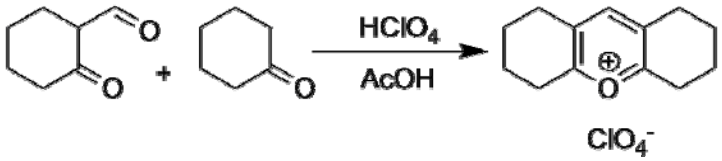
After the failures of the three component reactions, it was theorized that the carbon-carbon bond forming step was difficult under the acidic conditions. Therefore the first intermediate in the reaction was synthesized and isolated, and then carried on in a second reaction to form the pyrylium. 3-Benzoyl camphor was synthesized by a modified literature procedure in 92% yield.[41] The 1,3-diketone was then reacted with camphor in acetic anhydride or acetic anhydride/acetic acid mixtures as an excess of 48% HBF_4 (aq) was dripped slowly into the reaction. Reactions were run at both 100 ^oC and 0 ^oC. It was thought that the acetic anhydride would act as a dehydrating agent, to consume the water produced during the course of the reaction to push the equilibrium to favor the products. However, the reactions yielded only a brown tar-like substance, except the case of the 0 ^oC reaction, which yielded back the starting 1,3-diketone. When the reaction was run with BF_3:Et_2O as the acid, a crystalline adduct (**30**) was isolated.

In order to better understand successful reaction conditions, and to gain experience in isolating and characterizing pyrylium salts, a literature preparation of a



Scheme 2.4. Attempted synthesis of biscamphorpyrylium **29** from (+)-camphor and 3-benzoylcamphor.

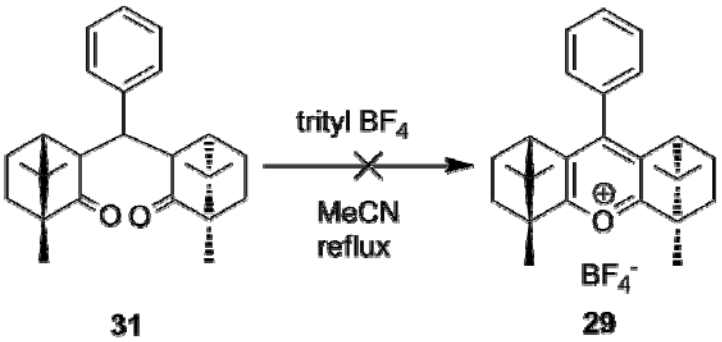
similar pyrylium salt was performed. 1,2,3,4,5,6,7,8-octahydroxanthylium perchlorate was synthesized from 2-formylcyclohexanone and cyclohexanone, using 70% $HClO_4$ as the acid reagent, and refluxing glacial acetic acid as solvent.[42] After reacting for 30 min the pyrylium salt was isolated in 27% yield. Until this point, perchlorate salts had been avoided due to the explosion hazard they present, however for the higher substituted pyryliums this seemed to be less of an issue, and since this compound was known, it was deemed to be safe. The compound was characterized by ^{1}H and ^{13}C NMR spectroscopy, and was also converted to the corresponding pyridine analog, octahydroacridine, and the identity was confirmed using GC-MS. The same reaction conditions were then used, except that 48% HBF_4 (aq) was substituted for the perchloric acid, and the reaction yielded no product. When the reaction was again performed with perchloric acid, and 2-acetylcyclohexanone or 2-benzoylcyclohexanone were substituted for 2-formylcyclohexanone, again no pyrylium products were detected.



Scheme 2.5. Synthesis of 1,2,3,4,5,6,7,8-octahydroxanthylium perchlorate.

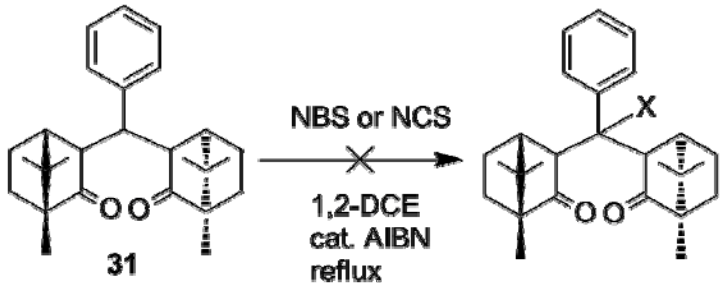
With the failure of the two component reactions, the next option was a one component synthesis. This would require all carbon-carbon bonds to be preformed, with only the cyclization/dehydration/aromatization to occur. For this, the 1,5-diketone **31 (**biscamphortoluene, BCT) was synthesized according to literature methods.[43] BCT was then subjected to conditions Balaban et al used for the alternative synthesis of 1,2,3,4,5,6,7,8-octahydroxanthylium perchlorate using triphenylcarbenium perchlorate as Lewis acid/hydride abstractor.[42] BCT was reacted with 2.5 equivalents of triphenylcarbenium tetrafluoroborate (trityl BF_4) in refluxing acetonitrile. Following these literature conditions, no pyrylium was observed by ^{13}C NMR. The reaction was retried using acetic acid, acetic anhydride or a 1:1 mixture of acetic acid and acetic anhydride as solvent, and only a dark sticky tar-like substance was produced. No pyrylium product was evident by NMR spectroscopy of the reaction mixture. According to a report by D. Farcasiu, hexachloroantimonate anions have proven to be useful for difficult-to-prepare pyryliums.[44] The reaction was re-examined using BCT, 2.5 equivalents of trityl Cl, and 2.5 equivalents of $SbCl_5$, with 1,2-DCE or acetic anhydride as solvent. However, this reaction also proved fruitless.

It was hypothesized that by oxidizing the BCT, in this case converting the benzylic H to a halogen, it would less difficult to remove X^- instead of H^-, and the reaction might proceed. Oxidation of BCT was attempted first by a free radical



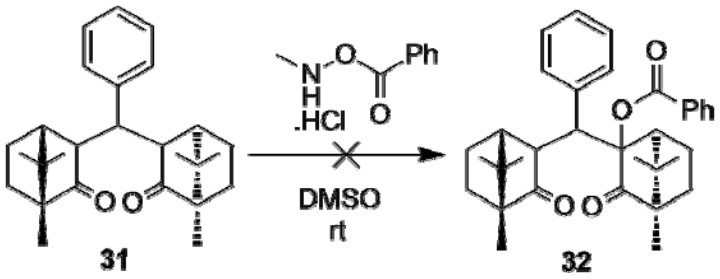
Scheme 2.6. Attempted synthesis of biscamphorpyrylium **29** from biscamphortoluene **31**.

halogenation. BCT was reacted with *N*-bromosuccinimide (NBS) or *N*-chlorosuccinimide (NCS) with catalytic azobisisobutyronitrile (AIBN) in refluxing 1,2-DCE. No bromination or chlorination was observed by GC-MS. α-Oxygenation was also attempted. BCT was reacted with 1.1 equivalents of *N*-methyl-*O*-benzoylhydroxylamine hydrochloride in DMSO.[45] The reaction was monitored by GC-MS, however, no peaks with the correct mass or an appropriate mass fragment were observed.



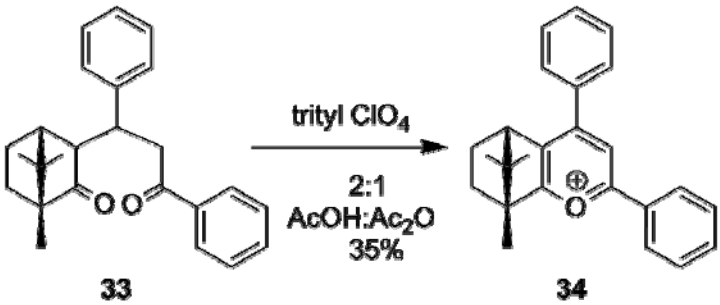
Scheme 2.7. Attempted halogenation of biscamphortoluene **31**.

Fortuitously, a reference by Simalty et al. was discovered which described the preparation of pyrylium **34**.[46] Simalty utilized conditions similar to those previously described for the BCT conversion to pyrylium, which had all failed. Simalty described the results of his reactions as ending in an "intractable tar" as occurred for our BCT

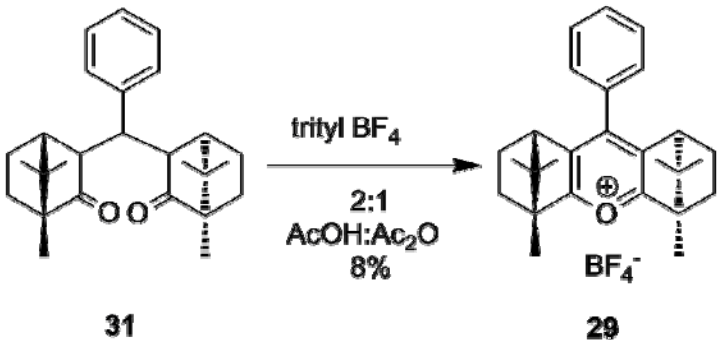


Scheme 2.8. Failed α-oxygenation reaction of biscamphortoluene **31**.

reactions. However, though a 1:1 ratio of acetic acid to acetic anhydride failed with BCT,Simalty reported that a 2:1 ratio of acetic acid to acetic anhydride yielded 35% of the pyrylium **34**. These conditions were then used with 1 equivalent of BCT and 2.5 equivalents of trityl BF_4, in a refluxing 2:1 mixture of acetic acid and acetic anhydride. The reaction was quenched by pouring into diethyl ether and cooling to -20 ^{o}C for 24 hours. A few colorless crystals were removed from the tar, washed and recrystallized from acetone/diethyl ether to yield 8% of the biscamphorpyrylium tetrafluoroborate **29**. The compound's identity was confirmed by ^{1}H, and ^{13}C NMR spectroscopy as well as X-ray crystallography (Figure 2.1).



Scheme 2.9. Synthesis of pyrylium **34** reported by Simalty et al.



Scheme 2.10. First synthesis of biscamphorpyrylium tetrafluoroborate (**29**).

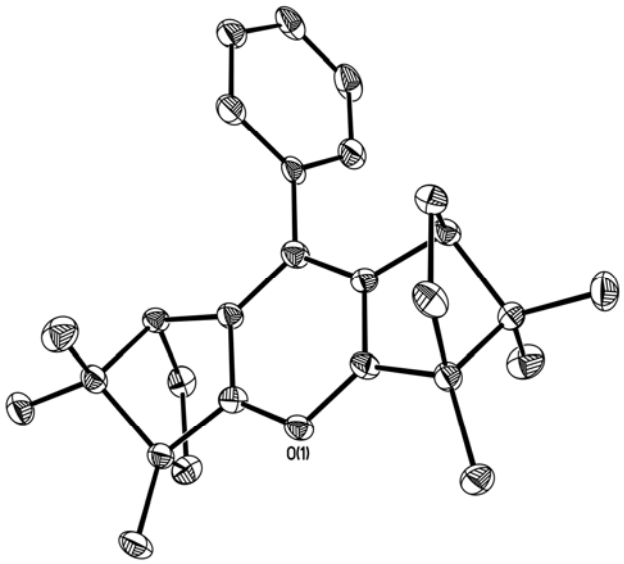


Figure 2.1. X-ray crystal structure of biscamphorpyrylium tetrafluoroborate (**29**). The tetrafluoroborate anion has been omitted for clarity.

Discussion and Conclusions

It is known that camphor and its related compounds can rearrange under strongly acidic conditions.[47] This is most likely the prevalent mechanism for the tar-forming, strongly acidic, one pot reactions shown in Scheme 2.2, Scheme 2.3, and Scheme 2.4. The nucleophilic attack of the camphor enol formed must be much slower than the carbocationic rearrangement, leading to decomposition of the starting materials. It was thought that using BF_3/Et_2O as a Lewis acid would be milder than the strong protic acid

conditions using HBF_4, however this did not prove to be the case. In all cases of using BF_3 similar decomposition occurred, or in the case of the 3-benzoylcamphor (Scheme 2.4) a colorless, crystalline adduct (**30**) of the diketone and BF_2 was formed.

Though the literature reaction to form the octahydroxanthylium perchlorate was easily replicated, attempts at modifying the substituent that would result in substitution at the *para* position (e.g., replacing H with methyl or phenyl groups) were met with failure. Balaban describes making the 9-methyloctahydroxanthylium, however only by cyclization of the appropriate 1,5-diketone and using trityl ClO_4, not under the conditions used in this case.[42] The fact that simply changing the acid from $HClO_4$ to HBF_4 resulted in failure, both of which are strong, non-nucleophilic acids, proves the fickle nature of these reactions.

Balaban's success at using the trityl reagent to synthesize both octahydroxanthylium and 9-methyloctahydroxanthylium encouraged the use of those conditions to cyclize the 1,5-diketone, BCT (**31**). Commercially available trityl BF_4 was used in place of trityl ClO_4, which is not available, is light sensitive, and potentially explosive. The sticky tar-like substances produced by the reactions of BCT with trityl reagents in acetonitrile, acetic acid, and acetic anhydride could reasonably be presumed to be a polymer byproduct. The tar's consistency, solubility characteristics, and lack of carbons in the ^{13}C NMR spectrum are all consistent with this assumption. Since it has been observed that the identity of the acid can have an affect on the reaction, trityl $SbCl_6$ was also employed as acid reagent due to its facile generation *in situ*. Unfortunately, the change in counterion did not affect the outcome of this reaction.

The failure of the α-oxygenation reaction (Scheme 2.8) was not unexpected due to the large steric bulk of the camphor ring system, and the relative bulkiness of the benzoate group that was adding to an already tertiary carbon. However, the complete lack of reaction of the free radical halogenation reactions was quite unexpected (Scheme 2.7). Due to the highly reactive nature of radicals it was expected that they would not be affected by any steric hindrance in this case. When the bromination displayed no new products by GC-MS, chlorination was tried with the reasoning that the chlorine radical was both smaller (less steric hindrance) and more reactive; however GC-MS revealed no new products for this reaction either.

A successful synthetic route for biscamphorpyrylium **29** was found using the reported solvent ratio of 2:1 acetic acid to acetic anhydride. This ratio yielded 8% of the target pyrylium. Since there are no H atoms directly on the pyrylium ring, the ^{1}H NMR spectrum did not provide information that was diagnostic for pyrylium formation. However, the ^{13}C NMR spectrum contained resonances that were clearly pyrylium ring *ortho* and *para* carbons at 184.4 and 155.7 ppm, respectively. These signals are upfield of typical carbonyl resonances, and far downfield of the normal aromatic region, giving a good diagnostic tool for determining any pyrylium formation in further reactions. The biscamphorpyrylium structure was verified by X-ray crystallography (Figure 2.1). This represents the first C_2 chiral pyrylium salt to be reported, and along with Simalty's pyrylium **34**, is one of only two non-racemic pyrylium salts reported in the literature. It displays a large optical rotation, $[\alpha]^{20}_{D}$ +378^{o} (*c* 0.37, CH_2Cl_2), consistent with a highly polarized aromatic ring. Though the compound was finally obtained, the low yields,

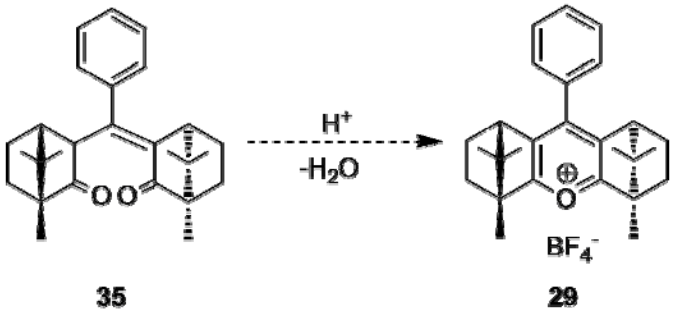
difficult purification, and expensive reagents made this route less than ideal: therefore a better route was sought.

CHAPTER THREE

Improved Synthesis of Biscamphorpyrylium and the Synthesis and Application of Biscamphorphosphinine to Asymmetric Catalysis.

Introduction

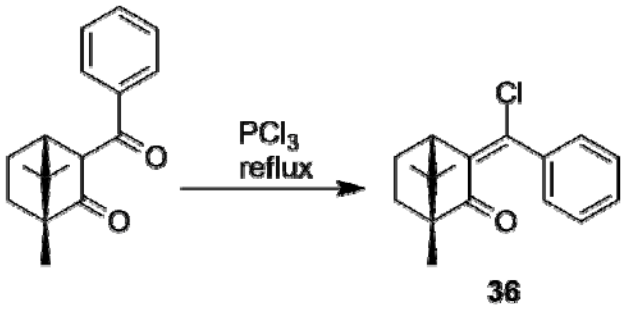
Despite obtaining very small amounts of the desired compound, it was still believed that the most difficult step of the pyrylium forming reaction was the formal loss of H^-. Up to this point acidic conditions had failed to prove effective in this reaction. Trityl reagents proved only marginally successful, and the relatively high cost per gram, high molecular weight, large excess required during the reaction, and subsequently low yield made this method unpractical. Attempts at modifying BCT prior to attempted cyclization had all failed as well. It was postulated that the unit of unsaturation must be installed early on in the synthesis, prior to attempted cyclization. A new target for the pyrylium precursor was established, the 3-ene-1,5-dione **35**, and the anticipated conversion to pyrylium is shown in Scheme 3.1.



Scheme 3.1. General scheme for conversion of 3-ene-1,5-dione to pyrylium.

Improved Synthesis of Biscamphorpyrylium

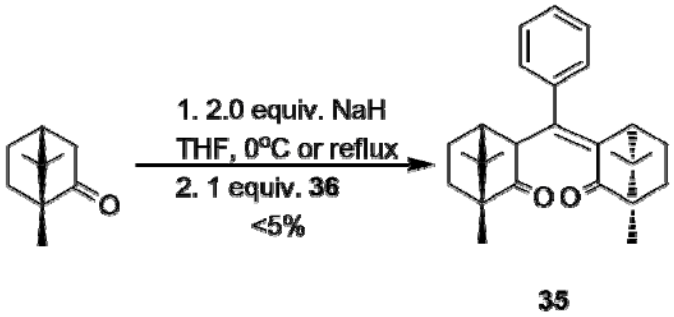
Since oxidation of BCT had been unsuccessful, synthesis of an oxidized version of the BCT precursor, 3-benzylidenecamphor, was the next goal. A literature search yielded a synthesis for 3-(α-chlorobenzylidene)camphor.[48] 3-Benzoylcamphor was refluxed in excess neat PCl_3 for two hours. The solution was poured onto ice, mixed with diethyl ether to dissolve the organic, and then made basic with potassium carbonate. After removal of the solvent the yellow oil was dissolved in warm methanol, and upon cooling to -20 ^{o}C and seeding, a 45% yield was obtained of the 3-(α-chlorobenzylidene)camphor (**36**).



Scheme 3.2. Synthesis of 3-(α-chlorobenzylidene)camphor.[48]

3-(α-Chlorobenzylidene)camphor (**36**) was initially reacted with the sodium enolate of camphor, in THF at either 0 ^{o}C or at reflux. The solution became dark yellow upon addition of the substrate **36**, and remained so until a water quench of the reaction. In either case (0 ^{o}C or reflux), no more than five percent of the product **35** was detected by GC-MS. No unreacted 3-(α-chlorobenzylidene)camphor was evident either.

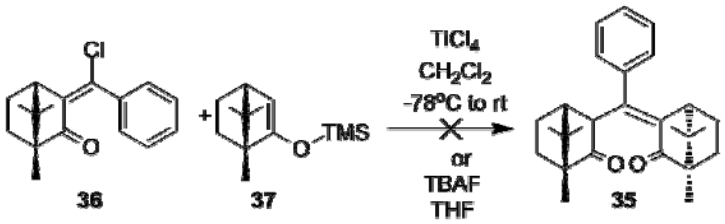
In order to determine if the strongly basic conditions were responsible for the product either not forming, or decomposing during the reaction, Mukayaima conditions



35

Scheme 3.3. Reaction of camphor enolate with **36** in THF.

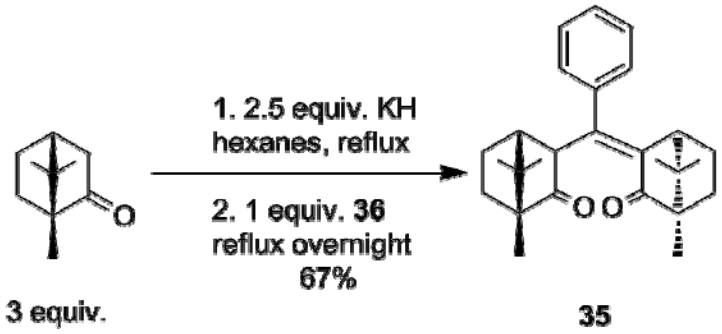
were investigated.[49] 3-(α-Chlorobenzylidene)camphor was stirred in anhydrous dichloromethane with 10 mol % of $TiCl_4$ at -78 ^oC. After ten minutes, the TMS enol ether of (+)-camphor **37** was added dropwise, and the solution was allowed to stir overnight at room temperature. GC-MS showed a small peak (<1%) for the addition product, with the starting materials remaining largely unreacted. The next approach involved the deprotection of the TMS enol ether **37** *in situ* to generate the tetrabutylammonium enolate of (+)-camphor. To a solution of THF, one equiv. of **36** and one equiv. of **37** were both added. Subsequently, an excess of TBAF (1.0 M in THF) was added dropwise at room temperature. The solution color changed from yellow to black over a period of 18 hours. According to GC-MS no products of the correct mass were observed. The same reaction was retried in toluene as well, with the same results. A reaction was performed to test **37** and the general technique by adding **37** and benzaldehyde to a THF solution, and using the TBAF solution to form the tetrabutylammonium enolate of camphor. GC-MS reported 33% yield of products which were a 1:1 mixture of the aldol and aldol condensation products. This suggests the technique itself was sound, and the problem lies in the specific substrates being used.



Scheme 3.4. Attempts to use TMS enol ether of (+)-camphor as the nucleophile under milder reaction conditions.

Though the camphor sodium enolate reaction produced less than five percent of the desired product, it was more successful than the routes involving **37**. Therefore, we sought to optimize conditions utilizing strong bases. It has been our experience that potassium hydride is a much more reactive base and produces more reactive enolates. Based on this, potassium hydride was used as the base for all further studies. To a slurry of 2.5 equiv. of KH in toluene, 2.0 equiv. of (+)-camphor was added dropwise as a toluene solution. After refluxing for two hours to ensure complete conversion to the enolate, one equivalent of **36** was added dropwise as a toluene solution. The solution immediately turned from light yellow to orange, and eventually to dark red. The dark red indicated the formation of the highly conjugated anion of **35**. After refluxing overnight, the reaction was quenched with saturated aqueous ammonium chloride, and extracted into ether. GC-MS reported approximately 30% camphor, 30% of **35**, 30% of 3-benzylidenecamphor, and 10% of **31**. Benzene was also studied as a solvent. Using the same reaction conditions, benzene gave 60% of **35,** the balance being a by-product whose identity is thought to be 3-(diphenylmethylene)camphor, though the only support for this identity is the mass spectrum. Only a trace amount of BCT (**31**) was observed in the product mixture. Believing that solvent polarity and reflux temperature were controlling the decomposition of the desired product and formation of the undesired **31**, hexanes was

chosen as a lower boiling, non-polar solvent. The same conditions were applied, 2.5 equiv. of KH, 2.2 equiv. of camphor, refluxed for two hours, and then **36** was added dropwise, with the solution immediately turning orange then dark red. The solution was refluxed overnight, and after workup yielded 62% of the desired enedione **35**, along with 9% of BCT (**31**), which was separated by column chromatography. To prevent any reduction by excess hydride, the reaction was run again using similar conditions, but this time using excess camphor (three equivalents). This produced enedione **35** in 67% yield, as a mixture of two isomers in a 93:7 ratio. No BCT was observed by GC-MS. The isomers of **35** were separated by fractional crystallization from methanol. The X-ray crystal structure for **35**, as shown in Figure 3.1., shows the major isomer to be the *endo*-*E*-(**35)**.



Scheme 3.5. Synthesis of enedione **35**.

Once a practical synthesis for the enedione intermediate was determined, it was only a matter of dehydration/cyclization under acidic conditions to form the pyrylium salt. Indeed, by simply refluxing **35** in toluene with a five-fold excess of HBF_4/ether, using a Dean-Stark trap to remove water, pyrylium **29** was easily obtained by cooling the toluene solution and diluting in diethyl ether to precipitate the pyrylium salt. The solution

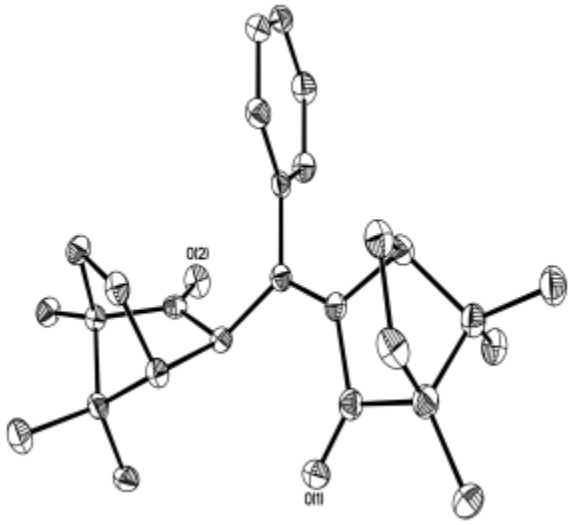
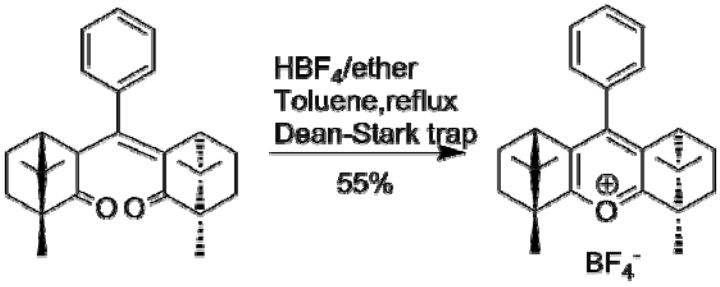


Figure 3.1. X-ray crystal structure of the major isomer of **35**.

was filtered through Celite, and washed with ether to remove excess acid. The pyrylium was then flushed through the Celite pad with dichloromethane, leaving any insoluble impurities behind. The solvent was removed *in vacuo* and the pyrylium was recrystallized from acetone/diethyl ether in 55% yield.



Scheme 3.6. Synthesis of pyrylium **29** from **35** using acid and a Dean-Stark trap.

Discussion

Though the synthesis of **36** was a literature preparation, the compound was insufficiently characterized. Sotiropoulos purified the compound by distillation, followed

by column chromatography over alumina. The reported melting point was 50 ^{o}C. After synthesizing the compound recrystallization was attempted, however the compound proved resistant to this, repeatedly oiling out from several solvent systems. An initial batch was purified in the manner Sotiropoulos described, and a solid material was obtained instead of the yellow-green oil. GC-MS confirmed the presence of a minor isomer (approximately 5%) in this solid material. On subsequent batches, seed crystals were then used to recrystallize the compound from methanol, yielding a compound with a m.p. of 61-62 ^{o}C. GC-MS and ^{1}H NMR confirmed the purity of the compound. An X-ray crystal structure was obtained, proving the identity of the major isomer to be the *E*-(**36**).

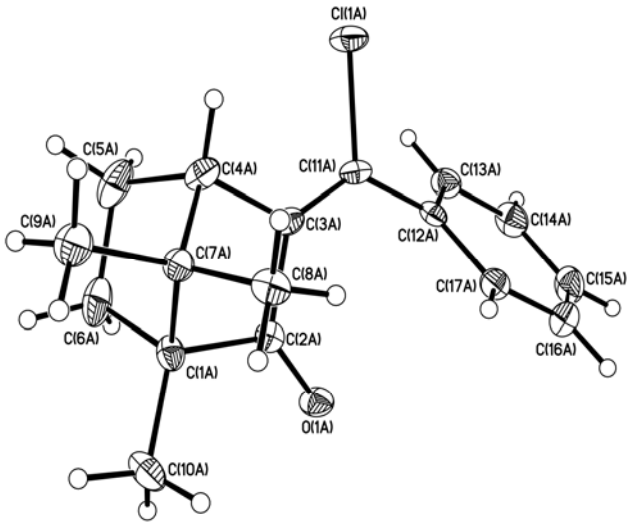


Figure 3.2. X-ray crystal structure of *E*- 3-(α-chlorobenzylidene)camphor (**36**).

The failure of the initial attempts of synthesizing **35** using THF as solvent was discouraging. However, it was known from studies to increase the yield of diketone **31**, that this compound could only be synthesized in very low yields in polar solvents such as THF or DME. The best yields as of this point had been from toluene. It was hypothesized that the same issue was occurring in the case of the enedione **35** also, and was the

impetus for investigating low polarity solvents. Though not optimal, the fair to moderate yields initially exhibited by the reactions to form **35** using KH and toluene were encouraging. The presence of BCT in the reactions was presumed to be from the reduction of **35** by excess hydride. Therefore, by using an excess of camphor, the only base in solution would be camphor enolate, the first equivalent would act as nucleophile, the second equivalent would deprotonate the enedione (**35**) as it formed. This strategy proved successful, as no BCT was present in the product mixtures, and camphor is easily removed from the product during recrystallization, whereas BCT inhibited recrystallization of the product. The mixture of isomers (93:7) was easily separated by crystallization from methanol. Though the identity of the major isomer was determined to be the *endo-E*-(**35**), an x-ray crystal structure of the minor isomer has not been obtained. It was observed that the two isomers equilibrate under acidic conditions. When pure *endo-E*-(**35**) isomer was used in the pyrylium forming reaction, a mixture of isomers of unreacted enedione with the same ratio could be isolated.

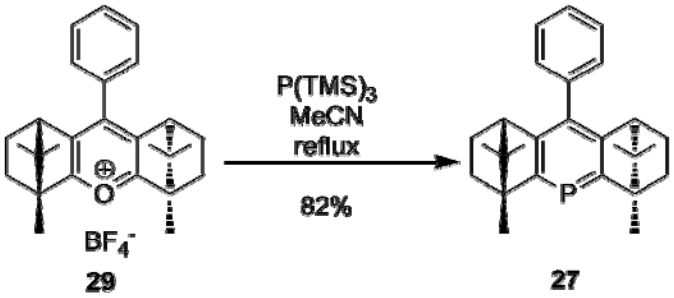
^{1}H and ^{13}C NMR spectroscopy of *endo-E*-(**35**) displayed temperature dependant behavior, at 25 °C giving broadened peaks in the aromatic region of the ^{1}H NMR spectrum and missing aromatic peaks in the ^{13}C NMR spectrum. This was attributed to hindered rotation in the molecule, probably around the single bond between the vinyl carbon and the camphor ring. In an attempt to obtain averaged spectra at higher temperature, NMR spectra were obtained in C_6D_6 at 65 °C, but neither the ^{1}H nor ^{13}C spectra were qualitatively different and there was evidence of isomerization occurring. However, in $CDCl_3$ at -40 ^{o}C, rotation was sufficiently slowed that all expected ^{13}C peaks

were observed. In fact, rotation was slowed so that all six phenyl carbons produced individual peaks.

The pyrylium forming reaction occurred with little to no degradation of the enedione precursor, which can be recovered from the reaction mixture after precipitation of the pyrylium product. The main limiting factor to the yield is the degradation of the tetrafluoroboric acid. During the reaction, a white solid forms along the inner walls of the condenser and Dean-Stark trap. Qualitative tests suggest that this solid is boric acid, $B(OH)_3$. Etching of the glassware from this reaction is also evident, presumably from liberated HF. It is known that the HBF_4 decomposes at the 130 ^oC,[50] so it is likely that these decomposition products could produce HF and $B(OH)_3$ upon reaction with water vapor from the dehydration reaction. Large excesses of acid have been used, with no improvement. Use of a lower boiling solvent, such as benzene, has been explored, with the hope that it would not decompose the tetrafluoroboric acid. The reaction produced only a 20% yield of the pyrylium during the same time period as toluene, so the use of toluene was continued. *p*-Toluenesulfonic acid was used also, however the acid proved to be difficult to remove from the reaction mixture as it was also insoluble in toluene and toluene/ether mixtures. When a sample of the pyrylium tosylate salt was isolated and recrystallized from acetone/diethyl ether, ^1H NMR spectroscopy showed a 1:1 ratio of the pyrylium tosylate salt with *p*-toluenesulfonic acid.

*Synthesis of Phosphinine **27***

With a suitable route to the pyrylium precursor established, synthesis of the phosphinine and its evaluation as a ligand could begin. Using standard conditions, the pyrylium **29** was dissolved in anhydrous acetonitrile, to which 2.5 equivalents of $P(TMS)_3$ was added and the solution was brought to reflux overnight. The solvent was removed *in vacuo* and the residue was purified by column chromatography to yield the biscamphorphosphinine (**27**), as an air stable crystalline solid, in 82% yield. The compound was recrystallized from methanol to give analytically pure material, and fully characterized by ^{1}H, ^{13}C, ^{31}P NMR spectroscopies, and X-ray crystallography.



Scheme 3.7. Conversion of pyrylium salt **29** to phosphinine **27**.

*Coordination Chemistry of **27***

Once the phosphinine **27** was obtained, its coordination behavior was explored. Phosphinine **27** was added to a solution of $[Pd(II)(COD)Cl_2]$ in dichloromethane. The solution was slowly evaporated to produce orange crystals. Some of the crystals were dissolved in $CDCl_3$ for characterization by ^{1}H and ^{31}P NMR spectroscopy. The ^{31}P NMR spectrum shows a 20 ppm upfield shift of the phosphinine, from 138.9 ppm for the free phosphinine to 119.1ppm for the Pd(II) coordinated compound. The crystals were

examined for X-ray crystallographic studies; however they were of insufficient quality for publication.

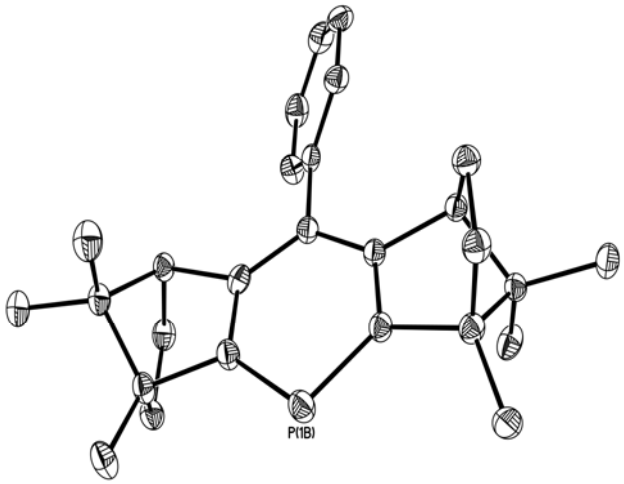


Figure 3.3. X-ray crystal structure of phosphinine **27**.

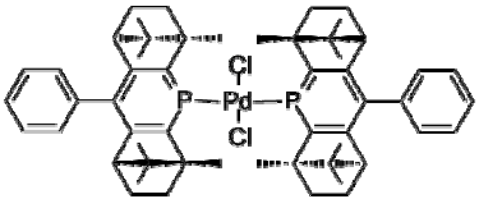


Figure 3.4. Structure of *trans*-palladium(II)/**27** complex.

Platinum(II) complexes were also attempted. Initially phosphinine **27** was reacted with [Pt(II)$(CH_3)_2$(COD)] in dichloromethane, however the solution instantly turned dark, probably due to the addition of the nucleophilic methyl of the platinum(II) complex to the electrophilic phosphorus atom of the phosphine. A second attempt utilized [Pt(II)(COD)Cl_2] as the platinum source. When **27** (2.2 equiv.) was added to an NMR tube containing one equivalent of Pt(II) in dichloromethane, the ^{31}P NMR spectrum displayed only one peak at 138 ppm, which represents the uncoordinated phosphinine.

Rhodium(I) complexes were derived from $[ClRh(CO)_2]_2$. In an NMR tube one equiv. of Rh(I) was reacted with 2 equiv. of **27** in dichloromethane. Gas evolution was seen during the addition. ^{31}P NMR displayed two signals, one at 133 ppm for the uncoordinated phosphinine, and another at 122.5 ppm that shows a doublet (J = 152 Hz) due to Rh-P coupling, consistent with literature reports for other phosphinines.[36]

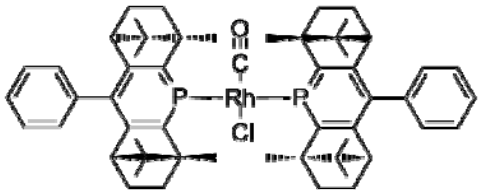
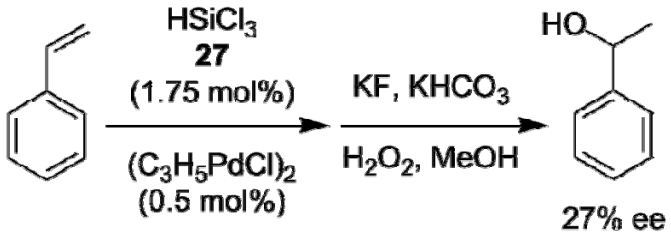


Figure 3.5. Proposed structure of *trans*-rhodium(I)/**27** complex.

*Asymmetric Catalysis with **27***

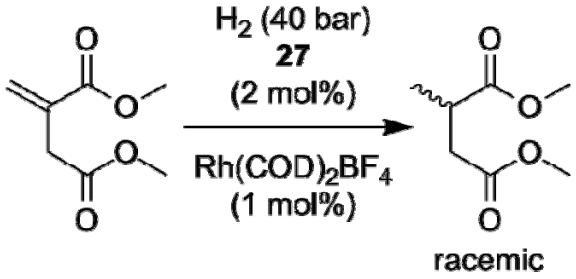
The first asymmetric catalytic reaction explored was asymmetric hydrosilylation. Styrene and 1-octene were treated with 0.5 mol% allylpalladium (II) chloride dimer and 1.75 mol% of phosphinine **27**, conditions patterned after those employing other monodentate phosphine ligands.[51] For styrene, the reaction proceeds quantitatively at room temperature in 5 days, or at 40 ^{o}C in 24 hours to give the trichlorosilane product; however, no reaction occurred for 1-octene. After isolation of the trichlorosilane product by Kugelrohr distillation, it was oxidized by Tamao-Fleming oxidation conditions[52] to the alcohol. The 1-phenylethanol product was found to have 27% ee (*S*-phenylethanol was the major enantiomer) by chiral GC. Enantiomeric purity was determined by chiral GC analysis using a Restek Rt-βDEXsa chiral column.

Asymmetric hydrogenation was performed in a 100 mL Parr Reactor. To the pressure reactor 1 mol% $Rh(COD)_2BF_4$, and 2 mol% of ligand **27** (or 1 mol% of ligand



Scheme 3.8. Hydrosilylation/oxidation of styrene using phosphinine ligand **27**.

27 and 1 mol% triphenylphosphite),[53] were dissolved in 30 mL of dichloromethane. The substrate, dimethyl itaconate, was added, and the reactor was then purged with H_2. The reactor was pressurized with H_2 (40 bar) and allowed to stir overnight (18 hours) at 25°C. Samples were analyzed by GC/FID using the Restek Chiraldex βDEXsa chiral column for enantiomeric purity. Though quantitative conversion to the hydrogenated product was observed, there was no enantioselectivity in any of the trials.

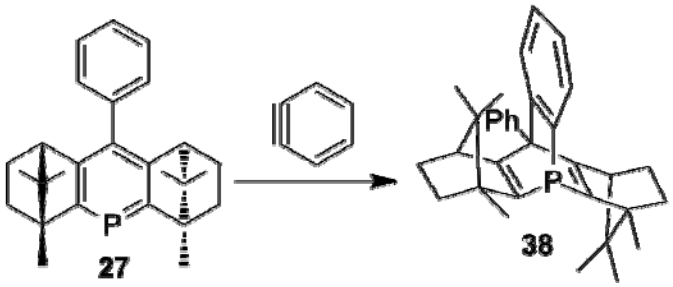


Scheme 3.9. Rh(I) catalyzed hydrogenation of dimethyl itaconate using **27** as ligand.

Phosphabarrelenes

Biscamphorphosphinine **27** was reacted with 2.5 equivalents of benzyne, generated *in situ* from 2-fluoroiodobenzene and magnesium turnings, in refluxing THF. The dark red solution was quenched with water, and the reaction mixture was separated

by column chromatography. The crude phosphabarrelene (**38**) was then purified further by recrystallization from hot ethyl acetate for an average yield of 25%.



Scheme 3.10. Synthesis of biscamphorphosphabarrelene **38**.

Discussion

The synthesis of phosphinine **27** is the first report of a C_2 asymmetric phosphinine in the literature. The yield for the conversion of the pyrylium precursor to the phosphinine, using $P(TMS)_3$, is unusually high (82%). Typical reaction yields for triarylphosphinines are 15 – 40%. It is believed that this is due to the *meta* substituents hindering attack of the phosphorus nucleophile at the *para* position, thereby shutting down a major side reaction. Interestingly, the ^{13}C NMR of this compound shows carbon-phosphorus coupling as far as five bonds. The *ortho* carbons of the phosphinine at 176.7 ppm show a 49.3 Hz C-P coupling constant. Only the two phenyl carbons farthest from the phosphorus and one of the bridgehead methyl carbons show no coupling.

Though the synthesis of the palladium/**27** complex was facile, no crystals of sufficient quality could be isolated to obtain publishable data. From what data was obtained it was evident that dichloromethane was incorporated in the crystal structure, there was significant disorder in the phenyl substituent. Structurally, it was determined that there are two phosphinine ligands bound to the square planar Pd(II) center in a *trans* fashion.

The absence of any coordination behavior with the phosphinine and [Pt(II)(COD)Cl_2] according to ^{31}P NMR spectroscopy was surprising. Breit has shown coordination of triarylphosphinines to Ir(I) complexes,[35d] and Mathey has shown coordination of phosphinines to Au(0),[33] and with the synthesis of the Pd(II) complex in our own lab, it was thought that the Pt(II) complex would be readily made. Since none of the asymmetric reactions to be investigated utilized Pt(II) no further studies were performed.

The procedure for the formation of the Rh(I) complex was derived from Breit's method.[35] Upon addition of the phosphinine to the [ClRh(I)$(CO)_2]_2$, evolution of carbon monoxide was evident. The fact that only one doublet was seen in the ^{31}P NMR spectrum indicates that the two phosphinines are equivalent. Attempts at growing crystals using either slow evaporation or vapor diffusion failed to yield X-ray quality crystals.

Hydrosilylation involves using a Pd(II) catalyst to add $HSiCl_3$ across a carbon-carbon double bond with Markovnikov regiochemistry, generating the chiral trichloroalkylsilane product. This product is then oxidized to the secondary alcohol using Tamao-Fleming oxidation conditions, which is known to retain stereoconfiguration. The Pd(II) in this reaction requires a monodentate ligand. Since palladium is only four coordinate a bidentate ligand will shut down all reactivity of this system, making this reaction an ideal test case for monodentate ligand **27.** The reaction is run at ambient pressure, so it was a convenient test reaction. MOP is the most widely used ligand for palladium catalyzed asymmetric hydrosilylation[51] due to its high enantioselectivity, and wide range of substrates that it works well with. Therefore, reaction conditions and substrates were chosen to be similar to those of MOP to allow for a general comparison.

We attempted the asymmetric hydrosilylation of styrene and 1-octene. 1-Octene was shown to be inert to the catalyst under our conditions. However, styrene reacted to form the trichlorosilane product in nearly quantitative yield, however with only 27% ee of the (*S*)-phenylethanol. The low level of asymmetric induction can be attributed to two features that are evident from the X-ray structure of **27**. The phosphinine ligand influences the metal environment primarily through the bridgehead methyl groups. Unfortunately, these methyl groups cannot extend appreciably into the metal's coordination sphere (Figure 3.6), which limits the ligand's ability to enforce an asymmetric environment. In addition, the methyl groups deviate only marginally (~ 18°) from the plane of the phosphinine ring. If the methyl groups were coplanar with the phosphinine ring, there would be no effective asymmetry at the metal. Though the enantioselectivity was low, the reaction was successful in that this was the first chiral *monodentate* phosphinine to show any enantioselectivity, and this was the first application of phosphinines to a palladium(II) catalyzed hydrosilylation reaction.

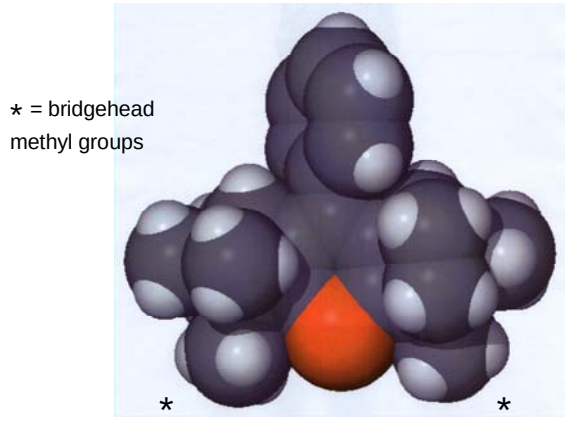


Figure 3.6. Face-on space filling view of phosphinine **27**. Phosphorus is at bottom center.

Asymmetric hydrogenation is a very common catalytic asymmetric reaction, often used as a benchmark for a new ligands efficacy. Though bidentate ligands are most commonly used in rhodium catalyzed asymmetric hydrogenation, bulky monodentate ligands,[54] or combinations of chiral and achiral monodentate ligands[53] have been found to be effective also. Thus, we investigated the asymmetric hydrogenation of dimethyl itaconate, using two equivalents of the ligand **27** to the metal, and a combination of one equivalent **27** with one equivalent of triphenylphosphite. Though complete hydrogenation occurred, no enantioselectivity was observed. This could be due to the ligand not being coordinated during the enantioselective step, the active catalyst in the system not being ligated to **27** at all, or the stereoinduction of the ligand is too weak to be observable. These reactions are quite sensitive to substrate as well, with some catalyst systems proving excellent for certain substrates and giving nearly racemic product for other substrates. As of so far, we have only tested one substrate, therefore we cannot fully discern the scope or mechanistic reasons for the lack of enantioselectivity.

Phosphabarrelene **38** was synthesized according to literature methods.[34] The yield of 25% is considerably lower than the yields of most other phosphabarrelenes (typically around 40%). It was postulated that the dark red color, and large amount of residue formed from the reaction could be due to the formation of a λ^5-phosphinine, which are typically known to be colored species. The reaction to form the benzyne essentially forms a Grignard intermediate species, a 2-fluorophenyl magnesium iodide intermediate that decomposes to benzyne. Depending on its lifetime, this organometallic intermediate could potentially act as a carbon nucleophile attacking the electrophilic phosphorus atom, resulting in red byproduct. It was considered that by forming benzyne by a different

method, this side reaction could be avoided. A sample of triphenylphosphinine was dissolved in refluxing DME, with an excess of anthranilic acid. To this reaction, isoamyl nitrite was added dropwise. The reaction proceeded to form a transparent yellow solution, with no precipitation. GC-MS indicated quantitative conversion to the phosphabarrelene, though an isolated yield was not obtained. This could represent a much improved route to phosphabarrelenes that has not been reported in the literature as of yet.

CHAPTER FOUR

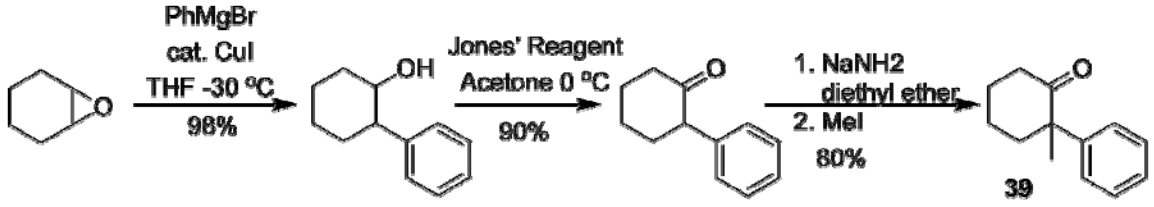
Other Ligand Systems

Introduction

Nature only makes a limited number of α-quaternary cyclic ketones. While exploring the use of (+)-camphor as a starting material for chiral pyrylium salts and phosphinines, other synthetic ketones were investigated as well. Specifically systems based on 2-methyl-2-phenylcyclohexanone were investigated. Once the method for synthesizing the camphor-based phosphinine was found, it was assumed that the process would be applicable to most any α-quaternary cyclic ketones.

2-Methyl-2-phenylcyclohexanone

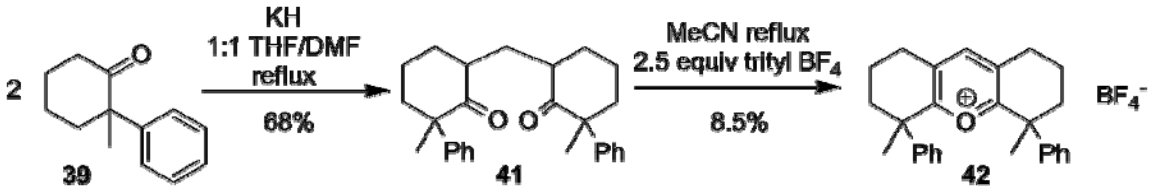
2-Methyl-2-phenylcyclohexanone was synthesized by first using phenyl magnesium bromide to ring open the epoxide, cyclohexene oxide.[55] The *trans*-2-phenylcyclohexanol was then oxidized using Jones' Reagent at 0 ^{o}C to prevent ring cleavage. The 2-phenylcyclohexanone was then deprotonated using a hydride or amide base, and alkylated with methyl iodide to produce *rac*-2-methyl-2-phenylcyclohexanone (**39)**.[56]



Scheme 4.1. Synthesis of *rac*-2-methyl-2-phenylcyclohexanone.

The first approach for synthesizing a pyrylium salt based on this ketone was taken from Balaban's synthesis of the 1,2,3,4,5,6,7,8-octahydroxanthylium perchlorate from 2-formylcyclohexanone and cyclohexanone.[42] The sodium enolate of **39** was reacted with methyl formate in THF to yield the *rac*-6-formyl-2-methyl-2-phenylcyclohexanone (**40**). This dicarbonyl was then reacted with **39** in refluxing glacial acetic acid with 70% $HClO_4$. The only product of this reaction was brown tar, similar to what was found for the camphor-based reactions in Chapter Two.

Still considering Balaban's work, a 1,5-diketone was synthesized from **39**. The ketone (**39**) was reacted with 1.5 equivalents of potassium hydride in a 1:1 mixture of DMF/THF. The product 1,5-diketone **41** was purified by Kugelrohr distillation as a mixture of four isomers according to GC-MS. The compound was then dissolved in acetonitrile and reacted with 2.5 equivalents of trityl tetrafluoroborate at reflux temperatures. ^{13}C NMR of the mixture showed small peaks suggesting pyrylium formation. The compound could not be recrystallized from a variety of solvents, so column chromatography was performed to give pyrylium **42** with 95% purity (the impurity being an unknown red compound) in 8.5% yield.

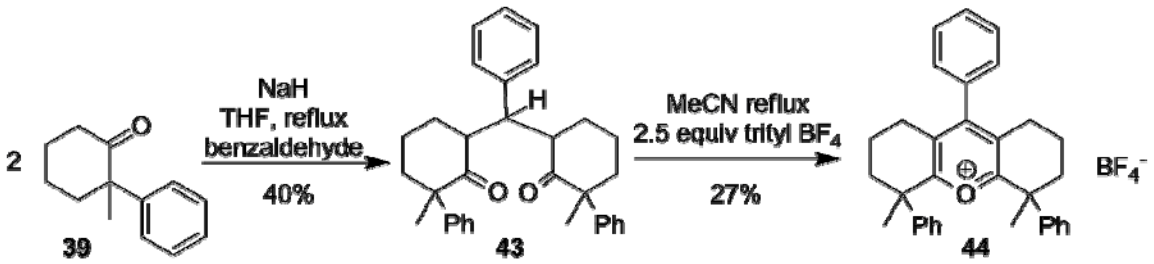


39 41 42

Scheme 4.2. Synthesis of pyrylium **42**.

Based on this success, a corresponding pyrylium containing a *para* phenyl group was synthesized. Two equivalents of **39** were reacted with a slight excess of sodium

hydride in refluxing THF. The solution was cooled, and a solution of benzaldehyde in THF was added dropwise to the solution. Upon complete addition the solution was returned to reflux for 2 hours, before quenching. The diketone **43** was purified, first by column chromatography which was inefficient at removing the 6-benzylidene-2-methyl-2-phenylcyclohexanone by-product, and afterwards by Kugelrohr distillation which yields the diketone in 40% yield as a mixture of isomers. The mixture of **43** was then reacted with trityl BF_4 in refluxing acetonitrile as in previous reactions to yield the pyrylium **44** in 27% yield. Pyrylium **44** also contained a red/orange impurity which could not be removed by recrystallization or column chromatography.

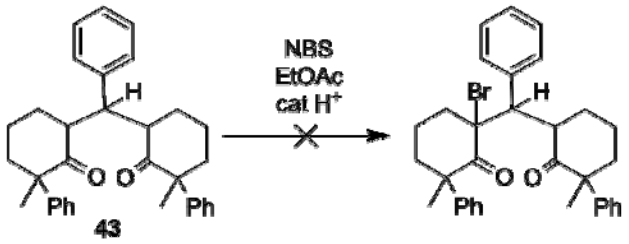


Scheme 4.3. Synthesis of pyrylium **44**.

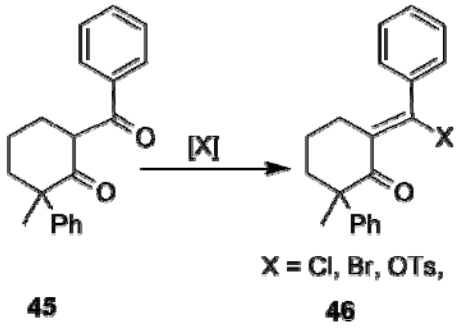
As in Chapter Two when the oxidation of BCT (**31**) was attempted, and proved futile, the oxidation of **43** was investigated. Compound **43** was reacted with NBS in ethyl acetate, with Amberlyst acid resin as catalyst.[57] After stirring overnight, no reaction was observed by GC-MS.

After the success of the improved route for synthesizing the biscamphorpyrylium **29**, starting from the oxidized precursor **36**, it was postulated that if the corresponding halogenated alkene for the 2-methyl-2-phenylcyclohexanone system could be

synthesized, a higher yielding, more cost effective route to the pyrylium could be found. Therefore, efforts were made to synthesize molecule **46**.



Scheme 4.4. Failed oxidation of **43** using NBS/acid conditions.



Scheme 4.5. Synthetic plan for making compound **46**.

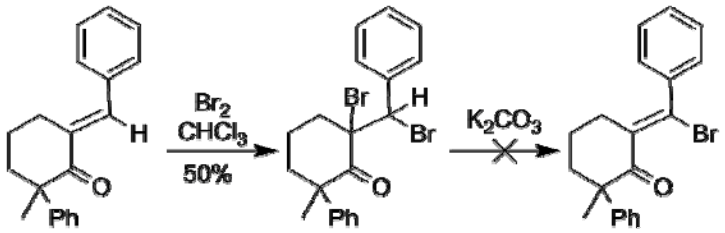
Several reactions were investigated for the transformation of the 1,3-diketone **45** to the derivative **46**, based on the reaction used to convert 3-benzoylcamphor to **36**. It was found that using similar reaction conditions, refluxing **45** in PCl_3 did not furnish the chloro-derivative of **46**. PBr_3 was tried with the results being inconclusive. The first attempt yielded 3 peaks according to GC-MS with the correct m/z ratio, however little product was isolated for characterization. A second trial gave no correct peaks on the GC-MS chromatogram. Several reagents that are known to perform the conversion of a 1,3-diketone to the β-halo-α,β-unsaturated ketone were examined, and of those tested, all

failed to give the correct product, or showed little or no reaction at all. These results are summarized in Table 4.1 below.

Table 4.1. Reagents used for the attempted conversion of **45** to **46**.

Reagent	Base	Result
PCl_3[48]	__	<10% after 6 days
PBr_3[58]	__	Inconclusive
PCl_5[59]	__	No reaction
$POCl_3$[60]	__	No reaction
Triphenylphosphine / Br_2[61]	Et_3N	No reaction
Tosyl chloride	Et_3N	No reaction
Tosyl chloride	NaH	Reduction

Oxidation of 6-benzylidene-2-methyl-2-phenylcyclohexanone using elemental bromine was tried as well. According to literature, reaction of 6-benzylidene-2,2-dimethylcyclohexanone with Br_2 and potassium carbonate in chloroform would form the dibromo-compound followed by elimination to give the product 6-(α-bromobenzylidene)-2,2-dimethylcyclohexanone in high yield.[62] This reaction did not prove as efficient for the phenyl-substituted cyclohexanone. After stirring overnight (versus 30 minutes for the literature dimethyl system) the reaction displayed only 50% conversion to a dibromo derivative according to GC-MS, with no evidence of the desired bromo-alkene product.



Scheme 4.6. Attempted synthesis of 6-(α-bromobenzylidene)-2-methyl-2-phenylcyclohexanone.

Discussion

All work with 2-methyl-2-phenylcyclohexanone was performed using racemic material with the understanding that racemic material is far easier to synthesize, and that once an efficient route to the pyrylium was found, asymmetric methodologies such as Koga imines,[63] or Ender's SAMP[64] would be applied to make the enantiomerically pure ketones. Synthesis of pyrylium **42**, though racemic and in low yield, was an encouraging sign, that pyrylium salts from synthetic ketones could be successfully synthesized *via* Balaban's method. It is unknown whether using the 2:1 acetic acid:acetic anhydride solvent system used in Chapter Two would be beneficial here as, chronologically, that information was not found until after this compound had been synthesized, and the reaction was not revisited with the new information. The ^{1}H NMR spectrum of **42** shows the characteristic downfield resonance for the *para* H on the pyrylium ring at 8.76 ppm and 8.67 ppm. The two peaks in a 1.8/1.0 ratio (8.67 ppm/8.76ppm) presumably represent the two sets of diastereomers, with the larger peak representing the enantiomeric pairs (*R,R* and *S,S*) and the meso (*R,S*) diastereomer. The ^{13}C NMR spectrum displays peaks that also support formation of the aromatic pyrylium salt. Peaks at 180.8, 144.4 and 134.7 ppm represent the *ortho*, *para*, and *meta* carbons, respectively. The *para* carbon for this pyrylium compared to the biscamphorpyrylium **29** is higher field (by approximately 10

ppm) which is consistent with published data.[28] ^{13}C NMR spectra also shows a set of two peaks for each carbon in a similar ratio representing the *d,l* and the meso compounds. The identity of the red impurity is unknown, since it could not be isolated. Recrystallization from various solvent systems was tried, and failed to give a crystalline product, instead forming viscous oils. This may be due to the fact that the compound is a mixture of the racemic and meso compounds. In order to confirm the identity of the compound, a few milligrams were added to three milliliters of concentrated aqueous ammonia. The solution was extracted with diethyl ether, and the ether phase was ran on GC-MS. Two peaks were observed with the correct m/z ratio for the pyridine analog of the pyrylium **42**.

Similar to the problems experienced when synthesizing BCT (**31**), diketone **43** was plagued with difficulties. The formation of the benzylidene intermediate does not seem to be a problem, since it shows to be a major product on the GC-MS, however the addition of the second enolate is very slow, and often the hydride or amide bases used can lead to reduction of benzaldehyde or the benzylidene intermediate before that second addition takes place. Pyrylium **44** was formed in 27% yield, which is considerably higher than either of the previous pyryliums formed using trityl conditions. This may be due to the combination of having the *para* phenyl and not having multiple ring systems (like the camphor system), susceptible to rearrangement/ring opening. Pyrylium **44** also shows two sets of peaks in ^{1}H and ^{13}C NMR, for the *d,l* and meso compounds. ^{13}C NMR indicated the formation of the pyrylium ring with peaks at 180.2, 171.7, and 145.1 ppm. This compound also contained a red/orange impurity which could not be removed by recrystallization, or column chromatography.

It is known in the literature that 3-benzoylcamphor usually exists not as the diketo-form, but nearly 100% as the keto/enol tautomer.[65] This is evident in the ^{1}H NMR of the compound, which exhibits a characteristic enol peak at approximately 14 ppm. However, 6-benzoyl-2-methyl-2-phenylcyclohexanone shows no evidence of an enol structure at all. It appears that this diketone remains essentially in the diketone form at all times, with no enolization occurring. This may explain the lack of reactivity of **45** with so many various reagents which are known to convert diketones into β-halo-α,β,-unsaturated ketones, as seen in Table 4.1.

It is interesting that 6-benzylidene-2,2-dimethylcyclohexanone is reported to undergo bromination rapidly and quantitatively followed by spontaneous elimination of HBr, even with no base present, to give the 6-(α-bromobenzylidene)-2,2-dimethylcyclohexanone nearly quantitatively in as little as 15 minutes. However when one of the methyl groups is replaced with phenyl, the reactivity is severely limited. The reaction gave only 50% bromination over 24 hours and no elimination even with the addition of potassium carbonate. The reaction was monitored by GC-MS only, so it is assumed that bromination occurred at the double bond, and not elsewhere on the molecule. How changing one methyl group to a phenyl on the 2-position can so drastically affect bromination of the alkene at the 6-position is not yet understood.

CHAPTER FIVE

Materials and Methods

General Section

All reactions which required the use of air or water sensitive reagents were carried out in flame- or oven-dried glassware under nitrogen or argon atmosphere, unless otherwise stated. Reagents and solvents were generally purchased from the Aldrich Chemical Company or from Alfa Aesar, and were used as received unless otherwise noted. Tris-(trimethylsilyl)phosphine was obtained from Strem Chemical. Hexanes, petroleum ether, ethyl acetate, and methylene chloride, were distilled prior to use. THF was distilled from potassium metal. NMR spectra were obtained using a Varian 500 MHz NMR operating at 500 MHz for ^{1}H, 125 MHz for ^{13}C, and 202 MHz for ^{31}P. Spectra obtained in $CDCl_3$ were referenced to TMS (0 ppm) for ^{1}H and to $CDCl_3$ (77.0 ppm) for ^{13}C. ^{31}P spectra were referenced to an external standard of 85% H_3PO_4 (0 ppm) . GC-MS was done on a Hewlett-Packard GCD using a 30 m x 0.25 mm HP-5 capillary column with helium carrier and EI ionization. Analysis for enantiomeric purity was by capillary gas chromatography using an HP5890 with a Restek Rt-βDEXsa, 30 m x 0.25 mm column and hydrogen carrier. High resolution mass spectra were obtained from the Baylor University mass spectrometry facility. Elemental analyses were performed by Atlantic Microlabs, Norcross, GA. Melting points were calibrated against accepted standards.

Initial Attempts

Synthesis of pyrylium **29** *from diketone* **31.** To a 100 ml flask equipped with a condenser and magnetic stir bar under inert atmosphere, 5.0 g (13 mmol) of **31** synthesized by previous literature methods,[43] 4.77 g (14.4 mmol) of triphenylcarbenium tetrafluoroborate, glacial acetic acid (26.6 mL), and acetic anhydride (13 mL) were added.[46] The solution was brought to reflux overnight, during which time it turned from dark red to black/brown. After cooling to room temperature, the solution was poured into 400 mL of diethyl ether, and placed in a freezer (-20 °C) overnight. The suspension was filtered and white crystals collected. The filtrate volume was reduced, and a second crystallization from 200 mL of diethyl ether was performed. The total yield was 470 mg (8%) from two recrystallizations.

Improved Synthesis of Biscamphorpyrylium

(E)-3-(α-chlorobenzylidene)camphor (**36**). (E)-3-(α-chlorobenzylidene)camphor was synthesized according to the method of Sotiropoulos et al.[48] The reported melting point was found to be incorrect, probably due to a mixture of (E) and (Z) isomers. Sotiropoulos purified the compound by distillation followed by column chromatography on alumina, reporting a melting point of 50 ^{o}C. However by recrystallizing from methanol, we were able to obtain a melting point of 61-62 ^{o}C. The structure was confirmed by X-ray crystallography to be the (E) isomer. Our procedure is given below.

To 21.80 g (85.2 mmol) of 3-benzoylcamphor was added 28.0 mL of PCl_3. The solution was refluxed under nitrogen for 2 hours, until the cessation of HCl evolution. The solution was poured onto ice, and neutralized with K_2CO_3. The aqueous solution was extracted with diethyl ether three times, and the combined organic phase was washed

with saturated sodium bicarbonate, then brine, and dried over magnesium sulfate. The solvent was subsequently removed under reduced pressure, and the green oil was taken up in warm methanol. After cooling to -20 ^{o}C, 9.80 g (35.7 mmol) of pale yellow crystals were obtained in 42% yield. mp 61-62 ^{o}C; $[\alpha]^{20}_{D}$ +87.4^{o} (*c* 0.465, EtOAc); ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.45 –7.42 (m, 2H, ArH), 7.38 – 7.34 (m, 3H, ArH), 3.11 (d, *J* = 4.1 Hz, 1H), 2.10 (ddt, J = 12.5, 11.4. 4.7, 1H), 1.74 (ddd, J = 13.5, 11.4, 4.0, 1H), 1.62 (td, J = 9.3, 4.1, 1H), 1.48 (ddd, J = 13.8, 9.3, 4.8, 1H), 1.00 (s, 3H), 0.96 (s, 3H), 0.93 (s, 3H); ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 202.7, 139.7, 139.0, 136.4, 129.7, 129.1 (2C), 127.7 (2C), 59.8, 52.8, 45.5, 30.6, 25.7, 20.6, 18.3, 9.6; IR (KBr): 2962, 970, 903 cm^{-1}; HRMS (EI): calcd for $C_{17}H_{19}OCl$ [M^{+}] 274.1124, found 274.1120; elemental analysis: calcd (%) for $C_{17}H_{19}ClO$: C 74.31, H 6.97; found C 74.14, H 6.88.

Enedione **35.** To 1.1 g (27 mmol, 2.5 equiv) of KH in hexanes (30 mL), 5.42 g (35.7 mmol, 3 equiv) of (+)-camphor was added and refluxed for 2 hours. Then 3.00 g (10.9 mmol, 1 equiv) of (+)-(E)-3-(α-chlorobenzylidene) camphor in hexanes (20 mL) was slowly added by syringe, and the reaction was refluxed for 18 hours. The reaction was quenched by addition of saturated ammonium chloride solution, and brought to neutral pH with 6.0 M HCl. The mixture was extracted with diethyl ether, dried with magnesium sulfate, filtered and evaporated to a solid. The mixture was dissolved in warm methanol and, after cooling to -20 ^{o}C, filtered to give crystalline enedione **35** (2.87 g, 7.36 mmol, 68% yield). mp 142 - 144 ^{o}C; $[\alpha]^{20}_{D}$ +82.6^{o} (*c* 0.33, EtOAc); ^{1}H NMR (500 MHz, $CDCl_3$, -40 ^{o}C): δ 7.38 - 7.32 (m, 4H, ArH), 7.13 (br d, *J* = 7.8 Hz, 1H, ArH), 5.32 (br d, *J* = 3.6 Hz, 1H), 2.38 (br t, *J* = 3.8 Hz, 1H), 2.17 (br d, *J* = 4.0 Hz, 1H), 1.99 – 1.91 (m, 1H), 1.76 – 1.68 (m, 1H), 1.56 – 1.39 (m, 4H), 1.23 – 1.15 (m, 1H), 1.04 (s, 3H), 0.98

(s, 3H), 0.93 (s, 3H), 0.88 (s, 3H), 0.85 (s, 3H), 0.82 (s, 3H), 0.80 – 0.74 (m, 1H); ^{13}C NMR (125.7 MHz, $CDCl_3$, -40 ^{o}C): δ 217.9, 209.9, 143.6, 142.9, 140.2, 128.5, 128.0, 127.7, 127.6, 127.1, 59.2, 59.0, 52.6, 50.5, 49.4, 46.4, 46.0, 30.0, 29.0, 26.4, 21.7, 20.3, 19.3, 18.8, 18.1, 9.7, 9.5; IR (KBr) 2960, 1741, 1711, 1622 cm^{-1}; HRMS (EI) calcd for $C_{27}H_{34}O_2$ [M^+] 390.2559, found 390.2560; elemental analysis calcd (%) for $C_{27}H_{34}O_2$: C 83.03, H 8.77; found C 82.86, H 8.91.

Biscamphorpyrylium tetrafluoroborate (**29**)**.** To 0.431 g (1.11 mmol) of **35** dissolved in toluene (20 mL) in a flask equipped with a Dean-Stark trap was added 1.00 mL (5.9 mmol) of ~52% HBF_4 in diethyl ether (~5.92 M) and the solution refluxed overnight. The toluene solution was diluted with diethyl ether (100 mL), cooled to 0 ^{o}C, and filtered through a Celite pad. The fine precipitate was then rinsed into a separate flask with dichloromethane. The solvent was removed under vacuum, and the compound was recrystallized from acetone/diethyl ether to yield biscamphorpyrylium tetrafluoroborate **29** (0.278 g, 0.604 mmol, 55%). mp 272 – 274 °C; $[\alpha]^{20}_{D}$ +309° (*c* 0.44, CH_3CN), +378° (c = 0.37, CH_2Cl_2); ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.66 – 7.63 (m, 3H, ArH), 7.56 – 7.54 (m, 2H, ArH), 3.25 (d, *J* = 4.0 Hz, 2H), 2.39 (ddt, *J* = 13.0, 9.8, 4.0 Hz, 2H), 2.22 (ddd, *J* = 13.2, 9.8, 4.0 Hz, 2H), 1.79 (ddd, *J* = 13.2, 9.3, 3.9 Hz, 2H), 1.60 (ddd, *J* = 13.0. 9.3, 3.9 Hz, 2H), 1.50 (s, 6H), 1.05 (s, 6H), 0.77 (s, 6H); ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 184.4 (2C), 155.7 (1C), 137.5 (2C), 132.5 (1C, CH), 131.1 (1C), 129.65 (2C, CH), 129.64 (2C, CH), 60.6 (2C), 57.0 (2C), 50.4 (2C, CH), 31.3 (2C, CH_2), 25.0 (2C, CH_2), 19.7 (2C, CH_3), 19.0 (2C, CH_3), 8.6 (2C, CH_3); IR (KBr) 2960, 1608, 1415, 1055 cm^{-1}. HRMS (EI) calcd for $C_{27}H_{33}O$ [M^+] 373.2531, found 373.2530; elemental analysis calcd (%) for $C_{27}H_{33}OBF_4$: C 70.44, H 7.23; found C 70.58, H 7.33.

Biscamphorphosphinine (**27**)**.** To 0.913 g of biscamphorpyrylium tetrafluoroborate (**29**) dissolved in anhydrous acetonitrile (10 mL) under nitrogen, was added 1.0 g of $P(TMS)_3$ and the solution was refluxed for 24 hours. The solution turned from orange to dark red/black. After cooling to room temperature, the solvent was removed by rotary evaporation and the phosphinine was purified by silica gel column chromatography (5% ethyl acetate in petroleum ether). The resulting yellow solid was recrystallized from methanol to give phosphinine **27** as colorless needles (0.631 g, 1.63 mmol, 82%). mp 123-124 ^{o}C; $[\alpha]^{20}_{D}$ +51.8^{o} (*c* 0.55, EtOAc); ^{1}H NMR ($CDCl_3$, 500 MHz): δ 7.43 (t, *J* = 7.4, 2H, ArH), 7.38 – 7.33 (m, 1H, ArH), 7.24 – 7.20 (m, 2H, ArH), 2.69 (d, *J* = 3.9, 2H), 2.00-1.93 (m, 2H), 1.89 (tdd, *J* = 11.2, 3.6, 2.2, 2H), 1.43 (s, 6H), 1.16 (ddd, *J* = 11.5, 9.3, 3.2, 2H), 1.07 (ddd, *J* = 11.5, 9.1, 3.3, 2H), 0.90 (s, 6H), 0.55 (s, 6H); ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 176.7 (2C, d, *J* = 49.3), 148.9 (1C, d, *J* = 12.1), 140.3 (d, *J* = 1.9), 132.6 (d, *J* = 15.0), 129.4 (2C, d, *J* = 1.9, CH), 128.0 (2C, CH), 126.6 (CH), 57.7 (2C, d, *J* = 16.7), 56.8 (2C, d, *J* = 2.3), 53.1 (2C, d, *J* = 1.4, CH), 34.5 (2C, d, *J* = 3.3, CH_2), 25.9 (2C, d, *J* = 1.8, CH_2), 19.9 (2C, CH_3), 19.3 (2C, d, *J* = 1.4, CH_3), 13.6 (2C, d, *J* = 11.2, CH_3); ^{31}P NMR (202.3 MHz, $CDCl_3$): δ 138.9; IR (KBr): 3075, 3020, 2964, 1491, 1437, 1385, 1376 cm^{-1}; HRMS (EI) calcd for $C_{27}H_{33}P$ [M^+] 388.2320, found 388.2320; elemental analysis calcd (%) for $C_{27}H_{33}P$: C 83.47, H 8.68; found C 83.65, H 8.68.

General Method for Asymmetric Hydrosilylation. To 0.5 mg (1.3 μmole) of $[(allyl)Pd(II)Cl]_2$ in a 10 mL flask fitted with a reflux condenser under nitrogen was added 3.7 mg (9.5 μmole) of biscamphorphosphinine **27**, followed by 25 mmol of neat

olefin (styrene or 1-octene). After stirring at room temperature for 10 min, 3 mL (30 mmoles) of trichlorosilane was syringed into the flask, and the mixture was brought to reflux overnight. The alkyltrichlorosilane product was isolated by Kugelrohr distillation (100 ^{o}C at ~ 0.5 torr). The isolated product was subjected to Tamao-Fleming oxidation conditions.[52] The resulting alcohol was analyzed by GC/FID for enantiomeric purity using a Restek Chiraldex βsa column. The enantiomers were well-resolved (12.18 min vs 12.48 min, resolution = 3.18, temperature program 80-180 ^{o}C at 4 ^{o}C per min).

General Method for Asymmetric Hydrogenation. To a 100 mL Parr Reactor 9.4 mg (0.023 mmol) of $Rh(COD)_2BF_4$, 20.4 mg (0.053 mmol) of biscamphorphosphinine (**27**), in dichloromethane (30 mL) were added. Then 400 mg (2.53 mmol) of dimethyl itaconate was added, and the reactor purged with H_2. The reactor was pressurized with H_2 (40-60 bar) and allowed to stir overnight (18 hours) at the designated temperature (25 - 60^{o}C). Samples were analyzed by GC/FID using Restek Chiraldex βsa chiral column for enantiomeric purity.

Biscamphorphosphabarrelene (**38**). To 0.652 g (1.68 mmol) of biscamphorphosphinine (**27**) was added 95.4 mg (3.98 mmol) of magnesium turnings, placed under nitrogen and dry stirred for 30 minutes with a Teflon coated magnetic stirrer. To this anhydrous diethyl ether (10 mL) was added. The solution was placed in a sonicator. A solution of 0.43 mL of 2-fluoro-iodobenzene dissolved in anhydrous ether (5 mL) was syringed in slowly to the sonicating solution. After addition, the solution was allowed to sonicate for a further 2 hours. The solution turned to dark red/black. The reaction was quenched with water. After a water workup, the organic phase was evaporated, and methanol (20 mL) was added to the residue. The solution was refluxed

for 2 hours. The solution was cooled, and the white solid was filtered and collected. The solid was then recrystallized from ethyl acetate to yield 0.210 g (0.453 mmol), 26% of phosphabarrelene **38**. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 7.66 (s, 1H), 7.64 (s, 1H), 7.54 (m, 1H), 7.50 (t, *J* = 7.8, 2H), 7.37 (m, 2H), 6.91 (t, *J* = 7.4, 1H), 6.86 (t, *J* = 7.1, 1H), 3.13 (d, *J* = 3.5, 1H), 1.78 (d, *J* = 2.9, 1H), 1.52 (m, 2H), 1.34 (m, 2H), 1.29 (m, 2H), 1.21 (s, 3H), 1.16 (s, 3H), 0.73 (s, 3H), 0.71 (s, 3H), 0.63 (s, 3H), 0.47 (s, 3H), 0.07 (ddd, *J* = 11.8, 9.0, 2.9, 1H), -0.19 (ddd, *J* = 11.8, 9.1, 3.0, 1H); ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 166.6 (d, *J* = 3.3), 164.8 (d, *J* = 6.1), 156.2 (d, *J* = 26.2), 152.8 (d, *J* = 5.0), 147.1 (d, *J* = 16.2), 146.9 (d, *J* = 12.0), 139.9, 131.1 (d, *J* = 38.5), 130.7, 128.1, 126.4, 125.1 (d, *J* = 1.5), 124.7, 123.1 (d, *J* = 13.0), 63.0, 57.4 (d, *J* = 3.1), 57.3 (d, *J* = 17.2), 57.1 (d, *J* = 1.5), 57.0 (d, *J* = 17.1), 56.4 (d, *J* = 3.3), 56.0 (d, *J* = 1.8), 31.6, 24.1, 23.63, 23.62, 19.4, 19.0, 18.32 (d, *J* = 2.3), 18.27 (d, *J* = 2.2), 12.9 (d, *J* = 4.4), 12.73 (d, *J* = 4.02); MS (EI) 464 (M^+, Base), 421, 354, 311.

2-Methyl-2-phenylcyclohexanone

2-Phenylcyclohexanol.[55] To a 250 mL flask equipped with a 25 mL addition funnel, 0.283g (2.86 mmol) CuCl was added. THF (40.0 mL) was added and cooled to -50 to -30 ^{o}C in a dry ice/acetone bath. After cooling to temperature, 23 mL (69 mmol, 1.5 equiv.) of 3.0M phenylmagnesium bromide in ether was added *via* syringe. The solution was stirred for 10 minutes at -30^{o}C. A mixture of 4.40 g (44.8 mmol) cyclohexene oxide and THF (5 mL) was added dropwise from the addition funnel over a period of 30 min, never letting the temperature rise above -20^{o}C. The solution was then stirred at 0^{o}C for 2.5 hours. The reaction was quenched by adding saturated ammonium sulfate (5 mL). The layers were separated, and the organic layer was washed with

saturated ammonium sulfate until the aqueous layer no longer turned blue. The organic phase was washed with brine, and dried over anhydrous magnesium sulfate. The alcohol was recrystallized from hot hexanes to yield 7.72 g (43.9 mmol), 98%. MS (EI) 176 (M^+)

2-Phenylcyclohexanone. 2-Phenylcyclohexanol was dissolved in acetone, and brought to 0 ^oC using an ice bath. Jones reagent was added dropwise until the orange color was persistent for >20 min. Once the orange color remained the solution was allowed to warm up to room temperature over a period of 2 hours (if the color seems to persist before enough Jones reagent was added, the solution may need to be acidified with a few mL of conc. sulfuric acid). The reaction was quenched by adding an excess of isopropanol and stirring for 2 hours. The solution was diluted with a 4 fold excess of a 1:1 mixture of petroleum ether and diethyl ether, and the reaction mixture was filtered through a large silica gel pad, which retained the colored chromium products. Solution volume was reduced by rotary evaporation, and the product ketone was recrystallized from hot hexanes. Yield 90%. MS (EI) 174 (M+), 130 (Base), 117, 104, 91.

Rac-2-methyl-2-phenylcyclohexanone **39**.[56] To a 50 mL round bottom flask was added $NaNH_2$ (0.720 g, 17.5 mmol, 1.1 equiv) and the flask was equipped with a magnetic stir bar and reflux condenser.. Diethyl ether (9.0 mL) was added, and the solution refluxed for 30 minutes. To a separate 25 mL round bottom flask, 2.510 g (14.43 mmol) 2-phenylcyclohexanone was dissolved in diethyl ether (4.5 mL) and benzene (2 mL). The solution was syringed into the refluxing base slowly. The solution was allowed to reflux for 2 hours. The solution was then cooled to 0 ^oC with an ice bath. Then 1.5 mL (1.5 equiv) of iodomethane dissolved in ether (3 mL) was added. The solution was allowed to come to room temperature, and refluxed for 2 hrs. The reaction was quenched

with water, extracted with ether, dried over magnesium sulfate and concentrated followed by purification by column chromatography. In this manner, 7.8 g of *rac*-2-methyl-2-phenylcyclohexanone was purified on a column of 150 g silica gel, in 15% diethyl ether/petroleum ether. Yield 2.170 g (11.54 mmol), 80% as an amber oil. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 7.34 (m, 2H), 7.23 (m, 1H), 7.18 (m, 2H), 2.69 (m, 1H), 2.34 (m, 2H), 1.95 (m, 1H), 1.72 (m, 4H), 1.27 (s, 3H); ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 213.9, 143.2, 128.9, 126.5, 126.0, 54.3, 39.9, 38.1, 28.43, 28.42, 21.8; MS (EI) 188 (M^+), 144 (Base), 131, 117, 91, 77.

Bis(rac-2-methyl-2-phenylcyclohexanone)methane **41**. To a 50 mL round bottom flask with stirrer, 1.7 g (71 mmol) of KH was added, followed by dry DMF (20 mL). A mixture of 2.760 g (14.7 mmol) 2-methyl-2-phenylcyclohexanone in THF (20 mL) was added slowly. The solution was brought to reflux overnight. The reaction was quenched with water, extracted with ether, dried over magnesium sulfate, and compound purified by Kugelrohr distillation (150^{o}C at 1 torr.). Yield 3.878 g (10.0 mmol), 68% of amber glassy solid. MS (EI) 388 (M^+), 360, 188 (base), 144, 118, 105.

Pyrylium **42**. To 1.952 g (5.03 mmol) of bis(*rac*-2-methyl-2-phenylcyclohexanone)methane in acetonitrile (6 mL), 1.87 g (5.6 mmol) of triphenylcarbenium tetrafluoroborate was added. The solution was refluxed for 4 hours and then the solution was heated to ~70^{o}C (not refluxing) for 8 hours. Compound could NOT be recrystallized from diethyl ether, ethanol, hexanes, toluene, THF or diffusion recrystallization with dichloromethane/petroleum ether. The compound was purified by column chromatography in 100% dichloromethane ramped to 6.6% ethanol/dichloromethane. Yield 195 mg (0.428 mmol), 8.5 %. ^{13}C NMR (125.7 MHz,

$CDCl_3$): δ 180.9, 180.5, 144.5, 144.3, 134.64, 134.61, 128.9, 128.8, 127.4, 127.2, 126.3, 126.1, 99.9, 46.1, 46.0, 38.7, 37.9, 27.05, 26.98, 26.3, 26.1, 17.8, 17.7.

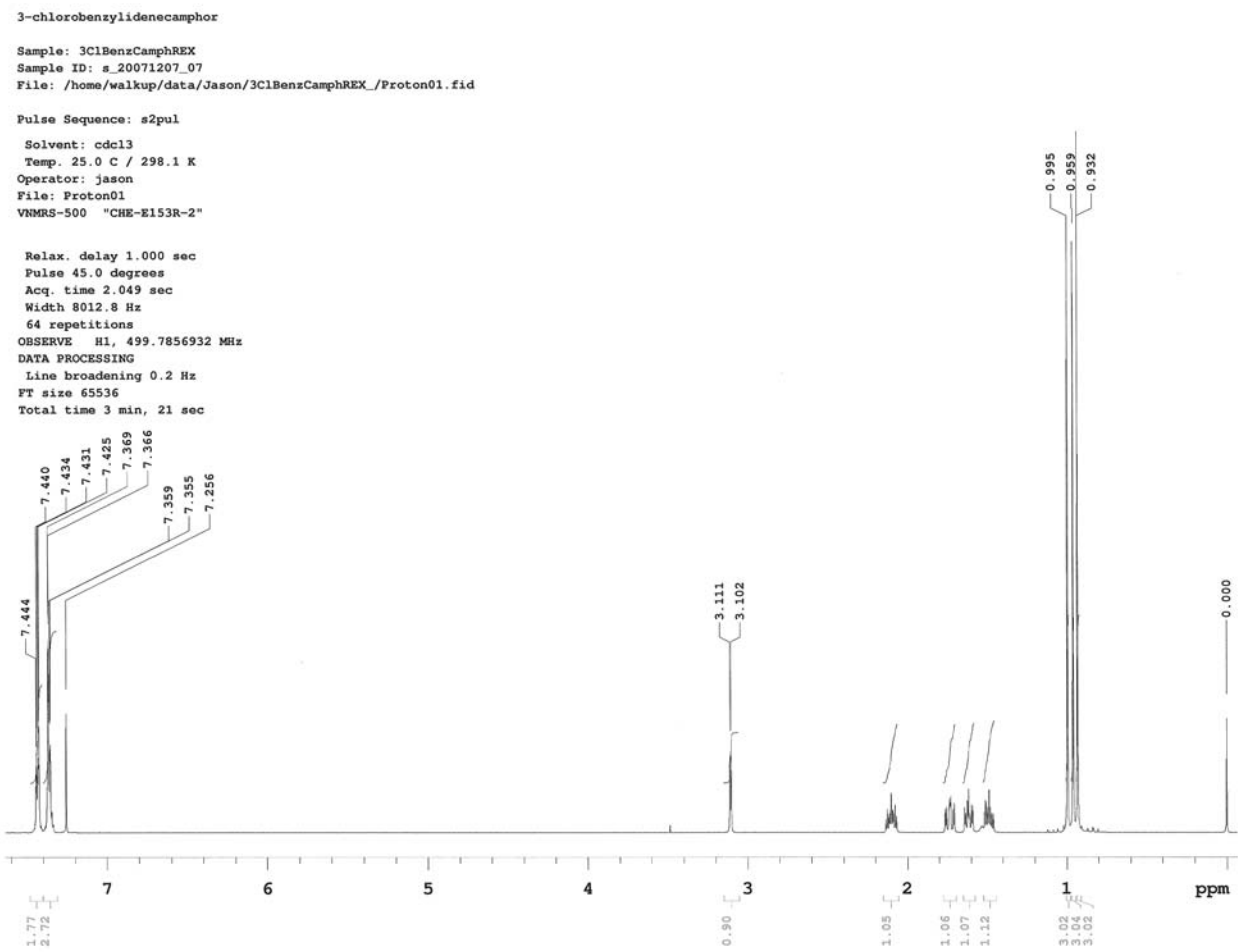
Bis(rac-2-methyl-2-phenylcyclohexanone)toluene **43**. R*ac*-2-methyl-2-phenylcyclohexanone (0.9412 g, 5.01 mmol) was dissolved in THF (5 mL). In a 25 mL round bottom flask, 0.25 g (6.3 mmol) of 60% NaH in mineral oil dispersion in THF (10 mL) was brought to reflux, and the ketone solution was added dropwise. The solution was refluxed for 1 hour, and then cooled in an ice bath. Then 0.255 g (2.4 mmol) of benzaldehyde was added carefully. The solution was returned to reflux for 3 hours. The reaction was then quenched with water, extracted with ether, and dried over magnesium sulfate. Product purified by Kugelrohr distillation, 150 ^{o}C at 0.5 torr. Yield 1.065 g (2.00 mmol), 40%.

Pyrylium **44**. 1.2836 g (2.763 mmole) of **43**, 2.0 g (6.1 mmol) of triphenylcarbenium tetrafluoroborate, and acetonitrile (10 mL) were refluxed for 4 hours, and allowed to sit at room temperature for 4 days. The solvent was removed under vacuum. Column chromatography was performed with 6.6% ethanol/dichloromethane as the mobile phase. Yield 397 mg (0.746 mmol, 27%). ^{13}C NMR (125.7 MHz, $CDCl_3$): δ 180.2, 179.7, 171.7, 171.2, 144.9, 144.8, 133.5, 133.4, 130.07, 129.96, 129.93, 129.4, 128.9, 128.8, 127.2, 127.1, 127.0, 126.4, 126.3, 126.1, 125.3, 46.51, 46.49, 38.2, 37.2, 26.87, 26.84, 26.6, 26.4, 17.90, 17.85.

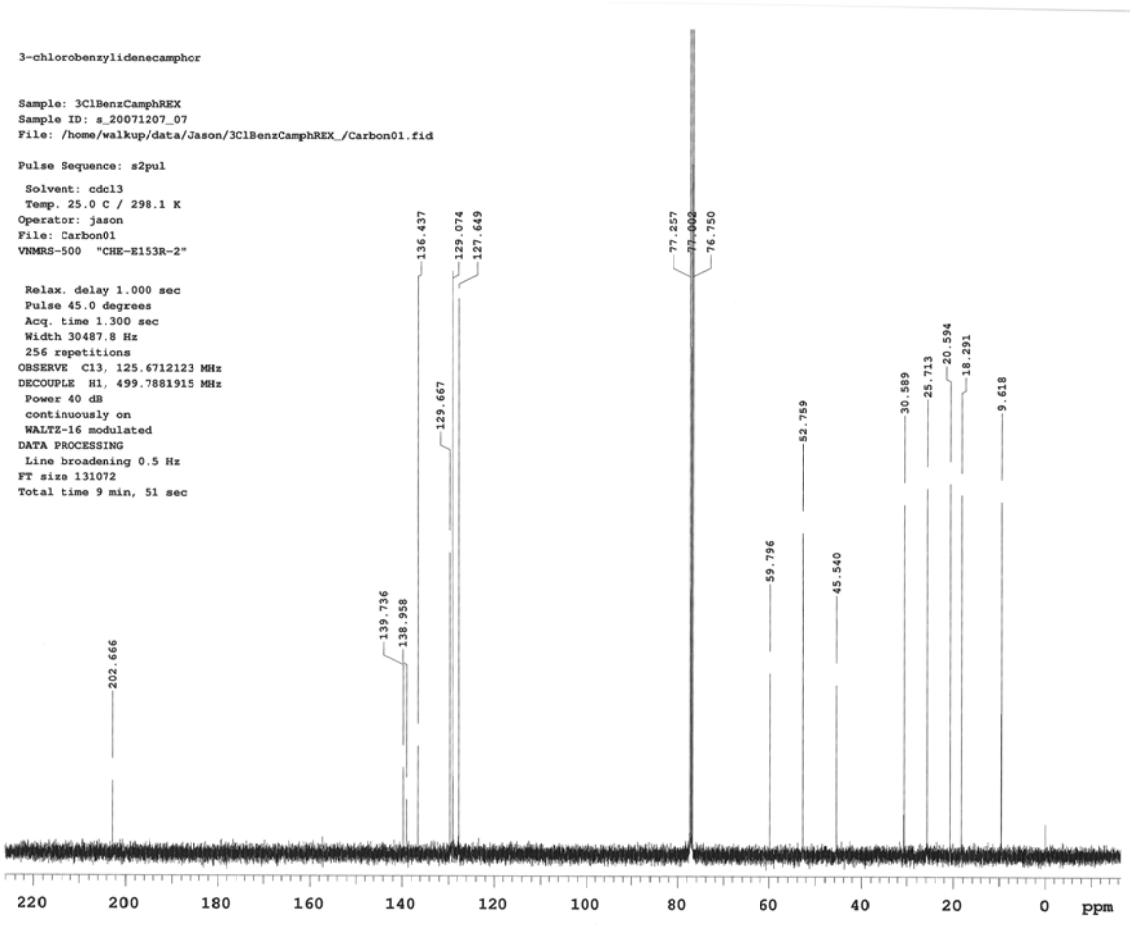
APPENDICES

APPENDIX A

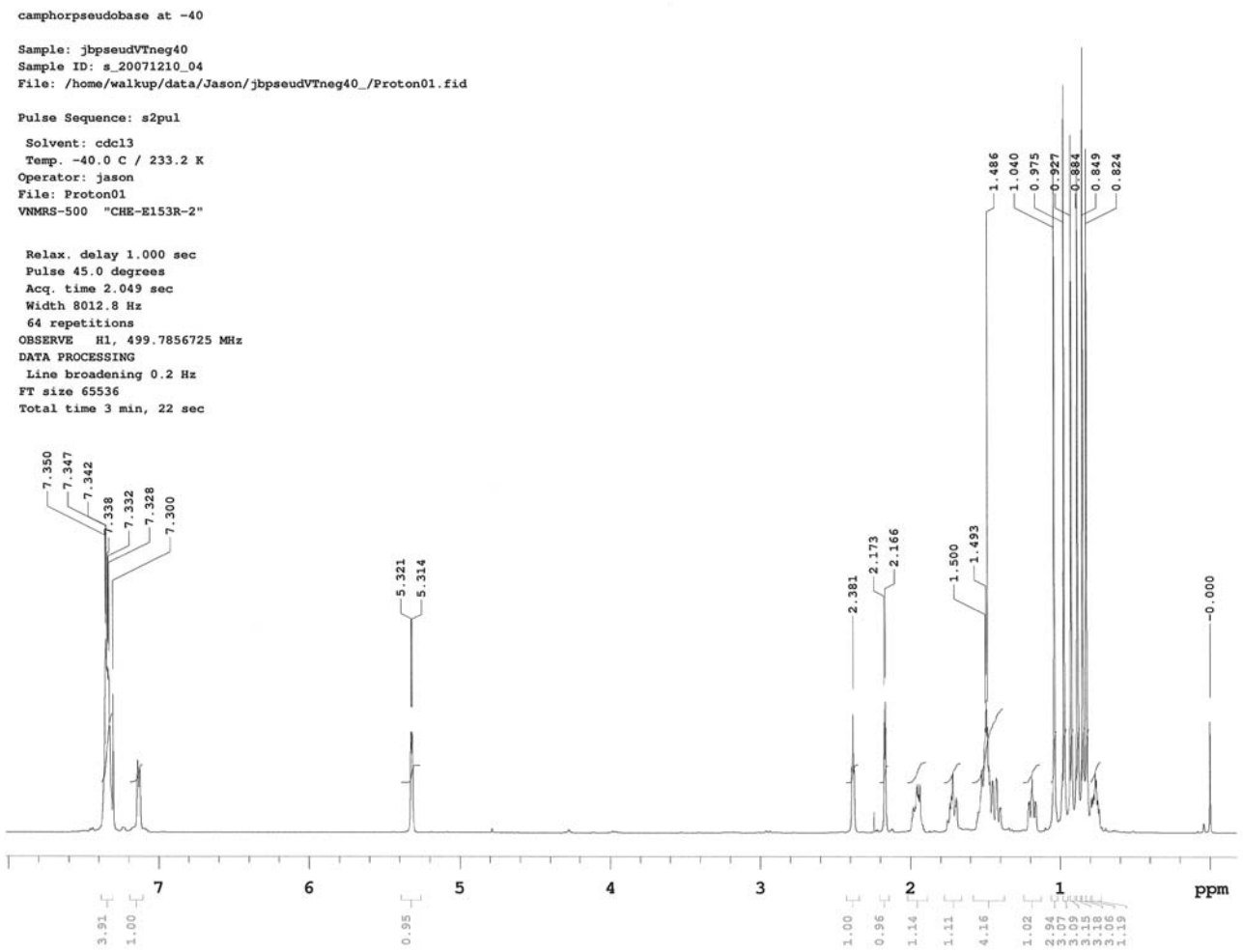
Selected NMR spectra



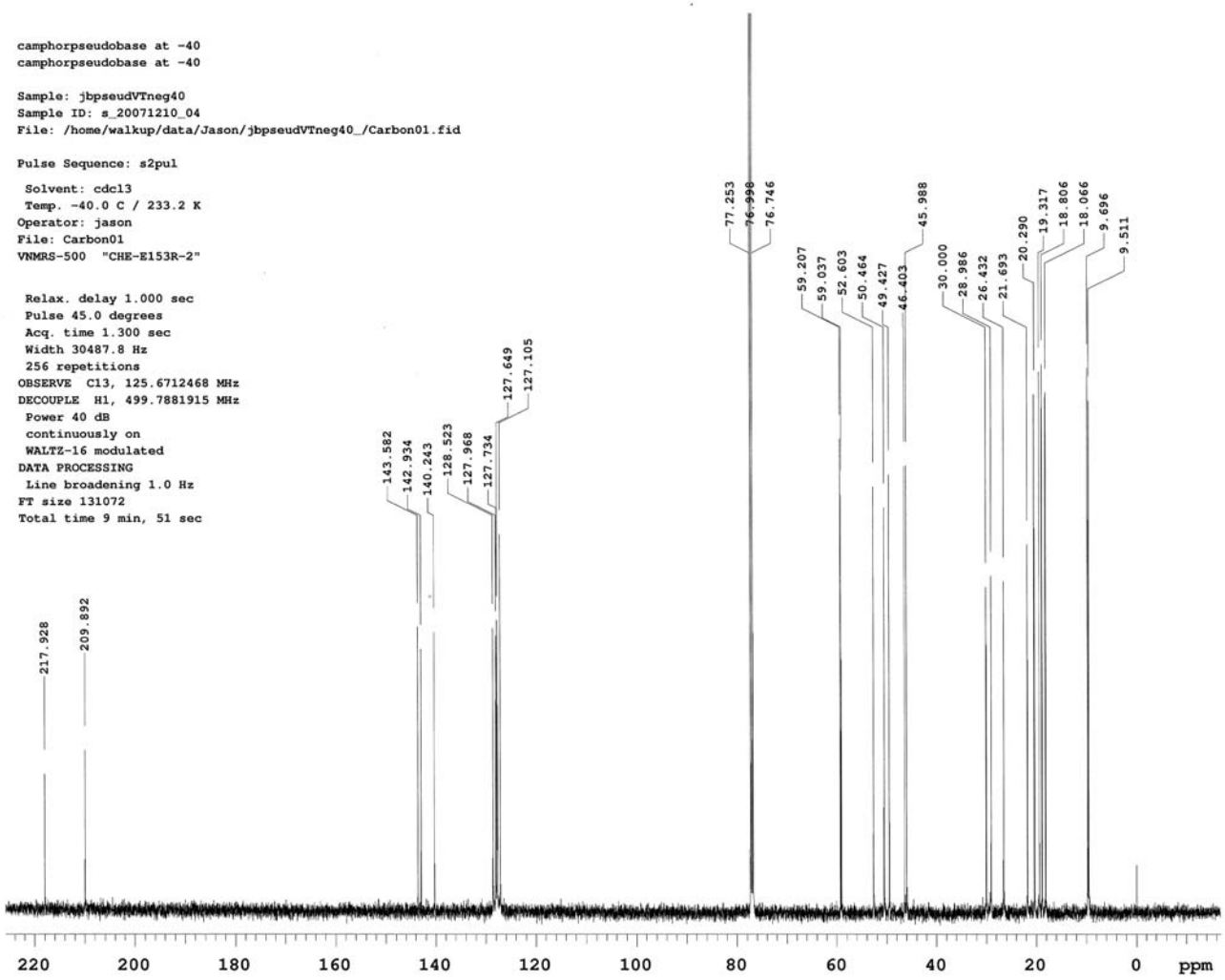
A.2.1 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **36**



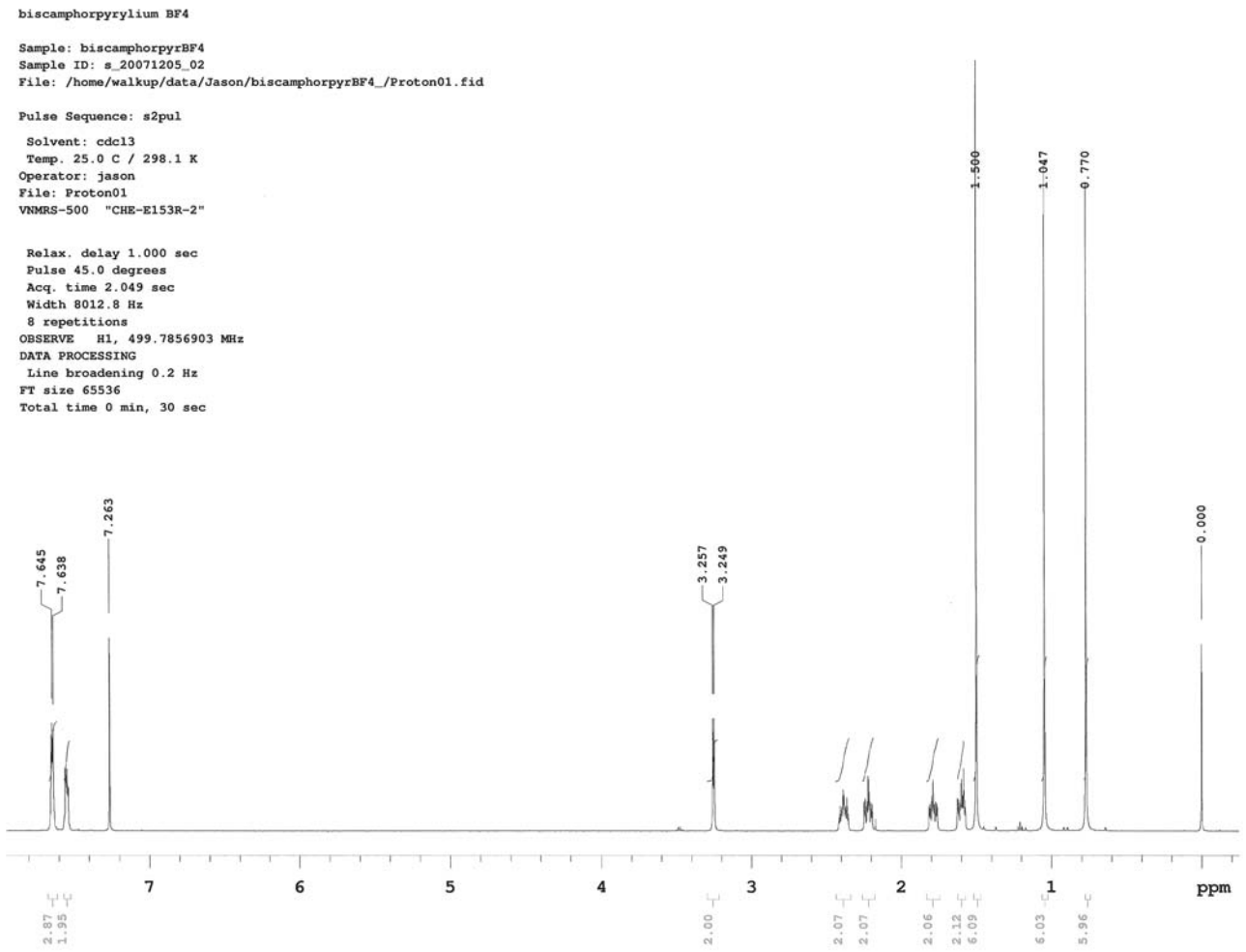
A.2.2 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **36**



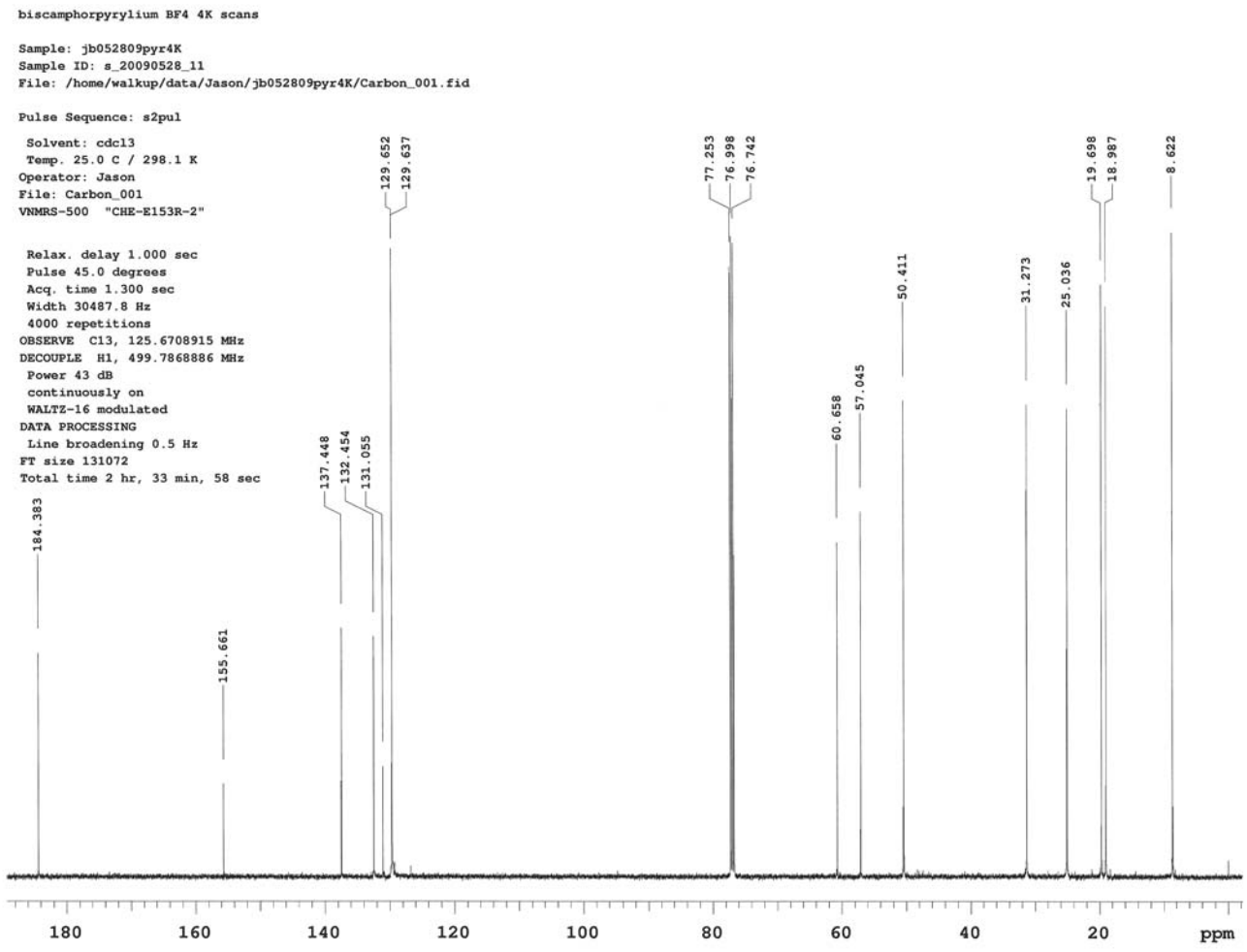
A.2.3 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **35** at -40^{o}C.



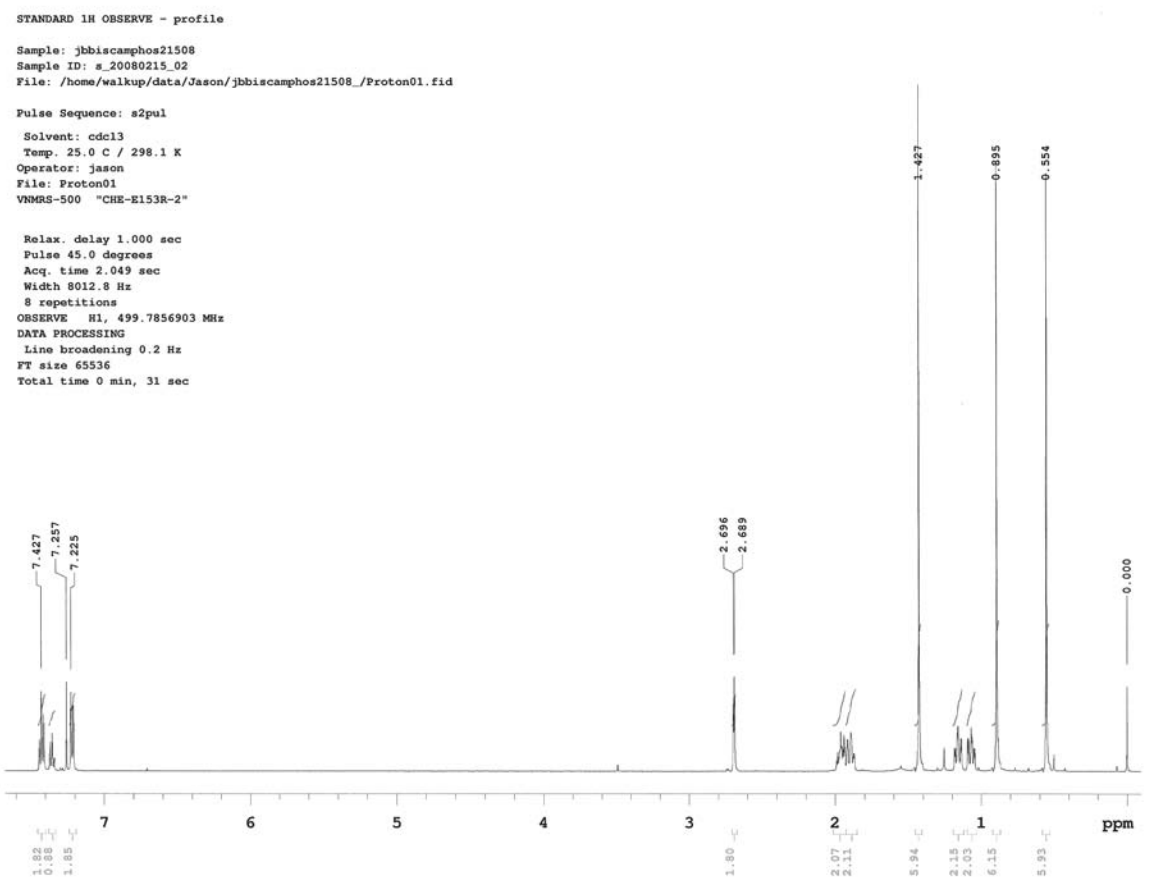
A.2.4 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **35** at -40^{o}C.



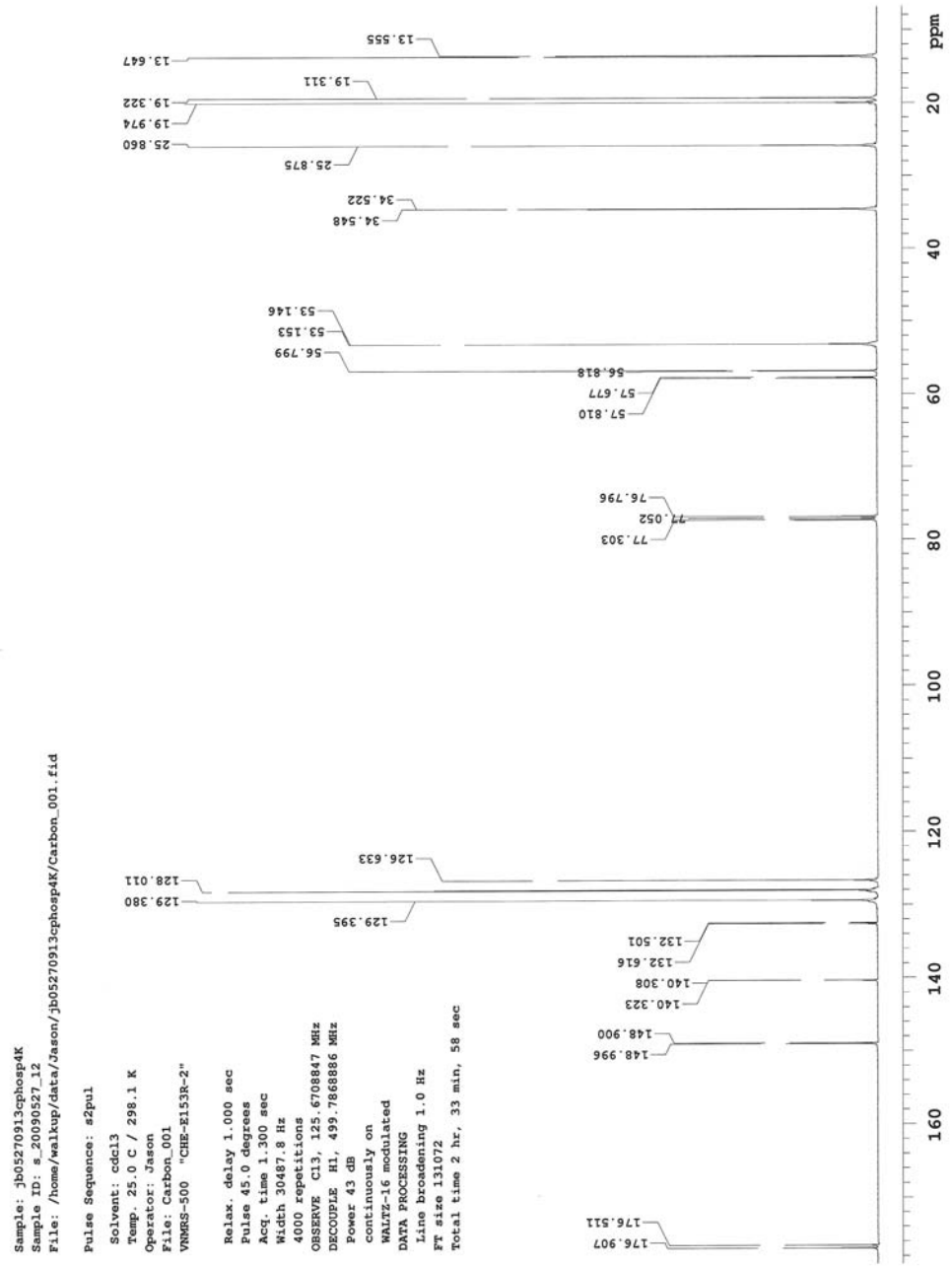
A.2.5 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **29**.



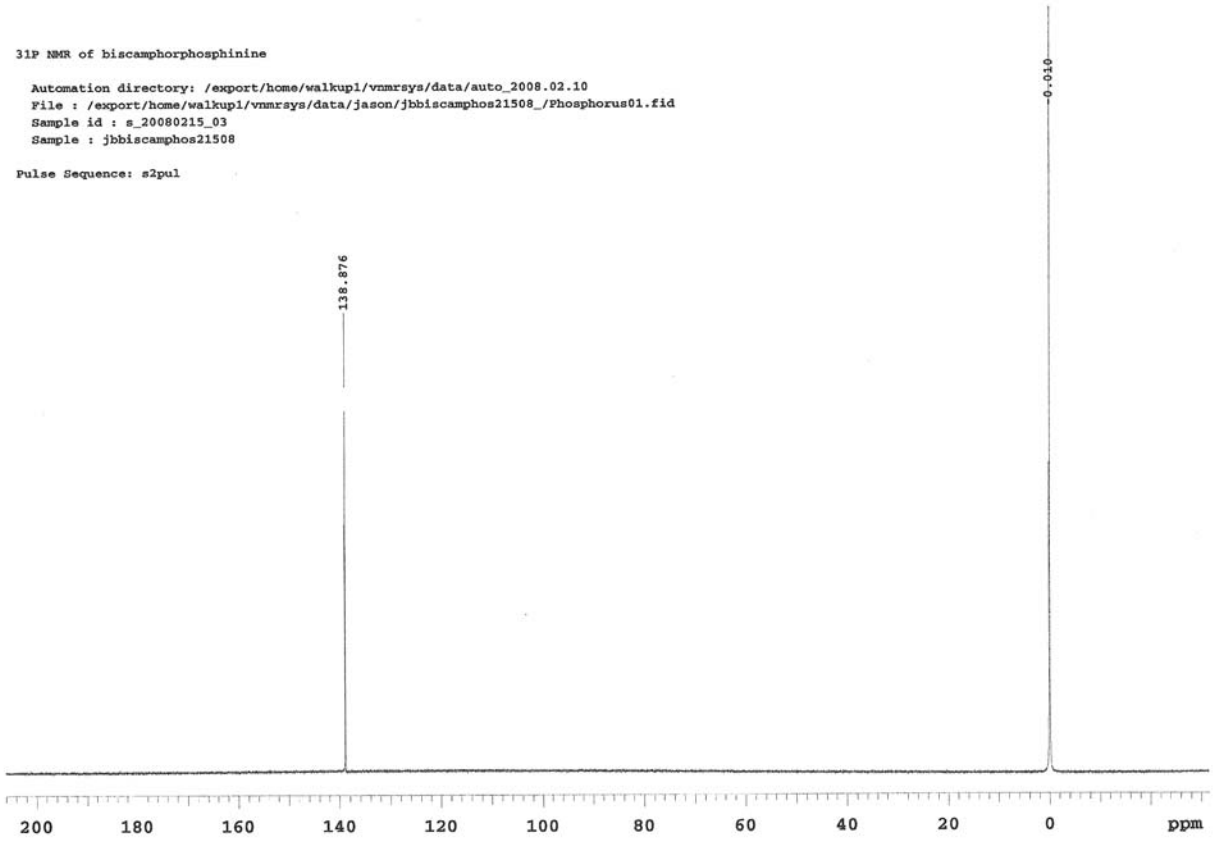
A.2.6 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **29**.



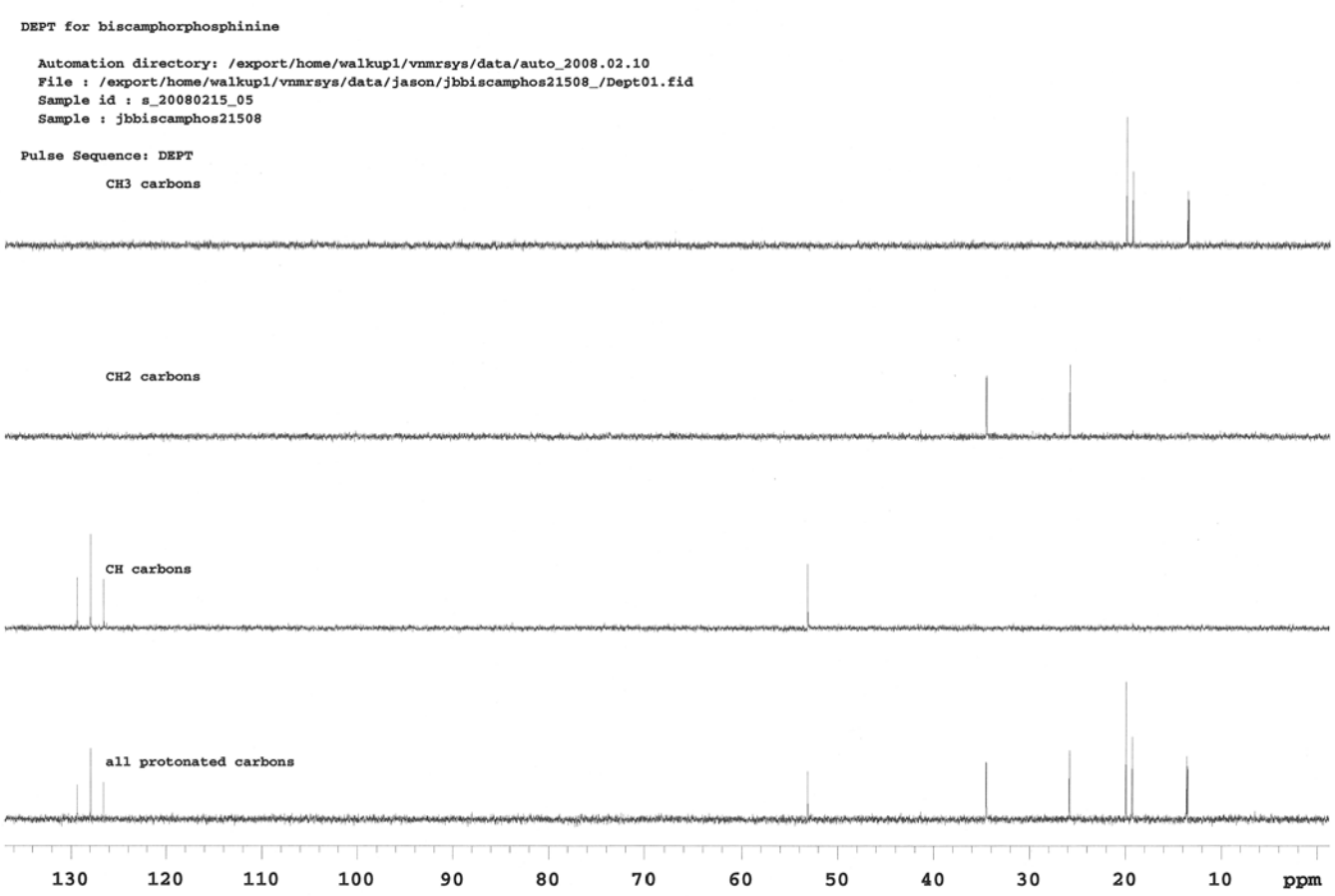
A.2.7 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **27**.



A.2.8 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **27**.



A.2.9 ^{31}P NMR ($CDCl_3$, 202 MHz) of Compound **27**.



A.2.10 DEPT NMR ($CDCl_3$, 125 MHz) of Compound **27**.

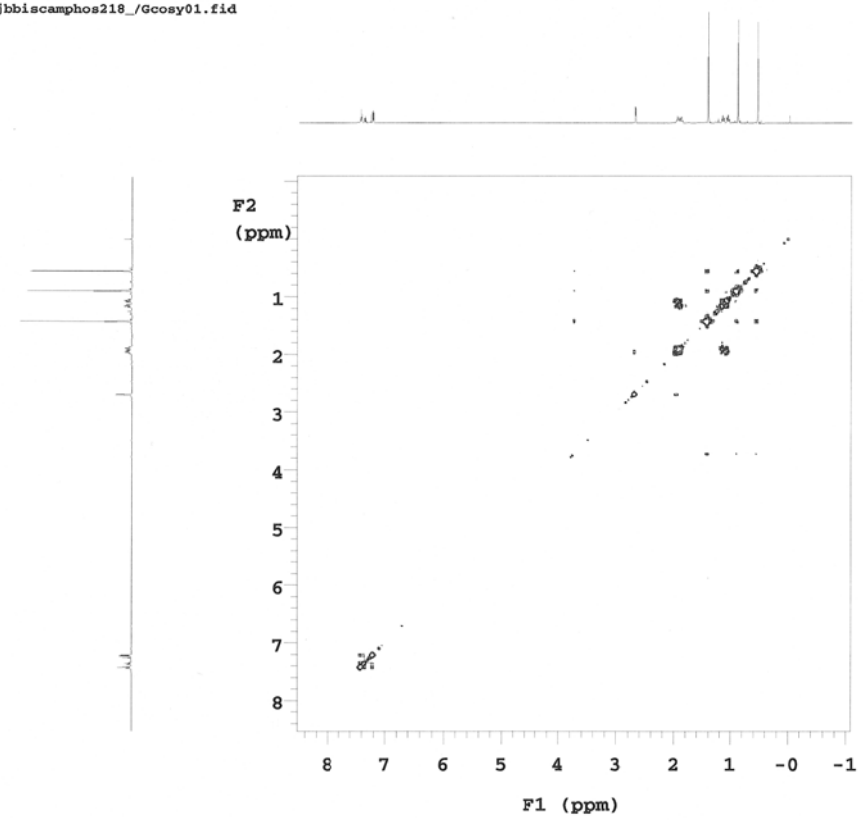
GCOSY Biscamphorphoshinine 2/18/08

Automation directory: /export/home/walkup1/vnmrsys/data/auto_2008.02.10
File : /export/home/walkup1/vnmrsys/data/jason/jbbiscamphos218_/Gcosy01.fid
Sample id : s_20080218_09
Sample : jbbiscamphos218

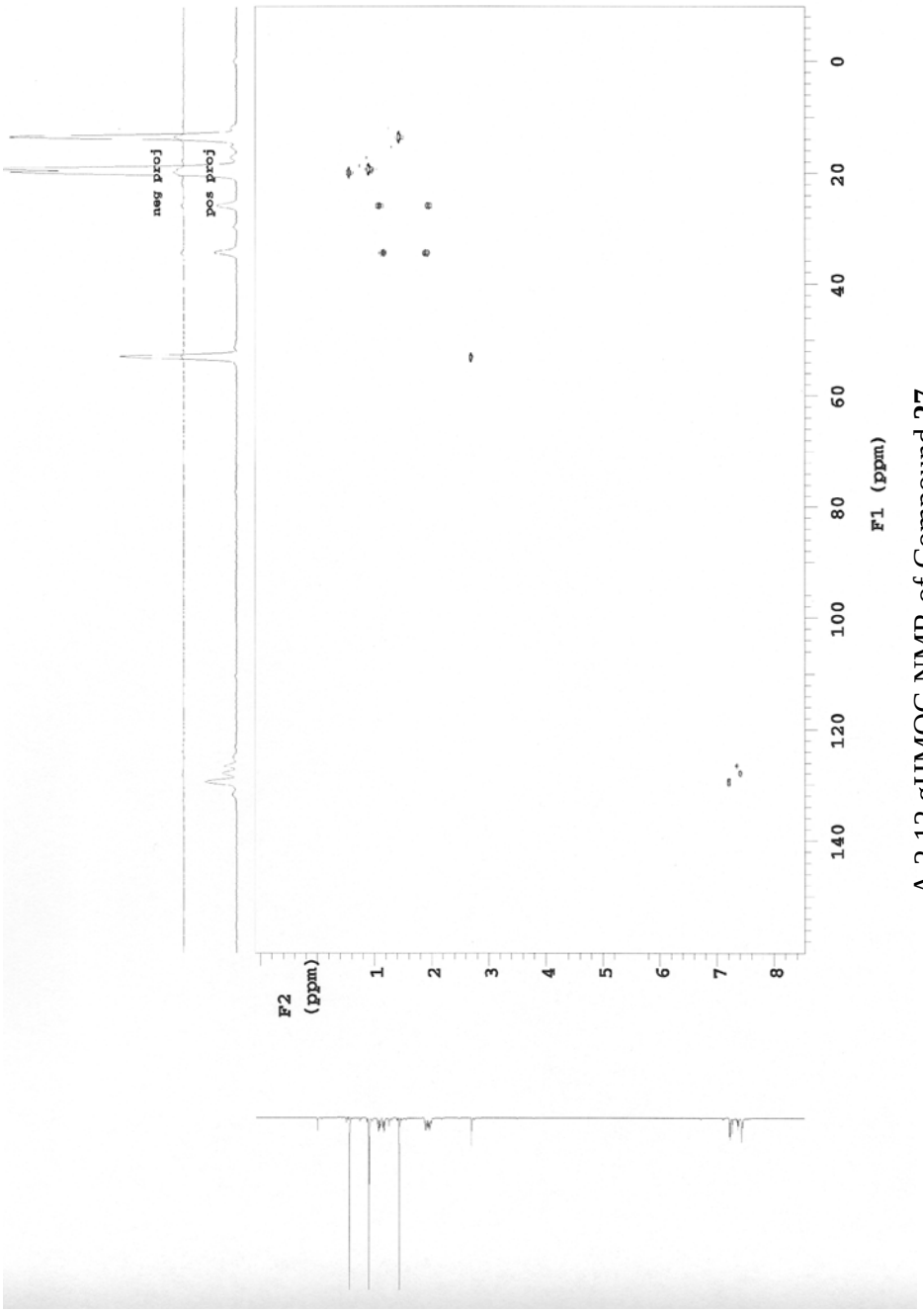
Pulse Sequence: gCOSY

Solvent: cdcl3
Temp. 25.0 C / 298.1 K
Operator: jason
File: Gcosy01
VNMRS-500 "che-e153r-sun2"

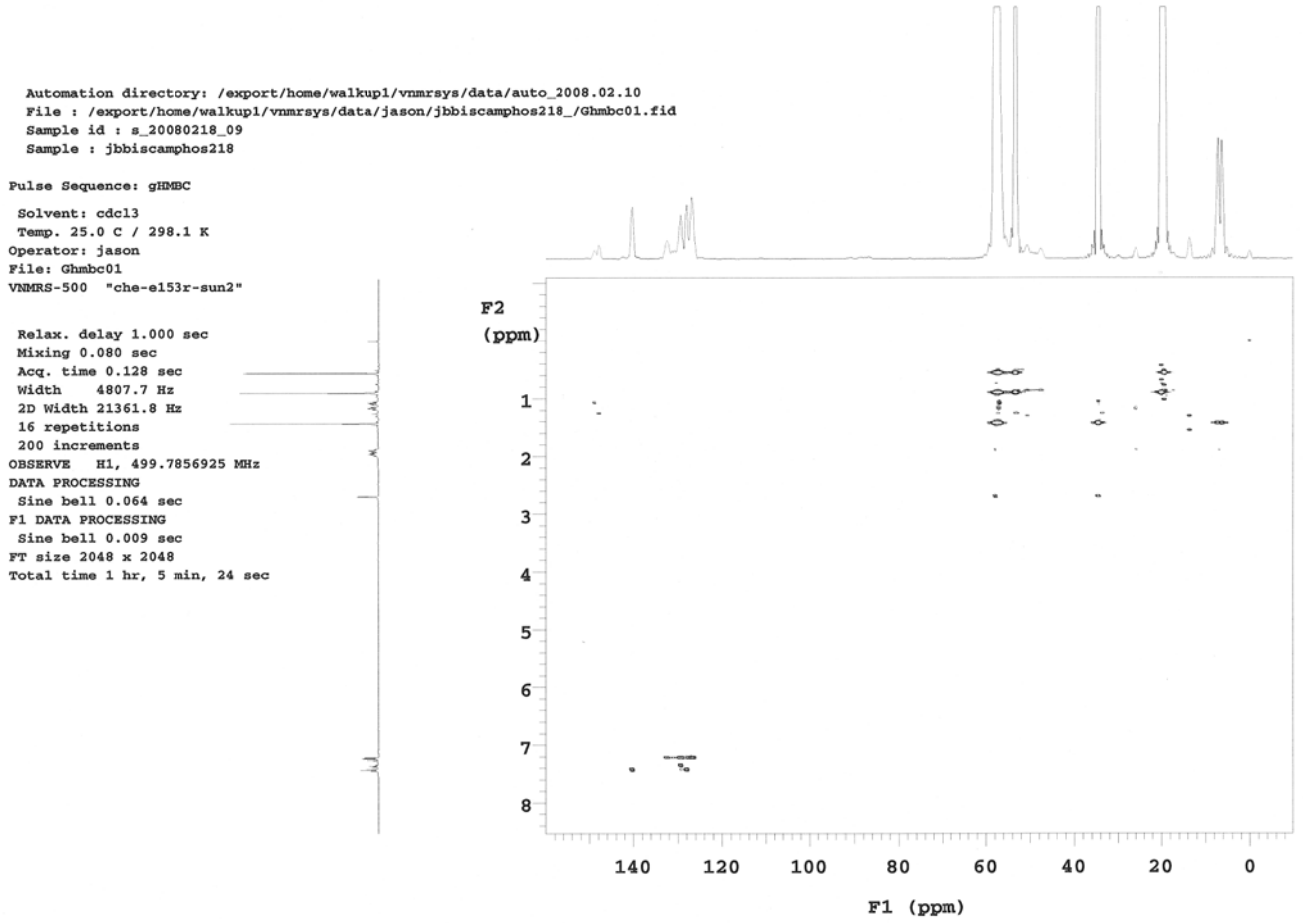
Relax. delay 1.301 sec
Acq. time 0.213 sec
Width 4807.7 Hz
2D Width 4807.7 Hz
Single scan
128 increments
OBSERVE H1, 499.7856925 MHz
DATA PROCESSING
Sine bell 0.106 sec
F1 DATA PROCESSING
Sine bell 0.053 sec
FT size 2048 x 2048
Total time 3 min, 41 sec



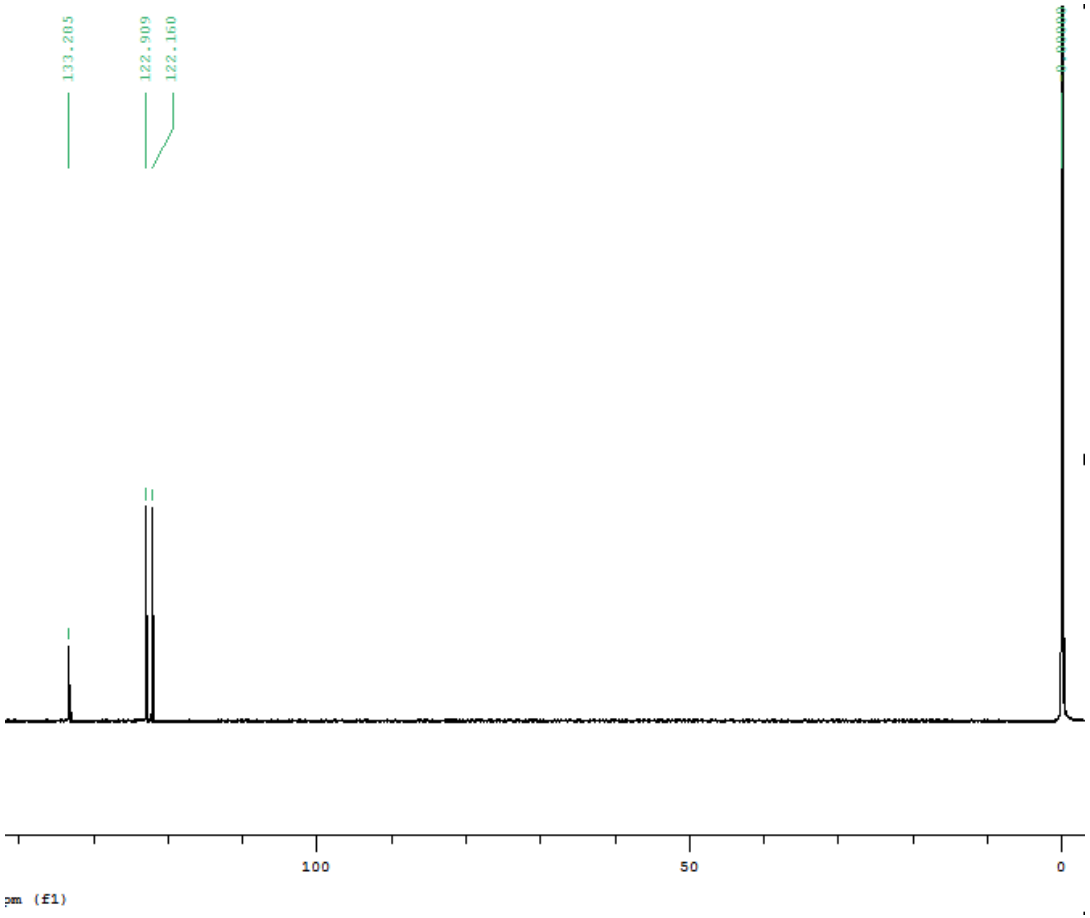
A.2.11 gCOSY NMR of Compound **27**.



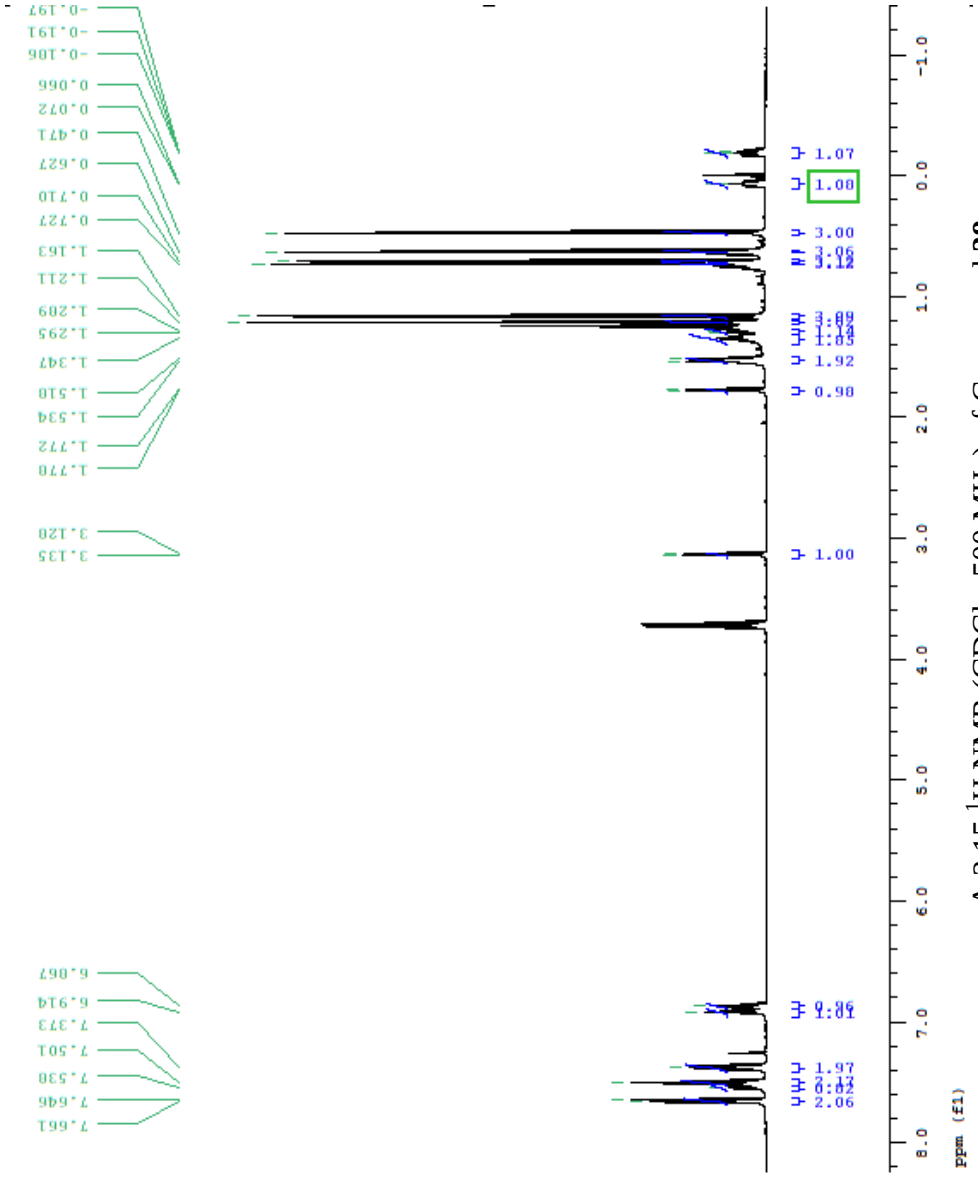
A.2.12 gHMQC NMR of Compound **27**.



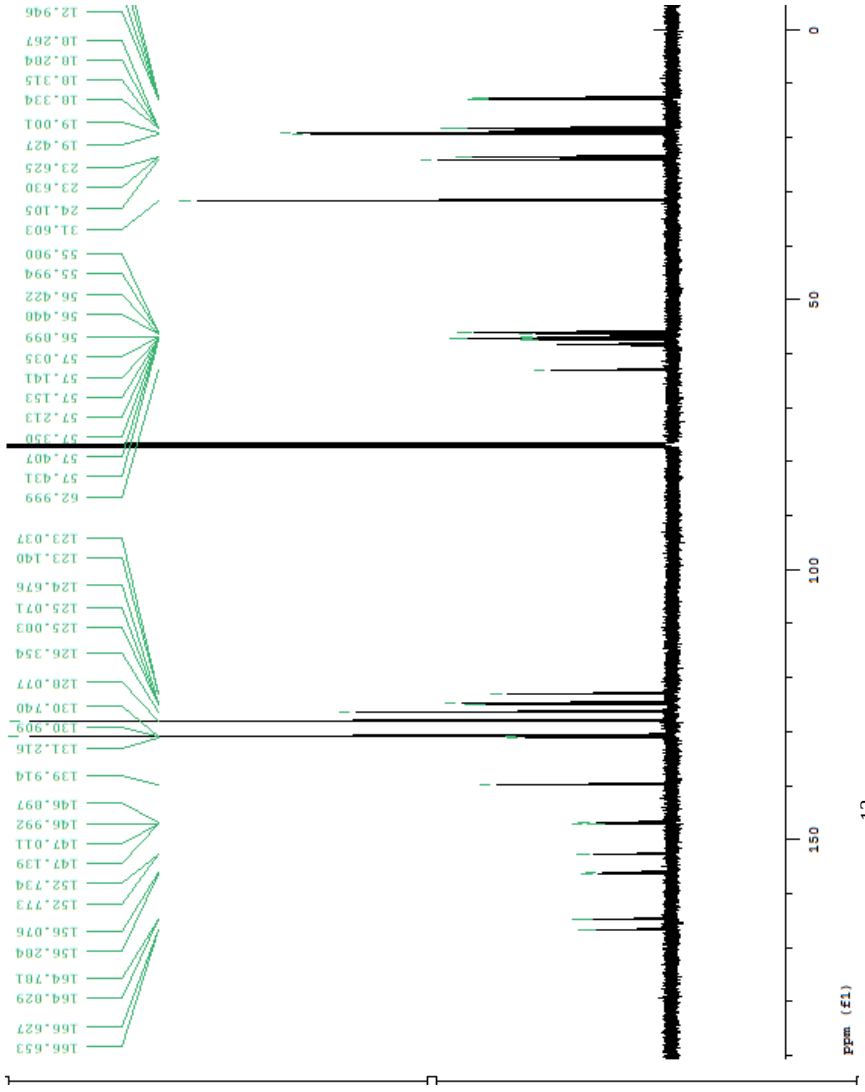
A.2.13 gHMBC NMR of Compound **27**.



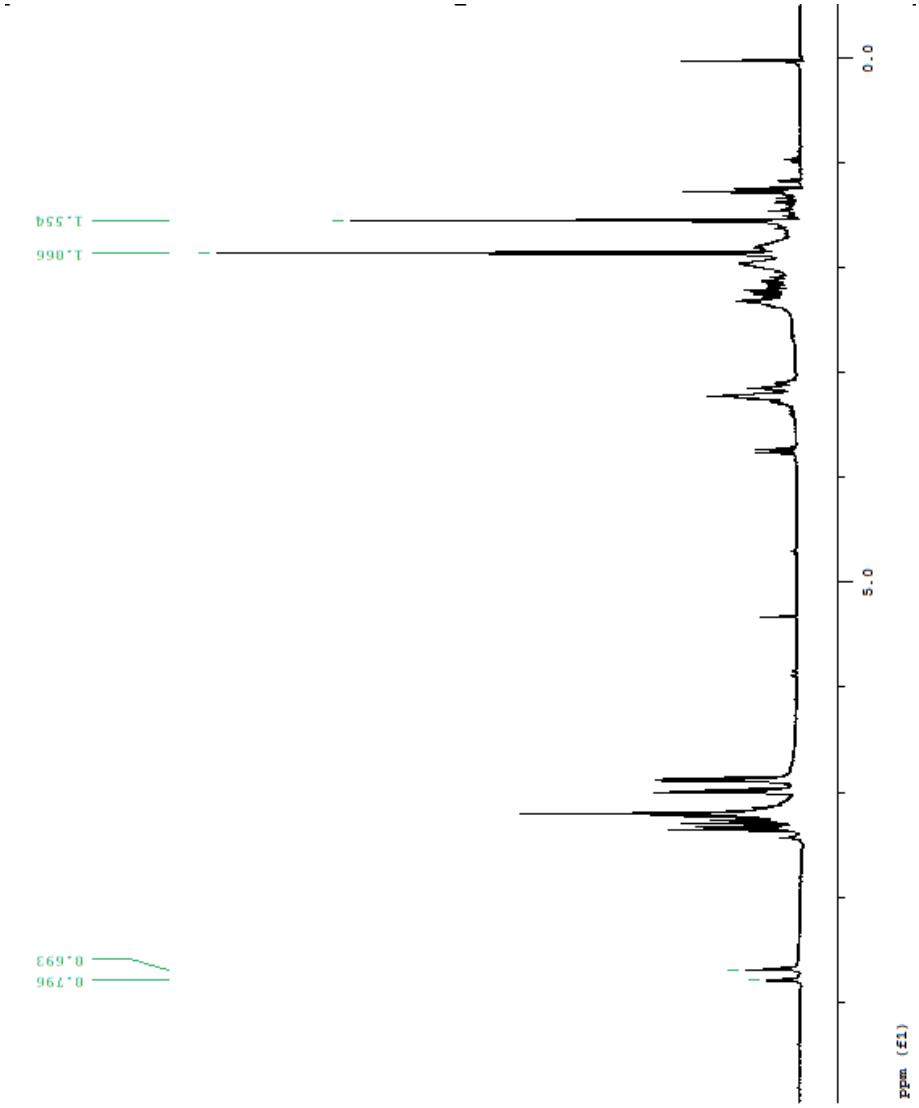
A.2.14 ^{31}P NMR ($CDCl_3$, 202 MHz) of Rh(I)/**27** complex.



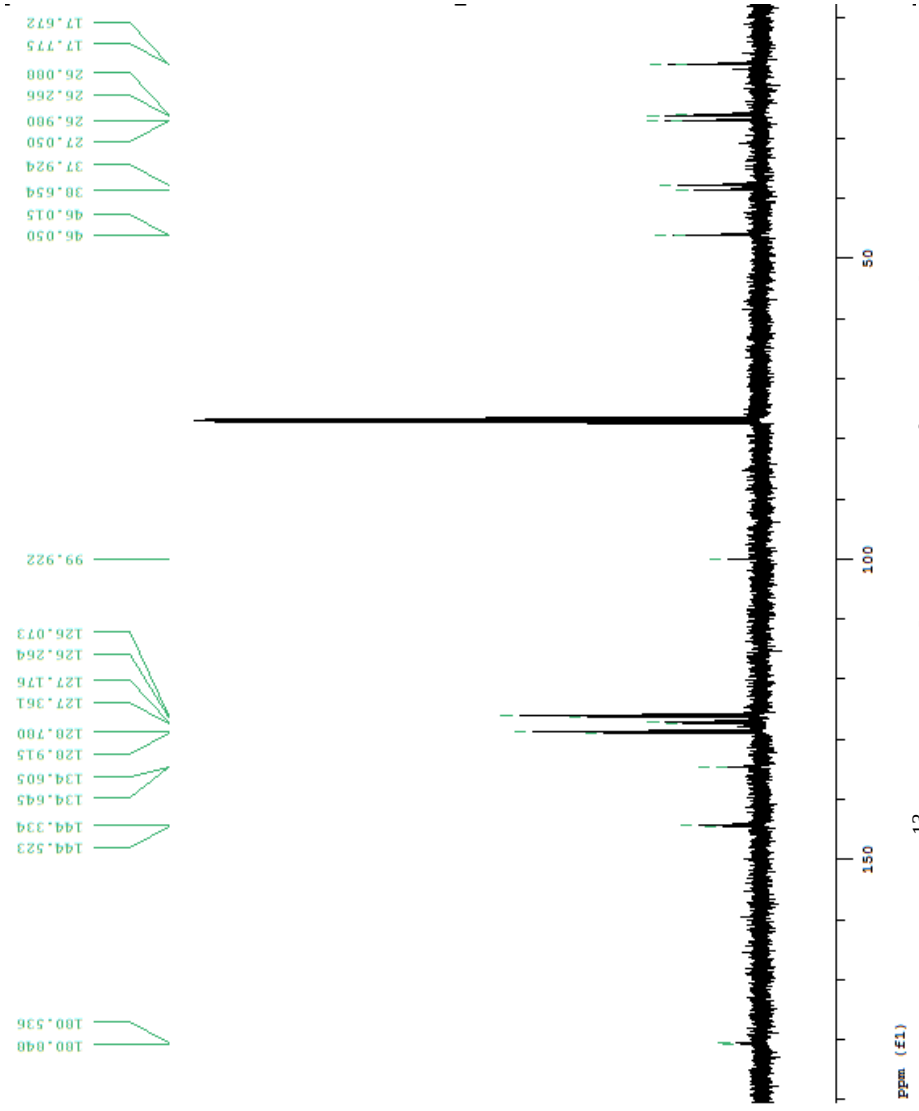
A.2.15 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **38**.



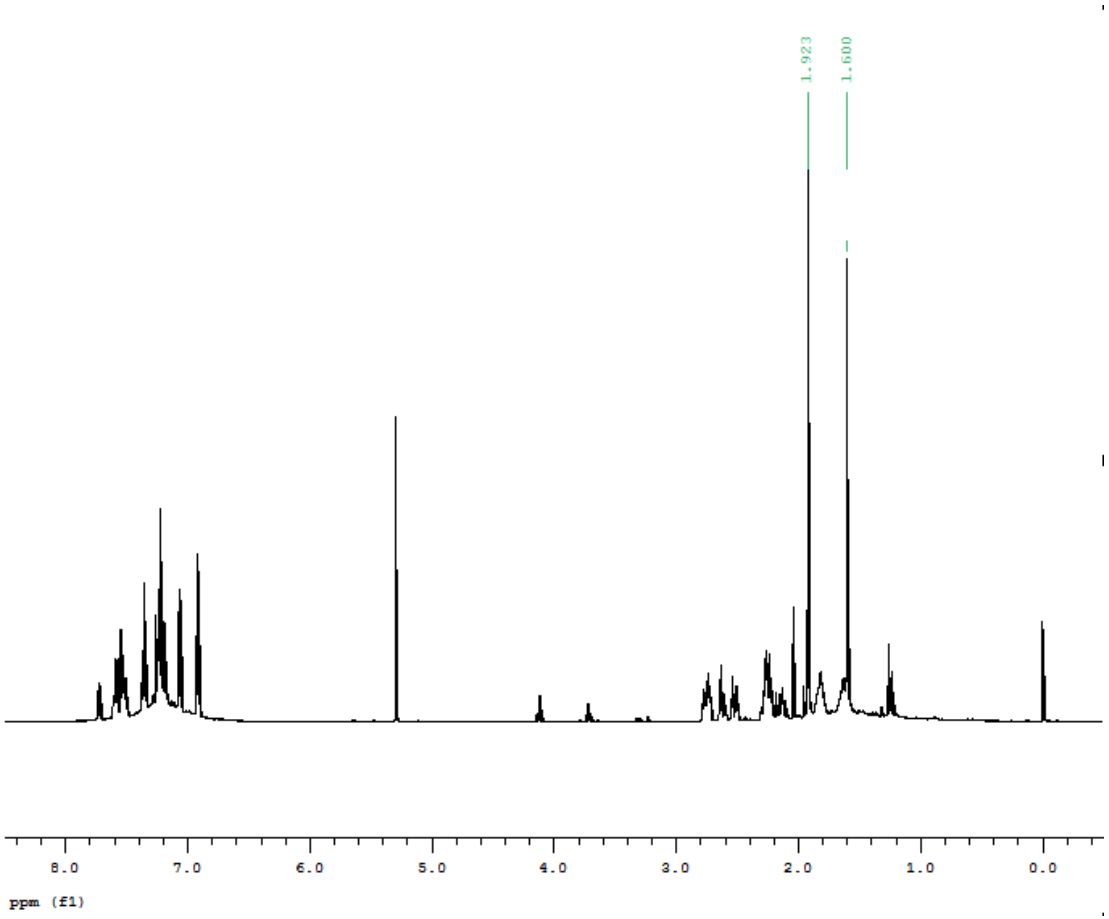
A.2.16 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **38**.



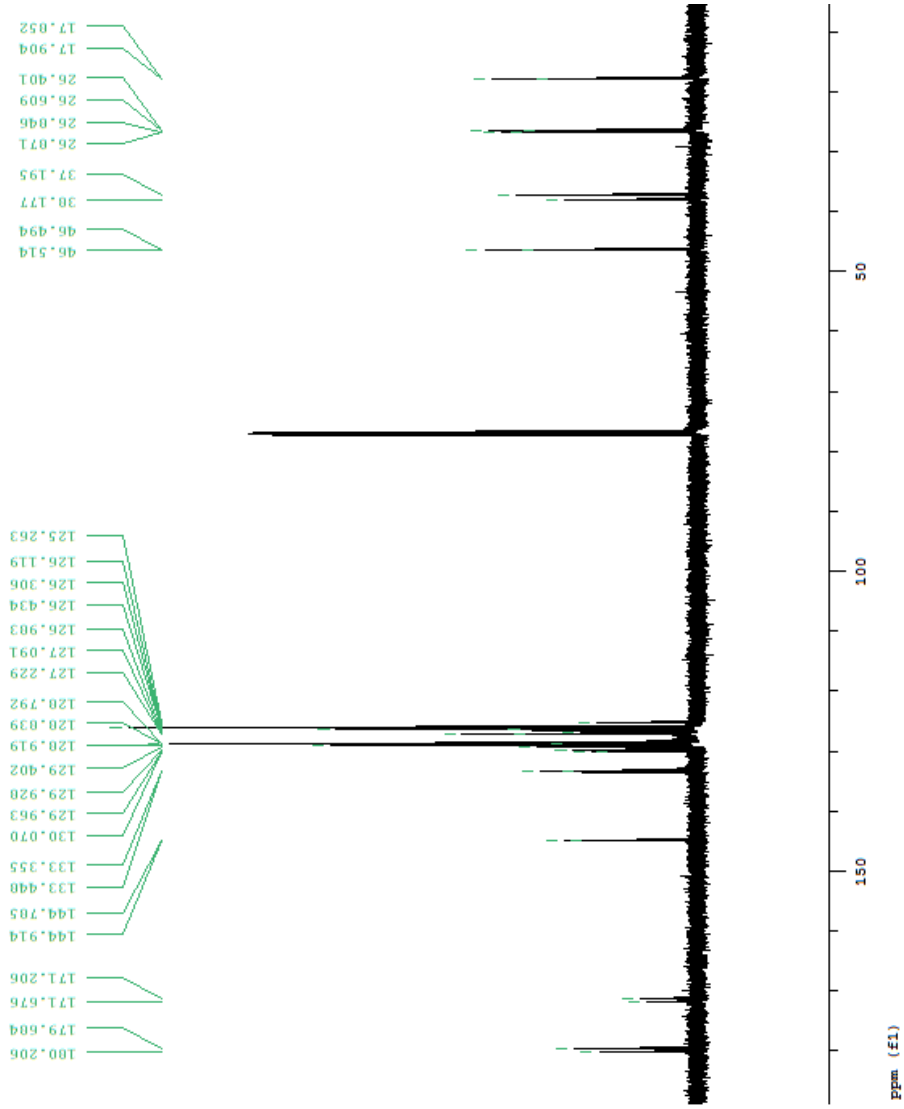
A.3.1 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **42**.



A.3.2 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **42**.



A.3.3 ^{1}H NMR ($CDCl_3$, 500 MHz) of Compound **44**.



A.3.4 ^{13}C NMR ($CDCl_3$, 125 MHz) of Compound **44**.

APPENDIX B

X-ray Crystallographic Data

Table B.1.1. Crystal data and structure refinement for **29**.

Identification code	xxix66a	
Empirical formula	C27 H33 B F4 O	
Formula weight	460.34	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	P2(1)2(1)2	
Unit cell dimensions	a = 14.931(3) Å	α= 90°.
	b = 7.4327(19) Å	β= 90°.
	c = 10.861(3) Å	γ = 90°.
Volume	1205.3(5) $Å^3$	
Z	2	
Density (calculated)	1.268 Mg/m^3	
Absorption coefficient	0.096 mm^{-1}	
F(000)	488	
Crystal size	0.21 x 0.15 x 0.13 mm^3	
Theta range for data collection	3.06 to 25.85°.	
Index ranges	-17<=h<=18, -9<=k<=9, -13<=l<=13	
Reflections collected	8444	
Independent reflections	2310 [R(int) = 0.0589]	
Completeness to theta = 25.00°	98.6 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9877 and 0.9802	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2310 / 0 / 174	
Goodness-of-fit on F^2	1.042	
Final R indices [I>2sigma(I)]	R1 = 0.0495, wR2 = 0.1089	
R indices (all data)	R1 = 0.0664, wR2 = 0.1214	
Absolute structure parameter	0.3(18)	
Largest diff. peak and hole	0.540 and -0.192 $e.Å^{-3}$	

Table B.1.2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **29**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
F(1)	-9248(6)	390(20)	-5088(10)	156(6)
O(1)	-10000	-5000	-3343(2)	25(1)
C(1)	-7824(2)	-3817(3)	-2188(2)	25(1)
B(1)	-10000	0	-4464(4)	33(1)
F(2)	-9261(6)	-502(11)	-5073(10)	89(4)
C(2)	-8312(1)	-4975(4)	-3211(2)	24(1)
F(3)	-10045(4)	-1729(5)	-4255(6)	90(1)
C(3)	-7993(2)	-6929(3)	-2853(2)	29(1)
F(4)	-10057(3)	-868(6)	-3317(4)	70(1)
C(4)	-7936(2)	-6883(3)	-1424(2)	29(1)
C(5)	-8225(2)	-4929(4)	-1105(2)	23(1)
C(6)	-9211(2)	-4879(3)	-1426(2)	23(1)
C(7)	-9236(1)	-4907(3)	-2697(2)	23(1)
C(8)	-6799(2)	-3906(4)	-2255(2)	36(1)
C(9)	-8101(2)	-1830(3)	-2186(2)	37(1)
C(10)	-8172(2)	-4499(4)	-4557(2)	33(1)
C(11)	-10000	-5000	-727(3)	23(1)
C(12)	-10000	-5000	642(3)	25(1)
C(13)	-9647(2)	-3549(4)	1284(2)	34(1)
C(14)	-9659(2)	-3540(4)	2572(2)	42(1)
C(15)	-10000	-5000	3198(3)	47(1)

Table B.1.3. Bond lengths [Å] and angles [°] for **29**.

F(1)-F(2)	0.665(18)
F(1)-B(1)	1.344(10)
F(1)-F(3)#1	1.708(12)
O(1)-C(7)	1.340(2)
O(1)-C(7)#2	1.340(2)
C(1)-C(9)	1.533(3)
C(1)-C(8)	1.533(3)
C(1)-C(5)	1.558(3)
C(1)-C(2)	1.583(3)
B(1)-F(3)#1	1.307(4)
B(1)-F(3)	1.307(4)
B(1)-F(2)	1.340(7)
B(1)-F(2)#1	1.340(7)
B(1)-F(1)#1	1.344(10)
B(1)-F(4)#1	1.405(5)
B(1)-F(4)	1.405(5)
F(2)-F(3)	1.730(11)
C(2)-C(7)	1.490(3)
C(2)-C(10)	1.518(3)
C(2)-C(3)	1.578(3)
F(3)-F(4)	1.203(5)
F(3)-F(1)#1	1.708(12)
C(3)-C(4)	1.554(3)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
F(4)-F(4)#1	1.302(9)
C(4)-C(5)	1.554(4)
C(4)-H(4A)	0.9900
C(4)-H(4B)	0.9900
C(5)-C(6)	1.513(3)
C(5)-H(5)	1.0000
C(6)-C(7)	1.381(3)
C(6)-C(11)	1.404(3)
C(8)-H(8A)	0.9800

C(8)-H(8B)	0.9800
C(8)-H(8C)	0.9800
C(9)-H(9A)	0.9800
C(9)-H(9B)	0.9800
C(9)-H(9C)	0.9800
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(11)-C(6)#2	1.404(3)
C(11)-C(12)	1.487(4)
C(12)-C(13)	1.388(3)
C(12)-C(13)#2	1.388(3)
C(13)-C(14)	1.399(3)
C(13)-H(13)	0.9500
C(14)-C(15)	1.378(3)
C(14)-H(14)	0.9500
C(15)-C(14)#2	1.378(3)
C(15)-H(15)	0.9500

F(2)-F(1)-B(1)	75.3(15)
F(2)-F(1)-F(3)#1	123.4(17)
B(1)-F(1)-F(3)#1	48.9(4)
C(7)-O(1)-C(7)#2	116.9(2)
C(9)-C(1)-C(8)	108.09(19)
C(9)-C(1)-C(5)	114.0(2)
C(8)-C(1)-C(5)	113.36(19)
C(9)-C(1)-C(2)	113.6(2)
C(8)-C(1)-C(2)	113.73(19)
C(5)-C(1)-C(2)	93.72(16)
F(3)#1-B(1)-F(3)	160.0(6)
F(3)#1-B(1)-F(2)	108.5(5)
F(3)-B(1)-F(2)	81.6(5)
F(3)#1-B(1)-F(2)#1	81.6(5)
F(3)-B(1)-F(2)#1	108.5(5)
F(2)-B(1)-F(2)#1	120.7(10)
F(3)#1-B(1)-F(1)#1	110.2(6)

F(3)-B(1)-F(1)#1	80.2(6)
F(2)-B(1)-F(1)#1	112.2(4)
F(2)#1-B(1)-F(1)#1	28.7(8)
F(3)#1-B(1)-F(1)	80.2(6)
F(3)-B(1)-F(1)	110.2(6)
F(2)-B(1)-F(1)	28.7(8)
F(2)#1-B(1)-F(1)	112.2(4)
F(1)#1-B(1)-F(1)	119.4(10)
F(3)#1-B(1)-F(4)#1	52.5(3)
F(3)-B(1)-F(4)#1	107.5(5)
F(2)-B(1)-F(4)#1	121.1(5)
F(2)#1-B(1)-F(4)#1	111.1(5)
F(1)#1-B(1)-F(4)#1	126.7(5)
F(1)-B(1)-F(4)#1	107.3(6)
F(3)#1-B(1)-F(4)	107.5(5)
F(3)-B(1)-F(4)	52.5(3)
F(2)-B(1)-F(4)	111.1(5)
F(2)#1-B(1)-F(4)	121.1(5)
F(1)#1-B(1)-F(4)	107.3(6)
F(1)-B(1)-F(4)	126.7(5)
F(4)#1-B(1)-F(4)	55.2(4)
F(1)-F(2)-B(1)	76.0(12)
F(1)-F(2)-F(3)	124.0(15)
B(1)-F(2)-F(3)	48.4(4)
C(7)-C(2)-C(10)	118.71(19)
C(7)-C(2)-C(3)	102.66(19)
C(10)-C(2)-C(3)	114.2(2)
C(7)-C(2)-C(1)	98.32(17)
C(10)-C(2)-C(1)	119.0(2)
C(3)-C(2)-C(1)	100.86(17)
F(4)-F(3)-B(1)	68.0(3)
F(4)-F(3)-F(1)#1	97.5(5)
B(1)-F(3)-F(1)#1	50.8(5)
F(4)-F(3)-F(2)	99.5(5)
B(1)-F(3)-F(2)	50.0(3)
F(1)#1-F(3)-F(2)	80.7(4)

C(4)-C(3)-C(2)	104.00(18)
C(4)-C(3)-H(3A)	111.0
C(2)-C(3)-H(3A)	111.0
C(4)-C(3)-H(3B)	111.0
C(2)-C(3)-H(3B)	111.0
H(3A)-C(3)-H(3B)	109.0
F(3)-F(4)-F(4)#1	121.7(3)
F(3)-F(4)-B(1)	59.5(2)
F(4)#1-F(4)-B(1)	62.4(2)
C(3)-C(4)-C(5)	103.24(19)
C(3)-C(4)-H(4A)	111.1
C(5)-C(4)-H(4A)	111.1
C(3)-C(4)-H(4B)	111.1
C(5)-C(4)-H(4B)	111.1
H(4A)-C(4)-H(4B)	109.1
C(6)-C(5)-C(4)	103.9(2)
C(6)-C(5)-C(1)	100.76(17)
C(4)-C(5)-C(1)	102.72(18)
C(6)-C(5)-H(5)	115.8
C(4)-C(5)-H(5)	115.8
C(1)-C(5)-H(5)	115.8
C(7)-C(6)-C(11)	121.1(2)
C(7)-C(6)-C(5)	104.87(18)
C(11)-C(6)-C(5)	133.61(19)
O(1)-C(7)-C(6)	123.2(2)
O(1)-C(7)-C(2)	126.16(18)
C(6)-C(7)-C(2)	110.50(18)
C(1)-C(8)-H(8A)	109.5
C(1)-C(8)-H(8B)	109.5
H(8A)-C(8)-H(8B)	109.5
C(1)-C(8)-H(8C)	109.5
H(8A)-C(8)-H(8C)	109.5
H(8B)-C(8)-H(8C)	109.5
C(1)-C(9)-H(9A)	109.5
C(1)-C(9)-H(9B)	109.5
H(9A)-C(9)-H(9B)	109.5

C(1)-C(9)-H(9C)	109.5
H(9A)-C(9)-H(9C)	109.5
H(9B)-C(9)-H(9C)	109.5
C(2)-C(10)-H(10A)	109.5
C(2)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(2)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(6)#2-C(11)-C(6)	114.6(3)
C(6)#2-C(11)-C(12)	122.71(13)
C(6)-C(11)-C(12)	122.72(13)
C(13)-C(12)-C(13)#2	119.6(3)
C(13)-C(12)-C(11)	120.18(15)
C(13)#2-C(12)-C(11)	120.18(15)
C(12)-C(13)-C(14)	120.1(3)
C(12)-C(13)-H(13)	119.9
C(14)-C(13)-H(13)	119.9
C(15)-C(14)-C(13)	119.6(3)
C(15)-C(14)-H(14)	120.2
C(13)-C(14)-H(14)	120.2
C(14)#2-C(15)-C(14)	120.9(3)
C(14)#2-C(15)-H(15)	119.5
C(14)-C(15)-H(15)	119.5

Symmetry transformations used to generate equivalent atoms:

#1 -x-2,-y,z #2 -x-2,-y-1,z

Table B.1.4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **29**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

Atom	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
F(1)	60(6)	352(16)	54(4)	35(8)	10(4)	-95(8)
O(1)	21(1)	35(1)	18(1)	0	0	2(1)
C(1)	24(1)	30(1)	22(1)	1(1)	1(1)	-2(1)
B(1)	31(2)	33(2)	34(2)	0	0	2(2)
F(2)	55(6)	133(6)	80(5)	-25(4)	23(4)	51(6)
C(2)	21(1)	31(1)	20(1)	0(1)	1(1)	0(1)
F(3)	106(4)	32(2)	131(4)	15(2)	-15(4)	4(3)
C(3)	31(1)	30(1)	27(1)	-3(1)	0(1)	4(1)
F(4)	46(2)	103(3)	62(2)	34(2)	3(2)	11(3)
C(4)	27(2)	31(1)	27(1)	2(1)	-4(1)	5(1)
C(5)	19(1)	33(1)	17(1)	-3(1)	-2(1)	3(1)
C(6)	23(1)	26(1)	18(1)	0(1)	-1(1)	2(1)
C(7)	22(1)	27(1)	19(1)	2(1)	-1(1)	1(1)
C(8)	26(1)	50(2)	31(1)	-1(1)	2(1)	-7(1)
C(9)	48(2)	28(1)	34(1)	2(1)	0(1)	-3(1)
C(10)	30(1)	48(2)	20(1)	2(1)	4(1)	3(1)
C(11)	23(2)	27(2)	19(2)	0	0	2(2)
C(12)	16(2)	43(2)	16(1)	0	0	5(2)
C(13)	22(1)	53(2)	25(1)	-1(1)	2(1)	-3(1)
C(14)	29(2)	73(2)	24(1)	-12(1)	1(1)	-7(1)
C(15)	21(2)	103(4)	17(2)	0	0	-8(3)

Table B.2.1. Crystal data and structure refinement for **36**.

Identification code	AFXXX30A	
Empirical formula	C17 H19 Cl O	
Formula weight	274.77	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P21	
Unit cell dimensions	a = 6.9230(9) Å	α= 90°.
	b = 12.4494(15) Å	β= 93.181(5)°.
	c = 16.783(2) Å	γ = 90°.
Volume	1444.2(3) $Å^3$	
Z	4	
Density (calculated)	1.264 Mg/m^3	
Absorption coefficient	0.254 mm^{-1}	
F(000)	584	
Crystal size	0.15 x 0.08 x 0.06 mm^3	
Theta range for data collection	2.04 to 25.37°.	
Index ranges	-7<=h<=8, -14<=k<=14, -18<=l<=20	
Reflections collected	21198	
Independent reflections	5255 [R(int) = 0.0424]	
Completeness to theta = 25.00°	99.7 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9852 and 0.9626	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	5255 / 1 / 349	
Goodness-of-fit on F^2	1.035	
Final R indices [I>2sigma(I)]	R1 = 0.0271, wR2 = 0.0608	
R indices (all data)	R1 = 0.0305, wR2 = 0.0630	
Absolute structure parameter	0.02(3)	
Largest diff. peak and hole	0.177 and -0.152 e.$Å^{-3}$	

Table B.2.2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **36**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
Cl(1A)	10252(1)	5207(1)	-5521(1)	30(1)
O(1A)	12245(2)	5645(1)	-2752(1)	25(1)
C(1A)	9658(2)	4315(1)	-2668(1)	22(1)
C(2A)	10946(2)	5122(1)	-3073(1)	19(1)
C(3A)	10282(2)	5087(1)	-3943(1)	19(1)
C(4A)	8622(2)	4299(2)	-3973(1)	25(1)
C(5A)	9539(3)	3175(2)	-3856(1)	37(1)
C(6A)	10312(3)	3205(1)	-2976(1)	36(1)
C(7A)	7721(2)	4503(1)	-3162(1)	21(1)
C(8A)	6950(2)	5641(1)	-3080(1)	24(1)
C(9A)	6115(3)	3712(2)	-2983(1)	32(1)
C(10A)	9704(3)	4421(2)	-1768(1)	32(1)
C(11A)	11118(2)	5558(1)	-4550(1)	20(1)
C(12A)	12677(2)	6360(1)	-4536(1)	20(1)
C(13A)	14247(2)	6235(1)	-5015(1)	25(1)
C(14A)	15718(3)	6987(2)	-5001(1)	32(1)
C(15A)	15628(3)	7882(2)	-4515(1)	34(1)
C(16A)	14061(3)	8026(2)	-4046(1)	31(1)
C(17A)	12594(3)	7268(1)	-4054(1)	24(1)
Cl(1B)	6039(1)	5986(1)	2921(1)	24(1)
O(1B)	7307(2)	4701(1)	292(1)	26(1)
C(1B)	4828(2)	6064(2)	-21(1)	22(1)
C(2B)	6142(2)	5347(1)	510(1)	21(1)
C(3B)	5668(2)	5640(1)	1356(1)	20(1)
C(4B)	4017(2)	6426(1)	1247(1)	22(1)
C(5B)	4948(3)	7491(2)	991(1)	28(1)
C(6B)	5569(3)	7225(2)	136(1)	28(1)
C(7B)	2967(2)	6024(2)	463(1)	23(1)
C(8B)	2148(2)	4887(2)	522(1)	27(1)
C(9B)	1351(2)	6776(2)	152(1)	30(1)
C(10B)	4709(3)	5723(2)	-889(1)	29(1)

C(11B)	6676(2)	5374(1)	2023(1)	19(1)
C(12B)	8330(2)	4631(1)	2136(1)	19(1)
C(13B)	10040(2)	4977(1)	2525(1)	22(1)
C(14B)	11604(3)	4300(2)	2620(1)	27(1)
C(15B)	11482(3)	3257(2)	2335(1)	30(1)
C(16B)	9773(3)	2897(2)	1963(1)	32(1)
C(17B)	8205(3)	3580(1)	1861(1)	27(1)

TableB.2.3. Bond lengths [Å] and angles [°] for **36**.

Cl(1A)-C(11A)	1.7602(16)
O(1A)-C(2A)	1.2128(19)
C(1A)-C(10A)	1.514(2)
C(1A)-C(2A)	1.528(2)
C(1A)-C(6A)	1.551(3)
C(1A)-C(7A)	1.555(2)
C(2A)-C(3A)	1.507(2)
C(3A)-C(11A)	1.335(2)
C(3A)-C(4A)	1.510(2)
C(4A)-C(5A)	1.544(3)
C(4A)-C(7A)	1.550(2)
C(4A)-H(4A)	1.0000
C(5A)-C(6A)	1.543(3)
C(5A)-H(5A1)	0.9900
C(5A)-H(5A2)	0.9900
C(6A)-H(6A1)	0.9900
C(6A)-H(6A2)	0.9900
C(7A)-C(8A)	1.523(2)
C(7A)-C(9A)	1.527(2)
C(8A)-H(8A1)	0.9800
C(8A)-H(8A2)	0.9800
C(8A)-H(8A3)	0.9800
C(9A)-H(9A1)	0.9800
C(9A)-H(9A2)	0.9800
C(9A)-H(9A3)	0.9800
C(10A)-H(10A)	0.9800
C(10A)-H(10B)	0.9800
C(10A)-H(10C)	0.9800
C(11A)-C(12A)	1.469(2)
C(12A)-C(17A)	1.392(2)
C(12A)-C(13A)	1.397(2)
C(13A)-C(14A)	1.382(2)
C(13A)-H(13A)	0.9500
C(14A)-C(15A)	1.384(3)

C(14A)-H(14A)	0.9500
C(15A)-C(16A)	1.387(3)
C(15A)-H(15A)	0.9500
C(16A)-C(17A)	1.385(3)
C(16A)-H(16A)	0.9500
C(17A)-H(17A)	0.9500
Cl(1B)-C(11B)	1.7657(16)
O(1B)-C(2B)	1.210(2)
C(1B)-C(10B)	1.515(2)
C(1B)-C(2B)	1.526(2)
C(1B)-C(6B)	1.551(3)
C(1B)-C(7B)	1.561(2)
C(2B)-C(3B)	1.519(2)
C(3B)-C(11B)	1.328(2)
C(3B)-C(4B)	1.507(2)
C(4B)-C(5B)	1.545(3)
C(4B)-C(7B)	1.549(2)
C(4B)-H(4B)	1.0000
C(5B)-C(6B)	1.556(3)
C(5B)-H(5B1)	0.9900
C(5B)-H(5B2)	0.9900
C(6B)-H(6B1)	0.9900
C(6B)-H(6B2)	0.9900
C(7B)-C(9B)	1.528(2)
C(7B)-C(8B)	1.531(3)
C(8B)-H(8B1)	0.9800
C(8B)-H(8B2)	0.9800
C(8B)-H(8B3)	0.9800
C(9B)-H(9B1)	0.9800
C(9B)-H(9B2)	0.9800
C(9B)-H(9B3)	0.9800
C(10B)-H(10D)	0.9800
C(10B)-H(10E)	0.9800
C(10B)-H(10F)	0.9800
C(11B)-C(12B)	1.476(2)
C(12B)-C(13B)	1.388(2)

C(12B)-C(17B)	1.389(2)
C(13B)-C(14B)	1.375(2)
C(13B)-H(13B)	0.9500
C(14B)-C(15B)	1.385(3)
C(14B)-H(14B)	0.9500
C(15B)-C(16B)	1.381(3)
C(15B)-H(15B)	0.9500
C(16B)-C(17B)	1.382(3)
C(16B)-H(16B)	0.9500
C(17B)-H(17B)	0.9500

C(10A)-C(1A)-C(2A)	114.00(14)
C(10A)-C(1A)-C(6A)	114.78(15)
C(2A)-C(1A)-C(6A)	104.41(14)
C(10A)-C(1A)-C(7A)	119.28(14)
C(2A)-C(1A)-C(7A)	99.82(13)
C(6A)-C(1A)-C(7A)	102.40(14)
O(1A)-C(2A)-C(3A)	128.73(15)
O(1A)-C(2A)-C(1A)	126.24(15)
C(3A)-C(2A)-C(1A)	105.00(13)
C(11A)-C(3A)-C(2A)	127.22(15)
C(11A)-C(3A)-C(4A)	128.43(15)
C(2A)-C(3A)-C(4A)	103.98(13)
C(3A)-C(4A)-C(5A)	106.15(14)
C(3A)-C(4A)-C(7A)	101.95(13)
C(5A)-C(4A)-C(7A)	102.65(15)
C(3A)-C(4A)-H(4A)	114.8
C(5A)-C(4A)-H(4A)	114.8
C(7A)-C(4A)-H(4A)	114.8
C(6A)-C(5A)-C(4A)	102.64(14)
C(6A)-C(5A)-H(5A1)	111.2
C(4A)-C(5A)-H(5A1)	111.2
C(6A)-C(5A)-H(5A2)	111.2
C(4A)-C(5A)-H(5A2)	111.2
H(5A1)-C(5A)-H(5A2)	109.2
C(5A)-C(6A)-C(1A)	104.39(14)

C(5A)-C(6A)-H(6A1)	110.9
C(1A)-C(6A)-H(6A1)	110.9
C(5A)-C(6A)-H(6A2)	110.9
C(1A)-C(6A)-H(6A2)	110.9
H(6A1)-C(6A)-H(6A2)	108.9
C(8A)-C(7A)-C(9A)	108.63(14)
C(8A)-C(7A)-C(4A)	113.12(14)
C(9A)-C(7A)-C(4A)	113.58(14)
C(8A)-C(7A)-C(1A)	112.80(14)
C(9A)-C(7A)-C(1A)	114.43(14)
C(4A)-C(7A)-C(1A)	93.82(12)
C(7A)-C(8A)-H(8A1)	109.5
C(7A)-C(8A)-H(8A2)	109.5
H(8A1)-C(8A)-H(8A2)	109.5
C(7A)-C(8A)-H(8A3)	109.5
H(8A1)-C(8A)-H(8A3)	109.5
H(8A2)-C(8A)-H(8A3)	109.5
C(7A)-C(9A)-H(9A1)	109.5
C(7A)-C(9A)-H(9A2)	109.5
H(9A1)-C(9A)-H(9A2)	109.5
C(7A)-C(9A)-H(9A3)	109.5
H(9A1)-C(9A)-H(9A3)	109.5
H(9A2)-C(9A)-H(9A3)	109.5
C(1A)-C(10A)-H(10A)	109.5
C(1A)-C(10A)-H(10B)	109.5
H(10A)-C(10A)-H(10B)	109.5
C(1A)-C(10A)-H(10C)	109.5
H(10A)-C(10A)-H(10C)	109.5
H(10B)-C(10A)-H(10C)	109.5
C(3A)-C(11A)-C(12A)	129.44(15)
C(3A)-C(11A)-Cl(1A)	117.23(12)
C(12A)-C(11A)-Cl(1A)	113.32(12)
C(17A)-C(12A)-C(13A)	118.88(16)
C(17A)-C(12A)-C(11A)	120.49(15)
C(13A)-C(12A)-C(11A)	120.62(15)
C(14A)-C(13A)-C(12A)	120.69(17)

C(14A)-C(13A)-H(13A)	119.7
C(12A)-C(13A)-H(13A)	119.7
C(13A)-C(14A)-C(15A)	119.93(17)
C(13A)-C(14A)-H(14A)	120.0
C(15A)-C(14A)-H(14A)	120.0
C(14A)-C(15A)-C(16A)	119.98(18)
C(14A)-C(15A)-H(15A)	120.0
C(16A)-C(15A)-H(15A)	120.0
C(17A)-C(16A)-C(15A)	120.17(18)
C(17A)-C(16A)-H(16A)	119.9
C(15A)-C(16A)-H(16A)	119.9
C(16A)-C(17A)-C(12A)	120.33(16)
C(16A)-C(17A)-H(17A)	119.8
C(12A)-C(17A)-H(17A)	119.8
C(10B)-C(1B)-C(2B)	113.36(15)
C(10B)-C(1B)-C(6B)	115.01(15)
C(2B)-C(1B)-C(6B)	105.37(13)
C(10B)-C(1B)-C(7B)	119.30(14)
C(2B)-C(1B)-C(7B)	99.22(13)
C(6B)-C(1B)-C(7B)	102.50(14)
O(1B)-C(2B)-C(3B)	128.69(15)
O(1B)-C(2B)-C(1B)	126.68(15)
C(3B)-C(2B)-C(1B)	104.63(13)
C(11B)-C(3B)-C(4B)	128.60(15)
C(11B)-C(3B)-C(2B)	126.67(15)
C(4B)-C(3B)-C(2B)	104.10(13)
C(3B)-C(4B)-C(5B)	105.39(13)
C(3B)-C(4B)-C(7B)	102.19(13)
C(5B)-C(4B)-C(7B)	102.96(14)
C(3B)-C(4B)-H(4B)	114.9
C(5B)-C(4B)-H(4B)	114.9
C(7B)-C(4B)-H(4B)	114.9
C(4B)-C(5B)-C(6B)	102.39(14)
C(4B)-C(5B)-H(5B1)	111.3
C(6B)-C(5B)-H(5B1)	111.3
C(4B)-C(5B)-H(5B2)	111.3

C(6B)-C(5B)-H(5B2)	111.3
H(5B1)-C(5B)-H(5B2)	109.2
C(1B)-C(6B)-C(5B)	104.37(14)
C(1B)-C(6B)-H(6B1)	110.9
C(5B)-C(6B)-H(6B1)	110.9
C(1B)-C(6B)-H(6B2)	110.9
C(5B)-C(6B)-H(6B2)	110.9
H(6B1)-C(6B)-H(6B2)	108.9
C(9B)-C(7B)-C(8B)	108.77(14)
C(9B)-C(7B)-C(4B)	113.16(15)
C(8B)-C(7B)-C(4B)	113.73(14)
C(9B)-C(7B)-C(1B)	114.33(14)
C(8B)-C(7B)-C(1B)	112.42(15)
C(4B)-C(7B)-C(1B)	93.97(12)
C(7B)-C(8B)-H(8B1)	109.5
C(7B)-C(8B)-H(8B2)	109.5
H(8B1)-C(8B)-H(8B2)	109.5
C(7B)-C(8B)-H(8B3)	109.5
H(8B1)-C(8B)-H(8B3)	109.5
H(8B2)-C(8B)-H(8B3)	109.5
C(7B)-C(9B)-H(9B1)	109.5
C(7B)-C(9B)-H(9B2)	109.5
H(9B1)-C(9B)-H(9B2)	109.5
C(7B)-C(9B)-H(9B3)	109.5
H(9B1)-C(9B)-H(9B3)	109.5
H(9B2)-C(9B)-H(9B3)	109.5
C(1B)-C(10B)-H(10D)	109.5
C(1B)-C(10B)-H(10E)	109.5
H(10D)-C(10B)-H(10E)	109.5
C(1B)-C(10B)-H(10F)	109.5
H(10D)-C(10B)-H(10F)	109.5
H(10E)-C(10B)-H(10F)	109.5
C(3B)-C(11B)-C(12B)	129.21(15)
C(3B)-C(11B)-Cl(1B)	117.83(13)
C(12B)-C(11B)-Cl(1B)	112.94(11)
C(13B)-C(12B)-C(17B)	118.98(16)

C(13B)-C(12B)-C(11B)	120.07(15)
C(17B)-C(12B)-C(11B)	120.95(15)
C(14B)-C(13B)-C(12B)	120.65(16)
C(14B)-C(13B)-H(13B)	119.7
C(12B)-C(13B)-H(13B)	119.7
C(13B)-C(14B)-C(15B)	120.17(17)
C(13B)-C(14B)-H(14B)	119.9
C(15B)-C(14B)-H(14B)	119.9
C(16B)-C(15B)-C(14B)	119.62(17)
C(16B)-C(15B)-H(15B)	120.2
C(14B)-C(15B)-H(15B)	120.2
C(15B)-C(16B)-C(17B)	120.22(18)
C(15B)-C(16B)-H(16B)	119.9
C(17B)-C(16B)-H(16B)	119.9
C(16B)-C(17B)-C(12B)	120.33(17)
C(16B)-C(17B)-H(17B)	119.8
C(12B)-C(17B)-H(17B)	119.8

Symmetry transformations used to generate equivalent atoms:

Table B.2.4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **36**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

Atom	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Cl(1A)	31(1)	40(1)	17(1)	-6(1)	-2(1)	-5(1)
O(1A)	19(1)	34(1)	22(1)	-1(1)	-3(1)	-6(1)
C(1A)	20(1)	20(1)	26(1)	5(1)	0(1)	0(1)
C(2A)	16(1)	20(1)	21(1)	0(1)	2(1)	5(1)
C(3A)	17(1)	23(1)	19(1)	-5(1)	2(1)	-1(1)
C(4A)	22(1)	29(1)	24(1)	-8(1)	4(1)	-6(1)
C(5A)	34(1)	25(1)	53(1)	-15(1)	13(1)	-4(1)
C(6A)	30(1)	19(1)	59(1)	3(1)	1(1)	2(1)
C(7A)	17(1)	24(1)	21(1)	1(1)	1(1)	-3(1)
C(8A)	18(1)	32(1)	23(1)	0(1)	2(1)	2(1)
C(9A)	23(1)	38(1)	34(1)	1(1)	2(1)	-8(1)
C(10A)	25(1)	45(1)	25(1)	14(1)	-2(1)	-6(1)
C(11A)	19(1)	25(1)	15(1)	-6(1)	-2(1)	2(1)
C(12A)	21(1)	23(1)	14(1)	5(1)	-3(1)	2(1)
C(13A)	26(1)	30(1)	21(1)	1(1)	4(1)	-2(1)
C(14A)	26(1)	40(1)	30(1)	6(1)	7(1)	-6(1)
C(15A)	32(1)	31(1)	38(1)	7(1)	1(1)	-10(1)
C(16A)	37(1)	24(1)	32(1)	-2(1)	-2(1)	-4(1)
C(17A)	26(1)	25(1)	22(1)	1(1)	1(1)	2(1)
Cl(1B)	28(1)	28(1)	17(1)	-4(1)	-1(1)	1(1)
O(1B)	23(1)	33(1)	23(1)	-1(1)	0(1)	7(1)
C(1B)	17(1)	29(1)	19(1)	3(1)	-1(1)	4(1)
C(2B)	16(1)	26(1)	19(1)	-1(1)	0(1)	-2(1)
C(3B)	18(1)	23(1)	19(1)	0(1)	-1(1)	-1(1)
C(4B)	19(1)	29(1)	18(1)	0(1)	0(1)	3(1)
C(5B)	25(1)	28(1)	30(1)	-4(1)	-3(1)	5(1)
C(6B)	22(1)	30(1)	30(1)	6(1)	3(1)	4(1)
C(7B)	19(1)	32(1)	17(1)	0(1)	-1(1)	2(1)
C(8B)	20(1)	39(1)	22(1)	0(1)	0(1)	-3(1)
C(9B)	19(1)	45(1)	27(1)	1(1)	-3(1)	8(1)
C(10B)	26(1)	45(1)	17(1)	4(1)	1(1)	6(1)

C(11B)	21(1)	22(1)	16(1)	-2(1)	2(1)	-3(1)
C(12B)	24(1)	19(1)	13(1)	2(1)	-1(1)	-1(1)
C(13B)	25(1)	22(1)	18(1)	2(1)	-2(1)	-3(1)
C(14B)	25(1)	30(1)	24(1)	5(1)	-3(1)	-1(1)
C(15B)	34(1)	30(1)	26(1)	9(1)	0(1)	10(1)
C(16B)	44(1)	21(1)	29(1)	1(1)	-2(1)	5(1)
C(17B)	33(1)	24(1)	24(1)	2(1)	-7(1)	-4(1)

Table B.3.1. Crystal data and structure refinement for **35**.

Identification code	xxx29c	
Empirical formula	C27 H34 O2	
Formula weight	390.54	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	P2(1)2(1)2(1)	
Unit cell dimensions	a = 6.6892(14) Å	α= 90°.
	b = 15.409(3) Å	β= 90°.
	c = 21.528(4) Å	γ = 90°.
Volume	2219.0(7) $Å^3$	
Z	4	
Density (calculated)	1.169 Mg/m^3	
Absorption coefficient	0.072 mm^{-1}	
F(000)	848	
Crystal size	0.13 x 0.11 x 0.08 mm^3	
Theta range for data collection	1.63 to 25.29°.	
Index ranges	-8<=h<=8, -16<=k<=18, -25<=l<=22	
Reflections collected	14567	
Independent reflections	4030 [R(int) = 0.0522]	
Completeness to theta = 25.00°	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9942 and 0.9905	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4030 / 0 / 268	
Goodness-of-fit on F^2	1.033	
Final R indices [I>2sigma(I)]	R1 = 0.0407, wR2 = 0.0828	
R indices (all data)	R1 = 0.0598, wR2 = 0.0917	
Absolute structure parameter	0.00	
Largest diff. peak and hole	0.168 and -0.191 e.$Å^{-3}$	

Table B.3.2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **35**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
O(1)	3753(2)	343(1)	316(1)	31(1)
O(2)	287(2)	1741(1)	2233(1)	29(1)
C(1)	6198(3)	-799(1)	539(1)	28(1)
C(2)	4799(3)	-45(1)	690(1)	24(1)
C(3)	4963(3)	87(1)	1376(1)	21(1)
C(4)	6398(3)	-619(1)	1582(1)	23(1)
C(5)	8494(3)	-317(1)	1361(1)	29(1)
C(6)	8336(3)	-413(2)	648(1)	31(1)
C(7)	5915(3)	-1368(1)	1127(1)	26(1)
C(8)	3777(3)	-1711(1)	1200(1)	32(1)
C(9)	7367(4)	-2139(1)	1165(1)	34(1)
C(10)	5868(4)	-1195(1)	-96(1)	37(1)
C(11)	4036(3)	687(1)	1728(1)	19(1)
C(12)	2082(3)	2911(1)	1714(1)	20(1)
C(13)	1546(3)	1978(1)	1859(1)	21(1)
C(14)	2772(3)	1397(1)	1431(1)	19(1)
C(15)	3946(3)	2092(1)	1051(1)	21(1)
C(16)	5534(3)	2487(1)	1475(1)	24(1)
C(17)	4274(3)	3004(1)	1948(1)	25(1)
C(18)	2388(3)	2834(1)	997(1)	21(1)
C(19)	489(3)	2580(1)	644(1)	28(1)
C(20)	3189(3)	3665(1)	701(1)	31(1)
C(21)	630(3)	3578(1)	1965(1)	27(1)
C(22)	4297(3)	666(1)	2419(1)	20(1)
C(23)	6084(3)	910(1)	2697(1)	25(1)
C(24)	6304(4)	893(1)	3338(1)	31(1)
C(25)	4751(4)	621(1)	3710(1)	31(1)
C(26)	2972(4)	356(1)	3441(1)	30(1)
C(27)	2743(3)	380(1)	2803(1)	26(1)

Table B.3.3. Bond lengths [Å] and angles [°] for **35**.

O(1)-C(2)	1.222(2)
O(2)-C(13)	1.221(2)
C(1)-C(10)	1.513(3)
C(1)-C(2)	1.526(3)
C(1)-C(7)	1.552(3)
C(1)-C(6)	1.567(3)
C(2)-C(3)	1.495(3)
C(3)-C(11)	1.347(3)
C(3)-C(4)	1.517(3)
C(4)-C(7)	1.548(3)
C(4)-C(5)	1.552(3)
C(4)-H(4)	1.0000
C(5)-C(6)	1.546(3)
C(5)-H(5A)	0.9900
C(5)-H(5B)	0.9900
C(6)-H(6A)	0.9900
C(6)-H(6B)	0.9900
C(7)-C(8)	1.533(3)
C(7)-C(9)	1.536(3)
C(8)-H(8A)	0.9800
C(8)-H(8B)	0.9800
C(8)-H(8C)	0.9800
C(9)-H(9A)	0.9800
C(9)-H(9B)	0.9800
C(9)-H(9C)	0.9800
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(11)-C(22)	1.499(3)
C(11)-C(14)	1.524(3)
C(12)-C(13)	1.513(3)
C(12)-C(21)	1.514(3)
C(12)-C(17)	1.558(3)
C(12)-C(18)	1.563(3)

C(13)-C(14)	1.525(3)
C(14)-C(15)	1.560(3)
C(14)-H(14)	1.0000
C(15)-C(16)	1.527(3)
C(15)-C(18)	1.551(3)
C(15)-H(15)	1.0000
C(16)-C(17)	1.544(3)
C(16)-H(16A)	0.9900
C(16)-H(16B)	0.9900
C(17)-H(17A)	0.9900
C(17)-H(17B)	0.9900
C(18)-C(20)	1.528(3)
C(18)-C(19)	1.531(3)
C(19)-H(19A)	0.9800
C(19)-H(19B)	0.9800
C(19)-H(19C)	0.9800
C(20)-H(20A)	0.9800
C(20)-H(20B)	0.9800
C(20)-H(20C)	0.9800
C(21)-H(21A)	0.9800
C(21)-H(21B)	0.9800
C(21)-H(21C)	0.9800
C(22)-C(23)	1.388(3)
C(22)-C(27)	1.398(3)
C(23)-C(24)	1.388(3)
C(23)-H(23)	0.9500
C(24)-C(25)	1.377(3)
C(24)-H(24)	0.9500
C(25)-C(26)	1.385(3)
C(25)-H(25)	0.9500
C(26)-C(27)	1.383(3)
C(26)-H(26)	0.9500
C(27)-H(27)	0.9500

C(10)-C(1)-C(2)	114.14(18)
C(10)-C(1)-C(7)	119.39(17)

C(2)-C(1)-C(7)	100.52(16)
C(10)-C(1)-C(6)	114.90(19)
C(2)-C(1)-C(6)	103.87(16)
C(7)-C(1)-C(6)	101.78(17)
O(1)-C(2)-C(3)	128.72(19)
O(1)-C(2)-C(1)	125.69(18)
C(3)-C(2)-C(1)	105.57(17)
C(11)-C(3)-C(2)	128.05(19)
C(11)-C(3)-C(4)	128.20(18)
C(2)-C(3)-C(4)	103.74(16)
C(3)-C(4)-C(7)	102.59(15)
C(3)-C(4)-C(5)	105.50(15)
C(7)-C(4)-C(5)	102.62(16)
C(3)-C(4)-H(4)	114.9
C(7)-C(4)-H(4)	114.9
C(5)-C(4)-H(4)	114.9
C(6)-C(5)-C(4)	102.34(17)
C(6)-C(5)-H(5A)	111.3
C(4)-C(5)-H(5A)	111.3
C(6)-C(5)-H(5B)	111.3
C(4)-C(5)-H(5B)	111.3
H(5A)-C(5)-H(5B)	109.2
C(5)-C(6)-C(1)	104.30(17)
C(5)-C(6)-H(6A)	110.9
C(1)-C(6)-H(6A)	110.9
C(5)-C(6)-H(6B)	110.9
C(1)-C(6)-H(6B)	110.9
H(6A)-C(6)-H(6B)	108.9
C(8)-C(7)-C(9)	108.59(17)
C(8)-C(7)-C(4)	112.73(17)
C(9)-C(7)-C(4)	114.25(18)
C(8)-C(7)-C(1)	113.10(18)
C(9)-C(7)-C(1)	113.81(18)
C(4)-C(7)-C(1)	93.91(15)
C(7)-C(8)-H(8A)	109.5
C(7)-C(8)-H(8B)	109.5

H(8A)-C(8)-H(8B)	109.5
C(7)-C(8)-H(8C)	109.5
H(8A)-C(8)-H(8C)	109.5
H(8B)-C(8)-H(8C)	109.5
C(7)-C(9)-H(9A)	109.5
C(7)-C(9)-H(9B)	109.5
H(9A)-C(9)-H(9B)	109.5
C(7)-C(9)-H(9C)	109.5
H(9A)-C(9)-H(9C)	109.5
H(9B)-C(9)-H(9C)	109.5
C(1)-C(10)-H(10A)	109.5
C(1)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(1)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(3)-C(11)-C(22)	119.40(17)
C(3)-C(11)-C(14)	120.78(17)
C(22)-C(11)-C(14)	119.80(16)
C(13)-C(12)-C(21)	114.81(16)
C(13)-C(12)-C(17)	104.14(16)
C(21)-C(12)-C(17)	115.19(16)
C(13)-C(12)-C(18)	99.34(15)
C(21)-C(12)-C(18)	119.24(17)
C(17)-C(12)-C(18)	101.73(15)
O(2)-C(13)-C(12)	125.68(18)
O(2)-C(13)-C(14)	126.43(17)
C(12)-C(13)-C(14)	107.81(16)
C(11)-C(14)-C(13)	117.82(15)
C(11)-C(14)-C(15)	115.69(16)
C(13)-C(14)-C(15)	100.64(15)
C(11)-C(14)-H(14)	107.3
C(13)-C(14)-H(14)	107.3
C(15)-C(14)-H(14)	107.3
C(16)-C(15)-C(18)	102.62(15)
C(16)-C(15)-C(14)	108.10(16)

C(18)-C(15)-C(14)	101.93(15)
C(16)-C(15)-H(15)	114.3
C(18)-C(15)-H(15)	114.3
C(14)-C(15)-H(15)	114.3
C(15)-C(16)-C(17)	102.76(16)
C(15)-C(16)-H(16A)	111.2
C(17)-C(16)-H(16A)	111.2
C(15)-C(16)-H(16B)	111.2
C(17)-C(16)-H(16B)	111.2
H(16A)-C(16)-H(16B)	109.1
C(16)-C(17)-C(12)	104.62(15)
C(16)-C(17)-H(17A)	110.8
C(12)-C(17)-H(17A)	110.8
C(16)-C(17)-H(17B)	110.8
C(12)-C(17)-H(17B)	110.8
H(17A)-C(17)-H(17B)	108.9
C(20)-C(18)-C(19)	107.34(16)
C(20)-C(18)-C(15)	114.43(17)
C(19)-C(18)-C(15)	113.99(16)
C(20)-C(18)-C(12)	113.23(16)
C(19)-C(18)-C(12)	113.65(17)
C(15)-C(18)-C(12)	94.02(15)
C(18)-C(19)-H(19A)	109.5
C(18)-C(19)-H(19B)	109.5
H(19A)-C(19)-H(19B)	109.5
C(18)-C(19)-H(19C)	109.5
H(19A)-C(19)-H(19C)	109.5
H(19B)-C(19)-H(19C)	109.5
C(18)-C(20)-H(20A)	109.5
C(18)-C(20)-H(20B)	109.5
H(20A)-C(20)-H(20B)	109.5
C(18)-C(20)-H(20C)	109.5
H(20A)-C(20)-H(20C)	109.5
H(20B)-C(20)-H(20C)	109.5
C(12)-C(21)-H(21A)	109.5
C(12)-C(21)-H(21B)	109.5

H(21A)-C(21)-H(21B)	109.5
C(12)-C(21)-H(21C)	109.5
H(21A)-C(21)-H(21C)	109.5
H(21B)-C(21)-H(21C)	109.5
C(23)-C(22)-C(27)	118.14(17)
C(23)-C(22)-C(11)	121.44(17)
C(27)-C(22)-C(11)	120.41(18)
C(24)-C(23)-C(22)	120.93(19)
C(24)-C(23)-H(23)	119.5
C(22)-C(23)-H(23)	119.5
C(25)-C(24)-C(23)	120.2(2)
C(25)-C(24)-H(24)	119.9
C(23)-C(24)-H(24)	119.9
C(24)-C(25)-C(26)	119.67(19)
C(24)-C(25)-H(25)	120.2
C(26)-C(25)-H(25)	120.2
C(27)-C(26)-C(25)	120.2(2)
C(27)-C(26)-H(26)	119.9
C(25)-C(26)-H(26)	119.9
C(26)-C(27)-C(22)	120.8(2)
C(26)-C(27)-H(27)	119.6
C(22)-C(27)-H(27)	119.6

Symmetry transformations used to generate equivalent atoms:

Table B.3.4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **35**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

Atom	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
O(1)	41(1)	28(1)	25(1)	-1(1)	-5(1)	6(1)
O(2)	22(1)	32(1)	35(1)	3(1)	10(1)	1(1)
C(1)	34(1)	24(1)	25(1)	-1(1)	4(1)	4(1)
C(2)	26(1)	20(1)	26(1)	1(1)	1(1)	-3(1)
C(3)	22(1)	18(1)	23(1)	1(1)	0(1)	-3(1)
C(4)	25(1)	22(1)	23(1)	3(1)	2(1)	2(1)
C(5)	23(1)	27(1)	37(1)	2(1)	2(1)	1(1)
C(6)	27(1)	32(1)	34(1)	8(1)	9(1)	4(1)
C(7)	29(1)	22(1)	29(1)	-1(1)	3(1)	2(1)
C(8)	32(1)	25(1)	38(1)	-2(1)	2(1)	-2(1)
C(9)	44(2)	25(1)	35(1)	0(1)	5(1)	7(1)
C(10)	52(2)	33(1)	26(1)	-6(1)	1(1)	8(1)
C(11)	18(1)	18(1)	23(1)	1(1)	1(1)	-2(1)
C(12)	20(1)	20(1)	21(1)	-1(1)	1(1)	0(1)
C(13)	16(1)	26(1)	21(1)	0(1)	-4(1)	1(1)
C(14)	18(1)	20(1)	20(1)	-1(1)	1(1)	-1(1)
C(15)	21(1)	20(1)	22(1)	2(1)	6(1)	1(1)
C(16)	18(1)	23(1)	32(1)	4(1)	4(1)	-2(1)
C(17)	22(1)	25(1)	29(1)	-2(1)	-2(1)	-4(1)
C(18)	25(1)	18(1)	21(1)	2(1)	0(1)	2(1)
C(19)	32(1)	29(1)	25(1)	1(1)	-7(1)	4(1)
C(20)	38(1)	25(1)	31(1)	4(1)	8(1)	5(1)
C(21)	25(1)	26(1)	30(1)	-5(1)	1(1)	4(1)
C(22)	23(1)	15(1)	22(1)	1(1)	1(1)	3(1)
C(23)	23(1)	25(1)	27(1)	3(1)	1(1)	-2(1)
C(24)	38(1)	26(1)	30(1)	0(1)	-10(1)	3(1)
C(25)	52(2)	22(1)	18(1)	-1(1)	-2(1)	8(1)
C(26)	41(1)	28(1)	22(1)	3(1)	11(1)	2(1)
C(27)	24(1)	24(1)	30(1)	0(1)	2(1)	-1(1)

Table B.4.1. Crystal data and structure refinement for **27**.

Identification code	xxx83c	
Empirical formula	C27 H33 P	
Formula weight	388.50	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1	
Unit cell dimensions	a = 6.866(2) Å	α= 78.525(12)°.
	b = 12.056(4) Å	β= 82.284(14)°.
	c = 14.084(6) Å	γ = 74.282(12)°.
Volume	1095.7(7) $Å^3$	
Z	2	
Density (calculated)	1.178 Mg/m^3	
Absorption coefficient	0.135 mm^{-1}	
F(000)	420	
Crystal size	0.22 x 0.17 x 0.14 mm^3	
Theta range for data collection	1.78 to 25.50°.	
Index ranges	-8<=h<=8, -14<=k<=14, -16<=l<=16	
Reflections collected	18334	
Independent reflections	7158 [R(int) = 0.0399]	
Completeness to theta = 25.00°	99.8 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9820 and 0.9703	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	7158 / 3 / 517	
Goodness-of-fit on F^2	1.024	
Final R indices [I>2sigma(I)]	R1 = 0.0405, wR2 = 0.0908	
R indices (all data)	R1 = 0.0516, wR2 = 0.0970	
Absolute structure parameter	0.00(7)	
Largest diff. peak and hole	0.193 and -0.230 $e.Å^{-3}$	

Table B.4.2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **27**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
P(1A)	6173(1)	2012(1)	6354(1)	30(1)
C(1A)	5726(4)	498(2)	5084(2)	25(1)
C(2A)	5849(4)	1682(2)	5263(2)	22(1)
C(3A)	5694(4)	2425(2)	4377(2)	21(1)
C(4A)	5490(4)	1707(2)	3643(2)	26(1)
C(5A)	7608(4)	850(2)	3518(2)	32(1)
C(6A)	7757(4)	28(2)	4496(2)	30(1)
C(7A)	4238(4)	896(2)	4280(2)	25(1)
C(8A)	2121(4)	1554(3)	4625(2)	40(1)
C(9A)	4033(4)	-95(2)	3798(2)	32(1)
C(10A)	5230(5)	-344(3)	5971(2)	37(1)
C(11A)	6396(4)	4315(2)	6575(2)	25(1)
C(12A)	6237(4)	3450(2)	5951(2)	23(1)
C(13A)	6079(4)	4061(2)	5008(2)	23(1)
C(14A)	6130(4)	5304(2)	5044(2)	23(1)
C(15A)	4082(4)	5852(2)	5568(2)	28(1)
C(16A)	4253(4)	5168(2)	6612(2)	29(1)
C(17A)	7618(4)	5078(2)	5829(2)	26(1)
C(18A)	9751(4)	4397(3)	5528(3)	40(1)
C(19A)	7753(4)	6182(2)	6164(2)	33(1)
C(20A)	7204(5)	3795(3)	7541(2)	41(1)
C(21A)	5803(4)	3594(2)	4218(2)	23(1)
C(22A)	5585(4)	4330(2)	3244(2)	26(1)
C(23A)	7151(4)	4810(2)	2756(2)	32(1)
C(24A)	6925(5)	5497(3)	1853(2)	41(1)
C(25A)	5154(5)	5712(3)	1421(2)	45(1)
C(26A)	3605(5)	5245(3)	1884(2)	44(1)
C(27A)	3804(4)	4556(2)	2793(2)	33(1)
P(1B)	1227(1)	628(1)	8410(1)	31(1)
C(1B)	-92(4)	-1438(2)	8289(2)	25(1)
C(2B)	516(4)	-661(2)	8869(2)	24(1)

C(3B)	365(4)	-1185(2)	9836(2)	21(1)
C(4B)	-343(4)	-2271(2)	9853(2)	22(1)
C(5B)	-2583(4)	-1828(2)	9612(2)	27(1)
C(6B)	-2399(4)	-1242(2)	8541(2)	27(1)
C(7B)	732(4)	-2665(2)	8893(2)	22(1)
C(8B)	3027(4)	-3043(3)	8892(2)	33(1)
C(9B)	30(4)	-3657(2)	8625(2)	30(1)
C(10B)	548(4)	-1274(3)	7207(2)	33(1)
C(11B)	2248(4)	2027(2)	9626(2)	25(1)
C(12B)	1591(4)	967(2)	9495(2)	25(1)
C(13B)	1376(4)	302(2)	10417(2)	24(1)
C(14B)	1871(4)	968(2)	11119(2)	24(1)
C(15B)	4190(4)	824(2)	10950(2)	28(1)
C(16B)	4440(4)	1533(2)	9930(2)	28(1)
C(17B)	1050(4)	2247(2)	10631(2)	25(1)
C(18B)	-1255(4)	2607(3)	10608(2)	35(1)
C(19B)	1638(4)	3154(2)	11077(2)	34(1)
C(20B)	2022(4)	3037(3)	8788(2)	34(1)
C(21B)	784(4)	-750(2)	10606(2)	21(1)
C(22B)	645(4)	-1408(2)	11616(2)	23(1)
C(23B)	2255(4)	-1690(2)	12188(2)	29(1)
C(24B)	2155(4)	-2323(2)	13115(2)	33(1)
C(25B)	441(4)	-2706(2)	13483(2)	34(1)
C(26B)	-1180(4)	-2427(2)	12934(2)	30(1)
C(27B)	-1075(4)	-1794(2)	12007(2)	25(1)

Table B.4.3. Bond lengths [Å] and angles [°] for **27**.

P(1A)-C(2A)	1.719(3)
P(1A)-C(12A)	1.724(3)
C(1A)-C(10A)	1.508(4)
C(1A)-C(2A)	1.524(4)
C(1A)-C(7A)	1.544(4)
C(1A)-C(6A)	1.550(4)
C(2A)-C(3A)	1.382(4)
C(3A)-C(21A)	1.403(4)
C(3A)-C(4A)	1.516(4)
C(4A)-C(7A)	1.549(4)
C(4A)-C(5A)	1.550(4)
C(4A)-H(4A)	1.0000
C(5A)-C(6A)	1.527(4)
C(5A)-H(5A1)	0.9900
C(5A)-H(5A2)	0.9900
C(6A)-H(6A1)	0.9900
C(6A)-H(6A2)	0.9900
C(7A)-C(8A)	1.522(4)
C(7A)-C(9A)	1.533(3)
C(8A)-H(8A1)	0.9800
C(8A)-H(8A2)	0.9800
C(8A)-H(8A3)	0.9800
C(9A)-H(9A1)	0.9800
C(9A)-H(9A2)	0.9800
C(9A)-H(9A3)	0.9800
C(10A)-H(10A)	0.9800
C(10A)-H(10B)	0.9800
C(10A)-H(10C)	0.9800
C(11A)-C(20A)	1.493(4)
C(11A)-C(12A)	1.523(4)
C(11A)-C(16A)	1.551(4)
C(11A)-C(17A)	1.565(4)
C(12A)-C(13A)	1.388(4)
C(13A)-C(21A)	1.398(4)

C(13A)-C(14A)	1.519(3)
C(14A)-C(15A)	1.540(3)
C(14A)-C(17A)	1.541(4)
C(14A)-H(14A)	1.0000
C(15A)-C(16A)	1.538(4)
C(15A)-H(15A)	0.9900
C(15A)-H(15B)	0.9900
C(16A)-H(16A)	0.9900
C(16A)-H(16B)	0.9900
C(17A)-C(18A)	1.523(4)
C(17A)-C(19A)	1.527(4)
C(18A)-H(18A)	0.9800
C(18A)-H(18B)	0.9800
C(18A)-H(18C)	0.9800
C(19A)-H(19A)	0.9800
C(19A)-H(19B)	0.9800
C(19A)-H(19C)	0.9800
C(20A)-H(20A)	0.9800
C(20A)-H(20B)	0.9800
C(20A)-H(20C)	0.9800
C(21A)-C(22A)	1.480(4)
C(22A)-C(27A)	1.390(4)
C(22A)-C(23A)	1.394(4)
C(23A)-C(24A)	1.375(4)
C(23A)-H(23A)	0.9500
C(24A)-C(25A)	1.371(5)
C(24A)-H(24A)	0.9500
C(25A)-C(26A)	1.366(4)
C(25A)-H(25A)	0.9500
C(26A)-C(27A)	1.382(4)
C(26A)-H(26A)	0.9500
C(27A)-H(27A)	0.9500
P(1B)-C(12B)	1.724(3)
P(1B)-C(2B)	1.731(3)
C(1B)-C(10B)	1.517(4)
C(1B)-C(2B)	1.525(4)

C(1B)-C(6B)	1.539(4)
C(1B)-C(7B)	1.552(4)
C(2B)-C(3B)	1.386(4)
C(3B)-C(21B)	1.386(3)
C(3B)-C(4B)	1.511(3)
C(4B)-C(5B)	1.545(4)
C(4B)-C(7B)	1.547(3)
C(4B)-H(4B)	1.0000
C(5B)-C(6B)	1.539(4)
C(5B)-H(5B1)	0.9900
C(5B)-H(5B2)	0.9900
C(6B)-H(6B1)	0.9900
C(6B)-H(6B2)	0.9900
C(7B)-C(8B)	1.517(4)
C(7B)-C(9B)	1.531(4)
C(8B)-H(8B1)	0.9800
C(8B)-H(8B2)	0.9800
C(8B)-H(8B3)	0.9800
C(9B)-H(9B1)	0.9800
C(9B)-H(9B2)	0.9800
C(9B)-H(9B3)	0.9800
C(10B)-H(10D)	0.9800
C(10B)-H(10E)	0.9800
C(10B)-H(10F)	0.9800
C(11B)-C(20B)	1.508(4)
C(11B)-C(12B)	1.517(4)
C(11B)-C(16B)	1.545(4)
C(11B)-C(17B)	1.571(4)
C(12B)-C(13B)	1.396(4)
C(13B)-C(21B)	1.401(4)
C(13B)-C(14B)	1.513(4)
C(14B)-C(17B)	1.543(4)
C(14B)-C(15B)	1.544(4)
C(14B)-H(14B)	1.0000
C(15B)-C(16B)	1.533(4)
C(15B)-H(15C)	0.9900

C(15B)-H(15D)	0.9900
C(16B)-H(16C)	0.9900
C(16B)-H(16D)	0.9900
C(17B)-C(18B)	1.526(4)
C(17B)-C(19B)	1.528(3)
C(18B)-H(18D)	0.9800
C(18B)-H(18E)	0.9800
C(18B)-H(18F)	0.9800
C(19B)-H(19D)	0.9800
C(19B)-H(19E)	0.9800
C(19B)-H(19F)	0.9800
C(20B)-H(20D)	0.9800
C(20B)-H(20E)	0.9800
C(20B)-H(20F)	0.9800
C(21B)-C(22B)	1.490(4)
C(22B)-C(23B)	1.382(4)
C(22B)-C(27B)	1.391(4)
C(23B)-C(24B)	1.378(4)
C(23B)-H(23B)	0.9500
C(24B)-C(25B)	1.379(4)
C(24B)-H(24B)	0.9500
C(25B)-C(26B)	1.370(4)
C(25B)-H(25B)	0.9500
C(26B)-C(27B)	1.378(4)
C(26B)-H(26B)	0.9500
C(27B)-H(27B)	0.9500

C(2A)-P(1A)-C(12A)	98.02(13)
C(10A)-C(1A)-C(2A)	116.2(2)
C(10A)-C(1A)-C(7A)	117.9(2)
C(2A)-C(1A)-C(7A)	100.1(2)
C(10A)-C(1A)-C(6A)	114.4(2)
C(2A)-C(1A)-C(6A)	104.7(2)
C(7A)-C(1A)-C(6A)	101.3(2)
C(3A)-C(2A)-C(1A)	106.8(2)
C(3A)-C(2A)-P(1A)	126.9(2)

C(1A)-C(2A)-P(1A)	126.2(2)
C(2A)-C(3A)-C(21A)	125.0(2)
C(2A)-C(3A)-C(4A)	106.3(2)
C(21A)-C(3A)-C(4A)	128.6(2)
C(3A)-C(4A)-C(7A)	100.4(2)
C(3A)-C(4A)-C(5A)	105.2(2)
C(7A)-C(4A)-C(5A)	102.0(2)
C(3A)-C(4A)-H(4A)	115.7
C(7A)-C(4A)-H(4A)	115.7
C(5A)-C(4A)-H(4A)	115.7
C(6A)-C(5A)-C(4A)	102.9(2)
C(6A)-C(5A)-H(5A1)	111.2
C(4A)-C(5A)-H(5A1)	111.2
C(6A)-C(5A)-H(5A2)	111.2
C(4A)-C(5A)-H(5A2)	111.2
H(5A1)-C(5A)-H(5A2)	109.1
C(5A)-C(6A)-C(1A)	104.0(2)
C(5A)-C(6A)-H(6A1)	111.0
C(1A)-C(6A)-H(6A1)	111.0
C(5A)-C(6A)-H(6A2)	111.0
C(1A)-C(6A)-H(6A2)	111.0
H(6A1)-C(6A)-H(6A2)	109.0
C(8A)-C(7A)-C(9A)	108.3(2)
C(8A)-C(7A)-C(1A)	113.3(2)
C(9A)-C(7A)-C(1A)	114.2(2)
C(8A)-C(7A)-C(4A)	113.1(2)
C(9A)-C(7A)-C(4A)	114.2(2)
C(1A)-C(7A)-C(4A)	93.27(19)
C(7A)-C(8A)-H(8A1)	109.5
C(7A)-C(8A)-H(8A2)	109.5
H(8A1)-C(8A)-H(8A2)	109.5
C(7A)-C(8A)-H(8A3)	109.5
H(8A1)-C(8A)-H(8A3)	109.5
H(8A2)-C(8A)-H(8A3)	109.5
C(7A)-C(9A)-H(9A1)	109.5
C(7A)-C(9A)-H(9A2)	109.5

H(9A1)-C(9A)-H(9A2)	109.5
C(7A)-C(9A)-H(9A3)	109.5
H(9A1)-C(9A)-H(9A3)	109.5
H(9A2)-C(9A)-H(9A3)	109.5
C(1A)-C(10A)-H(10A)	109.5
C(1A)-C(10A)-H(10B)	109.5
H(10A)-C(10A)-H(10B)	109.5
C(1A)-C(10A)-H(10C)	109.5
H(10A)-C(10A)-H(10C)	109.5
H(10B)-C(10A)-H(10C)	109.5
C(20A)-C(11A)-C(12A)	116.0(2)
C(20A)-C(11A)-C(16A)	115.0(2)
C(12A)-C(11A)-C(16A)	104.5(2)
C(20A)-C(11A)-C(17A)	117.8(2)
C(12A)-C(11A)-C(17A)	100.1(2)
C(16A)-C(11A)-C(17A)	101.1(2)
C(13A)-C(12A)-C(11A)	106.5(2)
C(13A)-C(12A)-P(1A)	127.1(2)
C(11A)-C(12A)-P(1A)	126.4(2)
C(12A)-C(13A)-C(21A)	124.5(2)
C(12A)-C(13A)-C(14A)	106.5(2)
C(21A)-C(13A)-C(14A)	128.9(2)
C(13A)-C(14A)-C(15A)	105.7(2)
C(13A)-C(14A)-C(17A)	100.7(2)
C(15A)-C(14A)-C(17A)	102.5(2)
C(13A)-C(14A)-H(14A)	115.4
C(15A)-C(14A)-H(14A)	115.4
C(17A)-C(14A)-H(14A)	115.4
C(16A)-C(15A)-C(14A)	102.6(2)
C(16A)-C(15A)-H(15A)	111.2
C(14A)-C(15A)-H(15A)	111.2
C(16A)-C(15A)-H(15B)	111.2
C(14A)-C(15A)-H(15B)	111.2
H(15A)-C(15A)-H(15B)	109.2
C(15A)-C(16A)-C(11A)	104.1(2)
C(15A)-C(16A)-H(16A)	110.9

C(11A)-C(16A)-H(16A)	110.9
C(15A)-C(16A)-H(16B)	110.9
C(11A)-C(16A)-H(16B)	110.9
H(16A)-C(16A)-H(16B)	109.0
C(18A)-C(17A)-C(19A)	108.9(2)
C(18A)-C(17A)-C(14A)	113.0(2)
C(19A)-C(17A)-C(14A)	114.1(2)
C(18A)-C(17A)-C(11A)	113.2(2)
C(19A)-C(17A)-C(11A)	114.2(2)
C(14A)-C(17A)-C(11A)	92.92(19)
C(17A)-C(18A)-H(18A)	109.5
C(17A)-C(18A)-H(18B)	109.5
H(18A)-C(18A)-H(18B)	109.5
C(17A)-C(18A)-H(18C)	109.5
H(18A)-C(18A)-H(18C)	109.5
H(18B)-C(18A)-H(18C)	109.5
C(17A)-C(19A)-H(19A)	109.5
C(17A)-C(19A)-H(19B)	109.5
H(19A)-C(19A)-H(19B)	109.5
C(17A)-C(19A)-H(19C)	109.5
H(19A)-C(19A)-H(19C)	109.5
H(19B)-C(19A)-H(19C)	109.5
C(11A)-C(20A)-H(20A)	109.5
C(11A)-C(20A)-H(20B)	109.5
H(20A)-C(20A)-H(20B)	109.5
C(11A)-C(20A)-H(20C)	109.5
H(20A)-C(20A)-H(20C)	109.5
H(20B)-C(20A)-H(20C)	109.5
C(13A)-C(21A)-C(3A)	118.4(2)
C(13A)-C(21A)-C(22A)	120.4(2)
C(3A)-C(21A)-C(22A)	121.1(2)
C(27A)-C(22A)-C(23A)	118.4(3)
C(27A)-C(22A)-C(21A)	120.5(2)
C(23A)-C(22A)-C(21A)	121.1(2)
C(24A)-C(23A)-C(22A)	120.6(3)
C(24A)-C(23A)-H(23A)	119.7

C(22A)-C(23A)-H(23A)	119.7
C(25A)-C(24A)-C(23A)	120.1(3)
C(25A)-C(24A)-H(24A)	119.9
C(23A)-C(24A)-H(24A)	119.9
C(26A)-C(25A)-C(24A)	120.2(3)
C(26A)-C(25A)-H(25A)	119.9
C(24A)-C(25A)-H(25A)	119.9
C(25A)-C(26A)-C(27A)	120.4(3)
C(25A)-C(26A)-H(26A)	119.8
C(27A)-C(26A)-H(26A)	119.8
C(26A)-C(27A)-C(22A)	120.2(3)
C(26A)-C(27A)-H(27A)	119.9
C(22A)-C(27A)-H(27A)	119.9
C(12B)-P(1B)-C(2B)	98.26(13)
C(10B)-C(1B)-C(2B)	116.5(2)
C(10B)-C(1B)-C(6B)	114.2(2)
C(2B)-C(1B)-C(6B)	104.2(2)
C(10B)-C(1B)-C(7B)	117.0(2)
C(2B)-C(1B)-C(7B)	101.0(2)
C(6B)-C(1B)-C(7B)	101.9(2)
C(3B)-C(2B)-C(1B)	106.4(2)
C(3B)-C(2B)-P(1B)	126.8(2)
C(1B)-C(2B)-P(1B)	126.8(2)
C(21B)-C(3B)-C(2B)	124.8(2)
C(21B)-C(3B)-C(4B)	129.1(2)
C(2B)-C(3B)-C(4B)	106.1(2)
C(3B)-C(4B)-C(5B)	105.5(2)
C(3B)-C(4B)-C(7B)	101.70(19)
C(5B)-C(4B)-C(7B)	101.9(2)
C(3B)-C(4B)-H(4B)	115.3
C(5B)-C(4B)-H(4B)	115.3
C(7B)-C(4B)-H(4B)	115.3
C(6B)-C(5B)-C(4B)	102.5(2)
C(6B)-C(5B)-H(5B1)	111.3
C(4B)-C(5B)-H(5B1)	111.3
C(6B)-C(5B)-H(5B2)	111.3

C(4B)-C(5B)-H(5B2)	111.3
H(5B1)-C(5B)-H(5B2)	109.2
C(5B)-C(6B)-C(1B)	103.6(2)
C(5B)-C(6B)-H(6B1)	111.0
C(1B)-C(6B)-H(6B1)	111.0
C(5B)-C(6B)-H(6B2)	111.0
C(1B)-C(6B)-H(6B2)	111.0
H(6B1)-C(6B)-H(6B2)	109.0
C(8B)-C(7B)-C(9B)	107.8(2)
C(8B)-C(7B)-C(4B)	113.2(2)
C(9B)-C(7B)-C(4B)	113.7(2)
C(8B)-C(7B)-C(1B)	114.2(2)
C(9B)-C(7B)-C(1B)	115.1(2)
C(4B)-C(7B)-C(1B)	92.38(19)
C(7B)-C(8B)-H(8B1)	109.5
C(7B)-C(8B)-H(8B2)	109.5
H(8B1)-C(8B)-H(8B2)	109.5
C(7B)-C(8B)-H(8B3)	109.5
H(8B1)-C(8B)-H(8B3)	109.5
H(8B2)-C(8B)-H(8B3)	109.5
C(7B)-C(9B)-H(9B1)	109.5
C(7B)-C(9B)-H(9B2)	109.5
H(9B1)-C(9B)-H(9B2)	109.5
C(7B)-C(9B)-H(9B3)	109.5
H(9B1)-C(9B)-H(9B3)	109.5
H(9B2)-C(9B)-H(9B3)	109.5
C(1B)-C(10B)-H(10D)	109.5
C(1B)-C(10B)-H(10E)	109.5
H(10D)-C(10B)-H(10E)	109.5
C(1B)-C(10B)-H(10F)	109.5
H(10D)-C(10B)-H(10F)	109.5
H(10E)-C(10B)-H(10F)	109.5
C(20B)-C(11B)-C(12B)	116.8(2)
C(20B)-C(11B)-C(16B)	114.0(2)
C(12B)-C(11B)-C(16B)	104.7(2)
C(20B)-C(11B)-C(17B)	118.2(2)

C(12B)-C(11B)-C(17B)	99.9(2)
C(16B)-C(11B)-C(17B)	100.8(2)
C(13B)-C(12B)-C(11B)	107.2(2)
C(13B)-C(12B)-P(1B)	126.3(2)
C(11B)-C(12B)-P(1B)	126.5(2)
C(12B)-C(13B)-C(21B)	124.8(2)
C(12B)-C(13B)-C(14B)	105.7(2)
C(21B)-C(13B)-C(14B)	129.5(2)
C(13B)-C(14B)-C(17B)	101.7(2)
C(13B)-C(14B)-C(15B)	105.5(2)
C(17B)-C(14B)-C(15B)	101.8(2)
C(13B)-C(14B)-H(14B)	115.3
C(17B)-C(14B)-H(14B)	115.3
C(15B)-C(14B)-H(14B)	115.3
C(16B)-C(15B)-C(14B)	102.8(2)
C(16B)-C(15B)-H(15C)	111.2
C(14B)-C(15B)-H(15C)	111.2
C(16B)-C(15B)-H(15D)	111.2
C(14B)-C(15B)-H(15D)	111.2
H(15C)-C(15B)-H(15D)	109.1
C(15B)-C(16B)-C(11B)	104.2(2)
C(15B)-C(16B)-H(16C)	110.9
C(11B)-C(16B)-H(16C)	110.9
C(15B)-C(16B)-H(16D)	110.9
C(11B)-C(16B)-H(16D)	110.9
H(16C)-C(16B)-H(16D)	108.9
C(18B)-C(17B)-C(19B)	107.3(2)
C(18B)-C(17B)-C(14B)	113.4(2)
C(19B)-C(17B)-C(14B)	114.7(2)
C(18B)-C(17B)-C(11B)	114.3(2)
C(19B)-C(17B)-C(11B)	114.1(2)
C(14B)-C(17B)-C(11B)	92.79(19)
C(17B)-C(18B)-H(18D)	109.5
C(17B)-C(18B)-H(18E)	109.5
H(18D)-C(18B)-H(18E)	109.5
C(17B)-C(18B)-H(18F)	109.5

H(18D)-C(18B)-H(18F)	109.5
H(18E)-C(18B)-H(18F)	109.5
C(17B)-C(19B)-H(19D)	109.5
C(17B)-C(19B)-H(19E)	109.5
H(19D)-C(19B)-H(19E)	109.5
C(17B)-C(19B)-H(19F)	109.5
H(19D)-C(19B)-H(19F)	109.5
H(19E)-C(19B)-H(19F)	109.5
C(11B)-C(20B)-H(20D)	109.5
C(11B)-C(20B)-H(20E)	109.5
H(20D)-C(20B)-H(20E)	109.5
C(11B)-C(20B)-H(20F)	109.5
H(20D)-C(20B)-H(20F)	109.5
H(20E)-C(20B)-H(20F)	109.5
C(3B)-C(21B)-C(13B)	119.1(2)
C(3B)-C(21B)-C(22B)	120.3(2)
C(13B)-C(21B)-C(22B)	120.5(2)
C(23B)-C(22B)-C(27B)	117.7(2)
C(23B)-C(22B)-C(21B)	120.9(2)
C(27B)-C(22B)-C(21B)	121.4(2)
C(24B)-C(23B)-C(22B)	121.2(3)
C(24B)-C(23B)-H(23B)	119.4
C(22B)-C(23B)-H(23B)	119.4
C(25B)-C(24B)-C(23B)	120.1(3)
C(25B)-C(24B)-H(24B)	120.0
C(23B)-C(24B)-H(24B)	120.0
C(26B)-C(25B)-C(24B)	119.7(3)
C(26B)-C(25B)-H(25B)	120.2
C(24B)-C(25B)-H(25B)	120.2
C(25B)-C(26B)-C(27B)	120.1(3)
C(25B)-C(26B)-H(26B)	120.0
C(27B)-C(26B)-H(26B)	120.0
C(26B)-C(27B)-C(22B)	121.3(3)
C(26B)-C(27B)-H(27B)	119.4
C(22B)-C(27B)-H(27B)	119.4

Symmetry transformations used to generate equivalent atoms:

Table B.4.4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **27**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ...\ + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

Atom	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
P(1A)	43(1)	27(1)	24(1)	-4(1)	-7(1)	-14(1)
C(1A)	26(1)	21(1)	28(2)	-8(1)	-2(1)	-7(1)
C(2A)	20(1)	22(2)	26(2)	-7(1)	-3(1)	-9(1)
C(3A)	25(1)	20(2)	20(2)	-5(1)	-2(1)	-10(1)
C(4A)	36(2)	24(2)	21(2)	-7(1)	-5(1)	-11(1)
C(5A)	36(2)	34(2)	33(2)	-18(1)	6(1)	-16(1)
C(6A)	27(2)	27(2)	41(2)	-14(1)	-6(1)	-5(1)
C(7A)	23(1)	24(1)	31(2)	-10(1)	-4(1)	-7(1)
C(8A)	27(2)	35(2)	64(2)	-24(2)	-4(1)	-8(1)
C(9A)	36(2)	30(2)	38(2)	-11(1)	-9(1)	-13(1)
C(10A)	58(2)	27(2)	29(2)	2(1)	-5(2)	-20(1)
C(11A)	33(2)	26(2)	20(2)	-7(1)	-6(1)	-11(1)
C(12A)	22(1)	26(2)	21(2)	-6(1)	-2(1)	-8(1)
C(13A)	23(1)	23(1)	24(2)	-4(1)	-1(1)	-11(1)
C(14A)	31(2)	21(1)	21(1)	-7(1)	-1(1)	-10(1)
C(15A)	25(1)	26(2)	34(2)	-9(1)	-6(1)	-3(1)
C(16A)	29(2)	35(2)	28(2)	-14(1)	2(1)	-11(1)
C(17A)	24(1)	29(2)	30(2)	-11(1)	-1(1)	-10(1)
C(18A)	27(2)	36(2)	62(2)	-19(2)	-4(1)	-11(1)
C(19A)	39(2)	29(2)	36(2)	-12(1)	-6(1)	-14(1)
C(20A)	57(2)	42(2)	27(2)	-6(2)	-16(2)	-14(2)
C(21A)	25(1)	26(2)	22(2)	-6(1)	-2(1)	-9(1)
C(22A)	42(2)	20(1)	21(2)	-7(1)	-4(1)	-11(1)
C(23A)	42(2)	33(2)	27(2)	-11(1)	-1(1)	-14(1)
C(24A)	69(2)	36(2)	24(2)	-4(1)	7(2)	-25(2)
C(25A)	87(3)	33(2)	22(2)	-3(1)	-11(2)	-26(2)
C(26A)	69(2)	29(2)	40(2)	-5(1)	-26(2)	-13(2)
C(27A)	47(2)	27(2)	30(2)	-5(1)	-11(1)	-16(1)
P(1B)	48(1)	28(1)	22(1)	-2(1)	-6(1)	-18(1)
C(1B)	32(2)	26(2)	20(2)	-5(1)	-5(1)	-9(1)
C(2B)	29(2)	24(2)	21(2)	-7(1)	-5(1)	-9(1)

C(3B)	24(1)	19(1)	20(2)	-5(1)	-3(1)	-6(1)
C(4B)	29(1)	20(1)	19(1)	-4(1)	-2(1)	-8(1)
C(5B)	28(2)	29(2)	26(2)	-6(1)	-3(1)	-8(1)
C(6B)	32(2)	27(1)	23(2)	-4(1)	-8(1)	-7(1)
C(7B)	27(1)	22(1)	21(1)	-6(1)	-3(1)	-10(1)
C(8B)	29(2)	39(2)	34(2)	-18(2)	-6(1)	-4(1)
C(9B)	39(2)	26(2)	29(2)	-11(1)	-5(1)	-9(1)
C(10B)	46(2)	40(2)	21(2)	-5(1)	-2(1)	-23(1)
C(11B)	31(2)	21(1)	27(2)	-6(1)	-6(1)	-10(1)
C(12B)	31(2)	21(2)	25(2)	-5(1)	-5(1)	-9(1)
C(13B)	26(1)	25(2)	21(2)	-9(1)	-5(1)	-3(1)
C(14B)	30(2)	23(2)	22(2)	-7(1)	-5(1)	-9(1)
C(15B)	27(1)	26(1)	33(2)	-9(1)	-10(1)	-5(1)
C(16B)	27(2)	25(2)	33(2)	-7(1)	-4(1)	-9(1)
C(17B)	26(1)	21(1)	30(2)	-9(1)	-6(1)	-6(1)
C(18B)	30(2)	30(2)	47(2)	-10(1)	-11(1)	-3(1)
C(19B)	39(2)	25(2)	40(2)	-13(1)	-6(1)	-8(1)
C(20B)	44(2)	25(2)	39(2)	-3(1)	-10(1)	-16(1)
C(21B)	26(1)	18(1)	20(2)	-4(1)	-3(1)	-5(1)
C(22B)	32(2)	18(1)	22(2)	-8(1)	-3(1)	-6(1)
C(23B)	37(2)	24(2)	26(2)	-3(1)	-8(1)	-9(1)
C(24B)	48(2)	27(2)	25(2)	-5(1)	-12(1)	-7(1)
C(25B)	54(2)	24(2)	19(2)	0(1)	-2(1)	-4(1)
C(26B)	38(2)	26(2)	24(2)	-5(1)	6(1)	-7(1)
C(27B)	33(2)	23(1)	19(1)	-3(1)	-2(1)	-5(1)

REFERENCES

1. Botting, J. *Drug News Perspect.* **2002**, *15*, 604-611.

2. Jacques, J.; Collet, A.; Wilen, S. H. *Enantiomers, Racemates and Resolutions*; Wiley: New York, 1981.

3. Brown, H. C. *Organic Synthesis via Boranes*; Wiley: New York, 1975.

4. Nozaki, H.; Moriuti, S., Tayaka, H.; Noyori, R. *Tetrahedron Lett.* **1966**, *43*, 5239-5244.

5. Noyori, R. *Asymmetric Catalysis in Organic Synthesis;* Wiley: New York, 1994.

6. Miyashita, A.; Yasuda, A.; Takaya, H.; Toriumi, K.; Ito, T.; Souchi, T.; Noyori, R. *J. Am. Chem. Soc.* **1980**, *102*, 7932-7934.

7. van Leeuwen, P.W.N.M. *Homogeneous Catalysis:Understanding the Art.* Kluwer: Boston, 2004.

8. Kolb, M.; Van Nieuwenhze, M.; Sharpless, K.B. *Chemical Reviews* **1994**, *94*, 2483-2547.

9. Burk, M, *Journal of the American Chemical Society* **1991**, *113*, 8518–8519.

10. Cobley, C.; Gardner, K.; Klosin, J.; Praquin, C.; Hill, C.; Whiteker, G.; Zanotti-Gerosa, A. *Journal of Organic Chemistry* **2004**, *69*, 4031-4040.

11. Bartels, B.; Garcia-Yebra, C.; Rominger, F.; Helmchen, G. *European Journal of Inorganic Chemistry* **2002**, *10*, 2569-2586.

12. Gomez-Bengoa, E.; Heron, N.; Didiuk, M.; Luchaco, C.; Hoveyda, A, *Journal of the American Chemical Society* **1998**, *120*, 7649-7650.

13. Hayashi, T. *Accounts of Chemical Research* **2000**, *33*, 354-362.

14. Chen, C.; Li, X.; Schreiber, S. *Journal of the American Chemical Society* **2003**, *125*, 10174-10175.

15. Doucet, H.; Fernandez, E.; Layzell, T.; Brown, J. *Chemistry - A European Journal* **1999**, *5*, 1320-1330.

16. (a) Ashimori, A.; Bachand, B.; Overman, L.; Poon, D. *Journal of the American Chemical Society* **1998**, *120*, 6477-6487. (b) Ashimori, A.; Bachand, B.; Overman, L.; Poon, D. *Journal of the American Chemical Society* **1998**, *120*, 6488-6499.

17. Clark, T.; Landis, C.; Freed, S.; Klosin, J.; Abboud, K. *Journal of the American Chemical Society* **2005**, *127*, 5040-5042.

18. Sakai, N.; Mano, S.; Nozaki, K.; Takaya, H. *Journal of the American Chemical Society* **1993**, *115*, 7033-7034.

19. Yan, Y.; Zhang, X., *Journal of the American Chemical Society* **2006**, *128*¸ 7198-7202.

20. Märkl, G. *Angewandte Chemie International Edition* **1966**, *5*, 846-847.

21. Ashe III, A. J. *J. Am. Chem. Soc.* **1971**, *93*, 3293.

22. Baldridge, K.; Gordon, M. *J. Am. Chem. Soc.* **1988**, *110*, 4204.

23. Nyulaszi, L.; Veszpremi, T. *J. Phys. Chem.* **1996**,*100*, 6456.

24. Müller, C.; Lutz, M.; Spek, A.; Vogt, D. *Chem. Crystallogr.* **2006**, *36*, 869.

25. DiMauro, E. F.; Kozlowski, M. C. *Journal of the Chemical Society, Perkins Transactions 1* **2002**, *3*, 439-444.

26. Märkl, G.; Lieb, F.; Merz, A. *Angewandte Chemie International Edition* **1967**, *6*, 458-459.

27. Märkl, G.; Lieb, F.; Merz, A., *Angewandte Chemie International Edition* **1967**, *6*, 944-945.

28. Katritzky, A.R. *Pyrylium Salts: Syntheses, Reactions, and Physical Properties.* Academic Press: New York, 1982.

29. For a review see: Mathey, F.; Le Floch, P. λ^3-Phosphinines in *Science of Synthesis: Houben Weyl Methods of Molecular Transformations.* Black, D. Ed.; Vol 15: Six Member Hetarenes with One Nitrogen or One Phosphorus Atom, George Thieme Verlag: Stuttgart, 2004; 1097-1155.

30. Mathey, F. *Phosphorus-Carbon Heterocyclic Chemistry: The Rise of a New Domain.* Pergamon: Amsterdam, 2001.

31. Pham-Tran, N.; Bouchoux, G.; Delaere, D.; Nguyen, M. *J. Phys. Chem A,* **2005**, *109*, 2957.

32. Mathey, F.; Le Floch, P. *Chem. Ber.* **1996**, *129*, 263-268.

33. Le Floch, P.; Mathey, F. *Coord. Chem. Rev.* **1998**, *179-180*, 771-791.

34. Märkl, G. *Tet. Let.* **1971**, *17*, 1249.

35. (a) Breit, B., *Chemical Communications* **1996**, *17*, 2071-2072. (b) Breit, B.; Winde, R.; Harms, K. *Journal of the Chemical Society, Perkins Transactions 1* **1997**, *18*, 2681-2682. (c) Briet, B *Journal of Molecular Catalysis A* **1999,** *143*, 143-154. (d) Breit, B.; Winde, R.; Mackewitz, T.; Paciello, R.; Harms, K., *Chemistry - A European Journal* **2001**, *7*, 3106-3121.

36. Müller, C.; Lopez, L. G.; Kooijman, H.; Spek, A.; Vogt, D., *Tetrahedron Letters* **2006**, *47*, 2017-2020.

37. Reetz, M.; Guo, H. *Synlett* **2006**, *13*, 2127-2129.

38. Wender, P.; Jenkins, T. *Journal of the American Chemical Society* **1989**,*111*, 6432-6434.

39. Whitesell, J. *Chemical Reviews* **1989**, *89*, 1581-90.

40. (a) Müller, C.; Pidko, E.; Totev, D.; Lutz, M.; Spek, A.; van Santen, R.; Vogt, D. *Dalton Trans.* **2007**, 5372-5375. (b) Müller, C.; Pidko, E.; Staring, A.; Lutz, M.; Spek, A.; van Santen, R.; Vogt, D. *Chem. Eur J.* **2008**, *14*, 4899-4905.

41 Tognia, A. *Organometallics* **1990**, *9*, 3106-3113.

42 Balaban, A. T.; Barbalescu, N. S. *Revue Roumaine de Chimie* **1966**, *11*, 109-112.

43 Sotiropoulos, J.; Batouti, N.; Lamazouère, A. *Journal of Heterocyclic Chemistry* **1987**, *24*, 907-912.

44 Farcasiu, D. *Tetrahedron* **1969**, *25*, 1209-1211.

45 Beshara, C.; Hall, A.; Jenkins, R.; et al. *Org. Let.* **2005**, *7*, 5729-5732.

46 Barnaud, Y.; Maroni, P.; Simalty, M.; Madaule, Y. *Bull. Soc. Chim. Fr.* **1970**, *4*, 1398-1403.

47 Rodig, R.; Sysco, R. *J. Am. Chem. Soc.* **1972**, *94*, 6475 -6479.

48 Sotiropoulos, J. *C.R. Acad. Sci.* **1970**, *270*, 1727-1730

49 Narasaka, K.; Soai, K.; Mukaiyama, T. *Chem. Lett.*, **1974** 1223.

50 Budavari, S. *The Merck Index* 12th ed. Merck Research Laboratories: Whitehouse Station, NJ, 1996.

51 Hayashi, T. *Catal. Today* **2000**, *62*, 3-15.

52 Tamao, K.; Ishida, N.; Tanaka, T.; Kumada, M. *Organometallics* **1983**, *2*, 1694-1696.

53 Reetz, M. T.; Sell, T.; Meiswinkel, A.; Mehler, G. *Angew. Chem. Int. Ed.* **2003**, *42*, 790-793.

54 (a) van den Berg, M.; Minnaard, A.; Haak, R.; Leeman, M.; Schudde, E.; Meetsma, A.; Feringa, B.; de Vries, A.; Maljaars, C.; Willans, C.; Hyett, D.; Boogers, J.; Henderixkx, H.; de Vries, J. *Advanced Synthesis & Catalysis* **2003**, *345*, 308-323. (b) Hua, Z.; Vassar, V.; Ojima, I. *Organic Letters* **2003**, *5*, 3831-3834. (c) Jerphagnon, T.; Renaud, J.; Bruneau, C., *Tetrahedron: Asymmetry* **2004**, *15*, 2101-2111. (d) Giacomina, F.; Meetsma, A.; Panella, L.; Lefort, L.; de Vries, A.; de Vries, J. *Angewandte Chemie International Edition* **2007**, *46*, 1497-1500. (e)Chapsal, B.; Hua, Z.; Ojima, I. *Tetrahedron: Asymmetry* **2006**, *17*, 642-657.

55 Huynh, C.; Derguini-Boumechal, F.; Linstrumelle, G. *Tet. Let.* **1979**, *17*, 1503-1506.

56 Newman, M.; Farbman, M. *J. Am. Chem. Soc.* **1944**, *66*, 1550-1552.

57 Meshram, H. M.; Reddy, P. N.; Sadashiv, K.; Yadav, J. S. *Tet. Lett.* **2005**, *46*, 623-626.

58 Benson, W.; Pohland, A. *J. Org. Chem.* **1965**, *30*, 1129-1133.

59 Zav'yalov, S. I.; Kondrat'eva, G.V. *J. Gen. Chem USSR*, **1961,** *31*, 3719.

60 Pfleiderer, W.; Schunderbutte, K. H.; *Ann.* **1958,** *612*, 158.

61 Piers, E.; Grierson, J. R.; Lau, C.; Nagakura, I. *Canadian Journal of Chemistry* **1982**, *60*, 210-223.

62 Hassner, A.; Mead, T. C. *Tetrahedron*, **1964**, *20*, 2201-2210.

63 Hashimoto, S.; Koga, K. *Tet. Lett.* **1978**, *6*, 573-576.

64 Enders, D.; Zamponi, A.; Schäfer-Nübling, C.; Eichenauer, H.; Demir, A.; Raabe, G. *Chemische Berichte* **1994**, *127*, 1707-1721.

65 Kabachnik, M. I.; Ioffe, S. T.; Vatsuro, K. V. *Tetrahedron* **1957**, *1*, 317-27.