SYNTHESIS AND MODELING OF ALICYCLIC ORGANIC LIGANDS

Daniël Van Niekerk, B.Sc. Hons. (PU for CHE)

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Supervisor : Dr. AM Viljoen
Co-supervisor : Prof. HCM Vosloo

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I dedicate this dissertation to my mother, Jeannie Van Niekerk, for her support and help throughout my studies.

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List of abbreviations

APT	Attached Proton Test
bpy	2,2′-bipyridine
Bz	Benzyl
^{13}C NMR	Carbon-13 nuclear magnetic spectroscopy
DSC	Differential scanning calorimetry
EI	Electron ionization
EDX	Energy Dispersive spectrometer
FAB	Fast atom bombardment
GC-MS	Gas chromatograph mass spectroscopy
HHS	Homohypostophene
^{1}H NMR	Hydrogen-1 nuclear magnetic spectroscopy
IR	Infrared
LAH	Lithium aluminium hydride
MS	Mass spectroscopy
TG	Termogravimetry
MSD	Mass selective detector
Np	Neopentyl
PPA	Polyphosphoric acid
ppm	Parts per million
SEM	Scanning electron microscopy

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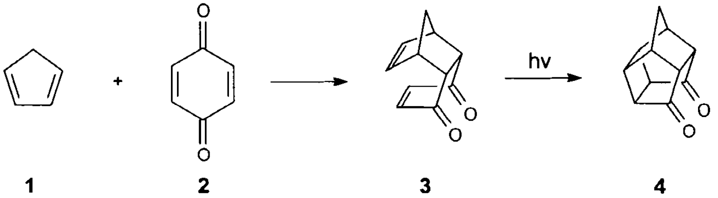
- I thank my Creator for everything.

CHAPTER 1

Introduction and goal of study

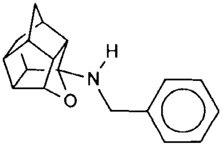
The study of alicyclic cage molecules has in recent years increased due to possibilities in the application of these compounds. Alicylic compounds are defined as organic compounds that have both aliphatic and cyclic characteristics or structures.[1] The photocyclization of the endo conformation Diels-Alder adduct (**3**) of p-benzoquinone (**2**) and cyclopentadiene (**1**) yields the pentacyclic cage compound derivative pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane-8,11-dione (**4**) that is a classical starting material for the synthesis of different alicyclic cage compounds (Scheme 1).[2-4]



Scheme 1

Cage compounds possess rigid structures and contain considerable strain energy. This strain energy is caused by the unusually long framework of carbon-carbon sigma-bonds, and by the unusual C-C-C bond angles that deviate from the "normal" values associated with sp^3 hybridised carbon atoms (109.5°). Steric strain can also express itself in a cage system through increased heat of combustion and increased positive heat of formation relative to that of a corresponding unstrained system.[4]

The synthesis and chemistry of novel nitrogen-containing alicyclic hydrocarbon cage molecules have been the aim of many research groups over the past few decades. Nitrogen-containing alicyclic compounds was found to be of great interest in pharmacological research due to their potential as biologically active agents.[4-7] The hydrophobicity of alicyclic cage molecules enables it to cross the blood-brain barrier and to enter the central nervous system.[6] Because the target of these alicyclic amines is within the central nervous system, numerous studies have been done to investigate the neuroprotective activity and anti-Parkinson activity of these compounds.[5-8] Compound **5** and **6** are two examples of alicyclic amines that exhibit neuroprotective activity.[5,7]



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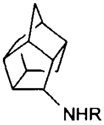

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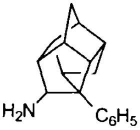
It was also found that some alicyclic cage amines exhibit antiviral activity. Compounds **7** and **8**, for example, were reported to possess antiviral properties.[6,7]



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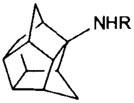

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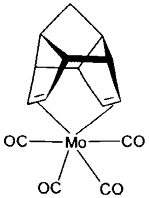
An important challenge in the study of alicyclic cage compounds is the possible use of these compounds as ligands in metal complexes. Electron-rich organic ligands have the ability to bind to metals in solution to form stable metal complexes that can be used in metal extraction, catalysis and in biomolecular fields. It is clear from literature that limited research is being done in the field of alicyclic cage ligand activity and catalysis.[4-20]

Chow *et al.*[9] succeeded with the thermolysis of homohypostophene (HHS) with $Mo(CO)_6$ for the formation of two cage metal complexes. Two metal carbonyl complexes, $(HHS)Mo(CO)_4$ (**9**) and $(HHS)_2Mo(CO)_2$ (**10**) were successfully isolated.



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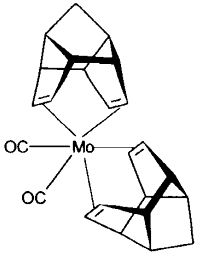

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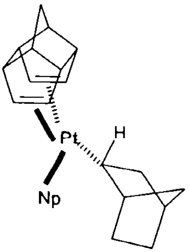
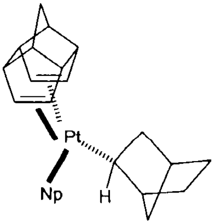
The research of Chow *et al.*[9] was based on research done by Marchand *et al.*[10,11] on the dimerization of norbornadiene by reaction with $Mo(CO)_6$.

Lee *et al.*[12,13] synthesised alicyclic cage compounds that bind to platinum to form HHS platinum complexes. The synthesised HHS platinum complexes, **11** and **12**, can be used for the heterogeneous platinum-catalysed hydrogenation of olefins.[13]



exo

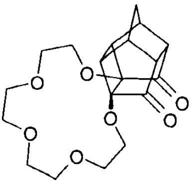
11



endo

12

Crown ethers coordinate strongly to alkali and alkaline earth metals to form very stable metal-ligand complexes. Compound **13** and **14** are two examples of cage crown ethers that were synthesised and their ligand activity were tested using MS-MS techniques.[14,15] The ligand coordinates successfully with lithium, sodium, potassium, rubidium and cesium.



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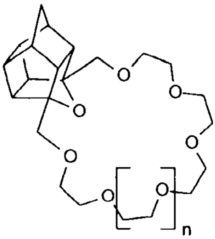

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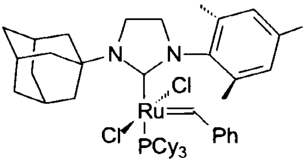
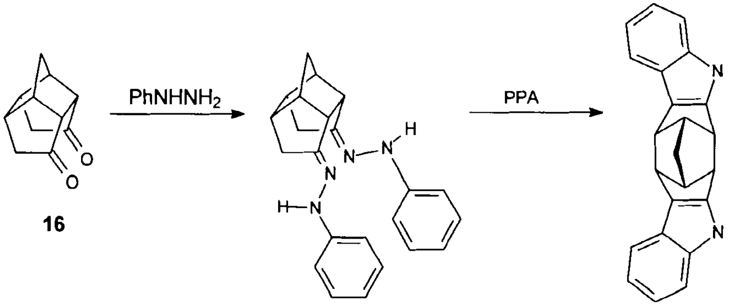
Limited research has been done on alicyclic amine compounds as ligands and catalysts. Dinger *et al.*[16] synthesised a Grubbs metathesis catalyst with adamantyl as an alicyclic component. The Grubbs catalyst **15** was prepared by treating 1-adamantyl-3-mesityl-4-5-dihydro-imidazol-2-ylidene with $[RuCl_2(=CHPh)(PCy_3)_2]$.



15

Complex **15** was found to be a very poor olefin metathesis catalyst, likely a consequence of the excessive steric crowding imparted by the 1-adamantyl side chain.[16]

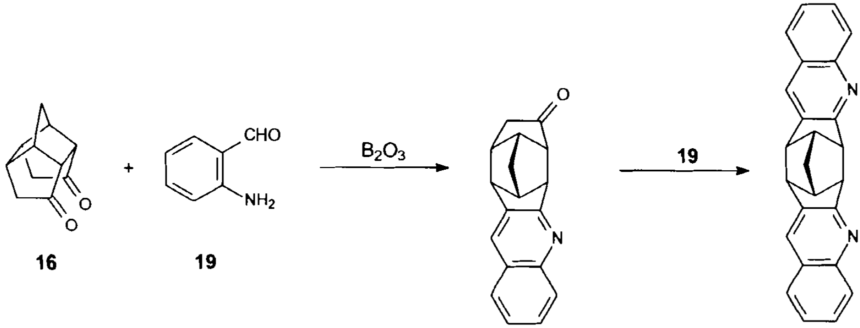
Thummel *et al.*[17] demonstrated the utility of the tetracyclo[6.3.0.0^{4,11}.0^{5,9}]-undecane-3,6-dione (**16**) in the construction of rigid orthocyclophanes (**18**) via the Friedländer methodology (Scheme 2).



Scheme 2

The rigid orthocyclophane compound (**18**) was not studied for metal binding activity.

Research has also been done on synthesising polyaza cavity shaped molecules (**20** and **21**) from aromatic ortho-aminoaldehyde (**19**) and alicyclic diketone (**16**) (Scheme 3).[18-20]



Scheme 3

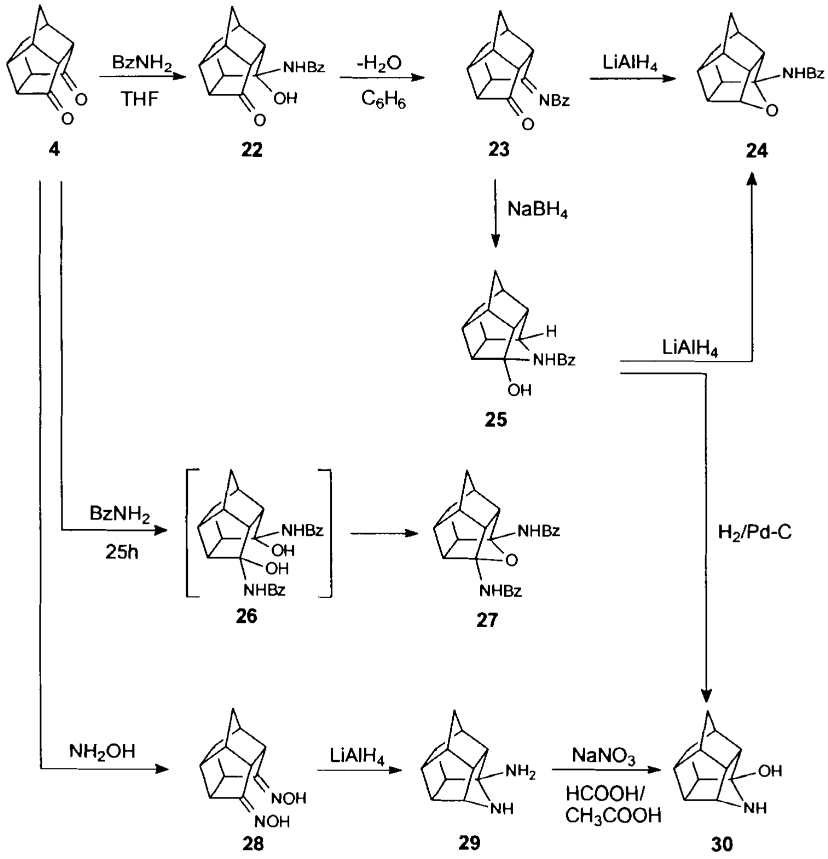
These compounds can be considered to be analogues to 2,2′-bipyridine (bpy) which are very useful ligands in coordination chemistry. These compounds were not studied for metal binding activity.

The aim of this study was to identify alicyclic amines in literature that could possibly bind to transition metals to form stable ligand-metal complexes. Once these compounds were identified, they were synthesized and characterized using infrared spectroscopy, mass spectroscopy and NMR. These compounds were tested for ligand activity using a transition metal associated with the molecular system. In addition to the synthesis, these ligands were also modelled using Spartan Pro and Accelrys Materials Studio to determine specific molecular characteristics.

CHAPTER 2

Literature overview of alicyclic cage amine synthesis

Several methods exist for the synthesis of nitrogen-containing alicyclic cage compounds from pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) and its derivatives. Sasaki *et al.*[21,22] synthesised numerous nitrogen-containing heterocage compounds via transannular cyclization reactions (Scheme 4).

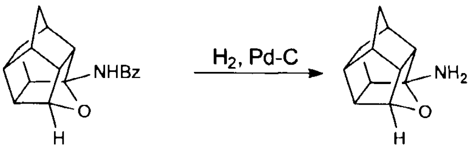


Scheme 4

Transannular cyclizations often provide a convenient method for the preparation of alicyclic heterocage compounds, which are otherwise difficult to obtain.[21,22] When diketone **4** was treated with an equimolar amount of benzylamine in tetrahydrofuran, the corresponding product **22** was afforded. Compound **22** was easily converted to the corresponding Schiff base **23** on refluxing in benzene. Reduction of **23** with lithium aluminium hydride afforded the oxa-bridged cage **24**, while sodium borohydride reduction of **23** afforded the aza-bridged cage **25**. Reduction of **25** with lithium aluminium hydride gave the oxa-bridged cage **24**.

Treatment of diketone **4** with two molar equivalents of benzylamine at 0 °C and then stirred at room temperature for 12 h afforded compound **26** which undergoes transannular cyclization to afford compound **27**. Due to transannular cyclization compound **26** could not be isolated. Treatment of diketone **4** with hydroxylamine afforded the bisoxime **28**. Reduction of the bisoxime **28** with lithium aluminium hydride afforded 3-amino-4-aza-cage **29**. Deamination of **29** with sodium nitrite in a formic acid and acetic acid mixture afforded compound **30**. Compound **30** can also be prepared by the catalytic hydrogenation of **25** over 10% palladium on carbon in ethanol.

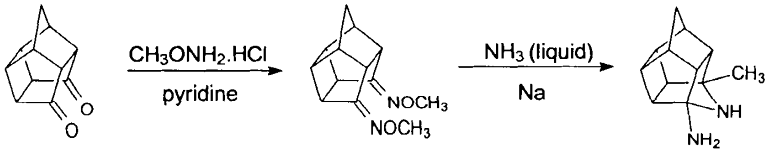
Marchand *et al.*[23] confirmed most of the results of Sasaki *et al.*[21,22] They found that compound **24** can also undergo catalytic hydrogenation over palladium on carbon to form the amine-oxa cage compound **31** (Scheme 5).



24 **31**

Scheme 5

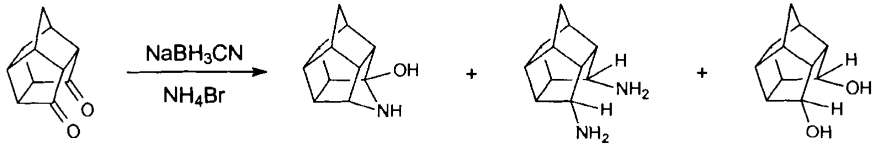
Singh *et al.*[24] found that treatment of the diketone **4** with methoxyamine hydrochloride in pyridine afforded a mixture of stereoisomeric di-O-methyloximes similar to **32**. Different heterocage compounds can be synthesised from compound **32** via transannnular cyclization reactions. An interesting example is the diamine cage **33**.[24] The diamine **33** was prepared by the reduction of **32** with sodium in liquid ammonia (Scheme 6).



4 **32** **33**

Scheme 6

Marchand *et al.*[25] investigated the reductive amination of diketone **4** by using sodium cyanoborohydride in the presence of ammonium bromide. The reaction afforded a mixture of three products **30**, **34** and **35** (Scheme 7).

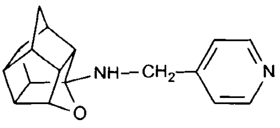


4 **30** **34** **35**

Scheme 7

Product **30** could be isolated using fractional crystallisation of the product mixture. Product **34** and **35** was isolated by acetylation of the product mixture and doing fractional crystallization (afford compound **34** after hydrolysis) and column chromatography (afford compound **35** after hydrolysis). The yield after separation was 10% for compound **34** and 14% for compound **30**.

8-Benzylamino-8,11-oxapentacyclo[5.4.0.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$]undecane (**24**) was studied by various research groups due to its possible pharmacological character. Malan *et al.*[26] and Zah *et al.*[7] synthesised various derivatives of this compound and studied them for pharmacological activity. Two examples of polycyclic amines synthesised are 8-[(4-aminomethyl)pyridine]-8,11-oxapentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane (**36**) and 8-(4-aminobenzylamino)-8,11-oxapentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane (**37**).



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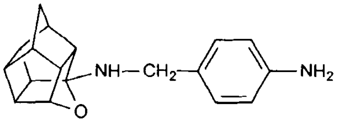
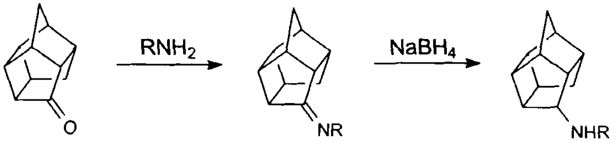


37

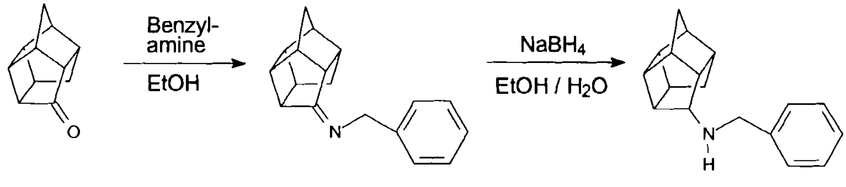
Monosubstituted pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylamines can be synthesised using pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (**38**) as a starting material (Scheme 8).[6] The monoketone **38** was treated with a primary amine in ethanol for 12 h at 100 °C to yield the imine **39**. This imine was treated with sodium borohydride in ethanol and heated for 5 h. This reduction reaction yielded the monosubstituted pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecylamine **40**.[6]



38 **39** **40**

Scheme 8

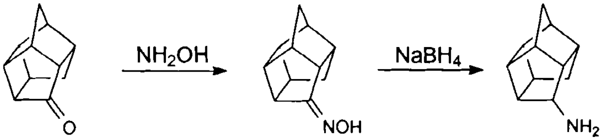
Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (**38**) was treated with benzylamine in ethanol and refluxed for 24 h to yield imine **41**.[26] The imine **41** was dissolved in ethanol and water, treated with sodium borohydride and then stirred at room temperature for 24 h to yield product **42**.



38 **41** **42**

Scheme 9

The monoketone **38** was treated with hydroxylamine hydrochloride in 30% sodium hydroxide and ethanol and refluxed for 5 h to yield the oxime cage **43** (Scheme 10).[6] Lithium aluminium hydride reduction was done on oxime **43** in tetrahydrofuran to yield pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylamine (**44**).



38 **43** **44**

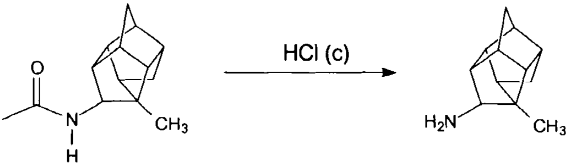
Scheme 10

The monoketone **38** can also be converted to 8-methylpentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-ol (**45**) when treated with an appropriate Grignard reagent.[5] Compound **45** was then treated with nitrile **46** in H_2SO_4 for 3 h to yield product **47** (Ritter reaction) (Scheme 11).

45 **46** **47**

Scheme 11

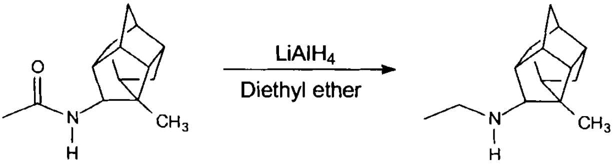
Product **47** was treated with concentrated hydrochloric acid to form the corresponding primary amine cage **48** (Scheme 12).



47 **48**

Scheme 12

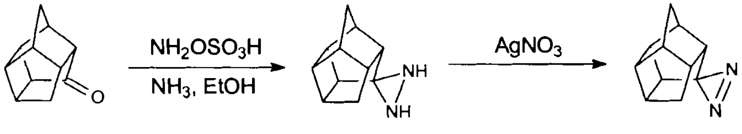
Compound **47** can also undergo lithium aluminium hydride reduction in diethyl ether to form a secondary amine cage **49** (Scheme 13).



47 **49**

Scheme 13

When the monoketone **38** was treated with NH_2OSO_3H and liquid ammonia in ethanol at –70 °C a diaziridine cage **50** was formed. Oxidation of **50** with silver nitrate afforded pentacyclo[$5.4.0^{2,6}.0^{3,10}.0^{5,9}$]undecane-8-diazirine (**51**) (Scheme 14).[27]

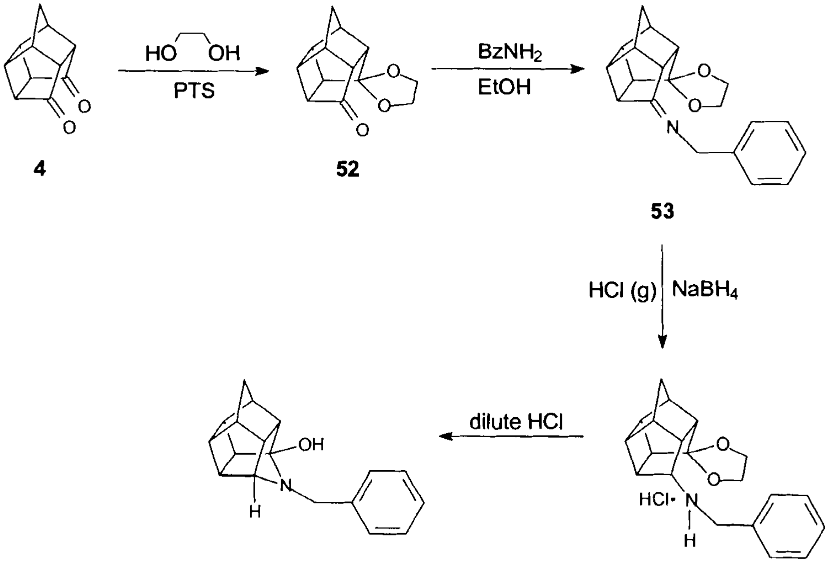


38 **50** **51**

Scheme 14

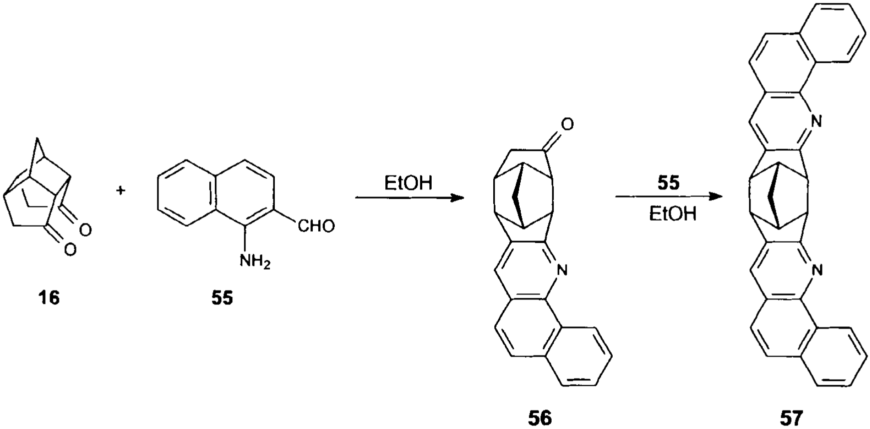
Another derivative of the diketone **4** that can be used in the synthesis of amine cage compounds is the ketal **52**. Reaction of **4** with ethane-1,2-diol and *p*-toluene sulfonic acid in boiling benzene for 5 h yielded ketal **52**.

Ketal **52** was treated with benzylamine in ethanol at 100 °C for 14 h to yield the intermediate imine **53**.[28] The reaction mixture containing the imine was treated with excess sodium borohydride at room temperature for 4 h to form the corresponding amine **54**. Hydrolysis of compound **54** using dilute HCl resulted in the formation of the aza-caged product **25** (Scheme 15).[28]



Scheme 15

The last example of cage amines is the synthesis of rigid ortho-cyclophane cage compounds. In this synthesis diketone **16** and ortho-aminoaldehyde **55** was used in the preparation of rigid ortho-cyclophanes via the Friedlander methodology (Scheme 16).[18-20,29] One of many examples is the synthesis of the benzo[*g*]quinoline cage compounds **56** and **57**.



Scheme 16

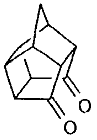
From this short literature overview it can be concluded that various nitrogen-containing alicyclic cage compounds exists. The type of nitrogen-containing cage compound synthesised depends on the starting material used.

CHAPTER 3

Synthesis and modelling of alicyclic amine ligands

3.1 Introduction

In literature the following three cage compounds have been identified as very reliable starting materials for the synthesis of nitrogen-containing alicyclic cage compounds.



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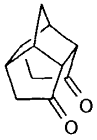

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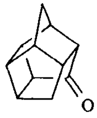
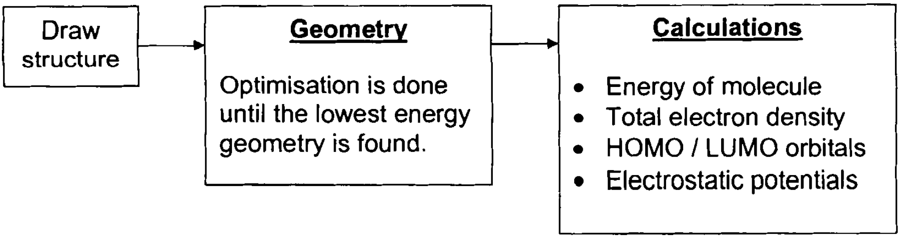


38

Both the tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione (**16**) and pentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (**38**) derivatives can be synthesised from pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-6,8-dione (**4**). [2,3,4,6] All three of these compounds have the ability to react with primary amines to form stable amine cage compounds. In the case of monoketone **38** and diketone **16** an imine is formed when reacting with an primary amine.[6] Diketone **4** is well known for undergoing transannular cyclization in the presence of a primary amine. [21,22] The reaction with diketone can be controlled by the molar amount of primary amine added to the reaction to form either oxa or aza transannular cyclization products.

In addition to the synthesis, these ligands were also modelled using Spartan Pro and Accelrys Materials Studio (VAMP). Spartan Pro was used to obtain the lowest possible geometry energy of the ligand by doing a geometry conformation search on the molecules. This was used to confirm that the lowest energy geometry for the molecule was reached. All molecular modelling calculations were done using semi-empirical calculations (AM1 base set).[30] The molecular modelling process for this project was as follows:



A geometry optimization was done on the ligand to obtain the energy and the electron density surface. The energy of a molecule depends on its geometry.[31] Therefore the correct molecular geometry is important before carrying out any calculations. The total electron density surface demarks the locations of the electrons of the molecule. The density surface serves to locate the chemical bonds and to indicate overall molecular size and shape.[31,32]

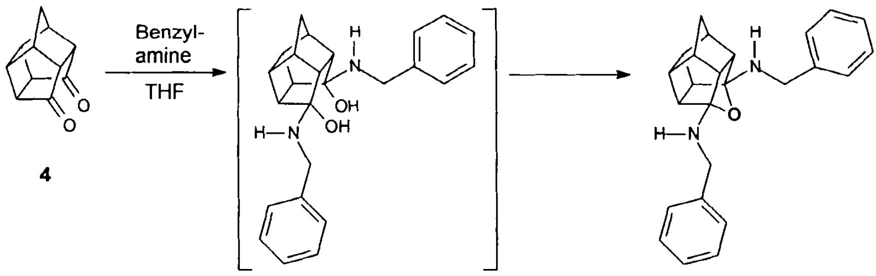
Two of the most significant orbitals that can be calculated using molecular modelling is the Highest Occupied Molecular Orbital (HOMO) and the Lowest Unoccupied Molecular Orbital (LUMO).[31] These orbitals are called the frontier orbitals, because they lie at the outermost boundaries of the molecules and they determine the way molecules interacts with other species. The HOMO is the orbital that could act as an electron donor (nucleophile), since it is the outermost (highest energy) orbital containing electrons. The LUMO is the orbital that could act as the electron acceptor (electrophile), since it is the innermost (lowest energy) orbital that has room to accept electrons.[31-33]

Molecular modelling was therefore used in this chapter to determine the lowest energy geometry and to calculate the HOMO and LUMO orbitals.

3.2 Synthesis of cage amines using pentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (4)

3.2.1 Synthesis of 3,5-bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane (27)[21,22]

Treatment of the diketone **4** with two molar equivalents of benzylamine at room temperature for 12 h afforded 3,5-bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane (**27**). This synthetic method used by Sasaki *et al.*[21,22] gave a yield of 70% (Scheme 17).



4 **26** **27**

Scheme 17

Nucleophilic attack on the ketone by the lone-pair electrons of the nitrogen of benzylamine leads to the formation of a neutral dicarbinolamine **26**. The dicarbinolamine undergoes immediate transannular cyclization to afford the oxa-cage **27**. Due to this immediate cyclization compound **26** could not be isolated.[21,22]

It was found that when diketone **4** was dissolved in two molar equivalents of benzylamine and heated at 100 °C for 10 min the oxa-cage **27** could also be afforded. This second method was found to be more successful with respect to both time of synthesis and yield (80%). After repeated recrystallization with n-hexane-methylene chloride (1:1), the product was analysed using GC-MSD (Figure 3.1).

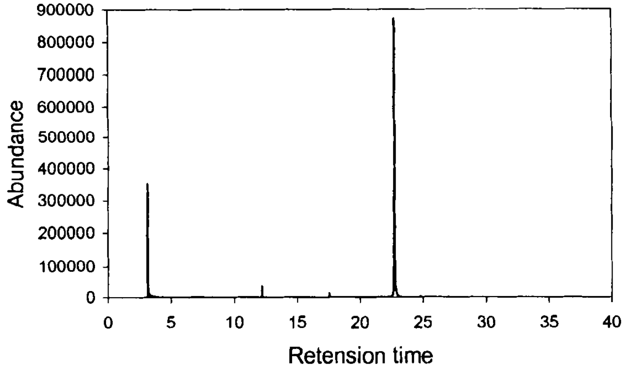
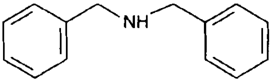


Figure 3.1 GC Chromatogram of compound **27**

The first peak (3.14 min) was identified as benzylamine (m/z 107, M^+) (EI MS spectrum 10) and the third peak (22.74 min) as the oxa-cage compound **27** (m/z 352, M^+) (EI MS spectrum 6). The second compound (12.20 min) was identified as dibenzylamine **58** (m/z 196, M^+) (EI MS spectrum 11), which was found to be a contaminant in the benzylamine reagent.



58

It was very difficult to get a pure sample of **27** as result of the benzylamine contamination. Various separation techniques were used in an effort to remove the benzylamine from the sample. Distillation, fractional distillation, recrystallization, column chromatography, sublimation and various other techniques were employed but with no success. Only with repeated recrystallisation from n-hexane-methylene chloride (1:1) could a purity of about 85%, as determined by GC analysis and ^{13}C NMR, be obtained which resulted in a very low yield of product.

The mass spectrum (EI MS spectrum 6) shows a molecular ion at m/z 352 (M^+) that is 18 less than the expected molecular formula of $C_{25}H_{26}N_2O$. It is speculated that a H_2O fragment (m/z 18) is lost during the ionisation process in the electron impact MS to yield the m/z 352 molecular ion.

The infrared spectrum (IR spectrum 6) of **27** exhibits a single N-H stretching vibration at 3400 cm^{-1}, which is typical of a secondary amine. There is a strong C-H stretching vibration at 2950 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that compound **27** has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the overtone bands in the 1700-2000 cm^{-1} region and the =C-H out-of-plane bending vibrations at 700 cm^{-1} and 740 cm^{-1}. The infrared spectrum is identical to that in literature.[21,22]

The ^{13}C NMR and DEPT NMR (NMR spectra 15 & 16) in $CDCl_3$ show signals that can be associated with eleven different carbon atoms. The ^{13}C DEPT NMR data is summarised in Table 1.

Table 1 ^{13}C DEPT NMR data of **27**

Carbon	Position (δ_C, ppm)
CH_2	48.65, 48.01
Unprotonated C	93.48, 141,29
Aliphatic CH	41.99, 44.41, 48,68
Aromatic CH	126.51, 127.86, 128.09, 128.26, 128.46

The DEPT spectrum shows that 2 CH_2, 3 aliphatic CH and 5 aromatic CH groups are present in the compound. Two unprotonated (quaternary) carbons are also present. The position of the signal at δ_C 126.18 correlates with the position of the aromatic CH signal of pure benzylamine and may thus be attributed to benzylamine contamination. The DEPT spectrum shows the presence of 3 aliphatic CH signals instead of 4 CH groups. It is possible that the CH signals overlay each other. To resolve this HETCOR and COSY

NMR should be done. Two-dimensional NMR was not done due to the impurities in the sample. The ^{1}H NMR data (NMR spectra 14) was identical to that of literature. The correlation between Sasaki's proton NMR and the NMR obtained in this study shows that Sasaki et al.[21,22] also had a benzylamine impurity in their analytical sample.

Thermal analysis of compound **27** was done with DSC and TG (DSC and TG curve 1). The DSC data shows a melting point of 134.10 °C and a decomposition peak in the temperature range 160 – 180 °C. Benzylamine has a boiling point of 180 °C and this peak is the benzylamine contaminant in the sample going into a gas phase. The sample start to decompose from 200 °C. According to the TG about 18.85% of the mass of the sample is lost by the time that a temperature of 200 °C is reached. This correlates to the amount of benzylamine in the sample.

3.2.2 Molecular modelling of 3,5-bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane (27)

Spartan Pro's conformational search calculation was used to determine the lowest possible geometry energy for 3,5-bis(N-benzylamino)-4-oxa-hexacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane (**27**). Figure 3.2 shows the geometry that was found to be the most stable.

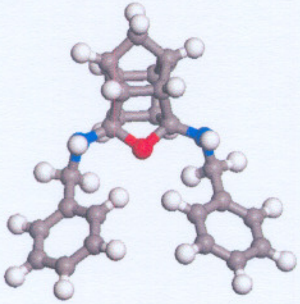


Figure 3.2 Calculated stable geometry of **27**

This geometry shows that the compound is symmetrical and this supports the NMR data (symmetry is present in the NMR spectra). The electron density surface of the compound was calculated as well as the HOMO and LUMO frontier orbitals (Figure 3.3 and Figure 3.4).

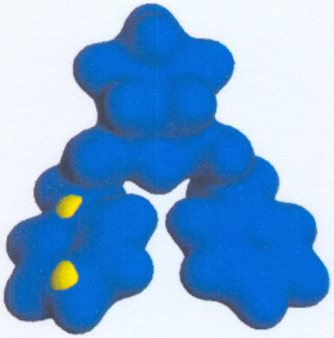


Figure 3.3 Calculated electron cloud with LUMO orbitals of **27**

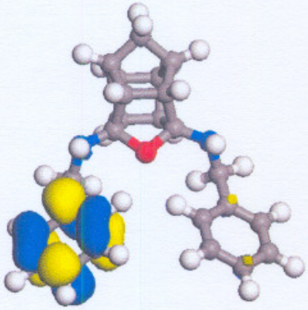
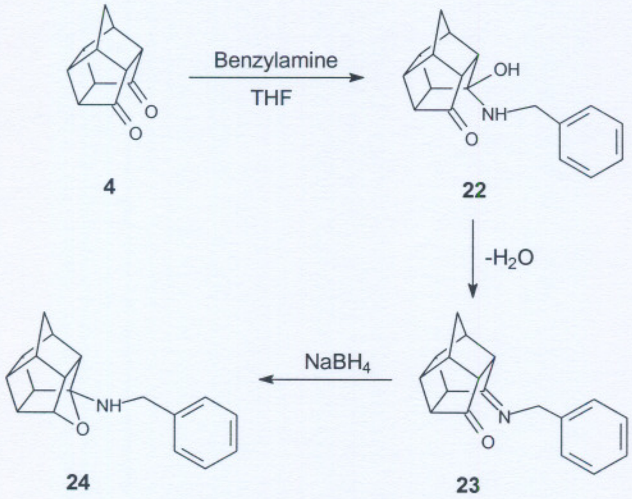


Figure 3.4 Calculated LUMO orbitals of **27**

It was found that only the LUMO orbitals pierce through the electron density surface. The compound is thus still prone to nucleophilic attack (compound acts as a electrophile) on the one benzene ring.

3.2.3 Synthesis of 8-benzylamino-8,11-oxa-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane (24)[7,34]

Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) was treated with an equimolar quantity of benzylamine in tetrahydrofuran. After ten minutes the white hydroxylamine (**22**) precipitates. Refluxing of **22** in benzene under Dean-Stark conditions gave the imine **23,** which was then reduced using sodium borohydride to afford 8-benzylamino-8,11-oxapentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane **24** (Scheme 18).[7,34] A very pure sample of compound **24** could be obtained for characterization.



Scheme 18

The mass spectrum (EI MS spectrum 5) shows a molecular ion at m/z 265 (M^+) and is supportive of a molecular formula of $C_{18}H_{19}NO$.

The infrared spectrum (IR spectrum 5) of compound **24** exhibits a single N-H stretching vibration at 3300 cm^{-1}, which is typical for a secondary amine. There is a strong C-H stretching vibration at 2950 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that this compound has both an aliphatic and aromatic character. The C-O stretch vibration is observed at 1020 cm^{-1}. The infrared spectrum is identical to that in literature.[7,34]

The ^{13}C NMR (NMR spectra 13) in $CDCl_3$ show signals that can be associated with 16 different carbon atoms. The ^{13}C DEPT data is summarised in Table 2.

Table 2 ^{13}C NMR data of **24**

Carbon	Position (δ_C , ppm)
CH_2	47.73, 43.18
Unprotonated C	109.62, 140.96
Aliphatic CH	82.48, 55.22, 54.73, 44.83, 44.79, 44.50, 43.07, 41.93, 41.47
Aromatic CH	128.40, 127.92, 126.85

The ^{13}C NMR spectrum shows that 2 CH_2, 9 aliphatic CH and 3 aromatic CH groups are present in the compound. Two unprotonated (quaternary) carbons are also present. The ^1H NMR (NMR spectrum 12) and ^{13}C NMR data are identical to that of literature.[7,34]

3.2.4 Molecular modelling of 8-benzylamino-8,11-oxapentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane (24)

The lowest energy geometry for 8-benzylamino-8,11-oxapentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane (**24**) was calculated using Materials Studio Vamp (Figure 3.5). This geometry supports the NMR data obtained (no symmetry was observed in the NMR spectra).

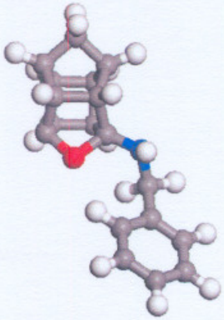


Figure 3.5 Calculated stable geometry of **24**

The electron density surface of the compound **24** was calculated as well as the HOMO and LUMO frontier orbitals (Figure 3.6 and Figure 3.7).

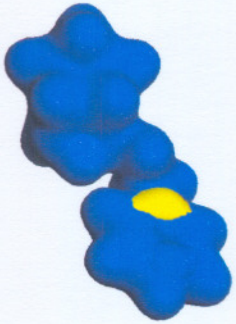


Figure 3.6 Calculated electron cloud with HOMO orbitals of **24**

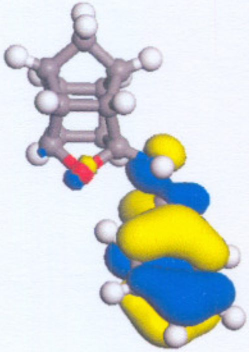


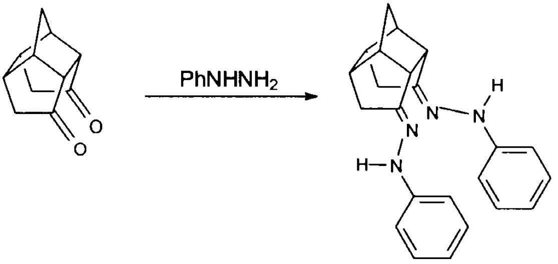
Figure 3.7 Calculated HOMO orbitals of **24**

It was found that only the HOMO orbitals pierce through the electron density surface. The benzene ring is thus still prone to electrophilic attack.

3.3 Synthesis of cage amines using tetracyclo[6.3.0.0^{4,11}.0^{5,9}]-undecane-3,6-dione (16)

3.3.1 Synthesis of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecanedione-bis-(phenylhydrazone) (17)[17]

Treatment of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) with zinc and acetic acid causes reductive cyclobutane ring cleavage to yield tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione (**16**).[35-37] Diketone **16** was treated with two molar equivalents of phenylhydrazine and refluxed at 100 °C for 1 h to yield 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecanedione-bis(phenylhydrazone) **17** (Scheme 19).[17]



16 **17**

Scheme 19

After recrystallisation from ethanol, product **17** was isolated as pale-yellow crystals.

The mass spectrum (EI MS spectrum 7) shows a molecular ion at m/z 356 (M^+) and is supportive of a molecular formula of $C_{23}H_{24}N_4$.

The infrared spectrum (IR spectrum 7) of **17** exhibits a single N-H stretching vibration at 3350 cm^{-1} which is typical for a secondary amine. There is a strong C-H stretching vibration at 2950 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that this compound has both an aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the overtone bands in the 1700-2000 cm^{-1} region, the =C-H out-of-plane bending vibrations at 700 cm^{-1} and 740 cm^{-1} and the C=C vibration at 1500 cm^{-1}. There is a strong C=N stretch vibration of the imine at 1680 cm^{-1}. The infrared spectrum of **17** is identical to that of literature.[17]

The ^{13}C NMR and DEPT NMR (NMR spectra 18 & 19) in $CDCl_3$ show signals that can be associated with eighteen different carbon atoms. The ^{13}C DEPT NMR is summarised in Table 3.

Table 3 ^{13}C DEPT NMR data of **17**

Carbon	Position (δ_C , ppm)
CH_2	28.58, 33.45, 34.28
Unprotonated C	145.11, 146.49, 155.39, 159.73
Aliphatic CH	40.26, 40.65, 47.12, 48.09, 48.62, 51.87
Aromatic CH	113.08, 113.90, 119.52, 119.69, 128.69

The DEPT spectrum shows that 3 CH_2 groups and 13 CH groups are present in the compound. Seven of the CH groups absorb in the aromatic and unsaturated region of the spectra and the other 6 CH groups absorb in the non-aromatic (saturated) region of the spectra. The 4 unprotonated carbon signals are found in the δ_C 140-160 region. The ^{13}C NMR spectrum corresponds to the desired product. The ^1H NMR (NMR spectrum 17) of **17** is identical to that of literature.[17]

3.3.2 Molecular modelling of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(phenylhydrazone) (17)

The lowest energy geometry of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(phenylhydrazone) (**17**) was found using Materials Studio Vamp. Molecular modelling of **17** yielded three very stable geometries. The first geometry (Figure 3.8) with the N-H groups in a trans (opposite) and the remaining two geometries with cis configurations (N-H above and N-H below).

The heat of formation of these compounds are 144.74 Kcal/mol (Figure 3.8), 146.14 Kcal/mol (Figure 3.9) and 145.96 Kcal/mol (Figure 3.10). It is therefore concluded that different isomers for this compound exist.

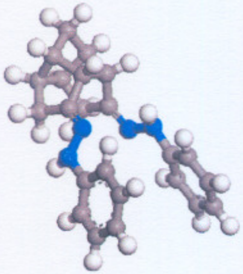


Figure 3.8 Calculated geometry

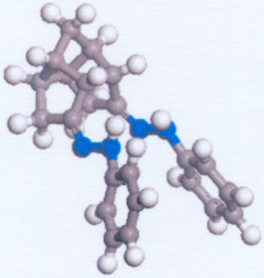


Figure 3.9 Calculated geometry

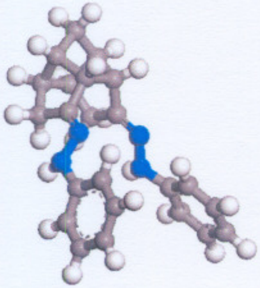


Figure 3.10 Calculated Geometry

Figure 3.8 is the lowest energy geometry for compound **17**. This geometry conformation shows that the compound is not symmetrical and supports the NMR data. The electron density surface of compound **17** was calculated as well as the HOMO and LUMO frontier orbitals (Figure 3.11, 3.12, 3.13, and 3.14).

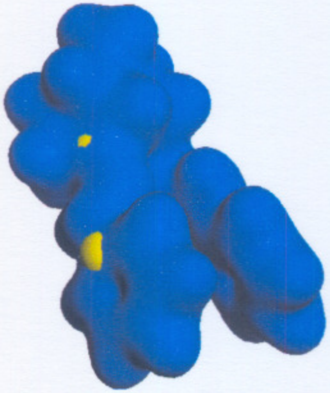


Figure 3.11 Calculated electron cloud with LUMO orbitals of 17

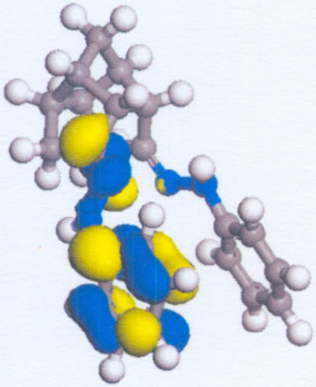


Figure 3.12 Calculated LUMO orbitals of 17

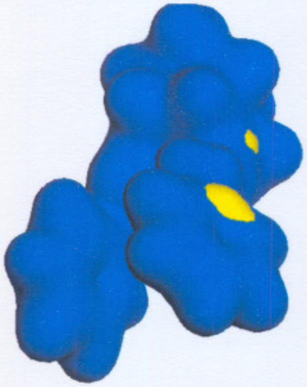


Figure 3.13 Calculated electron cloud with HOMO orbitals of 17

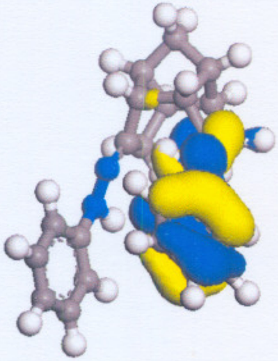
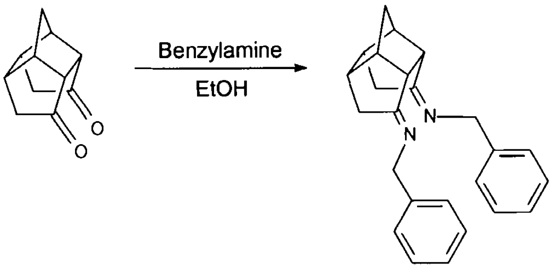


Figure 3.14 Calculated HOMO orbitals of 17

It was found that both the LUMO and HOMO frontier orbitals pierce through the electron density surface. This compound is prone to both nucleophilic attack and electophillic attack, in other words compound **17** can act as both electrophile and nucleophile. When the electron density surface is removed it is observed that nucleophilic attack can take place on the one benzene ring and electrophilic attack can take place one the other benzene ring (Figure 3.12 and 3.14).

3.3.3 Synthesis of novel 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecanedione-bis-(benzylamine) (59)

Tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione was treated with two molar equivalents of benzylamine and refluxed at 100 °C for 1 h to yield novel 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-bis(benzylamine) **59** (Scheme 20).



16 **59**

Scheme 20

After recrystallization from ethanol the product was analysed using GC-MS. The GC-MS profile showed the presence of two compounds (Figure 3.15). The first peak (3.14 min) was identified as benzylamine (m/z 107, M^+) (EI MS spectrum 10) and the second peak (22.74 min) as the imine compound **59** (m/z 354, M^+) (EI MS spectrum 8). Various separation techniques were used in an effort to remove the benzylamine from the sample, but with no success.

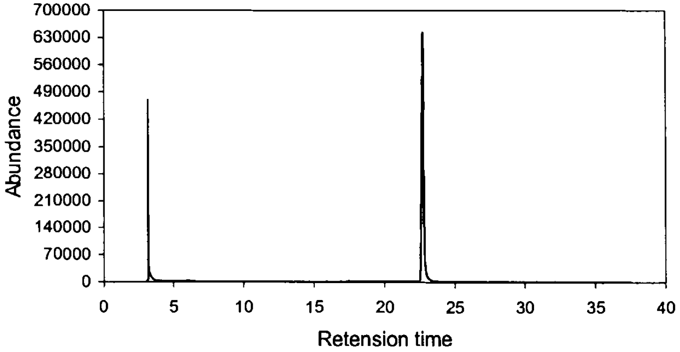


Figure 3.15 GC Chromatogram of compound **27**

The mass spectrum (EI MS spectrum 8) shows a molecular ion at m/z 354 (M^+) and is supportive of a molecular formula of $C_{25}H_{26}N_2$.

The infrared spectrum (IR spectrum 8) of compound **59** exhibits a strong C-H stretching vibration at 2950 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that this compound has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the overtone bands in the 1800-2000 cm^{-1} region, the =C-H out-of-plane bending vibrations at 700 cm^{-1} and 740 cm^{-1} and the C=C vibration at 1500 cm^{-1}. The infrared spectrum also exhibits N-H stretching vibration at 3400 cm^{-1} which may be from the benzylamine contaminant.

Thermal analysis of novel compound **59** was done with DSC and TG (DSC and TG curve 2). The DSC data shows a melting point of 103.07 °C and a decomposition peak in the temperature range 135 – 160 °C. The decomposition peak is due to the benzylamine contaminant in the sample going into a gas phase. According to the TG about 23.8% of the mass of the sample is lost by the time that a temperature of 200 °C is reached. This correlates to the amount of benzylamine in the sample.

The ^{13}C NMR and DEPT NMR (NMR spectra 21 & 22) in $CDCl_3$ show signals that can be associated with seventeen different carbon atoms. The ^{13}C DEPT NMR is summarised in Table 4.

Table 4 ^{13}C DEPT NMR data of **59**

Carbon	Position (δ_C , ppm)
CH_2	35.65, 36.01, 47.12, 48.69
Unprotonated C	89.10, 141.96, 142.34
Aliphatic CH	42.37, 47.12, 48.69, 51.56
Aromatic CH	126.12, 126,25, 127.65, 128.04, 128.20, 129.13

The DEPT spectrum shows that 4 CH_2 groups are present in the compound. Four aliphatic CH, and 6 aromatic CH groups are present in the compound. Three unprotonated (quaternary) carbons are also present. The ^{13}C NMR spectrum shows that the compound contains a impurity that was identified as benzylamine using GC-MS. Due to the contaminants present the ^{1}H NMR spectrum gave no detailed information regarding the molecular stucture. To characterize this compound a pure analytical sample of **59** is needed. Due to the contaminants present a HETCOR and COSY NMR spectra could not be obtained.

3.3.4 Molecular modelling of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(benzylamine) (59)

The lowest energy geometry for 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecanedione-bis(benzylamine) (**59**) was calculated using Materials Studio Vamp (Figure 3.16).

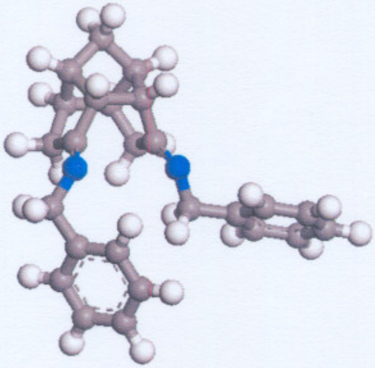


Figure 3.16 Calculated stable geometry of **59**

The electron density surface of compound **59** was calculated as well as the HOMO and LUMO frontier orbitals (Figure 3.17, 3.18, 3.19 and 3.20).

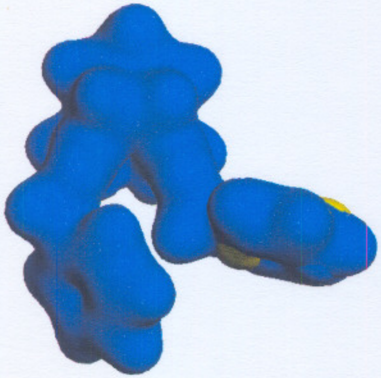


Figure 3.17 Calculated electron cloud with HOMO orbitals of **59**

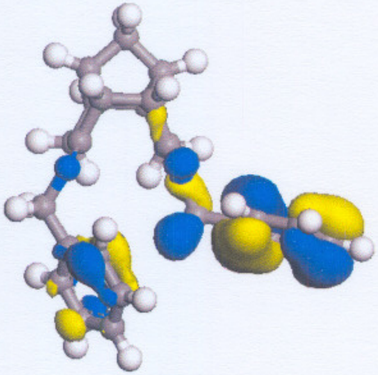


Figure 3.18 Calculated HOMO orbitals of **59**

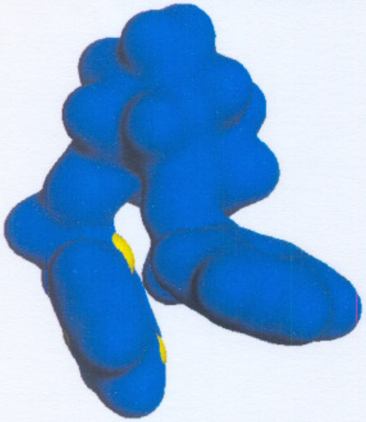


Figure 3.19 Calculated electron cloud with LUMO orbitals of **59**

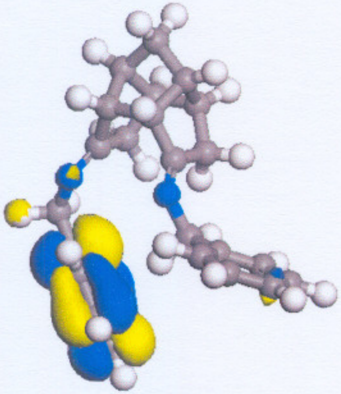


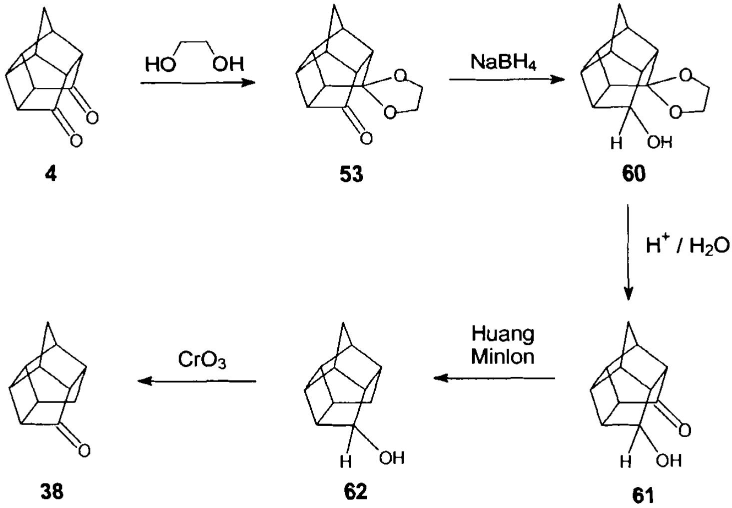
Figure 3.20 Calculated LUMO orbitals of **59**

It was found that both the LUMO and HOMO frontier orbitals pierce through the electron density surface. This compound can undergo nucleophilic attack and electrophillic attack, in other words compound **59** can act as both electrophile and nucleophile. When the electron density surface is removed it is observed that nucleophilic attack can take place on the one benzene ring and electrophilic attack can take place one the other benzene ring (Figure 3.18 and 3.20).

3.4 Synthesis of cage amines using pentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (38)

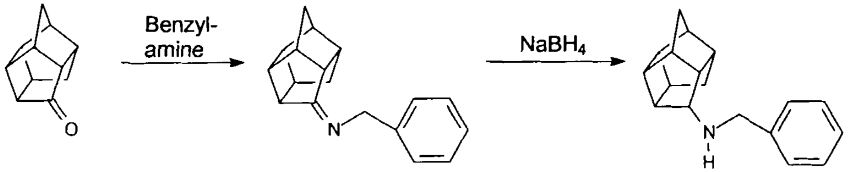
3.4.1 *Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-amine (42)*

Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one **38** was prepared from diketone **4** in a multi-step synthesis. Different synthesis routes exist for the monoketone but Scheme 21 was found to be the best with respect to both ease and yield.[26]



Scheme 21

The monoketone **38** could easily be converted by condensation with various primary alkylamines, to the respective amines. When monoketone **38** was treated with an equimolar amount of benzylamine and refluxed in ethanol for 25 h, the corresponding imine **41** was afforded. Reduction of the unpurified imine with sodium borohydride afforded the mono amine cage **42** (80% yield).[6]



38 **41** **42**

Scheme 22

It was found that when monoketone **38** was dissolved in an equivalent amount benzylamine and heated at 100 °C for 10 minutes compound **41** was also afforded. The second method was found to be more effective due to shorter time of synthesis but gave the same yield (80%). The amine cage was isolated by conversion of the free base to the corresponding amine salt. The amine salt was recrystalised in ethanol and was analysed using GC-MS. The GC-MS profile showed the presence of three compounds (Figure 3.21).

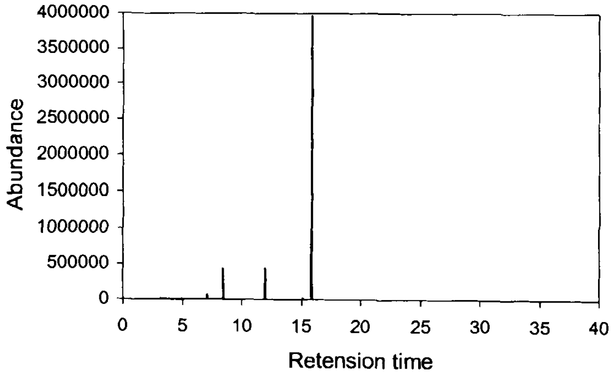


Figure 3.21 GC Chromatogram of compound **42**

The first peak (8.414 min) was identified as compound **62** (162 m/z, M^+) and the third peak (22.745 min) as the amine compound **42** (251 m/z, M^+) (EI MS spectrum 9). The second peak shows the presence of the dibenzylamine contaminant (196 m/z, M^+) (EI MS spectrum 11).

The mass spectra (EI MS spectrum 9) shows a molecular ion at m/z 251 (M^+) and is supportive of a molecular formula of $C_{18}H_{21}N$.

The infrared spectrum (IR spectrum 9) of **42** showed a strong N-H stretching vibration in the 2470 cm^{-1} to 3080 cm^{-1} region consisting of multiple bands. This is typical for salts of secondary amines. A N-H bending vibration can be observed in the 1600 cm^{-1} region. The aromatic character of the compound can be confirmed by the =C-H out-of-plane bending vibrations at 710 cm^{-1} and 780 cm^{-1}. This spectra is identical to that of literature.[6]

The ^{13}C NMR and DEPT NMR (NMR spectra 24 & 25) in $CDCl_3$ of compound **42** show signals that can be associated with eighteen different carbon atoms (Table 5).

Table 5 ^{13}C DEPT NMR data of **42,**

Carbon	**Position (δ_C , ppm)**
CH_2	29.627, 34.140, 51.05
Unprotonated C	130.920
Aliphatic CH	35.901, 35.095, 39.814, 40.945, 41895, 42.488, 44.116, 46.911, 57.43
Aromatic CH	128.846, 128.923, 128.976, 130.152, 130.350

The DEPT spectra shows that 3 CH_2 groups, 9 aliphatic CH and 5 aromatic CH groups are present in the compound. One unprotonated (quaternary) carbon was also present. The N-H proton in the ^1H NMR spectra was identified in the δ_H 9.4 – 10.0 region. The ^1H (NMR spectrum 23) and ^{13}C NMR are identical to that of literature.

3.4.2 *Molecular modelling of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-amine (42)*

The lowest energy geometry for compound **42** was calculated using Materials Studio Vamp and Spartan Pro (Figure 3.22).

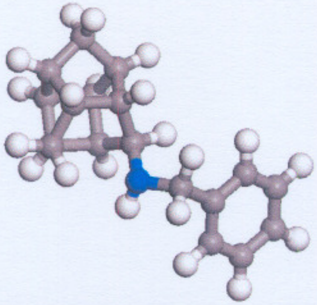


Figure 3.22 Calculated stable geometry of **42**

This geometry supports the NMR data obtained (no symmetry is present in the NMR spectra). The electron density surface of compound **42** was calculated as well as the HOMO and LUMO frontier orbitals (Figure 3.23).

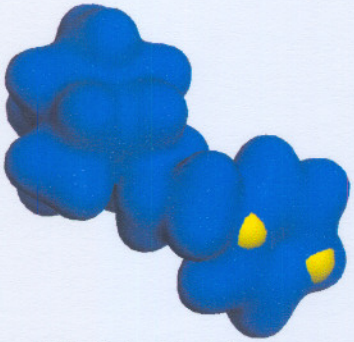


Figure 3.23 Calculated electron cloud with LUMO orbitals of **42**

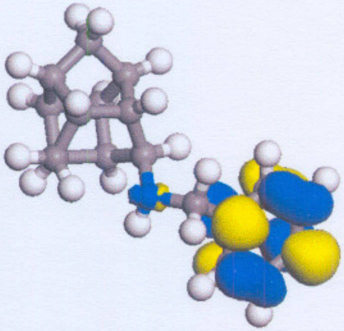
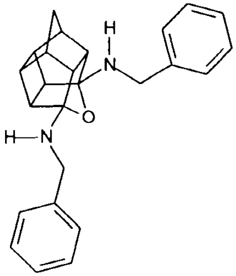


Figure 3.24 Calculated LUMO orbitals of **42**

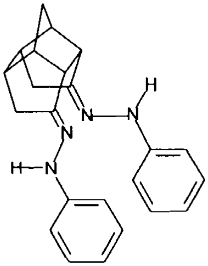
It was found that only the LUMO orbitals pierce through the electron density surface (Figure 3.24).

3.5 Conclusion

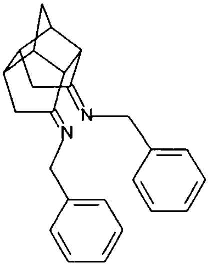
Different pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylamines were identified in literature and synthesised in this study:



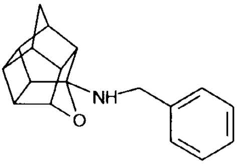
27



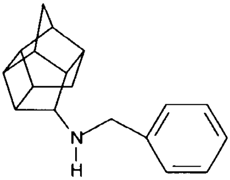
17



59



24



42

It was found (as confirmed in literature) that pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane-8,11-dione **4** reacts with primary amines to yield transannular cyclization products. Monoketone **38** and diketone **16** did not undergo transannular cyclization when reacting to amines. No analytical pure samples of compound **27** or **59** could be obtained due to benzylamine contamination. This contamination was supported by thermal analysis, GC-MS and ^{13}C NMR.

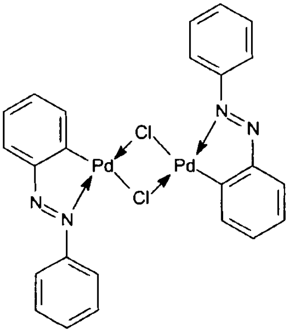
These compounds were modelled using semi-empirical calculations to determine the lowest energy geometry. With electron density surface and HOMO and LUMO calculations it was shown that all the ligands can undergo either nucleophilic or/and electrophilic attack on the benzene ring (under specific reaction conditions).

CHAPTER 4

Ligand activity of nitrogen-containing alicyclic ligands with palladium(II)

4.1 Introduction

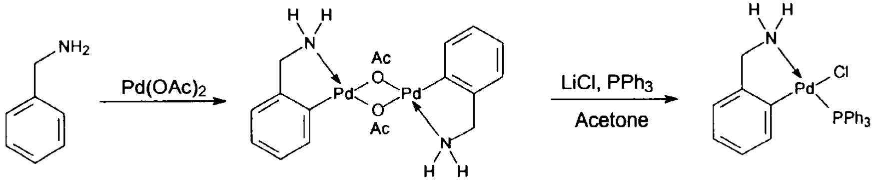
Benzylamine and derivatives of benzylamine has the ability to undergo cyclopalladation reactions in the presence of palladium(II) compounds.[38-43] Cope and Siekman[38] observed that azobenzene reacts with palladium(II) chlorides to afford complex **64**.



64

Cope and Friedrich[39] investigated benzylamine and other aromatic compounds containing nitrogen groups which could coordinate to the metal to form complexes similar to **64**. It was concluded that aromatic compounds with substituents containing nitrogen at positions suitable for forming chelating rings with palladium undergo cyclopalladation at an ortho position to form a carbon-to-metal sigma bond. Cyclopalladation at an ortho position occurs via an electrophilic aromatic substitution reaction. These ortho-palladation products were found to be very stable in air and light.

Recently, Fuchita *et al.*[40] showed that benzylamine **65** treated with palladium actetate in a one-to-one molar ratio in benzene at 60 °C for 24 h gave a acetato bridged cyclopalladated dimer $(\mu\text{-OAc})_2[Pd(C_6H_4CH_2NH_2)]_2$ **(66)**. These results was verified by various research groups.[41-43] Albert et al.[41] treated complex **66** with lithiumchloride and PPH_3 in acetone at room temperature to afford complex **67**.



65 **66** **67**

Scheme 23

Molecular modelling is a tool that can be used to determine the possible interaction sites for a metal to bind to a ligand. One characteristic property that can be calculated is the electrostatic potentials of the ligands.

The electrostatic potential is defined as the energy of interaction of a positive point charge with the nuclei and electrons of a molecule.[31,32] Electrostatic potentials provide information about electron-poor and electron-rich sites in a molecule, and electrostatic interactions between molecules.[31,32] Electrostatic potential can successfully be used to identify electron-rich regions (negative electrostatic potential) where electrophilic attack is likely to take place.

Positive electrostatic potential surface tend to be less informative because they encompass all of the nuclei, i.e. the electrostatic potential always become positive near each of the nuclei. [31,32]

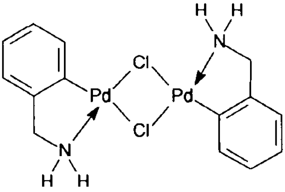
In this study only the negative electrostatic potentials of the ligands were calculated to determine the electron-rich regions of the molecule. This gives an indication of the highest possible binding site for the metal to the ligand.

4.2 Synthesis of palladium-ligand complexes

4.2.1 Introduction

Due to the ease of synthesis described by Cope *et al.*[39] it was decided to use lithium tetrachloropalladate(II) as the transition metal in this study. Lithium tetrachloropalladate(II) can be easily synthesised by reaction of palladium(II) dichloride with lithium chloride in distilled water.[39] This material, which is very soluble in water and slightly warming in methanol, was used in the reactions without further purification. This metal is highly hygroscopic and also corrosive to metal utensils when wet.

The activity of lithium tetrachloropalladate(II) was tested in a reaction with benzylamine in the presence of methanol at room temperature. After standing for 4 h the precipitate was filtered and recrystallised from boiling methanol. The dichlorobis(benzylamine)palladium(II) (**68**) has a yellow crystalline structure.



68

To confirm the presence of palladium in the compound, analysis was done with a SEM equipped with an EDS system. The micrograph obtained by the SEM showed a rod-like morphology (Micrograph 4.1). EDS analysis confirmed the presence of palladium, nitrogen, carbon and chlorine.

Micrograph 4.1 SEM of **68**

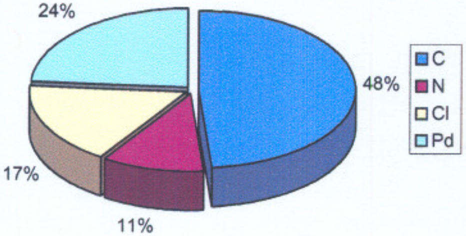


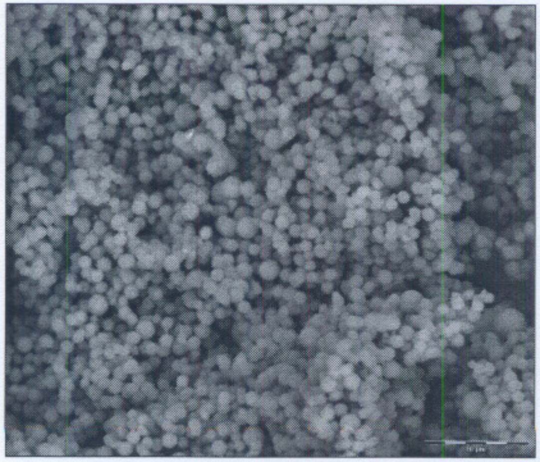
Figure 4.1 Elemental analysis by EDS of complex **68**

It can be concluded that a benzylamine-metal complex was formed with palladium as metal. It must be mentioned that the elementary analysis should not be considered to be the absolute composition due to contamination of the carbon background. It must also be noted that hydrogen cannot be calculated by the EDS system.

4.2.2 *Ligand activity of 3,5-bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane* (27)

The GC-MS and ^{13}C NMR data of compound **27** shows the presence of benzylamine, which is a contaminant associated with this ligand. Benzylamine is well known in literature to undergo cyclopalladation in the presence of lithium tetrachloropalliadate(II) and will therefore compete with ligand **27** when the metal is added. To overcome this, ligand **27** was treated with small amounts of lithium tetrachloropalladate(II) in methanol. An immediate precipitate was formed which was the product of the benzylamine reaction with the metal to form dichlorobis(benzylamine)palladium(II) (**68**). The benzylamine-palladium complex **68** was removed and the solution was then again treated with excess lithium tetrachloropalladate(II). After 6 h of stirring the precipitate **69** was filtered and analysed using IR, NMR, FAB$^+$ MS and SEM.

The micrograph obtained by SEM showed a spherical morphology with crystal structures of about the same size (Micrograph 4.2). No rode-like crystal structures were observed and indicated that a pure sample of complex **69** was obtained (no benzylamine-palladium complex present).



Micrograph 4.2 SEM of **69**

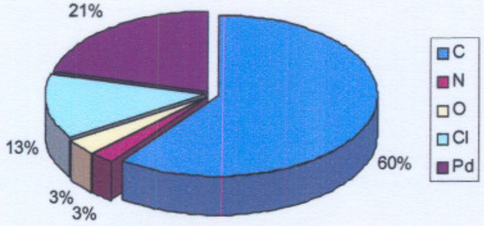


Figure 4.2 Elemental analysis by EDS of complex **69**

EDS analysis confirmed that carbon, nitrogen, chlorine and palladium were present in the compound. It can be concluded that a palladium-ligand complex was afforded by the reaction.

The electron surface density of the ligand **27** was calculated and the electrostatic potential was superimposed on the surface (Figure 4.4)

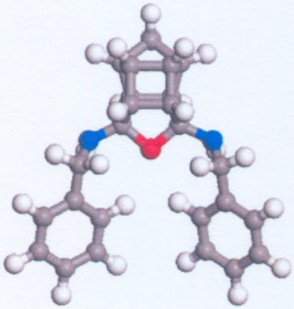


Figure 4.3 Calculated stable geometry of **27**

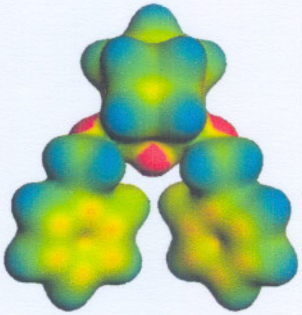


Figure 4.4: Calculated electrostatic potential of **27**

The red regions indicate electron-rich regions, in contrast to the blue that indicates electron-poor regions. It was found that three electron-rich regions are present in the ligand. As expected these regions are associated with the two nitrogen and one oxygen atoms of the molecule and are due to the lone-pair electrons of these atoms. Coordination with a metal can be formed via the two nitrogen groups, the oxygen group and at the ortho position of the aromatic ring.

The mass spectrum (FAB MS spectrum 12) of **69** shows a molecular ion at m/z 458 (M-1). This corresponds to a ligand-metal complex where one palladium is bonded to one ligand (expected mass of m/z 459 (M-1)). The mass of the metal-complex is one less than expected and may be due to the loss of a hydrogen for cyclopalladation. This needs to be confirmed by NMR. The mass spectra also shows a fragmentation peak at m/z 351 (M-1) which is the free dissociated ligand (expected mass of m/z 353 (M-1)). The FAB^+ MS spectrum correlates to ligand **69** that has one bonded palladium metal without chlorine groups. It is possible that the chlorine groups are lost during the MS process as HCl or $Cl^\bullet$. Although the EDS show the presence of chlorine it is possible that chlorine may be a contaminant in the crystal structure.

The infrared spectrum (IR spectrum 11) of **69** exhibits strong C-H and =C-H stretching vibrations at 2950 cm^{-1} to 3150 cm^{-1}. This confirms that the complex has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the =C-H out-of-plane bending vibrations at 700 cm^{-1} and 740 cm^{-1}. The vibrations in the 3250 - 3700 cm^{-1} region may be attributed to a N-H stretch vibrations and/or vibrations of the palladium complex. The IR spectrum of lithium tetrachloropalladate(II) shows vibrations in the 3100 - 3700 cm^{-1} region (IR spectrum 10). No Pd-C vibration could be observed at 300 cm^{-1}.[42]

Complex **69** produced unsatisfactory NMR spectra (NMR spectra 29). The ^1H NMR spectrum shows a strong singlet at δ_H 1.65 and undefined signals in the δ_H 2.0 - 5.1 region. Signals in the δ_H 7.0 - 8.0 region indicates that a aromatic character is present in complex **69**. Temperature-dependant ^1H NMR spectrum (NMR spectrum 32) was obtained to determine if proton exchange takes place in complex **69**. At temperatures 25 °C, 30 °C and 35 °C proton exchange occurred at δ_H 1.65. The N-H proton is the only exchangeable proton in the molecule, therefore the signal can be assigned to the N-H group in complex **69**.

The ^{13}C NMR (NMR spectra 30) shows undefined signals in the δ_C 38 - 52 region that absorb in the non-aromatic (saturated) region of the spectra. Undefined signals are also present at δ_C 124 - 140 that absorb in the aromatic region. The APT spectrum (NMR spectra 31) shows undefined aliphatic CH and CH_2 groups at δ_C 38 - 52 and aromatic CH groups at δ_C 124 - 140. It can be concluded from the NMR data that the compound has both an aliphatic and aromatic character.

Thermal analysis of complex **69** was done with DSC and TG (DSC and TG curve 3). The DSC curve shows a decomposition peak at 240.3 °C. The TG curve confirms that decomposition takes place at this temperature.

The above analytical data indicated that one ligand bonded to one palladium metal. The presence of chlorine in compound **69** could not be confirmed and complex **69** produced unsatisfactory NMR spectra. It could therefore not be confirmed that ortho palladation took place on the aromatic ring of the ligand. Thermal analysis indicated that complex **69** is stable up to a temperature of 240.3 °C. A proposed structure of complex **69** is given in Figure 4.5 and indicates that bonding of the metal can take place on the nitrogen and oxygen groups and/or on the ortho position of the aromatic ring.

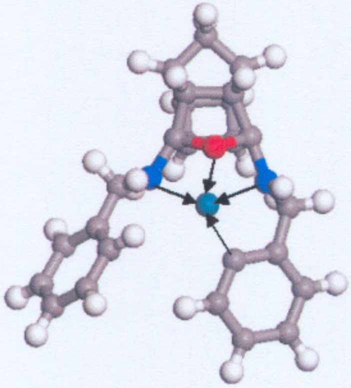
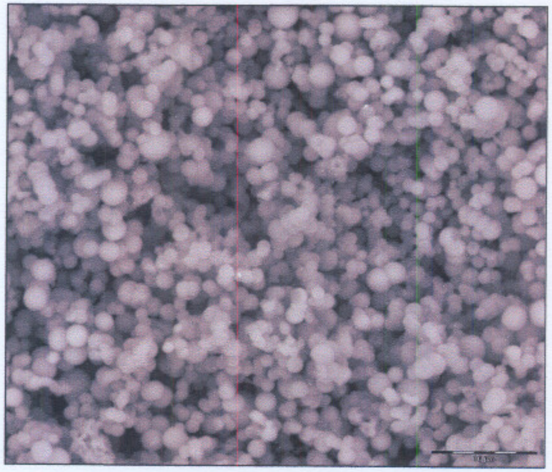


Figure 4.5 Proposed structure of complex **69**

4.2.3 Ligand activity of pentacyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(phenylhydrazone) (17)

Ligand **17** was treated with equamolar amounts of lithium tetrachloropalladate(II) in methanol. After 6 h of stirring the brown-orange precipitate was filtered and analysed using IR, NMR, FAB$^+$ MS and SEM.



Micrograph 4.3 SEM of **70**

The micrograph obtained by SEM showed a spherical morphology with crystal structures of about the same size (Micrograph 4.3). It was concluded that a pure sample of complex **70** was obtained.

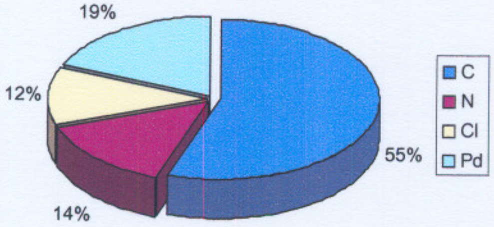


Figure 4.6 Elemental analysis by EDS of complex **70**

EDS analysis (Figure 4.6) confirmed that carbon, nitrogen, chlorine and palladium were present in the compound. It can be concluded that a palladium-ligand complex was afforded by the reaction.

The electron surface density of the ligand **17** was calculated and the electrostatic potential was superimposed on the surface (Figure 4.8 and 4.10)

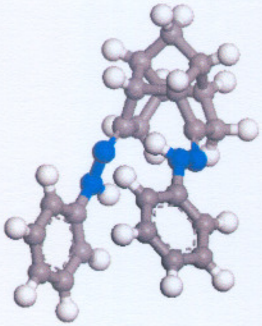


Figure 4.7 Calculated stable geometry of **17**

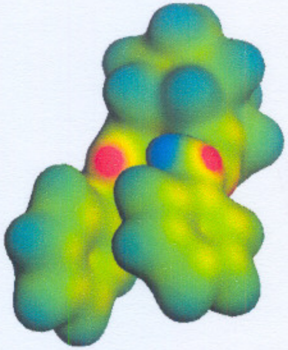


Figure 4.8 Calculated electrostatic potential of **17**

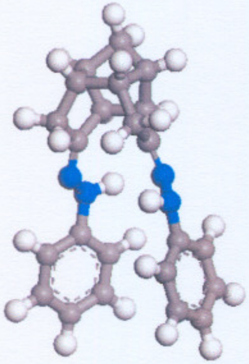


Figure 4.9 Calculated stable geometry of **17**

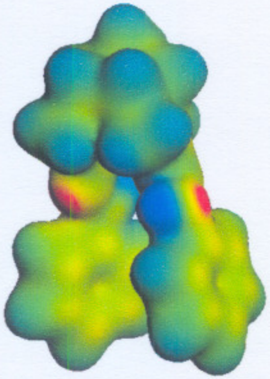


Figure 4.10 Calculated electrostatic potential of **17**

Electrostatic potential calculation indicated that four electron-rich regions are present in the ligand. As expected these regions are associated with the four nitrogen atoms of the molecule and are due to the lone-pair electrons of these atoms. Coordination with a metal can be formed via the four nitrogen groups and at the ortho position of the aromatic ring.

The mass spectrum (FAB MS spectra 13) of **70** shows a molecular ion at m/z 462 (M-1). This corresponds to a ligand-metal complex where one palladium is bonded to one ligand (expected mass of m/z 463 (M-1)). As in the case of complex **69** the mass of the metal complex is one less than expected and may be due to the loss of a hydrogen for cyclopalladation. This needs to be confirmed by NMR.

The mass spectra also shows a fragmentation peak at m/z 357 (M-1) which is the free dissociated ligand. The FAB$^+$ MS spectrum correlates to ligand **70** that has one palladium metal without chlorine groups. As mentioned with complex **69** it is possible that the chlorine groups are lost during the MS process or it is possible that chlorine may be a contaminant in the crystal structure.

The infrared spectrum (IR spectrum 12) of **70** exhibits a strong C-H stretching vibration at 2970 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that the complex has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the =C-H out-of-plane bending vibrations at 700 cm^{-1} and 760 cm^{-1}. The vibrations in the 3200 - 3500 cm^{-1} region may be attributed to a N-H stretch vibrations and/or vibrations of the palladium complex. No Pd-C vibration could be observed at 300 cm^{-1}.[42]

Complex **70** produced unsatisfactory NMR spectra (NMR spectra 37). The ^1H NMR spectrum shows very undefined signals in the δ_H 1.4 - 3.55 region. Signals in the δ_H 6.5 - 8.0 region indicate a aromatic region in complex **70**. Temperature-dependant ^1H NMR spectrum (NMR spectra 40) was obtained to determine if proton exchange takes place in complex **70**. At temperatures 25 °C, 30 °C and 35 °C proton exchange occurred at δ_H 1.55. The N-H proton is the only exchangeable proton in the molecule, therefore the signal can be assigned to the N-H group in complex **70**.

The ^{13}C NMR (NMR spectra 38) of complex **70** show undefined signals in the δ_C 32 - 60 region that absorb in the non-aromatic (saturated) region of the spectra. Undefined signals are also present at δ_C 120 - 132 that absorb in the aromatic region. The APT spectrum (NMR spectra 39) of complex **70** gives no useful information. It can be concluded from the NMR data that the compound has both an aliphatic and aromatic character.

Thermal analysis of complex **70** was done with DSC and TG (DSC and TG curve 5). The DSC curve shows a decomposition peak at 254.03 °C. The TG curve confirms that decomposition takes place at this temperature.

The above analytical data indicated that one ligand bonded to one palladium metal. The presence of chlorine in compound **70** could not be confirmed and complex **70** produced unsatisfactory NMR spectra. It could therefore not be confirmed that ortho palladation took place on the aromatic ring of the ligand. Thermal analysis indicated that complex **70** is stable up to a temperature of 254.03 °C. A proposed structure of complex **70** is given in Figure 4.11 and indicates that bonding of the metal can take place on one or more of the four nitrogen groups and/or on the ortho position of the aromatic ring.

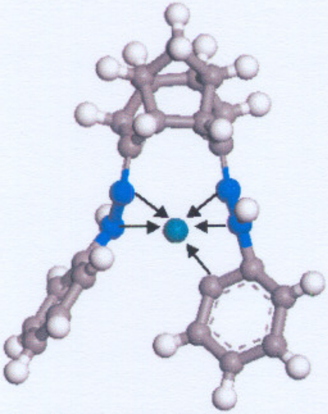
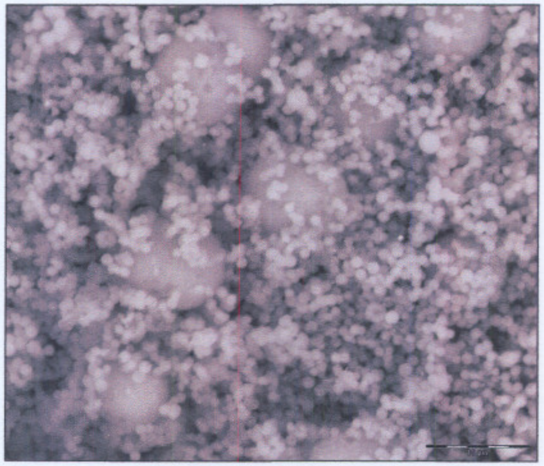


Figure 4.11 Proposed structure of complex **70**

4.2.4 Ligand activity of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecanedione-bis(benzylamine) (59)

The GC-MS and ^{13}C NMR data of compound **59** shows the presence of benzylamine, which is a contaminant associated with this ligand. To remove benzylamine, ligand **59** was treated with small amounts of lithium tetrachloropalladate(II) in methanol. A immediate precipitate was formed which was the benzylamine reacting with the metal to form dichlorobis(benzylamine)palladium(II) (**68**). The benzylamine-palladium complex **68** was removed and the solution was treated with equamolar amounts of lithium tetrachloropalladate(II). After 6 h of stirring the precipitate was filtered and analysed using IR, NMR, FAB$^+$ MS and SEM.

The micrograph obtained by SEM showed a spherical morphology with large and small spherical crystalline structures (Micrograph 4.4). No rode-like crystal structures were observed and indicated that a pure sample of complex **71** was obtained (no benzylamine-palladium complex present).



Micrograph 4.4 SEM of **71**

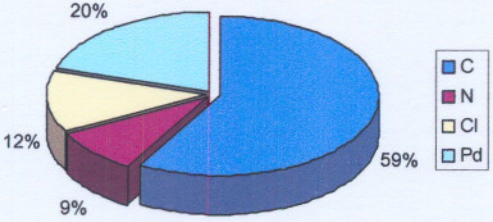


Figure 4.12 Elemental analysis by EDS of complex **71**

EDS analysis (Figure 4.12) confirmed that carbon, nitrogen, chlorine and palladium were present in the compound. It was also found that the large spherical structures were identical to the small spherical structures in chemical composition. It can be concluded that a palladium-ligand complex **71** was afforded by the reaction.

The electron surface density of the ligand **59** was calculated and the electrostatic potential was superimposed on the surface (Figure 4.14)

Figure 4.13 Calculated stable geometry of **59**

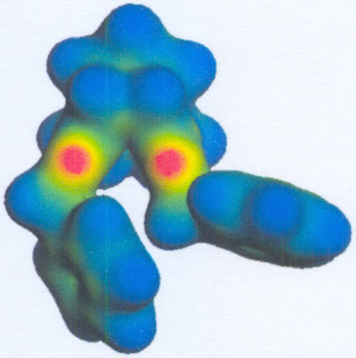


Figure 4.14 Calculated electrostatic potential of **59**

Electrostatic potential calculation indicated that two electron-rich regions were present in the ligand. As expected these regions are associated with the two nitrogen atoms of the molecule and were due to the lone-pair electrons of these atoms. Coordination with a metal can be formed via the two nitrogen groups and at the ortho position of the aromatic ring.

The mass spectrum (FAB MS spectrum 14) of **71** shows a molecular ion at m/z 460 (M-1). This corresponds to a ligand-metal complex where one palladium is bonded to one ligand (expected mass of m/z 461 (M-1)). The mass of the metal-complex is one less than expected an may be due to the loss of a hydrogen for cyclopalladation. This needs to be confirmed by NMR.

The mass spectra also shows a fragmentation peak at m/z 354 (M-1) which is the free dissociated ligand (expected mass of m/z 355 (M-1)). The FAB$^+$ MS spectrum correlates to ligand **71** that has one palladium metal without chlorine groups. As mentioned with complex **69** and **70** it is possible that the chlorine groups are lost during the MS process or it is possible that chlorine may be a contaminant in the crystal structure.

The infrared spectrum (IR spectrum 13) of **71** exhibits a strong C-H stretching vibration at 2940 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that the complex has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the =C-H out-of-plane bending vibrations at 700 - 740 cm^{-1}. The vibrations in the 3250 cm^{-1} to 3500 cm^{-1} region may be attributed to a N-H stretch vibrations and/or vibrations of the palladium complex. No Pd-C vibration could be observed at 300 cm^{-1}.

Complex **71** produced unsatisfactory NMR spectra (NMR spectra 33). The ^{1}H NMR spectrum showes a very strong singlet at δ_H 1.65 and very undefined signals in the δ_H 1.7 - 5.3 region. Signals in the δ_H 7.0 - 8.0 region indicates a aromatic region in complex **71**. Temperature-dependant ^{1}H NMR spectrum (NMR spectra 36) was obtained to determine if proton exchange takes place in complex **71**. At temperatures 25 °C, 30 °C and 35 °C proton exchange occurred at δ_H 1.65. The N-H proton is the only exchangeable proton in the molecule, therefore the signal can be assigned to the N-H group in complex **71**.

The ^{13}C NMR (NMR spectra 34) shows signals in the δ_C 32 - 66 region that absorb in the non-aromatic (saturated) region of the spectra. Undefined signals are also present at δ_C 124 - 140 that absorb in the aromatic region. The APT spectrum (NMR spectra 35) shows aliphatic CH and CH$_2$ groups in the δ_C 32 - 66 region. In contrast to complex **69** and **70** it can clearly be observed that various CH_2 and CH groups are present in the compound. These signals are a combination of the ligand and of the contamination present. Aromatic CH groups are observed at δ_C 124 - 140. It can be concluded from the NMR data that the compound has both an aliphatic and aromatic character.

Thermal analysis of complex **71** was done with DSC and TG (DSC and TG curve 4). The DSC curve showed a decomposition peak at 233.8 °C. The TG curve confirms that decomposition takes place at this temperature.

The above analytical data indicated that one ligand bonded to one palladium metal. The presence of chlorine in compound **71** could not be confirmed and complex **71** produced unsatisfactory NMR spectra. It could therefore not be confirmed that ortho palladation took place on the aromatic ring of the ligand. Thermal analysis indicated that complex **71** is stable up to a temperature of 233.8 °C. A proposed structure of complex **71** is given in figure 4.15 and indicates that bonding of the metal can take place on one or more of the nitrogen groups and/or on the ortho position of the aromatic ring.

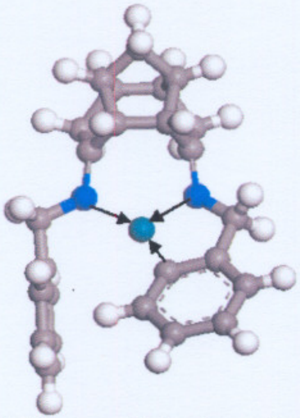
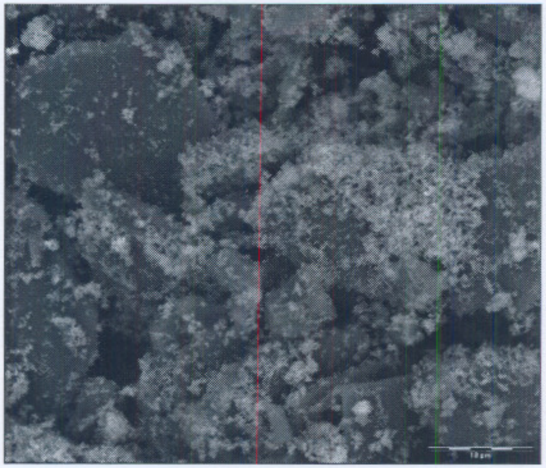


Figure 4.15 Proposed structure of complex **71**

4.2.5 Ligand activity of pentacyclo[5.4.0.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$]undecane-8-amine (42)

Ligand **42** was treated with equamolar amounts of lithium tetrachloropalladate(II) in methanol. An immediate black precipitate formed that was filtered and analysed.

The micrograph obtained by SEM showed that a rock-shaped morphology and white cotton-shaped morphology was present in the sample (Micrograph 4.5). A mixture of two compounds was thus present in the sample.



Micrograph 4.5 Sem of **72**

The chemical composition of the rock-shaped morphology and white cotton-shaped morphology was determined using EDS. It was found that the white structures were composed almost entirely of palladium, whereas the gray structures were composed of carbon and metal (Figure 4.16 and 4.17).

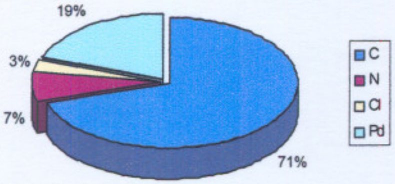


Figure 4.16 Rock-shaped structures of **72**

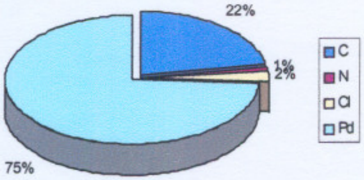


Figure 4.17 Cotton-shaped structures of **72**

It was concluded a mixture of ligand-palladium complex and free palladium metal was formed during the reaction.

The electron surface density of the ligand **42** was calculated and the electrostatic potential was superimposed on the surface (Figure 4.19).

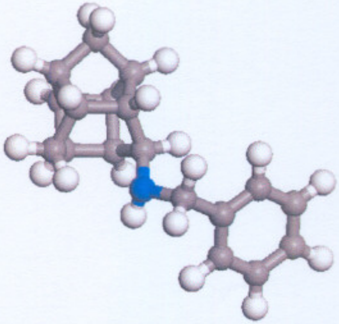


Figure 4.18 Calculated stable geometry of **42**

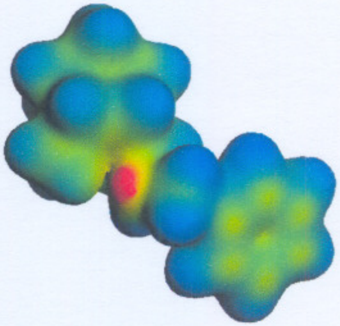


Figure 4.19 Calculated electrostatic potential of **42**

Electrostatic potential calculation indicated that one electron-rich region is present in the ligand. As expected this region is associated with the nitrogen atom of the molecule and is due to the lone-pair electrons of this atom. Coordination with a metal can be formed via the nitrogen group and at the ortho position of the aromatic ring.

The mass spectrum (FAB MS spectrum 15) of **72** shows a molecular ion at m/z 355 (M-1). This corresponds to a ligand-metal complex where one palladium is bonded to one ligand (expected mass of m/z 358 (M-1)). The mass spectra also shows a fragmentation peaks at m/z 250 (M-1) which is the free dissociated ligand (expected mass of m/z 252 (M-1)). The FAB$^+$ MS spectrum correlates to ligand **72** that has one palladium metal without chlorine groups. As mentioned with the previous complexes it is possible that the chlorine groups are lost during the MS process or it is possible that chlorine may be a contaminant in the crystal structure.

The infrared spectrum (IR spectrum 14) of **72** exhibits a strong C-H stretching vibration at 2970 cm^{-1} and a smaller =C-H stretch vibration at 3050 cm^{-1}. This confirms that the complex has both aliphatic and aromatic character. The aromaticity of the compound can be confirmed by the =C-H out-of-plane bending vibrations at 700 - 760 cm^{-1}. The vibrations in the 3290 – 3500 cm^{-1} region may be attributed to N-H stretch vibrations and/or vibrations of the palladium complex. No Pd-C vibration could be observed at 300 cm^{-1}.

The complex was insoluble and no NMR spectra could be obtained of complex **72**.

The above analytical data indicated that one ligand bonded to one palladium metal. The presence of chlorine in compound **72** cannot be confirmed. A proposed structure of complex **72** is given in Figure 4.20 and indicates that bonding of the metal can take place on the nitrogen group and/or on the ortho position of the aromatic ring.

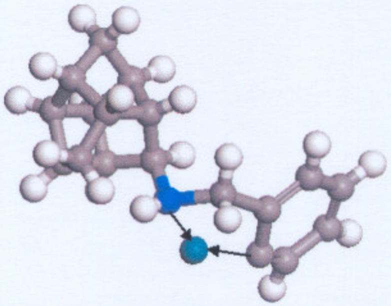
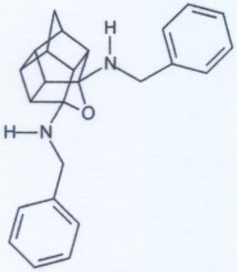


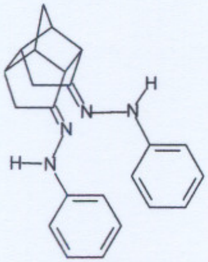
Figure 4.20 Proposed structure of complex 72

4.3 Conclusion

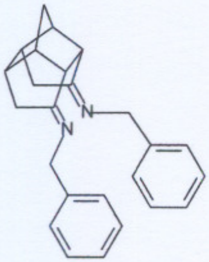
Benzylamine and derivatives of benzylamine have the ability to undergo cyclopalladation reactions in the presence of palladium(II) compounds. Due to the ease of synthesis described by Cope et al.[41] it was decided to use lithium tetrachloropalladate(II) as the transition metal in this study. The following ligands were tested for ligand activity:



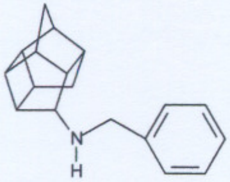
27



17



59



42

It was found that ligands **27**, **17** and **59** reacted immediately with lithium tetrachloropalladate(II) to form very stable metal-ligand complexes. The SEM with an EDS system confirmed that palladium-ligand complexes were afforded by the reaction. FAB$^+$ MS showed that metal complexes were formed where one palladium metal bonded to one ligand. The MS spectrum correlates to ligands that have one bonded palladium metal without chlorine groups. It is possible that the chlorine groups are lost during the MS process as HCl or Cl$^\bullet$. Although the EDS shows the presence of chlorine it is possible that chlorine may be a contaminant in the crystal structure. The mass of all the metal complexes was one less than expected and may be due to the loss of a hydrogen for cyclopalladation. This could not be confirmed by NMR due to very unsatisfactory NMR spectra.

Ligand **42** reacts immediately with lithium tetrachloropalladate(II) to form a black precipitate that was insoluble to organic solvents. The SEM with a EDS system showed that a mixture of palladium metal and palladium-ligand complex was afforded by the reaction.

Molecular modelling only gave an indication where a metal might possibly bond to the ligand. It was found as expected that the metal will bond to nitrogen and / or oxygen atoms that have lone-pair electrons.

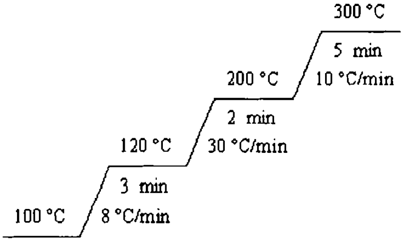
The aim of this study was to determine if alicyclic ligands could be used to form stable metal-ligand complexes with palladium. The goal of this study was achieved where three of the four ligands formed very stable metal complexes. The characterization of these compounds was done, but a more in-depth study must be conducted to determine the absolute structure of the organometallic complexes.

CHAPTER 5

Experimental

Experimental data was obtained using the following instruments:

Infrared spectra	: Nicolett 5 DX FT-spectrophotometer.
Mass spectra	: EI mass spectra were obtained at 70 eV on a Micromass Autospec-TOF mass spectrometer.
	: FAB mass spectra were obtained by bombardment with 1 mA beam of 8 keV accelerated neutral xenon atoms produced by an Ion-Tech FAB gun, filtered to a VG 7070-E mass spectrometer
NMR spectra	: Varian Gemini-300 nuclear magnetic resonance spectrometer.
ESEM	: FEI Quanta 200 ESEM with Oxford INCA 400 EDS system.
GC-MS	: 6890 Agilent GC equipped with a MSD detector. A HP-5 capillary column (30m x 320μm x 0.25μm) with He (2 mL/min) as carrier gas, an inlet temperature of 280°C and the following oven heating temperature programme were used:

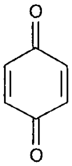


TGA : TGA 2050.

DSC : DSC 2010.

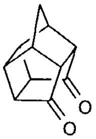
Melting points : Buchi melting point. B-540.
Melting points are uncorrected.

5.1 Oxidation of p-benzoquinone (2)



p-Benzoquinone (50 g) was dissolved in 800 cm^3 methanol. To the mixture was added manganese dioxide and activated charcoal. The mixture was heated at 90 °C for 10 min. The mixture was filtered to remove the manganese dioxide and activated charcoal. The filtrate was used in the synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**).

5.2 Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (4)

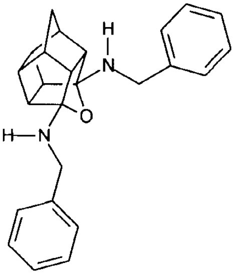


Equivalent molar amounts of p-benzoquinone **2** (50 g) and freshly distilled cyclopentadiene (32 g) was dissolved in methanol (1500 cm^3) and stirred in darkness for 24 h. The solvent was removed and recrystallisation was done with petroleum ether (40 – 60°C) to yield the adduct as light yellow crystals (76 °C). The adduct (4 g) was dissolved in acetone (100 cm^3) and irradiated for 6 hours with a medium pressure ultraviolet lamp in a water bath. The solution was concentrated, whereupon pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane-8,11-dione crystallized as a colourless, crystalline solid. Soxhlet extraction with cyclohexane as solvent yields pure dione as colourless crystals (38 g, 40% yield, mp 245 °C, mp lit 245 °C).

The **IR** (IR spectrum 1), **MS** (EI MS spectrum 1) and **NMR** data (NMR spectra 1, 2 & 3) was identical to that of literature.[2-4]

MS	: m/z 174 (M^+)
IR (KBr)	: 2980, 1770, 1740 and 1100 cm^{-1}
^{1}H NMR ($CDCl_3$)	: δ_H 1.8 (d), 2.0 (d), 2.6 (s), 2.75 (m), 3.85 (m), 3.15 (m) ppm
^{13}C NMR ($CDCl_3$)	: δ_C 38.62, 40.33, 43.68, 44.52, 54.61, 211.89 ppm

5.3 Synthesis of 3,5-bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane (27)



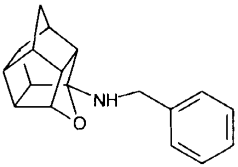
An adapted method of Sasaki *et al.*[21,22] was used. Pentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) (0,45 g) was dissolved in benzylamine (1,1 g) and kept at 100 °C for 15 min. After cooling, recrystallisation was done with ethanol to yield 3,5-bis(N-benzylamino)-4-oxa-hexacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane **27** as colourless crystals (0,75 g, 79% yield, mp 134.10 °C, mp lit 95 °C). It was very difficult to get a pure sample of

27 as a result of the benzylamine contamination. Repeated recrystallisation from n-hexane-methylene chloride (1:1) increases the purity of the compound to 88% (determined by GC-MS). Various separation techniques were used in an effort to remove the benzylamine from the sample. Distillation, fractional distillation, recrystallization, column chromatography, sublimation and various other techniques were employed but with no success.

The **IR** (IR spectrum 6), **MS** (EI MS spectrum 6) and **NMR** data (NMR spectra 14, 15 & 16) was identical to that of literature. [21,22]

MS : m/z 352 (M^+)
IR (KBr) : 3400, 3050, 2950, 1600, 1500, 1450,1150, 750 and 700 cm^{-1}
^{1}H NMR ($CDCl_3$) : δ_H 1.5 (d), 1.65 (s), 1.85 (s), 2.65 (m), 2.75 (m), 3.5-3.8 (m), 7-7.6 (m) ppm
^{13}C NMR ($CDCl_3$) : δ_C 41.99, 44.41, 48.01, 48.66, 93.48, 126.18, 126.51, 127.86, 128,09, 128.26, 128.46, 141.29 ppm

5.4 Synthesis of 8-benzylamino-8,11-oxapentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane (24)



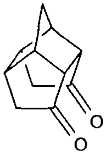
Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) (5 g) was dissolved in tetrahydrofuran (50 cm^3) and cooled down to 5 °C while stirring in an ice bath. Benzylamine (3,2 g) was added slowly, with continued stirring of the reaction mixture at 5 °C. The carbinolamine (**22**) started precipitating after approximately 10 min, but the reaction was allowed to reach completion for an additional 20 min. The carbinolamine was isolated by filtration (80% yield). Water was removed from **22** azeotropically by refluxing it in 60 cm^3

sodium-dried benzene using a Dean-Stark apparatus for 1 h or until no water was collected in the trap. The benzene was removed under reduced pressure and the Schiff base, 8-benzyliminopentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-undecane-11-one **23**, a yellow oil (100% yield), was dissolved in a mixture of anhydrous methanol (30 cm^3) and anhydrous THF (150 cm^3). Without any purification a reduction was carried out by adding sodium borohydride (2 g) in excess and stirring the mixture overnight (18 h) at room temperature. The solvents were removed in vacuo, the residue was suspended in water (100 cm^3) and extracted with dichloromethane. The combined organic fractions were washed with water (2 x 100 cm^3), dried over anhydrous magnesium sulphate and evaporated in vacuo to yield a yellowish oil. Crystallisation from absolute ethanol rendered the final product as a colourless microcrystalline solid (2,8 g, 38% yield, mp 78.°C, mp lit 78.7°C).

The **IR** (IR spectrum 5), **MS** (EI MS spectrum 5) and **NMR** data (NMR spectra 12 & 13) was identical to that of literature.[7,34]

MS : m/z 265 (M$^+$)
IR (KBr) : 3300, 2950, 1500, 1020, 740 and 700 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 7.34-7.15 (m), 4.62 (t), 3.98 (s), 2.83-2.47 (m), 2.38 (t), 2.16 (m), 1.81 (d), 1.51 (d) ppm
^{13}C NMR (CDCl$_3$) : δ_C 140.96, 128.40, 127.92, 126.85, 109.62, 82.48, 55.22, 54.73, 47.73, 44.83, 44.79, 44.50. 43.18, 43.07, 41.93, 41.47 ppm

5.5 Synthesis of tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione (16)

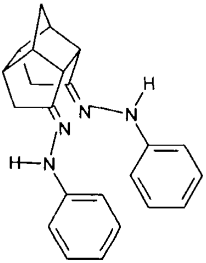


Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) (2 g) and activated zinc (5 g) was added to glacial acetic acid (100 cm^3) and stirred for 5 h at room temperature. The reaction mixture was filtered and the residue was washed with dichloromethane. Most of the acetic acid was removed under reduced pressure and the remainder was then neutralized with sodium bicarbonate. Extraction with dichloromethane and dried over anhydrous magnesium sulphate yielded the dione **16**. Recrystallisation from ethanol gave product **16** as colourless crystals (1,4 g, 64% yield, mp 253°C, mp lit 253°C).

The **IR** (IR spectrum 4), **MS** (EI MS spectrum 4) and **NMR** data (NMR spectra 10 & 11) was identical to that of literature.

MS : m/z 176 (M$^+$)
IR (KBr) : 2900-2985, 1750 and 1100 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 1.8 (d), 2.0 (d), 2.65 (s), 2.75 (m), 2.8 (m), 3.15 (m) ppm
^{13}C NMR (CDCl$_3$) : δ_C 38.62, 40.33, 43.68, 44.52, 45.61, 211.61 ppm

5.6 Synthesis of 2,7-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-bis(phenylhydrazone) (17)

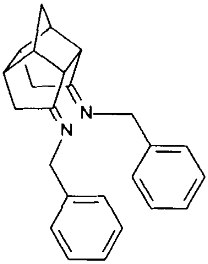


Tetracyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-3,6-dione (**16**) (0,40 g) was treated with 0.50 g phenylhydrazine in absolute ethanol (10 cm^3) and kept under reflux for 45 min. After cooling the solution to room temperature, pale yellow crystals of **17** (0.75 g, 93% yield, 160 °C, mp lit 159-162 °C) precipitates and were collected by filtration, washed with cold ethanol (5-10 cm^3) and dried under vacuum.

The **IR** (IR spectrum 7), **MS** (EI MS spectrum 7) and **NMR** data (NMR spectra 17, 18 & 19) was identical to that of literature.[17]

MS : m/z 356 (M^+)
IR (KBr) : 3350, 3100, 3050, 2950, 2900, 1680, 1500, 750 and 700 cm^{-1}
^{1}H NMR ($CDCl_3$) : δ_H 6.6-7.2 (m), 3.0-3.2 (m), 1.75 (q) ppm
^{13}C NMR ($CDCl_3$) : δ_C 28.58, 33.45, 34.28, 40.26, 40.65, 47.12, 48.09, 48.62, 51.87, 113.08, 113.90, 119.52, 119.69, 128.69, 113.08, 113.90, 119.52, 119.69, 128.69 ppm

5.7 Synthesis of noval 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-bis-(benzylamine) (59)



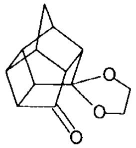
Tetracyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-3,6-dione (**16**) (0.80 g) was treated with benzylamine (1,00 g) in absolute ethanol (10 cm^3) and kept under reflux for 45 min. After cooling the solution to room temperature, pale white crystals of **59** (1.3 g, 81% yield, mp 103.07 °C) precipitates and were collected by filtration, washed with cold ethanol (5-10 cm^3) and dried under vacuum. It was difficult to obtain a pure sample of **59** as result of benzylamine contamination.

Repeated recrystallisation from ethanol increases the purity of the compound to 80% (determined by GC-MS). Various separation techniques were used in an effort to remove the benzylamine from the sample. Distillation, fractional distillation, re-crystallization, column chromatography, sublimation and various other techniques were employed but with no success.

The **IR** (IR spectrum 8), **MS** (EI MS spectrum 8) and **NMR** data (NMR spectra 20, 21 & 22) was obtained.

MS : m/z 354 (M^+)
IR (KBr) : 3050, 2950, 1800-2000, 1500, 740 and 700 cm^{-1}
^{1}H NMR ($CDCl_3$) : δ_H 7.0-7.5 (m), 3.93 (s), 3.7 (d), 2.4 (m), 2.2 (m), 1.7 (d), 1.5 (m) ppm
^{13}C NMR ($CDCl_3$) : δ_C 35.65, 36.01, 42.37, 47.12, 47.12, 51.56, 89.10, 126.25, 127.65, 128.01, 128.03, 129.12, 141.96 ppm

5.8 Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione monoethylene-acetal (53)

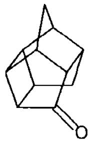


A mixture of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**4**) (10 g), ethylene glycol (3,57 g), p-toluenesulfonic acid (0,125 g) and benzene (50 cm^3) was refluxed (Dean Stark trap) with stirring for 5 h. The reaction mixture was cooled and slowly poured into 50 cm^3 ice cold 10% aqueous sodium carbonate. Extraction with dichloromethane and recrystallisation of the crude product from n-hexane yielded the monoketal **53** (11 g, 88% yield, mp 73°C, mp lit 73°C).

The **IR** (IR spectrum 2), **MS** (EI MS spectrum 2) and **NMR** data (NMR spectra 4, 5 & 6) was identical to that of literature.

MS : m/z 218 (M^+)
IR (KBr) : 2980, 1750, 1350, and 1120 cm^{-1}
^{1}H NMR ($CDCl_3$) : δ_H 3.7-4.0 (m), 2.9 (m), 2.75 (m)2.3-2.6 (m), 1.8 (d), 1.5 (d) ppm
^{13}C NMR ($CDCl_3$) : δ_C 214.84, 113.84, 65.42, 64.42, 52.93, 50.66, 45.78, 42.79, 42.23, 41.42, 41.26, 38.63, 36.28 ppm

5.9 Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (38)



To an ice-cold solution of the monoketal **53** (10 g) in ethanol (100 cm^3), a cold solution of sodium borohydride (3,5 g) in ethanol (50 cm^3) was added with stirring over 6 min. The reaction mixture was left for 2 h in the ice bath and then kept at room temperature for another 2 h. The mixture was placed back in the ice bath and 10% hydrochloric acid (200 cm^3) was added cautiously. The solution was then stirred at room temperature for another 2 h. Extraction with dichloromethane and drying with anhydrous magnesium sulphate yielded a racemic mixture of hydroxyketone **60**.

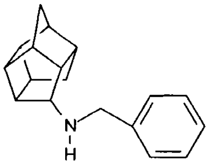
A mixture of hydroxyketone **60** (13 g) and hydrazine hydrate (20 cm^3, 98%) in diethylene glycol (200 cm^3) was maintained at 120 °C for 1.5 h. The mixture was allowed to cool down for 5 min, after which potassium hydroxide (10 g) was added and the excess hydrazine hydrate and water was distilled until the temperature of the reaction mixture reached 190 °C. The reaction mixture was refluxed for 3 h at 190 °C and then steam distilled. Extraction of the distillate with dichloromethane and drying with anhydrous magnesium sulphate gave the alcohol **62** (6,5 g) (230 °C).

To a mixture of chromium trioxide (12 g) in water (12 cm^3) and acetic acid (150 cm^3, 98%), the alcohol **62** (10 g) in acetic acid (50 cm^3) was added dropwise over a period of 10 minutes with stirring. The reaction was then stirred at 90 °C for 4 hours. The reaction was cooled, diluted with water (600 cm^3) and extracted with dichloromethane. The extract was washed successively with water and saturated aqueous sodium hydrogen carbonate. The extract was dried with anhydrous magnesium sulphate. Removal of the dichloromethane afforded pure monoketone (3 g, 30% yield, mp 194 °C, mp lit 194 °C).

The **IR** (IR spectrum 3), **MS** (EI MS spectrum 3) and **NMR** data (NMR spectra 7, 8 & 9) was identical to that of literature.

MS : m/z 160 (M$^+$)
IR (KBr) : 2950, 1750, and 500 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 2.9 (m), 2.7 (m), 2.5 (m), 2.25 (m), 1.85 (d), 1.45 (d), 1.3-1.4 (m) ppm
^{13}C NMR (CDCl$_3$) : δ_C 53.01, 48.58, 48.29, 48.27, 44.44, 43.67, 43.26, 39.47, 37.57, 36.70, 31.05 ppm

5.10 Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-amine (42)



Pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-one (**38**) (1,00 g) was dissolved in benzylamine (1,5 g) and heated at 100 °C for 30 min. The resulting imine was then cooled in ice and a solution of sodium borohydride (2 g) in cold water (20 cm^3) was added slowly. The mixture was then stirred for 5 hours at room temperature. The solution was then treated with a 10% HCl solution until a neutral pH was reached. Extraction of the product was done with dichloromethane and dried over anhydrous magnesium sulphate. The solvent was removed under reduced pressure and the product was dissolved in a small amount (10 cm^3) of ether. Ether saturated with HCl was added to the ether solution containing the product **42**. The resultant precipitate was recrystallised from ethanol to yield colourless crystals of **42** (1.35 g, 60% yield, mp 276 °C, mp lit 275 °C).

The **IR** (IR spectrum 9), **MS** (EI MS spectrum 9) and **NMR** data (NMR spectra 23, 24 & 25) was identical to that of an authentic sample.

MS : m/z 251 (M$^+$)
IR (KBr) : 2470-3080, 710 and 780 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 7.65 (m), 7.25 (m), 4.05 (s), 2.3-2.9 (m), 2-2.2 (m), 1.6 (d), 1.2 (m), 1.05 (d) ppm
^{13}C NMR (CDCl$_3$) : δ_C 29.627, 34.140, 35.901, 35.095, 39.814, 40.945, 41895, 42.488, 44.116, 46.911, 51.05, 128.846, 128.923, 128.976, 130.152,130.350 ppm

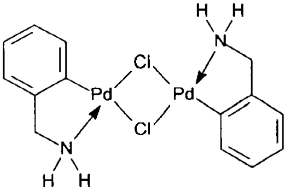
5.11 Synthesis of Lithium Tetrachloropalladate(II)

A mixture of palladium(II) chloride (3 g) and lithium chloride (1,4 g) in distilled water (100 cm^3) was heated and stirred until the solution was complete. The resulting dark red solution was cooled and filtered. All the water was removed on a rotary vacuum evaporator. This material was used without any further purification.

IR data (IR spectrum 10) was obtained.

MS : m/z 262 (M^+)
IR (KBr) : 3250-3600, 3130, 1650 and 570 cm^{-1}

5.12 Synthesis of dichlorobis(benzylamine)palladium(II) (68)



The reaction of benzylamine (0,5 g) and lithium tetrachloropalladate(II) (0,6g) in methanol (40 cm^3) at room temperature gave an immediate yellow precipitate. After standing for 4 h the precipitate was filtered and washed well with methanol. Recrystallisation with boiling methanol gave product **69** as long yellow needles (0,50 g, 20% yield, mp 180 °C, mp lit 180 °C).

5.13 Synthesis of 3,5-Bis(N-benzylamino)-4-oxa-hexacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]dodecane palladium complex (69)

The reaction of 3,5-bis(N-benzylamino)-4-oxa-hexacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]-dodecane **27** (0,15 g) and lithium tetrachloropalladate(II) (0,05 g) in methanol (10 cm^3) at room temperature gave an immediate yellow precipitate (benzylamine contamination). After standing for 4 h the precipitate (benzylamine contaminant) was filtered and discarded. To the remaining solution was added lithium tetrachloropalladate(II) (0,2 g) at room temperature. A pale yellow precipitate formed immediately. After standing for 6 h product **69** was filtered (170 mg).

MS (FAB$^+$ MS spectrum 12) , **IR** (IR spectrum 11) and **NMR** data (NMR spectra 29, 30, 31 and 32) was obtained.

MS : m/z 458 (M-1)
IR (KBr) : 3500, 3300, 3200, 3050, 2950, 2880, 1680, 1500, 1450, 740 and 700 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 1.65 (s), 2.0 - 5.1 (m), 7.0-8.0 (m) ppm
^{13}C NMR (CDCl$_3$) : δ_C 38 – 52, 124 – 140 ppm

5.14 Synthesis of 2,7-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-bis(phenylhydrazone palladium complex (70)

The reaction of 2,7-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(phenylhydrazone) **17** (0.15 g) and lithium tetrachloropalladate(II) (0,15 g) in 10 cm^3 of methanol at room temperature gave an immediate brown-yellow precipitate. After standing for 6 hours the precipitate of **70** was filtered (110 mg).

MS (FAB$^+$ MS spectrum 13) , **IR** (IR spectrum 12) and **NMR** data (NMR spectra 37, 38, 39 and 40) was obtained.

MS : m/z 462 (M-1)
IR (KBr) : 3500, 3210, 3050, 2970, 1600, 1500, 740 and 700 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 1.55 (s), 1.4 - 3.55, 6.5-8.0 (m) ppm
^{13}C NMR (CDCl$_3$) : δ_C 32 – 60, 120 – 132 ppm

5.15 Synthesis of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-bis(benzylamine) palladium complex (71)

The reaction of 2,6-tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-dione-bis(benzylamine) **59** (0.15 g) and lithium tetrachloropalladate(II) (0,05g) in 10 cm^3 of methanol at room temperature gave an immediate yellow precipitate (benzylamine contamination). After standing for 4 h the precipitate (benzylamine contaminant) was filtered and discarded. To the remaining solution was added lithium tetrachloropalladate(II) (0.2 g) at room temperature. A pale yellow precipitate formed immediately. After standing for 6 h the precipitate of **71** was filtered (80 mg).

MS (FAB$^+$ MS spectrum 14) , **IR** (IR spectrum 13) and **NMR** data (NMR spectra 33, 34, 35 and 36) was obtained.

MS : m/z 460 (M-1)
IR (KBr) : 3500, 3280, 3200, 3050, 2940, 1660, 1500, 1450, 740 and 700 cm^{-1}
^{1}H NMR (CDCl$_3$) : δ_H 1.65 (s), 1.7 - 5.3, 7.0-8.0 (m) ppm
^{13}C NMR (CDCl$_3$) : δ_C 32 – 66, 124 – 140 ppm

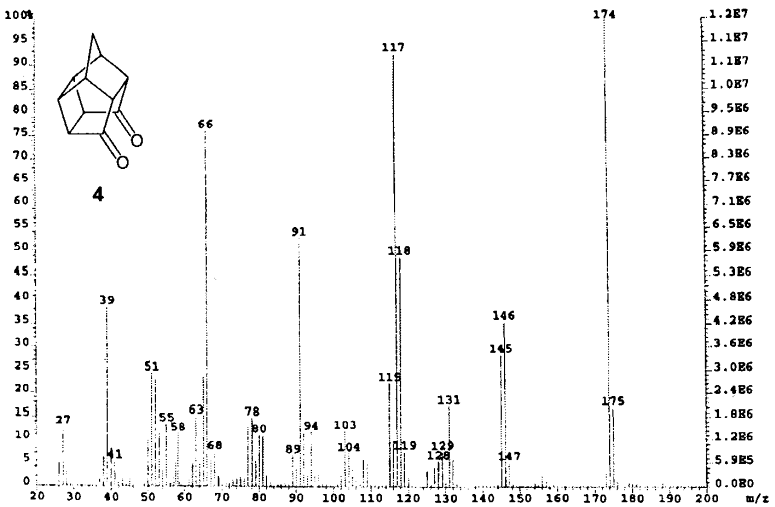
5.16 Synthesis of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-amine palladium complex (72)

The reaction of pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8-amine **42** (0,1 g) and lithium tetrachloropalladate(II) (0,05 g) in 10 cm^3 of methanol at room temperature gave an immediate black precipitate. After standing for 4 hours the precipitate of **72** was filtered (10 mg).

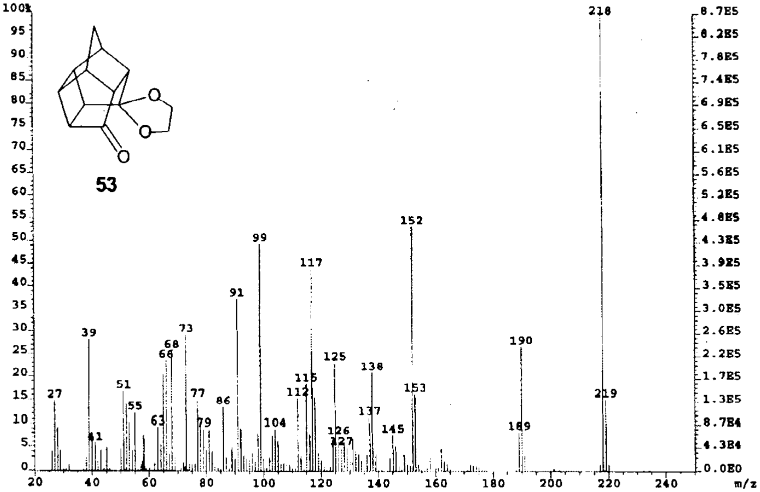
MS (FAB$^+$ MS spectrum 15) and **IR** (IR spectrum 14) data was obtained.

MS : m/z 355 (M-1)
IR (KBr) : 3500, 3290, 3050, 2970, 2900, 1650, 740 and 700 cm^{-1}

SPECTRA



EI MS spectrum 1



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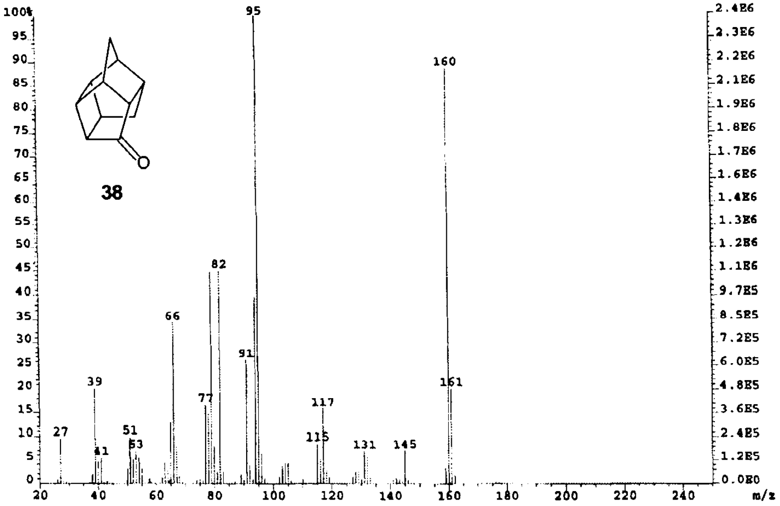

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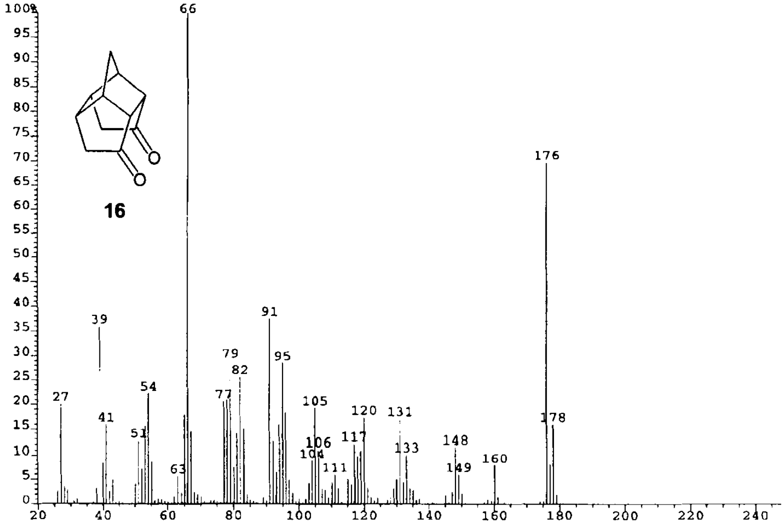

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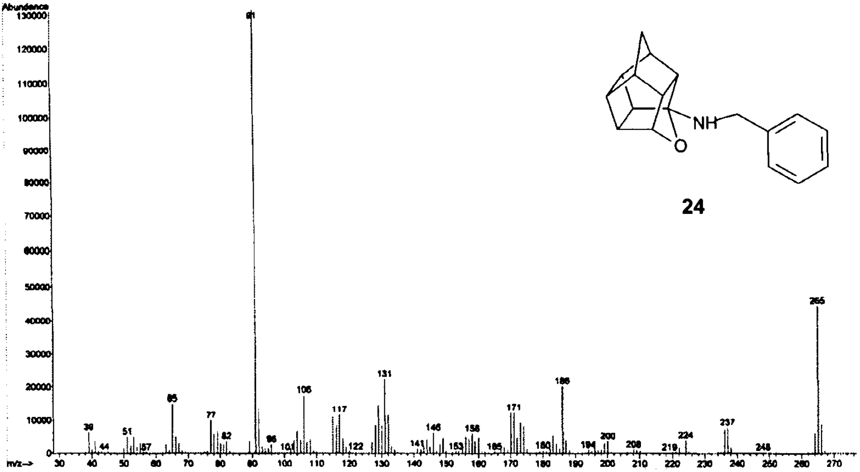

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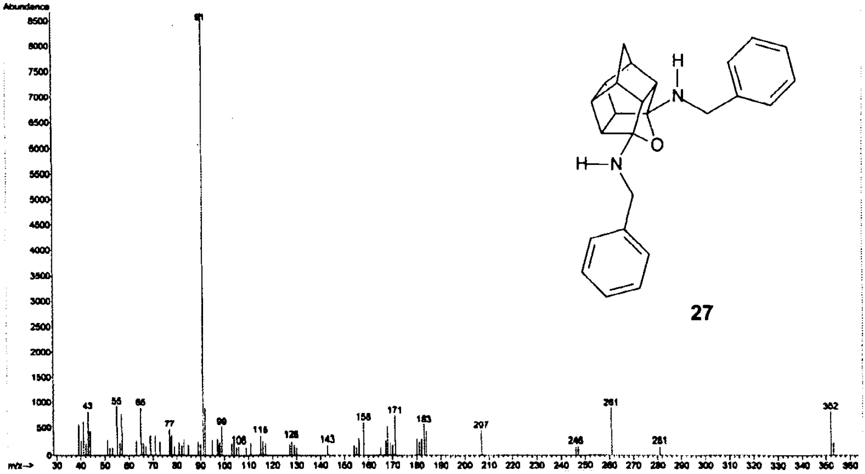

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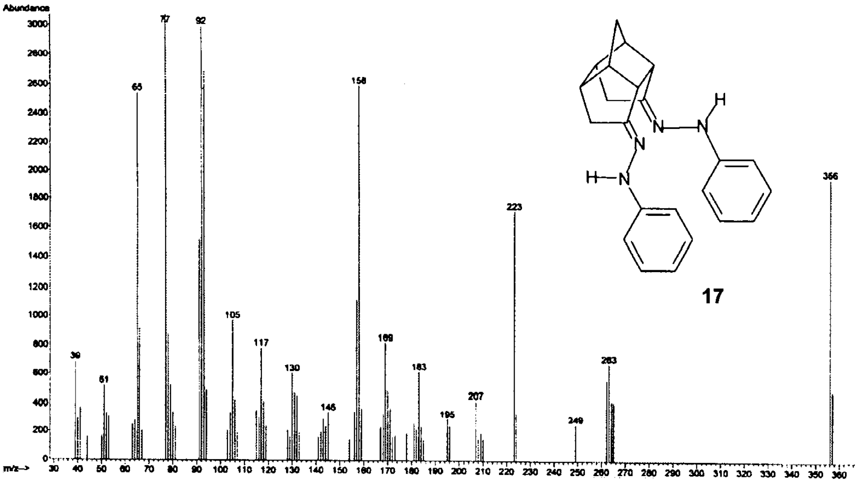

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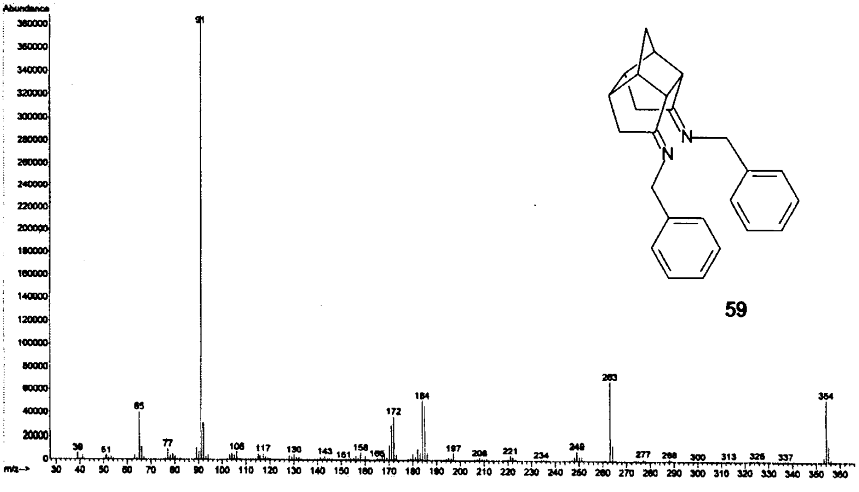
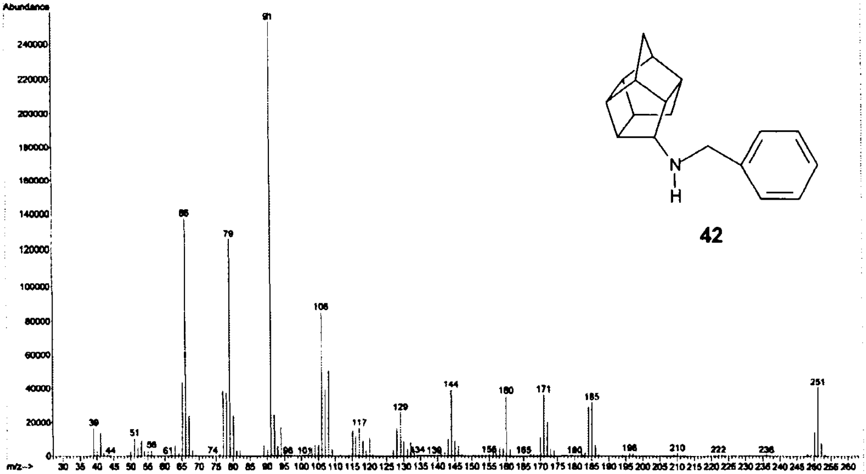
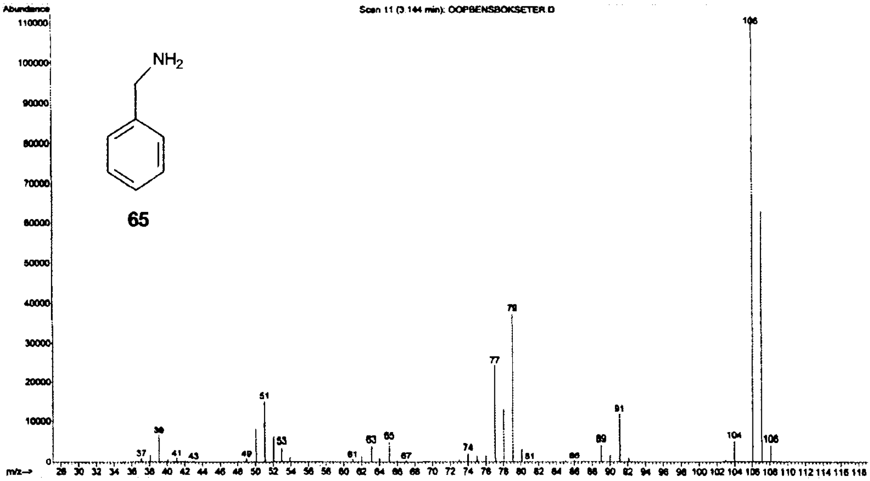


EI MS spectrum 8



EI MS spectrum 9



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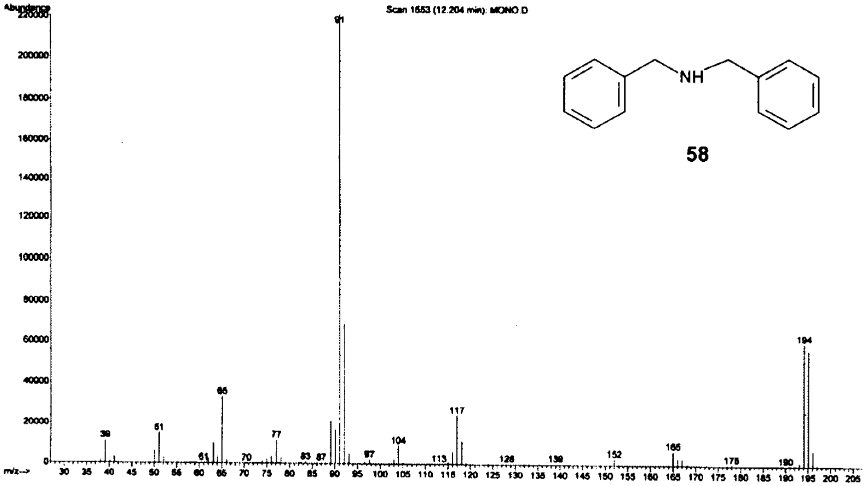

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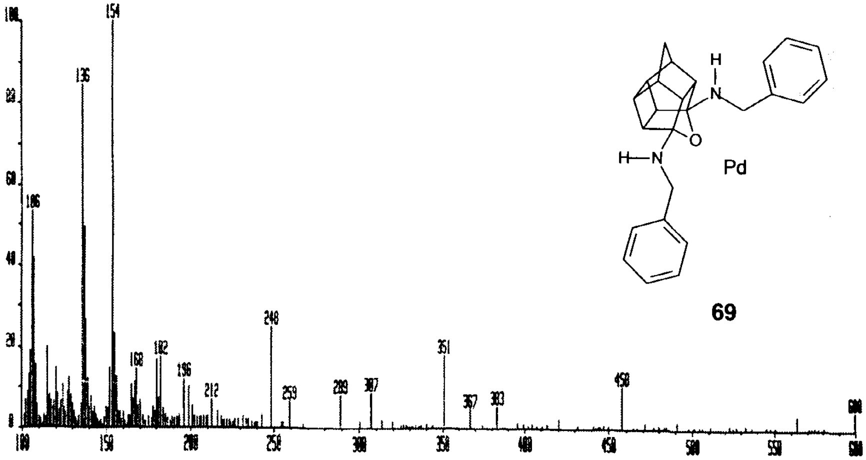

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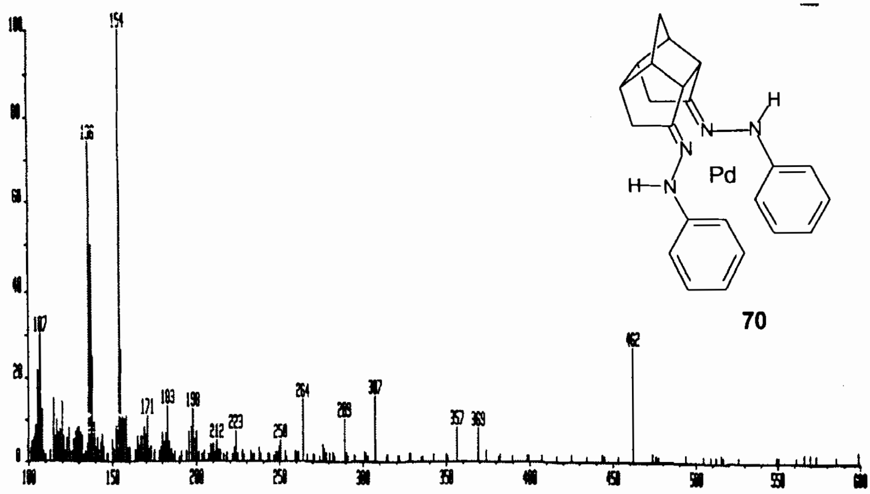

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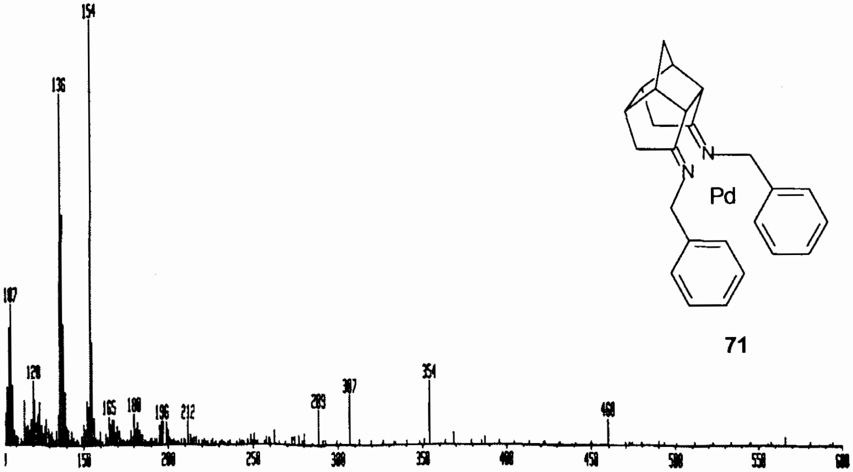

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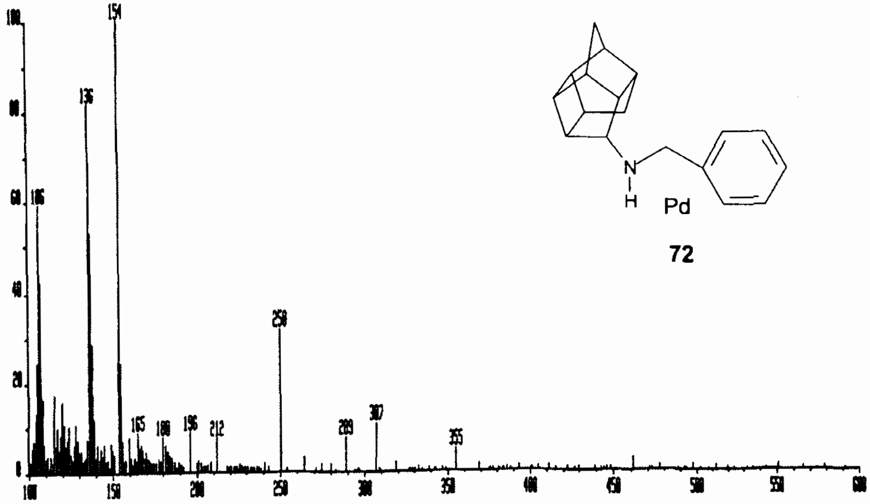

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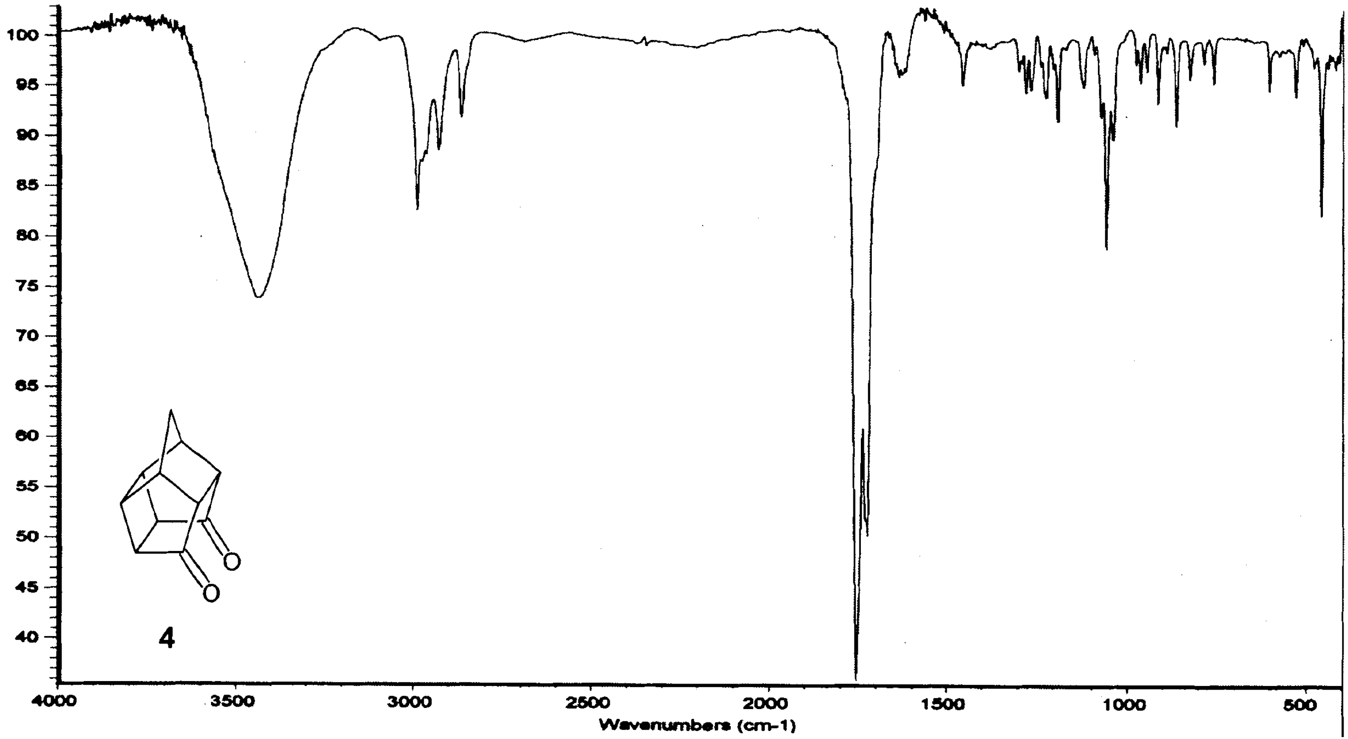
FAB MS spectrum 15



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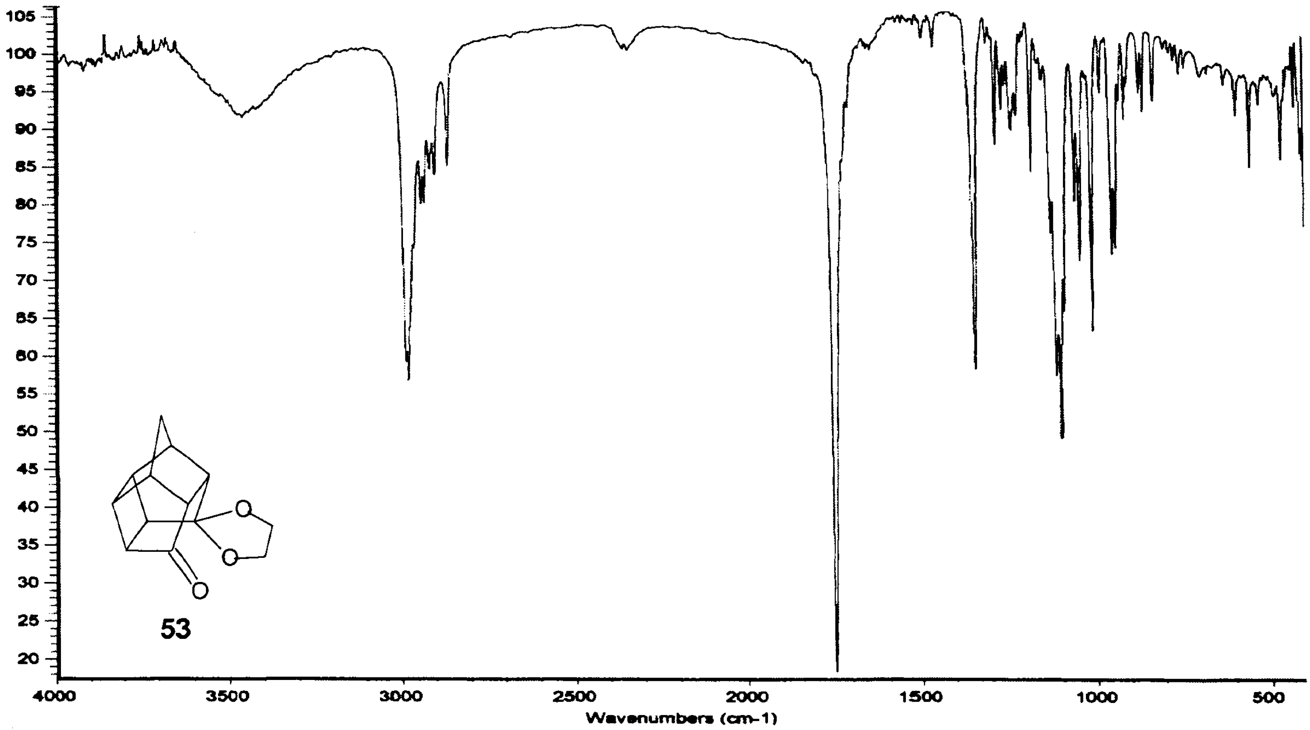

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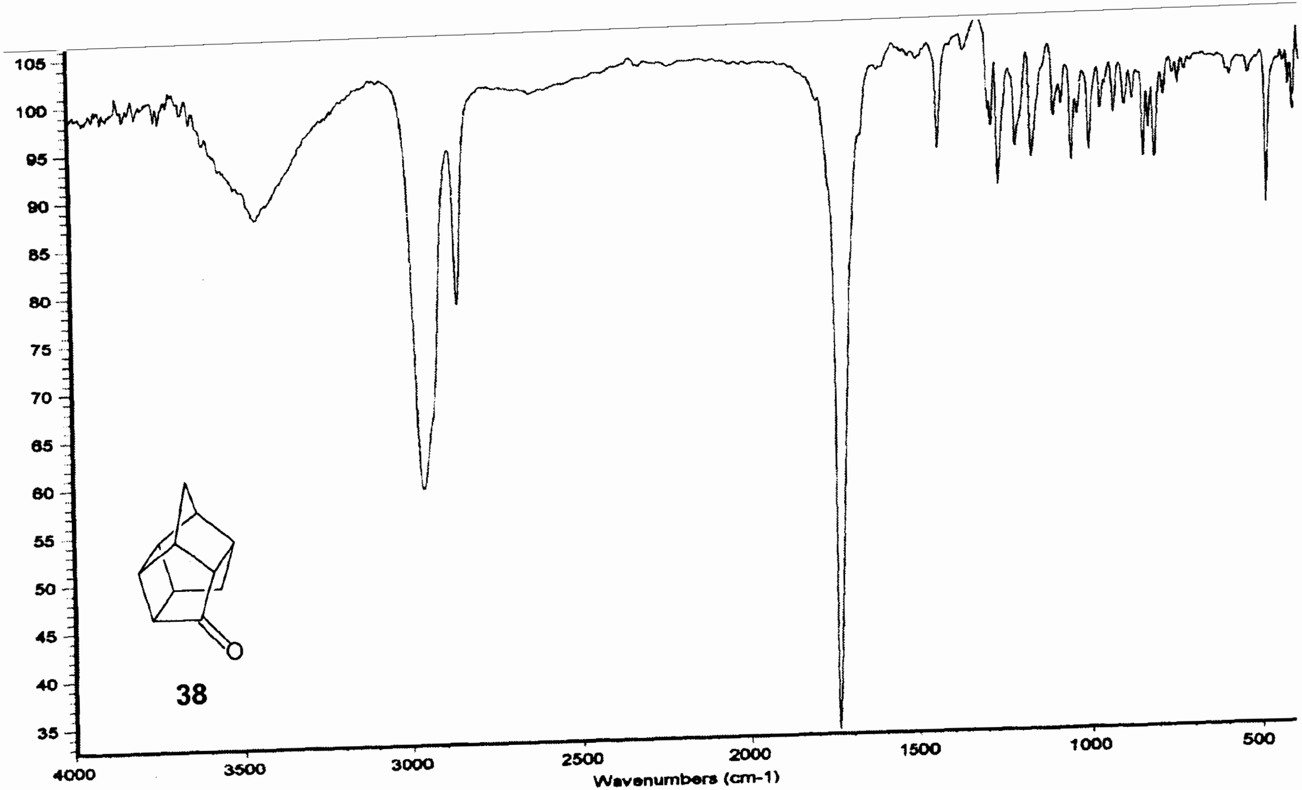
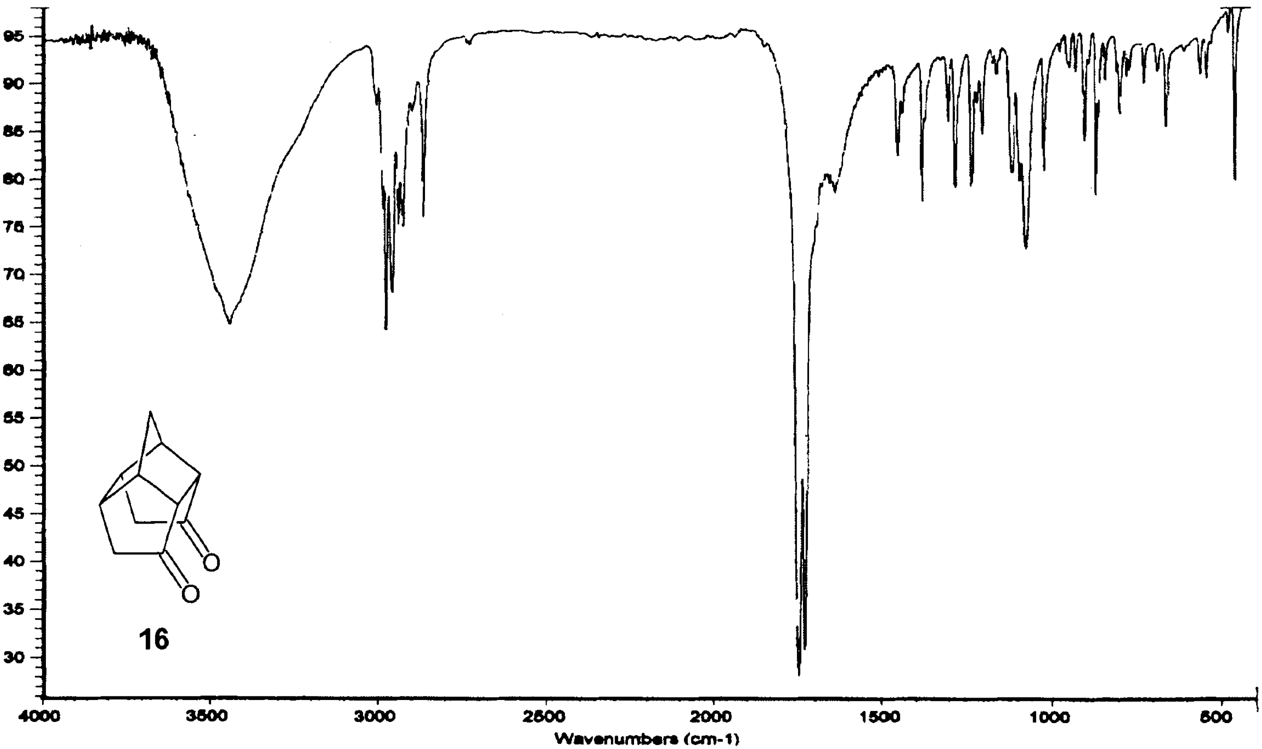
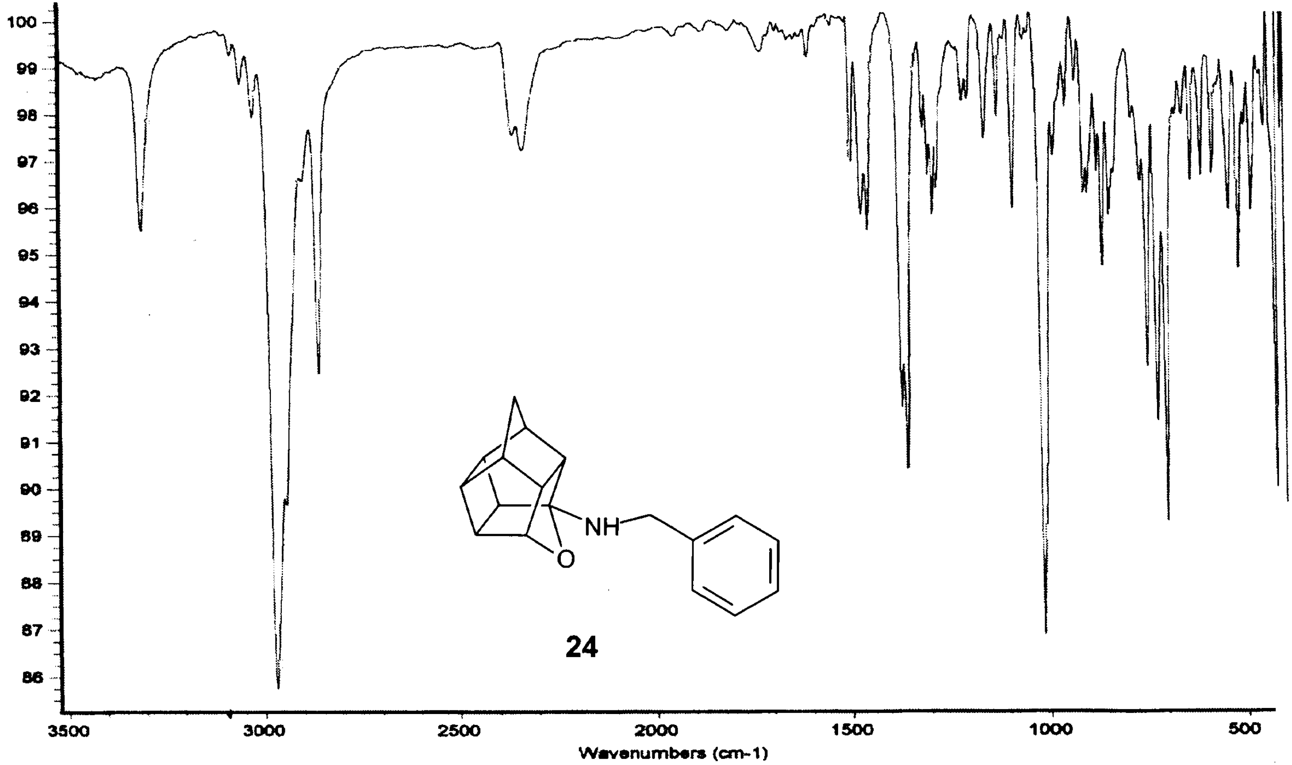


IR spectrum 3



IR spectrum 4



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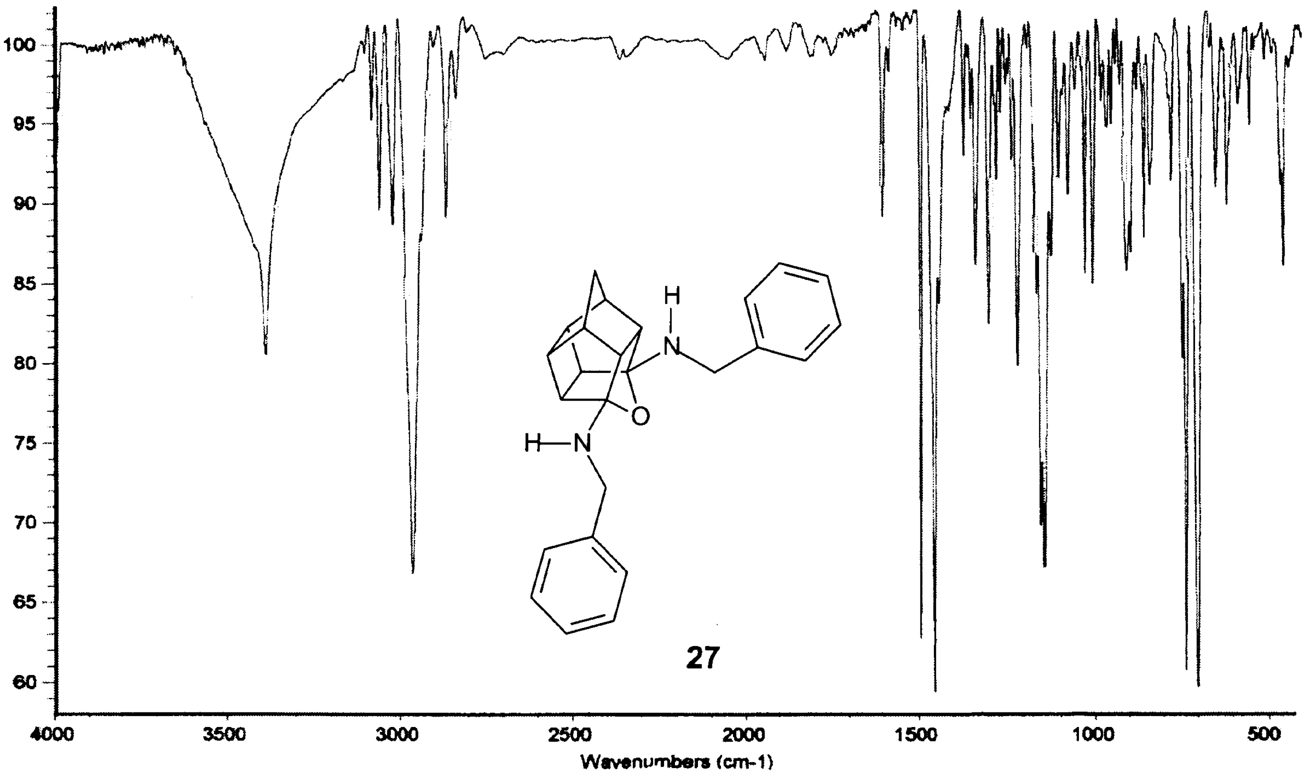
IR spectrum 5



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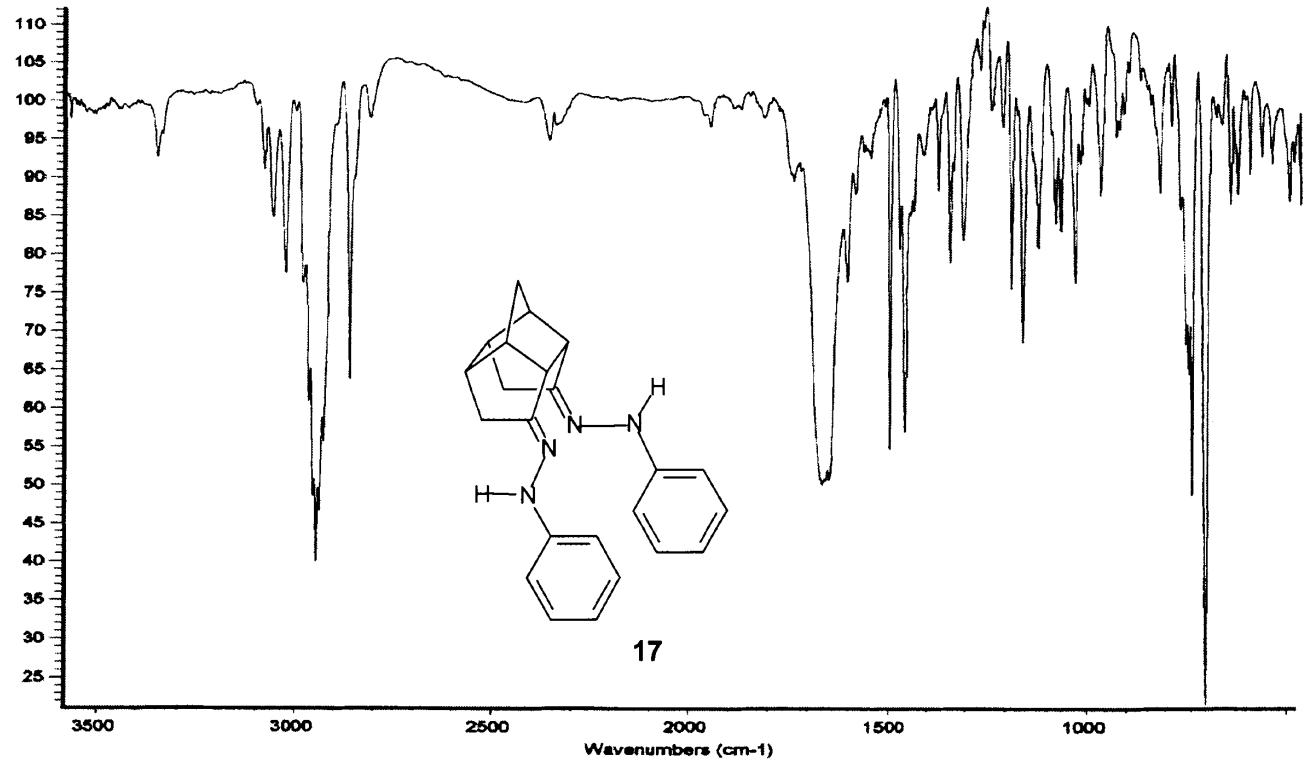
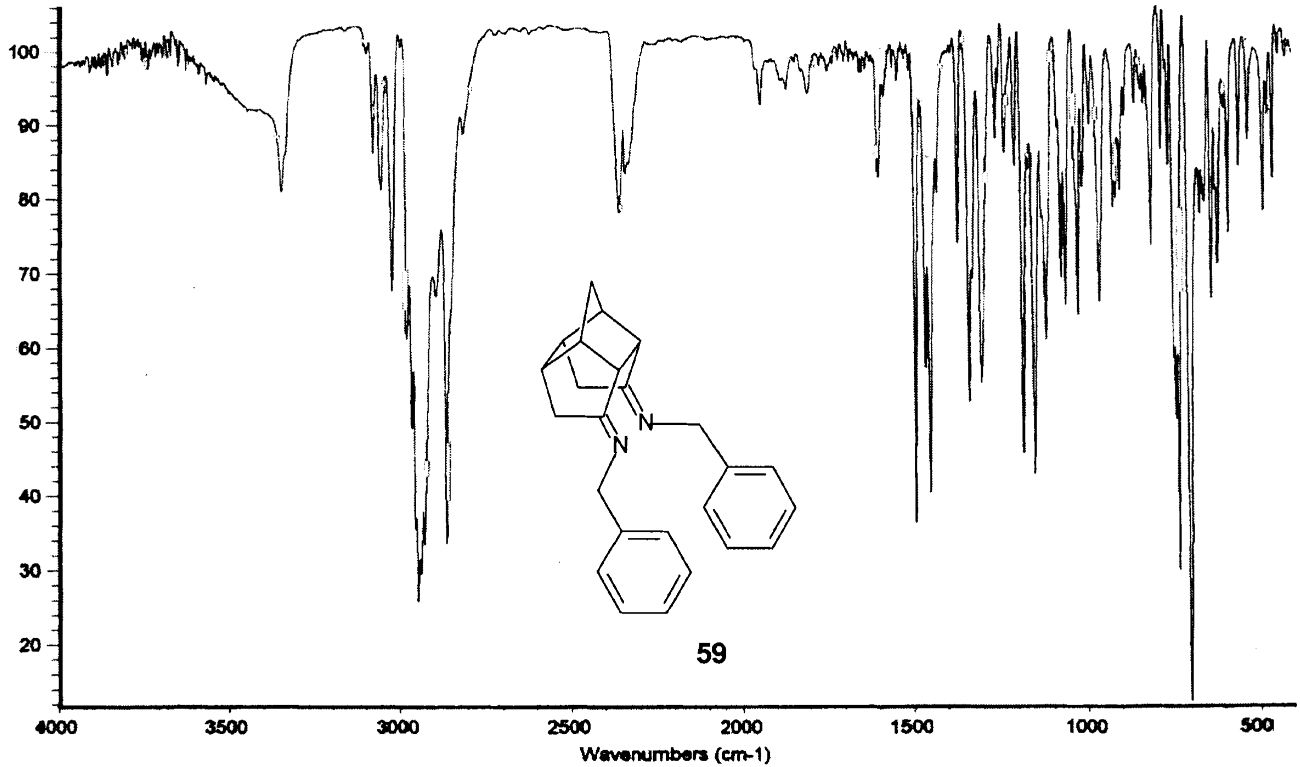
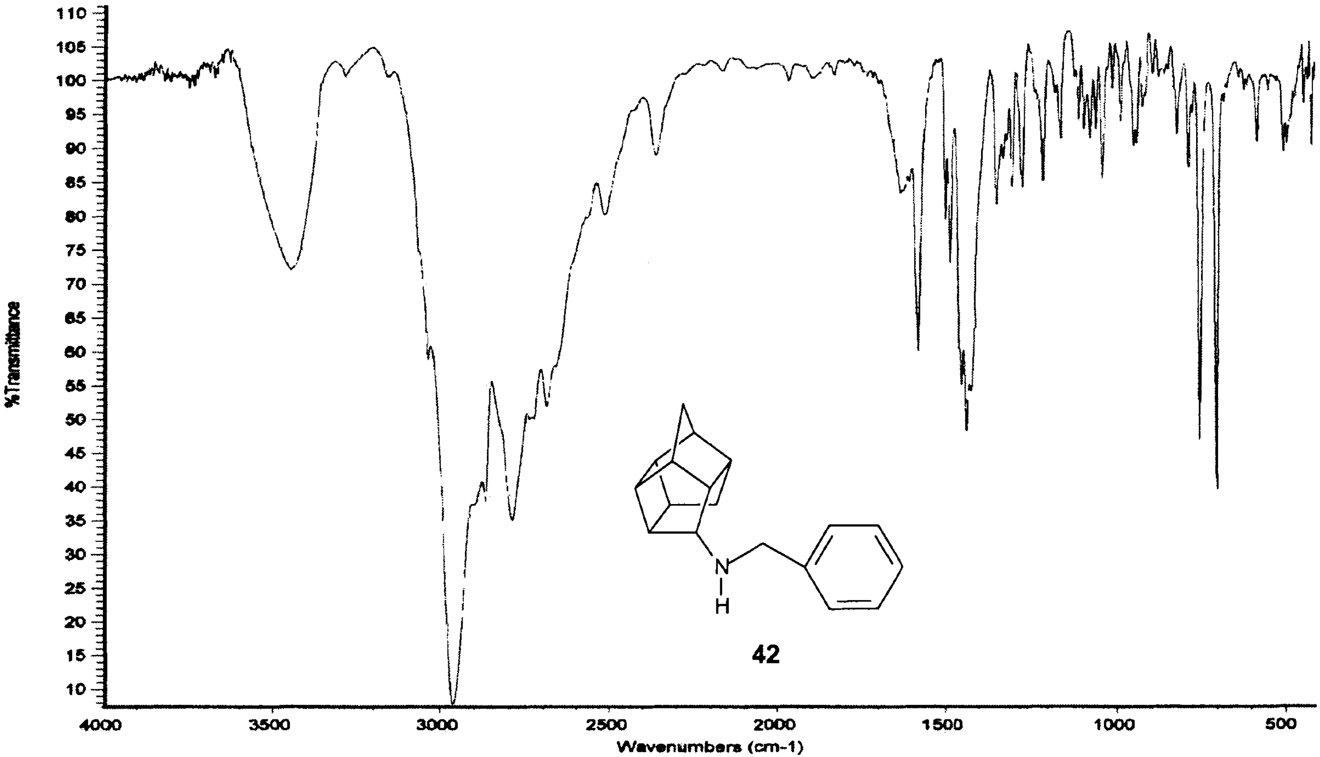
IR spectrum 6



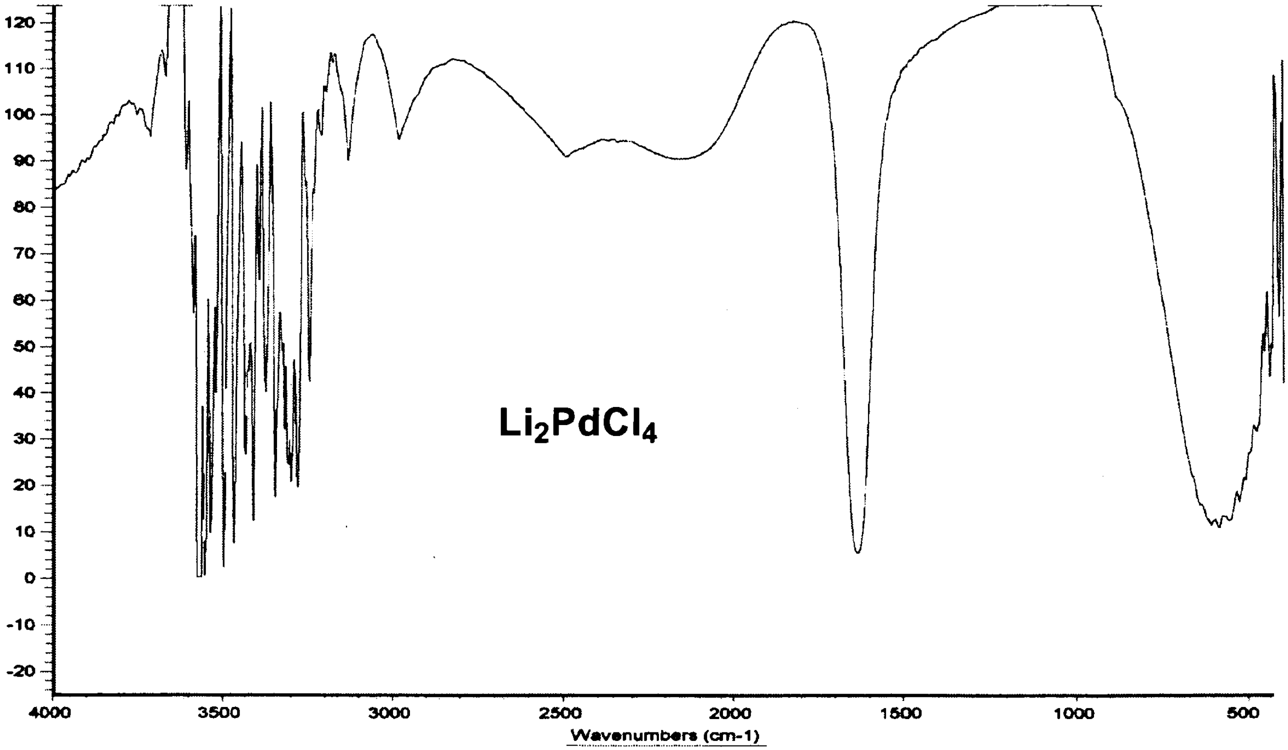
IR spectrum 7



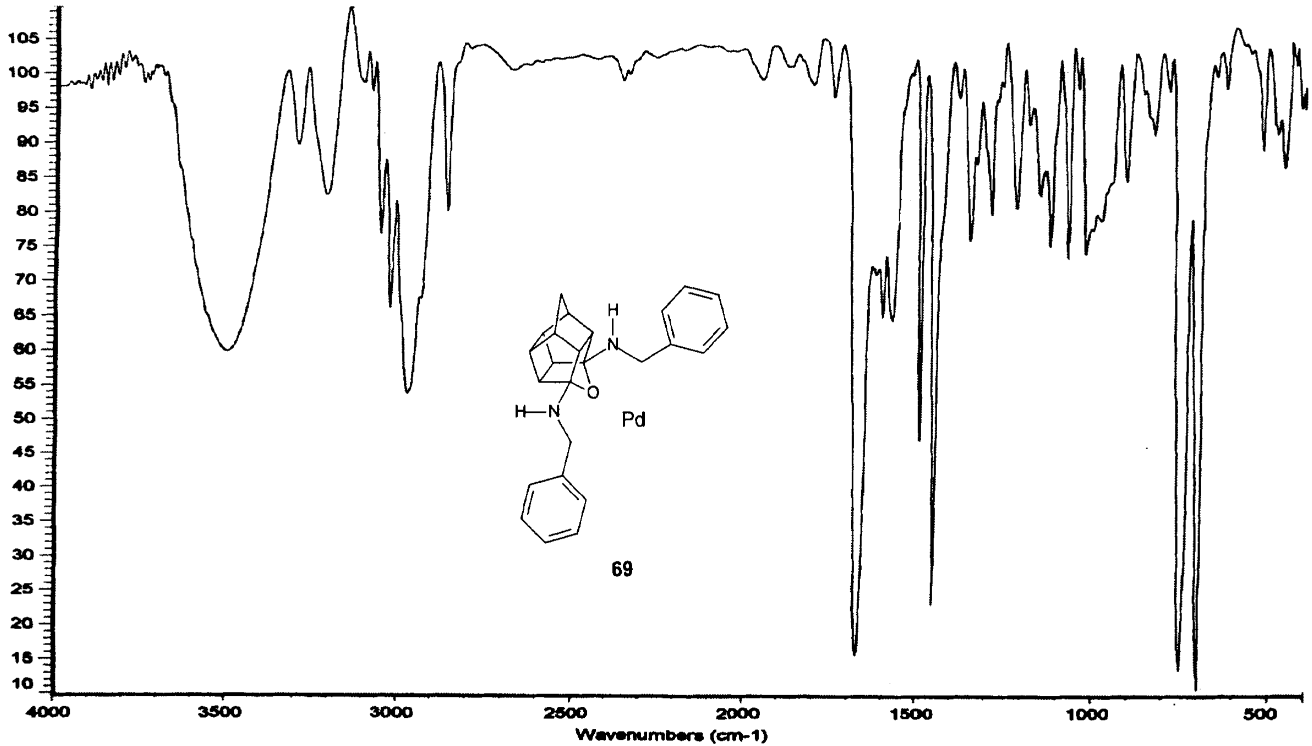
IR spectrum 8



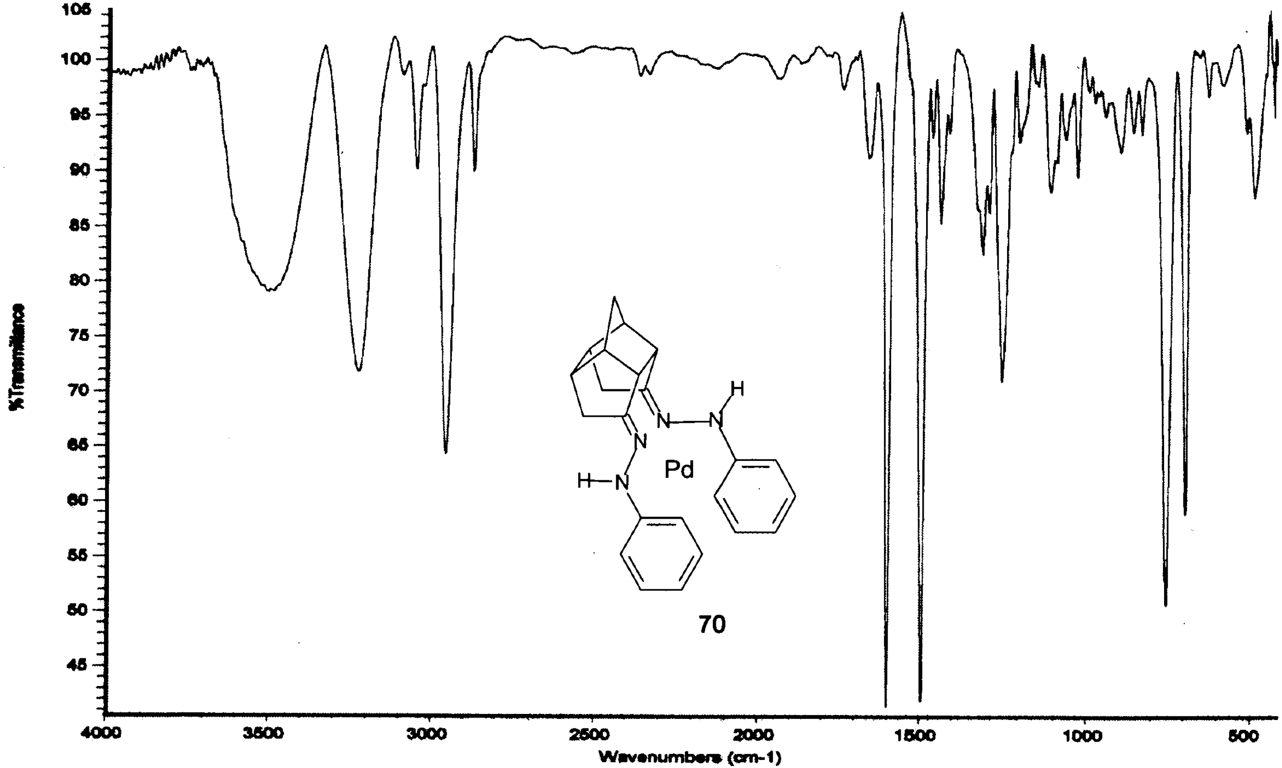
IR spectrum 9



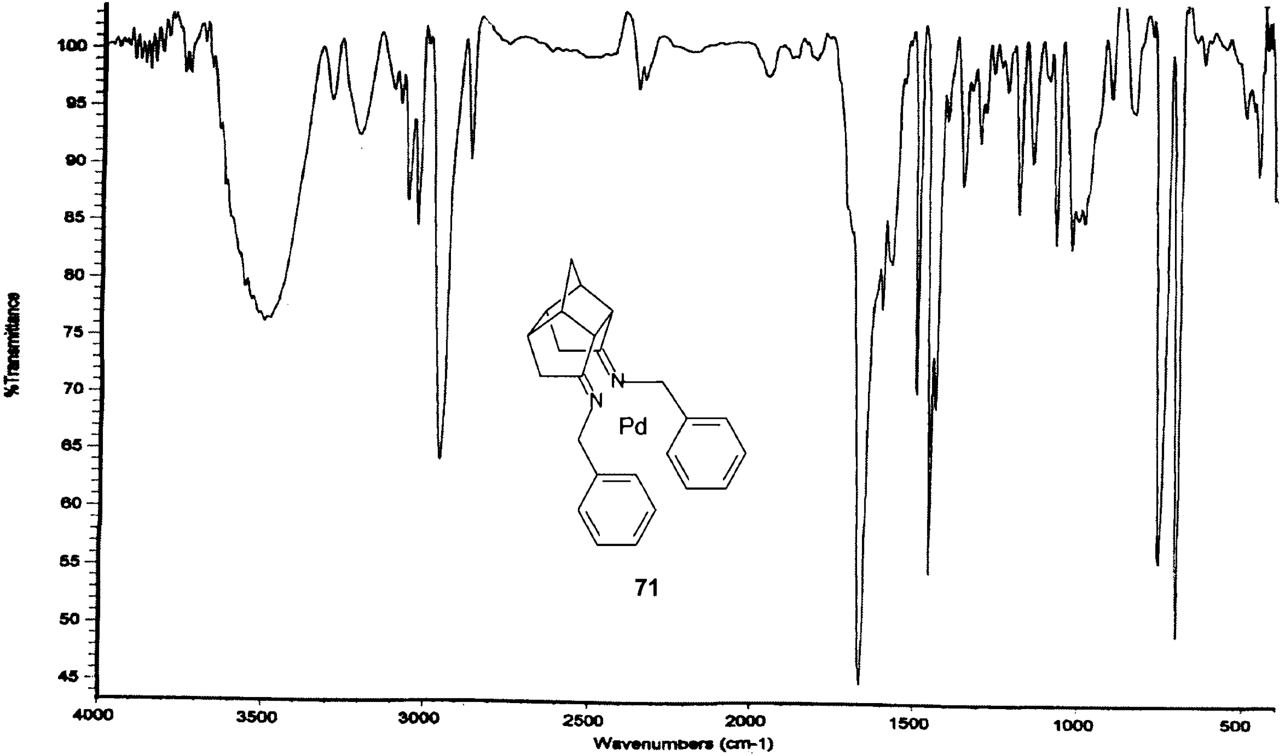
IR spectrum 10



IR spectrum 11



IR spectrum 12



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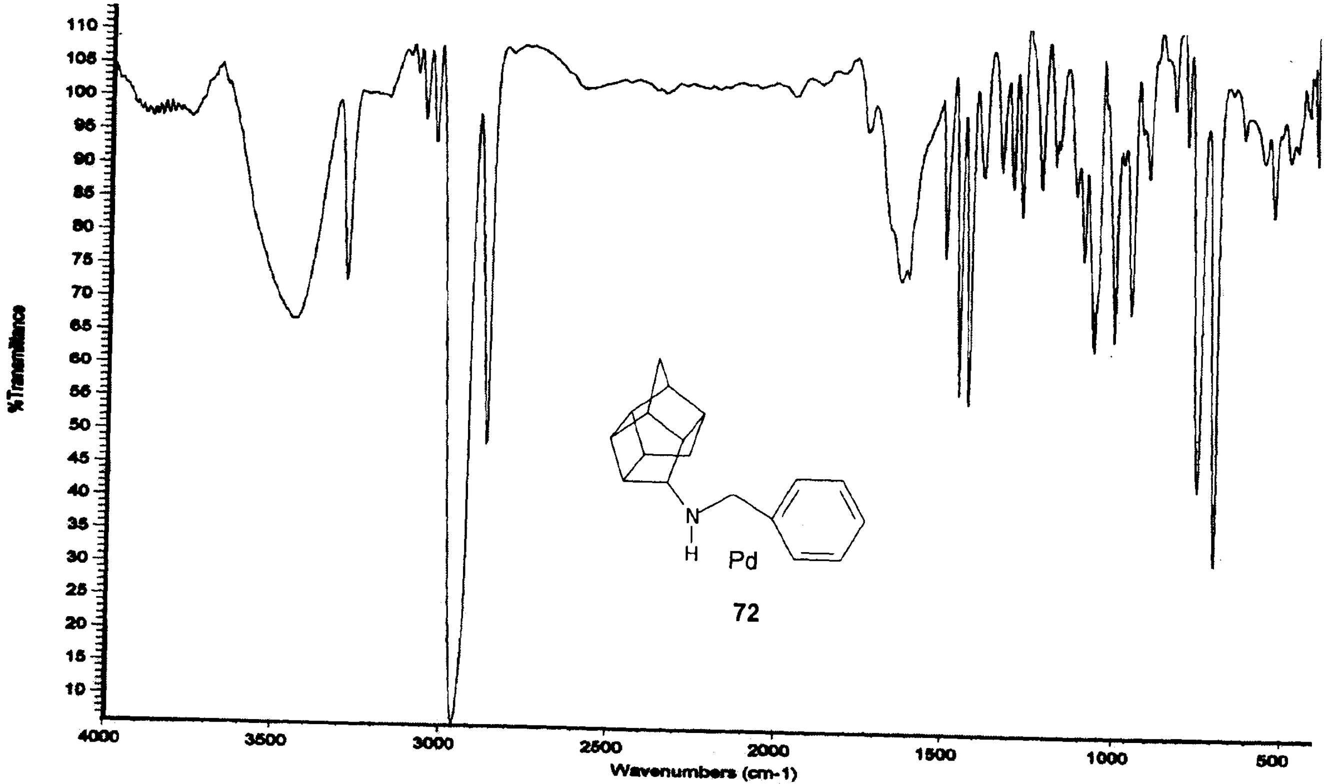
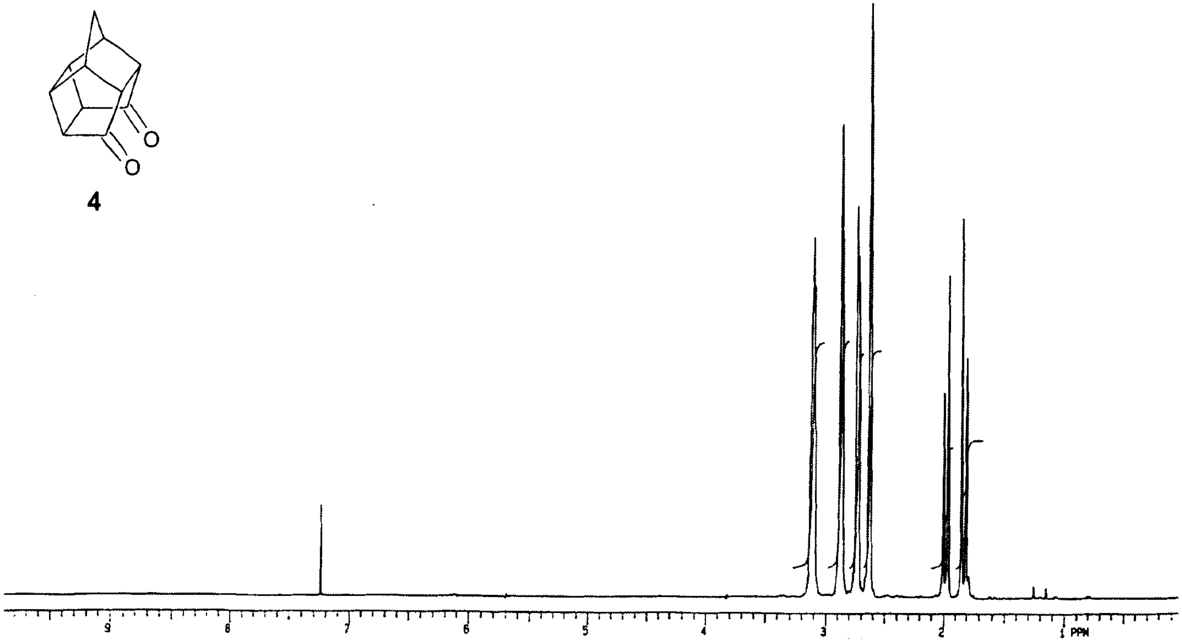
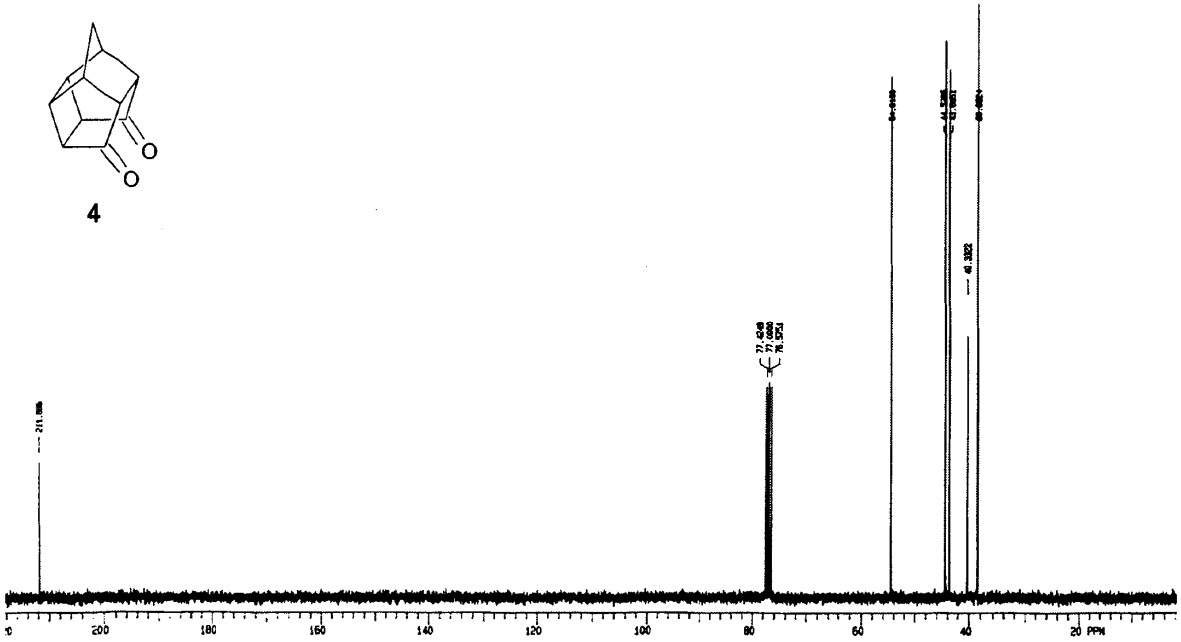
IR spectrum 13



IR spectrum 14



NMR spectrum 1: ^1H NMR ($CDCl_3$) 300 MHz



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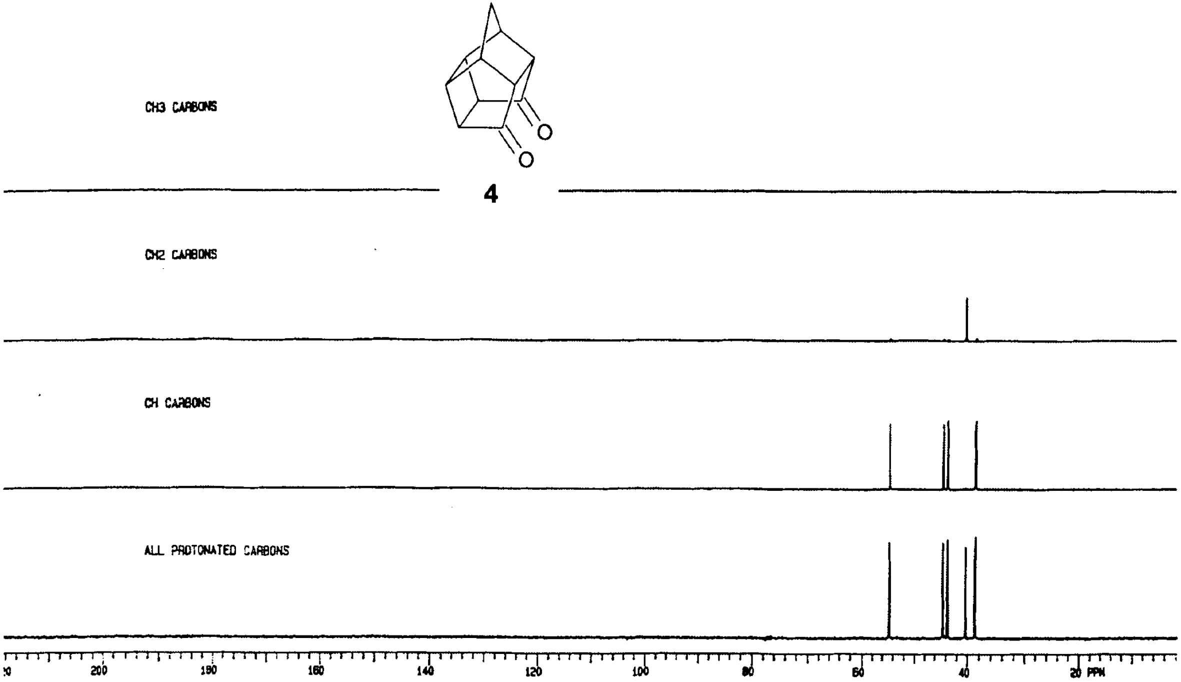
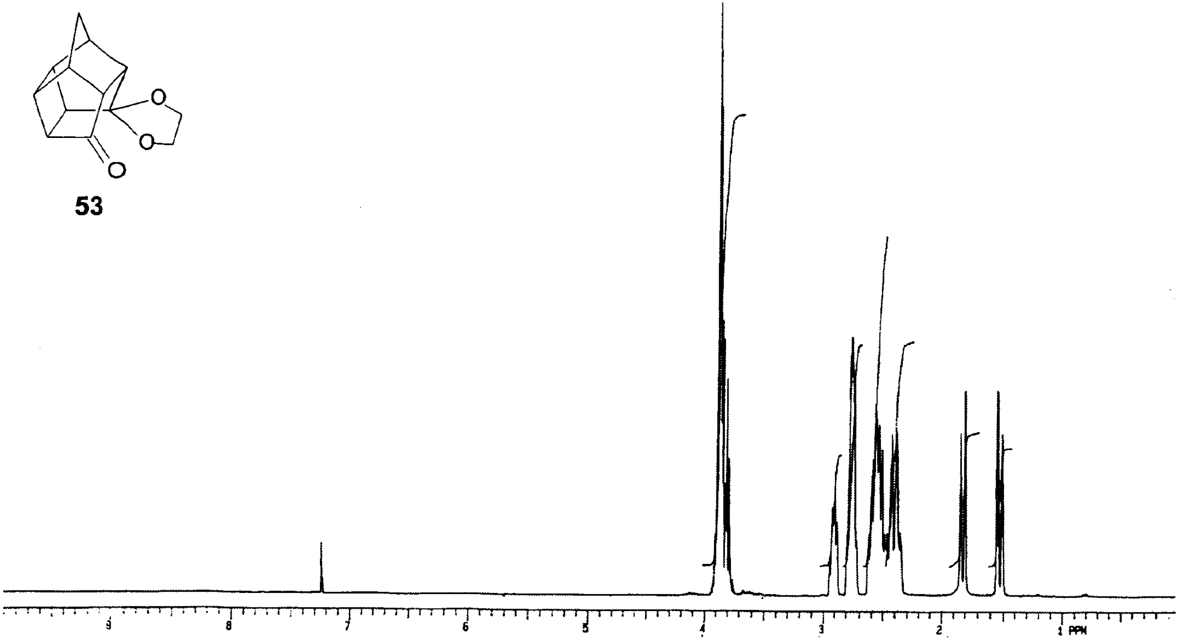
NMR spectrum 2: ^{13}C NMR ($CDCl_3$) 300 MHz

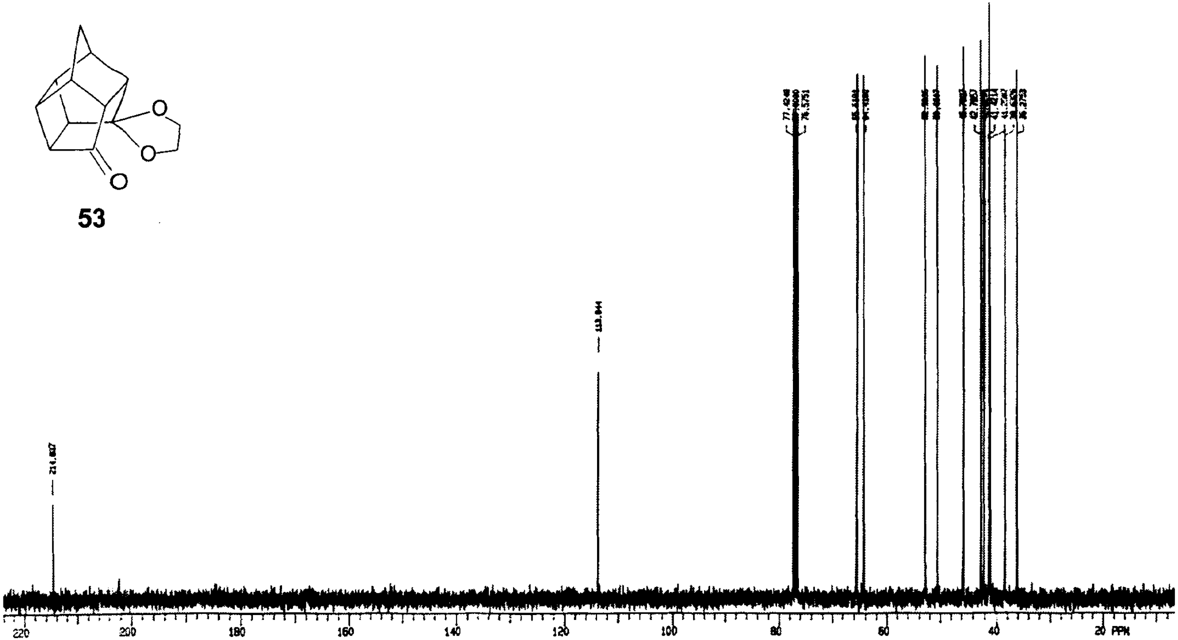


NMR spectrum 3: ^{13}C APT NMR ($CDCl_3$) 300 MHz



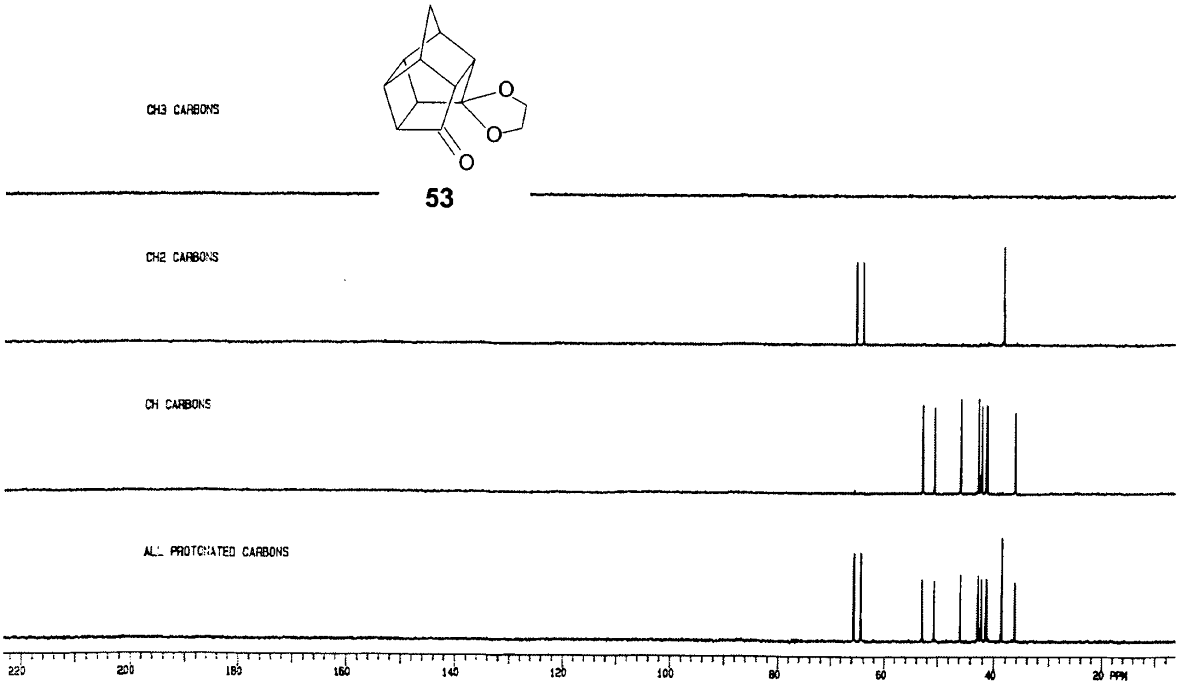
53

NMR spectrum 4: ^1H NMR ($CDCl_3$) 300 MHz

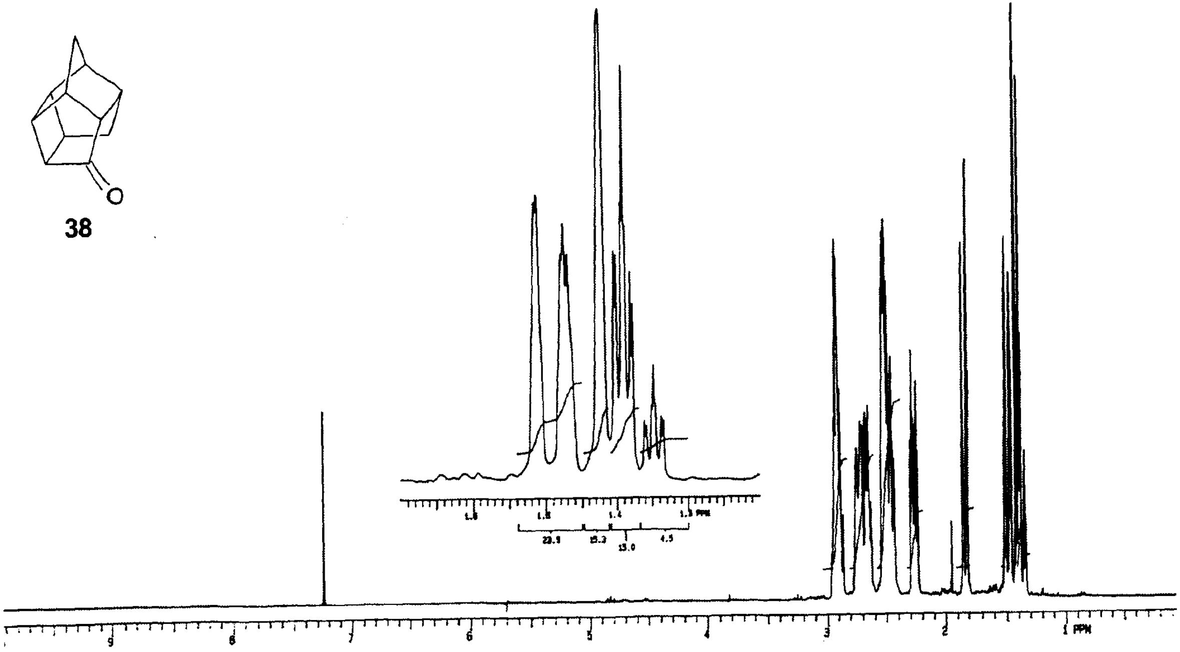


53

NMR spectrum 5: ^{13}C NMR ($CDCl_3$) 300 MHz



NMR spectrum 6: ^{13}C DEPT NMR ($CDCl_3$) 300 MHz



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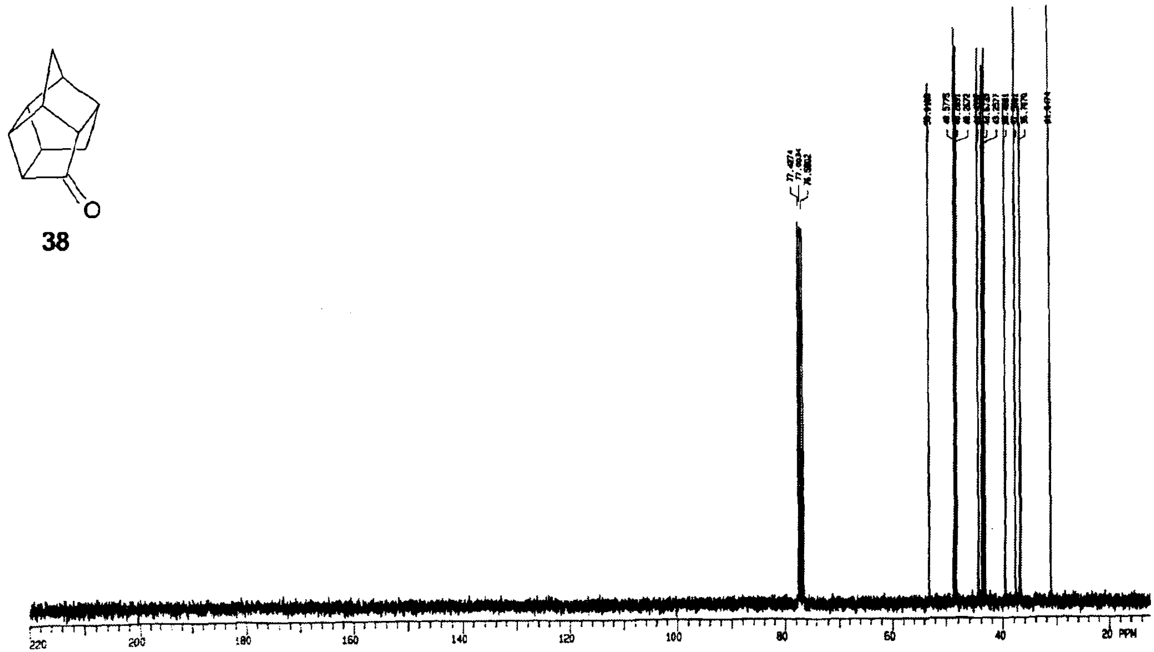
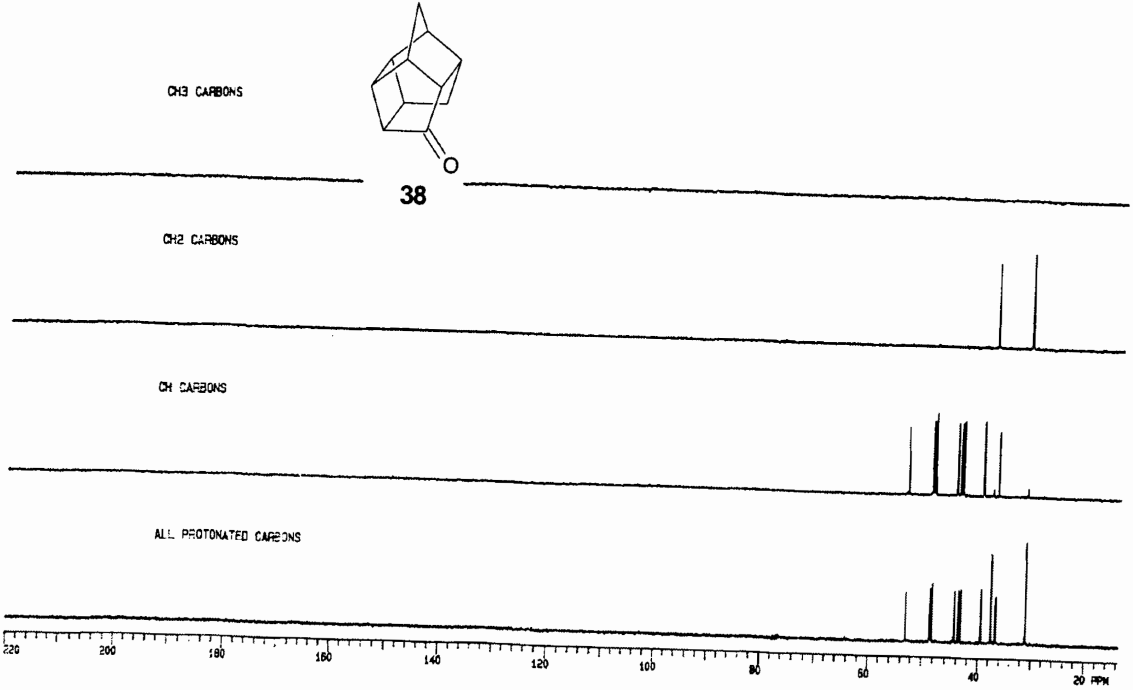
NMR spectrum 7: ^1H NMR ($CDCl_3$) 300 MHz

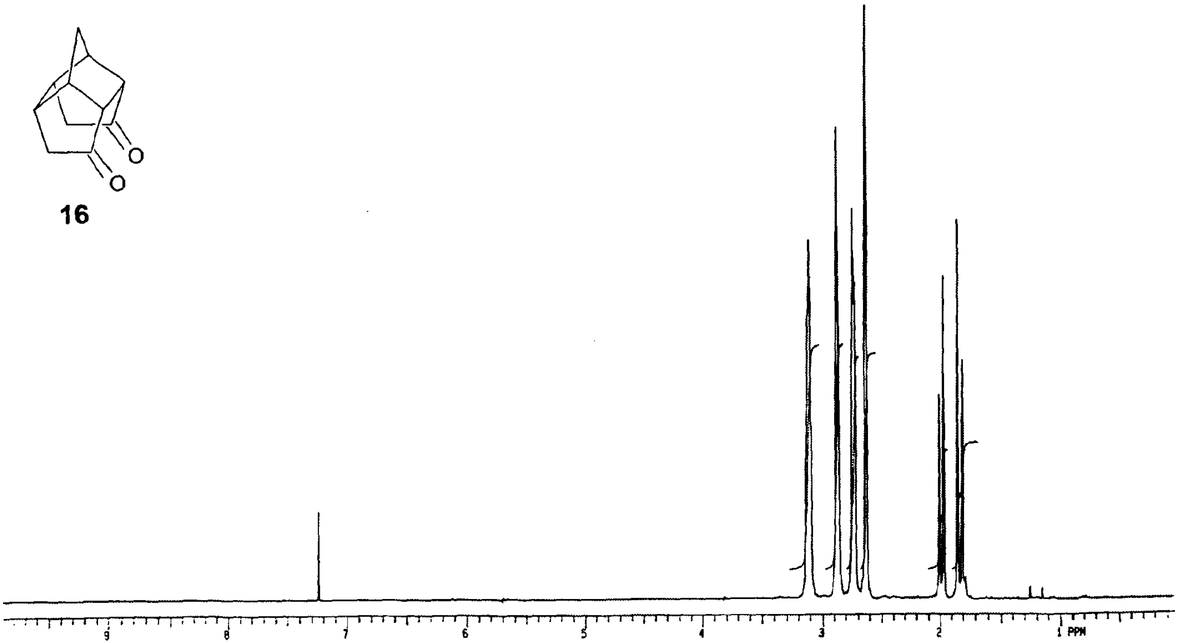


38

NMR spectrum 8: ^{13}C NMR ($CDCl_3$) 300 MHz



NMR spectrum 9: ^{13}C APT NMR ($CDCl_3$) 300 MHz



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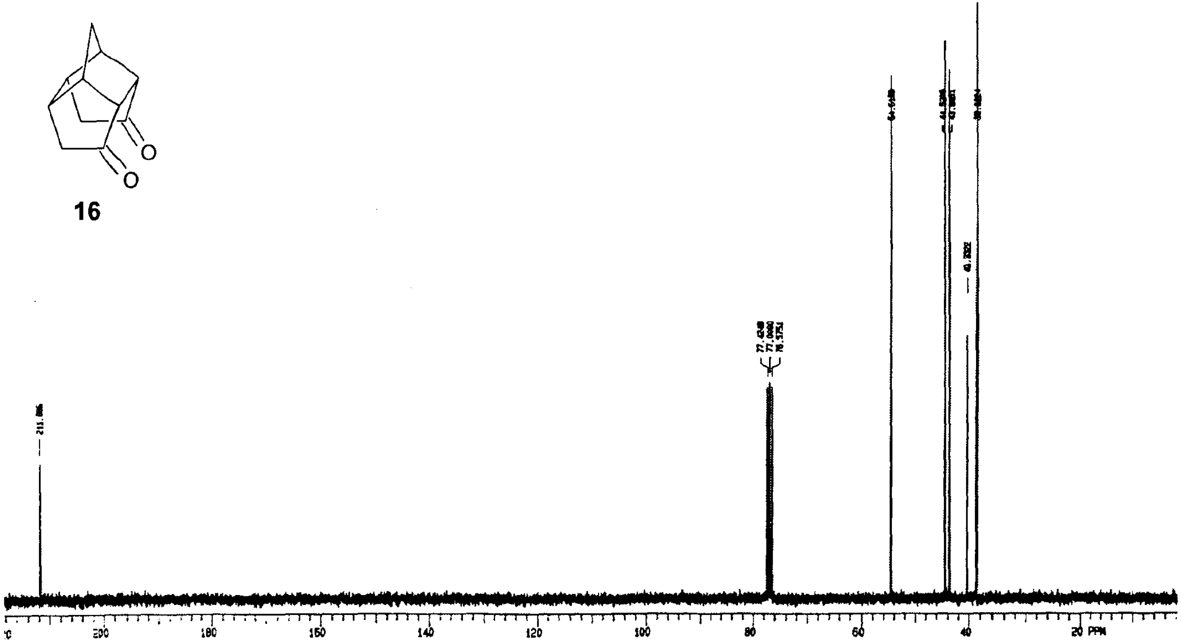
NMR spectrum 10: ^{1}H NMR (CDCl$_3$) 300 MHz



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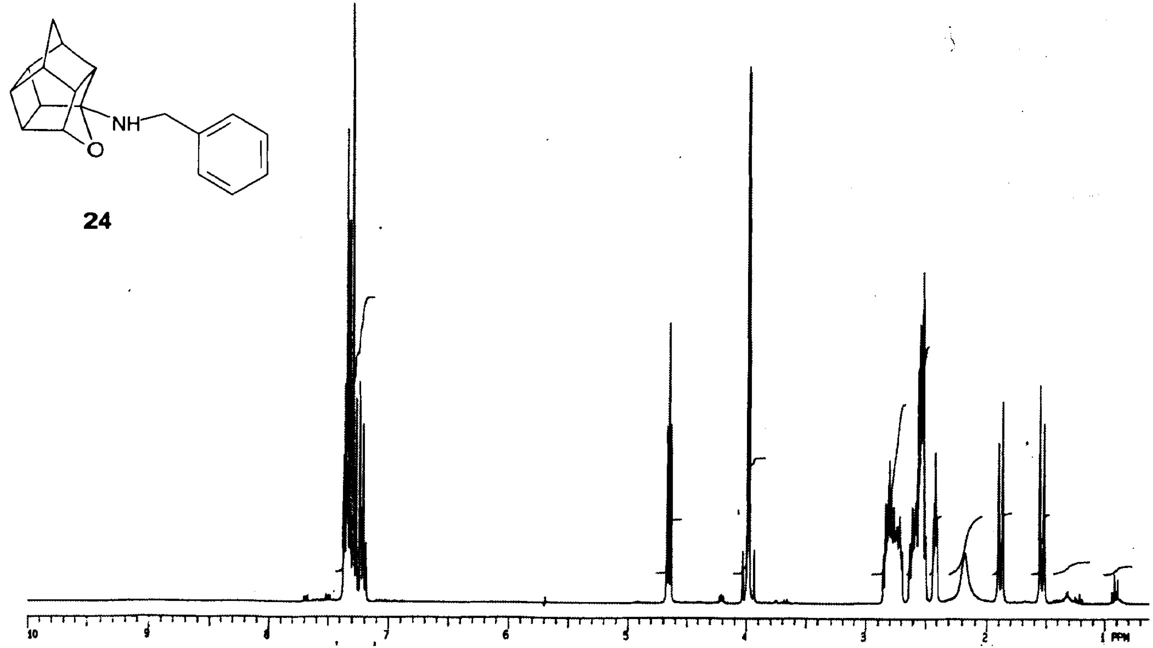
NMR spectrum 11: ^{13}C NMR ($CDCl_3$) 300 MHz



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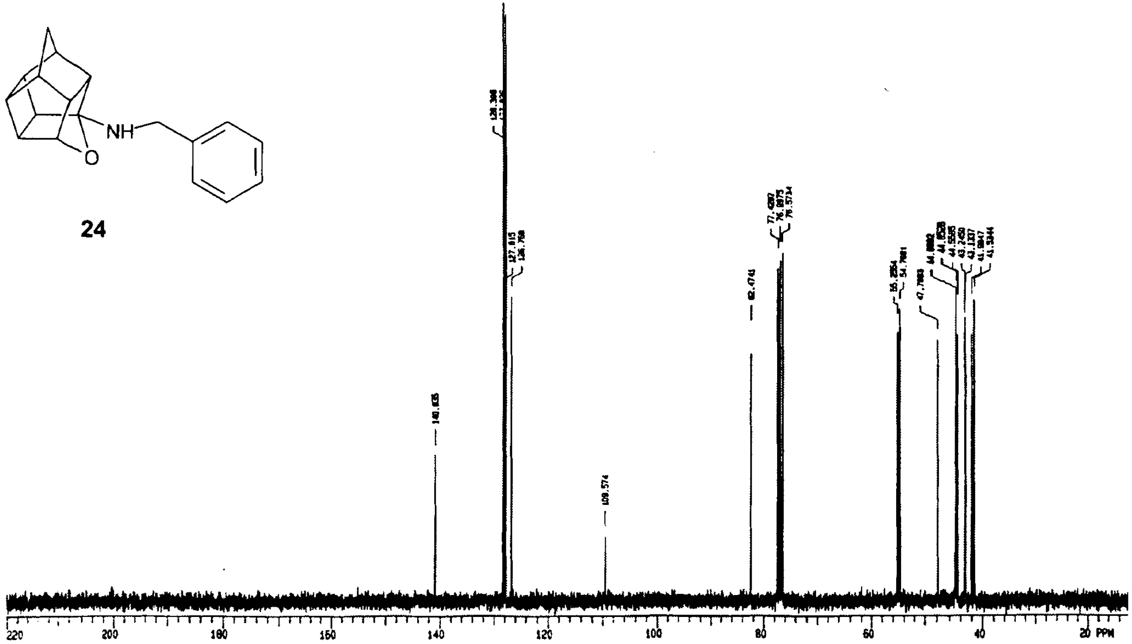
NMR spectrum 12: ^{1}H NMR ($CDCl_3$) 300 MHz



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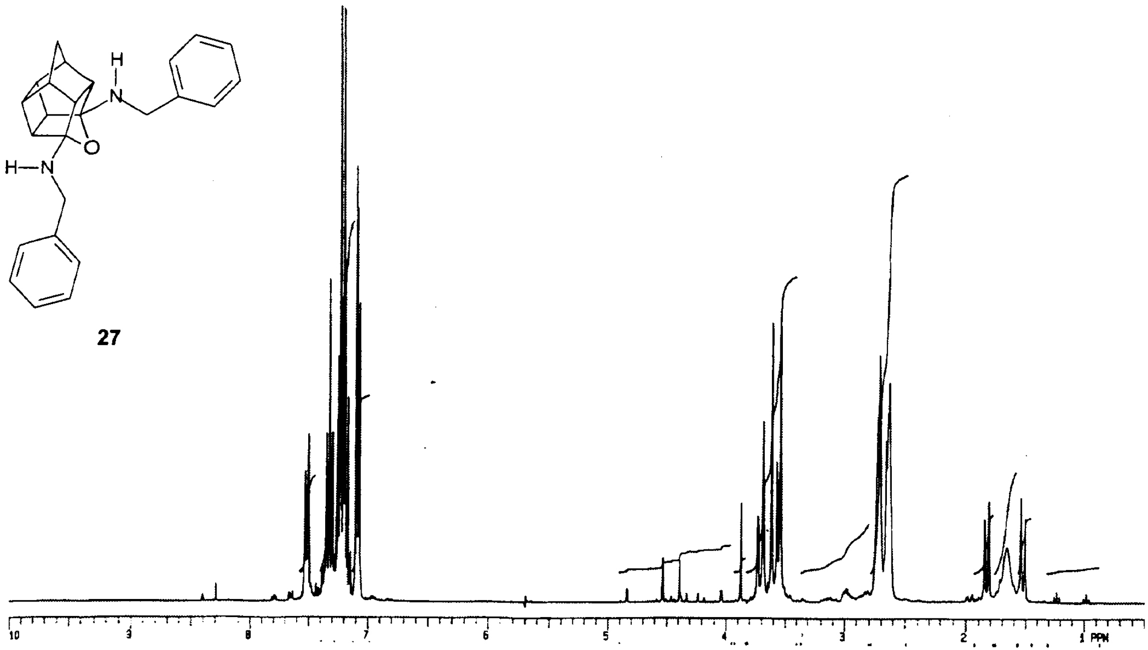
NMR spectrum 13: ^{13}C NMR (CDCl$_3$) 300 MHz



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NMR spectrum 14: ^{1}H NMR (CDCl$_3$) 300 MHz

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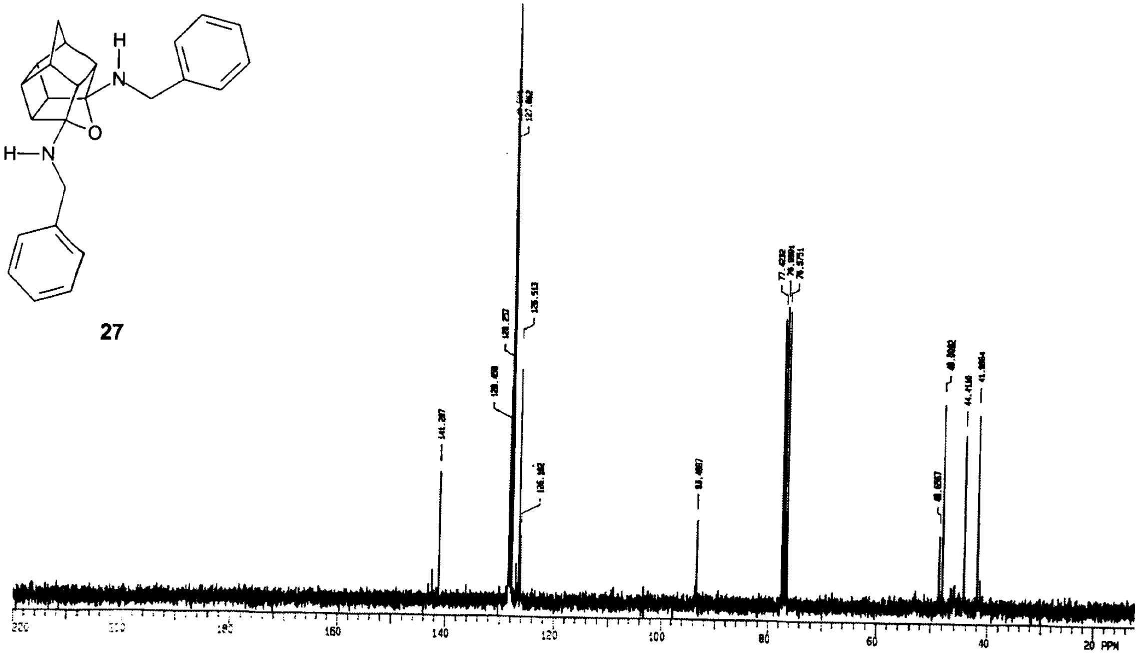

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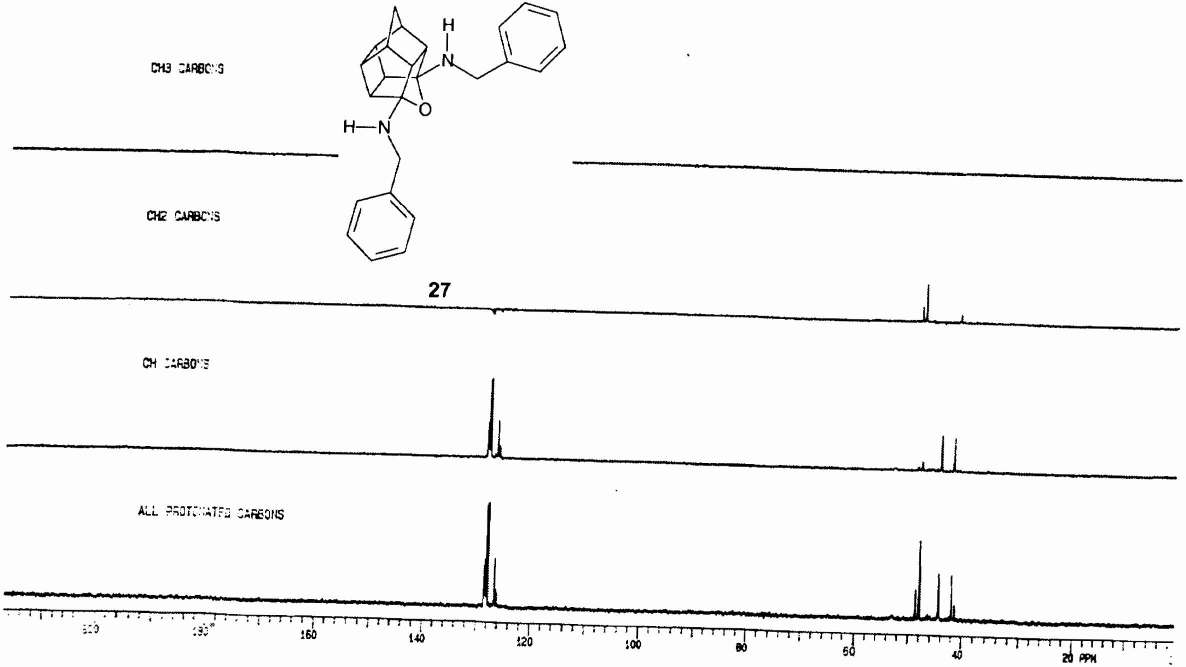

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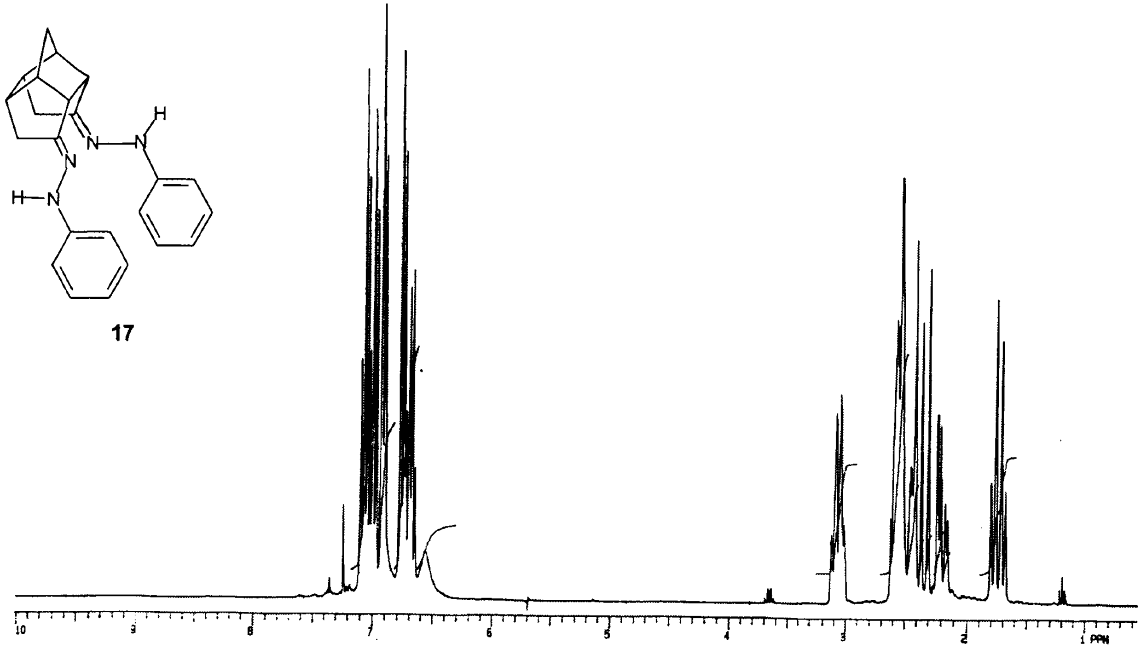
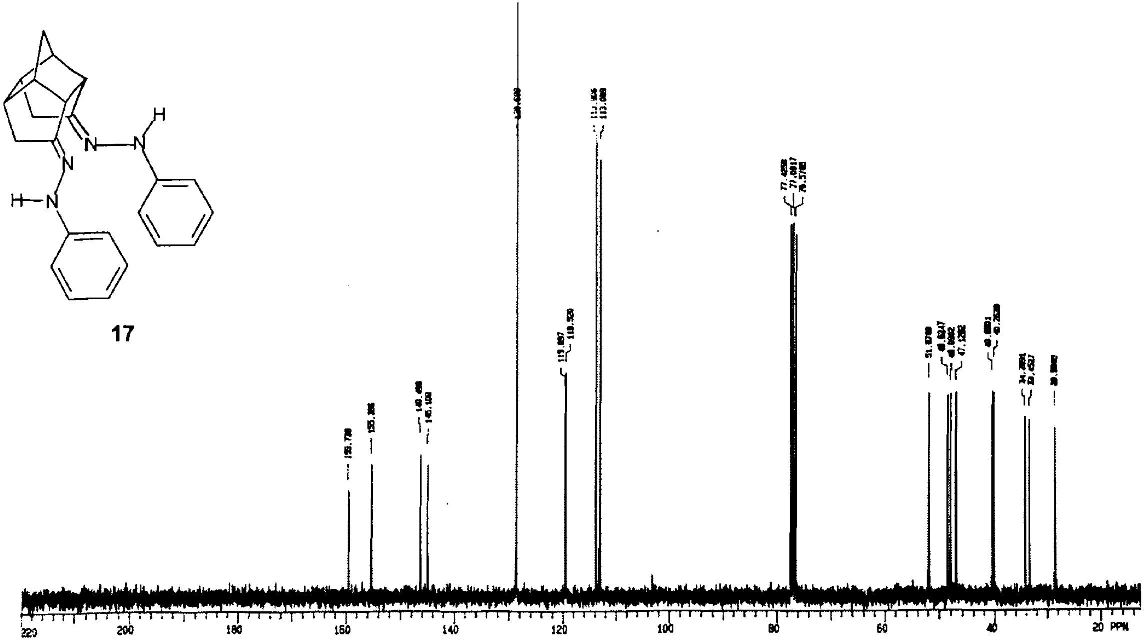
NMR spectrum 16: ^{13}C APT NMR ($CDCl_3$) 300 MHz



NMR spectrum 17: ^{1}H NMR ($CDCl_3$) 300 MHz



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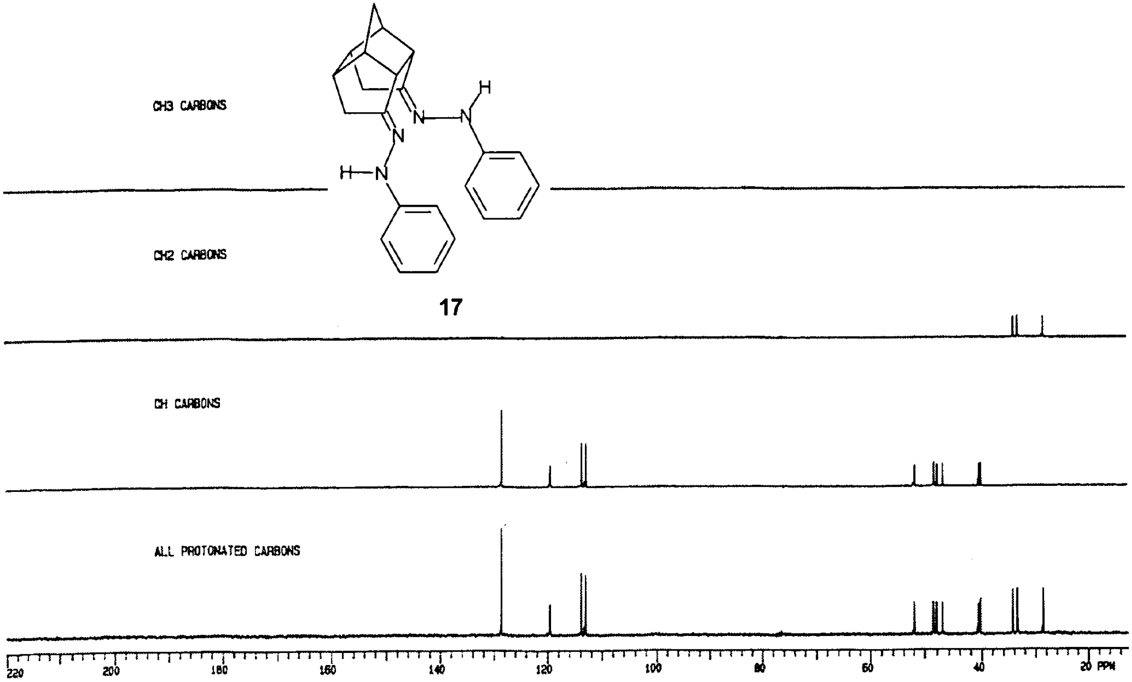

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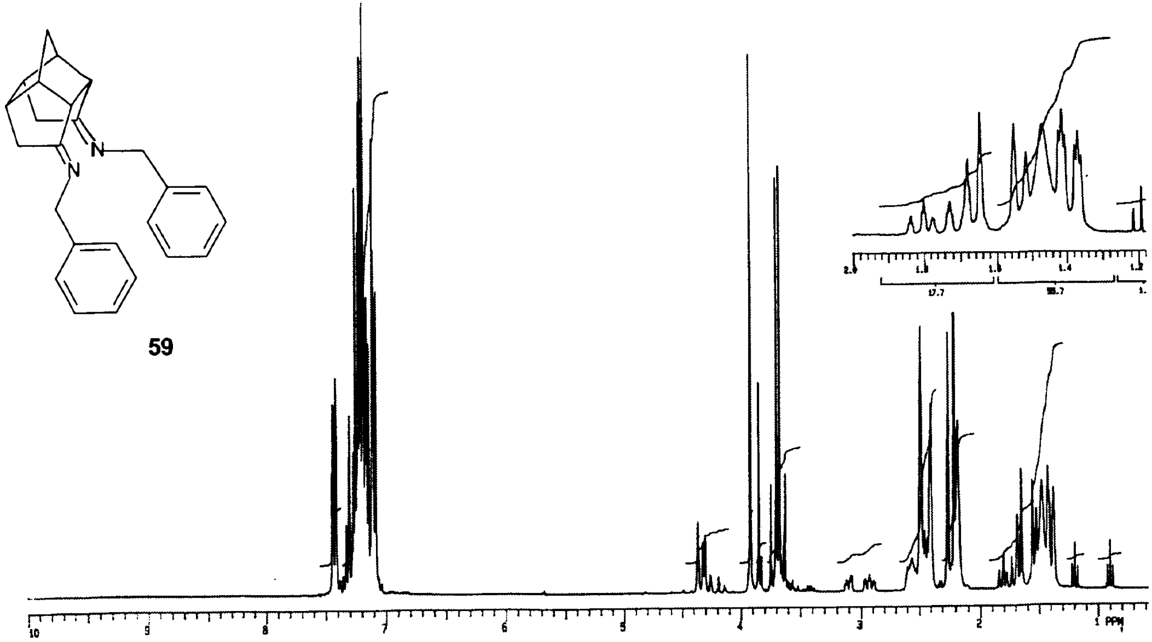
NMR spectrum 19: ^{13}C APT NMR ($CDCl_3$) 300 MHz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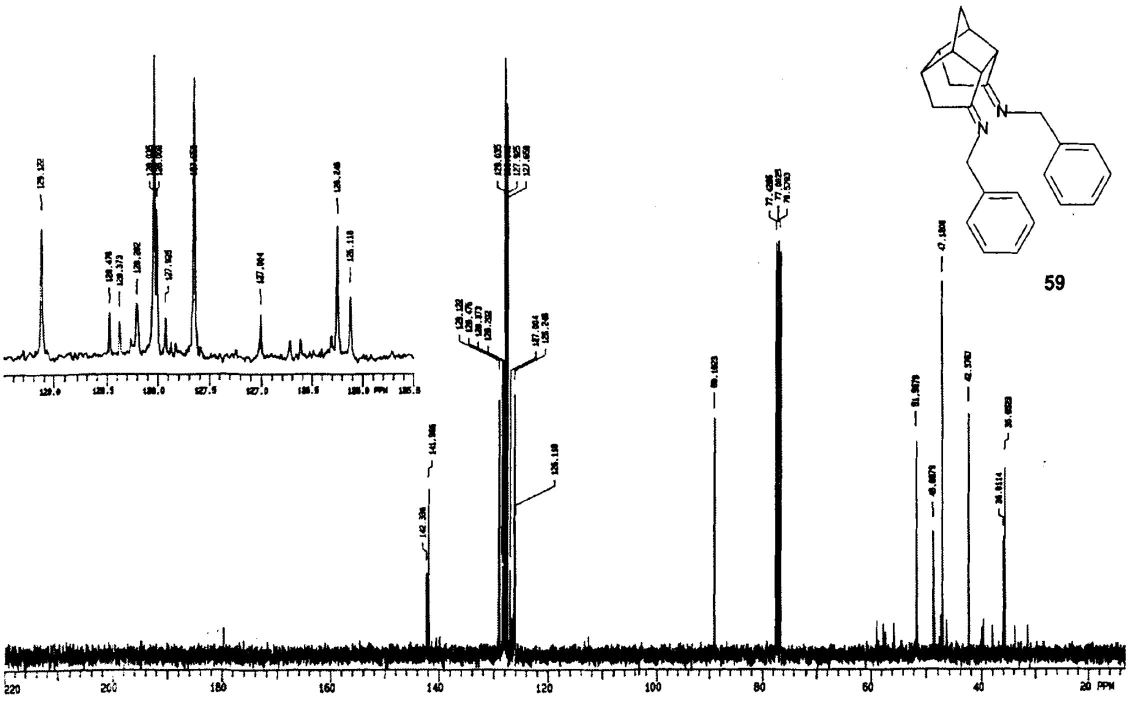
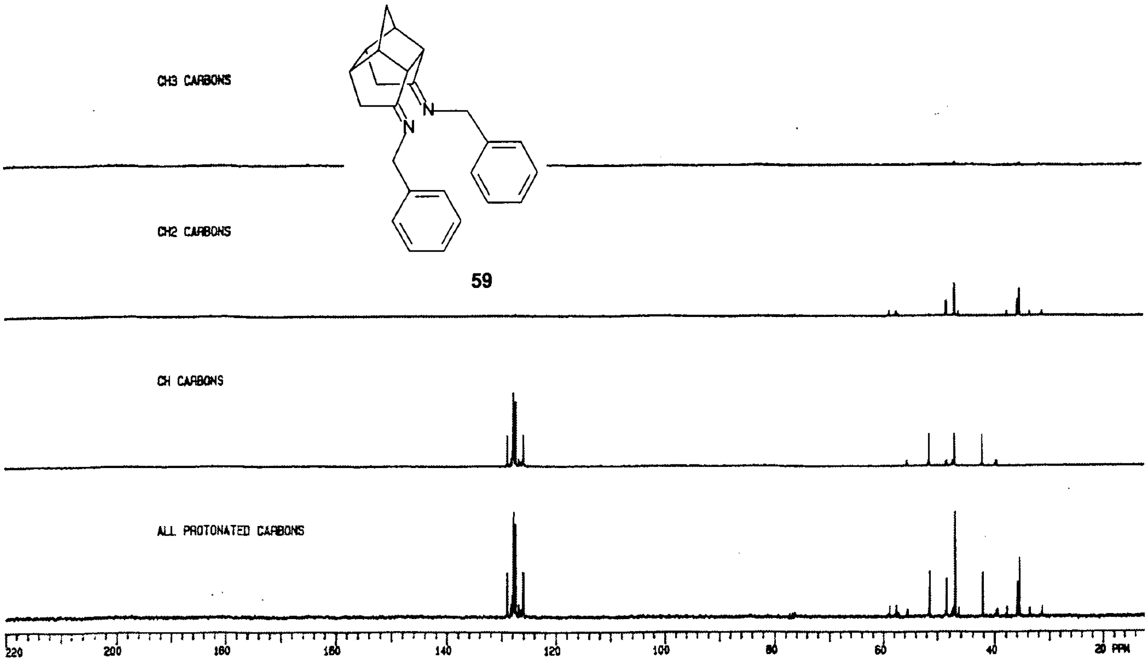
NMR spectrum 20: ^1H NMR ($CDCl_3$) 300 MHz



NMR spectrum 21: ^{13}C NMR ($CDCl_3$) 300 MHz



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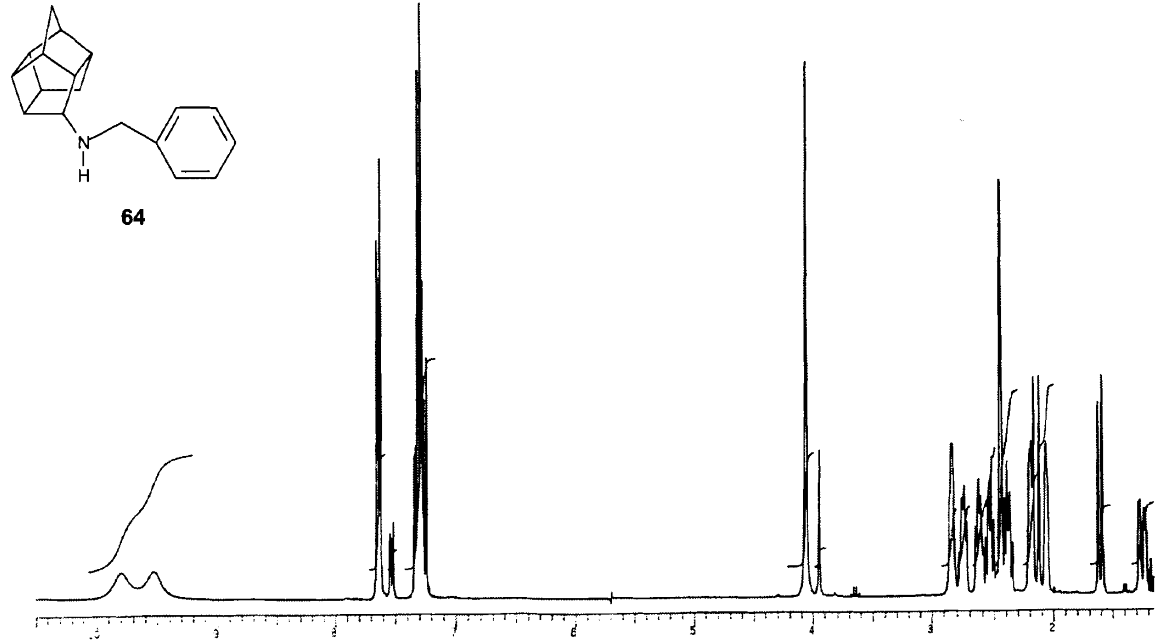
NMR spectrum 22: ^{13}C APT NMR ($CDCl_3$) 300 MHz



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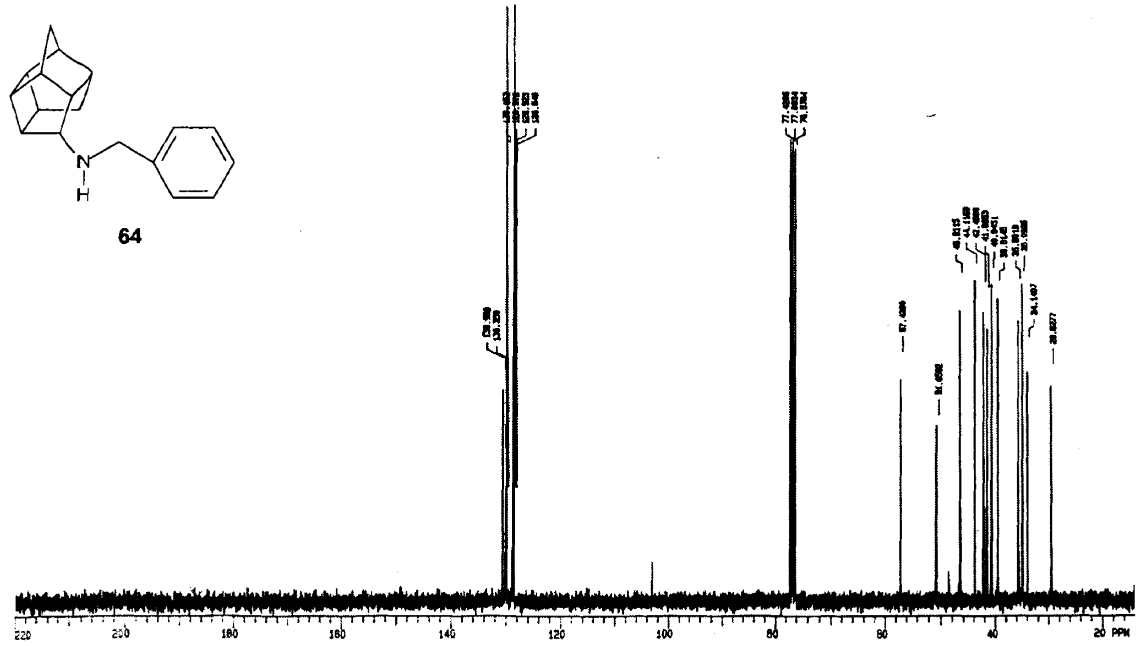
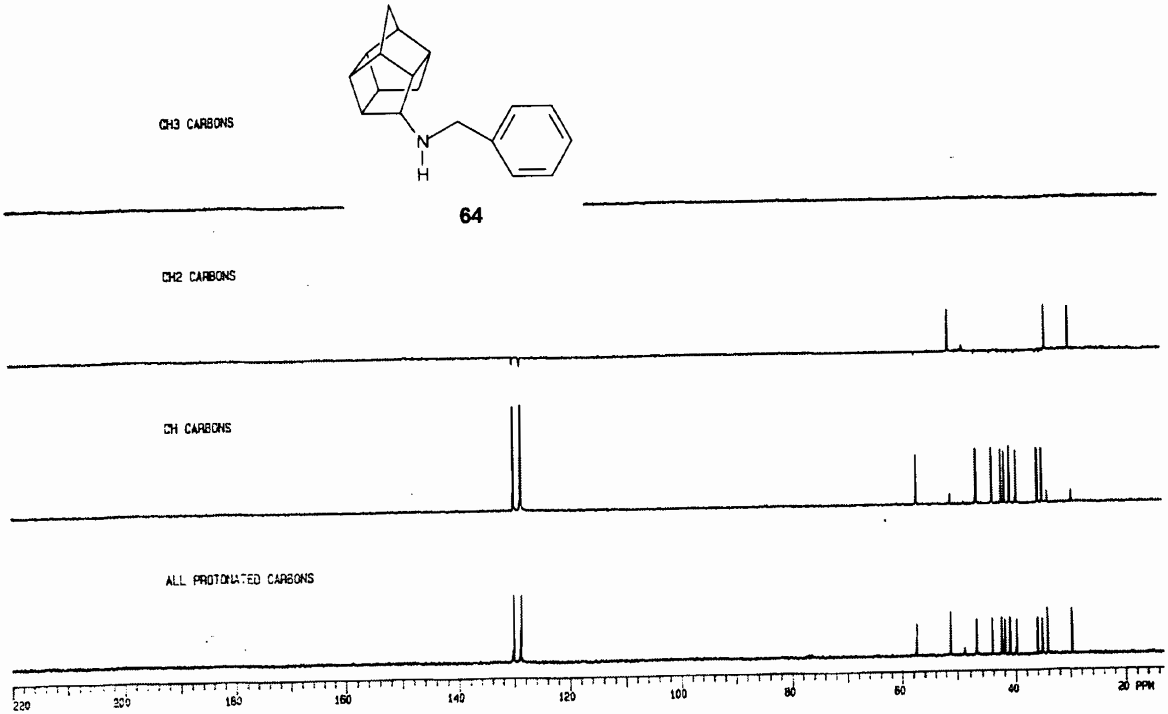
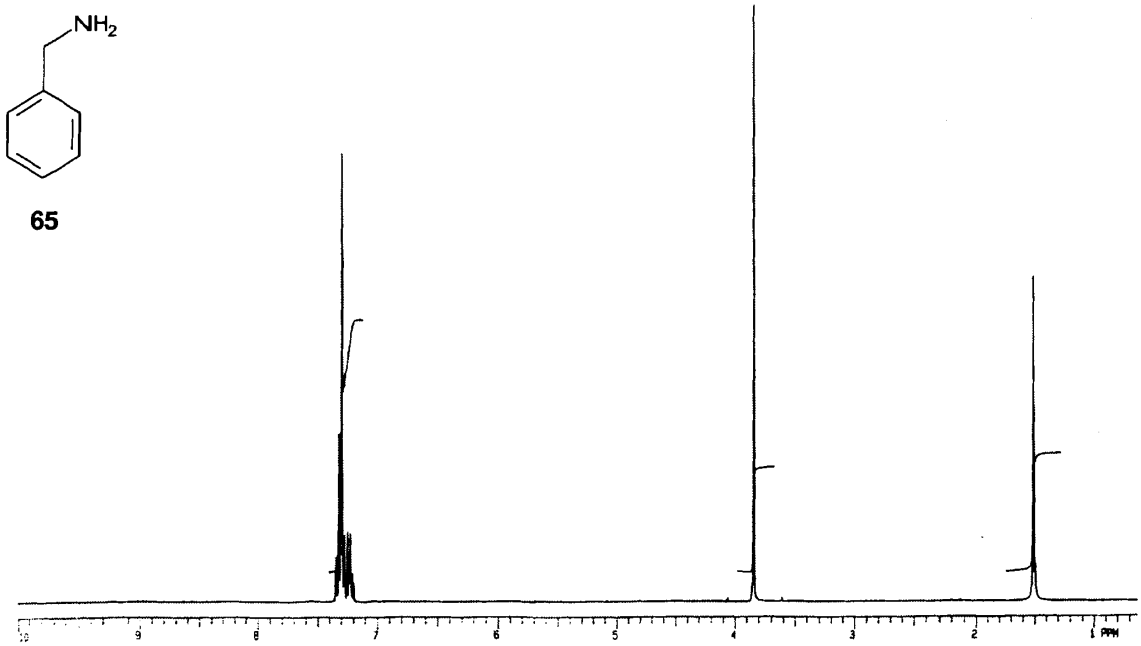
NMR spectrum 23: ^{1}H NMR ($CDCl_3$) 300 MHz



NMR spectrum 24: ^{13}C NMR ($CDCl_3$) 300 MHz



NMR spectrum 25: ^{13}C APT NMR ($CDCl_3$) 300 MHz



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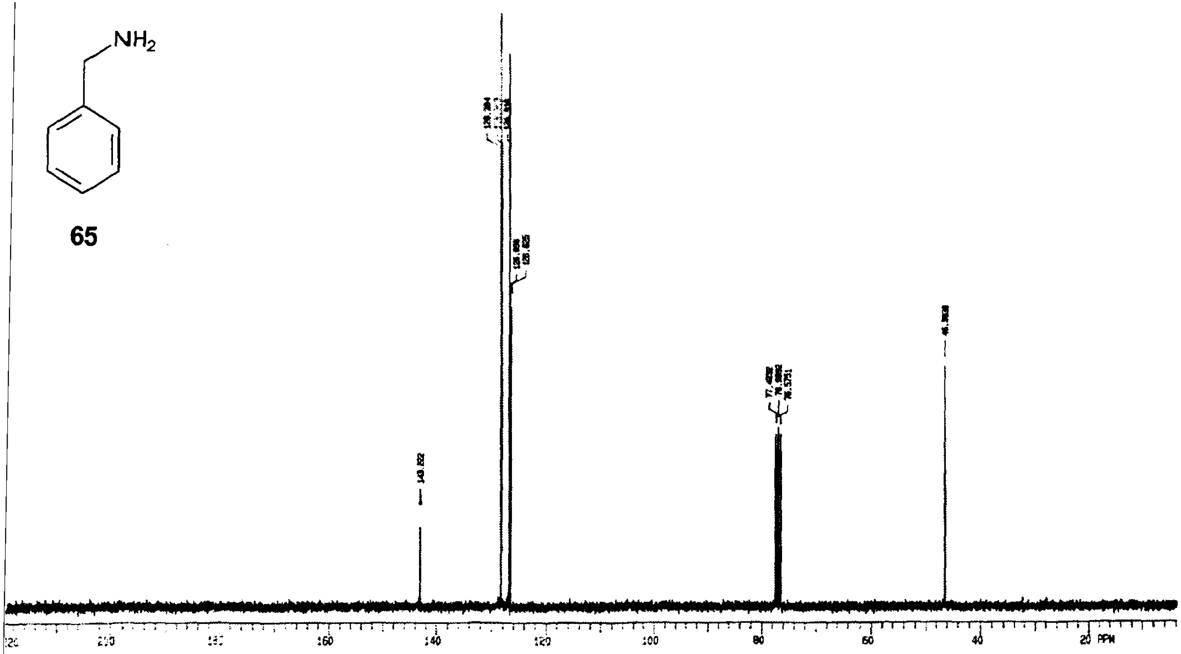

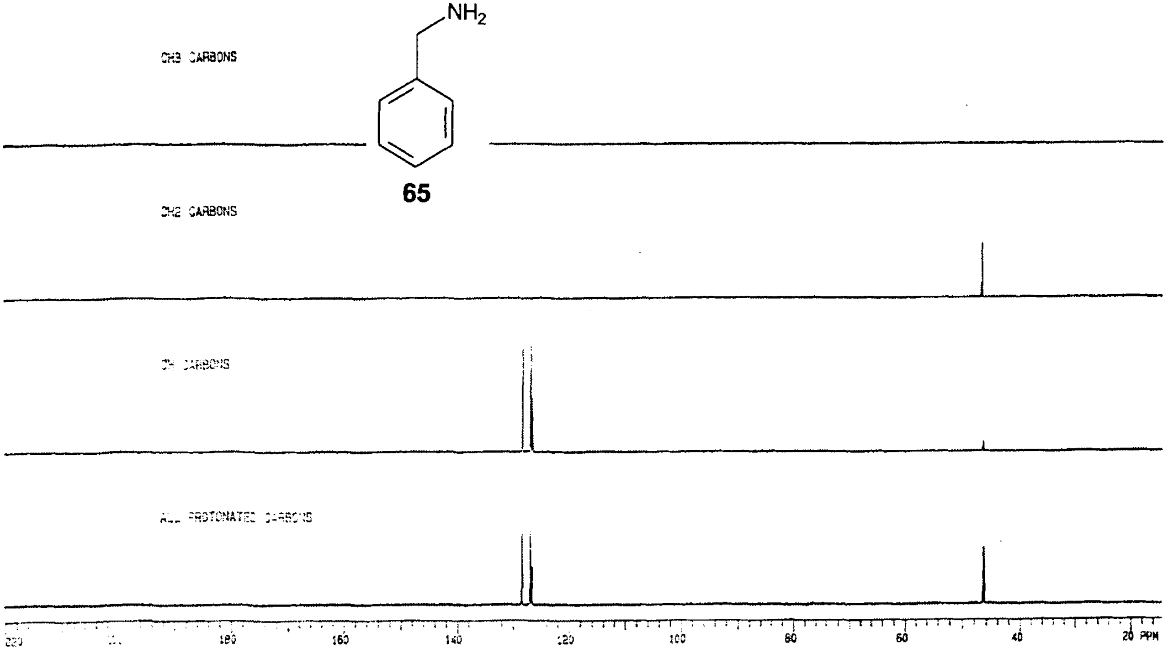

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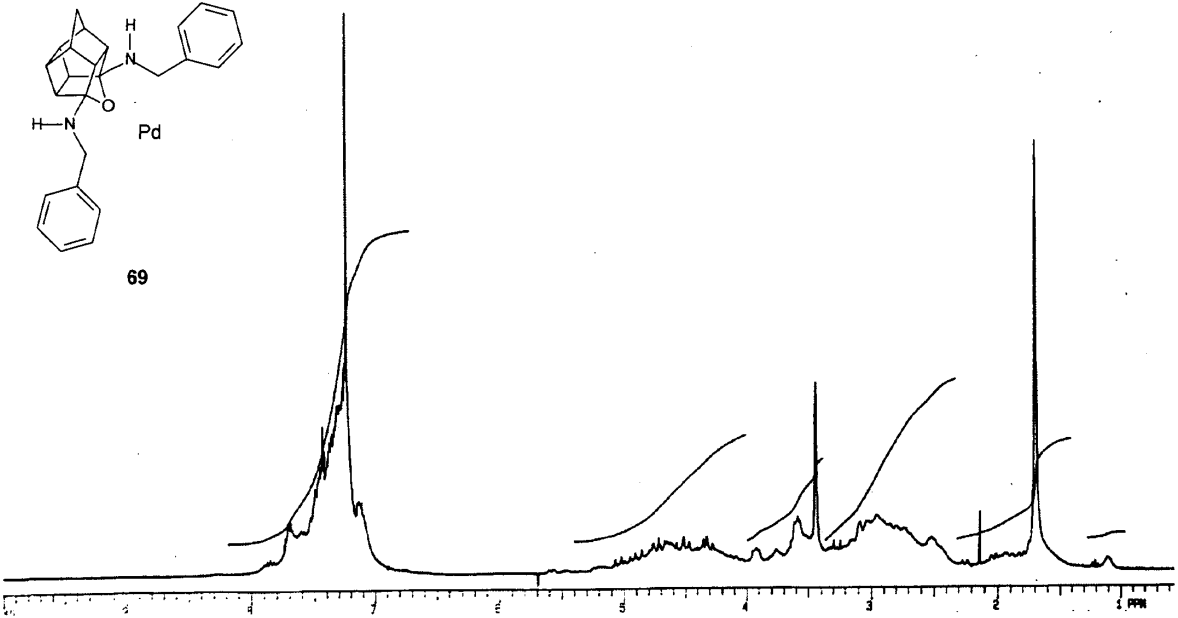
NMR spectrum 28: ^{13}C APT NMR ($CDCl_3$) 300 MHz



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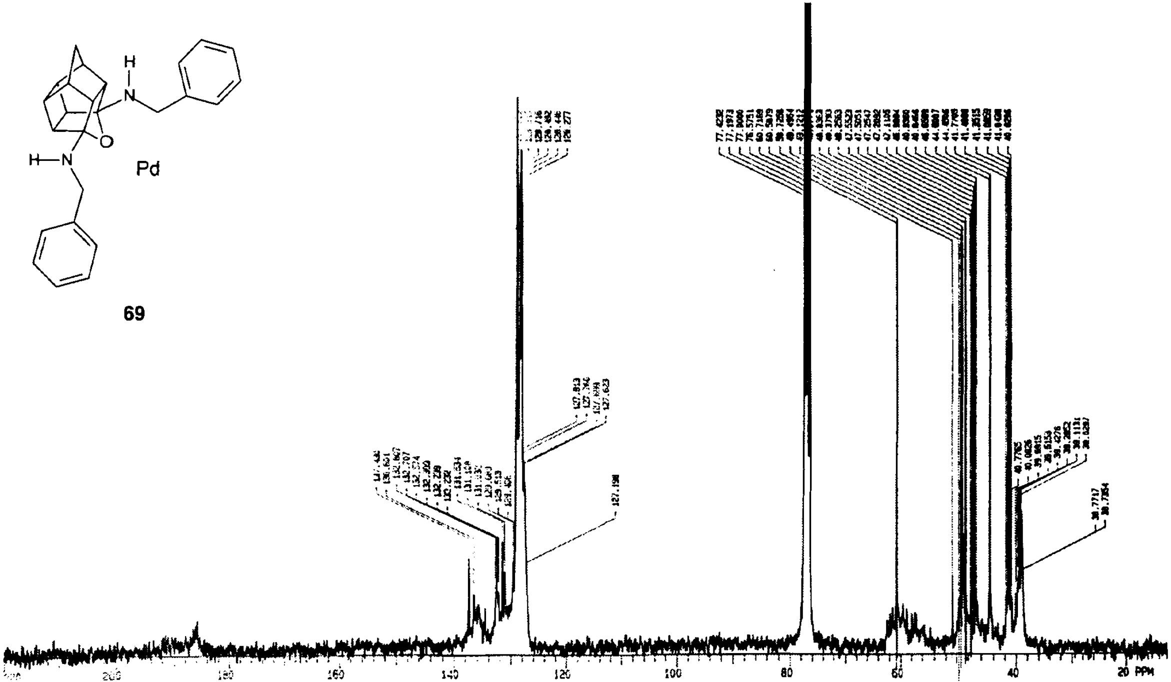

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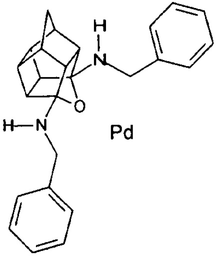

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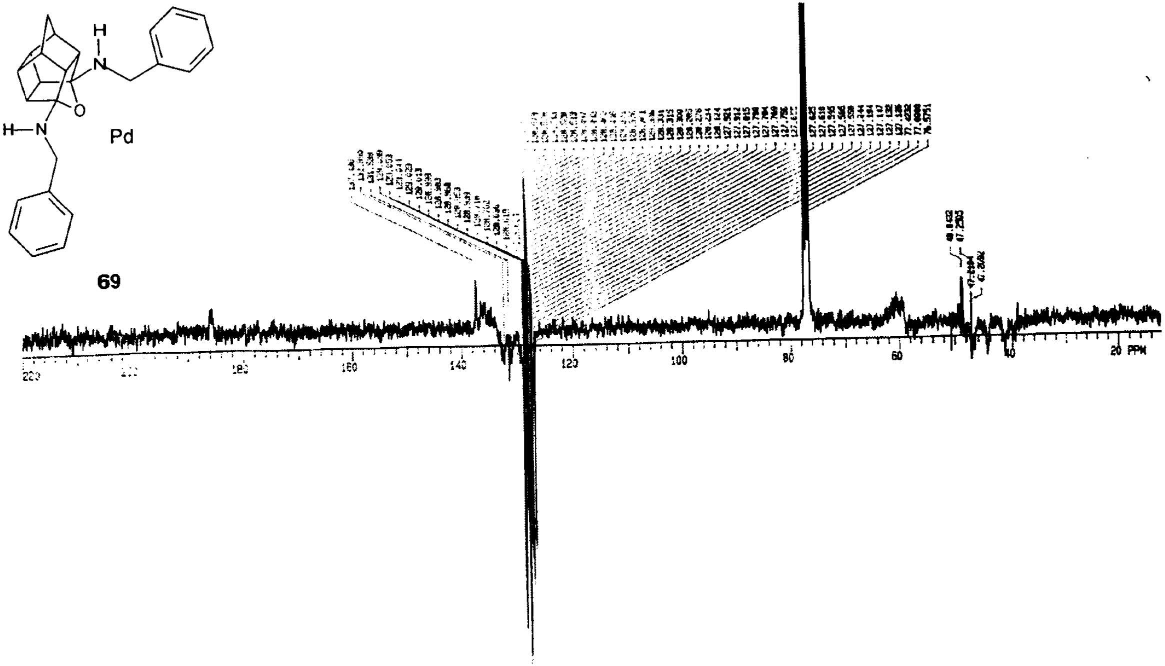

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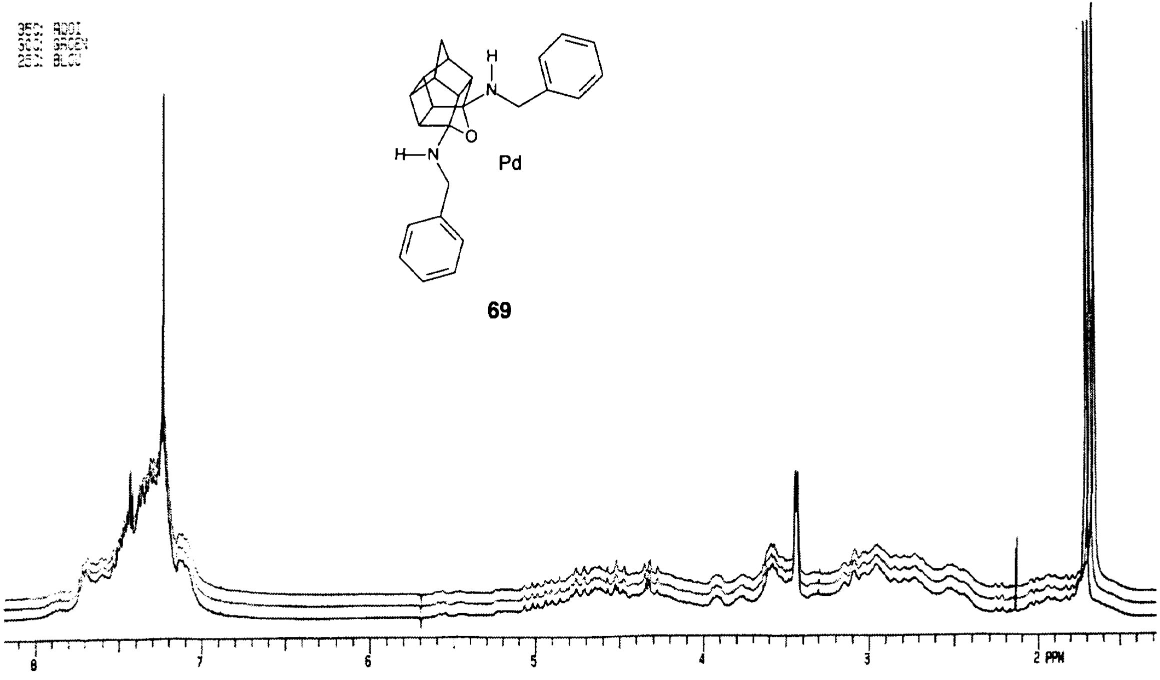
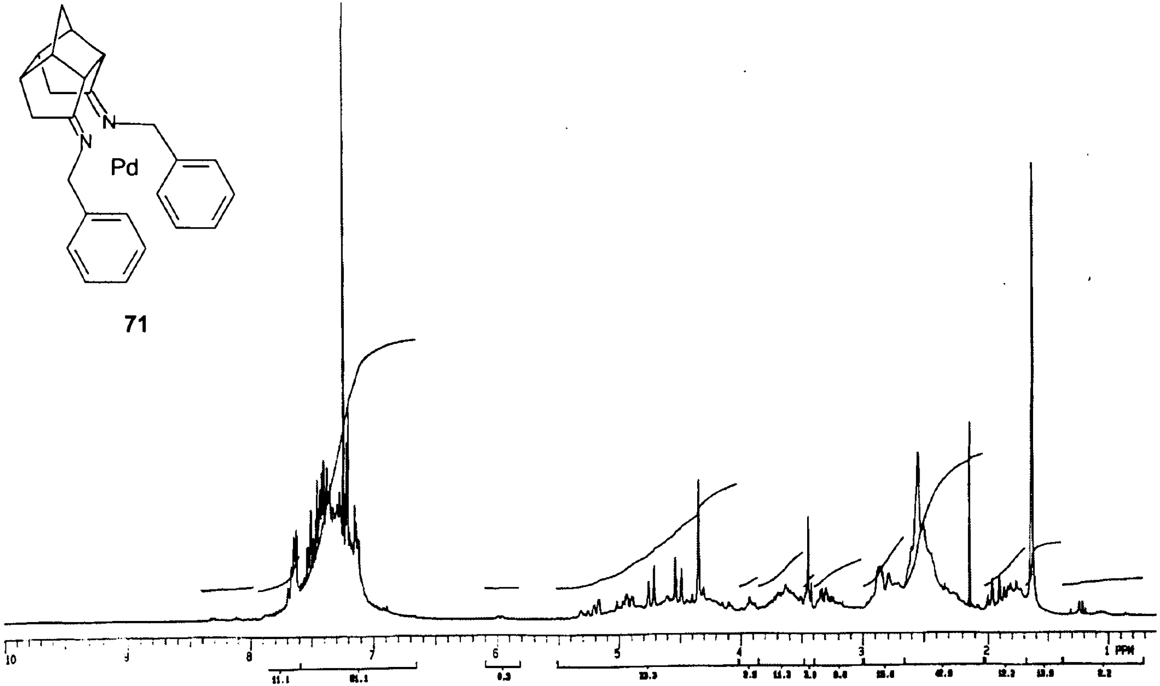


NMR spectrum 32: Temperature dependent ^1H NMR ($CDCl_3$) 300 MHz



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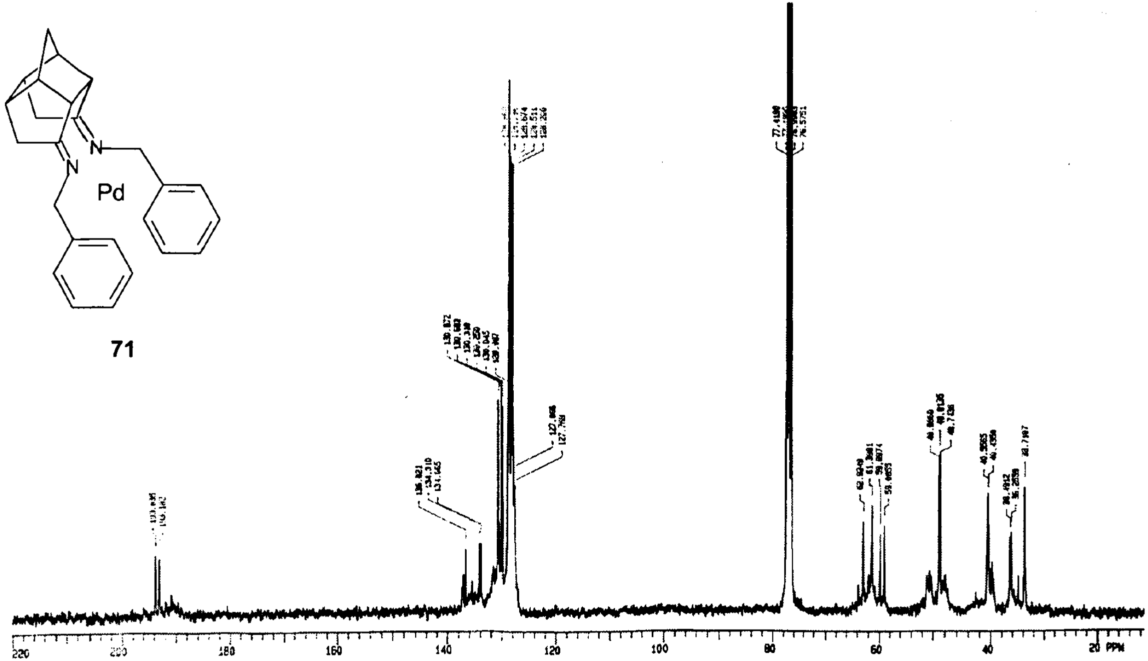
NMR spectrum 33: ^1H NMR ($CDCl_3$) 300 MHz



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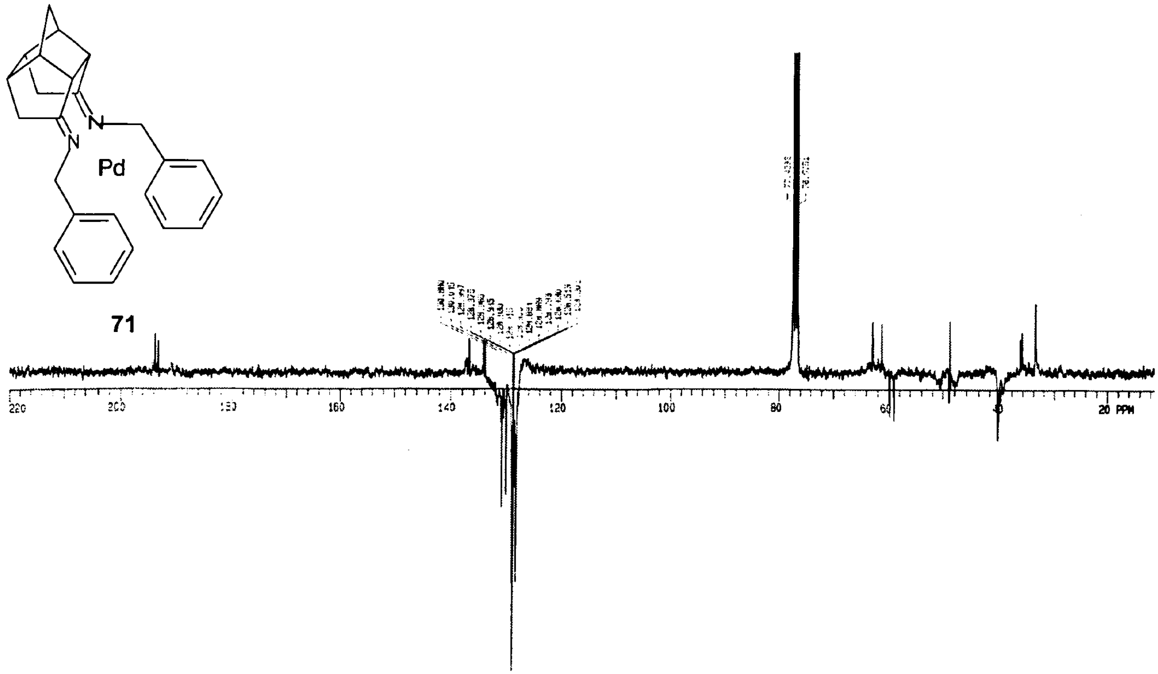

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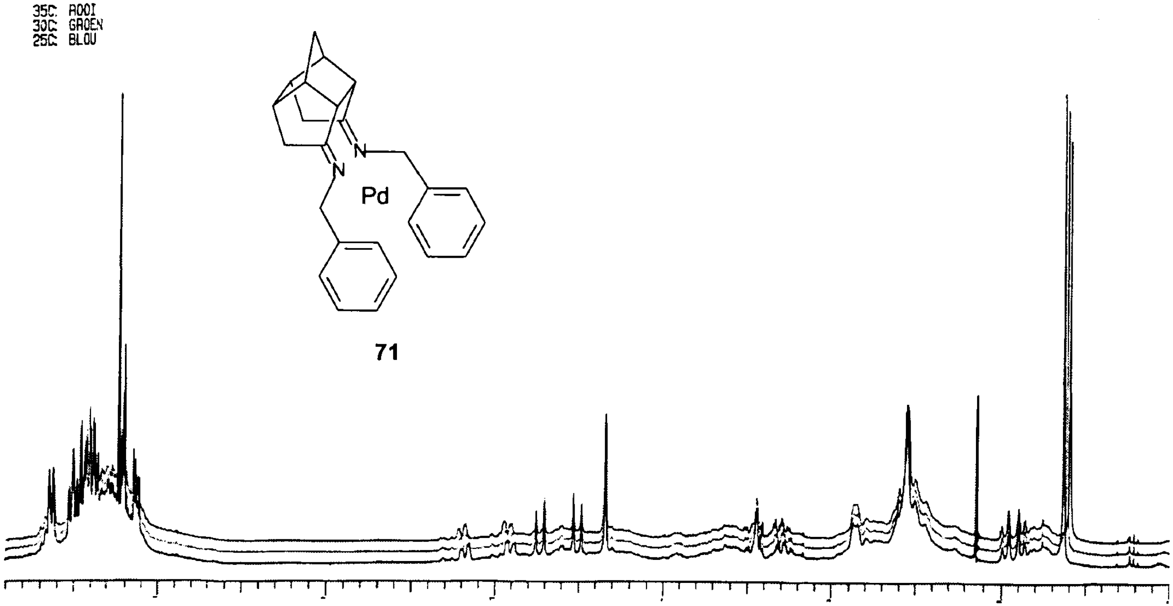

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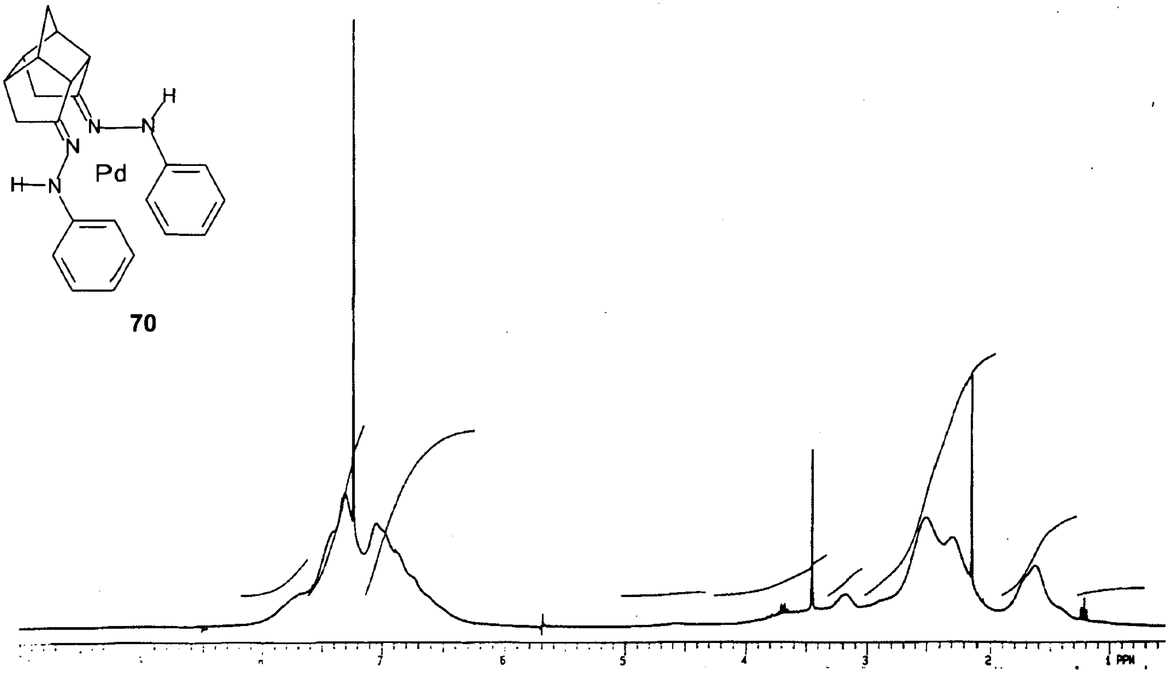
NMR spectrum 36: Temperature dependent ^1H NMR ($CDCl_3$) 300 MHz



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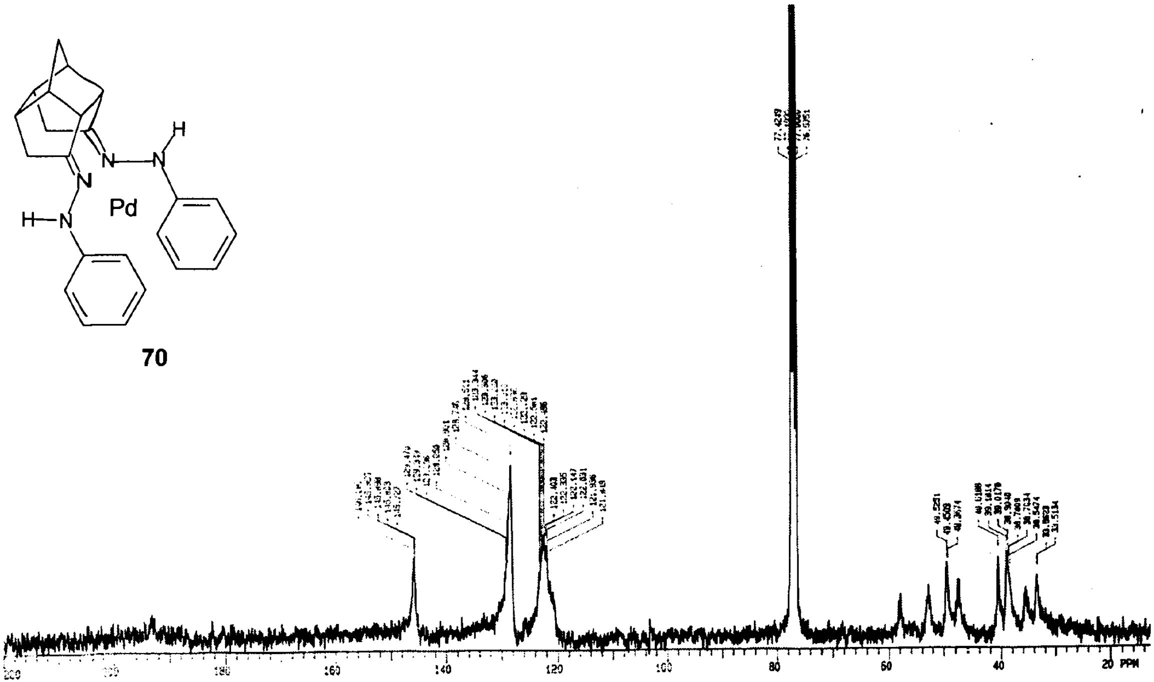
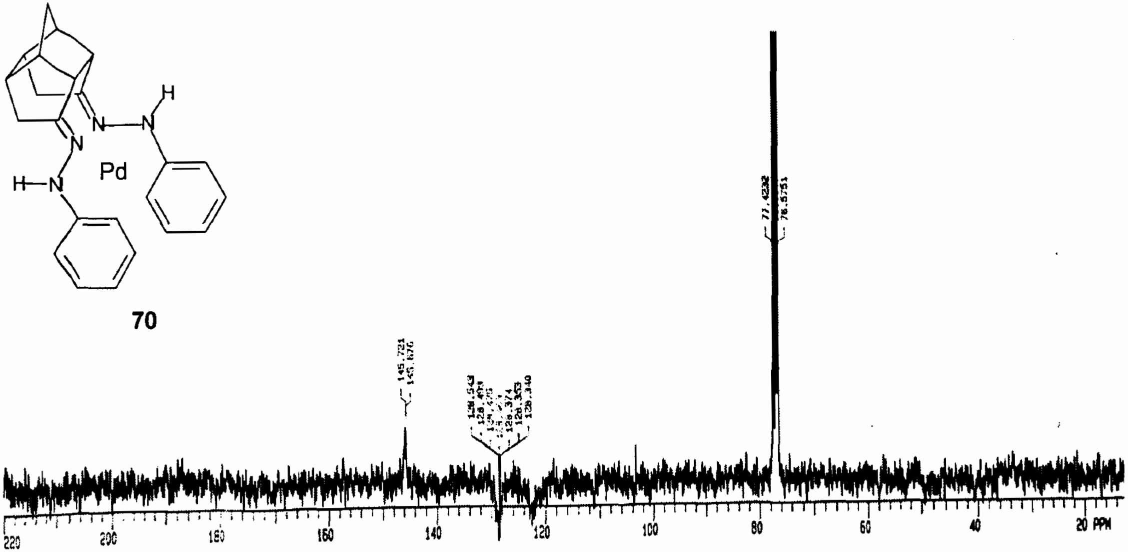
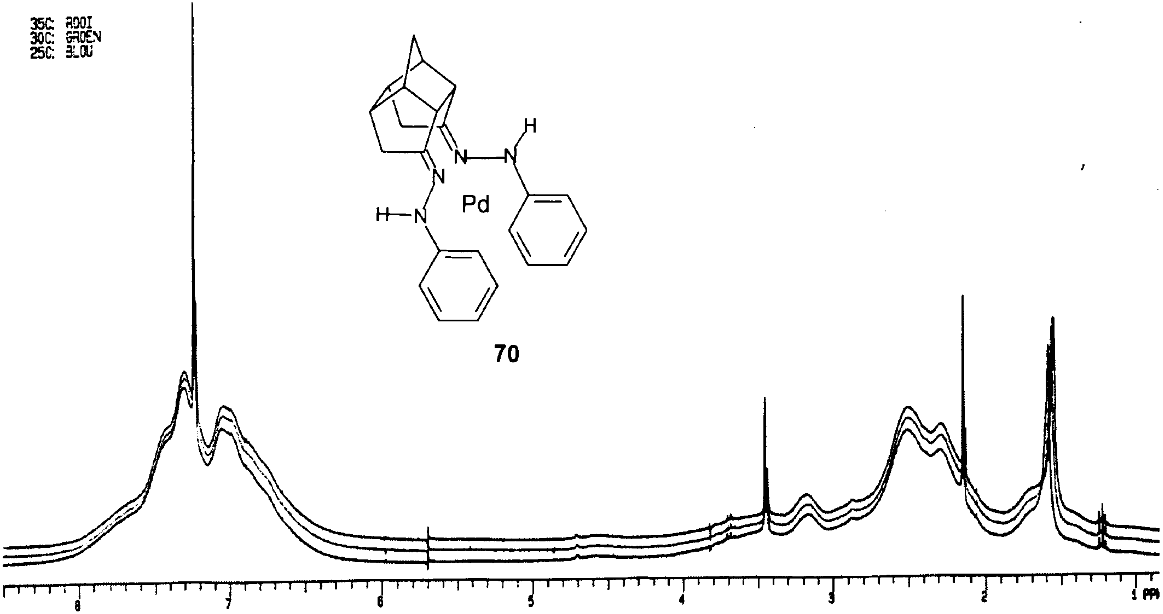
70



NMR spectrum 38: ^{13}C NMR (CDCl$_3$) 300 MHz

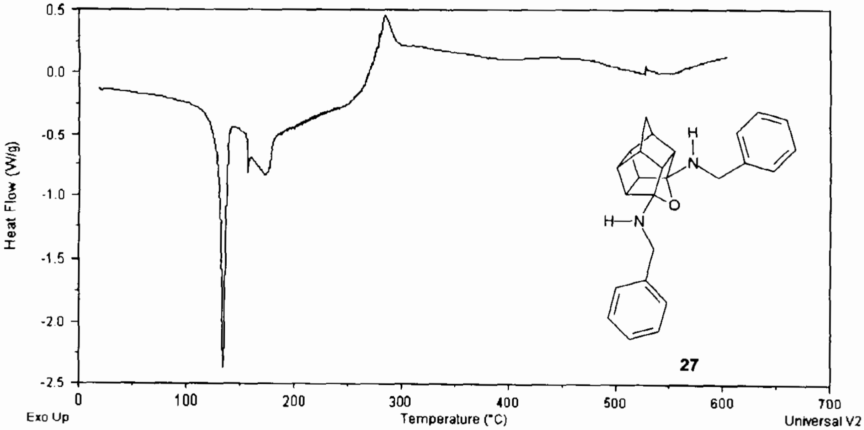


NMR spectrum 39: ^{13}C APT NMR (CDCl$_3$) 300 MHz

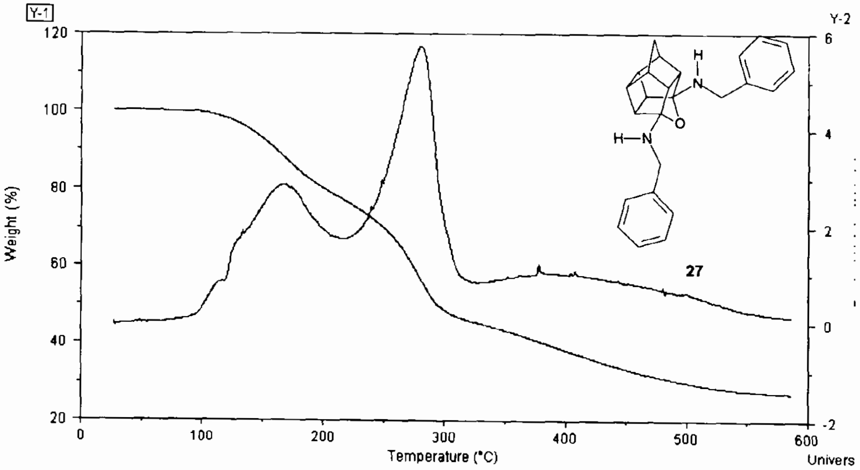


NMR spectrum 40: ^{13}C DEPT NMR ($CDCl_3$) 300 MHz

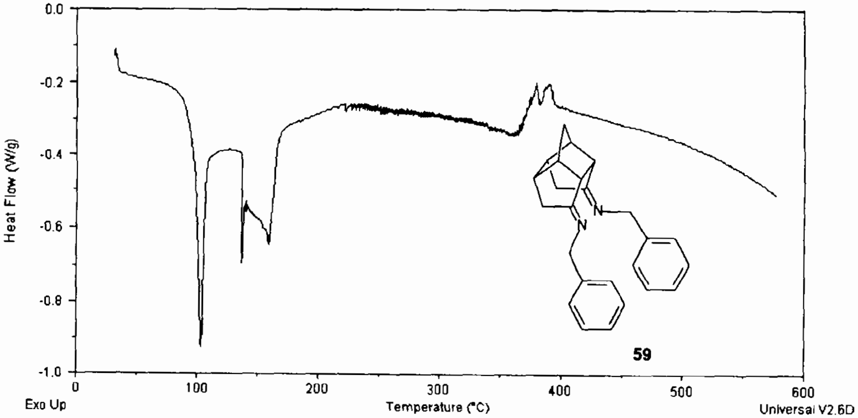
Thermal analysis



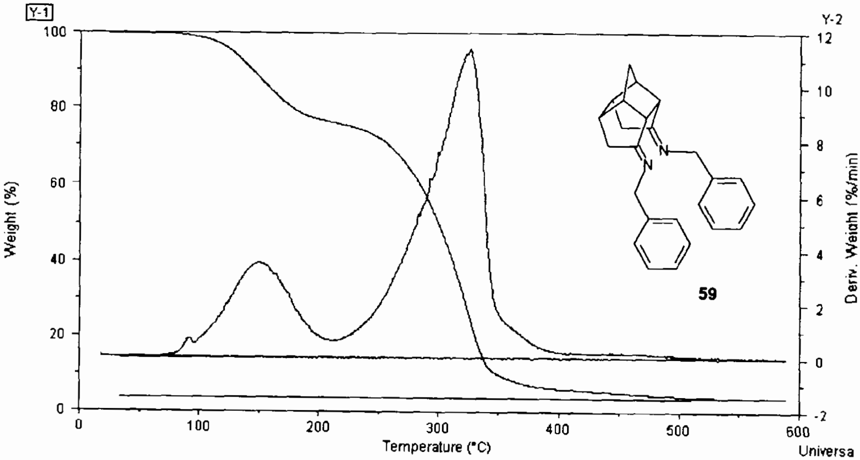
DSC curve 1 (ligand 27)



TG curve 1 (ligand 27)



DSC curve 2 (ligand 59)



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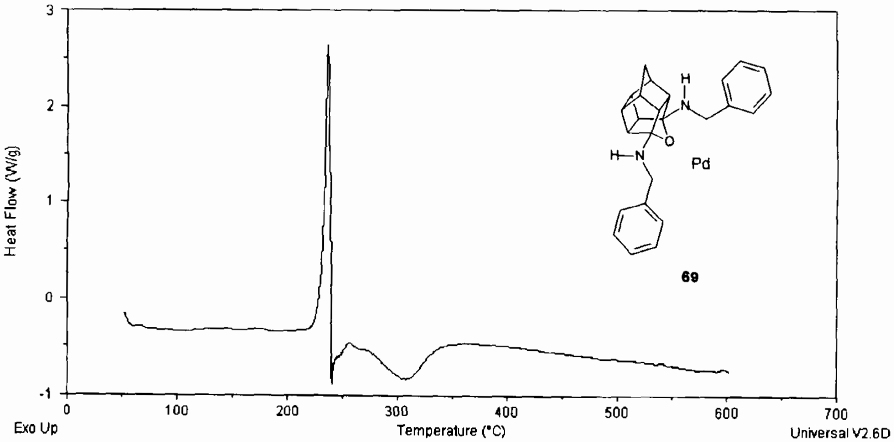
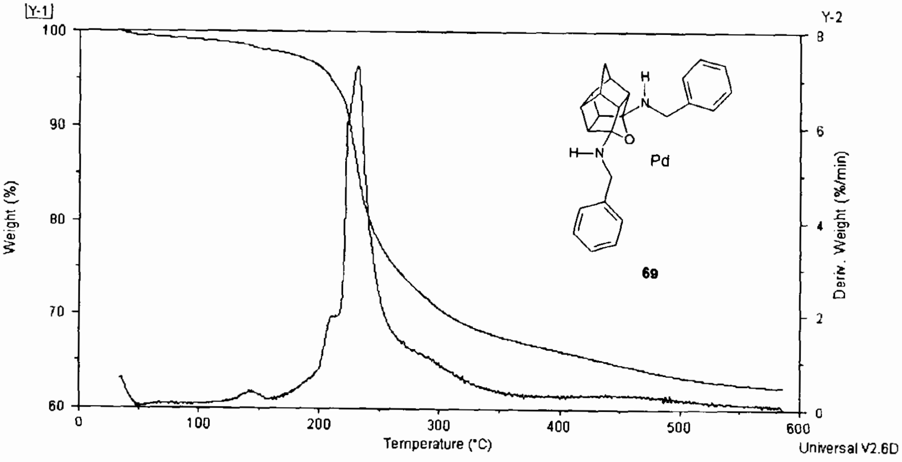


DSC curve 3 (complex 69)



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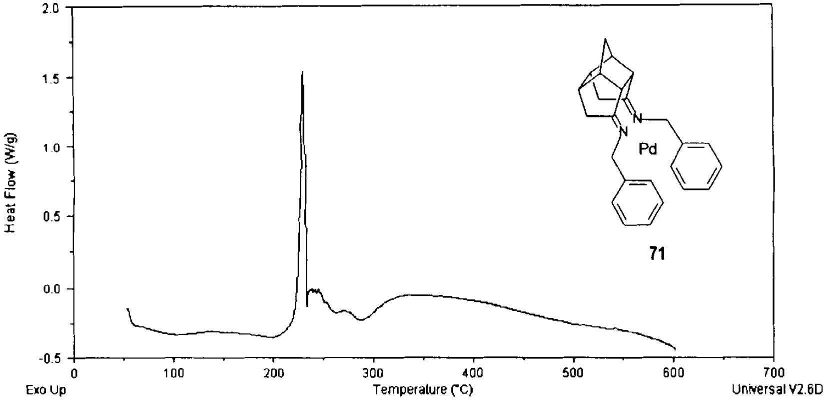

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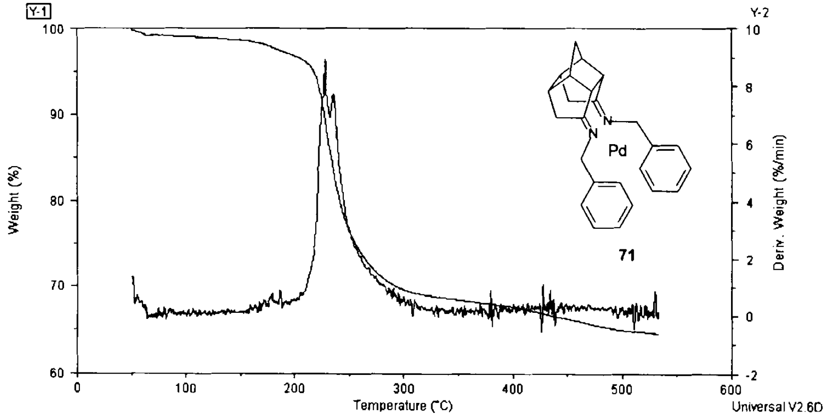

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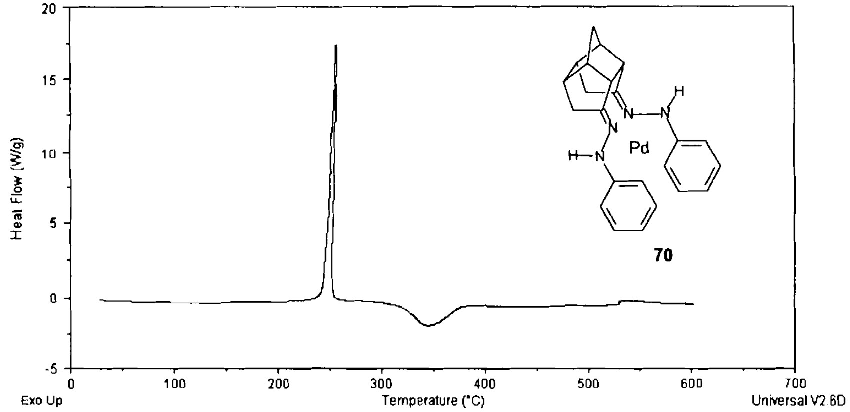
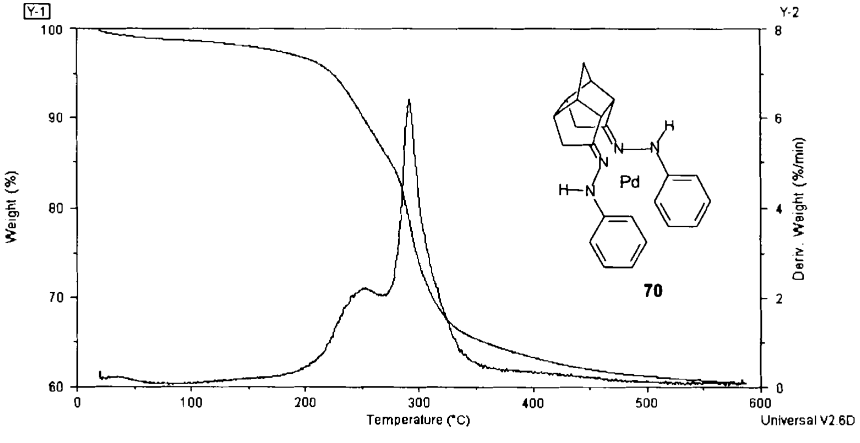


DSC curve 5 (complex 70)



TG curve 5 (complex 70)

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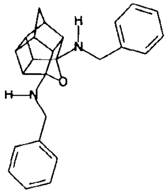
ABSTRACT

Synthesis and modelling of alicyclic organic ligands

The study of alicyclic cage molecules has in recent years increased due to the possibilities in application of these compounds. The photocyclization of the endo conformation Diels-Alder adduct of p-benzoquinone and cyclopentadiene yields the pentacyclic cage compound derivative pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane that is a classical starting compound for the synthesis of different alicyclic cage compounds.

An important part in the study of alicyclic cage compounds is the possible use of these compounds as ligands in metal complexes. Literature studies showed that limited research is being done in the field of alicyclic cage ligand activity and catalysis. Marchand *et al.* and Lee *et al.* synthesized alicyclic cage compounds that have the ability bind to transition metals to form relative stable alicyclic-metal complexes
Different pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylamines was identified in literature and synthesised in this study:



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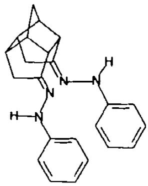

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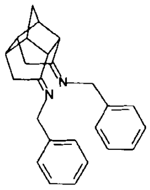

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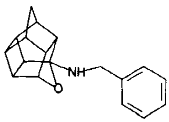

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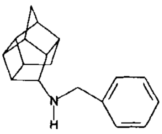


5

These ligands was characterised using MS, IR and NMR and investigated by molecular modelling using Accelrys Material Studio and Spartan Pro. The ligand activity of these compounds was investigated by using lithium tetrachloropalladate(II) that lead to the formation of cyclopalladation complexes. Ligand 1,2,3 and 5 were investigated and formed very stable metal-ligand complexes with the palladium metal. These complexes were characterised using FAB$^+$ M.S, ^{1}H and ^{13}C NMR, I.R and ESEM with a INCA 400 EDS system.

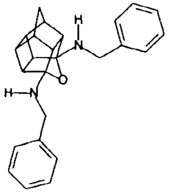
OPSOMMING

Sintese en modelering van alisikliese organiese ligande

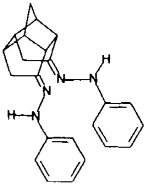
Die studie van alisikliese koolwaterstofverbindings het in die laaste paar jaar op grond van die moonlike gebruike van hierdie verbindings toegeneem. Die fotosiklisering van die endo-Diels-Alder-adduk van p-bensokinoon en siklopentadieen lewer die gespanne pentasikliese verbinding, pentasiklo[5.4.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$]undekaan-8,11-dioon. Hierdie verbinding is 'n klassieke vertekpunt vir die sintese van 'n wye verskeidenheid alisikliese verbindings.

'n Potensieël belangrike gebruik van alisikliese verbindings is as ligande in organometaalverbindings. Elektronryk organiese ligande het die vermoë om in oplossing aan metale te bind om stabiele metaal-ligandkomplekse te vorm. Literatuurstudies het getoon dat geen navorsing gedoen is oor die gebruik van stikstofbevattende alisikliese ligande nie. Slegs enkele voorbeelde bestaan waar alisikliese verbindings aan platinum en molibdeen gebind is.[1-5]

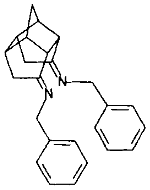
Verskillende pentasiklo[5.4.0.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$]undekaanamien derivate was ge-identifiseer in literatuur en in hierdie studie gesintetiseer:



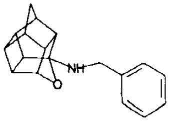
1



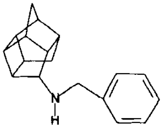
2



3



4



5

Die verbindings was met I.R, MS en KMR gekarakteriseer en ook met behulp van Accelrys Material Studio en Spartan gemodelleer om spesifieke kwantum en fisiese eienskappe te bepaal (orbitaalberekeninge, elektrondigthede, geometrie, ens).

Die ligand aktiwiteit van hierdie ligande was ondersoek deur kompleksering met litiumtetrachloropalidaat. Ligande 1,2,3 en 5 was ondersoek en het baie stabiele metaal-ligand komplekse gevorm met palladium metaal. Die metaal-ligand komplekse was gekarakteriseer met FAB$^+$ M.S, ^{1}H en ^{13}C NMR, I.R en ESEM met 'n INCA 400 EDS stelsel.