

UNIVERSITY OF KWAZULU-NATAL

**IMIDAZOLIUM, PHOSPHONIUM AND
PYRIDINIUM IONIC LIQUIDS WITH
FLUORINATED ANIONS: SYNTHESIS
CHARACTERIZATION AND APPLICATIONS**

2013

HAMISU IBRAHIM

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PYRIDINIUM IONIC LIQUIDS WITH
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HAMISU IBRAHIM

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A thesis submitted to the School of Chemistry and Physics, College of Agriculture Engineering and Science, University of KwaZulu-Natal, Westville, for the degree of Doctor of Philosophy.

This Thesis has been prepared according to **Format 4** as outlined in the guidelines from the College of Agriculture, Engineering and Science and which states:

This is a thesis in which chapters are written as a set of discrete research papers, with an overall introduction and final discussion, where one (or all) of the chapters have already been published. Each chapter conforms to the formatting style of the journal intended for. Typically these chapters will have been published in internationally recognized, peer-reviewed journals.

As the candidate's supervisor, I have approved this thesis for submission.

Supervisor: Prof. Neil A. Koorbanally



20th November 2013

Signed: -----

Date: -----

ABSTRACT

Four sets of ionic compounds were synthesized, each with an organic spacer between two ligands creating a dication with the bromide as the counter anion. In each of the sets of ionic compounds, the counter anion was exchanged in a metathesis reaction with either all or some of NaBF₄, KPF₆, CF₃SO₃Li and CF₃COONa in an effort to produce fluorinated ionic liquids.

The first set of ionic salts was based on the reaction between 1-methylimidazole and α,α -dibromo-*p*-xylene to form a *bis*(methylimidazolium) cation with an aromatic spacer between them. This was followed by metathesis reactions with four fluorinated anion sources, which yielded new fluorinated imidazolium salts [C₆H₄(CH₂(C₄H₆N₂)₂)₂]²⁺ 2[A]⁻ where A = BF₄ (**A-2**), PF₆ (**A-3**), CF₃SO₃ (**A-4**) and CF₃COO (**A-5**). The compounds were characterized by ¹H-, ¹³C-, ¹⁹F-, ³¹P-NMR and IR spectroscopy. Single crystal X-ray diffraction data of compounds **A-2**, **A-3** and **A-4** were carried out where the study revealed that the different fluorinated anions affected the spatial arrangement of atoms and the extent of cation-anion interactions and hence, influenced the stability and coordination properties of the imidazolium salts. A trend was observed which related the strength of cation-anion interaction to physical properties such as melting point.

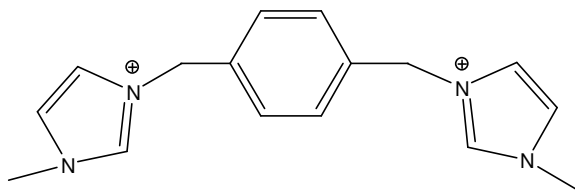
A further set of ionic salts, keeping the same organic moiety, the α,α -dibromo-*p*-xylene but this time changing the ligand to that of triphenylphosphine (PPh₃) was synthesized to first produce the dibromide (**B-1**) and then the fluorinated salts **B2-B5** with CF₃SO₃Li, NaBF₄, KPF₆ and CF₃COONa respectively. Compounds **B2-B5** were all novel compounds whose synthesis have not been reported previously. The salts were characterized by ¹H, ¹³C, ¹⁹F, ³¹P NMR, and IR spectroscopy. The organic salts were tested for their antimicrobial activity and showed significant activity against *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Salmonella typhi*, *Candida albicans*, and *Streptococcus pyogenes* when

compared with the activities of the standard antimicrobial chloramphenicol and antifungal nystatin. The crystal structure of **B-3**, the ditetrafluoroborate is also discussed.

In the third set of ionic salts, the solvent free reaction of 1-methylimidazole and alkyl dibromides (RBr_2 ; $\text{R} = -\text{CH}_2-$, $-(\text{CH}_2)_3-$, $-(\text{CH}_2)_4-$, and $-(\text{CH}_2)_5-$), were synthesized (**C1a-4a**) in a highly exothermic reaction. This was followed by metathesis reactions with fluorinated anion sources, NaBF_4 and KPF_6 to produce the fluorinated imidazolium ionic compounds **C1b-4b** and **C1c-4c** respectively. All twelve compounds were characterized by ^1H -, ^{13}C -, ^{19}F -, ^{31}P -NMR, and IR spectroscopy. A trend was observed relating the length of the alkyl chain in the cations and the strength of cation-anion interactions to the melting point of the compounds. The dibromide ionic compounds decreased in melting point as the length of the alkyl spacers increased. The strength of the cation-anion interactions were strongest for the Br^- ionic liquids followed by the PF_6^- and the BF_4^- counteranions as demonstrated by their melting points which increased in the order of $\text{M}(\text{BF}_4)_2 < \text{M}(\text{PF}_6)_2 < \text{MBr}_2$. NMR studies of the synthesised ionic salts were also carried out to determine how the shifts of the alkyl groups and ligands changed as the anion changed.

In the last set of compounds, pyridine was explored as the ligand with *p*- α,α -dibromoxylene and 1,1-dibromomethane respectively to yield the quarternized salts **D1a** and **D2a** respectively, followed by metathesis reactions with the fluorinated anion sources, NaBF_4 and KPF_6 to produce fluorinated pyridinium ionic liquids **D1b-c** and **D2b-c**. Compounds **D1b** and **D2c** are novel compounds as the combination of cation and anion had not been synthesised previously. The synthesis of **D2a** was carried out without the use of solvents and the metathesis reactions carried out with ethanol and water and can be considered as green reactions. 2D NMR studies of the synthesised compounds are reported here.

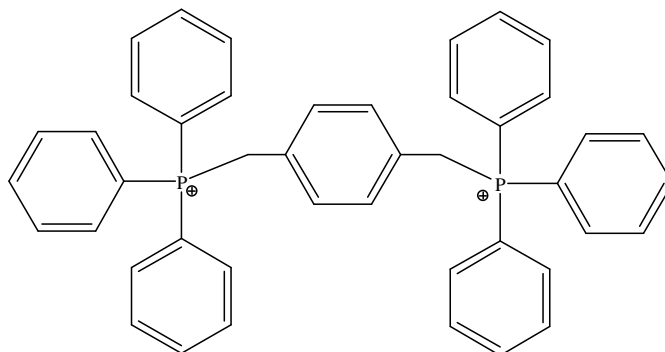
Structures and Nomenclature of Compounds for Chapter 2



A-1 2Br⁻; **A-2** 2BF₄⁻; **A-3** 2PF₆⁻; **A-4** 2CF₃SO₃⁻; **A-5** 2CF₃COO⁻

- A-1** 1,1-(1,4-phenylenedimethylene)*bis*(3-methyl-1H-imidazolium-1-yl) dibromide
[C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[Br]⁻
- A-2** 1,1-(1,4-phenylenedimethylene)*bis*(3-methyl-1H-imidazolium-1-yl)
ditetrafluoroborate [C₆H₄(CH₂(C₄H₆N₂))₂]²⁺ 2[BF₄]⁻
- A-3** 1,1-(1,4-phenylenedimethylene)*bis*(3-methyl-1H-imidazolium-1-yl)
dihexafluorophosphate [C₆H₄(CH₂(C₄H₆N₂))₂]²⁺ 2[PF₆]⁻
- A-4** 1,1-(1,4-phenylenedimethylene)*bis*(3-methyl-1H-imidazolium-1-yl)
ditrifluoromethanesulfonate [C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[CF₃SO₃]⁻
- A-5** 1,1-(1,4-phenylenedimethylene)*bis*(3-methyl-1H-imidazolium-1-yl)
ditrifluoroacetate [C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[CF₃COO]⁻

Structures and Nomenclature of Compounds for Chapters 3, 4 and 5

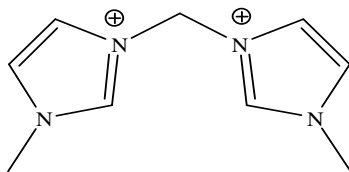


B-1 2Br^- ; **B-2** $2\text{CF}_3\text{SO}_3^-$; **B-3** 2BF_4^- ; **B-4** 2PF_6^- ; **B-5** $2\text{CF}_3\text{COO}^-$

- B-1** 1,1-(1,4-phenylenedimethylene)*bis*(triphenylphosphonium) dibromide,
 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+} [2\text{Br}^-]$
- B-2** 1,1-(1,4-phenylenedimethylene)*bis*(triphenylphosphonium)
dinitrifluoromethanesulphonate $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+} [2\text{CF}_3\text{SO}_3^-]$
- B-3** 1,1-(1,4-phenylenedimethylene)*bis*(triphenylphosphonium) ditetrafluoroborate
 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+} [2\text{BF}_4^-]$
- B-4** 1,1-(1,4-phenylenedimethylene)*bis*(triphenylphosphonium) dihexafluorophosphate
 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+} [2\text{PF}_6^-]$
- B-5** 1,1-(1,4-phenylenedimethylene)*bis*(triphenylphosphonium) dinitrifluoroacetate
 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+} [2\text{CF}_3\text{COO}^-]$

Structures and Nomenclature of Compounds for

Chapter 6



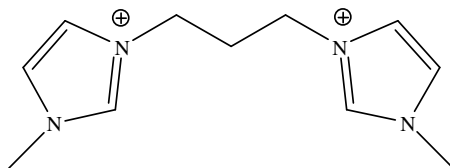
C-1a 2Br⁻; **C-1b** 2BF₄⁻; **C-1c** 2PF₆⁻

C-1a (1,1-methylene)*bis*(3-methylimidazolium) dibromide [(C₄H₆N₂)₂CH₂]²⁺ 2[Br]⁻

C-1b (1,1-methylene)*bis*(3-methylimidazolium) ditetrafluoroborate



C-1c (1,1-methylene)*bis*(3-methylimidazolium) dihexafluorophosphate



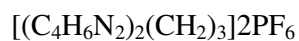
C-2a 2Br⁻; **C-2b** 2BF₄⁻; **C-2c** 2PF₆⁻

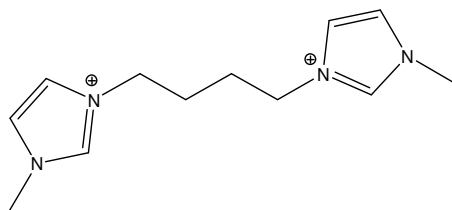
C-2a (1,3-Propylene)*bis*(3-methylimidazolium) dibromide [(C₄H₆N₂)₂(CH₂)₃]²⁺ 2[Br]⁻

C-2b (1,3-propylene)*bis*(3-methylimidazolium) ditetrafluoroborate [(C₄H₆N₂)₂(CH₂)₃]²⁺



C-2c (1,3-propylene)*bis*(3-methylimidazolium) dihexafluorophosphate



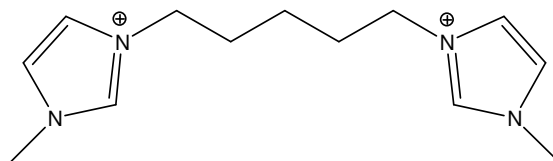


C-3a 2Br⁻; **C-3b** 2BF₄⁻; **C-3c** 2PF₆⁻

C-3a (1,4-butylene)*bis*(3-methylimidazolium) dibromide [(C₄H₆N₂)₂(CH₂)₃]²⁺ 2[Br]⁻

C-3b (1,4-butylene)*bis*(3-methylimidazolium) ditetrafluoroborate [(C₄H₆N₂)₂(CH₂)₃]²⁺ 2[BF₄]⁻

C-3c (1,4-butylene)*bis*(3-methylimidazolium) dihexafluorophosphate [(C₄H₆N₂)₂(CH₂)₄]²⁺ 2[PF₆]⁻



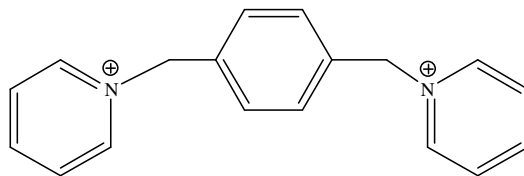
C-4a 2Br⁻; **C-4b** 2BF₄⁻; **C-4c** 2PF₆⁻

C-4a (1,5-pentylene)*bis*(3-methylimidazolium) dibromide [(C₄H₆N₂)₂(CH₂)₅]²⁺ 2[Br]⁻

C-4b (1,5-pentylene)*bis*(3-methylimidazolium) ditetrafluoroborate [(C₄H₆N₂)₂(CH₂)₅]²⁺ 2[BF₄]⁻

C-4c (1,5-pentylene)*bis*(3-methylimidazolium) dihexafluorophosphate [(C₄H₆N₂)₂(CH₂)₅]²⁺ 2[PF₆]⁻

Structures and Nomenclature of Compounds for Chapter 7

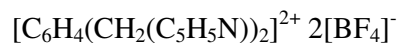


D-1a 2Br⁻; **D-1b** 2BF₄⁻; **D-1c** 2PF₆⁻

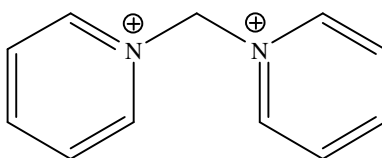
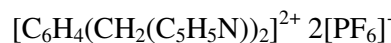
D-1a 1,1-(1,4-phenylenedimethylene)*bis*(pyridinium) dibromide



D-1b 1,1-(1,4-phenylenedimethylene)*bis*(pyridinium) ditetrafluoroborate



D-1c 1,1-(1,4-phenylenedimethylene)*bis*(pyridinium) dihexafluorophosphate



D-2a 2Br⁻; **D-2b** 2BF₄⁻; **D-2c** 2PF₆⁻

D-2a (1,1-methylene)*bis*(pyridinium) dibromide $[(\text{C}_5\text{H}_5\text{N})_2\text{CH}_2]^{2+} 2[\text{Br}]^-$

D-2b (1,1-methylene)*bis*(pyridinium) ditetrafluoroborate $[(\text{C}_5\text{H}_5\text{N})_2\text{CH}_2]^{2+} 2[\text{BF}_4]^-$

D-2c (1,1-methylene)*bis*(pyridinium) dihexafluorophosphate $[(\text{C}_5\text{H}_5\text{N})_2\text{CH}_2]^{2+} 2[\text{PF}_6]^-$

ABBREVIATIONS

^{13}C NMR	C-13 nuclear magnetic resonance spectroscopy
^{19}F NMR	Fluorine-19 nuclear magnetic resonance spectroscopy
^1H NMR	proton nuclear magnetic resonance spectroscopy
^{31}P NMR	Phosphorus-31 nuclear magnetic resonance spectroscopy
aq	aqueous
br	broad
CD_3OD	deuterated methanol
COSY	correlated spectroscopy
d	doublet
dd	double doublet
DEPT	distortionless enhancement by polarization transfer
DMSO-d_6	deuterated dimethyl sulfoxide
EtOH	ethanol
HMBC	heteronuclear multiple bond coherence
HREIMS	high resolution electron impact mass spectroscopy
HSQC	heteronuclear single quantum coherence
Hz	hertz
IR	infrared
m	multiplet
Me	methyl
MeOH	methanol
MIC	minimum inhibitory concentration
Mp	melting point
MS	mass spectroscopy
NOESY	nuclear overhauser effect spectroscopy
s	singlet
t	triplet
td	triplet of doublets
TGI	total growth inhibition
TLC	thin layer chromatography
UV	ultraviolet

DECLARATIONS

DECLARATION 1 – PLAGIARISM

I, **Hamisu Ibrahim** declare that

1. The research reported in this thesis is my original research, except where otherwise indicated.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
 - a. their words have been re-written but the general information attributed to them have been referenced
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.



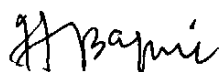
Signed

DECLARATION 2-PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication)

1. Ibrahim, H., Koorbanally, N. A., Ramjugernath, D., Bala, M. D., Nyamori, V. O. Synthesis and characterization of imidazolium salts bearing fluorinated anions. *Zeitschrift fur Anorgorganishche und Allgemeine Chemie*. **2012**, 2304-2309.
2. Ibrahim, H., Koorbanally, N. A., Ramjugernath, D., Bala, M. D., Nyamori, V. O. Synthesis, characterization and antimicrobial activities of *dicationic triphenyl phosphonium organic* salts with a para-xylene bridge and fluorinated counter anions. *to be submitted to Acta Polonia Pharmaceutica*.
3. Ibrahim, H., Koorbanally, N. A., Ramjugernath, D., Bala, M. D., Nyamori, V. O. *P*-phenylenebis(methylene)bis(triphenylphosphonium) ditetrafluoroborate. *Acta Crystallographica Section E*, **2011**, E67, o3391.
4. Ibrahim, H., Koorbanally, N. A., Ramjugernath, D., Bala, M. D., Nyamori, V. O. Solvent Free synthesis and NMR studies of bidentate imidazolium based Ionic liquids. Manuscript in preparation .
5. Ibrahim, H., Koorbanally, N. A., Ramjugernath, D., Bala, M. D., Nyamori, V. O. The synthesis and NMR characterisation of (1,4-phenylenedimethylene)bis(pyridinium) and (1,1-methylene)bis(pyridinium) ionic compounds. Manuscript in preparation.

From all the above publications, my role included carrying out all the experimental work and contributing to the writing of the publications along with the guidance of my supervisors. My supervisors' roles were that of an editorial nature and checking on the scientific content and my correct interpretation. Based on their expertise, they have added minor parts to the manuscripts.



Signed:

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Chapter 1 Introduction

Ionic liquids (ILs) are compounds of the 21st century attracting much attention from both scientists and industrialists. The popularity of the subject and the ease with which these compounds can be made resulted in a considerable amount of publications from 2010 onward reporting on the synthesis, characteristics and application of these compounds. ILs are defined as materials containing only ionic species without any neutral molecules (Drummond and Greaves, 2008). They are formed by mixing neutral organic ligands with alkyl or aryl halides to give quarternized salts which on subsequent metathesis reactions with either organic or inorganic salts yield various ILs bearing different types of anions. An example of the synthesis of nitrile-functionalized ILs is given in Figure 1-1 below (Dyson et al., 2004).

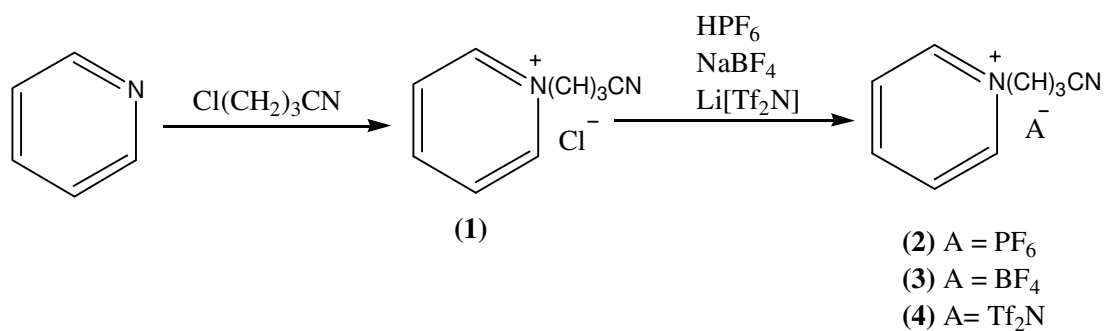


Figure 1-1 An example of the preparation of a nitrile-functionalised IL

The number of permutations with the available anions and cations are endless, leading to the popularity of this exciting field of chemistry and the numerous publications weekly. There have been many reviews on ILs in the last five years (Akman et al., 2007; Drummond and Greaves, 2008, Hajipour and Rafiee, 2009) which highlight the synthesis and their applications as solvent catalysts with notable activity and selectivity. ILs also have biological application as biocatalysts (Galonde et al., 2012), antimicrobials (Choi et al., 2011) as active

pharmaceutical ingredients (Hough et al., 2007), and are used in bacterial endospore detection (Greaves and Drummond, 2008) and lubricants (Stolte et al., 2012).

1.1 Uses and applications

The many uses of ILs range from being used in simple laboratory experiments to major industrial applications. In laboratories they are used as catalysts, green solvents and additives in many reactions (Zanoni et al., 2009, Chiappe and Pieracinni, 2005, Deng et al., 2005, Earle and Seddon, 2000, Gores et al., 2010, Cai et al., 2010, Ranu and Jana, 2006).

In chemistry, ILs are equally used as solvents and catalysts in various multiphase reactions including the Heck (Bellini and Chiappe, 2010), Suzuki (Dyson et al., 2008), Diels-Alder (Fischer et al., 1999, Kumar and Khupse, 2011), Friedel-Crafts (Malhotra and Xiao, 2005), epoxidation (Smith et al., 2004), and Pechmann condensation reactions (Deng et al., 2005). Examples of the ILs used for these reactions are given in Table 1-1. ILs confined in nanoporous silica gel were used as catalysts in many chemical reactions. With this method, catalysis is achieved with much lower amounts of ionic liquids (Deng et al., 2005; Deng and Shi, 2005). Their activity is also increased by entrapping them in metallic salts such as AgNO_3 (Litschauer and Alexandra, 2008). The ability to recycle ILs without affecting its productivity makes it a very attractive and environmentally friendly chemical and catalyst (Livington et al., 2006).

In electrochemistry, ILs are used in electrochemical devices, in the preservation of energy in solar cells (Kloo and Gorlov, 2008), battery cells (Armand et al., 2009) and heat storage (Zhang and Reddy, 2006). They are also used in extraction (Li et al., 2007) and membrane

separation (Matsumoto et al., 2005). ILs have also found applications as refrigerants and are currently replacing a few CFC refrigerants (Scurto and Ren, 2009).

Table 1-1 ILs used as solvents and catalysts in various multiphase reactions

Reaction	ILs used as solvent and catalysts	Reference
Heck reaction	[C ₆ Py][PF ₆]; [C ₆ Py][BF ₄], (solvents).	(Bellini and Chiappe, 2010)
Suzuki cross coupling reaction	[N1-butyl-N2-methyl Imidazolium][BF ₄], (solvent).	(Dyson et al., 2008)
Diels Alder	[N1-butyl-N2-methyl Imidazolium][BF ₄], (Catalyst/solvent).	(Fischer et al., 1999, Kumar and Khupse, 2011)
Friedel-Crafts	[EtPy][CF ₃ COO], [EtPy][BF ₄], (Catalysts).	(Malhotra and Xiao, 2005)
Epoxidation reaction	[N1-butyl-N2-methyl Imidazolium][BF ₄], [N1-butyl-N2-methyl Imidazolium] [PF ₆], (solvents).	(Smith et al., 2004)
Pechman condensation reaction	[N1-butylsulphonic acid-N2-methyl Imidazolium][CF ₃ SO ₃], (catalyst).	(Deng et al., 2005)

Imidazolium based ionic salts are good starting materials to *N*-heterocyclic carbenes (NHC), popular ligands in organometallic chemistry and catalysis, probably due to its ability to stabilize both low and high valent metal centers (Wassercheid and Keim, 2009). The ease with which both the electronic and steric properties of the imidazolium based salts may be widely varied also adds to their popularity (Gusev, 2009), leading to a variety of applications

in catalysis (Ivanova et al., 2011), medicine (Howarth and Hanlon, 2001) and as ionic liquid solvents (Egashira et al., 2006).

ILs are very important materials in the pharmaceutical industries being antibiofilm agents and being used to synthesise intermediates and bioactive molecules (Sekhon, 2011). They have also been reported to be local anesthetics, antibiotics and non-steroidal anti-inflammatory drugs (NSAID) (Rogers et al., 2008).

1.2 Physical properties

Ionic Liquids have unique properties which differentiate them from other solvents. They are good solvents for a number of organic, inorganic and organometallic compounds with lower viscosities, absent or negligible vapour pressure, high thermal stability, electrical conductivity and large electrochemical windows. Ionic liquids generally have nucleophilic sites and are capable of providing a weakly coordinating or non-coordinating environment to many reactions. Examples of the physical properties of some of the 1-butyl-3-methylimidazolium ILs are given in

Table 1-2 below to illustrate some of the differences in physical properties as opposed to common organic solvents.

Table 1-2 Physical properties of some common ionic liquids (Kumar and Singh, 2008 and Zhang et al., 2006)

IL	Mp (K)	Density(ρ) (g cm⁻³)	Viscosity (cP)	Electrical conductivity (mS cm⁻¹)	Surface Tension (δ_s)(Pa cm)	Decomp. Point (K)
[BMIM][BF ₄]	190.65	1.120	1.70	233	4.66	676.15
[BMIM][PF ₆]	283.15	1.368	450	na	4.88	622.5
[BMIM][CF ₃ CO ₂]	233.15	1.210	73.0	3.2	na	Na
[BMIM][Tf ₂ N]	na	1.510	88.0	3.2	na	Na
[BMIM][TfO]	189.15	1.290	90.0	3.7	na	Na
Methanol	175	0.792	0.59	na	22.50	Na
tetrahydrofuran (THF)	165	0.889	0.48	na	29.50	Na
Chloroform	210	1.483	0.57	na	26.67	Na
diethyl ether	156.9	0.713	0.22	na	17.00	Na

na = not available.

1.3 Synthesis

Basically there are two stages in the synthesis of ILs. The first stage is a quarternization reaction where the alkyl halide reacts with a neutral organic ligand to form the quarternized salt. This reaction normally takes place between molecules with a nitrogen or phosphorus

nucleophile and an alkyl halide, which can be aliphatic or aromatic. The second stage is a metathesis reaction in which the salt reacts with other organic or inorganic metallic salts which displaces the halide ion to form the desired ILs which can be purified by several washings with methanol to remove the metallic halide by extracting it into the methanol. The first stage therefore normally involves an S_N1 or S_N2 type mechanism and normally requires the neutral organic ligand to be a stronger base than the alkyl halide. An example is given in Figure 1-2 below as reported by Swatloski et al. (2003).

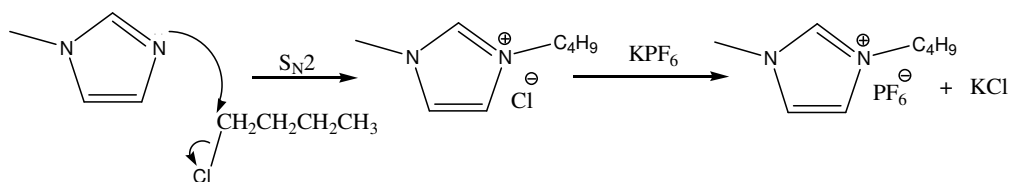


Figure 1-2 An example of a S_N2 mechanism followed by a metathesis reaction to produce the corresponding IL

In the first stage, the neutral ligand nucleophile (electron pair donor) attacks the electrophilic carbon of the alkyl halide to form the quaternized salt. Halides are generally weak bases and good leaving groups and are readily displaced by nitrogen and phosphorus nucleophiles. It is in the second stage that various anions are substituted mainly for the halides in a metathesis reaction.

Although the methodology for the synthesis of ILs is a straightforward nucleophilic type reaction followed by displacement of the halides, there are slight variations reported in the literature. In the conventional preparation method, the alkyl halide and the neutral ligand are reacted either at room temperature or slightly elevated temperature (Akman et al., 2007, Klamt et al., 2002). The reactions are normally carried out under inert atmosphere (nitrogen)

in a closed vessel either in a suitable solvent or without solvents since the reactants in many cases are liquids and do not require the use of solvents. At times, temperatures up to 70 °C are used for the synthesis (Klamt et al., 2002).

Microwave synthesis was also used to prepare ILs (Seddon et al., 2003), with the advantages of avoiding the use of solvents, being more "green" and leading to a large scale preparation. "Green synthesis" of ILs has also been reported in open glass containers, sometimes without the addition of solvents and in other cases, using a mixture of water and ethanol for the metathesis reaction, producing yields of up to 94% (Varma and Namboodiri, 2001). Reactions were also carried out in spinning tube-in-tube reactors, where reactants are continuously introduced into the reactor which spin continuously. The products are collected in excellent yields of up to 99%. This method also leads to large scale preparation of tens of kilograms of ILs per day (Gonzalez and Ciszewski, 2009).

1.4 Classification of ILs

ILs are most commonly classified according to the cation present, which is derived from the neutral organic ligand. For example, imidazolium ILs are derived from imidazole and pyridinium ILs are derived from pyridine. They have also been known to be classified according to the pH of the IL as either acidic, basic or neutral ILs and depend on both the cation and anion in the IL (Hajipour and Rafiee, 2009, Deng et al., 2005). This acid-base classification can be particularly useful if a particular IL is needed for a solvent in a synthesis as some reagents may be acid sensitive and others base sensitive. Figure 1-3 to Figure 1-5 contain some examples of acidic (Deng et al., 2005), basic (Hajipour and Rafiee, 2009) and neutral ILs (He et al., 2010).

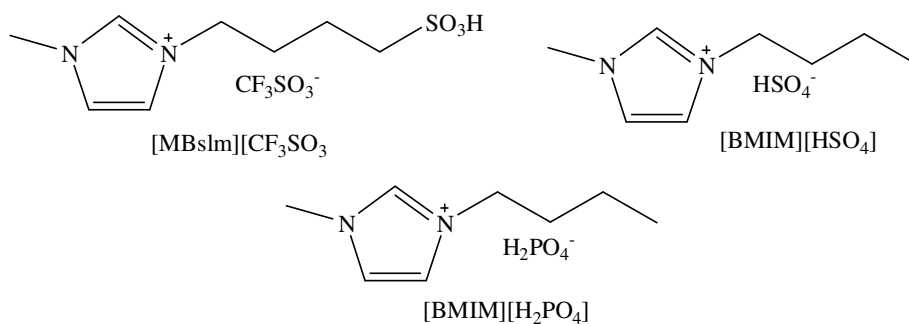


Figure 1-3 Acidic Imidazolium ILs

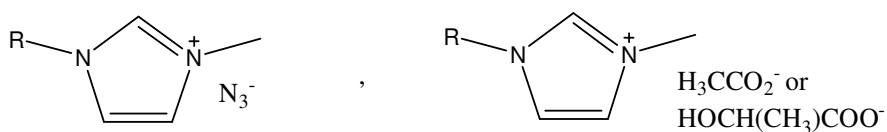
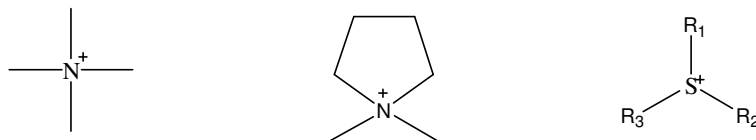


Figure 1-4 Basic Imidazolium ILs

Cations:



Anions:

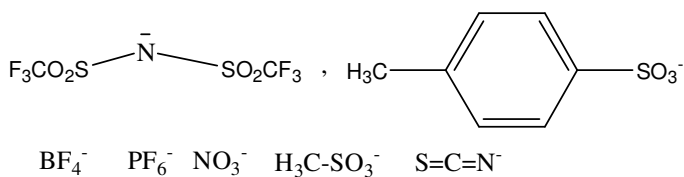


Figure 1-5 Neutral ILs (contains any combination of cation and anion listed)

1.5 Commonly encountered anions and cations

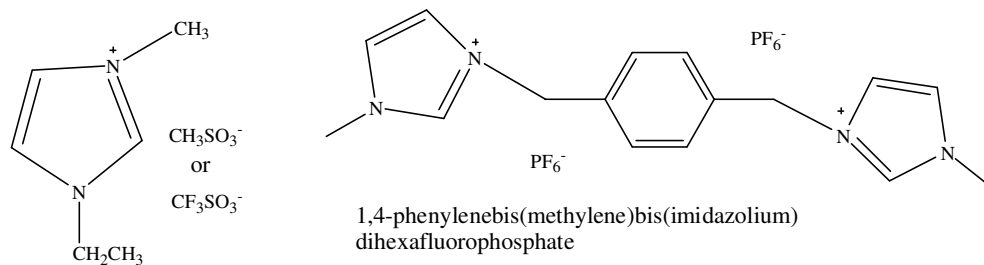
The most commonly encountered cations are those containing ammonium, imidazolium, pyridinium, phosphonium and sulfonium ligands (Figure 1-6). These ligands are reacted with alkyl chains of varying length as well as aromatic groups. The most commonly encountered

anions used in the metathesis reactions all contain fluorine. These are PF_6^- , BF_4^- , CF_3SO_3^- , CF_3COO^- and Tf_2N^- (trifluoromethylsulfonyl imide). Those not so frequently used are $(\text{CF}_3\text{SO}_3)_2\text{N}^-$, SCN^- , RCOS^- , RCO_2^- , $\text{C}_6\text{H}_5\text{CF}_2\text{SO}_3^-$ and RCS_2^- (Dyson et al., 2007; Ganesan and Alias, 2008; Scammells et al., 2009; Deng et al., 2009, Deng et al 2011).

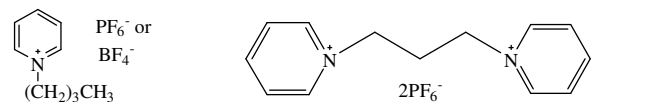
1.6 Bidentate and chelating salts

In spite of the popularity and vast amount of literature on the chemistry and application of monodentate imidazoli(ni)um salts and NHCs, the corresponding area of bidentate and chelating salts has received far less attention. Recently, the design of new ligand structures and the development of new applications for bi- and multi-dentate chelating imidazoli(ni)um salts have been reported (Nan et al., 2011). These compounds have the ability to act as pincer NHC ligand precursors with added stability to metal centers in catalysis. This is illustrated by the bidentate NHC-Pd complex (Muehlhoper et al., 2002) which efficiently catalyses the conversion of methane to methanol in an acidic and highly oxidizing environment, which made it possible to achieve high catalytic efficiency.

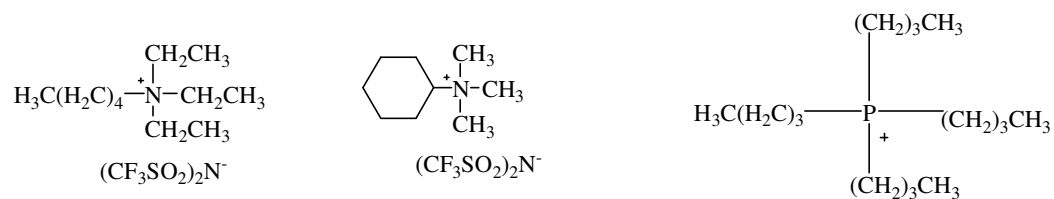
Applications and the efficiency of the ILs in these applications may differ significantly from the monodentate ILs considering the ionic strength of the bidentate ILs as well as the complexity of their structures (Zhang et al., 2010, Ganesan and Alias 2008, Kofinas et al., 2011).



1-Ethyl-3-methylimidazolium
Methanesulfonate or trifluoromethanesulfonate



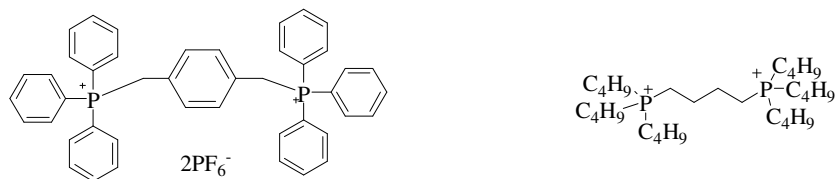
1-Butylpyridinium
Hexafluorophosphate or tetrafluoroborate



Amyltriethylammonium
Bis(trifluoromethanesulfonyl)
imide

Cyclohexyltrimethylammonium
Bis(trifluoromethanesulfonyl)
imide

tetrabutylphosphoniumbromide



1,4-Phenylene(methylene)bis(triphenylphosphonium) dihexafluorophosphate.

1,4-Butylene(bistributylphosphonium) ditetrafluoroborates



Triethylsulfonium
Bis(trifluoromethanesulfonyl)-
imide

Cyclohexyldiethylsulfonium tetrafluoroborate

Figure 1-6 Examples of ILs with commonly encountered cations (imidazolium, pyridinium, ammonium, phosphonium and sulphonium)

Chelation is the term used to describe a coordinate bond between a ligand (electron donor) and a metal (electron acceptor). The phosphonium, imidazolium and pyridinium moieties all have lone pairs capable of chelation with metals. ILs can also be functionalised in order to have more electron donating groups for the chelation of metals (Singer et al., 2008) to remove metal ions from aqueous solutions. This is illustrated in Figure 1-7 below.

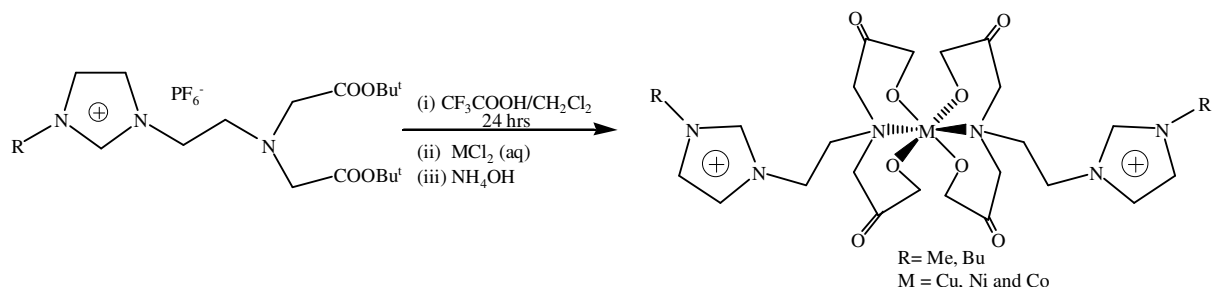


Figure 1-7 An example of chelation of an IL with a metal centre

Ziessel et al. (2009) also synthesized monodentate functionalized ILs with terpyridine alkyl halides. Due to the many co-ordinating sites in these ILs (Figure 1-8), these are well suited for extraction of metals.

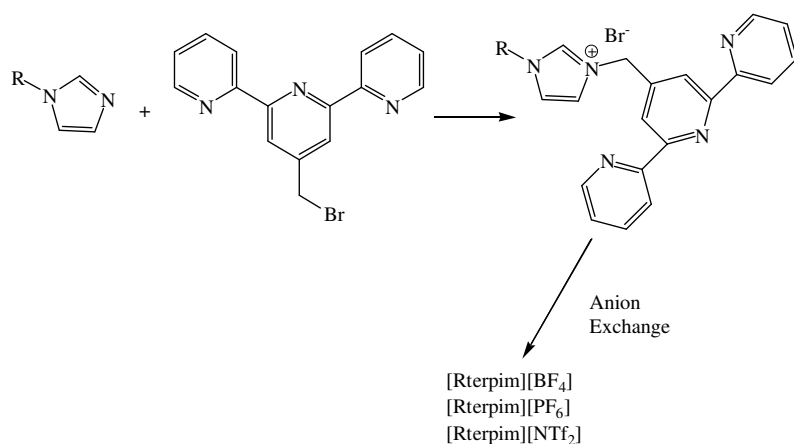


Figure 1-8 ILs with a terpyridine moiety with many co-ordinating sites for removal of metals

More exciting studies have been reported where the anionic part of the ILs contain metal complexes of Co, Cu, Mn and Ni and the cations contain complexes of ammonium, phosphonium, pyridinium and imidazolium (Li et al., 2012). These ILs are air and water stable, have good thermal stability and are hydrophobic. Chelating orthoborate anionic complexes were also used in the synthesis of ILs (Welz-Biermann et al., 2011; Antzutkin et al., 2012). These ILs had low temperature and heat capacities. Extensive studies on the thermodynamic properties of these ILs were carried out (Welz-Biermann et al., 2011). Figure 1-9 illustrates a few examples of these chelating anion complexes.

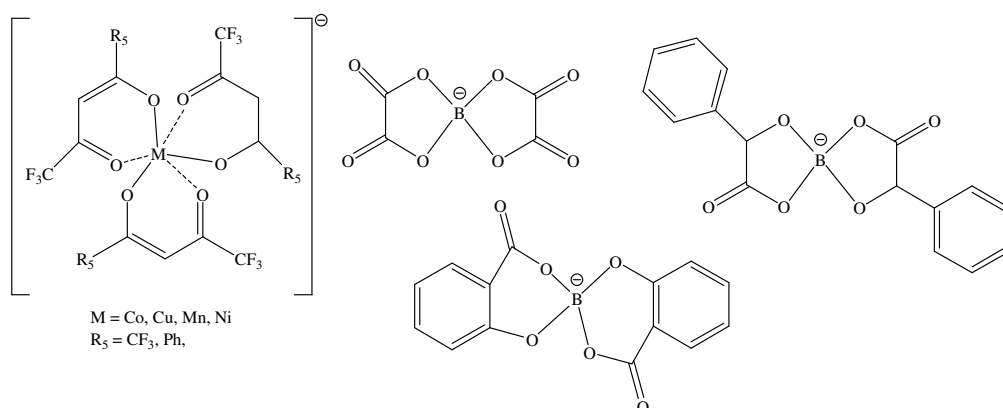


Figure 1-9 Examples of some metal and boron anionic complexes

Bidentate ionic liquids having two sites available for co-ordination should be better than the monodentate co-ordinating ILs in binding to metal ions and thus should be more efficient at removing these metals from aqueous solutions. To date, a few poly NHC ligands in complexes of iron and ruthenium have been reported (Smith et al., 2005 and Poyatos et al., 2003). These contained a bridged pyridine ring between two imidazolium rings (Figure 1-10). However, there are limited reports on the catalytic performance of these compounds (Poyatos et al., 2009).

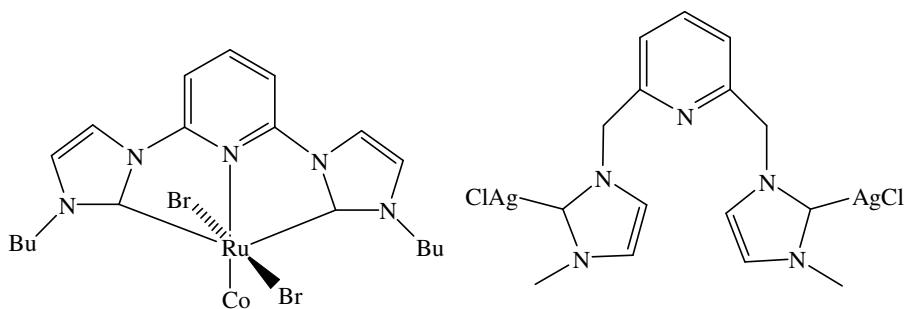


Figure 1-10 Examples of poly NHC ligands

1.7 Aims and objectives

The aim of the research was to synthesize and characterise various ILs with imidazolium, pyridinium and phosphonium cations and in particular, bidentate cations, as information on the synthesis, characterization and applications of these were not as well studied as the monodentate cations, and to carry out the metathesis reactions with fluorinated anions and find applications for some of these fluorinated materials that would add to South Africa's Fluorine Expansion Initiative (FEI).

1.8 Highlights of the thesis

The thesis is divided into six chapters which include the synthesis, characterization and application of ionic compounds that are imidazolium, phosphonium and pyridinium based. Antimicrobial assays were carried out on some of the compounds in an effort to determine their suitability to being used in the pharmaceutical industry.

Chapter 2 is an account of the synthesis and characterization of five bidentate Imidazolium ILs. The crystal structure of three of the ILs is also reported in this chapter. The different counter ions affect the spatial arrangement of atoms which has subsequent effects on the stability and coordination properties of the imidazolium salts. This set of compounds could

be used to synthesize Nitrogen Heterocyclic Carbenes (NHC) which can be utilized in making various metallic complexes that may be useful in catalytic applications.

Chapter 3 is based on the synthesis of phosphonium compounds in which the neutral ligand used is triphenylphosphine. Five novel compounds were synthesized, characterized and subjected to antimicrobial assays against five standard microorganisms, *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Salmonella typhi*, *Streptococcus pyogenes* and *Candida albicans*. Significant activities were observed when compared with the activities of the standard antimicrobial, chloramphenicol and antifungal nystatin. One of the compounds was crystalline and the X-ray structural data was reported in a follow up chapter, chapter 4. Interestingly the protons of the central aromatic group and that of the phenyl group is in close proximity through space as confirmed from the X-ray structure and verified by NOESY spectra.

Chapters 5 and 6 contain reports on the solvent free synthesis and characterization of imidazolium and pyridinium based ionic liquids. These reactions were highly exothermic and were carried out in an ice bath at temperatures below 5 °C with the slow addition of imidazole and pyridine. NMR studies of the synthesized compounds are reported in each of the chapters and the trends in melting point as the anions are exchanged are also discussed.

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Chapter 2 Synthesis and characterization of imidazolium salts bearing fluorinated anions

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Abstract. Reaction of 1-methylimidazole and α,α -dibromo-*p*-xylene was followed by a metathesis reaction with fluorinated anion sources, which yielded new fluorinated imidazolium salts $[\text{C}_6\text{H}_4(\text{CH}_2(\text{C}_4\text{H}_6\text{N}_2)_2)^{2+} 2[\text{A}]^-$ where A = BF_4 (**A-2**), PF_6 (**A-3**), CF_3SO_3 (**A-4**) and CF_3COO (**A-5**). The compounds were characterized by ^1H -, ^{13}C -, ^{19}F -, ^{31}P -NMR and IR spectroscopy. Single crystal X-ray diffraction data of compounds **A-2**, **A-3** and **A-4** are also reported while compound **A-5** was found to be a liquid. The solid compounds crystallized in the monoclinic $P2(1)/c$ space group and have comparable crystallographic parameters. The study revealed that the different fluorinated anions affected the spacial arrangement of atoms and the extent of cation-anion interactions and hence, influenced the stability and coordination properties of the imidazolium salts. A trend was observed which related the strength of cation-anion interaction to physical properties such as melting point.

Keywords: Fluorinated anion. Imidazolium ionic salt. X-ray diffraction. 1,4-Phenylenedimethylene.

2.1 Introduction

Imidazolium based ionic salts are good precursors to *N*-heterocyclic carbenes (NHCs) popular as ligands in organometallic chemistry and catalysis, while low melting versions are important sources of ionic liquids (ILs) used as green solvents.^[1] The NHCs have found application in many catalytic systems as phosphine mimics or as total replacement for phosphine ligands.^[2] Unlike phosphines, the coordination of NHCs to metal centres required activation of the imidazolium precursor, and in this respect the nature of the cation-anion interaction in the precursor salt plays an important role in the stabilization of the salt during the deprotonation step towards formation of the free NHC ligand.^[3] Towards this end, the deprotonation of imidazolium based ionic salts with bases is the most common technique employed for the generation of preformed, isolated free carbenes.^[4] Halogenated compounds are generally used as the anionic species in ionic salts, and the nucleophilicity of the resulting NHC ligand may be controlled by the structure of the halogen bearing ion used in the synthesis of the parent ionic salt.^[5] This also modulates the strength of the cation-anion interaction in a solution or melt which is important in determining the stability and hence subsequent application of the salt for other uses such as an ionic solvent or a pharmaceutical ingredient. Hence, in this report we wish to report on the synthesis and structural elucidation of a series of new imidazolium salts bearing several fluorinated anions. We also explored the effects of varying the fluorinated counter-anion on the properties of the salts.

2.2 Results and Discussion

The synthesis of compounds **A-1** - **A-5** (Scheme 2-1) was successfully carried out with excellent yields of up to 99%. The synthesis of dimeric imidazolium ion based ILs was first reported by Ganesan *et al.* in 2008^[6] and similar compounds bearing different alkyl chains on

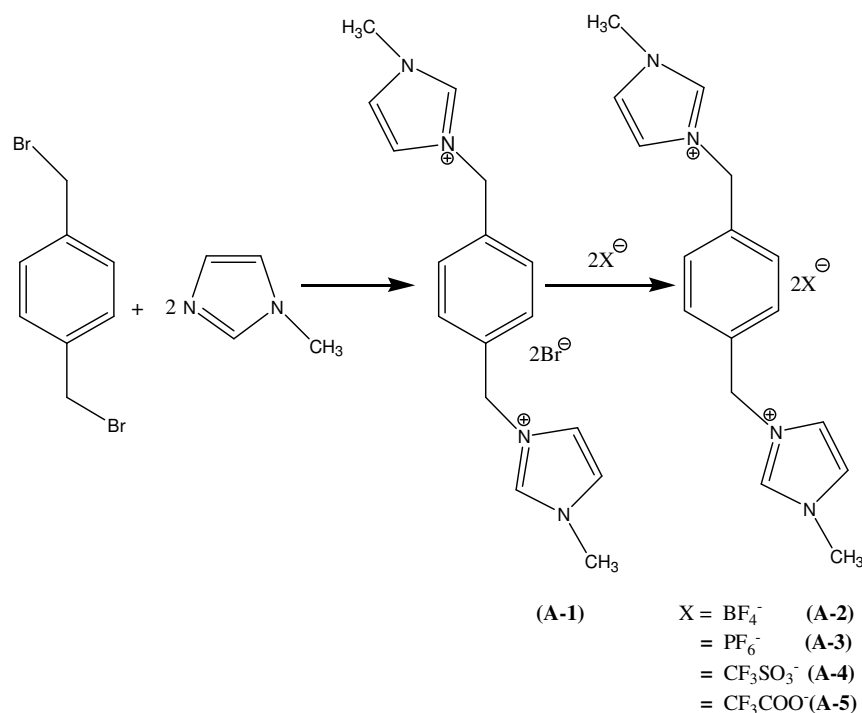
the imidazole ring were later synthesized by Neouze *et. al.* in 2010.^[7] The compounds **A-1** - **A-5** all contain a similar structural backbone which was synthesized via a well-established experimental technique.^[6] Characterization techniques including ¹H-, ¹³C-, ³¹P- and ¹⁹F-NMR as well as IR spectroscopy were used to confirm formation of the reported compounds. In addition, compounds **A-2**, **A-3** and **A-4** are colorless crystalline solids and were structurally characterized by single crystal X-ray diffraction. As presented in Table 2-1, the gradual decrease in the melting points of compounds **A-1** – **A-4** (MX₂) moving from MBr₂ to M(CF₃SO₃)₂ was observed to be dependent on the chemical nature of the anion (X⁻, Scheme 2-1). The compound M(CF₃COO)₂ was an ionic liquid. This could be explained in terms of a “covalent” effect^[8] whereby the strength of the inter-ionic bonding shifted from a purely ionic character in MBr₂ to gradually assume more covalent nature for M(CF₃SO₃)₂, while M(CF₃COO)₂ had the weakest inter-ionic interactions.

Contrary to a previous report,^[6] we found compound **A-4** to be a crystalline solid with a melting point of 155-156 °C as confirmed by the X-ray structural data presented in Table 2-1 and shown in Figure 2-6.

NMR studies

Due to a similarity in the back-bone structure of the parent cation, all the compounds showed similar ¹H- and ¹³C-NMR patterns with only slight shifts in signal positions attributable to the various counter-anions. A previous study has discussed the influence of varying the nature of the anion or solvent on NMR peak positions of ionic compounds.^[9] The proton NMR spectrum of compound **A-1** for instance is shown in Figure 2-1, which showed two strong resonances at $\delta_{\text{H}} = 3.88$ and 5.49 ppm for the three *N*-methyl (H^a) and two

methylene (H^c) protons respectively. These were the most shielded protons in the compound and were found to be in agreement with published data for related compounds.^[10] The spectrum also showed a downfield signal at $\delta_H = 9.37$ ppm due to the methine proton (H^d) on the carbon bridging the two nitrogen atoms of the imidazolium moiety. Normally, the loss of this proton signal is diagnostic when imidazolium based compounds such as **A-1** - **A-5** are complexed to metal centers as NHC ligands. The proton signal was observed to be shifted downfield due to the delocalization of electron density from the nitrogen atoms to the neighboring carbon atom, the role of the nitrogen atoms in the stabilization of reactive NHCs is well established. The aromatic protons on the phenyl ring and the protons on the imidazolium rings were observed in the expected region, downfield at $\delta_H = 7.52, 7.75, 7.84$ and 9.37 for H^f, H^c, H^b and H^d respectively (Figure 2-1). The H^b and H^c protons couple to each other with a very small coupling constant of 1.44 Hz.



Scheme 2-1 Synthetic route to the imidazolium salts A-1-A-5

The proton resonances of the cations in the ionic salts were observed to show a very small downfield shift due to hydrogen bonding to the anion in the order $M(\text{CF}_3\text{COO})_2 > M(\text{CF}_3\text{SO}_3)_2 > M(\text{BF}_4)_2 > M(\text{PF}_6)_2$, which was stronger for Br^- and CF_3COO^- and weaker in the other two salts (triflate is much less basic than trifluoroacetate). Strong hydrogen bonding to the Br^- anion has been observed in other previously reported salts.^[10]

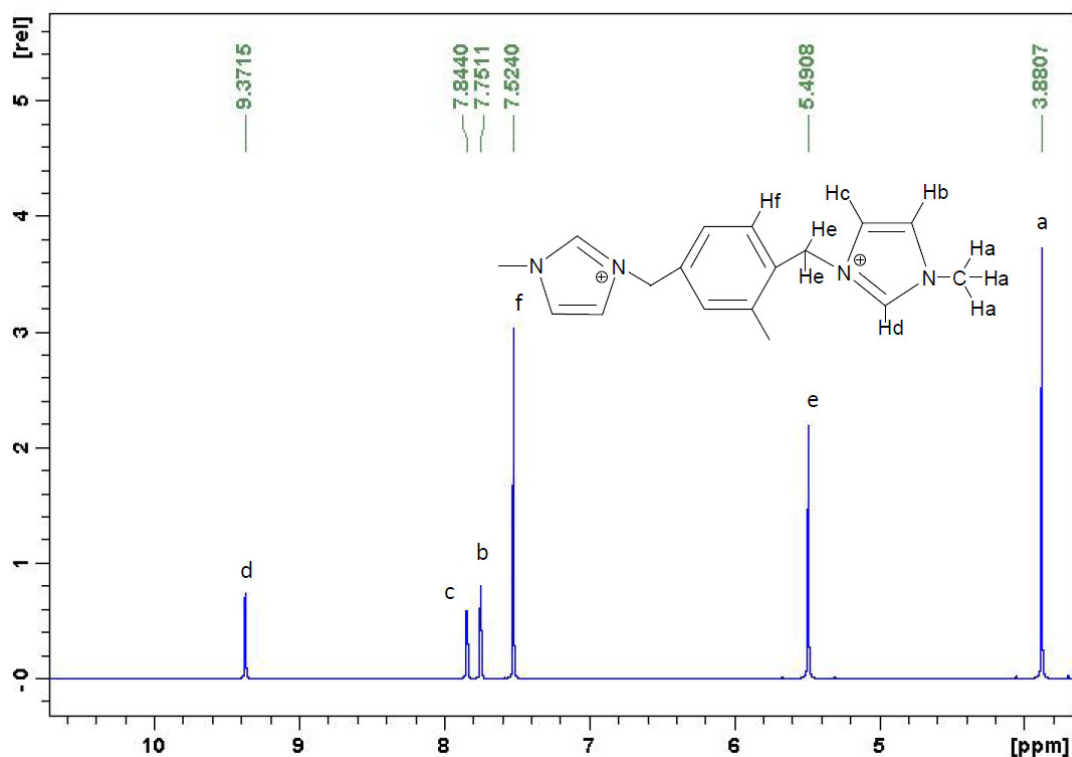


Figure 2-1 ¹H NMR spectrum of compound A-1 in DMSO.

The ¹³C NMR spectrum of compound A-1 is shown in Figure 2-2 which indicated the methyl and methylene carbon resonances at $\delta_c = 35.99$ and 51.23 ppm respectively. The phenyl quaternary carbon resonated at $\delta_c = 135.40$ ppm, while the *ortho* carbon resonance appeared as a sharp signal at $\delta_c = 128.93$ ppm. The carbon C⁴ of the imidazolium ring was recorded at $\delta_c = 136.62$ ppm,^[10] highly deshielded due to the positive charge on the nitrogen

being conjugated with the double bond to the carbon. The two olefinic carbon resonances, C² and C³ appeared at δ_c 122.26 and δ_c 123.97 ppm respectively.^[9]

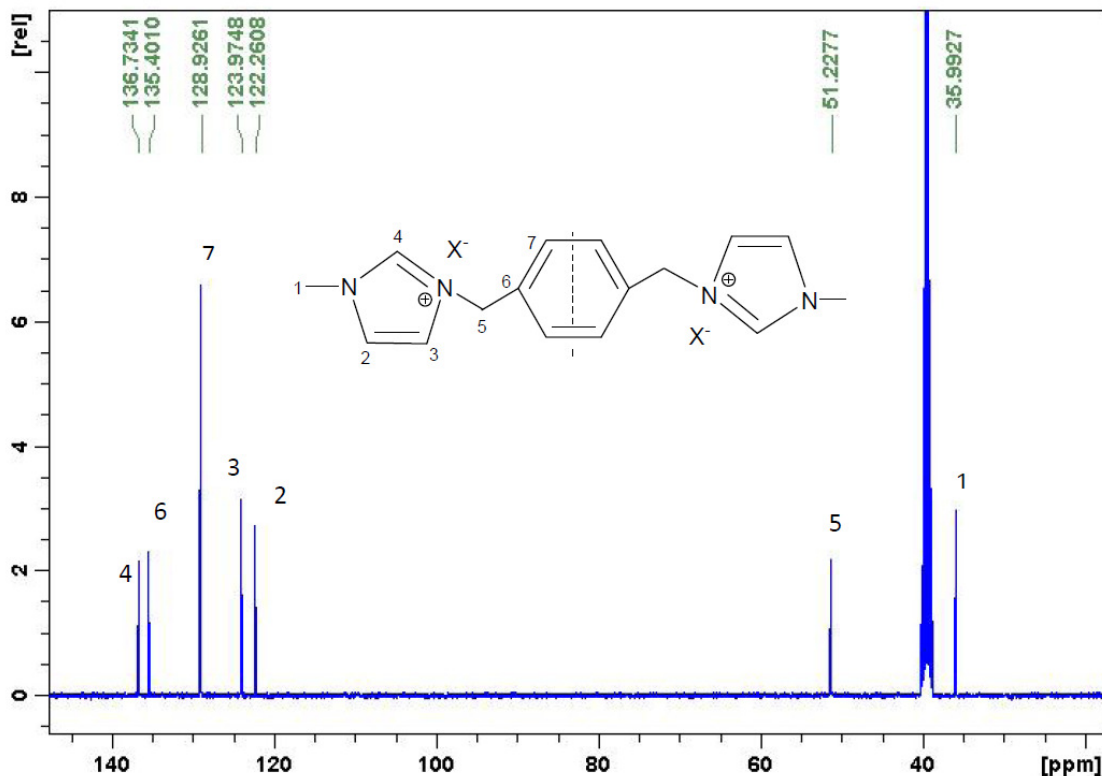
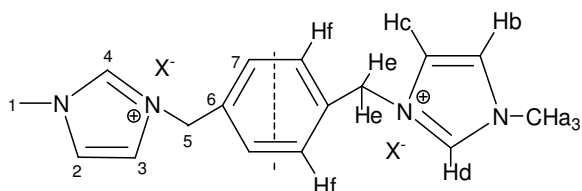


Figure 2-2 ¹³C NMR spectrum of compound A-1 in DMSO

All the ionic salts exhibited similar ¹³C NMR patterns, but in **A-5** (CF₃COO⁻ as the counter ion), the chemical shifts were generally further downfield as compared to peak positions in **A-1** – **A-4**. This may be attributed to weakened cation-anion interaction due to a combination of electronegative fluorine atoms and an electron withdrawing –COO⁻ group in the anion resulting in the delocalization of the negative charge, hence the downfield shift in NMR signals.^[11] In the spectrum of compound **A-4**, a resonance at $\delta_c = 120$ ppm was assigned to the CF₃ carbon of the anion. In compound **A-5**, resonances at $\delta_c = 117$ and 158 ppm were due to CF₃ and COO carbon resonances respectively.

Table 2-1. NMR data (ppm) in DMSO and melting points of compounds A1-A5.

Compd	δC^1 (δH^a)	δC^2 (δH^b)	δC^3 (δH^c)	δC^4 (δH^d)	δC^5 (δH^e)	δC^6	δC^7 (δH^f)	^{31}P	^{19}F	$CF_3SO_3^-$	CF_3COO^-	Melting Pt. ($^{\circ}C$)
1	35.89 (3.88)	122.24 (7.84)	123.96 (7.75)	136.62 (9.37)	51.25 (5.49)	135.39	128.94 (7.52)					245-247
2	35.83 (3.85)	122.24 (7.74)	124.03 (7.68)	136.64 (9.17)	51.36 (5.42)	135.37	128.86 (7.47)		-148.142			225-228
3	35.82 (3.83)	122.23 (7.72)	124.01 (7.67)	136.65 (9.16)	51.36 (5.40)	135.35	128.85 (7.45)	-144.195	-70.114			213
4	35.84 (3.85)	122.24 (7.75)	124.02 (7.70)	136.65 (9.18)	51.37 (5.42)	135.35	128.87 (7.47)		-77.767	120.27 (CF_3)		155-157
5	36.33 (3.85)	122.70 (7.83)	124.43 (7.72)	137.12 (9.39)	51.71 (5.47)	135.88	129.44 (7.49)		-73.733		158.73 (CF_3) 117.57 (COO)	liquid



The proton (a-f) and carbon (1-7) environments in the cation of compounds **A-1** - **A-5**;
 Multiplicities and coupling constants are given in the experimental section.

In the ^{31}P NMR spectrum of compound **A-3**, the only compound containing a phosphorus atom, a resonance at -144 ppm was due to the PF_6^- anion which was split into a septet with a coupling constant of 711 Hz. The Fluorine NMR spectrum of compound **A-2** showed two signals for BF_4^- due to the two isotopes of boron (B-10 and B-11), which were observed at -148.14 and -148.20 ppm respectively, while **A-4** and **A-5** showed resonances at -77 and -73 ppm respectively.

The infrared spectra of compounds **A-1 – A-5** are presented in **Error! Reference source not found.** The band at 1558 cm^{-1} which is characteristic of the in-plane stretching vibrations of the C-N and C-C bonds of the imidazolium moiety^[12] was generally shifted to slightly higher wavenumbers in **A-2 – A-4** and shifted down to 1515 cm^{-1} in **A-5**. The shifts in the absorption frequencies of the cation were probably due to its interaction with the various anions with the electronically weaker CF_3COO^- anion showing a strong shift to lower wavenumbers due to its poor ability to pull electron density away from the imidazolium center. Similarly, the intense C-H in-plane vibration band of the imidazolium ring observed at 1159 cm^{-1} in compound **A-1** was observed as a very broad band shifted to 1039 cm^{-1} in **A-5**. All the compounds displayed high energy peaks ($>3100\text{ cm}^{-1}$) characteristic of C-H symmetrical stretching vibration of the imidazolium ring and the alkyl chain, which was observed at 3036 cm^{-1} in **A-1**.^[13]

Single crystal X-ray diffraction studies

A summary of the crystal data for compounds A-2, A-3 and A-4 is presented in

Table 2-2 while Table 2-3 shows a comparison of selected bond lengths and angles for the three compounds. All the compounds crystallized in the same monoclinic $P2(1)/C$ space group. The quality of the crystals for **A-2**, **A-3** and **A-4** is very high with R indices of 4.3, 7.1 and 3.9% respectively.

In the imidazolium moiety, the bonds involving the C(4) carbon had the shortest C-N bond lengths, which is because it was directly bonded to the two nitrogen atoms. For the same reason the C(4) carbon was also assigned the most downfield position in the ^{13}C NMR analysis.

Table 2-2. Crystal data and X-ray data collection parameters for compounds A-2 – A-4.

Compound	2	3	4
Empirical Formula	C ₁₆ H ₂₀ B ₂ F ₈ N ₄	C ₁₆ H ₂₀ F ₁₂ N ₄ P ₂	C ₁₈ H ₂₀ F ₆ N ₄ O ₆ S ₂
Formula weight	441.98	558.30	566.50
Temperature (K)	173(2)	223(2)	173(2)
Wavelength (Å)	0.71073	0.71073	0.71073
Crystal system	Monoclinic	Monoclinic	Monoclinic
Space group	P2(1)/c	P2(1)/c	P2(1)/c
Unit cell dimensions (Å, °)	a = 4.9699(2) b = 12.8898(4) β = 92.879(2) c = 15.3337(6)	a = 6.0714(2) b = 12.5819(4) β = 93.187(2) c = 14.9951(5)	a = 9.5783(3) b = 9.9824(2) β = 104.800(2) c = 12.6947(3)
Volume (Å ³)	981.05(6)	1143.70(6)	1173.53(5)
Z	2	2	2
Crystal size (mm ³)	0.38 x 0.12 x 0.11	0.44 x 0.14 x 0.12	0.47 x 0.13 x 0.09
Goodness-of-fit on F ²	1.012	0.987	0.959
Final R indices [I>2σ(I)] R indices (all data)	R1 = 0.0427 wR2 = 0.0980	R1 = 0.0711 wR2 = 0.2008	R1 = 0.0388 wR2 = 0.0888

Table 2-3. Selected bond lengths (Å) and angles (°) in compounds A-2 – A-4.

	2, BF₄⁻	3, PF₆⁻	4, CF₃SO₃⁻
Lengths (Å)			
C(1)-N(1)	1.460(2)	1.465(5)	1.469(2)
C(4)-N(1)	1.325(2)	1.317(5)	1.321(2)
C(3)-N(2)	1.3791(9)	1.378(5)	1.372(2)
C(4)-N(2)	1.322(2)	1.322(5)	1.325(2)
C(5)-N(2)	1.4695(19)	1.445(5)	1.477(2)
Angles (°)			
C(3)-C(2)-N(1)	107.62(14)	106.5(4)	107.09(18)
C(2)-N(1)-C(1)	126.29(15)	125.6(4)	126.69(17)
N(1)-C(4)-N(2)	108.83(14)	109.8(4)	108.78(17)
C(4)-N(2)-C(3)	108.86(14)	107.4(4)	108.34(17)
C(4)-N(2)-C(5)	125.18(13)	126.0(4)	108.34(17)
N(2)-C(5)-C(6)	111.04(13)	113.3(4)	111.28(16)

Ortep diagrams for **A-2**, **A-3** and **A-4** are presented in **Error! Reference source not found.**, Figure 2-5 and Figure 2-6 respectively. In all the compounds, the benzyl backbone of the dication was essentially planar with the two symmetrical 3-methylimidazolium moieties pointed in the same direction but away from each other to minimize intramolecular steric repulsions. For balance of electronic charges, all the three compounds contained a counter anion and half a molecule of the dication in the unit cell. These lie about a center of inversion in the asymmetric unit. All the three compounds are stabilized by weak intermolecular electrostatic attractive forces between the respective anions and the dication.

The strength of these electronic interactions and the steric size of the anions account for the differences in crystal packing and in key physical properties such as the variation in melting temperatures of the compounds (*vide infra*).

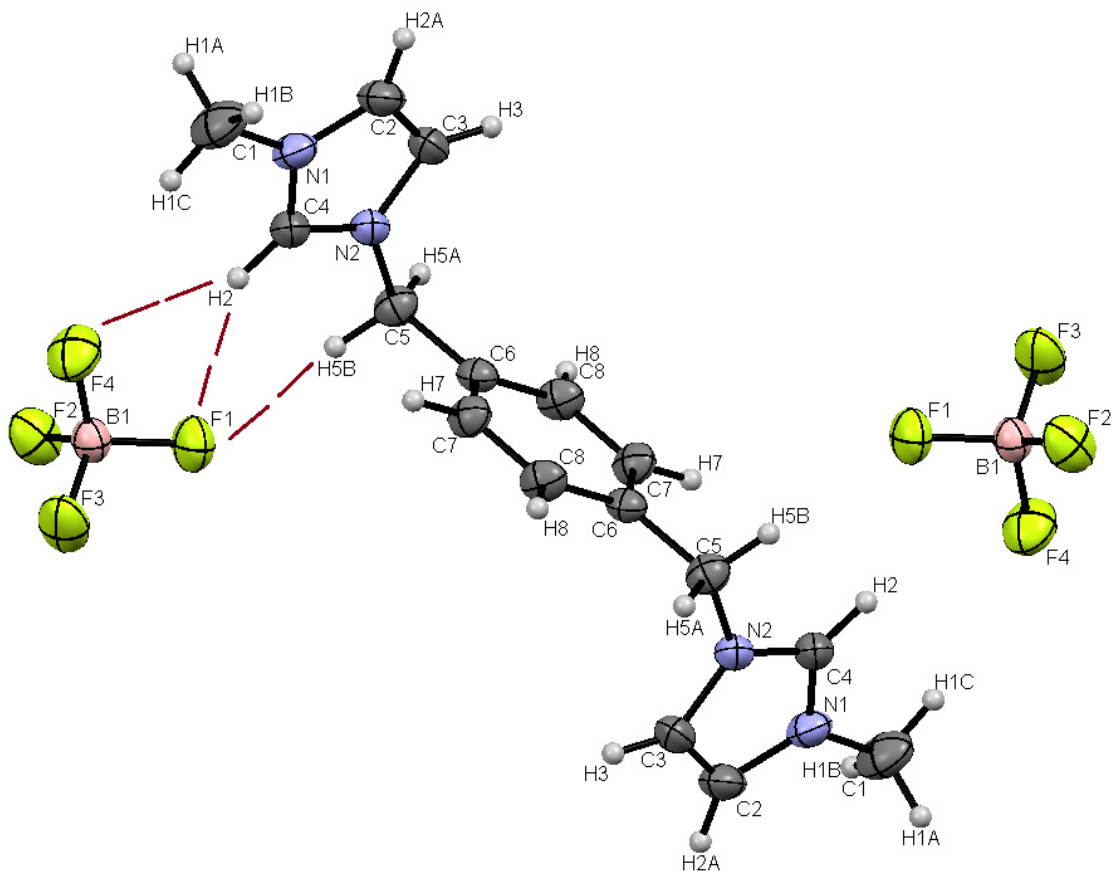


Figure 2-3. ORTEP diagram of compound A-2 with ellipsoids shown at 50% probability level.

The molecular packing in these compounds is also affected by the arrangement of the dications relative to the anions. The compounds show discrete anions- BF_4^- , PF_6^- and CF_3SO_3^- interspersed between the dication in A-2, A-3 and A-4 respectively.

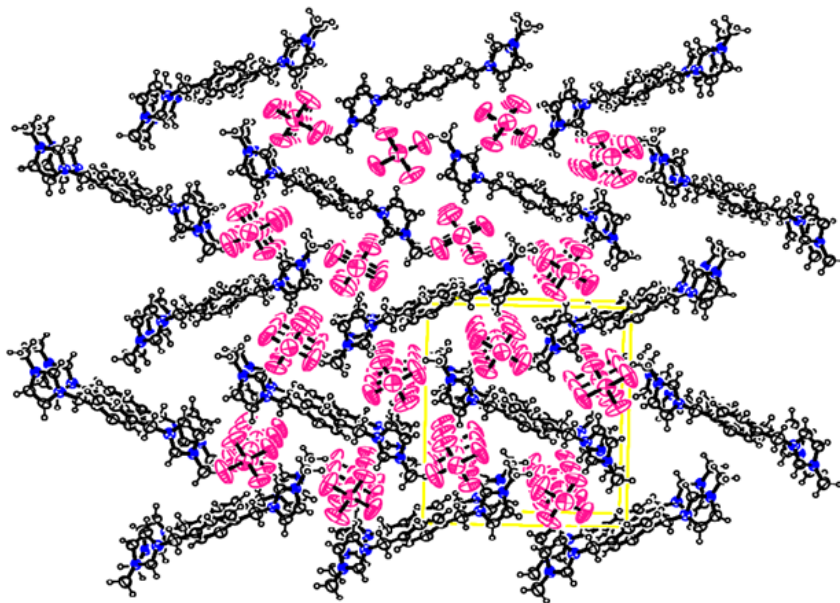


Figure 2-8 Figure 2-4. The packing diagrams of compounds A-2 and A-3

Figure 2-8 show that the compounds pack in a related pattern. When viewed along the *a*-axis, Figure 2-7 shows that the packing in a crystal of **A-2** comprises the dication forming a Z-shaped zigzag pattern in layers around rows of the counter anions BF_4^- . The anion and cations are stabilized by short C-H \cdots F contacts (C4-H2 \cdots F4, C4-H2 \cdots F1, C5-H5B \cdots F1) involving the electrophilic fluorine atoms as shown in figure 2-3.

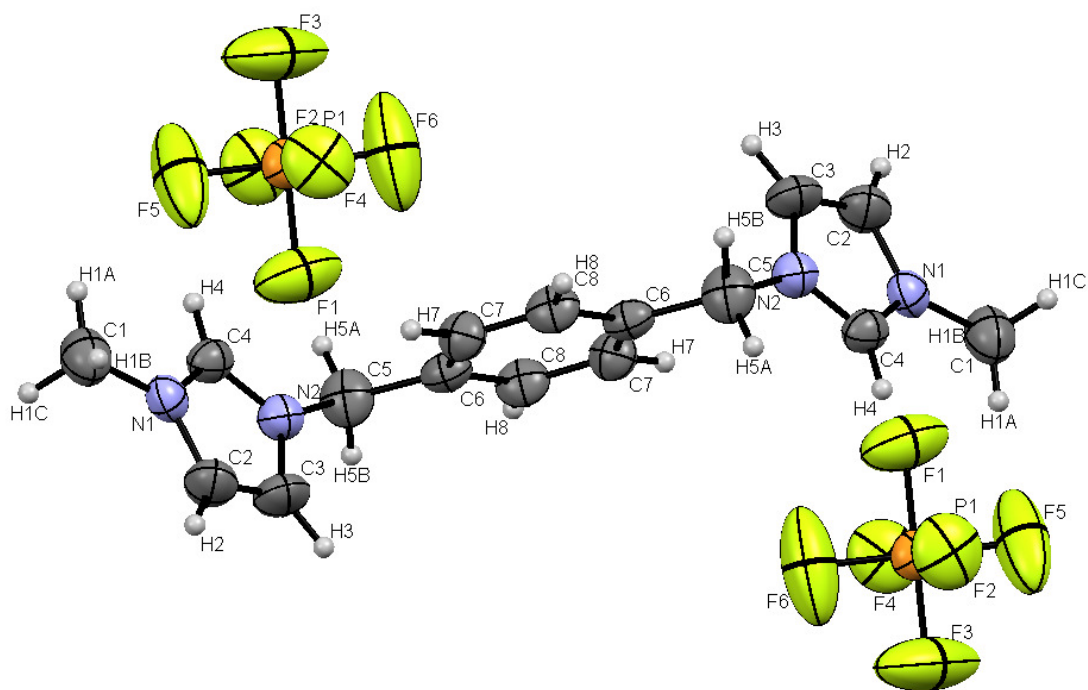


Figure 2-5. ORTEP diagram of compound A-3 with ellipsoids shown at 50% probability level.

A similar type of molecular arrangement is observed for the packing in a crystal of **A-3** where the fluorine atoms of the PF_6^- are involved. Both compounds are stabilized by a series of the $\text{C-H}\cdots\text{F}$ contacts with intermolecular distances ranging from 2.394 to 2.697 Å. These are significant contacts that are shorter than the sum of the van der Waals radii of hydrogen (1.2 Å) and fluorine (1.5 Å), and are responsible for the relatively high melting temperatures of **A-2** and **A-3**.

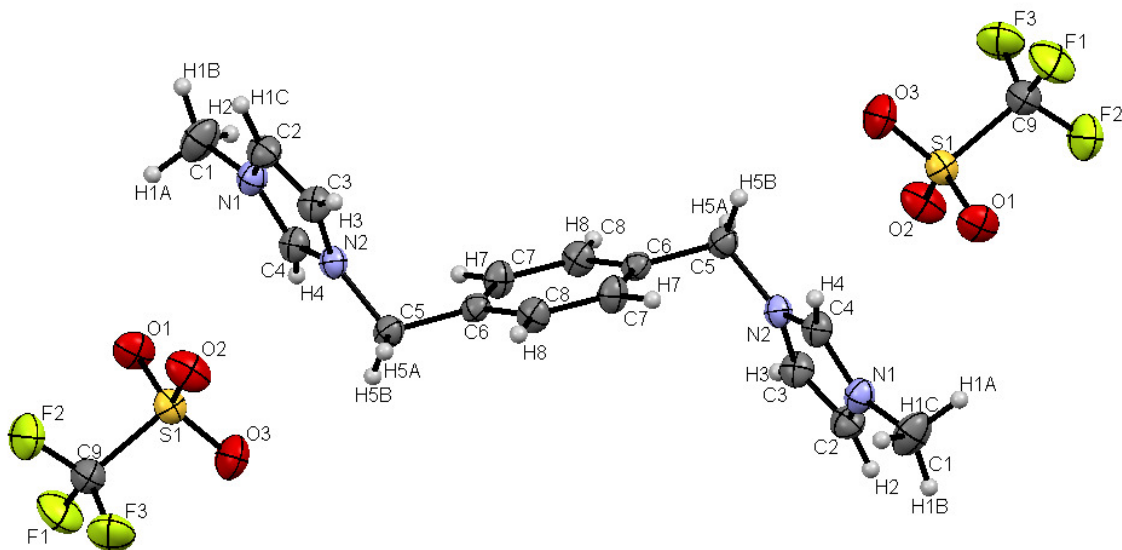


Figure 2-6. ORTEP diagram of compound A-4 with ellipsoids shown at 50% probability level.

The packing in compound **A-4** is very compact with the dications bend into inverted S-shaped structures that formed containing pockets for the counter anions (Figure 2-9). The cation and anions are related through C-H \cdots O hydrogen bonding interactions and unlike in compounds **A-2** and **A-3** no C-H \cdots F short contacts to the CF₃SO₃⁻ anion was detected. This is because the anions are packed in a head-to-head (CF₃-CF₃) fashion involving adjacent CF₃SO₃⁻ units that were directed towards each other with the SO₃-SO₃ tails directed toward the imidazolium moiety of the dication.

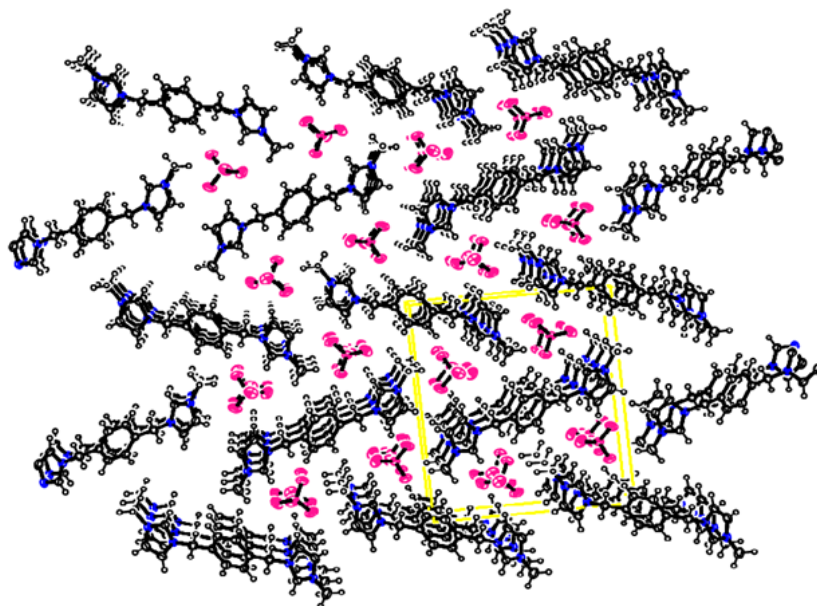


Figure 2-7. Packing arrangement of A-2 viewed along the crystallographic a direction.

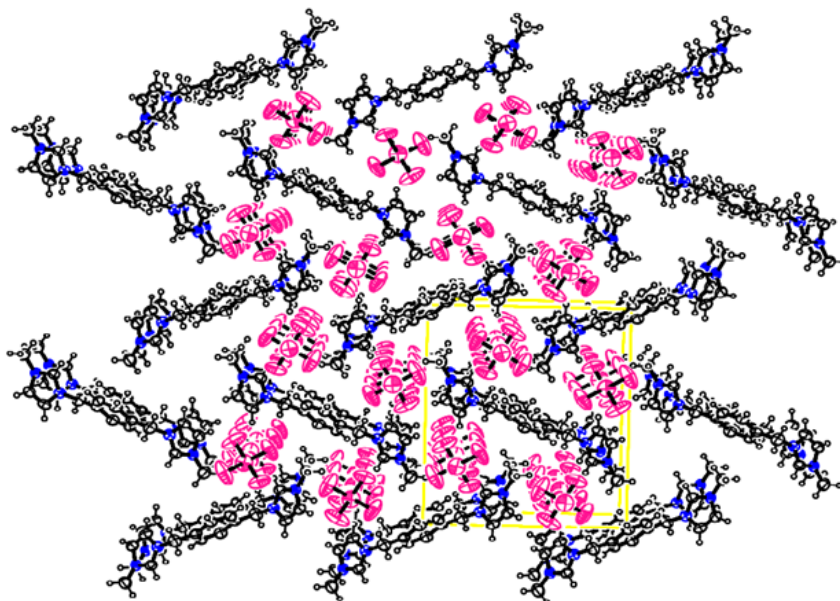


Figure 2-8. Packing arrangement of A-3 viewed along the crystallographic a direction.

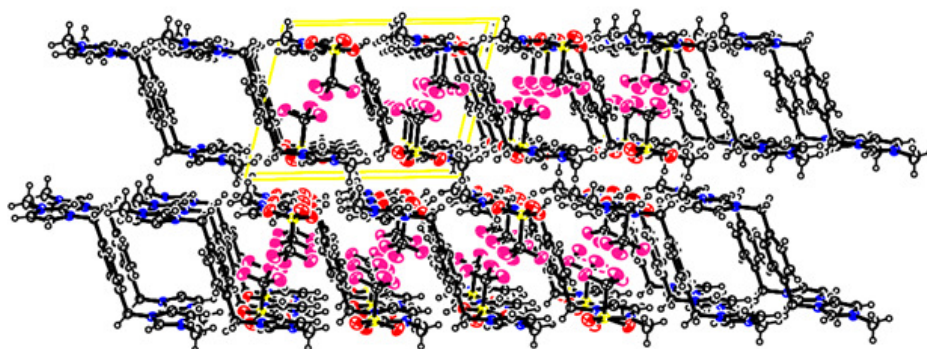


Figure 2-9. Packing arrangement of A-4 viewed along the crystallographic b direction.

2.3 Experimental Section

Spectroscopic analysis: The NMR spectra of all the compounds were measured in deuterated DMSO at room temperature on a Bruker 400 MHz NMR spectrometer. The chemical shifts were referenced to tetramethylsilane for ^1H and ^{13}C NMR, triphenyl phosphate for ^{31}P NMR and trifluorotoluene for ^{19}F NMR and the operating frequencies on the 400 MHz NMR spectrometer for the, ^1H , ^{13}C , ^{31}P and ^{19}F NMR spectra were 400, 100, 162 and 376.5 MHz respectively. IR spectra were recorded on a Perkin Elmer Spectrum 100 FT-IR Spectrometer with a universal ATR sampling accessory. Melting points were recorded on an Ernst Leitz Wetzlar micro-hot stage melting point apparatus.

Single crystal structure determination: Intensity data were collected on a Bruker APEX II CCD area detector diffractometer with graphite monochromated Mo K_α radiation (50kV, 30mA) using the APEX 2 data collection software. The collection method involved ω -scans

of width 0.5° and 512x512 bit data frames. Data reduction was carried out using the program *SAINT+*. The crystal structure was solved by direct methods using *SHELXTL*. Non-hydrogen atoms were first refined isotropically followed by anisotropic refinement by full matrix least-squares calculations based on F^2 using *SHELXTL*. Hydrogen atoms were first located in the difference map then positioned geometrically and allowed to ride on their respective parent atoms.^[14]

Synthesis of 1,1-(1,4-phenylenedimethylene)bis(3-methyl-1H-imidazolium-1-yl) dibromide $[\text{C}_6\text{H}_4(\text{CH}_2(\text{C}_4\text{H}_6\text{N}_2))_2]^{2+}2[\text{Br}]^-$ (**A-1**): The method of Ganesan and Alias^[6] was adapted with change of solvent. In distilled dichloromethane, α,α -dibromo-*p*-xylene, used as obtained from Aldrich (0.528 g, 0.00200 moles) was dissolved, to which 1-methylimidazole (0.328 g, 0.00400 moles) was added and stirred for 24 hrs at room temperature to afford the quaternised salt. The solvent was removed under reduced pressure and the residue collected and washed with acetone to remove unreacted material. The residue was filtered and dried, from where it yielded white precipitates of dicationic imidazolium salt (**A-1**), $\text{C}_{16}\text{H}_{20}\text{N}_4\text{Br}_2$ (96.4% yield), m.p. 245-247 °C. $^1\text{H-NMR}$ (400 MHz, DMSO-d_6 , 298 K), (δ_{H} , ppm): 3.88 (s, 6H), 5.49 (s, 4H), 7.52 (s, 4H), 7.75 (d, 2H, $J = 1.44$ Hz), 7.84 (d, 2H, $J = 1.44$ Hz) and 9.37 (s, 2H). $^{13}\text{C-NMR}$ (100 MHz, DMSO-d_6 , 298 K), (δ_{C} , ppm): 35.89, 51.25, 122.24, 123.96, 128.94, 135.39 and 136.62. IR (FTIR, cm^{-1}): 3394, 3037, 1558, 1159. NMR resonances are assigned in Table 2-1.

General procedure for the synthesis of compounds A-2 – A-5: The prepared dicationic salt (**A-1**) was dissolved in a mixture of water and ethanol (1:4) and the anionic source $\text{CF}_3\text{SO}_3\text{Li}$, NaBF_4 , KPF_6 and CF_3COONa was added stoichiometrically in a 1:2 molar ratio respectively. The resulting mixture was stirred for 4 hrs at room temperature, and then concentrated under

reduced pressure, followed by addition of MgSO_4 to remove the water. The solid material was extracted with ethanol to afford the corresponding anionic exchange ionic salt. The solvent was evaporated and the samples dried to yield ionic salts **A-2** – **A-4** and an ionic liquid **A-5**. Compounds **A-2** – **A-4** were recrystallized in methanol to yield colourless solids, while compound **A-5** remained a liquid at room temperature. Spectroscopic data are presented below:

[C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[BF₄]⁻ (A-2): C₁₆H₂₀B₂F₈N₄, white crystalline solid, 70.1% yield, melting point 225-228 °C. ¹H-NMR (400 MHz, DMSO-d₆, 298 K), (δ_H, ppm): 3.85 (s, 6H), 5.42 (s, 4H), 7.47 (s, 4H), 7.68 (d, 2H, *J* = 1.76 Hz), 7.74 (d, 2H, *J* = 1.76 Hz), 9.17 (s, 2H). ¹³C-NMR (100 MHz, DMSO-d₆, 298 K), (δ_C, ppm): 35.83, 51.36, 122.24, 124.03, 128.86, 135.37, 136.64. ¹⁹F NMR (376.5 MHz, DMSO-d₆, 298 K), (δ_F, ppm): -148.14 (¹⁰BF₄⁻), -148.20 (¹¹BF₄⁻). IR (FTIR, cm⁻¹): 3158, 3102, 1578, 1170.

[C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[PF₆]⁻ (A-3): C₁₆H₂₀F₁₂N₄P₂, white crystalline solid, 98.6% yield, melting point 213 °C. ¹H-NMR (400 MHz, DMSO-d₆, 298 K), (δ_H, ppm): 3.83 (s, 6H), 5.40 (s, 4H), 7.45 (s, 4H), 7.67 (d, 2H, *J* = 1.68 Hz), 7.72 (d, 2H, *J* = 1.68 Hz), 9.16 (s, 2H). ¹³C-NMR (100 MHz, DMSO-d₆, 298 K), (δ_C, ppm): 35.82, 51.36, 122.23, 124.01, 128.85, 135.35, 136.65. ¹⁹F NMR (376.5 MHz, DMSO-d₆, 298 K), (δ_F, ppm): -70.114 (d, *J* = 711.73 Hz). ³¹P-NMR (162 MHz, DMSO-d₆, 298 K), (δ_P, ppm): -144.195 (septet, *J* = 711.73 Hz). IR (FTIR, cm⁻¹): 3418, 3173, 1567, 1173.

[C₆H₄(CH₂(C₄H₆N₂))₂]²⁺2[CF₃SO₃]⁻ (A-4): C₁₈H₂₀F₆N₄O₆S₂, white crystalline solid, 95.4% yield, melting point 155-157 °C. ¹H-NMR (400 MHz, DMSO-d₆, 298 K), (δ_H, ppm): 3.85 (s, 6H), 5.42 (s, 4H), 7.47 (s, 4H), 7.70 (d, 2H, *J* = 1.68 Hz), 7.75 (d, 2H, *J* = 1.68 Hz), 9.18 (s, 2H). ¹³C-NMR (100 MHz, DMSO-d₆, 298 K), (δ_C, ppm): 35.84, 51.37, 122.24, 124.02,

128.87, 135.35, 136.65, 120.27(q, $J = 320.0$ Hz $\underline{\text{CF}}_3$). ^{19}F NMR (376.5 MHz, DMSO- d_6 , 298 K), (δ_{F} , ppm) : -77.76. IR (cm^{-1}): 3150, 1576, 1248, 1154.

$[\text{C}_6\text{H}_4(\text{CH}_2(\text{C}_4\text{H}_6\text{N}_2))_2]^{2+}2[\text{CF}_3\text{COO}^-]$ (**A-5**): $\text{C}_{20}\text{H}_{20}\text{F}_6\text{N}_4\text{O}_4$, colorless liquid, 98.0% yield, decomposition point 198 °C. ^1H -NMR (400 MHz, DMSO- d_6 , 298 K), (δ_{H} , ppm): 3.85 (s, 6H), 5.47 (s, 4H), 7.49 (s, 4H), 7.72 (d, 2H, $J = 1.68$ Hz), 7.83 (d, 2H, $J = 1.68$ Hz), 9.39 (s, 2H). ^{13}C -NMR (100 MHz, DMSO- d_6 , 298 K), (δ_{C} , ppm): 36.33, 51.71, 122.70, 124.43, 129.44, 135.88, 137.12, 158.73, (q, $J = 31.36$ Hz, $\text{CF}_3\underline{\text{C}}\text{OO}$), 117.57 (q, $J = 297.43$ Hz, $\underline{\text{C}}\text{F}_3\text{COO}$). ^{19}F NMR (376.5 MHz, DMSO- d_6 , 298 K), (δ_{F} , ppm): -73.73. IR (FTIR, cm^{-1}): 3407, 2253, 1690, 1201.

2.4 Conclusions

In conclusion, the synthesis of four fluorinated imidazolium based ionic salts was carried out using modified simple techniques and a cheaper solvent. The molecular structures were characterized by IR and NMR analyses, while the crystal structures of three compounds **A-2**, **A-3** and **A-4** were studied and reported. It was found that the chemical nature of the various fluorinated anions affected key crystallographic parameters such as bond lengths and nature of packing of the imidazolium salts. It was also observed that the melting points of the salts were related to packing patterns and extent of three-dimensional networking within compounds, which was least extensive for trifluoroacetate, thus melting points decrease in the order: $\text{Br}^- > \text{PF}_6^- > \text{BF}_4^- > \text{CF}_3\text{SO}_3^- > \text{CF}_3\text{COO}^-$.

Supplementary Materials: Crystallographic data in cif format have been deposited with the Cambridge Crystallographic Data Centre (CCDC) as supplementary material for this paper. The CCDC numbers are 815392 for **A-2**, 815393 for **A-3** and 815394 for **A-4**. These

data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk

Supporting information: ^{31}P and ^{19}F NMR spectra for the respective compounds are provided.

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Chapter 3 Synthesis, characterization and antimicrobial activities of dicationic triphenylphosphonium organic salts with a *para* xylene bridge and fluorinated counter anions

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ABSTRACT

Four fluorinated triphenylphosphine (PPh₃)-based organic salts were synthesised from PPh₃ and α,α -dibromo-*p*-xylene by first producing quaternised salts, followed by anionic exchange with fluorinated anions, NaBF₄, KPF₆, CF₃SO₃Li and CF₃COONa. The salts were characterized by ¹H, ¹³C, ¹⁹F and ³¹P NMR, and IR spectroscopy. The organic salts showed significant activity against *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, *Salmonella typhi*, *Candida albicans*, and *Streptococcus pyogenes* when compared with the activities of the standard antimicrobial chloramphenicol and antifungal nystatin.

Keywords: Fluorinated phosphonium organic salts, antimicrobial activity, triphenylphosphine organic salts.

3.1 Introduction

Phosphonium cations possess a tetrahedral geometry about the positively charged phosphorus atom, which is similar in structure to the ammonium cations commonly used as disinfectants and detergents (Kanazawa and Ikeda, 2000). The ammonium salts combine the features of a positive charge and a long hydrophobic alkyl chain which has been shown to be important in bactericidal action. The alkyl tails seem to improve interaction with the cell membrane and longer alkyl chains favour insertion into the hydrophobic region of the membranes and cause cell disruption (Kanazawa and Ikeda, 2000). While there is much literature on the antibacterial activity of ammonium salts, the literature on the antibacterial activity of phosphonium salts is rather limited with most of the reports published in Japanese patents. While both quaternary ammonium and phosphonium salts have shown high antibacterial activities with broad spectrums (Chen et al., 1997), the phosphonium salts were shown to have higher activities than their ammonium counterparts and are expected to be the next generation of antibacterial agents.

Trimethyl and dimethyl quaternary phosphonium salts functionalised with alkyl chains of varying lengths or aromatic groups ($^+P(CH_3)_2R_2$ or $^+P(CH_3)_3R$ where R = alkyl or Ph) were shown to be active against several strains of *S. aureus* including methicilin-resistant *S. aureus* (MRSA) and *E. coli* (Kanazawa et al., 1994; Jin et al., 2008). The trimethyl phosphonium salts with long alkyl chains had particularly good antimicrobial activity. In contrast, the activity of the dimethyl phosphonium salts was found to decrease on increasing the length of the alkyl chain (Kanazawa et al., 1994). Of particular importance is the fact that the phosphonium salts containing double decyl groups displayed the broadest spectrum of activity against the microorganisms tested and the greatest bacteriostatic properties. Further to this, the phosphonium salts showed a greater level of bactericidal activity and higher

potency as compared to their ammonium counterparts (Kanazawa and Ikeda, 2000). Tetradecyl tributyl phosphonium bromide intercalated with clay minerals also showed activity against *S. aureus* and *E. coli* (Wu et al., 2011).

Antibacterial copolyesters prepared from tributylhexadecylphosphonium salts or tributyl-dodecylphosphonium salts with polyethylene terephthalate, dimethyl terephthalate and dimethyl-5-sulfoisophthalate were incorporated into laminates, which showed good antibacterial activity against *S. aureus* and *E. coli* and was used for packaging food and medical products (Hayakawa, 1999; 2000a; 2000b; Konagaya et al., 2000; 2004; Ohashi and Kohaze, 1999). A quaternary phosphonium salt was also used as part of a bactericide in an apparatus used in the treatment of waste gas discharged from a wastewater treatment plant (Zhao et al., 2012).

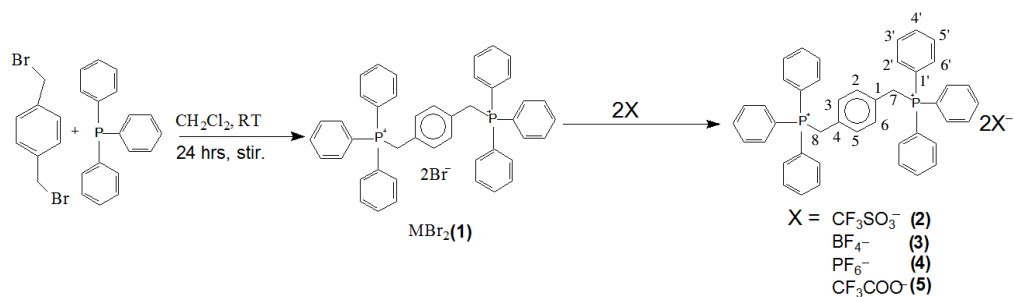
The salts reported to have antibacterial activity were mainly prepared with either the chloride or bromide anion. A range of phosphonium ionic liquids functionalized with alkyl groups of varying chain lengths ranging from C2 to C16 on a trihexyl(alkyl)phosphonium salt were seen to have both antibacterial and antifungal activity (Cieniecka-Roslonkiewicz et al., 2005). The trihexyl(tetradecyl) phosphonium salts were studied with counter anions other than chloride or bromide which included BF_4^- and PF_6^- anions and the results showed a decrease in activity with their incorporation.

There are a few methods involved in the synthesis of tertiary phosphonium salts, but the simplest remains the mixing of a neutral organic compound with an alkyl or aryl halide followed by subsequent metathesis reaction with either organic or inorganic salts (Wasserscheid and Welton, 2008). In this study we have substituted the conventional long

chain alkylated phosphonium salts with a *bis*(triphenylphosphonium) salt bridged by a *para* xylene moiety to which four fluorinated anions, CF_3SO_3^- , BF_4^- , PF_6^- and CF_3COO^- were exchanged for the bromide in the initial reaction. All the anions contain fluorine bound to carbon, boron or phosphorus. To the best of our knowledge, the anions are commonly encountered in the preparation of ionic liquids, but in conjunction with the quaternary phosphonium cation their antimicrobial effect has not yet been studied. Hence, in this study we report on the synthesis and characterisation of four novel fluorinated organic salts with the phenylene*bis*(methylene)*bis*(triphenylphosphine) cation and CF_3SO_3^- , BF_4^- , PF_6^- and CF_3COO^- anions and studied their antimicrobial activity with five bacterial and one fungal strain.

3.2 Results and Discussion

The synthesis of dimeric ionic liquids using imidazole as the neutral organic compound was adopted from Ganesan and Alias (2008) and modified by using dichloromethane in place of acetonitrile and changing the neutral organic compound to triphenylphosphine. The reaction of α,α -dibromoxylene and triphenylphosphine resulted in the formation of the quaternised salt, 1,4-phenylene*bis*(methylene)*bis*(triphenylphosphonium) dibromide (**B-1**), which was followed by metathesis with four fluorinated anions (CF_3SO_3^- , BF_4^- , PF_6^- and CF_3COO^-) to afford the organic salts as anionic exchange products (**B-2 – B-5**) (Scheme 3-1). This is the first reported synthesis of these fluorine containing phosphonium based organic salts, which has been achieved in excellent yields (80-98%) using relatively simple techniques. They are all high melting organic salts (250 - 320 °C) and therefore have the potential to be incorporated into packaging and medical products to confer their antimicrobial properties to them.



Scheme 3-1 Reaction scheme for the synthesis of the phosphonium organic salts **B-1 – B-5**

Characterisation

A full characterization of compound **B-1** was carried out and compared to **B-2 - B-5** in order to understand the effect of changing the anion on the chemical and structural behaviour of the various organic salts. The salts (**B-1 – B-5**) were characterized by ^1H , ^{13}C , ^{19}F and ^{31}P NMR, and IR spectroscopy. The ^1H NMR spectrum of compound **B-1** in DMSO-d_6 showed a doublet resonance for the methylene group at δ_{H} 5.12 (d, $J = 14.58$ Hz) since the protons are split by phosphorus of the PPh_3 group. The aromatic methine protons of the phenyl groups attached to the phosphorus are present as multiplet resonances at δ_{H} 7.67 (*ortho* and *meta* protons) and 7.90 (*para* proton) in a 4:1 integral ratio. The four aromatic protons of the central aromatic ring are all equivalent and appear as a singlet at δ_{H} 6.81.

The ^{13}C NMR spectrum shows the methylene carbon resonance as a doublet at δ_{C} 28.49 ($J_{\text{P,C}} = 46.25$ Hz) and the carbon methine resonances of the central aromatic group at δ_{C} 131.63 (evidenced by a HSQC correlation with aromatic protons of the central aromatic group at δ_{H} 6.81). The C-4' carbon resonance of all the phenyl groups attached to the phosphonium cation are equivalent and is located at δ_{C} 135.59, which was confirmed by a HSQC correlation to H-4'. However, the C-2'/6' and C-3'/5' carbon resonances of the phenyl

groups at each end of the central aromatic ring are not equivalent with the other four phenyl groups. They were assigned with the aid of data from the literature (Weigert and Roberts, 1973). The two C-2'/6' resonances of the triphenylphosphine group appear as overlapping doublets at δ_c 134.42 ($J = 4.82$ Hz) and δ_c 134.39 ($J = 4.97$ Hz) respectively. The small coupling constant is due to $^2J_{P-C}$ coupling. The resonances appeared as a triplet resulting from coalescence of these resonances. The C-3'/5' resonances appeared at δ_c 130.56 ($J = 6.36$ Hz) and δ_c 130.52 ($J = 5.92$ Hz). This also appeared as a triplet as for C-2'.

The quaternary carbon resonance of the phosphine phenyl groups (C-1') can be seen at δ 118.12 ($J = 86.37$ Hz), also consistent with literature (Weigert and Roberts, 1973) and C-1/4 of the central aromatic group could be detected as a doublet due to $^2J_{P-C}$ coupling at δ 128.67 ($J = 4.04$ Hz), confirmed by an HMBC correlation to H-2/3/5/6 of the central aromatic group as well as with the methylene group proton resonance. The C-1' carbon resonance also shows HMBC coupling to the methylene group resonance further supporting its assignment. Coupling in the NOESY spectrum is evident between the methylene group and H-2'/6' of the phenyl groups as well as with the central aromatic protons. Also present in the NOESY spectrum is coupling between the central aromatic protons and that assigned to H-2'/3'/5'/6', putting the phenyl groups attached to phosphorus in close proximity to the central aromatic group. A crystal structure of **B-3** (Ibrahim et al., 2011) shows the interaction of the phenyl groups of the phosphine moieties with the central benzene group.

The ^{31}P NMR spectrum showed the phosphorus resonance of the phosphonium moieties at δ 23.06. Compounds **B-2** – **B-5** all showed the same 1H and ^{13}C NMR resonances for the cation when compared to compound **B-1** indicating the anion had no effect on the NMR resonances of the cation. For the $CF_3SO_3^-$ anion **B-2**, an additional CF_3 carbon resonance

was seen at δ_C 120.63 (q, $J = 320.10$ Hz). This CF_3 carbon resonance was also present in the ^{13}C NMR spectrum of **B-5** at δ_C 117.48 (q, $J = 296.24$ Hz) along with the carbonyl quartet at δ 157.68 ($J = 30.57$ Hz). In the case of $M(PF_6)_2$, an additional phosphorus resonance for the PF_6^- anion could be seen at δ -144.20, which is split into a septet with a coupling constant of 711.18 Hz. The fluorine NMR resonance for compound **B-4** (the PF_6^- anion) was detected at δ -70.14 as a doublet resulting from P-F coupling with $J_{P,F} = 755.36$ Hz. As expected, as the electronegativity of the central atom in the anion decreased from phosphorus through to boron, the chemical shift of the fluorine resonance decreased from δ -70.14 in **B-4** ($M(PF_6^-)_2$) to δ -73.44 in **B-5** ($M(CF_3COO^-)_2$), δ -77.4 in **B-2** ($M(CF_3SO_3^-)_2$), and δ -148.22 ($M(^{10}BF_4^-)_2$) and δ -148.27 ($M(^{11}BF_4^-)_2$) in **B-3** ($M(BF_4^-)_2$). The ^{13}C , ^{31}P and ^{19}F NMR resonances of the anions compare well with that in the literature (Pampolini et al., 2005; Macchioni et al., 2001).

Antimicrobial Activity

All of the five samples synthesized were sensitive to the six microorganisms tested. Chloramphenicol (**B-6**), a broad spectrum antibiotic, effective against a wide variety of gram positive and gram negative bacteria, and nystatin (**B-7**), a polyene antifungal drug to which *Candida* is sensitive, were used as antibacterial and antifungal controls respectively. Zones of inhibition of the samples and the controls (Table 3-1) indicate that in general, the samples **B-1 – B-5** showed greater inhibition zones than the controls, with compound **B-5** having the highest inhibition zones of 53 and 50 mm for *S. aureus* and *S. pyogenes* respectively.

Table 3-1 Zones of inhibition of the phosphonium salts (B-1 – B-5) against the microorganism (mm)

Sample/							
Test organisms	1	2	3	4	5	6 [#]	7 [#]
<i>S. aureus</i>	43	30	42	45	53	27	*
<i>S. pyogenes</i>	38	42	40	34	50	24	*
<i>E. coli</i>	45	45	20	45	42	31	*
<i>S. typhi</i>	45	40	38	42	42	38	*
<i>K. pneumoniae</i>	45	40	38	38	45	0	*
<i>C. albicans</i>	40	38	45	45	40	*	32

* test not performed

[#] **6** and **7** are the controls, chloramphenicol and nystatin respectively

Minimum inhibitory concentration (MIC) and Minimum bactericidal concentration (MBC) were determined for the five samples and the controls. In general, compounds **B-1 – B-5** showed MIC values of between 0.312 and 0.625 mg/mL (Table 3-2) and MBC values of between 0.625 and 1.250 mg/mL (Table 3-3). The greatest antibacterial activity was shown by compound **B-1**, the bromide and metathesis with the various anions seemed to decrease the activity except in the case of compounds **B-2**, **B-3** and **B-5** in *S. pyogenes*. The decrease in activity on exchange of the halide by other anions was also reported earlier (Cieniecka-Roslonkiewicz et al., 2005). Compounds **B-2** and **B-4** also showed good activity in four of the six antimicrobial strains tested. The same effect was observed for the MBC values. In comparison to the controls, the synthesised compounds are in some cases only 2.5 times less active than the known antibiotic, chloramphenicol. No real trend could be observed between the various anions and the antimicrobial activity except that in general, compounds **B-2** (CF₃SO₃⁻) and **B-4** (PF₆⁻) showed better activity than **B-3** (BF₄⁻) and **B-5** (CF₃COO⁻). Thus, the SO₃⁻ group compares better than the COO⁻ group when attached to CF₃ and the expanded

octet of phosphorus seems to be better than boron to co-ordinate to fluorine for antimicrobial activity.

Table 3-2 The Minimum Inhibitory Concentrations (MIC's) of compounds B-1 – B-5 in mg/mL

Sample/ Test organisms	1	2	3	4	5	6 [#]	7 [#]
<i>S. aureus</i>	0.312	0.625	0.312	0.312	0.312	0.125	*
<i>S. pyogenes</i>	0.625	0.312	0.312	0.625	0.312	0.125	*
<i>E. coli</i>	0.312	0.312	1.250	0.312	0.625	0.063	*
<i>S. typhi</i>	0.312	0.312	0.625	0.312	0.625	0.063	*
<i>K. pneumoniae</i>	0.312	0.312	0.625	0.625	0.625	R	*
<i>C. albicans</i>	0.312	0.625	0.312	0.312	0.625	*	0.025

R denotes resistance

* indicates experiment not carried out

[#] 6 and 7 are the controls, chloramphenicol and nystatin respectively

Table 3-3 The Minimum Bactericidal Concentration (MBC) of compounds B-1 – B-5 in mg/mL

Sample/ Test organisms	1	2	3	4	5	6 [#]	7 [#]
<i>S. aureus</i>	0.625	1.250	0.625	0.625	0.625	0.250	*
<i>S. pyogenes</i>	1.250	0.625	0.625	1.250	0.625	0.250	*
<i>E. coli</i>	0.625	0.625	2.500	0.625	1.250	0.125	*
<i>S. typhi</i>	0.625	0.625	1.250	0.625	1.250	0.125	*
<i>K. pneumoniae</i>	0.625	0.625	1.250	1.250	1.250	R	*
<i>C. albicans</i>	0.625	1.250	0.625	0.625	1.250	*	0.050

R denotes resistance

* indicates experiment not carried out

[#] 6 and 7 are the controls, chloramphenicol and nystatin respectively

In conclusion, the synthesis of four novel fluorinated phosphonium organic salts has been achieved in excellent yields using relatively simple techniques and their structures have been characterised by NMR analysis. Changing the anion had no effect on the NMR resonances of the cation. It is also shown that the dimeric phosphonium organic salts are potential sources of new antimicrobials with different characteristics to those of established drugs. Comparatively, the CF_3SO_3^- anion is a better source of antimicrobial anion than CF_3COO^- and PF_6^- is better than BF_4^- .

3.3 Experimental

3.3.1 General experimental procedures

NMR spectra of all compounds were measured in DMSO-d_6 at room temperature on either a Bruker 400 or 600 MHz NMR spectrometer. The chemical shifts were referenced to tetramethylsilane for ^1H and ^{13}C NMR, triphenyl phosphate for ^{31}P NMR and trifluorotoluene for ^{19}F NMR and the operating frequencies on the 400 MHz NMR spectrometer for the ^{13}C , ^{31}P and ^{19}F NMR spectra were 100, 162 and 376.5 MHz respectively. The ^1H and ^{13}C NMR spectrum of compound **B-1** was acquired on the 600 MHz NMR instrument at operating frequencies of 600 MHz and 150 MHz respectively at a temperature of 50 °C. ESI and FAB Mass Spectrometry was carried out by UPLC-DAD-MS with a Waters SYNAPT HDMS system (4KDA) connected in series to a SYNAPT G1 QTOF mass spectrometer and equipped with an Acquity HSS T3 Waters column (1.8 μm , 150 x 2.1 mm). IR spectra were recorded on a Perkin Elmer Spectrum 100 FT-IR Spectrometer with a universal ATR sampling accessory. Melting points were recorded on a Ernst Leitz Wetzlar micro-hot stage melting point apparatus. CHN analysis was carried out on a LECO CHNS Model 932 instrument and the analysis done in duplicate on 2.0 mg of sample.

3.3.2 Synthesis of 1,4-phenylenebis(methylene)bis(triphenylphosphonium) dibromide, $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+}[\text{2Br}^-]$ (**B-1**)

In distilled dichloromethane, α,α -dibromo-*p*-xylene (0.528 g, 0.002 moles) was dissolved, to which triphenylphosphine (1.049 g, 0.004 moles) was added and stirred for 24 hrs at room temperature to afford the quaternised salt. The solvent was removed under pressure and the residue collected and washed with acetone to remove unreacted material. The residue was filtered and dried, yielding white precipitates of dicationic phosphonium salt, $\text{C}_{44}\text{H}_{38}\text{Br}_2\text{P}_2$ (90.0% yield), M.p. decomp. 320 °C.

$^1\text{H-NMR}$ (600 MHz, DMSO-d_6 , 323 K), (δ_{H} , ppm): 5.12 (d, $J = 14.58$ Hz, 4H, Ar- $\underline{\text{CH}_2}$), 6.81 (s, 4H, Ar-H), 7.67 (m, 24H, Ar-H), and 7.90 (m, 6H, Ar-H). $^{13}\text{C-NMR}$ (δ_{C} , ppm): 28.49 (d, $J = 46.25$ Hz, (methylene)), 118.12 (d, $J = 86.37$ Hz, C-1'), 128.67 (d, $J = 4.04$ Hz, C-1/4), 130.52 (d, $J = 5.92$ Hz, C-3'/5')*, 130.56 (d, $J = 6.36$ Hz, C-3'/5')*, 131.63 (s, C-2/3/5/6/), 134.39 (d, $J = 4.97$ Hz, C-2'/6')*, 134.42 (d, $J = 4.82$ Hz, C-2'/6')*, 135.60 (s, C-4'). $^{31}\text{P-NMR}$ (δ_{P} , ppm): 23.06. IR (cm^{-1}): 3474, 3409, 2852, 1434, 1101. FAB-MS (m/z): 707.5 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2\text{Br}]^+$; ESI-MS (m/z): 314 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+}$. Anal. C 66.72, H 4.88%, calcd for $\text{C}_{44}\text{H}_{38}\text{Br}_2\text{P}_2$, C 67.02, H 4.86%.

*The C-2'/6' and C-3'/5' resonances of the triphenylphosphine groups at each end are not equivalent with the other four phenyl groups and hence there are two separate signals, very close to each other.

3.3.3 General procedure for the metathesis reaction

The salt prepared in 3.2, (**B-1**) was dissolved in a mixture of water and ethanol (1:4) and the anionic source $\text{CF}_3\text{SO}_3\text{Li}$, NaBF_4 , KPF_6 , and CF_3COONa was added stoichiometrically in a ratio of 1:2 and the mixture was stirred respectively for 4 hrs at room temperature. It was concentrated under reduced temperature and MgSO_4 was added to remove the water. The

solid material was extracted with ethanol to afford the corresponding anionic exchange salt. The solvent was evaporated and the samples dried to yield the fluorinated phosphonium organic salt (**B-2 – B-5**).

The ^{31}P , ^1H and ^{13}C NMR resonances of the cations of compounds **B-2 – B-5** are the same as for compound **B-1** and are not repeated below. The ^{19}F NMR resonances of the anions as well as any additional ^{13}C or ^{31}P resonances from the anions are however given below.

phenylenebis(methylene)bis(triphenylphosphonium) ditrifluoromethanesulphonate,

$[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+}[\text{CF}_3\text{SO}_3^-]$ (**B-2**) $\text{C}_{46}\text{H}_{38}\text{F}_6\text{O}_6\text{P}_2\text{S}_2$, white powdery substance, yield 96.0%, melting point 258 °C, ^{13}C -NMR (100 MHz, δ_c , ppm): 120.63 (q, $J = 320.10$ Hz, $\underline{\text{C}}\text{F}_3\text{SO}_3^-$), ^{19}F NMR (400 MHz, DMSO- d_6 , 298 K), (δ_F , ppm): -77.74 (s, $\underline{\text{C}}\text{F}_3\text{SO}_3^-$), IR (cm^{-1}): 3065, 2955, 2916, 1439 and 1254. ESI MS (m/z): 777 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2\text{CF}_3\text{SO}_3]^+$. Anal. C 58.03, H 4.74%, calcd for $\text{C}_{46}\text{H}_{38}\text{F}_6\text{O}_6\text{P}_2\text{S}_2$, C 59.61, H 4.13%.

phenylenebis(methylene)bis(triphenylphosphonium) ditetrafluoroborate,

$[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+}[\text{BF}_4^-]$ (**B-3**) $\text{C}_{44}\text{H}_{38}\text{B}_2\text{F}_8\text{P}_2$, white crystalline substance, yield 79.8%, decomp. 295 °C, ^{19}F NMR (400 MHz, DMSO- d_6 , 298 K), (δ_F , ppm): -148.22 ($^{10}\text{BF}_4^-$), -148.27 ($^{11}\text{BF}_4^-$), IR (cm^{-1}): 3062, 2977, 2935, 1438, 1111, 1046. ESI-MS (m/z): 716 $[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2^{11}\text{BF}_4]^+$. Anal. C 64.68, H 4.81%, calcd for $\text{C}_{44}\text{H}_{38}\text{B}_2\text{F}_8\text{P}_2$, C 65.87, H 4.77%.

phenylenebis(methylene)bis(triphenylphosphonium) dihexafluorophosphate,

$[\text{C}_6\text{H}_4(\text{CH}_2)_2(\text{PPh}_3)_2]^{2+}[\text{PF}_6^-]$ (**B-4**) $\text{C}_{44}\text{H}_{38}\text{F}_{12}\text{P}_4$, white powdery substance, yield 93.6%, melting point 274 °C, ^{31}P -NMR (δ , ppm): -144.20 (septet, $J = 711.18$ Hz, $\underline{\text{P}}\text{F}_6^-$), ^{19}F NMR

(DMSO-d₆, 298 K), (δ_F , ppm): -70.14 (d, $J_{P,F} = 711.18$ Hz, PF_6^-), IR (cm⁻¹): 3066, 1438, 1112. ESI-MS (m/z): 773 [$C_6H_4(CH_2)_2(PPh_3)_2PF_6$]⁺. Anal. C 57.93, H 4.01%, calcd for $C_{44}H_{38}F_{12}P_4$, C 57.53, H 4.17%.

phenylenebis(methylene)bis(triphenylphosphonium) ditrifluoroacetate,

[$C_6H_4(CH_2)_2(PPh_3)_2$]²⁺ [$2CF_3COO^-$] (**B-5**) $C_{48}H_{38}F_6O_4P_2$, white powdery substance, yield 98.0%, decomp. 300 °C, ¹³C-NMR (100 MHz, δ_c , ppm): 157.68 (q, $J_{C,F} = 30.57$ Hz, CF_3COO^-), 117.48 (q, $J_{C,F} = 296.24$ Hz), ¹⁹F NMR (DMSO-d₆, 298 K), (δ_F , ppm): -73.44 (CF_3COO^-), IR (cm⁻¹): 3648, 3390, 3053, 3009, 2878, 2843, 2777, 1435 and 1109. ESI-MS (m/z): 314 [$C_6H_4(CH_2)_2(PPh_3)_2$]²⁺, the monocation could not be detected. Due to impurities, the CHN analysis was not reported.

3.3.4 Antimicrobial assays

The antimicrobial activities, (MIC's and MBC's) of compounds **B-1 – B-5** were determined using standard American Type Culture Collection (ATCC), National Collection Type Cultures (NCTC) and clinical isolates from the department of Medical Microbiology, Ahmadu Bello University, Teaching Hospital, Zaria, Nigeria: *Staphylococcus aureus* ATCC 13709, *Escherichia coli* NCTC 10418, *Klebsiella pneumoniae* ATCC 10031, *Salmonella typhi* ATCC 9184, *Candida albicans* ATCC 10231 and *Streptococcus pyogenes* (clinical isolate). All the bacteria and fungi (*Candida albicans*) were checked for purity and maintained in slants of nutrient agar and sabouraud dextrose agar respectively. The “well diffusion” method was used to determine the antimicrobial activity of the compounds (Andrews, 2001). Chloramphenicol and nystatin were used as positive controls. A 250 mg capsule of chloramphenicol was diluted into 1 L of distilled water to obtain a concentration of 0.250 mg/mL, which was used as a stock solution for further two-fold dilutions. For nystatin,

10 mL was dissolved in 100 mL of water to reach a concentration of 0.1 mL/mL, which was used as the stock solution.

To calculate the zones of inhibition, blood agar medium was used as the growth medium for the microbes and was prepared according to the manufacturer's instruction; it was boiled to dissolve and sterilized at 121 °C for 15 minutes. The medium was dispensed into sterilized petri dishes and left to solidify, after which it was seeded with standard inoculums of the microbes by means of a sterile swab, spreading the inoculum evenly over the surface of the medium and allowing it to dry at 37 °C for 30 minutes. A standard cork borer of 6 mm in diameter was used to cut a well at the centre of each seeded medium. Compounds **B-1- B-5** (0.05 g) were weighed and dissolved in 10 ml of distilled water to a concentration of 5 mg/mL and 100 µL was introduced into each well and incubated at 37 °C for 24 hrs. The activity of the compound was determined by the presence of inhibition zones which were measured in millimeters using a transparent ruler.

The Minimum Inhibitory Concentration (MIC) of compounds **B-1 – B-5** was determined against the microbes using the “broth dilution” method (Andrews, 2001). MIC is the lowest concentration of an antimicrobial that will inhibit the visible growth of a microorganism. Nutrient broth was prepared according to the manufacturer's instruction and 10 ml of the broth dispensed into each test tube after which it was sterilized at 121 °C for 15 minutes and allowed to cool. The microbial inoculum was standardized using Mc-Farland's standard no. 0.5 to yield a microbial density of 1.5×10^8 cfu/ml or its optical equivalent. A two-fold serial dilution of the compound in the broth was done to obtain concentrations of 5 mg/mL, 2.5 mg/mL, 1.25 mg/mL, 0.625 mg/mL, 0.312 mg/mL, 0.1565 mg/mL and 0.0781 mg/mL. The stock solution was prepared by dissolving 0.05 g of the compounds in 10 ml of the sterilized

broth. The micro-organisms (0.1 ml in normal saline) were then introduced into the test tubes with different concentrations and were incubated at 37 °C for 24 hrs, after which the test tubes were observed for turbidity. The lowest concentration of the compound in which the broth showed no turbidity was recorded as the MIC.

Minimum bactericidal concentration (MBC) of the compounds **B-1 – B-5** was determined in order ascertain whether the micro-organisms were killed as opposed to only their growth being inhibited. MBC is the lowest concentration of antimicrobial that will prevent the growth of an organism after subculture onto antibiotic free media (Andrews, 2001). Blood agar was prepared, sterilized at 121 °C for 15 minutes and dispensed into sterile petri dishes. The contents of the MIC in the serial dilution were then sub-cultured into the labeled plates, the plates were incubated at 37 °C for 24 hrs, after which the plates were observed for growth. The MBC was the plate with lowest concentration of the compound without growth. All experiments were repeated in triplicate.

Acknowledgements

We thank the NRF and University of KwaZulu-Natal for financial support. Appreciation also goes to Mal. Mikailu S. Abdullahi from the National Research Institute of Chemical Technology (NARICT) in Nigeria for assistance with the antimicrobial studies and the Mass Spectrometry Unit at the University of the Witwatersrand for carrying out the mass spectral data. This work is based upon research supported by the South African Research Chairs Initiative of the Department of Science and Technology.

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Chapter 4 Crystal structure of [1,4-Phenylenebis(methylene)]bis (triphenylphosphonium) bis(tetrafluoroborate)]

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Abstract

The crystal structure of the title salt, $C_{44}H_{38}P_2^{2+}2BF_4^-$ (**B-3**), consists of discrete dicationic cations interlaced with the BF_4^- counter-ions. In each cation, both phosphonium groups lie on the side of the plane of the central benzene ring. The tetrafluoroborate anions are involved in intensive thermal motion, thus some B-F bond lengths [range 1.329(6) to 1.391(6) Å] deviate significantly from their standard values.

4.1 Comment

The title compound was obtained in our effort to develop fluorinated antimicrobial compounds. Preliminary investigation of related compounds, like linear phosphonium ionic liquids, has indicated activities against some strains of bacteria and fungi (*Candida albicans*) as reported by Cieniecka-Roslonkiewicz *et al.* (2005).

The compound (**B-3**) (Figure 4-1 and Figure 4-2) crystallizes as white block crystals in the monoclinic space group *Cc* with one dication and two BF_4^- anions in the asymmetric unit. Bond lengths for C(7) – P(1) and C(8) – P(2) linking the methylene carbon atoms with the phosphorus atoms are 1.811 (3) and 1.817(3) Å respectively, which is comparable with the 1.817 (2) Å reported by Hafiz (2008) for a related mono-phosponium compound.

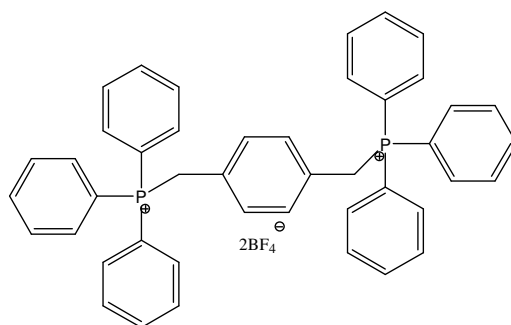


Figure 4-1 Structure of [1,4-Phenylenebis(methylene)]bis (triphenylphosphonium) bis(tetrafluoroborate) (**B-3**)

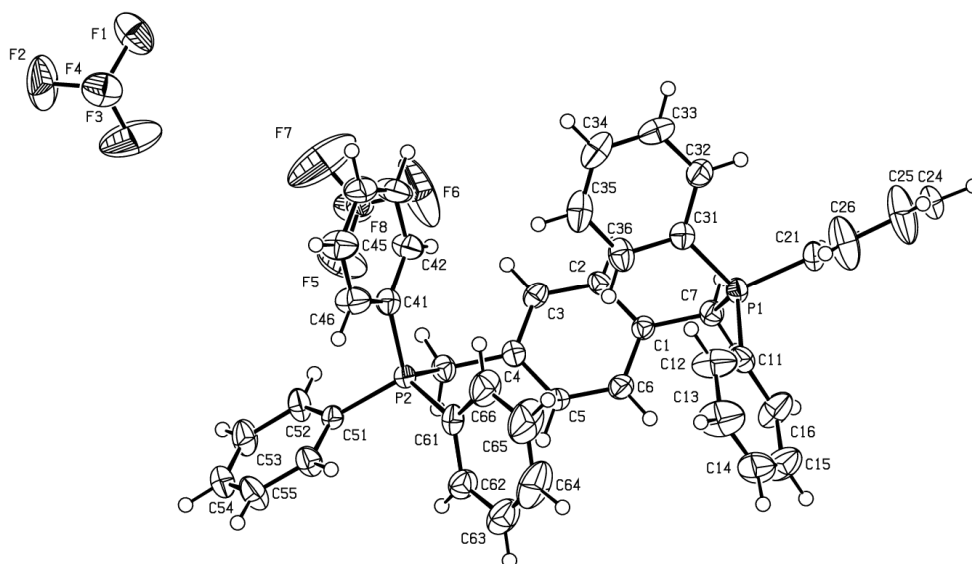


Figure 4-2 The structure of the title compound (**B-3**) showing the atom numbering scheme and the displacement ellipsoids drawn at the 50% probability level. H atoms are omitted for clarity.

Related literature

For a related synthetic strategy, see: Ganesan & Alias (2008). For salts containing the triphenylphosphonium cation, see: Kariuki *et al.* (2009). For applications of phosphonium salts as ionic liquids, see: Cieniecka-Roslonkiewicz *et al.* (2005). For a similar monophosphonium compounds, see: Hafiz (2008).

4.2 Experimental

The compound was synthesized according to a slightly modified method reported by Ganesan and Alias (2008). α,α -Dibromo-*p*-xylene (0.528 g, 0.002 moles) was dissolved in distilled anhydrous dichloromethane. Triphenylphosphine (1.049 g, 0.004 moles) was added to this solution, and the mixture was stirred for 24 hrs at room temperature to afford the quaternised salt. The solvent was removed *in vacuo* and the residue washed with acetone to remove unreacted material. The washed residue was filtered and dried, yielding white precipitates of dicationic phosphonium salt.

The salt was then dissolved in a mixture of water and ethanol (1:4) and the salt NaBF₄ was added (1:2). The mixture was stirred for 4 hrs at room temperature, dried with MgSO₄ and concentrated. The solid residue was extracted with ethanol, and the solvent was evaporated. The yield of (**B-3**) was 79%. X-ray quality crystals were grown from ethanol solution m.p. 292 °C (decomp).

¹H-NMR (600 MHz, DMSO-d₆, 323 K), (δ_{H} , ppm): 5.08 (d, J = 14.69 Hz, 4H, Ar-CH₂), 6.76 (s, 4H, Ar-H), 7.68 (m, 24H, Ar-H), and 7.90 (m, 6H, Ar-H). ¹³C-NMR (δ_{C} , ppm): 27.65 (d, J = 46.25 Hz, (methylene)), 117.51 (d, J = 86.45 Hz, C-1'), 128.12 (d, J = 4.04 Hz, C-1/4), 130.09 (d, J = 6.29 Hz, C-3'/5'), 130.56 (d, J = 6.29 Hz, C-3'/5'), 131.11 (s, C-2/3/5/6/),

133.86 (d, $J = 4.92$ Hz, C-2'/6'), 134.53 (d, $J = 4.92$ Hz, C-2'/6'), 135.13 (s, C-4'). ^{19}F NMR (400 MHz, DMSO- d_6 , 298 K), (δ_{F} , ppm): -148.22 ($^{10}\text{BF}_4^-$), -148.27 ($^{11}\text{BF}_4^-$), IR (cm^{-1}): 3062, 2977, 2935, 1438, 1111, 1046.

Data collection: APEX2 (Bruker, 2009); cell refinement: SAINTPlus (Bruker, 2009); data reduction: SAINT-Plus; program(s) used to solve structure: SHELXS97 (Sheldrick, 2008); program(s) used to refine structure: SHELXL97 (Sheldrick, 2008); molecular graphics: ORTEP-3 (Farrugia, 1997); software used to prepare material for publication: WinGX (Farrugia, 1999).

Crystal structure solution and refinement

Intensity data were collected on a Bruker APEX II CCD area detector diffractometer with graphite monochromated Mo K_{α} radiation (50kV, 30mA) using the APEX 2 (Bruker, 2005a) data collection software. The collection method involved ω -scans of width 0.5° and 512x512 bit data frames. Data reduction was carried out using the program *SAIN*T+ (Bruker, 2005b).

The crystal structure was solved by direct methods using *SHELXTL* (Bruker, 1999). Non-hydrogen atoms were first refined isotropically followed by anisotropic refinement by full matrix least-squares calculations based on F^2 using *SHELXTL*. Hydrogen atoms were first located in the difference map then positioned geometrically and allowed to ride on their respective parent atoms. Diagrams and publication material were generated using *SHELXTL*, *PLATON* (Spek, 2003) and *ORTEP-3* (Farrugia, 1997).

Crystal Data.

Identification code	9m_kznd_hi3_of
Empirical formula	C44 H38 B2 F8 P2
Formula weight	802.30
Temperature	173(2) K
Wavelength	0.71073 Å

Crystal system	Monoclinic	
Space group	Cc	
Unit cell dimensions	a = 21.8874(5) Å	$\alpha = 90^\circ$.
	b = 14.4610(3) Å	$\beta = 123.8980(10)^\circ$.
	c = 15.2818(3) Å	$\gamma = 90^\circ$.
Volume	4014.78(15) Å ³	
Z	4	
Density (calculated)	1.327 Mg/m ³	
Absorption coefficient	0.177 mm ⁻¹	
F(000)	1656	
Crystal size	0.52 x 0.22 x 0.13 mm ³	
Theta range for data collection	1.80 to 28.00°.	
Index ranges	-28<=h<=28, -19<=k<=18, -20<=l<=20	
Reflections collected	25162	
Independent reflections	9351 [R(int) = 0.0502]	
Completeness to theta = 28.00°	100.0 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F ²	
Data / restraints / parameters	9351 / 2 / 506	
Goodness-of-fit on F ²	0.957	
Final R indices [I>2sigma(I)]	R1 = 0.0481, wR2 = 0.1060	
R indices (all data)	R1 = 0.0716, wR2 = 0.1156	
Absolute structure parameter	0.0(19)	
Largest diff. peak and hole	0.451 and -0.326 e.Å ⁻³	

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Chapter 5 Solvent free synthesis and NMR studies of bidentate imidazolium based ionic liquids

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Abstract.

The solvent free reaction of 1-methylimidazole and alkyl dibromides (RBr_2 ; $\text{R} = -\text{CH}_2-$, $-(\text{CH}_2)_3-$, $-(\text{CH}_2)_4-$, and $-(\text{CH}_2)_5-$), yielded quaternised salts **C1a-4a** in a highly exothermic reaction. This was followed by metathesis reactions with fluorinated anion sources, NaBF_4 and KPF_6 to produce the fluorinated imidazolium ionic compounds **C1b-4b** and **C1c-4c** respectively. All twelve compounds were characterized by ^1H -, ^{13}C -, ^{19}F - and ^{31}P -NMR, and IR spectroscopy. A trend is observed relating the length of the alkyl chain in the cations and the strength of cation-anion interactions to the melting point of the compounds. The dibromide ionic compounds decreased in melting point as the length of the alkyl spacers increased. The strength of the cation-anion interactions were strongest for the Br^- ionic liquids followed by the PF_6^- and the BF_4^- counteranions as demonstrated by their melting points which increased in the order of $\text{M}(\text{BF}_4)_2 < \text{M}(\text{PF}_6)_2 < \text{MBr}_2$.

Keywords: Solvent free synthesis, fluorinated anions, imidazolium ionic liquids

5.1 Introduction

Ionic Liquids (ILs) have many uses, both in laboratories and industries. They are used as solvents for reactions and have importantly attracted recent interest as media for green synthesis, since they do not evaporate under ambient conditions (Dyson and Geldbach, 2007, Earle and Seddon, 2000). They also find application as catalysts for reactions (Dyson and Geldbach, 2007) and in analytical chemistry for sample preparation, chromatographic/capillary electrophoretic (CE) separation, and detection (Liu et al., 2005).

There are numerous publications on the synthesis and applications of imidazolium ILs with approximately seventy journal articles being published in 2012 alone. Some of the more recent work describes the use of imidazolium (IM) organic liquids as potential drug solvents since it was shown to increase the lipophilicity of the nimesulide-IL system and shown to affect the binding of nimesulide to human serum albumin (Azevedo et al., 2013). Treatment with imidazolium ILs enhanced growth inhibition and cell death in a concentration dependent manner in both the T98G and HEK cell lines, showing the potential to be used in brain cancer chemotherapy (Kaushik et al., 2012). Imidazolium ILs were also shown to be used for the solvent extraction of La^{3+} and Ba^{2+} , showing the potential to be used in future systems for radioisotope separation (Bell et al., 2012). In addition, phosphine oxide functionalised imidazolium ILs demonstrated their ability to act as lanthanide complexing agents (Vicente et al., 2012). Together with the benzotriazole group, imidazolium ILs were shown to have anticorrosion properties when used as additives in polyethylene glycol (PEG) for steel/Cu-Sn alloys (Cai et al., 2012) and ether functionalised imidazolium ILs were also shown to have a significantly high absorption capacity for CO_2 (Sharma et al., 2012).

The synthesis of 2-aryl and 2-heteroaryl benzoxazoles and benzothiazoles with a palladium acetate catalyst in imidazolium ILs were reported without the use of additives and recycling of the IL (Kalkhambkar and Laali, 2012). Imidazolium ILs themselves were shown to be catalysts in the synthesis of (*E*)-3-arylidene(thio)chroman-4-ones under microwave irradiation (Li et al., 2012). They were also shown to stabilise the ruthenium nanoparticle catalysts used in the reduction of cyclohexene (Lusaka et al., 2012). Sputter deposited gold nanoparticles were also seen to be stabilised by imidazolium ILs (Vanecht et al., 2012).

In comparison to the numerous reports on imidazolium ILs, reports on dimeric ILs where the two cations are linked to each other via an organic spacer are limited and find application mainly as surfactants and as liquid crystals used in electronic devices. There are also reports on dimeric ionic liquids being investigated for their potential as the next generation of surfactants, since these molecules contain two hydrophilic headgroups covalently attached through a hydrophobic alkyl group. For this purpose several ammonium ionic liquids were synthesised with hydrophobic alkyl chains of varying length both as the spacer and as the hydrophobic portion bonded to the ammonium cation (Bhattacharya and De, 1995; De et al., 1996). In analogous molecules, the spacer was made hydrophilic by using an oligo(oxyethylene) unit and their thermotropic behaviour characterised (Dreja et al., 1998).

Dimeric imidazolium based ionic liquid crystals were also synthesised and tested for their mesomorphic and other properties (Li et al., 2009; Bara et al., 2010; Kumar and Gupta, 2010; Gao et al., 2011). Liquid crystal dimers are known to have interesting mesomorphic properties due to restricted molecular motions (Imrie and Henderson, 2007). Imidazolium ionic liquids with a phenylenebismethylene spacer were also synthesised and their NMR shifts examined in various deuterated solvents (Ganesan and Alias, 2008).

5.2 Results and discussion

The solvent free synthesis of the quaternized salt was achieved successfully with excellent yields of up to 97%. All compounds except **C1b** had been synthesised previously and their spectroscopic and physical data compare well with that published in the literature (Anderson et al., 2005; Nielson et al., 2006; Wang et al., 2009; Kumar and Gupta, 2010; Lee et al., 2010; LeClerq et al., 2011; Shirota et al., 2011; Cao et al., 2012). The [1,1-methylene]bis(3-methylimidazolium) tetrafluoroborate (**C1b**) is reported here for the first time. The reaction is highly exothermic and violent and was therefore carried out in the cold at temperatures between 0-5 °C. A similar vigorous reaction was reported by Zhang et al. (2007) in which 1-methylimidazole reacted with bromoethane and 1-bromobutane respectively for the synthesis of monodentate ionic liquids. The green metathesis reactions with fluorinated salts in an ethanol and water mixture were also achieved producing ionic liquids bearing fluorinated anions with yields of up to 95%.

The compounds were characterised by ^1H and ^{13}C NMR spectroscopy where the four cations **C1-4** were distinctly different because of the difference in the number of methylene groups in the spacer between the imidazole rings. Each of the cations with different counter anions showed very similar resonances. The [1,1-methylene]bis(3-methylimidazolium) (**C1**) cation showed a singlet for the spacer methylene group in the ^1H NMR spectrum at δ_{H} 6.78 (δ_{C} 57.76). As the length of the spacer increases, this methylene resonance adjacent to the nitrogen decreases to δ_{H} 4.25, 4.22 and 4.20 for the propylene (**C2a**), butylene (**C3a**) and pentylene (**C4a**) compounds respectively, since the distance between the second nitrogen atom and the methylene group increases, lessening the deshielding effect that the second nitrogen exerts on the methylene group. Each of these resonances appeared as triplets since they are adjacent to another methylene group. Similarly, as the chain length increases, the inner methylene groups experience less and less of the deshielding effect of the nitrogen; the

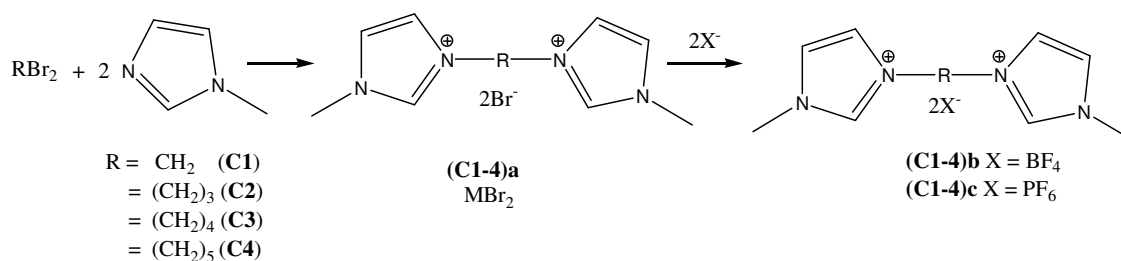
central methylene group in the pentylene compound (**C4a**) resonates at δ 1.23 compared to the inner methylene protons resonating at δ 1.78 in the butylene compound (**C3a**). The inner methylene proton resonances appear as quintets since they are adjacent to four protons in similar chemical environments.

In general, the methylimidazolium ring consisted of four proton resonances, each typically singlets at δ 3.89 (CH₃), 7.81 and 8.09 (CH resonances for the *cis* protons) and δ 9.56 (N-CH-N). The *cis* protons for **C2a** occur as a pair of doublets with $J = 1.60$ Hz. The carbon resonances of the methylimidazolium group appear at δ 36.24 (CH₃), and δ 121.80, 124.25 and 137.94 for the three Imidazolium protons. This is consistent with that reported in the literature (Ibrahim et al., 2012). The slight shifts in the proton resonances for the Imidazolium protons in the *bis*(tetrafluoroborate) anions when compared to the dibromide compounds (Table 5.1) could be due to hydrogen bonding that could occur between the fluorine on the BF₄⁻ anion and the protons on the Imidazolium ring, hence the shift in these proton resonances. In general the 1-methylimidazolium resonances for the *bis*(tetrafluoroborate) anionic compounds all resonated at a slightly lower frequency than that for the dibromide salts with δ values lower by 0.01-0.03 for the methyl group, 0.04-0.07 and 0.09-0.17 for the *cis* imidazolium protons and the largest difference experienced by the N-CH-N proton of between 0.21-0.28 ppm lower. This indicates that this latter proton experiences the largest hydrogen bonding interaction with the fluorine atoms of the tetrafluoroborate group. This is due to electron donation from the lone pairs of the fluorine atoms causing the N-CH-N proton to resonate at a slightly lower frequency. The same trend is observed for compounds with the hexafluorophosphate anions (Table 5.1).

For the BF₄⁻ anions, the fluorine resonance appears as a singlet at δ -148.35 and for the PF₆⁻ anions, the fluorine splits the phosphorus resonance into a septet at δ 144.21, which in turn

splits the fluorine resonance into a doublet at δ -70.17. The coupling constant for these two resonances is 711 Hz.

With an increase in the number of methylene groups in the spacer, there was a decrease in the melting points of the compounds. This is probably due to an increase in entropy with a longer alkyl spacer, which decreases the intermolecular forces of the compound. Substitution of the bromide ion with BF_4^- and PF_6^- ions respectively lead to lower melting points. Generally, the melting point of the PF_6^- ILs was higher than that of the BF_4^- ILs, with the exception of **C1b** and **C1c**, which were very similar. The trend of the melting points in general were $M(\text{BF}_4)_2 < M(\text{PF}_6)_2 < M\text{Br}_2$.



Scheme 5-1 Synthetic route to the imidazolium ionic liquids (**C1-4**) a-c.

Table 5-1 Comparison of the ^1H NMR resonances for the 1-methylimidazolium group for the dibromide, the *bis*(tetrafluoroborate) and the hexafluorophosphate anions.

No.	CH_3 (δ_{H})	CH (δ_{H})	CH (δ_{H})	CH (δ_{H})
C1a	3.89	7.81	8.09	9.56
C1b	3.88	7.75	7.92	9.30
C1c	3.89	7.76	7.92	9.30
$\Delta(\text{C1a-1b})$	0.01	0.06	0.17	0.26
$\Delta(\text{C1a-1c})$	0.00	0.05	0.17	0.26
C2a	3.86	7.72	7.79	9.20
C2b	3.83	7.65	7.68	8.99
C2c	3.84	7.68	7.75	9.15
$\Delta(\text{C2a-2b})$	0.03	0.07	0.11	0.21
$\Delta(\text{C2a-2c})$	0.02	0.04	0.04	0.05
C3a	3.85	7.71	7.78	9.19
C3b	3.83	7.66	7.70	9.04
C3c	3.84	7.69	7.72	9.06
$\Delta(\text{C3a-3b})$	0.02	0.05	0.08	0.15
$\Delta(\text{X3a-3b})$	0.01	0.02	0.06	0.13
C4a	3.87	7.73	7.83	9.31
C4b	3.85	7.69	7.74	9.03
C4c	3.84	7.69	7.74	9.09
$\Delta(\text{C4a-4b})$	0.02	0.04	0.09	0.28
$\Delta(\text{C4a-4c})$	0.03	0.04	0.09	0.22

Table 5-2 Melting points of the solid ILs at ambient conditions (data from literature reported where available).

Comp.	Alkyl Chain	Melting points of compounds 1-4 (a-c) ($^{\circ}\text{C}$)		
		a (Br^-)	b (BF_4^-)	c (PF_6^-)
C1	$-\text{CH}_2-$	290-292; 300 (lit ¹)	138-140	136-137
C2	$-(\text{CH}_2)_3-$	156-158; 162 (lit ²)	110-111; 117 (lit ²)	120-122; 131 (lit ²)
C3	$-(\text{CH}_2)_4-$	122-124; 132 (lit ³)	89-92; 99 (lit ⁴)	105-106; 112 (lit ³)
C4	$-(\text{CH}_2)_5-$	65-66	112-113; 117 (lit ⁴)	92-95

¹ LeClerq et al. (2011); ² Anderson et al. (2005); ³ Lee et al. (2010); ⁴ Shirota et al. (2011)

5.3 Experimental

Reagent grade chemicals were purchased from Aldrich Chemicals and were used without further purification. NMR spectra were recorded in DMSO- d_6 at room temperature using a Bruker Avance^{III} 400 MHz spectrometer with chemical shifts (δ) recorded against the internal standards, tetramethylsilane for ^1H and ^{13}C NMR, triphenyl phosphate for ^{31}P NMR and trifluorotoluene for ^{19}F NMR. The operating frequencies on the 400 MHz NMR spectrometer for the ^{13}C , ^{31}P and ^{19}F NMR spectra were 100, 162 and 376.5 MHz respectively. Melting points were recorded on an Ernst Leitz Wetzlar micro-hot stage melting point apparatus and are uncorrected. IR spectra were recorded on a Perkin Elmer Spectrum 100 FT-IR spectrometer with universal ATR sampling accessory.

Each of the alkyl dihalides (0.001 moles) was reacted with 1-methylimidazole (0.002 moles, 0.16 g) at a temperature of between 0-5 °C under nitrogen. Imidazole was added slowly to the dihalide and the temperature maintained between 0-5 °C since the reaction was vigorous. The reaction mixture was allowed to stand for 24 hours with constant stirring affording the quaternized dibromide salts **(C1-4)a**. The salts were purified by several washings with methylene dichloride and acetone to remove any unreacted starting materials and dried using a vacuum pump before being stored in a desiccator.

The dibromide ILs were dissolved in a mixture of ethanol and water (4:1; 20 ml) and the metathesis reaction carried out with NaBF_4 and KPF_6 respectively to afford the ionic liquids **(C1-4)b** and **(C1-4)c** containing the BF_4^- and PF_6^- counteranions. The products were washed with acetone and with ethanol several times to remove the NaBr that formed, then dried and kept in a desiccator. The ^1H , ^{13}C , ^{31}P , ^{19}F NMR and IR spectra of all the samples were recorded and the compounds confirmed by their analysis.

[1,1-Methylene]bis(3-methylimidazolium)dibromide (C1a); [(C₄H₆N₂)₂CH₂]Br₂; Yield 72%; ¹H NMR (δ_H): 3.89 (s, CH₃), 6.78 (s, CH₂), 7.81 (s, CH), 8.09 (s, CH), 9.56 (s, CH); ¹³C NMR (δ_C): 36.2 (CH₃), 57.8 (CH₂), 121.8 (CH), 124.3 (CH), 137.9 (CH); IR (cm⁻¹): 3411, 3044, 1582, 1560, 1546, 1168.

[1,1-Methylene]bis(3-methylimidazolium)bistetrafluoroborate (C1b);

[(C₄H₆N₂)₂CH₂][BF₄]₂; Yield 77%; ¹H NMR (δ_H): 3.88 (s, CH₃), 6.61 (s, CH₂), 7.75 (s, CH), 7.92 (s, CH), 9.30 (s, CH); ¹³C NMR (δ_C): 36.1 (CH₃), 58.1 (CH₂), 121.9 (CH), 124.4 (CH), 138.0 (CH). ¹⁹F NMR (δ_F): -148.35 (s); IR (cm⁻¹): 3420, 3166, 3143, 1172, 1033.

[1,1-Methylene]bis(3-methylimidazolium)bishexafluorophosphate (C1c);

[(C₄H₆N₂)₂CH₂][PF₆]₂; Yield 83%; ¹H NMR (δ_H): 3.89 (s, CH₃), 6.61 (s, CH₂), 7.76 (s, CH), 7.92 (s, CH), 9.30 (s, CH); ¹³C NMR (δ_C): 36.1 (CH₃), 58.1 (CH₂), 121.9 (CH), 124.4 (CH), 138.0 (CH). ³¹P NMR (δ_P): 144.21 (septet, *J* = 711.2 Hz); ¹⁹F NMR (δ_F): -70.17 (d, *J* = 711.2 Hz). IR (cm⁻¹): 3420, 3166, 3143, 1659, 1172, 1033, 1000.

[1,3-Propylene]bis(3-methylimidazolium)dibromide (C2a); [(C₄H₆N₂)₂(CH₂)₃]Br₂; Yield 96%; ¹H NMR (δ_H): 2.39 (quintet, *J* = 7.0 Hz, CH₂), 3.86 (s, CH₃), 4.25 (t, *J* = 7.0 Hz, CH₂), 7.72 (d, *J* = 1.6 Hz, CH), 7.79 (d, *J* = 1.6 Hz, CH), 9.20 (s, CH); ¹³C NMR (δ_C): 29.5 (CH₂), 35.8 (CH₃), 45.7 (CH₂), 122.1 (CH), 123.7 (CH), 136.7 (CH); IR (cm⁻¹): 3398, 3146, 3075, 1562, 1164.

[1,3-Propylene]bis(3-methylimidazolium)bistetrafluoroborate (C2b);

[(C₄H₆N₂)₂(CH₂)₃][BF₄]₂; Yield 95%; ¹H NMR (δ_H): 2.37 (quintet, *J* = 7.0 Hz, CH₂), 3.83 (s, CH₃), 4.19 (t, *J* = 7.0 Hz, CH₂), 7.65 (s, CH), 7.68 (s, CH), 8.99 (s, CH); ¹³C NMR (δ_C): 29.4 (CH₂), 35.7 (CH₃), 45.6 (CH₂), 122.0 (CH), 123.7 (CH), 136.7 (CH); ¹⁹F NMR (δ_F): -148.67; IR (cm⁻¹): 3376, 1003.

[1,3-propylene]bis(3-methylimidazolium)bishexafluorophosphate (C2c);

$[(C_4H_6N_2)_2(CH_2)_3][PF_6]_2$; Yield 95%; 1H NMR (δ_H): 2.39 (quintet, $J = 7.0$ Hz, CH_2), 3.84 (s, CH_3), 4.25 (t, $J = 7.0$ Hz, CH_2), 7.68 (s, CH), 7.75 (s, CH), 9.15 (s, CH); ^{13}C NMR (δ_C): 29.4 (CH_2), 35.8 (CH_3), 45.7 (CH_2), 122.1 (CH), 123.7 (CH), 136.7 (CH); ^{31}P NMR (δ_P): 144.25 (septet, $J = 711.8$ Hz); ^{19}F NMR (δ_F): -70.14 (d, $J = 711.8$ Hz); IR (cm^{-1}): 3174, 3125, 1580, 1564, 1168, 817.

[1,4-butylene]bis(3-methylimidazolium)dibromide (C3a); $[(C_4H_6N_2)_2(CH_2)_4]Br_2$; Yield 97%; 1H NMR (δ_H): 1.78 (brs, CH_2), 3.85 (s, CH_3), 4.22 (brs, CH_2), 7.71 (s, CH), 7.78 (s, CH), 9.19 (s, CH); ^{13}C NMR (δ_C): 26.0 (CH_2), 35.8 (CH_3), 47.9 (CH_2), 122.2 (CH), 123.6 (CH), 136.5 (CH); IR (cm^{-1}): 3391, 3090, 1628, 1569, 1164.

[1,4-butylene]bis(3-methylimidazolium)bistetrafluoroborate (C3b);

$[(C_4H_6N_2)_2(CH_2)_4][BF_4]_2$; Yield 73%; 1H NMR (δ_H): 1.77 (brs, CH_2), 3.83 (s, CH_3), 4.19 (brs, CH_2), 7.66 (s, CH), 7.70 (s, CH), 9.04 (s, CH); ^{13}C NMR (δ_C): 25.9 (CH_2), 35.7 (CH_3), 47.9 (CH_2), 122.1 (CH), 123.6 (CH), 136.4 (CH); ^{19}F NMR (δ_F): -148.50. IR (cm^{-1}): 3172, 3126, 1582, 1566, 1174, 1018.

[1,4-butylene]bis(3-methylimidazolium)bishexafluorophosphate (C3c);

$[(C_4H_6N_2)_2(CH_2)_4][PF_6]_2$; Yield 82 %; 1H NMR (δ_H): 1.77 (brs, CH_2), 3.84 (s, CH_3), 4.19 (brs, CH_2), 7.69 (s, CH), 7.72 (s, CH), 9.06 (s, CH); ^{13}C NMR (δ_C): 26.0 (CH_2), 35.7 (CH_3), 48.0 (CH_2), 122.2 (CH), 123.7 (CH), 136.5 (CH); ^{31}P NMR (δ_P): 144.22 (septet, $J = 711.2$ Hz); ^{19}F NMR (δ_F): -70.18 (d, $J = 711.2$ Hz); IR (cm^{-1}): 3174, 3125, 1575, 1567, 1164, 817.

[1,5-pentylene]bis(3-methylimidazolium)dibromide (C4a); $[(C_4H_6N_2)_2(CH_2)_5]Br_2$; Yield

98%; 1H NMR (δ_H): 1.23 (quintet, $J = 7.0$ Hz, CH_2), 1.83 (quintet, $J = 7.0$ Hz, CH_2), 3.87 (s, CH_3), 4.20 (t, $J = 6.8$ Hz, CH_2), 7.73 (s, CH), 7.83 (s, CH), 9.31 (s, CH); ^{13}C NMR (δ_C): 21.9

(CH₂), 28.6 (CH₂), 35.8 (CH₃), 48.3 (CH₂), 122.2 (CH), 123.5 (CH), 136.5 (CH); IR (cm⁻¹): 3388, 3150, 3093, 1628, 1574, 1564, 1165.

[1,5-pentylene]bis(3-methylimidazolium)bistetrafluoroborate (C4b);

[(C₄H₆N₂)₂(CH₂)₅][BF₄]₂; Yield 70%; ¹H NMR (δ_H): 1.22 (quintet, *J* = 7.6 Hz, CH₂), 1.80 (quintet, *J* = 7.4 Hz, CH₂), 3.85 (s, CH₃), 4.16 (t, *J* = 7.2 Hz, CH₂), 7.69 (s, CH), 7.74 (s, CH), 9.08 (s, CH); ¹³C NMR (δ_C): 21.9 (CH₂), 28.6 (CH₂), 35.7 (CH₃), 48.4 (CH₂), 122.2 (CH), 123.6 (CH), 136.4 (CH); ¹⁹F NMR (δ_F): -148.30; IR (cm⁻¹): 3410, 3045, 2974, 1582, 1560, 1547, 1330, 1168.

[1,5-pentylene]bis(3-methylimidazolium)bishexafluorophosphate (C4c);

[(C₄H₆N₂)₂(CH₂)₅][PF₆]₂; Yield 91%; ¹H NMR (δ_H): 1.22 (quintet, *J* = 6.9 Hz, CH₂), 1.81 (quintet, *J* = 7.2 Hz, CH₂), 3.84 (s, CH₃), 4.15 (t, *J* = 6.8 Hz, CH₂), 7.69 (s, CH), 7.74 (s, CH), 9.09 (s, CH); ¹³C NMR (δ_C): 22.0 (CH₂), 28.6 (CH₂), 35.7 (CH₃), 48.4 (CH₂), 122.2 (CH), 123.6 (CH), 136.5 (CH); ³¹P NMR (δ_P) 144.23 (septet, *J* = 711.2 Hz); ¹⁹F NMR (δ_F) -70.16 (d, *J* = 711.2 Hz); IR (cm⁻¹): 3371, 2949, 1629, 1574, 1170, 1001, 715.

5.4 Conclusion

In conclusion we have successfully synthesized twelve dimeric ionic compounds with alkyl spacers of the type (CH₂)_n (where n = 1, 3, 4, 5) between two Imidazolium cations and Br⁻, BF₄⁻ and PF₆⁻ as counter anions without the use of solvents for the synthesis of the bromides. The melting point in this series is seen to decrease with increasing length of the alkyl spacer. This solvent free reaction between the alkyl dihalides and imidazole is highly exothermic. The substitution of the bromide anion with fluorinated anions showed a general increase in their melting points to the order of M(BF₄)₂ < M(PF₆)₂ < MBr₂.

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Chapter 6 The synthesis and NMR characterisation of (1,4-phenylenedimethylene)*bis*(pyridinium) and (1,1-methylene)*bis*(pyridinium) ionic compounds

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Abstract.

Pyridine was reacted with *p*- α,α -dibromoxylene and 1,1-dibromomethane respectively to yield the quaternised salts **D1a** and **D2a** respectively, followed by metathesis reactions with the fluorinated anion sources, NaBF₄ and KPF₆ to produce fluorinated pyridinium ionic liquids **D1b-c** and **D2b-c**. Compounds **D1b** and **D2c** are novel as the combination of cation and anion had not been made previously. The synthesis of **D2a** was carried out without the use of solvents and the metathesis reactions carried out with ethanol and water and can be considered as green reactions. 2D NMR studies of the synthesised compounds are reported here.

Keywords: Solvent free synthesis, Fluorinated anions, Pyridinium ionic liquids, NMR studies.

6.1 Introduction

Ionic liquids have recently attracted much interest due to their non-volatility and high ion conductivity (Wasserscheid and Welton, 2008). Being non-volatile, they are ideal candidates for solvents in inorganic and organic reactions, which could render the methods based on these syntheses environmentally friendly as it avoids the release of harmful gases into the atmosphere (Wasserscheid and Welton, 2008). There are also reports that these ionic liquids can act as catalysts for various organic reactions thereby being a solvent and catalyst in one (Wasserscheid and Keim, 2000; Dyson and Geldbach, 2007). Their high ion-conductivity also makes them attractive chemicals for use in electronic devices (Min et al., 2013; Ferrari et al., 2013).

Nitrogenous based cations such as ammonium, imidazolium and pyridinium cations are commonly used in the synthesis of ionic liquids as these nucleophiles can easily substitute weaker bases forming organic cations as the basis of the ionic liquid. Of the three cations, the pyridinium ionic liquids have received the least attention. However, pyridinium ionic liquids have found important applications in the pharmaceutical industry, being known to be antimicrobial (Ito et al., 2008), antimalarial (Ito et al., 2008; Sasaki et al., 2008), and industrial microbicides (Koma et al., 2000). They were also shown to have antiproliferative activity against HT-29 (a human colon adenocarcinoma cell line) as well as inhibit choline kinase (ChoK), an anticancer molecular target (Martin-Cantalejo et al., 2011). In addition they were shown to be acetylcholinesterase reactivators and inhibitors (Musilek et al., 2005; 2010; Palafox et al., 2011). They were also found to be putative gene delivery agents (Plotniece et al., 2009).

In chemistry, *N*-alkyl-pyridinium based ionic liquids find applications in the desulfurization of gasoline and diesel oil (Jian-long et al., 2007; Zhao et al., 2009; Gao et al., 2012). Thoi and Chang (2011) have reported a series of nickel (II) complexes supported by *N*-heterocyclic carbene-pyridine which selectively reduce carbon dioxide over water, thereby converting CO₂, which contributes to global warming, into useful products. Pyridinium ionic liquids were reported to react with palladium and form palladium-pyridylidene *N*-heterocyclic carbene complexes, which are active catalysts in Suzuki cross coupling reactions (Albrecht and Stoeckli-Evans, 2005).

A number of *p*-xylenebis(pyridinium) ionic compounds with various anions have been prepared and the structures determined by X-ray crystallography (see for example Ashwell et al., 1975; Tang et al., 2007; Wu et al., 2007; Rahim et al, 2010). *p*-Xylenebis(pyridinium) dibromide is widely used as a cationic quencher for the anionic fluorophore 8-aminonaphthalene-1,3,6-trisulfonic acid which is used as a fluorescent marker in liposomes, vesicles that are used for site-specific drug delivery in medicine (Gradauer et al., 2012, Noshiro et al., 2012). The ditetraphenylborate is used in electrostatographic toners (Wilson and Alexandrovich, 1991) and the dibromide has shown some activity against acetylcholinesterase (Musilek et al., 2010).

The 1,1-methylenebis(pyridinium) ionic compounds have also been synthesised with a number of various anions among which are the dibromide and the tetrafluoroborate ionic compounds (Olofson et al., 1972; Sugimoto et al., 1982; Almarzoqi et al., 1986; Munavalli et al., 1986). The crystal structures of the cations with decaborate and tungsten anions have also been reported (Preetz and Nachtigal, 1995; Brencic and Modec, 2011).

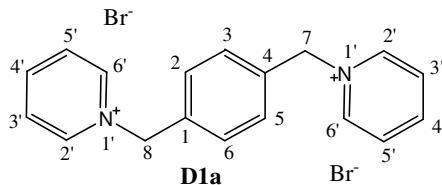
To our knowledge there has been no reports on the 2D NMR studies of either the *p*-xylenebis(pyridinium) or the 1,1-methylenebis(pyridinium) ionic compounds. These results are hence presented here.

6.2 Results and discussion

The synthesis of six pyridinium bidentate ionic compounds with phenylenedimethylene and methylene spacers were synthesised successfully using modified procedures of that published in Ganesan and Alias (2008) (scheme 1). Yields of up to 99% were obtained for the quaternized salts and up to 80% for the metathesis reactions with the tetrafluoroborate and hexafluorophosphate anions. Compounds **D1a**, **D1c**, **D2a** and **D2b** have been synthesised previously (Li et al., 2009; Musilek et al., 2010; Sugimoto et al., 1982) and the crystal structure of **D1c** has been reported (Rahim et al., 2010), but their structural elucidation using 2D NMR have not been reported. Furthermore, the melting points of **D1c** and **D2b** have not been reported previously. The synthesis of **D2a** can be considered a "green" synthesis as it was carried out without the use of solvents. Furthermore, the metathesis reactions with sodium tetrafluoroborate and potassium hexafluorophosphate were carried out with ethanol and water, which is also a green process. The ease with which these reactions can be carried out to make new ionic compounds is highly desirable as it avoids the use of harsh and environmentally unfriendly solvents, high temperatures and pressures and catalysts.

Although the melting points of the bromides (**D1a** and **D2a**) are quite high (>250 °C), upon metathesis with a larger fluorinated anion such as BF₄⁻ and PF₆⁻, the melting point drops to below 100 °C in **D1b-c** and **D2b-c**, and thereby satisfying the definition of an ionic liquid.

As such, these ionic compounds are suitable to be used as solvents for organic and inorganic reactions where the temperature exceeds 100 °C.

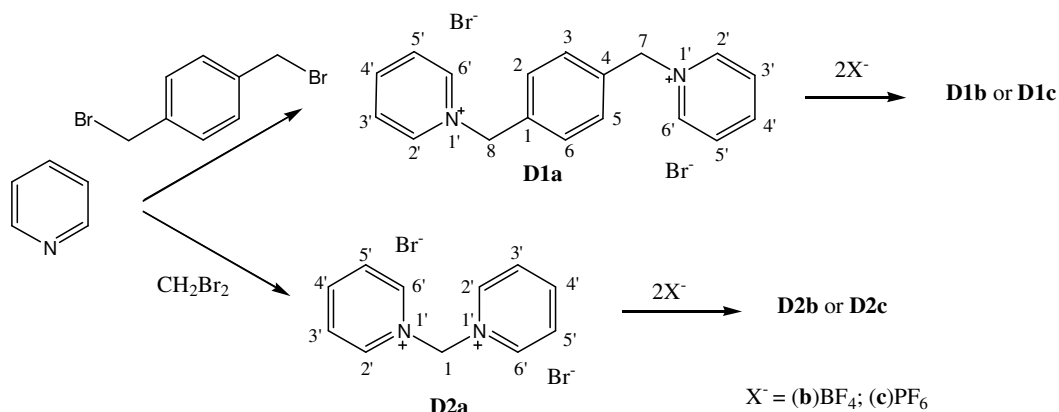


The ^1H NMR spectrum of **D1a**, the pyridinium salt with the phenylenedimethylene spacer showed five proton resonances. Three of these at δ_{H} 9.24 (d), 8.61 (t) and 8.18 (dd) were attributed to the 2'/6', 4' and 3'/5' positions on the pyridinium ring, consistent with that reported in the literature (Vo-Thanh et al., 2010). The remaining resonances at δ_{H} 7.62 and 5.91, both singlets, were ascribed to the equivalent aromatic protons H-2/3/5/6 and the equivalent methylene groups (H-7/8) respectively. The phenylenedimethylene moiety bridged the two pyridinium cations. In the ^{13}C NMR spectrum of **D1a**, there were six carbon resonances, three of which were that of the carbon resonances of the pyridinium ring at δ_{C} 143.7 (C-2'/6'), 127.3 (C-3'/5') and 144.9 (C-4'). The two resonances at δ_{C} 128.4 and 134.2 were attributed to the equivalent carbon atoms of C-2/3/5/6 and C-1/4 respectively. The remaining resonance at δ_{C} 61.4 was assigned to the equivalent methylene carbon atoms C-7/8. The COSY spectrum of **D1a** clearly indicates correlations between the aromatic proton resonance (H-2/3/5/6) at δ_{H} 7.62 and the methylene carbon resonance at δ_{H} 5.91 as well as between the methylene resonance and the pyridinium proton resonance of H-2'/6', indicating that the cation had indeed formed. This is further supported by HMBC correlations between the aromatic carbon resonances (both C-2/3/5/6 and C-1/4) as well as C-2'/6' of the pyridinium ring with the methylene proton resonance of H-7/8. In addition, NOESY correlations are observed for both the aromatic protons and the H-2'/6' protons with the methylene proton resonance.

Subtle downfield NMR shifts are seen for the methylene (H-7/8) and H-2'/6' proton resonances of the metathesized compounds indicative of the close proximity of the BF_4^- and PF_6^- ions to the nitrogen cation as these two proton groups flank the nitrogen cations on either side. The BF_4^- and PF_6^- pyridinium salts were further verified by the fluorine resonance at δ -148.28 for the BF_4^- fluorine atom and the fluorine and phosphorus resonances at δ -70.13 and δ -144.20 being a doublet and septet respectively with a coupling constant of 711.1 Hz.

The ^1H NMR spectrum of **D2a**, the pyridinium salt with the methylene spacer showed four proton resonances. As in **D1a**, the resonances at δ_{H} 9.63 (d), 8.79 (t) and 8.33 (dd) were attributed to the 2'/6', 4' and 3'/5' positions on the pyridinium ring. The remaining resonance at δ_{H} 7.46, a singlet, was ascribed to the methylene group that bridged the two pyridinium cations. The fact that this resonance is so far downfield is indicative that the methylene group is bonded to two nitrogen based cations on either side as electron density from these protons are removed by the inductive effects of the cationic nitrogen atoms, deshielding the methylene protons to such an extent that it appears in the aromatic region of the ^1H NMR spectrum. The ^{13}C NMR spectrum provided further confirmation of the product **D2a** as four resonances were seen. Beside the three carbon resonances of the pyridinium ring at δ_{C} 148.6 (C-4'), 145.8 (C-2'/6') and 128.6 (C-3'/5'), there was also the methylene resonance at δ_{C} 76.1, somewhat more downfield than that of a normal C-N carbon resonance, due to it being flanked by two nitrogen atoms. The COSY spectrum of **D2a** shows a correlation between the methylene carbon resonance and H-2'/6' of the pyridinium ring as well as correlations between each of the proton resonances on the pyridine ring as expected. An HMBC correlation between C-2'/6' and the methylene proton resonance is also seen quite prevalently.

As in **D1b** and **D1c**, small NMR shifts are seen for the methylene and the H-2'/6' proton resonances of the metathesized compounds (**D2b** and **D2c**), also indicative of the close proximity of the BF_4^- and PF_6^- ions to the nitrogen cation. The same fluorine and phosphorus resonances observed in **D1b** and **D1c** were also observed in **D2b** and **D2c**.

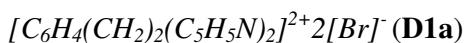


Scheme 6-1: Synthetic route to the synthesis of the ionic compounds **D1a-c** and **D2a-c**

6.3 Experimental

Reagent grade chemicals were purchased either from Aldrich Chemicals via Capital Laboratories, South Africa or Merck, South Africa. NMR spectra of all compounds were acquired in deuterated DMSO-d_6 at room temperature on a Bruker Avance^{III} 400 MHz NMR spectrometer. The chemical shifts were referenced to tetramethylsilane for ^1H and ^{13}C NMR, triphenyl phosphate for ^{31}P NMR and trifluorotoluene for ^{19}F NMR and the operating frequencies on the 400 MHz NMR spectrometer for the ^{13}C , ^{31}P and ^{19}F NMR spectra were 100, 162 and 376.5 MHz respectively. IR spectra were recorded on a Perkin Elmer Spectrum 100 FT-IR Spectrometer with a universal ATR sampling accessory. Melting points were recorded on an Ernst Leitz Wetzlar micro-hot stage melting point apparatus.

Synthesis of 1,1-(1,4-phenylenedimethylene)bis(pyridinium)dibromide



α,α -Dibromoxylene (0.001 mol, 5.28 g) was dissolved in acetonitrile followed by the addition of pyridine (0.002 mol, 3.22 mL) and the mixture stirred constantly at room temperature for 24 hrs to afford the quaternized bromide salt (**D1a**), which was filtered and washed several times with acetone to remove any unreacted reagents. The product was dried under vacuum and kept in a desiccator for further metathesis reactions. Yield 90%; m.p. 285-287 °C (Musilek et al., 2010 (296-297 °C)) ; 1H -NMR (400 MHz, DMSO- d_6 , 323 K) δ 9.24 (d, 4H, J = 5.6 Hz, H-2'/6'), 8.61 (t, 2H, J = 7.5 Hz, H-4'), 8.18 (dd, 4H, J = 5.6, 7.5 Hz, H-3'/5'), 7.63 (s, 4H, H-2/3/5/6), 5.91 (s, 4H, CH₂-7/8); ^{13}C -NMR (100 MHz, DMSO- d_6 , 323 K) δ 144.9 (C-4'), 143.7 (C-2'/6'), 134.2 (C-1/4), 128.4 (C-2/3/5/6), 127.3 (C-3'/5'), 61.4 (C-7/8). IR (cm⁻¹): 3704, 3681, 3355, 2961, 2965, 2844, 1627, 1481.

Metathesis reaction of D1a with NaBF₄ and KPF₆

The dibromide salt (**D1a**) (0.001 mol, 0.42 g) was dissolved in a mixture of ethanol and water (4:1) and reacted with NaBF₄ and KPF₆ respectively (0.002 mol each) to produce the fluorinated tetrafluoroborate salt **D1b** and hexafluorophosphate salt **D1c**. The water was removed using MgSO₄ and the salt was filtered, washed several times with ethanol, dried completely and kept in an inert atmosphere under nitrogen in a desiccator. The structures of the compounds were confirmed by 1H , ^{13}C , ^{31}P and ^{19}F NMR as well as IR Spectroscopy.

1,1-(1,4-phenylenedimethylene)bis(pyridinium)ditetrafluoroborate (D1b)

$$[C_6H_4(CH_2)_2(C_5H_5N)_2]^{2+}2[BF_4]^-$$

Yield 73%, m.p. 93-95 °C; 1H NMR (400 MHz, DMSO- d_6 , 323 K) δ 9.17 (d, 4H, J = 5.6 Hz, H-2'/6'), 8.62 (t, 2H, J = 7.8 Hz, H-4'), 8.18 (dd, 4H, J = 5.6, 7.8 Hz, H-3'/5'), 7.60 (s, 4H, H-2/3/5/6), 5.85 (s, 4H, CH₂-7/8); ^{13}C -NMR (100 MHz,

DMSO-d₆, 323 K) δ 146.1 (C-4'), 144.8 (C-2'/6'), 135.3 (C-1/4), 129.5 (C-2/3/5/6), 128.5 (C-3'/5'), 62.8 (C-7/8), ¹⁹F NMR (δ_F) -148.23; IR (cm⁻¹): 3701, 3681, 2969, 2867, 2844, 1632, 1487, 1053, 1032, 1015.

1,1-(1,4-phenylenedimethylene)*bis*(pyridinium)dihexafluorophosphate (**D1c**)

[C₆H₄(CH₂)₂(C₅H₅N)₂]²⁺2[PF₆]⁻; Yield 83%, m.p. 97-98 °C[#], ¹H-NMR (400 MHz, DMSO-d₆, 323 K) δ 9.17 (d, 4H, *J* = 5.8 Hz, H-2'/6'), 8.62 (t, 2H, *J* = 7.8 Hz, H-4'), 8.18 (dd, 4H, *J* = 5.6, 7.8 Hz, H-3'/5'), 7.59 (s, 4H, H-2/3/5/6), 5.86 (s, 4H, CH₂-7/8); ¹³C-NMR (100 MHz, DMSO-d₆, 323 K) δ 146.1 (C-4'), 144.8 (C-2'/6'), 135.3 (C-1/4), 129.5 (C-2/3/5/6), 128.5 (C-3'/5'), 62.7 (C-7/8); ³¹P-NMR (δ_P) -144.20 (septet, *J* = 711.1 Hz); ¹⁹F NMR (δ_F) -70.13 (*J* = 711.1 Hz); IR (cm⁻¹): 3701, 3681, 2970, 2923, 2867, 2844, 1489, 1162, 1055, 1032, 1014.

[#]Although this compound has been synthesised previously, its melting point has not been reported.

*Synthesis of [1,1-methylene]bis(pyridinium)dibromide [(C₅H₅N)₂CH₂]²⁺2Br⁻ (**D2a**)*

Dibromomethane (0.001 mol, 2.80 mL) was added to pyridine (0.002 mol, 6.44 mL) without the use of solvents. The reaction was highly exothermic and therefore carried out in the cold with the slow addition of pyridine. The reaction mixture was allowed to stand for 24 hrs with constant stirring to afford the pyridinium bromide salt (**D2a**), a white salt, which was washed several times with acetone. The product was dried under vacuum and kept in a desiccator for further metathesis reactions with fluorinated anion sources. Yield 99%; m.p. 253-255 °C (Musilek et al., 2010 (270 °C), Munavalli et al., 1986 (255-259 °C)); ¹H-NMR (400 MHz, DMSO-d₆, 323 K), δ 9.64 (d, 4H, *J* = 5.6 Hz, H-2'/6'), 8.79 (t, 2H, *J* = 7.8 Hz, H-4'), 8.32 (dd, 4H, *J* = 7.8, 5.6 Hz, H-3'/5'), 7.46 (s, 2H, CH₂-1); ¹³C-NMR (100 MHz, DMSO-d₆, 323 K) δ

148.7 (C-4'), 145.8 (C-2'/6'), 128.6 (C-3'/5'), 76.1 (C-1); IR (cm⁻¹): 3458, 3415, 3029, 3005, 2871, 1629, 1493, 1298, 1179.

Metathesis reaction of D2a with NaBF₄ and KPF₆

The dibromide salt **D2a** (0.001 mol, 0.33 g) was dissolved in a mixture of ethanol and water in a ratio of 4:1 and reacted with NaBF₄ and KPF₆ respectively (0.002 mol each) to yield compounds **D2b**, the tetrafluoroborate and **D2c**, the hexafluorophosphate salts respectively. The water was removed using MgSO₄, before being filtered and washed several times with ethanol. The compounds were dried completely and kept in an inert atmosphere using desiccators under nitrogen. The structures of the compounds were confirmed by ¹H, ¹³C, ³¹P and ¹⁹F NMR as well as IR Spectroscopy and high resolution mass spectrometry.

[1,1-Methylene]bis(pyridinium)ditetrafluoroborate (**D2b**) [(C₅H₅N)₂CH₂]²⁺2BF₄⁻; Yield 77%; m.p. 97-98 °C; ¹H NMR (400 MHz, DMSO-d₆, 323 K) δ 9.58 (d, 4H, *J* = 5.8 Hz, H-2'/6'), 8.79 (t, 2H, *J* = 7.8 Hz, H-4'), 8.33 (dd, 4H, *J* = 7.8, 5.6 Hz, H-3'/5'), 7.40 (s, 2H, CH₂-1); ¹³C-NMR (100 MHz, DMSO-d₆, 323 K) δ 148.7 (C-4'), 145.8 (C-2'/6'), 128.6 (C-3'/5'), 76.4 (CH₂-1); ¹⁹F NMR (δ_F) -148.28; IR (cm⁻¹): 3457, 3413, 3188, 3029, 3005, 2871, 1631, 1493, 1437, 1182, 1090.

[1,1-Methylene]bis(pyridinium)dihexafluorophosphate (**D2c**) [(C₅H₅N)₂CH₂]²⁺2PF₆⁻. Yield 80%; m.p. 95-96 °C; ¹H NMR (400 MHz, DMSO-d₆, 323 K) δ 9.43 (d, 4H, *J* = 5.7 Hz, H-2'/6'), 8.79 (t, 2H, *J* = 7.9 Hz, H-4'), 8.32 (dd, 4H, *J* = 7.8, 5.6 Hz, H-3'/5'), 7.25 (s, 2H, CH₂-1); (100 MHz, DMSO-d₆, 323 K) δ 148.7 (C-4'), 145.8 (C-2'/6'), 128.7 (C-3'/5'), 77.0 (CH₂-1); ³¹P NMR (δ_P) -144.22 (septet, *J* = 710.1 Hz); ¹⁹F NMR (δ_F) -70.14 (d, *J* = 710.1 Hz); IR (cm⁻¹): 3701, 3681, 2970, 2923, 2867, 2844, 1634, 1494, 1185, 1055, 1032, 1015.

6.4 Conclusion

The synthesis of six ionic compounds was successfully synthesised in good yields and their structures characterised by 1D and 2D NMR spectroscopy. Compounds **D1b** and **D2c** are novel compounds as the combination of anion and cation had not been prepared previously. The fluorinated ionic compounds have melting points of less than 100 °C and can be considered as ionic liquids by definition in some texts. It is highly likely that they can be used as solvents as well as catalysts for organic and inorganic synthetic reactions whose reaction temperatures exceed that of 100 °C.

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Chapter 7 Conclusion

Four series of bidentate ionic compounds were synthesized using fairly simple techniques with different ligands and organic spacers in their structure. The studies showed that phosphonium, imidazolium and pyridinium based ionic salts could be synthesized in good yields. Some of the syntheses reported in this thesis can be considered "green" as they do not make use of environmentally unfriendly solvents.

From the crystal structure studies of the imidazolium compounds with the *p*- α,α -dibromoxylene organic spacer and different fluorinated counter anions we were able to show that the melting points of the salts were related to the packing patterns and extent of the three-dimensional network within the compounds. It was demonstrated that the fluorinated counter anions had a significant effect on the crystal packing and the melting point of the ionic compounds. The data provided here could significantly be used to design solvents with particular physical characteristics to be used in applications such as solvents and catalysts for organic reactions.

The synthesis of four novel fluorinated phosphonium organic salts (**B-2** – **B-5**) has been achieved in excellent yields using relatively simple techniques and their structures characterised by NMR analysis. It was found that changing the anion had no effect on the NMR resonances of the cation in these compounds. It was also shown that the dimeric phosphonium organic salts are potential sources of new antimicrobials with different characteristics to those of established drugs. Comparatively, the CF_3SO_3^- anion is a better source of antimicrobial anion than CF_3COO^- and PF_6^- is better than BF_4^- . The crystal structure of the ditetrafluoroborate showed that it consisted of discrete dications interlaced

with the BF_4^- counter-ions. In each cation, both phosphonium groups lie on the side of the plane of the central benzene ring. The tetrafluoroborate anions are involved in intensive thermal motion, thus some B-F bond lengths [range 1.329(6) to 1.391(6) Å] deviate significantly from their standard values.

Twelve dimeric ionic compounds with alkyl spacers of the type $(\text{CH}_2)_n$ (where $n = 1, 3, 4, 5$) between two imidazolium cations and Br^- , BF_4^- and PF_6^- as counter anions were synthesised using green methods without the use of solvents for the synthesis of the bromides. The melting point in this series is seen to decrease with increasing length of the alkyl spacer. This solvent free reaction between the alkyl dihalides and imidazole is highly exothermic. The substitution of the bromide anion with fluorinated anions showed a general increase in their melting points to the order of $\text{M}(\text{BF}_4)_2 < \text{M}(\text{PF}_6)_2 < \text{MBr}_2$. Thus, the fluorinated anions had the effect of lowering the melting point of the ionic salts. NMR studies showed that the metathesis reactions affected the chemical shifts of the ligand protons slightly.

The synthesis of the pyridinium salts with aromatic (xylene) and aliphatic (methylene) spacers were successfully synthesised in good yields and their structures characterised by 1D and 2D NMR spectroscopy. Two of the synthesised compounds are novel compounds as the combination of anion and cation had not been prepared previously. The fluorinated ionic compounds have melting points of less than 100 °C and can be considered as ionic liquids by definition in some texts. It is highly likely that they can be used as solvents as well as catalysts for organic and inorganic synthetic reactions whose reaction temperatures exceed that of 100 °C.

Appendix A

Supplementary information for Chapter 4

Table 1. Atomic coordinates ($\times 10^4$) and equivalent isotropic displacement parameters ($\text{\AA}^2 \times 10^3$) for 9m_kznd_hi3_of. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
C(1)	2957(2)	8761(2)	3996(2)	25(1)
C(2)	3534(2)	8962(2)	3897(2)	28(1)
C(3)	3444(2)	8941(2)	2923(2)	29(1)
C(4)	2764(2)	8711(2)	2018(2)	27(1)
C(5)	2179(2)	8531(2)	2114(2)	33(1)
C(6)	2271(2)	8548(2)	3084(2)	32(1)
C(7)	3067(2)	8732(2)	5050(2)	29(1)
C(8)	2650(2)	8717(2)	938(2)	31(1)
C(11)	2369(2)	6953(2)	4901(2)	32(1)
C(12)	2282(2)	6088(2)	4463(3)	58(1)
C(13)	1603(2)	5654(3)	3966(3)	70(1)
C(14)	1027(2)	6053(3)	3941(3)	55(1)
C(15)	1112(2)	6927(3)	4360(3)	61(1)
C(16)	1782(2)	7372(3)	4839(3)	55(1)
C(21)	3575(2)	7611(2)	6955(2)	34(1)
C(22)	3793(2)	8410(2)	7519(2)	50(1)

C(23)	4054(2)	8404(3)	8586(3)	58(1)
C(24)	4102(2)	7607(3)	9069(2)	54(1)
C(25)	3923(3)	6796(3)	8525(3)	94(2)
C(26)	3640(3)	6781(3)	7460(3)	77(1)
C(31)	3883(2)	6992(2)	5404(2)	31(1)
C(32)	4589(2)	6800(2)	6277(2)	39(1)
C(33)	5090(2)	6363(2)	6127(3)	49(1)
C(34)	4899(2)	6137(2)	5133(3)	52(1)
C(35)	4212(2)	6333(2)	4280(3)	51(1)
C(36)	3696(2)	6760(2)	4395(2)	40(1)
C(41)	3354(2)	6988(2)	830(2)	29(1)
C(42)	4019(2)	7307(2)	1684(2)	39(1)
C(43)	4652(2)	6789(3)	2063(2)	52(1)
C(44)	4633(2)	5969(2)	1601(3)	44(1)
C(45)	3975(2)	5654(2)	734(3)	49(1)
C(46)	3341(2)	6167(2)	351(3)	45(1)
C(51)	2114(2)	7843(2)	-1064(2)	26(1)
C(52)	2344(2)	8609(2)	-1342(2)	38(1)
C(53)	2024(2)	8817(2)	-2394(2)	46(1)
C(54)	1486(2)	8259(2)	-3166(2)	45(1)
C(55)	1271(2)	7476(2)	-2899(2)	48(1)
C(56)	1578(2)	7262(2)	-1851(2)	37(1)
C(61)	1914(2)	6889(2)	464(2)	33(1)
C(62)	1166(2)	7105(2)	-64(2)	41(1)
C(63)	716(2)	6593(3)	114(3)	58(1)

C(64)	1007(3)	5871(3)	828(4)	77(1)
C(65)	1742(3)	5658(3)	1362(4)	76(1)
C(66)	2200(2)	6164(2)	1186(3)	54(1)
B(1)	1000(2)	9769(3)	4235(3)	42(1)
B(2)	4718(2)	10386(2)	6577(3)	33(1)
F(1)	1625(1)	9542(1)	5214(2)	70(1)
F(2)	1130(2)	9490(2)	3495(2)	99(1)
F(3)	410(2)	9335(2)	4085(3)	119(1)
F(4)	910(1)	10711(1)	4165(2)	60(1)
F(5)	4055(1)	10708(2)	5749(2)	78(1)
F(6)	4802(2)	10623(2)	7479(2)	144(2)
F(7)	5243(2)	10771(2)	6517(4)	142(2)
F(8)	4767(1)	9440(1)	6506(2)	55(1)
P(1)	3229(1)	7570(1)	5577(1)	28(1)
P(2)	2511(1)	7603(1)	303(1)	25(1)

Table 2. Bond lengths [\AA] and angles [$^\circ$] for 9m_kznd_hi3_of.

C(1)-C(2)	1.384(4)
C(1)-C(6)	1.399(4)
C(1)-C(7)	1.491(4)
C(2)-C(3)	1.389(4)
C(2)-H(2)	0.9500
C(3)-C(4)	1.394(4)
C(3)-H(3)	0.9500
C(4)-C(5)	1.391(4)
C(4)-C(8)	1.526(4)
C(5)-C(6)	1.380(4)
C(5)-H(5)	0.9500
C(6)-H(6)	0.9500
C(7)-P(1)	1.811(3)
C(7)-H(7A)	0.9900
C(7)-H(7B)	0.9900
C(8)-P(2)	1.817(3)
C(8)-H(8A)	0.9900
C(8)-H(8B)	0.9900
C(11)-C(16)	1.376(4)
C(11)-C(12)	1.380(4)
C(11)-P(1)	1.798(3)
C(12)-C(13)	1.387(5)
C(12)-H(12)	0.9500

C(13)-C(14)	1.367(5)
C(13)-H(13)	0.9500
C(14)-C(15)	1.382(5)
C(14)-H(14)	0.9500
C(15)-C(16)	1.379(5)
C(15)-H(15)	0.9500
C(16)-H(16)	0.9500
C(21)-C(22)	1.360(4)
C(21)-C(26)	1.391(5)
C(21)-P(1)	1.797(3)
C(22)-C(23)	1.395(4)
C(22)-H(22)	0.9500
C(23)-C(24)	1.341(5)
C(23)-H(23)	0.9500
C(24)-C(25)	1.362(6)
C(24)-H(24)	0.9500
C(25)-C(26)	1.382(5)
C(25)-H(25)	0.9500
C(26)-H(26)	0.9500
C(31)-C(32)	1.395(4)
C(31)-C(36)	1.398(4)
C(31)-P(1)	1.801(3)
C(32)-C(33)	1.392(4)
C(32)-H(32)	0.9500
C(33)-C(34)	1.372(5)

C(33)-H(33)	0.9500
C(34)-C(35)	1.362(5)
C(34)-H(34)	0.9500
C(35)-C(36)	1.381(4)
C(35)-H(35)	0.9500
C(36)-H(36)	0.9500
C(41)-C(42)	1.384(4)
C(41)-C(46)	1.387(4)
C(41)-P(2)	1.785(3)
C(42)-C(43)	1.387(4)
C(42)-H(42)	0.9500
C(43)-C(44)	1.369(5)
C(43)-H(43)	0.9500
C(44)-C(45)	1.380(4)
C(44)-H(44)	0.9500
C(45)-C(46)	1.383(4)
C(45)-H(45)	0.9500
C(46)-H(46)	0.9500
C(51)-C(52)	1.378(4)
C(51)-C(56)	1.398(4)
C(51)-P(2)	1.793(3)
C(52)-C(53)	1.382(4)
C(52)-H(52)	0.9500
C(53)-C(54)	1.372(4)
C(53)-H(53)	0.9500

C(54)-C(55)	1.372(5)
C(54)-H(54)	0.9500
C(55)-C(56)	1.383(4)
C(55)-H(55)	0.9500
C(56)-H(56)	0.9500
C(61)-C(66)	1.393(4)
C(61)-C(62)	1.398(4)
C(61)-P(2)	1.786(3)
C(62)-C(63)	1.375(4)
C(62)-H(62)	0.9500
C(63)-C(64)	1.383(6)
C(63)-H(63)	0.9500
C(64)-C(65)	1.373(6)
C(64)-H(64)	0.9500
C(65)-C(66)	1.385(5)
C(65)-H(65)	0.9500
C(66)-H(66)	0.9500
B(1)-F(3)	1.337(5)
B(1)-F(2)	1.371(4)
B(1)-F(4)	1.372(4)
B(1)-F(1)	1.390(4)
B(2)-F(7)	1.326(4)
B(2)-F(6)	1.329(4)
B(2)-F(5)	1.370(4)
B(2)-F(8)	1.381(4)

C(2)-C(1)-C(6)	118.3(2)
C(2)-C(1)-C(7)	121.1(2)
C(6)-C(1)-C(7)	120.5(2)
C(1)-C(2)-C(3)	121.3(2)
C(1)-C(2)-H(2)	119.3
C(3)-C(2)-H(2)	119.3
C(2)-C(3)-C(4)	120.2(2)
C(2)-C(3)-H(3)	119.9
C(4)-C(3)-H(3)	119.9
C(5)-C(4)-C(3)	118.5(2)
C(5)-C(4)-C(8)	120.6(3)
C(3)-C(4)-C(8)	120.7(3)
C(6)-C(5)-C(4)	121.1(3)
C(6)-C(5)-H(5)	119.4
C(4)-C(5)-H(5)	119.4
C(5)-C(6)-C(1)	120.5(3)
C(5)-C(6)-H(6)	119.7
C(1)-C(6)-H(6)	119.7
C(1)-C(7)-P(1)	112.4(2)
C(1)-C(7)-H(7A)	109.1
P(1)-C(7)-H(7A)	109.1
C(1)-C(7)-H(7B)	109.1
P(1)-C(7)-H(7B)	109.1
H(7A)-C(7)-H(7B)	107.9

C(4)-C(8)-P(2)	116.75(19)
C(4)-C(8)-H(8A)	108.1
P(2)-C(8)-H(8A)	108.1
C(4)-C(8)-H(8B)	108.1
P(2)-C(8)-H(8B)	108.1
H(8A)-C(8)-H(8B)	107.3
C(16)-C(11)-C(12)	119.7(3)
C(16)-C(11)-P(1)	117.3(2)
C(12)-C(11)-P(1)	123.0(2)
C(11)-C(12)-C(13)	119.4(3)
C(11)-C(12)-H(12)	120.3
C(13)-C(12)-H(12)	120.3
C(14)-C(13)-C(12)	121.0(3)
C(14)-C(13)-H(13)	119.5
C(12)-C(13)-H(13)	119.5
C(13)-C(14)-C(15)	119.3(3)
C(13)-C(14)-H(14)	120.3
C(15)-C(14)-H(14)	120.3
C(16)-C(15)-C(14)	120.1(4)
C(16)-C(15)-H(15)	120.0
C(14)-C(15)-H(15)	120.0
C(11)-C(16)-C(15)	120.5(3)
C(11)-C(16)-H(16)	119.8
C(15)-C(16)-H(16)	119.8
C(22)-C(21)-C(26)	119.4(3)

C(22)-C(21)-P(1)	122.7(2)
C(26)-C(21)-P(1)	117.8(3)
C(21)-C(22)-C(23)	120.4(3)
C(21)-C(22)-H(22)	119.8
C(23)-C(22)-H(22)	119.8
C(24)-C(23)-C(22)	120.3(3)
C(24)-C(23)-H(23)	119.9
C(22)-C(23)-H(23)	119.9
C(23)-C(24)-C(25)	119.7(3)
C(23)-C(24)-H(24)	120.1
C(25)-C(24)-H(24)	120.1
C(24)-C(25)-C(26)	121.4(4)
C(24)-C(25)-H(25)	119.3
C(26)-C(25)-H(25)	119.3
C(25)-C(26)-C(21)	118.7(4)
C(25)-C(26)-H(26)	120.7
C(21)-C(26)-H(26)	120.7
C(32)-C(31)-C(36)	119.6(3)
C(32)-C(31)-P(1)	120.0(2)
C(36)-C(31)-P(1)	120.4(2)
C(33)-C(32)-C(31)	119.1(3)
C(33)-C(32)-H(32)	120.4
C(31)-C(32)-H(32)	120.4
C(34)-C(33)-C(32)	120.6(3)
C(34)-C(33)-H(33)	119.7

C(32)-C(33)-H(33)	119.7
C(35)-C(34)-C(33)	120.2(3)
C(35)-C(34)-H(34)	119.9
C(33)-C(34)-H(34)	119.9
C(34)-C(35)-C(36)	121.1(3)
C(34)-C(35)-H(35)	119.5
C(36)-C(35)-H(35)	119.5
C(35)-C(36)-C(31)	119.4(3)
C(35)-C(36)-H(36)	120.3
C(31)-C(36)-H(36)	120.3
C(42)-C(41)-C(46)	119.0(3)
C(42)-C(41)-P(2)	122.6(2)
C(46)-C(41)-P(2)	118.4(2)
C(41)-C(42)-C(43)	119.6(3)
C(41)-C(42)-H(42)	120.2
C(43)-C(42)-H(42)	120.2
C(44)-C(43)-C(42)	121.1(3)
C(44)-C(43)-H(43)	119.5
C(42)-C(43)-H(43)	119.5
C(43)-C(44)-C(45)	119.7(3)
C(43)-C(44)-H(44)	120.1
C(45)-C(44)-H(44)	120.1
C(44)-C(45)-C(46)	119.6(3)
C(44)-C(45)-H(45)	120.2
C(46)-C(45)-H(45)	120.2

C(45)-C(46)-C(41)	121.0(3)
C(45)-C(46)-H(46)	119.5
C(41)-C(46)-H(46)	119.5
C(52)-C(51)-C(56)	119.5(3)
C(52)-C(51)-P(2)	119.5(2)
C(56)-C(51)-P(2)	121.0(2)
C(51)-C(52)-C(53)	119.9(3)
C(51)-C(52)-H(52)	120.1
C(53)-C(52)-H(52)	120.1
C(54)-C(53)-C(52)	120.5(3)
C(54)-C(53)-H(53)	119.8
C(52)-C(53)-H(53)	119.8
C(55)-C(54)-C(53)	120.2(3)
C(55)-C(54)-H(54)	119.9
C(53)-C(54)-H(54)	119.9
C(54)-C(55)-C(56)	120.2(3)
C(54)-C(55)-H(55)	119.9
C(56)-C(55)-H(55)	119.9
C(55)-C(56)-C(51)	119.7(3)
C(55)-C(56)-H(56)	120.2
C(51)-C(56)-H(56)	120.2
C(66)-C(61)-C(62)	119.4(3)
C(66)-C(61)-P(2)	120.2(3)
C(62)-C(61)-P(2)	120.2(2)
C(63)-C(62)-C(61)	120.2(3)

C(63)-C(62)-H(62)	119.9
C(61)-C(62)-H(62)	119.9
C(62)-C(63)-C(64)	119.8(4)
C(62)-C(63)-H(63)	120.1
C(64)-C(63)-H(63)	120.1
C(65)-C(64)-C(63)	120.6(4)
C(65)-C(64)-H(64)	119.7
C(63)-C(64)-H(64)	119.7
C(64)-C(65)-C(66)	120.2(4)
C(64)-C(65)-H(65)	119.9
C(66)-C(65)-H(65)	119.9
C(65)-C(66)-C(61)	119.8(4)
C(65)-C(66)-H(66)	120.1
C(61)-C(66)-H(66)	120.1
F(3)-B(1)-F(2)	110.1(3)
F(3)-B(1)-F(4)	111.7(3)
F(2)-B(1)-F(4)	108.4(3)
F(3)-B(1)-F(1)	110.5(3)
F(2)-B(1)-F(1)	106.7(3)
F(4)-B(1)-F(1)	109.3(3)
F(7)-B(2)-F(6)	109.8(4)
F(7)-B(2)-F(5)	107.8(3)
F(6)-B(2)-F(5)	109.4(3)
F(7)-B(2)-F(8)	107.6(3)
F(6)-B(2)-F(8)	111.4(3)

F(5)-B(2)-F(8)	110.7(3)
C(21)-P(1)-C(11)	108.17(14)
C(21)-P(1)-C(31)	109.72(14)
C(11)-P(1)-C(31)	110.38(14)
C(21)-P(1)-C(7)	109.88(14)
C(11)-P(1)-C(7)	108.81(14)
C(31)-P(1)-C(7)	109.85(13)
C(41)-P(2)-C(61)	107.58(13)
C(41)-P(2)-C(51)	109.20(13)
C(61)-P(2)-C(51)	110.86(13)
C(41)-P(2)-C(8)	112.19(14)
C(61)-P(2)-C(8)	110.89(14)
C(51)-P(2)-C(8)	106.14(13)

Symmetry transformations used to generate equivalent atoms:

Table 3. Anisotropic displacement parameters ($\text{\AA}^2 \times 10^3$) for 9m_kznd_hi3_of. The anisotropic displacement factor exponent takes the form: $-2\pi^2 [h^2 a^{*2} U^{11} + \dots + 2 h k a^* b^* U^{12}]$

	U ¹¹	U ²²	U ³³	U ²³	U ¹³	U ¹²
C(1)	26(2)	24(1)	26(1)	0(1)	16(1)	3(1)
C(2)	27(1)	30(1)	23(1)	-4(1)	11(1)	-5(1)
C(3)	30(1)	27(1)	37(2)	-2(1)	22(1)	-5(1)
C(4)	34(2)	22(1)	27(2)	2(1)	18(1)	6(1)
C(5)	23(1)	46(2)	27(2)	-3(1)	12(1)	4(1)
C(6)	28(1)	37(2)	32(2)	-5(1)	18(1)	0(1)
C(7)	31(2)	30(2)	29(2)	-5(1)	17(1)	-4(1)
C(8)	36(2)	29(2)	29(2)	0(1)	19(1)	3(1)
C(11)	33(2)	31(2)	26(2)	-2(1)	14(1)	-6(1)
C(12)	38(2)	39(2)	81(3)	-16(2)	22(2)	0(2)
C(13)	58(2)	44(2)	94(3)	-31(2)	33(2)	-16(2)
C(14)	41(2)	57(2)	56(2)	-12(2)	20(2)	-20(2)
C(15)	46(2)	65(2)	81(3)	-16(2)	41(2)	-17(2)
C(16)	52(2)	54(2)	79(3)	-30(2)	49(2)	-19(2)
C(21)	41(2)	39(2)	27(2)	-1(1)	23(1)	-2(1)
C(22)	72(2)	46(2)	32(2)	-3(1)	30(2)	-7(2)
C(23)	73(3)	66(2)	33(2)	-14(2)	29(2)	-11(2)
C(24)	55(2)	84(3)	26(2)	3(2)	23(2)	7(2)

C(25)	173(5)	72(3)	55(2)	20(2)	74(3)	15(3)
C(26)	141(4)	48(2)	53(2)	1(2)	60(3)	-8(2)
C(31)	36(2)	26(1)	32(2)	2(1)	20(1)	1(1)
C(32)	37(2)	47(2)	39(2)	-4(1)	24(2)	-5(1)
C(33)	32(2)	49(2)	66(2)	2(2)	28(2)	-1(2)
C(34)	61(2)	44(2)	79(3)	2(2)	56(2)	3(2)
C(35)	84(3)	38(2)	56(2)	2(2)	54(2)	6(2)
C(36)	57(2)	33(2)	36(2)	2(1)	29(2)	7(1)
C(41)	33(2)	26(1)	30(2)	3(1)	19(1)	1(1)
C(42)	33(2)	38(2)	35(2)	-3(1)	12(1)	4(1)
C(43)	31(2)	60(2)	39(2)	-6(2)	4(2)	10(2)
C(44)	34(2)	47(2)	47(2)	6(2)	19(2)	12(2)
C(45)	43(2)	36(2)	58(2)	-8(2)	22(2)	7(2)
C(46)	35(2)	39(2)	52(2)	-12(1)	18(2)	-1(1)
C(51)	26(1)	29(1)	25(1)	3(1)	16(1)	1(1)
C(52)	50(2)	41(2)	29(2)	-7(1)	25(2)	-15(1)
C(53)	62(2)	46(2)	38(2)	5(1)	33(2)	-10(2)
C(54)	48(2)	59(2)	29(2)	4(2)	23(2)	0(2)
C(55)	54(2)	53(2)	26(2)	-3(1)	15(2)	-14(2)
C(56)	41(2)	37(2)	30(2)	-4(1)	18(1)	-13(1)
C(61)	43(2)	32(2)	32(2)	-1(1)	27(2)	-5(1)
C(62)	39(2)	43(2)	45(2)	-2(1)	27(2)	-7(1)
C(63)	53(2)	65(2)	70(3)	-19(2)	44(2)	-19(2)
C(64)	95(4)	73(3)	107(4)	-3(3)	83(3)	-28(3)
C(65)	92(3)	74(3)	94(3)	30(2)	71(3)	0(2)

C(66)	63(2)	51(2)	62(2)	17(2)	44(2)	4(2)
B(1)	44(2)	45(2)	45(2)	-13(2)	29(2)	-7(2)
B(2)	27(2)	38(2)	34(2)	-5(2)	16(2)	1(2)
F(1)	90(2)	50(1)	47(1)	4(1)	24(1)	-14(1)
F(2)	137(2)	117(2)	78(2)	12(2)	81(2)	57(2)
F(3)	66(2)	100(2)	184(3)	-29(2)	65(2)	-42(2)
F(4)	54(1)	49(1)	66(1)	-3(1)	26(1)	7(1)
F(5)	62(1)	60(1)	65(2)	-4(1)	7(1)	16(1)
F(6)	224(4)	139(3)	54(2)	29(2)	69(2)	127(3)
F(7)	124(2)	63(2)	307(5)	-15(2)	163(3)	-23(2)
F(8)	45(1)	44(1)	60(1)	-2(1)	20(1)	1(1)
P(1)	32(1)	29(1)	24(1)	-3(1)	17(1)	-3(1)
P(2)	25(1)	28(1)	23(1)	1(1)	14(1)	1(1)

Table 4. Hydrogen coordinates ($\times 10^4$) and isotropic displacement parameters ($\text{\AA}^2 \times 10^3$)

for 9m_kznd_hi3_of.

	x	y	z	U(eq)
H(2)	4001	9118	4507	34
H(3)	3847	9084	2873	35
H(5)	1708	8394	1501	39
H(6)	1866	8415	3132	38
H(7A)	2625	8988	4990	35
H(7B)	3492	9127	5547	35
H(8A)	3084	9015	1012	37
H(8B)	2217	9111	462	37
H(12)	2684	5793	4501	70
H(13)	1536	5071	3639	85
H(14)	573	5733	3638	66
H(15)	709	7221	4320	73
H(16)	1838	7973	5127	66
H(22)	3768	8976	7185	60
H(23)	4199	8967	8972	70
H(24)	4260	7607	9788	65
H(25)	3995	6230	8885	113
H(26)	3494	6215	7080	92

H(32)	4726	6967	6966	47
H(33)	5569	6219	6719	58
H(34)	5247	5843	5039	62
H(35)	4085	6173	3595	62
H(36)	3219	6896	3794	48
H(42)	4042	7877	2010	46
H(43)	5108	7006	2653	62
H(44)	5070	5617	1875	53
H(45)	3958	5090	404	59
H(46)	2889	5953	-249	54
H(52)	2722	8993	-811	46
H(53)	2178	9351	-2584	55
H(54)	1261	8415	-3887	54
H(55)	910	7080	-3436	57
H(56)	1426	6724	-1666	44
H(62)	968	7606	-547	49
H(63)	206	6735	-253	69
H(64)	695	5518	950	93
H(65)	1936	5162	1854	91
H(66)	2709	6017	1557	64

Table 5. Torsion angles [°] for 9m_kznd_hi3_0f.

C(6)-C(1)-C(2)-C(3)	-1.0(4)
C(7)-C(1)-C(2)-C(3)	176.5(3)
C(1)-C(2)-C(3)-C(4)	-0.3(4)
C(2)-C(3)-C(4)-C(5)	1.8(4)
C(2)-C(3)-C(4)-C(8)	177.9(2)
C(3)-C(4)-C(5)-C(6)	-2.1(4)
C(8)-C(4)-C(5)-C(6)	-178.2(3)
C(4)-C(5)-C(6)-C(1)	0.9(4)
C(2)-C(1)-C(6)-C(5)	0.7(4)
C(7)-C(1)-C(6)-C(5)	-176.8(3)
C(2)-C(1)-C(7)-P(1)	-96.0(3)
C(6)-C(1)-C(7)-P(1)	81.4(3)
C(5)-C(4)-C(8)-P(2)	-72.6(3)
C(3)-C(4)-C(8)-P(2)	111.3(3)
C(16)-C(11)-C(12)-C(13)	-0.1(5)
P(1)-C(11)-C(12)-C(13)	179.1(3)
C(11)-C(12)-C(13)-C(14)	-2.6(6)
C(12)-C(13)-C(14)-C(15)	4.0(6)
C(13)-C(14)-C(15)-C(16)	-2.7(6)
C(12)-C(11)-C(16)-C(15)	1.3(6)
P(1)-C(11)-C(16)-C(15)	-178.0(3)
C(14)-C(15)-C(16)-C(11)	0.1(6)
C(26)-C(21)-C(22)-C(23)	-2.5(6)

P(1)-C(21)-C(22)-C(23)	179.7(3)
C(21)-C(22)-C(23)-C(24)	1.0(6)
C(22)-C(23)-C(24)-C(25)	2.7(6)
C(23)-C(24)-C(25)-C(26)	-4.9(8)
C(24)-C(25)-C(26)-C(21)	3.3(8)
C(22)-C(21)-C(26)-C(25)	0.4(7)
P(1)-C(21)-C(26)-C(25)	178.3(4)
C(36)-C(31)-C(32)-C(33)	-1.4(4)
P(1)-C(31)-C(32)-C(33)	-179.3(2)
C(31)-C(32)-C(33)-C(34)	1.2(5)
C(32)-C(33)-C(34)-C(35)	-0.5(5)
C(33)-C(34)-C(35)-C(36)	0.0(5)
C(34)-C(35)-C(36)-C(31)	-0.3(5)
C(32)-C(31)-C(36)-C(35)	0.9(4)
P(1)-C(31)-C(36)-C(35)	178.8(2)
C(46)-C(41)-C(42)-C(43)	-1.9(5)
P(2)-C(41)-C(42)-C(43)	179.2(3)
C(41)-C(42)-C(43)-C(44)	0.5(5)
C(42)-C(43)-C(44)-C(45)	0.9(5)
C(43)-C(44)-C(45)-C(46)	-0.8(5)
C(44)-C(45)-C(46)-C(41)	-0.6(5)
C(42)-C(41)-C(46)-C(45)	2.0(5)
P(2)-C(41)-C(46)-C(45)	-179.1(3)
C(56)-C(51)-C(52)-C(53)	2.5(5)
P(2)-C(51)-C(52)-C(53)	-177.8(2)

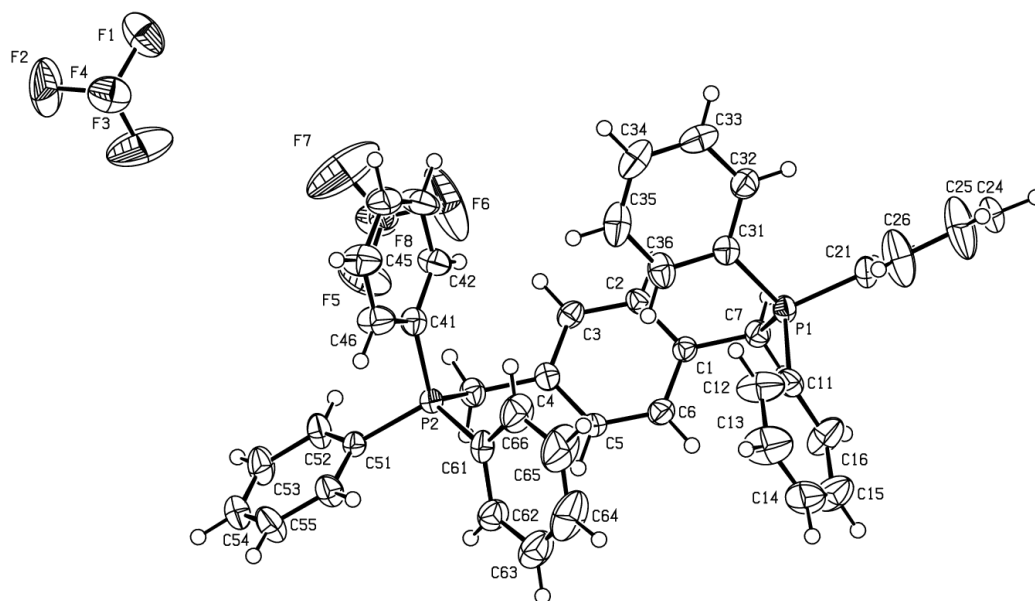
C(51)-C(52)-C(53)-C(54)	-1.0(5)
C(52)-C(53)-C(54)-C(55)	-1.4(5)
C(53)-C(54)-C(55)-C(56)	2.2(6)
C(54)-C(55)-C(56)-C(51)	-0.6(5)
C(52)-C(51)-C(56)-C(55)	-1.7(5)
P(2)-C(51)-C(56)-C(55)	178.6(2)
C(66)-C(61)-C(62)-C(63)	-1.3(5)
P(2)-C(61)-C(62)-C(63)	-175.6(2)
C(61)-C(62)-C(63)-C(64)	0.9(5)
C(62)-C(63)-C(64)-C(65)	-0.1(6)
C(63)-C(64)-C(65)-C(66)	-0.3(7)
C(64)-C(65)-C(66)-C(61)	-0.1(6)
C(62)-C(61)-C(66)-C(65)	0.9(5)
P(2)-C(61)-C(66)-C(65)	175.2(3)
C(22)-C(21)-P(1)-C(11)	-129.0(3)
C(26)-C(21)-P(1)-C(11)	53.2(3)
C(22)-C(21)-P(1)-C(31)	110.5(3)
C(26)-C(21)-P(1)-C(31)	-67.3(3)
C(22)-C(21)-P(1)-C(7)	-10.3(3)
C(26)-C(21)-P(1)-C(7)	171.8(3)
C(16)-C(11)-P(1)-C(21)	68.5(3)
C(12)-C(11)-P(1)-C(21)	-110.8(3)
C(16)-C(11)-P(1)-C(31)	-171.5(3)
C(12)-C(11)-P(1)-C(31)	9.3(3)
C(16)-C(11)-P(1)-C(7)	-50.8(3)

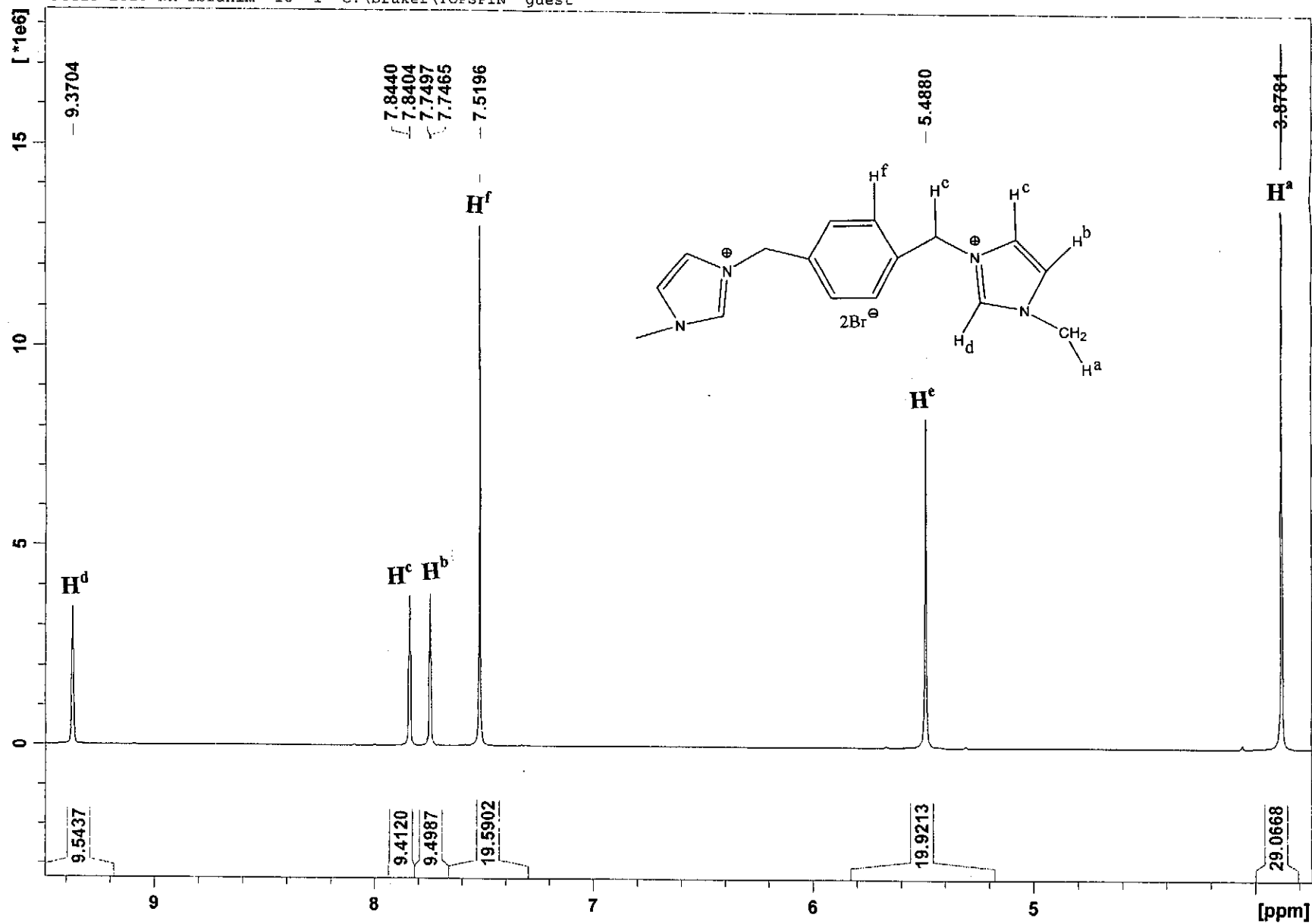
C(12)-C(11)-P(1)-C(7)	129.9(3)
C(32)-C(31)-P(1)-C(21)	-11.0(3)
C(36)-C(31)-P(1)-C(21)	171.2(2)
C(32)-C(31)-P(1)-C(11)	-130.1(2)
C(36)-C(31)-P(1)-C(11)	52.0(3)
C(32)-C(31)-P(1)-C(7)	109.9(2)
C(36)-C(31)-P(1)-C(7)	-67.9(3)
C(1)-C(7)-P(1)-C(21)	166.0(2)
C(1)-C(7)-P(1)-C(11)	-75.7(2)
C(1)-C(7)-P(1)-C(31)	45.2(2)
C(42)-C(41)-P(2)-C(61)	-117.1(3)
C(46)-C(41)-P(2)-C(61)	64.0(3)
C(42)-C(41)-P(2)-C(51)	122.6(3)
C(46)-C(41)-P(2)-C(51)	-56.4(3)
C(42)-C(41)-P(2)-C(8)	5.2(3)
C(46)-C(41)-P(2)-C(8)	-173.8(2)
C(66)-C(61)-P(2)-C(41)	18.8(3)
C(62)-C(61)-P(2)-C(41)	-166.9(2)
C(66)-C(61)-P(2)-C(51)	138.1(3)
C(62)-C(61)-P(2)-C(51)	-47.6(3)
C(66)-C(61)-P(2)-C(8)	-104.2(3)
C(62)-C(61)-P(2)-C(8)	70.0(3)
C(52)-C(51)-P(2)-C(41)	-84.0(3)
C(56)-C(51)-P(2)-C(41)	95.7(3)
C(52)-C(51)-P(2)-C(61)	157.7(2)

C(56)-C(51)-P(2)-C(61)	-22.7(3)
C(52)-C(51)-P(2)-C(8)	37.2(3)
C(56)-C(51)-P(2)-C(8)	-143.2(2)
C(4)-C(8)-P(2)-C(41)	-78.5(2)
C(4)-C(8)-P(2)-C(61)	41.8(3)
C(4)-C(8)-P(2)-C(51)	162.3(2)

Symmetry transformations used to generate equivalent atoms:

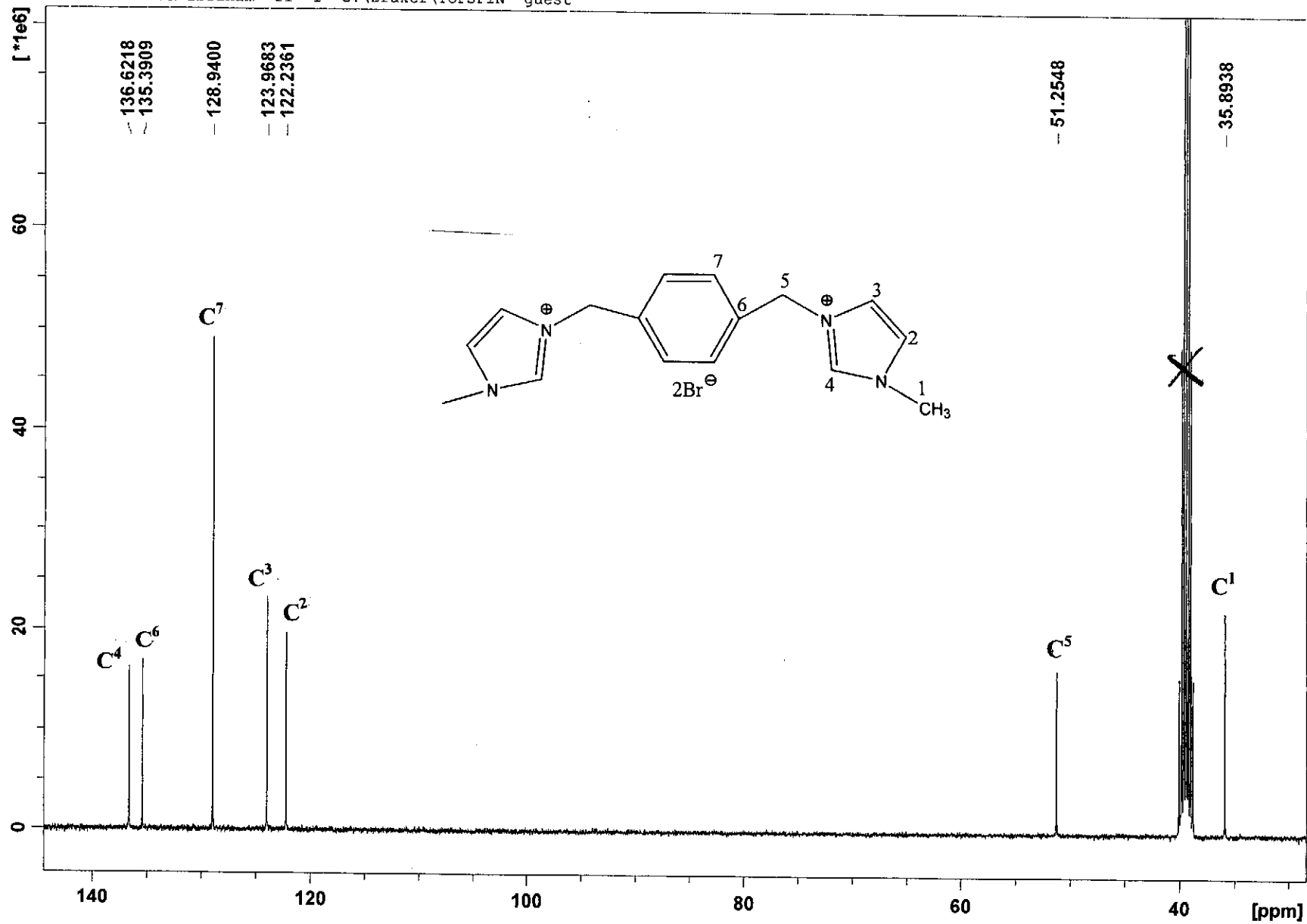
ORTEP diagram (50%)



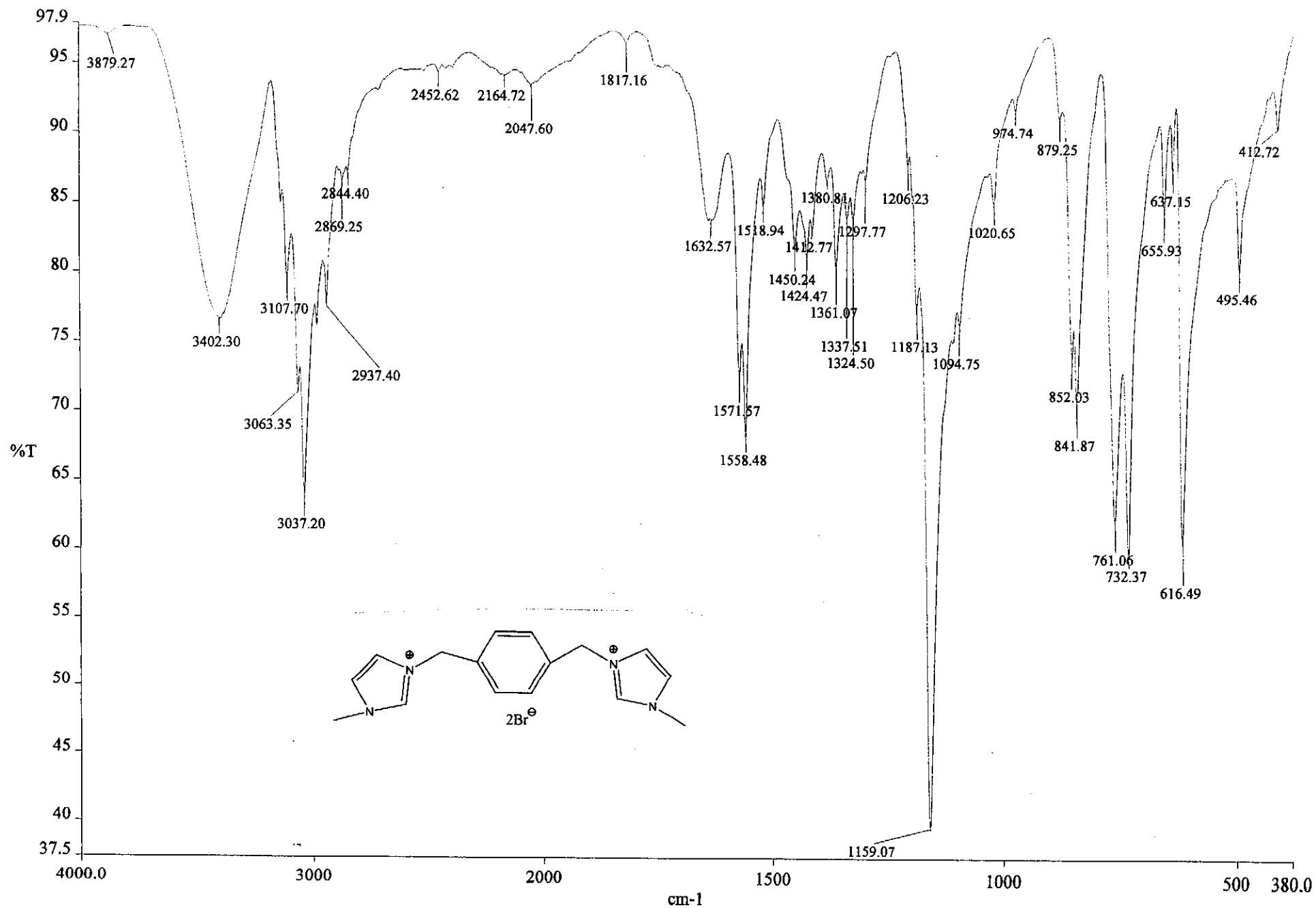


¹H NMR spectrum of Compound A-1

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¹³C NMR spectrum of Compound A-1

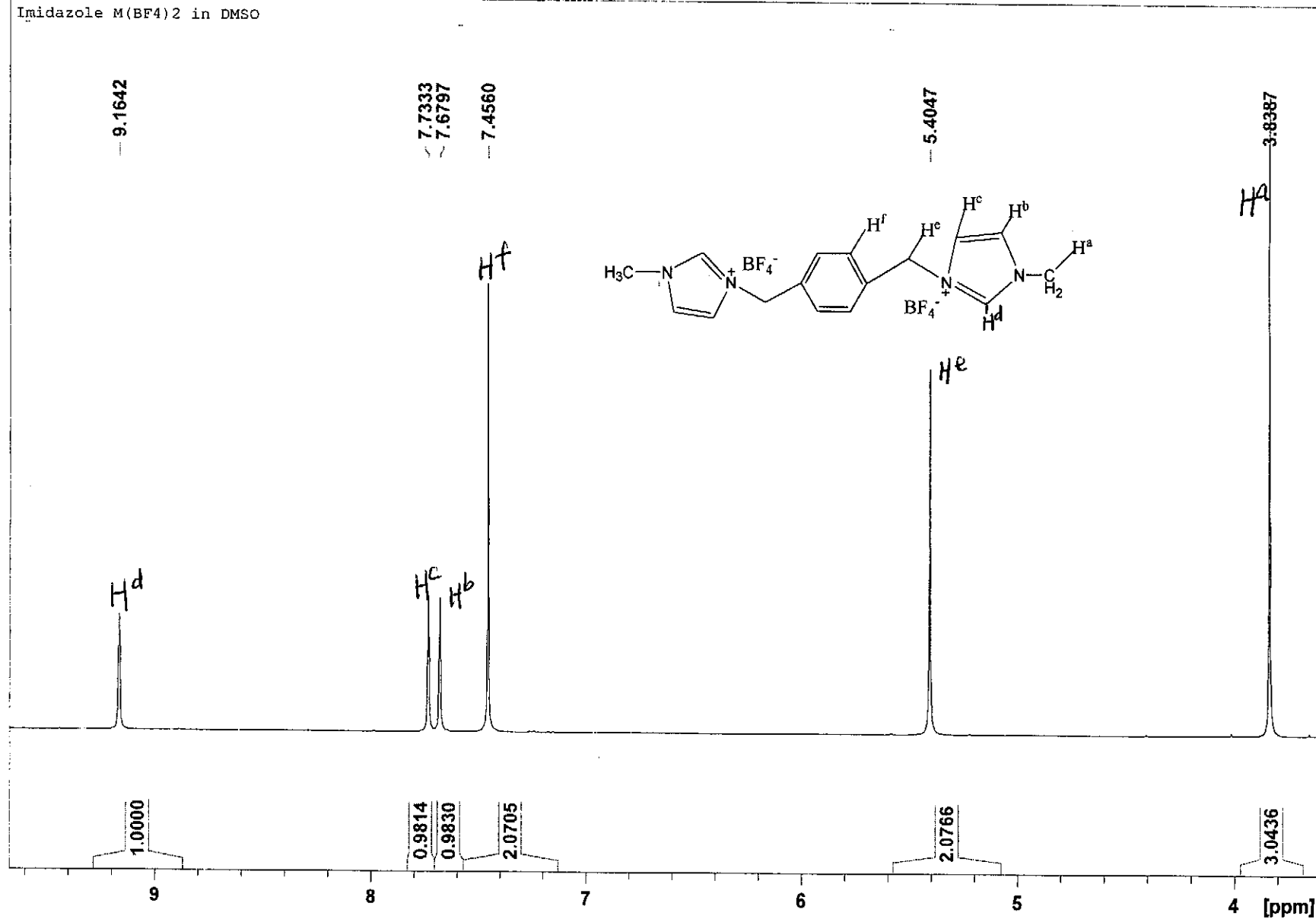


c:\pel_data\spectra\brahim\imidazole il, mbr2.002 - White crystalline subs.

IR spectrum of Compound A-1

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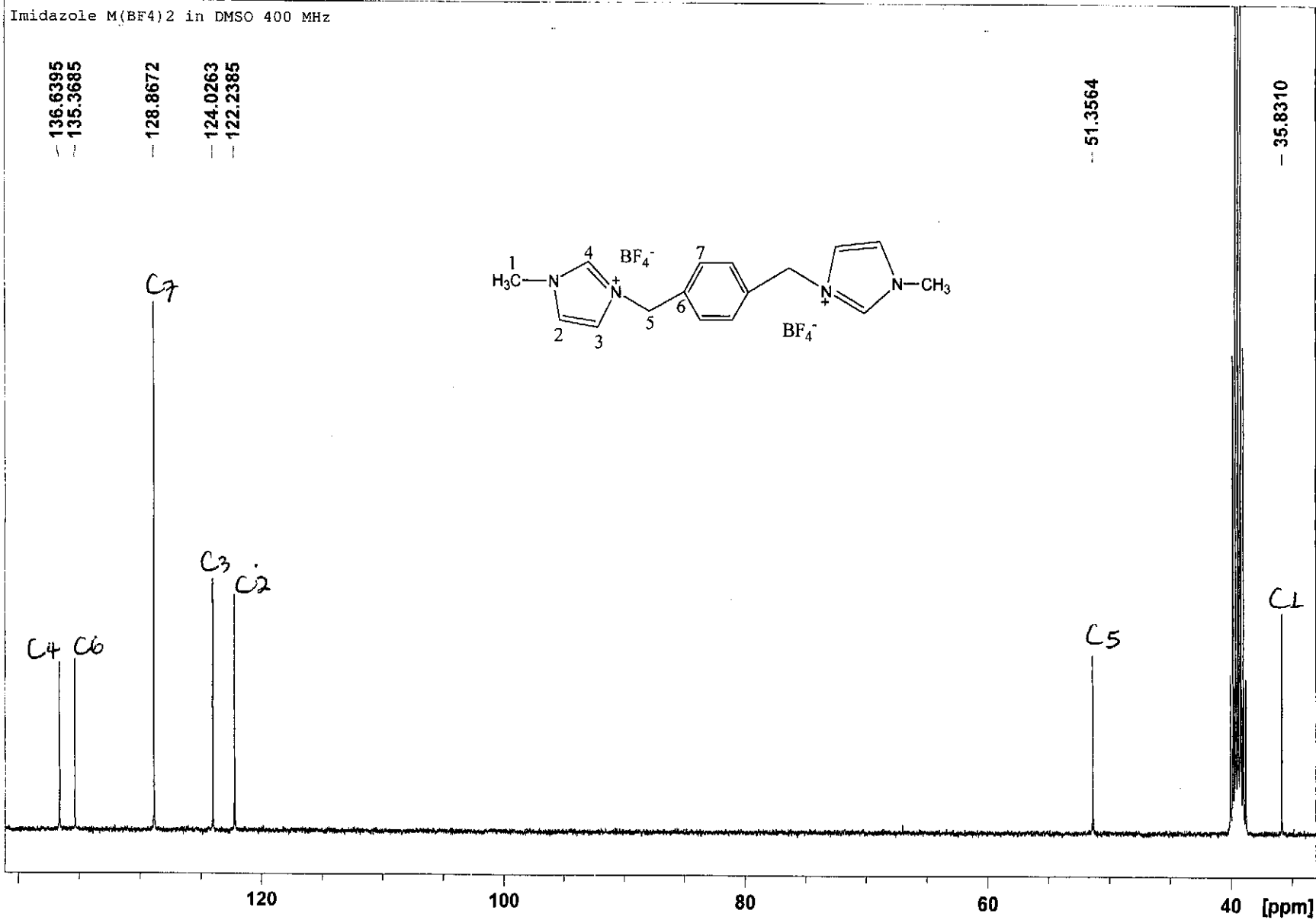
Imidazole M(BF4)2 in DMSO



^1H NMR spectrum of Compound A-2

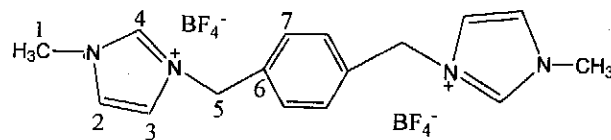
Sep28-2009-NK-Ibrahim 11 1 C:\Bruker\TOPSPIN guest

Imidazole M(BF₄)₂ in DMSO 400 MHz



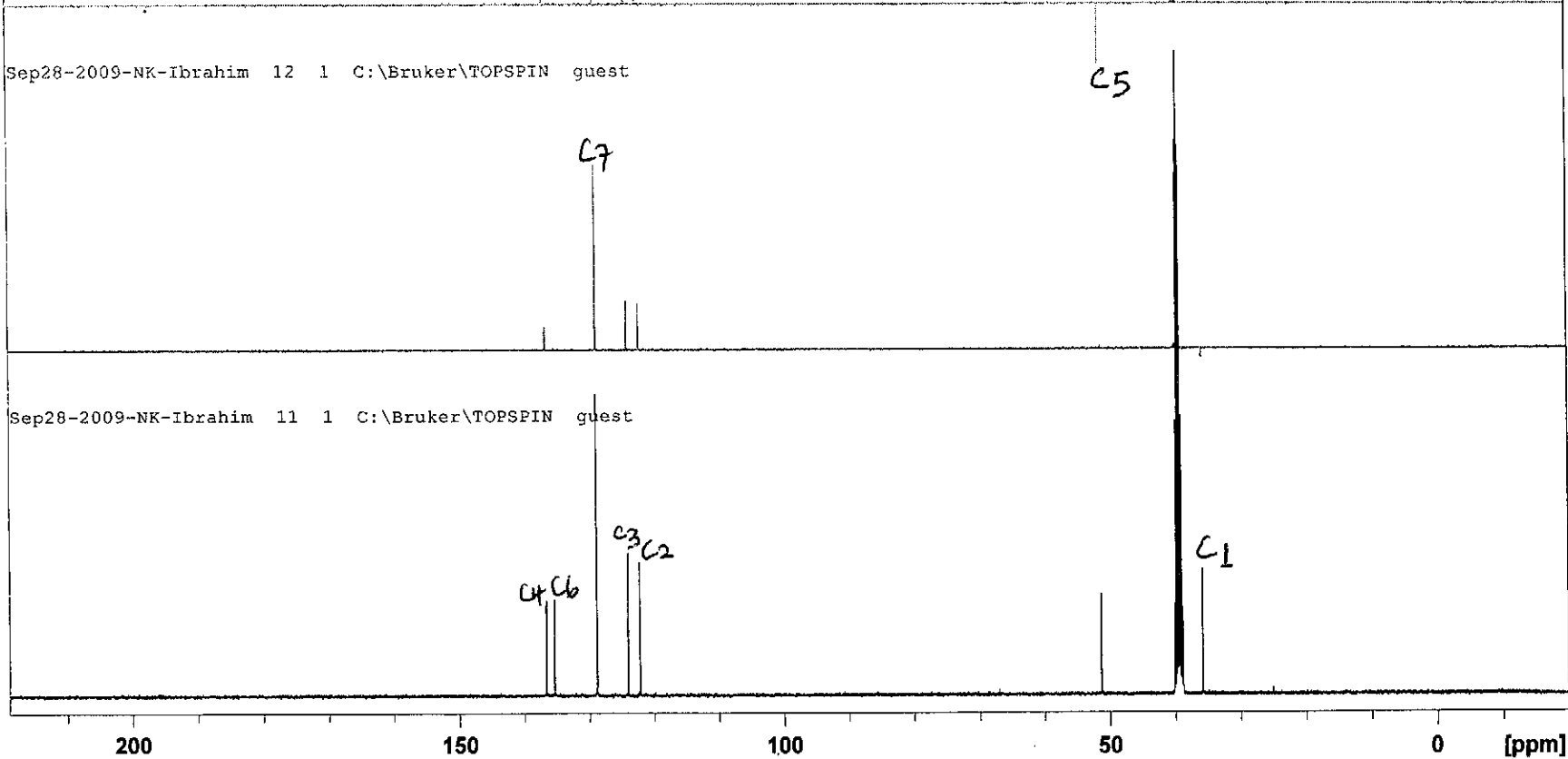
Sep28-2009-NK-Ibrahim 11 1 C:\Bruker\TOPSPIN guest

Sep28-2009-NK-Ibrahim 13 1 C:\Bruker\TOPSPIN guest



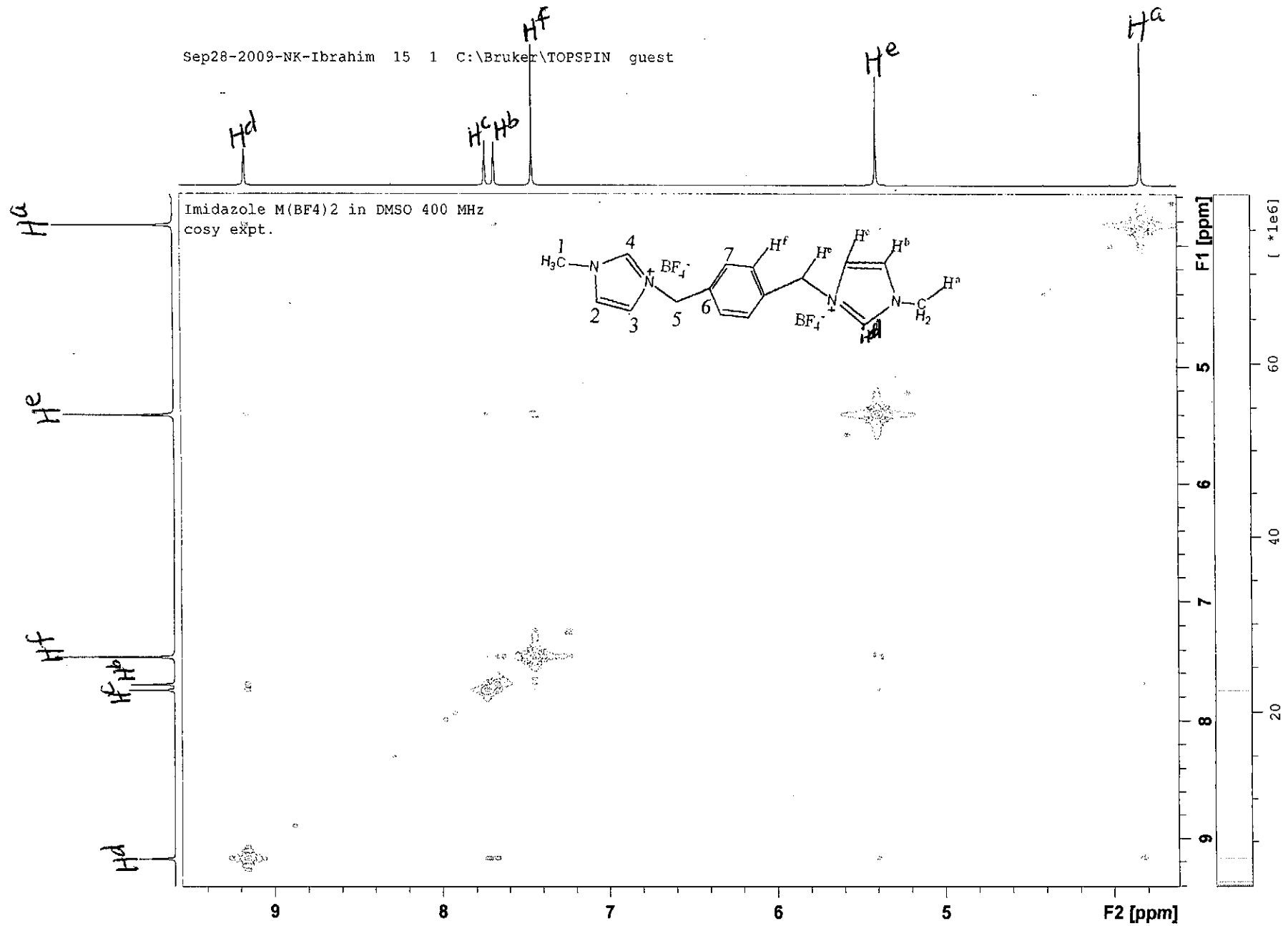
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Sep28-2009-NK-Ibrahim 11 1 C:\Bruker\TOPSPIN guest



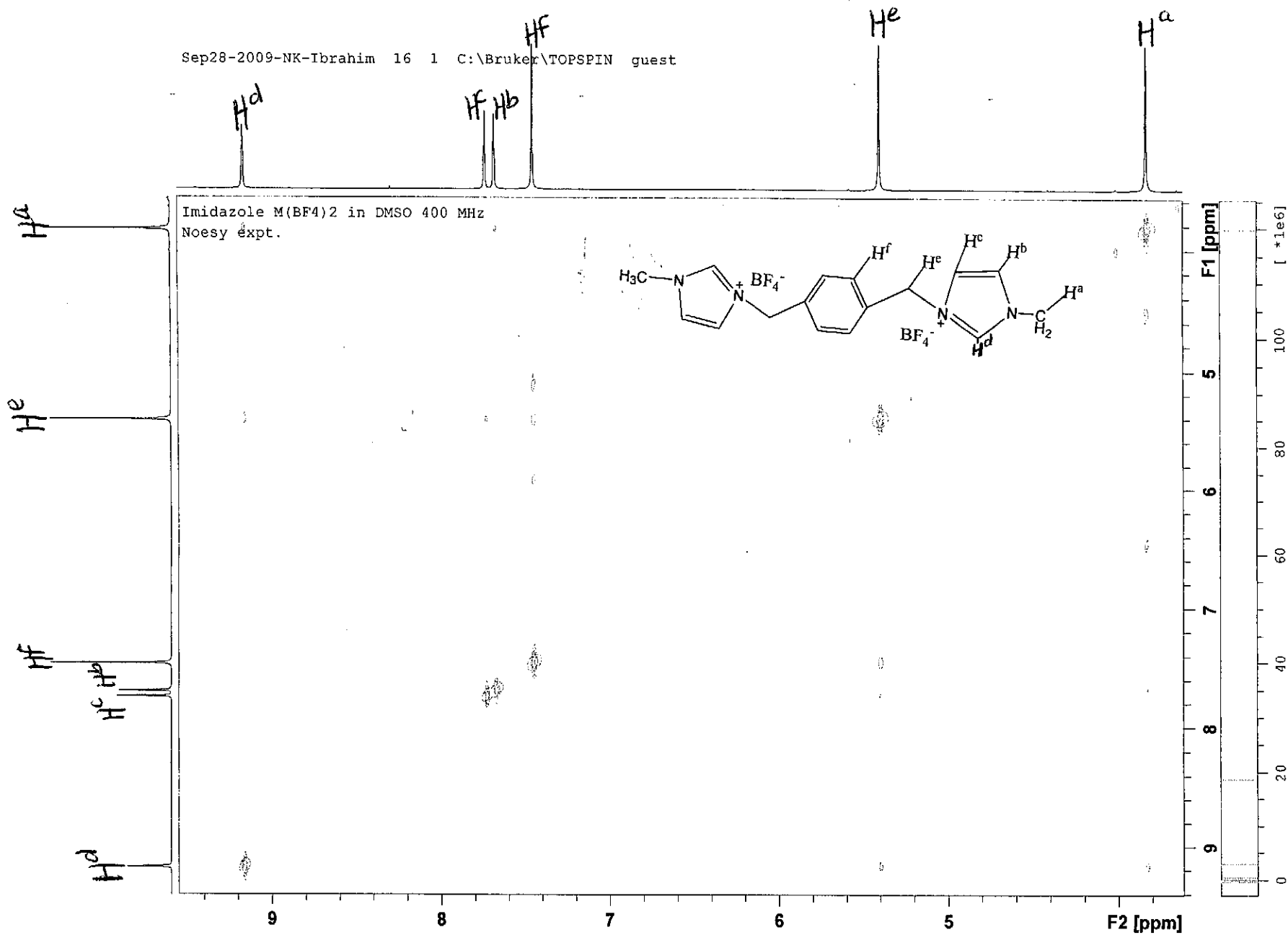
Dept 90 and 135 spectra of Compound A-2

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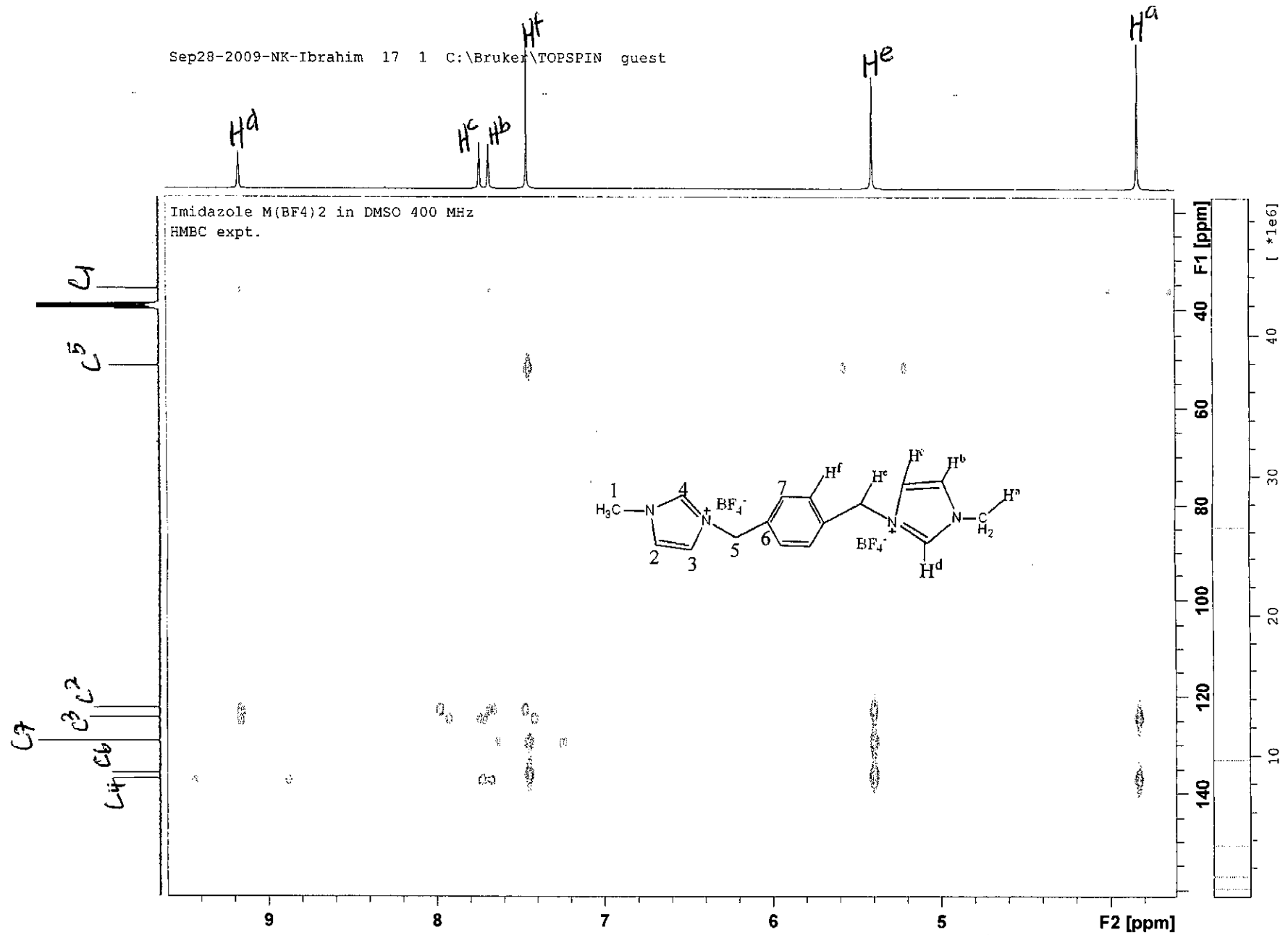
COSY spectrum of Compound A-2

Sep28-2009-NK-Ibrahim 16 1 C:\Bruker\TOPSPIN guest



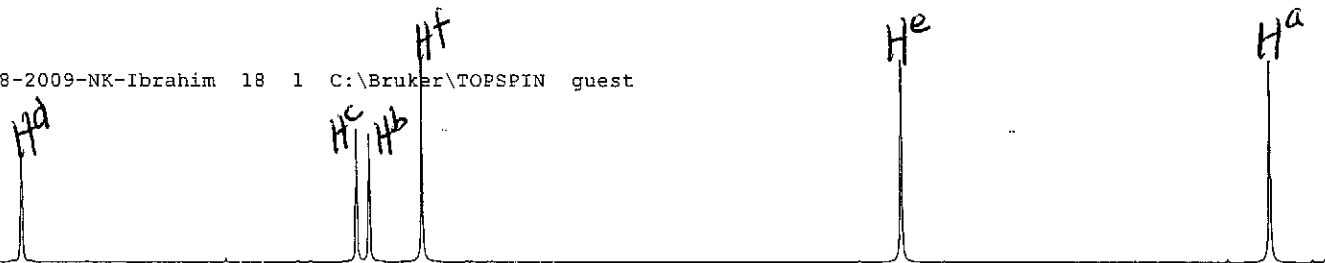
NOESY spectrum of Compound A-2

Sep28-2009-NK-Ibrahim 17 1 C:\Bruker\TOPSPIN guest

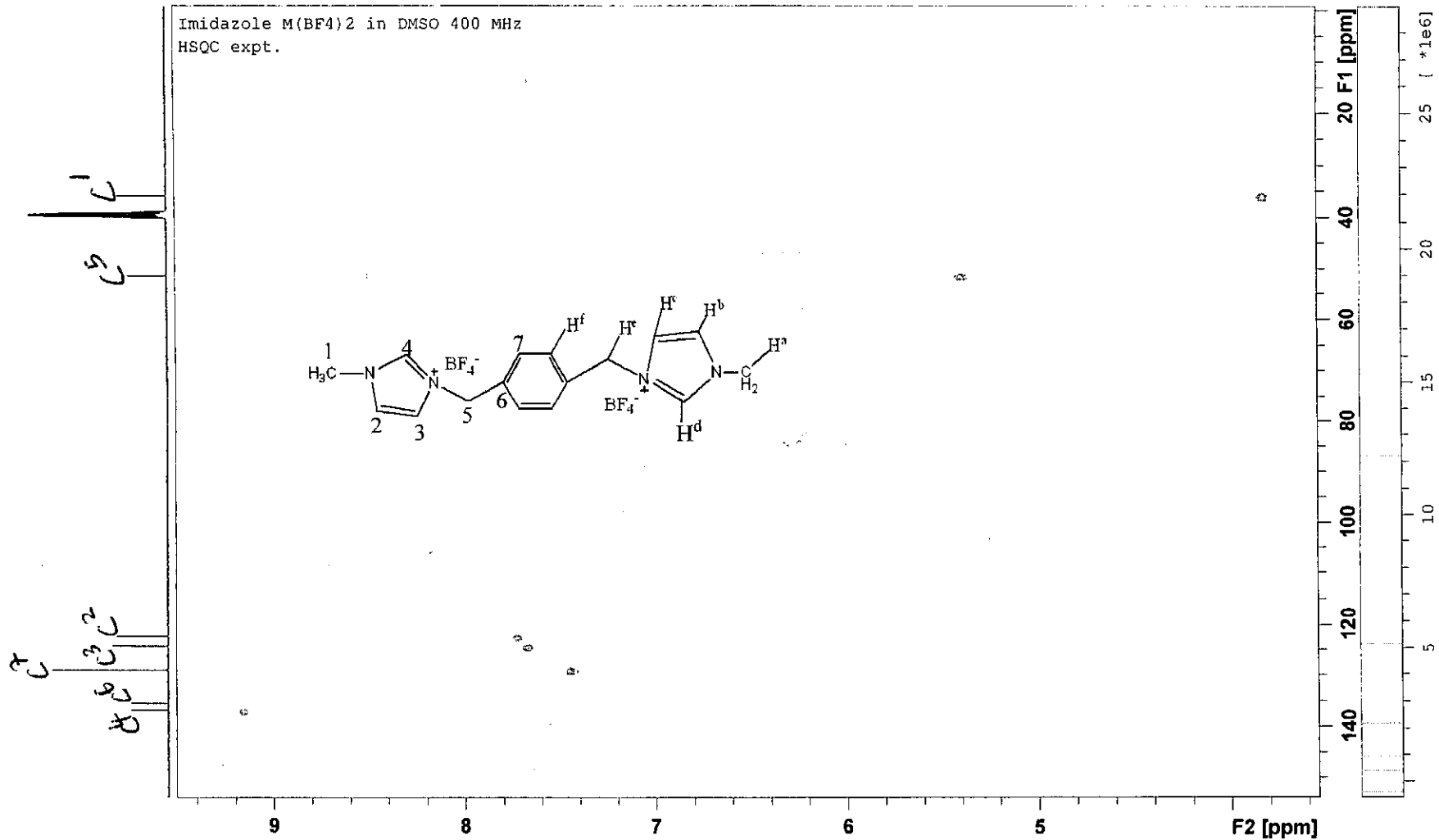


HMBC spectrum of Compound A-2

Sep28-2009-NK-Ibrahim 18 1 C:\Bruker\TOPSPIN guest



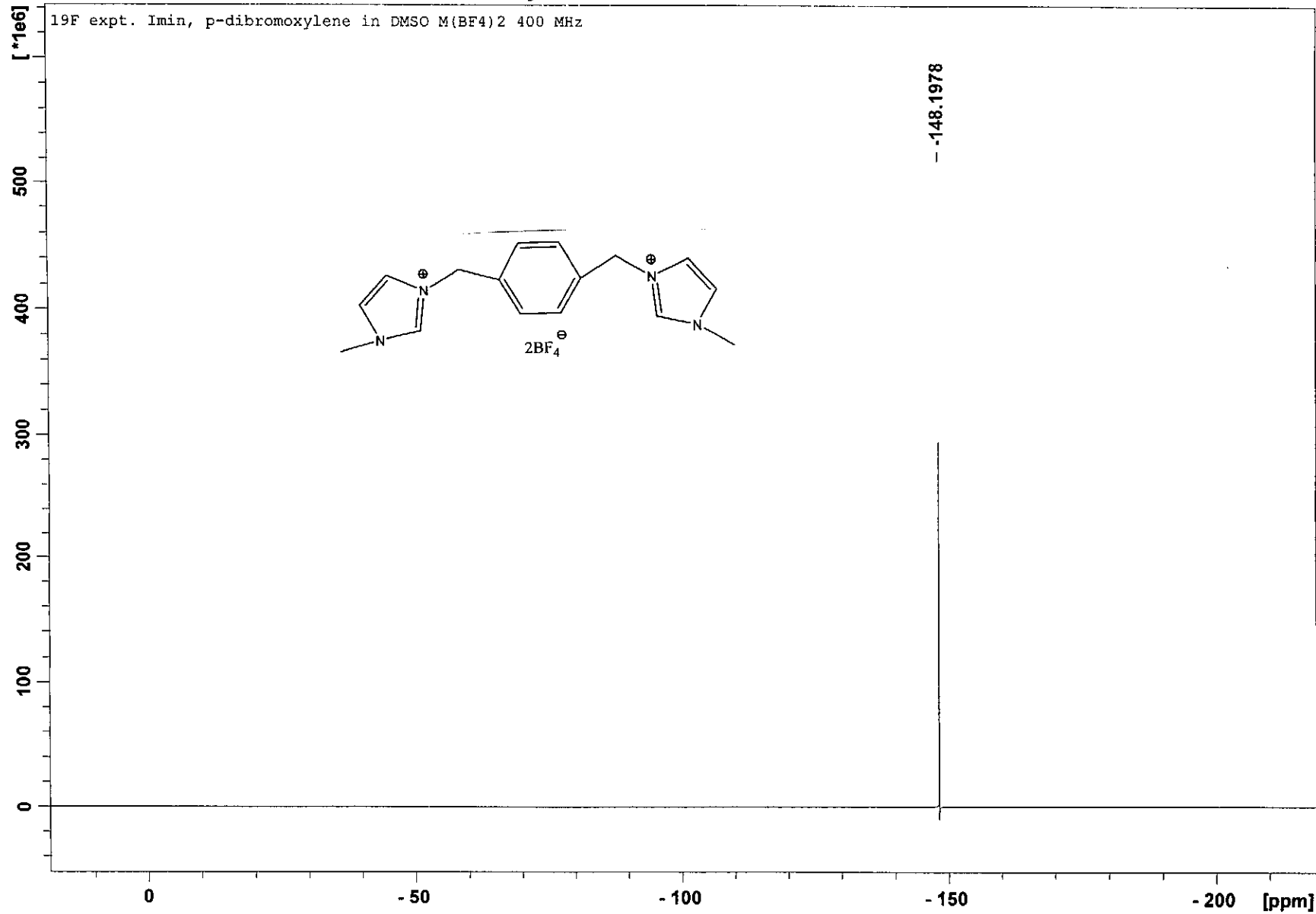
Imidazole M(BF4)2 in DMSO 400 MHz
HSQC expt.



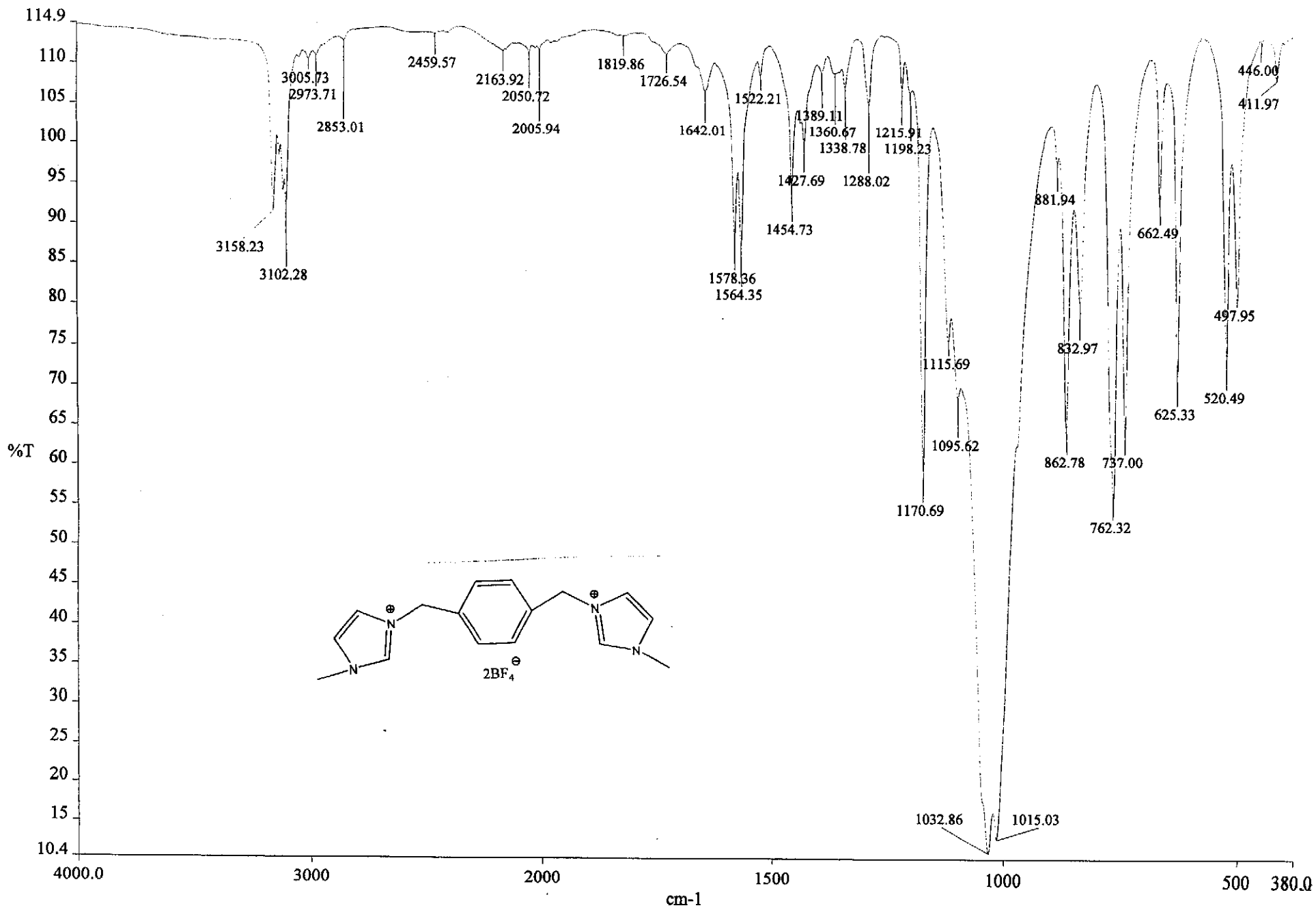
HSQC spectrum of Compound A-2

Nov23-2010-NK-Ibrahim 10 1 C:\Bruker\TOPSPIN guest

¹⁹F expt. Imin, p-dibromoxylene in DMSO M(BF₄)₂ 400 MHz



¹⁹F NMR spectrum of Compound A-2

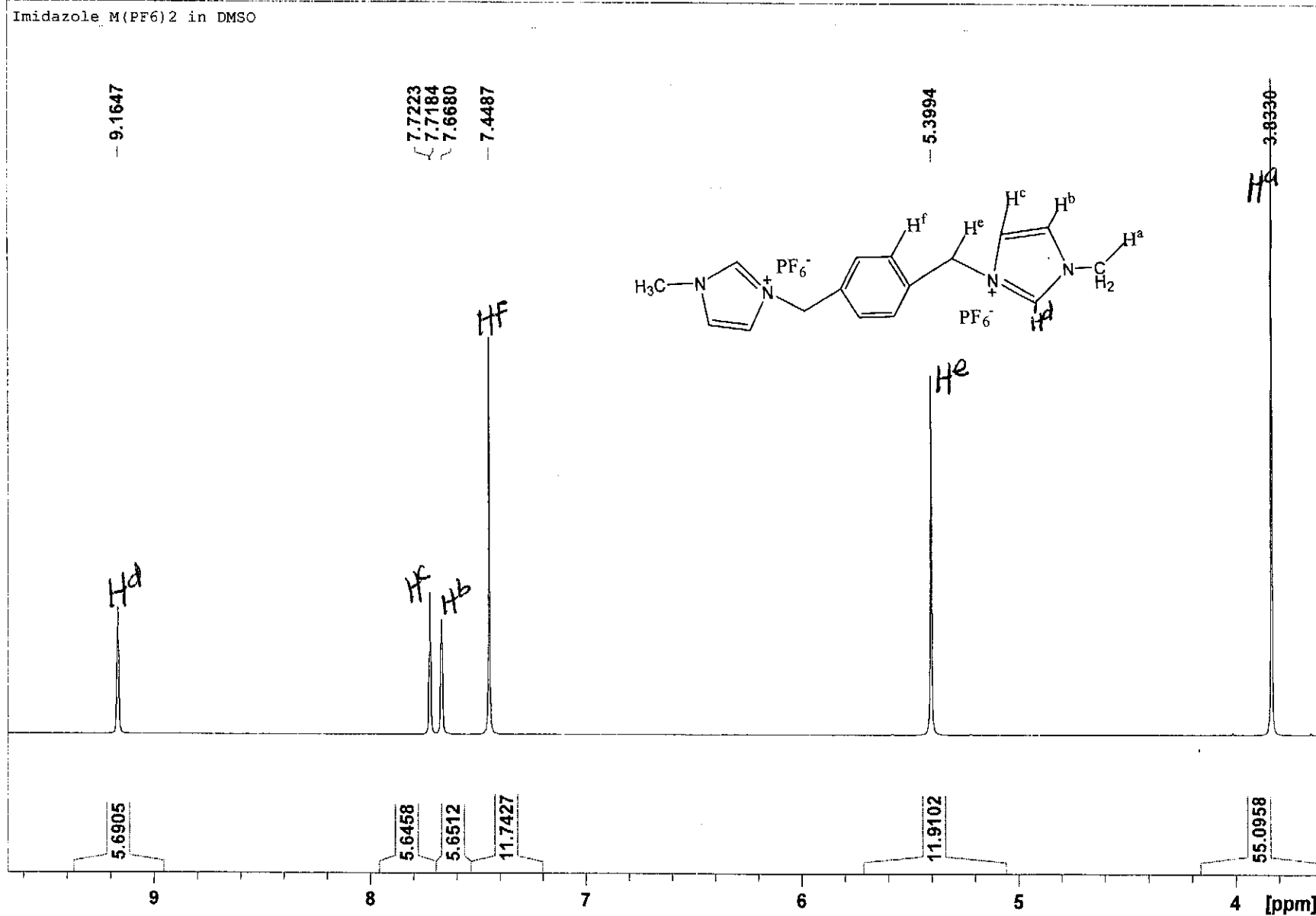


c:\pel_data\spectra\brahim\imidazole II, m(bf4)2.002 - White crystalline subs.

IR spectrum of Compound A-2

Sep28-2009-NK-Ibrahim 20 1 C:\Bruker\TOPSPIN guest

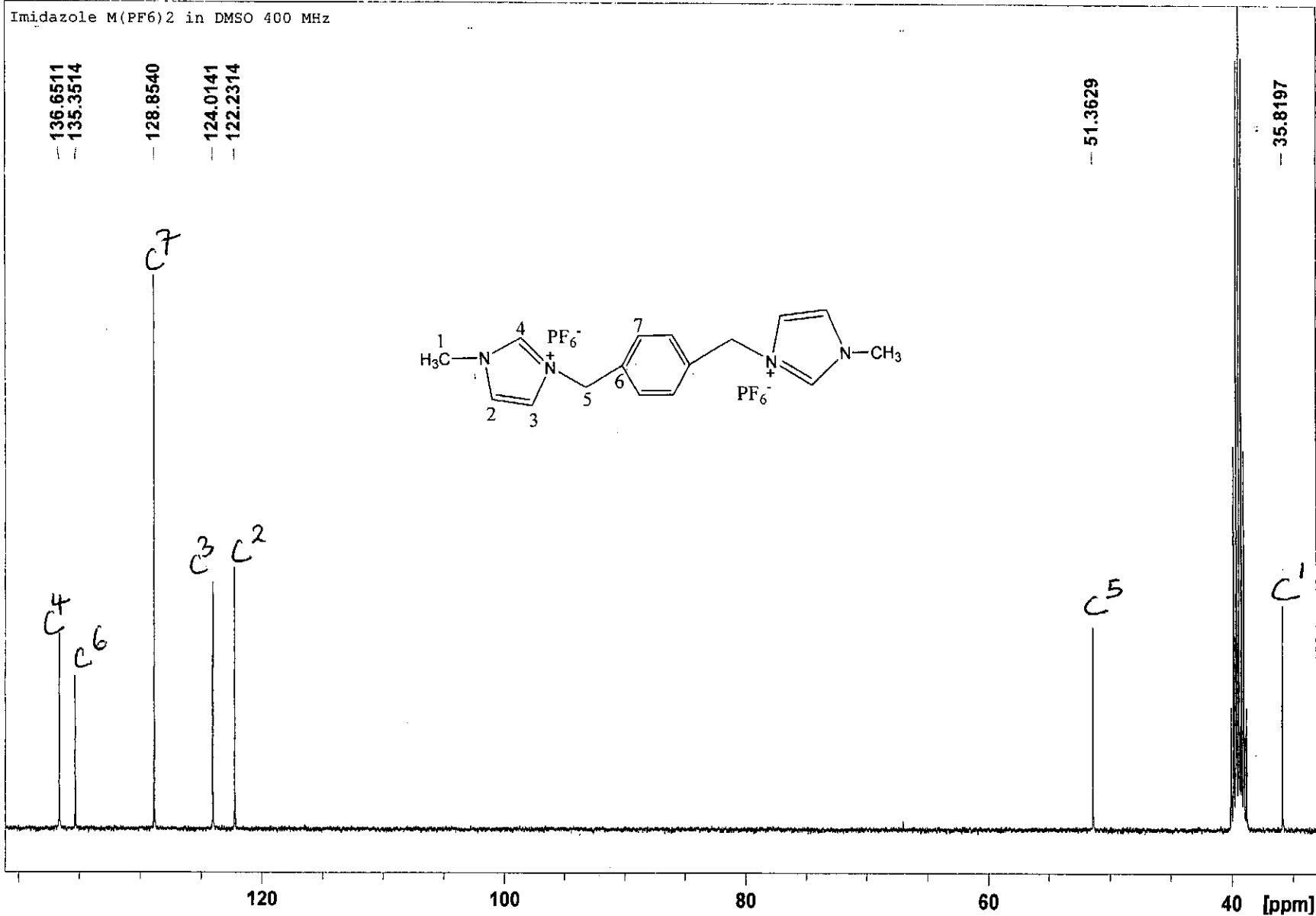
Imidazole M(PF6)2 in DMSO



¹H NMR spectrum of Compound A-3

Sep28-2009-NK-Ibrahim 21 1 C:\Bruker\TOPSPIN guest

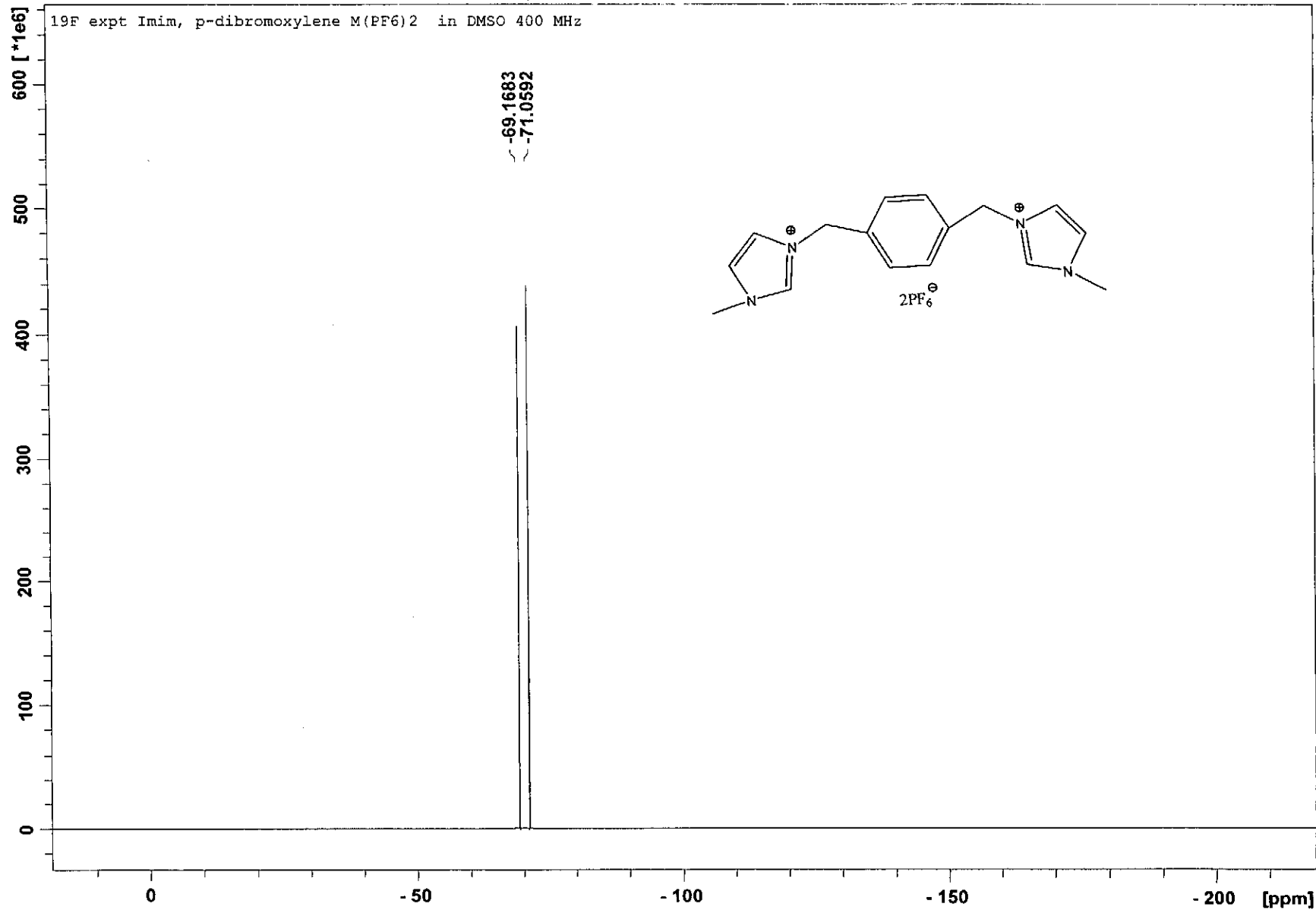
Imidazole M(PF6)2 in DMSO 400 MHz



¹³C NMR spectrum of Compound A-3

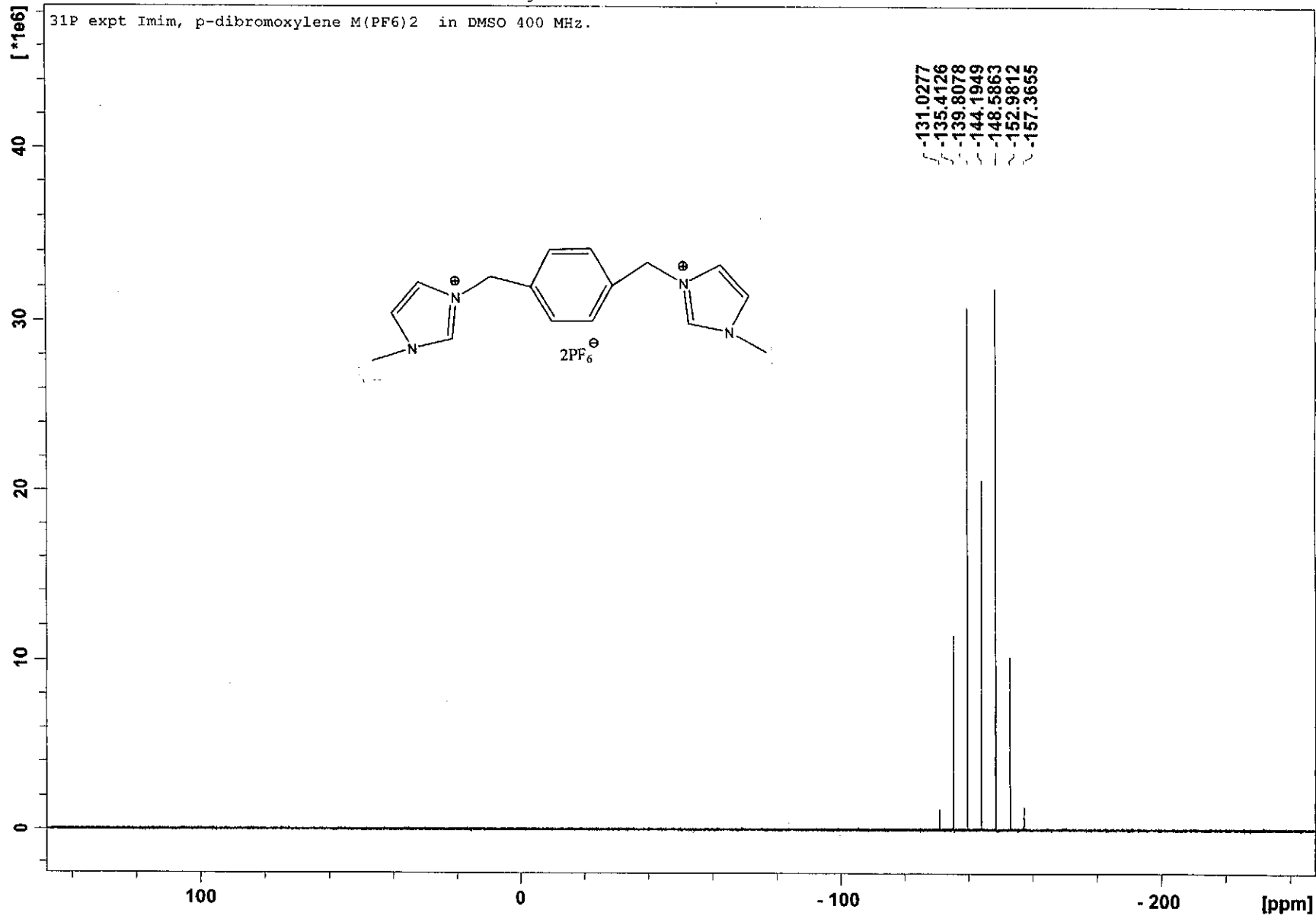
Nov23-2010-NK-Ibrahim 20 1 C:\Bruker\TOPSPIN guest

19F expt Imim, p-dibromoxylene M(PF6)2 in DMSO 400 MHz

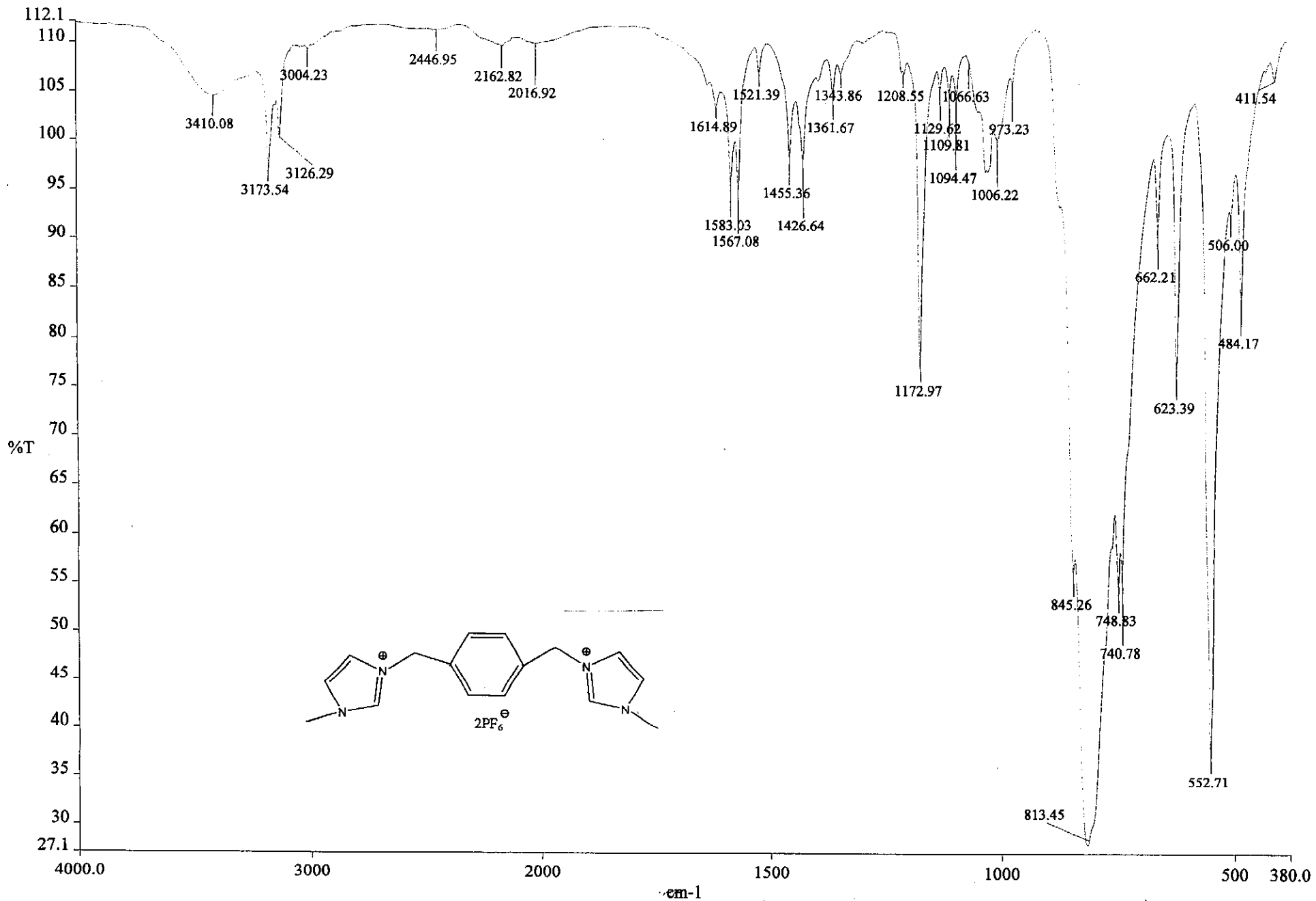


^{19}F NMR spectrum of Compound A-3

Nov23-2010-NK-Ibrahim 21 1 C:\Bruker\TOPSPIN guest



³¹P NMR spectrum of Compound A-3

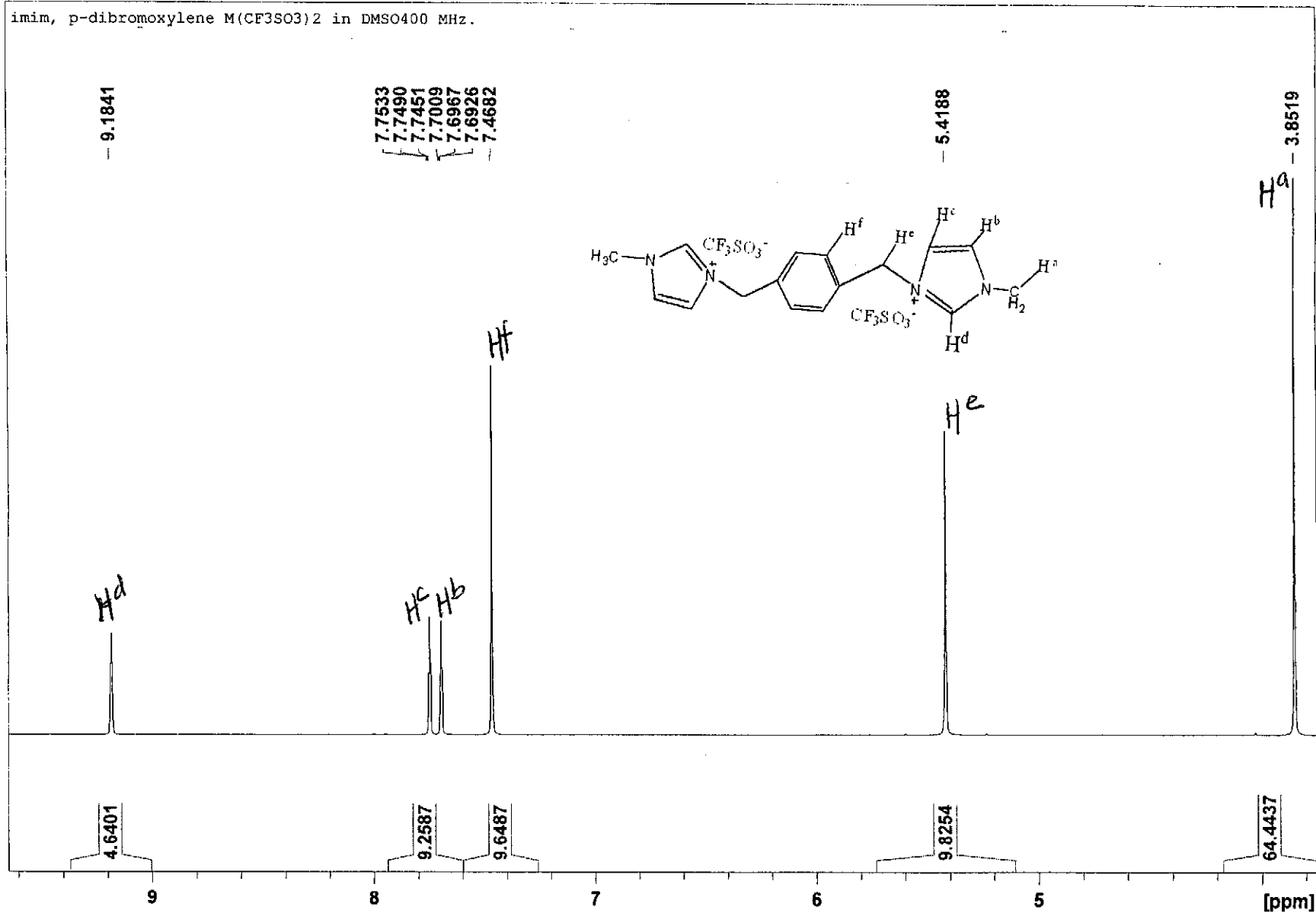


c:\pel_data\spectra\brahim\imidazole ii, m(pf6)2.002 - White crystalline subs.

IR spectrum of Compound A-3

Nov23-2010-NK-Ibrahim 32 1 C:\Bruker\TOPSPIN guest

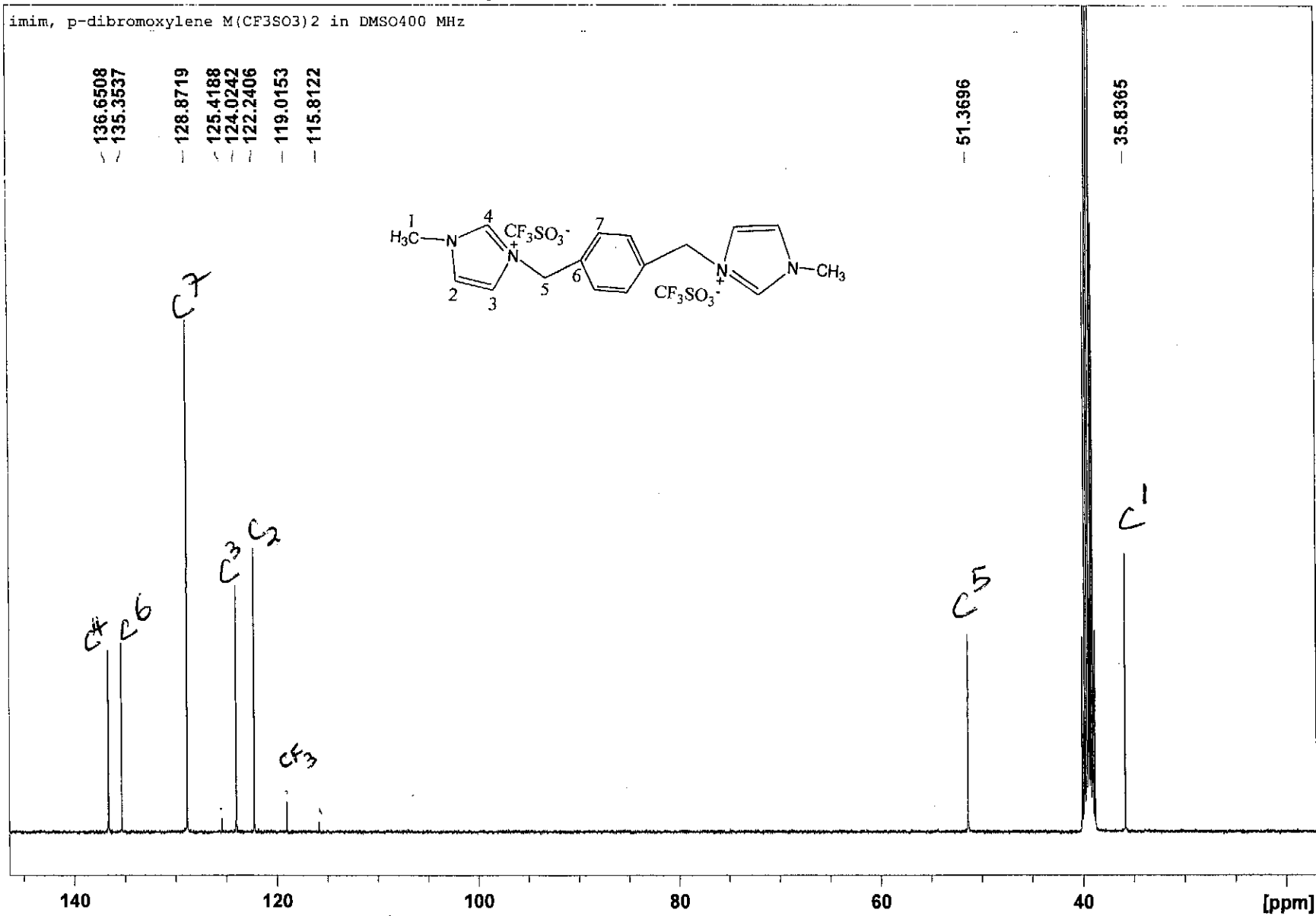
imim, p-dibromoxylene M(CF₃SO₃)₂ in DMSO400 MHz.



¹H NMR spectrum of Compound A-4

Nov23-2010-NK-Ibrahim 30 1 C:\Bruker\TOPSPIN guest

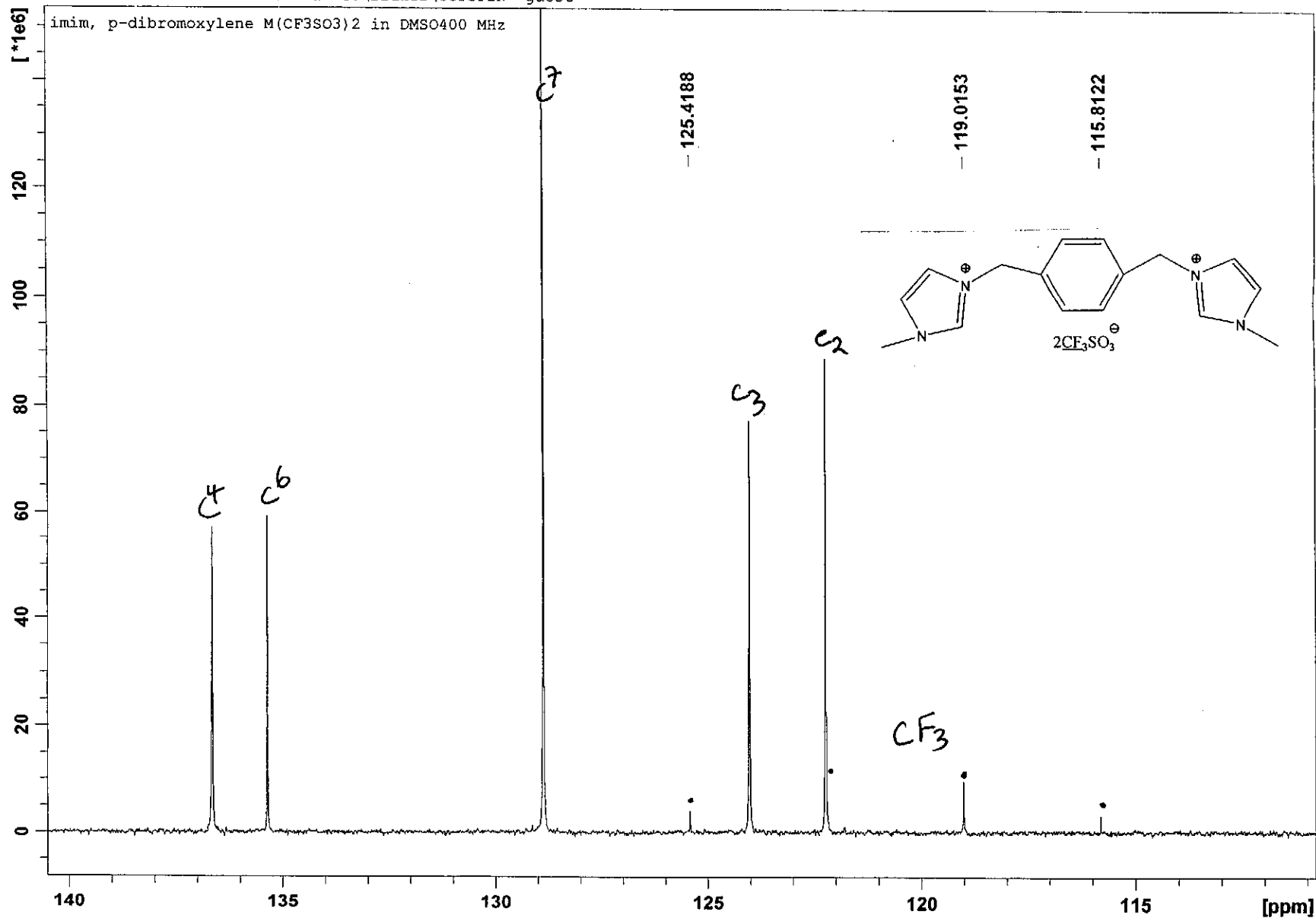
imim, p-dibromoxylene M(CF₃SO₃)₂ in DMSO400 MHz



¹³C NMR spectrum of Compound A-4

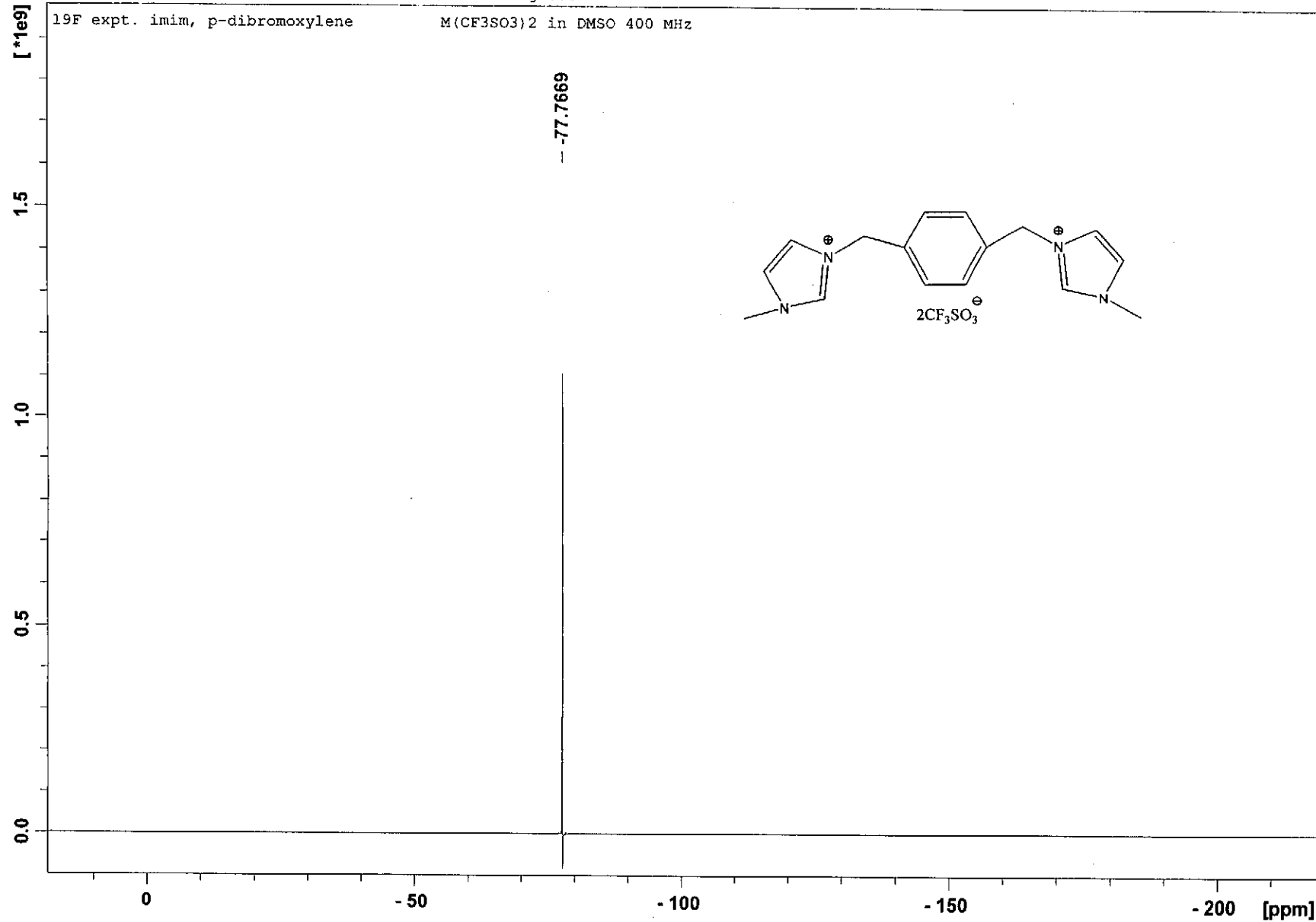
Nov23-2010-NK-Ibrahim 30 1 C:\Bruker\TOPSPIN guest

imim, p-dibromoxylene M(CF₃SO₃)₂ in DMSO400 MHz

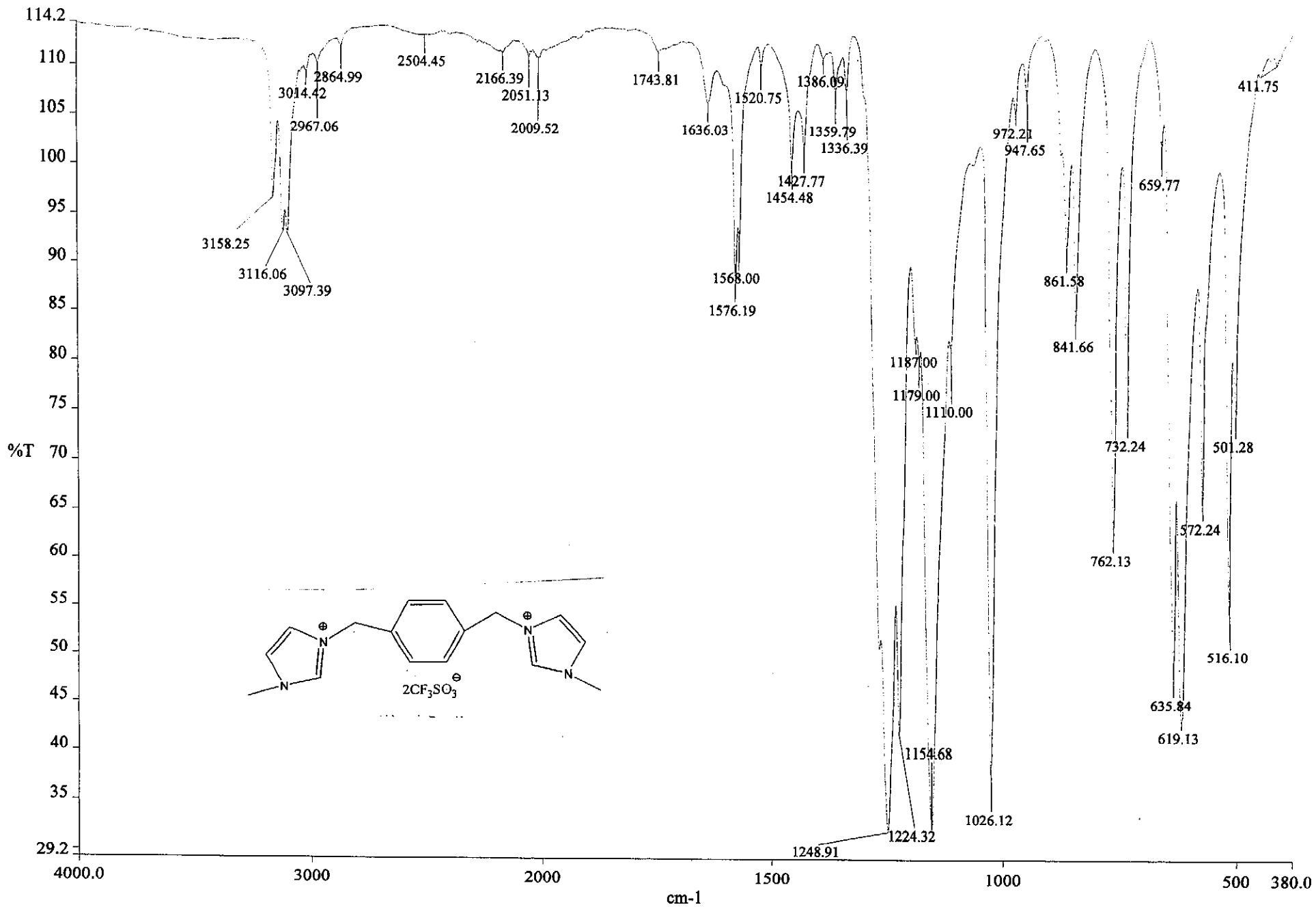


¹³C NMR spectrum of Compound A-4 (CF₃)

Nov23-2010-NK-Ibrahim 31 1 C:\Bruker\TOPSPIN guest



¹⁹F NMR spectrum of Compound A-4

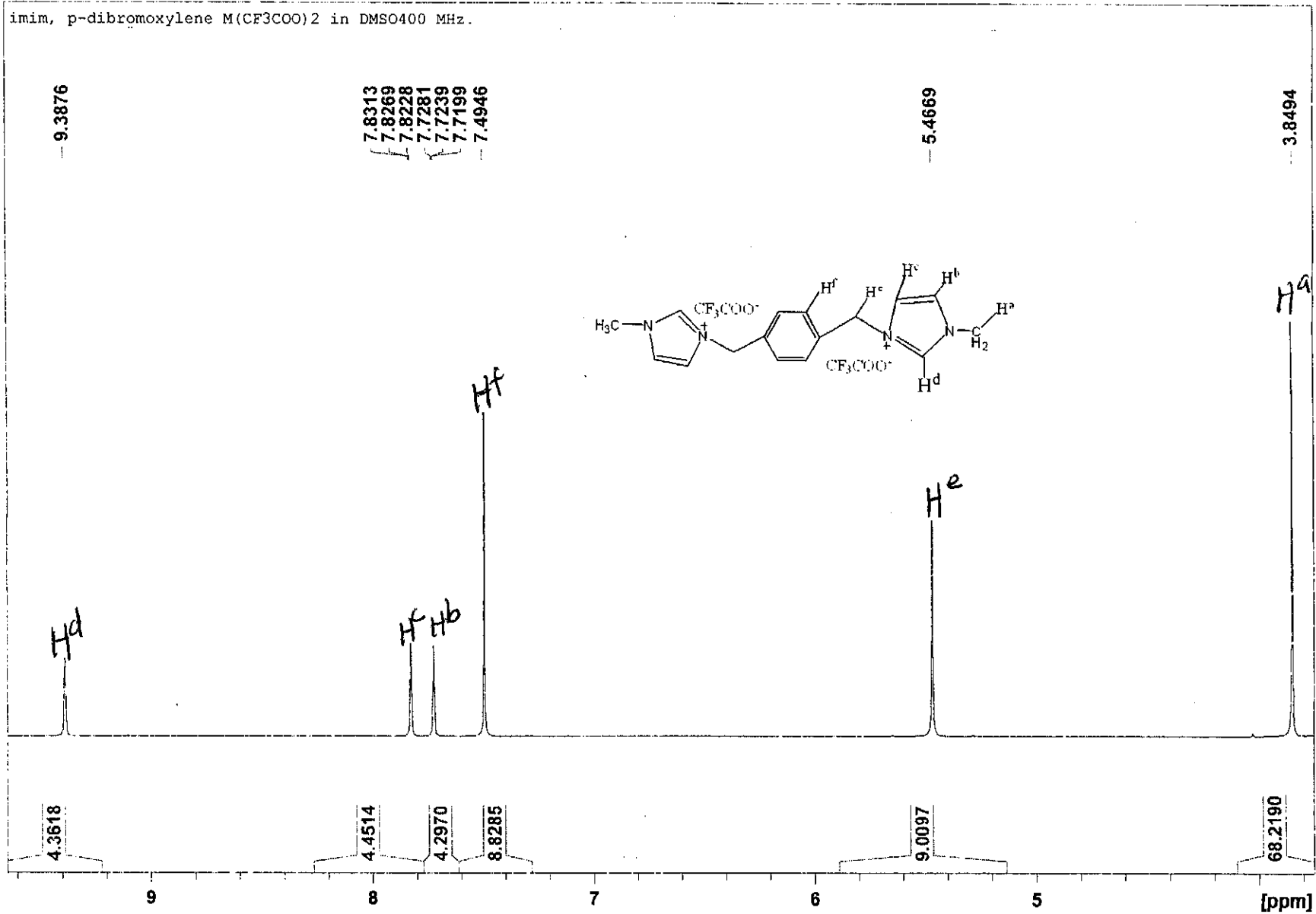


c:\pel_data\spectra\brahim\imidazole II, m(cf3so3)2.002 - White crystalline subs.

IR spectrum of Compound A-4

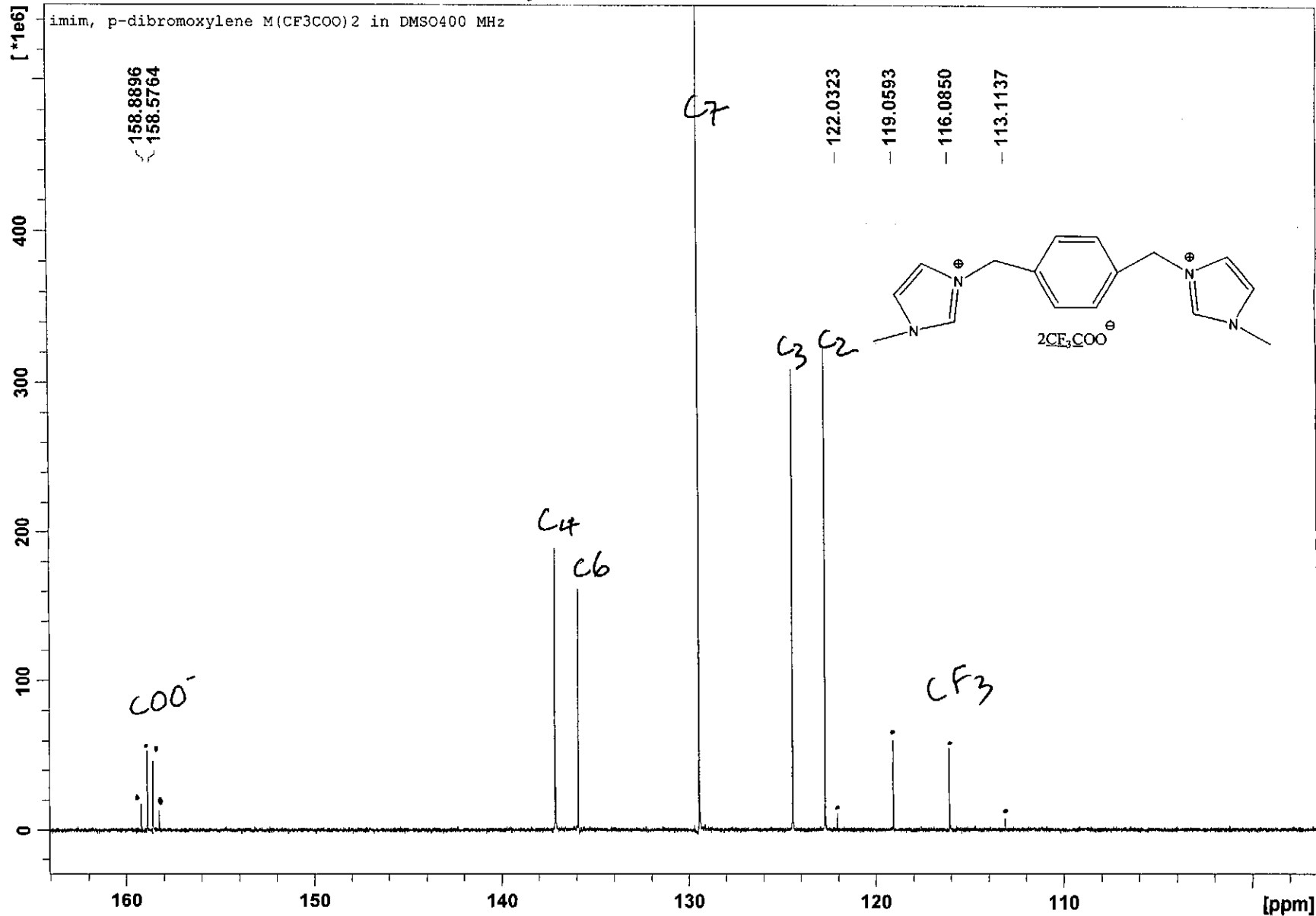
Nov23-2010-NK-Ibrahim 42 1 C:\Bruker\TOPSPIN quest

imim, p-dibromoxylene M(CF₃COO)₂ in DMSO400 MHz.



¹H NMR spectrum of Compound A-5

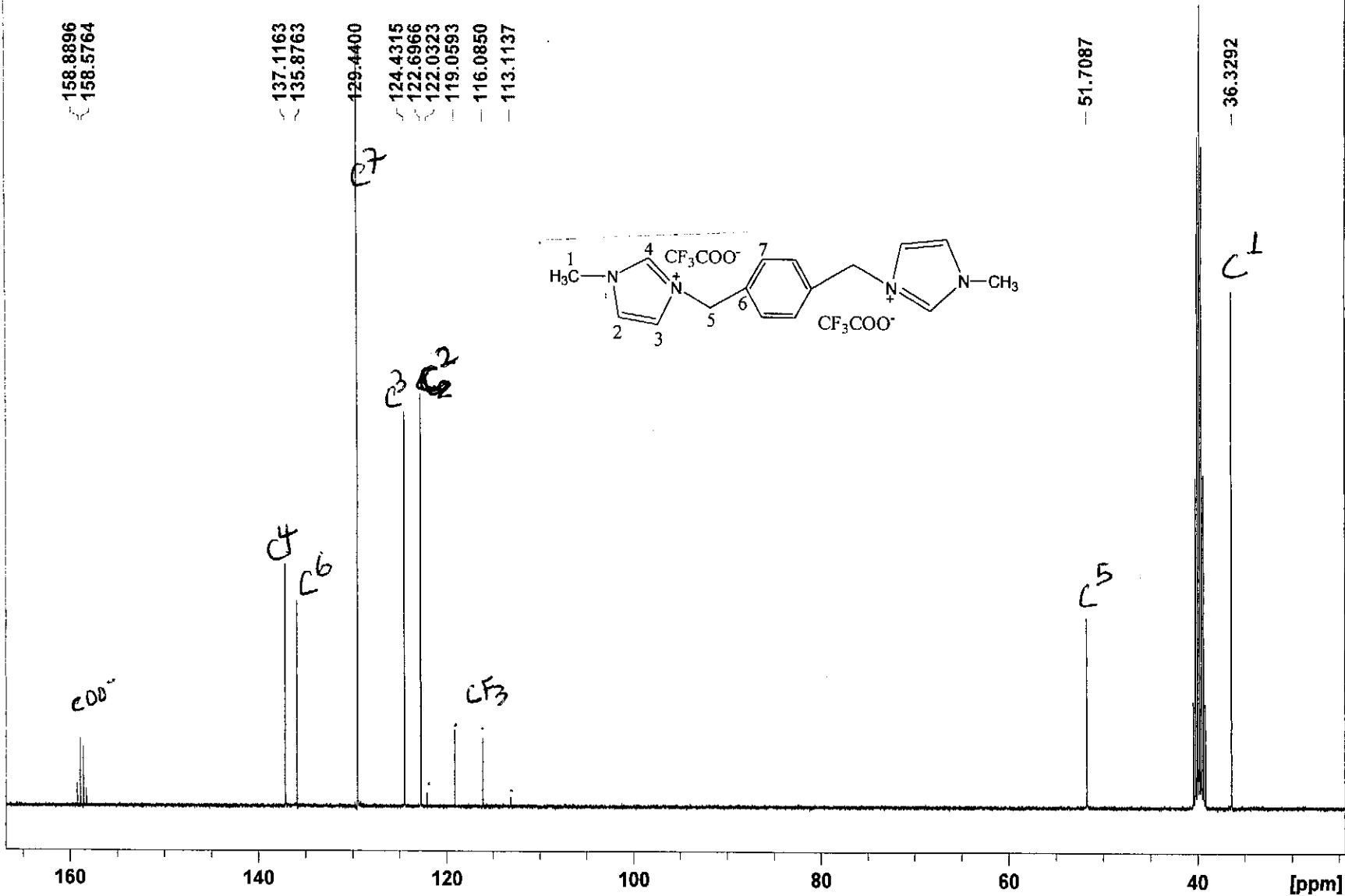
Nov23-2010-NK-Ibrahim 40 1 C:\Bruker\TOPSPIN guest



¹³C NMR spectrum of Compound A-5 (CF₃) and (C=O)

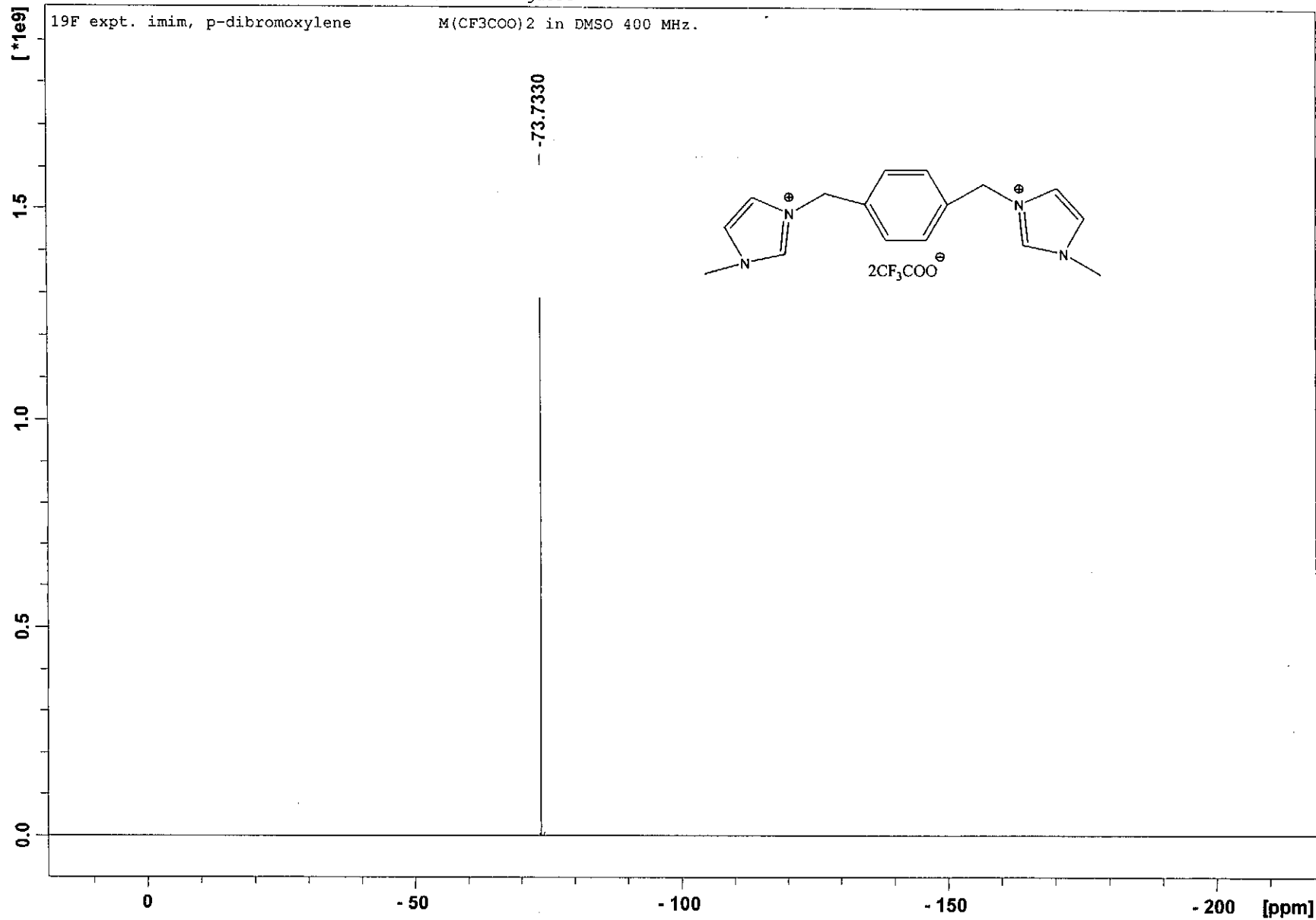
Nov23-2010-NK-Ibrahim 40 1 C:\Bruker\TOPSPIN guest

imim, p-dibromoxylylene M(CF₃COO)₂ in DMSO400 MHz

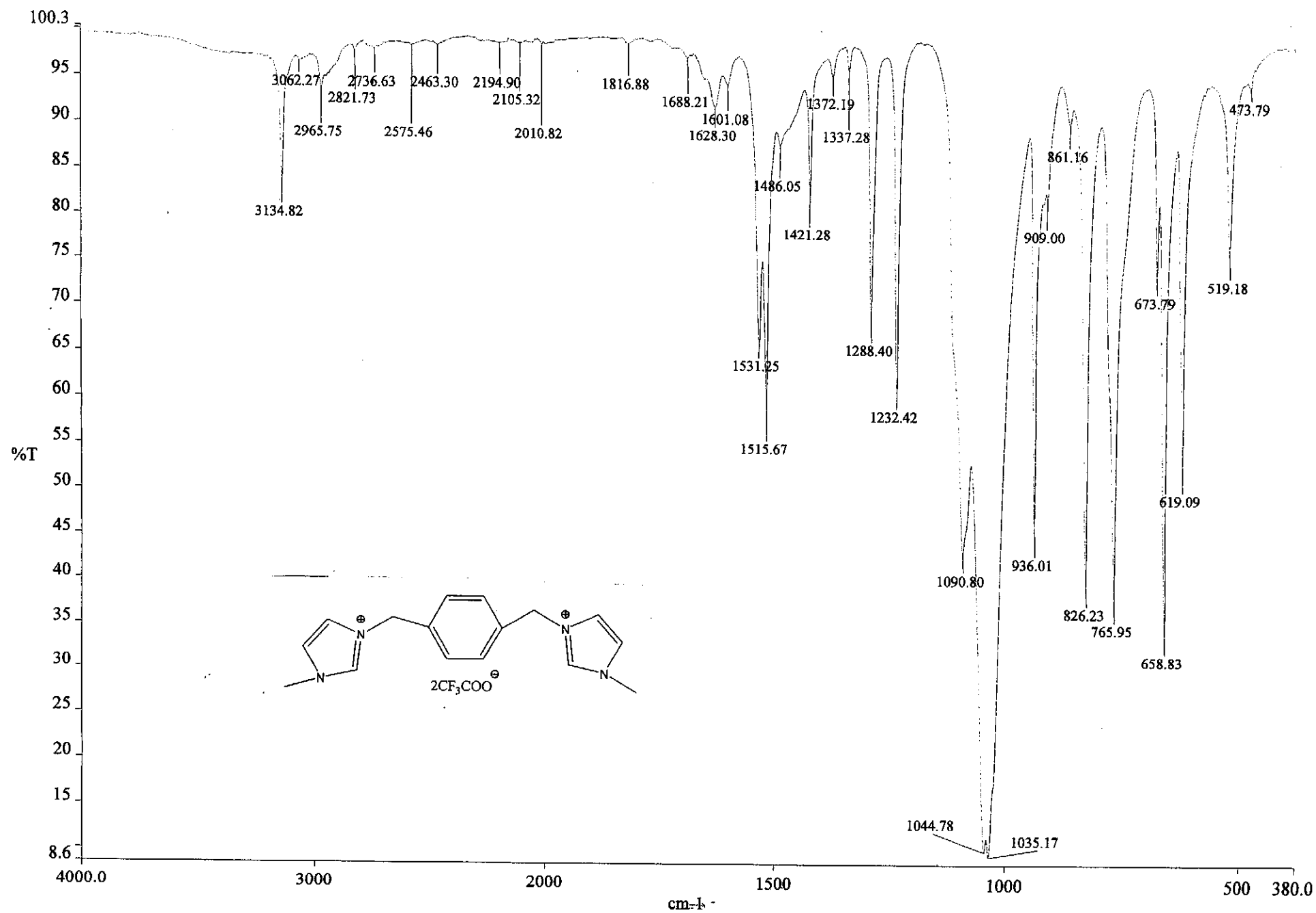


¹³C NMR spectrum of Compound A-5

Nov23-2010-NK-Ibrahim 41 1 C:\Bruker\TOPSPIN guest



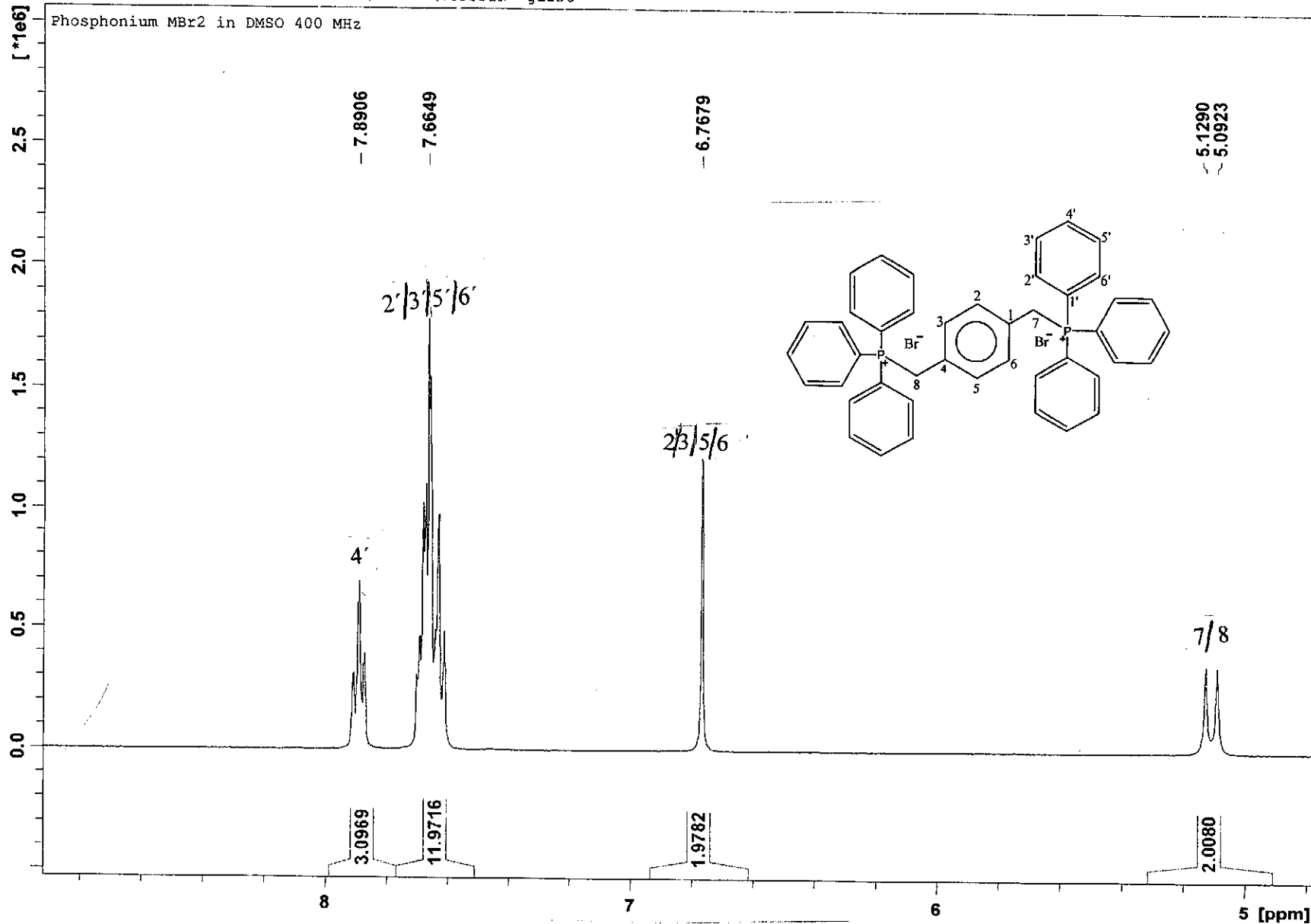
¹⁹F NMR spectrum of Compound A-5



c:\pel_data\spectra\brahim\combine lmin spectra.002

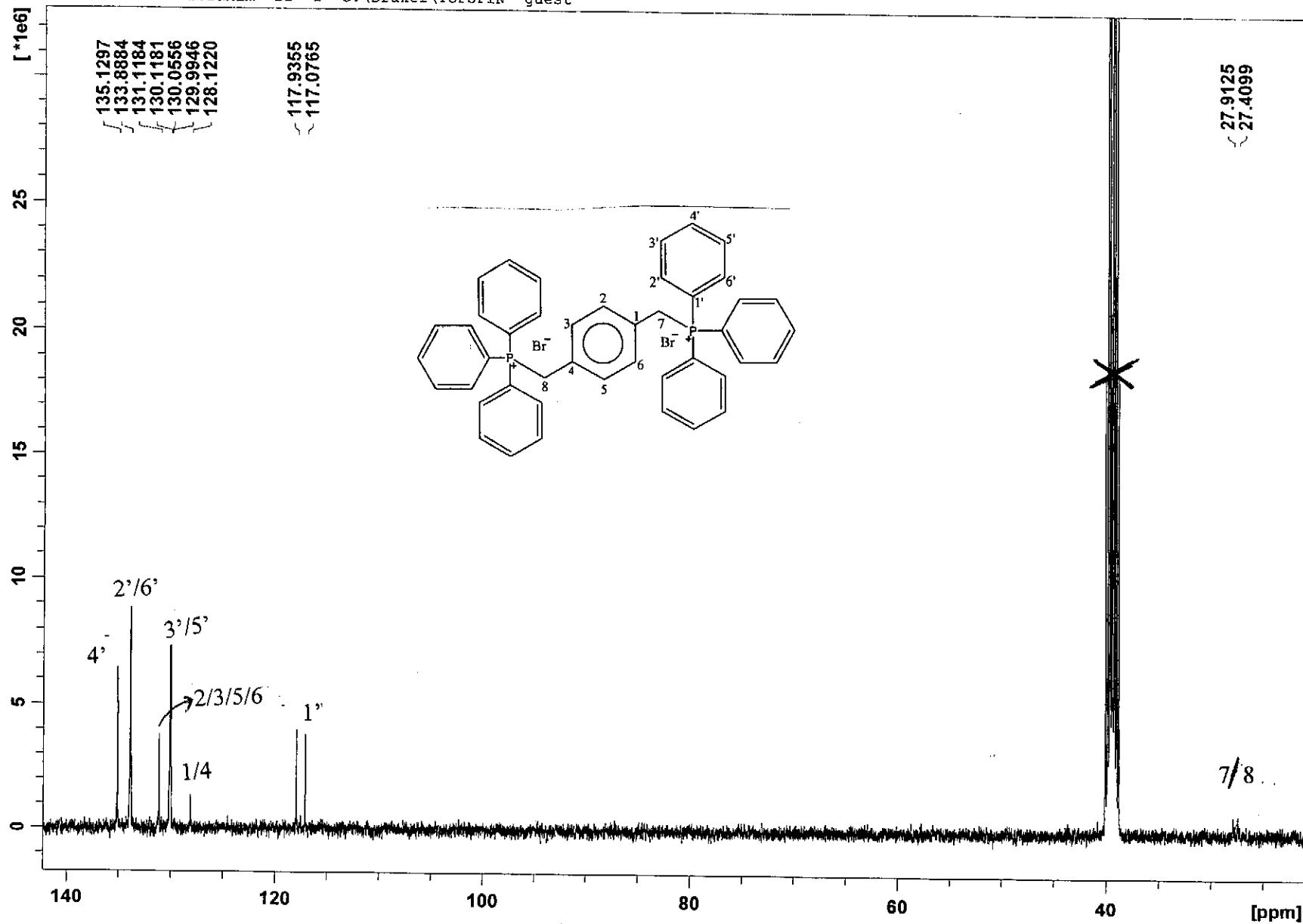
IR spectrum of Compound A-5

Oct15-2009-NK-Ibrahim 10 1 C:\Bruker\TOPSPIN guest

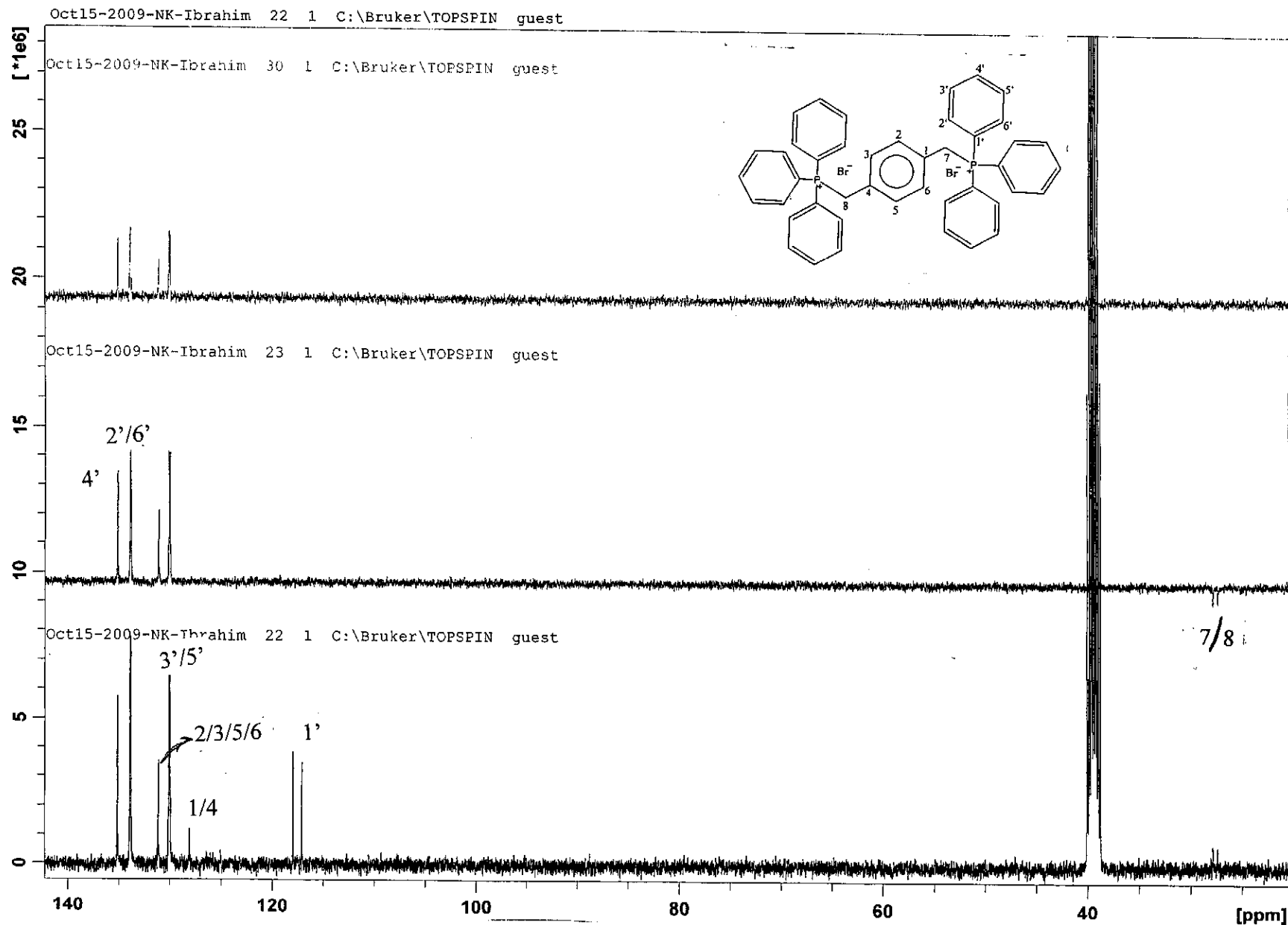


¹H NMR spectrum of Compound B-1

Oct15-2009-NK-Ibrahim 21 1 C:\Bruker\TOPSPIN guest

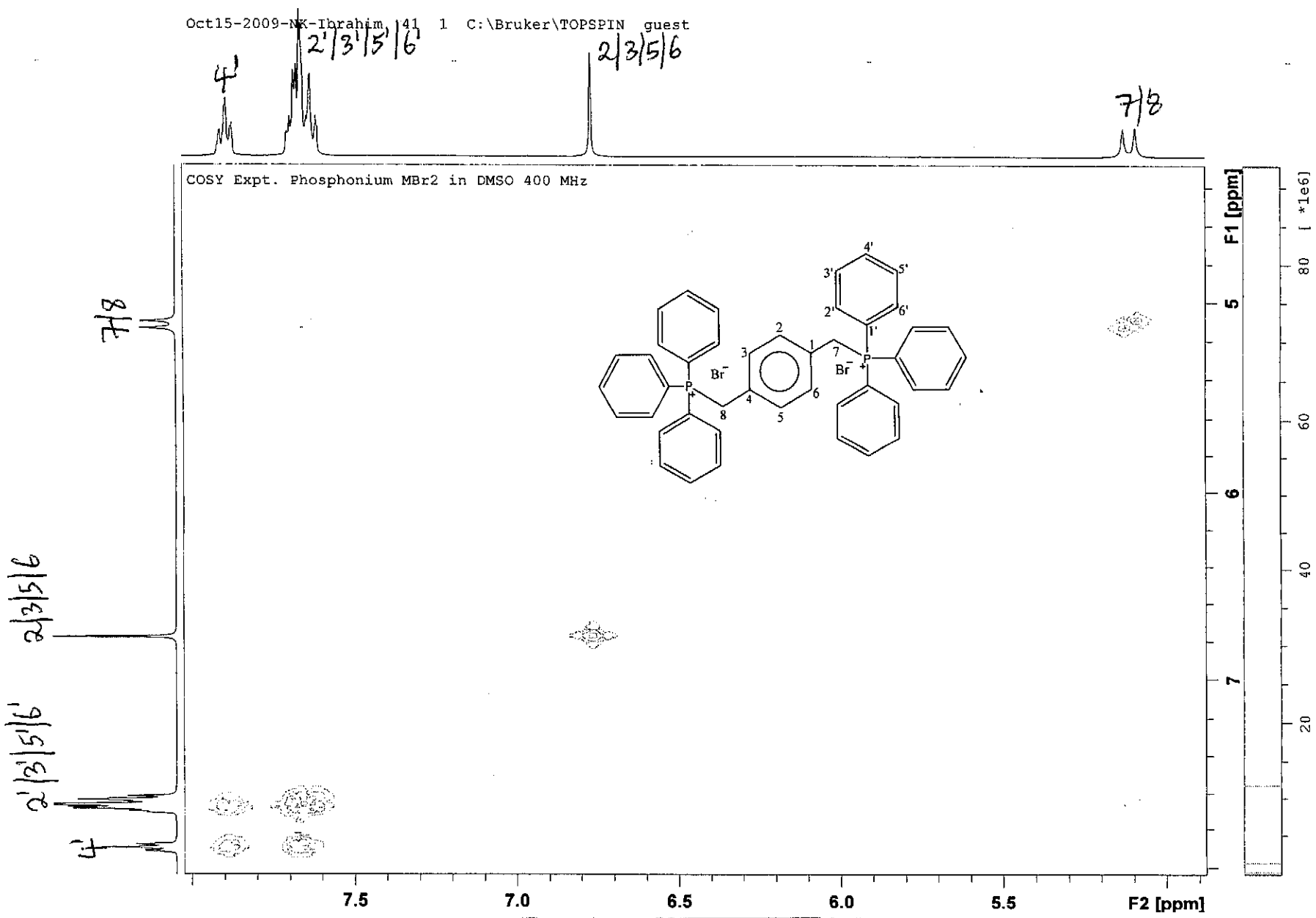


¹³C NMR spectrum of Compound B-1



Dept 90 and 135 spectra of Compound B-1

Oct15-2009-NK-Ibrahim, 41 1 C:\Bruker\TOPSPIN guest



COSY spectrum of Compound B-1

Oct15-2009-NK Ibrahim 42 1 C:\Bruker\TOPSPIN guest

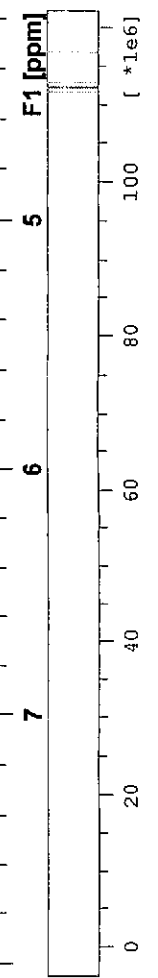
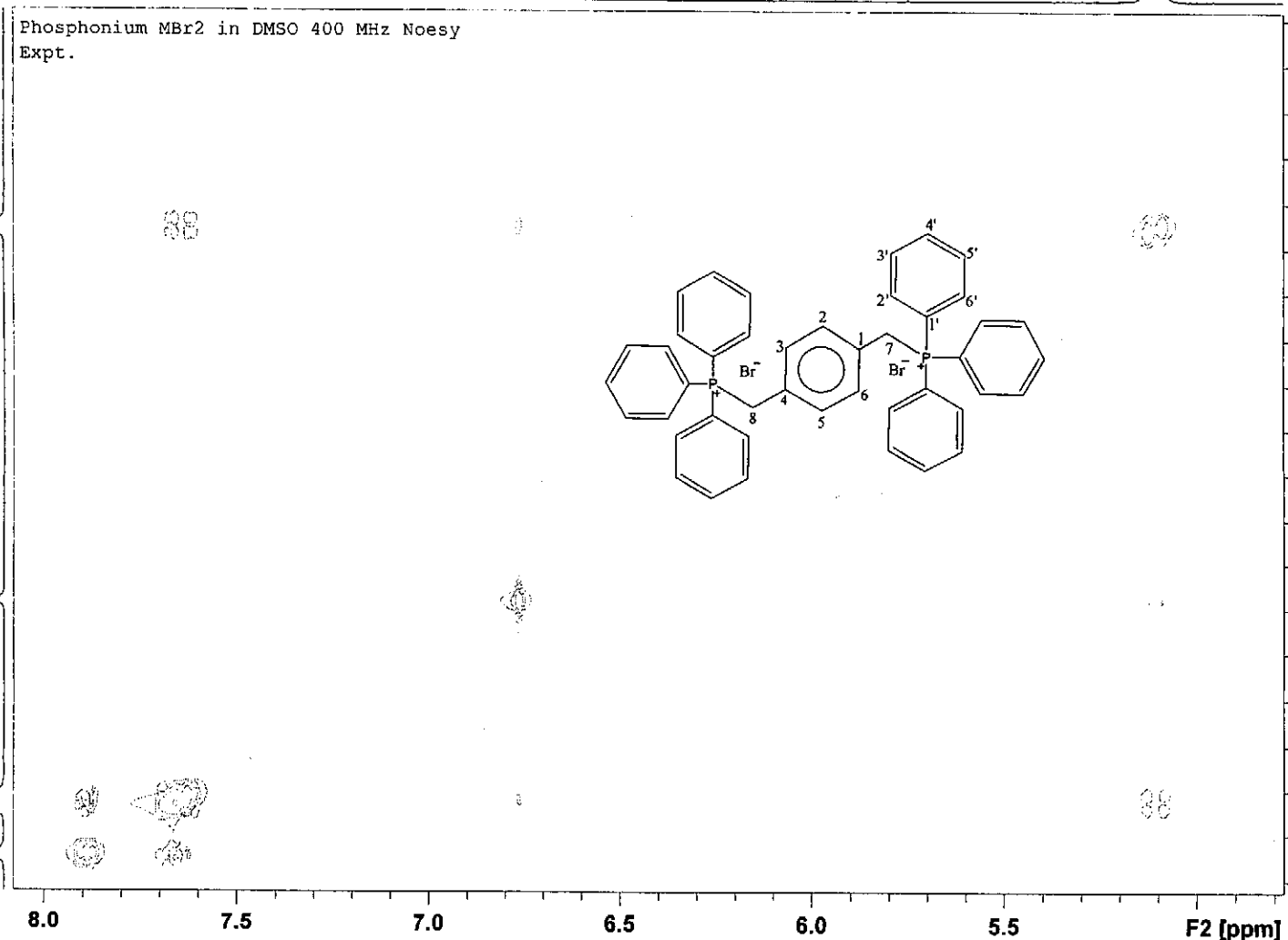
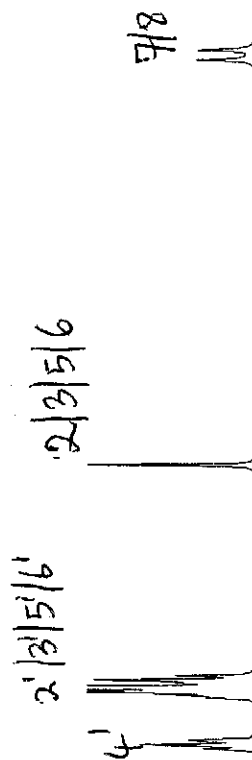
4'

2'|3'|5'|6'

2|3|5|6

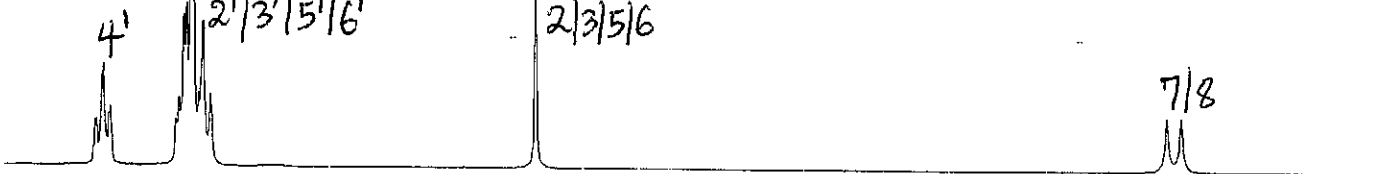
7|8

Phosphonium MBr₂ in DMSO 400 MHz Noesy Expt.

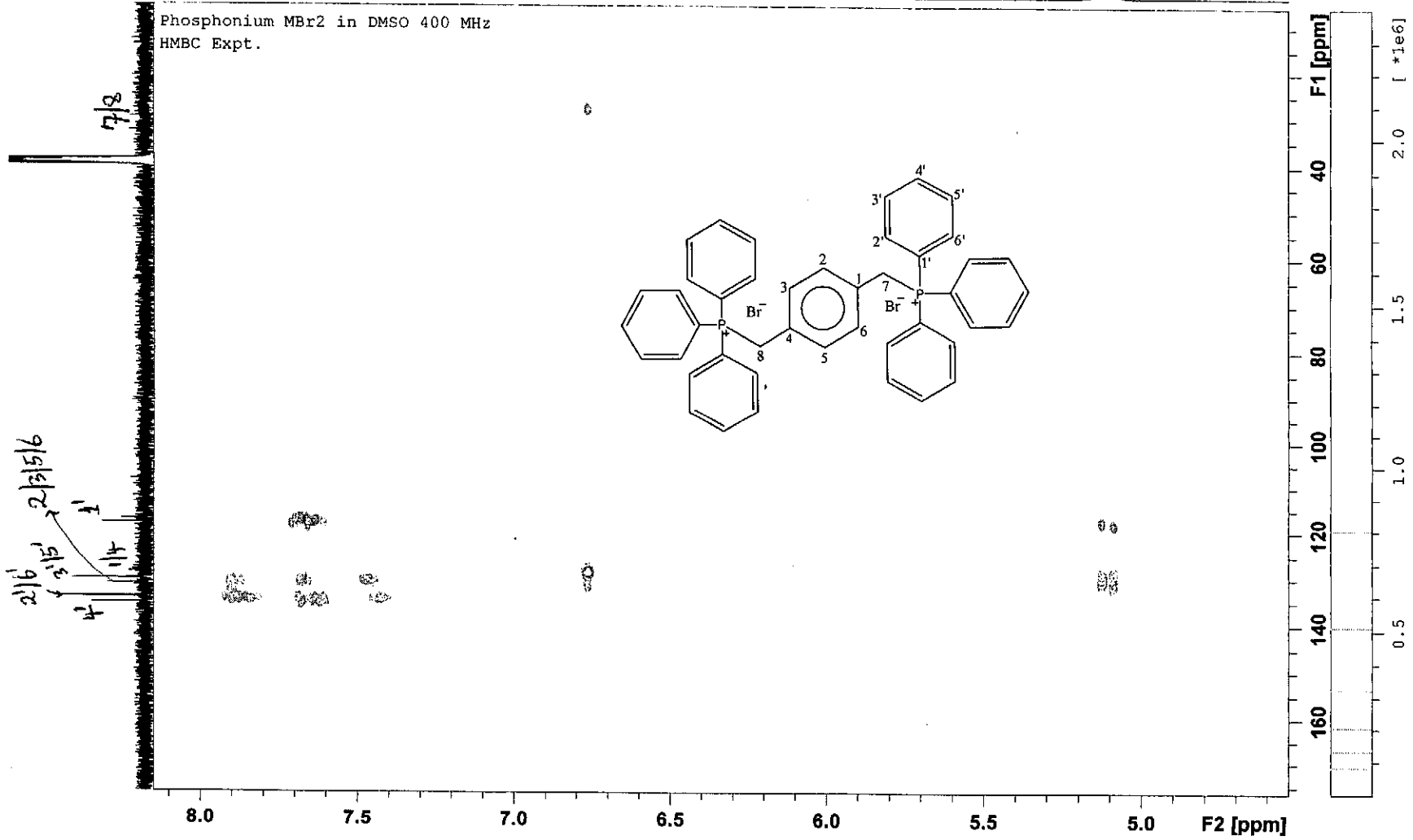


NOESY spectrum of Compound B-1

Oct15-2009-NK-Ibrahim 91_1 C:\Bruker\TOPSPIN guest

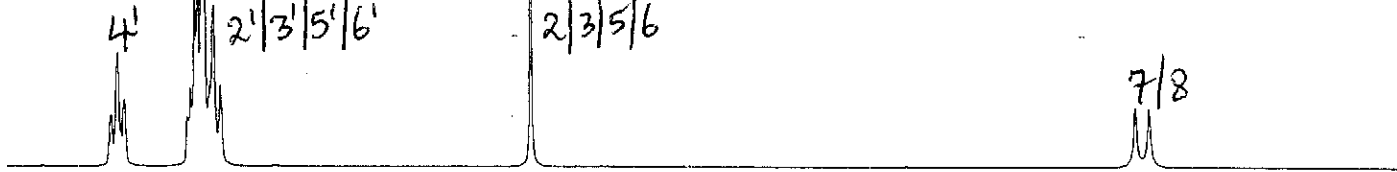


Phosphonium MBr2 in DMSO 400 MHz
HMBC Expt.

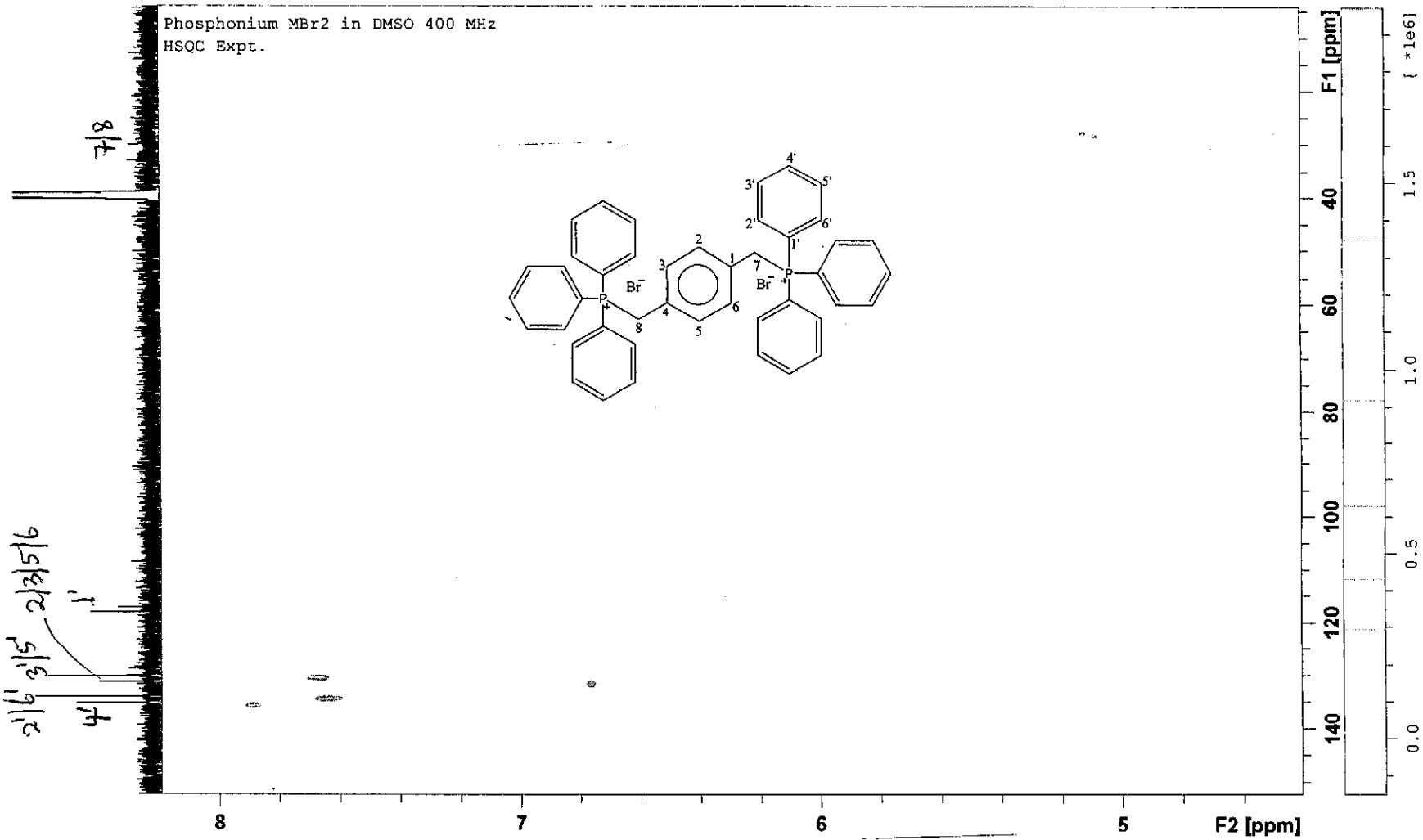


HMBC spectrum of Compound B-1

Oct15-2009-NK-Ibrahim 92 1 C:\Bruker\TOPSPIN guest



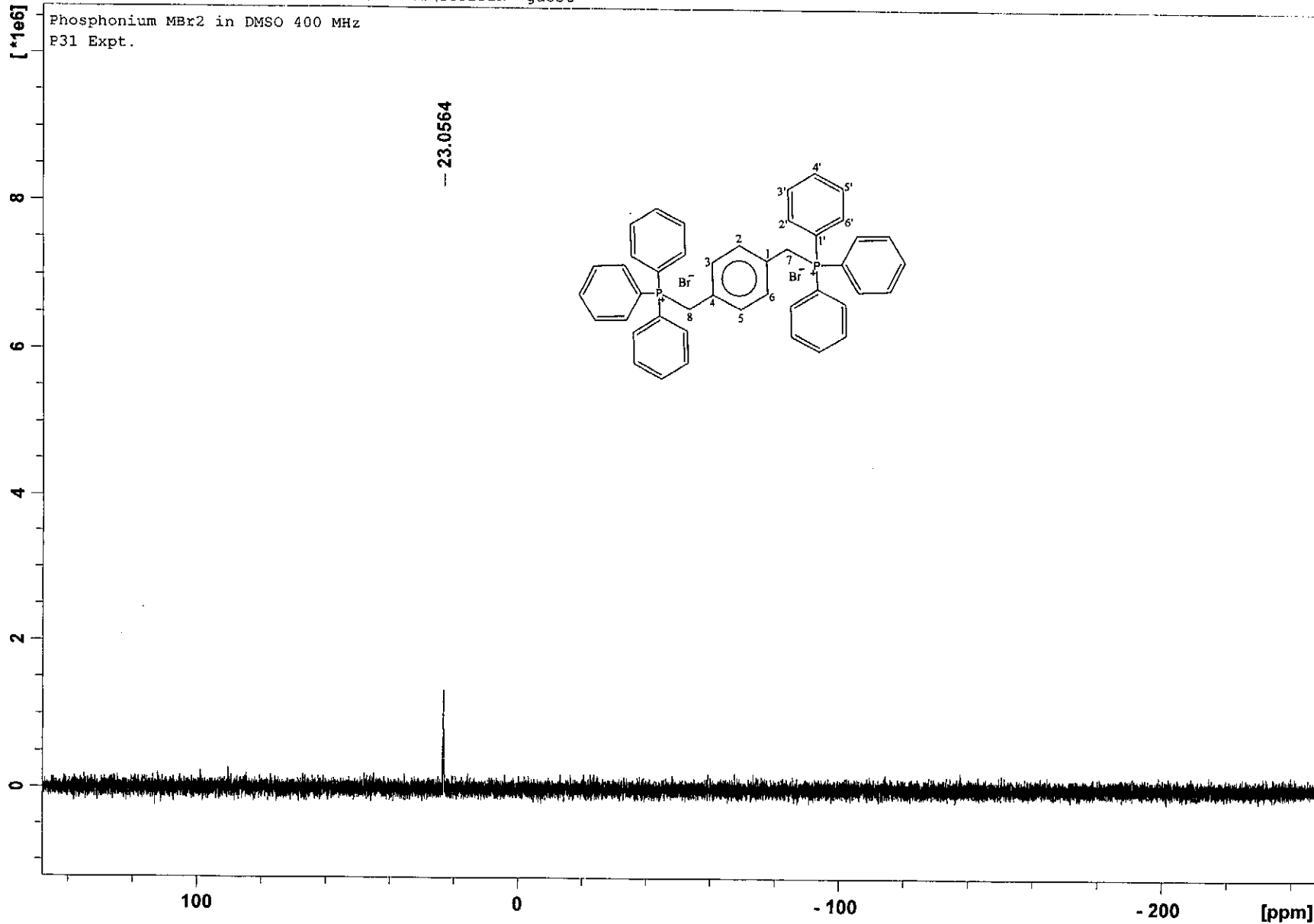
Phosphonium MBr2 in DMSO 400 MHz
HSQC Expt.



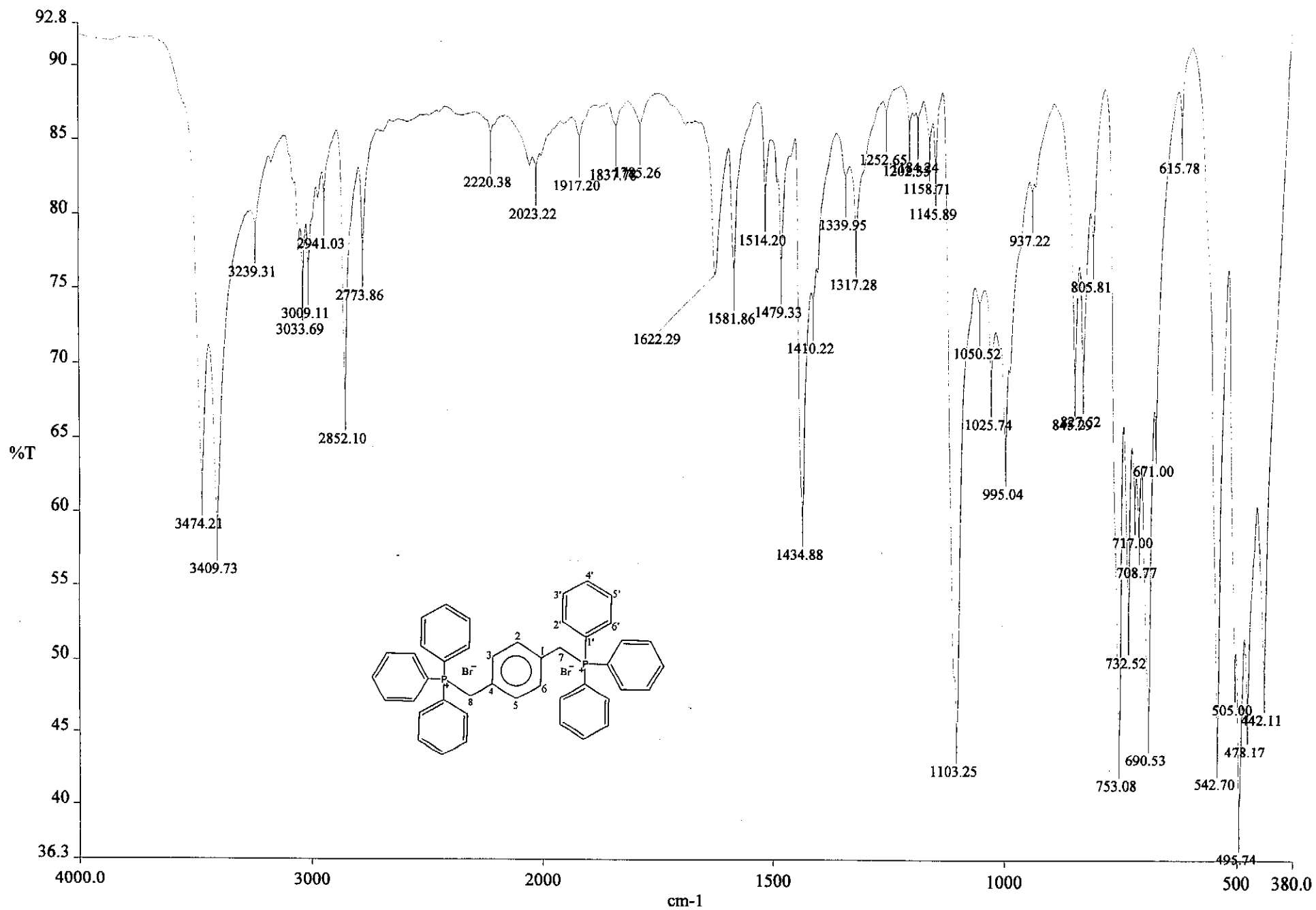
2|6 3|5 2|3|5|6
4' 1'

HSQC spectrum of Compound B-1

Oct15-2009-NK-Ibrahim 93 1 C:\Bruker\TOPSPIN guest



³¹P NMR spectrum of Compound B-1



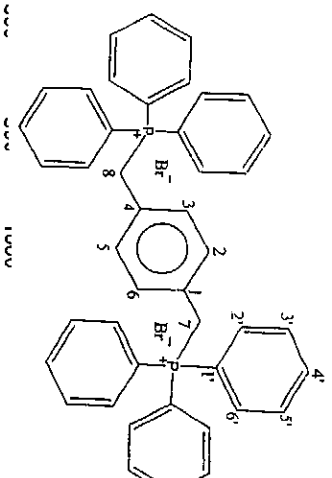
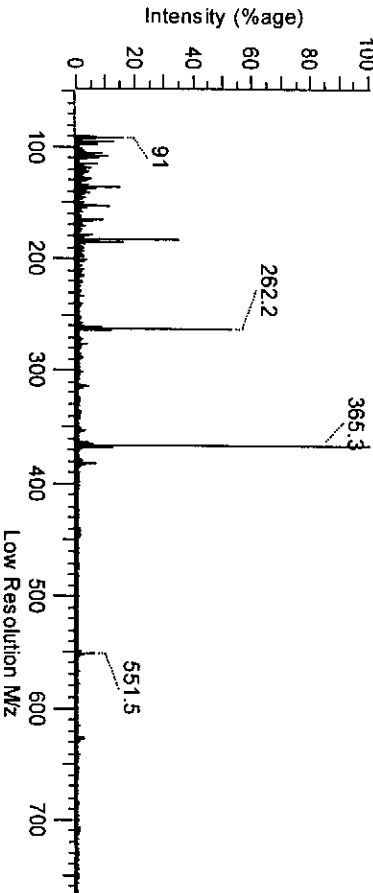
c:\pel_data\spectra\brahim\phosphonium II, mbr2.002 - White powdery subs.

IR spectrum of Compound B-1

Sample 1, dissolved in an nba matrix

SCAN GRAPH, Flagging=Low Resolution M/z, CId=[Thr:1000uV, Min.Hgt:1000uV, Min.Wid(MM):10(7), Inc:50%, Res:10%], †

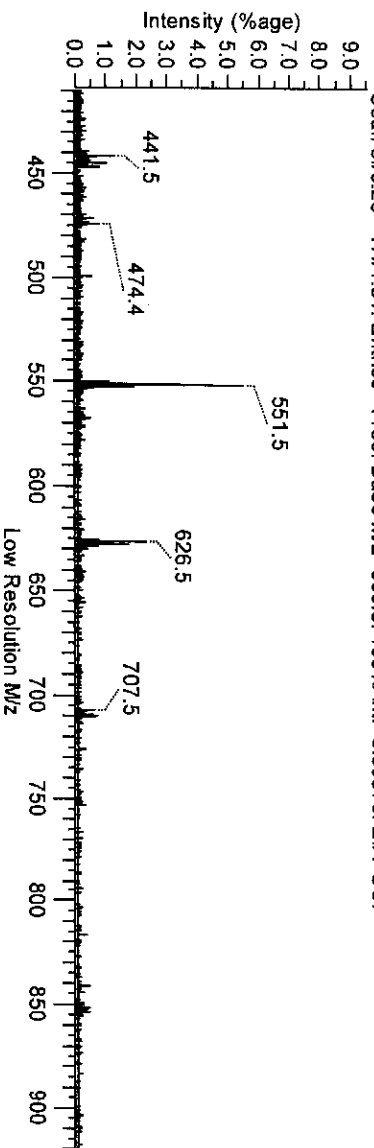
Scan 5#0:26 - 17#1:31, Entries=1100, Base M/z=365.3, 100% Int.=3.89376, El. POS.



Expansion of this spec show:

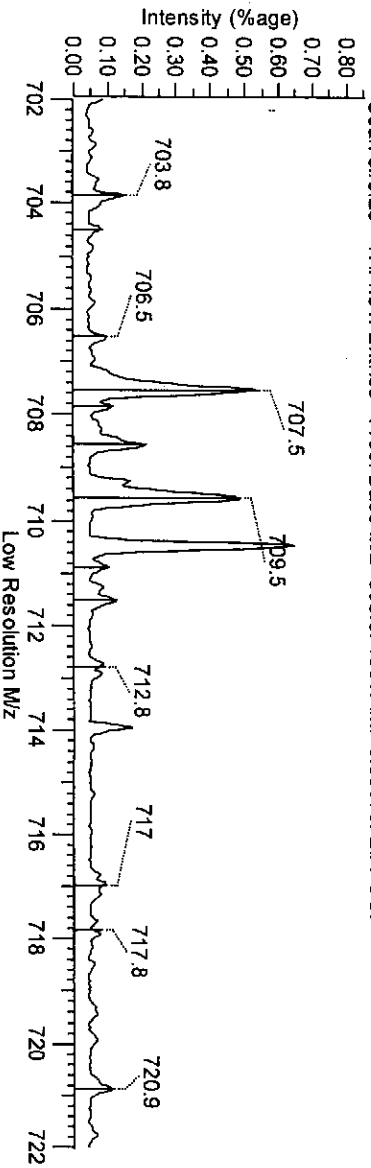
SCAN GRAPH, Flagging=Low Resolution M/z, CId=[Thr:1000uV, Min.Hgt:1000uV, Min.Wid(MM):10(7), Inc:50%, Res:10%], †

Scan 5#0:26 - 17#1:31, Entries=1100, Base M/z=365.3, 100% Int.=3.89376, El. POS.



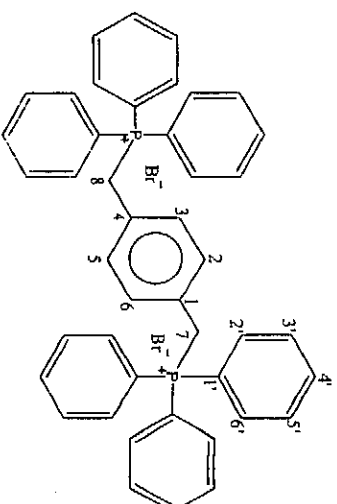
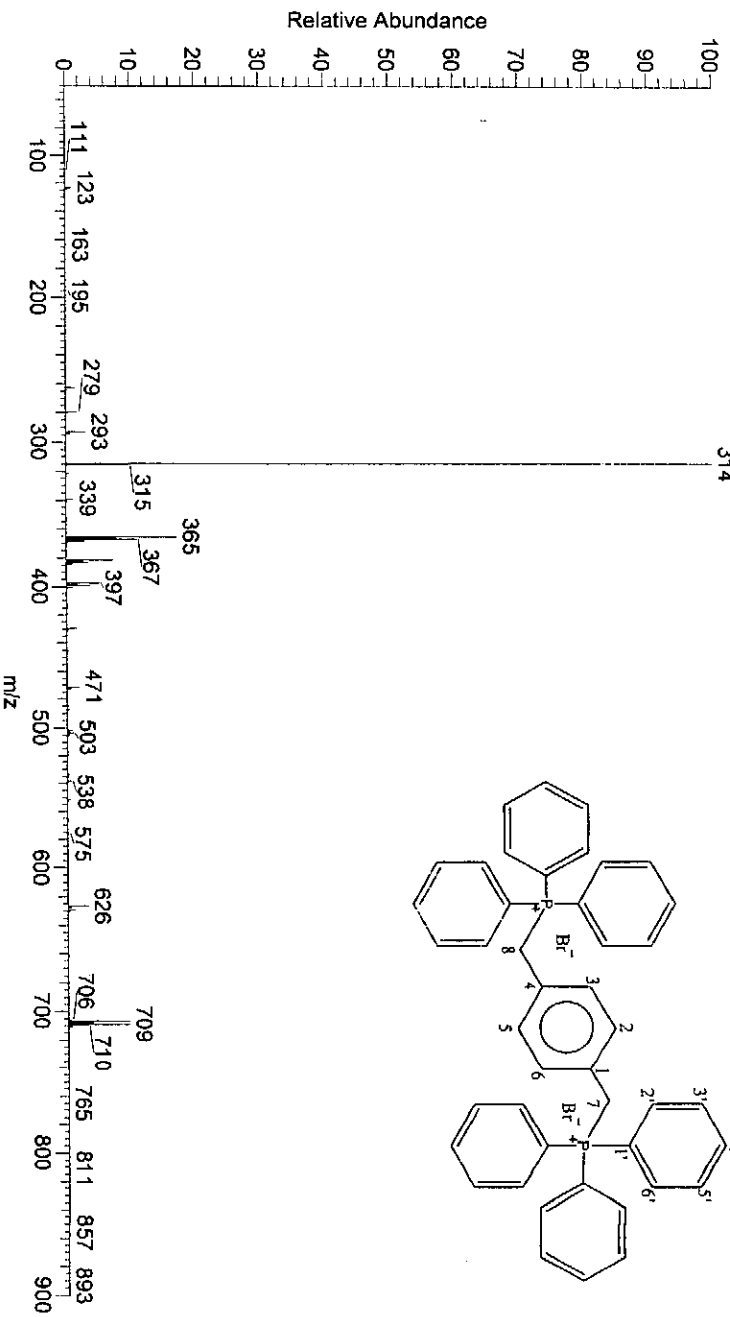
SCAN GRAPH, Flagging=Low Resolution M/z, CId=[Thr:1000uV, Min.Hgt:1000uV, Min.Wid(MM):10(7), Inc:50%, Res:10%], †

Scan 5#0:26 - 17#1:31, Entries=1100, Base M/z=365.3, 100% Int.=3.89376, El. POS.

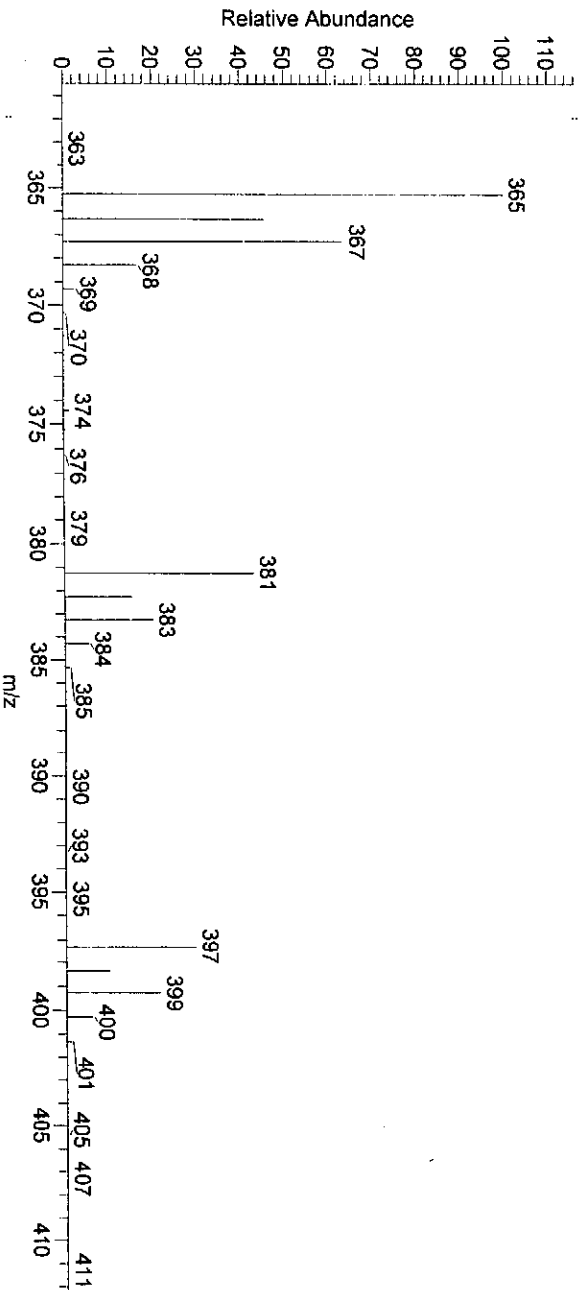


MS of Compound B-1

Hibrahim1_LRESI #4-69 RT: 0.06-1.38 AV: 66 NL: 1.89E6
T: ITMS + c ESI Full ms [50.00-900.00]

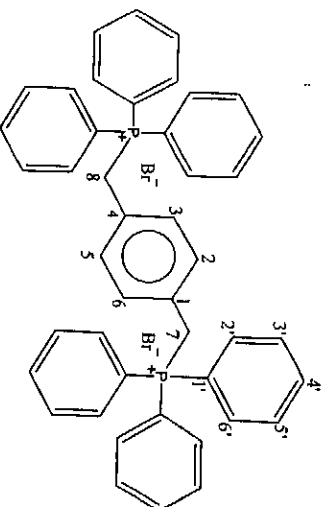
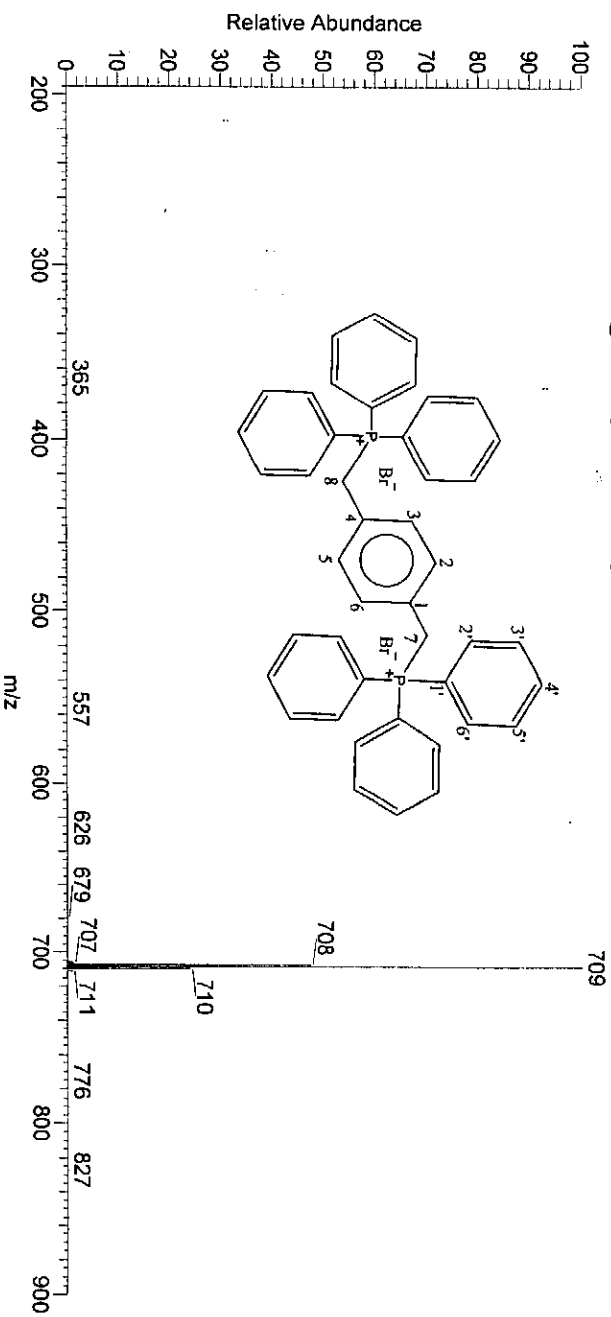


Hibrahim1_LRESI #4-67 RT: 0.06-1.34 AV: 64 NL: 3.22E5
T: ITMS + c ESI Full ms [50.00-900.00]

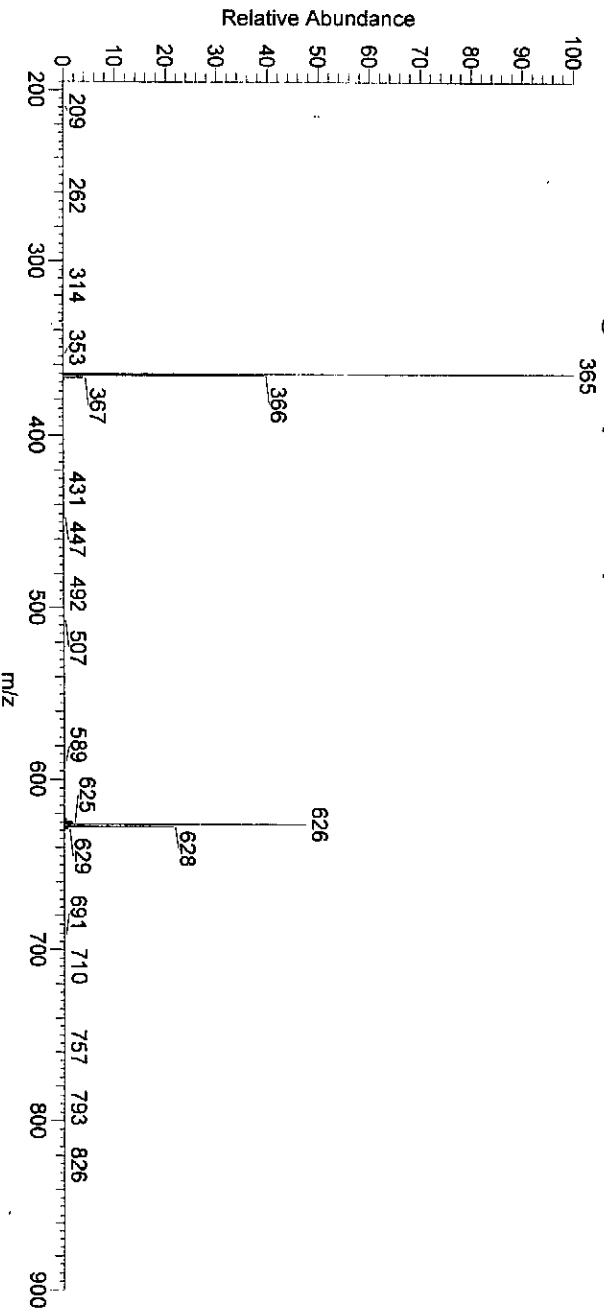


MS of Compound B-1

Hilbrahim1_LRESI #129-169 RT: 2.11-2.52 AV: 41 NL: 1.50E5
T: ITMS + c ESI Full ms2 710.00@cid0.00 [195.00-900.00]

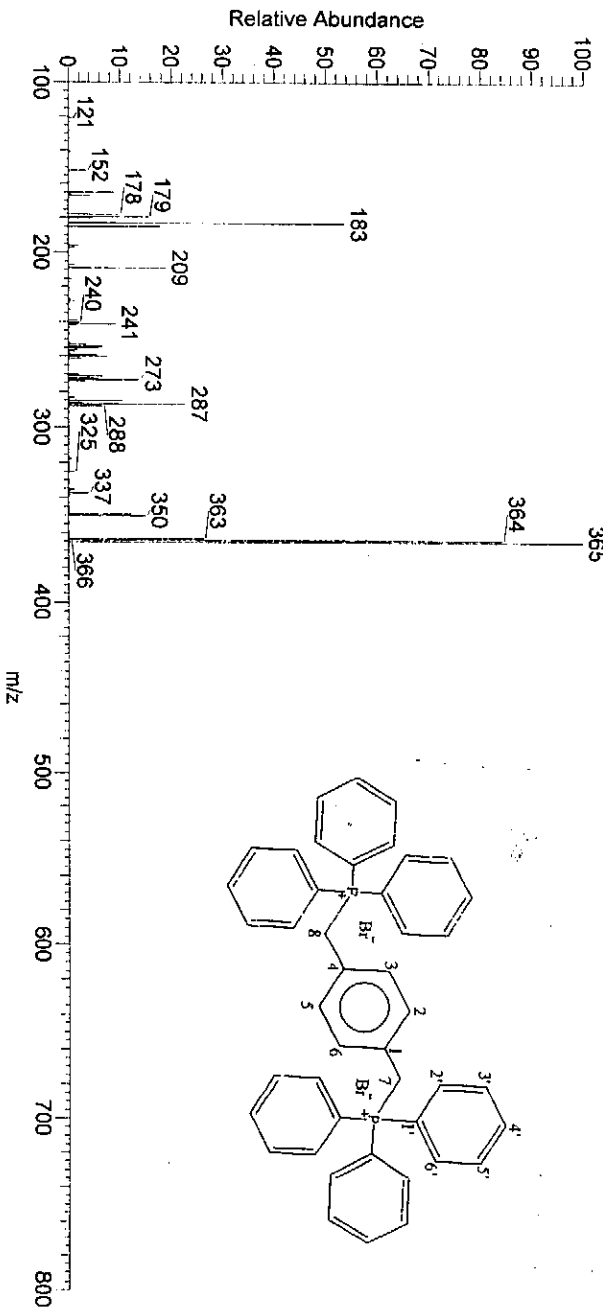


Hilbrahim1_LRESI #209-224 RT: 2.94-3.11 AV: 16 NL: 8.25E4
T: ITMS + c ESI Full ms2 710.00@cid20.00 [195.00-900.00]



MS of Compound B-1

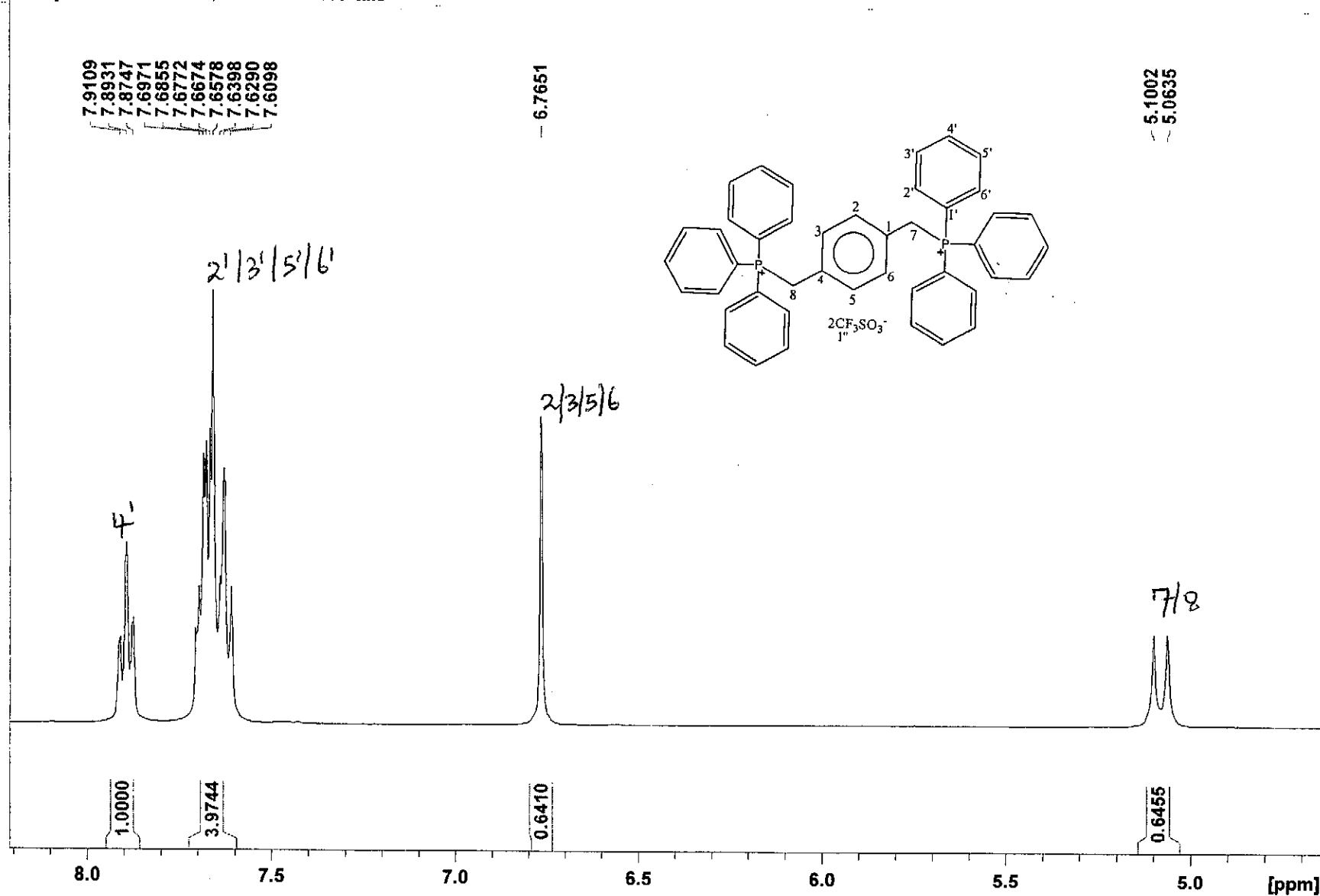
Hlbrahim1_LRESI #365-395 RT: 5.10-5.69 AV: 31 NL: 1.24E3
T: ITMS + c ESI Full ms3 710.00@cid20.00 365.00@cid70.00 [100.00-800.00]



MS of Compound B-1

Oct13-2009-NK-Ibrahim 30 1 C:\Bruker\TOPSPIN guest

Phosphonium M(CF₃SO₃)₂ in DMSO 400 MHz



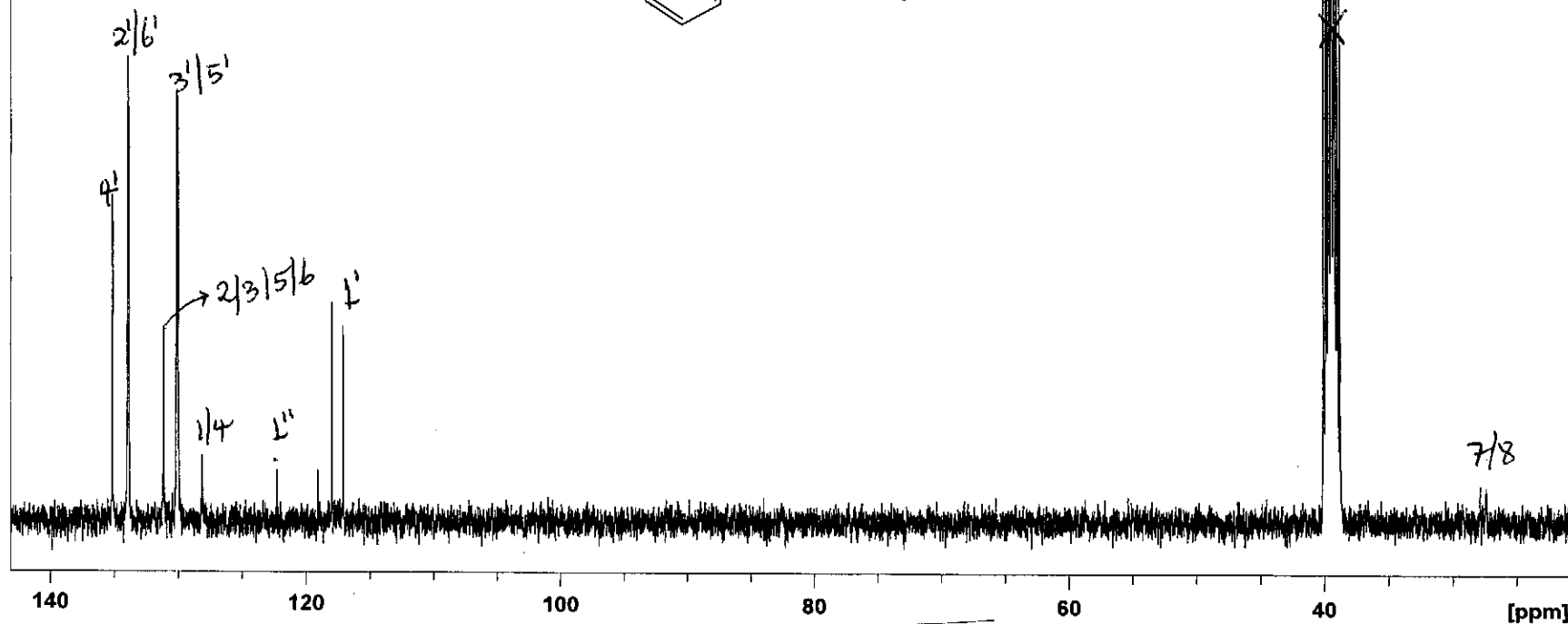
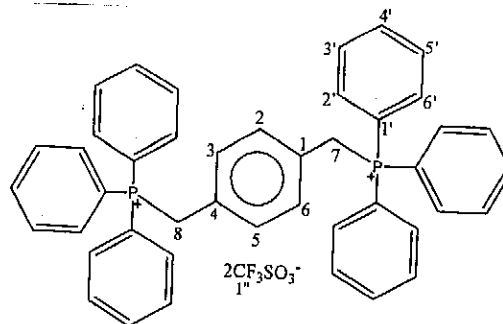
¹H NMR spectrum of compound B-2

Oct14-2009-NK-Ibrahim 20 1 C:\Bruker\TOPSPIN guest

Phosphonium M(CF₃SO₃)₂ in DMSO 400 Mhz

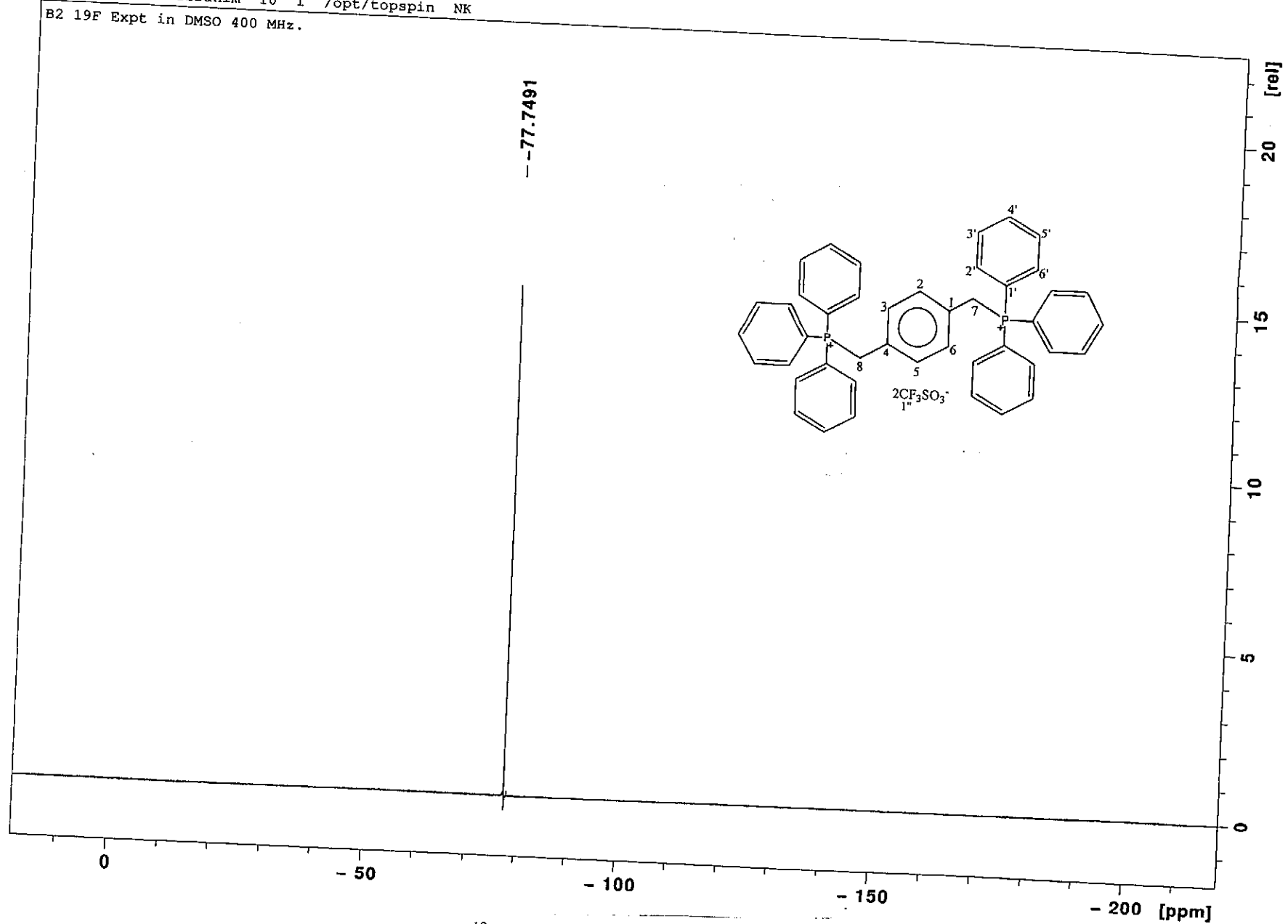
135.1232
133.9384
133.8891
133.8404
131.1169
130.1127
130.0501
129.9894
128.1140
- 122.2335
117.9379
117.0772

28.0440
27.3600

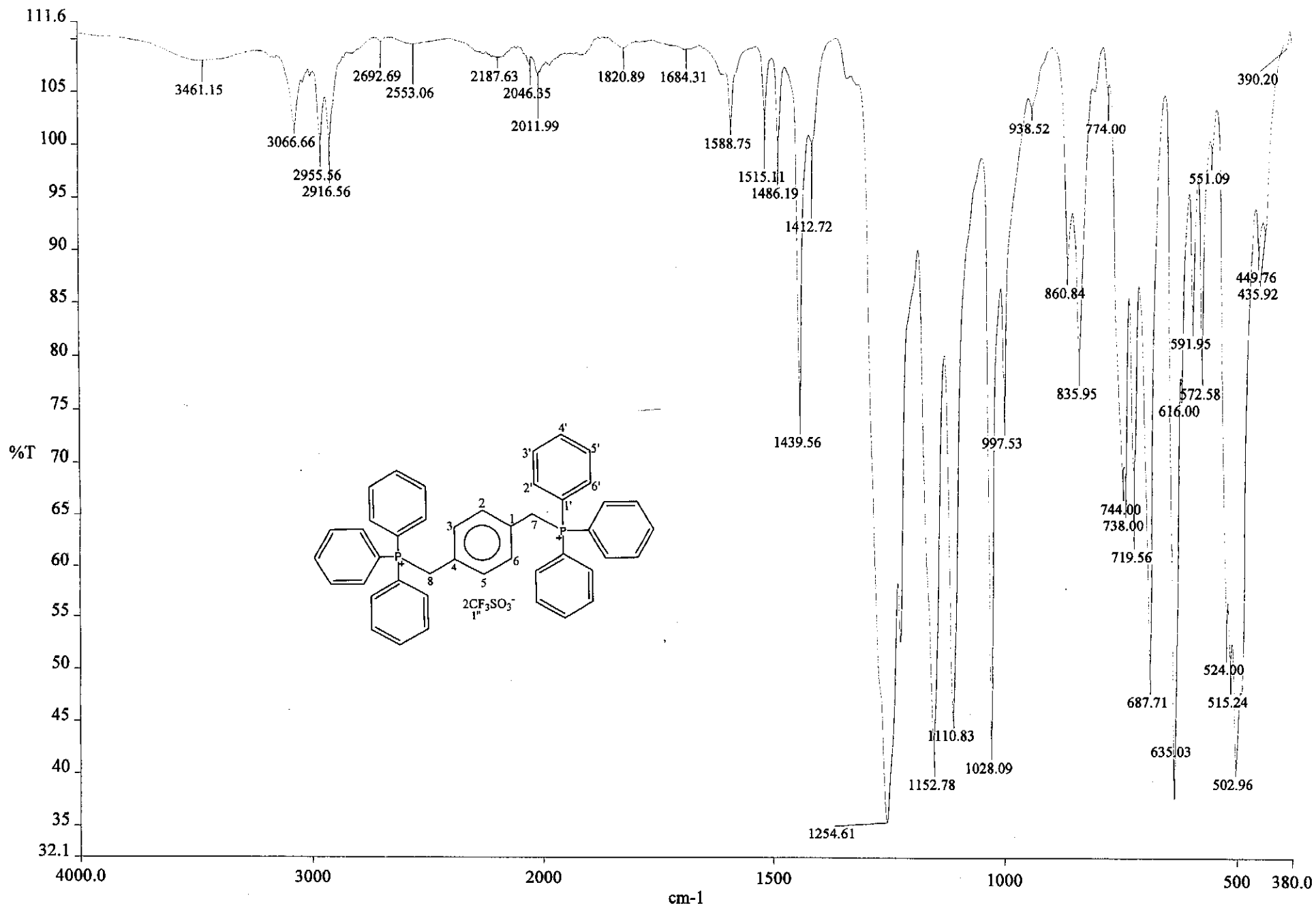


¹³C NMR spectrum of Compound B-2

Jan11-2013-NK-Ibrahim 10 1 /opt/topspin NK
B2 19F Expt in DMSO 400 MHz.



^{19}F NMR spectrum of Compound B-2

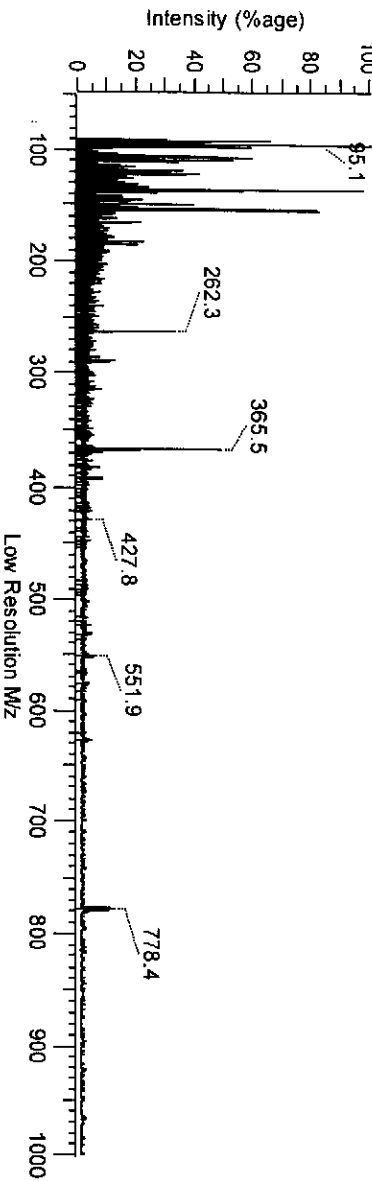


c:\pel_data\spectra\brahim\phosphonium II, m(cf3so3)2.002 - White Powdery subs.

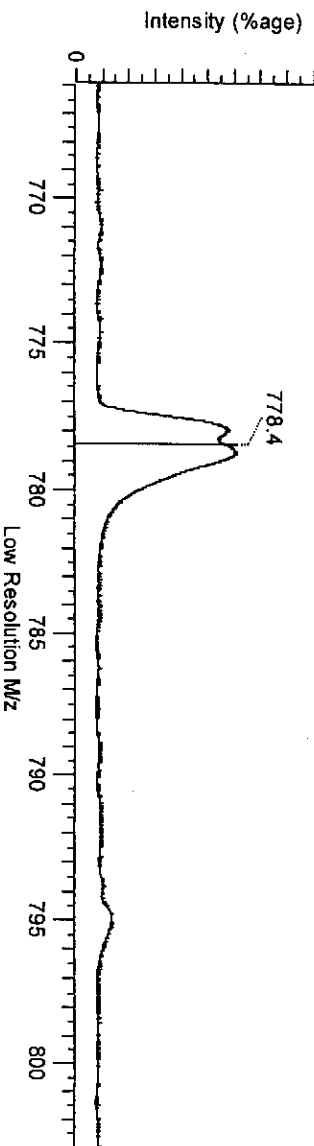
IR spectrum of Compound B-2

Sample 4

SCAN GRAPH Flagging=Low Resolution M/z. Ctd=[Thr:1000µV, Min.Hgt:1000µV, Min.Wid(MH):10(7), Inc:50%, Res:10%], f
 Scan 4#0:21 - 12#1:04. Entries=317. Base Mz=95.1, 100% Int.=0.112. El. POS.

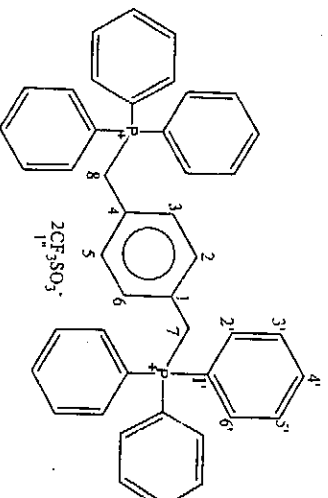
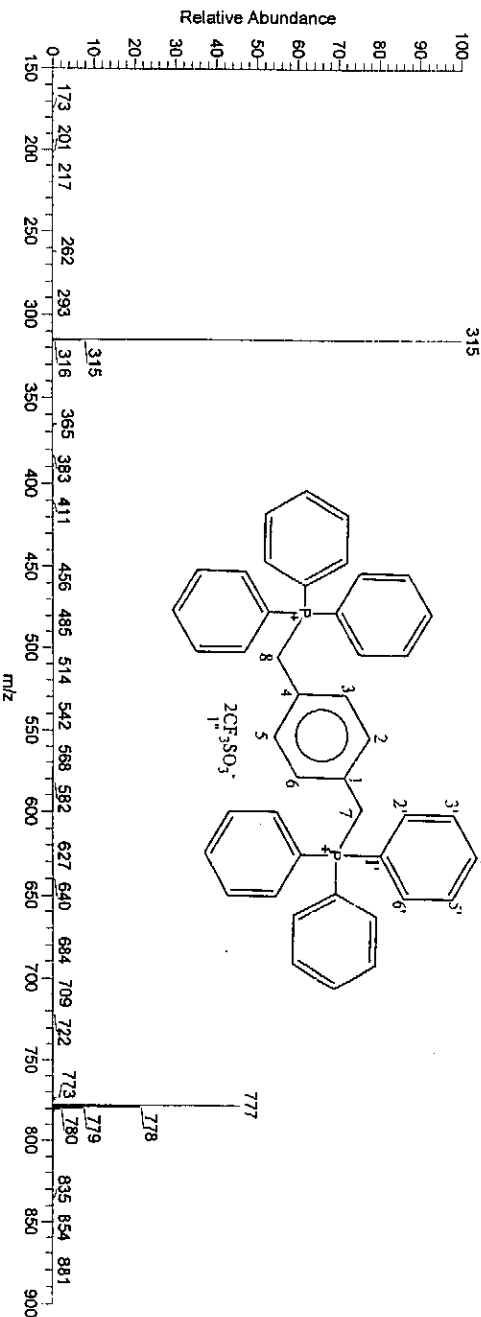


SCAN GRAPH Flagging=Low Resolution M/z. Ctd=[Thr:1000µV, Min.Hgt:1000µV, Min.Wid(MH):10(7), Inc:50%, Res:10%], f
 Scan 4#0:21 - 12#1:04. Entries=317. Base Mz=95.1, 100% Int.=0.112. El. POS.



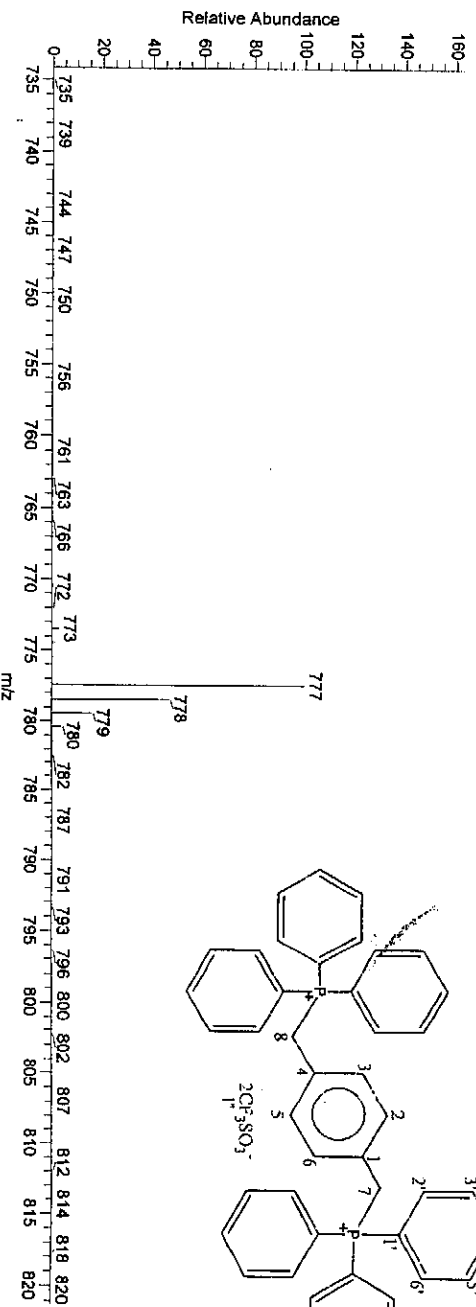
ESI-MS

Hitrahim_Samp4_11050911713 #1-5 RT: 0.00-0.07 AV: 5 NL: 594E6
 T: LTMS + c ESI Full ms [150.00-900.00]



M/S of Compound B-2

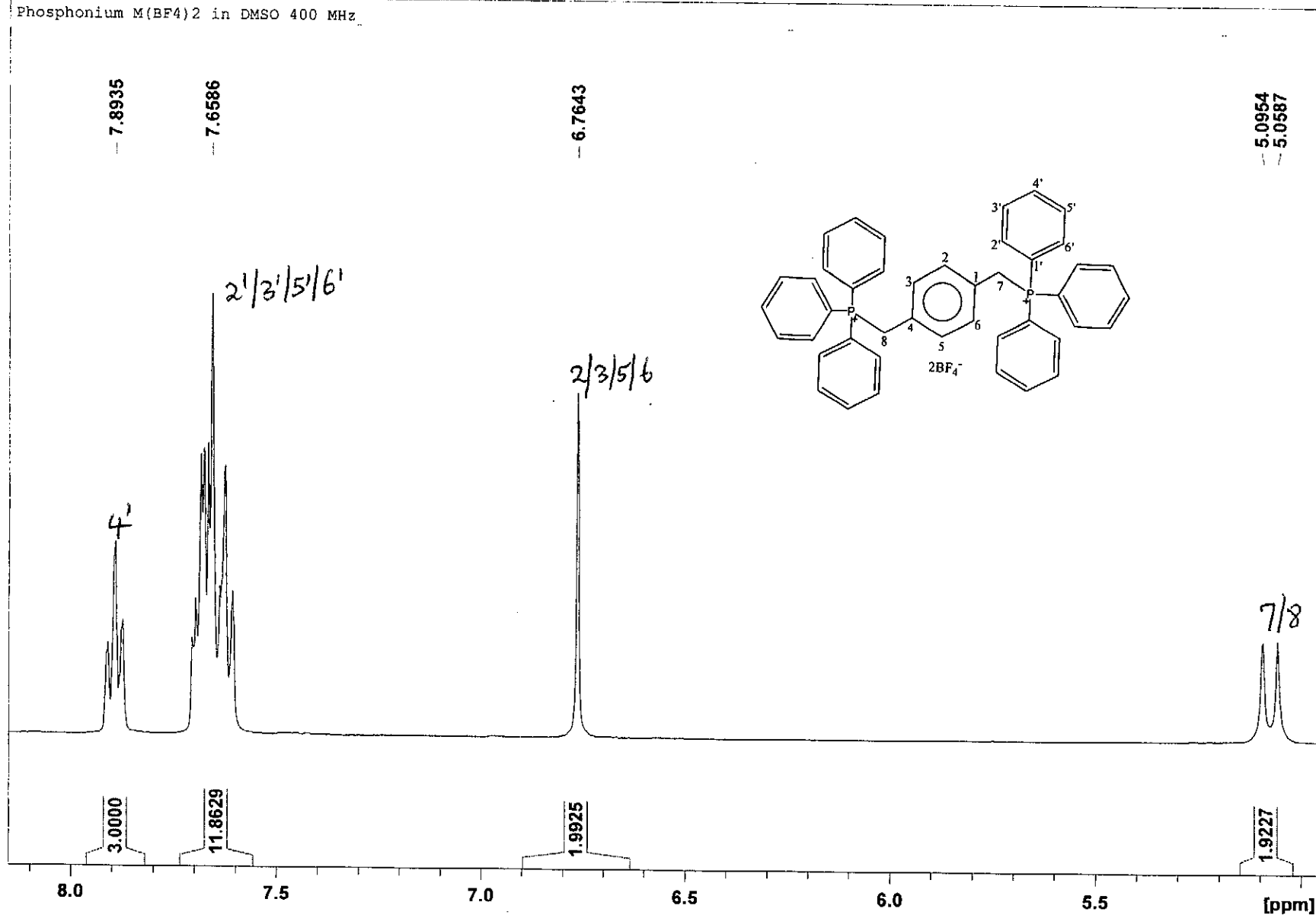
Hitrahin_Samp4_11050911713 #1-5 RT: 0.00-0.07 AV: 5 NL: 2.71E6
T: ITMS + e ESI Full ms [150.00-900.00]



MS of Compound B-2

Oct15-2009-NK-Ibrahim 20 1 C:\Bruker\TOPSPIN guest

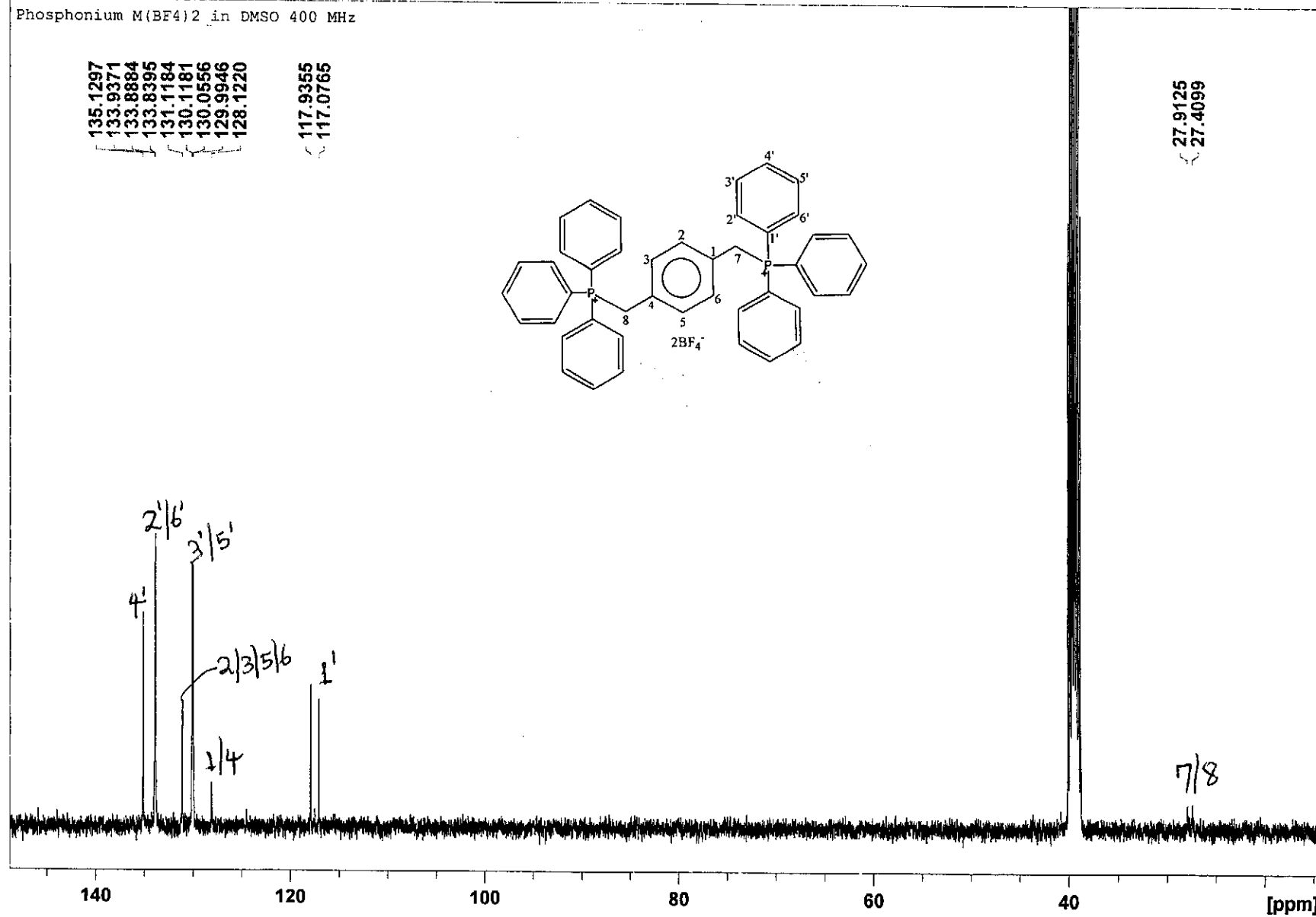
Phosponium M(BF₄)₂ in DMSO 400 MHz



¹H NMR spectrum of compound B-3

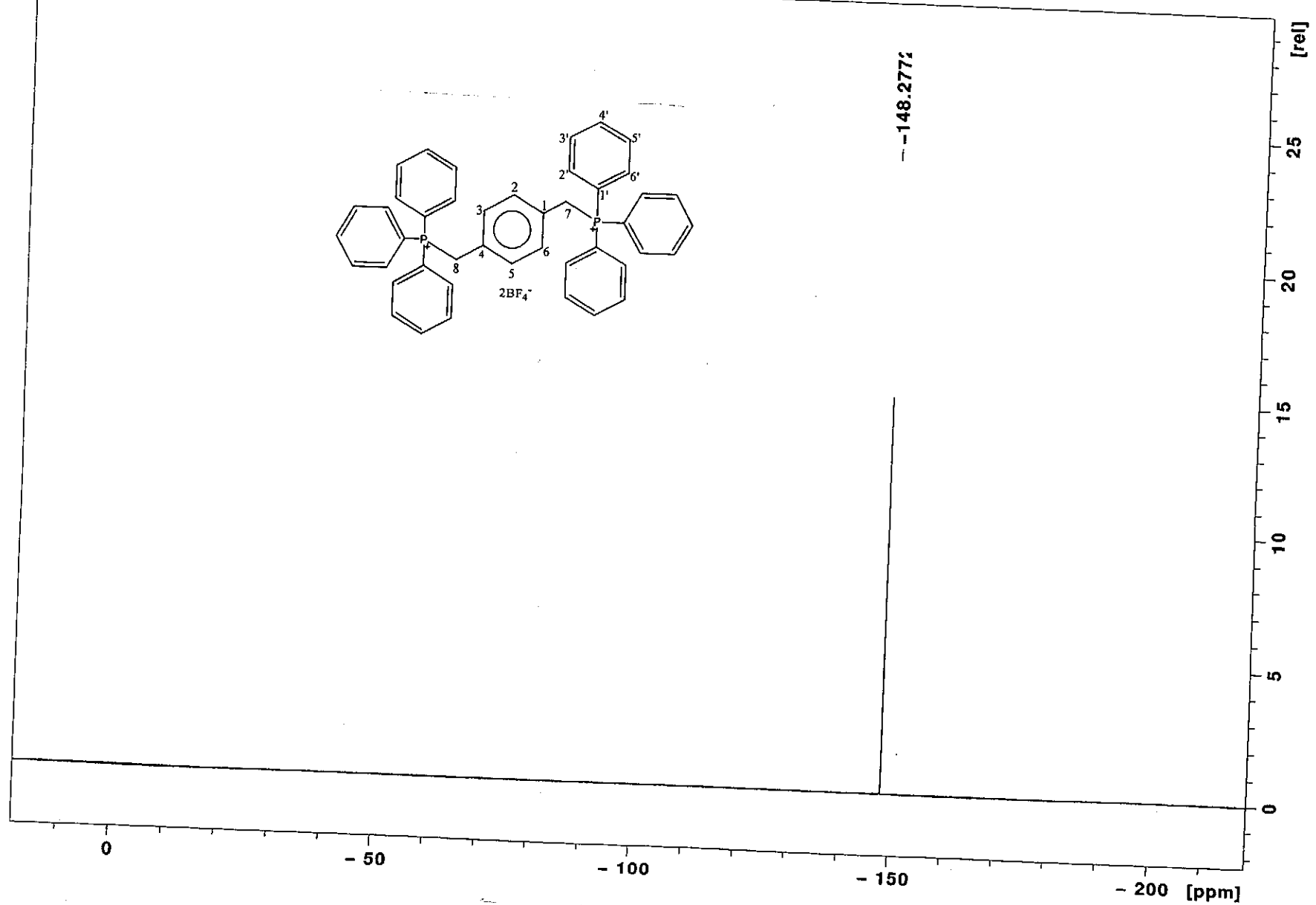
Oct15-2009-NK-Ibrahim 21 1 C:\Bruker\TOPSPIN guest

Phosphonium M(BF₄)₂ in DMSO 400 MHz



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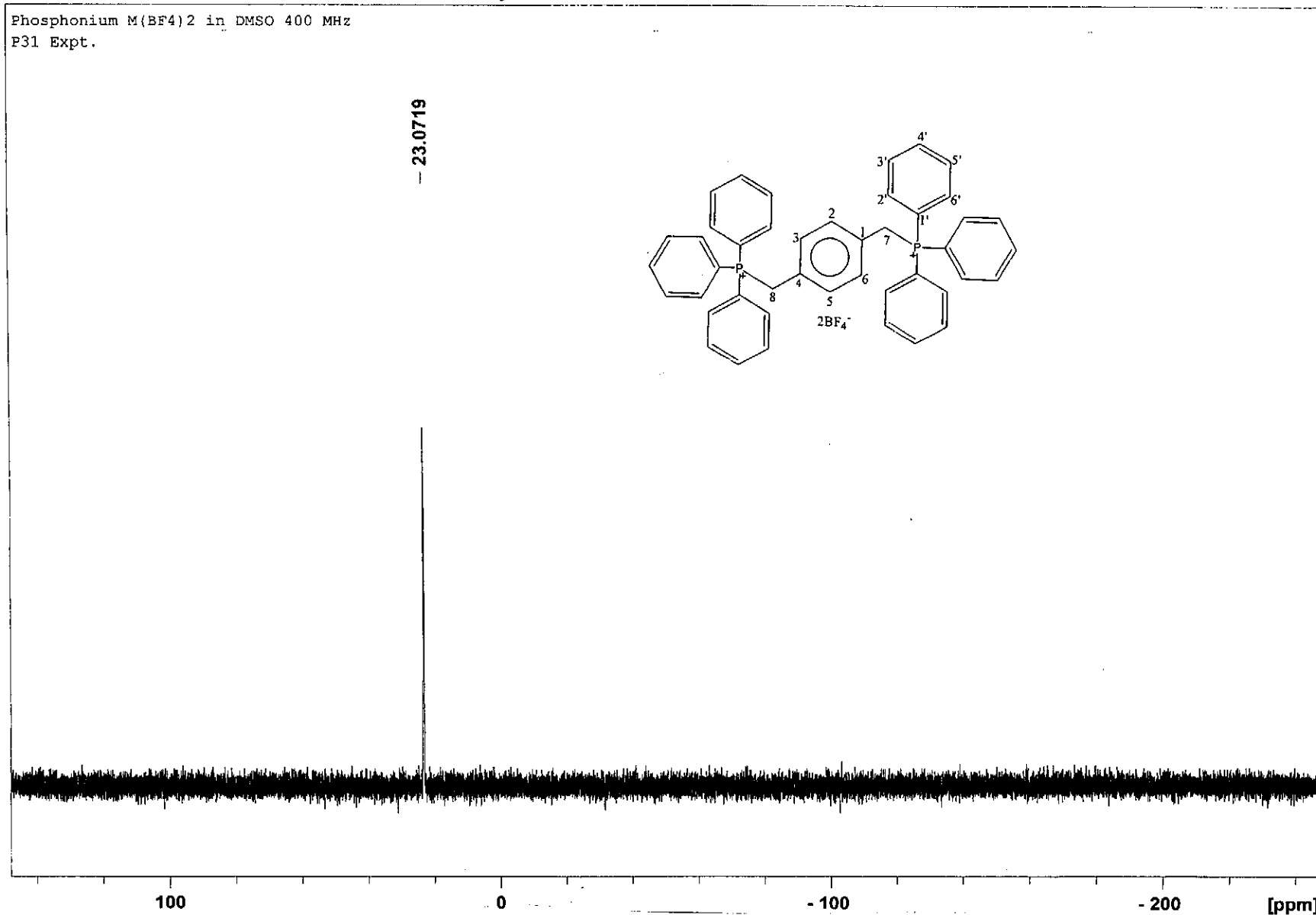
B3 19F Expt in DMSO 400 MHz



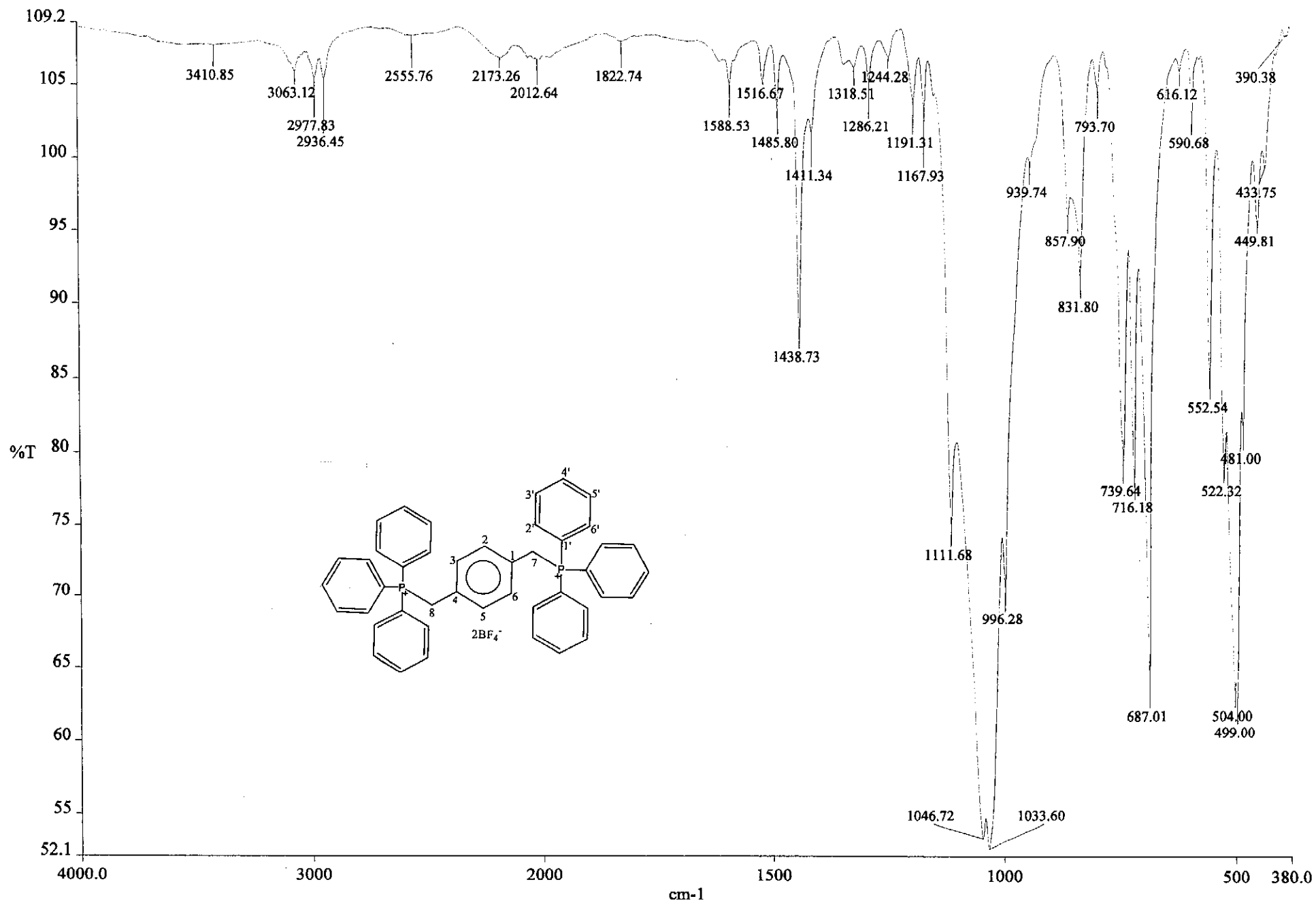
^{19}F NMR spectrum of Compound B-3

Oct15-2009-NK-Ibrahim 103 1 C:\Bruker\TOPSPIN guest

Phosphonium M(BF₄)₂ in DMSO 400 MHz
P31 Expt.



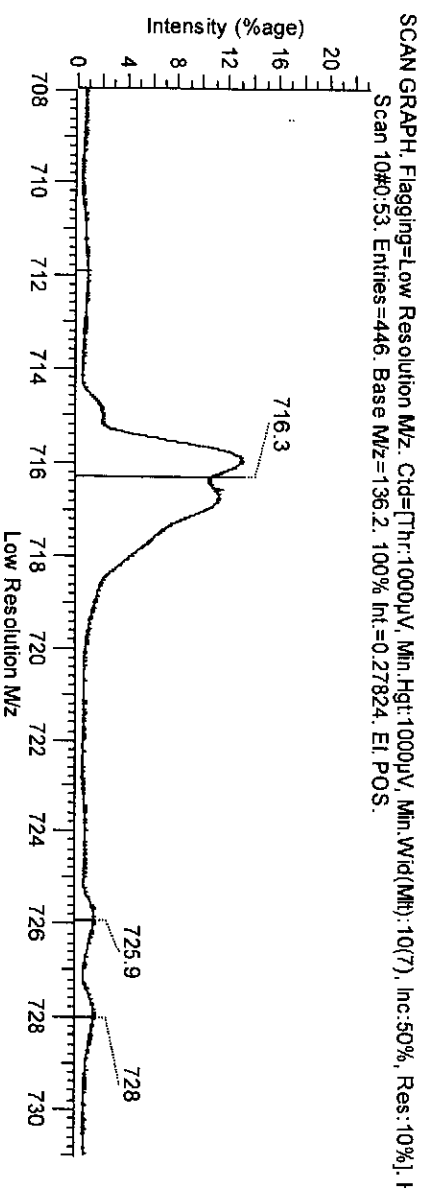
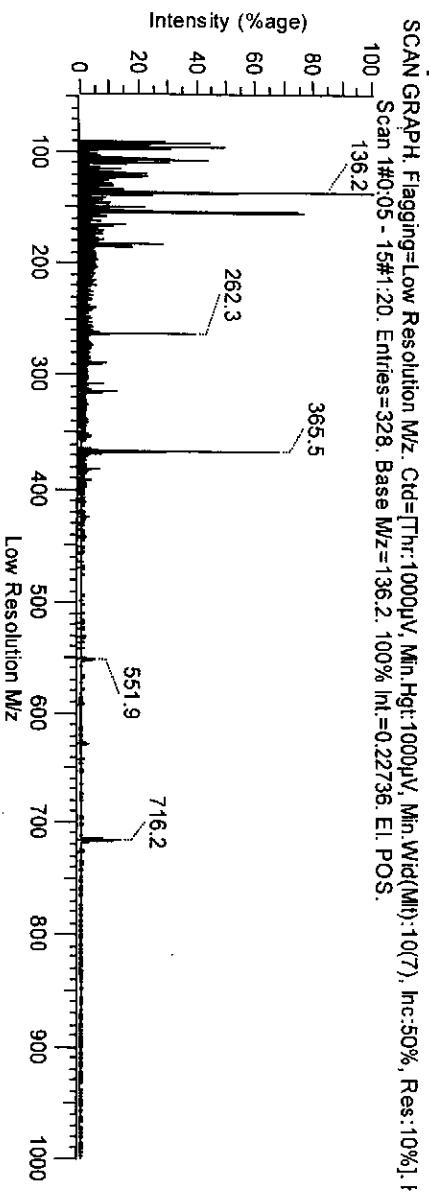
³¹P NMR spectrum of Compound B-3



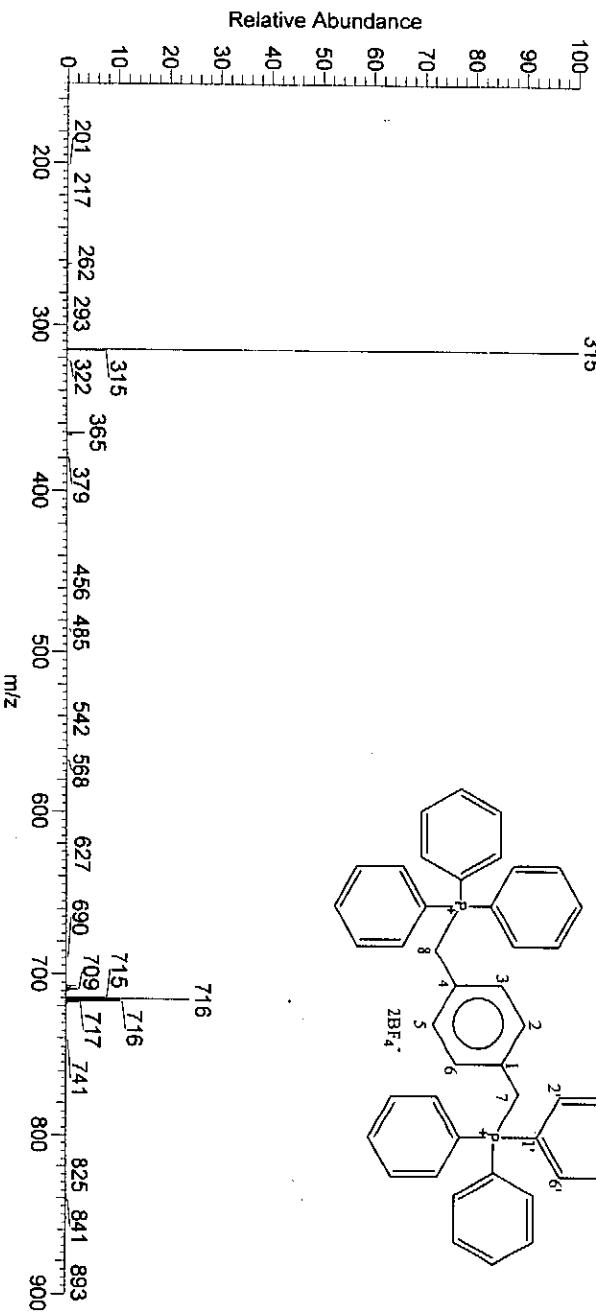
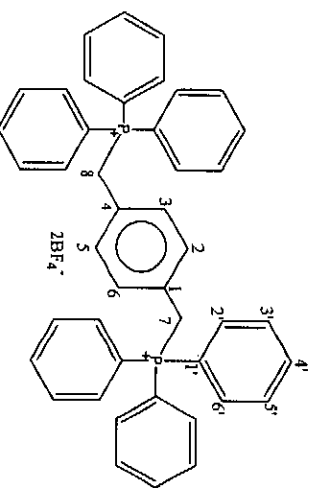
c:\pel_data\spectra\brahim\phosphonium il, m(bf4)2.002 - White crystals

IR spectrum of Compound B-3

Sample 2

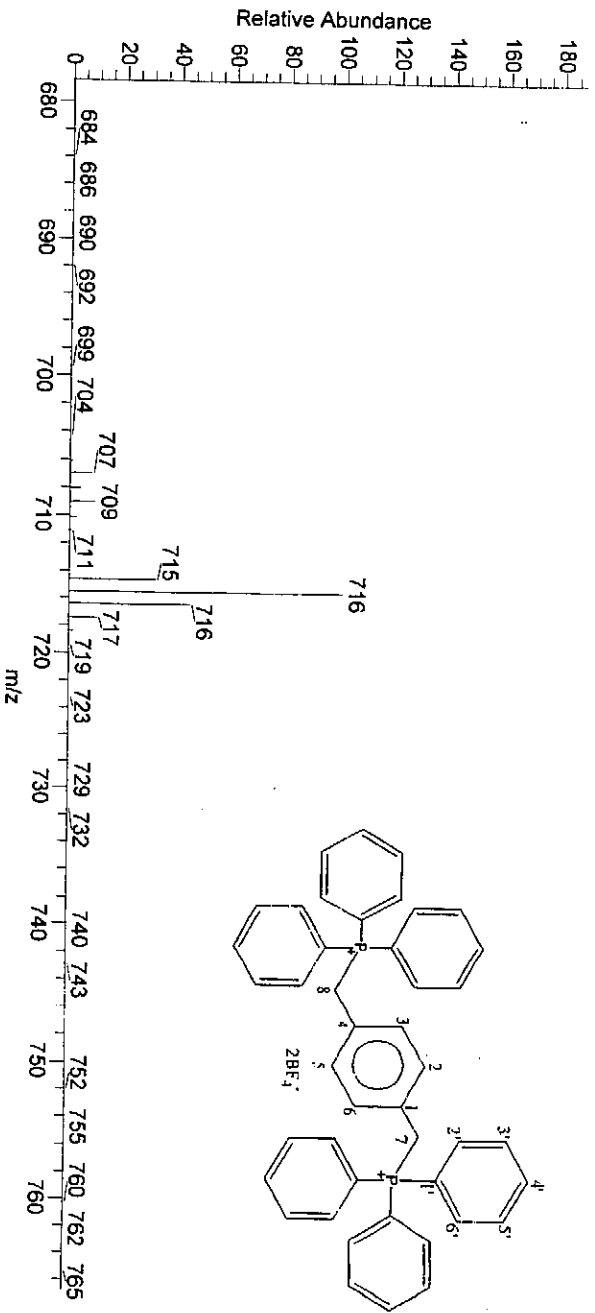


Hlbrahim_Samp2_LRESI#2-19 RT: 0.02-0.38 AV: 18 NL: 1.86E6
 T: ITMS + c ESI Full ms [150.00-900.00]



M/S of Compound B-3

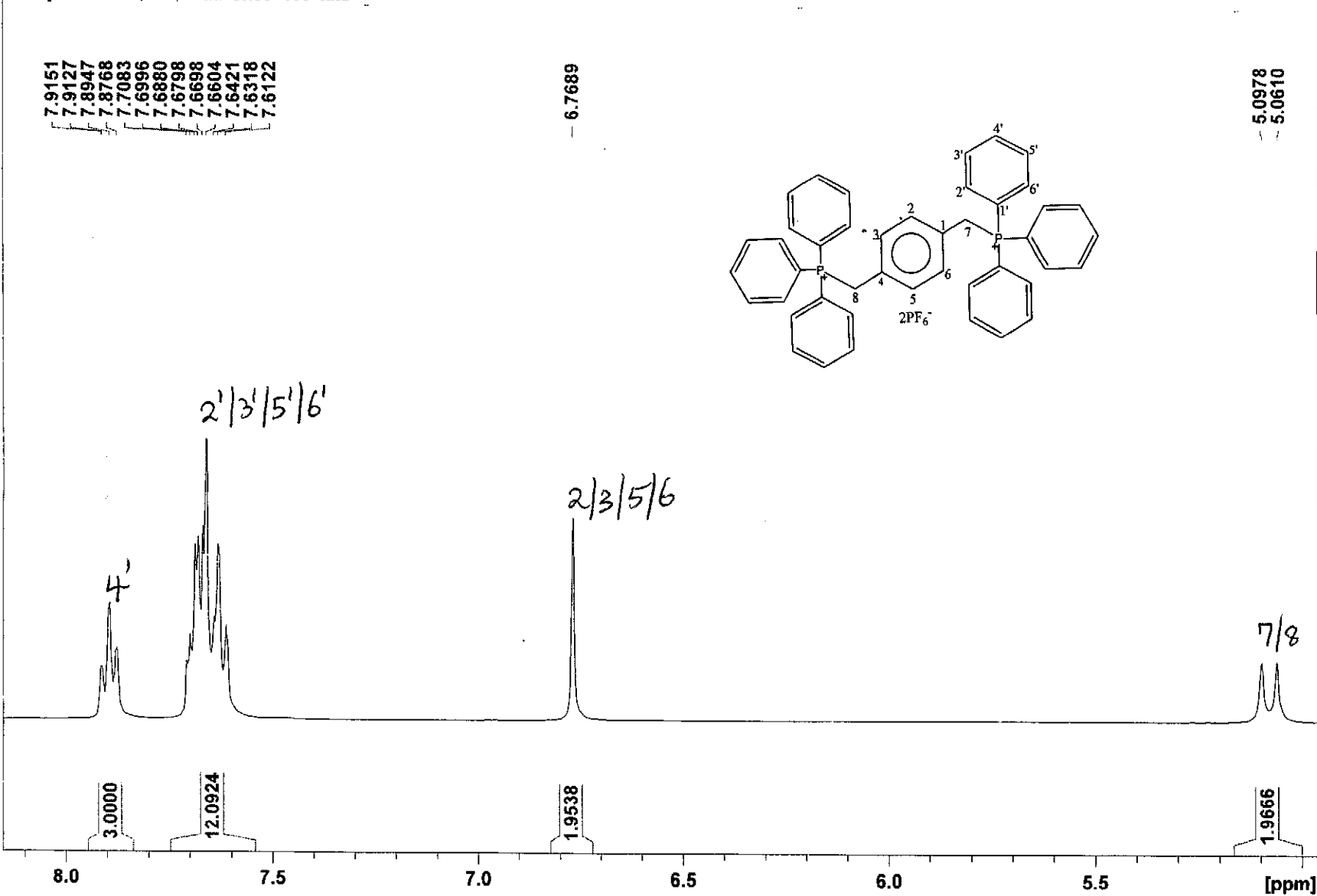
Hilbrahim_Samp2_LRESI #2-19 RT: 0.02-0.38 AV: 18 NL: 4.47E5
T: LTMS + c ESI Full ms [150.00-900.00]



MS of Compound B-3

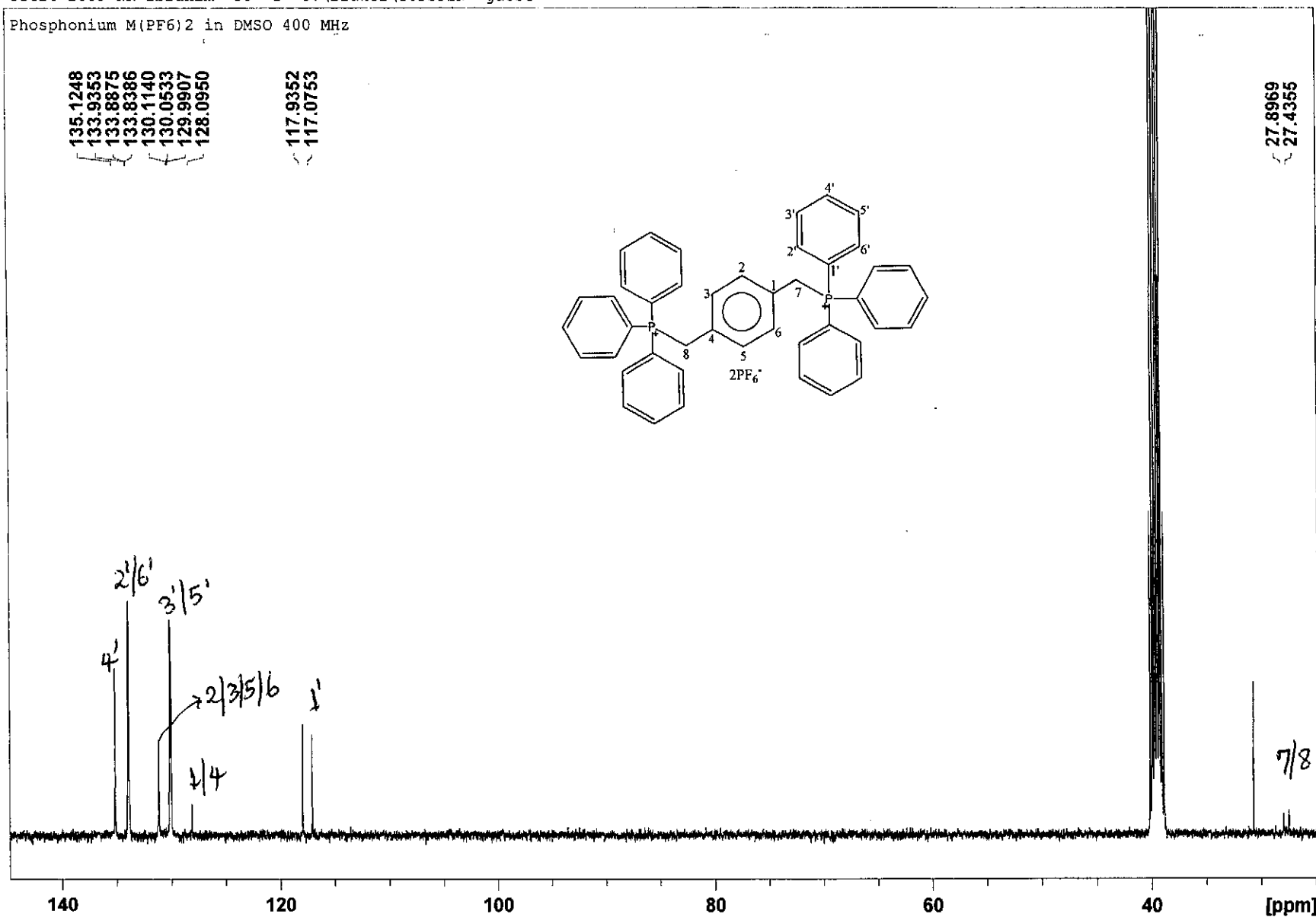
Oct13-2009-NK-Ibrahim 40 1 C:\Bruker\TOPSPIN guest

Phosphonium M(PF₆)₂ in DMSO 400 MHz



¹H NMR spectrum of compound B-4

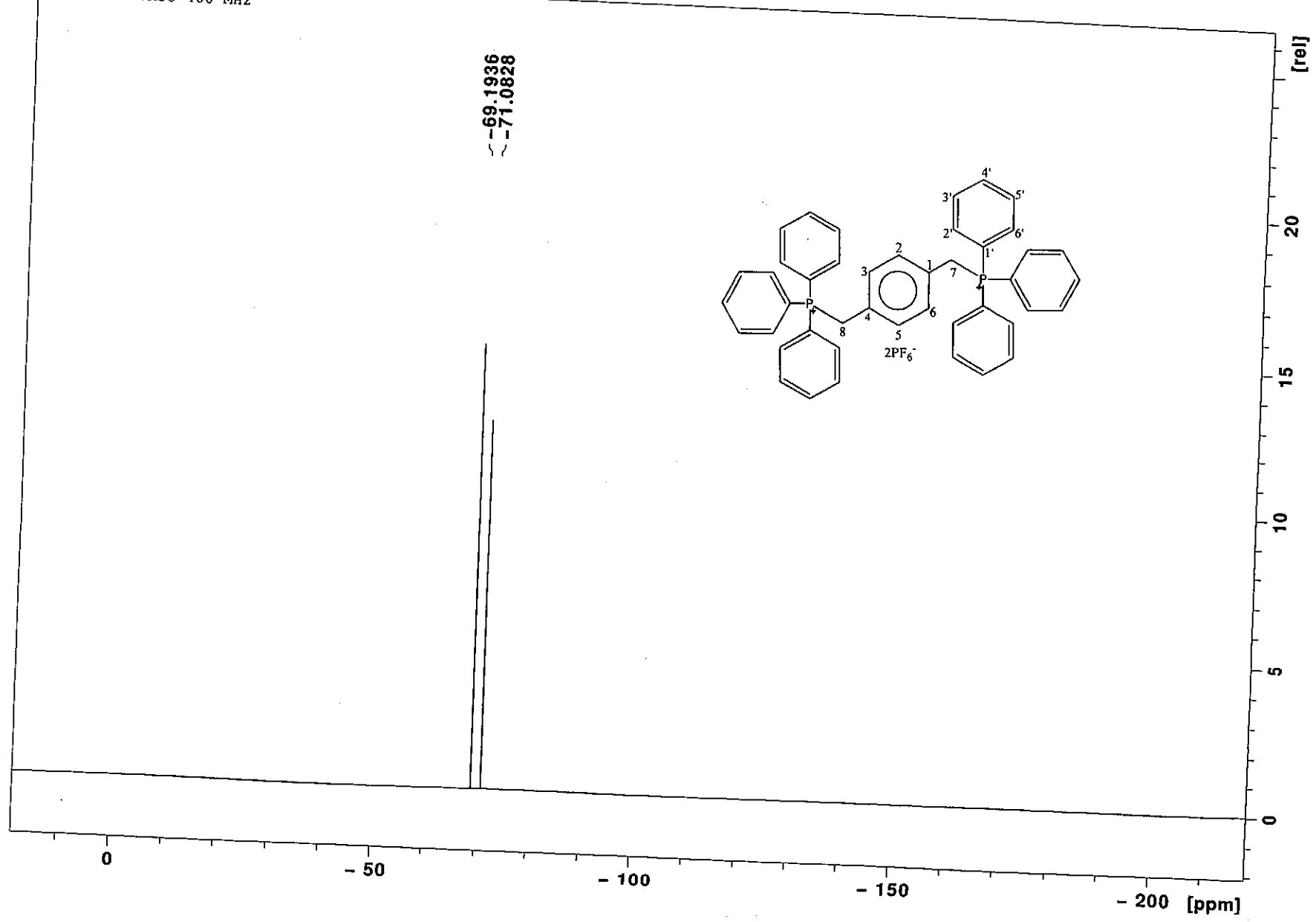
Phosponium M(PF6)2 in DMSO 400 MHz



¹³C NMR spectrum of Compound B-4

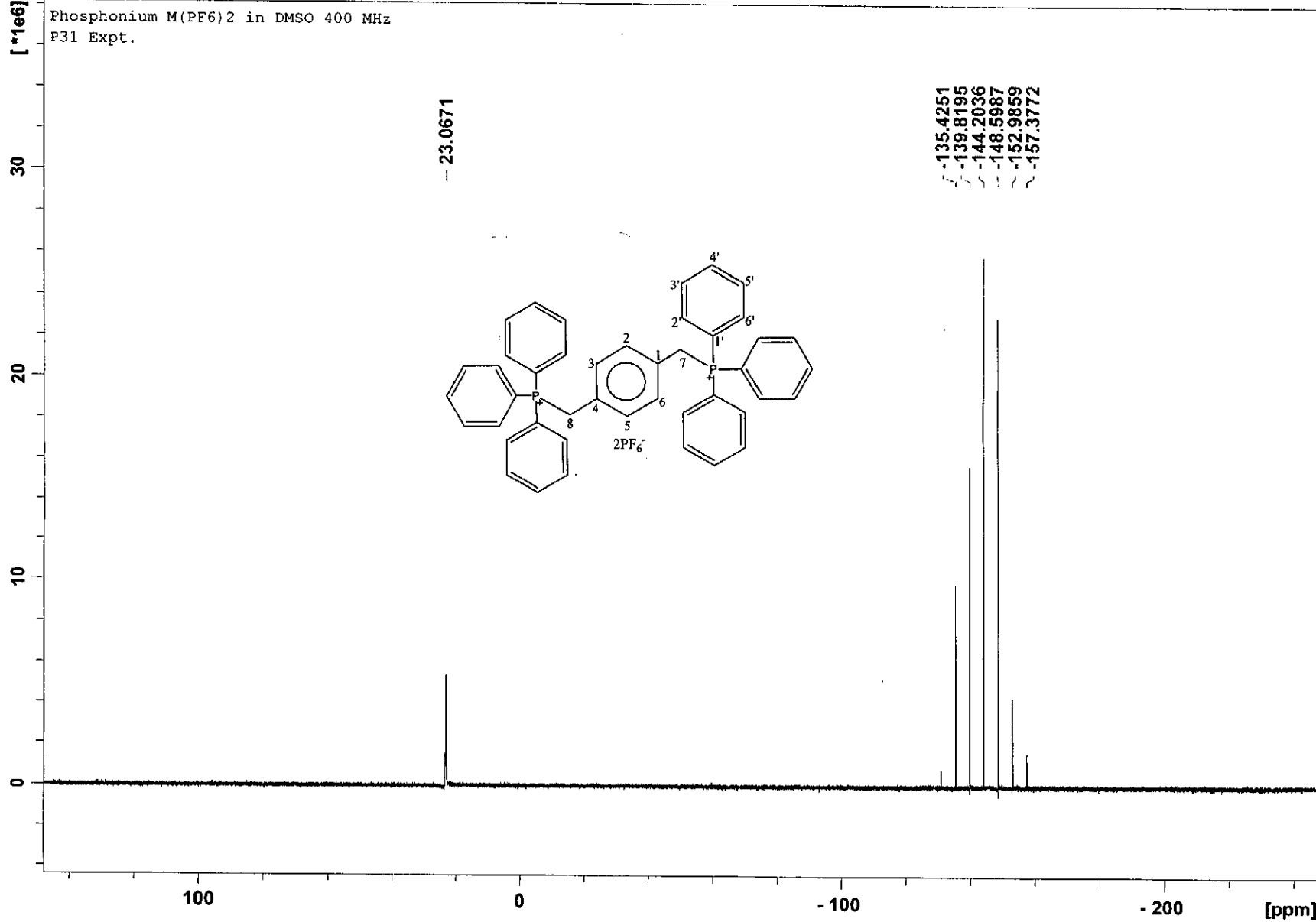
Jan11-2013-NK-Ibrahim 30 1 /opt/topspin NK

B4 19F in DMSO 400 MHz

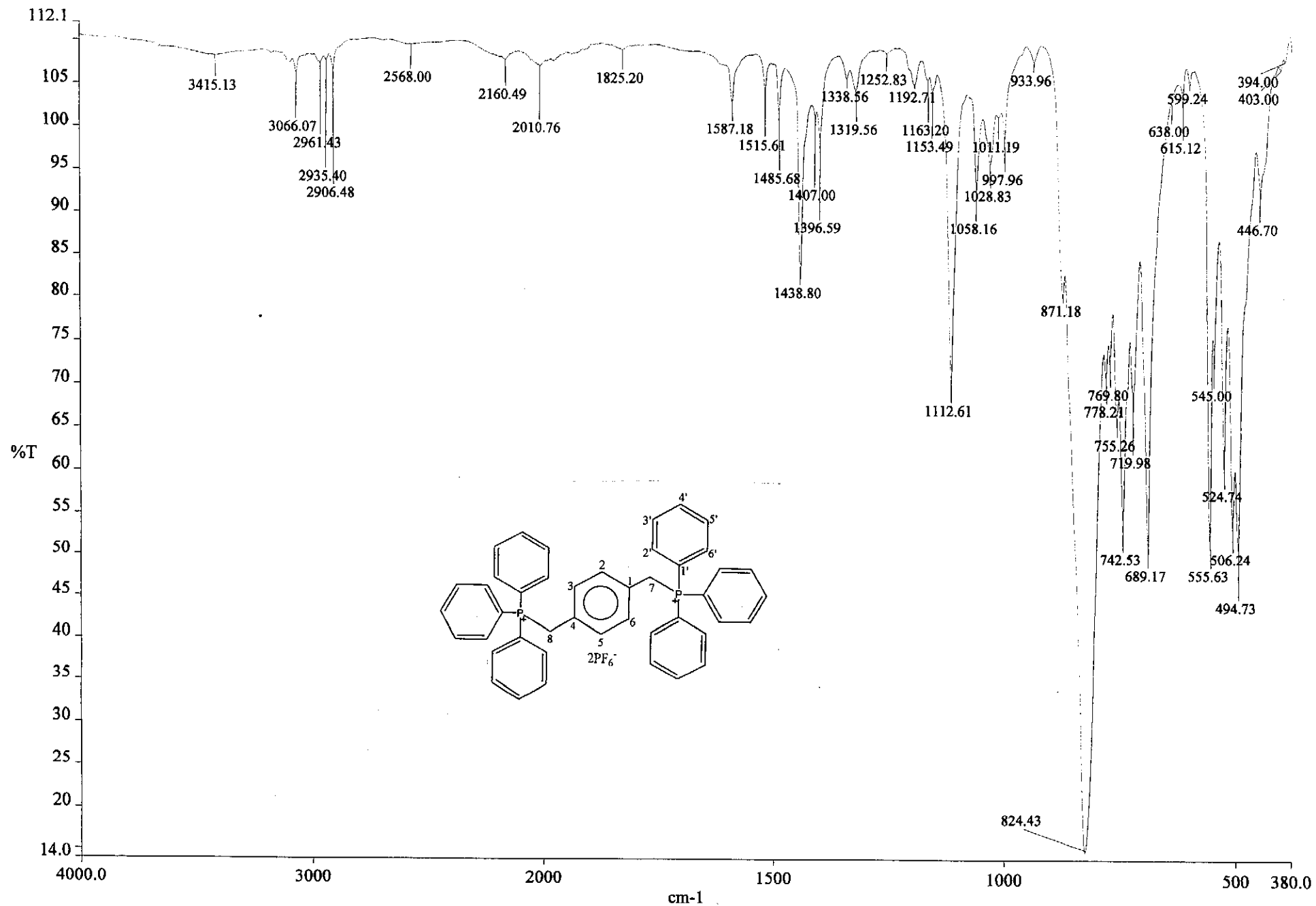


^{19}F NMR spectrum of Compound B-4

Oct15-2009-NK-Ibrahim 75 1 C:\Bruker\TOPSPIN guest



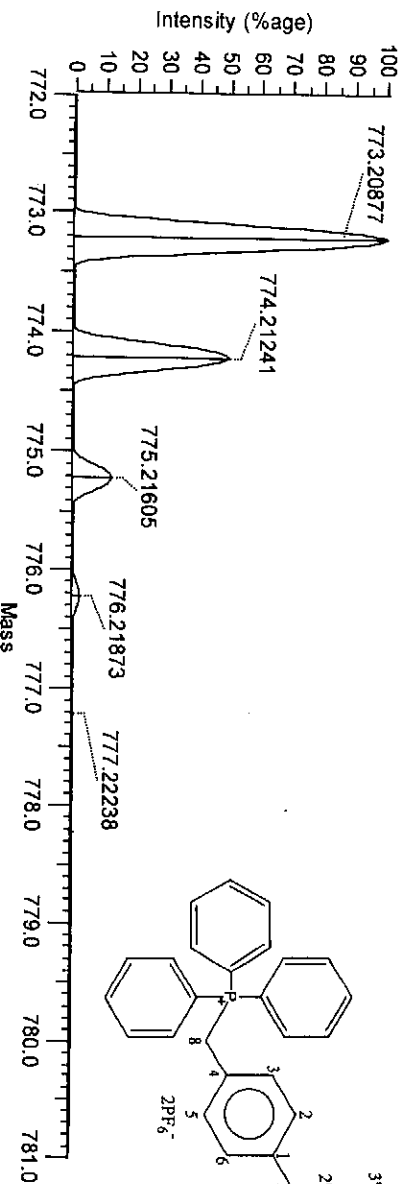
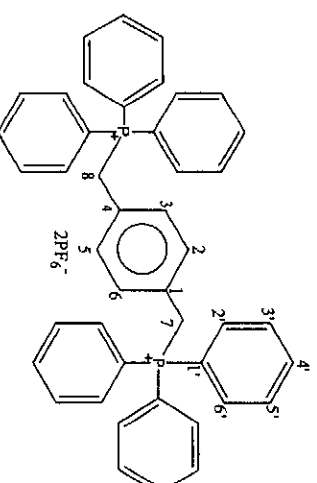
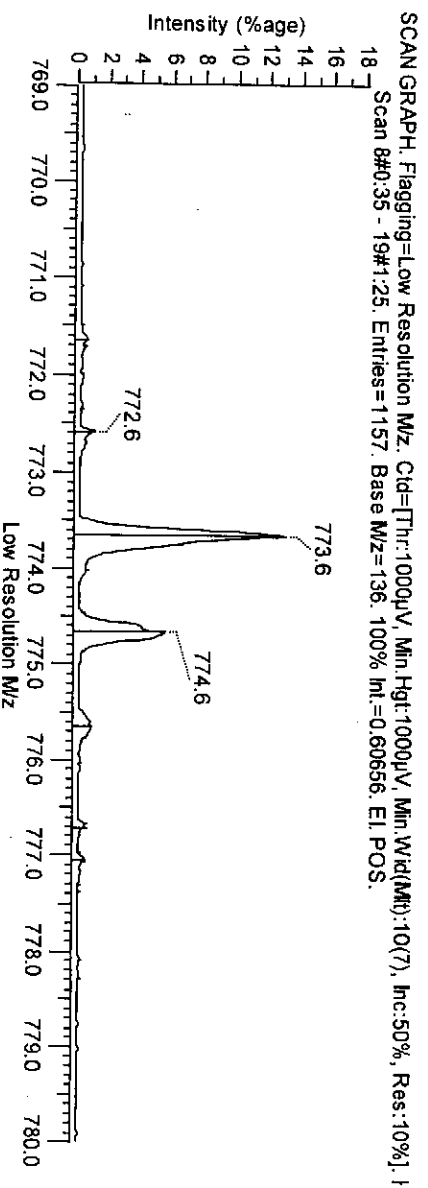
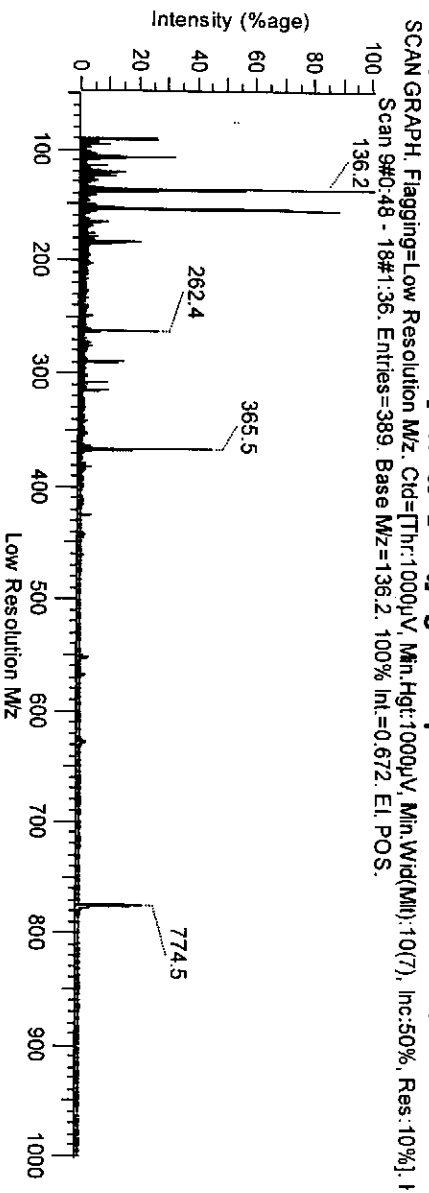
³¹P NMR spectrum of Compound B-4



c:\pel_data\spectra\brahim\phosphonium ii, m(pf6)2.002 - White Powdery subs.

IR spectrum of Compound B-4

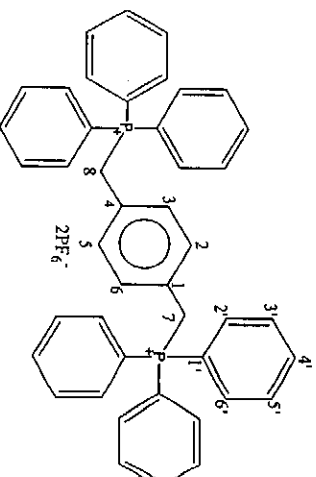
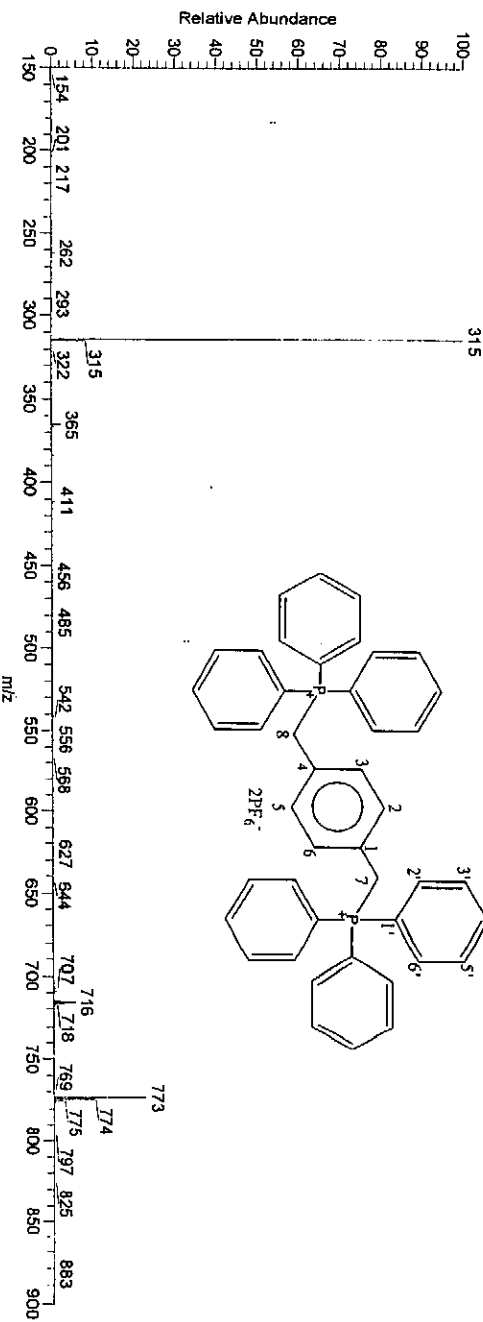
Sample 3, The mono cation $[C_{44}H_{38}P_2PF_6]^+$ gives a peak at m/z 773 / 774.



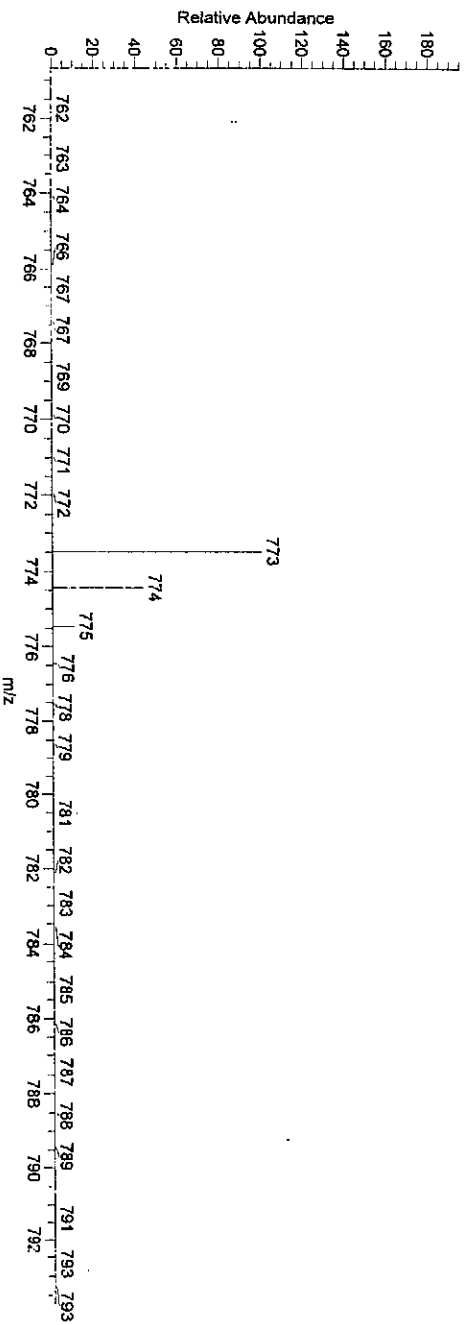
MS of Compound B-4

**Sample 3
ESI-MS,**

Hilbrakim_Samp3_LRESI #4-20 RT: 0.07-0.45 AV: 17 NL: 6.76E5
 T: ITMS + c ESI Full ms [150.00-900.00]



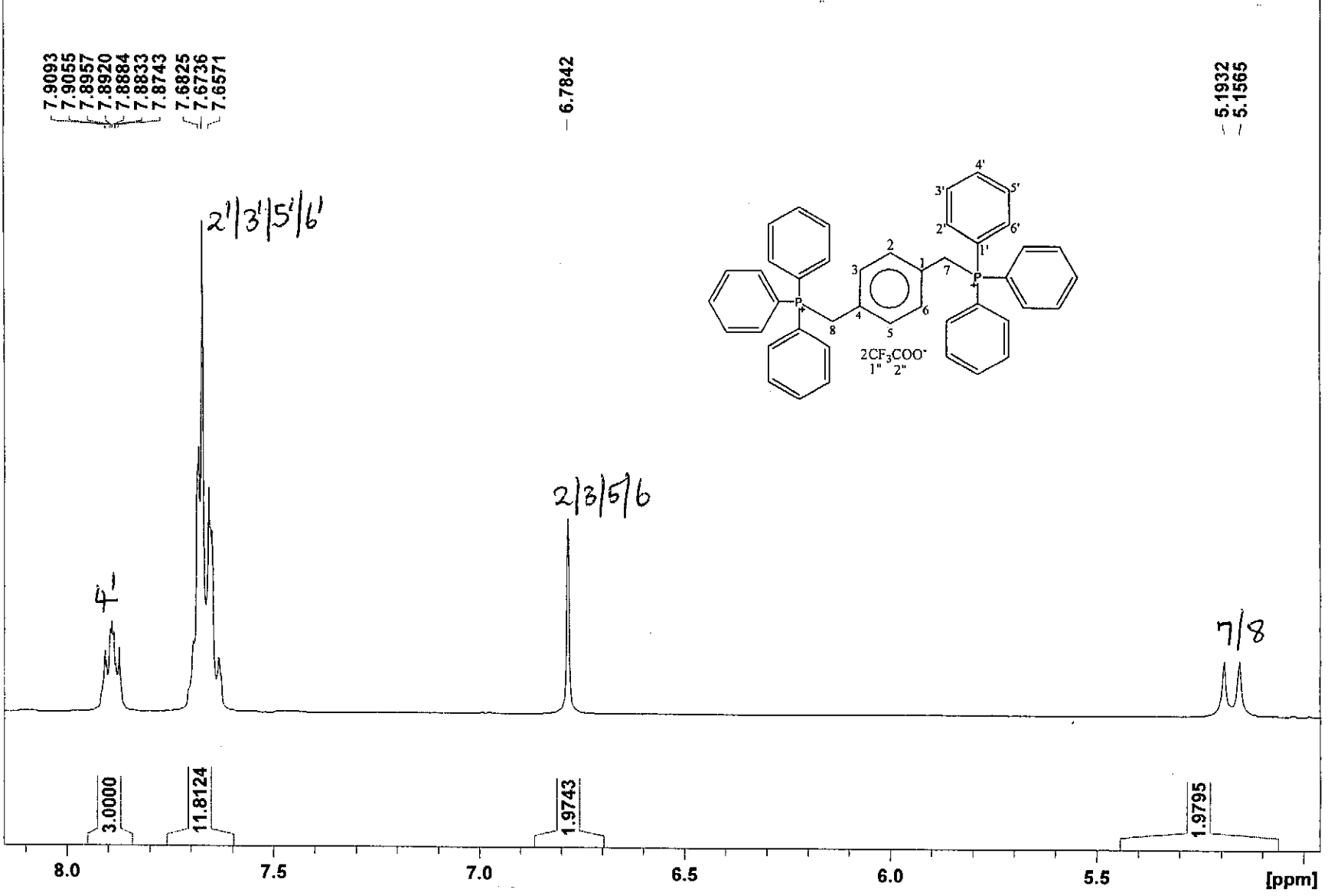
Hilbrakim_Samp3_LRESI #4-20 RT: 0.07-0.45 AV: 17 NL: 1.52E5
 T: ITMS + c ESI Full ms [150.00-900.00]



MS of Compound B-4

Oct13-2009-NK-Ibrahim 50 1 C:\Bruker\TOPSPIN guest

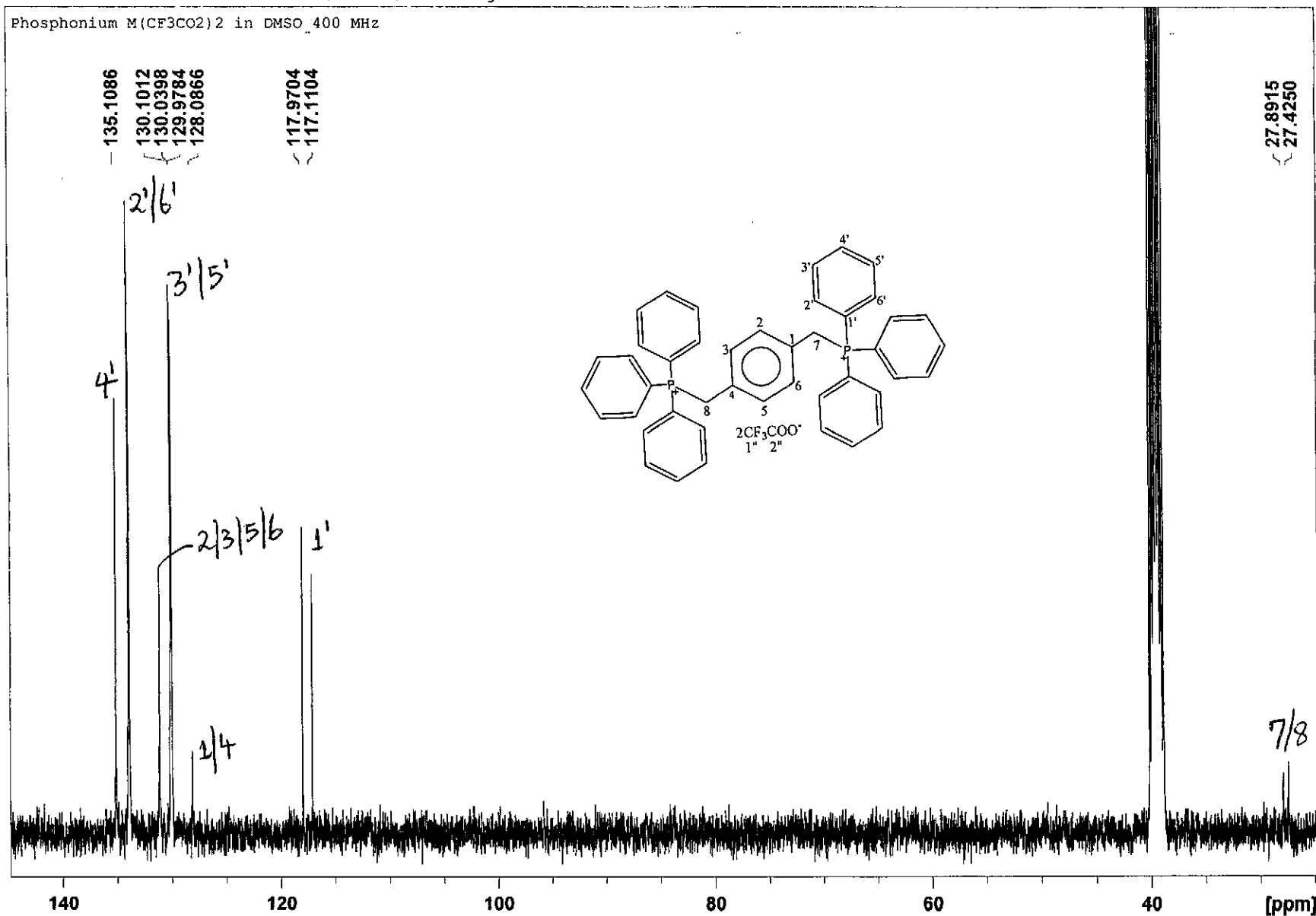
Phosphonium M(CF₃CO₂)₂ in DMSO 400 MHz



¹H NMR spectrum of compound B-5

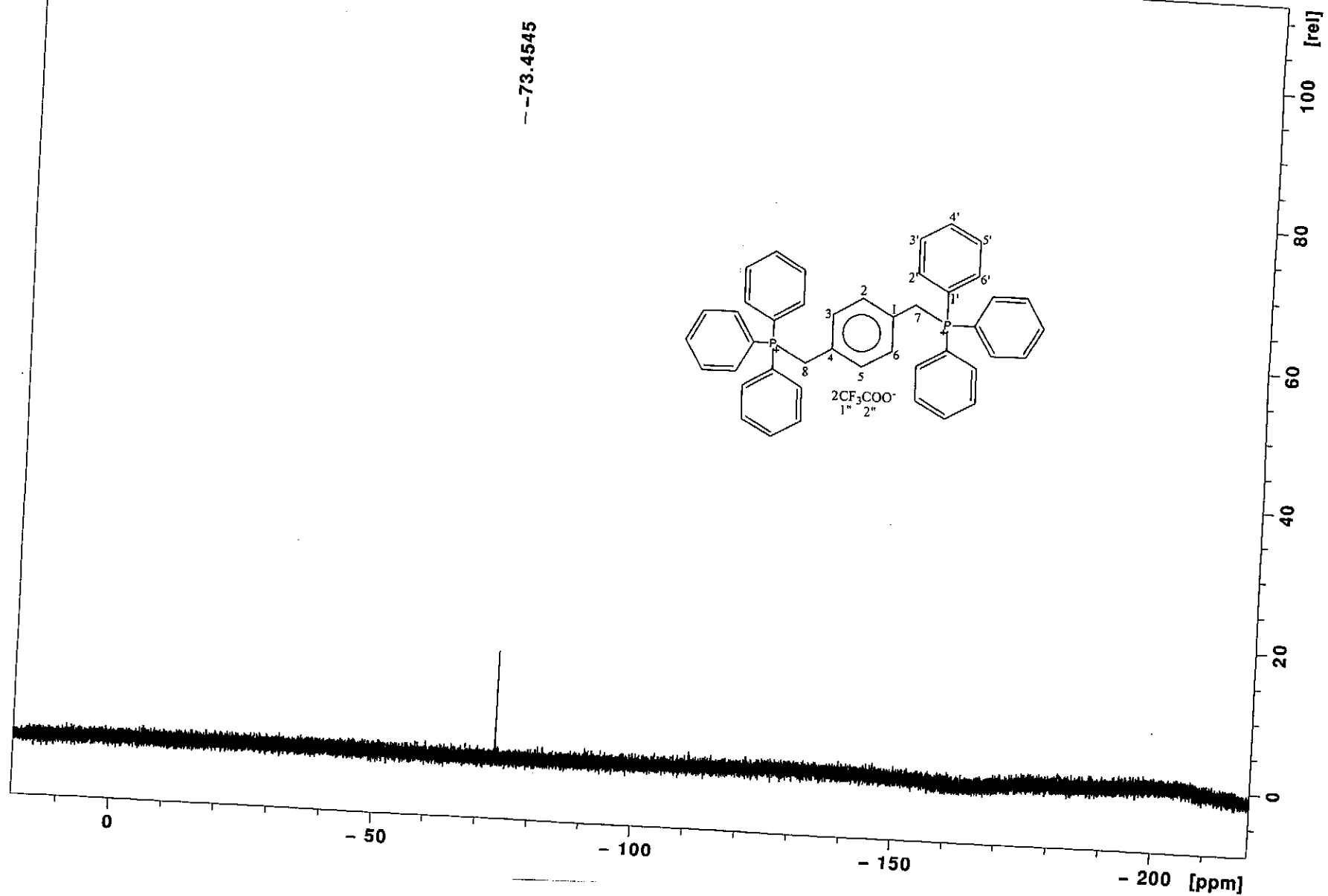
Oct14-2009-NK-Ibrahim 40 1 C:\Bruker\TOPSPIN guest

Phosphonium M(CF₃CO₂)₂ in DMSO_400 MHz



¹³C NMR spectrum of Compound B-5

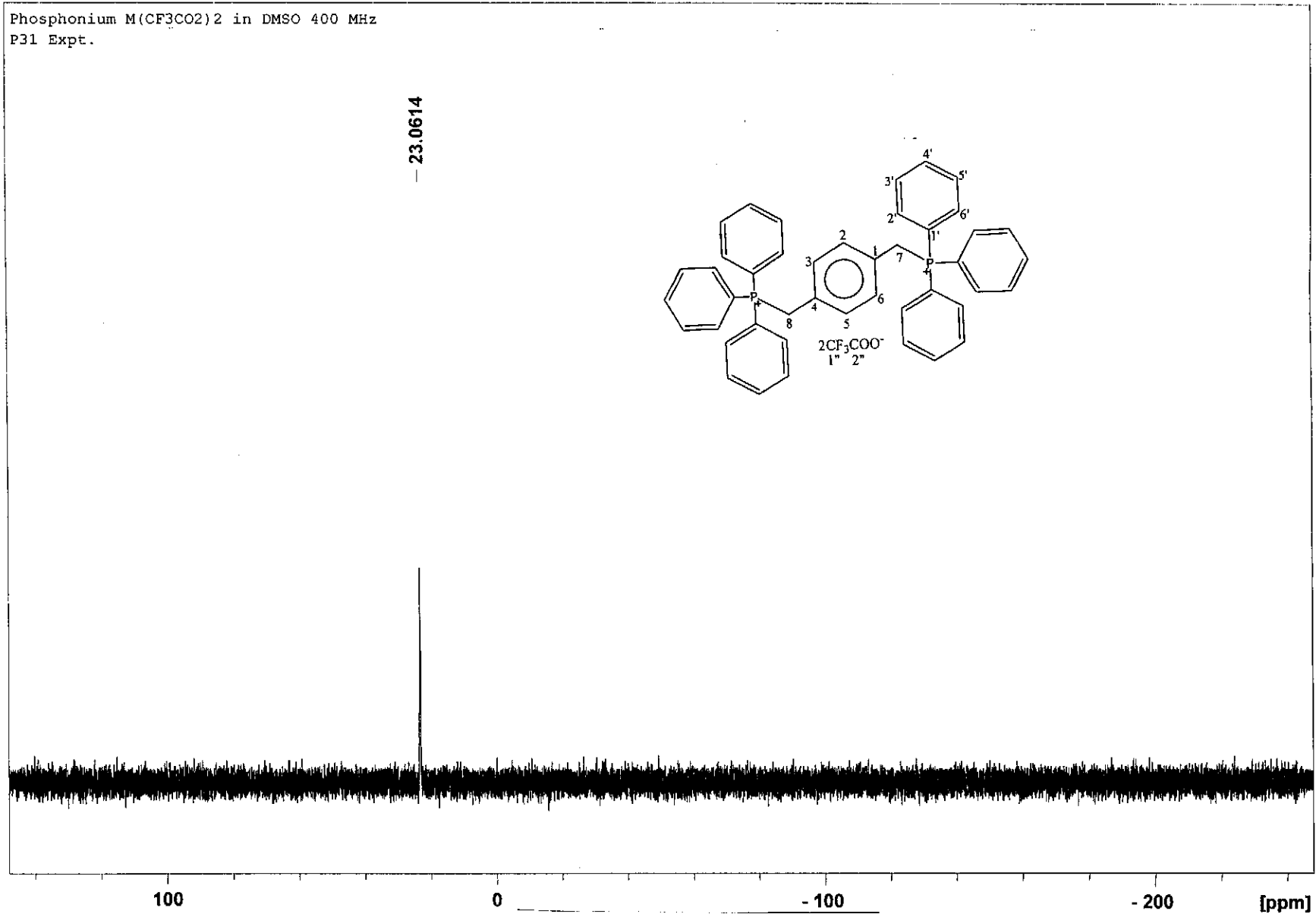
Jan11-2013-NK-Ibrahim 40 1 /opt/topspin NK
B5 19F in DMSO 400 MHz



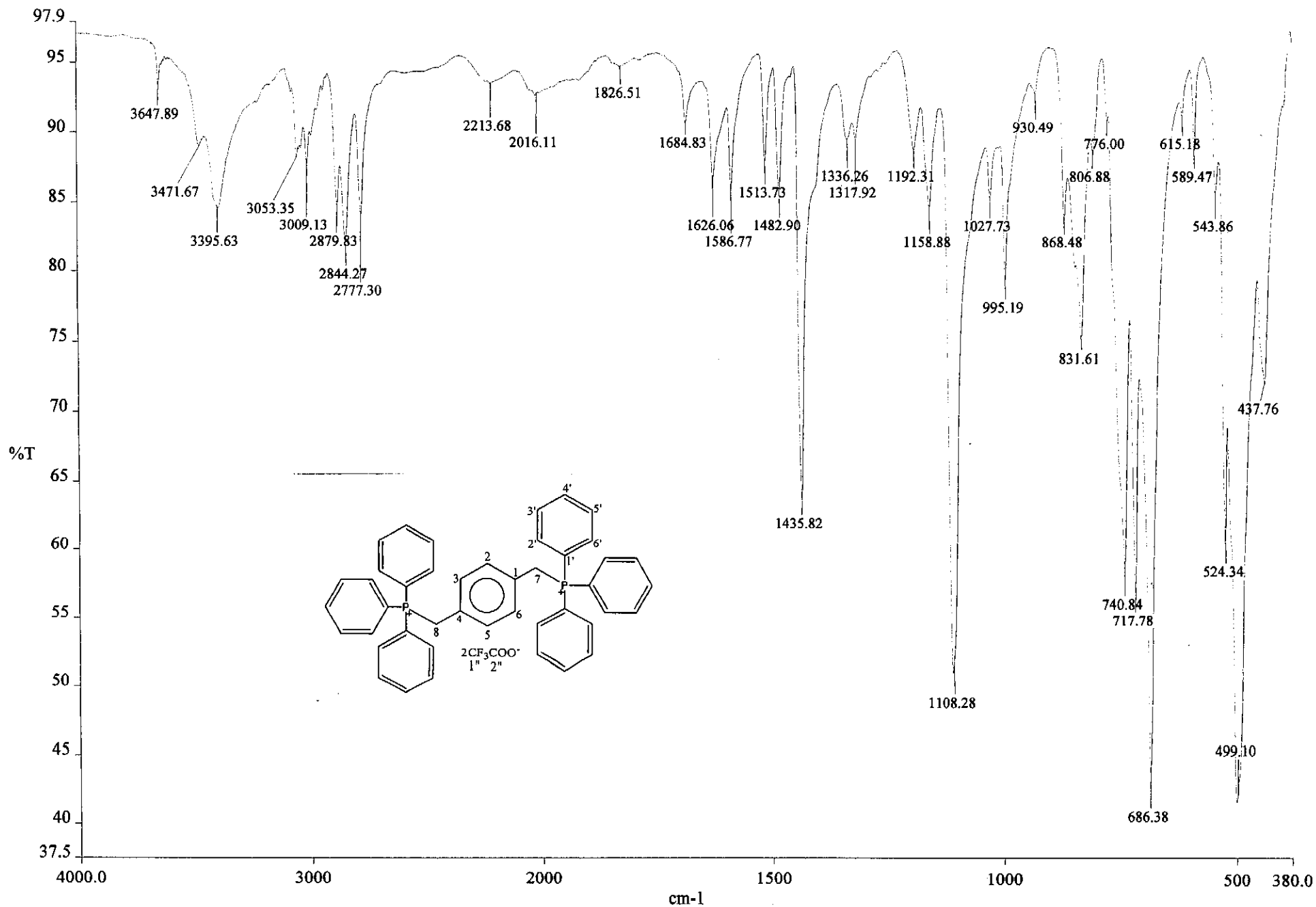
^{19}F NMR spectrum of Compound B-5

Oct15-2009-NK-Ibrahim 114 1 C:\Bruker\TOPSPIN guest

Phosphonium M(CF₃CO₂)₂ in DMSO 400 MHz
P31 Expt.



³¹P NMR spectrum of Compound B-5

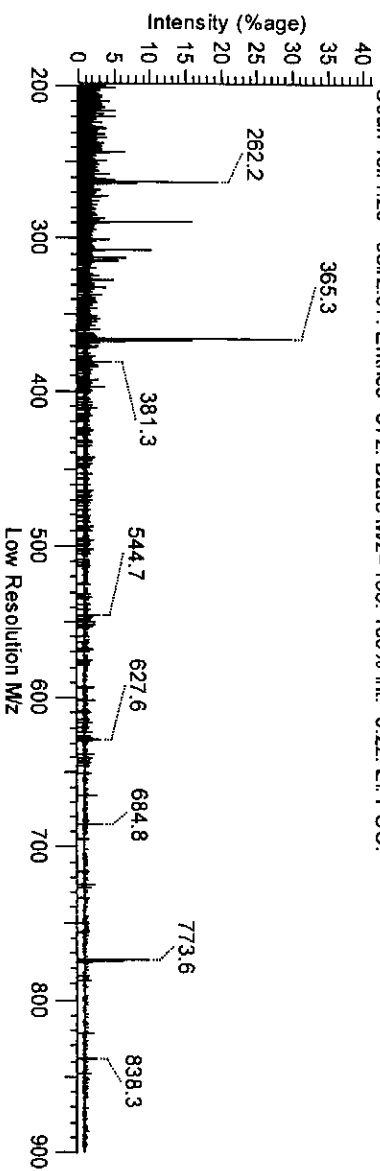


c:\pel_data\spectra\brahim\phosphonium il, m(cf3coo)2.002 - White Powdery subs.

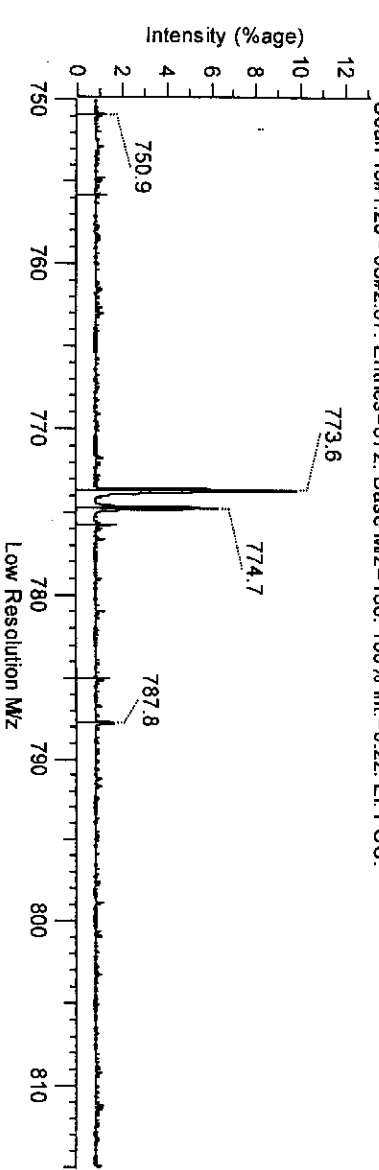
IR spectrum of Compound B-5

Sample 5

SCAN GRAPH. Flagging=Low Resolution M/z. Ctd=[Thr:1000µV, Min. Hgt:1000µV, Min. W/d(MN):10(T), Inc:50%, Res:10%]. I
 Scan 18#1:20 - 35#2:37. Entries=572. Base M/z=136. 100% Int.=0.22. EI POS.

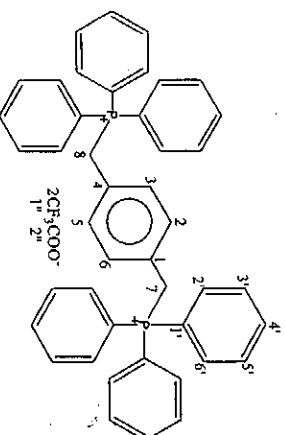
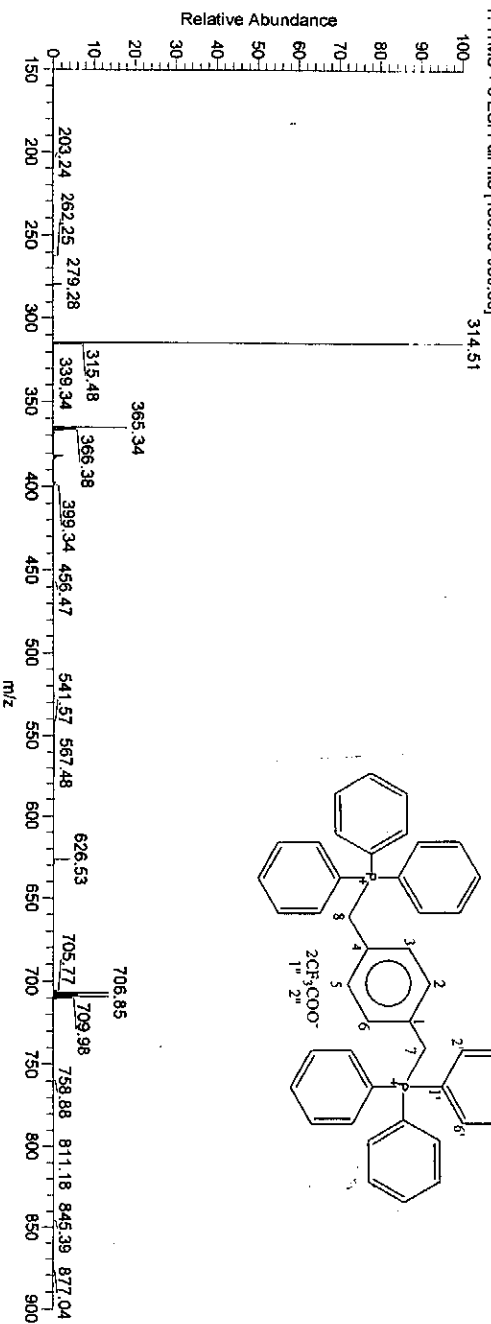


SCAN GRAPH. Flagging=Low Resolution M/z. Ctd=[Thr:1000µV, Min. Hgt:1000µV, Min. W/d(MN):10(T), Inc:50%, Res:10%]. I
 Scan 18#1:20 - 35#2:37. Entries=572. Base M/z=136. 100% Int.=0.22. EI POS.



ESI-MS

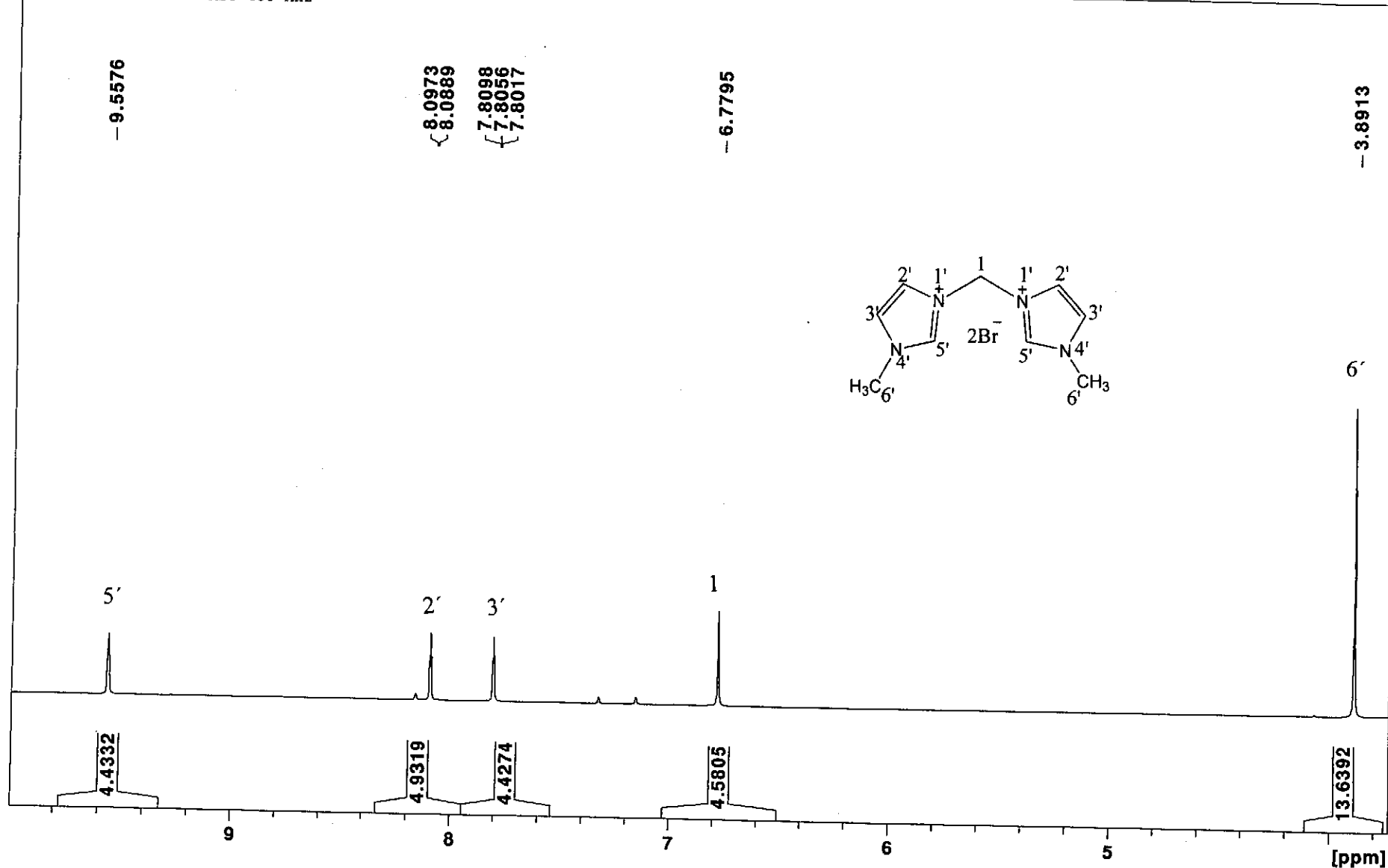
Hybration_Samp5_LRESI #6-20 RT: 0.10-0.37 AV: 15 NL: 2.51E6
 T: LTMS + c ESI/Full.ms [150.00-900.00]



MS of Compound B-5

Jun10-2012-NK-Ibrahim 10 1 /opt/topspin NK

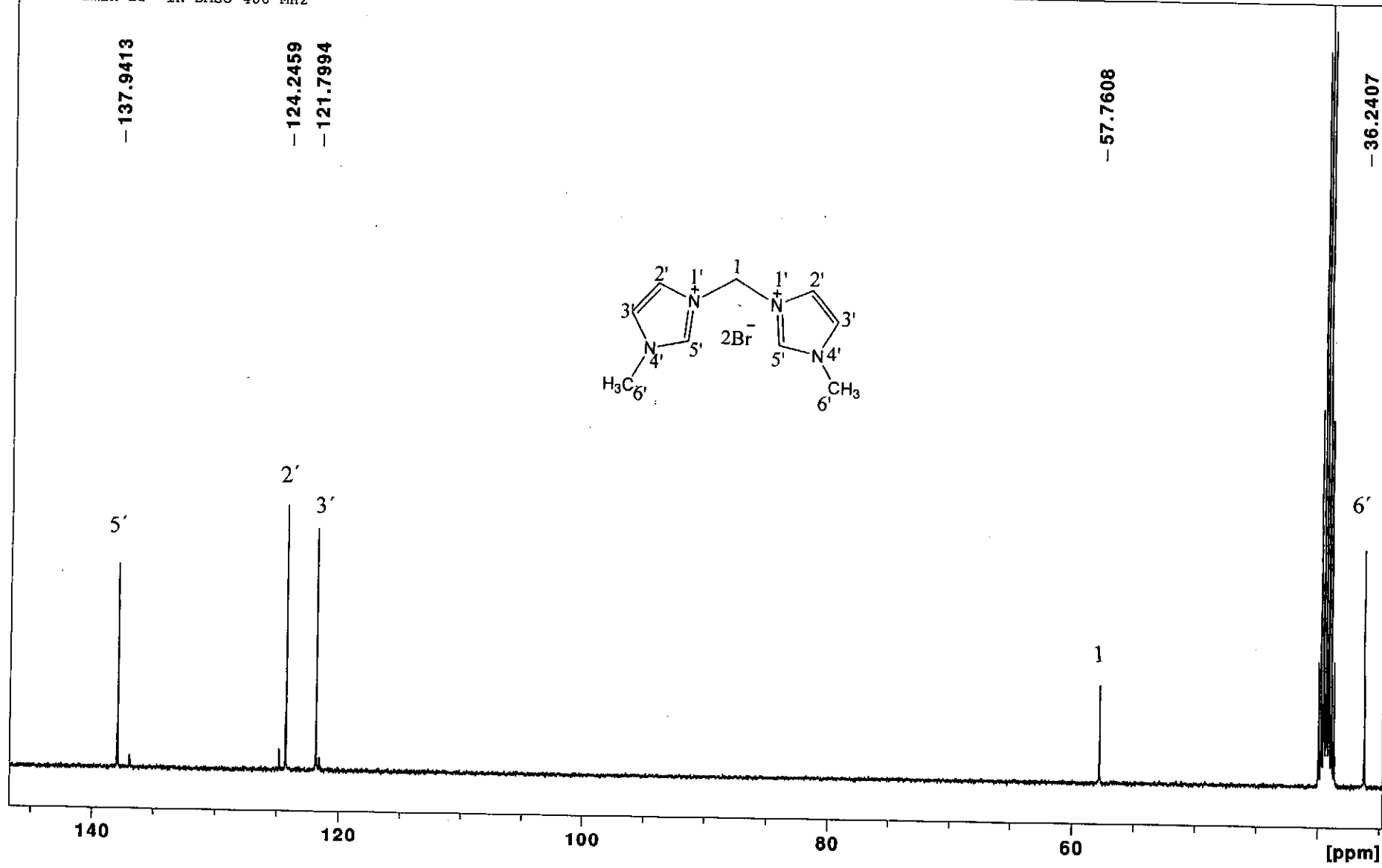
-CH2- Imin Br- in DMSO 400 MHz



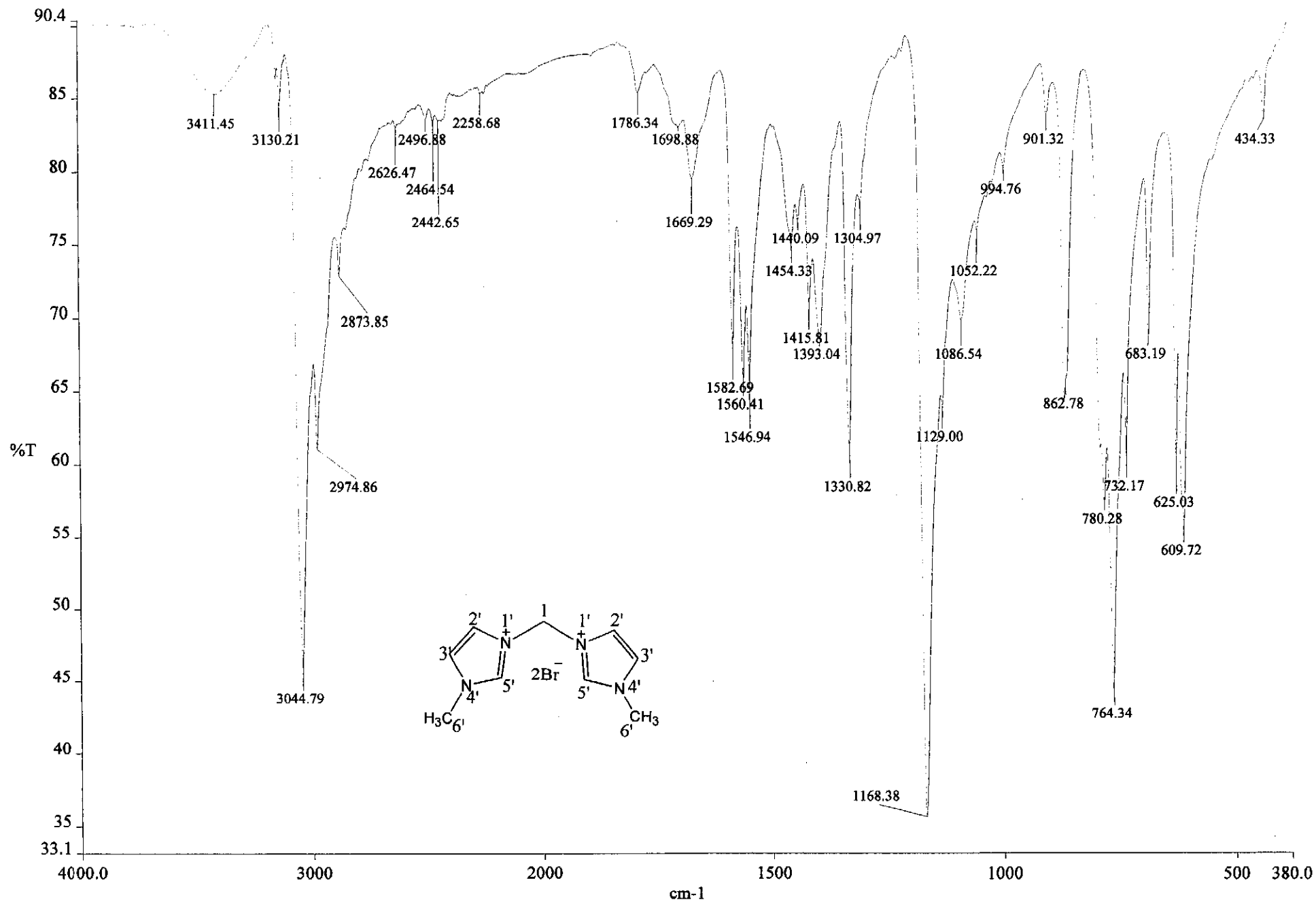
¹H NMR spectrum of Compound C-1a

Jun10-2012-NK-Ibrahim 11 1 /opt/topspin NK

-CH2- Imin Br- in DMSO 400 MHz



¹³C NMR spectrum of Compound C-1a

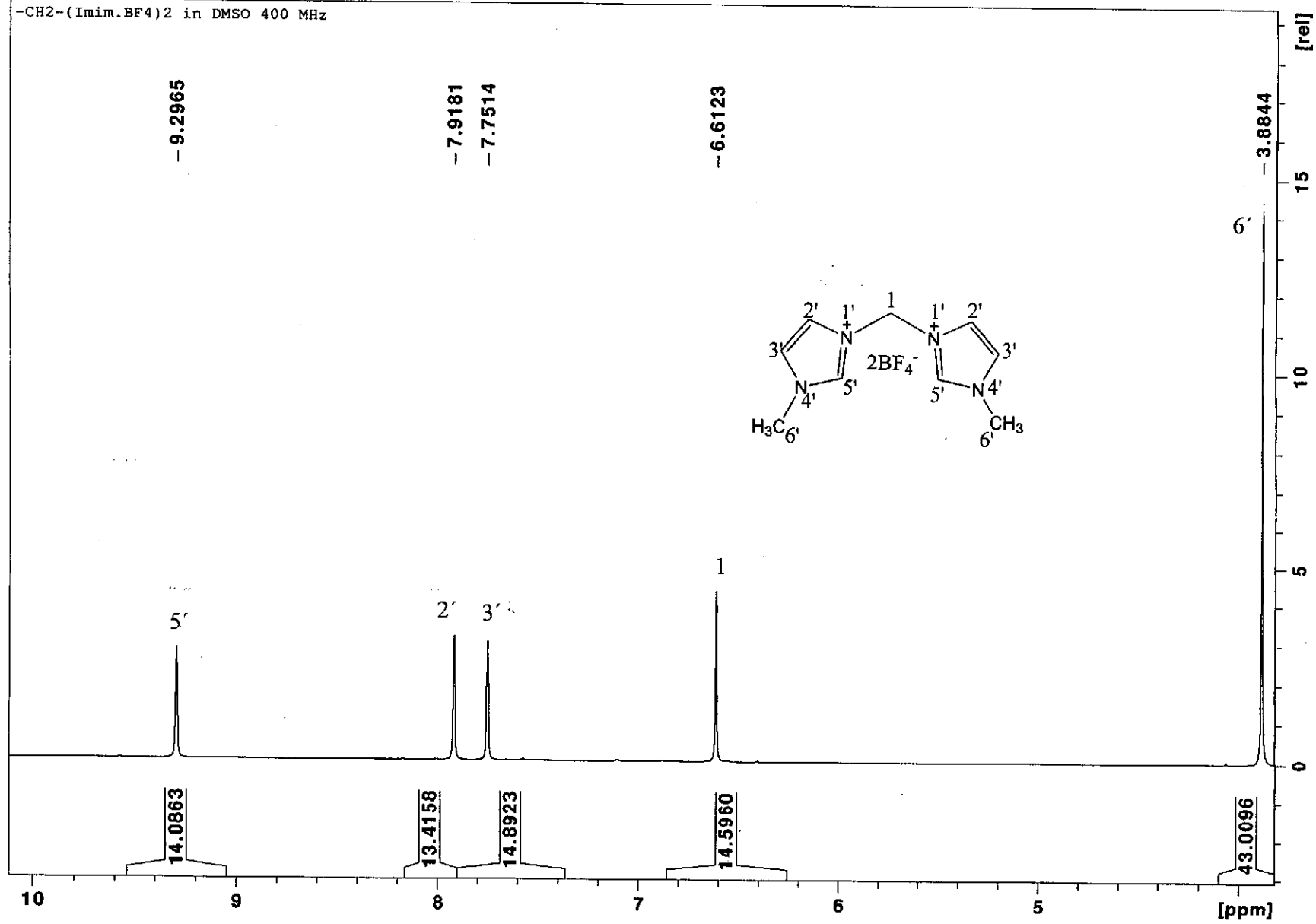


c:\pel_data\spectra\brahim\ch2- imin br.002 - White solid

IR spectrum of Compound C-1a

Jul10-2011-NK-Ibrahim 10 1 /opt/topspin NK

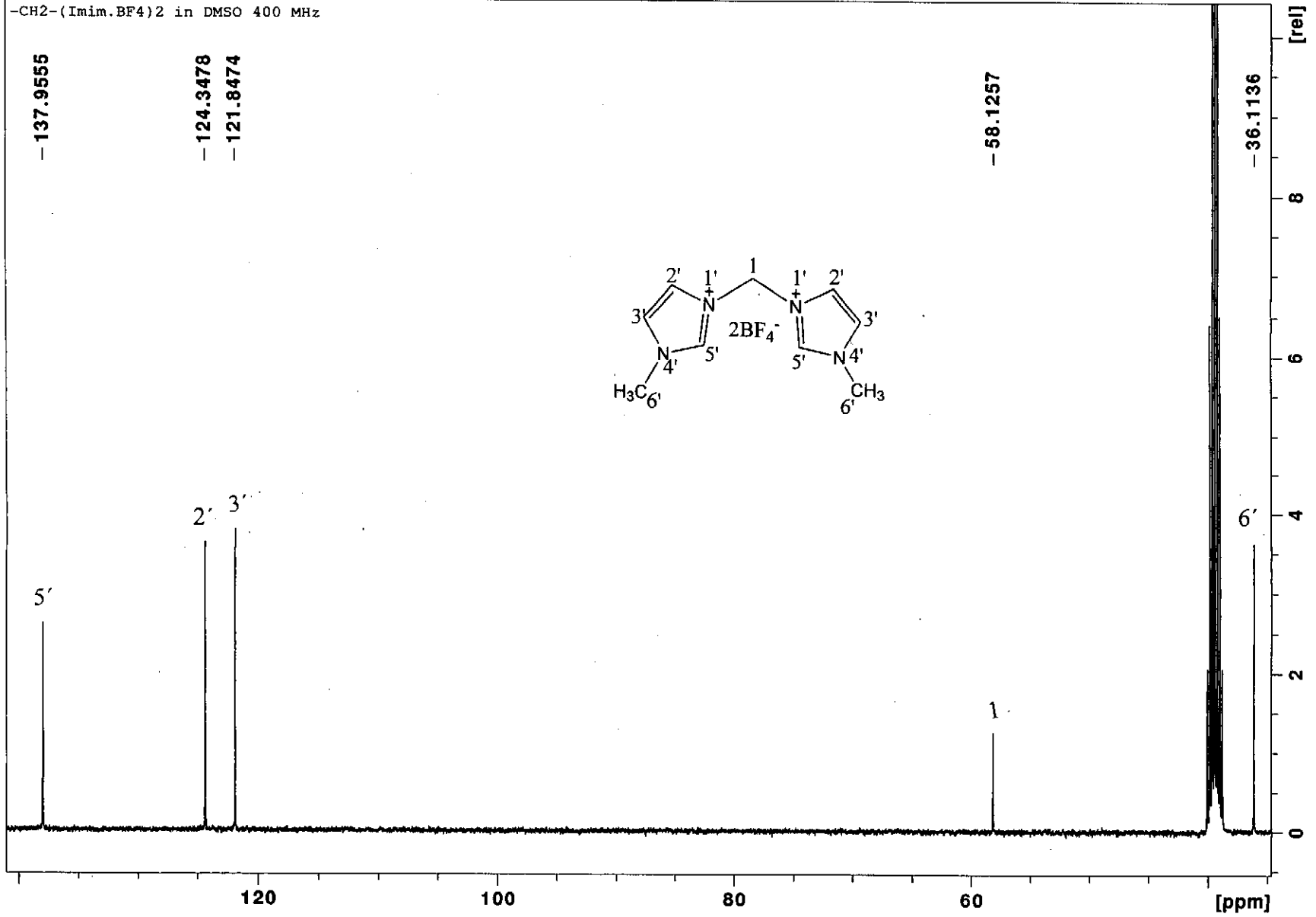
-CH2-(Imim.BF4)2 in DMSO 400 MHz



¹H NMR spectrum of Compound C-1b

Jul10-2011-NK-Ibrahim 11 1 /opt/topspin NK

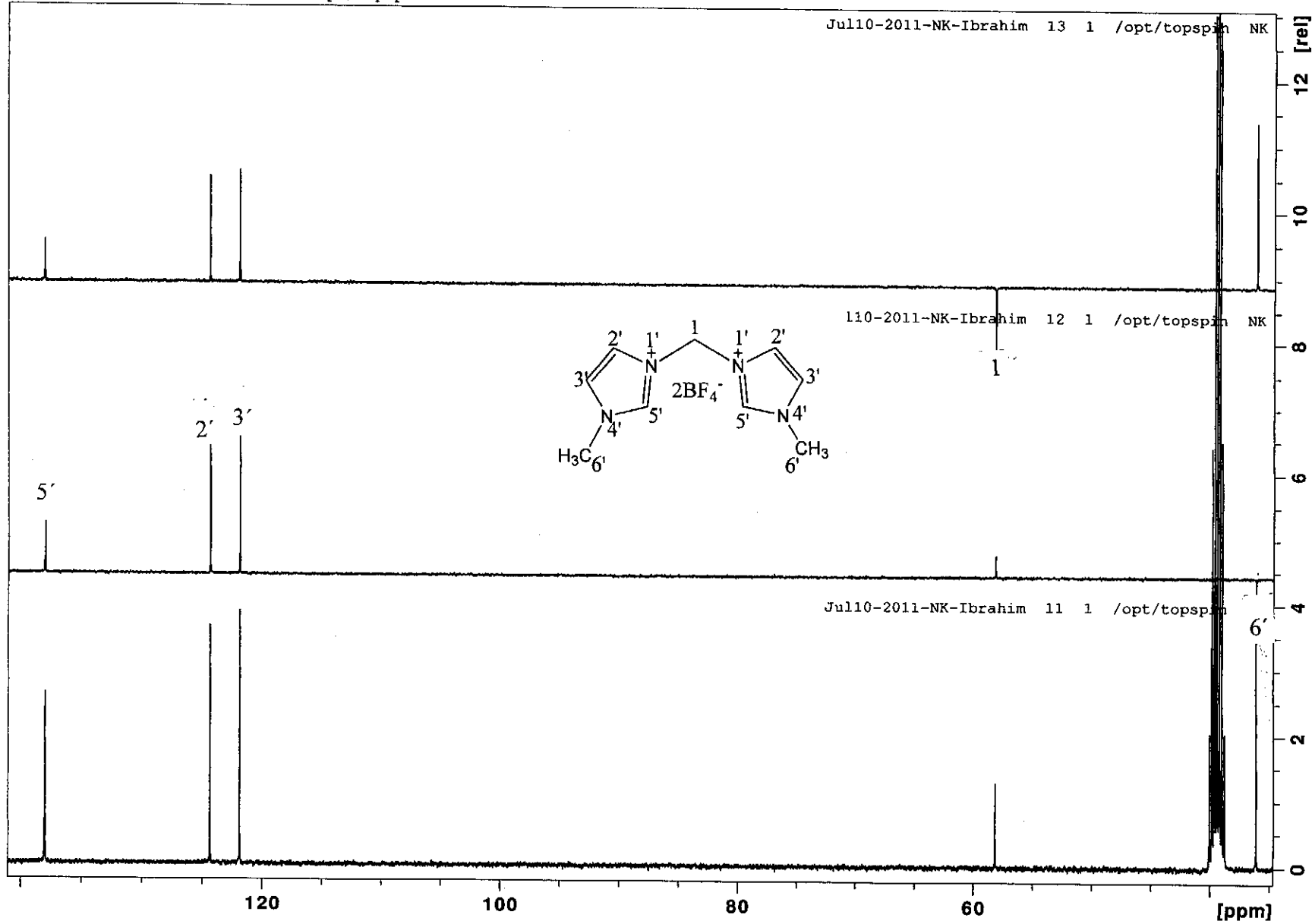
-CH2-(Imim.BF4)2 in DMSO 400 MHz



¹³C NMR spectrum of Compound C-1b

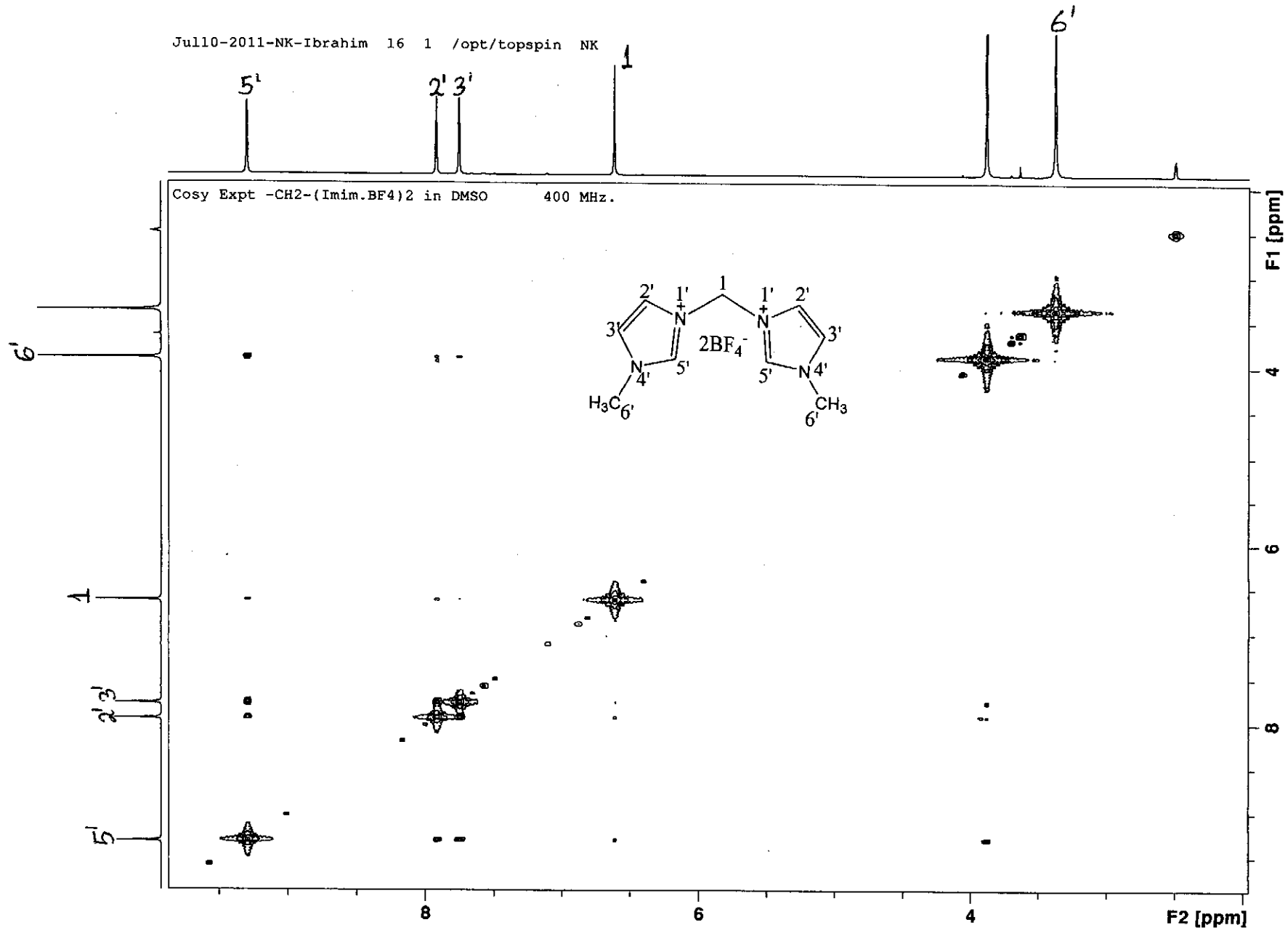
Jul10-2011-NK-Ibrahim 11 1 /opt/topspin NK

Jul10-2011-NK-Ibrahim 13 1 /opt/topspin NK



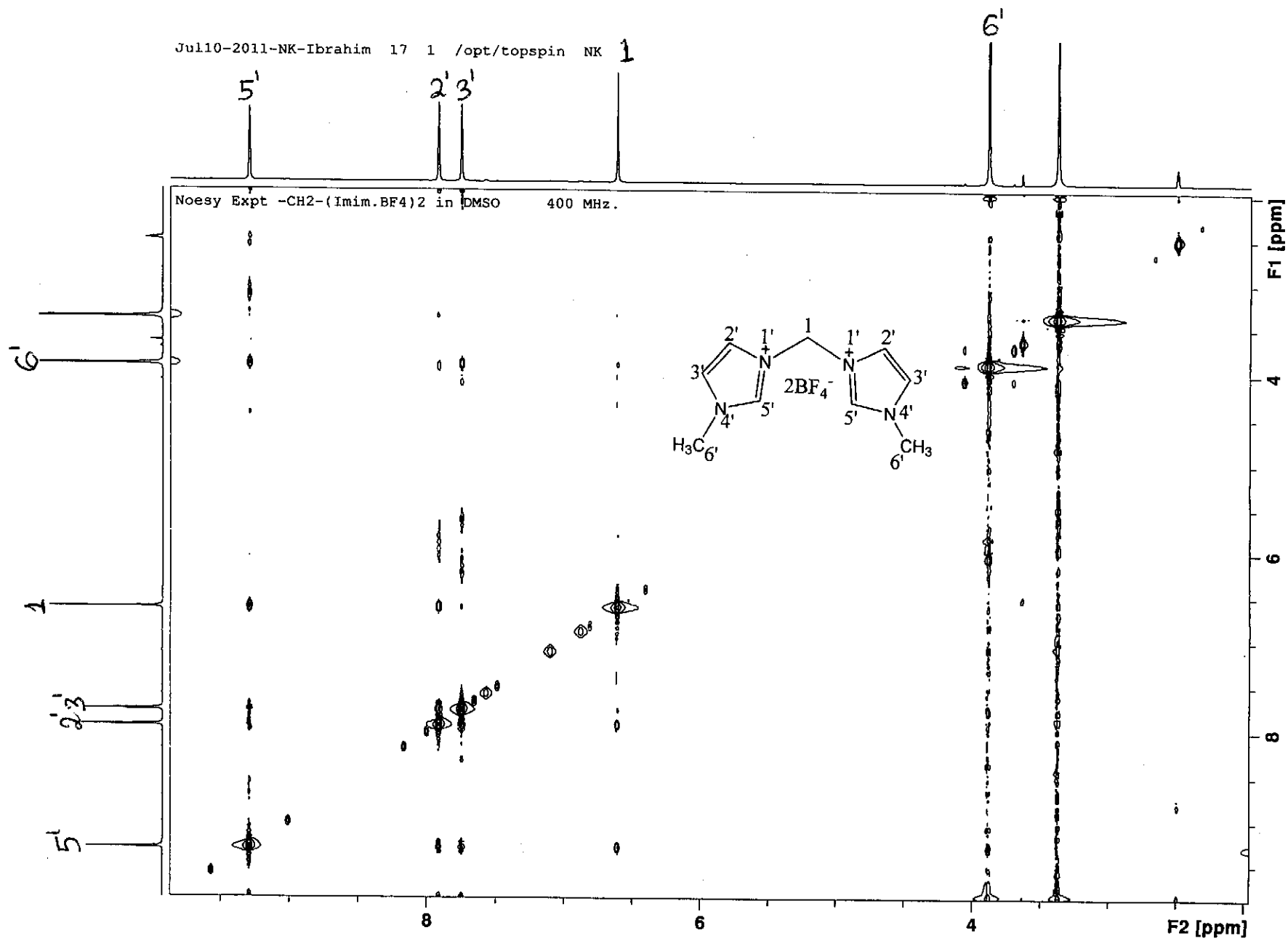
Dept 90 and 135 spectra of Compound C-1b

Jul10-2011-NK-Ibrahim 16 1 /opt/topspin NK



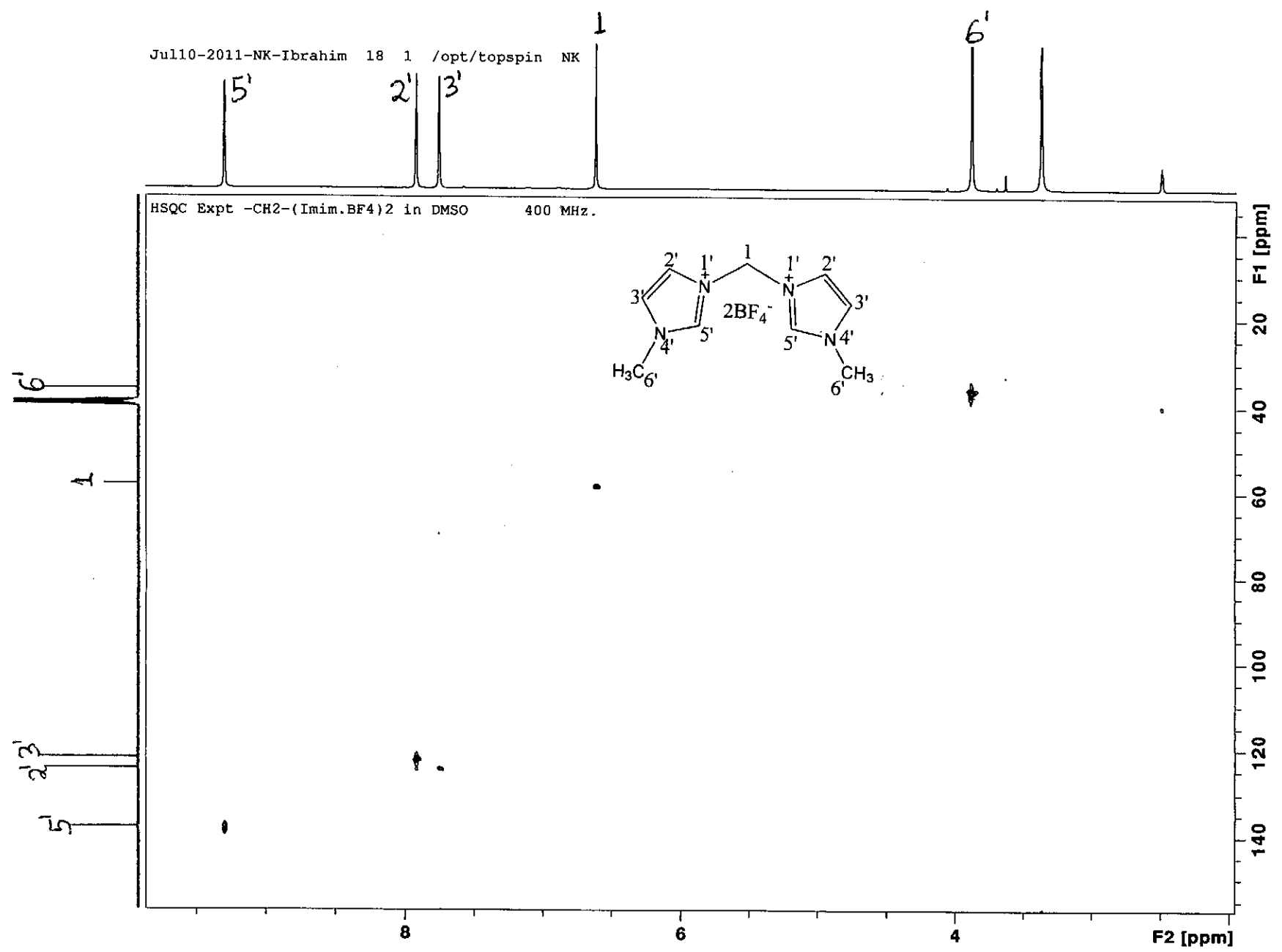
COSY spectrum of Compound C-1b

Jul10-2011-NK-Ibrahim 17 1 /opt/topspin NK 1



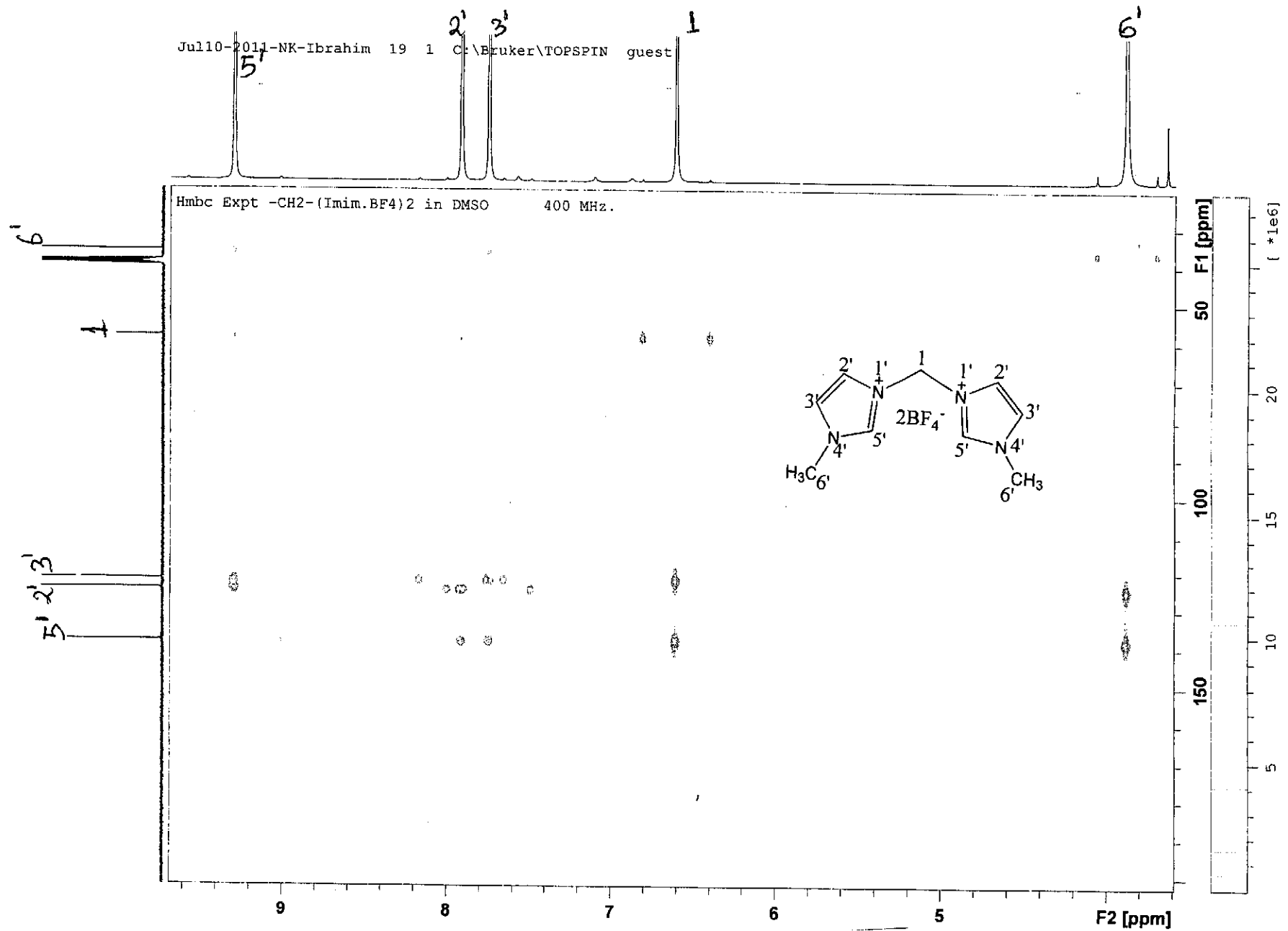
NOESY spectrum of Compound C-1b

Jul10-2011-NK-Ibrahim 18 1 /opt/topspin NK



HSQC spectrum of Compound C-1b

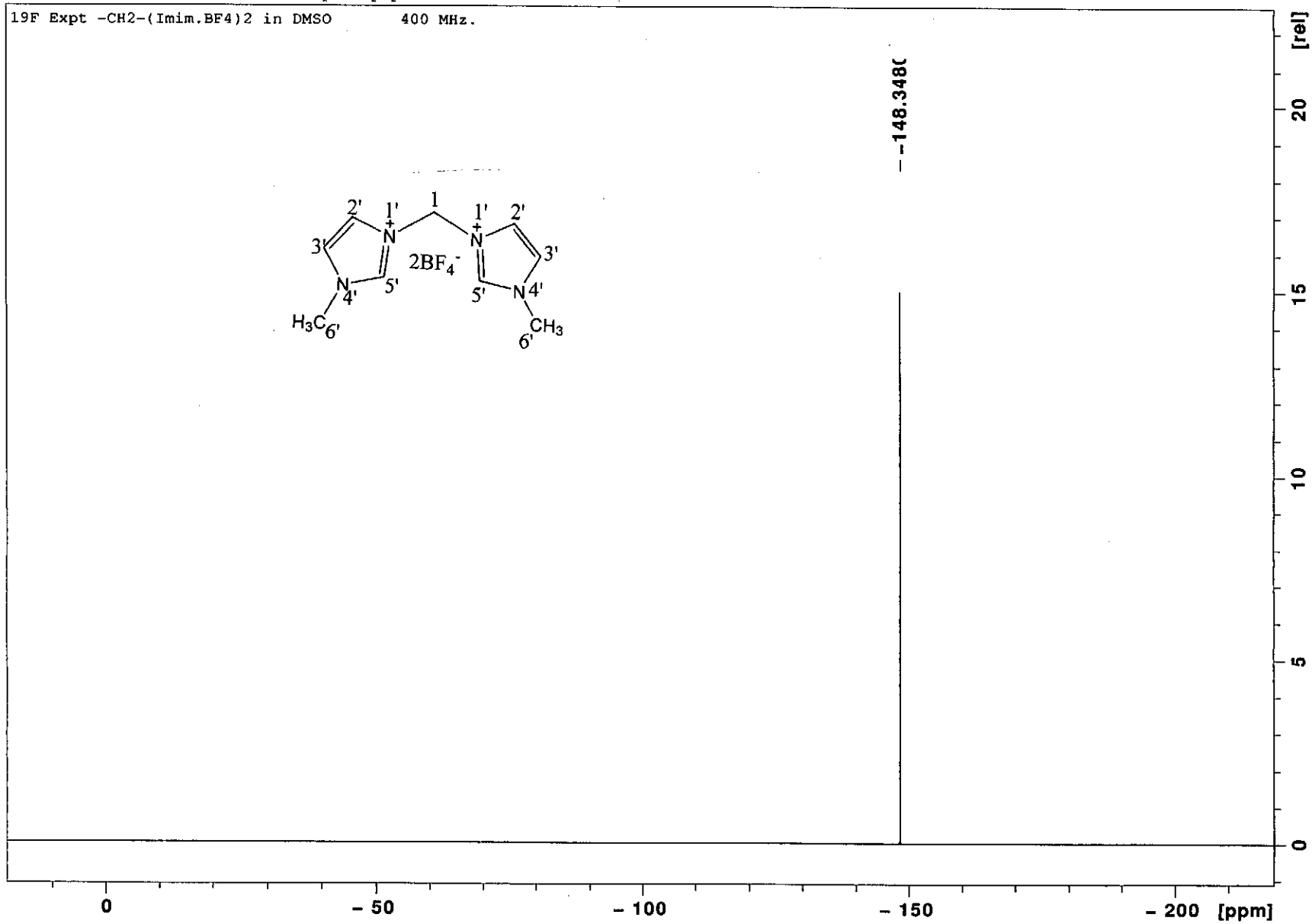
Jul10-2011-NK-Ibrahim 19 1 C:\Bruker\TOPSPIN guest



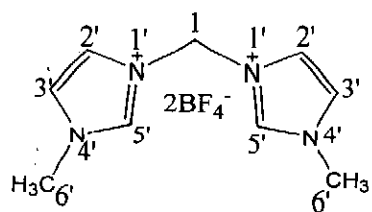
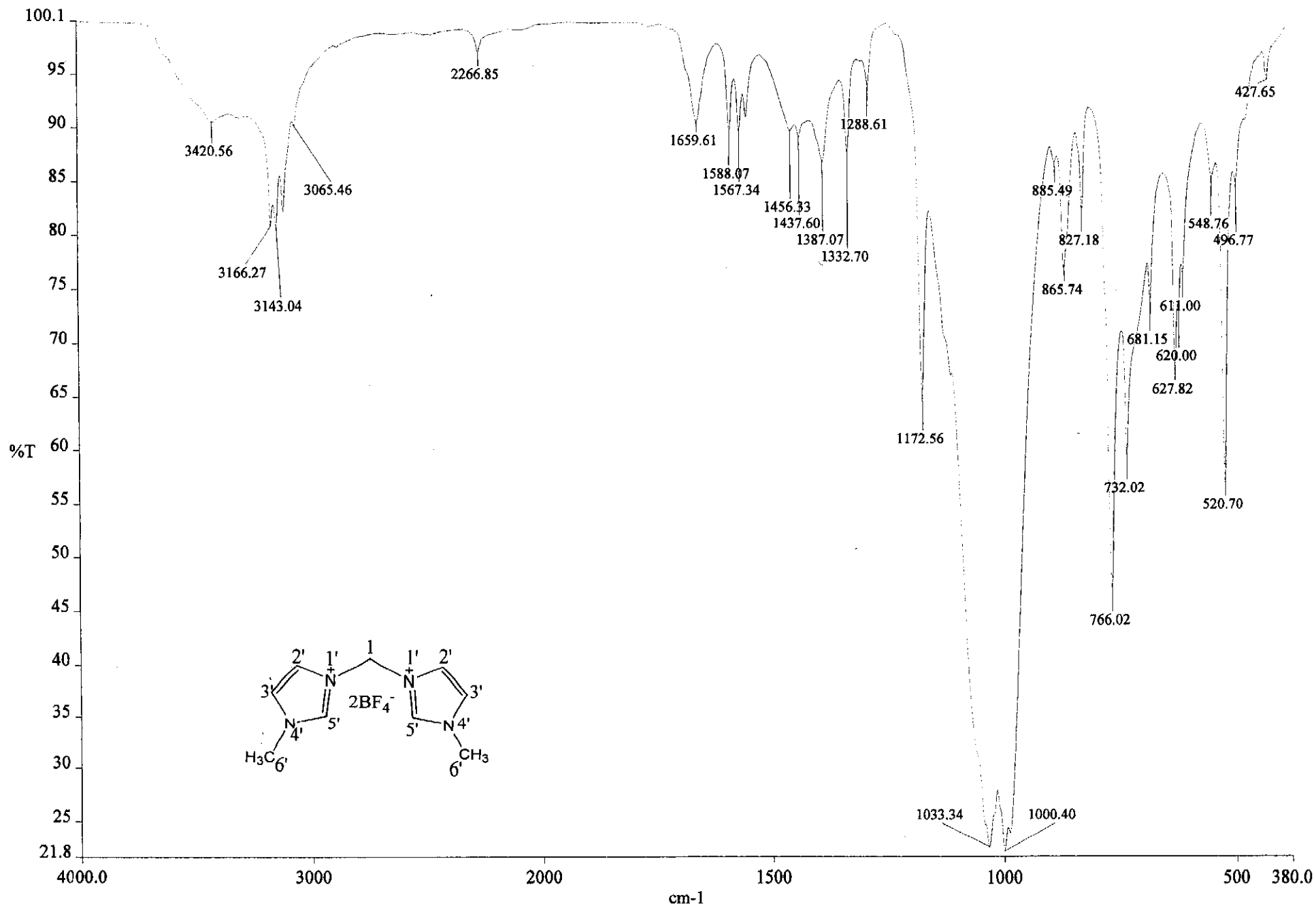
HMBC spectrum of Compound C-1b

Jul10-2011-NK-Ibrahim 14 1 /opt/topspin NK

19F Expt -CH2-(Imim.BF4)2 in DMSO 400 MHz.



^{19}F NMR spectrum of Compound C-1b

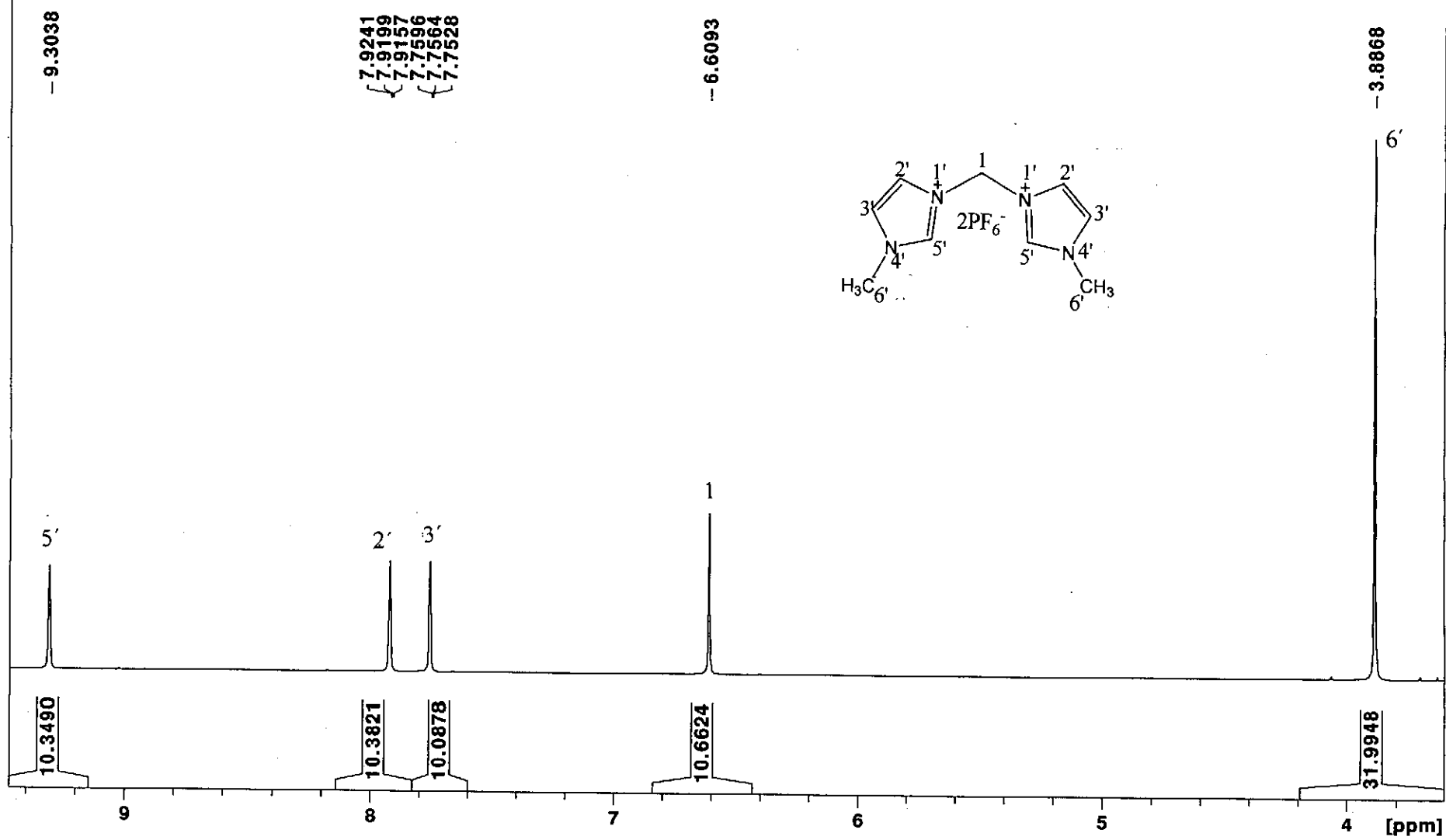


c:\pel_data\spectra\librahim\ch2- 2 imin, 2bf4.002 - White solid

IR spectrum of Compound C-1b

Jul22-2012-NK-Ibrahim 20 1 /opt/topspin NK

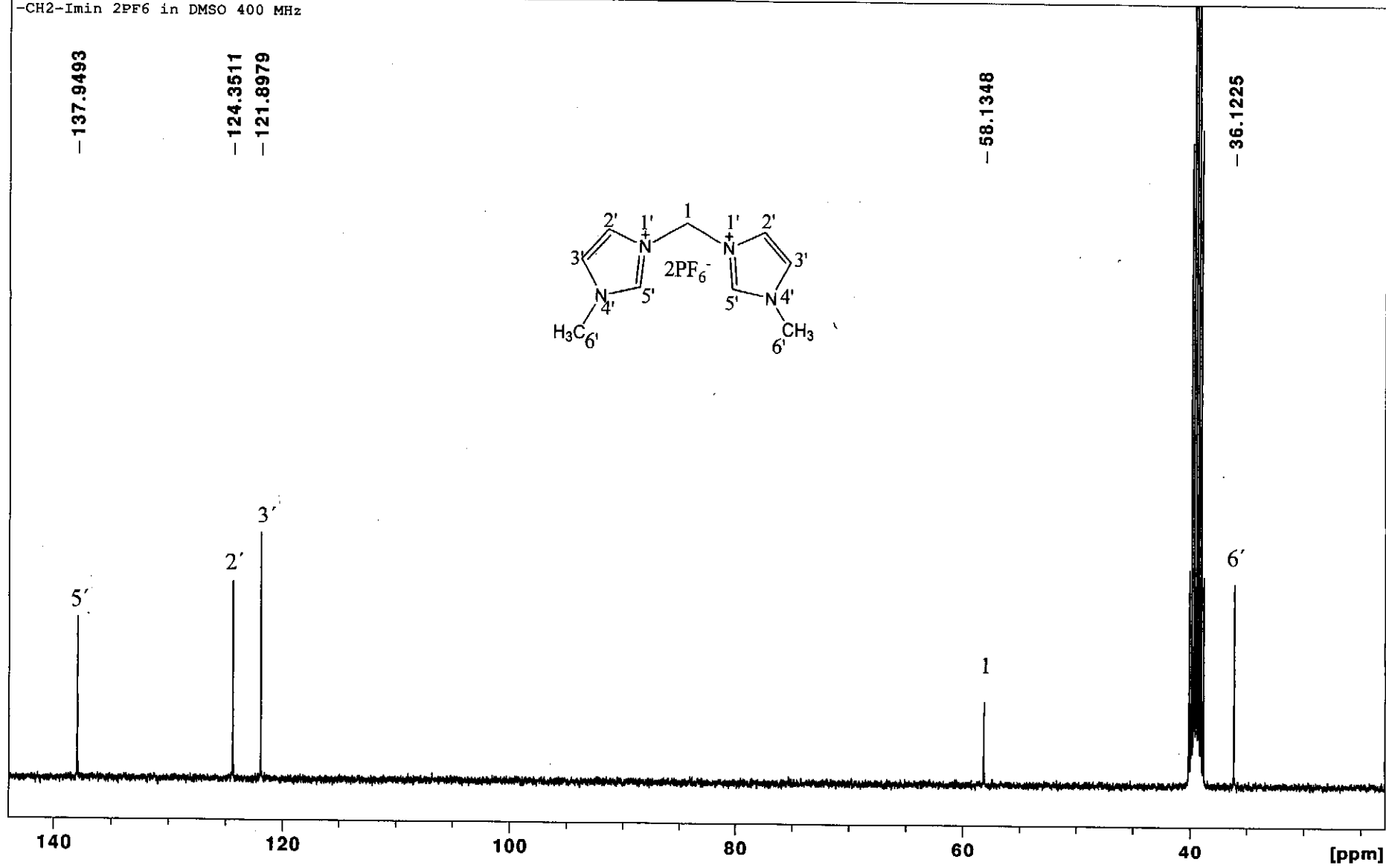
-CH2-Imin 2PF6 in DMSO 400 MHz



¹H NMR spectrum of Compound C-1c

Jul22-2012-NK-Ibrahim 21 1 /opt/topspin NK

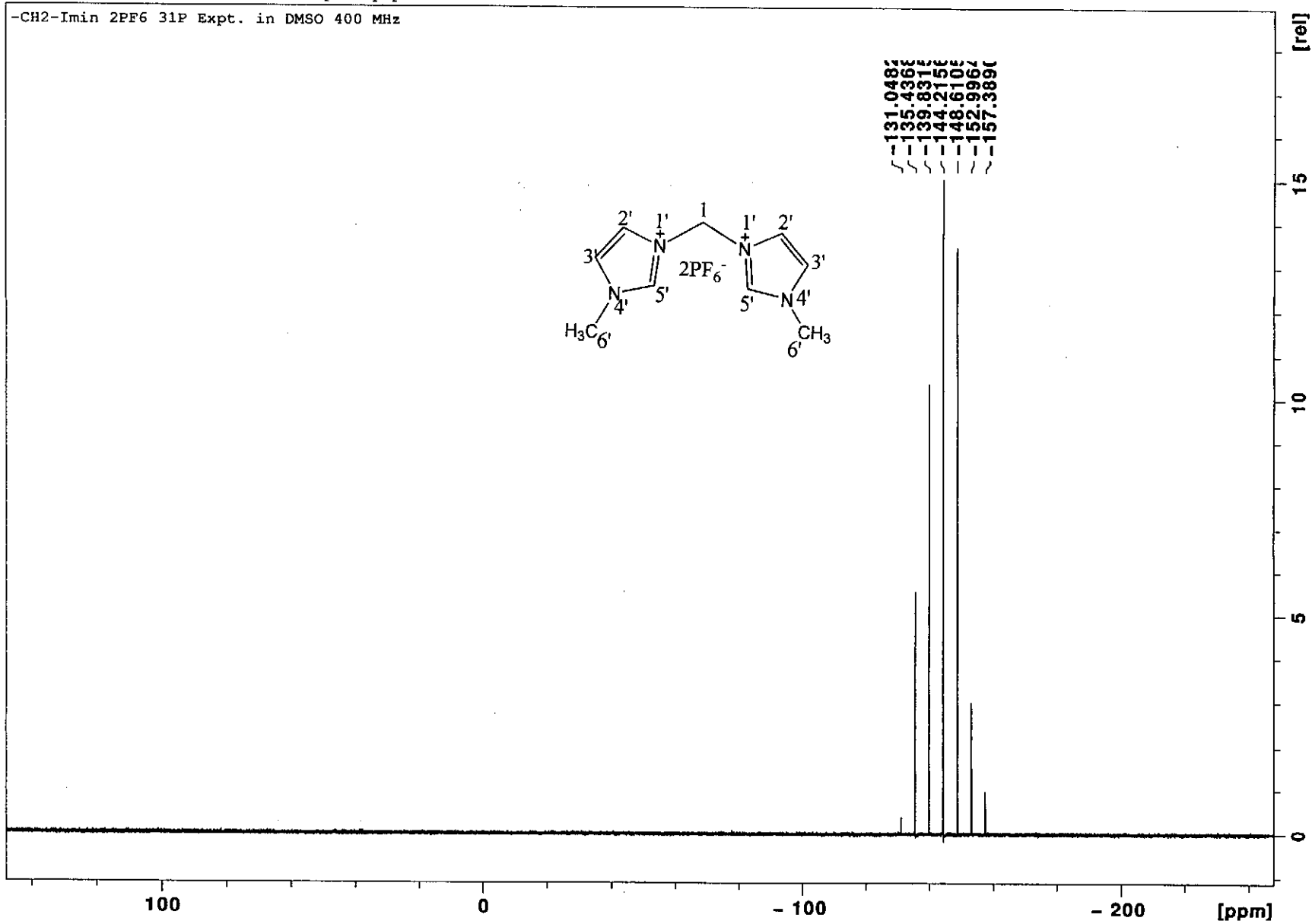
-CH2-Imin 2PF6 in DMSO 400 MHz



¹³C NMR spectrum of Compound C-1c

Jul22-2012-NK-Ibrahim 24 1 /opt/topspin NK

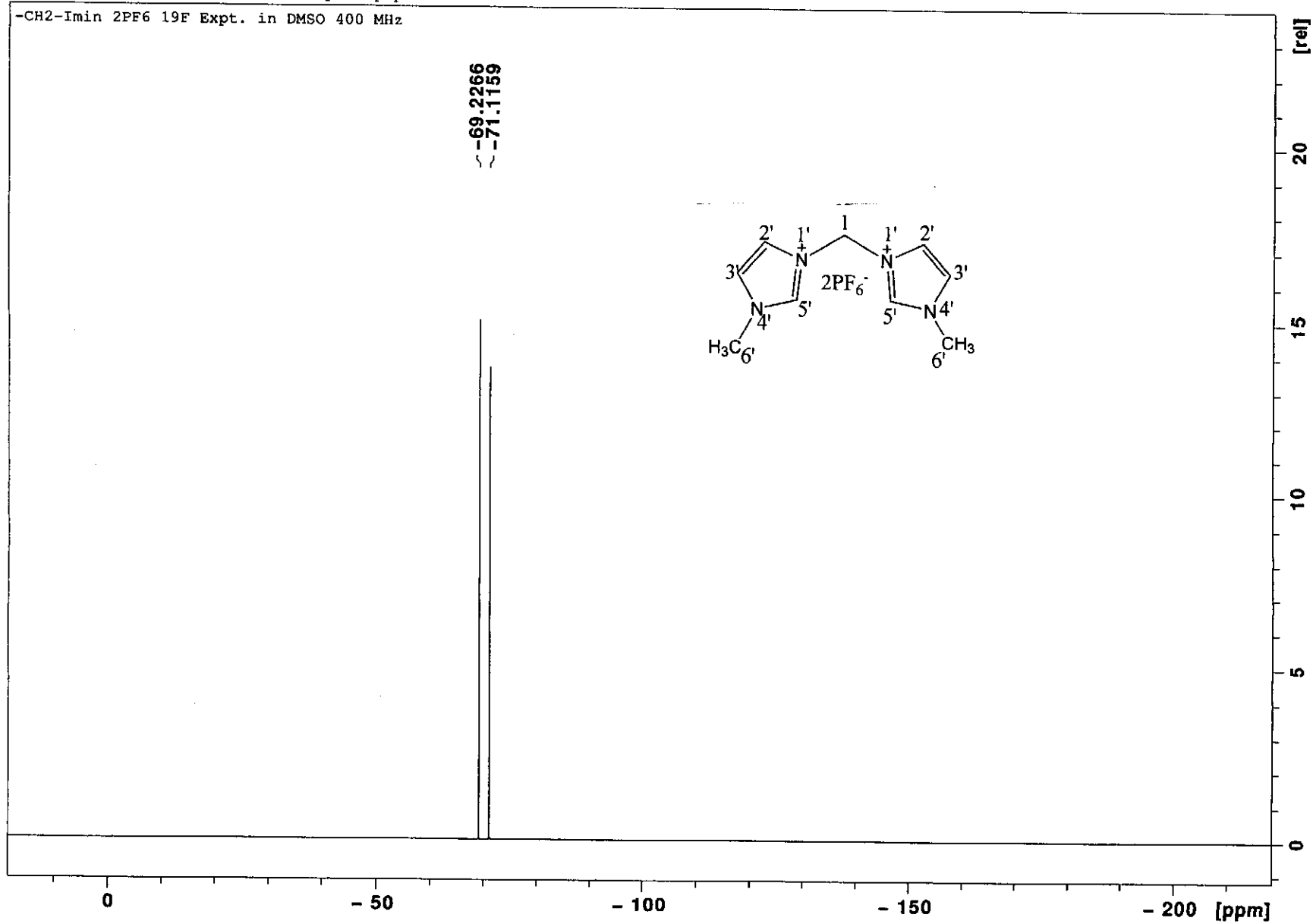
-CH2-Imin 2PF6 31P Expt. in DMSO 400 MHz



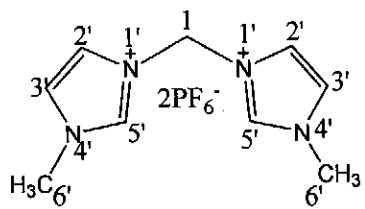
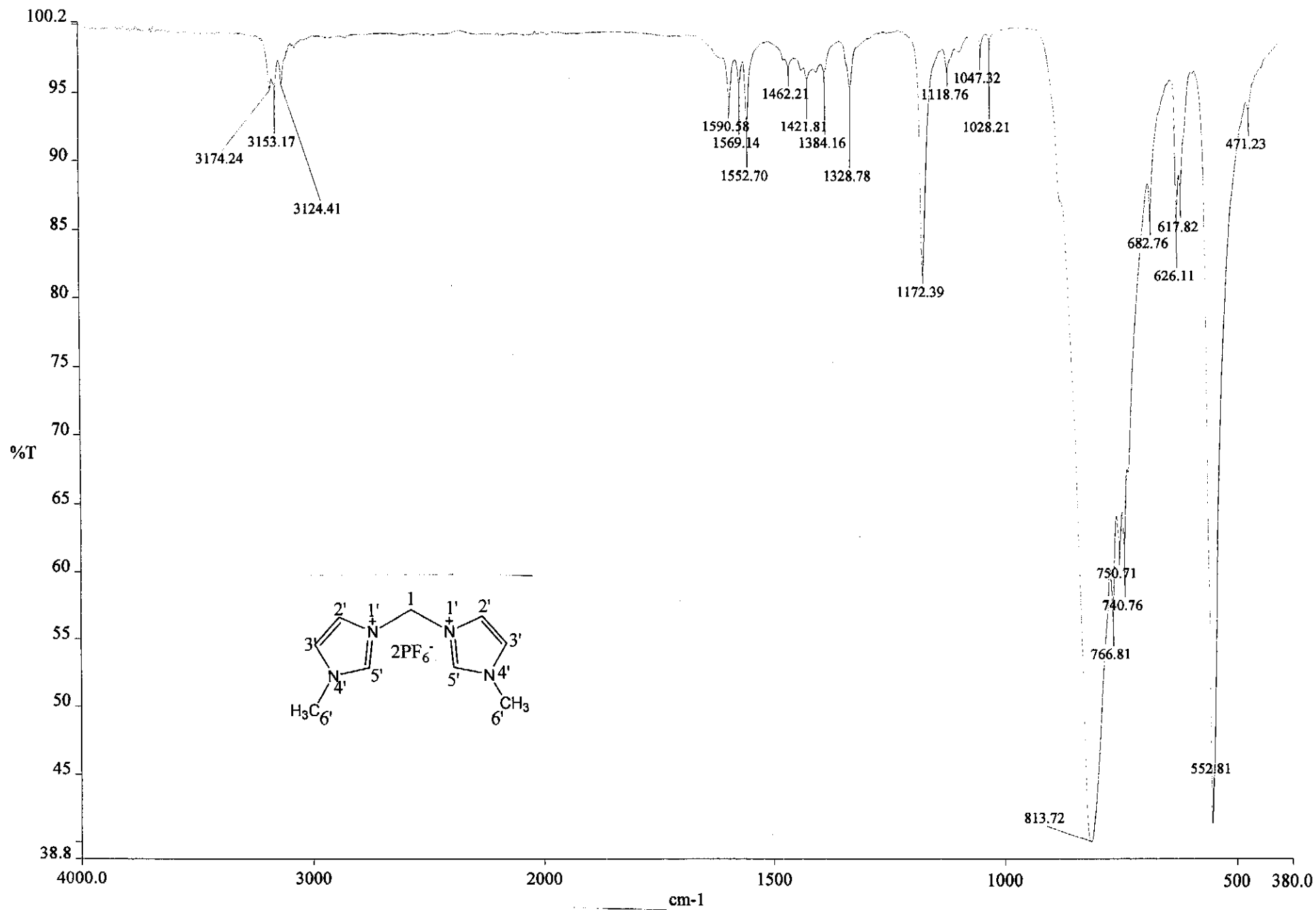
³¹P NMR spectrum of Compound C-1c

Jul22-2012-NK-Ibrahim 25 1 /opt/topspin NK

-CH2-Imin 2PF6 19F Expt. in DMSO 400 MHz



^{19}F NMR spectrum of Compound C-1c

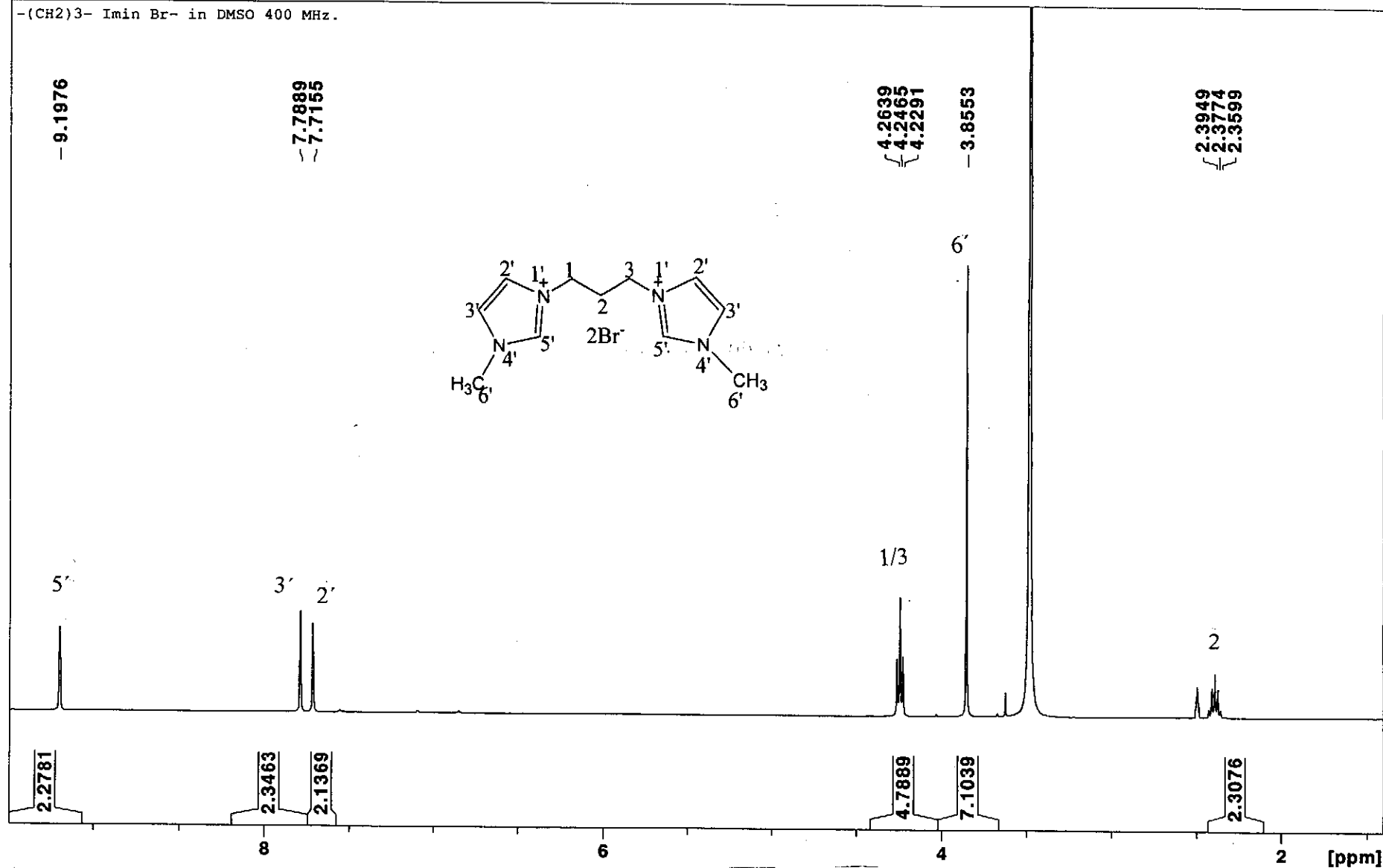


c:\pel_data\spectra\ch2-imin 2pf6.002 - White solid

IR spectrum of Compound C-1c

Jun10-2012-NK-Ibrahim 20 1 /opt/topspin NK

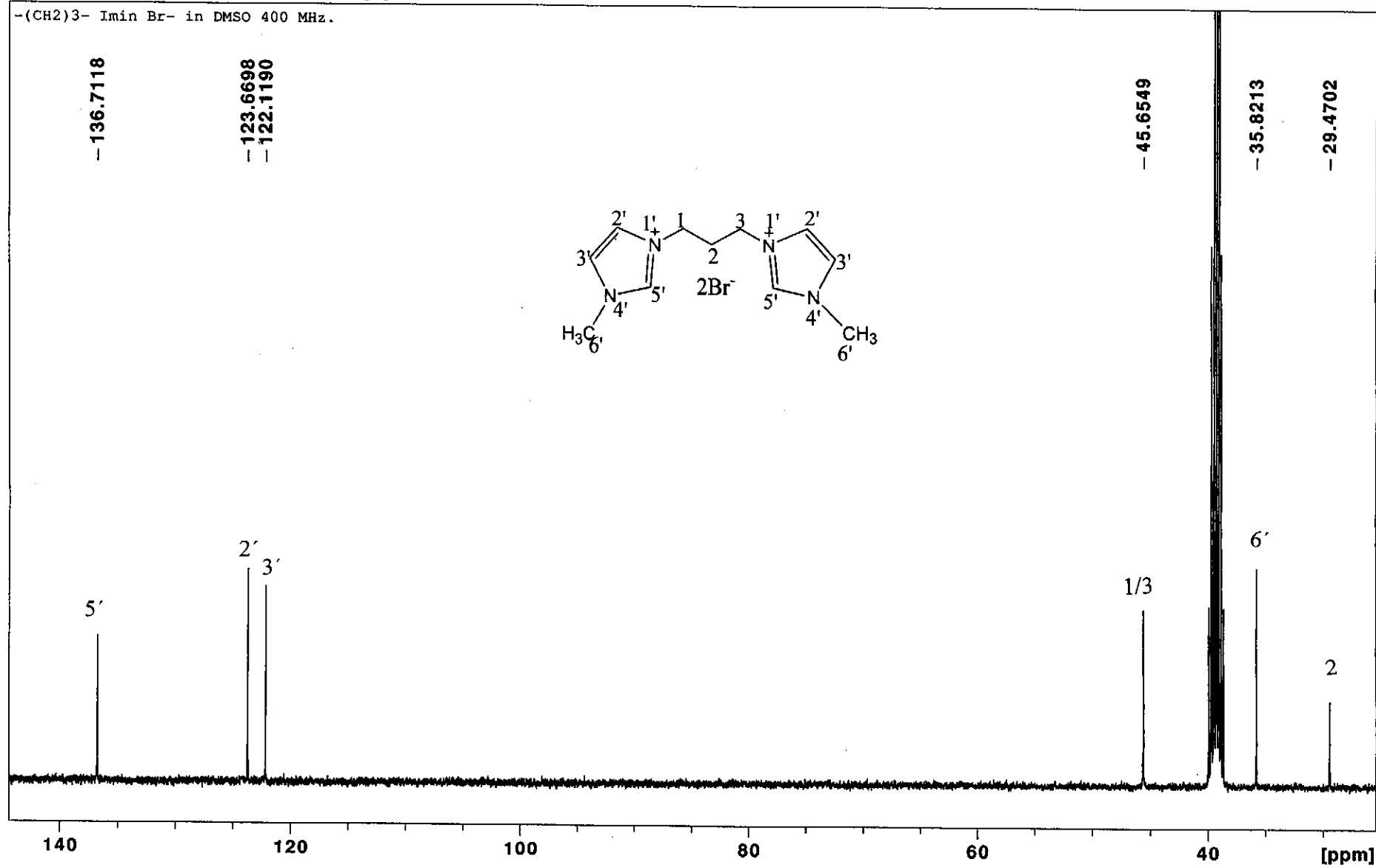
-(CH2)3- Imin Br- in DMSO 400 MHz.



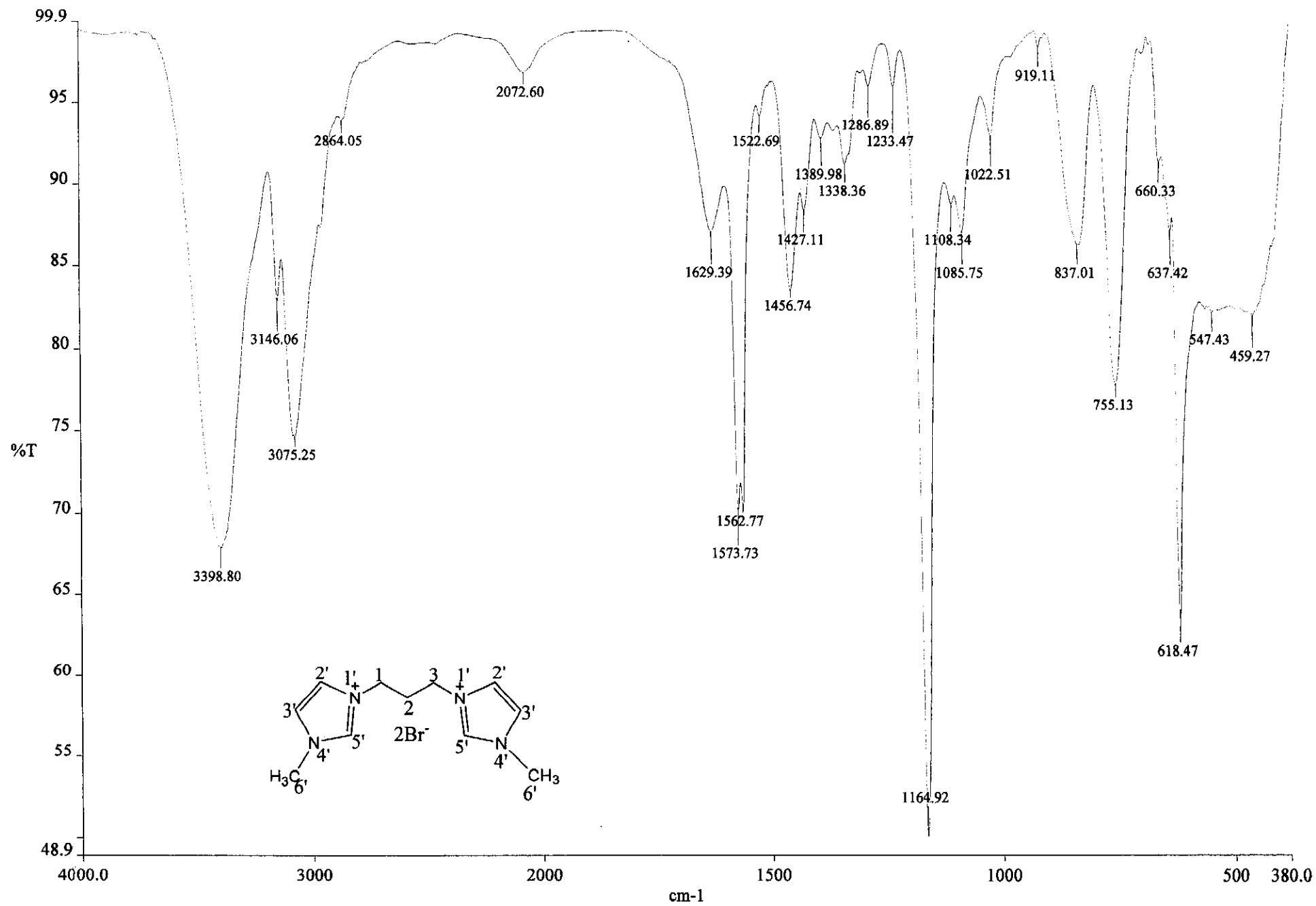
¹H NMR spectrum of Compound C-2a

Jun10-2012-NK-Ibrahim 21 1 /opt/topspin NK

-(CH2)3- Imin Br- in DMSO 400 MHz.



^{13}C NMR spectrum of Compound C-2a

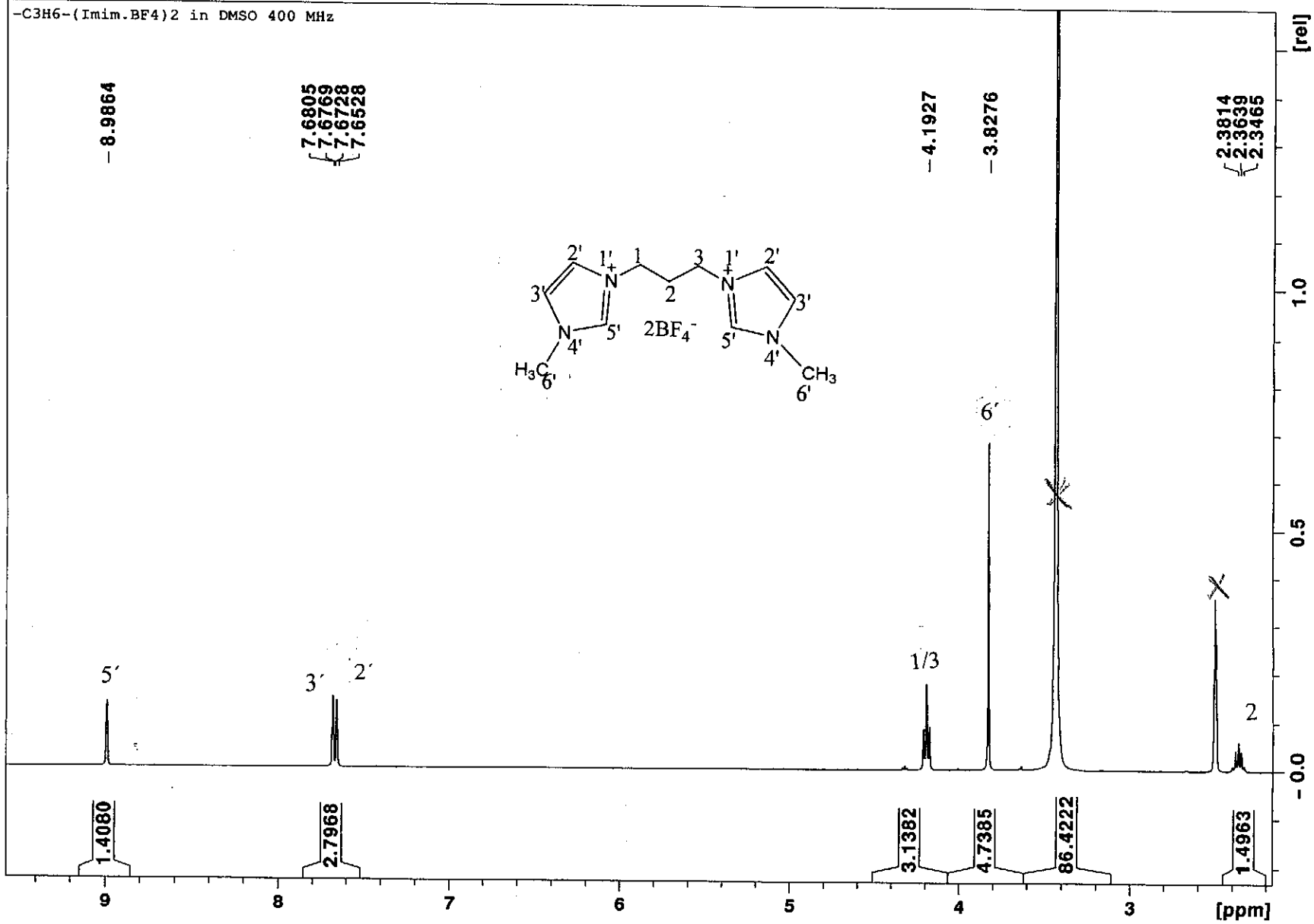


c:\pel_data\spectra\brahim\-(ch2)3- imin br.002

IR spectrum of Compound C-2a

Jul10-2011-NK-Ibrahim 20 1 /opt/topspin NK

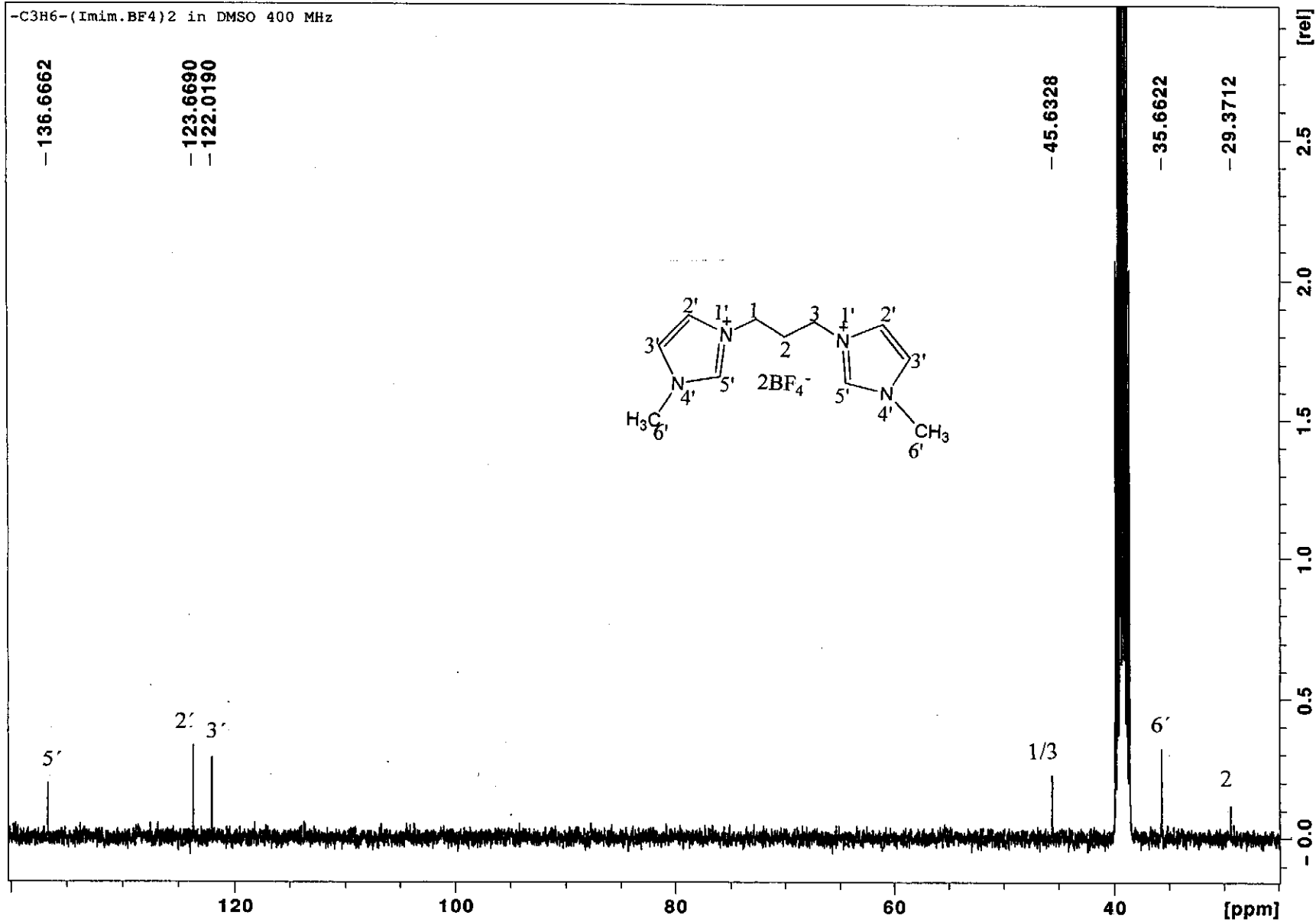
-C3H6-(Imim.BF4)2 in DMSO 400 MHz



¹H NMR spectrum of Compound C-2b

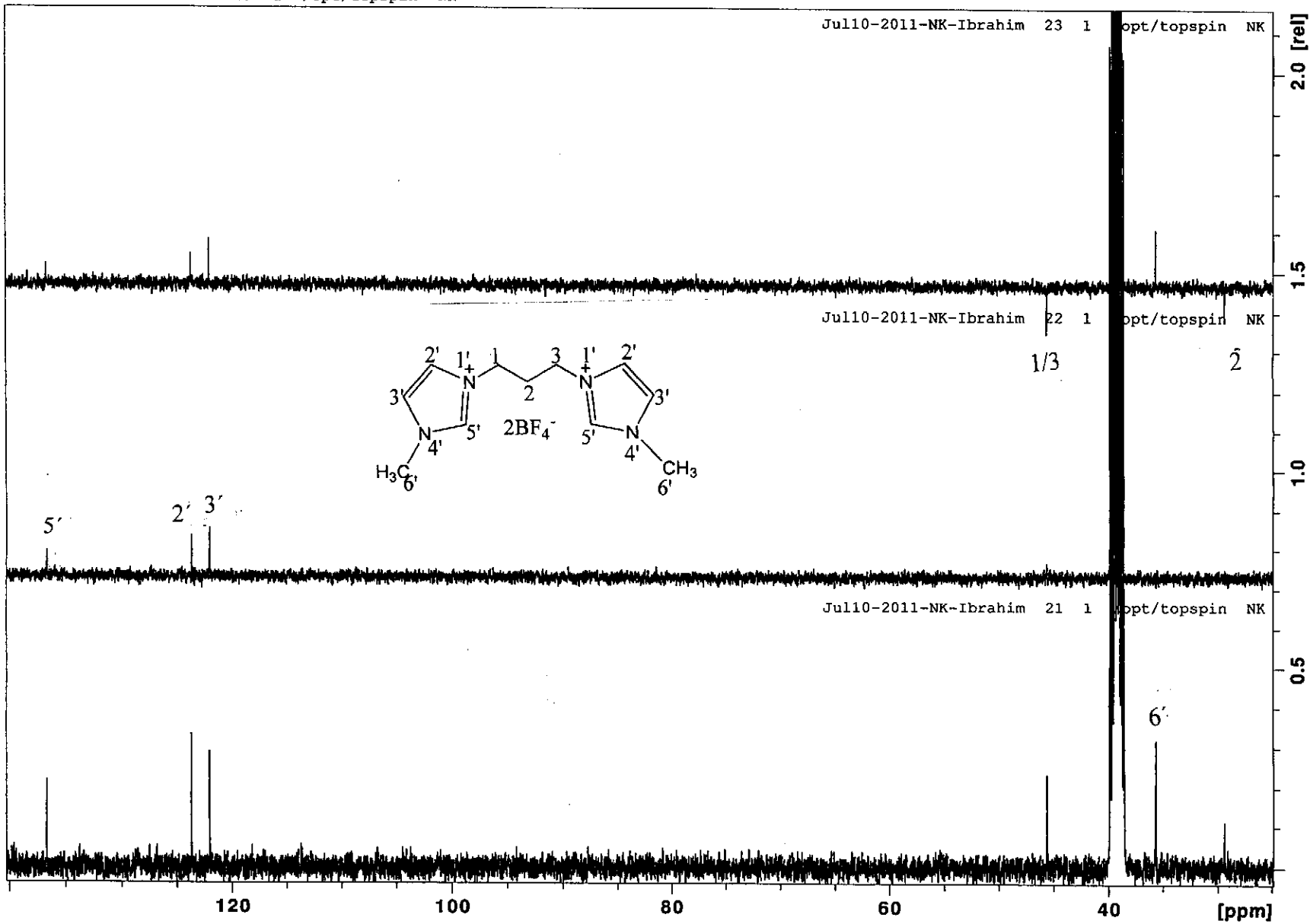
Jul10-2011-NK-Ibrahim 21 1 /opt/topspin NK

-C3H6-(Imim.BF4)2 in DMSO 400 MHz



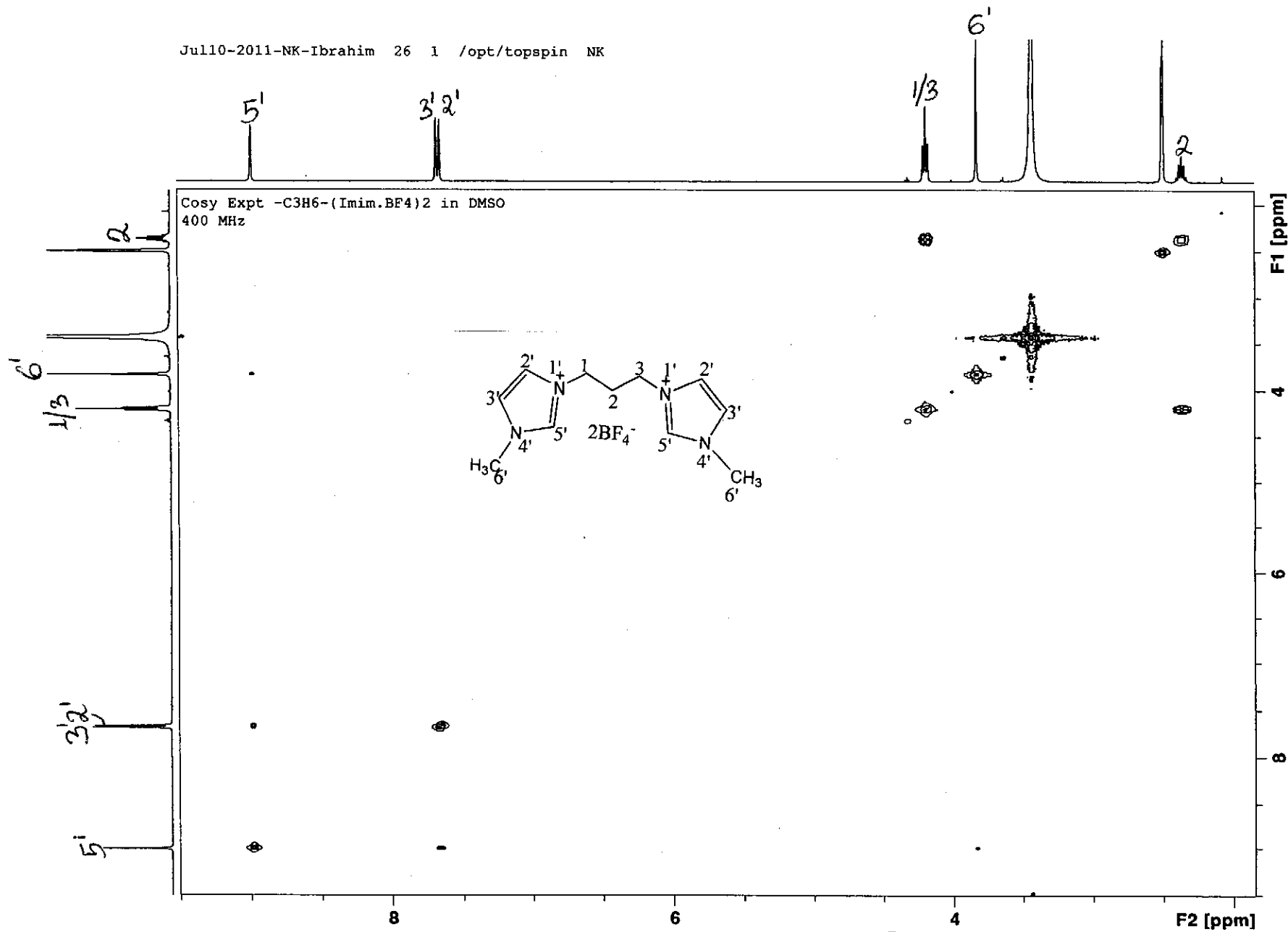
^{13}C NMR spectrum of Compound C-2b

Jul10-2011-NK-Ibrahim 21 1 /opt/topspin NK



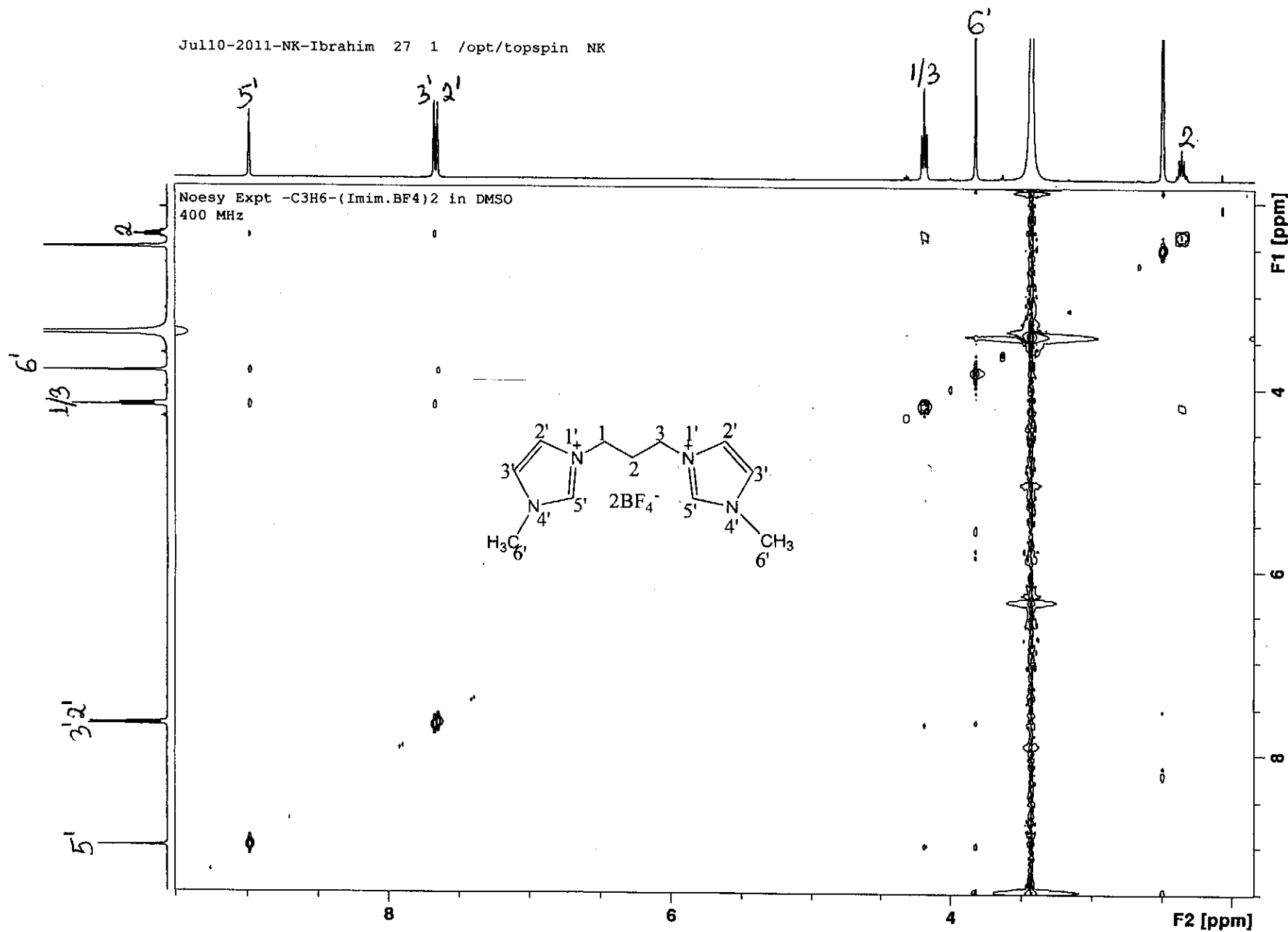
Dept 90 and 135 spectra of Compound C-2b

Jul10-2011-NK-Ibrahim 26 1 /opt/topspin NK



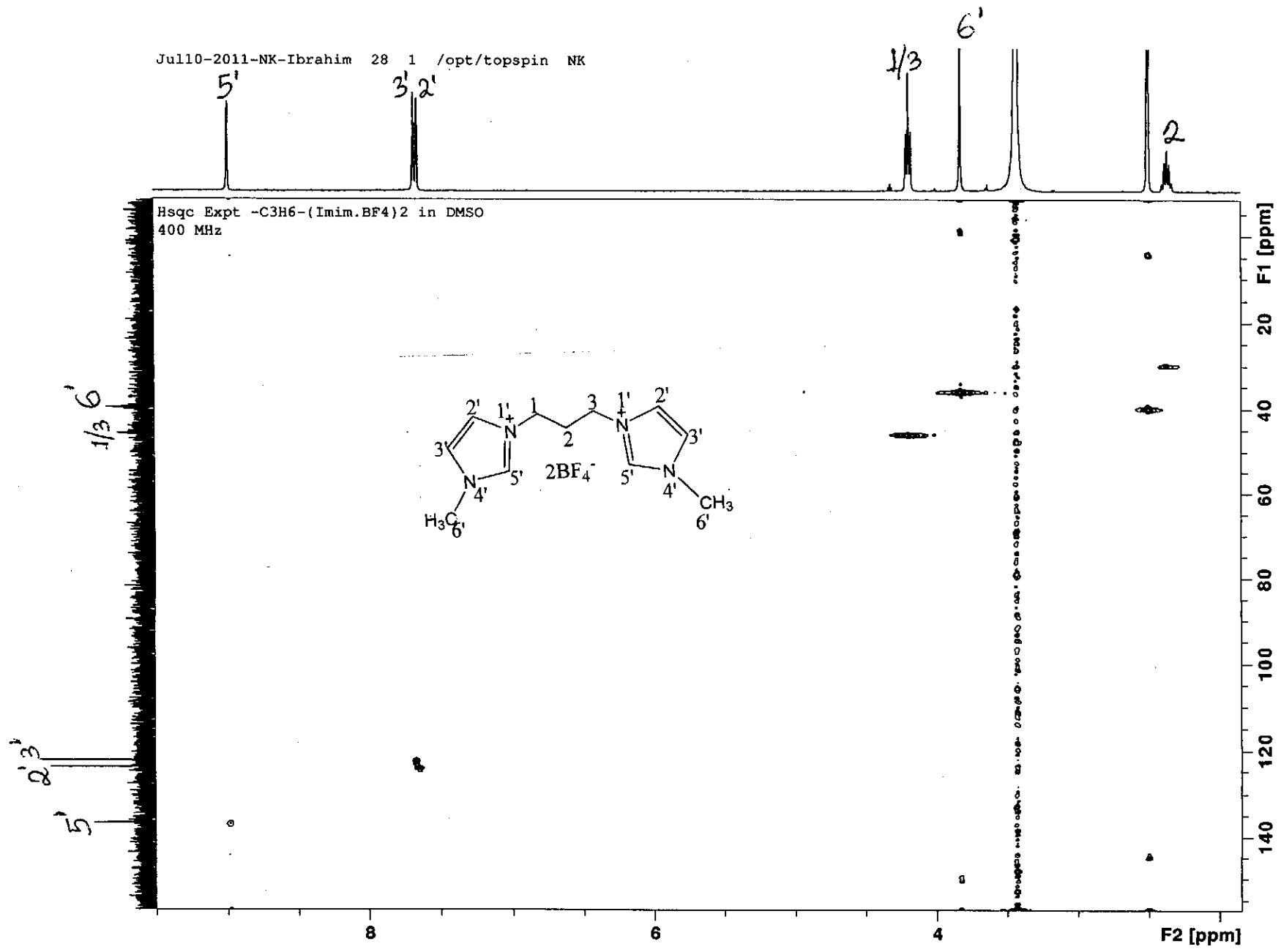
COSY spectrum of Compound C-2b

Jul10-2011-NK-Ibrahim 27 1 /opt/topspin NK



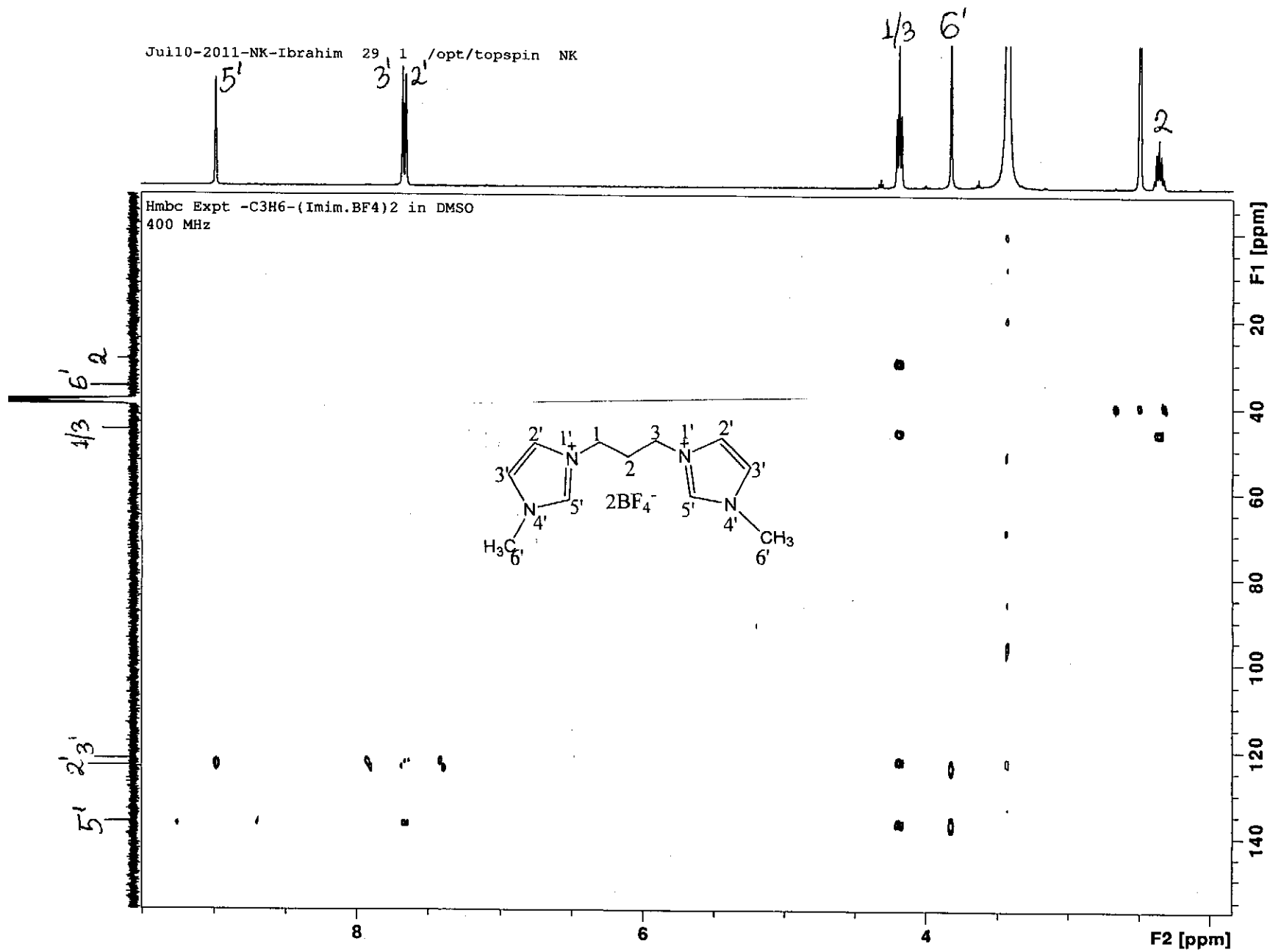
NOESY spectrum of Compound C-2b

Jul10-2011-NK-Ibrahim 28 1 /opt/topspin NK



HSQC spectrum of Compound C-2b

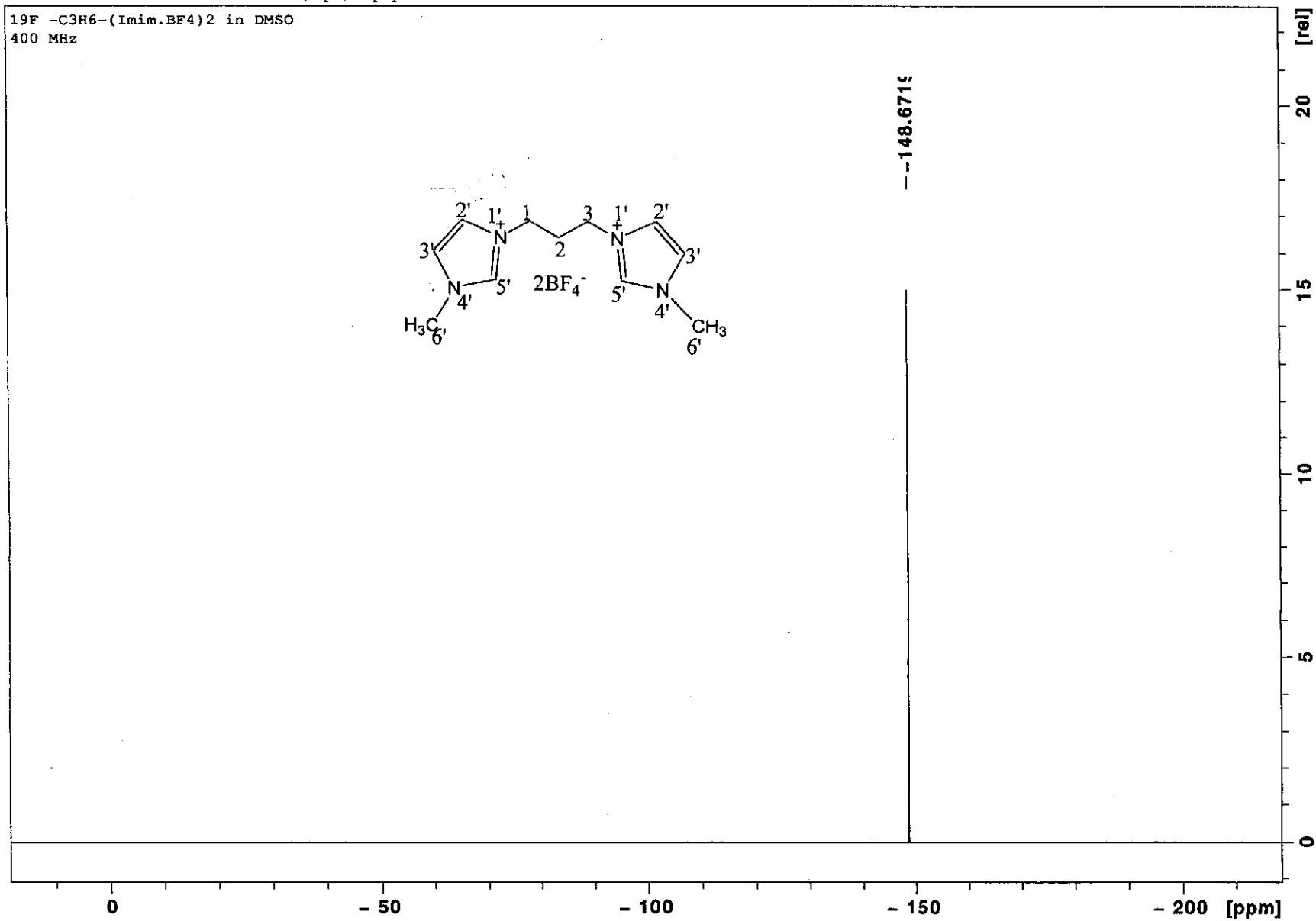
Jul10-2011-NK-Ibrahim 29 1 /opt/topspin NK



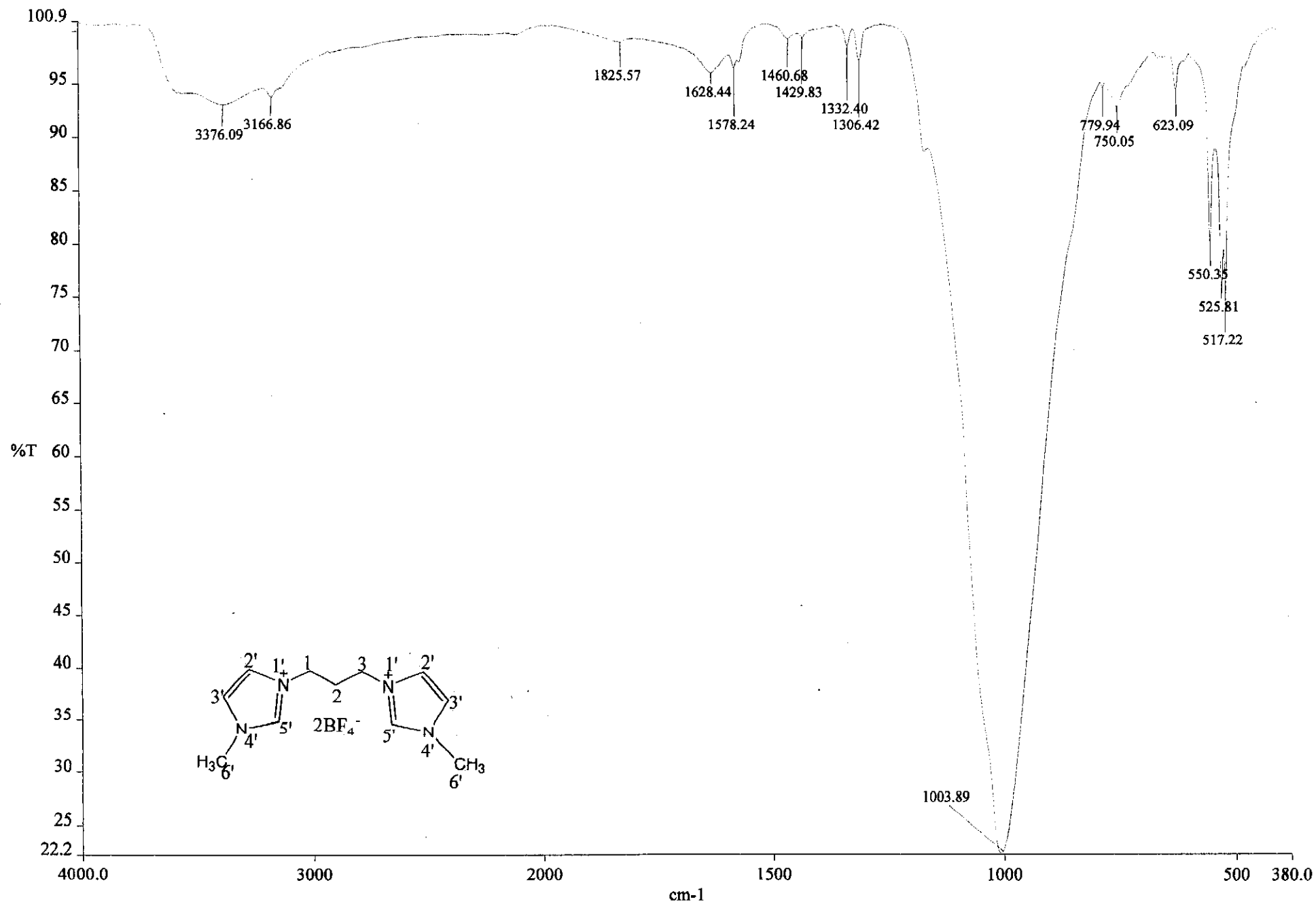
HMBC spectrum of Compound C-2b

Jul10-2011-NK-Ibrahim 24 1 /opt/topspin NK

^{19}F -C3H6-(Imim.BF₄)₂ in DMSO
400 MHz



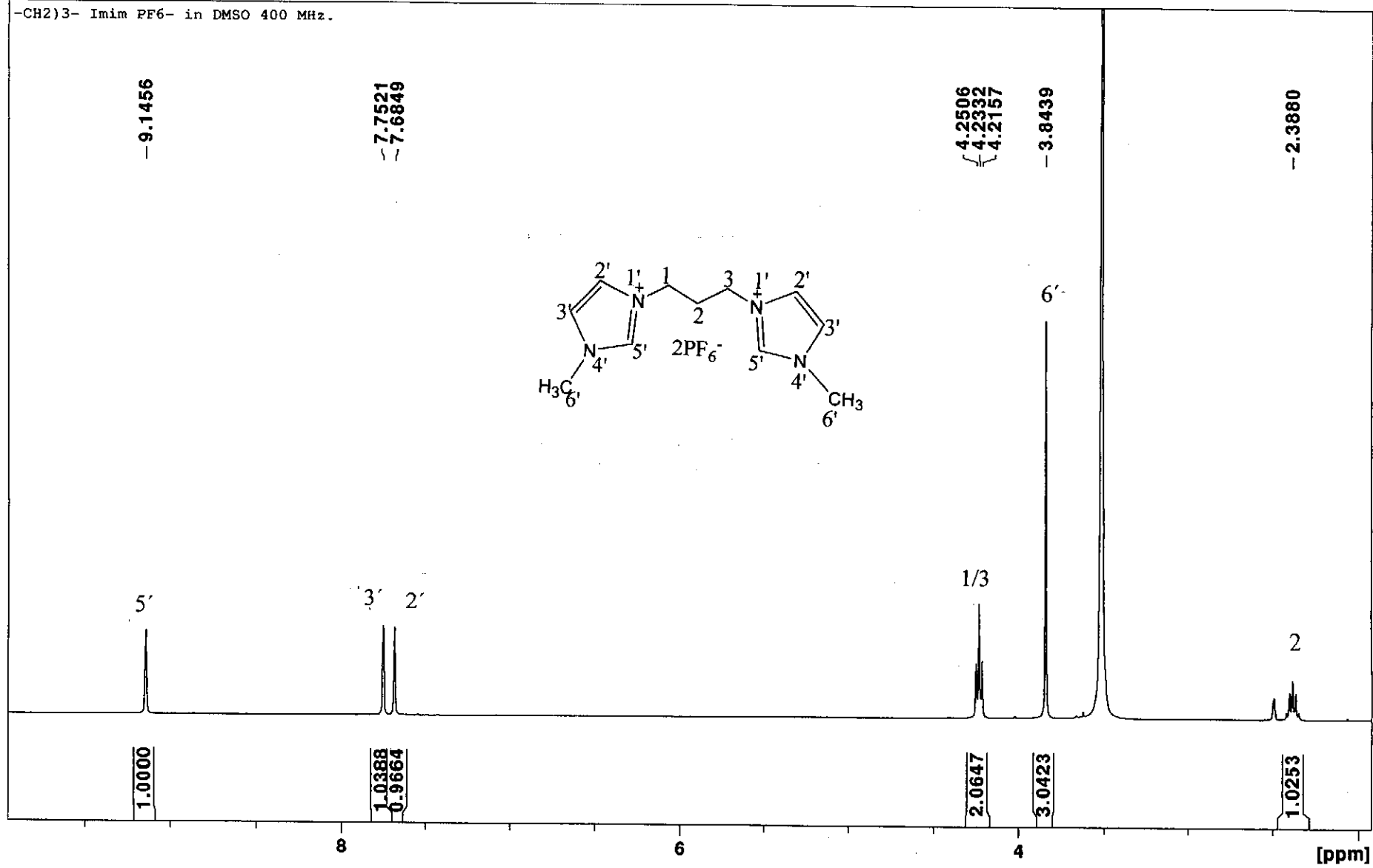
^{19}F NMR spectrum of Compound C-2b



c:\pel_data\spectra\ibrahim\-(ch2)-3 imin2bf4.002 - White Crystalline substar IR spectrum of Compound C-2b

Jun17-2012-NK-Ibrahim 10 1 /opt/topspin NK

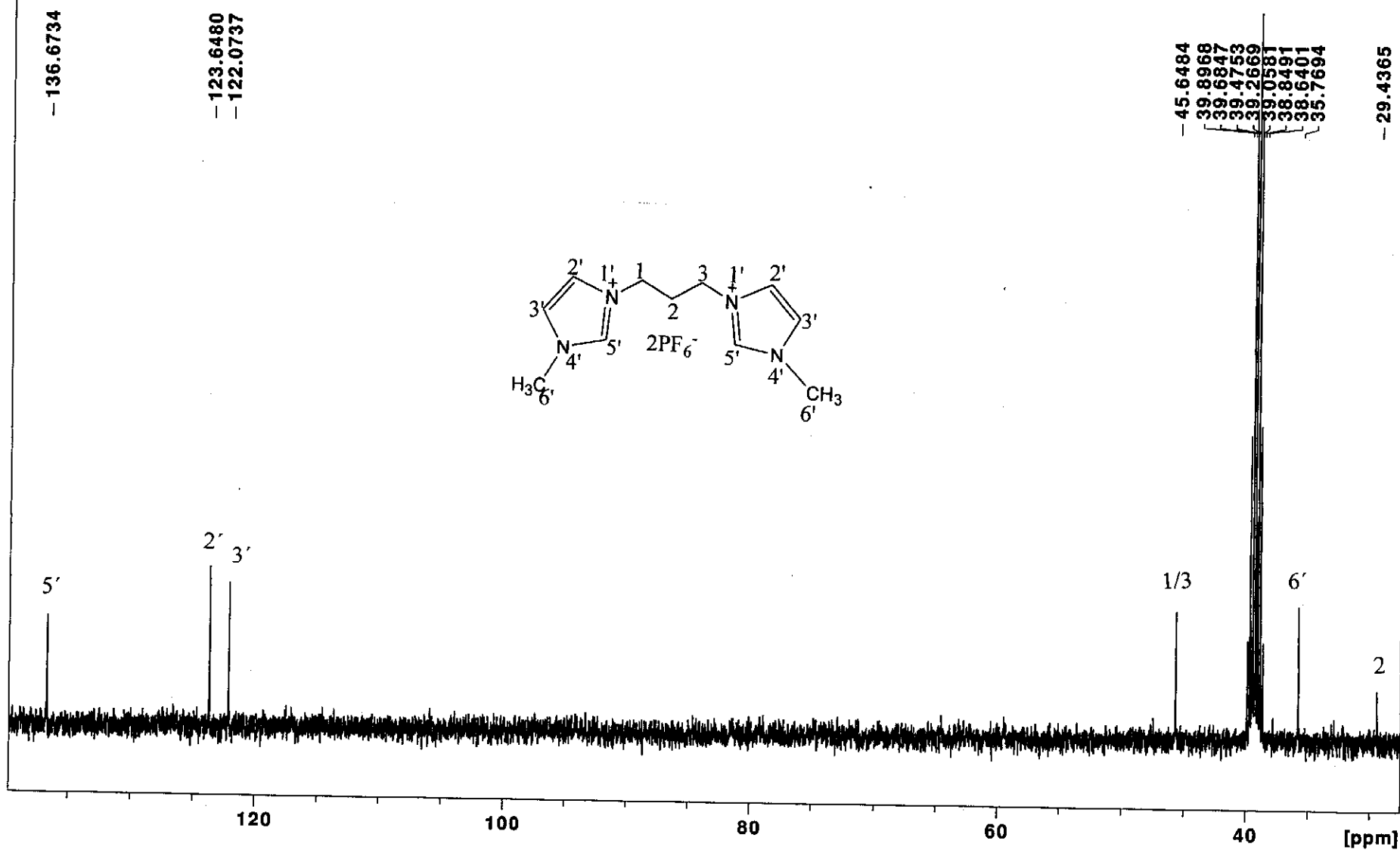
-CH2)3- Imim PF6- in DMSO 400 MHz.



¹H NMR spectrum of Compound C-2c

Jun17-2012-NK-Ibrahim 11 1 /opt/topspin NK

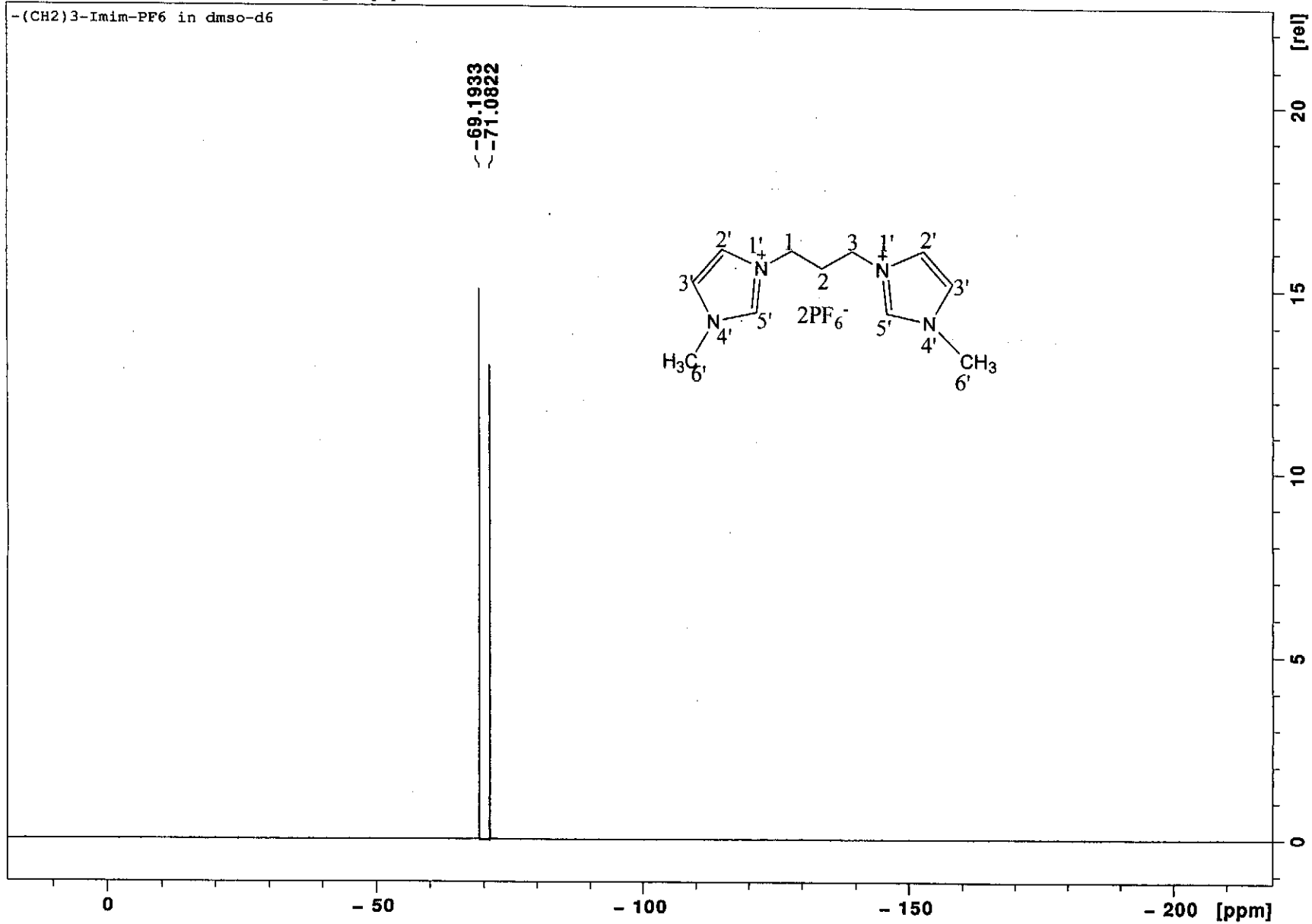
-(CH₂)₃-Imim-PF₆ in dms_o-d₆



¹³C NMR spectrum of Compound C-2c

Jun17-2012-NK-Ibrahim 14 1 /opt/topspin NK

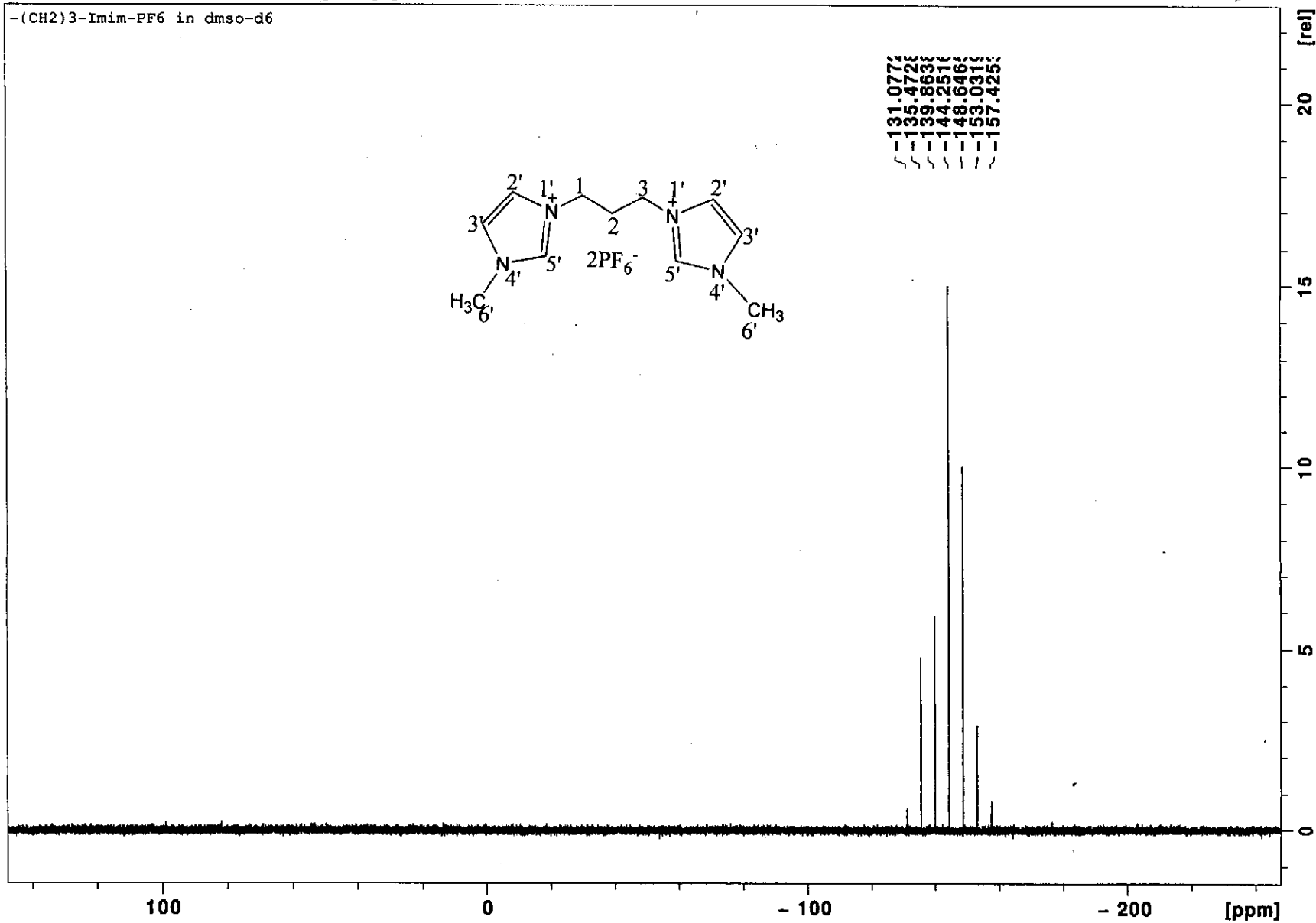
-(CH₂)₃-Imim-PF₆ in dms_o-d₆



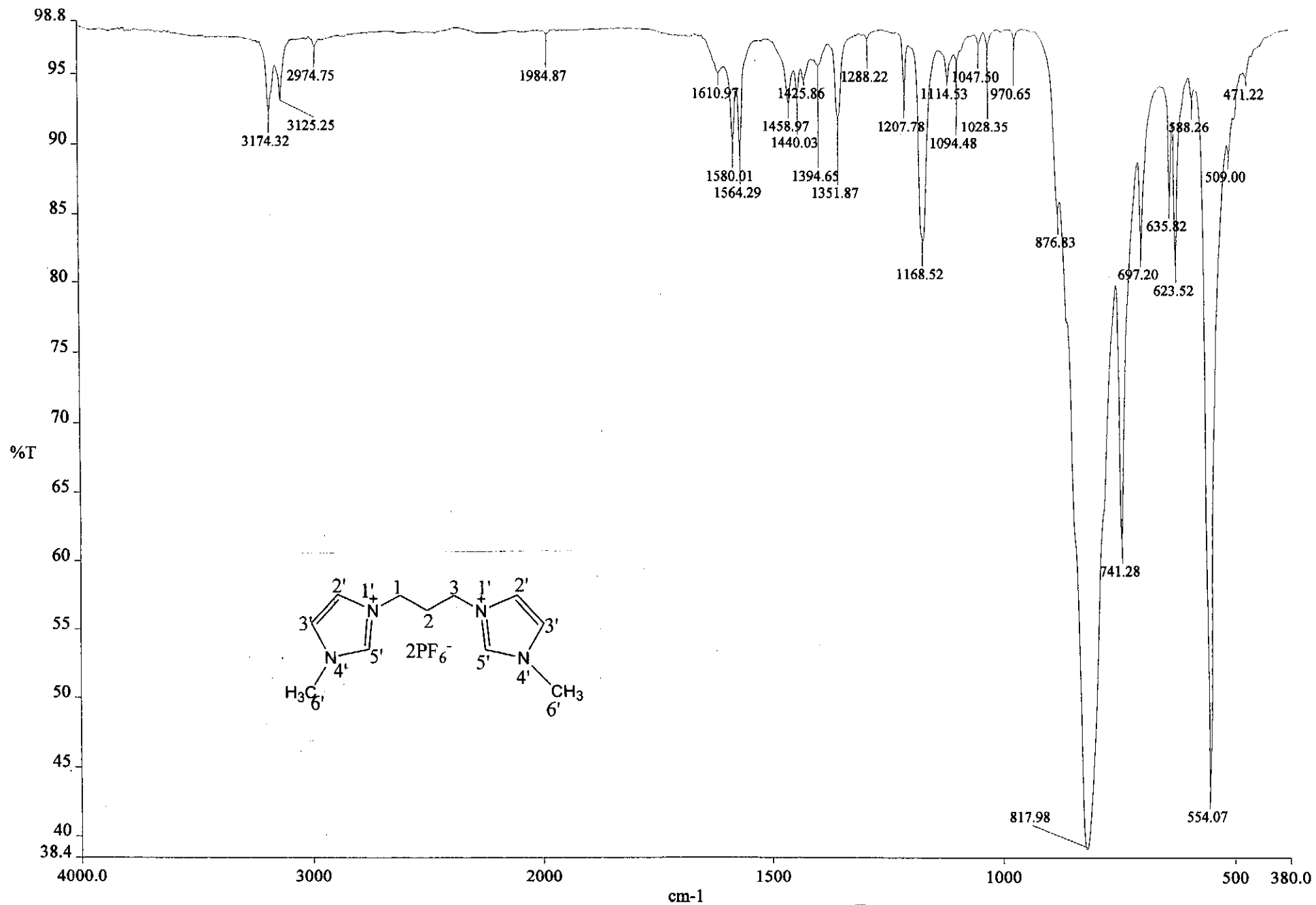
¹⁹F NMR spectrum of Compound C-2c

Jun17-2012-NK-Ibrahim 15 1 /opt/topspin NK

-(CH₂)₃-Imim-PF₆ in dms_o-d₆



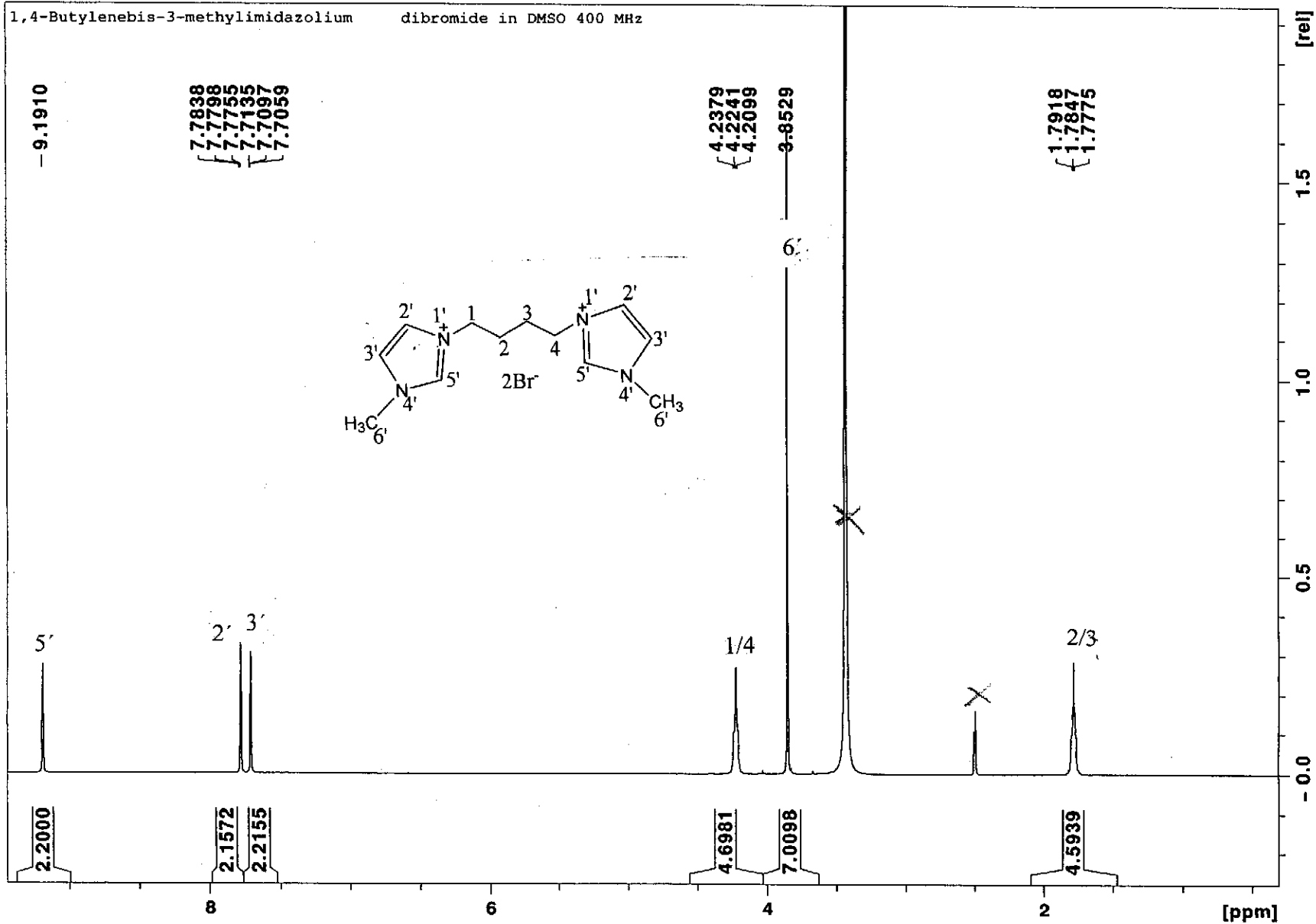
³¹P NMR spectrum of Compound C-2c



c:\pel_data\spectra\-(ch2)3-imin 2pf6.002 - White solid

IR spectrum of Compound C-2e

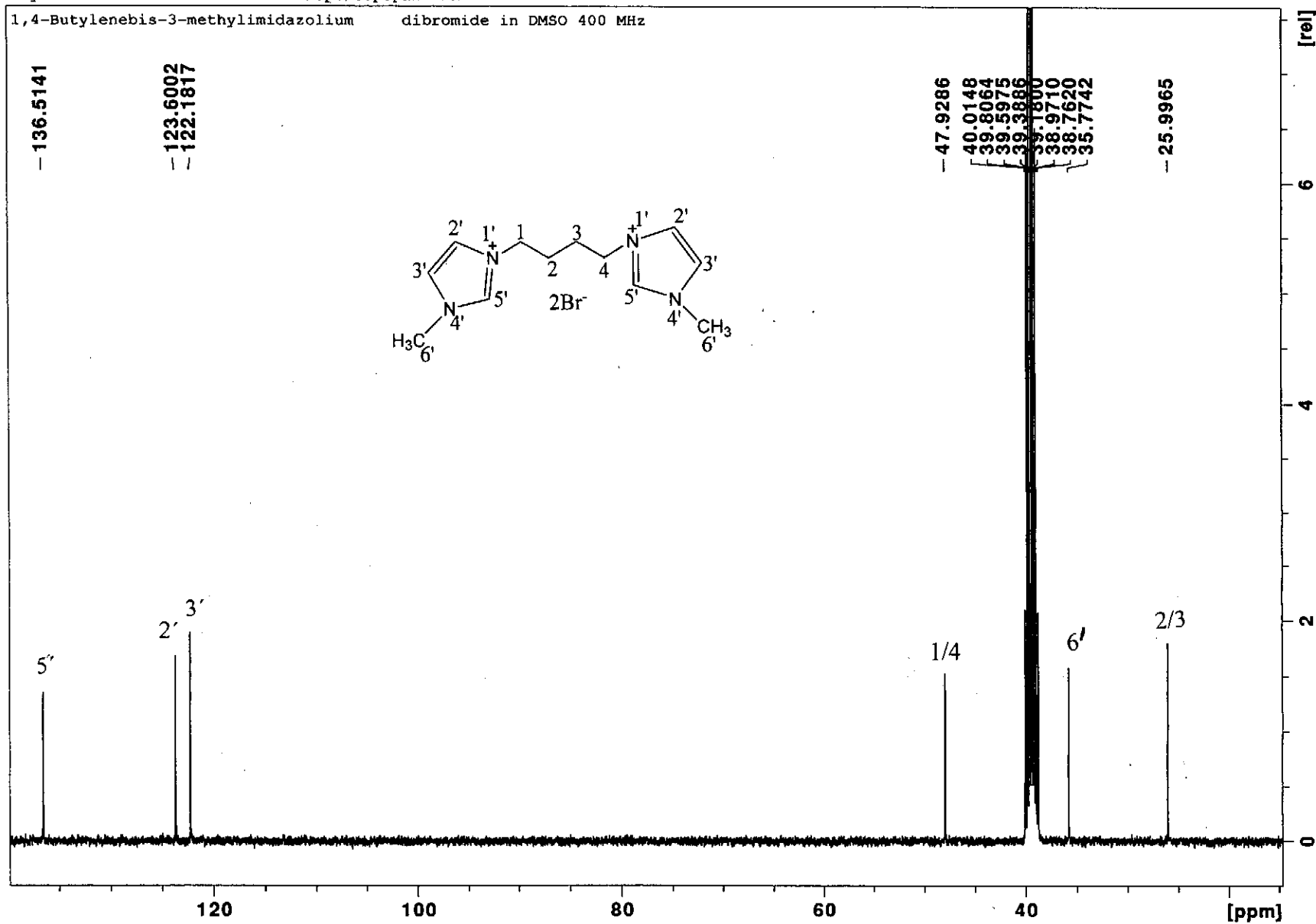
1,4-Butylenebis-3-methylimidazolium dibromide in DMSO 400 MHz



¹H NMR spectrum of Compound C-3a

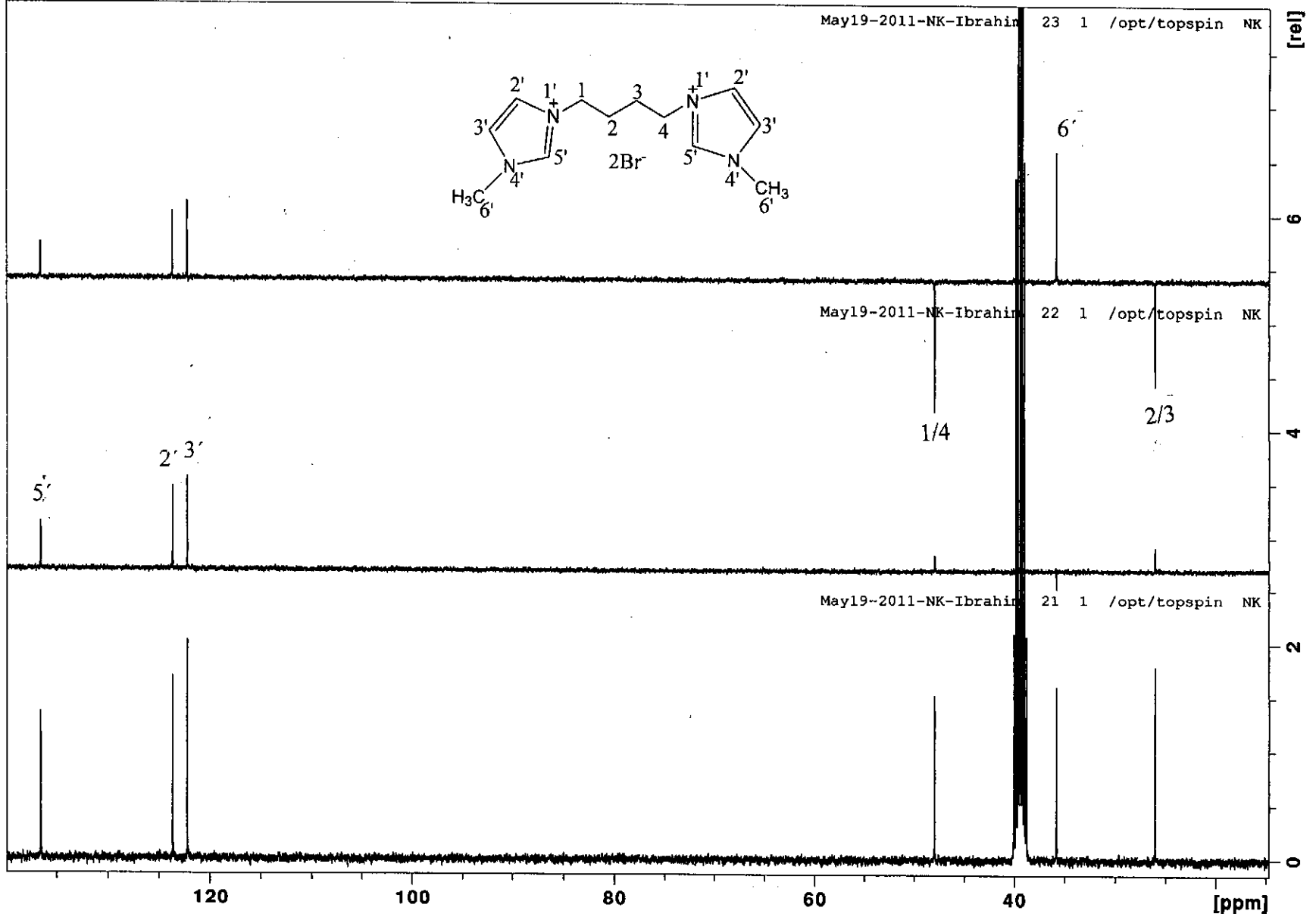
May19-2011-NK-Ibrahim 21 1 /opt/topspin NK

1,4-Butylenebis-3-methylimidazolium dibromide in DMSO 400 MHz



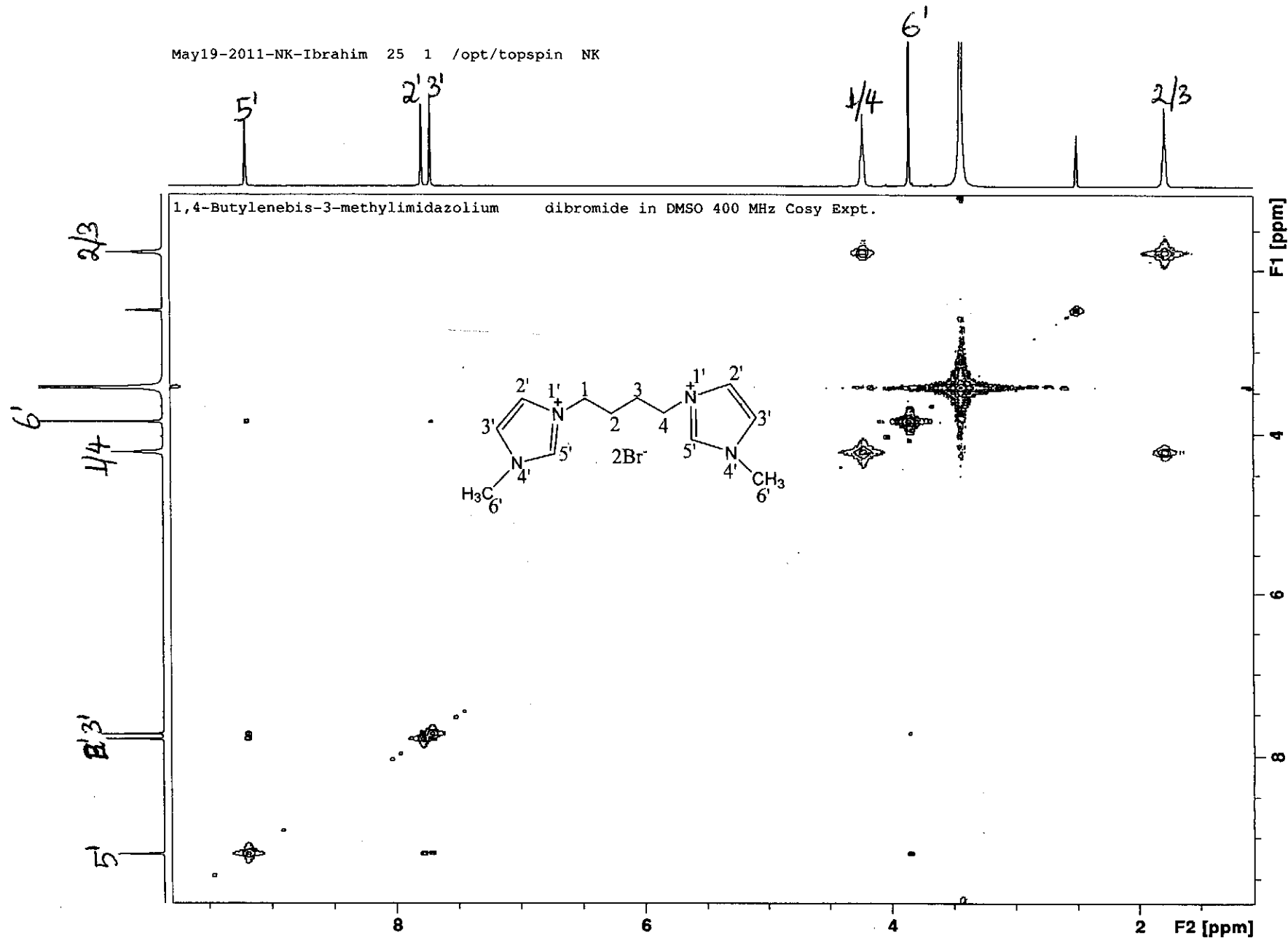
¹³C NMR spectrum of Compound C-3a

May19-2011-NK-Ibrahim 21 1 /opt/topspin NK



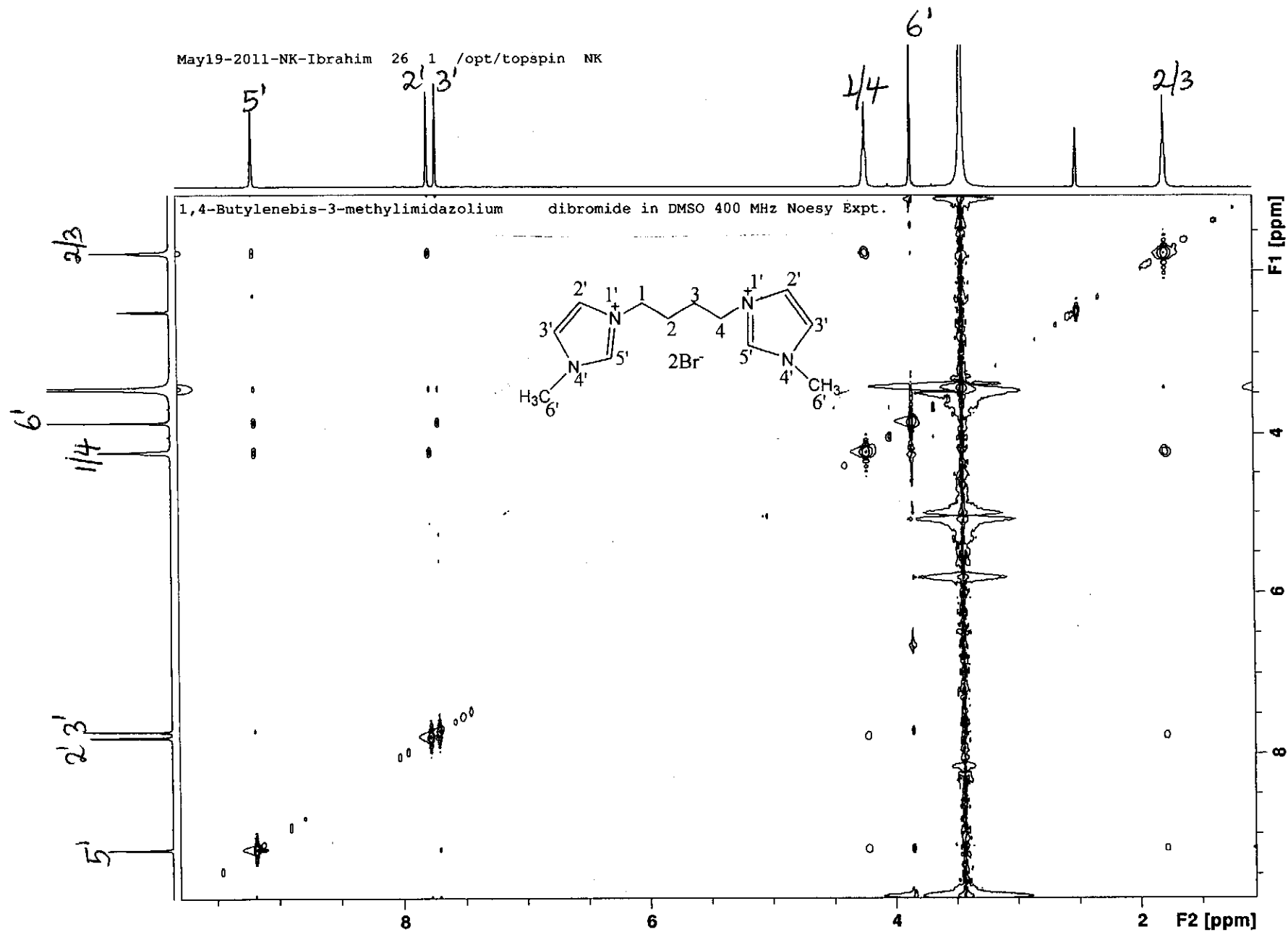
Dept 90 and 135 spectra of Compound C-3a

May19-2011-NK-Ibrahim 25 1 /opt/topspin NK



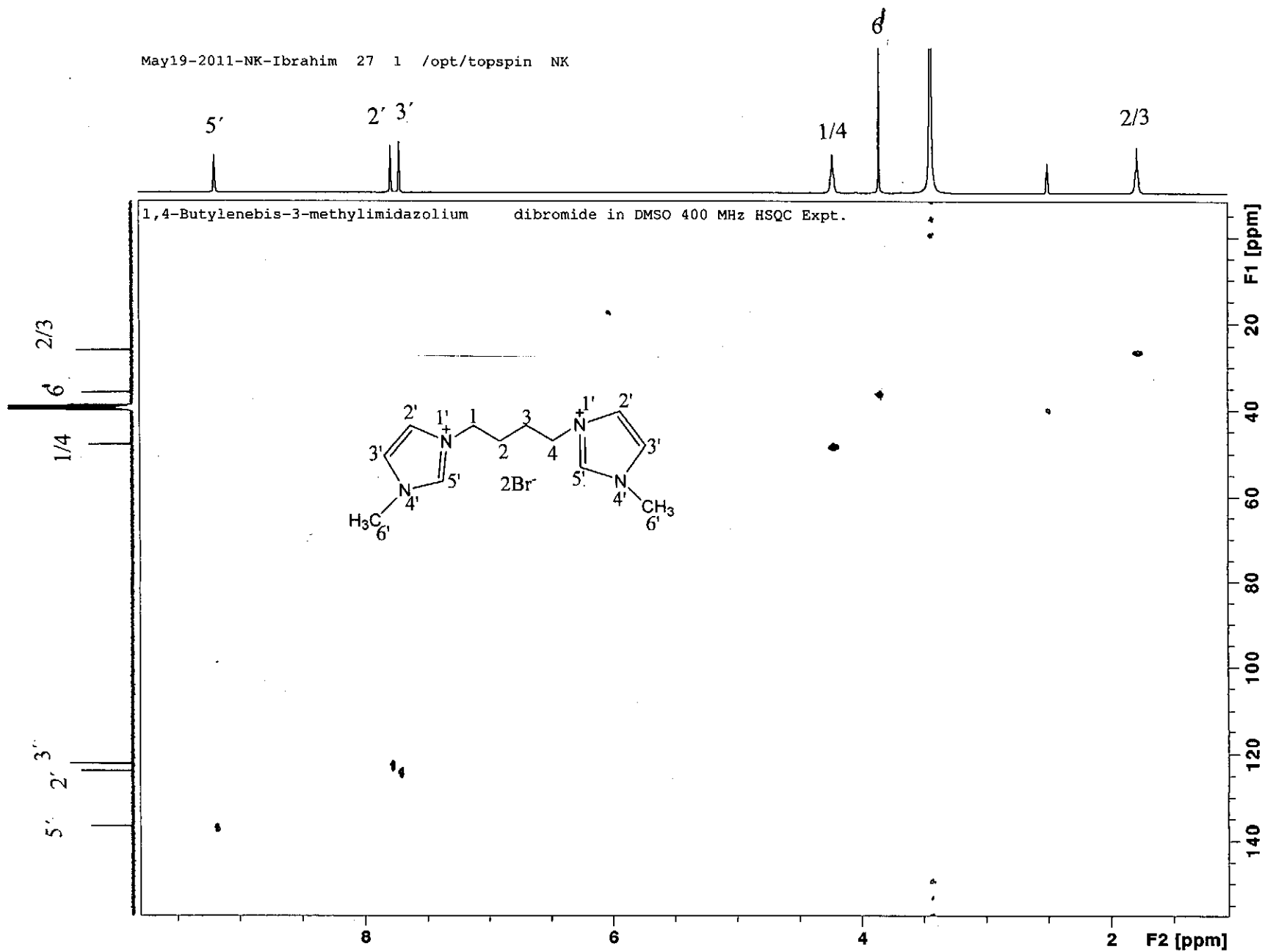
COSY spectrum of Compound C-3a

May19-2011-NK-Ibrahim 26 1 /opt/topspin NK

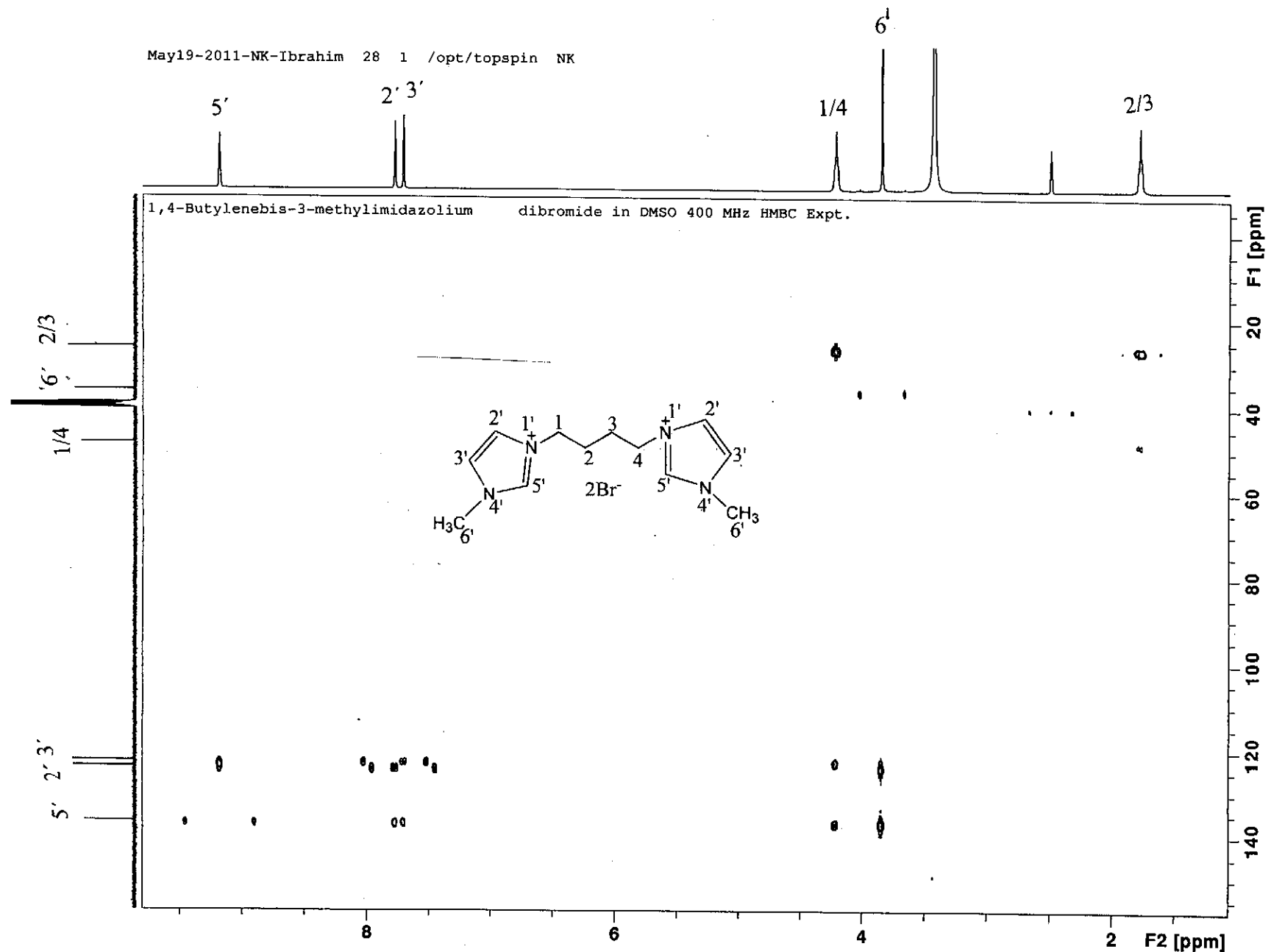


NOESY spectrum of Compound C-3a

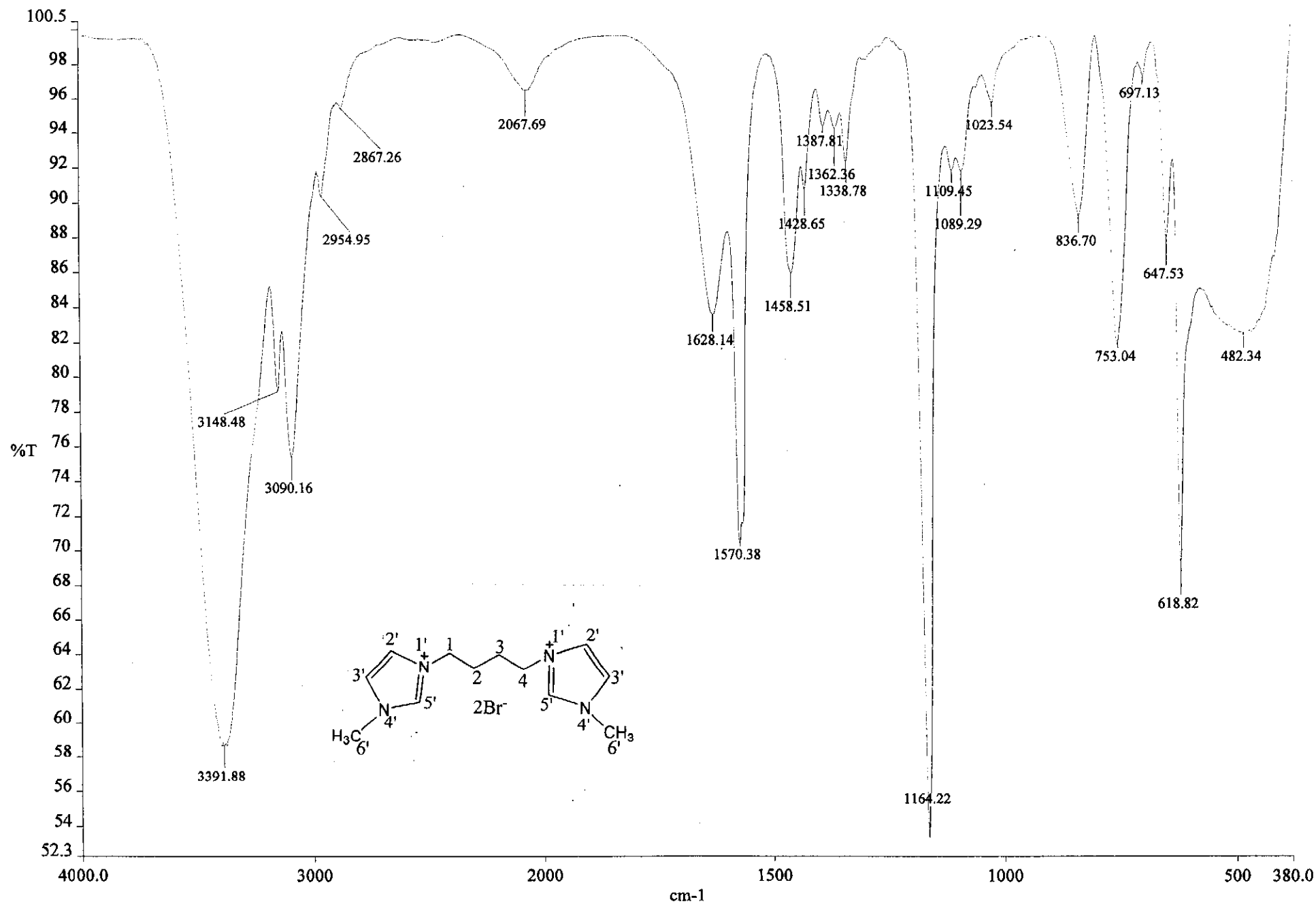
May19-2011-NK-Ibrahim 27 1 /opt/topspin NK



May19-2011-NK-Ibrahim 28 1 /opt/topspin NK



HMBC spectrum of Compound C-3a

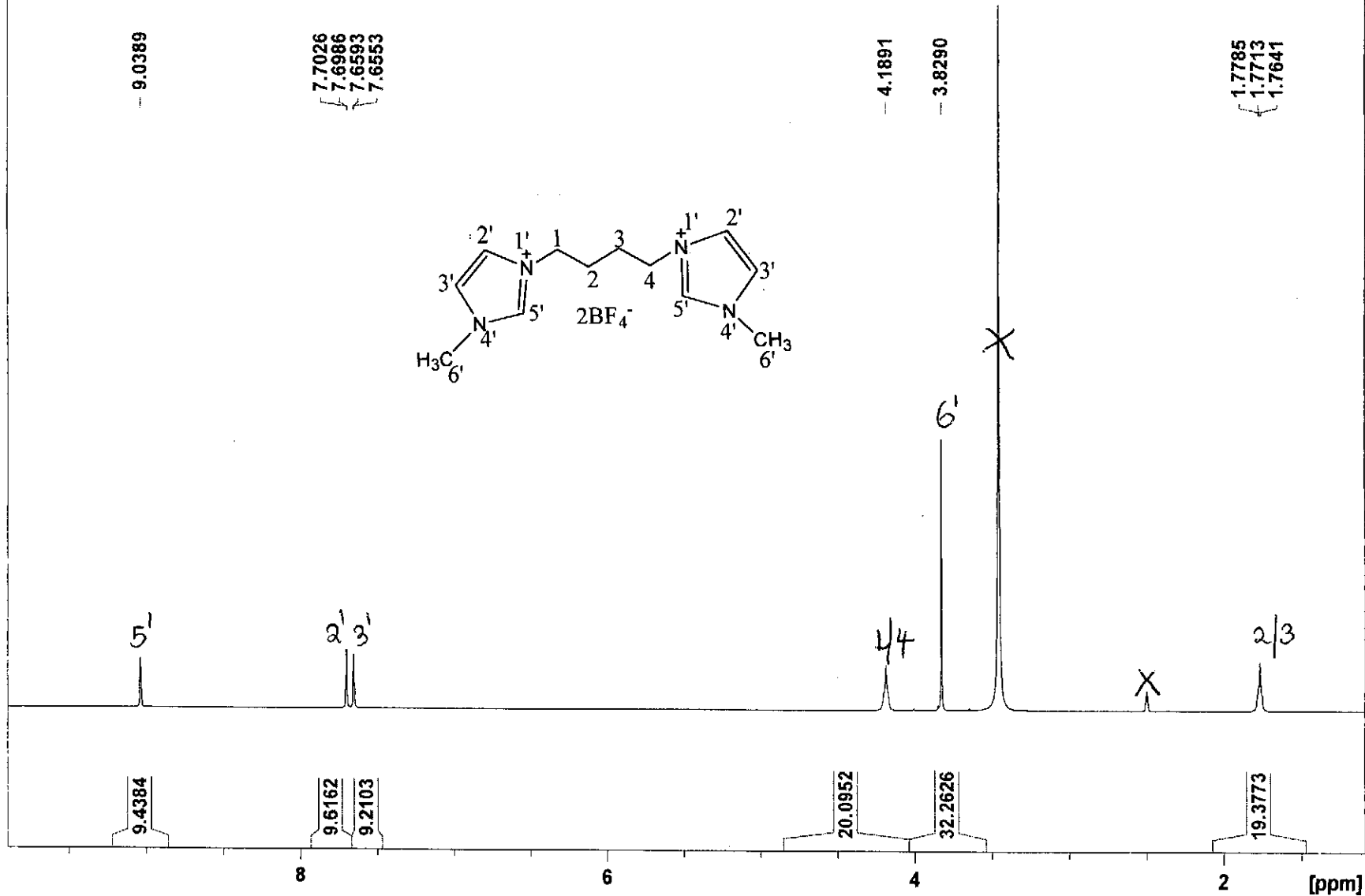


c:\pel_data\spectra\librahim\-(ch2)4- imIn br..002

IR spectrum of Compound C-3a

Jul10-2011-NK-Ibrahim 30 1 C:\Bruker\TOPSPIN guest

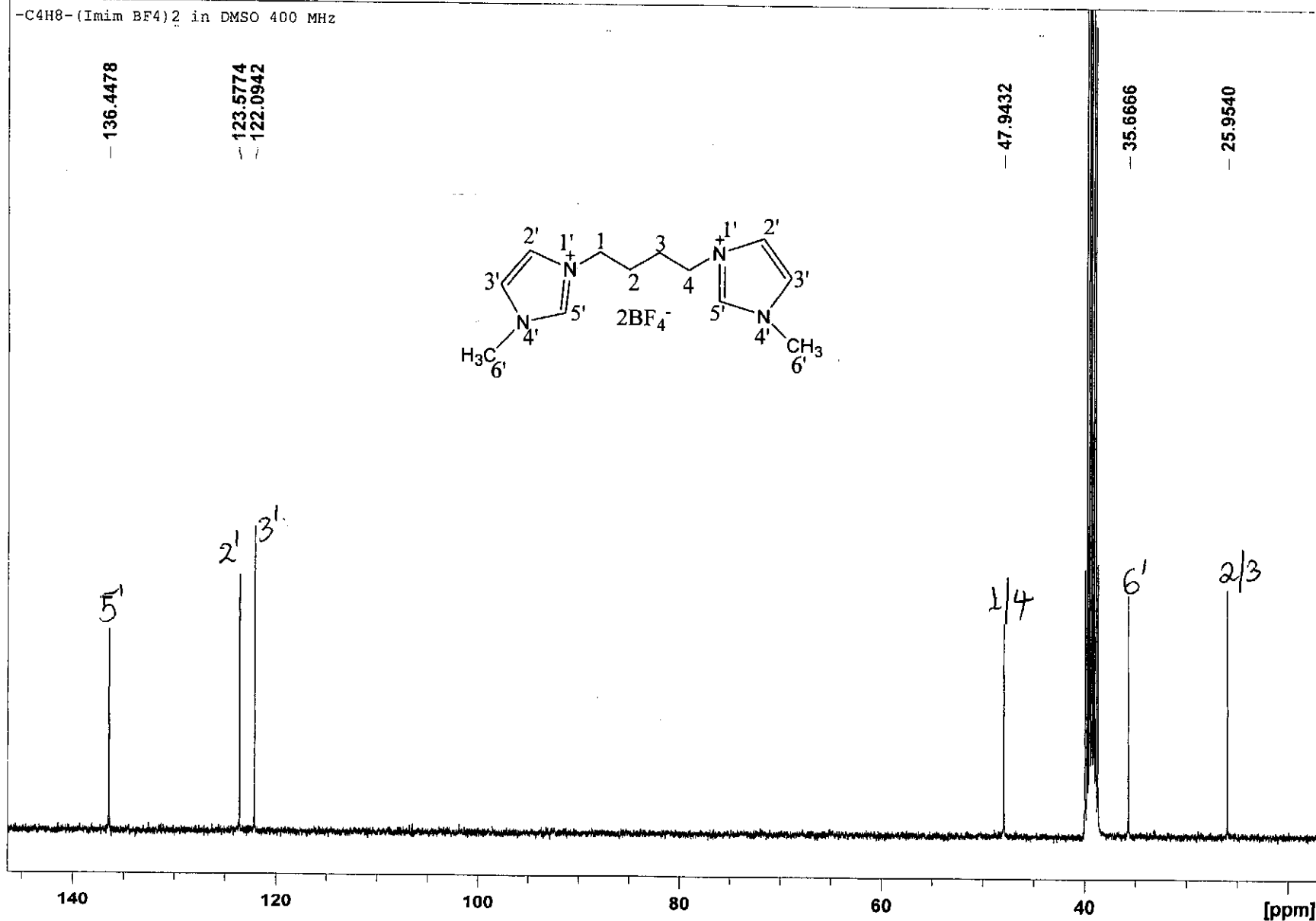
-C4H8-(Imim BF₄)₂ in DMSO 400 MHz



¹H NMR spectrum of Compound C-3b

Jul10-2011-NK-Ibrahim 31 1 C:\Bruker\TOPSPIN guest

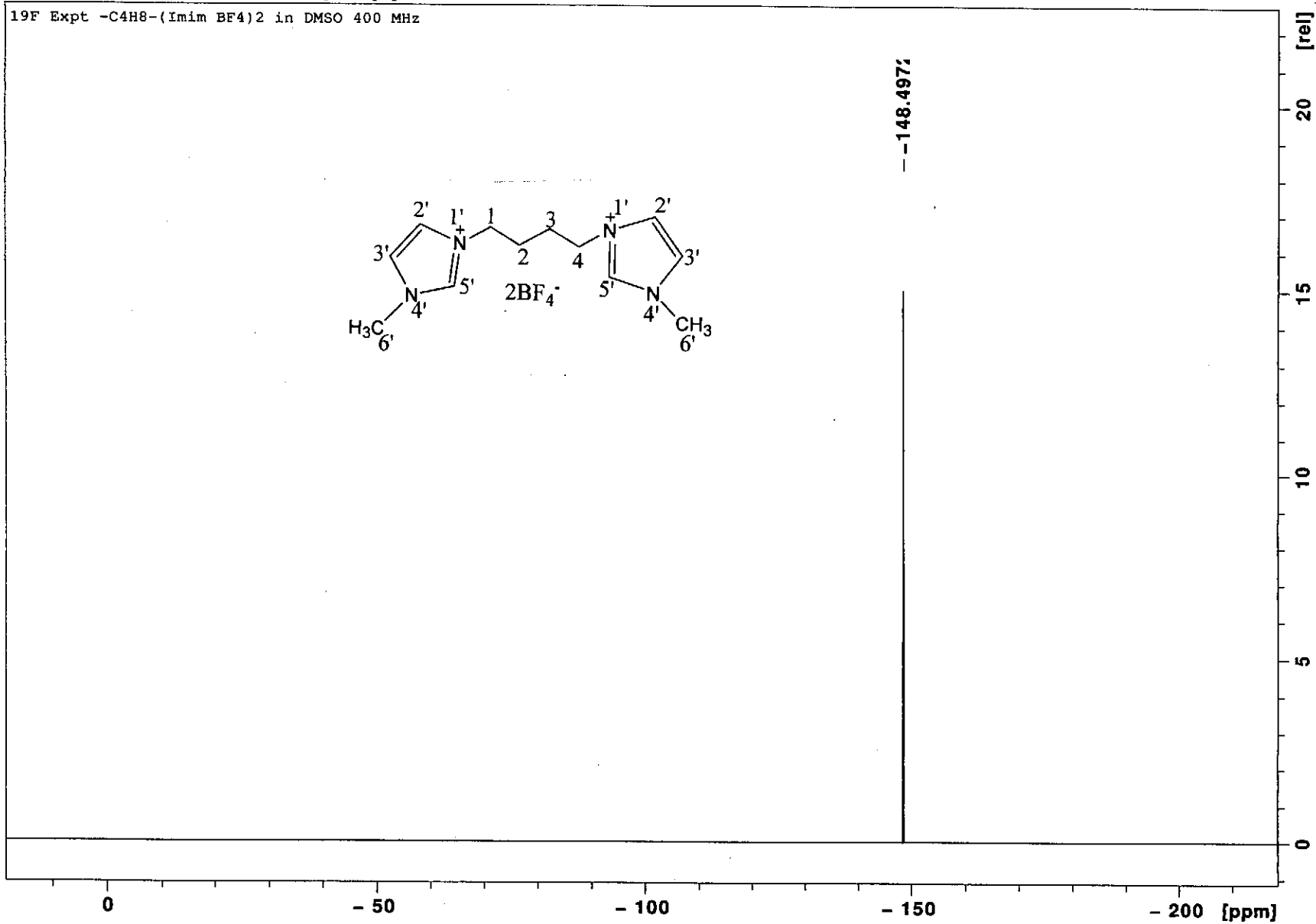
-C4H8-(Imim BF4)₂ in DMSO 400 MHz



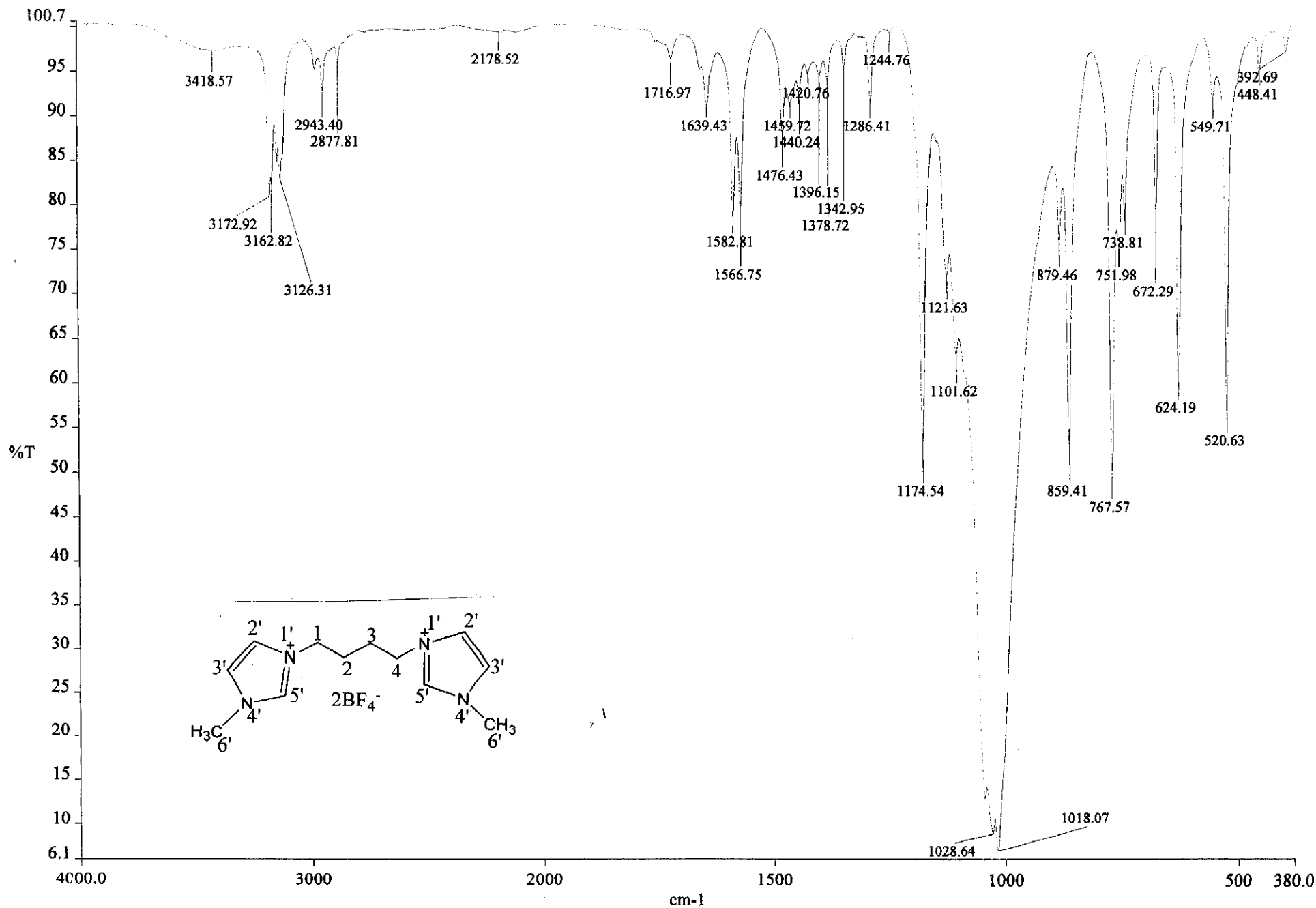
¹³C NMR spectrum of Compound C-3b

Jul10-2011-NK-Ibrahim 34 1 /opt/topspin NK

19F Expt -C4H8-(Imim BF4)2 in DMSO 400 MHz



^{19}F NMR spectrum of Compound C-3b

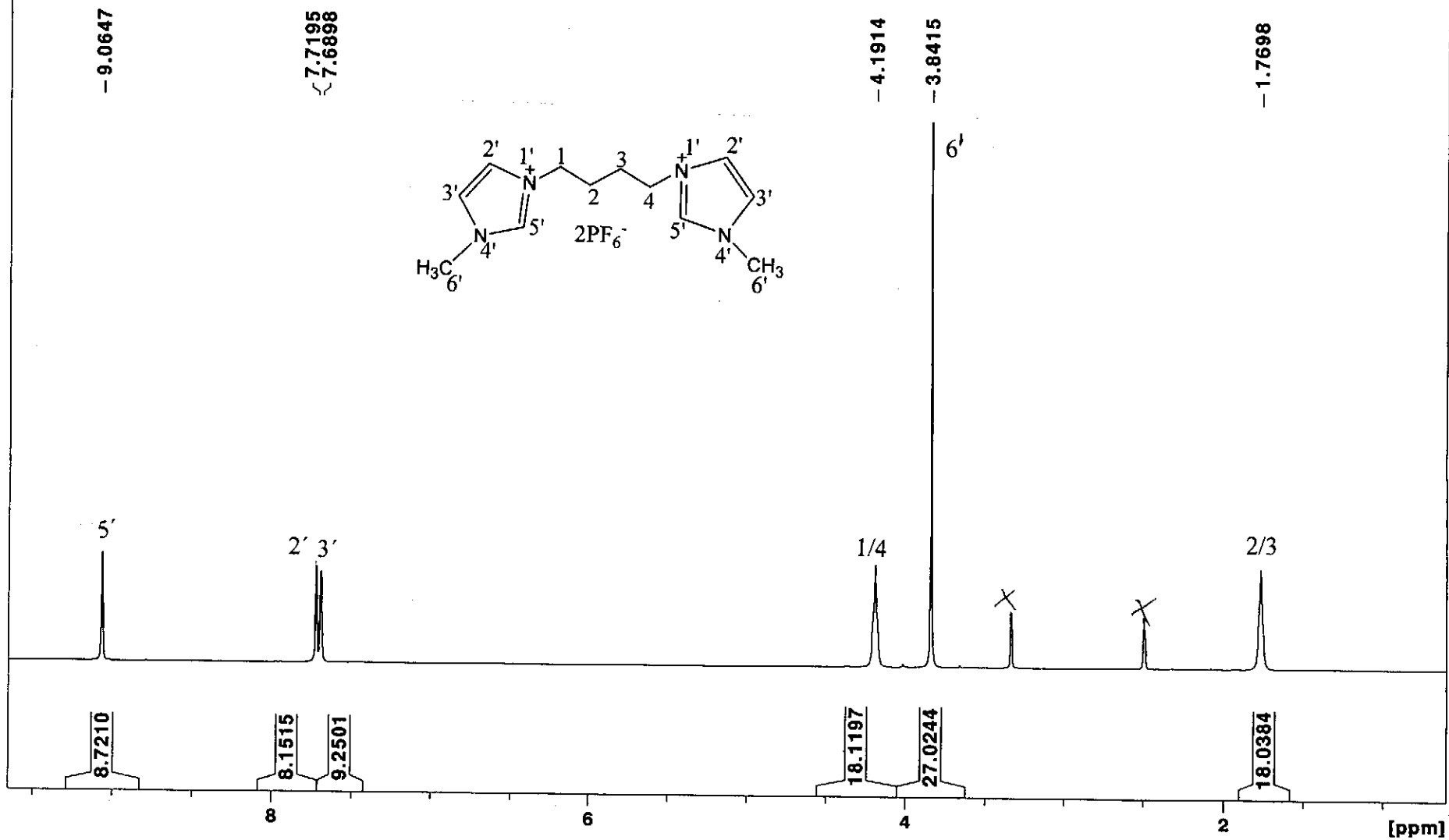


c:\pel_data\spectra\librahim\-(ch2)4- imin 2bf4.002 - White solid

IR spectrum of Compound C-3b

Jul22-2012-NK-Ibrahim 30 1 /opt/topspin NK

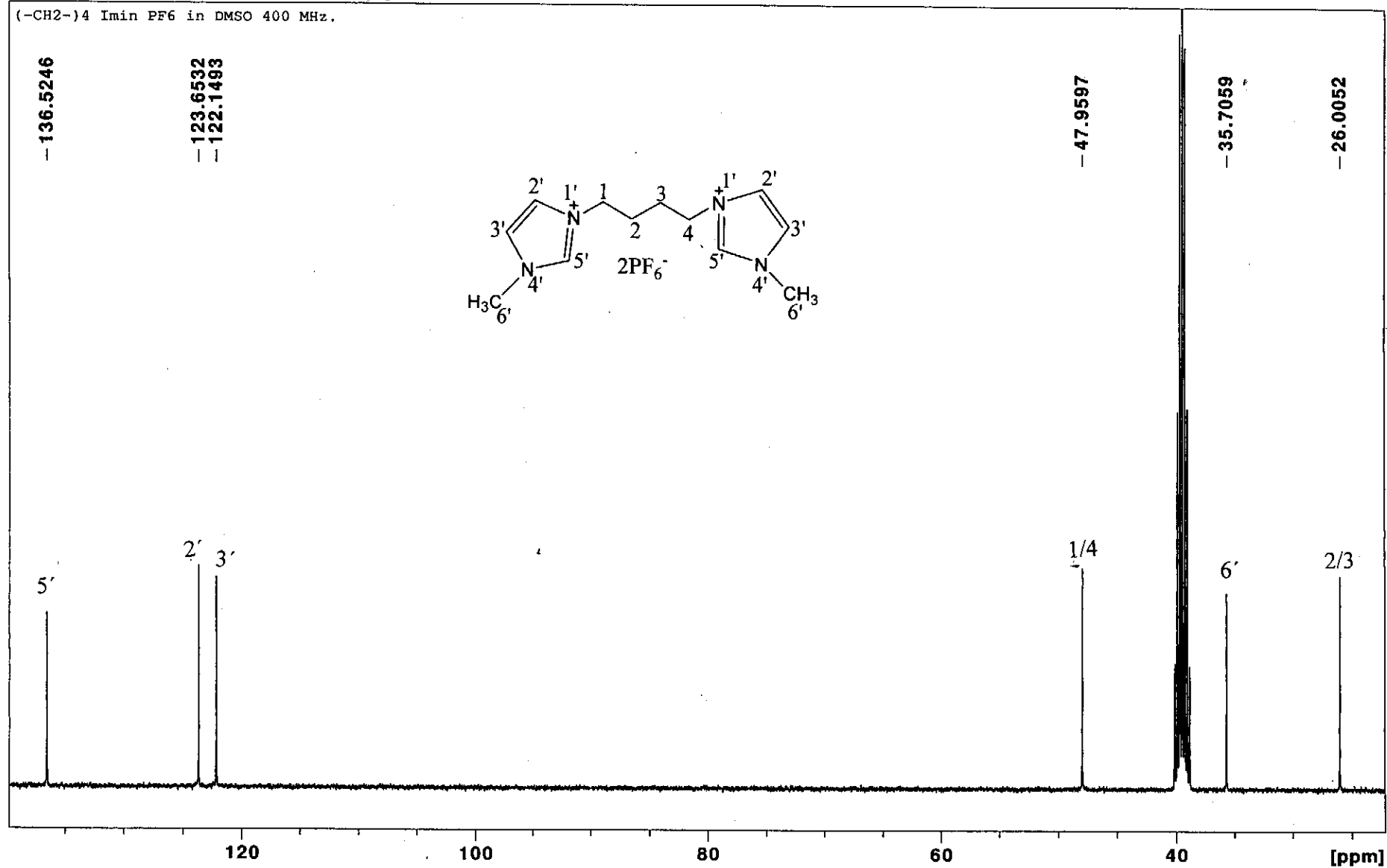
(-CH2-)4 Imin PF6 in DMSO 400 MHz.



¹H NMR spectrum of Compound C-3c

Jul22-2012-NK-Ibrahim 31 1 /opt/topspin NK

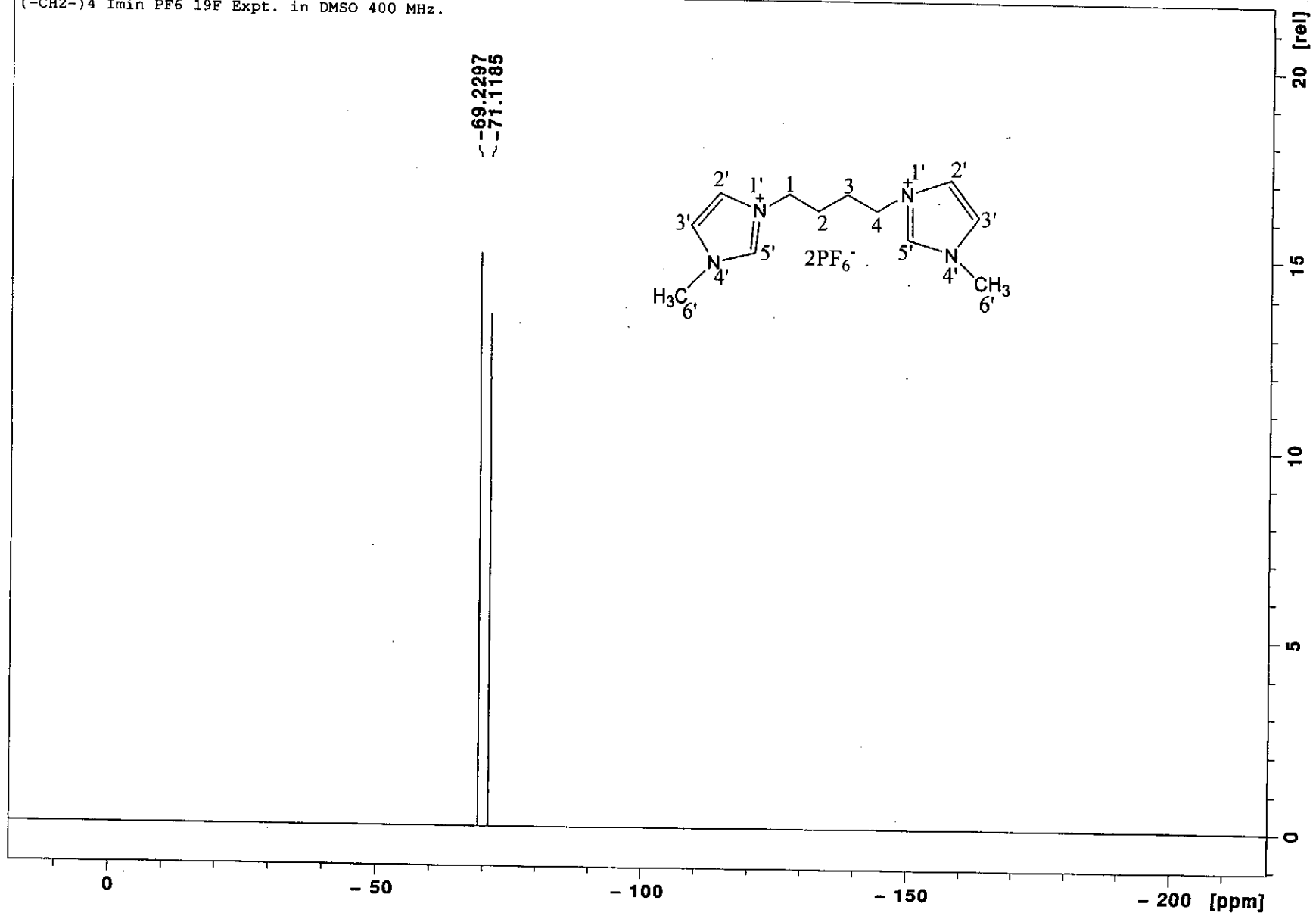
(-CH2-)4 Imin PF6 in DMSO 400 MHz.



¹³C NMR spectrum of Compound C-3c

Jul22-2012-NK-Ibrahim 35 1 /opt/topspin NK

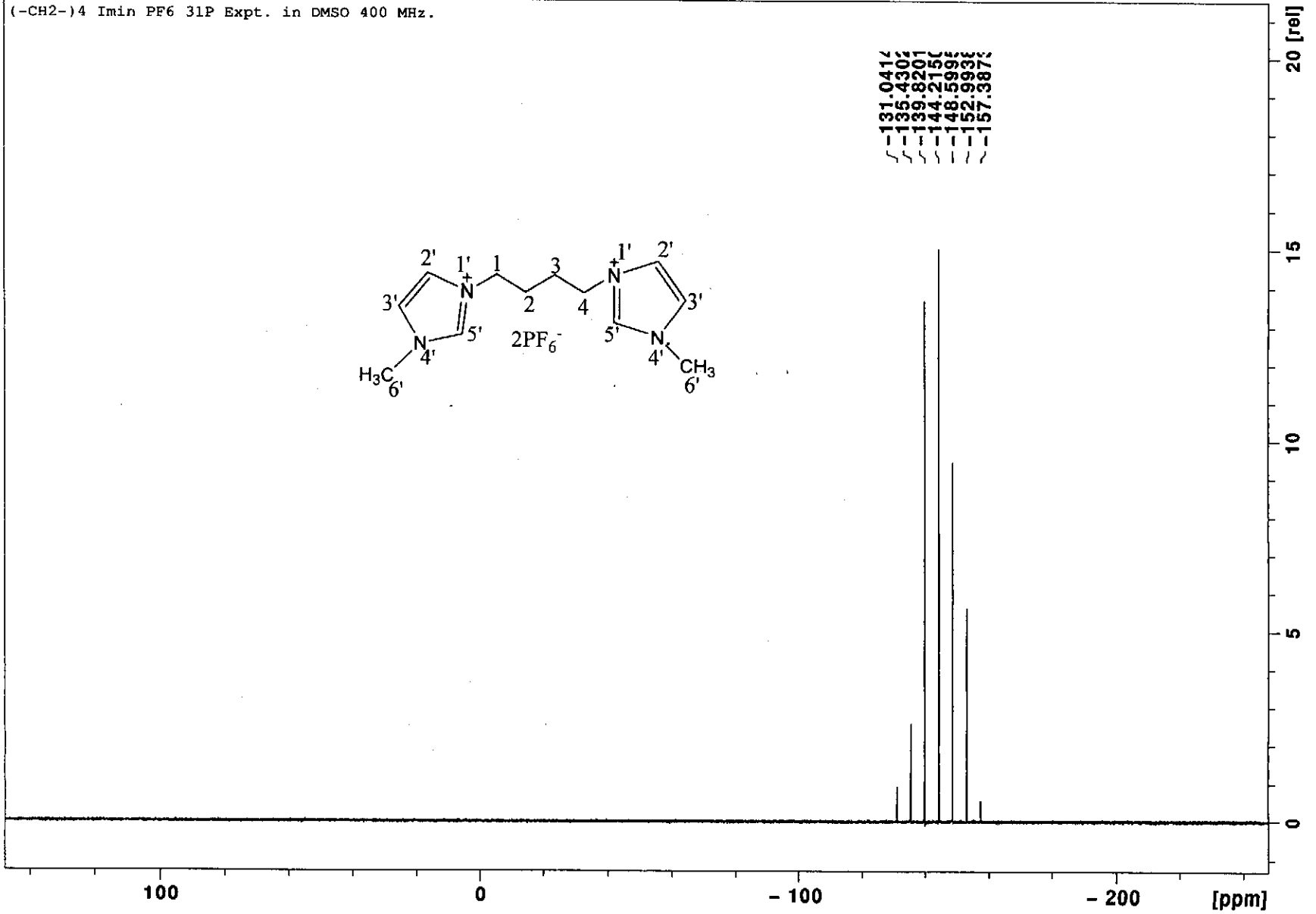
(-CH2-)4 Imin PF6 19F Expt. in DMSO 400 MHz.



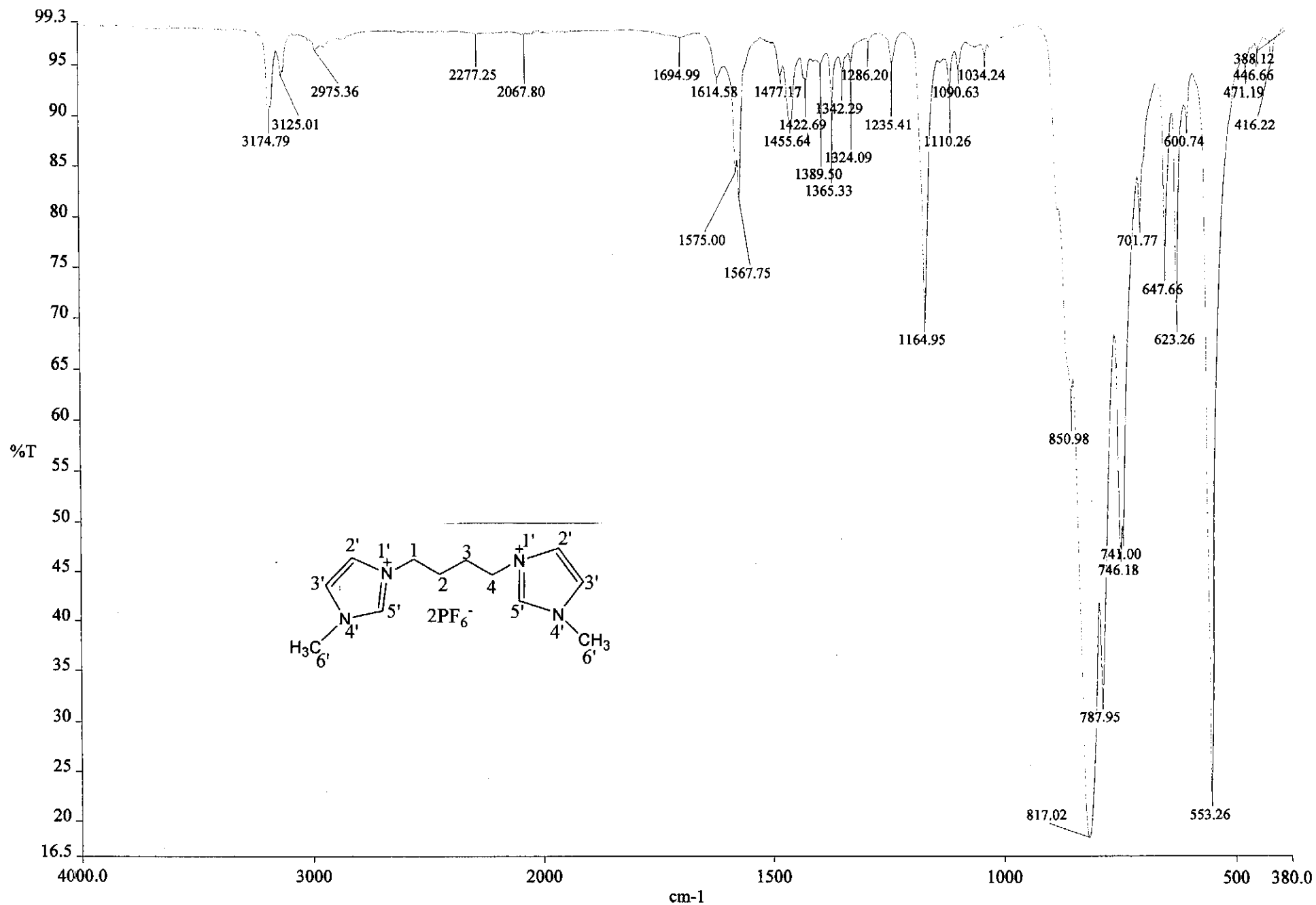
^{19}F NMR spectrum of Compound C-3c

Jul22-2012-NK-Ibrahim 36 1 /opt/topspin NK

(-CH2-)4 Imin PF6 31P Expt. in DMSO 400 MHz.

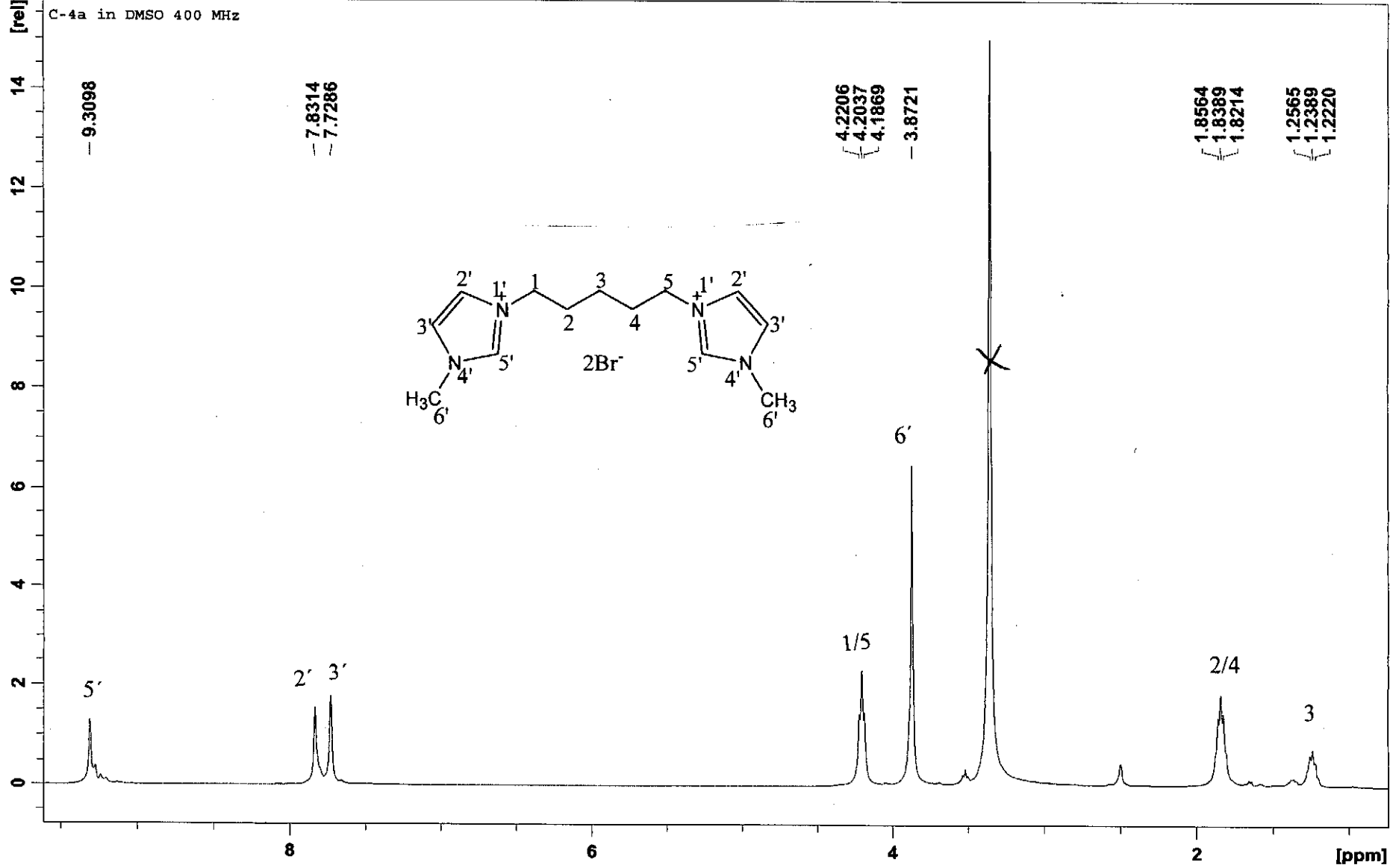


^{31}P NMR spectrum of Compound C-3c



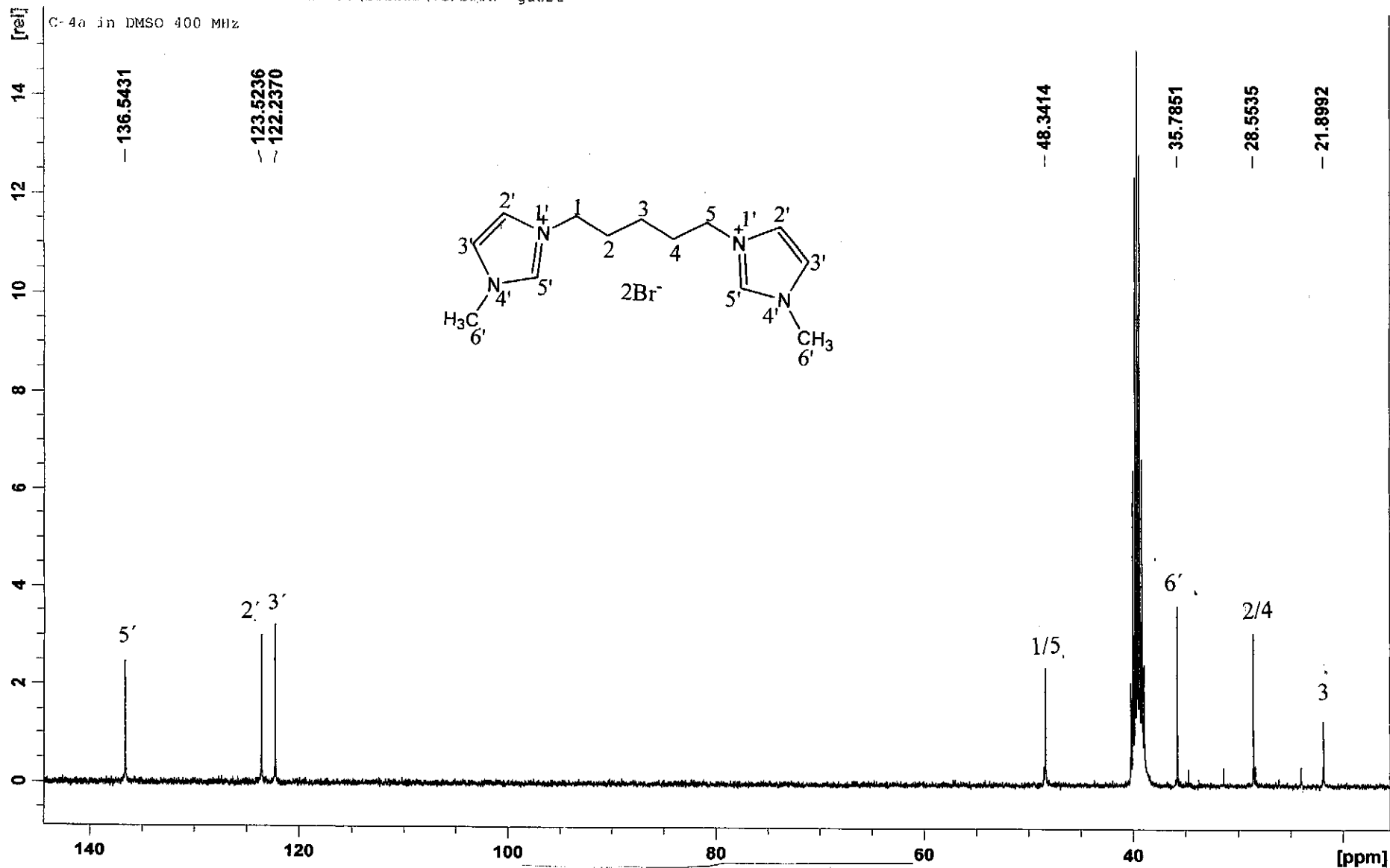
c:\pel_data\spectra\-(ch2)4-imin 2pf6.002 - White solid

IR spectrum of Compound C-3c



¹H NMR spectrum of Compound C-4a

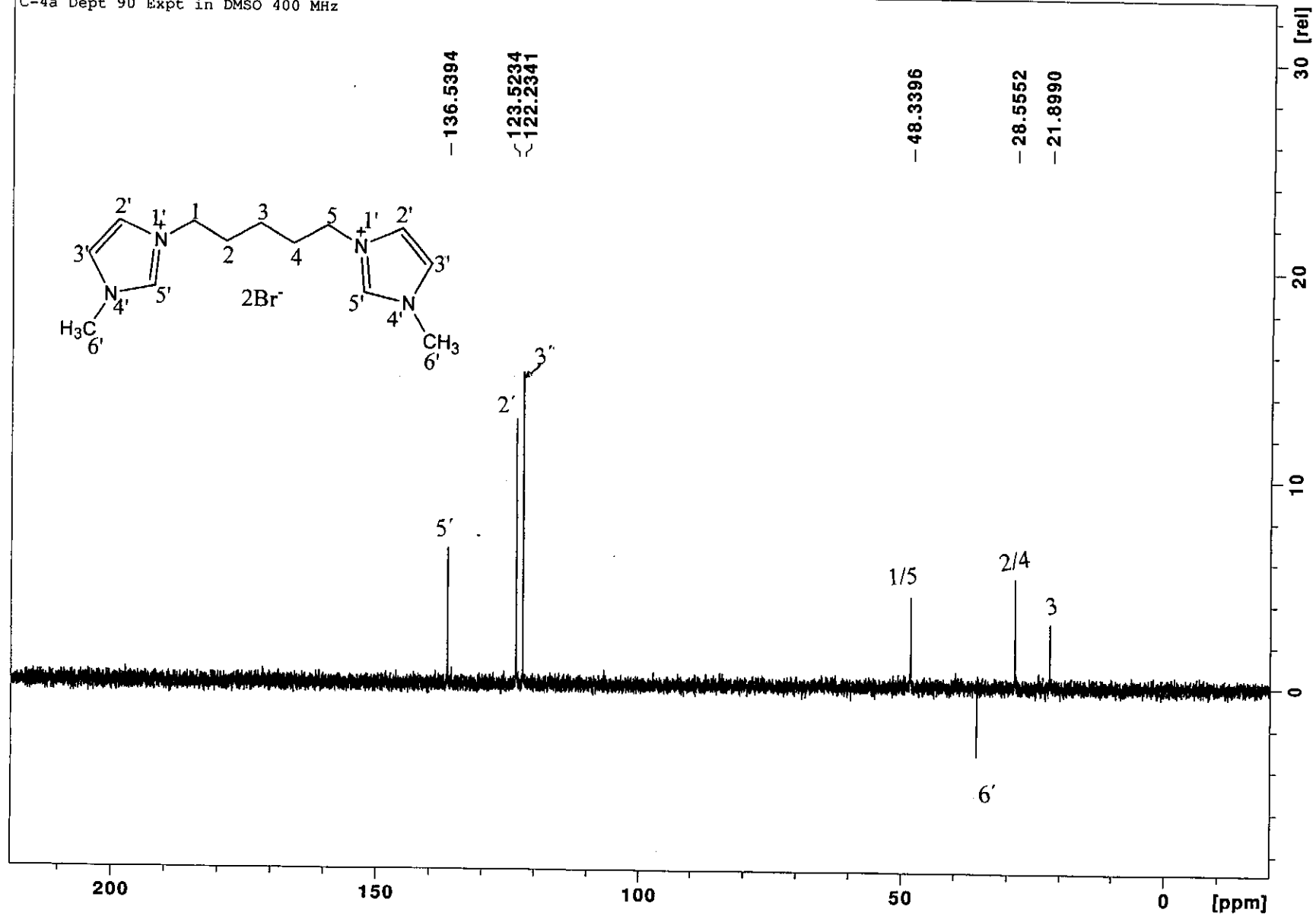
Jan11-2013-NK-Ibrahim 71 1 C:\Bruker\TOPSPIN guest



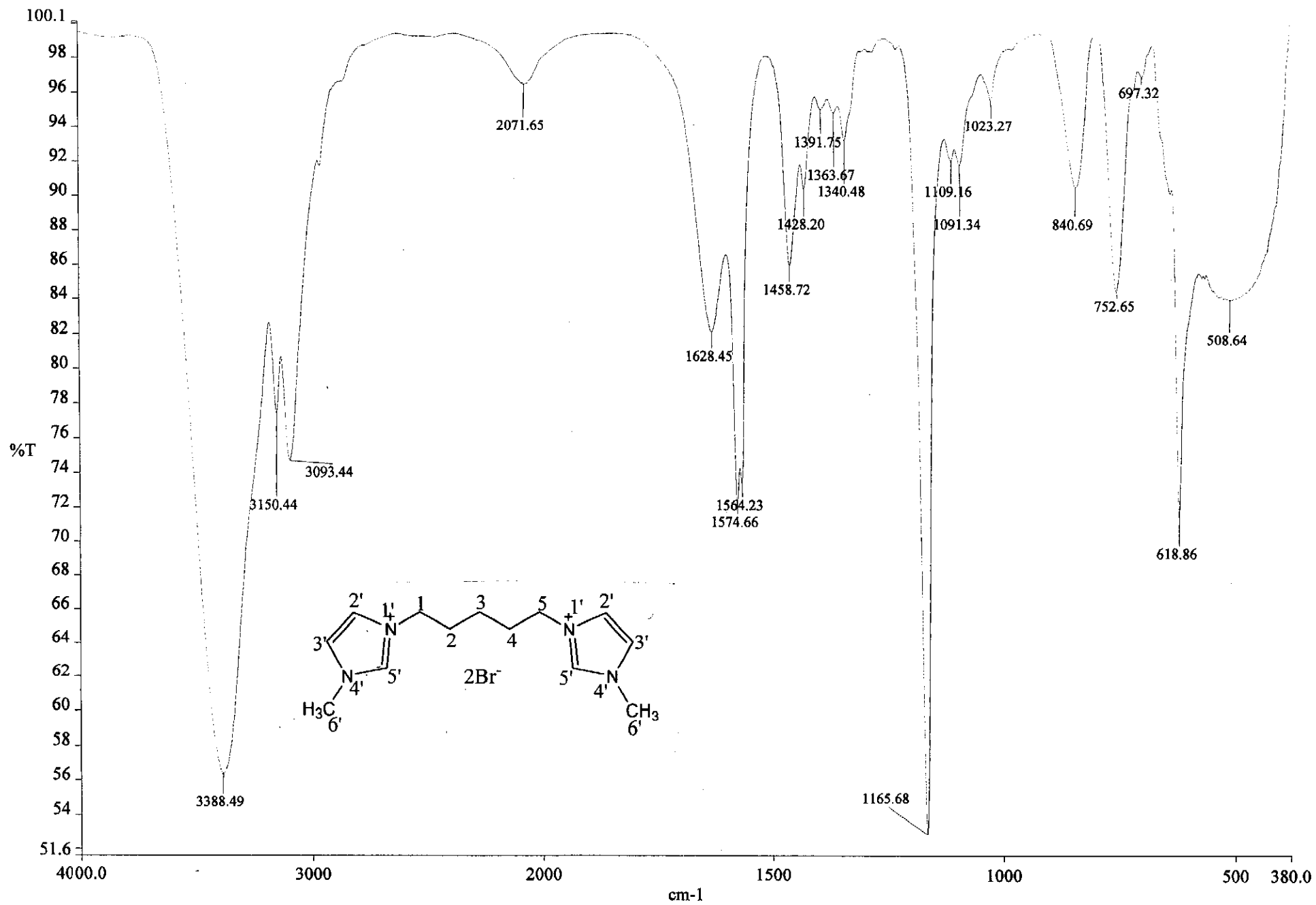
¹³C NMR spectrum of Compound C-4a

Jan11-2013-NK-Ibrahim 72 1 /opt/topspin NK

C-4a Dept 90 Expt in DMSO 400 MHz



Dept 90 spectrum of Compound C-4a



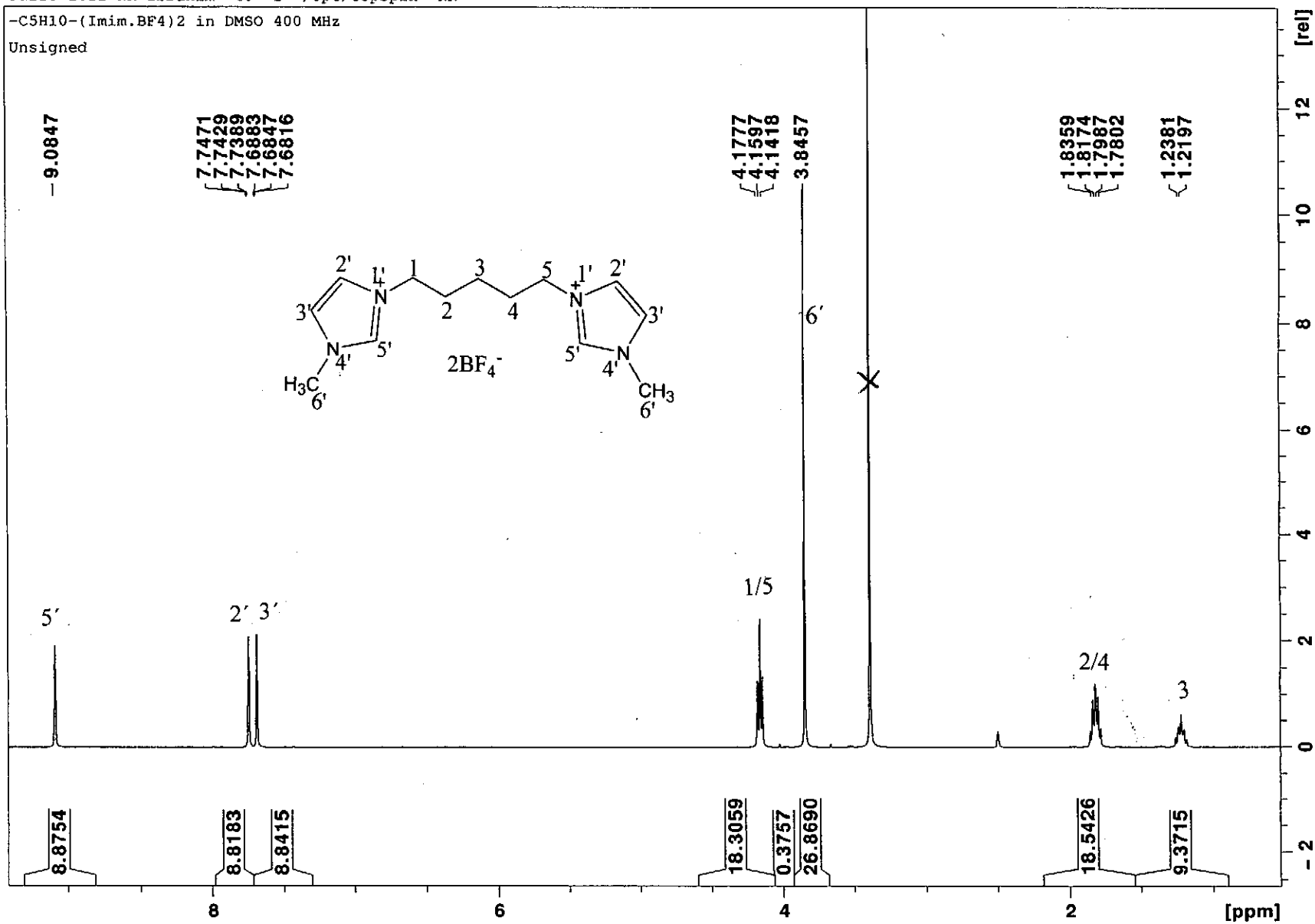
c:\pel_data\spectra\ibrahim\-(ch2)5- imin br..002

IR spectrum of Compound C-4a

Jul10-2011-NK-Ibrahim 40 1 /opt/topspin NK

-C5H10-(Imim.BF4)2 in DMSO 400 MHz

Unsigned

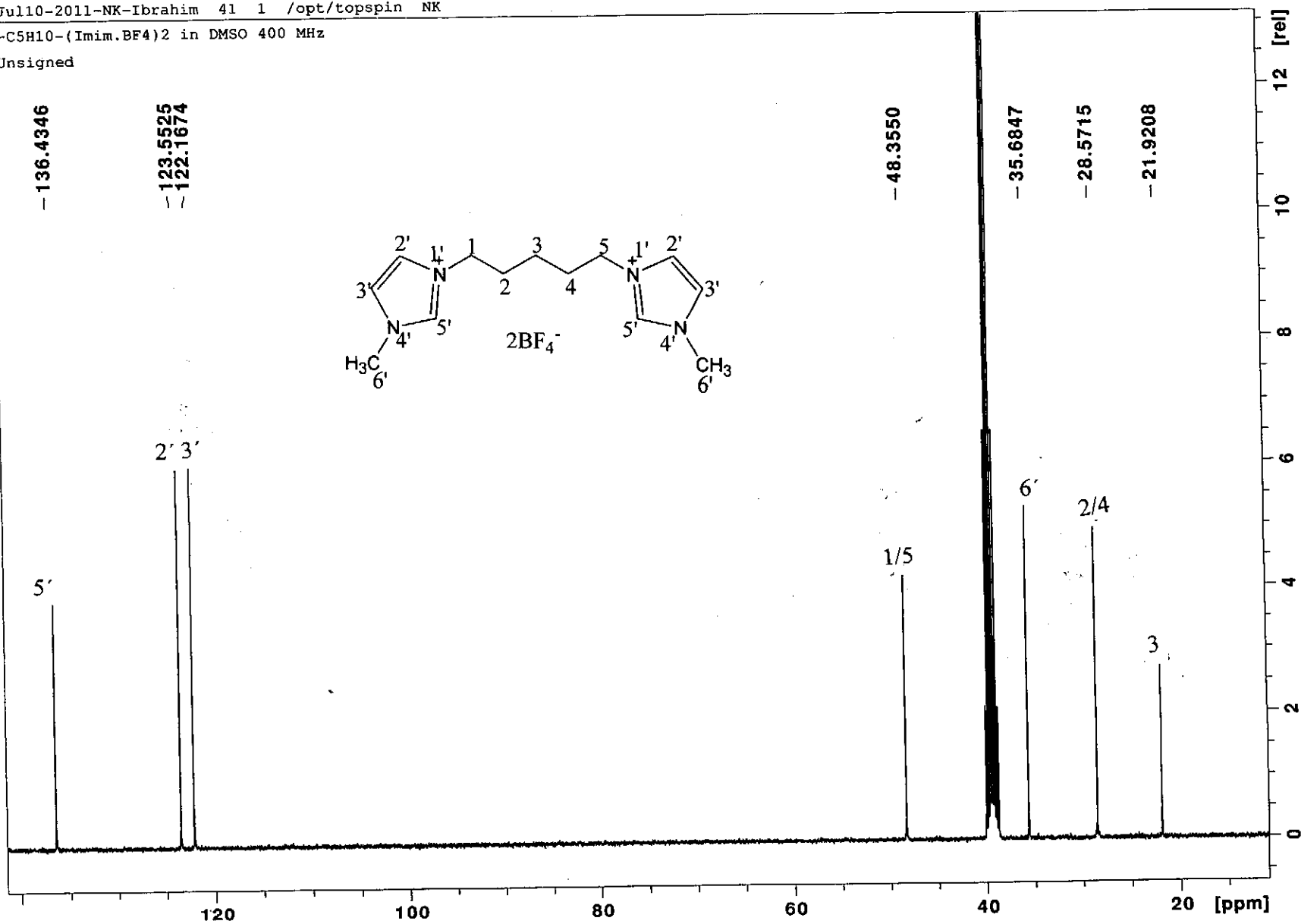


¹H NMR spectrum of Compound C-4b

Jul10-2011-NK-Ibrahim 41 1 /opt/topspin NK

-C5H10-(Imim.BF4)2 in DMSO 400 MHz

Unsigned

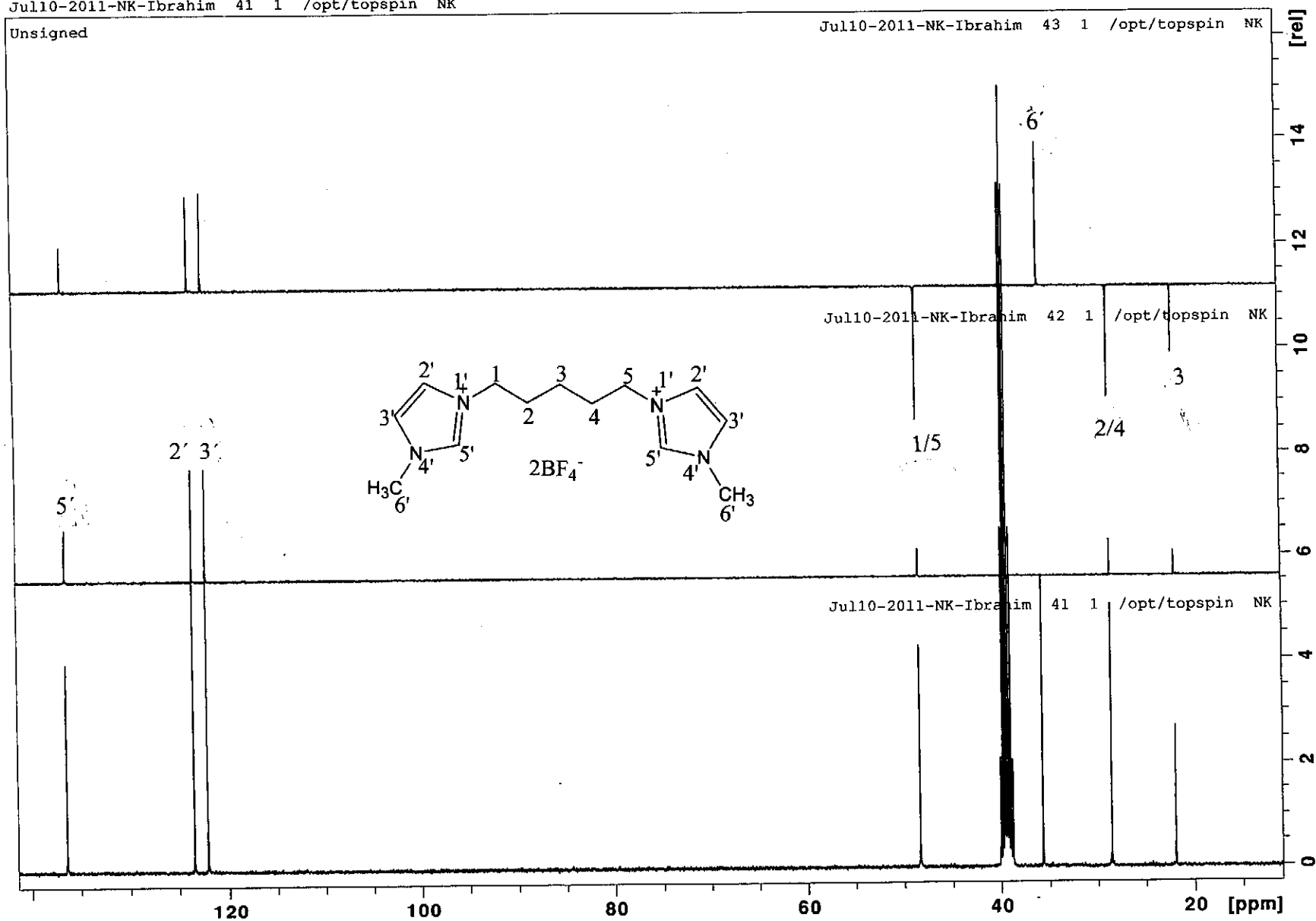


¹³C NMR spectrum of Compound C-4b

Jul10-2011-NK-Ibrahim 41 1 /opt/topspin NK

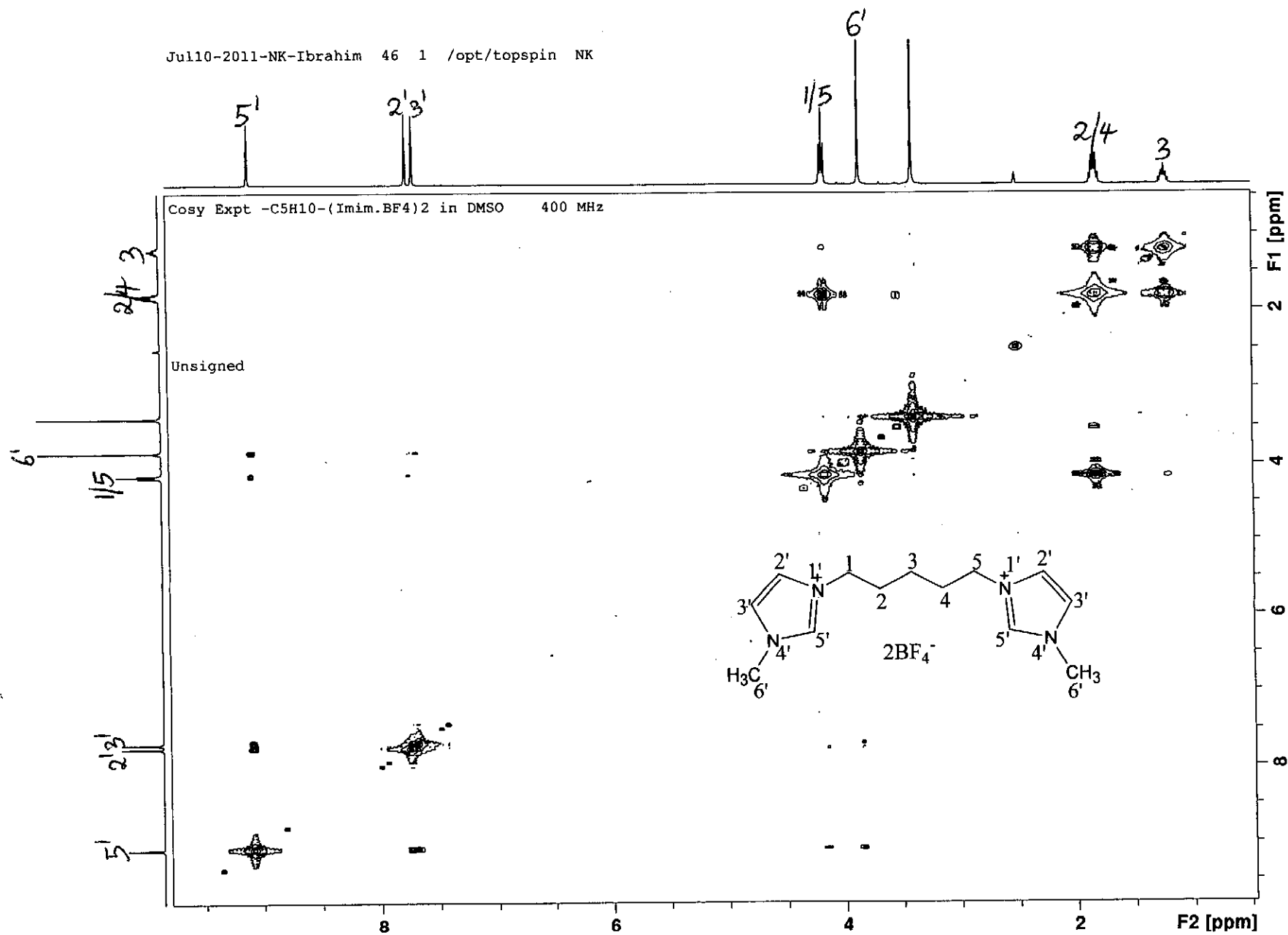
Unsigned

Jul10-2011-NK-Ibrahim 43 1 /opt/topspin NK



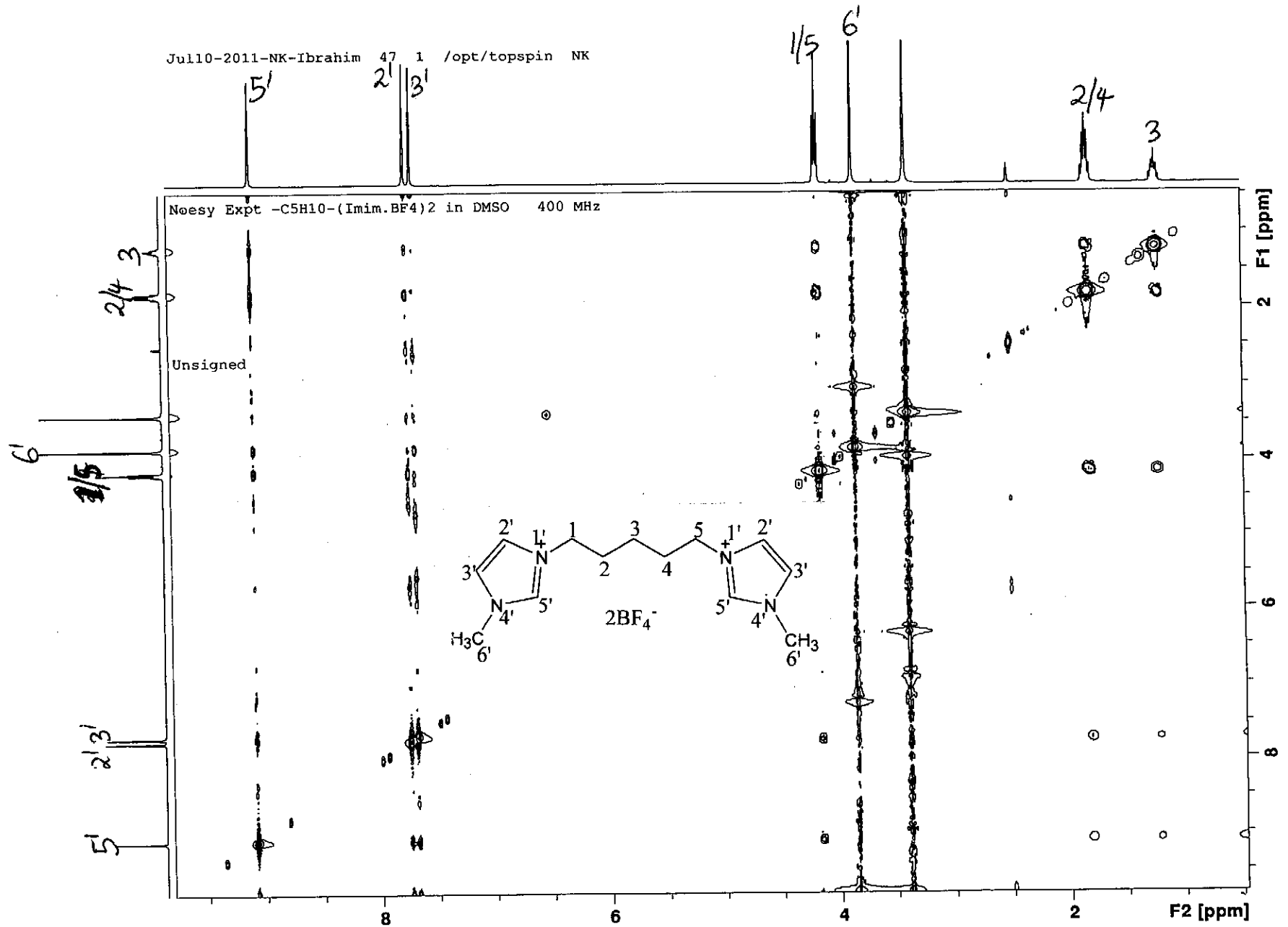
Dept 90 and 135 spectra of Compound C-4b

Jul10-2011-NK-Ibrahim 46 1 /opt/topspin NK



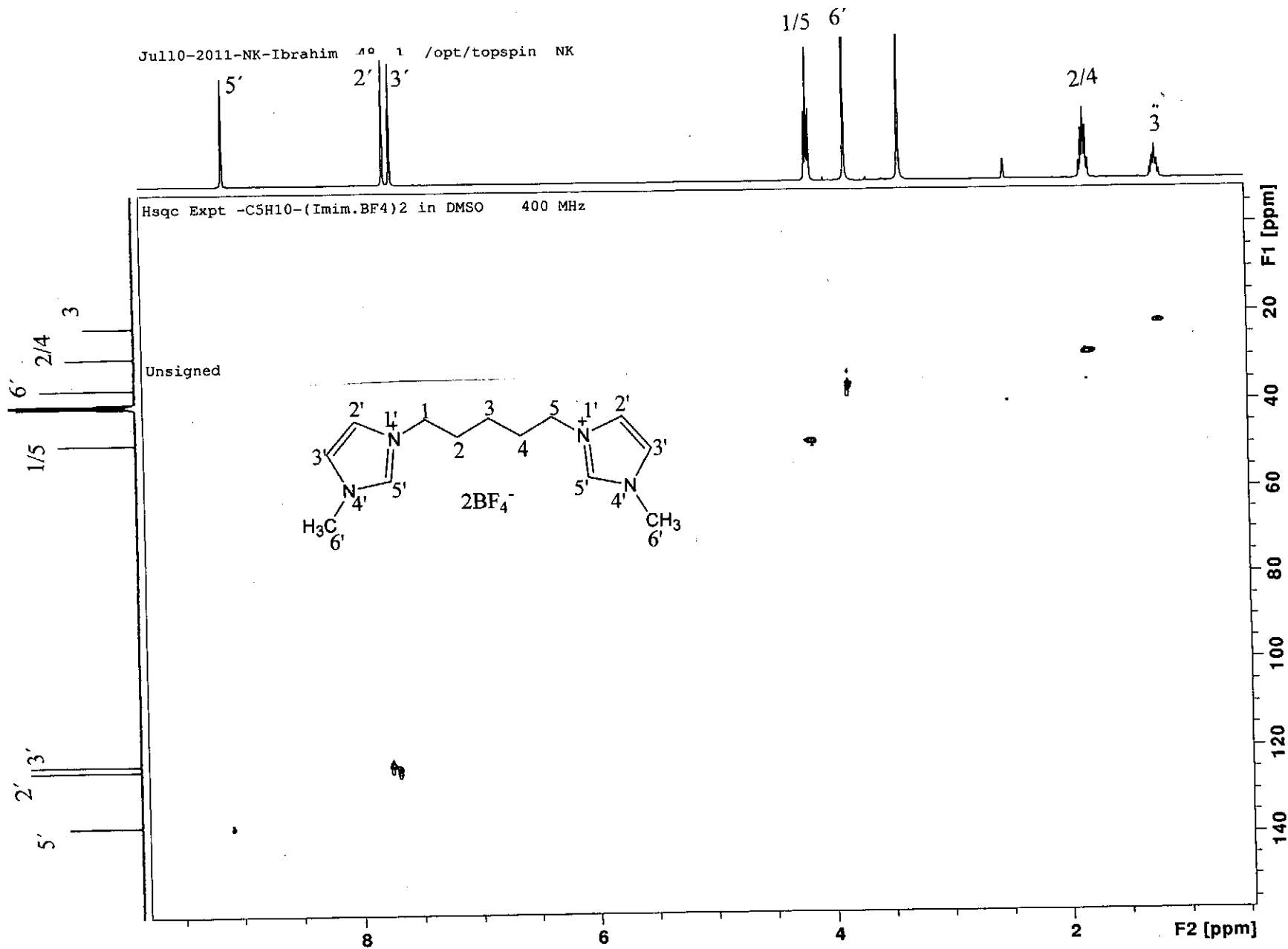
COSY spectrum of Compound C-4b

Jul10-2011-NK-Ibrahim 47 1 /opt/topspin NK



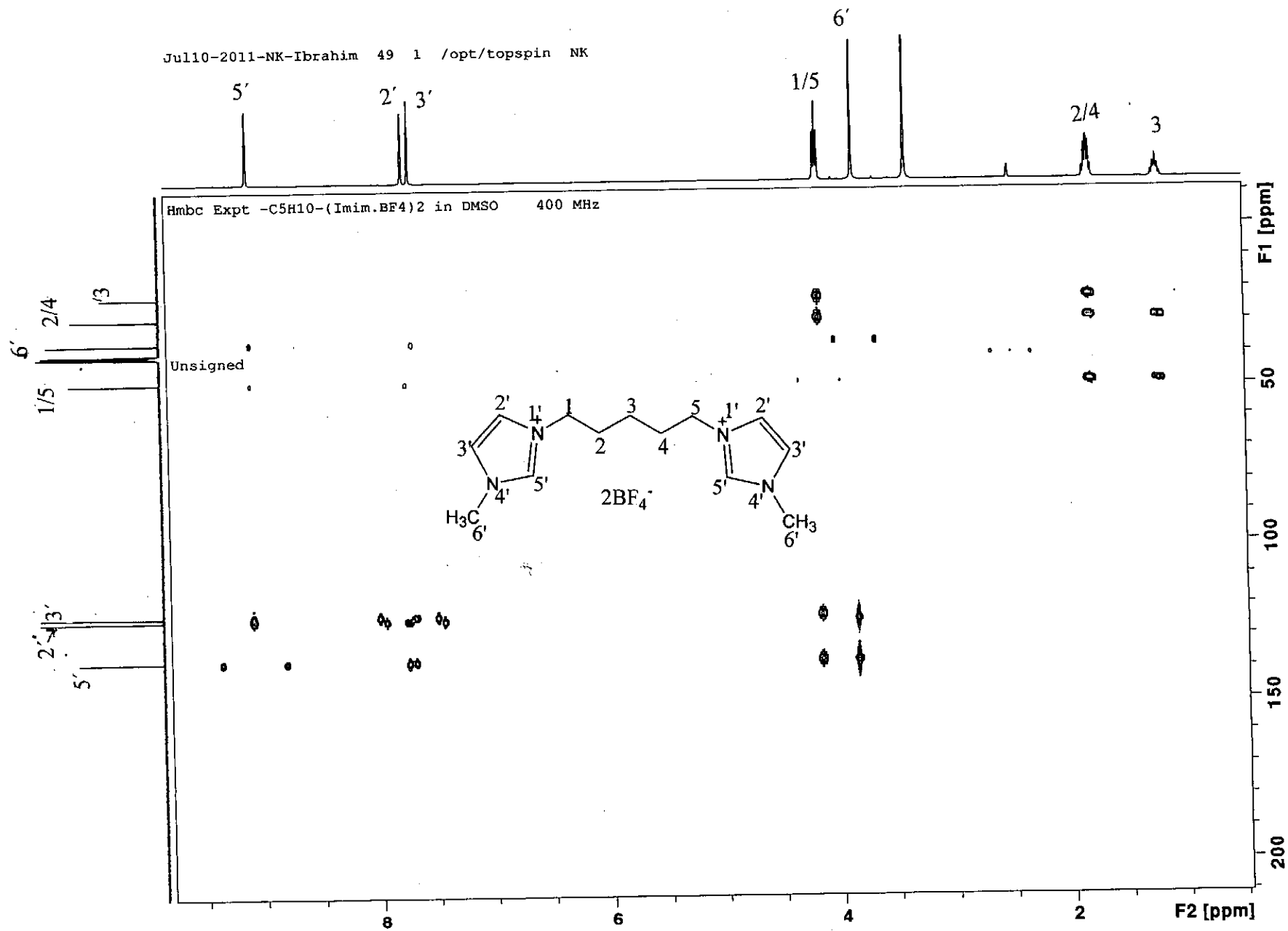
NOESY spectrum of Compound C-4b

Jul10-2011-NK-Ibrahim 40 1 /opt/topspin NK



HSQC spectrum of Compound C-4b

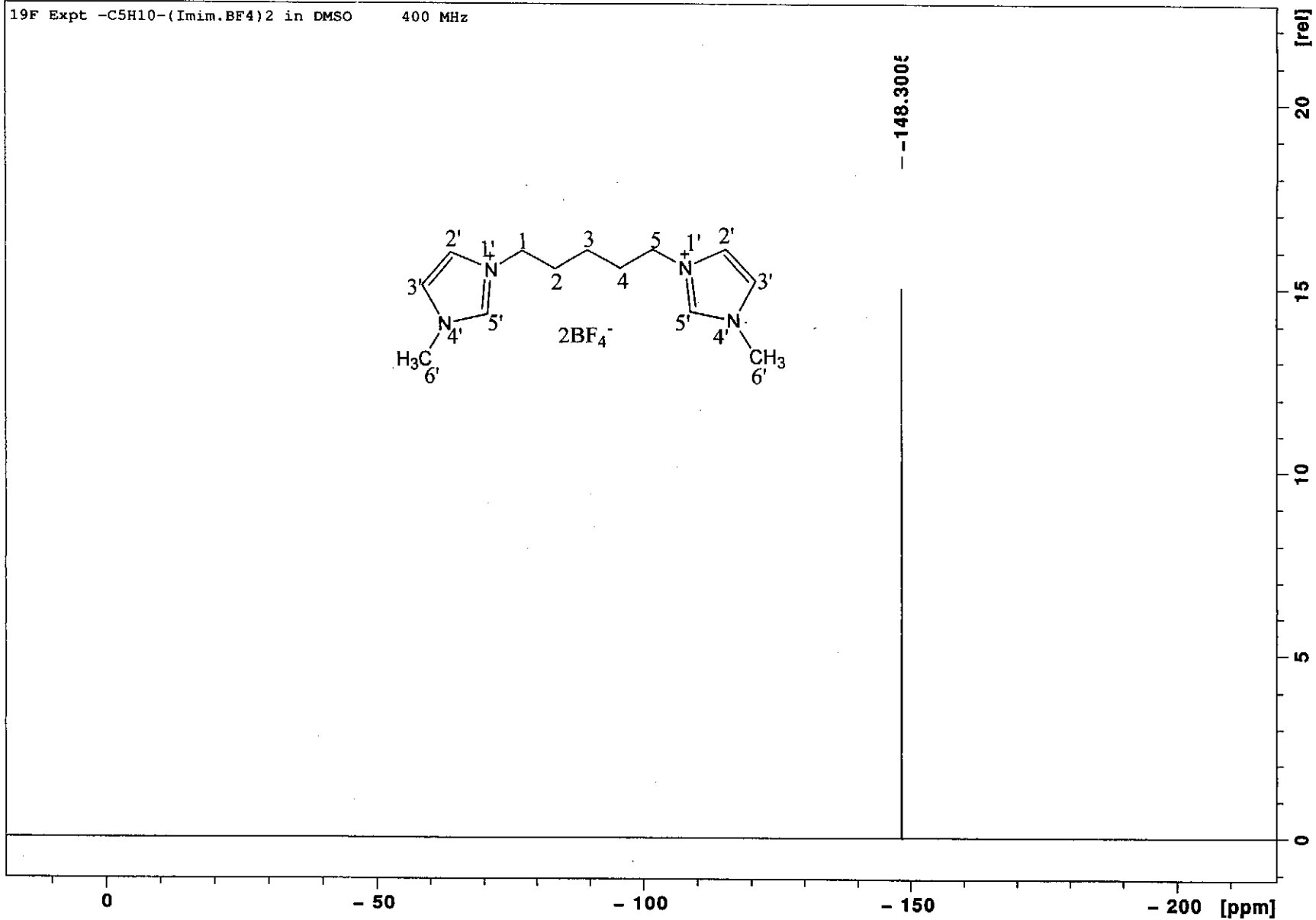
Jul10-2011-NK-Ibrahim 49 1 /opt/topspin NK



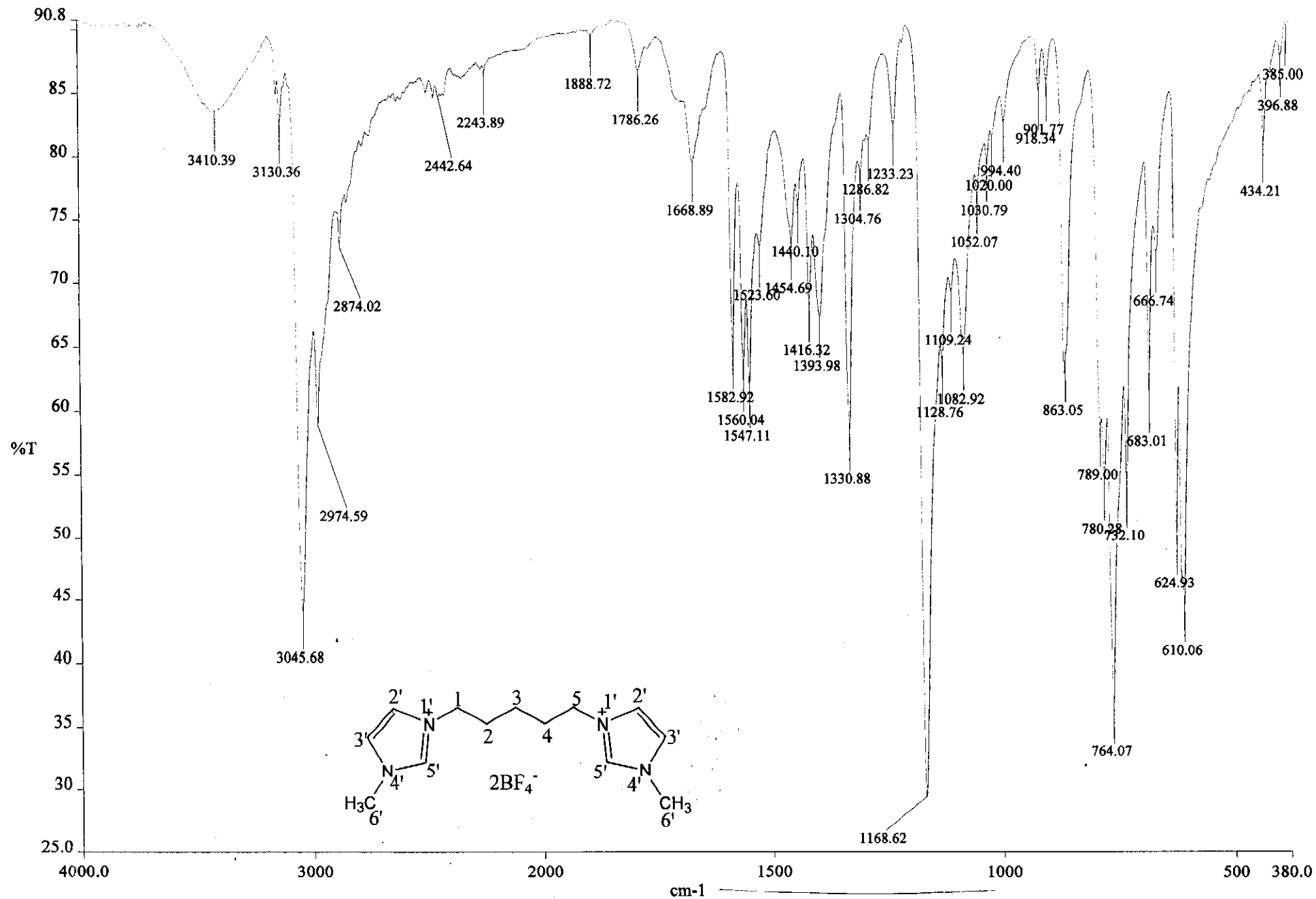
HMBC spectrum of Compound C-4b

Jul10-2011-NK-Ibrahim 44 1 /opt/topspin NK

19F Expt -C5H10-(Imim.BF4)2 in DMSO 400 MHz



^{19}F NMR spectrum of Compound C-4b

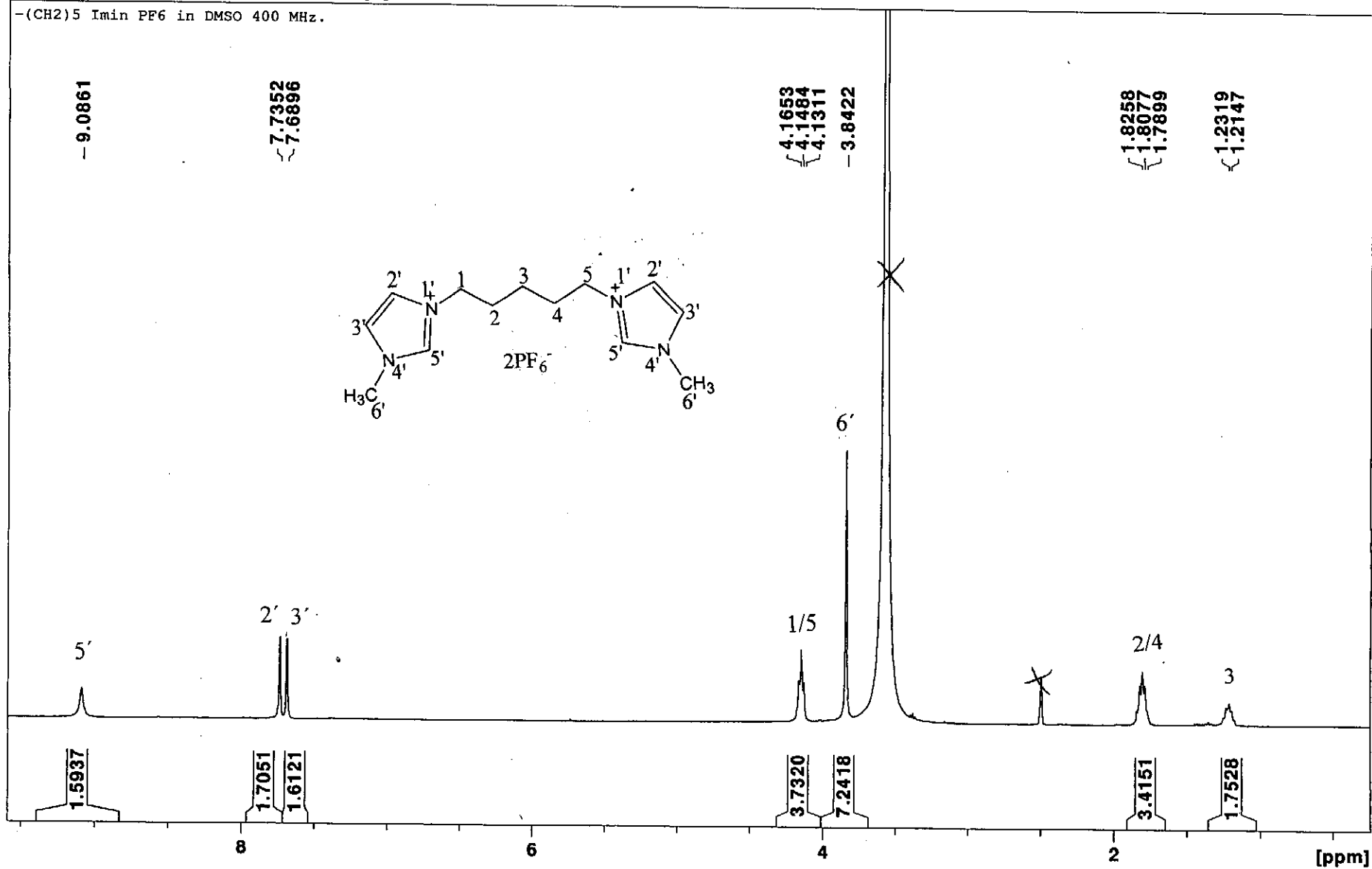


c:\pel_data\spectra\brahim\brahim.002 - Methylenebis-3-methylimidazolium dibromide

IR spectrum of Compound C-4b

Aug21-2012-NK-Ibrahim 10 1 /opt/topspin NK

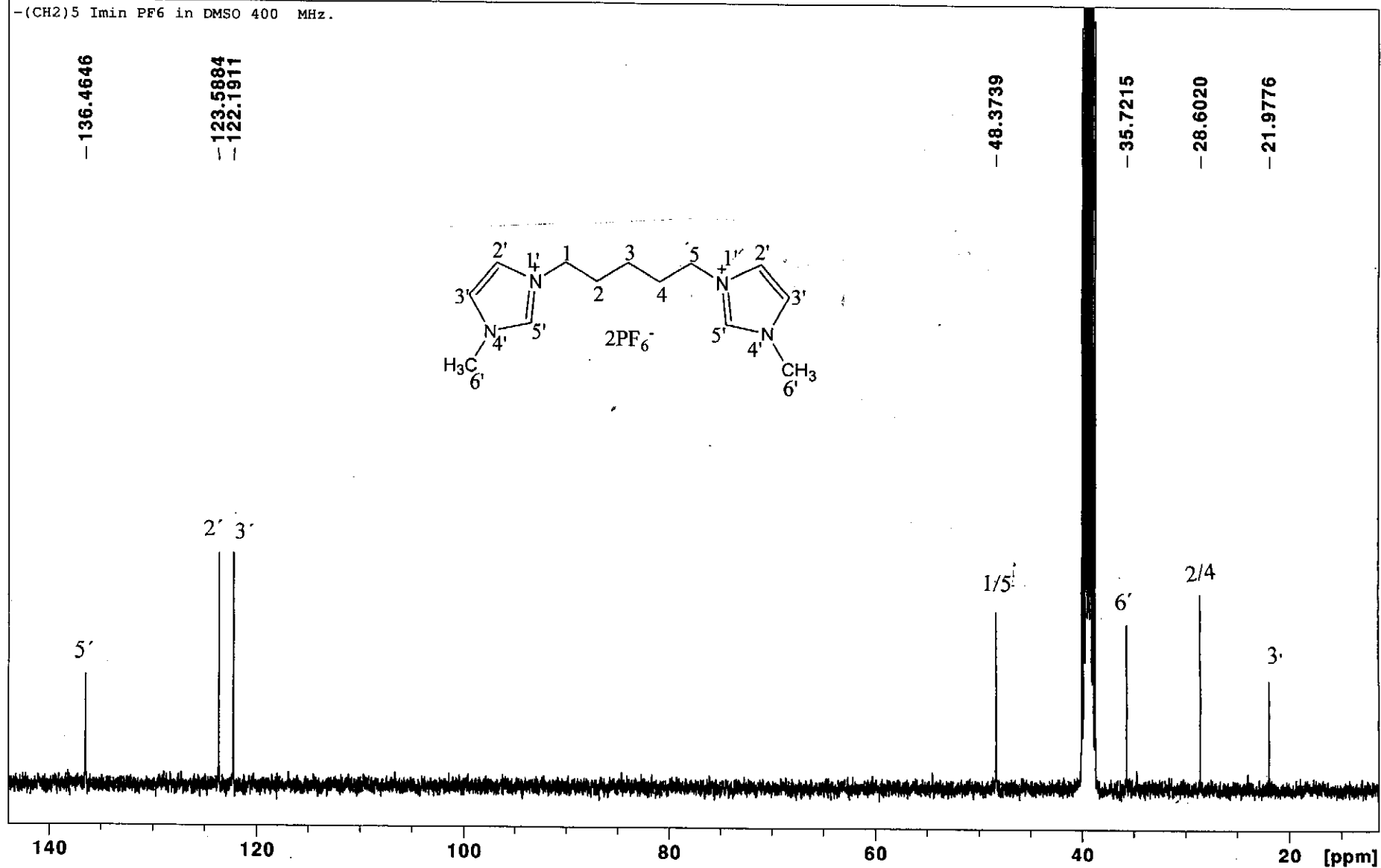
-(CH₂)₅ Imin PF₆ in DMSO 400 MHz.



¹H NMR spectrum of Compound C-4c

Aug21-2012-NK-Ibrahim 13 1 /opt/topspin NK

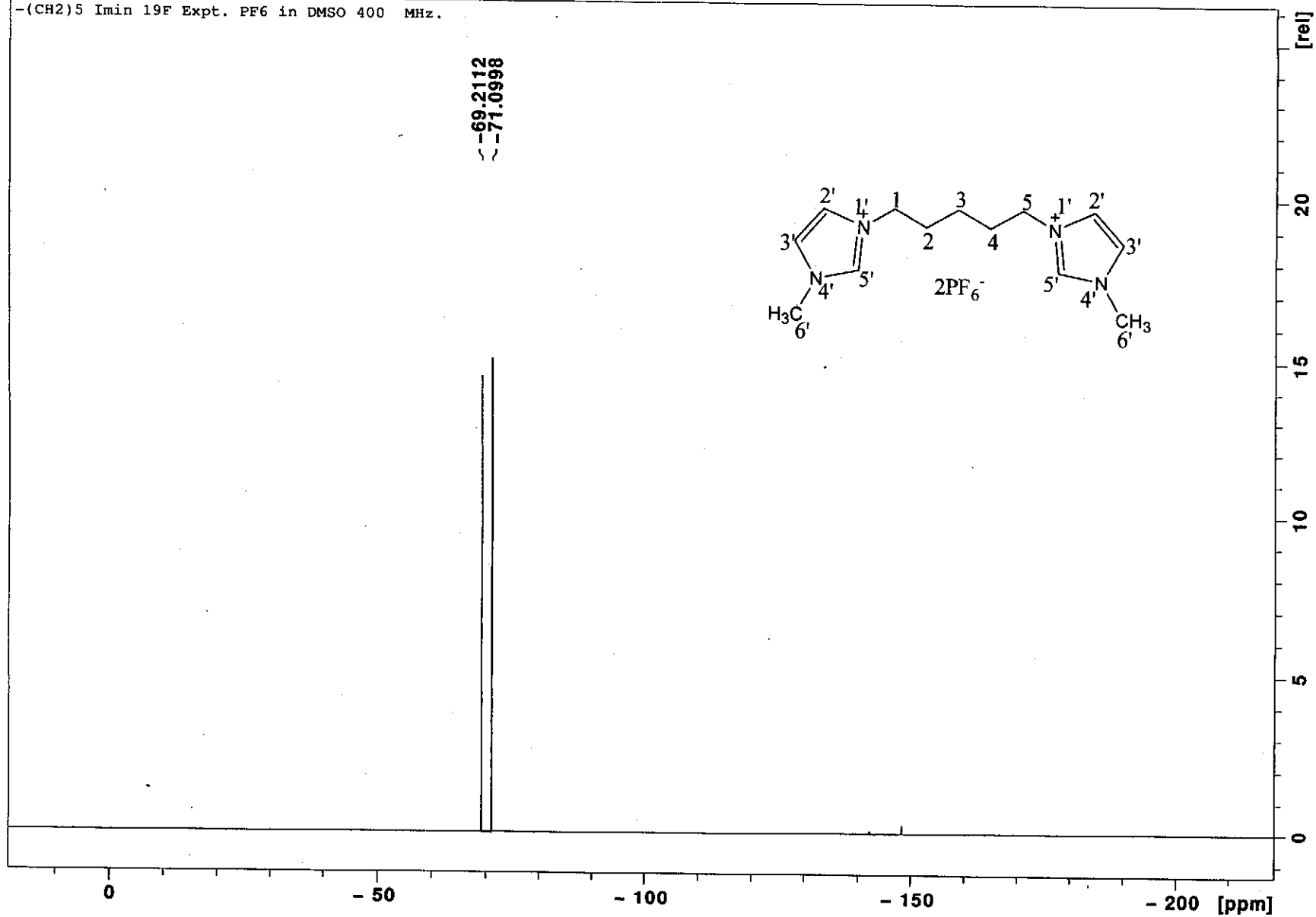
-(CH₂)₅ Imin PF₆ in DMSO 400 MHz.



¹³C NMR spectrum of Compound C-4c

Aug21-2012-NK-Ibrahim 12 1 /opt/topspin NK

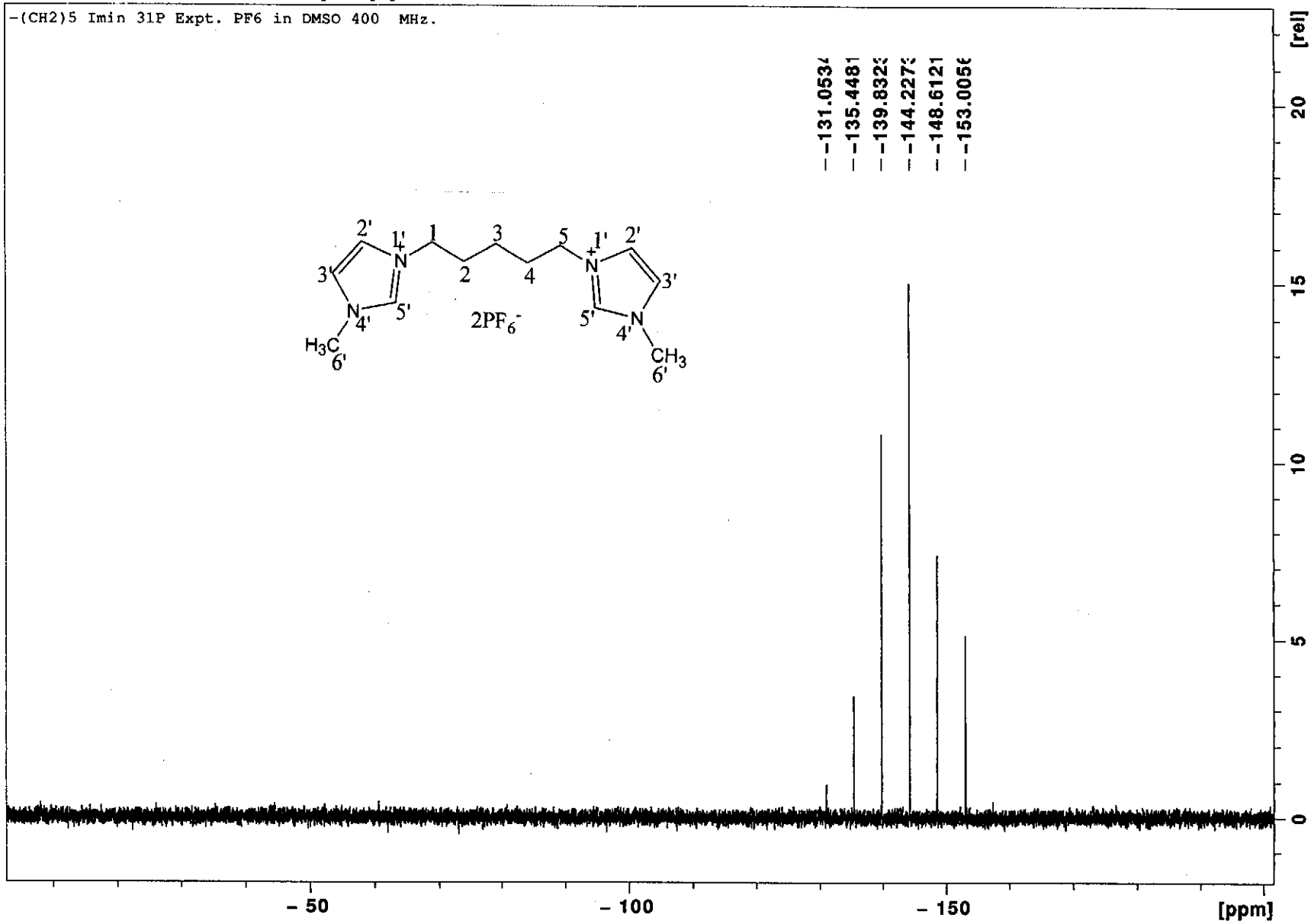
-(CH2)5 Imin 19F Expt. PF6 in DMSO 400 MHz.



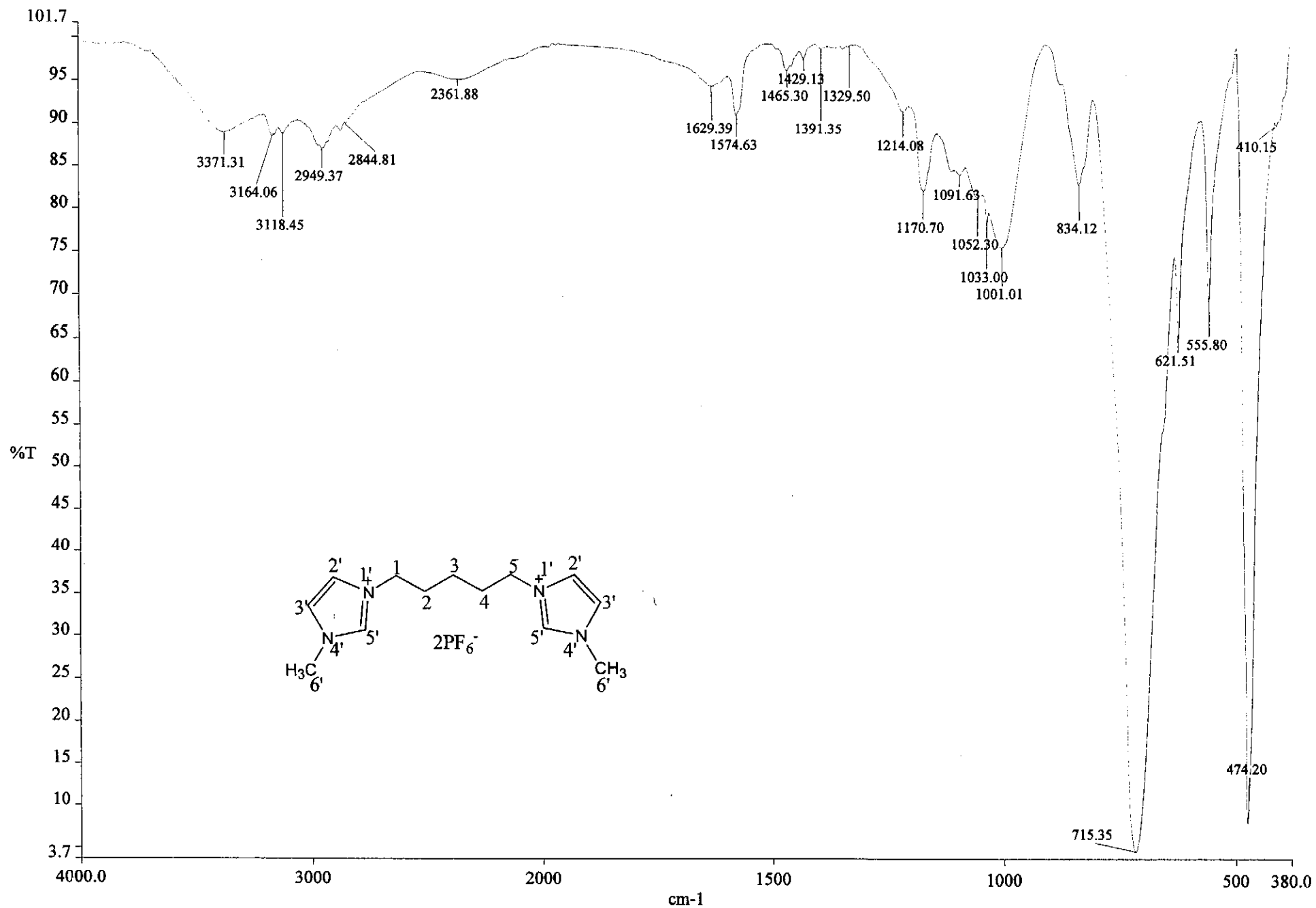
¹⁹F NMR spectrum of Compound C-4c

Aug21-2012-NK-Ibrahim 11 1 /opt/topspin NK

-(CH₂)₅ Imin 31P Expt. PF₆ in DMSO 400 MHz.



³¹P NMR spectrum of Compound C-4c

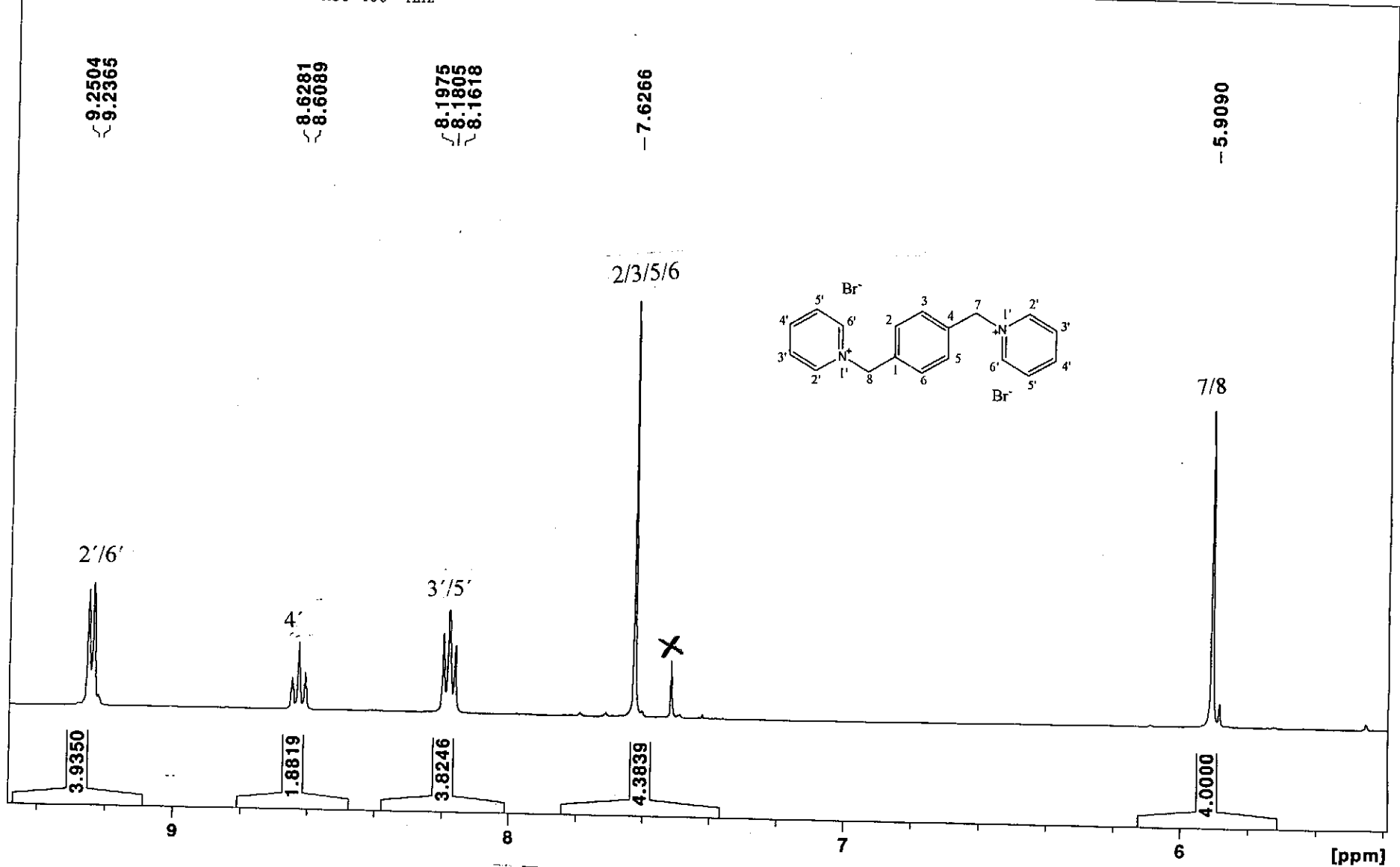


c:\pel_data\spectra\-(ch2)5-imin 2pf6.002 - White solid

IR spectrum of Compound C-4c

Jul22-2012-NK-Ibrahim 10 1 /opt/topspin NK

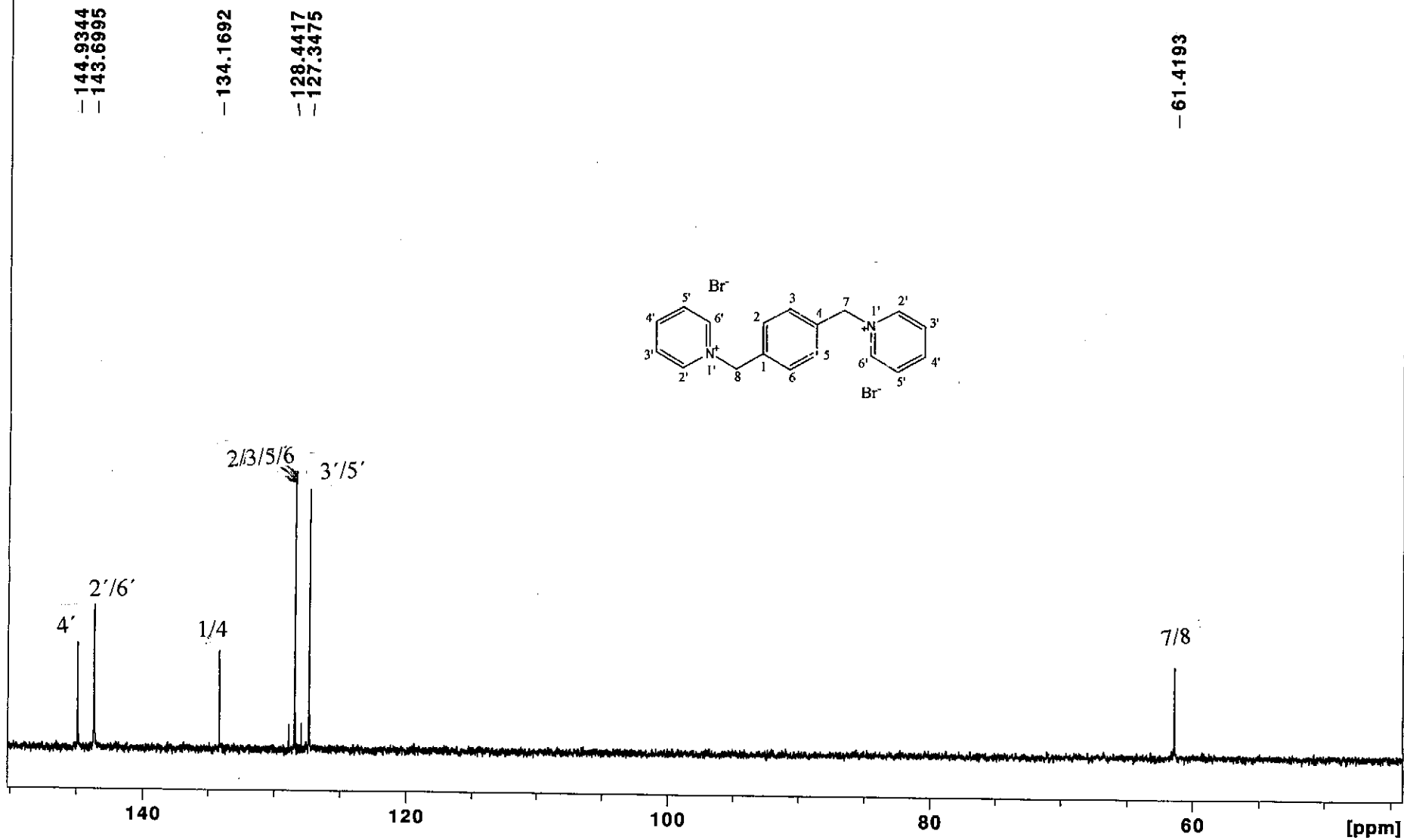
Pyridine+pxylene dibromide in DMSO 400 MHz



¹H NMR spectrum of Compound D-1a

Jul22-2012-NK-Ibrahim 11 1 /opt/topspin NK

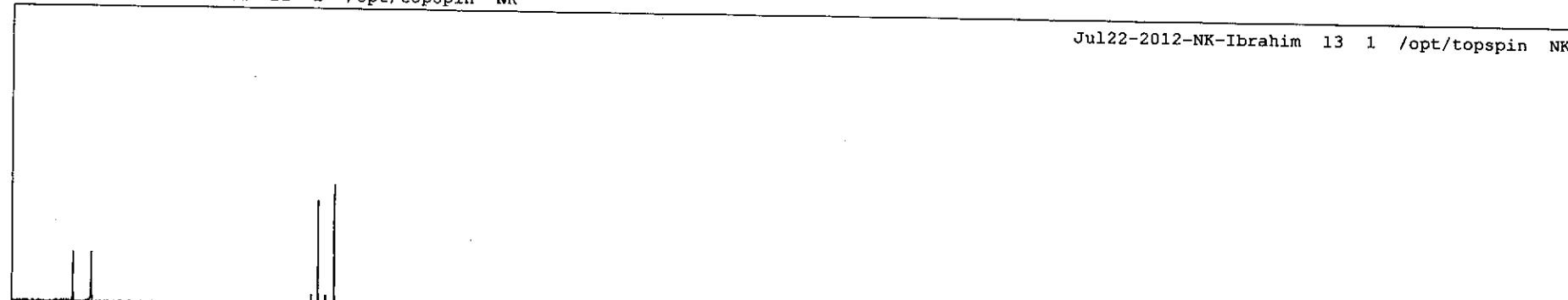
Pyridine+pxylene dibromide in DMSO 400 MHz



^{13}C NMR spectrum of Compound D-1a

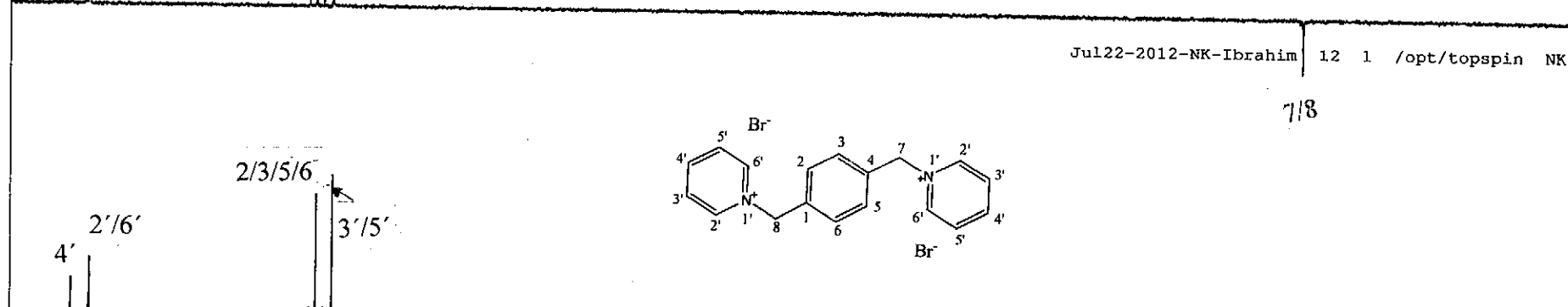
Jul22-2012-NK-Ibrahim 11 1 /opt/topspin NK

Jul22-2012-NK-Ibrahim 13 1 /opt/topspin NK

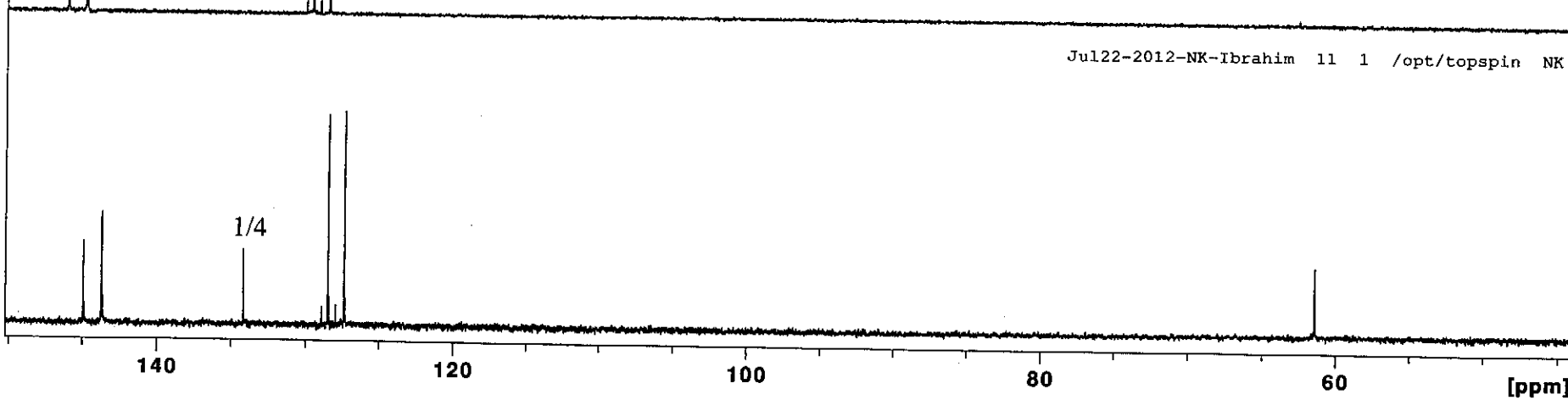


Jul22-2012-NK-Ibrahim 12 1 /opt/topspin NK

718

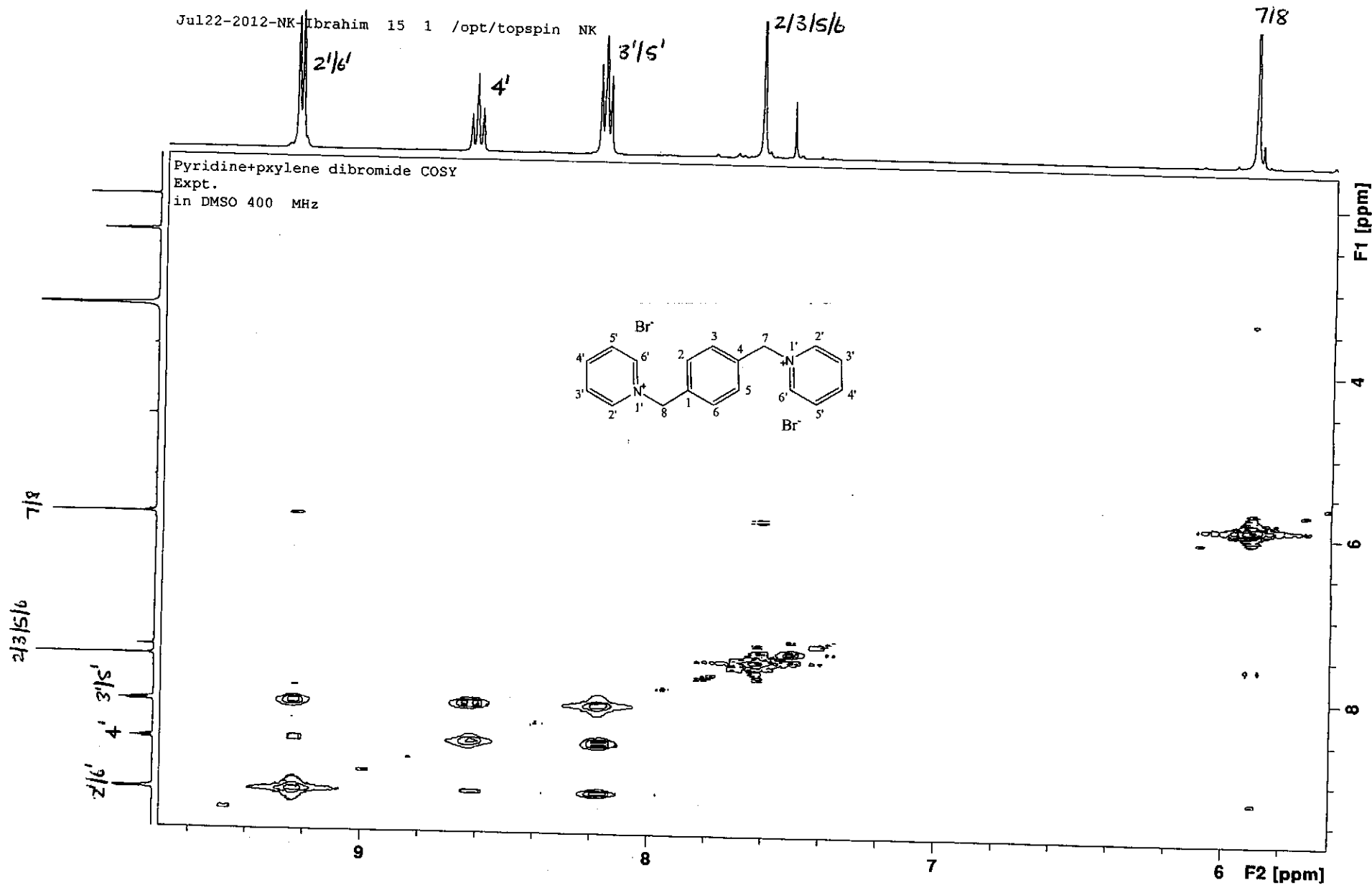


Jul22-2012-NK-Ibrahim 11 1 /opt/topspin NK



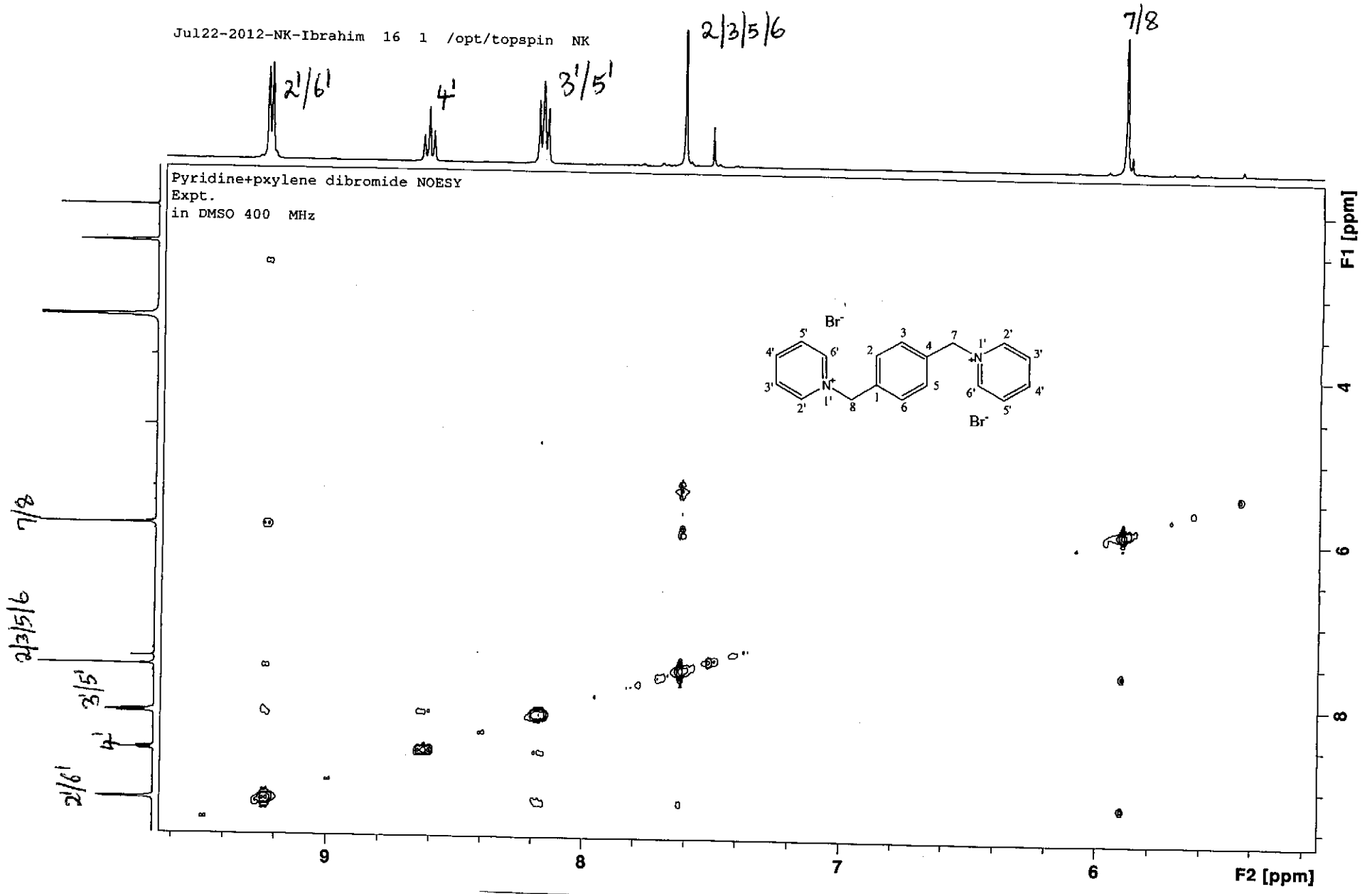
Dept 90 and 135 spectra of Compound D-1a

Jul22-2012-NK-Ibrahim 15 1 /opt/topspin NK

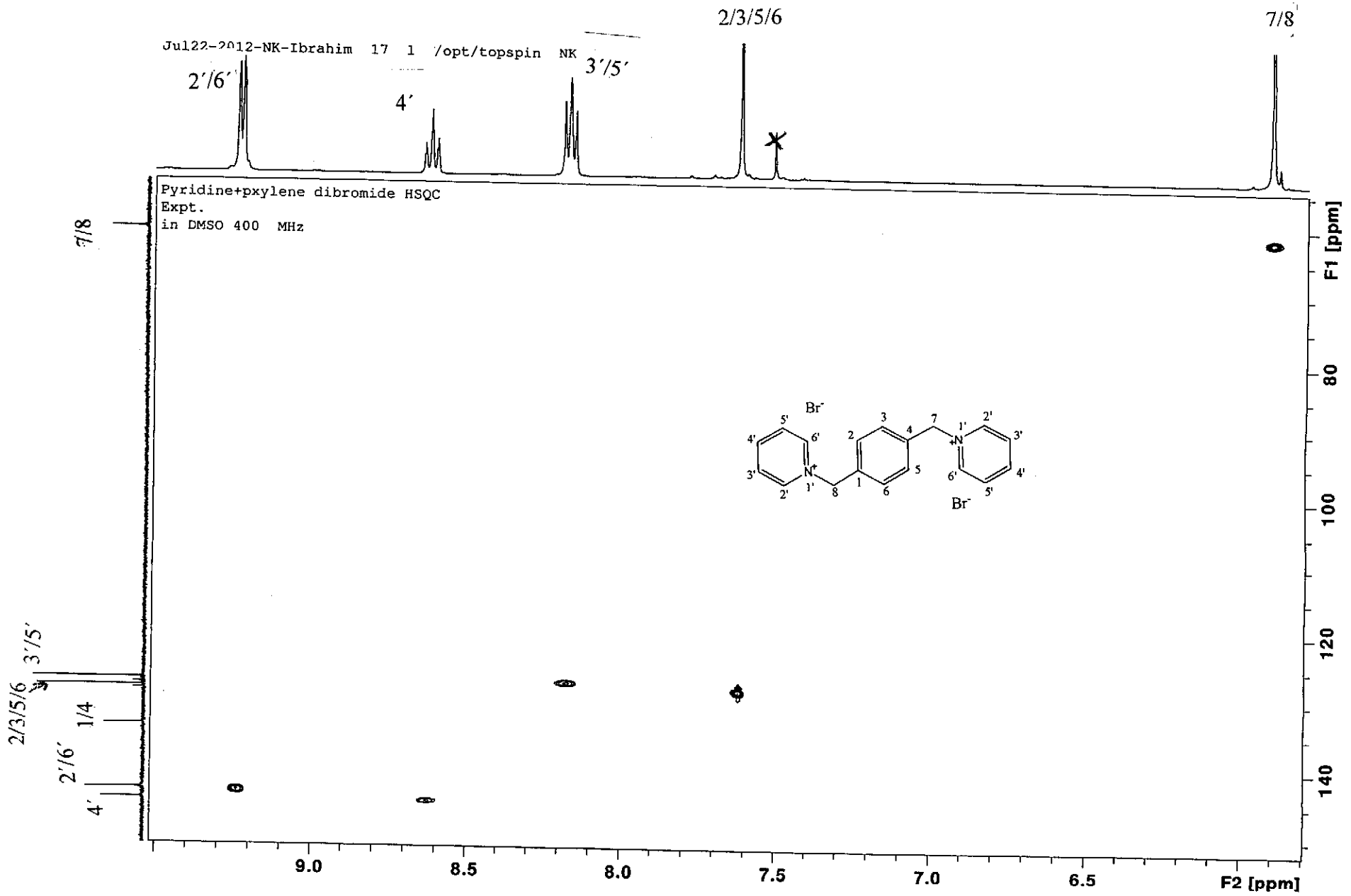


COSY spectrum of Compound D-1a

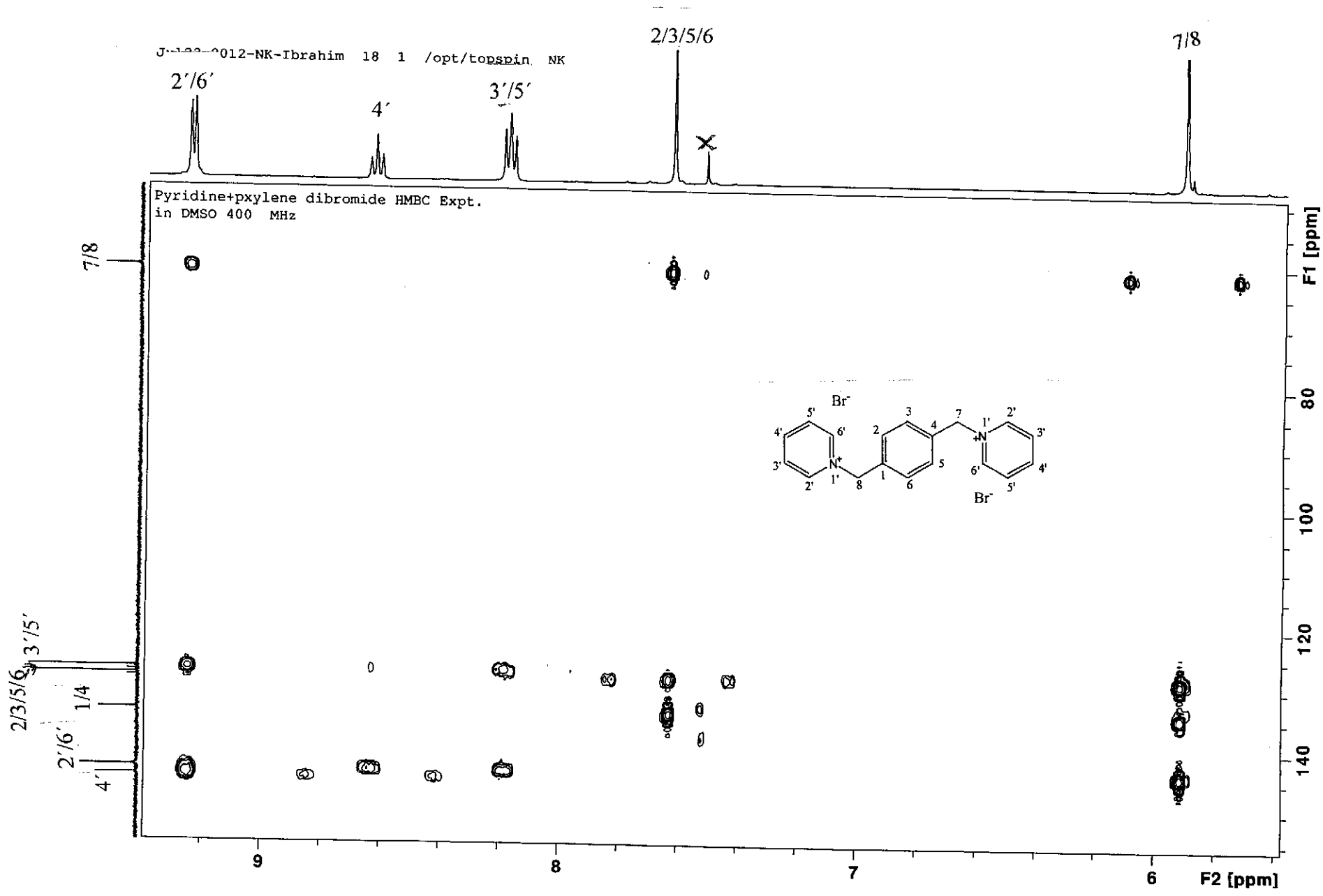
Jul22-2012-NK-Ibrahim 16 1 /opt/topspin NK



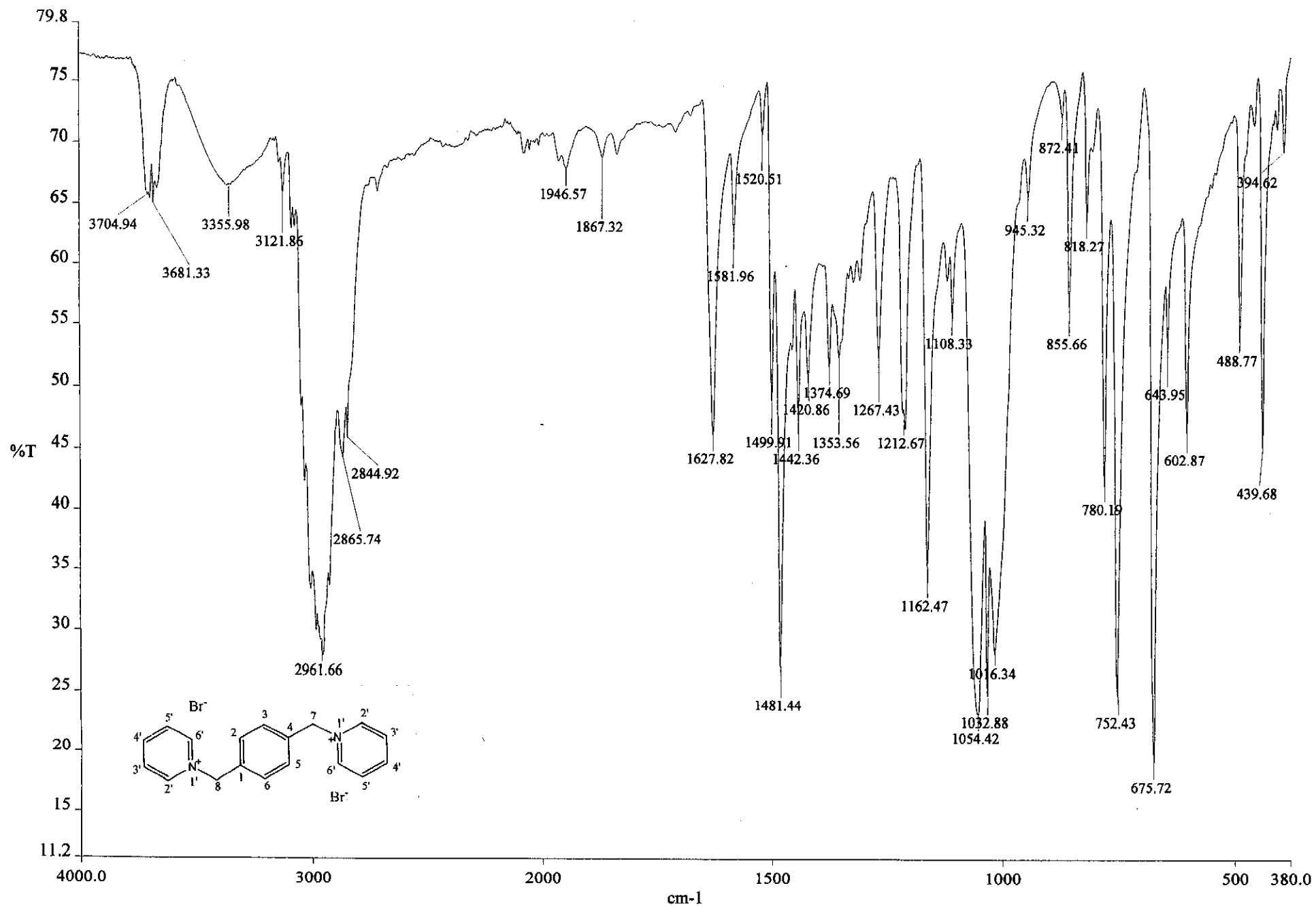
NOESY spectrum of Compound D-1a



HSQC spectrum of Compound D-1a



HMBC spectrum of Compound D-1a

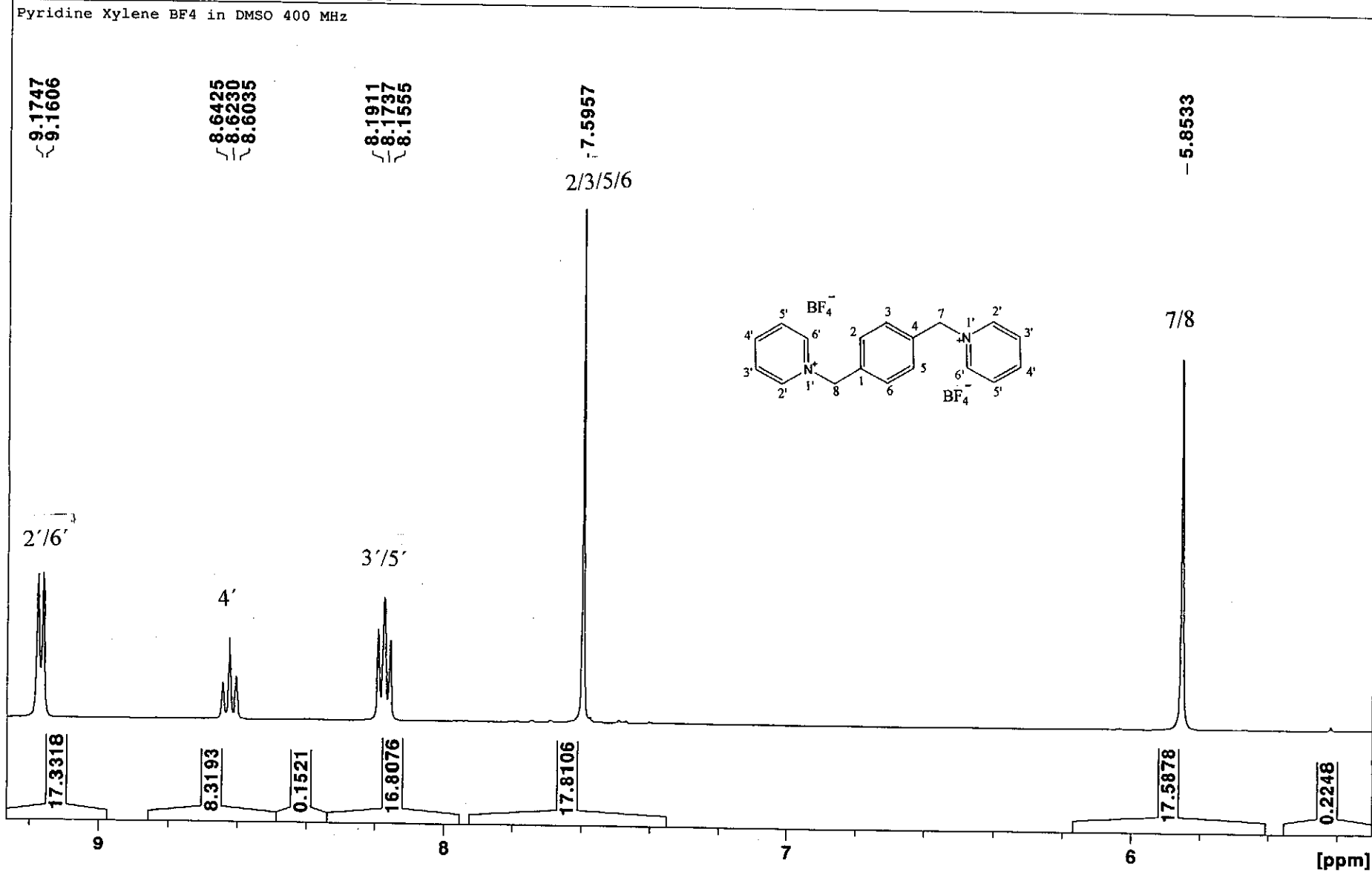


c:\pel_data\spectra\ch2)2c6h4py2br2.002 - White sample

IR spectrum of Compound D-1a

Sep08-2012-NK_Ibrahim 10 1 /opt/topspin NK

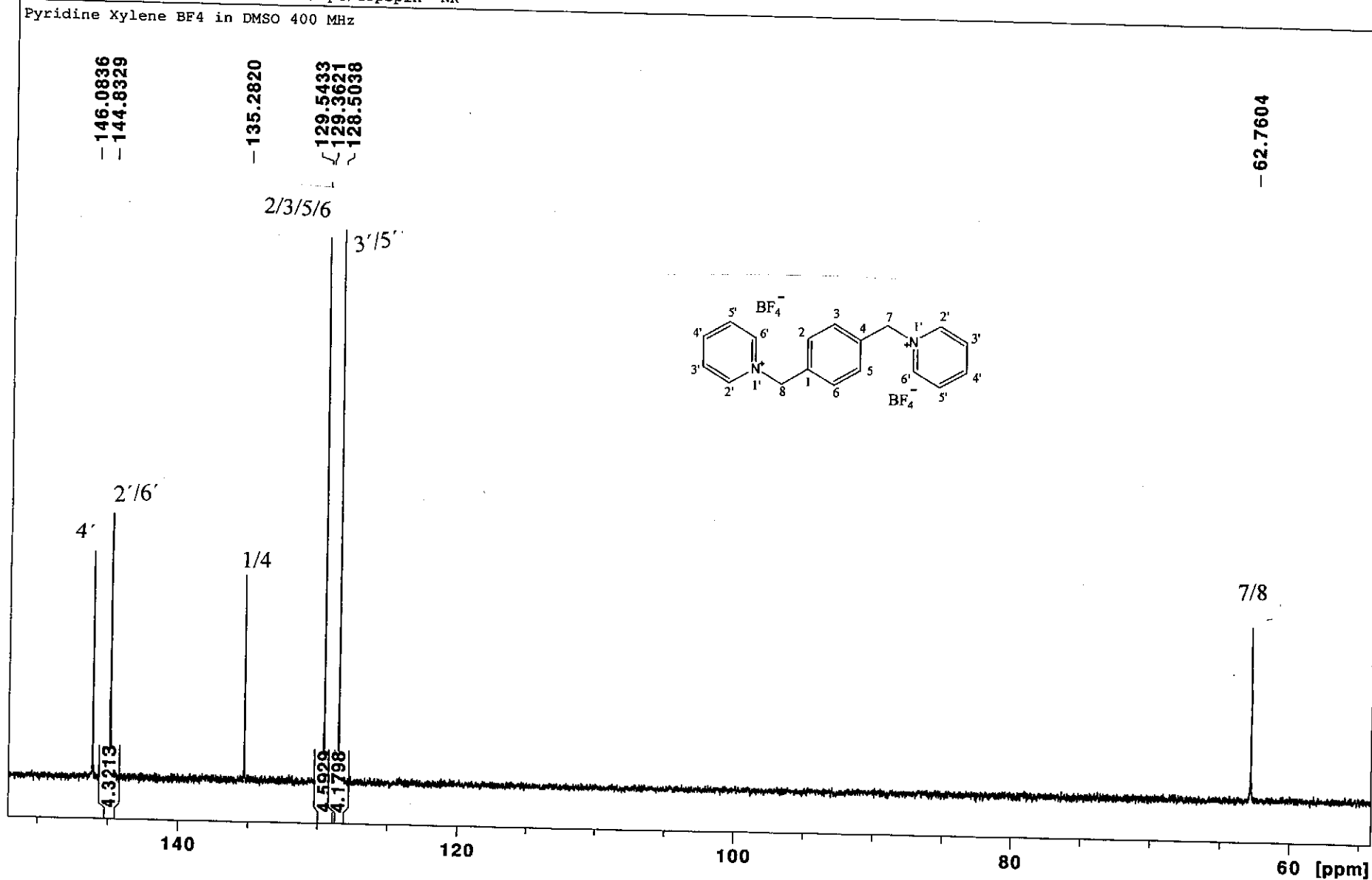
Pyridine Xylene BF4 in DMSO 400 MHz



¹H NMR spectrum of Compound D-1b

Sep08-2012-NK_Ibrahim 11 1 /opt/topspin NK

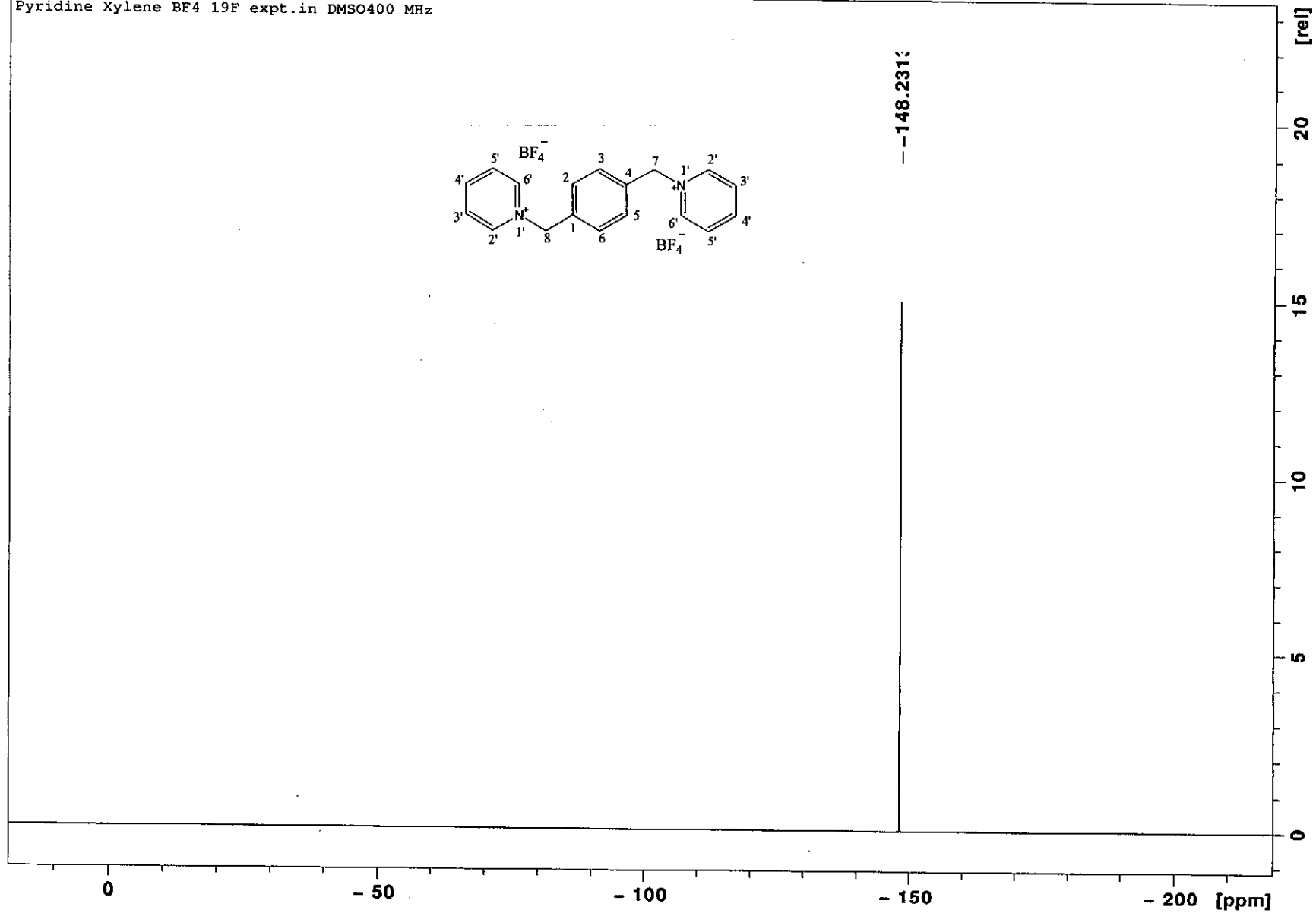
Pyridine Xylene BF4 in DMSO 400 MHz



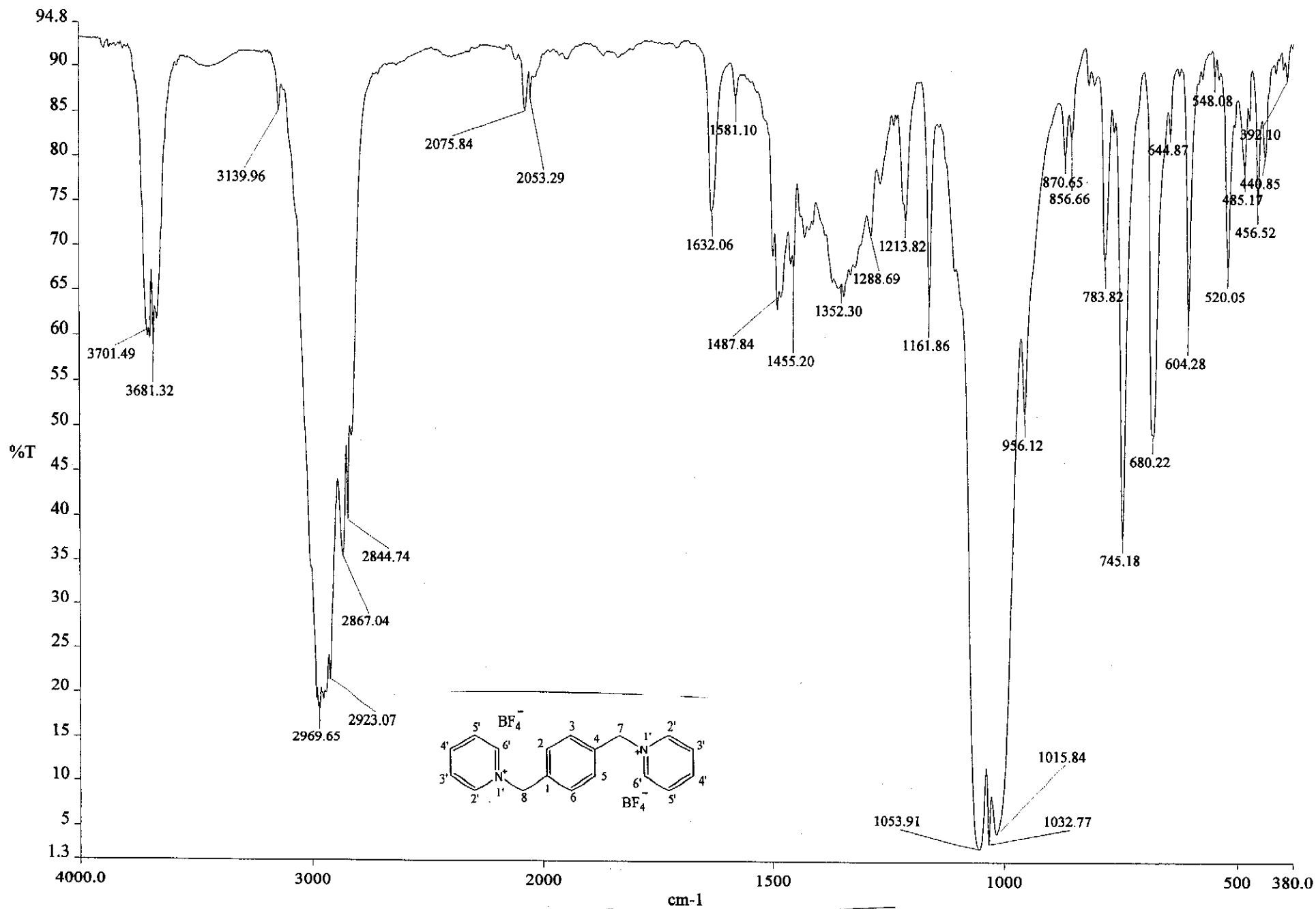
¹³C NMR spectrum of Compound D-1b.

Sep08-2012-NK_Ibrahim 14 1 /opt/topspin NK

Pyridine Xylene BF4 19F expt.in DMSO400 MHz



^{19}F NMR spectrum of Compound D-1b

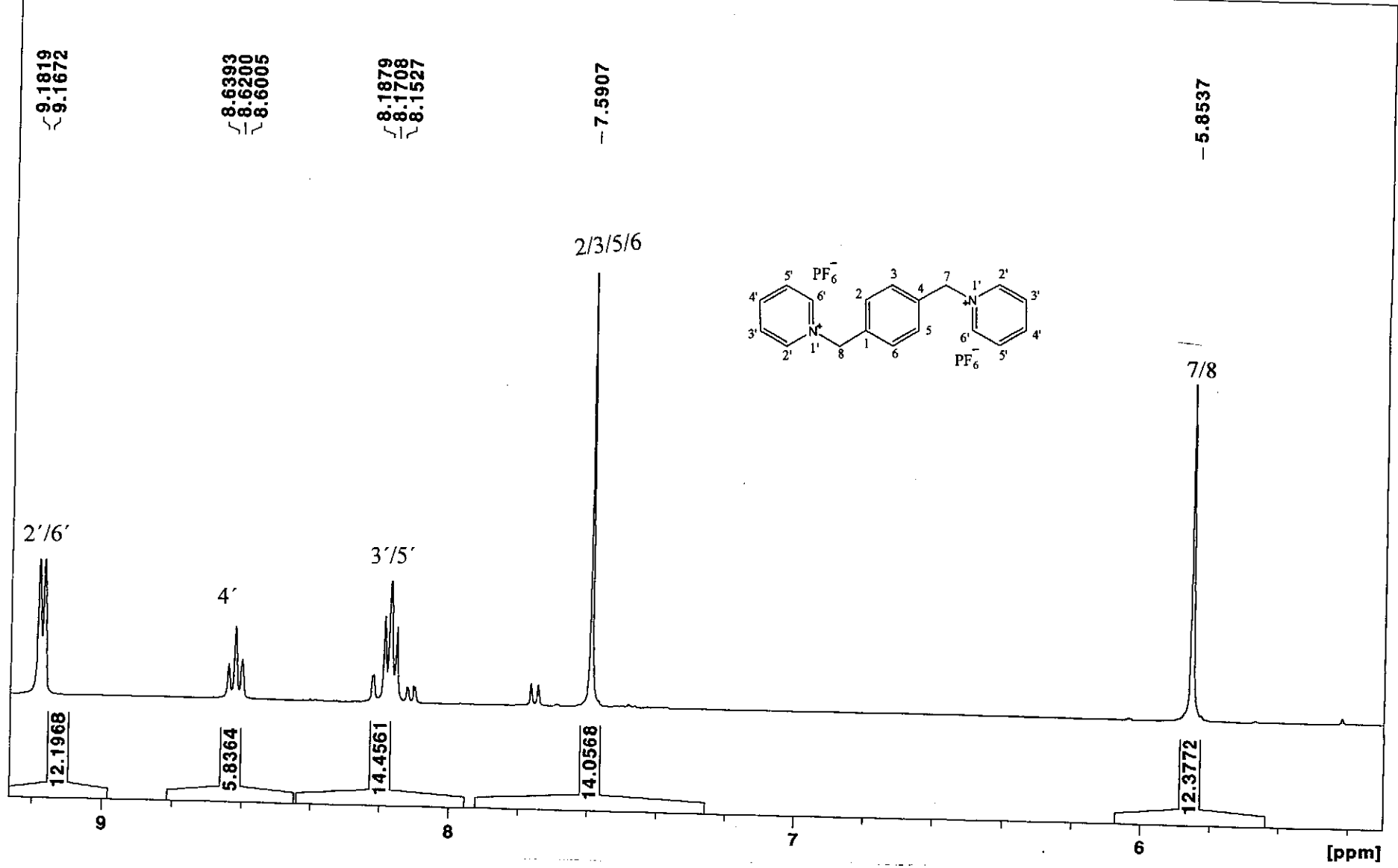


c:\pel_data\spectra\ch2)2c6h4py2(bf4)2.002 - White sample

IR spectrum of Compound D-1b

Sep08-2012-NK-Ibrahim 10 1 /opt/topspin NK

Pyridine p-xylene PF6 in DMSO 400 MHz



¹H NMR spectrum of Compound D-1c

Sep08-2012-NK-Ibrahim 11 1 /opt/topspin NK

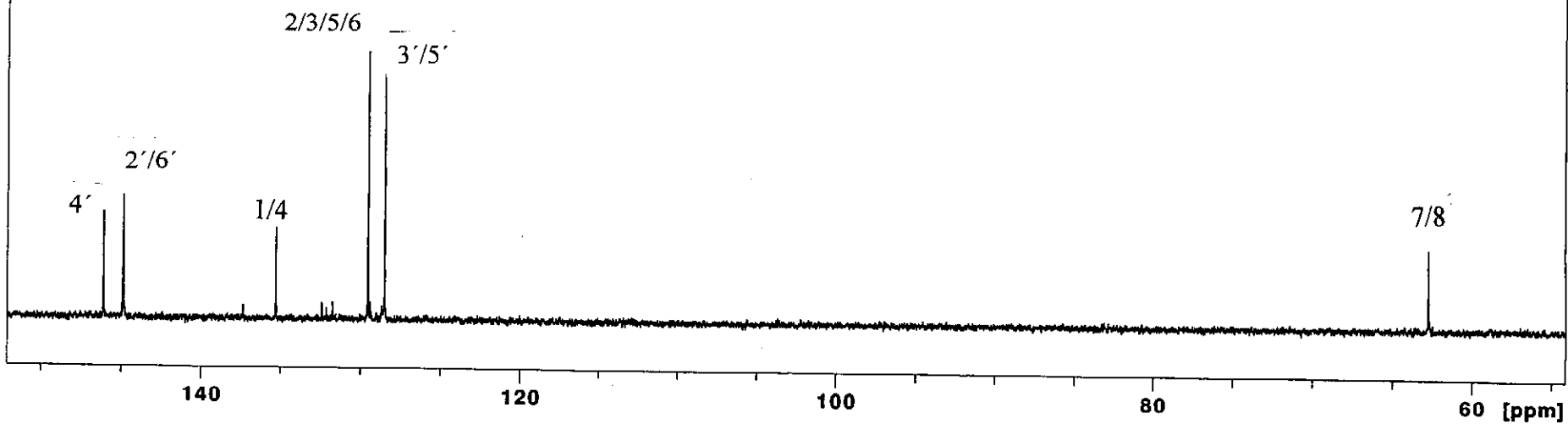
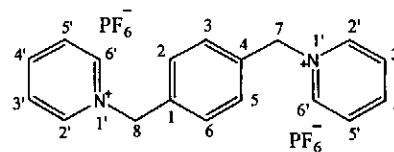
Pyridine p-xylene PF6 in DMSO 400 MHz

-146.0758
-144.8418

-135.2899

-129.5288
-128.4972

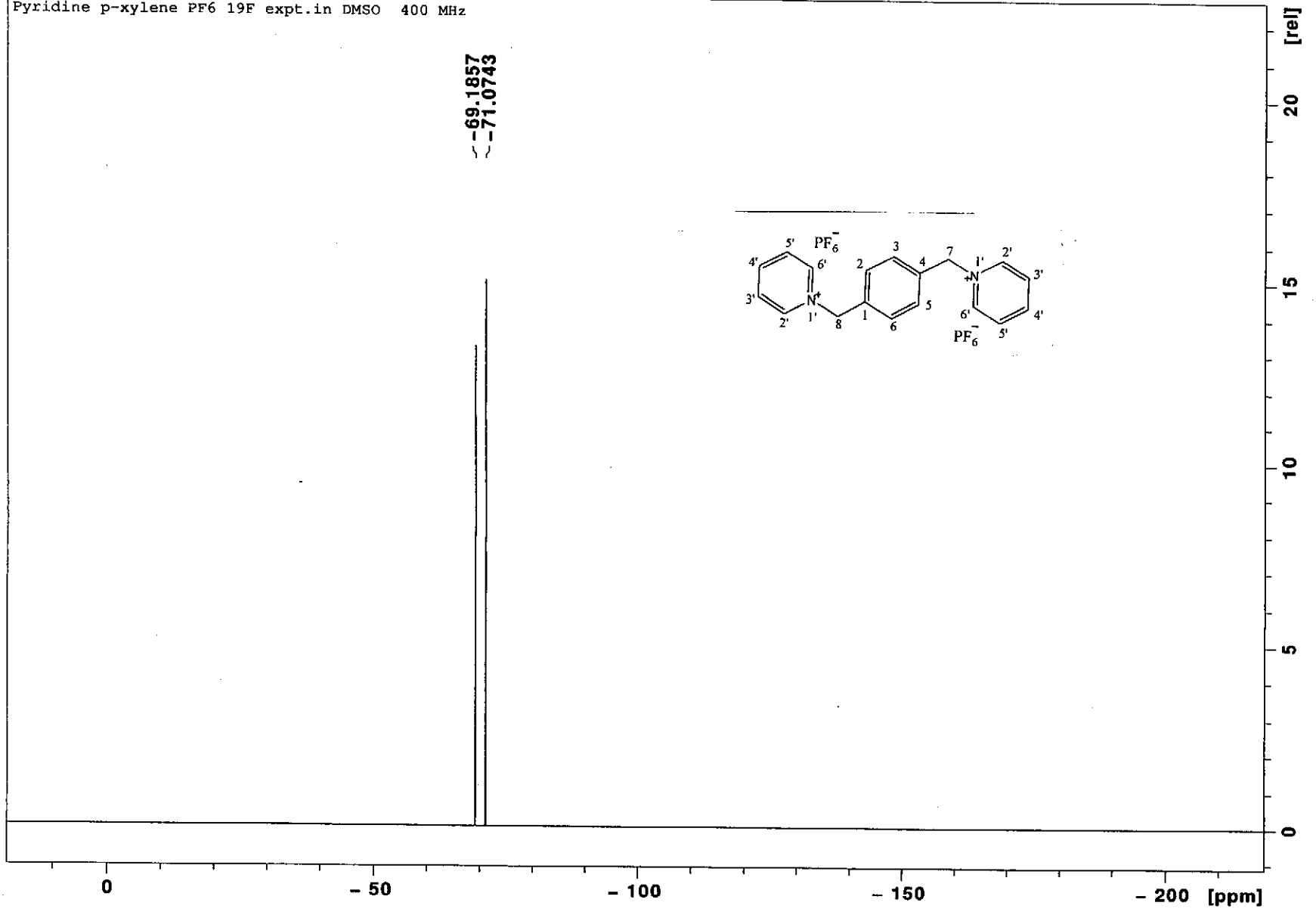
-62.7386



¹³C NMR spectrum of Compound D-1c

Sep08-2012-NK-Ibrahim 14 1 /opt/topspin NK

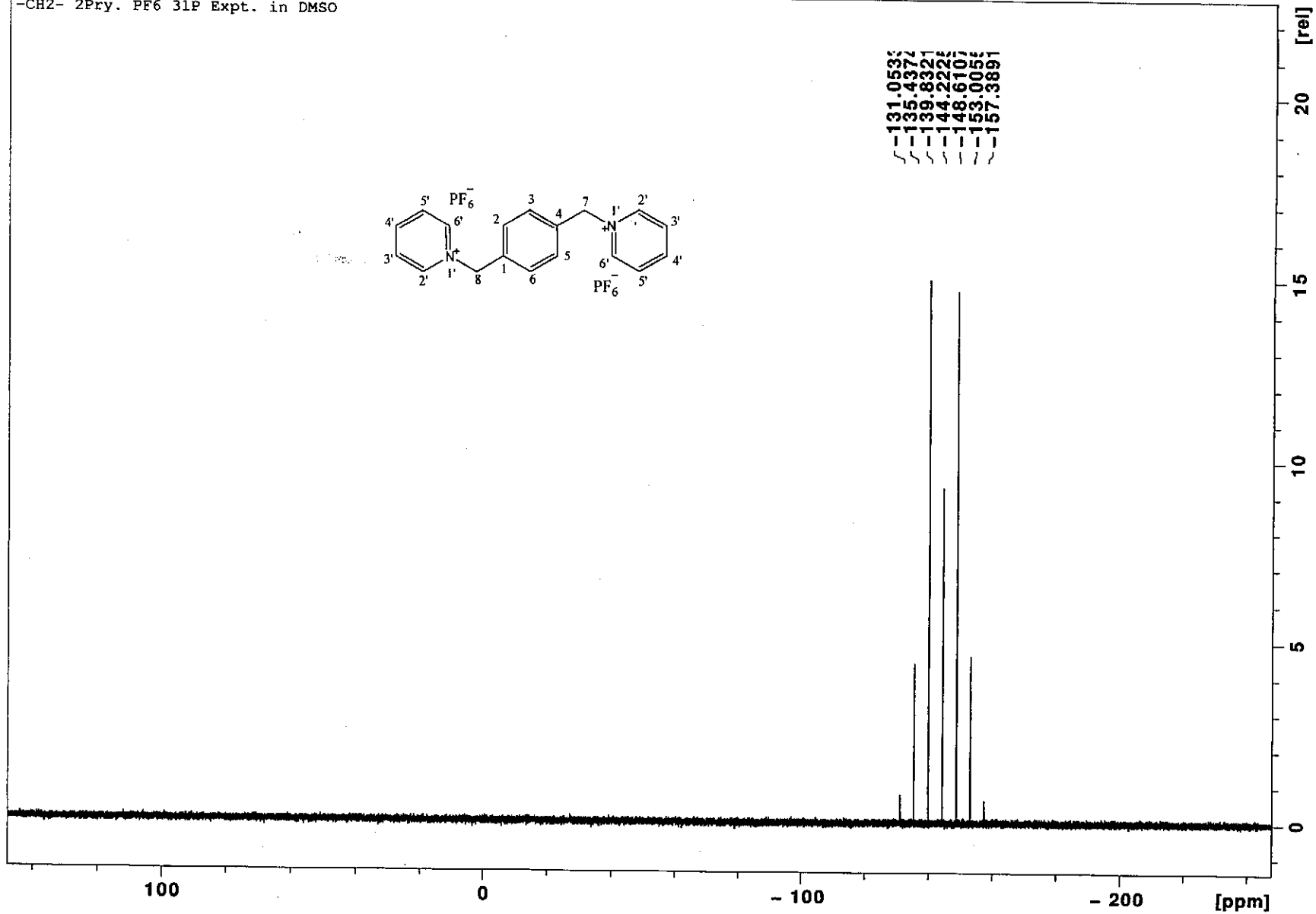
Pyridine p-xylene PF6 19F expt.in DMSO 400 MHz



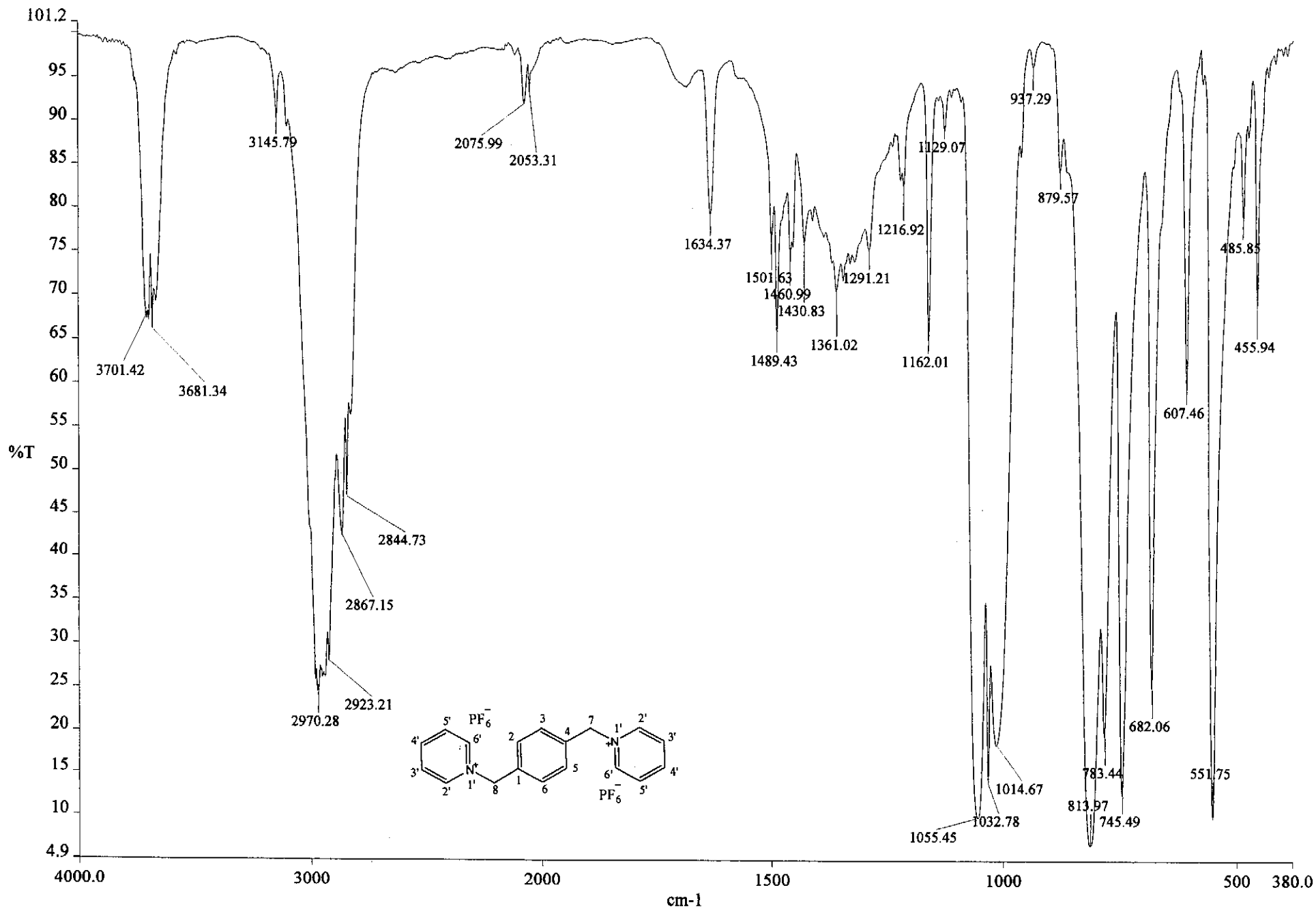
^{19}F NMR spectrum of Compound D-1c

Sep08-2012-NK-Ibrahim 35 1 /opt/topspin NK

-CH2- 2Pry. PF6 31P Expt. in DMSO



³¹P NMR spectrum of Compound D-1c

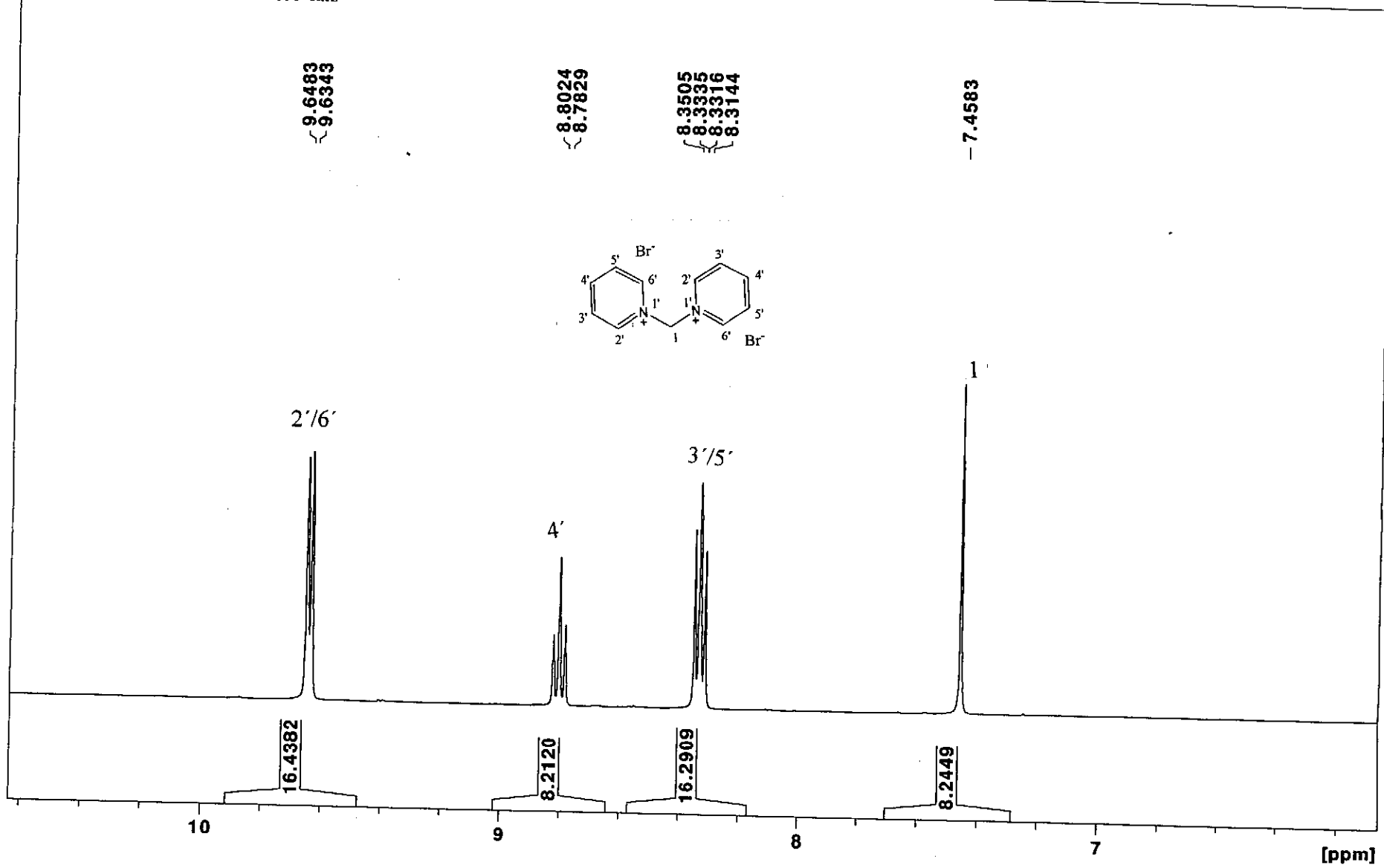


c:\pel_data\spectra\ch2)2c6h4py2(pf6)2.002 - White sample

IR spectrum of Compound D-1c

Jul23-2012-NK-Ibrahim 10 1 /opt/topspin NK

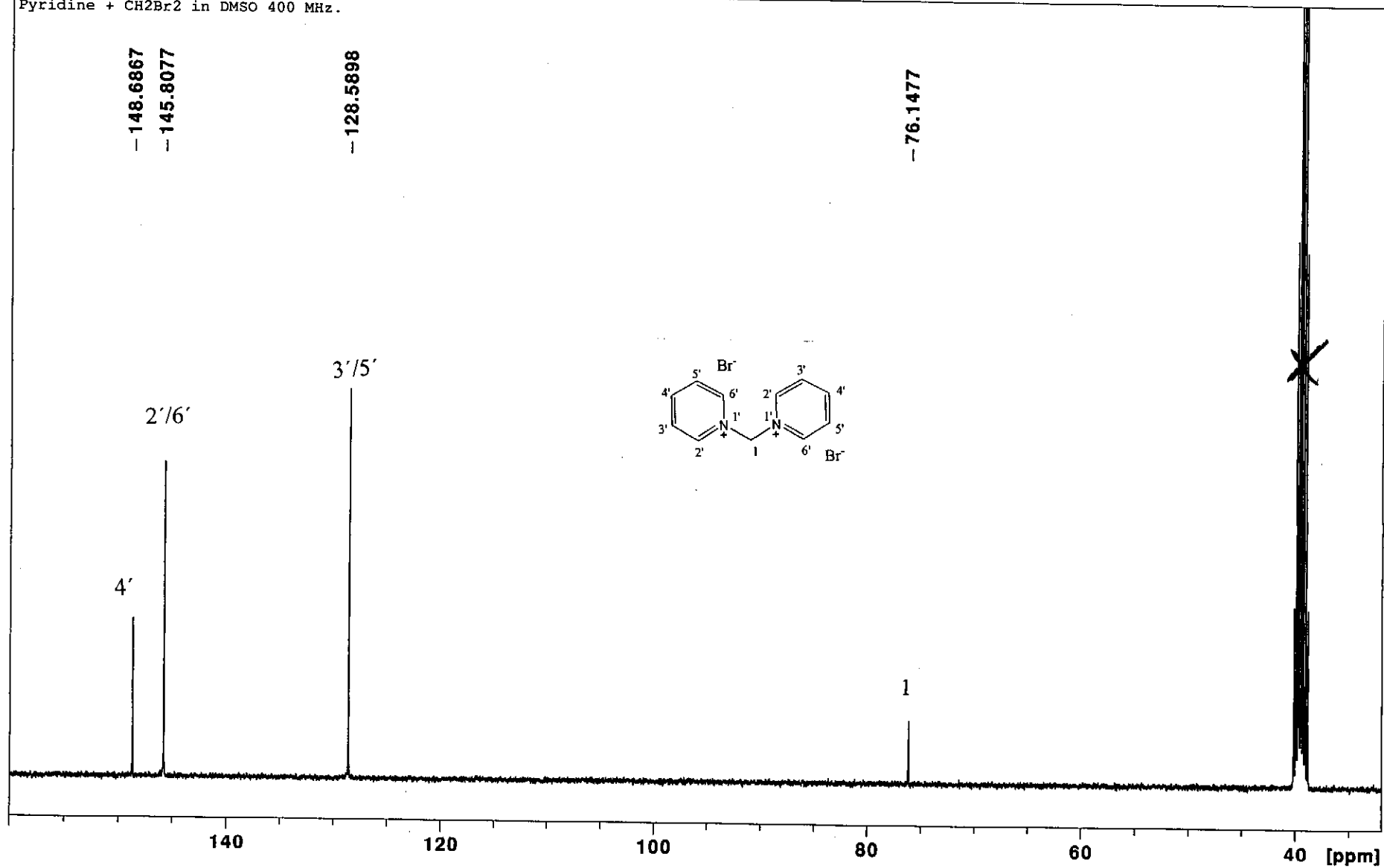
Pyridine + CH₂Br₂ in DMSO 400 MHz



¹H NMR spectrum of Compound D-2a

Jul22-2012-NK-Ibrahim 41 1 /opt/topspin NK

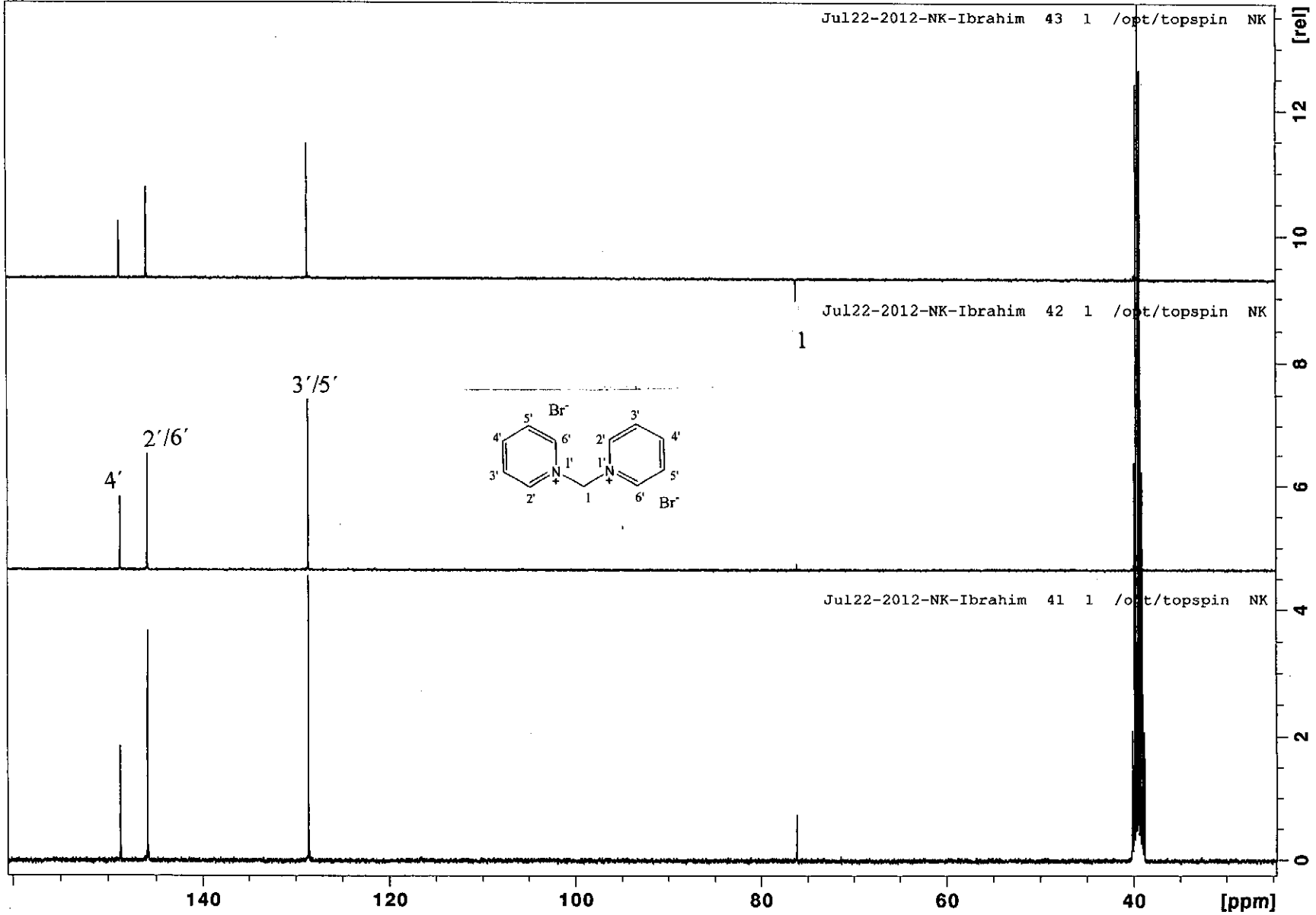
Pyridine + CH₂Br₂ in DMSO 400 MHz.



¹³C NMR spectrum of Compound D-2a

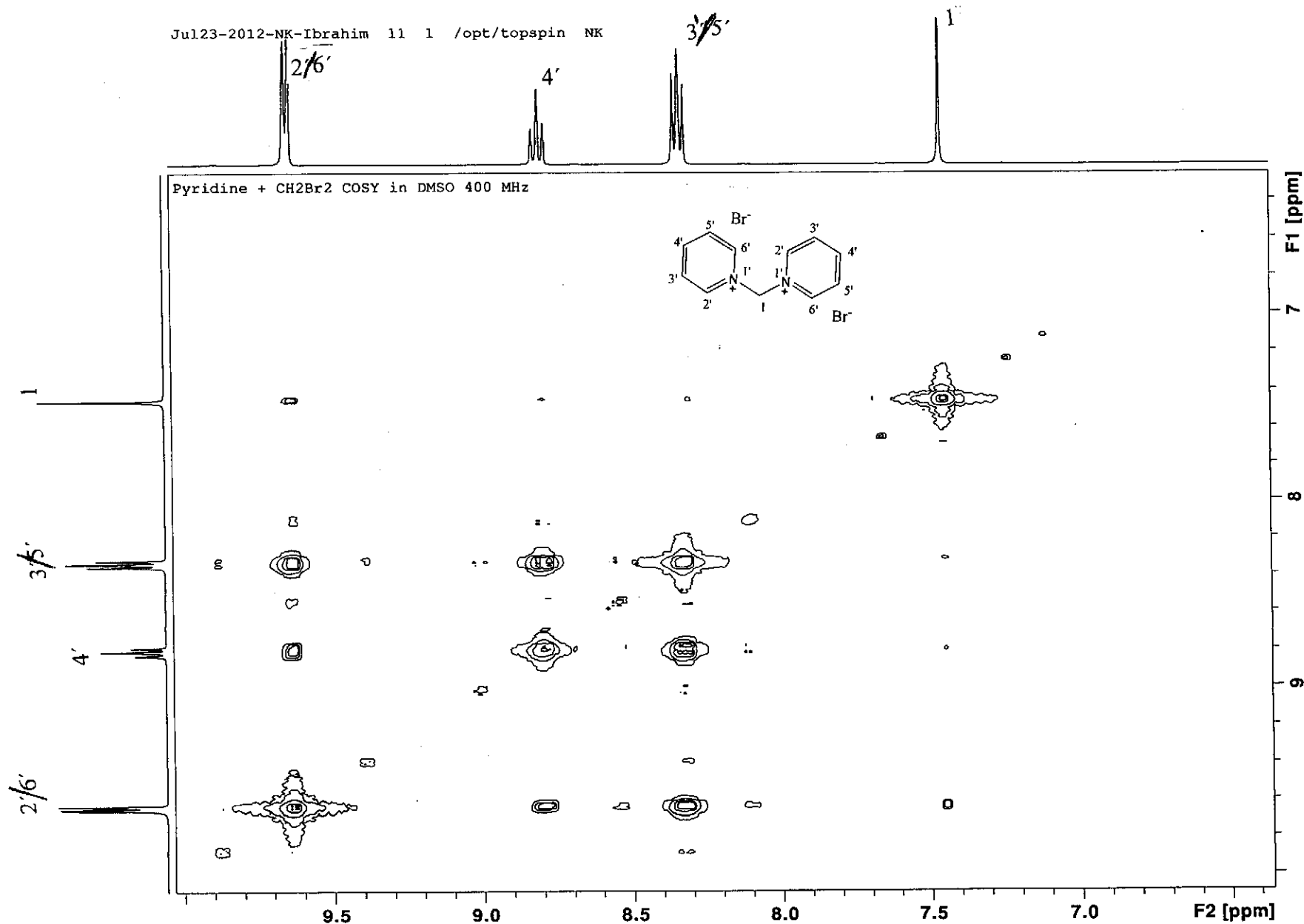
Jul22-2012-NK-Ibrahim 41 1 /opt/topspin NK

Jul22-2012-NK-Ibrahim 43 1 /opt/topspin NK



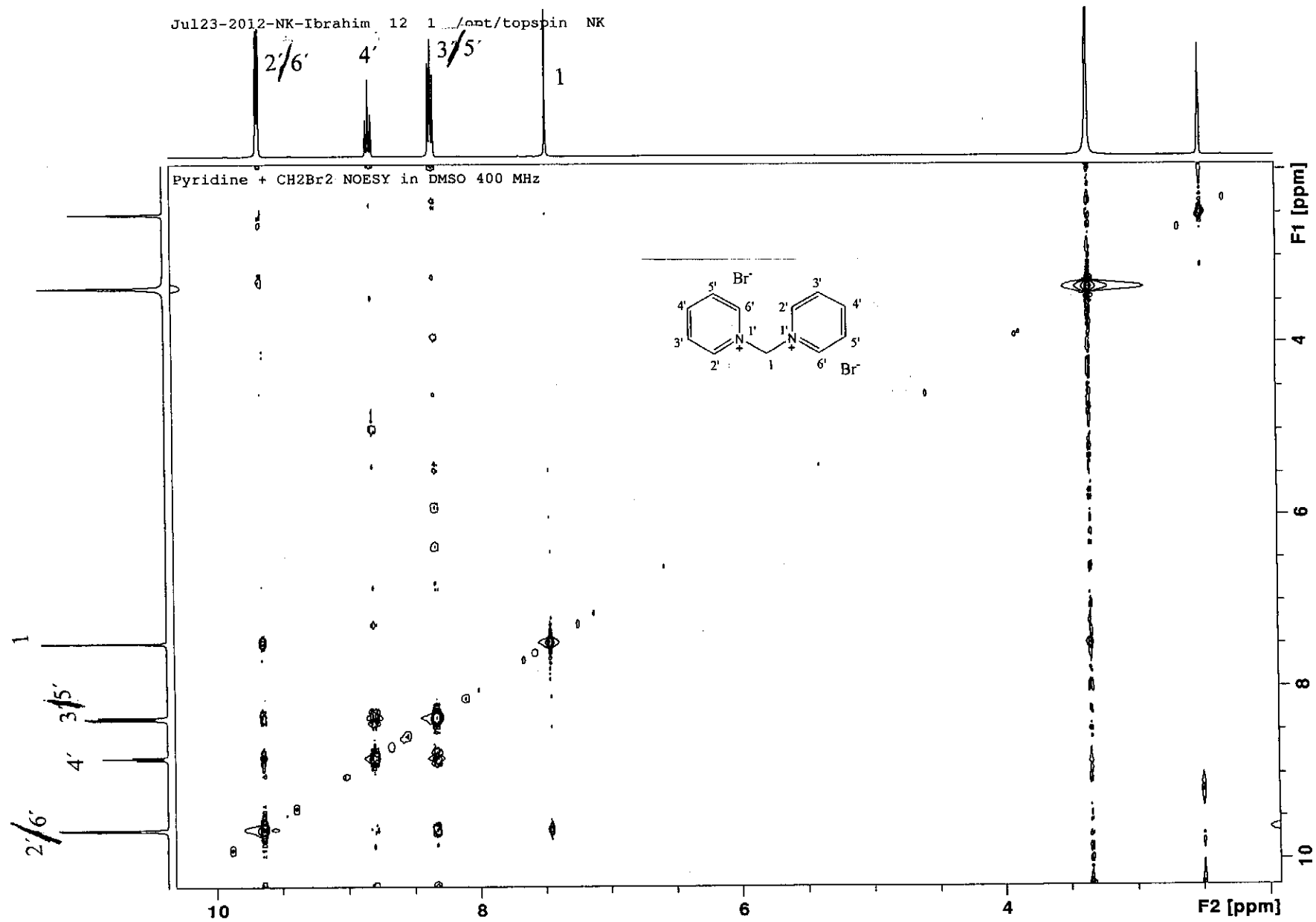
Dept 90 and 135 spectra of Compound D-2a

Jul23-2012-NK-Ibrahim 11 1 /opt/topspin NK



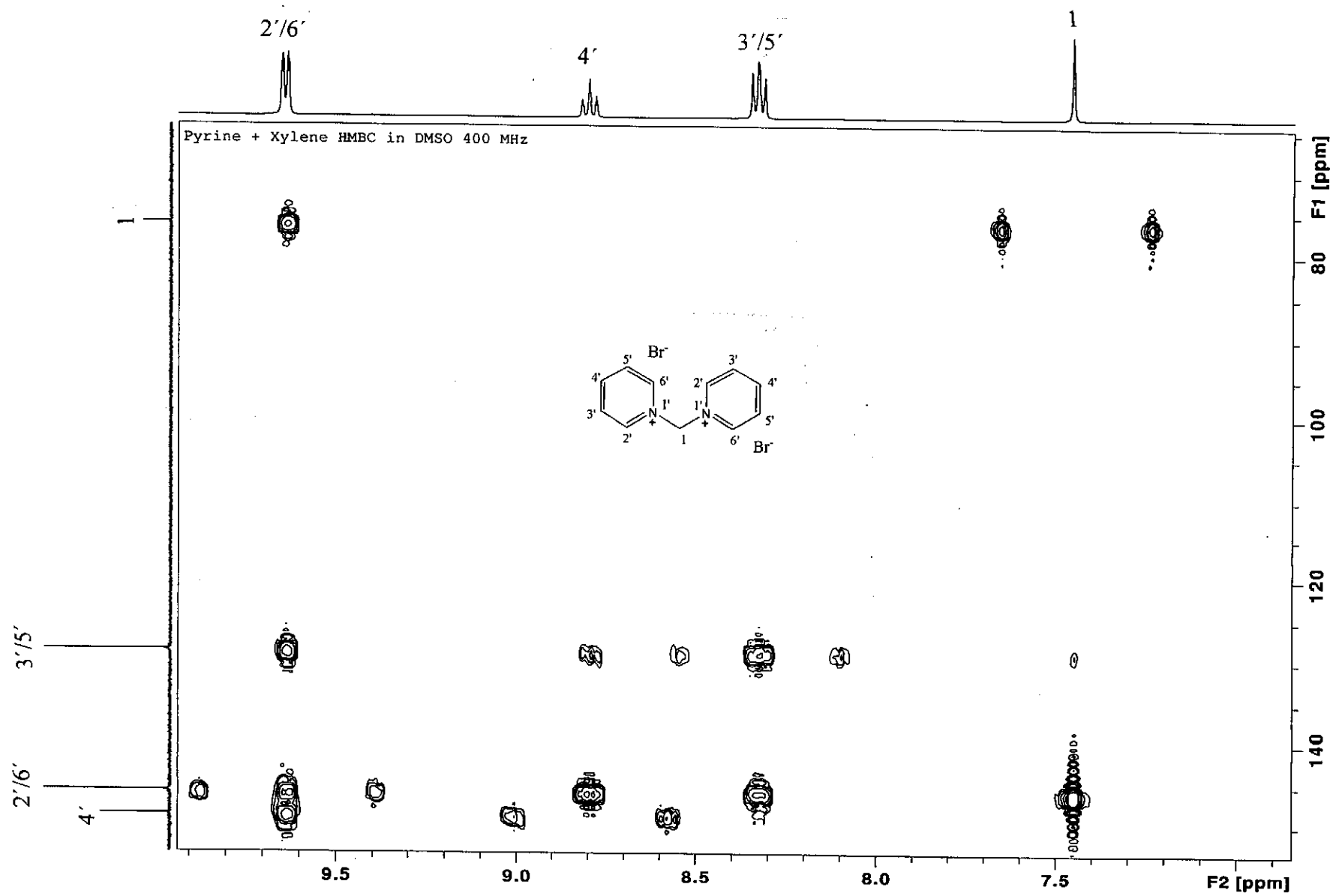
COSY spectrum of Compound D-2a

Jul23-2012-NK-Ibrahim_12_1_ant/topspin NK

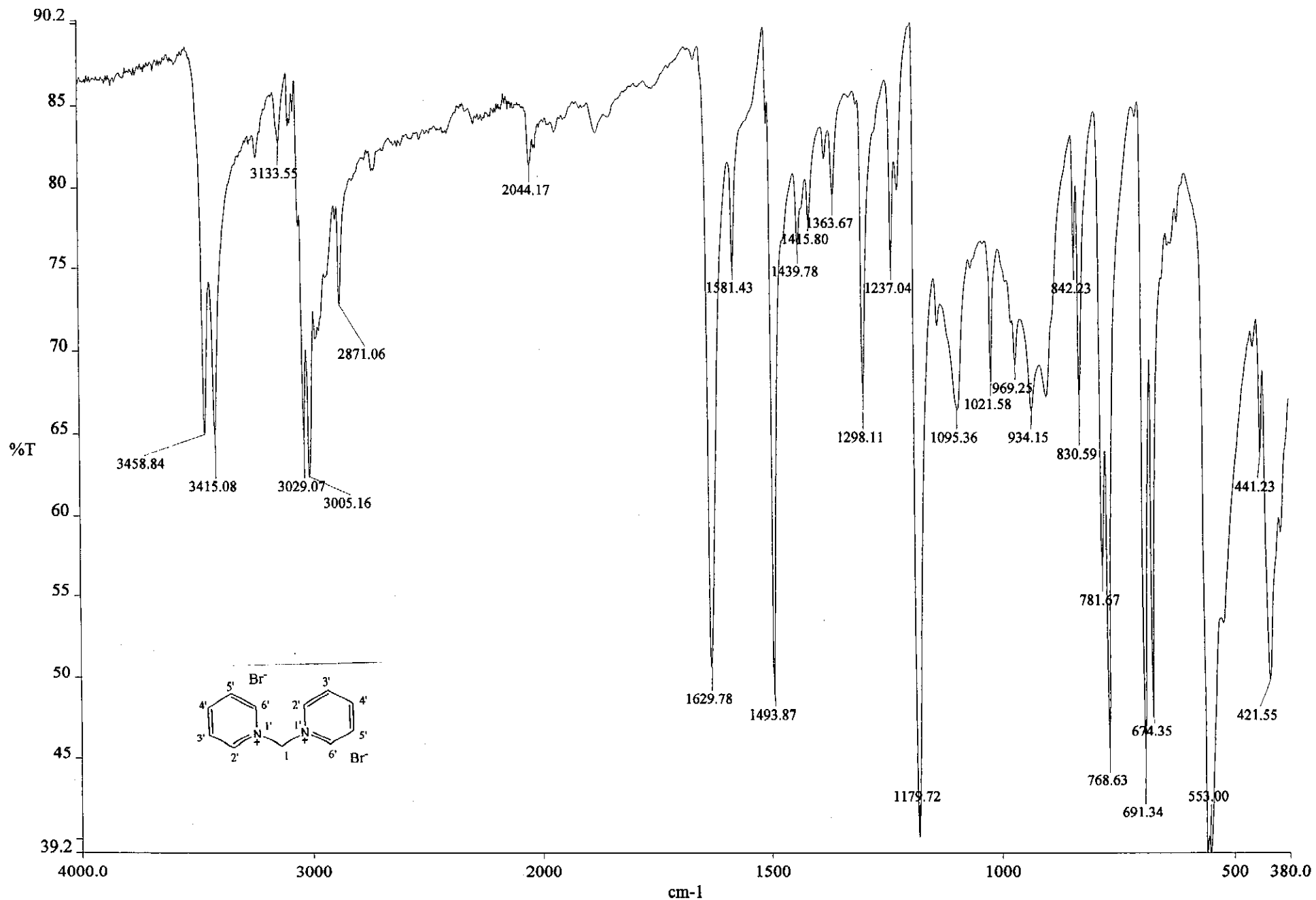


NOESY spectrum of Compound D-2a

Jul23-2012-NK-Ibrahim 14 1 /opt/topspin NK



HMBC spectrum of Compound D-2a

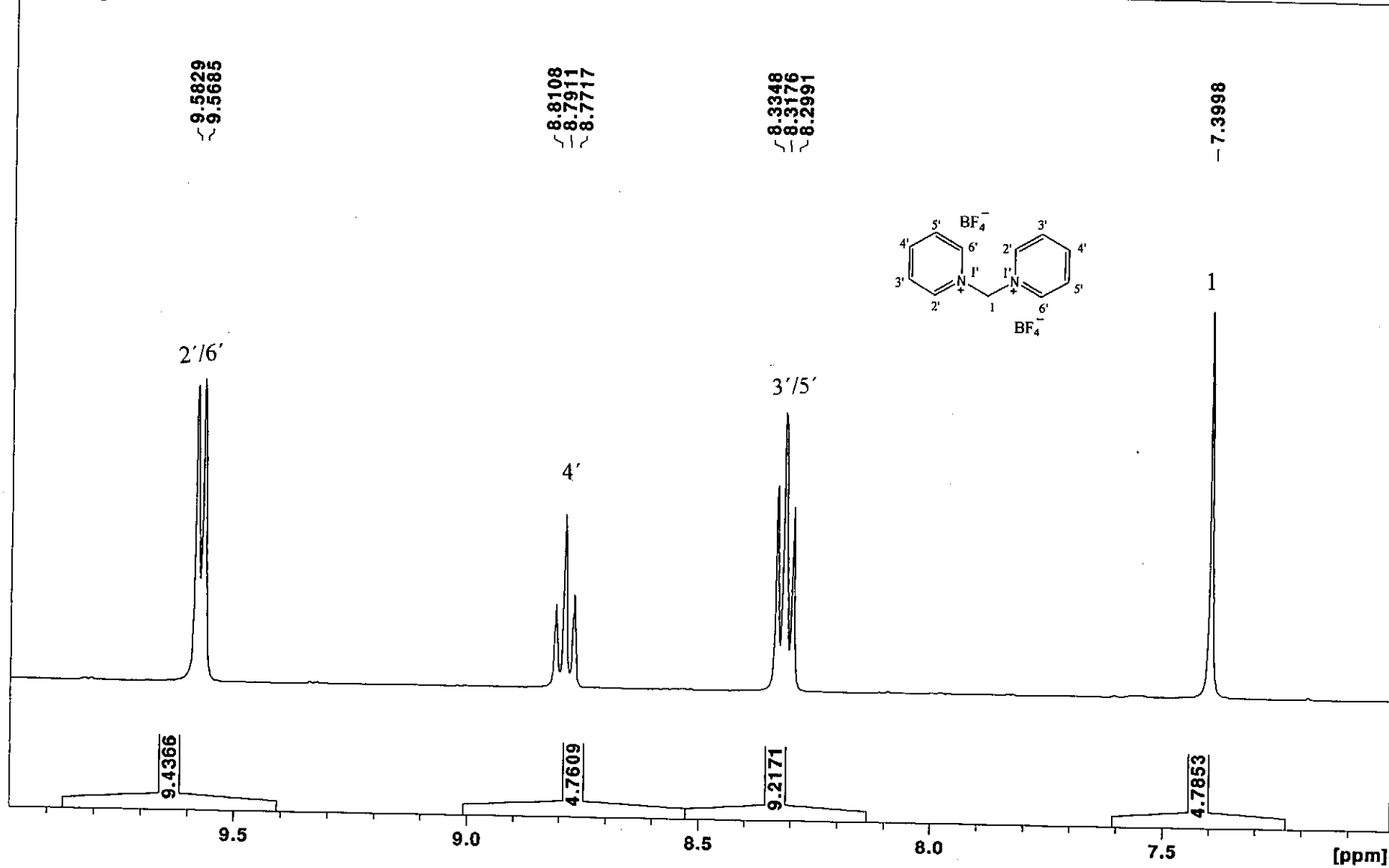


c:\pel_data\spectra\ch2-py2br2.sp - White sample

IR spectrum of Compound D-2a

Sep09-2012-NK-Ibrahim 10 1 /opt/topspin NK

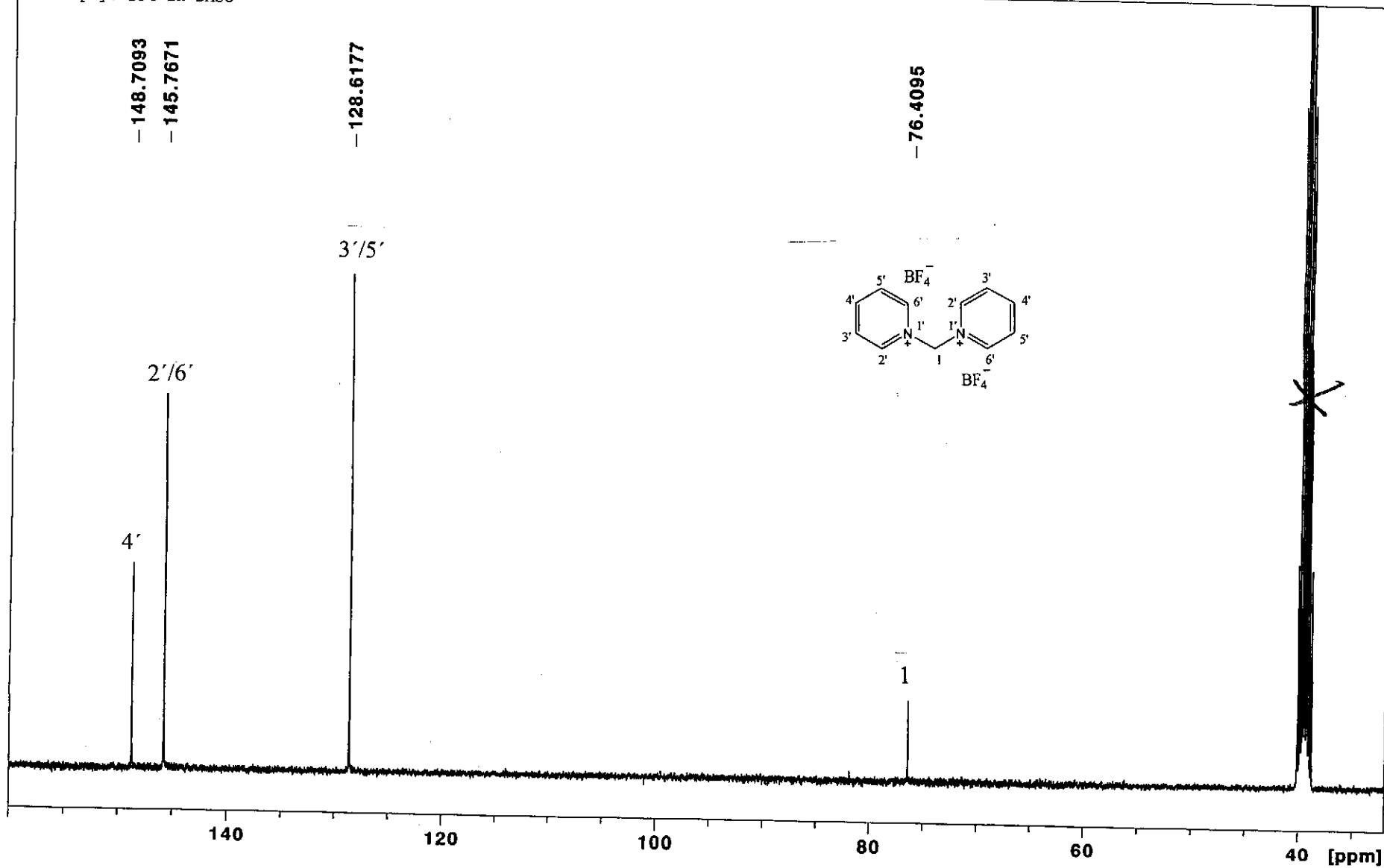
-CH2-2pry. BF4 in DMSO



¹H NMR spectrum of Compound D-2b

Sep09-2012-NK-Ibrahim 11 1 /opt/topspin NK

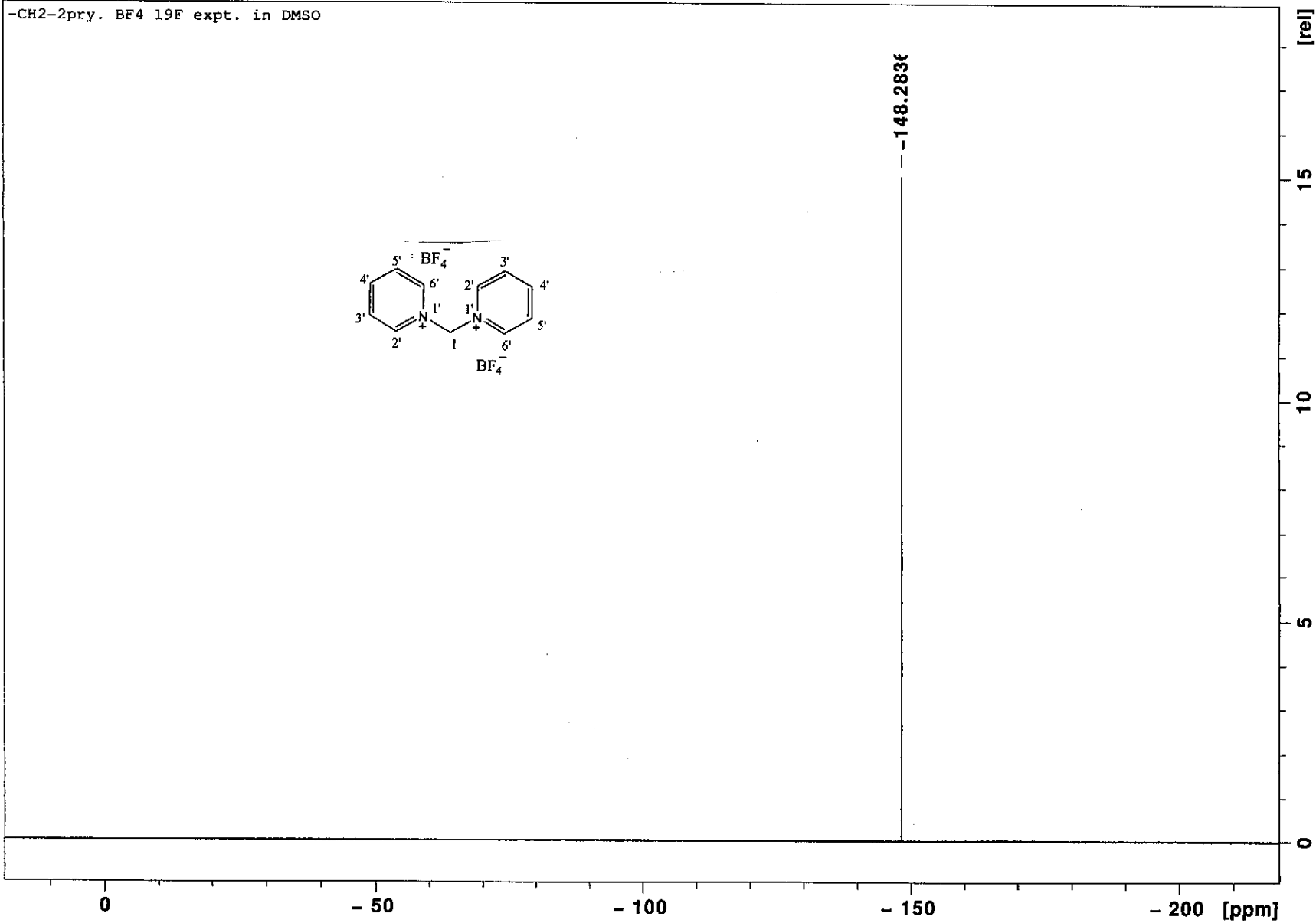
-CH2-2pyr. BF4 in DMSO



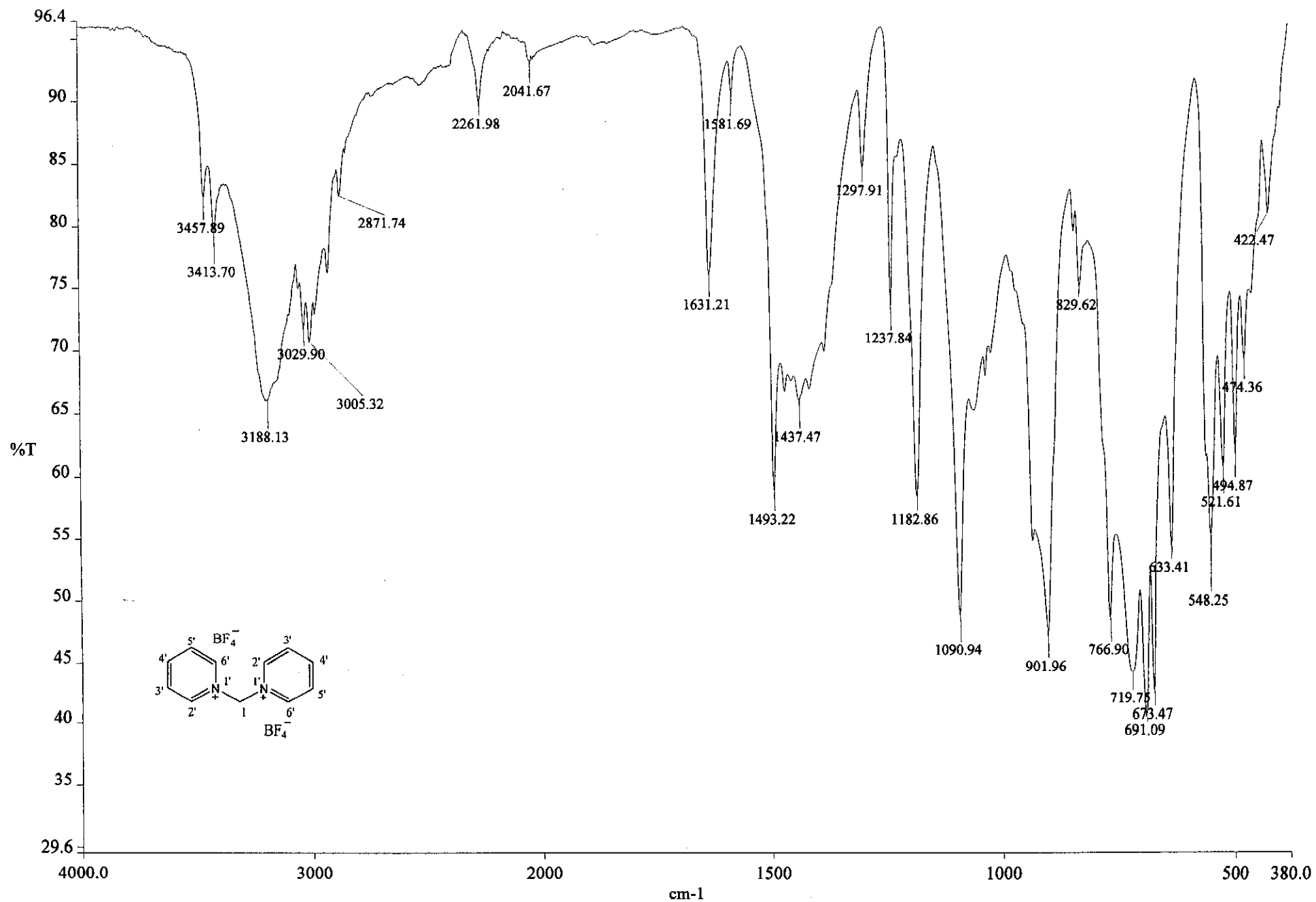
¹³C NMR spectrum of Compound D-2b

Sep09-2012-NK-Ibrahim 14 1 /opt/topspin NK

-CH2-2pry. BF4 19F expt. in DMSO



^{19}F NMR spectrum of Compound D-2b

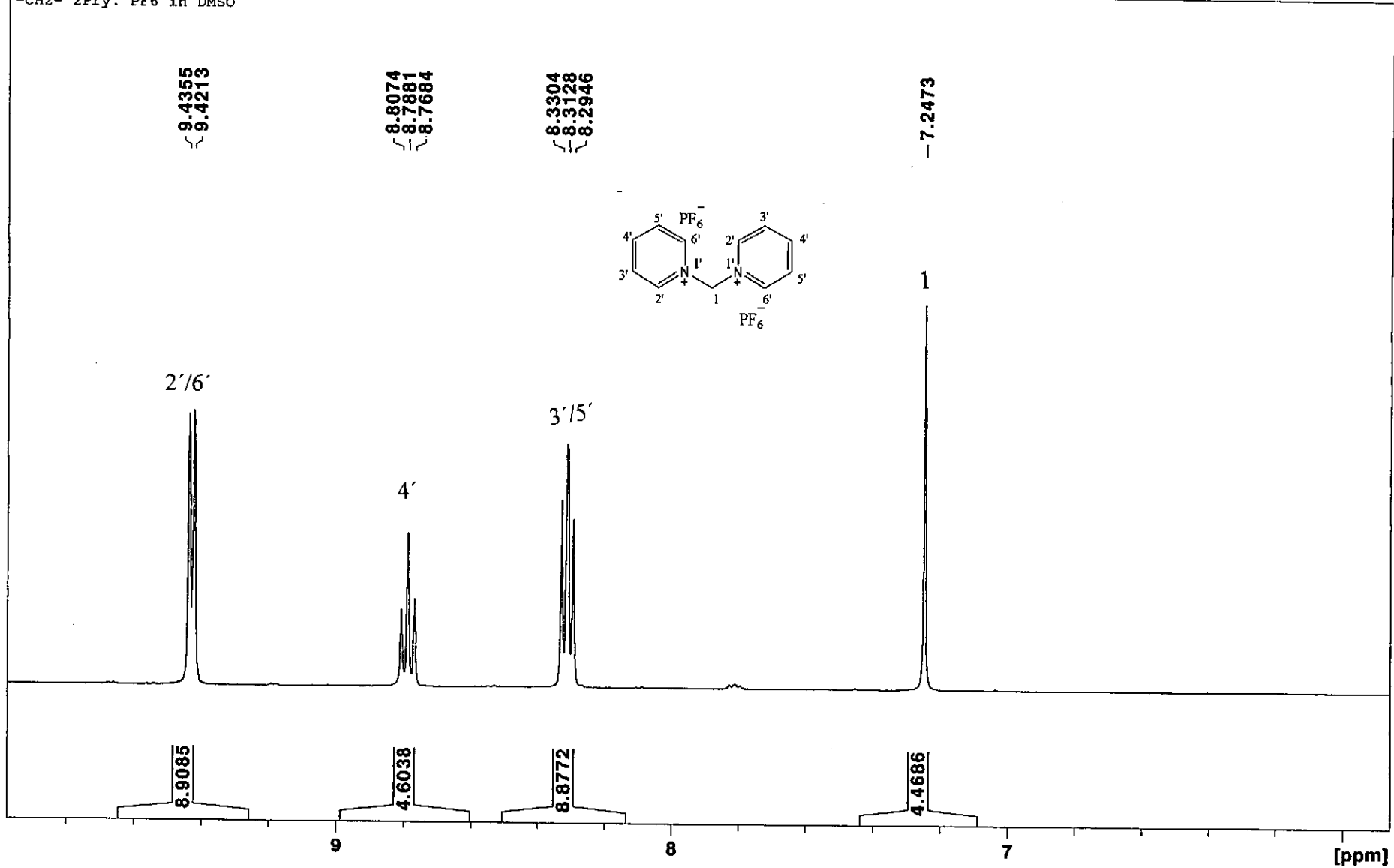


c:\pel_data\spectra\ch2-py2(bf4)2.002 - White sample

IR spectrum of Compound D-2b

Sep08-2012-NK-Ibrahim 30 1 /opt/topspin NK

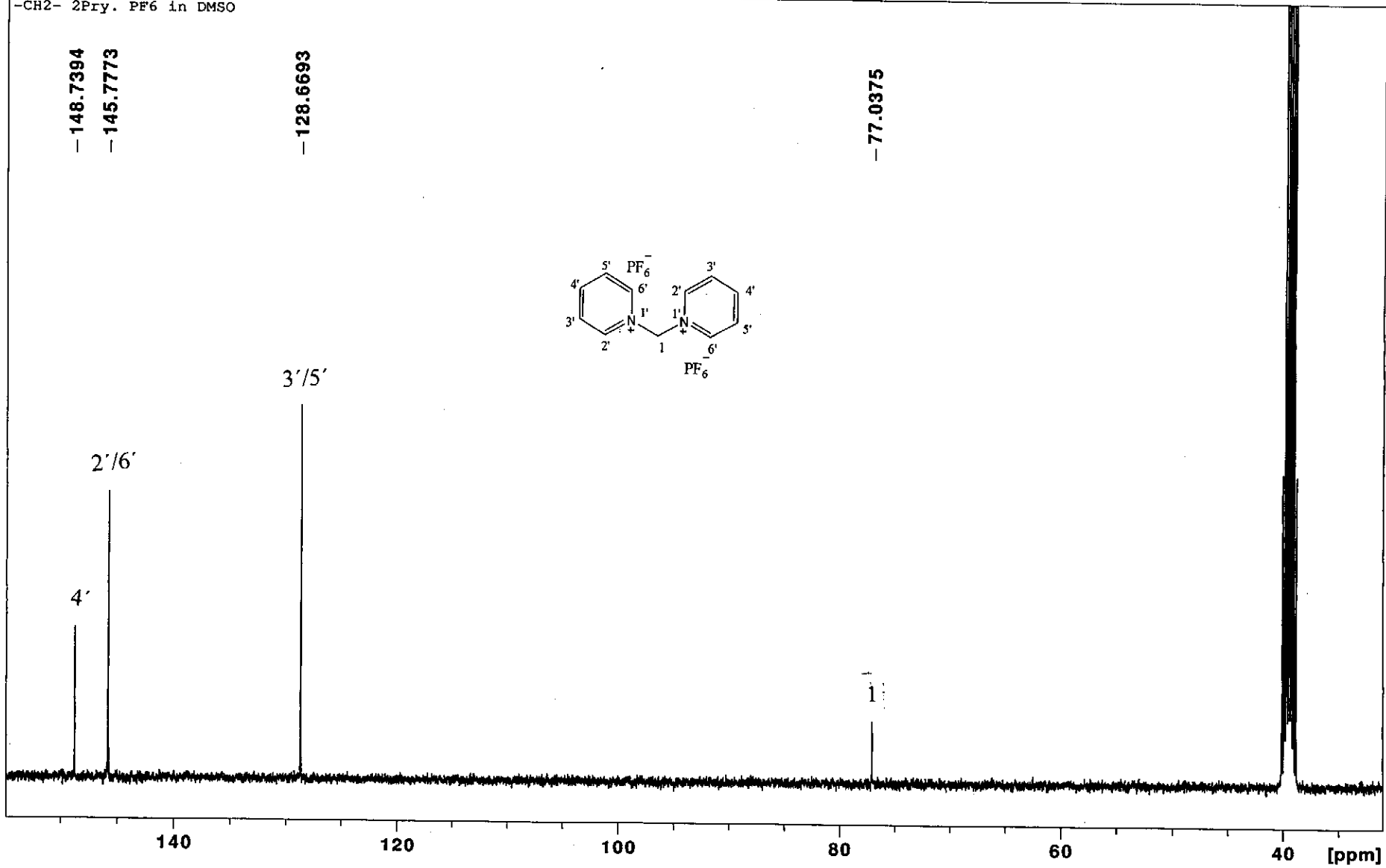
-CH2- 2Pry. PF6 in DMSO



¹H NMR spectrum of Compound D-2c

Sep08-2012-NK-Ibrahim 31 1 /opt/topspin NK

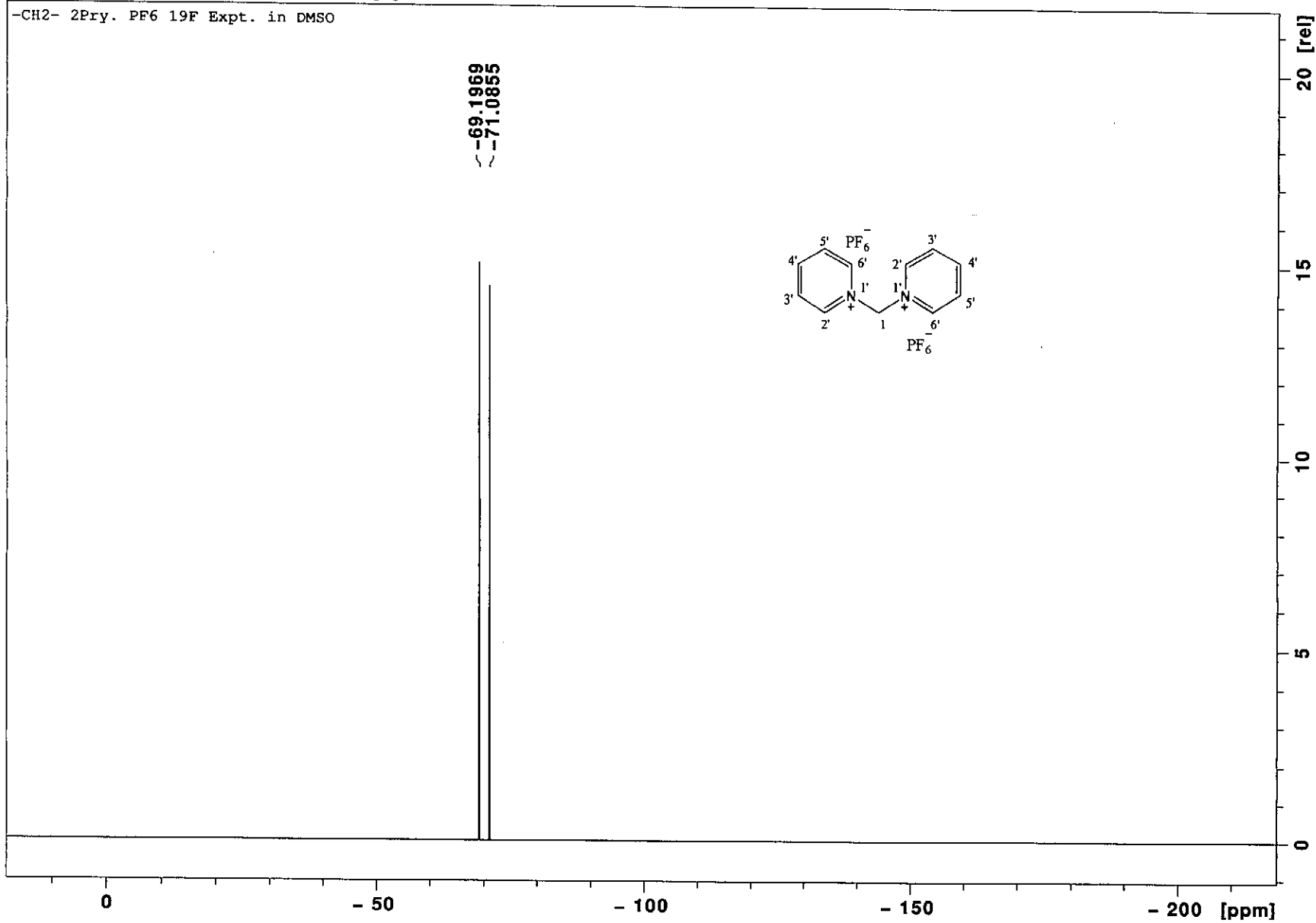
-CH2- 2Pry. PF6 in DMSO



^{13}C NMR spectrum of Compound D-2c

Sep08-2012-NK-Ibrahim 34 1 /opt/topspin NK

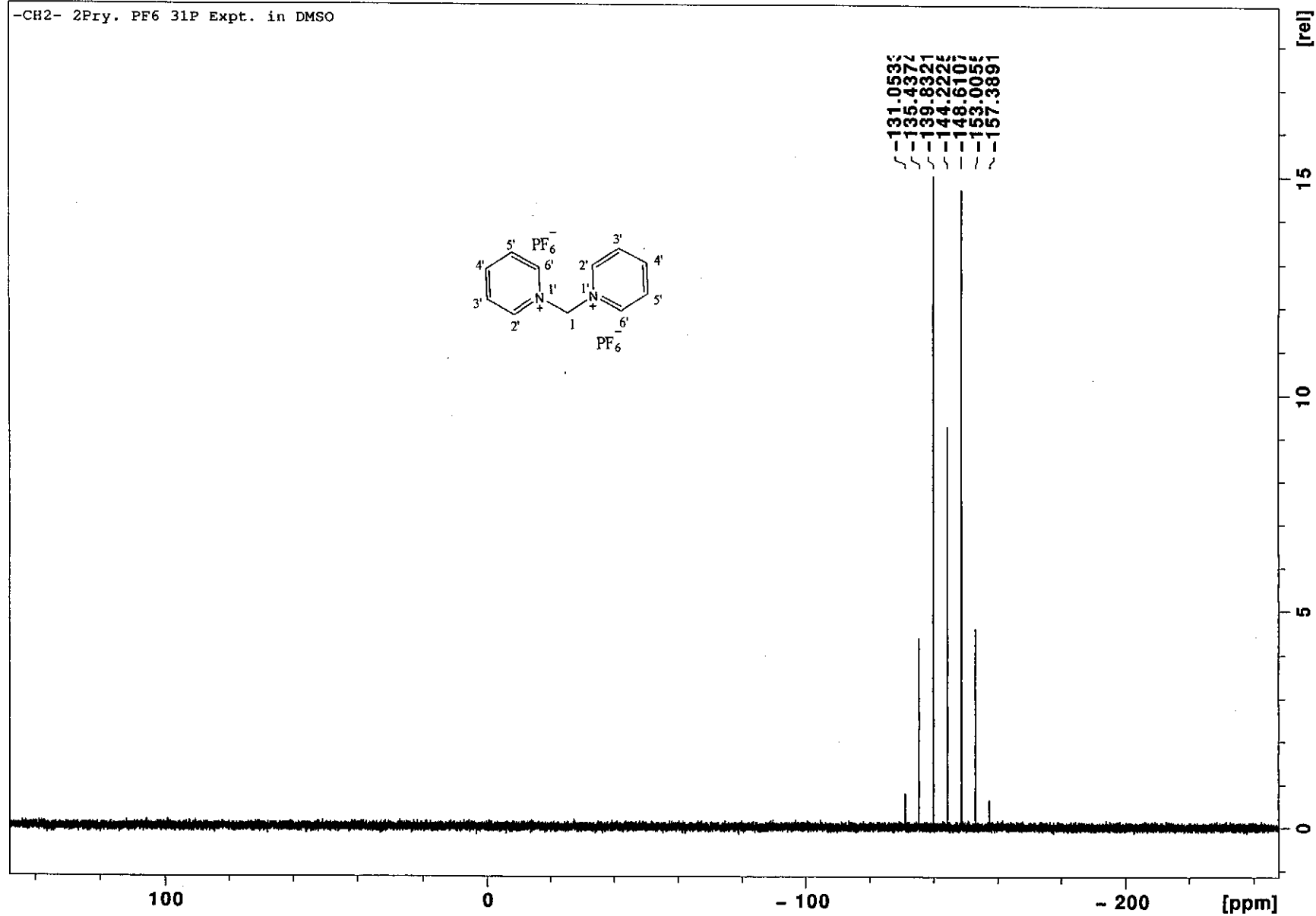
-CH2- 2Pry. PF6 19F Expt. in DMSO



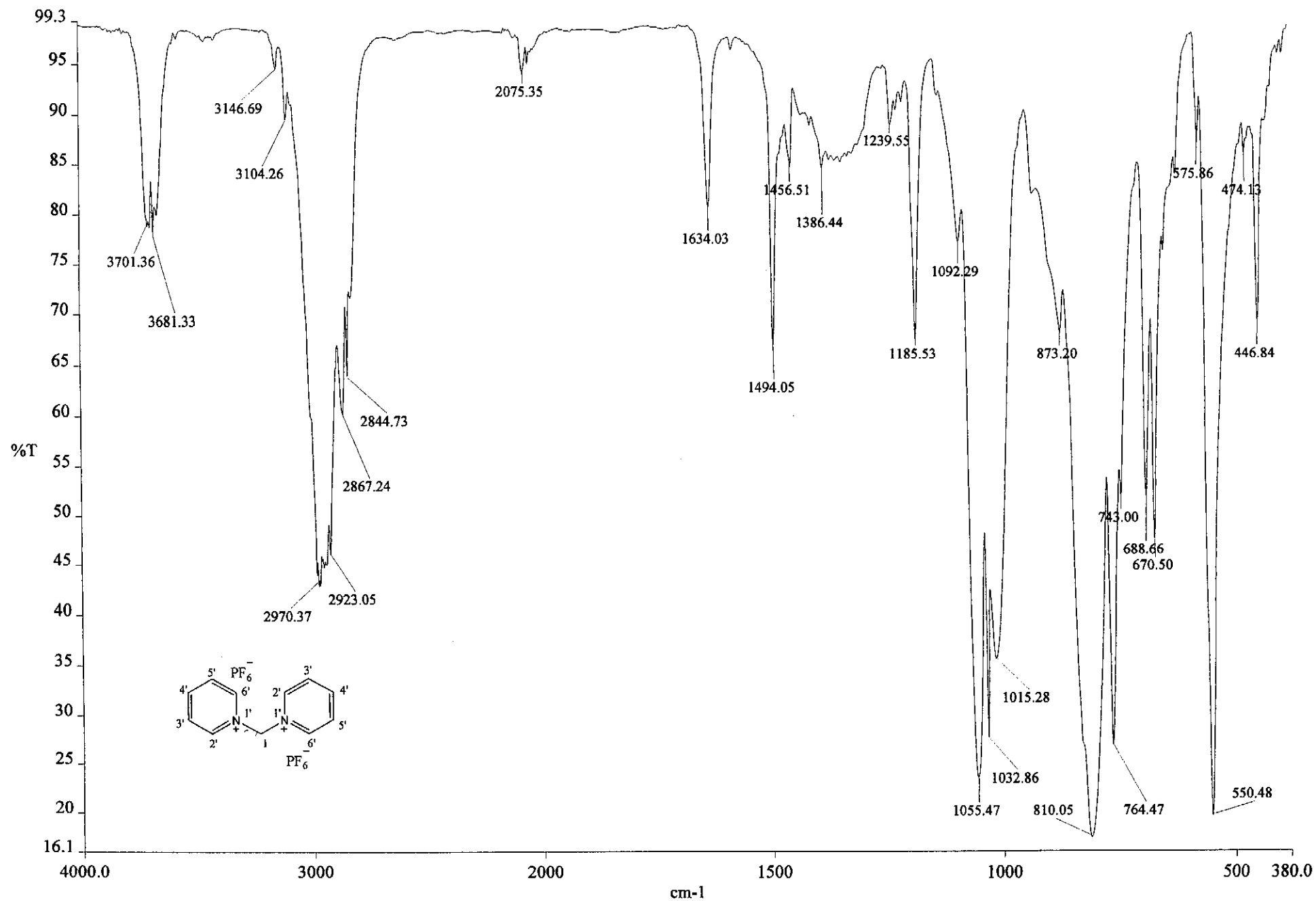
^{19}F NMR spectrum of Compound D-2c

Sep08-2012-NK-Ibrahim 35 1 /opt/topspin NK

-CH2- 2Pry. PF6 31P Expt. in DMSO



³¹P NMR spectrum of Compound D-2c



c:\pel_data\spectra\ch2-py2(pf6)2.002 - White sample

IR spectrum of Compound D-2c