

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

NITRONYL NITROXIDE CONTAINING RADICALS

İSMAİL FİDAN
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF CHEMISTRY

GEBZE
2017

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**NITRONYL NITROXIDE CONTAINING
RADICALS**

İSMAİL FİDAN
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF CHEMISTRY

THESIS SUPERVISOR
ASSIST. PROF. DR. CATHERINE HIREL

GEBZE
2017

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

NİTRONİL NİTROKSİT İÇEREN
RADİKALLER

İSMAİL FİDAN
DOKTORA TEZİ
KİMYA ANABİLİM DALI

DANIŞMANI
YRD. DOÇ. DR. CATHERINE HIREL

GEBZE

2017

GTÜ Fen Bilimleri Enstitüsü Yönetim Kurulu'nun 18/01/2017 tarih ve 2017/04 sayılı kararıyla oluşturulan jüri tarafından 13/02/2017 tarihinde tez savunma sınavı yapılan İSMAİL FİDAN'ın tez çalışması KİMYA Anabilim Dalında DOKTORA tezi olarak kabul edilmiştir.

JÜRİ

ÜYE

(TEZ DANIŞMANI) : Yrd. Doç. Dr. CATHERİNE HİREL

ÜYE

: Yrd. Doç. Dr. FABIENNE DUMOULIN

ÜYE

: Prof. Dr. ZEHRA NÜKET ÖCAL SUNGUROĞLU

ÜYE

: Prof. Dr. VEFA AHSEN

ÜYE

: Prof. Dr. DOMINIQUE LUNEAU

ONAY

Gebze Teknik Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun
...../...../..... tarih ve/..... sayılı kararı.

İMZA/MÜHÜR

SUMMARY

Among radicals, Ullman type radicals -imino and nitronyl nitroxide- draw our attention due to their excellent stability and versatile synthetic chemistry. More particularly, polyradical molecules were our main goal. In this optic two platforms were chosen to introduce Ullman radicals: cyclotriphosphazene and phthalocyanine.

Thanks to the cyclotriphosphazene core, six Ullman radicals - imino nitroxide **15** and nitronyl nitroxide **16**- were successfully implemented. Both molecules were obtained by two different synthetic pathways. **15** was obtained by the classical Ullman route consisting of the condensation of an adequate aldehyde with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) follow by its oxidation whereas **16** was synthesis by a so-called “pre-form strategy”. The radical character is bearing by the 2-(4-hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**) synthon and bonded to the cyclotriphosphazene core by nucleophilic substitution in acetone/ K_2CO_3 .

Phthalocyanines-based radical molecules require multi-steps synthesis that allows only the formation of the mono-(**38**) and tetra-(**44**) imino nitroxide derivative. In this case, a pre-form strategy was also envisaged to reach the nitronyl nitroxide counterpart. In this expectative, phthalonitrile bearing nitronyl nitroxide (**46**) was synthesized.

All structures were unambiguously characterized with a rich array of analyses such as melting point, FT-IR, NMR, MALDI-TOF MS, elemental analysis, UV-vis, CV, SWV, EPR, magnetic measurements and X-ray diffraction analysis.

Straightforward and rapid quantification methods by UV-vis and square wave voltammetry (SWV) were developed to determine the number of radical moieties present on a polyradical by techniques easily accessible in most laboratories. Both methods have demonstrated the presence of six imino or nitronyl nitroxide radical on cyclotriphosphazene **15** and **16** respectively.

Keywords: Cyclotriphosphazene, phthalocyanine, Ullman radicals, nitronyl nitroxide, imino nitroxide, quantification methods.

ÖZET

Radikaller arasında ise Ullman tipi radikaller (nitronil ve imino nitroksit) mükemmel kararlılığı ve çok yönlü sentetik kimyasından dolayı ilgimizi çekti. Özellikle esas hedefimiz ise poliradikal molekülleridir. Bu yönde Ullman radikallerini bağlamak üzere iki platform seçildi; siklotrifosfazen ve ftalosiyanın.

Siklotrifosfazen çekirdeğine altı Ullman radikali (imino nitroksit **15** ve nitronil nitroksit **16**) başarıyla yerleştirilmiştir. Her iki molekül de iki farklı sentetik yoldan elde edilmiştir. **15** klasik Ullman yolu ile elde edilmiş olup munasip bir aldehitin 2,3-bis(hidroksilamino)-2,3-dimetilbütan (**3**) ile kondenzasyonu ve peşinden yükseltgenmesini içerirken **16** ise “önceden oluşturulmuş strateji” de denilen yöntemle sentezlenmiştir. Radikal karakterini 2-(4-hidroksifenil)-4,4,5,5-tetrametil-2-imidazoline-3-oksid-1-oksil (**10**) sintonu taşımakta olup aseton/K₂CO₃ içerisindeki nükleofilik süstitüsyon ile siklotrifosfazen çekirdeğine bağlanmıştır.

Ftalosiyanın bazlı radikal molekülleri çok basamaklı sentez gerektirmekte olup bunlarla sadece mono-(**38**) and tetra-(**44**) imino nitroksit türevleri oluşmuştur. Bu durumda, nitronil nitroksit karşılığına ulaşmak için “önceden oluşturulmuş strateji” öngörülmüştür. Bu bağlamda nitronil nitroksit bağlı ftalonitril **46** sentezlenmiştir.

Tüm yapılar erime noktası, FT-IR, NMR, MALDI-TOF MS, elementel analiz, UV-vis, CV, SWV, EPR, manyetik ölçümler ve X-ray diffraksiyon analizi gibi zengin analiz dizileriyle karakterize edilmiştir.

Bir poliradikal üzerindeki radikal kısımlarının sayısını belirlemek üzere birçok laboratuvar da kolayca ulaşılabilen teknikler olan UV-vis ve kare dalga voltametri (SWV) ile basit ve hızlı kuantifikasyon metodları geliştirilmiştir. Bu metodlar **15** üzerinde altı adet imino nitroksit radikali ve **16** üzerinde ise altı adet nitroni nitroksit radikali olduğunu ispat etmiştir.

Anahtar Kelimeler: Siklotrifosfazen, ftalosiyanın, Ullman radikalleri, nitronil nitroksit, imino nitroksit, kuantifikasyon metodları.

ACKNOWLEDGEMENTS

I would like to express my highest gratitude to excellent supervisor named Assist. Prof. Dr. Catherine Hirel for the opportunity to work in her group. I will always be thankful for the role she has played in both my professional and personal developments. I am deeply grateful to committee members for their continuous support, valuable feedback, and great contributions; Assist. Prof. Dr. Catherine Hirel, Assist. Prof. Dr. Fabienne Dumoulin, Prof. Dr. Zehra Nüket Öcal Sunguroğlu, Prof. Dr. Vefa Ahsen, and Prof. Dr. Dominique Luneau. I thank to Prof. Dr. Yusuf Yerli for EPR measurements, Osman Cahit Demirci and Ahmet Şenocak for excellent photos of my compounds, and people of Hirel Group and Dumoulin Group for having funny times in the university.

I owe special thanks to Prof. Dr. Dominique Luneau in Groupe de Cristallographie et Ingenierie Molaculaire, Laboratoire Multimateriaux et Interfaces (UMR 5615) at Universite Claude Bernard Lyon1, France for the opportunity to conduct research there during a semester of my PhD study. I must acknowledge the Assoc. Prof. Dr. Natia L. Frank in the Chemistry Department at University of Victoria, Canada for the opportunity to carry out some research in her laboratories.

I gratefully acknowledge the Turkish National Agency for funding the Erasmus Program within that I spent a semester in Universite Claude Bernard Lyon1, France. TUBITAK is especially acknowledged for the 2214-A International Doctoral Research Fellowship Program that used in Chemistry Department at University of Victoria, Canada. Particularly, financial support from TUBITAK (projects 214Z267 and 114Z767) is gratefully acknowledged.

I cordially thanks to tenants of KYK Gebze Residence; Esra Nur Kaya, İpek Ömeroğlu, İsmail Erol, and Sedat Küçükköylü for making the residence an enjoyable place to live. Funny times having long discussions over the life and chemistry will be enduring memories in my life.

Finally, I am deeply grateful to my parents and siblings for their ceaseless and unconditional support. Thanks for believing in me.

TABLE of CONTENTS

	<u>Page</u>
SUMMARY	v
ÖZET	vi
ACKNOWLEDGEMENTS	vii
TABLE of CONTENTS	viii
LIST of ABBREVIATIONS and ACRONYMS	xiii
LIST of FIGURES	xvi
LIST of TABLES	xxv
1. INTRODUCTION	1
2. SURVEY OF ULLMAN RADICALS	4
2.1. What is Stable Radical?	4
2.2. Stable Radicals	5
2.2.1. Carbon-Based Radicals	5
2.2.2. Nitrogen-Based Radicals	6
2.2.3. Oxygen-Based Radicals	7
2.2.4. Nitroxide Radicals	8
2.3. Synthesis of Nitronyl Nitroxide and Imino Nitroxide	11
2.4. Characterizations of Nitronyl Nitroxides and Imino Nitroxides	13
2.4.1. Electronic Structure Characterizations	13
2.4.2. Electrochemical Characterizations	14
2.4.3. EPR Characterizations	14
2.4.4. Magnetic Characterizations	18
2.5. Applications of Nitroxides	20
2.5.1. Building Blocks in Magnetic Materials	20
2.5.2. Electrode Active Material in Organic Rechargeable Batteries	22
2.5.3. Dynamic Nuclear Polarizing Agents in NMR Spectroscopy	23
2.5.4. Probes in Chemical Sensors	24
3. MATERIALS AND METHODS	26
3.1. Reagents and solvents	26

3.2. Methods	26
3.3. Melting Points	26
3.4. Elemental Analysis	27
3.5. Infrared Spectroscopy	27
3.6. NMR Spectroscopy	27
3.7. Mass Spectra	28
3.8. Absorption Spectroscopy	28
3.9. Electrochemical Analyses	28
3.10. Electron Paramagnetic Resonance (EPR) Spectroscopy	29
3.11. Fluorescence Spectroscopy	29
3.12. X-ray Diffraction Analysis	29
3.13. Magnetic Measurements	30
4. IMINO NITROXIDE-BASED HEXARADICAL ARCHITECTURE ON A CYCLOTRIPHOSHAZENE SCAFFOLD: SYNTHESIS AND STRAIGHTFORWARD QUANTIFICATION METHODS OF IMINO NITROXIDE RADICALS BY ABSORPTION SPECTROSCOPY AND ELECTROCHEMISTRY	31
4.1. Phosphazenes	31
4.2. Imino Nitroxide Radicals	32
4.3. Cyclotriphosphazene-Nitroxide Hybrid Compounds	34
4.4. Scope and Objectives	39
4.5. Synthesis	42
4.6. Absorption Spectroscopy	47
4.7. Electrochemical Analyses	48
4.8. Electron Paramagnetic Resonance Spectroscopy	50
4.9. Magnetic Measurements	51
4.10. X-ray Diffraction Analyses	52
4.11. Summary and Conclusion	57
4.12. Synthetic Procedures	57
4.12.1. Synthesis of 2,3-Dimethyl-2,3-dinitrobutane (2)	58
4.12.2. Synthesis of 2,3-Bis(hydroxylamino)-2,3-dimethylbutane (3)	58
4.12.3. Synthesis of Hexa-(4-formylphenoxy)cyclotriphosphazene (12)	59

4.12.4. Synthesis of Phenyl-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl) (7)	60
4.12.5. Synthesis of Hexa-[4-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl)phenoxy]cyclotriphosphazene (15)	61
5. ALTERNATIVE SYNTHESIS OF NITRONYL NITROXIDE-BASED HEXARADICAL ARCHITECTURE ON A CYCLOTRIPHOSPHAZENE SCAFFOLD AND GENERALIZATION OF ABSORPTION SPECTROSCOPY AND ELECTROCHEMISTRY QUANTIFICATION METHODS TO NITRONYL NITROXIDE RADICALS	63
5.1. Specificity of Nitronyl Nitroxide Synthesis	63
5.2. Scope and Objectives	64
5.3. Synthesis	66
5.4. Absorption Spectroscopy	69
5.5. Electrochemical Analyses	71
5.6. Electron Paramagnetic Resonance Spectroscopy	75
5.7. Magnetic Measurements	76
5.8. X-ray Diffraction Analyses	77
5.9. Summary and Conclusion	78
5.10. Synthetic Procedures	79
5.10.1. Synthesis of 2-Phenyl-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (6)	79
5.10.2. Synthesis of 2-(4-Hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (10)	80
5.10.3. Synthesis of Hexa-[4-(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl-2-yl)phenoxy]-cyclotriphosphazene (16)	81
6. ULLMAN RADICALS FUNCTIONALIZED PHTHALOCYANINES	82
6.1. Phthalocyanines	82
6.2. Syntheses of Phthalocyanines	85
6.2.1. Synthesis of Symmetrical Phthalocyanines (A ₄)	86
6.2.2. Synthesis of Unsymmetrical Phthalocyanines	88
6.3. Syntheses of Phthalonitriles	92
6.3.1. 4,5-Dialkoxy- or 4,5-Diaryloxyphthalonitriles	92
6.3.2. 4-Alkoxy- or 4-Aryloxyphthalonitriles	93

6.4. Properties of Phthalocyanines	94
6.4.1. Electronic Structure	94
6.4.2. Fluorescence Property	96
6.5. Survey of Nitroxide Functionalized Phthalocyanines	98
6.6. Scope and Objectives	103
6.7. Synthesis	106
6.7.1. Synthesis of Phthalonitriles 25 and 31	106
6.7.2. Synthesis of Mono Ullman Radical Linked Phthalocyanines 37 and 38	110
6.7.3. Synthesis of Tetra Ullman Radicals Linked Phthalocyanines 43 and 44	117
6.8. Absorption Spectroscopy	121
6.9. Electrochemical Analysis	123
6.10. Electron Paramagnetic Resonance Spectroscopy	123
6.11. Magnetic Measurements	125
6.12. X-ray Diffraction Analyses	125
6.13. Summary and Conclusion	125
6.14. Synthetic Procedures of Phthalonitriles	126
6.14.1. Synthesis of 1,2-Dibromo-4,5-dineopentoxybenzene 24	126
6.14.2. Synthesis of 4,5-Dineopentoxyphthalonitrile 25	127
6.14.3. Synthesis of 1,2-Dibromo-4-(5,5-dimethyl-1,3-dioxane-2-yl) benzene 30	127
6.14.4. Synthesis of 4-(5,5-Dimethyl-1,3-dioxane-2-yl)-phthalonitrile 31	128
6.15. Synthetic Procedures of Mono Ullman Radical Linked Phthalocyanines	129
6.15.1. Synthesis of 32 and 33	129
6.15.2. Synthesis of 34	129
6.15.3. Synthesis of 38	130
6.16. Synthetic Procedures of Tetra Ullman Radicals Linked Phthalocyanines	131
6.16.1. Synthesis of 39	131
6.16.2. Synthesis of 40	132
6.16.3. Synthesis of 42	132
6.16.4. Synthesis of 44	133

7. PRE-FORMED RADICAL STRATEGY FOR THE SYNTHESIS OF ULLMAN RADICAL FUNCTIONALIZED PHTHALOCYANINES: ULLMAN RADICALS LINKED PHTHALONITRILES	134
7.1. Survey of Nitroxide Functionalized Phthalonitriles	134
7.2. Scope and Objectives	135
7.3. Synthesis	138
7.3.1. Synthesis of Ullman Radicals Linked Phthalonitriles 46 and 47	138
7.3.2. Preliminary Synthetic Studies of the Ullman Radicals Linked Symmetrical Phthalocyanines 48 and 49	140
7.4. Absorption Spectroscopy	141
7.5. Electrochemical Analyses	142
7.6. Electron Paramagnetic Resonance Spectroscopy	143
7.7. Magnetic Measurements	145
7.8. X-ray Diffraction Analyses	145
7.9. Summary and Conclusion	145
7.10. Synthetic Procedures	146
7.10.1. Syntheses of 4-[(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1- oxyl-2-yl)phenoxy]phthalonitrile (46) and 4-[(1-oxyl-4,4,5,5- tetramethyl-2-imidazoline-2-yl)phenoxy]phthalonitrile (47)	146
7.10.2. Syntheses of Phthalocyanines 48 and 49	147
8. SPECTRA AND STRUCTURES OF THE COMPOUNDS	148
9. CONCLUSION	217
REFERENCES	220
BIOGRAPHY	234
APPENDICES	235

LIST of ABBREVIATIONS and ACRONYMS

Abbreviations

and Acronyms

: Explanation

$\text{\AA}$	: Angstrom
a_N	: Isotropic Hyperfine Coupling Constants
ϵ	: Molar Extinction Coefficient
ΔH_{p-p}	: Line Width
μM	: Micromolar
μA	: Microamper
λ	: Wavelength
δ	: Chemical Shift
ν_{max}	: Absorption Maxima
χ	: Magnetic Susceptibility
χM	: Molar Magnetic Susceptibility
χT	: Magnetic Susceptibility With Temperature
θ	: Weiss Constant
$^\circ$	: Degree
ACN	: Acetonitrile
ATR	: Attenuated Total Reflection
BHA	: 2,3-Bis(hydroxylamino)-2,3-dimethylbutane
br	: Broad
C	: Celcius
CV	: Cyclic Voltammetry
d	: Doublet
DBN	: 1,5-Diazabicyclo[4.3.0]non-5-ene
DBU	: 1,8-Diazabicyclo[5.4.0]undec-7-ene
DMAE	: 2-(Dimethylamino)ethanol
DMF	: Dimethylformamide
DMSO	: Dimethyl sulfoxide
DNP	: Dynamic Nuclear Polarization
DPPH	: 1,1-Diphenyl-2-picrylhydrazyl

EtOAc	: Ethyl Acetate
EtOH	: Ethanol
Et ₂ O	: Diethyl ether
EPR	: Electron Paramagnetic Resonance
eq.	: Equivalent
ESR	: Electron Spin Resonance
E _{1/2}	: Half-Wave Potential
E _{pa}	: Anodic Peak Potential
E _{pc}	: Cathodic Peak Potential
Fc/Fc ⁺	: Ferrocene/Ferrocenium couple
FT-IR	: Fourier Transform Infrared
G	: Gauss
g	: Gram
HMPA	: Hexamethylphosphoramide
HOMO	: Highest Occupied Molecular Orbital
H ₂ Pc	: Metal Free Phthalocyanine
Hz	: Hertz
IN	: Imino Nitroxide
ISC	: Intersystem Crossing
J	: Coupling Constant
K	: Kelvin
LUMO	: Lowest Unoccupied Molecular Orbital
L	: Liter
M	: Molar
m	: Multiplet
MALDI-TOF	: Matrix-Assisted Laser Desorption/Ionization Time-of-Flight
max	: Maximum
MeOH	: Methanol
MHz	: Megahertz
min	: minute
mL	: Mililiter
mp	: Melting Point
MPc	: Metallo Phthalocyanine
<i>m/z</i>	: mass-to-charge ratio

MS	: Mass Spectrometry
nm	: Nanometer
NMP	: N-Methyl-2-pyrrolidone
NMR	: Nuclear Magnetic Resonance
NN	: Nitronyl Nitroxide
<i>o</i> -DCB	: <i>o</i> -Dichlorobenzene
ORB	: Organic Rechargeable Battery
Pc	: Phthalocyanine
PhMe	: Toluene
Pn	: Phthalonitrile
ppm	: parts per million
PROXYL	: 2,2,5,5-Tetramethylpyrrolidine 1-oxyl
q	: Quartet
rt	: Room Temperature
s	: Second, Singlet
SCE	: Saturated Calomel Electrode
S/N	: Signal-to-Noise Ratio
subPc	: Subphthalocyanine
SWV	: Square Wave Voltammetry
t	: Triplet
TEMPO	: 2,2,6,6-Tetramethylpiperidine 1-oxyl
THF	: Tetrahydrofuran
TLC	: Thin Layer Chromatography
TsOH	: <i>p</i> -Toluenesulfonic acid monohydrate
UV-vis	: Ultraviolet-visible
V	: Volt
vs.	: versus

LIST of FIGURES

<u>Figure No:</u>	<u>Page</u>
1.1: Schematic Representation of the Target Polyradicals.	2
2.1: Structures of Carbon-Based Radicals.	6
2.2: Structures of Nitrogen-Based Radicals.	7
2.3: Structures of Oxygen-Based Radicals.	8
2.4: Structures of Nitroxide Radicals.	10
2.5: Structural Origins of Nomenclature of Nitronyl Nitroxide and Imino Nitroxide Radicals.	11
2.6: Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.	13
2.7: Electrochemical Processes of the Nitroxides.	14
2.8: Zeeman Splitting of Energy Levels of an Electron Spin ($S = \pm 1/2$) under Applied Magnetic Field.	16
2.9: Hyperfine Splitting of Zeeman Energy Levels of an Electron Spin ($S = \pm 1/2$) with a Nucleus ($S = I$).	17
2.10: Schematic Classification of the Arrangement of Spins.	19
2.11: Structures of the Organic Magnets and Their Metal Complexes.	21
2.12: Structures of the Nitroxides Employed in Organic Rechargeable Batteries.	23
2.13: Structures of the Some Nitroxides as DNP Agents.	24
2.14: Schematic Representation of the Profluorescent Nitroxides.	25
4.1: General Structures of the Phosphazenes.	32
4.2: Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.	33
4.3: Library of the Nitroxide Family Radicals in Cyclotriphosphazene-Nitroxide Hybrid Compounds.	34
4.4: Synthesis of hexa-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy) cyclotriphosphazene (111).	35
4.5: Synthesis of Mono-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy) cyclotriphosphazene Derivatives (112 , 113 , 114).	36
4.6: Synthesis of Chiral and Achiral Nitroxide-Functionalized Cyclotriphosphazenes.	37

4.7:	Synthesis of Dendrimer-Like TEMPO-Functionalized Cyclotriphosphazenes.	38
4.8:	Schematic Representation of the Hypothetic Molecules.	40
4.9:	Structures of the Reference Radical 7 and the Hexaradical 15 .	41
4.10:	Synthetic Routes to the Reference Radical 7 and the Hexaradical 15 .	42
4.11:	Conversion of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (3) to Acetone Oxime.	44
4.12:	Acetone Oxime as Impurity in FT-IR Spectrum of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (3).	45
4.13:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 15 , Inset: 10^{-3} M Chloroform Solution of 15 and Crystals of 15 .	47
4.14:	Cyclic Voltammograms of the Reference Radical 7 and the Hexaradical 15 Recorded at rt in Acetonitrile, 0.1 M <i>n</i> -Bu ₄ NBF ₄ as Supporting Electrolyte, Scan Rate of 50 mV/s.	49
4.15:	Anodic Square-Wave Voltammetry Analyses in 0.1 M <i>n</i> -Bu ₄ NBF ₄ /acetonitrile Solutions of the Radicals: a) for (0/+1) Process of 7 ; b) Calibration Curve for (0/+1) Process of 7 ; and c) for (0/+1) Process of 15 .	50
4.16:	X-band EPR Spectrum of 15 in Dichloromethane–Toluene (1:1) Solution (10^{-4} M) at 253 K and Its Simulation. Inset: EPR Spectrum of 7 at the Same Conditions and Its Simulation.	51
4.17:	Temperature Dependence of the Product of the Magnetic Susceptibility with Temperature (χT) for 15 ·0.5 toluene.	52
4.18:	Crystal of 15 on the X-ray Mounter.	53
4.19:	Molecular Structure of 15 by X-ray Diffraction on a Single Crystal. The Hydrogen Atoms and the Disorder of the Imino Nitroxide Moiety Have Been Removed for Clarity.	54
4.20:	Explanation of the Disorder on the Imino Nitroxides Moieties Due to the (Head to Tail) Positionnement.	54
4.21:	Head-to-tail Disorder on the Toluene.	55
5.1:	Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.	64
5.2:	Structures of the Reference Radical 6 , the Synthone 10 and the Hexaradical 16 .	66

5.3:	Synthetic Routes to the Reference Radical 6 and the Hexaradical 16 .	69
5.4:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 16 , Inset: 10^{-3} M Chloroform Solution of 16 and Powder of 16 .	70
5.5:	Cyclic Voltammograms of the Reference Radical 6 and the Hexaradical 16 Recorded at rt in Acetonitrile, 0.1 M <i>n</i> -Bu ₄ NBF ₄ as Supporting Electrolyte, Scan Rate of 50 mV/s for 6 and of 100mV for 16 .	72
5.6:	Square-Wave Voltammetry Analyses in 0.1 M <i>n</i> -Bu ₄ NBF ₄ /acetonitrile Solutions of the Reference Radical 6 : a) Anodic Sweep for (0/+1) Process; b) Calibration Curve of Anodic Sweep for (0/+1) Process; c) Cathodic Sweep for (0/+1) Process; d) Calibration Curve of Cathodic Sweep for (0/+1) Process.	73
5.7:	Square-Wave Voltammetry Analyses in 0.1 M <i>n</i> -Bu ₄ NBF ₄ /acetonitrile Solutions of the Hexaradical 16 : a) Anodic Sweep for (0/+1) Process; b) Cathodic Sweep for (0/+1) Process.	74
5.8:	EPR Spectra of the Radicals 6 , 10 , and 16 at 293 K at 10^{-4} M in Dichloromethane-Toluene (1:1) Mixture.	76
5.9:	Temperature Dependence of the Product of the Magnetic Susceptibility with Temperature (χT) for 16 .	77
5.10:	Crystal of 16 on the X-ray Mounter.	78
6.1:	Relationship of the Phthalocyanines with the Porphyrin Macrocycle. (Adopted from reference 100 and 102).	82
6.2:	Various Metallo Phthalocyanines.	84
6.3:	Substituent Positions of Phthalocyanines.	85
6.4:	Starting Materials for Syntheses of the Phthalocyanines.	86
6.5:	Structures of the Four Constitutional Isomers of 2(3),9(10),16(17),23(24)-Tetrasubstituted Metallophthalocyanines.	88
6.6:	Phthalocyanines Structures Formed Upon the Statistical Cyclotetramerization of Two Different Precursors.	89
6.7:	Synthesis of Unsymmetrical ABAB Type Phthalocyanines.	90
6.8:	Synthesis of Unsymmetrical Pc Through Ring Expansion of Subphthalocyanine.	91

6.9:	Synthetic Pathways for the 4,5-Dialkoxy- or 4,5-Diaryloxyphthalonitriles.	93
6.10:	Synthetic Pathways for 4-Substituted Phthalonitriles.	93
6.11:	Synthetic Pathways for 4-Nitrophthalonitrile.	94
6.12:	Typical UV-vis Spectra for a Phthalocyanine as a) metal free and b) metallated (Left). The Scheme of Energy Levels in Metallated Phthalocyanines with the First Two $\pi \rightarrow \pi^*$ Transitions, the Q- and B-bands Marked (Right). (Taken from Reference 133).	95
6.13:	Jablonski Diagram of Fluorescence Processes. (Taken from Reference 136).	96
6.14:	Spectrum Profiles for Excitations at Different Wavelengths and Their Corresponding Emissions. (Taken from Reference 136).	97
6.15:	Excitation and Emission Spectra of a Phthalocyanine. (Taken from Reference 137).	97
6.16:	Library of Nitroxide Functionalized Phthalocyanines via Axial Ligation of Nitroxides.	99
6.17:	Library of Nitroxide Functionalized Phthalocyanines via Incorporation of Radical Units into the Phthalocyanine Ring.	102
6.18:	One Ullman Radical Linked Phthalocyanines.	104
6.19:	Four Ullman Radical Linked Phthalocyanines.	105
6.20:	Synthetic Pathway for 4,5-Dineopentoxypthalonitrile 25 .	107
6.21:	Synthetic Pathway for 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile 31 .	109
6.22:	Synthetic Pathway for Phthalocyanine Monoaldehyde 34 .	112
6.23:	Synthetic Pathway for the Condensation Products 35 and 36 .	114
6.24:	Synthetic Pathway for the Monoradical Phthalocyanine 38 .	116
6.25:	Synthetic Pathway for the Phthalocyanine Tetraaldehyde 40 .	118
6.26:	Synthetic Pathway for the Condensation Product 42 .	119
6.27:	Synthetic Pathway for the Phthalocyanine Tetra Imino Nitroxide 44 .	121
6.28:	UV-Vis Spectra of 32 and 38 .	122
6.29:	Cyclic Voltammogram of Phthalocyanine 38 Recorded at rt in Dichloromethane, 0.1 M <i>n</i> -Bu ₄ NClO ₄ as Supporting Electrolyte, Scan Rate of 100 mV/s.	123

6.30:	EPR Spectra of the Radical 38 at 293 K at 10^{-4} M in Dichloromethane-toluene (1:1) Mixture.	124
6.31:	EPR Spectra of 44 at 293 K.	124
6.32:	EPR Spectrum of 44 at 293 K.	125
7.1:	Synthesis of Nitroxide Functionalized Phthalonitrile.	135
7.2:	Target Phthalonitriles 46 and 47 .	136
7.3:	Ullman Radicals Linked Phthalocyanines 48 and 49 .	137
7.4:	Synthetic Pathway to Phthalonitriles 46 and 47 .	138
7.5:	Fractions of Phthalonitrile 46 and 47 in Silica-gel Column.	139
7.6:	Synthetic Pathway to Ullman Radicals Linked Phthalocyanines 48 and 49 .	141
7.7:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 46 and 47 .	142
7.8:	Cyclic Voltammogram of the Phthalonitrile 46 Recorded at rt in Acetonitrile, 0.1 M <i>n</i> -Bu ₄ NBF ₄ as Supporting Electrolyte, Scan Rate of 100 mV/s.	143
7.9:	Cyclic Voltammogram of the Phthalonitrile 47 Recorded at rt in Acetonitrile, 0.1 M <i>n</i> -Bu ₄ NBF ₄ as Supporting Electrolyte, Scan Rate of 100 mV/s.	143
7.10:	EPR spectrum of 46 in dichloromethane–toluene (1:1) solution (10^{-4} M) at 293 K and its simulation.	144
7.11:	EPR spectrum of 47 in dichloromethane–toluene (1:1) solution (10^{-4} M) at 293 K and its simulation.	145
8.1:	FT-IR Spectrum of 2 .	148
8.2:	¹ H NMR Spectrum of 2 in CDCl ₃ (400MHz).	149
8.3:	¹³ C NMR Spectrum of 2 in CDCl ₃ (100MHz).	149
8.4:	FT-IR Spectrum of 3 .	150
8.5:	FT-IR Spectrum of 7 .	150
8.6:	MALDI-TOF MS Spectrum of 7 .	151
8.7:	FT-IR Spectrum of 12 .	151
8.8:	¹ H NMR Spectrum of 12 in CDCl ₃ (400MHz).	152
8.9:	¹³ C NMR Spectrum of 12 in CDCl ₃ (100MHz).	152
8.10:	³¹ P NMR Spectrum of 12 in CDCl ₃ (162MHz).	153
8.11:	MALDI-TOF MS Spectrum of 12 .	153

8.12:	FT-IR Spectrum of 14 (Crude Product).	154
8.13:	Comparison of FT-IR Spectrum of 12 and 14 (Crude Product).	154
8.14:	MALDI-TOF MS Spectrum of 14 (Crude Product).	155
8.15:	FT-IR Spectrum of 15 .	155
8.16:	MALDI-TOF MS Spectrum of 15 .	156
8.17:	UV-Visible Spectra of 7 in Acetonitrile, Chloroform and Toluene.	156
8.18:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 7 in Acetonitrile.	157
8.19:	Calibration Curve of 7 in Acetonitrile at 441 nm.	157
8.20:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 7 in Chloroform.	158
8.21:	Calibration Curve of 7 in Chloroform at 443 nm.	158
8.22:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 7 in Toluene.	159
8.23:	Calibration Curve of 7 in Toluene at 445 nm.	159
8.24:	UV-Visible Spectra of 15 in Acetonitrile, Chloroform and Toluene.	160
8.25:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 15 in Acetonitrile.	160
8.26:	Calibration Curve of 15 in Acetonitrile at 444 nm.	161
8.27:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 15 in Chloroform.	161
8.28:	Calibration Curve of 15 in Chloroform at 447 nm.	162
8.29:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 15 in Toluene.	162
8.30:	Calibration Curve of 15 in Toluene at 448 nm.	163
8.31:	X-band EPR Spectrum of 7 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 253 K and Its Simulation (Best Fitting Parameters are $g = 2.0025$, $a_{N1} = 9.2$ G, $a_{N2} = 4.3$ G, and $\Delta H_{p-p} = 1.55$ G).	163
8.32:	X-band EPR Spectra of 7 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	164
8.33:	X-band EPR Spectra of 15 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	165
8.34:	FT-IR Spectrum of 6 .	166
8.35:	MALDI-TOF MS Spectrum of 6 .	166
8.36:	FT-IR Spectrum of 10 .	167
8.37:	MALDI-TOF MS Spectrum of 10 .	167
8.38:	FT-IR Spectrum of 16 .	168
8.39:	Comparison the FT-IR Spectrum of 16 with That of 10 .	168
8.40:	MALDI-TOF MS Spectrum of 16 .	169

8.41:	UV-vis Spectra of 6 in Acetonitrile, Chloroform and Toluene.	169
8.42:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 6 in Acetonitrile.	170
8.43:	Calibration Curve of 6 in Acetonitrile at 583 nm.	170
8.44:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 6 in Chloroform.	171
8.45:	Calibration Curve of 6 in Chloroform at 608 nm.	171
8.46:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 6 in Toluene.	172
8.47:	Calibration Curve of 6 in Toluene at 631 nm.	172
8.48:	UV-vis Spectra of 16 in Acetonitrile, Chloroform and Toluene.	173
8.49:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 16 in Acetonitrile.	173
8.50:	Calibration Curve of 16 in Acetonitrile at 584 nm.	174
8.51:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 16 in Chloroform.	174
8.52:	Calibration Curve of 16 in Chloroform at 616 nm.	175
8.53:	UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of 16 in Toluene.	175
8.54:	Calibration Curve of 16 in Toluene at 631 nm.	176
8.55:	X-band EPR Spectrum of 6 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 293 K and Its Simulation. (Best Fitting Parameters are $g = 2.0031$, $a_N = 7.5$ G, and $\Delta H_{p-p} = 2.0$ G).	176
8.56:	X-band EPR Spectra of 6 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	177
8.57:	X-band EPR Spectrum of 10 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 293 K and Its Simulation (Best Fitting Parameters are $g = 2.0752$, $a_N = 7.6$ G, and $\Delta H_{p-p} = 2.2$ G).	178
8.58:	X-band EPR Spectrum of 10 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	179
8.59:	X-band EPR Spectra of 16 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	180
8.60:	FT-IR Spectrum of 24 .	181
8.61:	^1H NMR Spectrum of 24 in CDCl_3 (500MHz).	181
8.62:	^{13}C NMR Spectrum of 24 in CDCl_3 (125MHz).	182
8.63:	FT-IR Spectrum of 25 .	182
8.64:	^1H NMR Spectrum of 25 in CDCl_3 (500MHz).	183
8.65:	^{13}C NMR Spectrum of 25 in CDCl_3 (125MHz).	183
8.66:	FT-IR Spectrum of 30 .	184

8.67:	^1H NMR Spectrum of 30 in CDCl_3 (500MHz).	184
8.68:	^{13}C NMR Spectrum of 30 in CDCl_3 (125MHz).	185
8.69:	FT-IR Spectrum of 31 .	185
8.70:	^1H NMR Spectrum of 31 in CDCl_3 (500MHz).	186
8.71:	^{13}C NMR Spectrum of 31 in CDCl_3 (125MHz).	186
8.72:	FT-IR Spectrum of 32 .	187
8.73:	MALDI-TOF MS Spectrum of 32 .	187
8.74:	FT-IR Spectrum of 33 .	188
8.75:	MALDI-TOF MS Spectrum of 33 .	188
8.76:	FT-IR Spectrum of 34 .	189
8.77:	^1H NMR Spectrum of 34 in CDCl_3 (500MHz).	189
8.78:	^{13}C NMR Spectrum of 34 in CDCl_3 (125MHz).	190
8.79:	MALDI-TOF MS Spectrum of 34 .	190
8.80:	FT-IR Spectrum of 36 .	191
8.81:	MALDI-TOF MS Spectrum of 36 .	191
8.82:	FT-IR Spectrum of 38 .	192
8.83:	MALDI-TOF MS Spectrum of 38 .	192
8.84:	FT-IR Spectrum of 39 .	193
8.85:	MALDI-TOF MS Spectrum of 39 .	193
8.86:	FT-IR Spectrum of 40 .	194
8.87:	MALDI-TOF MS Spectrum of 40 .	194
8.88:	FT-IR Spectrum of 42 .	195
8.89:	FT-IR Spectrum of 40 vs. 42 .	195
8.90:	MALDI-TOF MS Spectrum of 42 .	196
8.91:	MALDI-TOF MS Spectrum of 44 .	196
8.92:	UV-Vis Spectra of 32 in Dichloromethane.	197
8.93:	UV-Vis Spectra of 38 in Dichloromethane.	197
8.94:	Calibration Curve of 32 in Dichloromethane at 701 nm.	198
8.95:	Calibration Curve of 38 in Dichloromethane at 695 nm.	198
8.96:	FT-IR Spectrum of 46 .	199
8.97:	MALDI-TOF MS Spectrum of 46 .	199
8.98:	FT-IR Spectrum of 47 .	200
8.99:	MALDI-TOF MS Spectrum of 47 .	200

8.100:	UV-vis Spectra of 46 in Acetonitrile, Dichloromethane and Toluene.	201
8.101:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 46 in Acetonitrile.	201
8.102:	Calibration Curve of 46 in Acetonitrile at 615 nm.	202
8.103:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 46 in Dichloromethane.	202
8.104:	Calibration Curve of 46 in Dichloromethane at 621 nm.	203
8.105:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 46 in Toluene.	203
8.106:	Calibration Curve of 46 in Toluene at 637 nm.	204
8.107:	UV-vis Spectra of 47 in Acetonitrile, Dichloromethane and Toluene.	204
8.108:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 47 in Acetonitrile.	205
8.109:	Calibration Curve of 47 in Acetonitrile at 445 nm.	205
8.110:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 47 in Dichloromethane.	206
8.111:	Calibration Curve of 47 in Dichloromethane at 447 nm.	206
8.112:	UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 47 in Toluene.	207
8.113:	Calibration Curve of 47 in Toluene at 631 nm.	207
8.114:	X-band EPR Spectra of 46 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	208
8.115:	X-band EPR Spectra of 47 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.	209
8.116:	Structures of the Compounds.1/7.	210
8.117:	Structures of the Compounds.2/7.	211
8.118:	Structures of the Compounds.3/7.	212
8.119:	Structures of the Compounds.4/7.	213
8.120:	Structures of the Compounds.5/7.	214
8.121:	Structures of the Compounds.6/7.	215
8.122:	Structures of the Compounds.7/7.	216
9.1	Changes in Fluorescent Intensity Upon Addition of Cu^{2+} .	218

LIST of TABLES

<u>Table No:</u>	<u>Page</u>
2.1: Nuclear Properties for Selected Nuclei.	18
4.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of 7 and 15 at Room Temperaturea.	48
4.2: Square Wave Voltammetry (SWV) Analyses of 15 .	50
4.3: Crystal Data and Structure Refinement of 15.0.5(C₇H₈) (CCDC1498365).	55
4.4: Selected Bond Lengths (Å) of Hexaradical 15 .	56
4.5: Selected Bond Angles (°) of Hexaradical 15 .	56
5.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of 6 and 16 at Room Temperaturea.	70
5.2: Square-Wave Voltammetry (SWV) Analyses of 16 .	75
6.1: Optimization of Condensation Conditions.	113
6.2: Optimization of Oxidation Conditions.	116
7.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of Phthalonitriles 46 and 47 at Room Temperaturea.	142

1. INTRODUCTION

A renewed interest in radical chemistry appeared in recent years thanks to the potential of these molecules to be redox active and to present interesting magnetic and optical properties. In the framework of this dissertation, particular emphasis has been placed on the control, synthesis and characterization of polyradical structures containing nitronyl nitroxide and imino nitroxide.

Two platforms were investigated in this context; cyclotriphosphazene and phthalocyanine as cyclotriphosphazene could bear a maximum of 6 nitronyl nitroxide and phthalocyanine 4, respectively (Figure 1.1).

These choices were dictated principally by the applications expected:

- Cyclotriphosphazene is well-known compounds with their ring opening polymerization. Nitronyl nitroxides/imino nitroxides decorated cyclotriphosphazenes are as promising monomers to prepare ambipolar electrode active materials upon their polymerization.
- Phthalocyanines are well-known species for their fluorescent properties used in sensor application. Imino nitroxide or nitronyl nitroxide appended phthalocyanines are considered as profluorescent molecules in which fluorescent could be retrieved upon coordination of the nitroxide species to the Cu^{2+} ion.

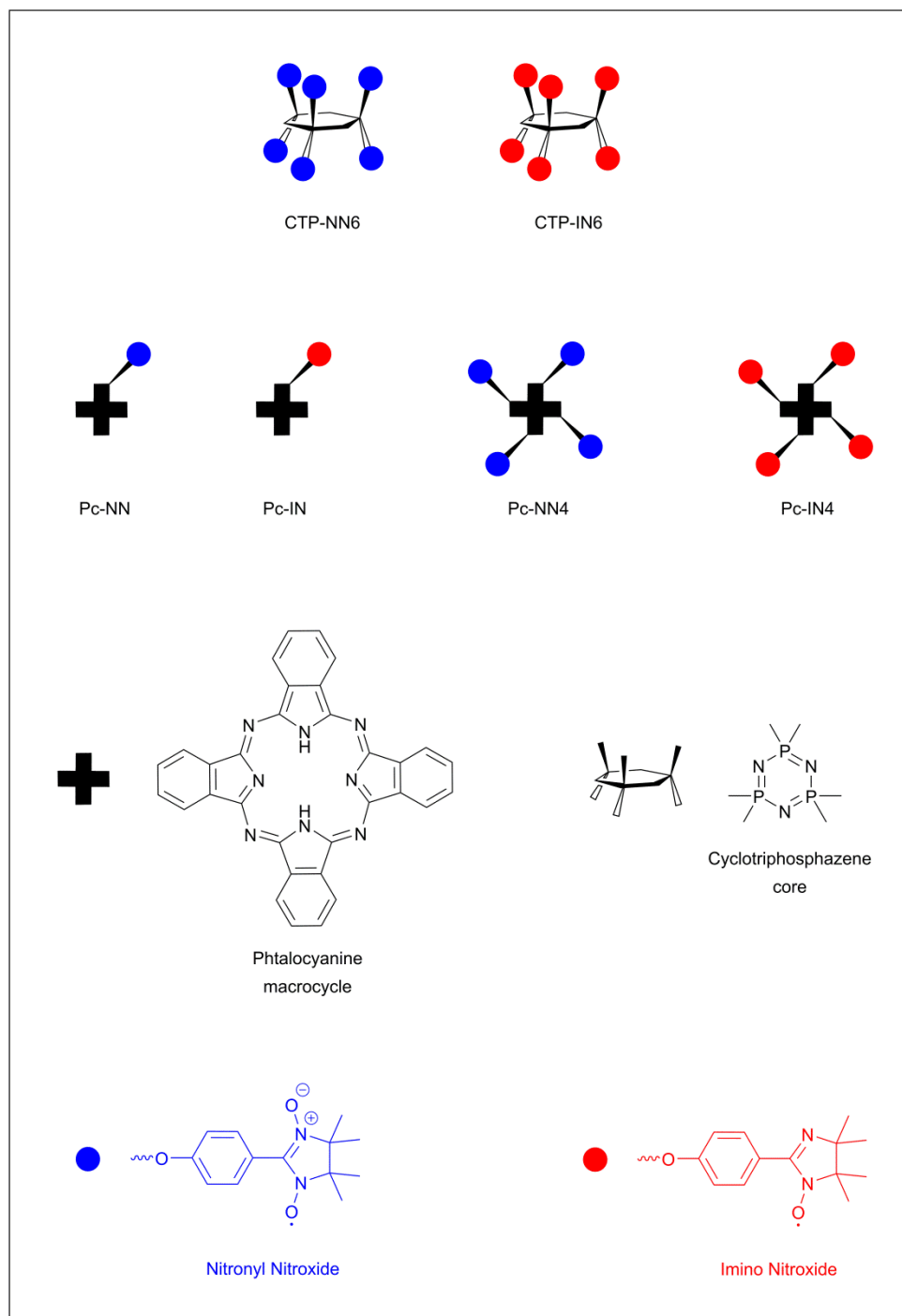


Figure 1.1: Schematic Representation of the Target Polyradicals.

This dissertation is composed of nine chapters. First chapter covers brief information about the dissertation.

Second chapter reviews the stable radicals, synthesis of imino nitroxide and nitronyl nitroxides, key characterizations of them and important applications of them as well.

Third chapter describes materials and methods.

Fourth chapter focuses on the synthesis of six imino nitroxide radicals appended cyclotriphosphazene derivative and its full characterizations such as melting point, FT-IR, MALDI-TOF MS, elemental analysis, absorption spectroscopy, electrochemical analysis, EPR, magnetic measurements, X-ray diffraction analysis. Additionally, two quantification methods –UV-vis and electrochemistry- are developed in order to determine the imino nitroxide radical content of a polyradical. Both methods successfully demonstrated the presence of six imino nitroxide moieties on the target compound **15**.

Fifth chapter describe the synthesis of six nitronyl nitroxide radicals bonded cyclotriphosphazene derivative and its full characterizations as like imino nitroxide counterpart. Developed quantification methods –UV-vis and electrochemistry- are transposed to the nitronyl nitroxide analogue and successfully demonstrated to presence of six nitronyl nitroxide on the title compound **16**.

Sixth chapter focuses on the synthesis and characterizations of imino nitroxide(s) appended phthalocyanine molecules. Phthalocyanine macrocycles are decorated with one or with four imino nitroxide radicals. Sensing ability of title compound to Cu^{2+} is investigated.

Seventh chapter depicts the preparation of imino nitroxide linked phthalonitrile and nitronyl nitroxide linked phthalonitrile and their characterizations.

Chapter eight contains the all spectra and structures of the compounds.

Chapter nine covers the overall results and conclusion.

2. SURVEY OF ULLMAN RADICALS

2.1. What is Stable Radical?

The radicals could be defined as molecules with one or more unpaired electrons. Virtually all of the molecules composed of p-block elements comply with the valence bond theory; obey the octet rule, have expected number of bonds and non-bonding electron (lone) pairs, and as a consequence they are diamagnetic. On the other hand, the radicals possess fewer bonds than anticipated and fewer lone pairs in association with the unpaired electron(s) and as a result they are paramagnetic. Many scientists conceptually consider the radicals as highly reactive short-lived species due to no or negligibly low activation barrier associated with spin loss reactions such as dimerization, hydrogen abstraction, disproportionation, oxidation or reduction.

On the basis of Ingold's definition [1], the radicals could be practically split into three groups in terms of stability;

- i) transient radicals which undergo fast decay,
- ii) persistent ones which have lifetime to be studied by spectroscopic methods,
- iii) stable radicals which could be isolated, handled, and stored in laboratory environment.

Stability of the radicals could be enhanced by employing two approaches. In the first, kinetic stability is derived from the incorporation of the bulky groups. Secondly, thermodynamic stability is provided by delocalization of the spin density over a number of atoms, which prevent dimerization and hydrogen abstraction due to the resonance stabilization. The radical always refers to stable radical within the framework of dissertation.

History of stable radicals dates back to the 19th century; first stable organic radical -triphenylmethyl or so-called trityl- was synthesized [2] by Gomberg at 1900. Afterwards, various classes of stable organic radicals were explored and successfully utilized in many applications.

Radicals are also synonymously named as open-shell compounds, odd-electron compounds, spin compound, or sub-valent compounds.

2.2. Stable Radicals

Numerous stable radicals have been reported up to date. The family of stable radicals are classified in a number of ways; chronological, structural, stability, or application based. Stable radicals are comprehensively reviewed by Hicks [3], [4] regarding their structures, synthesis, and applications as well. However, following sections will highlight the major classes of stable organic radicals classified by the atoms where the majority of spin density is located. Survey will primarily cover the structures of radicals briefly rather than chronological order or synthetic perspective.

2.2.1. Carbon-Based Radicals

The discovery of triphenylmethyl radical (Figure 2.1) was a landmark in the history of stable organic radicals as it marked the premier case of persistent organic radical [2]. Actually triphenylmethyl is in equilibrium with its dimeric form that prevents the isolation of the radical. Much of the spin density was found on the central carbon which sterically protected by three phenyl rings. Polychlorinated triphenylmethyl radical derivatives were found to display excellent stability [5].

Another type of carbon-based radical is phenalenyl radical (Figure 2.1). Spin density in phenalenyl radical was found chiefly on the six α carbon atoms which facilitate its stability. Phenalenyls are also in equilibrium with its dimer form which is connected through a σ -bond.

Kekule and non-Kekule biradicals (Figure 2.1) are also regarded as polycyclic conjugated carbon-based radicals. First representative example of Kekule biradical is the Tschitschibabin's radical synthesized in 1907 [6]. First non-Kekule biradical – trioxotriangulene- was prepared by Bushby in 1995 [7].

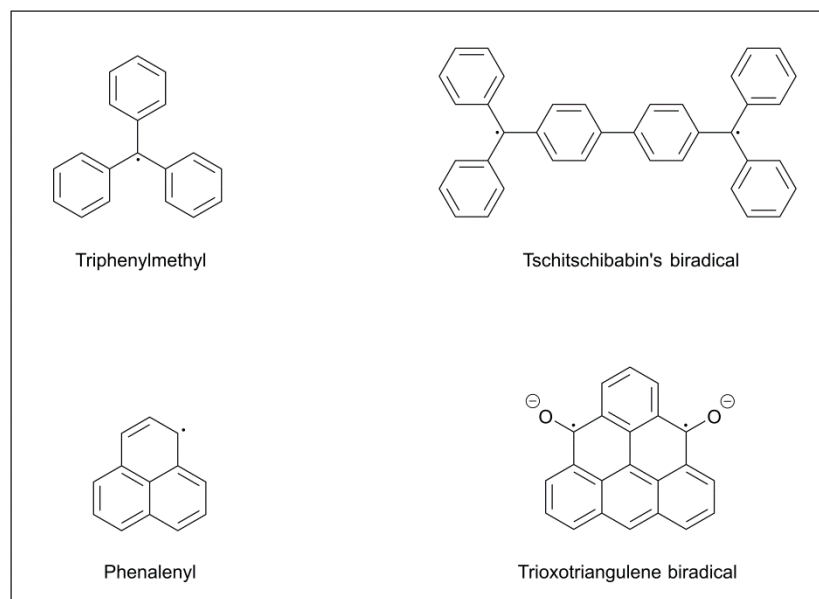


Figure 2.1: Structures of Carbon-Based Radicals.

2.2.2. Nitrogen-Based Radicals

Despite many of hydrazyl radicals are persistent in solution, 2,2-Diphenyl-1-picrylhydrazyl (DPPH, Figure 2.2) has an exceptional stability which is enhanced by the presence of electron-withdrawing groups lead to charge separated resonance contributions. Owing to its outstanding stability, DPPH has been used as reference standard for EPR spectroscopy [8].

The verdazyl radicals (Figure 2.2) can be considered as cyclic and resonance delocalized form of hydrazyl radicals. Kuhn synthesized the first verdazyl [9] in 1963. Since that, verdazyls are one of the comprehensively studied class of stable radicals.

The 1,2,4-benzotriazinyls (Figure 2.2) are another class of nitrogen-based radicals. Blatter synthesized the first example of 1,2,4-benzotriazinyl radicals [10] and claimed that “its stability comparable at least to that of DPPH” in 1968. The stability was derived from delocalization of the spin density which substantially found on all three nitrogen atoms and appreciable amount on the annulated benzene ring. Afterwards, their synthetic routes were diversified by Frank [11] and Koutentis Group [12]. Koutentis reported a super stable radical (Figure 2.2) which is thermally stable below its melting point of 160 °C and oxidatively stable even treating with KMnO_4 in refluxing benzene [13].

Dithiadiazolyl and dithiazolyl radicals (Figure 2.2) are also important members of nitrogen-based stable radicals.

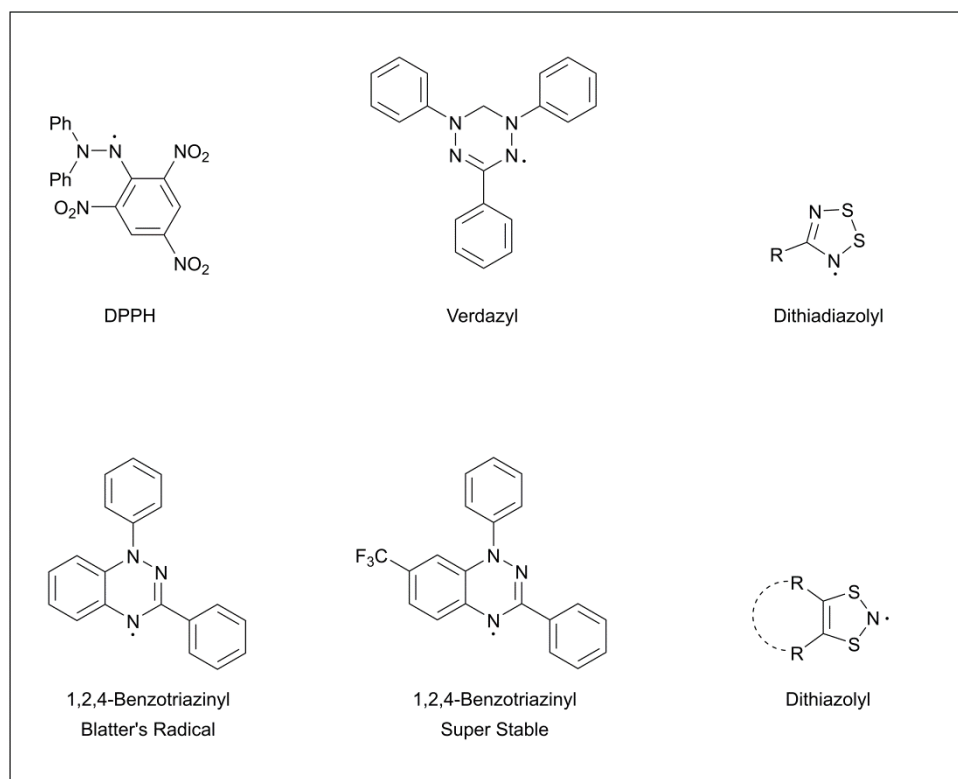


Figure 2.2: Structures of Nitrogen-Based Radicals.

2.2.3. Oxygen-Based Radicals

Phenoxy radicals (Figure 2.3) are another type of stable radicals. Stability was provided by the bulky substituents both at ortho and para positions. Computationally proven that spin density marginally found on the oxygen atoms rather than ortho and para carbons atoms [14]. Immense interest devoted to the phenoxy radicals due to their biological activities in living systems, and their antioxidant properties. Galvinoxyl radicals (Figure 2.3) are very similar form of phenoxy ones. Galvinoxyls are exceptionally stable due to both bulky substituents and delocalization of spin density over the structure. In general, they are isolable in pure form and essentially insensitive to oxygen.

Nitroxide radicals (Figure 2.3) are the most famous and probably the most studied class of stable radicals. The nitroxide radicals are discussed separately in Chapter 2.2.4 due to their paramount importance.

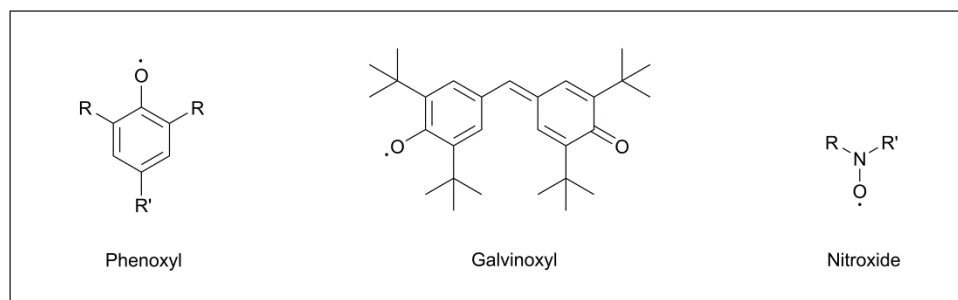


Figure 2.3: Structures of Oxygen-Based Radicals.

2.2.4. Nitroxide Radicals

Nitroxide chemistry has a long and fabulously rich history which dates back to 19th century. Ancestor of nitroxide is the Fremy's salt (Figure 2.4), an inorganic derivative [15]. First organic nitroxide (Figure 2.4) was prepared by Piloty in 1901 [16], just after the discovery of triphenylmethyl radical. Many of the nitroxide radicals are stable with respect to air, water, and dimerization. Their stability derived mainly from their sterically hindrance and resonance structure. Spin density of nitroxides primarily reside on nitrogen and oxygen atoms, with a preference for oxygen. The exceptional versatility and stability of nitroxide radicals allow post modification of the pre-form radical without destroying the radical character.

Synthesis of the first TEMPO radical (Figure 2.4) by Lebedev in 1960 was another landmark discovery in the history of nitroxide [17]. Spin of the TEMPO compounds was largely protected by the methyl groups or other bulky substituents. Outstanding stability of TEMPO led to preparation of various TEMPO derivatives and utilization in diverse applications.

Ullman reported the first nitronyl nitroxide radical (Figure 2.4) in 1968 [18]. Nitronyl nitroxide radicals have become center of attention for decades due to their electronic structure giving them extraordinary stability. Symmetrical ONCNO configuration of the nitronyl nitroxide structures have a nodal plane passing through the central carbon atom that resulted in the equally spreading of the spin distribution over the two NO groups [3]. The nature of the -R groups on the central carbon atom does not alter the electronic structure of nitronyl nitroxide and relevantly its stability because of the presence of node at central carbon. Turns out, numerous nitronyl nitroxide radicals were synthesized by varying the R group coming from the huge combination of aldehyde available.

Imino nitroxide (Figure 2.4) is one oxygen-loss analogue of nitronyl nitroxide. Accordingly, electronic structure is no longer symmetrical because the loss of one oxygen. Spin was localized mainly on the oxygen of nitroxide group. Additionally, spin density on the nitroxide nitrogen is more than that on the imino nitrogen.

Nitronyl nitroxide and imino nitroxide radicals are widely named as Ullman radicals in honor of nitronyl nitroxide's first report and his immense research on nitronyl nitroxide and its derivatives.

Rey developed two different methods [19],[20] to prepare some pyrimidinyl nitronyl nitroxide (Figure 2.4). Annelated nitronyl nitroxide, namely benzimidazole nitronyl nitroxide (Figure 2.4), was another analogue of nitronyl nitroxide. Computational and EPR studies of benzimidazole nitronyl nitroxide showed that spin density disposed mainly on the symmetrical ONCNO moiety and substantially on the annelated benzene ring [21]. Either trace of impurity in solution or highly vulnerable radical character leads such challenges; isolation in pure form and crystallization. Therefore, a few reports have been published regarding their X-ray structures and magneto-structural correlations [22]-[24].

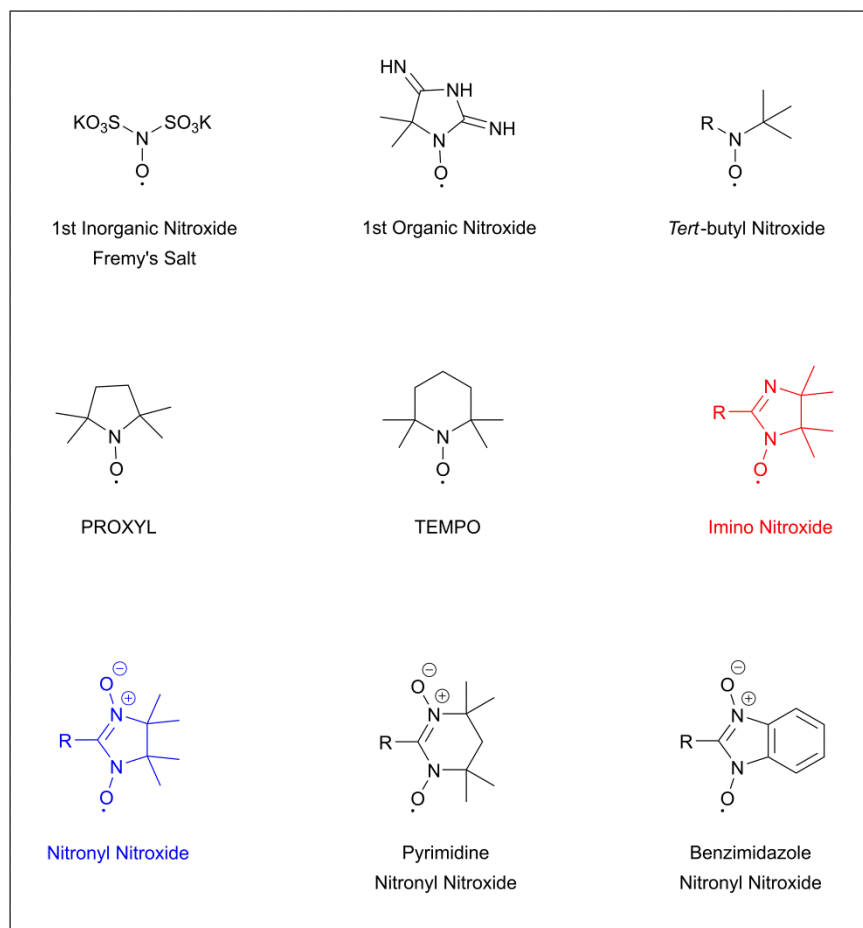


Figure 2.4: Structures of Nitroxide Radicals.

Trivial nomenclature of the compounds becomes mysterious for the non-specialists. Tracking the origins of the common names immensely used by specialists is sometimes a hard task. In order to better understanding the names of nitronyl nitroxide and imino nitroxide, structural origins of them were depicted in Figure 2.5.

Generally, nitronyl nitroxide is abbreviated as NN whereas imino nitroxide as IN.

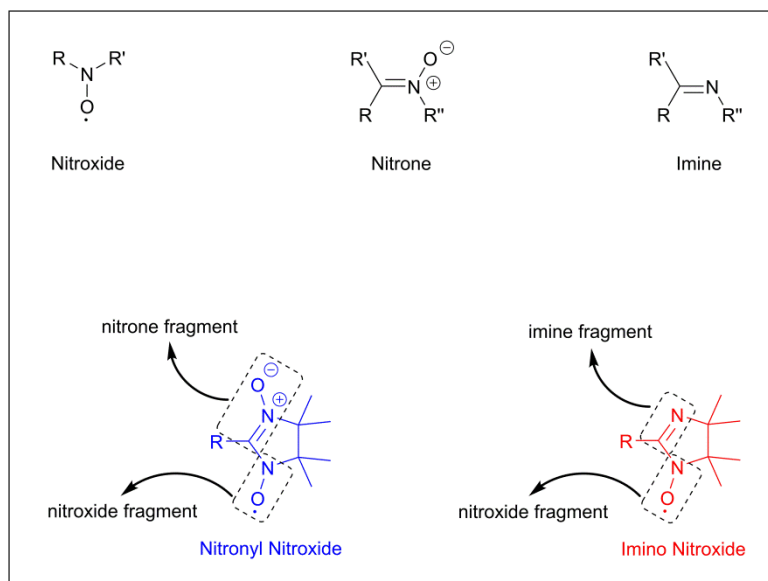


Figure 2.5: Structural Origins of Nomenclature of Nitronyl Nitroxide and Imino Nitroxide Radicals.

2.3. Synthesis of Nitronyl Nitroxide and Imino Nitroxide

The method developed by Ullman use mostly the commercial aldehydes and did not describe the preparation of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**). The Ullman's method consists in four steps;

- i) preparation of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**), (a key precursor),
- ii) preparation of an aldehyde (another key precursor),
- iii) condensation of the aldehyde with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) to form imidazolidine derivative (condensation product),
- iv) oxidation of condensation product using suitable oxidants (NaIO_4 , PbO_2 , MnO_2).

From the synthetic perspective, Ullman route (Figure 2.6) is a simple and straight way [25]. The versatility of this method has made it dominant synthetic strategy toward the synthesis of nitronyl nitroxide. Tamura made substantial contributions [26] to Ullman procedure. Such optimizations are solvent free reaction in the presence of *p*-toluene sulfonic acid as catalyst, room temperature process and

efficient conversion of the *vic*-dinitro ones to the bishydroxylamino derivative with Al/Hg amalgam.

Noteworthy that purity of the 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) have direct impact on the success of the synthesis of nitronyl nitroxide. As expected, condensation step generates the 1,3-dihydroxyimidazolidine derivatives observed for the majority of the cases (Figure 2.6). However, the 1,3-dihydroxyimidazolidine derivatives can also be dehydrated (Figure 2.6) to 1-hydroxy-2-imidazoline in certain cases in solution, particularly at elevated temperatures [27]. In highly exceptional case dehydration took place even at room temperature, as presented during the condensation of hexaaldehyde **12** with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) (Chapter 4.5). In some case, it is also possible to afford a mixture of both of them.

Condensation products suffer from low solubility. Consequently, the purification and characterization of such products are always a challenge, thus the synthesis is generally continued without further purification.

Oxidation (Figure 2.6) of the condensation product can be carried out by employing various oxidants such as NaIO₄, PbO₂, MnO₂, or even air.

Way I oxidation of 1,3-dihydroxyimidazolidine is entitled to expect the generation of corresponding nitronyl nitroxides. Similarly, way II oxidation of 1-hydroxy-2-imidazoline would afford solely the imino nitroxide. In rare cases, way III oxidations would take place in a media of excess oxidants [28] and give the imino nitroxide in contrary to anticipated nitronyl nitroxide one (Figure 2.6).

Such complex situations are encountered due to multiple factors;

- i) unknown identity of the condensation product,
- ii) whether the condensation product as being sole or as being mixture,
- iii) ungovernable oxidations conditions; whether way I oxidation or way III oxidation would proceed,
- iv) in some cases, labile nature of nitronyl nitroxide which being converted itself to the corresponding imino nitroxide.

Luneau developed a method allowing the conversion (Figure 2.6) of nitronyl nitroxide to imino nitroxide through treatment of the nitronyl nitroxide with sodium nitrite in acidic media [29].

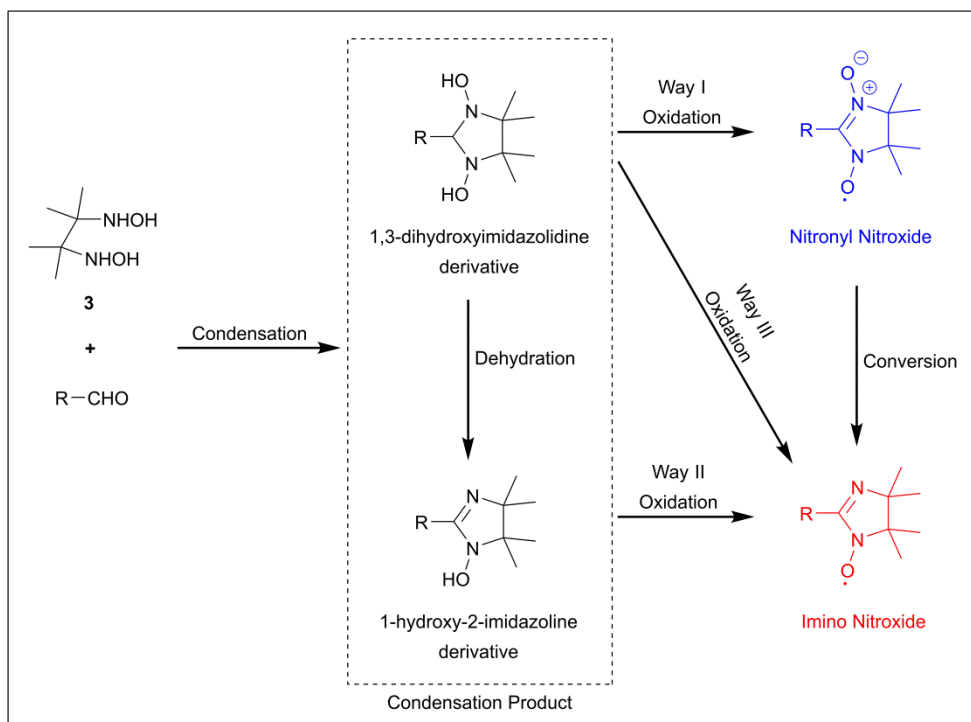


Figure 2.6: Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.

2.4. Characterizations of Nitronyl Nitroxides and Imino Nitroxides

Nitronyl nitroxides and imino nitroxide radicals are characterized with various spectroscopic methods. Their common characterizations are discussed briefly in the succeeding sections.

2.4.1. Electronic Structure Characterizations

Electronic structural characterizations of radicals are carried out by absorption spectroscopy. Each radical type has its own spectroscopic fingerprints which unambiguously identify it [30].

Nitronyl nitroxide radicals have a characteristic blue color both in solid state and in solution whereas imino nitroxides are from orange to crimson in solid state and orange to red in solution. Both nitroxides show a broad absorption band with vibronic constituents in the visible region. For the nitronyl nitroxides and imino nitroxides their specific band intrinsic of the nitroxide fragment are located around $\lambda_{\max} \approx 610$ nm and $\lambda_{\max} \approx 443$ nm, respectively. These bands are attributed to $n \rightarrow \pi^*$

transitions of the nitroxide residue. The longer wavelength (~610 nm) observed for the nitronyl nitroxide is attributed to the higher symmetrical structure of the ONCNO fragment, contrary to the unsymmetrical NCNO geometry of imino nitroxide counterparts [30].

2.4.2. Electrochemical Characterizations

Both nitronyl nitroxides and imino nitroxides are redox-active molecules to be either oxidized (p-type redox) to oxo-ammonium cation or reduced (n-type redox) to aminoxy anion (Figure 2.7).

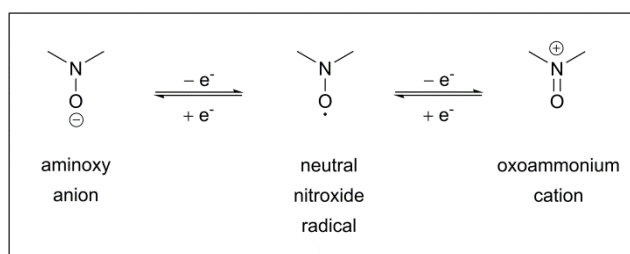


Figure 2.7: Electrochemical Processes of the Nitroxides.

Their electrochemical characteristics [31] are investigated mostly by cyclic voltammetry (CV). In general, nitronyl nitroxides display reversible oxidation and reversible reduction waves around -0.812 V vs. SCE and 0.748 V respectively. For imino nitroxides, quasi-reversible or irreversible oxidations are observed at 1.183 V and reversible reductions at -0.881 V.

Smaller oxidation potentials (0.748 V) of nitronyl nitroxides are attributed to their symmetrical ONCNO structure in comparison to higher potentials (1.183 V) of imino nitroxide counterparts which have unsymmetrical NCNO configuration.

2.4.3. EPR Characterizations

EPR (Electron Paramagnetic Resonance) is a spectroscopic technique that detects species that have unpaired electrons. It is also often called ESR (Electron Spin Resonance).

EPR is a magnetic resonance technique very similar to NMR (Nuclear Magnetic Resonance). However, instead of measuring the nuclear transitions in the sample, we are detecting the transitions of unpaired electrons in an applied magnetic field. Like a proton, the electron has “spin”, which gives it a magnetic property known as a magnetic moment. The magnetic moment makes the electron behave like a tiny bar magnet. When an external magnetic field is supplied, the paramagnetic electrons can either orient in a direction that parallel or antiparallel to the direction of the magnetic field. This creates two distinct energy levels (Figure 2.8) for the unpaired electrons and allows us to measure them as they are driven between the two levels [32], [33].

Initially, there will be more electrons in the lower energy level (i.e., parallel to the field) than in the upper level (antiparallel). We use a fixed frequency of microwave irradiation to excite some of the electrons in the lower energy level to the upper energy level. In order for the transition to occur we must also have the external magnetic field at a specific strength, such that the energy level separation between the lower and upper states is exactly matched by our microwave frequency. In order to achieve this condition, we sweep the external magnet’s field while exposing the sample to a fixed frequency of microwave irradiation. The condition where the magnetic field and the microwave frequency are “just right” to produce an EPR resonance (or absorption) is known as the resonance condition [33].

For a system with one unpaired electron placed in magnetic field experiences the quantization of spin state and exhibits discrete spin states according to the spin multiplicity rule, $2S + 1$. The interaction between spin and field is described by the Zeeman-effect. In the absence of an applied field α or β spin states of the electron are degenerate as shown in Figure 2.8. Application of an applied field perturbs the degeneracy of the two spin states. The α spin state with magnetic moment opposite to the applied field, rises in energy while the β spin state having magnetic moment aligned with the applied field, decreases in energy as the strength of the applied field increases (Figure 2.8). When a frequency of energy which matches the energy separation between the two spin states is applied, the absorption occurs; this causes a transition between two spin states. The energy difference between two spin states is proportional to the applied magnetic field. The selection rule for transition between two levels is $\Delta M_S = \pm 1$.

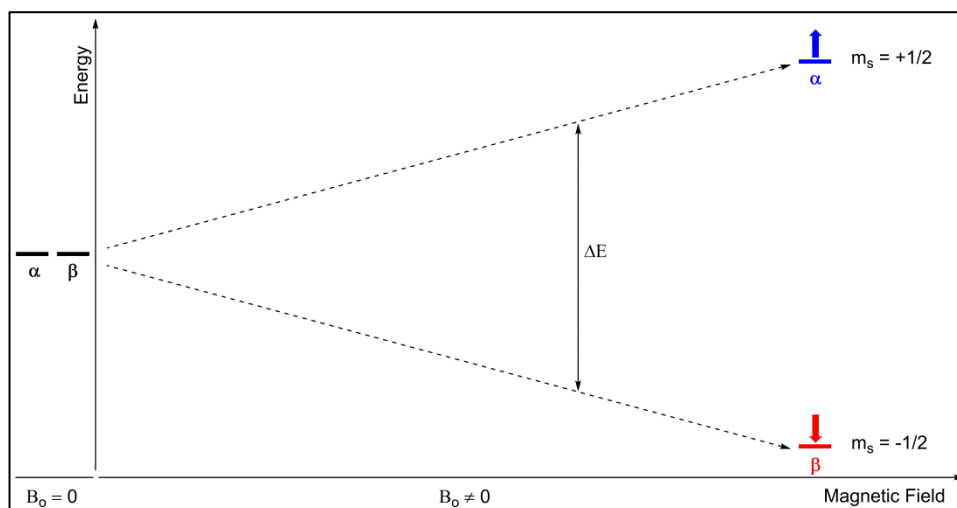


Figure 2.8: Zeeman Splitting of Energy Levels of an Electron Spin ($S = \pm 1/2$) under Applied Magnetic Field.

Unpaired electron in the molecules is not only interacting with solely the applied (outside) magnetic field but also interacting with nearby magnetically active atoms whose magnetism generated by their intrinsic nuclear spin. Each magnetic fields by the each of neighboring magnetically active atoms (nuclei with non-zero nuclear spin, $I \neq 0$) resulted in split extra states. Emphatically, split each energy levels (resulted from applied magnetic field) will be split additionally dependent on the nuclear spin number of the interacted atoms (Figure 2.9). Principally, each split energy levels correspond to a transition. Consequently, each transition from the degenerate state to the excited state could be monitored as a peak in EPR spectra.

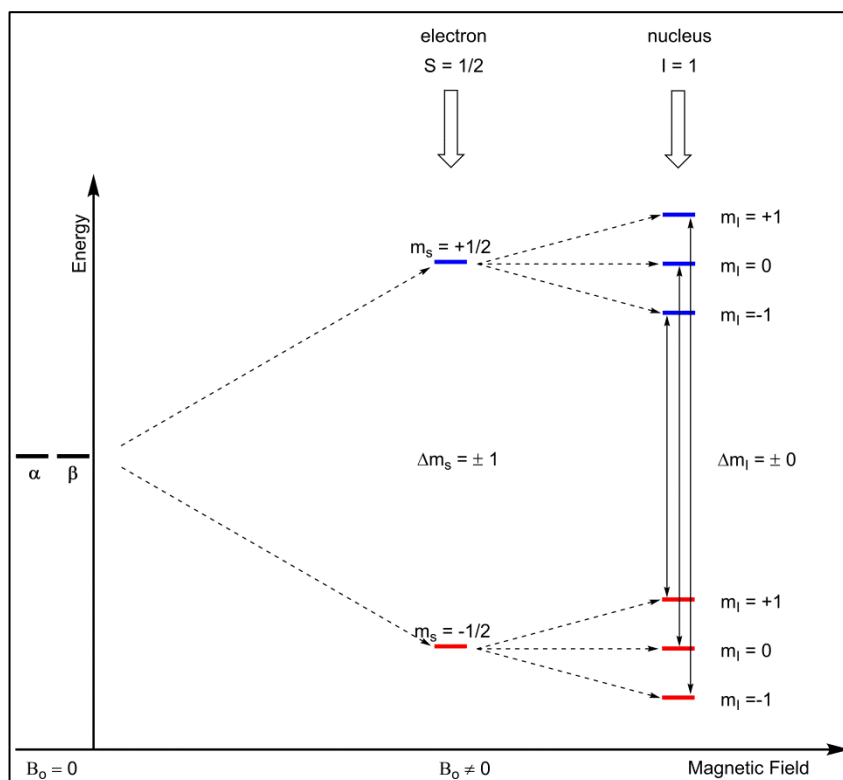


Figure 2.9: Hyperfine Splitting of Zeeman Energy Levels of an Electron Spin ($S = \pm 1/2$) with a Nucleus ($S = I$).

The interaction between the unpaired electron and magnetically active atoms is called hyperfine coupling which is observed as multi-lined spectra in EPR. In such cases, the spacing between the EPR spectral lines indicates the degree of interaction between the unpaired electron and the perturbing nuclei. The hyperfine coupling constant of a nucleus is directly related to the spectral line spacing and, in the simplest cases, is essentially the spacing itself.

EPR technique is very sensitive to local environments of spin. Therefore, the analysis of multi-lined ESR spectrum sheds light on the molecular structure (hyperfine structure) near the unpaired electron. The numbers of hyperfine lines grow multiplicatively with the number n of magnetic nuclei. Each additional nucleus splits every line into equidistant $2I + 1$ lines of same intensity. For n number of equivalent nuclei the number of lines can be given by $2nI + 1$. Distribution of intensities in an hyperfine pattern is calculated from the Pascal's triangle. Theoretical and practical aspects of EPR spectroscopy were comprehensively discussed in the reference books [34] but beyond scope of brief practical EPR aspects.

Nuclear spin number (I) of the perturbing nuclei plays a critical role in the splitting and shape of the related spectrum. Various nuclei with non-zero nuclear spin are tabulated in Table 2.1.

Table 2.1: Nuclear Properties for Selected Nuclei.

Nuclei	Spin (I)	Abundance (%)
^1H	$\frac{1}{2}$	99.988
^2H	1	0.011
^{19}F	$\frac{1}{2}$	100
^{13}C	$\frac{1}{2}$	1.07
^{29}Si	$\frac{1}{2}$	4.67
^{14}N	1	99.636
^{15}N	$\frac{1}{2}$	0.364
^{31}P	$\frac{1}{2}$	100
^{17}O	$\frac{5}{2}$	0.038
^{33}S	$\frac{3}{2}$	0.75

EPR spectra of the nitroxide radicals have characteristic features [4] in terms of splitting pattern, hyperfine coupling constant, and $g_{\text{isotropic}}$. If there is no perturbing nuclei other than nitroxide's nitrogen, nitroxide radicals exhibit three-line splitting pattern with intensity of 1:1:1. The three-line spectrum is raised by interaction of the unpaired electron with ^{14}N isotope of nitrogen atom of the nitroxide radical.

For the nitronyl nitroxide, EPR spectrum have five-line splitting pattern with the relative intensity of 1:2:3:2:1. The five-line spectrum originated from the interaction of the unpaired electron with two equivalent ^{14}N nitrogen atoms in the imidazoline ring. For the imino nitroxide, EPR spectrum have seven-line splitting pattern with the relative intensity of 1:1:2:1:2:1:1. The seven-line spectrum reasoned by the interaction of the unpaired electron with two unequivalent ^{14}N nitrogen atoms in the imidazoline ring.

2.4.4. Magnetic Characterizations

The magnetic susceptibility (χ) is one measure of the magnetic properties of a material. The susceptibility indicates whether a material is attracted into or repelled out of a magnetic field, which in turn has implications for practical applications. Quantitative measures of the magnetic susceptibility also provide insights into the

structure of materials, providing insight into bonding and energy levels. Magnetic susceptibility is a dimensionless proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field. Susceptibility is defined as $M = \chi H$ where M is the magnetization (magnetic moment per unit of volume) and H is magnetic field strength. The molar magnetic susceptibility, χ_M , is obtained by multiplying χ by the molar volume and is reported as emu/mol. Magnetic susceptibility is a solid-state phenomenon arising from the bonding (intramolecular) and spatial (intermolecular) interactions between individual open-shell units in a crystal lattice. The arrangement of spins in a bulk material can give rise to several different types of magnetism which are shown in Figure 2.10.

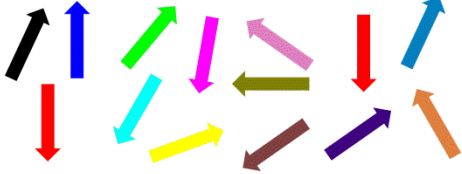
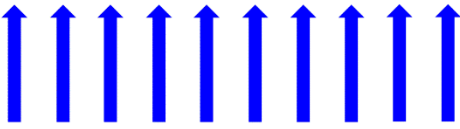
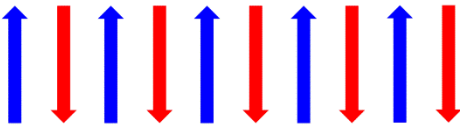
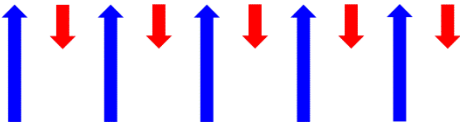
 Paramagnetic	Spins are randomly oriented (above any of the others T_C or T_N)
 Ferromagnetic	Below T_C, spins are aligned parallel in magnetic domain
 Antiferromagnetic	Below T_N, spins are aligned antiparallel in magnetic domain
 Ferrimagnetic	Below T_C, spins are aligned antiparallel, but do not cancel

Figure 2.10: Schematic Classification of the Arrangement of Spins.

Unpaired electron has a spin which produce magnetic moment. Emphatically, compounds with unpaired electron act as a magnet. Magnetic properties of the radicals in bulk are measured with SQUID (superconducting quantum interference

device) through either sweeping the magnetic field or sweeping the temperature. Various nitronyl nitroxide and imino nitroxide radicals are investigated in terms of magnetic behavior either as their pure organic form or as their complexes with metals [35].

2.5. Applications of Nitroxides

Nitroxide radicals have various structural properties stem from the unpaired electron(s) on their outermost shell. Numerous nitroxides were involved in a rich array of applications. Catalysis for the selective oxidation of alcohols to aldehyde [36], mediators for the controlled polymerization [37], sensor for ascorbic acid [38] are few examples of their applications. From the author's perspective, key applications of nitroxide radicals are discussed in the following sections.

2.5.1. Building Blocks in Magnetic Materials

The primary characteristic feature of the nitroxide radicals is their magnetic properties due to the possession of a spin which is generated by unpaired electron(s). Magnetism is regarded as a property of bulk materials. In order to achieve magnetic properties in these organic molecules, it is necessary to obtain cooperative interactions among their unpaired electrons, emphatically to keep the unpaired spins parallel to each other. However, governing such spin interactions turned out to be challenging task to accomplish. It is consequently not surprising that the first organic ferromagnet [39] was reported in 1991, decades after the theoretical suggestion published 1963 [40].

The creation of organic magnets is based on two axes; the preparation of spin-containing building blocks such as radicals and the study of their magnetic property.

Several strategies were followed to achieve molecular material with magnetic property.

Several spin carrying organic units are currently in active use towards building organic based magnets. For assembling a high spin molecule, the spin alignment in the organic compound must be arranged in such a way that interactions between the spins are allowed to be parallel (ferromagnetic, $S \geq 1$).

Pure Organic Approach: The first organic ferromagnet reported in 1991 was *p*-nitrophenyl nitronyl nitroxide (Figure 2.11) with $T_c = 0.65$ K [39]. Another organic ferromagnet was nitroxide biradical, *N,N'*-dioxy-1,3,5,7-tetramethyl-2,6-diazaadamantane (Figure 2.11) with $T_c = 1.48$ K [41]. These reports triggered the synthesis of various nitroxide radicals and analysis of their magnetic properties.

Organic-Inorganic Approach: Another approach relies on the combination between paramagnetic metal ions and pure organic radicals, leading to a new class of hybrid organic-inorganic materials. Most representative example is based on the chemistry coordination of nitroxide radicals with metal(hexafluoroacetylacetonate) mostly to $\text{Cu}(\text{hfac})_2$, $\text{Ni}(\text{hfac})_2$, $\text{Mn}(\text{hfac})_2$. Primarily, oxygen atoms of nitroxides (Figure 2.11) are employed as coordinating sites to the metals [42]-[44]. However, additional coordinating sites (Figure 2.11) such as nitrogen atoms of heterocyclic rings are also utilized in some complexes [29]. Nitroxide-metal complexes were extensively studied for decades, as demonstrated by the numerous examples present in literature [4],[29].

Several books and reviews comprehensively discussed those magnetic materials [4], [35].

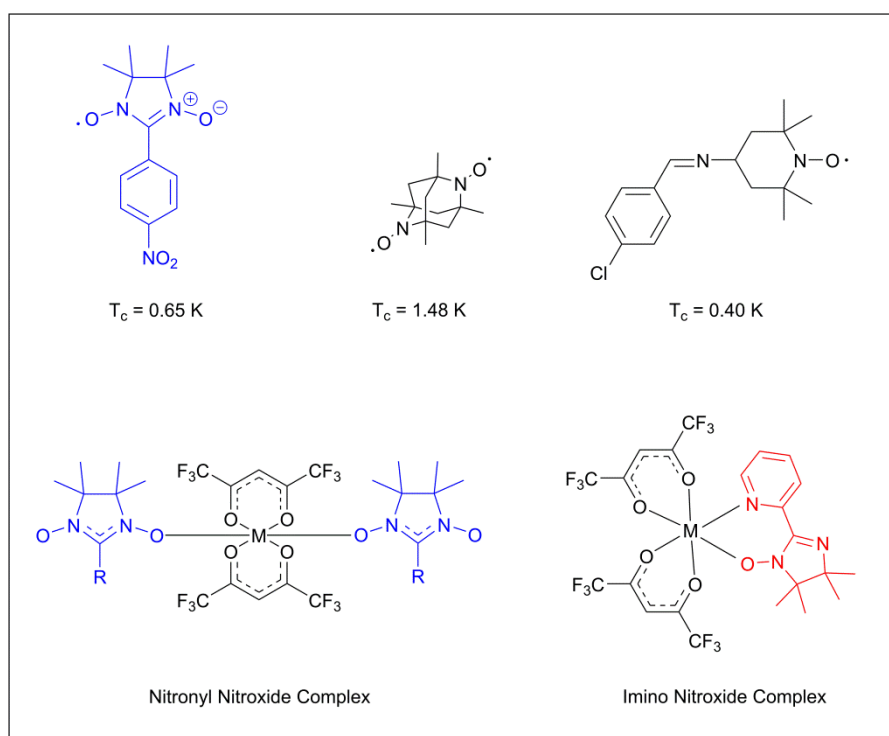


Figure 2.11: Structures of the Organic Magnets and Their Metal Complexes.

2.5.2. Electrode Active Material in Organic Rechargeable Batteries

Nitroxide radicals in particular are redox-active compounds. Nitroxides would be oxidized (p-type redox) to oxoammonium cation and reduced (n-type redox) to aminoxy anion. Reversibility of the redox processes is required for the materials to be utilized in rechargeable batteries. Their excellent electrochemical properties makes them ideal candidate as electrode active material for rechargeable batteries. With redox-active feature in hand, Nakahara explored new avenue on nitroxide chemistry by utilizing poly(2,2,6,6-tetramethylpiperidinylox-4-yl methacrylate), a polymer with pendant TEMPO radicals (Figure 2.12), as cathode active material [45] in organic rechargeable batteries (ORBs). Radical polymers carrying TEMPOs, PROXYLs, t-butyl nitroxides on various polymer backbone were synthesized and successfully demonstrated in ORBs [46],[47]. Features such as fast electron transfer rate, high cyclability and high battery electrode capacity make nitroxide polymers as good electrode active materials [48], [49]. However, those radicals mostly exhibit p-type redox and were employed only in cathode. Achievements on radical polymers battery can be regarded as milestones toward development of flexible, printable, and even wearable energy storage devices. Nishide demonstrated for the first time that poly(nitronyl nitroxide styrene) have the ability to be a bipolar (both n- and p-type) electrode active material [50]. However, the monomer structure (backbone of corresponding polymer) with pendant nitronyl nitroxides (Figure 2.12) are few up to date in literature; styrene [50], phenylacetylene [51], and norbornene [52]. Beyond the monomer structure, polymerization without loss of spin content is an important challenge. In synthetic sense, diversification of the monomer structure and polymerization technique are still tough challenge.

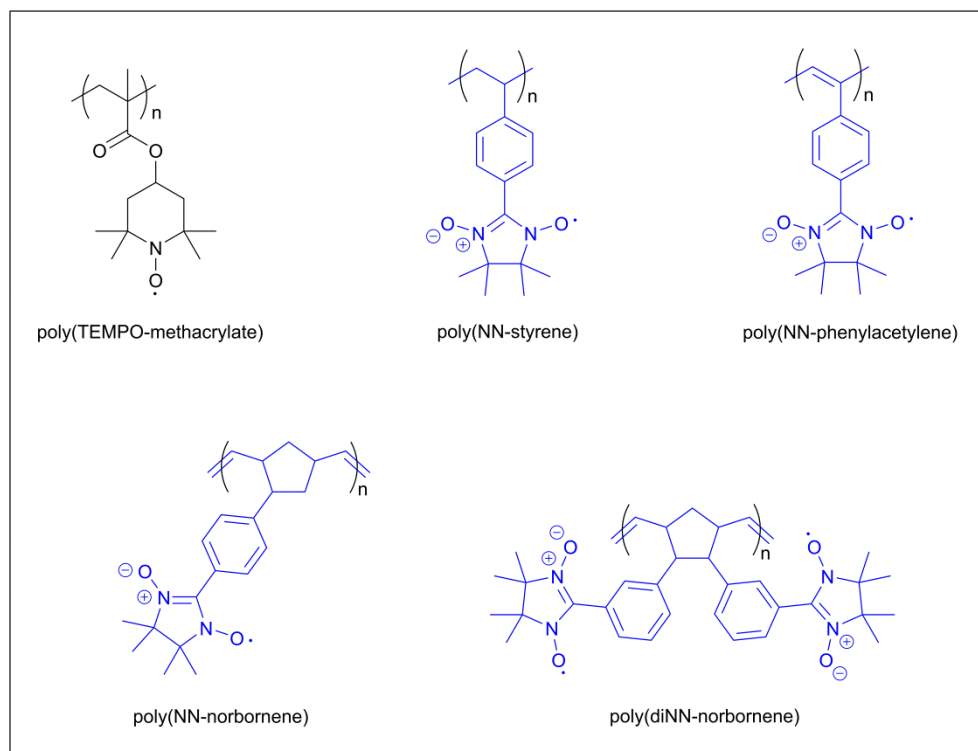


Figure 2.12: Structures of the Nitroxides Employed in Organic Rechargeable Batteries.

2.5.3. Dynamic Nuclear Polarizing Agents in NMR Spectroscopy

One of the most widely used spectroscopic technique is the nuclear magnetic resonance (NMR) spectroscopy in order to get information on the structure and dynamics of biological and chemical materials. A variety of samples such as solutions, powders and hydrated protein extracts can be studied in NMR. However, majority of the biological samples are so dilute to be directly analyzed in NMR spectroscopy which have intrinsically low sensitivity. Either concentration of the dilute biological samples or enhancement of the relevant signals is required in order to obtain practically valuable information from the biological samples. Latter one is technically viable with state-of-the-art instruments.

Dynamic nuclear polarization (DNP) is a method that increases the sensitivity of NMR by several orders of magnitude. It exploits a polarization transfer from unpaired electrons to neighboring nuclei which leads to an absolute increase of the signal-to-noise ratio (S/N). Consequently, biological samples with much lower concentrations can now be studied in hours or days compared to several weeks [53].

- by absorption spectroscopy for colorimetric changes,
- by EPR spectroscopy for changes in paramagnetic species,
- by electrochemistry for changes in redox characteristics,
- by fluorescence spectroscopy for changes in fluorescence properties.

One of the emerging fields is the fluorescence based sensors due to their high selectivity, high accuracy, and low detection limits [59]. Fluorescence based sensors have two mechanism for signaling; fluorescence on and fluorescence off. In the former one, probe molecule has no fluorescence in the absence of analyte, however fluorescence is restored upon recognition of the analyte. In the latter case, probe molecule has fluorescence in the absence of analyte, while fluorescence is quenched in the presence of the analyte.

Fluorescence turn-on probes are assembled with two constituents; fluorophore and quencher. In principal, quencher linked fluorophore display no fluorescence property but fluorescence is restored upon silencing of the quencher. The nitroxide radicals are effective fluorescence quencher which discovered by Griffith in 1965 [60]. In particular of nitroxides based fluorescence probes, quenching by nitroxide was accomplished through a number of ways; converting the nitroxide to hydroxylamine, and trapping the nitroxide with other radical species (Figure 2.14).

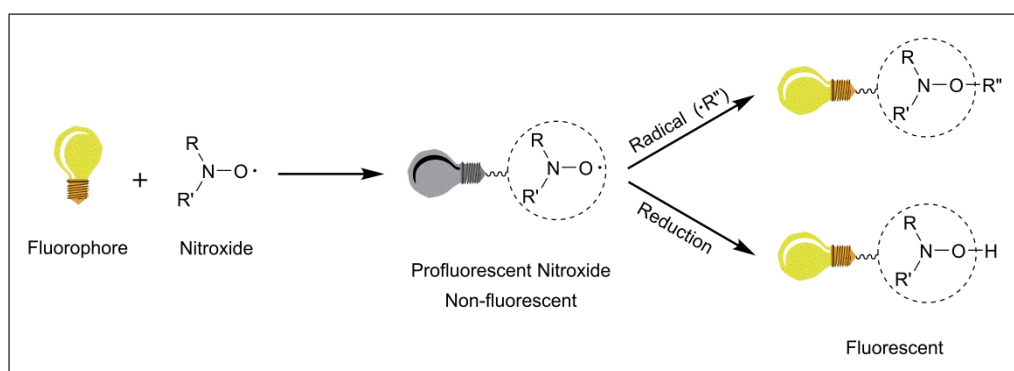


Figure 2.14: Schematic Representation of the Profluorescent Nitroxides.

3. MATERIALS AND METHODS

3.1. Reagents and solvents

All reagents, purchased from fine chemical suppliers Aldrich, Merck, Alfa Aesar, TCI, and Fluka, were used without further purification unless otherwise stated. Hexachlorocyclotriphosphazene was purified by sublimation. K_2CO_3 was dried at 150 °C under vacuum. Solvents were either used as commercially supplied or used as purified by standard techniques. Anhydrous THF was freshly distilled over sodium/benzophenone media.

3.2. Methods

Nonaqueous reactions were performed in oven-dried glassware under argon atmosphere at reported temperature. Microwave reactions were carried out in Milestone Start S Microwave Labstation for Synthesis at specified conditions. The reactions were carried out either in reagent grade solvents or in dry solvents if necessary. The reactions were monitored by thin layer chromatography on Merck silica gel 60 F254 precoated aluminum sheets. Spots were visualized either by UV 254 nm light or by staining with acidic ninhydrin solution. Column chromatography was performed on Merck silica gel 60 (230–400 mesh size) using the appropriate solvent system as eluent. Distilled technical solvents were used as eluent for column purifications.

3.3. Melting Points

Melting points were obtained using Stuart SMP3 melting point apparatus and were uncorrected.

3.4. Elemental Analysis

Elemental analysis was performed on a Thermo Finnigan Flash 1112 Series Elemental Analyzer operated at The Scientific and Technological Research Council of Turkey (TUBITAK), Marmara Research Center, Institute of Chemical Technology.

3.5. Infrared Spectroscopy

Infrared spectra were recorded on a PerkinElmer Spectrum 100 FT-IR spectrometer with an attenuated total reflection (ATR) accessory featuring diamond/ZnSe plate. Samples were deposited as neat on ATR module, and absorption maxima ($\nu_{\max}$) were quoted in wavenumbers (cm^{-1}) in the range of 4000–650 cm^{-1} . Intensities of absorptions are abbreviated as s, strong; m, medium; and w, weak.

3.6. NMR Spectroscopy

^1H , ^{13}C , and ^{31}P nuclear magnetic resonance spectra were taken on either a Varian Unity INOVA 500 MHz or a Bruker Ultrashield Plus 400 MHz FT-NMR spectrometer. Deuterated solvents were used in all NMR measurements. Chemical shifts (δ) are reported in parts per million (ppm) relative to residual solvent peaks as an internal reference for ^1H – ^{13}C nuclei or relative to 85% H_3PO_4 as an external reference for ^{31}P nucleus. Assignments were determined on the basis of either unambiguous chemical shift or coupling patterns. Peak multiplicities are defined as s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad, and coupling constants (J) are reported in hertz.

Radical species were not analyzed with NMR spectroscopy due to their paramagnetic nature which interfere the measurements.

3.7. Mass Spectra

Matrix-assisted laser desorption ionization time-of-flight (MALDI TOF) mass spectra were recorded on a Bruker Microflex LT spectrometer using reported matrixes.

3.8. Absorption Spectroscopy

Absorption spectra were recorded at room temperature on a Shimadzu UV-2600 UV-vis spectrometer using a 1 cm path length quartz cuvette between 200 and 900 nm. Solutions were prepared in spectro-grade solvents. Molar extinction coefficients (ϵ) were determined by measurement of the absorption of at least six solutions of differing concentration for each compound, followed by determination of the slope.

3.9. Electrochemical Analyses

Electrochemical measurements were carried out on a CH Instruments 842B model workstation. The setup was a conventional three-electrode cell equipped with a glassy carbon working electrode, platinum wire counter electrode, and Ag/AgNO₃ reference electrode. The glassy carbon electrode was polished routinely with 0.05 μ m alumina powder/water slurry on pads before running experiments. All measurements of samples were recorded as reported analyte concentration in 0.1 M *n*-Bu₄NBF₄ electrolyte solutions of acetonitrile. Solutions were deaerated with argon purge for 5 min and kept under a blanket of argon during the experiments. All electrochemical measurements were performed at ambient temperature. Ferrocene was used as internal reference, and all potentials were referenced to a ferrocene/ferrocenium (Fc/Fc⁺) redox couple ($E_{1/2}$: 0.416 V vs SCE [61]). All potentials as $E_{1/2} = (E_{pa} + E_{pc})/2$ were reported versus saturated calomel electrode (SCE). Scan rate was 50 mV/s for all cyclic voltammetry (CV) experiments. Parameters for all square wave voltammetry (SWV) experiments are amplitude 20 mV, frequency 8 Hz, and step increment 4 mV. The 3 mm-diameter glassy carbon working electrode (CHI104), nonaqueous Ag/Ag⁺ reference electrode with porous Teflon tip (CHI112), platinum

wire counter electrode (CHI115), and electrode polishing kit (CHI120) were purchased from CH Instruments. Supporting electrolyte, $n\text{-Bu}_4\text{NBF}_4$, was purchased from Alfa Aesar and dried overnight at 70 °C under vacuum. Supporting electrolyte, $n\text{-Bu}_4\text{NClO}_4$, was purchased from Aldrich. Ferrocene was supplied by Fluka, AgNO_3 by Carlo Erba, and anhydrous acetonitrile by VWR.

3.10. Electron Paramagnetic Resonance (EPR) Spectroscopy

The EPR solution spectra were recorded with a Jeol JES FA 300 X-band (9.6 GHz) spectrometer, with 100 kHz magnetic field modulation. Sample temperature was controlled by Jeol DVT Controller cryostat system. Modulation amplitude was kept below the estimated peak-to-peak width for all spectra. Spectra were simulated using the Jeol IsoSimu computer program to obtain the value of g , isotropic hyperfine coupling constants (a_N), and line width (ΔH_{p-p}). Typical concentration of the radicals is 10^{-4} M in the dichloromethane–toluene (1:1) mixture. Solutions in spectro-grade solvent mixture were degassed by bubbling argon through the solutions for 30 min. Spectra for degassed solutions of the radicals were recorded at the reported temperature.

3.11. Fluorescence Spectroscopy

Fluorescence emission spectra were recorded on a Varian Cary Eclipse spectrofluorometer using 10 mm path length cuvettes at room temperature. Fluorescence quenching and retrieving measurements were performed on the basis of literature method [62].

3.12. X-ray Diffraction Analysis

The X-ray diffraction data of the polyradical **15** were collected with a Bruker APEX II QUAZAR three-circle diffractometer using monochromatized $\text{Mo K}\alpha$ X-radiation ($\lambda = 0.71073$ Å) using φ and ω technique. The data reduction included a correction for Lorentz and polarization effects, with an applied multiscan absorption

correction (SADABS) [63]. Space groups were determined using XPREP implemented in APEX2 [64]. Final refinement and cif file were driven with SHELXTL package [65].

3.13. Magnetic Measurements

Magnetic susceptibility data were collected on a polycrystalline sample on a Quantum Design MPMSXL SQUID magnetometer under an applied magnetic field of 0.1 T and temperature range 2–300 K. All data were corrected for the contribution of the sample holder, and the diamagnetism of the samples was estimated from Pascal's constants [66].

4. IMINO NITROXIDE-BASED HEXARADICAL ARCHITECTURE ON A CYCLOTRIPHOSHAZENE SCAFFOLD: SYNTHESIS AND STRAIGHTFORWARD QUANTIFICATION METHODS OF IMINO NITROXIDE RADICALS BY ABSORPTION SPECTROSCOPY AND ELECTROCHEMISTRY

This chapter was originally published titled with “Synthesis and Straightforward Quantification Methods of Imino Nitroxide-Based Hexaradical Architecture on a Cyclotriphosphazene Scaffold” on *Inorganic Chemistry*, 2016, 55, 11447-11453, co-authored by Ismail Fidan, Emel Onal, Yusuf Yerli, Dominique Luneau, Vefa Ahsen and Catherine Hirel. The results and discussion sections are reproduced here in expanded version for entirety of research.

4.1. Phosphazenes

Phosphazenes are widely known inorganic compounds, chiefly present (Figure 4.1) in the cyclic form (cyclophosphazene), the short-chain linear form, and the polymer form (polyphosphazene). Cyclophosphazenes and polyphosphazenes have backbone of alternating phosphorus and nitrogen atoms (-P=N-) with one or two functional groups linked to each phosphorus atom. Phosphazene history dates back to the discovery of compound $\text{N}_3\text{P}_3\text{Cl}_6$ and determining its structure as ring molecule, in the 19th century [67], [68]. Polyphosphazene was prepared through thermal ring-opening polymerization of hexachlorocyclotriphosphazene to form an insoluble inorganic rubber. Milestone in the polyphosphazene history was the preparation of various soluble functionalized polyphosphazenes [69] achieved by Allcock at 1965. Thereafter, polyphosphazenes draw intense interest due to the ease of tailoring their physical properties, a critical point for targeted applications. Preparation of polyphosphazenes is performed chiefly via the Allcock’s method [70] which consists of thermal ring-opening polymerization of hexachlorocyclotriphosphazene to form polydichlorophosphazene followed by replacing of the chlorine atoms by nucleophilic groups.

In the case of cyclophosphazenes, a number of active chlorine atoms of cyclophosphazene are exchanged with nucleophilic groups in order to obtain partially- or fully-functionalized cyclophosphazenes. Among the other cyclic forms of phosphazene, research efforts were mostly devoted to cyclotriphosphazene derivatives (Figure 4.1) due to their higher stability and commercial availability of the precursor hexachlorocyclotriphosphazene. Reports cover various cyclotriphosphazene compounds and their applications such as chemical sensors, in vivo imaging or catalyst [71], [72].

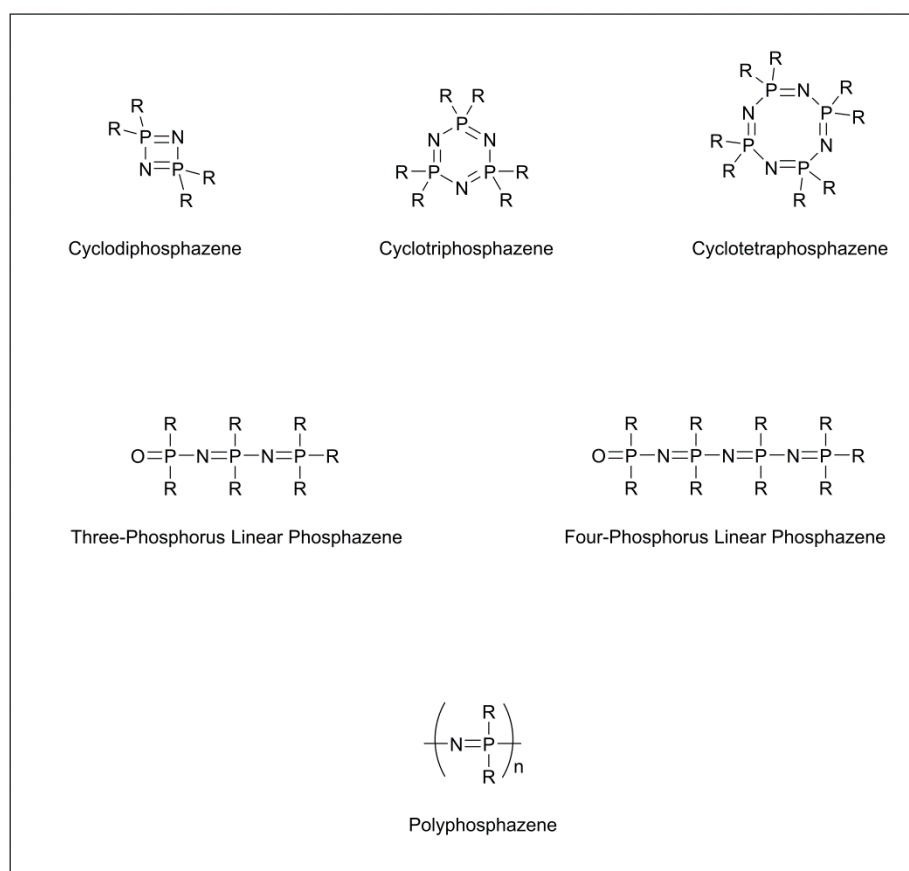


Figure 4.1: General Structures of the Phosphazenes.

4.2. Imino Nitroxide Radicals

General overview of nitroxide radicals was disclosed in Chapter 2.2.4. Imino nitroxide radical is a prominent subclass of the nitroxides. In terms of structure, imino nitroxide radical is one oxygen-loss analogue of nitronyl nitroxide. Briefly, the

conventional synthesis of imino nitroxide derivatives is summarized in Figure 4.2, and consists of several steps;

- i) condensation of an aldehyde with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) to generate the corresponding 1,3-dihydroxyimidazolidine adduct.
- ii) oxidation of the 1,3-dihydroxyimidazolidine adduct with oxidant such as NaIO_4 , PbO_2 to obtain the nitronyl nitroxide (way I oxidation; Figure 4.2) or a mixture of nitronyl and imino nitroxide (way III oxidation; Figure 4.2) by over oxidation.
- iii) lastly conversion of the nitronyl nitroxide by treating with NaNO_2 in acidic media to give solely the imino nitroxide derivatives.

Comprehensive details about the syntheses of nitronyl nitroxide and imino nitroxide were provided in Chapter 2.3.

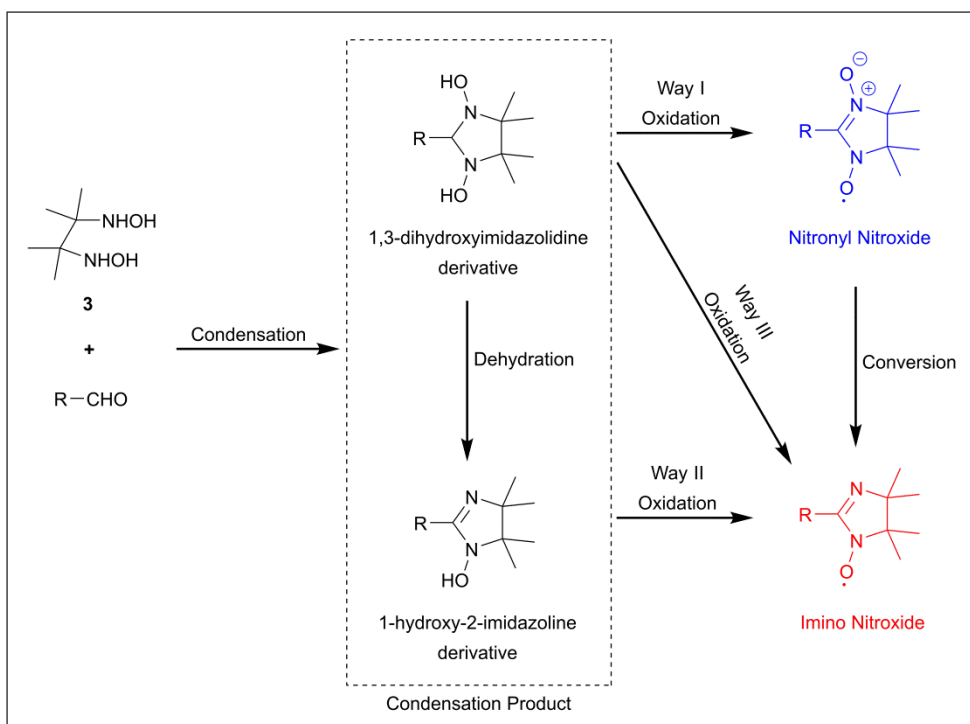


Figure 4.2: Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.

4.3. Cyclotriphosphazene-Nitroxide Hybrid Compounds

Throughout the dissertation, the word “hybrid” will always refer to nitroxide-functionalized cyclotriphosphazene derivatives.

Cyclotriphosphazene core provides a unique platform to be partially [73]-[75] or completely [74]-[79] functionalized by incorporating radical moieties depending on the needs of application. Library of the involved nitroxides are illustrated in the Figure 4.3.

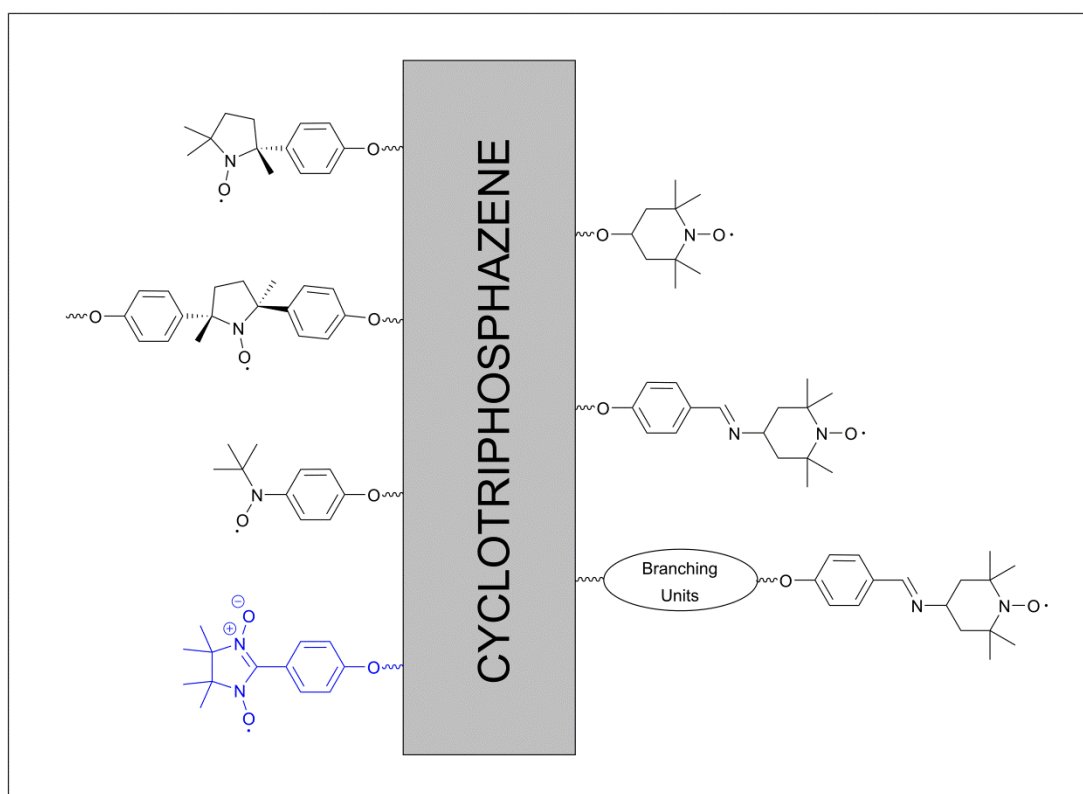


Figure 4.3: Library of the Nitroxide Family Radicals in Cyclotriphosphazene-Nitroxide Hybrid Compounds.

To the best of our knowledge, the first cyclotriphosphazene-nitroxide hybrid compound was hexa-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy)cyclotriphosphazene (**111**) prepared in 1988 [76] as a model structure (Figure 4.4) for optimization of nucleophilic reactions that intended to be carried out on the poly(dichlorophosphazene). Thereafter, as described in a patent, it was utilized as catalyst for the selective oxidation of alcohols to aldehyde [77].

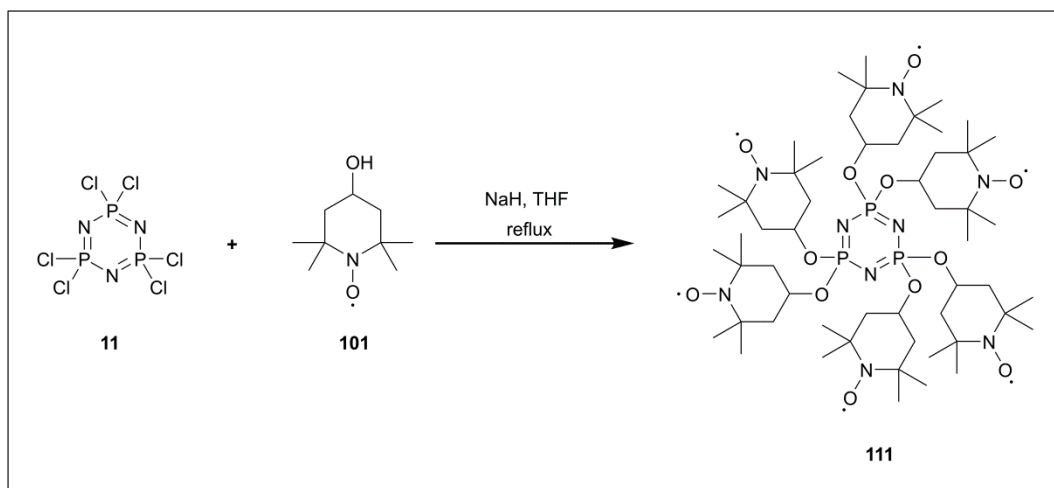


Figure 4.4: Synthesis of hexa-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy)cyclotriphosphazene (**111**).

Mono-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy)cyclotriphosphazene derivatives (**112**, **113**, **114**) were used as mediators (Figure 4.5) for the preparation of A_5B_1 type heteroatom star copolymers [73].

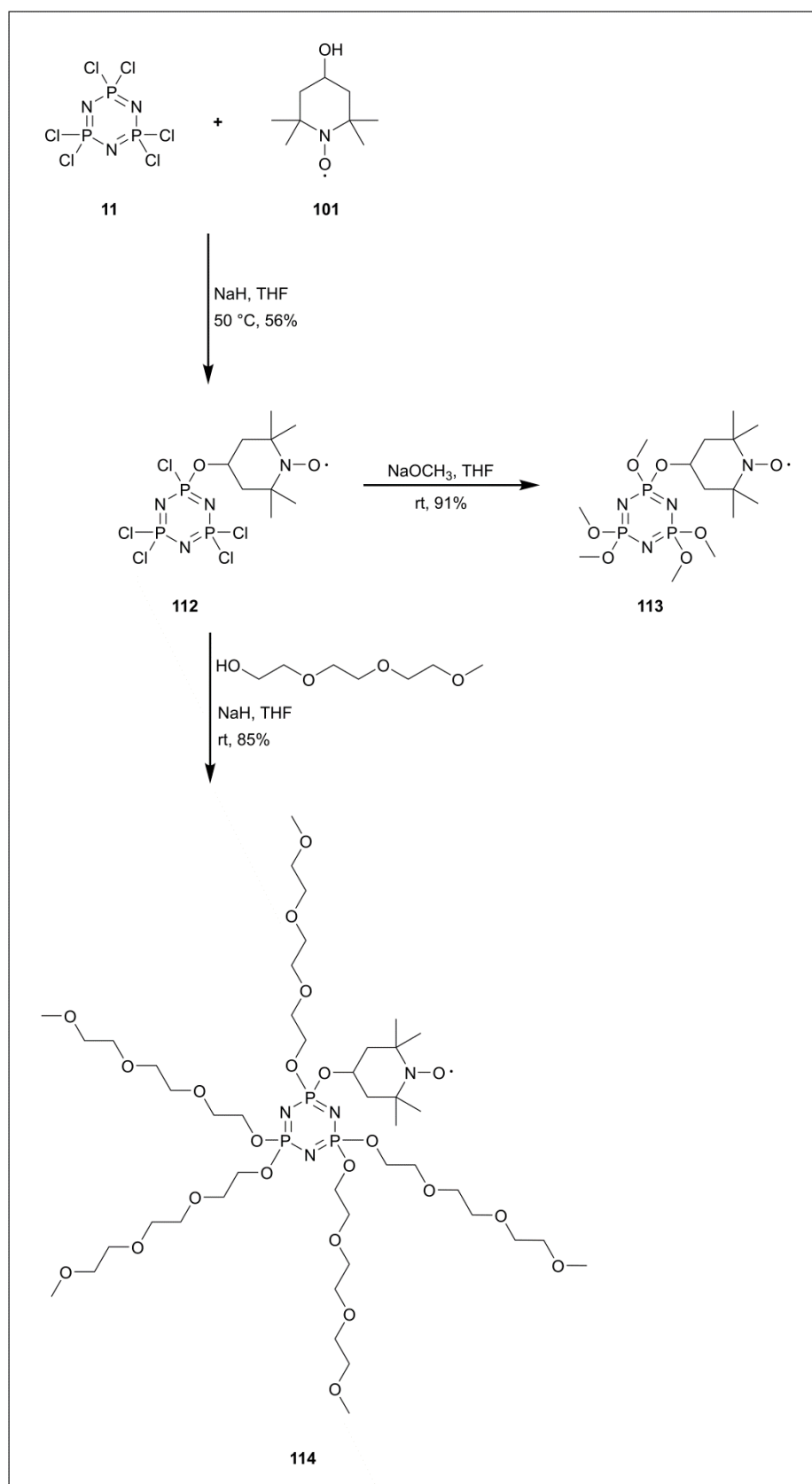


Figure 4.5: Synthesis of Mono-(2,2,6,6-tetramethylpiperidine-1-oxyl-4-oxy)cyclotriphosphazene Derivatives (**112**, **113**, **114**).

Tamura and co-workers synthesized a range of chiral (**115**, **116**, **117**, **124**, **125**) and achiral (**118**, **119**, **16**, **121**, **122**, **123**) nitroxide-functionalized cyclotriphosphazenes (Figure 4.6), isolated some of them, and investigated intramolecular interactions between the radical moieties by EPR spectroscopy and magnetic measurements [74], [75].

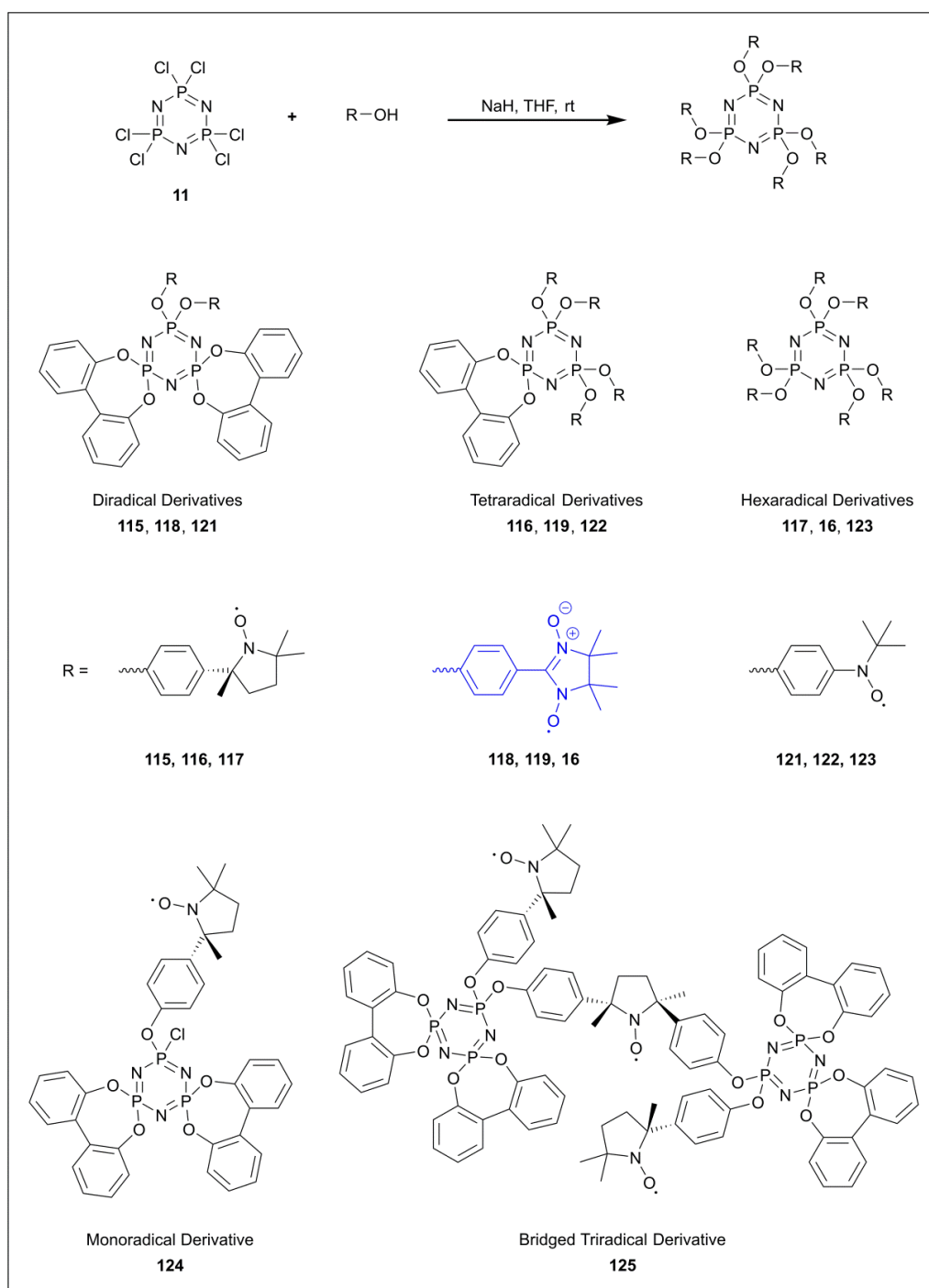


Figure 4.6: Synthesis of Chiral and Achiral Nitroxide-Functionalized Cyclotriphosphazenes.

Recent report disclosed synthesis of hexa-(TEMPO)cyclotriphosphazene (**126**) (Figure 4.7) and the determination of the orientation of its branches in solution via probing the radical units attached to the skeleton [78]. Another study reported the magnetic interactions between radical groups of the dendritic surface and their dynamic behavior by exemplifying five generations of phosphorus dendrimer [79].

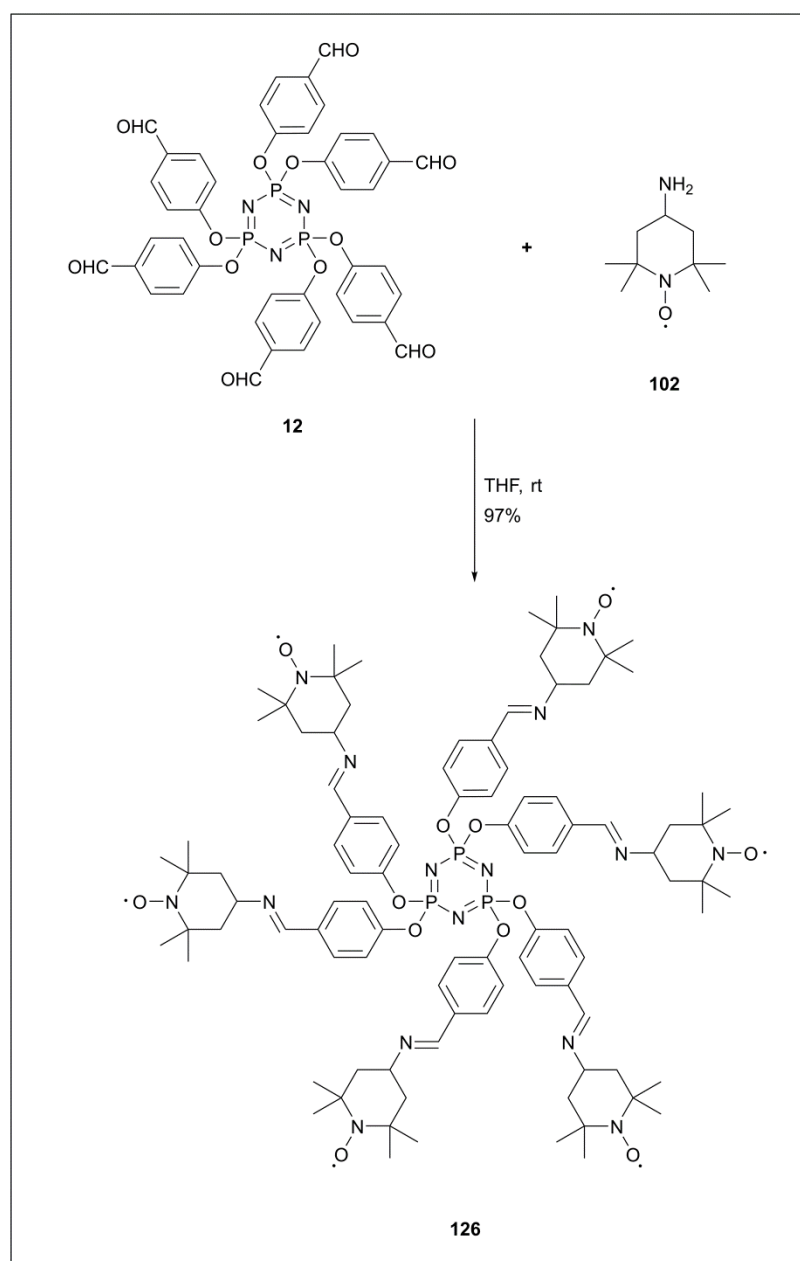


Figure 4.7: Synthesis of Dendrimer-Like TEMPO-Functionalized Cyclotriphosphazenes.

In order to insert the spin component to the skeleton, amino- or hydroxyl-functionalized pre-formed radical synthons were employed in all cases. In terms of spin content;

- i) a number of TEMPO derivatives (Figure 4.3, 4.4, 4.5, 4.7) were incorporated into the cyclotriphosphazene ring to assemble the hybrid compounds with mono-, hexa-, and higher degree of radical groups on the dendrimer structures [73], [76]-[79].
- ii) in the case of PROXYL radicals (Figure 4.3, 4.6); di-, tetra-, hexa-substitution, and bridged one were implemented successfully [74], [75].
- iii) *t*-butyl nitroxides (Figure 4.3, 4.6) appended compounds were designed principally; however none of them was crushed up due to labile nature [74].
- iv) in the case of Ullman radical (Figure 4.3, 4.6), only the di-substituted derivative was obtained for the nitronyl nitroxides whereas tetra- and hexa-functionalized ones were reported too much labile to be isolated [74] and no study yet was reported describing imino nitroxide moieties.

4.4. Scope and Objectives

Upon review the literature, the research about cyclotriphosphazene bearing Ullman radicals is still in infancy. Therefore, our attention was focused on the synthesis and study of properties of cyclotriphosphazenes bearing six Ullman radicals, either nitronyl nitroxide or imino nitroxide.

Considering the synthetic viewpoint of Ullman polyradicals, there are two key points to be taken into consideration;

- Condensation step
- Oxidation step

Depending on the conditions, during the condensation step there is always the risk to obtain the 1-hydroxy-2-imidazoline by dehydration instead of 1,3-dihydroxyimidazolidine or a mixture of both of them (Figure 4.2). Similarly, during the oxidation step there is always the possibility to over-oxidize the reaction (already

mentioned in Chapter 2.3) and to obtain cyclotriphosphazene bearing mixture of nitronyl/imino nitroxide. Such ungovernable drawbacks could lead to numerous combinations of hypothetic molecules difficult to isolate, as represented schematically in Figure 4.8.

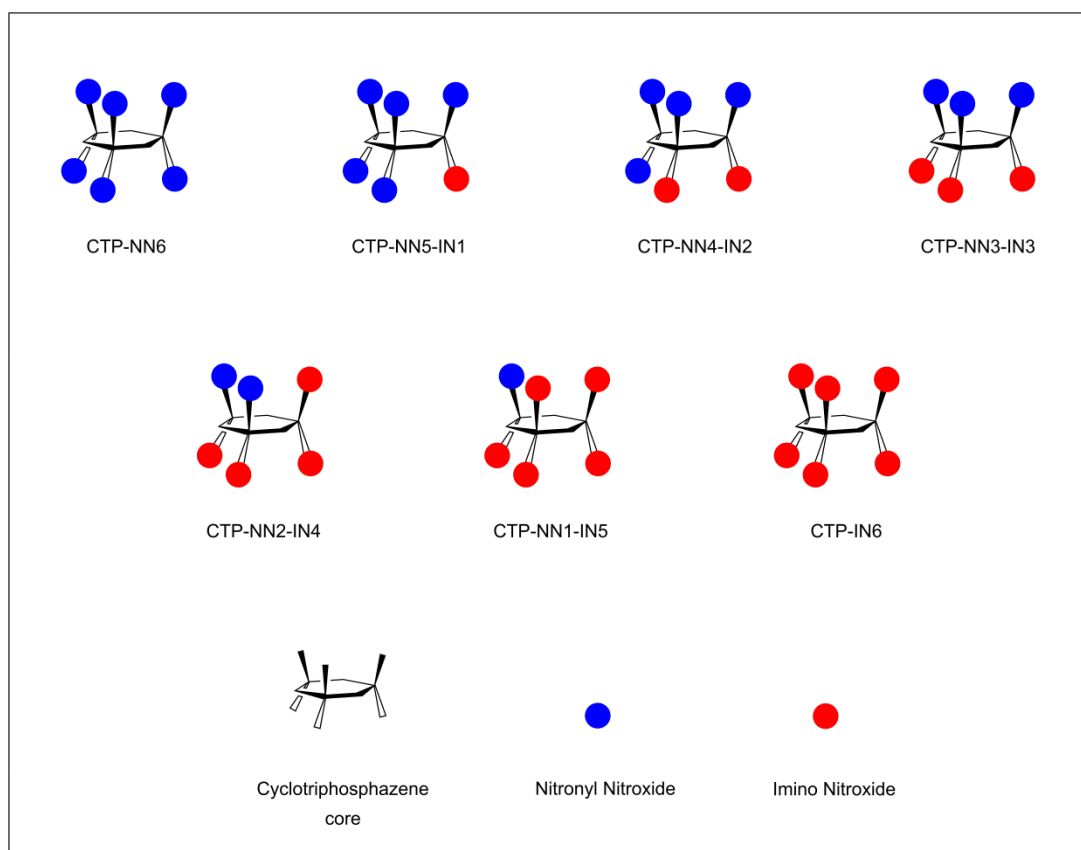


Figure 4.8: Schematic Representation of the Hypothetic Molecules.

In order to bypass these undesired possibilities, the synthesis of a cyclotriphosphazene bearing six imino nitroxide moieties was initially favored (see the representation of the targeted molecule in Figure 4.8 and the structure of it in Figure 4.9).

Studies on cyclotriphosphazene core multiradicals were mostly devoted to EPR and magnetic analysis [74]-[79]. Even if nitroxide radicals are well-known to be redox-active species, no studies filling electrochemical characterization of nitroxide-cyclotriphosphazene hybrid compounds were published yet. However, the electrochemical behaviors of the radical moieties as well as the influence of the scaffold on the potentials are critical points for the development of electrochemical application. Therefore, electrochemical analyses of cyclotriphosphazene-based

neutral hexaradical by comparing with its parent counterpart [phenyl-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl), **7**] need to be performed in great extent.

The number and the gender of radicals is generally confirmed by X-Ray diffraction and magnetometry techniques that require time, important quantities of compound, and specific equipments. Even if MALDI-TOF MS analysis is a rapid technique, the probability of false-positive is significant due to the ease of nitronyl nitroxide to lost one oxygen atoms to give the corresponding imino nitroxide (Figure 4.2). So, we are particularly focused on developing straightforward and rapid quantification methods of radicals by routine and easy available techniques such as absorption spectroscopy and electrochemistry.

Within the context, main objectives are;

- i) To synthesize a cyclotriphosphazene bearing six imino nitroxides (**15**).
- ii) To investigate the electrochemical behavior of cyclotriphosphazene-based neutral hexaradical (**15**) by comparing with its parent counterpart [phenyl-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl), **7**],
- iii) To explore alternative quantification methods by routine and easy available techniques such as absorption spectroscopy and electrochemistry in the way to replace X-ray analysis.

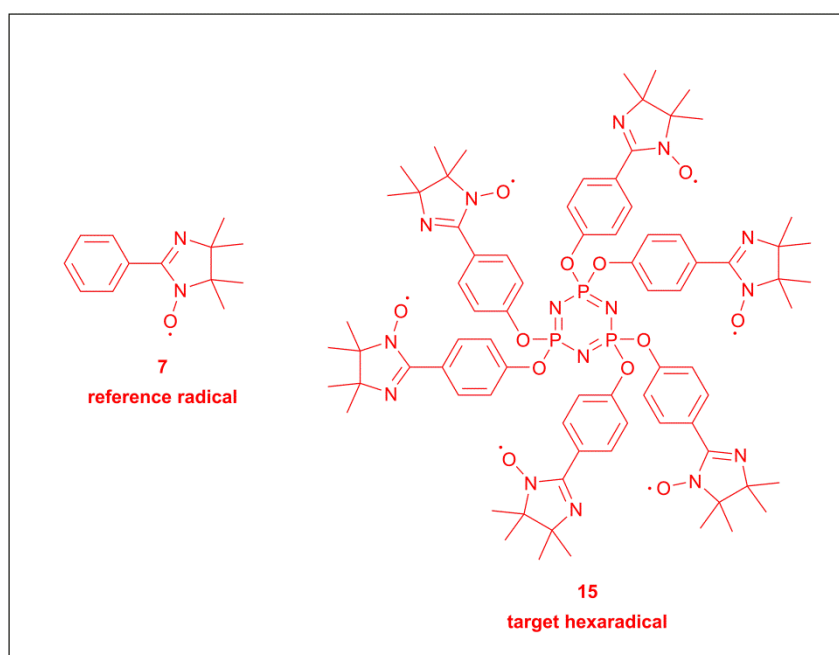


Figure 4.9: Structures of the Reference Radical **7** and the Hexaradical **15**.

4.5. Synthesis

The syntheses of the reference radical **7** and the hexaradical **15** are summarized in Figure 4.10.

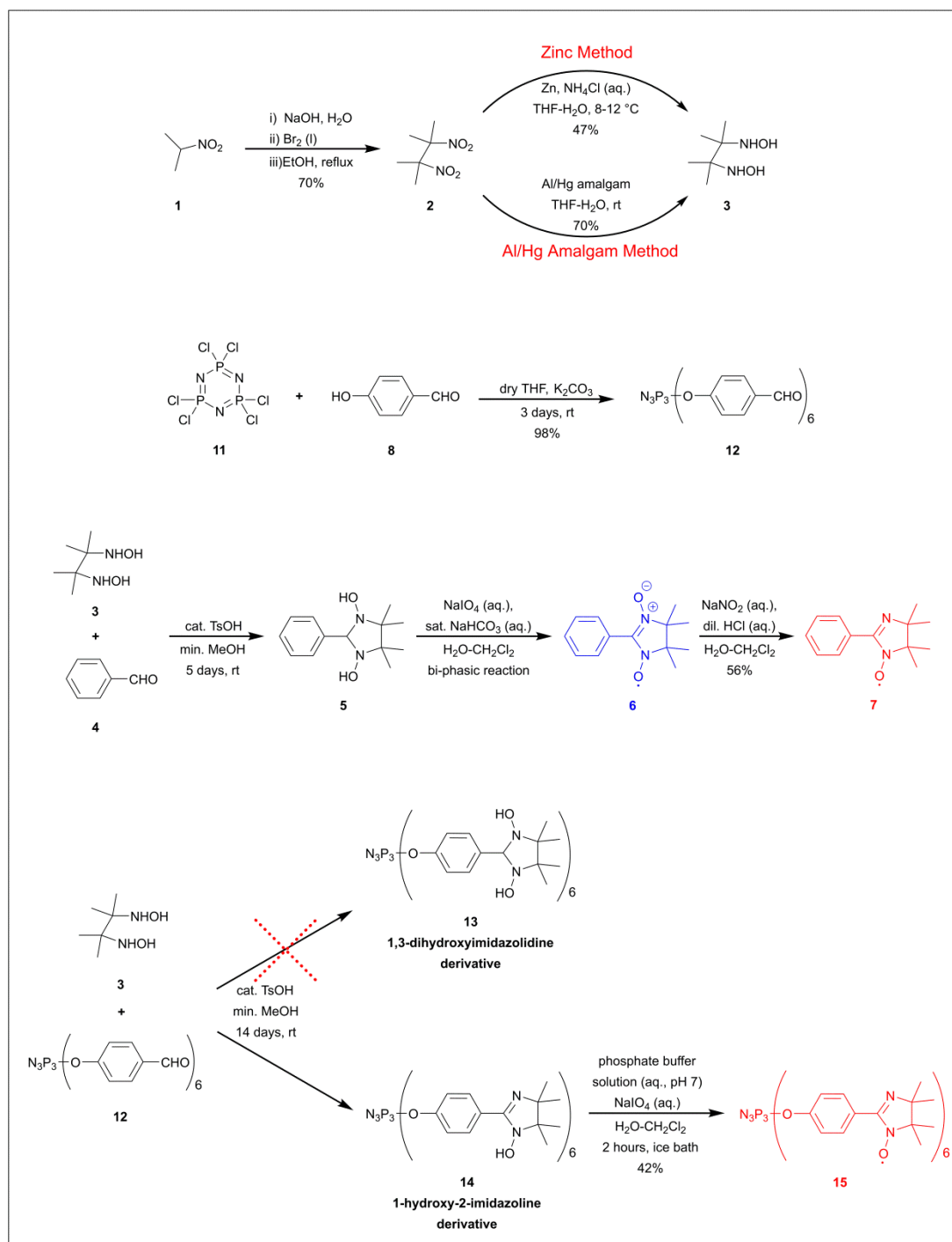


Figure 4.10: Synthetic Routes to the Reference Radical **7** and the Hexaradical **15**.

2,3-dimethyl-2,3-dinitrobutane (**2**) was prepared (Figure 4.10) starting from 2-nitropropane (**1**) [80], [81]. Recrystallization of the crude product from hot MeOH gave white shiny crystals in 70% yield. Melting point analysis, FT-IR, ^1H NMR, and ^{13}C NMR spectra (Figure 8.1, 8.2, 8.3) demonstrated the identity and the purity of compound **2**.

2,3-bis(hydroxylamino)-2,3-dimethylbutane (BHA, **3**) is a key intermediate in the synthesis of Ullman radicals. It was prepared from the corresponding dinitro counterpart (**2**) over a partial reduction (Figure 4.10).

Like for the overall synthesis of Ullman radical, the obtaining of the key intermediate 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) over a partial reduction of the corresponding 2,3-dimethyl-2,3-dinitrobutane (**2**) in pure and good yield is a tough challenge.

Basically, both of the nitro groups are reduced partially to hydroxylamino groups by metallic zinc or by Al/Hg amalgam (Figure 4.10). From the synthetic perspective, the magic terms in the reaction are both and partially which play prominent role in the success. Both refer to the two nitro groups in the structure. Partially refers to the partial reduction of nitro groups ($-\text{NO}_2$) to hydroxylamino one ($-\text{NHOH}$) but not to amine one ($-\text{NH}_2$), the amines being the final reduction products in this reaction. Only the 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) was targeted, and the mixture of all other possible derivatives have to be avoid, because only **3** will be able to condense with aldehyde derivatives to generate the desired 1,3-dihydroxyimidazolidine.

Method of reduction with metallic zinc was originally developed by Lamchen and Mittag who carried out the reduction in EtOH- H_2O mixture [82]. Afterwards, optimizations of zinc method were reported by Ovcharenko [83] and Rey [84]. Even many optimizations, Zn mediated reductions are less reproducible because of several reasons. Narrow temperature range (11-13 $^\circ\text{C}$) of the reaction proceeded was the primary one in my observations. Obtaining pure free base 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) in reproducible yields is still a challenge with metallic zinc. The one must need long hands on optimization to achieve that. This preparation was proceeded in our laboratory on the basis of Rey's optimizations [84] and reached 47% maximum yield. Another way of partial reduction is Al/Hg amalgamated process [26] developed by Tamura. Al/Hg system gave much better reproducibility and higher yields, 70% maximum yield in my experiments. Tamura proceeded the

reaction at 0 °C for 20 minutes, whereas in my case I observed better result when the reaction was maintained 2 hours at room temperature. Comparison on total work up burden of aforementioned methods, metallic Zn takes three days whereas Al/Hg does only one day. Both of the procedures (Figure 4.10) were run numerous times in our laboratory and afforded pure free base 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) in good yields.

Distinguishing features of BHA (**3**) are its –NH and –OH stretchings (Figure 8.4) in the 3351-3225 cm⁻¹ range of FT-IR spectrum which are absent in that (Figure 8.1) of dinitro analogue (**2**). In terms of appearance, BHA (**3**) is dull white powder whereas its dinitro counterpart (**2**) is very shiny white crystals. In the presence of oxygen, BHA (**3**) is eventually converted to acetone oxime (Figure 4.11) which appeared as shiny white substances. Presence of impurities in the bulk of BHA (**3**) would be determined in FT-IR spectrum as extra absorption appeared around 1536 cm⁻¹ which ascribed tentatively to acetone oximes (Figure 4.12). Different melting points were reported for pure free base BHA (**3**); 157–159 °C [82], 160–161 °C [83], 159 °C [85], 181 °C [84]. Though, we observed its melting point at 158–160 °C. Pure BHA (**3**) could be stored in the fridge without decomposition, of course in the oxygen free atmosphere. Noteworthy that preparation of good quality BHA (**3**) has paramount importance for success in the synthesis of nitronyl and imino nitroxide radicals.

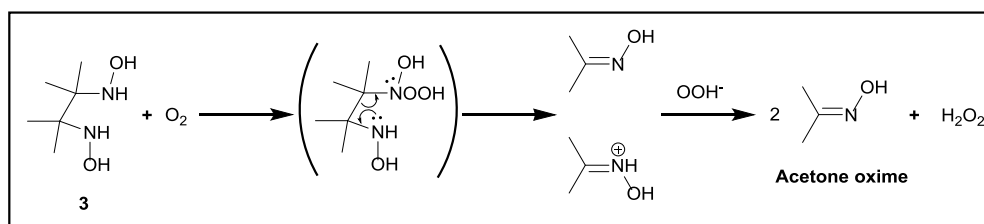


Figure 4.11: Conversion of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) to Acetone Oxime.

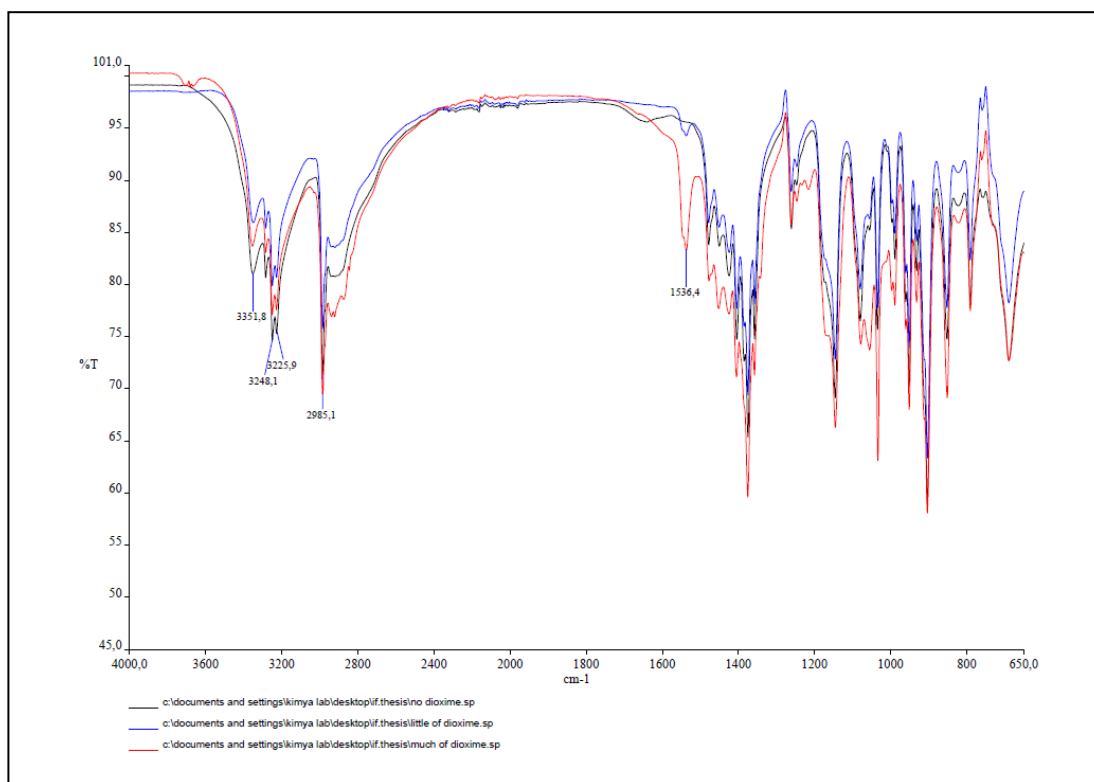


Figure 4.12: Acetone Oxime as Impurity in FT-IR Spectrum of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**).

Hexaaldehyde (**12**) was prepared in 98% yield according to literature [86] slightly modified by using K_2CO_3 -promoted substitution of hexachlorocyclotriphosphazene (**11**) by 4-hydroxybenzaldehyde (**8**) in anhydrous THF (Figure 4.10). Stirring reagents damped all at once at room temperature and simple workup as easy as just washing with water and then with Et_2O giving spectroscopically pure **12** in excellent yield. Using K_2CO_3 rather than NaH [87] or Cs_2CO_3 [88] as well as no need for phase transfer catalyst [89] made this method a cheaper way.

Formation of the compound **12** was monitored in FT-IR spectrum following the complete disappearance of the $-OH$ stretchings of **8**. Absorption at 1702 cm^{-1} was assigned to stretching of the aldehyde carbonyls of **12** (Figure 8.7). The sharp bands at 1205 , 1177 and 1153 cm^{-1} are assigned to $P=N$ stretching vibrations and the single band observed at 959 cm^{-1} is attributed to $P-O$ bond stretching vibration, which all (Figure 8.7) characteristics of cyclotriphosphazene ring [90]. Perfect assignments of the signals in ^1H NMR, ^{13}C NMR, and ^{31}P NMR spectra (Figure 8.8, 8.9, 8.10) demonstrated the identity and as well as the purity of the hexa-aldehyde **12**. MALDI-

TOF MS analysis (Figure 8.11) shows a peak at m/z of 862 $[M+H]^+$ which another identity proof of the hexa-aldehyde **12**. White powder of **12** could be stored in fridge and in oxygen free atmosphere for months. However, prolonged storage led to some beige colored impurities which could be easily get rid of by washing with diethyl ether.

The hexaaldehyde (**12**) was reacted with an excess of 2,3-bis(hydroxylamine)-2,3-dimethylbutane (**3**) in the presence of TsOH as catalyst in a minimum of MeOH to yield the radical precursor (Figure 4.10). The completion of the reaction was monitored by FT-IR following the disappearance of the aldehyde signal at 1702 cm^{-1} (Figure 8.12, 8.13). In general, condensation of an aldehyde with 2,3-bis(hydroxylamine)-2,3-dimethylbutane (**3**) generates the corresponding 1,3-dihydroxyimidazolidine adduct, but in some cases the dehydration process takes place at elevated temperatures [27], allowing the formation of 1-hydroxy-2-imidazoline in solution (Figure 4.2). However, in the present case, dehydration also took place at room temperature and led to the formation of 1-hydroxy-2-imidazoline derivative (**14**) instead of the anticipated 1,3-dihydroxyimidazolidine derivative (**13**) (Figure 4.10). 1-Hydroxy-2-imidazoline derivative (**14**) was isolated, and its structure (Figure 4.10) was confirmed by MALDI-TOF MS, m/z 1540 $[M + 6H]^+$ (Figure 8.14). In the last stage, oxidation of **14** was performed with aqueous NaIO_4 to afford **15**, as an orange solid, in 42% yield (Figure 4.10). X-ray and MALDI-TOF MS analysis (Figure 8.16) using *trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile as matrix shows a peak at an m/z of 1529 $[M+H]^+$, which is evidence of the formation of **15**, as well as elemental analyses demonstrate its purity. Structure of **15** was also confirmed by X-ray analysis (Figure 4.19). FT-IR spectrum of **15** (Figure 8.15) displayed two signals at 1375 and 1367 cm^{-1} which attributed to N-O stretchings of imino nitroxide fragment [30]. Distinguishing features of cyclotriphosphazene ring are observed for **15** in FT-IR spectrum (Figure 8.15) as well; the sharp bands at 1201, 1183 and 1161 cm^{-1} of P=N stretching vibrations and the single band at 944 cm^{-1} of P-O bond stretching vibration. As consequence, a homogeneous neutral hexaradical architecture consisting of six imino nitroxide radical moieties covalently bonded on a cyclotriphosphazene scaffold was synthesized. This is the first report for hexasubstituted cyclotriphosphazene bearing Ullman radicals appended on each arm.

Additionally, phenyl-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl) **7** as a reference radical was also synthesized through Ullman procedure. Synthetic sequence (Figure 4.10) consists firstly the formation of phenyl nitronyl nitroxide **6** which subsequently converted to the phenyl imino nitroxide **7** via cleavage the oxygen of **6** in the acidic medium of sodium nitrite [29]. FT-IR spectrum of **7** (Figure 8.5) displayed two signals at 1375 and 1367 cm^{-1} which attributed to N-O stretchings of imino nitroxide fragment [30]. MALDI-TOF MS analysis (Figure 8.6) shows a peak at m/z of 218 $[\text{M}+\text{H}]^+$ which another identity proof of the reference radical **7**.

In conclusion, the reference radical **7** and the target hexaradical **15** were successfully synthesized with our optimizations on the basis of Ullman [25] and Tamura protocols [26]. The hexaradical **15** was characterized unambiguously by melting point analysis, FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, SWV, EPR, magnetic measurements, and X-ray analysis.

4.6. Absorption Spectroscopy

Characteristic features of aromatic imino nitroxides are their colors, from orange to crimson in solid state and orange to red in solution with a broad absorption band accompanying vibronic components in visible region. A typical band around $\lambda_{\text{max}} \approx 443 \text{ nm}$, intrinsic of the nitroxide fragment, was assigned to $n \rightarrow \pi^*$ transitions. Vibronic components of radical band were best observed in toluene among the studied solvents; acetonitrile, chloroform, and toluene (Figure 4.13, 8.17, 8.24).

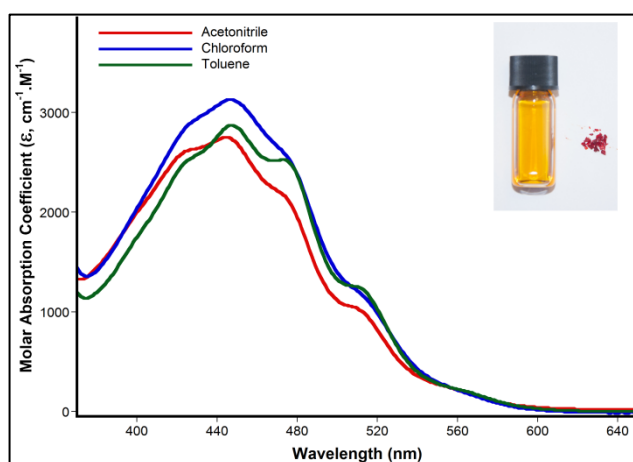


Figure 4.13: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **15**, Inset: 10^{-3} M Chloroform Solution of **15** and Crystals of **15**.

15 and **7** were soluble in numerous solvents including acetonitrile, chloroform, and toluene in which the Beer–Lambert Law was observed for both compounds in the range from 10^{-5} to 10^{-3} M for **7** (Figure 8.18-8.23) and from 10^{-5} to 4.10^{-4} M for **15** (Figure 8.25-8.30). According to molar extinction coefficient (ϵ) values calculated from the radical band centered around 443 nm, a hypochromic effect [91] (representative of the interaction between radical moieties) was not observed for **15**. As a result, the effects due to the cyclotriphosphazene core are negligible, and the molar extinction coefficient (ϵ) of **15** is linearly dependent on the radical number on the scaffold as was already observed for TEMPO moieties [79]. Consequently, simply dividing the ϵ of **15** by that of **7** will give us the number of radical moieties present on **15**. So, simple and rapid determination of the number of radicals on a polyradical by absorption spectroscopy was successfully demonstrated within the $\pm 10\%$ tolerance [79] of ϵ (Table 4.1).

Table 4.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of **7** and **15** at Room Temperature^a.

Solvent	$\lambda_{\max}$ 7	ϵ 7	$\lambda_{\max}$ 15	ϵ 15	Number of Radicals on 15
Acetonitrile	441	418	444	2751	6.58
Chloroform	443	484	447	3129	6.46
Toluene	445	442	448	2870	6.49

^a $\lambda_{\max}$ in nm, ϵ in $\text{cm}^{-1} \cdot \text{M}^{-1}$

As conclusion, UV-vis spectra proved gender of the reference radical **7** and the hexaradical **15** as imino nitroxide radicals. Quantification method was developed by absorption spectroscopy to determine the number of radical moieties in a polyradical; based on the molar extinction coefficient (ϵ) through tracking the $n \rightarrow \pi^*$ transitions of radical band. Quantification method by absorption spectroscopy proved the presence of six imino nitroxide moieties on **15** (Table 4.1).

4.7. Electrochemical Analyses

Imino nitroxides are redox-active molecules to be oxidized to oxo-ammonium cation or reduced to aminoxyl anion. Electrochemical behaviors of radical **7** and **15** were investigated by cyclic voltammetry (CV). Reference radical **7** showed a quasireversible oxidation wave at 1.183 V vs SCE and a reversible reduction one at

−0.881 V. For **15**, oxidation occurred at 1.184 V in a quasi-reversible process, and reduction occurred at −0.883 V in a reversible process. Redox processes of **15** almost overlap with those of phenyl imino nitroxide (**7**) (Figure 4.14). This suggests that cyclotriphosphazene core has almost no influence on the redox potentials of **15**. Redox characteristics and observed potentials of **7** and **15** are in accordance with the literature [31], [92].

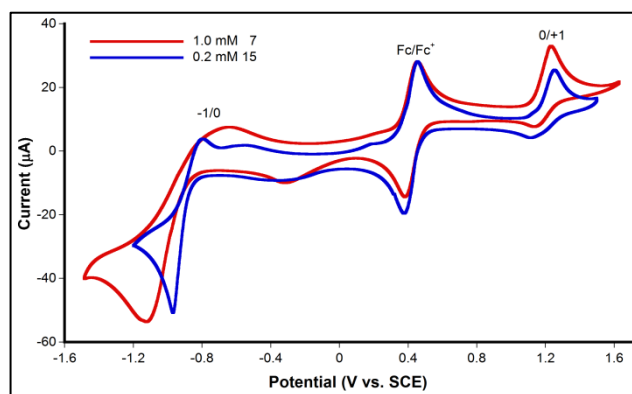


Figure 4.14: Cyclic Voltammograms of the Reference Radical **7** and the Hexaradical **15** Recorded at rt in Acetonitrile, 0.1 M n-Bu₄BF₄ as Supporting Electrolyte, Scan Rate of 50 mV/s.

Square-wave voltammetry (SWV) is a powerful technique [93] for quantification of organic species. To the best of our knowledge, SWV was not utilized for the quantification of imino nitroxides previously. A protocol was established for simple and rapid quantification of INs with a standard SWV run. After optimization of SWV experimental conditions, the oxidation process (0/+1) of **7** was studied by anodic sweeping to plot a calibration curve (concentration versus current), which was linear in the range of 3–130 μM (Figure 4.16a and b). Two known concentrations of **15** (C_{15}) then were analyzed under the same conditions (Figure 4.15c). For these known concentrations, a measured current response is obtained (I_{measured}) that corresponds to a theoretical concentration ($C_{\text{theoretical}}$) on the calibration plot of **7**. Simply dividing the $C_{\text{theoretical}}$ by C_{15} allows us to demonstrate that the cyclotriphosphazene scaffold of **15** contains six independent imino nitroxide radicals (Table 4.2 and Figure 4.16c). Consequently, SWV is a simple and straightforward technique to quantify radical moieties on the polyradical.

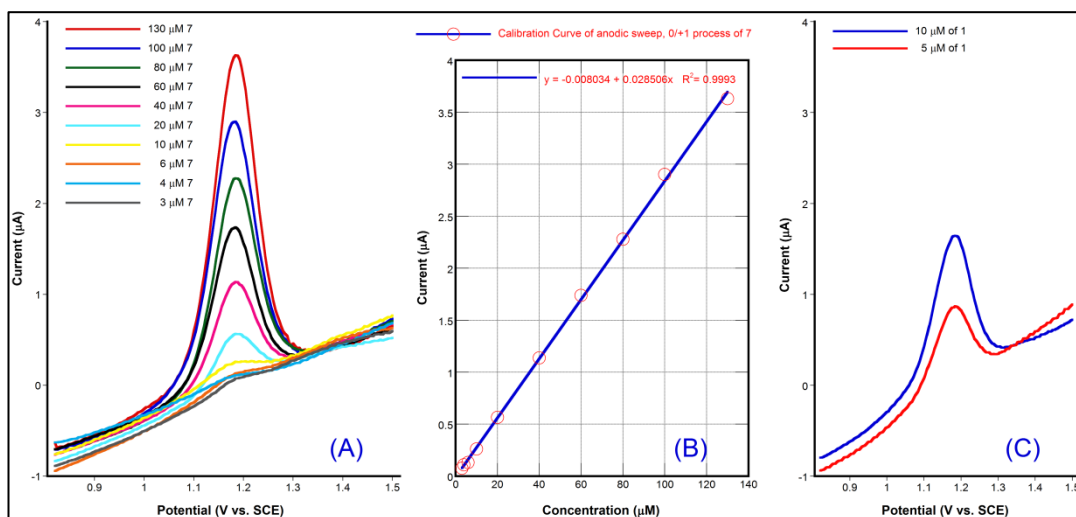


Figure 4.15: Anodic Square-Wave Voltammetry Analyses in 0.1 M $n\text{-Bu}_4\text{NBF}_4/\text{acetonitrile}$ Solutions of the Radicals: a) for (0/+1) Process of **7**; b) Calibration Curve for (0/+1) Process of **7**; and c) for (0/+1) Process of **15**.

Table 4.2: Square Wave Voltammetry (SWV) Analyses of **15**.

C_{15} (μM)	I_{measured} (μA)	$C_{\text{theoretical}}$ (μM)	Number of Radicals on 15 = $C_{\text{theoretical}} / C_{15}$
10	1.642	56.1	5.61
5	0.869	30.8	6.15

4.8. Electron Paramagnetic Resonance Spectroscopy

15 and **7** were investigated by EPR spectroscopy in 10^{-4} M dichloromethane–toluene (1:1) solutions in the temperature range of 293–123 K (Figure 8.32, 8.33). Both spectra showed a seven line hyperfine pattern typical of imino nitroxide [94] in solution. The spectrum of **7** is in accordance with the literature with an intensity ratio of 1:1:2:1:2:1:1 (Figure 4.16 inset, Figure 8.31), whereas the spectrum of **15** presents two main jagged peaks centered at $g = 2.0026$ separated by ca. 4.20 G due to the sum of at least two superposed different spectra (Figure 4.16). When the temperature was lowered, the ridges on the spectrum began to shrink and disappeared, so the spectrum changed to a single-narrowed signal [95] (Figure 8.33) due to the anisotropic and spin-exchange effects. The spectrum of **15** could be explained in terms of a through-space spin-exchange mechanism between the radicals [78]. The spectrum was simulated on the basis of interconversion of two

molecule conformations in solution. In the first conformation, radicals are too far from each other and act as independent radicals (independent form). In the second conformation, three radicals disposed on the same side of the cyclotriphosphazene scaffold are close enough to each other to undergo a strong exchange-interaction independently from the radicals of the other side (interacting form). The best fitting parameters have been obtained for a ratio 2:98 of the aforementioned conformations. Contributions are 2% molar abundance for the independent form with $a_{N1} = 9.1$ G, $a_{N2} = 4.1$ G, $\Delta H_{p-p} = 1.8$ G, and 98% molar abundance for the interacting form with $a_{N1} = 3.2$ G, $a_{N2} = 1.6$ G, and $\Delta H_{p-p} = 6.9$ G.

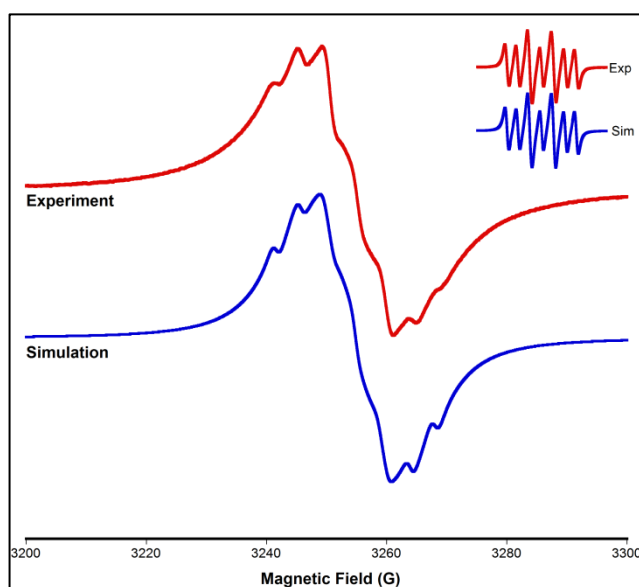


Figure 4.16: X-band EPR Spectrum of **15** in Dichloromethane–Toluene (1:1) Solution (10^{-4} M) at 253 K and Its Simulation. Inset: EPR Spectrum of **7** at the Same Conditions and Its Simulation.

4.9. Magnetic Measurements

At room temperature, the product of the magnetic susceptibility with temperature (χT) has the expected value for six magnetically independent radicals ($2.21 \text{ cm}^3 \text{ K mol}^{-1}$). Upon cooling, χT is almost constant down to 100 K, and then decreases continuously down to 2 K (Figure 4.17). The data were well fitted with a Curie–Weiss law considering six spins of $S = 1/2$ and a Weiss constant $\theta = -1.86$ K. This behavior is in agreement with six radical moieties in the compound and very small and almost nonsignificant antiferromagnetic interactions between.

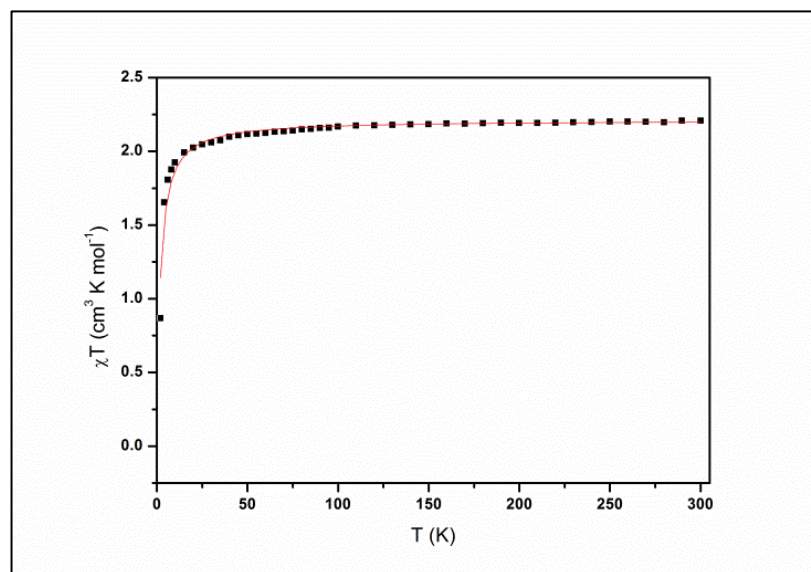


Figure 4.17: Temperature Dependence of the Product of the Magnetic Susceptibility with Temperature (χT) for 15:0.5 toluene.

4.10. X-ray Diffraction Analyses

Single crystals of polyradical **15** (Figure 4.18) were obtained from slow diffusion of heptane to a solution of **15** in ethyl acetate–toluene–heptane mixture, and the structure was determined by X-ray diffraction (Table 4.3).



Figure 4.18: Crystal of **15** on the X-ray Mounter.

Three radicals are situated above the cyclotriphosphazene core and the three others below (Figure 4.19). Meaningful bond distances and angles for **15** are reported in Tables 4.4 and 4.5, respectively. The P–N and P–O distances as well as the P–N–P and N–P–N angles are in accord with the previous structure of this type [90]. The same results were observed for the C–O distance between the first carbon atom of each phenyl ring and the O atom attached to the P atom of the cyclotriphosphazene ring. Different data were collected from many crystals obtained from different synthetic batches to determine the structure accurately. However, all attempts resulted in a highly disordered molecular structure. In the first step of the structure determination, it seems that there is a mixture of nitronyl and imino nitroxide radicals. However, in agreement with other characterizations, further refinements show that some imino nitroxides are disordered on two positions in a 180° rotation (head to tail). This is clearly evidenced by free refinement of their oxygen atom of the NO groups that closely reach half occupation. This is what causes the high disorder of the structure because of nonexact superposition of the 180° rotated imino nitroxide moiety. Further confirmation comes from the finding of

extra electron density, which was attributed to one toluene molecule on the 2 axis and disorder on two positions in a head-to-tail configuration as well (Figure 4.20 and Figure 4.21).

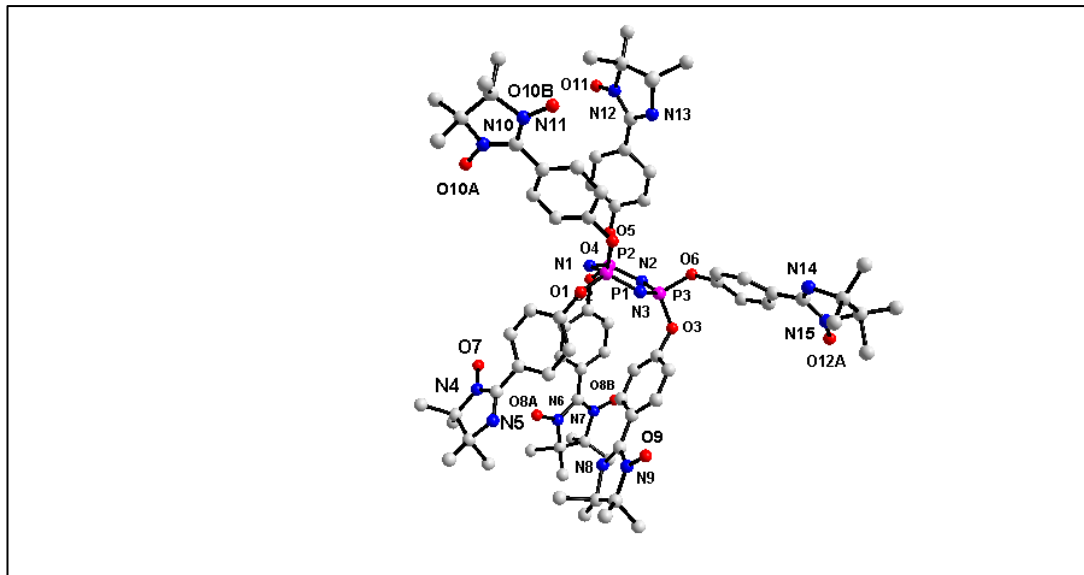


Figure 4.19: Molecular Structure of **15** by X-ray Diffraction on a Single Crystal. The Hydrogen Atoms and the Disorder of the Imino Nitroxide Moiety Have Been Removed for Clarity.

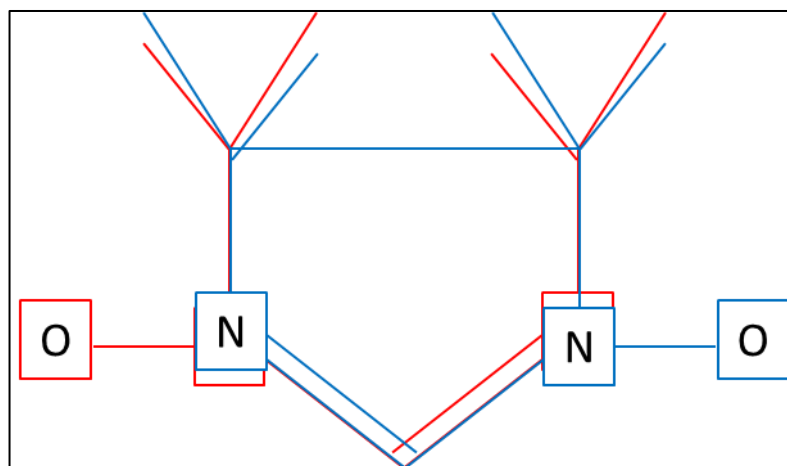


Figure 4.20: Explanation of the Disorder on the Imino Nitroxides Moieties Due to the (Head to Tail) Positionnement.

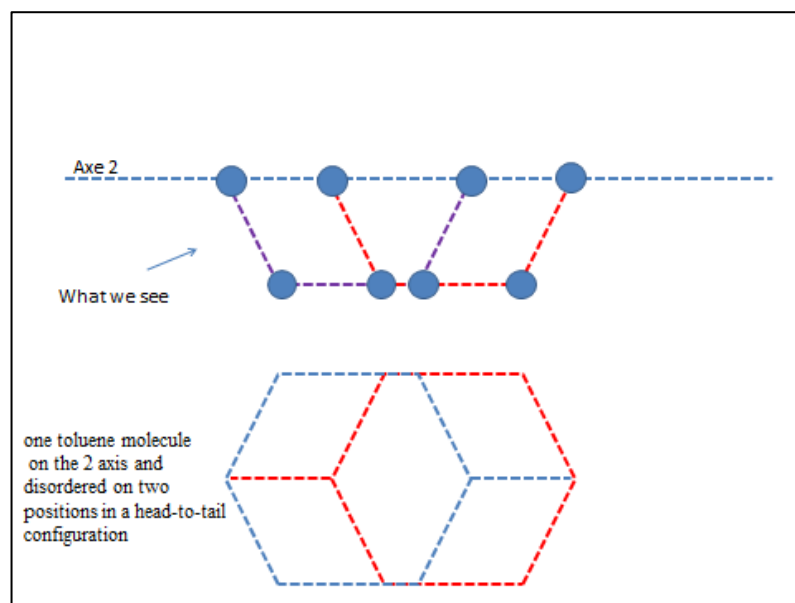


Figure 4.21: Head-to-tail Disorder on the Toluene.

Table 4.3: Crystal Data and Structure Refinement of **15.0.5(C₇H₈) (CCDC1498365)**.

Empirical formula	C81.50 H100 N15 O12 P3
Formula weight (g mol ⁻¹)	1574.68
Temperature (K)	188(2)
Wavelength [Å]	0.71073
Crystal system,	monoclinic
Space group	C 2/c
a [Å]	31.3499(9)
b [Å]	16.4996(5)
c [Å]	33.8577(8)
□□[°]	98.585(2)
Volume [Å ³]	17317.0(8)
Z	8
Dc [gcm ⁻³]	1.208
□□ [mm ⁻¹]	0.135
F(000)	6680
Crystal size (mm)	0.52 x 0.44 x 0.36
q range for data collection (°)	1.40 to 25.03
Limiting indices	-37<=h<=37, -19<=k<=19, -40<=l<=39
Reflections collected / unique	90769 / 15299 [R(int) = 0.1184]
Completeness to q = 25.03 ° (%)	100
Refinement method	Full-matrix least-squares on F ²
Data / restraints / parameters	15299 / 10 / 1036
Goodness-of-fit on F ²	1.257
Final R indices [I>2□(I)]	R1 = 0.1153, wR2 = 0.3312
R indices (all data)	R1 = 0.1813, wR2 = 0.3909
Extinction coefficient	0.00028(13)
Largest diff. peak and hole [e Å ³]	0.760 and -0.612

$$^a R1(F) = \frac{\sum |F_o| - |F_c|}{\sum |F_o|}, \quad ^b wR2(F) = \frac{\sum [w ((F_o^2 - F_c^2)^2 / \sum w F_o^4)]^{1/2}}{\sum w F_o^4}^{1/2}$$

Table 4.4: Selected Bond Lengths (Å) of Hexaradical **15**.

Cyclotriphosphazene moiety			
P1-O1	1.573(3)	P1-N1	1.573(4)
P1-O4	1.578(3)	P1-N3	1.575(4)
P2-O2	1.567(4)	P2-N2	1.555(5)
P2-O5	1.568(4)	P2-N1	1.577(4)
P3-O6	1.575(4)	P3-N3	1.571(4)
P3-O3	1.581(4)	P3-N2	1.585(5)
Cyclotriphosphazene imino nitroxide bridge			
C1-O1	1.401(6)	C40-O4	1.393(5)
C14-O2	1.400(7)	C53-O5	1.376(7)
C27-O3	1.396(7)	C66-O6	1.402(7)
imino nitroxide moiety			
N4-O7	1.318(11)	N10-O10A	1.298(2)
N6-O8A	1.299(2)	N11-O10B	1.298(2)
N7-O8B	1.300(2)	N12-O11	1.299(2)
N9-O9	1.297(2)	N15-O12A	1.299(2)

Table 4.5: Selected Bond Angles (°) of Hexaradical **15**.

Cyclotriphosphazene moiety			
P1)-N1)-P2)	121.5(3)	N1)-P1)-N3)	117.4(2)
P2-N2-P3	122.7(3)	N2-P2-N1	116.8(2)
P3-N3-P1	120.9(2)	N3-P3-N2	117.7(2)
Cyclotriphosphazene imino nitroxide bridge			
O1-P1-O4	99.43(18)	O6-P3-O3	99.7(2)
O2-P2-O5	94.9(2)	N1-P1-O4	112.9(2)
O1-P1-N1	109.6(2)	N3-P1-O4	105.4(2)
O1-P1-N3	110.55(19)	O5-P2-N1	109.5(2)
O2-P2-N1	111.5(3)	N2-P2-O5	112.7(3)
N2-P2-O2	109.3(2)	N3-P3-O6	112.6(2)
N3-P3-O3	108.8(2)	O6-P3-N2	105.1(2)
O3-P3-N2	111.4(3)	C27-O3-P3	123.9(3)
C1-O1-P1	123.8(3)	C40-O4-P1	128.2(3)
C14-O2-P2	122.4(3)	C53-O5-P2	122.1(3)
		C66-O6-P3	122.6(3)
imino nitroxide moiety			
N5-C7-N4	108.4(7)	N10-C46-N11	111.7(6)
N7-C20-N6	108.7(7)	N13-C59-N12	110.2(7)
N9-C33-N8	105.0(7)	N14-C72-N15	107.9(9)

4.11. Summary and Conclusion

In order to assemble the hexa-Ullman radicals appended on cyclotriphosphazene ring, synthetic sequence by utilizing the Ullman (divergent) route afforded the hexa-imino nitroxide one **15** instead of anticipated hexa-nitronyl nitroxide derivative. Surprisingly, dehydration even room temperature led to the mono-hydroxy condensation product **14** which subsequently oxidized with NaIO₄ to gave solely homogenous neutral hexaradical **15**, six imino nitroxide radical moieties covalently bonded on a cyclotriphosphazene scaffold. Emphatically, six Ullman radicals were successfully implemented on the cyclotriphosphazene core. The target compound **15** was unambiguously characterized with a rich array of analyses such as melting point analysis, FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, SWV, EPR, magnetic measurements, and X-ray analysis.

Cyclic voltammetry of the target hexaradical **15** revealed that the reduction process (-0.883 V vs SCE) is reversible while oxidation one (1.184 V) is quasi-reversible. Additionally, cyclotriphosphazene ring has virtually no impact either on the electrochemical behavior of appended imino nitroxide moieties or on the redox potentials of them.

Two quantification methods were developed to determine the number of radical moieties present on a polyradical. First method was absorption spectroscopy; on the basis of measuring the molar extinction coefficient (ϵ) of polyradical through tracking the $n \rightarrow \pi^*$ transitions of imino nitroxide radical band. Second one was square-wave voltammetry (SWV) method; on the basis of measuring the current through anodic sweeping the oxidation process (0/+1). Both methods successfully demonstrated the presence of six imino nitroxide radical moieties on the target hexaradical **15**. Developed quantification methods are straightforward and rapid techniques easily accessible in most laboratories.

4.12. Synthetic Procedures

As stated in the Chapter 4.5, all the intermediates, the reference radical **7** and the target hexaradical **15** were synthesized successfully. The intermediate **2** was synthesized with Hirel's optimizations [80] on the basis of Sayre protocols [81].

Synthesis of **3** was proceeded through both of metallic zinc method [84] and Al/Hg amalgam method [26]. The hexaaldehyde **12** was prepared with our optimizations on the basis of Carriedo protocols [86]. In cases of radical species **7** and **15**, procedures were optimized on the basis of Ullman [25] and Tamura protocols [26]. Conversion of the nitronyl nitroxide derivative **6** to the imino one **7** was achieved through Luneau method [29].

4.12.1. Synthesis of 2,3-Dimethyl-2,3-dinitrobutane (2)

To 170 mL 6 N NaOH solution (40.8 g=1.02 mol NaOH in 170 mL distilled water) in 1L-flask which placed in ice bath and stirred well, 2-nitropropane (**1**) (1 mole=89 g, 94 mL) was added. The mixture was stirred for 15 minutes, and Br₂ (0.54 mol, 28 mL) was added drop by drop in one hour. EtOH (320 mL) was added to the mixture and then refluxed for 3 hours. Color of mixture was changed to yellow-very pale orange. Reaction mixture was poured into 2-L beaker contains 500 mL H₂O-500 g ice mixture. White precipitate was formed immediately and was stirred for 10 minutes, then the white precipitate was filtered off by suction. Collected precipitate was washed with water twice then dried overnight to yield 65.736 g of slightly beige powder. Crude product was recrystallized in MeOH (~650 mL). 61.625 g white plate crystals were obtained. Yield 70%. mp. 214–216 °C. FT-IR (ATR, ν_{max} , cm⁻¹) : 3032w, 3004w, 2956w, 2869w, 1588w, 1547s, 1532s, 1470m, 1454s, 1435m, 1409s, 1393s, 1378s, 1340s, 1240w, 1220w, 1170s, 1134s, 1015w, 850s, 766w, 733w, 677w, 647w, 568w; ¹H NMR (400MHz, CDCl₃) : δ 1.72 (s, 12H, -CH₃) ppm; ¹³C NMR (100MHz, CDCl₃) : δ 91.55, 23.13 ppm.

4.12.2. Synthesis of 2,3-Bis(hydroxylamino)-2,3-dimethylbutane (3)

Metallic Zinc Method: 17.6 g 2,3-dimethyl-2,3-dinitrobutane (**2**) was dissolved in THF (300 mL) in 1L-erlenmayer flask, then water (50 mL) was added to the solution. The flask was placed in ice bath, stirred vigorously and temperature was kept between 10-12 °C. 27 g metallic zinc powder was added at once. NH₄Cl solution (0.8 mol =43g in 150 mL water) was added dropwise to the mixture in the course of 2 hours. The reaction mixture was stirred extra one hour without exceeding

the 12 °C, then stored in fridge overnight. The mixture was filtered off over Celite-545 plug, the precipitate was washed with THF (4x100 mL). Combined filtrates were evaporated in vacuum until THF ceased to distill off. 30 g Na₂CO₃ and 20 g NaCl were added to the solution to saturate it. The final solution was continuously extracted with CHCl₃ in liquid-liquid apparatus overnight. Evaporation of CHCl₃ yielded 7.025g white powder. Yield 47%. mp.158–160°C. FT-IR (ATR, $\nu_{\max}$, cm⁻¹) : 3351s, 3281s, 3250s, 3225s, 2985s, 2941s, 2916s, 2870s, 1598w, 1535s, 1471s, 1452s, 1426s, 1406s, 1393s, 1376s, 1355s, 1341s, 1261s, 1170s, 1144s, 1078s, 1034s, 988s, 951s, 931s, 903s, 851s, 816w, 790s, 730w, 690m.

Al/Hg Amalgam Method: 3% HgCl₂ solution (3.068 g in 100 mL H₂O) was added to the aluminum shreds (4.600 g) in 2L-beaker. After stirring the mixture at room temperature for 20 minutes, the liquid portion was decanted carefully. The residual solid was washed with H₂O (3 X 100 mL), then with THF (3 X 100 mL). After covering the amalgamated aluminum with THF (250 mL), H₂O (20 mL) and 2,3-dimethyl-2,3-dinitrobutane (**2**) (6.000 g) were added. The reaction mixture was stirred vigorously at room temperature for 2 hours and then filtered on a Celite-545 plug. The colorless filtrate was concentrated to dryness. Obtained solid was washed with pentane (3 X 50 mL), then dried under vacuum to afford 3.560 g white powder. Yield 70%.

Results of analyses were completely same as that of the product of Zinc Method, so not repeated here.

4.12.3. Synthesis of Hexa-(4-formylphenoxy)cyclotriphosphazene (12)

Hexachlorocyclotriphosphazene (**11**) (3 mmol, 1.044 g), 4-hydroxybenzaldehyde (**8**) (19.8 mmol, 2.416 g), and K₂CO₃ (59.4 mmol, 8.197 g) were charged into a 100 mL flask, and then dry THF (30 mL) was added. The mixture was stirred at ambient temperature for 3 days. Reaction was filtered off, and the precipitate was washed with THF (3 × 30 mL). The filtrates and mother liquor were combined, and then concentrated to dryness to afford a beige solid. The crude product was washed with water, then with Et₂O, and finally dried under vacuum to give 2.534 g of a white powder. Yield 98%. mp. 160–162 °C. FT-IR (ATR, $\nu_{\max}$,

cm⁻¹): 3103w, 3051w, 2823w, 2792w, 2733w, 1702s, 1596s, 1584s, 1500s, 1424m, 1389m, 1301m, 1267m, 1205s, 1177s, 1153s, 1104m, 1011m, 959s, 885s, 826s, 745s, 718s, 704s. ¹H NMR (400 MHz, CDCl₃): δ 9.93 (s, 6H, -CHO), 7.73 (d, 12H, J = 8.6 Hz), 7.14 (d, 12H, J = 8.6 Hz) ppm. ¹³C NMR (100 MHz, CDCl₃): δ 190.53, 154.63, 133.90, 131.52, 121.33 ppm. ³¹P NMR (162 MHz, CDCl₃): δ 7.09 ppm. MALDI-TOF MS (2,5 dihydroxycinnamic acid): *m/z* for C₄₂H₃₀N₃O₁₂P₃ [calculated]: 861, [found]: 862 [M+H]⁺.

4.12.4. Synthesis of Phenyl-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl) (7)

Benzaldehyde (**4**) (1 eq., 3 mmol, 0.318 g), 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) (2 eq., 6 mmol, 0.888 g) and TsOH (0.1 eq., 0.3 mmol, 0.057 g) were charged into Schlenk-tube. MeOH (2 mL) was added, and then purged with argon. Tube content was stirred vigorously at room temperature under argon for 5 days. The reaction mixture was washed twice; H₂O (20 mL) was added to reaction mixture and shook well, and eventually centrifuged. The obtained precipitate was dried under vacuum to give beige solid. Crude product **5** was directly used for next step without further purification.

Crude product **5** was suspended in CH₂Cl₂ (150 mL) and placed in ice-bath. Saturated NaHCO₃ (aq.) solution (100 mL) was added to the suspension and stirred vigorously. NaIO₄ (2 eq., 6 mmol, 1.284 g) in H₂O (30 mL) was added to the mixture drop by drop. The color of the mixture was turned to intense blue immediately. It was stirred for one hour in ice-bath, then phases were separated. Blue organic phase was washed with H₂O (2x100 mL), then reaction was continued without isolation of compound **6**.

Blue organic phase of compound **6** was placed in ice-bath. NaNO₂ (4 eq., 12 mmol, 0.828 g) in H₂O (80 mL) was added to organic phase and stirred vigorously. 0.25 M HCl (aq.) solution was added drop by drop to the mixture until blue color turns to steady orange. Approximately 15 mL of HCl solution was consumed. The mixture was stirred for 30 minutes, then phases were separated. Orange organic phase was washed with H₂O (3x150 mL), dried over Na₂SO₄, evaporated to dryness. Orange oily product was purified with column chromatography on silica gel eluting with hexane-ethyl acetate mixture. Column purification gave 0.365g orange oil of **7**

in 56% yield (from aldehyde). The product was liquid [96] at room temperature. FT-IR (ATR, $\nu_{\max}$, cm^{-1}): 3059w, 2978s, 2929w, 2866w, 1603w, 1584w, 1551m, 1487s, 1477s, 1449s, 1428s, 1388w, 1375s, 1367s, 1318s, 1289s, 1263s, 1220m, 1178w, 1155s, 1136s, 1100w, 1074m, 1029m, 955w, 932w, 878s, 847w, 763s, 691s, 662s; MALDI-TOF MS (α -cyano-4-hydroxycinnamic acid) : m/z for $\text{C}_{13}\text{H}_{17}\text{N}_2\text{O}$ [calculated]: 217, [found]: 218 $[\text{M}+\text{H}]^+$.

4.12.5. Synthesis of Hexa-[4-(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl)phenoxy]cyclotriphosphazene (15)

Hexa-(4-formylphenoxy)-cyclotriphosphazene (**12**) (1 equiv, 0.8 mmol, 0.690 g), 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) (1.5 equiv, 7.2 mmol, 1.066 g), and TsOH (0.1 eq., 0.48 mmol, 0.091 g) were charged into a Schlenk tube. MeOH (4 mL) was added and then purged with argon, and the content was stirred vigorously at room temperature under argon for 14 days. The reaction mixture was washed with H_2O (2×20 mL) twice, and eventually collected by centrifuge. The obtained precipitate was dried in a vacuum to give a yellowish solid. FT-IR and MALDI-TOF MS analyses of the yellowish solid (as crude product) confirmed its structure as hexa-[4-(1-hydroxy-4,4,5,5-tetramethyl-2-imidazoline-2-yl)phenoxy]cyclotriphosphazene (**14**). Crude product of **14** was subjected to NaIO_4 oxidation without further purification. mp. 214°C with decomposition. FT-IR (ATR, $\nu_{\max}$, cm^{-1}) of compound **14**: 3192w, 2977w, 2925w, 2866w, 1602m, 1537s, 1500s, 1456m, 1409m, 1394m, 1378m, 1341m, 1269m, 1202s, 1158s, 1120m, 1104m, 1050w, 1034w, 1011m, 943s, 884s, 849s, 746m, 680m. MALDI-TOF MS of compound **14** (sinapinic acid): m/z for $\text{C}_{78}\text{H}_{102}\text{N}_{15}\text{O}_{12}\text{P}_3$ [calculated]: 1534, [found]: 1540 $[\text{M}+6\text{H}]^+$.

Yellowish solid **14** was suspended in CH_2Cl_2 (200 mL) and placed in an ice-bath. Phosphate buffer solution (aqueous pH 7, 120 mL) was added to the suspension and stirred vigorously. NaIO_4 (2 equiv, 9.6 mmol, 2.054 g) in H_2O (30 mL) was added to the mixture. The color turned orange after 5 min. It was stirred for 2 h in an ice bath. Phases were separated. The orange organic phase was washed with H_2O (3×150 mL), dried over Na_2SO_4 , and evaporated to dryness. Orange oily product was purified with column chromatography on silica gel eluting with a diethyl ether–dichloromethane–methanol mixture of 80–40–4 solvent ratio. Column

purification gave 0.514 g of a crimson oil of **15** in 42% yield (from aldehyde). Crystallization of crimson oil in ethyl acetate–toluene–heptane mixture for 11 days in the dark at room temperature afforded crimson crystals suitable for X-ray diffraction. mp. 204–206 °C. FT-IR (ATR, ν_{max} , cm^{-1}): 3077w, 2979w, 2929w, 2862w, 1737w, 1606m, 1496s, 1460m, 1447m, 1407m, 1388w, 1375m, 1367m, 1306m, 1292w, 1265s, 1201s, 1183s, 1161s, 1100m, 1018m, 944s, 884s, 850s, 810w, 783m, 748s, 725m, 687w, 660m. MALDI-TOF MS (trans-2-[3-(4-tert -butylphenyl)-2-methyl-2-propenylidene]-malononitrile): m/z for $\text{C}_{78}\text{H}_{96}\text{N}_{15}\text{O}_{12}\text{P}_3$ [calculated]: 1528, [found]: 1529 $[\text{M}+\text{H}]^+$. Elemental Analysis for $\text{C}_{78}\text{H}_{96}\text{N}_{15}\text{O}_{12}\text{P}_3$ [calculated]: C, 61.29; H, 6.33; N, 13.74. [found]: C, 61.62; H, 6.42; N, 13.59.

5. ALTERNATIVE SYNTHESIS OF NITRONYL NITROXIDE-BASED HEXARADICAL ARCHITECTURE ON A CYCLOTRIPHOSHAZENE SCAFFOLD AND GENERALIZATION OF ABSORPTION SPECTROSCOPY AND ELECTROCHEMISTRY QUANTIFICATION METHODS TO NITRONYL NITROXIDE RADICALS

The state of the art concerning the phosphazenes was disclosed in Chapter 4.1 in details and the cyclotriphosphazene-nitroxide hybrid compounds did in Chapter 4.3.

The literature survey on the cyclotriphosphazene-nitroxide compounds is provided in Chapter 4.3. As pointed out in Chapter 4.4, there are many types and also many features of the cyclotriphosphazene-nitroxide compounds yet to be investigated.

5.1. Specificity of Nitronyl Nitroxide Synthesis

The synthesis of nitronyl nitroxide is a kind of gambling. Because, nitronyl nitroxide would be obtained/isolated under only elaborate circumstances and if executed with great minuteness. All the other conditions resulted in fails; either complete loss of nitronyl nitroxide radical or decomposition of it to the corresponding imino nitroxide radicals. The intermediates and the nitronyl nitroxide are sensitive to the exogenous factors such as oxygen, moisture, acid, temperature, and light. Therefore, the reactions in the synthetic sequence (Figure 5.1) need to be carried out with extreme care.

- i) 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) must be free base and of course in the pure form. Impurities such as particularly acetone oxime, diamino derivative, or unchanged dinitro compound (**2**) have direct impact on the success.

- ii) Temperature of condensation reaction needs to be as low as possible because higher temperature leads to dehydration [27].
- iii) Temperature of oxidation step also must be low because higher temperature or even room temperature may consequence the way III oxidation or conversion of NN to the corresponding IN even NN formed (Figure 5.1).
- iv) All the manipulations upon formation of nitronyl nitroxide need to be done in acid free media since even trace of acid causes the conversion of NN to the IN.

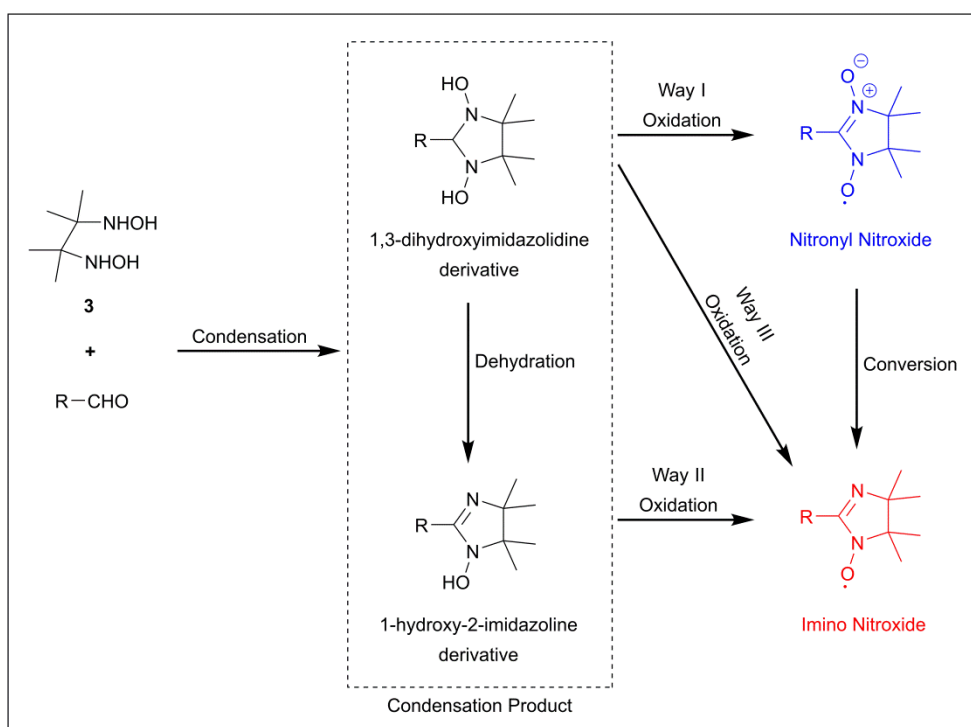


Figure 5.1: Syntheses of Nitronyl Nitroxide and Imino Nitroxide Radicals.

5.2. Scope and Objectives

According to the synthetic studies presented in Chapter 4, the classical Ullman route resulted in unintended delivering of the hexa-imino nitroxide derivative **15** instead of anticipated hexa-nitronyl nitroxide one **16**. Unexpected synthesis of the hexa-imino nitroxide derivative **15** was credited to the dehydration which took place even at room temperature. So, within Chapter 5, synthetic efforts are allocated particularly to the preparation of the hexa-nitronyl nitroxide cyclotriphosphazene **16** (Figure 5.2).

As pointed out in Chapter 4.3 and 4.4, there is only one study in the literature discussing the nitronyl nitroxide bonded cyclotriphosphazene compounds [74]. The report indicates that two nitronyl nitroxide radicals appended cyclotriphosphazene compound **118** was isolable whereas four and six nitronyl nitroxide radicals linked cyclotriphosphazene derivatives **119**, **16** (Figure 4.6) are too labile to be isolated [74]. Even worse, no characterization proof was provided for tetra- and hexa-nitronyl nitroxide substituted cyclotriphosphazene compounds **119**, **16**. Therefore, synthesis and isolation of the hexa-nitronyl nitroxide substituted cyclotriphosphazene **16** is still tough challenge.

Synthesis of nitronyl nitroxide (Ullman) radicals attached cyclotriphosphazene (Figure 4.6) was performed with pre-formed radicals [74]. Emphatically, Tamura's synthetic strategy [74] is a convergent synthesis because outer fragments were first prepared, subsequently bonding them to the core. We will revisit the synthesis of hexa-nitronyl nitroxide **16** via convergent route in order to incorporate six nitronyl nitroxides into the cyclotriphosphazene core. Extra attention will be paid in order to avoid the possible loss of the radical character during the post-synthetic manipulations. Combination of extra care and experienced synthetic talent would pave the way for synthesis of hexa-nitronyl nitroxide substituted cyclotriphosphazene **16**.

As stated in Chapter 4.4, electrochemical characterization of nitroxide-cyclotriphosphazene hybrid compounds has paramount importance for the development of electrochemical applications. Relevantly, electrochemical analyses of hexa-nitronyl nitroxide **16** by comparing with its parent analogue, 2-phenyl-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**6**), need to be performed in great extent.

Within the Chapter 4, two quantification methods -by absorption spectroscopy and electrochemistry- were developed for determination of imino nitroxide content of polyradicals. Those methods need to be transposed to the nitronyl nitroxide radicals to demonstrate the versatility of such techniques.

On the basis of aforementioned reasons, main objectives are;

- i) To synthesize, to isolate and to characterize the hexa-nitronyl nitroxide substituted cyclotriphosphazene **16** through convergent synthesis.

Emphatically, to synthesize the target hexaradical **16** by utilizing the pre-formed radical synthon **10**,

- ii) To explore the electrochemical behavior of hexa-nitronyl nitroxide substituted cyclotriphosphazene **16** by comparing with its parent analogue, 2-phenyl-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**6**),
- iii) To transpose the absorption spectroscopy and electrochemistry quantification methods -developed previously for the imino nitroxide radicals- to the nitronyl nitroxide derivatives to demonstrate the versatility of such techniques.

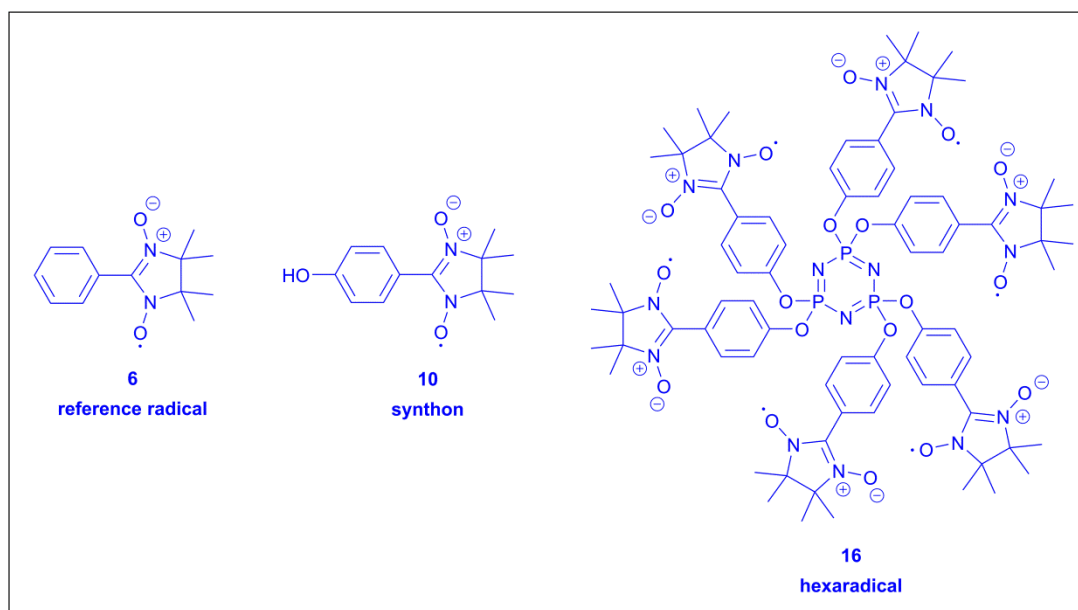


Figure 5.2: Structures of the Reference Radical **6**, the Synthon **10** and the Hexaradical **16**.

5.3. Synthesis

Synthesis of hexa-[4-(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl-2-yl)phenoxy]-cyclotriphosphazene (**16**) was initially planned through the classical Ullman procedure [25] based on the condensation of 2,3-bis(hydroxylamine)-2,3-dimethylbutane (**3**) with hexa-(4-formylphenoxy)cyclotriphosphazene (**12**) and oxidation of the condensation product by NaIO₄. Unfortunately during the oxidation step, the typical deep blue color of **16** was never observed despite our many attempts. Instead, solely the orange color of imino nitroxide derivative (**15**) was observed,

presumably because the **13** condensation adduct dehydrated [27] to **14** even at room temperature (Figure 5.3).

To bypass the unforeseen problem, the convergent route is considered as an alternative synthetic pathway (Figure 5.3). Phenolic compounds are well-known nucleophilic species [71] to be exchanged with the active chlorines of the hexachlorocyclotriphosphazene. Accordingly, phenolic analogue of nitronyl nitroxide **10** is perceived as desired synthon to employ in the regarding substitution reaction.

Our synthetic strategy toward the synthesis of the reference radical **6** and the synthon **10** followed also the Ullman's procedure which already described in Chapter 4.4. Nitronyl nitroxide species were successfully prepared on the basis of the Ullman [25] and Tamura protocols [26]. FT-IR spectrum of **6** (Figure 8.34) displayed a single signal at 1363 cm^{-1} which attributed to N-O stretchings of nitronyl nitroxide fragment [30]. MALDI-TOF MS analysis of **6** (Figure 8.35) shows a peak at m/z of 230 [M-3] which another identity proof of the reference radical **6**. Similarly, FT-IR spectrum of **10** (Figure 8.36) displayed broad absorption at 3102 cm^{-1} assigned to the -OH stretching and a single signal at 1335 cm^{-1} which attributed to N-O stretchings of nitronyl nitroxide trace [30]. MALDI-TOF MS analysis of **10** (Figure 8.37) shows a peak at m/z of 246 [M-3] which another identity proof of the synthon **10**. Elemental analysis of **10** confirmed the structure and the purity as well.

Naturally, our synthetic tactics to assemble the hexaradical **16** is that base promoted nucleophilic attacks of synthon **10** on the hexachlorocyclotriphosphazene **11** to be exchanged with the chlorines (Figure 5.3). As already practiced for the synthesis of hexaaldehyde **12** in Chapter 3, K_2CO_3 is evidently a suitable base in terms of primarily basicity, easy usage, and availability as well. The reaction in our early attempts – K_2CO_3 -promoted proceedings either in THF or in acetone at room temperature and at reflux temperature- was never completed, emphatically for the hexasubstituted derivative. Furthermore, prolonged reactions led to the loss of nitronyl nitroxide character. During critiquing the results, we came up with the idea of proceeding the reaction under microwave energy. Upon long optimizations, best result was observed at the conditions; K_2CO_3 -promoted reaction in acetone at $48\text{ }^\circ\text{C}$ for 6 hours under microwave irradiation. Among the THF, DMF, and HMPA; acetone was the best solvent for compelling reasons; firstly well progressing of the reaction in it and secondly easy removing of it. Utilizing the phase transfer catalysts

such as Aliquat 336 and tetra-*n*-heptylammonium bromide has no significant influence either on progress or on yield of the reaction. In terms of work-up, just washing with aqueous solution of K_2CO_3 and subsequently with water get rid of the unreacted synthon **10** and other impurities as well. In brief, the K_2CO_3 -promoted nucleophile substitution [86] of synthon **10** in acetone under microwave irradiation allow to isolate **16** as a blue powder (Figure 5.4, inset) in 96% yield (Figure 5.3) in contradiction with the labile nature [74] previously mentioned. This report is the first one for the synthesis of a cyclotriphosphazene bearing six nitronyl nitroxide radicals.

MALDI-TOF MS analysis of **16** (Figure 8.40) shows a peak at an m/z of 1625 $[M+H]^+$, which is proof of the formation of **16**, as well as elemental analyses demonstrate its purity. Formation of the compound **16** was also evidenced in FT-IR spectrum following the complete disappearance of the $-OH$ stretchings of **10** (Figure 8.39). FT-IR spectrum of **16** (Figure 8.38) displayed a single signal at 1358 cm^{-1} which assigned to N-O stretchings of nitronyl nitroxide residue [30]. Distinguishing features of cyclotriphosphazene ring are observed for **16** in FT-IR spectrum (Figure 8.38) as well; the sharp bands at 1206 , 1185 and 1161 cm^{-1} of P=N stretching vibrations and the single band at 942 cm^{-1} of P-O bond stretching vibration [90].

To conclude, the target hexaradical **16** was successfully synthesized in 96% isolated yield via the K_2CO_3 -promoted nucleophilic substitution of the synthon **10** in acetone under microwave irradiation. The hexaradical **16** was characterized unambiguously with a rich array of analyses such as melting point analysis, FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, SWV, EPR, magnetic measurements, and X-ray analysis. The reference radical **6** was successfully synthesized and fully characterized as well.

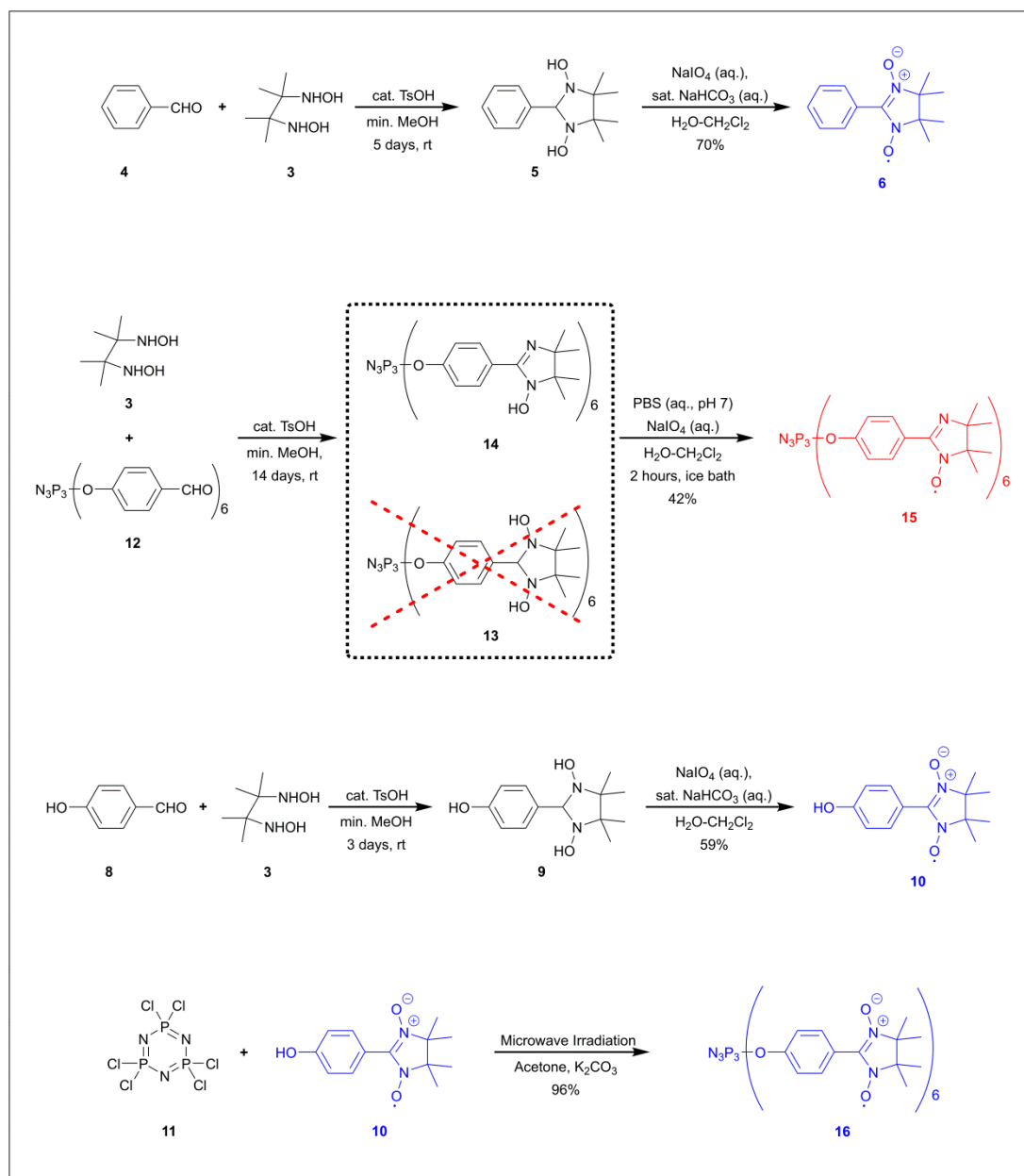


Figure 5.3: Synthetic Routes to the Reference Radical **6** and the Hexaradical **16**.

5.4. Absorption Spectroscopy

The characteristic fingerprint band of nitronyl nitroxide [27] around $\lambda_{\text{max}} \sim 610$ nm (Figure 5.4) was observed also for **6** and **16** which is assigned to $n \rightarrow \pi^*$ transitions of the nitroxide residue. The bathochromic shift of nitronyl nitroxide regarding imino nitroxide (~ 443 nm) [97] is attributed to the higher symmetry [98] of the ONCNO fragment in comparison with the unsymmetrical NCNO configuration. **16** was soluble in organic solvent such as chloroform, acetonitrile and toluene in

which the Beer–Lambert Law was observed in the range of 10^{-5} M to 4.10^{-4} M for **16** (Figure 8.48-8.54).

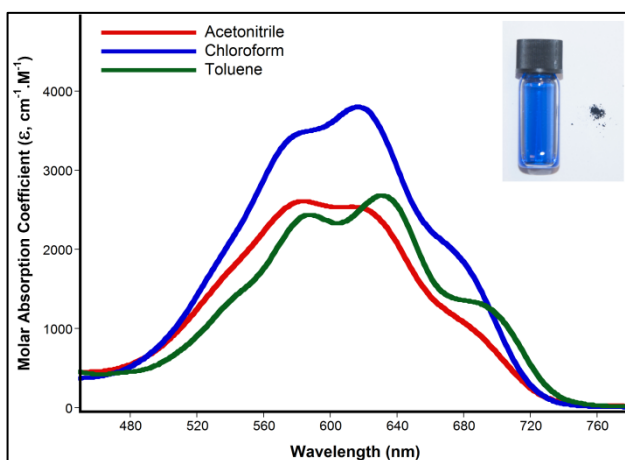


Figure 5.4: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **16**, Inset: 10^{-3} M Chloroform Solution of **16** and Powder of **16**.

Quantification method allowing the determination of the number of imino nitroxide radicals based on the molar extinction coefficient (ϵ) calculation was extrapolated to nitronyl nitroxide moieties to generalize the effectiveness of the techniques [97]. 2-Phenyl-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**6**) was used as reference standard. Basically, dividing the ϵ of **16** (Figure 8.48-8.54) by the one of **6** (Figure 8.41-8.47) allow us to determine the number of radical moieties present on **16** (Table 5.1). All the results are in agreement within the $\pm 10\%$ tolerance of ϵ except for the chloroform solution suggesting a loss of the radical character due to the chloroform acidity.

Table 5.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of **6** and **16** at Room Temperature^a.

Solvent	$\lambda_{\max}$ 6	ϵ 6	$\lambda_{\max}$ 16	ϵ 16	Number of Radicals on 16
Acetonitrile	583	485	584	2754	5.68
Chloroform	608	731	616	3842	5.26
Toluene	631	481	631	2680	5.57

^a $\lambda_{\max}$ in nm, ϵ in $\text{cm}^{-1} \cdot \text{M}^{-1}$

As conclusion, UV-vis spectra proved gender of the reference radical **6** and the hexaradical **16** as nitronyl nitroxide radicals. Quantification method by absorption

spectroscopy is well implemented to the nitronyl nitroxide radicals and demonstrated the presence of six nitronyl nitroxide moieties on **16**.

5.5. Electrochemical Analyses

Nitronyl nitroxides are redox-active molecules to be either oxidized (p-type redox) to oxo-ammonium cation or reduced (n-type redox) to aminoxy anion. Electrochemical characteristics of reference radical **6** and target hexaradical **16** were investigated by cyclic voltammetry (CV). Both radicals displayed two reversible redox waves which are in agreement with the literature [52],[99]. Reduction processes at -0.812 V vs. SCE for **6** and -0.879 V for **16** are assigned to NN/aminoxy anion couple. Oxidation ones at 0.748 V for **6** and 0.776 V for **16** are ascribed to NN/oxoammonium cation couple. Virtually overlapping the redox processes of **16** with those of phenyl nitronyl nitroxide **6** suggests that cyclotriphosphazene core has almost no influence on the redox potentials of **16** (Figure 5.5). Square Wave Voltammetry (SWV) quantification method developed for hexa-imino nitroxide radical [97] was effectuated for the hexa-nitronyl nitroxide counterpart **16** by comparing with phenyl nitronyl nitroxide **6** as a reference standard. Quantification could be performed either by anodic sweep or cathodic sweep as the oxidation process (0/+1) of NNs is reversible. Current responses of the reference radical **6** were linear in the concentration range of 2-120 μ M for both of anodic and cathodic sweep (Figure 5.6). SWV analyses of **16** demonstrated that the hexaradical **16** has six nitronyl nitroxide moieties on the cyclotriphosphazene core (Figure 5.7, Table 5.2). As consequence, SWV analysis is a simple and straightforward quantification method for nitronyl nitroxide appended polyradicals.

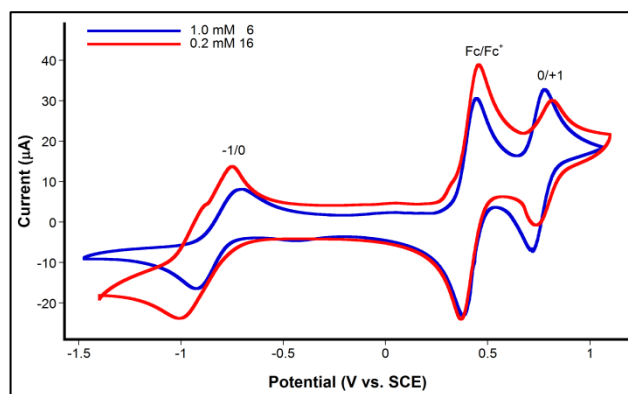


Figure 5.5: Cyclic Voltammograms of the Reference Radical **6** and the Hexaradical **16** Recorded at rt in Acetonitrile, 0.1 M $n\text{-Bu}_4\text{NBF}_4$ as Supporting Electrolyte, Scan Rate of 50 mV/s for **6** and of 100mV for **16**.

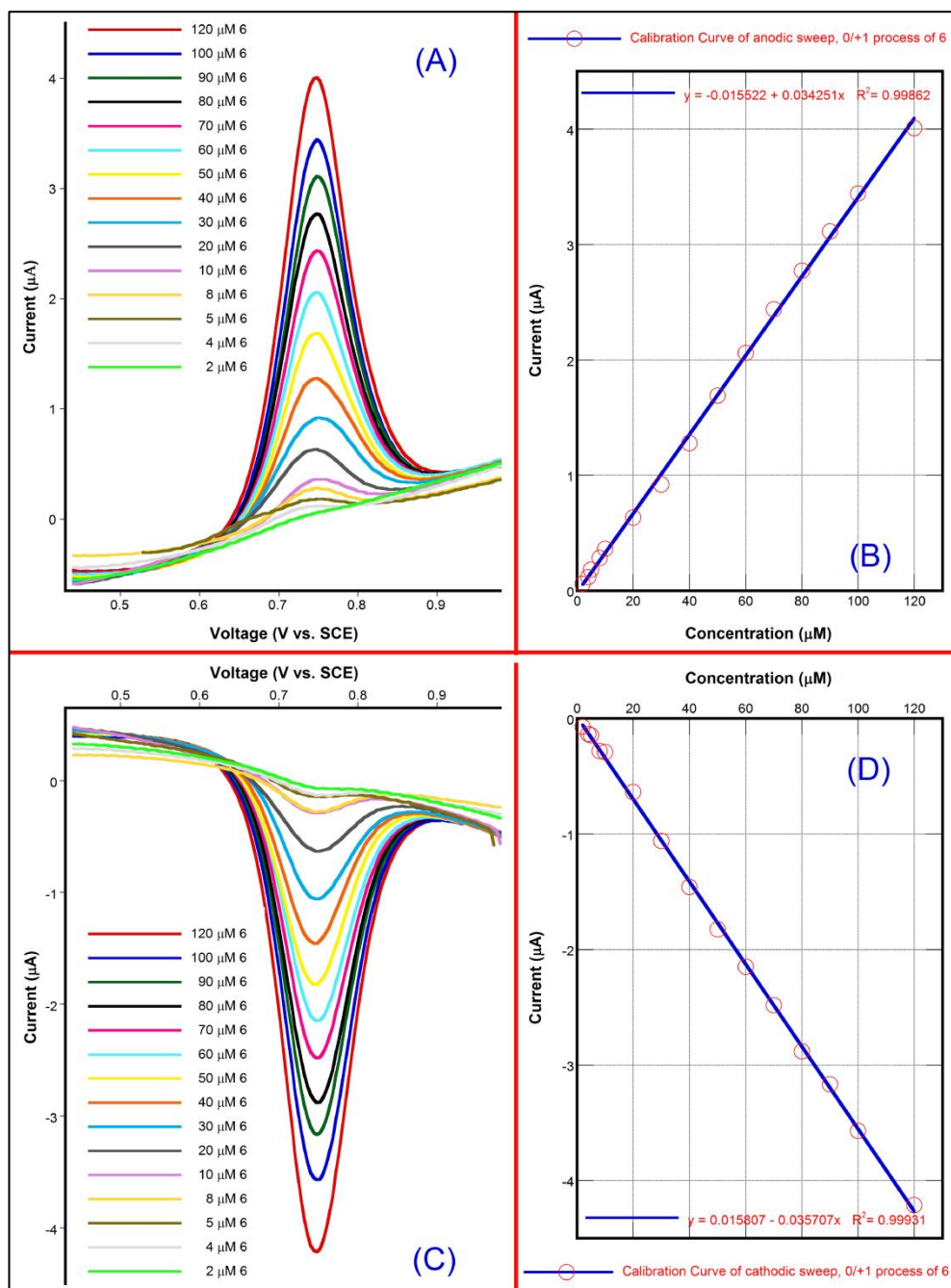


Figure 5.6: Square-Wave Voltammetry Analyses in 0.1 M $n\text{-Bu}_4\text{NBF}_4$ /acetonitrile Solutions of the Reference Radical **6**: a) Anodic Sweep for (0/+1) Process; b) Calibration Curve of Anodic Sweep for (0/+1) Process; c) Cathodic Sweep for (0/+1) Process; d) Calibration Curve of Cathodic Sweep for (0/+1) Process.

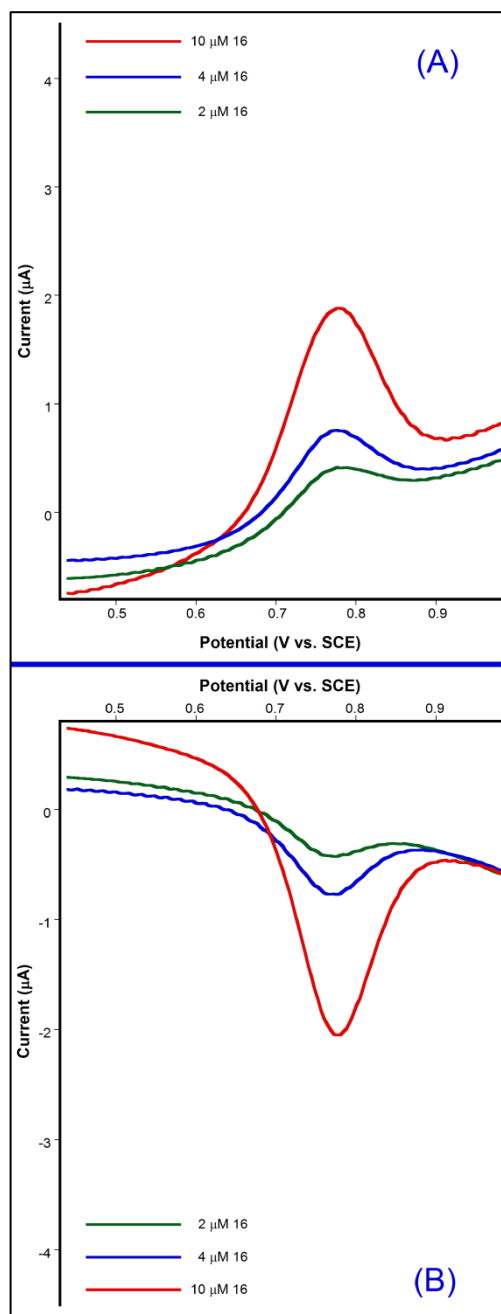


Figure 5.7: Square-Wave Voltammetry Analyses in 0.1 M *n*-Bu₄NBF₄/acetonitrile Solutions of the Hexaradical **16**: a) Anodic Sweep for (0/+1) Process; b) Cathodic Sweep for (0/+1) Process.

Table 5.2. Square-Wave Voltammetry (SWV) Analyses of **16**.

C_{16} (μM)	I_{measured} (μA)	$C_{\text{theoretical}}$ (μM)	Number of Radicals on 16 = $C_{\text{theoretical}} / C_{16}$
By Anodic Sweep			
2	0.416	12.60	6.30
4	0.758	22.58	5.64
10	1.883	55.43	5.54
By Cathodic Sweep			
2	-0.429	12.46	6.23
4	-0.772	22.06	5.52
10	-2.049	57.83	5.78

5.6. Electron Paramagnetic Resonance Spectroscopy

EPR spectra of **6**, **10** and **16** were presented in Figure 5.8. The spectra of **6** and **10** (Figure 5.8, 8.55-8.58) show five lines with the relative intensities of 1:2:3:2:1 arising from the hyperfine coupling of electron spin with two equivalent ^{14}N atoms (nuclear spin $I=1$), characteristic of nitronyl nitroxide radicals [52], [99]. Whereas **16** presents a broad single line centered at $g = 2.0031$ with $\Delta H_{p-p} = 11.8$ G despite all our attempts to observe the five line pattern. By lowering the temperature a wider signal was observed and contrariwise a narrow signal was obtained under heating (Figure 8.59). This kind of behavior was already observed for polyradical compounds [79]. The single line signal could be attributed to the strong intramolecular electron-exchange interactions between the six radical moieties [74]. The group of three radicals from each side of the cyclotriphosphazene ring are close enough to each other to interact by through-space mechanism, but they are independent from the radicals of the other side of the cyclotriphosphazene ring.

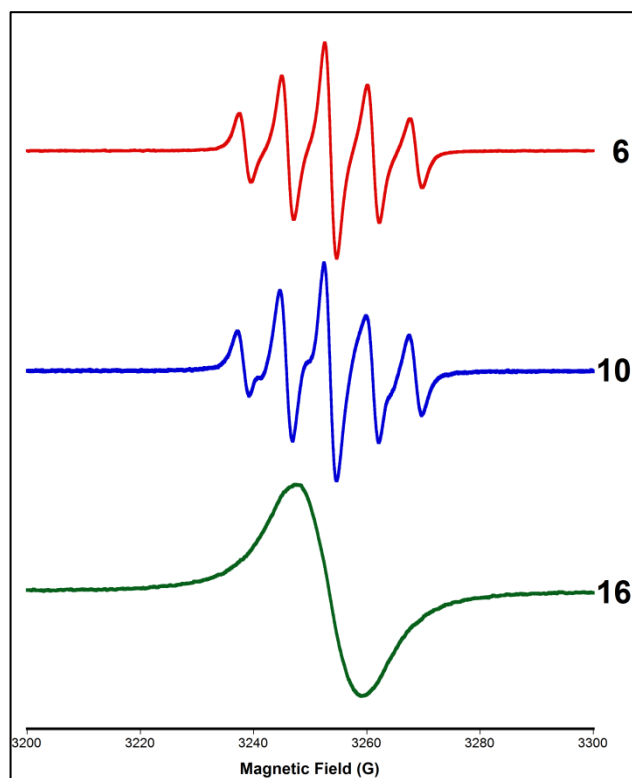


Figure 5.8: EPR Spectra of the Radicals **6**, **10**, and **16** at 293 K at 10^{-4} M in Dichloromethane-Toluene (1:1) Mixture.

5.7. Magnetic Measurements

At room temperature the product of the magnetic susceptibility with temperature (χT) has the expected value for 6 magnetically independent radicals ($2.22 \text{ cm}^3 \text{ K mol}^{-1}$). Upon cooling χT is almost constant down to 100 K then decrease continuously down to 2 K (Figure 5.9). The data were well fitted with a Curie-Weiss law considering 6 spin $S=1/2$ and Weiss constant $\theta = -2.16 \text{ K}$. This behavior is in agreement with 6 radical moieties in the compound and very small and almost non-significant antiferromagnetic interactions in between.

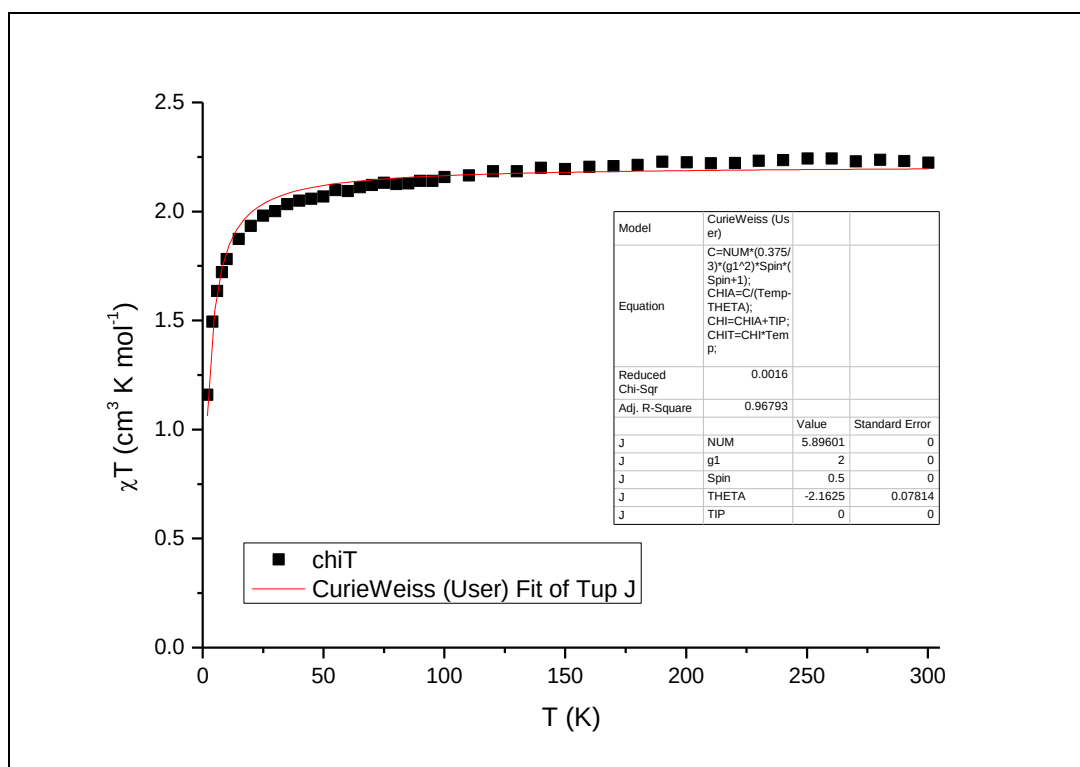


Figure 5.9: Temperature Dependence of the Product of the Magnetic Susceptibility with Temperature (χT) for **16**.

5.8. X-ray Diffraction Analyses

Dark blue crystals are obtained from the different batches (Figure 5.10). Their data collection, data refinement and determination of the structure are in progress.



Figure 5.10: Crystal of **16** on the X-ray Mounter.

5.9. Summary and Conclusion

The target hexaradical **16** (six nitronyl nitroxide radical moieties covalently bonded on the cyclotriphosphazene ring) was prepared through an alternative synthetic pathway involving the nucleophilic substitution of the hexachlorocyclotriphosphazene (**3**) by an adequate pre-formed radical synthon; the 2-(4-hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**). The K_2CO_3 -promoted nucleophilic substitution in acetone under microwave irradiation allows to isolate **16** as a blue powder in 96% yield in contradiction with the labile nature [74] previously mentioned. Noteworthy that a slightly excess of **10** (7.2 eq.) drive the reaction to completion which facilitate the synthesis and straightforward purification of the fully homo-substituted cyclotriphosphazene. The hexaradical **16** was characterized unambiguously with a wide combination of analyses such as melting point analysis, FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, SWV, EPR, magnetic measurements, and X-ray analysis.

Cyclic voltammetry of the target hexaradical **16** revealed that both the reduction process (-0.879 V vs SCE) and oxidation one (0.776 V) are reversible. Besides that, cyclotriphosphazene ring has virtually no impact either on the electrochemical behavior of appended nitronyl nitroxide moieties or on the redox potentials of them. Electrochemical characteristics of **16** in hand, it would be considered as ambipolar redox-active molecule which undergoes both oxidation (p-type redox) and reduction (n-type redox) processes.

Absorption spectroscopy and square-wave voltammetry (SWV) quantification methods are well implemented to the nitronyl nitroxide radicals. Both methods successfully demonstrated the presence of six nitronyl nitroxide radical moieties on the target hexaradical **16**. In particular, SWV method was expanded by employing both of the anodic and cathodic sweep.

5.10. Synthetic Procedures

As stated in the Chapter 5.3, the reference radical **6**, the synthon **10**, and the target hexaradical **16** were synthesized successfully. Synthesis of compound **3** was provided in Chapter 4.12.2. In cases of radical species **6** and **10**, procedures were optimized on the basis of Ullman [25] and Tamura protocols [26]. Synthesis of the target hexaradical **16** was accomplished under microwave energy with our optimizations on the basis of Carriedo protocols [86].

5.10.1. Synthesis of 2-Phenyl-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**6**)

Benzaldehyde (**4**) (1 eq., 3 mmol, 0.318 g), 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) (2 eq., 6 mmol, 0.888 g) and TsOH (0.1 eq., 0.3 mmol, 0.057 g) were charged into Schlenk-tube. MeOH (2 mL) was added, and then purged with argon. Tube content was stirred vigorously at room temperature under argon for 5 days. The reaction mixture was washed twice; H₂O (20 mL) was added to reaction mixture and shook well, and eventually centrifuged. The obtained precipitate was dried under vacuum to give beige solid. Crude product **5** was directly used for next step without further purification.

Crude product **5** was suspended in CH₂Cl₂ (150 mL) and placed in ice-bath. Saturated NaHCO₃ (aq.) solution (100 mL) was added to the suspension and stirred vigorously. NaIO₄ (2 eq., 6 mmol, 1.284 g) in H₂O (30 mL) was added to the mixture drop by drop. The color of the mixture was turned to intense blue immediately. It was stirred for one hour in ice-bath, then phases were separated. Blue organic phase was washed with H₂O (3x100 mL), dried over Na₂SO₄, evaporated to dryness. Crude product was purified with column chromatography on silica gel eluting with hexane-ethyl acetate mixture. Column purification gave 0.490 g blue powder of **6** in 70% yield (from aldehyde). mp. 85–86 °C. FT-IR (ATR, ν_{max} , cm⁻¹) : 3066w, 2987w, 2935w, 2866w, 1574w, 1540w, 1477m, 1458m, 1445m, 1423m, 1395s, 1363s, 1333m, 1311s, 1292m, 1217s, 1160s, 1144s, 1133s, 1113s, 1073m, 1028m, 1002w, 975w, 930w, 925w, 865m, 768s, 692s; MALDI-TOF MS (*trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile) : *m/z* for C₁₃H₁₇N₂O₂ [calculated]: 233, [found]: 230 [M-3]⁺.

5.10.2. Synthesis of 2-(4-Hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**)

4-Hydroxybenzaldehyde (**8**) (1 eq., 10 mmol, 1.220 g), 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**) (1.2 eq., 12 mmol, 1.800 g) and TsOH (0.1 eq., 1 mmol, 0.190 g) were charged into Schlenk-tube. MeOH (3 mL) was added, and then purged with argon. Tube content was stirred vigorously at room temperature under argon for 3 days. The reaction mixture was washed twice; H₂O (50 mL) was added to reaction mixture and shook well, and eventually centrifuged. The obtained precipitate was dried under vacuum to give white solid. Crude product **9** was directly used for next step without further purification.

Crude product **9** was suspended in CH₂Cl₂ (300 mL) and placed in ice-bath. Saturated NaHCO₃ (aq.) solution (160 mL) was added to the suspension and stirred vigorously. NaIO₄ (1.5 eq., 15 mmol, 3.210 g) in H₂O (50 mL) was added to the mixture drop by drop. The color of the mixture was turned to intense blue immediately. It was stirred for 90 minutes in ice-bath, then phases were separated. Blue organic phase was washed with H₂O (3x200 mL), dried over Na₂SO₄, evaporated to dryness. Crude product was purified with column chromatography on silica gel eluting with hexane-ethyl acetate mixture. Column purification gave 1.463

g blue powder of **10** in 59% yield (from aldehyde). mp. 134–135 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3102m, 3003m, 2980m, 2945m, 2800m, 2595w, 1608s, 1584m, 1538w, 1488s, 1474w, 1449s, 1427s, 1419s, 1393s, 1376m, 1362m, 1393s, 1282s, 1230s, 1210s, 1174w, 1165s, 1131s, 1104m, 1012w, 969w, 949w, 868m, 856w, 839s, 793m, 757w, 754w; MALDI-TOF MS (*trans*-2-[3-(4-*tert*-Butylphenyl)-2-methyl-2-propenylidene]malononitrile) : m/z for $\text{C}_{13}\text{H}_{17}\text{N}_2\text{O}_3$ [calculated]: 249, [found]: 246 $[\text{M}-3]^+$. Elemental Analysis for $\text{C}_{13}\text{H}_{17}\text{N}_2\text{O}_3$ [calculated]: C, 62.64; H, 6.87; N, 11.24. [found]: C, 62.50; H, 6.98; N, 11.41.

5.10.3. Synthesis of Hexa-[4-(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl-2-yl)phenoxy]-cyclotriphosphazene (**16**)

Hexachlorocyclotriphosphazene (**11**) (1 eq., 0.075 mmol, 0.026 g), 2-(4-Hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**) (1.2 eq., 0.54 mmol, 0.135 g), and K_2CO_3 (72 eq., 10 eq. for each –OH, 5.4 mmol, 0.745 g) were charged into a microwave tube. Acetone (6 mL) was added then purged with argon. The tube was placed in the cavity and stirred efficiently. Tube content was subjected to microwave irradiation (maximum energy 300 Watt) at 48 °C for 6 hours under argon. Reaction mixture was transferred into a flask and evaporated to dryness. Crude product was taken into CH_2Cl_2 (100 mL) and washed with aqueous solution of K_2CO_3 (3x100 mL), then with H_2O (4x100 mL). Resulting blue solution was dried over Na_2SO_4 , evaporated to dryness to give 0.117 g of a blue powder in 96% yield. mp. 178–180 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3096w, 2987w, 2933w, 1601m, 1523m, 1483m, 1450m, 1429m, 1421m, 1388s, 1358s, 1299s, 1269m, 1244w, 1206s, 1185s, 1161s, 1100m, 1017m, 942s, 884s, 837s, 777w, 732m, 714m; MALDI-TOF MS (*trans*-2-[3-(4-*tert*-Butylphenyl)-2-methyl-2-propenylidene]malononitrile) : m/z for $\text{C}_{78}\text{H}_{96}\text{N}_{15}\text{O}_{18}\text{P}_3$ [calculated]: 1624, [found]: 1625 $[\text{M}+\text{H}]^+$. Elemental Analysis for $\text{C}_{78}\text{H}_{96}\text{N}_{15}\text{O}_{18}\text{P}_3$ [calculated]: C, 57.67; H, 5.96; N, 12.93. [found]: C, 56.78; H, 5.74; N, 13.49 (1. analysis); C, 56.77; H, 5.89; N, 12.14 (2. analysis).

6. ULLMAN RADICALS FUNCTIONALIZED PHTHALOCYANINES

6.1. Phthalocyanines

Phthalocyanines –also known as tetrabenzotetraazaporphyrins- are planar macrocycles which consist of four isoindole sub-units (Figure 6.1). They possess 18 π electrons (Figure 6.1) well-delocalized over the macrocycle system [100] that turns out exceptional stability and outstanding electronic and physical properties [101].

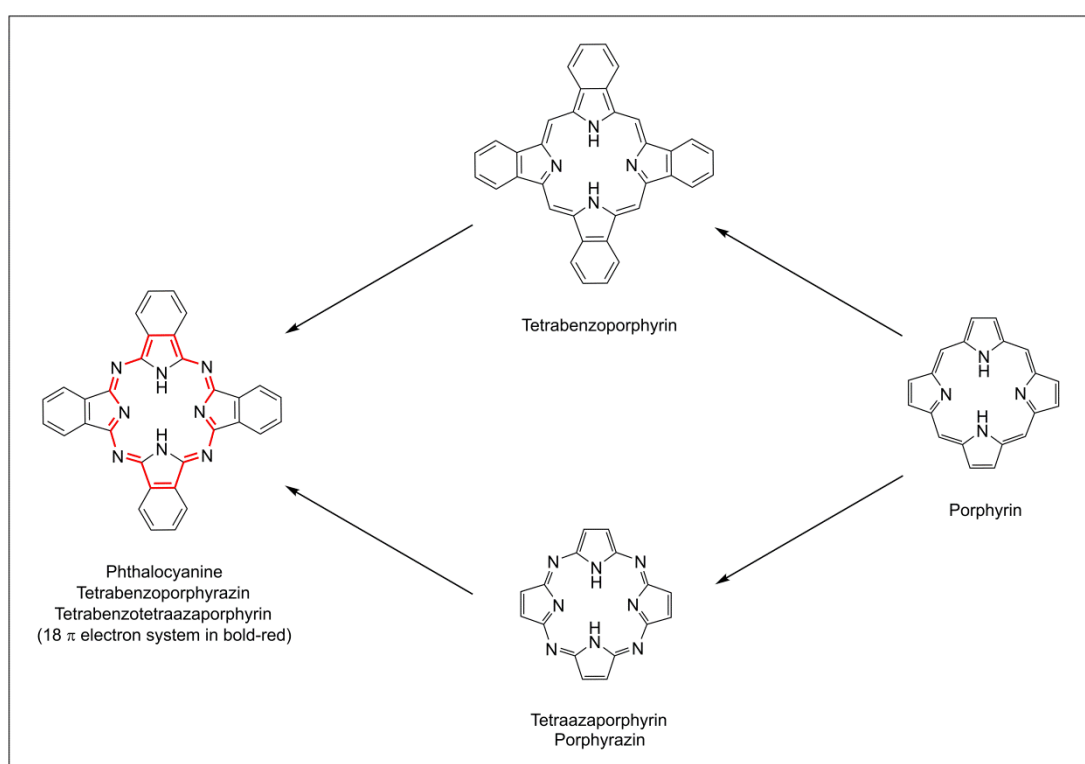


Figure 6.1: Relationship of the Phthalocyanines with the Porphyrin Macrocycle.
(Adopted from reference 100 and 102).

Phthalocyanines (Pcs) are blue to green colored aromatic macrocyclic compounds widely used as dyes. One of the most striking characteristics of Pcs is their strong absorption in the visible and near-IR regions ($\lambda_{\text{max}} \approx 670 \text{ nm}$) of spectrum which is the base of their extraordinary optical properties [101]. Properties of Pcs could be tailored by modifying the phthalocyanines structures.

Phthalocyanine molecules could be coordinated to virtually all of the metal ions in the periodic table (Figure 6.2). Their coordination number for the square-

planar phthalocyanines is four. Most of the transition metals such as Cu^{2+} , Ni^{2+} , Zn^{2+} form square-planar complexes with Pcs [103]. Higher coordination number such as five or six is possible with Pcs where inner metal axially coordinated to the ligands like chlorines, H_2O , pyridines, alkoxy, thioalkoxy groups. Famous representative example to six coordinated Pc is the axially-disubstituted silicon-phthalocyanines in square-bipyramide geometry [104]. Lanthanide elements forms sandwich (double-decker) complexes with Pc macrocycles. Coordination number of double-decker complexes is eight, where lanthanide metal ion coordinated to the two Pc macrocycles [105].

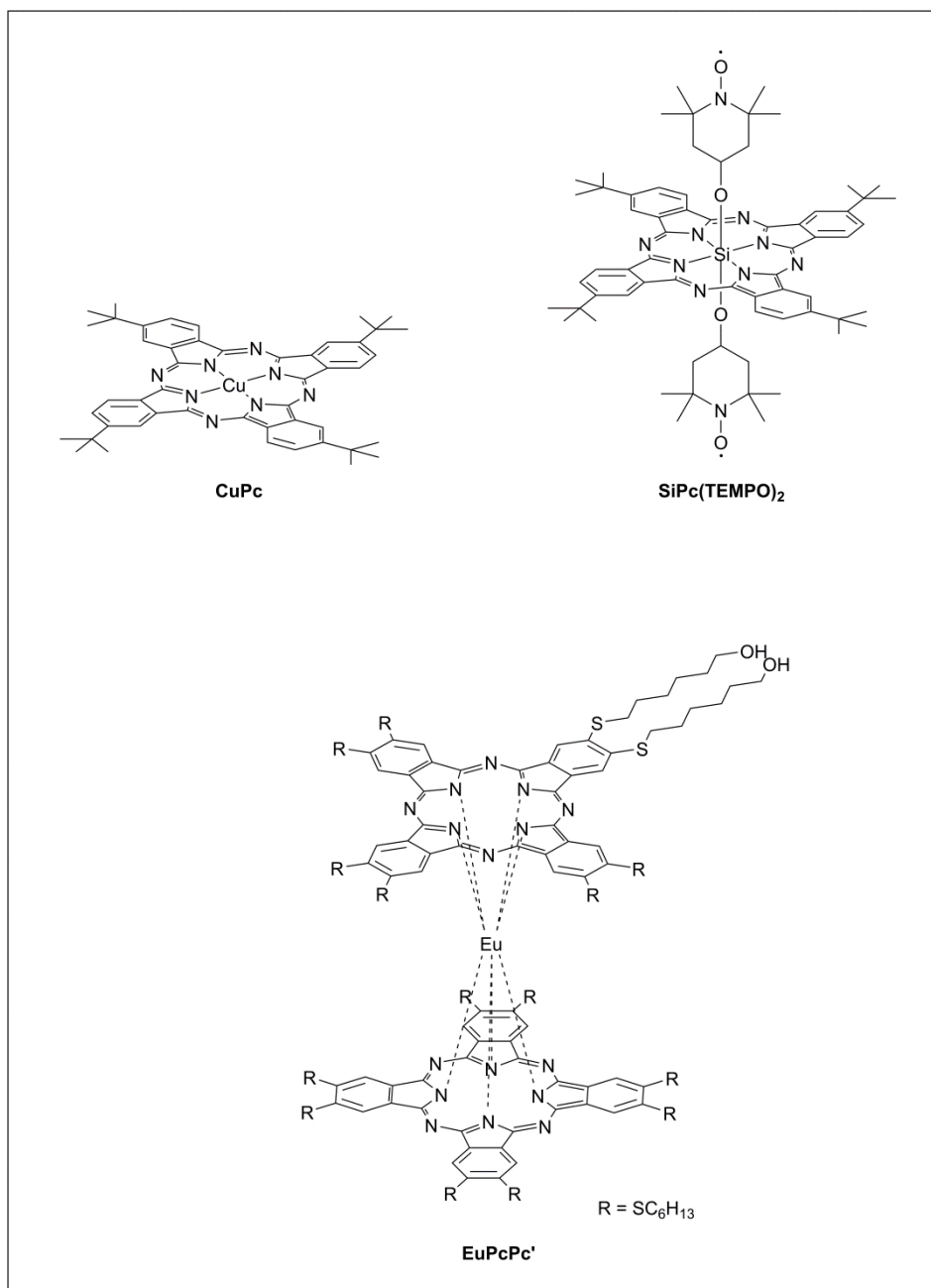


Figure 6.2: Various Metallo Phthalocyanines.

Unsubstituted phthalocyanines suffer from the poor solubility in common organic solvents. Early examples of phthalocyanines were mostly unsubstituted derivatives, and therefore insoluble. Because of the drawbacks such as low solubility, phthalocyanines while in its infancy did not attract the interest of academia. However, interest on the phthalocyanine research has been boosted upon the synthesis of soluble phthalocyanines that turns out tremendous library of Pc molecules and their wide variety of applications.

Substituents on the Pc macrocycle are categorized in three groups depending upon their position; peripheral, non-peripheral, (Figure 6.3) and axial (Figure 6.2). 4- and 5-substituted phthalonitriles generate the peripherally substituted phthalocyanine macrocycles, whereas 3- and 6-substituted phthalonitriles do non-peripherally substituted phthalocyanine ones. Substituents on the inner metals are classified as axial ligands (Figure 6.2).

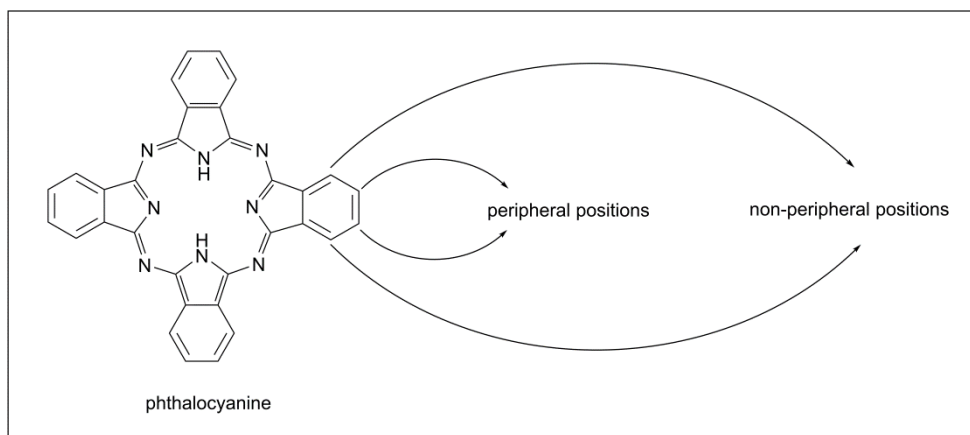


Figure 6.3: Substituent Positions of Phthalocyanines.

6.2. Syntheses of Phthalocyanines

Early phthalocyanines were observed during the chemical transformations of ortho-disubstituted benzene derivatives and reported as “insoluble colored material” without aware of their identity [106]-[108]. After decades, the structures of serendipitously synthesized “insoluble colored material” were shed lighted that they were identified as phthalocyanines [109]. First intended syntheses of the phthalocyanines were carried out by Linstead in 1934 [110] starting from o-cyanobenzamide and phthalimide.

Phthalocyanine molecules could be synthesized from the variety of starting materials (Figure 6.4). Among them, most versatile ones are the phthalonitrile and the 1,3-diiminoisoindoline. Therefore, we particularly focus on the conversion of phthalonitriles to phthalocyanines. Classical precursors -phthalonitrile and the 1,3-diiminoisoindoline- are boiled in high boiling point solvents or heated up directly in order to prepare metal free phthalocyanines. Presence of the metals (generally in salt

form of the metal) in the reaction display template effect to afford the metallo phthalocyanines as product.

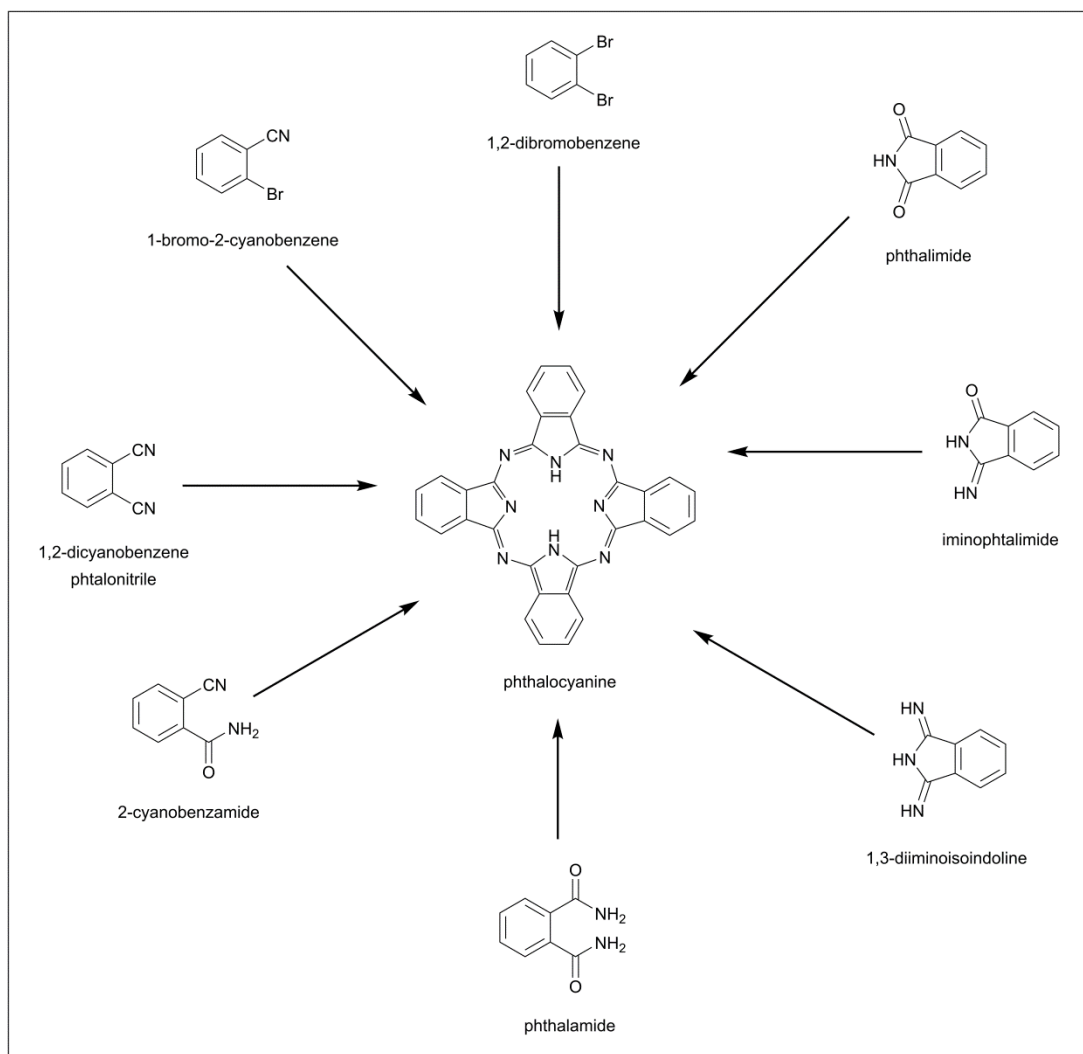


Figure 6.4: Starting Materials for Syntheses of the Phthalocyanines.

6.2.1. Synthesis of Symmetrical Phthalocyanines (A_4)

Symmetrically substituted Pcs (A_4) are synthesized through cyclotetramerization of appropriately substituted precursors, mostly phthalonitriles. Heating the phthalonitriles itself directly or heating the phthalonitriles in a solvent gave corresponding metal free phthalocyanine. In case of existence of a metal salt in the reaction, it acts as a template for the cyclotetramerization of phthalonitrile and affords the metallo phthalocyanines as product. Preparation of the metallo phthalocyanines is mostly carried out via metal-templated reaction in a high boiling

point solvent such as DMF, *o*-DCB, DMAE, pentanol, etc. Additionally, presence of a base like DBU, DBN or alkoxide promotes the Pc formation [111]. From the synthetic viewpoint of Pc formation, microwave reactions reduce the time and boost the yield in comparison to conventional techniques [112].

It is worth to note that these reactions are more efficient in the presence of a metal salt. However, template efficiency of metals varies depend upon the type of phthalonitrile employed in the reactions. Emphatically, some phthalonitriles undergo well cyclotetramerization with certain metal salts. In case of metal free H₂Pc as target, suitable phthalonitrile is reacted in the presence of metallic lithium in pentanol to generate the LiPc which subsequently washed with acidic water to get rid of lithium in the core to yield metal free H₂Pc [113]. On the other side, desired metal atoms could be inserted into the H₂Pc macrocycle by boiling the H₂Pc and desired metal salt in the appropriate solvent to yield metallo phthalocyanine MPc [114].

Cyclotetramerization of 3-substituted or 4-substituted phthalonitriles generates a mixture of four constitutional isomers with C_{4h}, C_{2h}, C_{2v}, and C_{2s} symmetry (Figure 6.5).

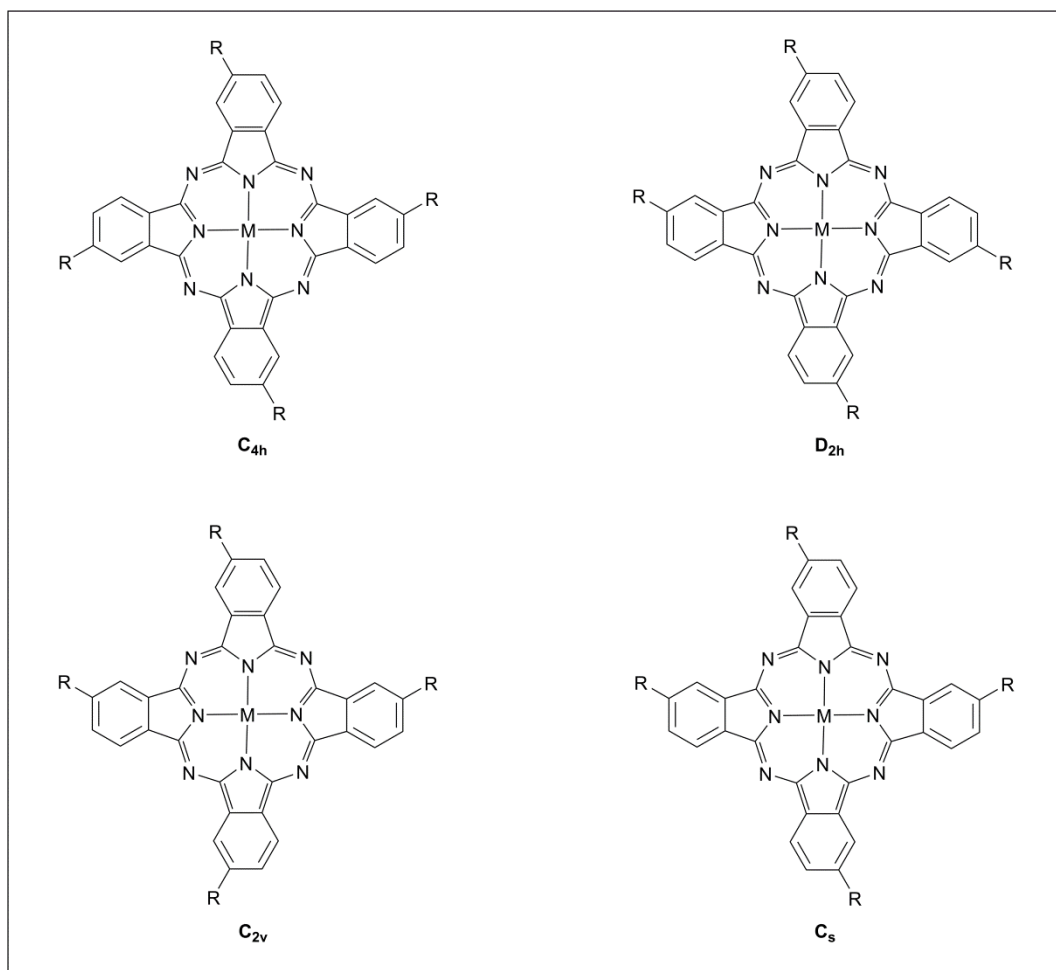


Figure 6.5: Structures of the Four Constitutional Isomers of 2(3),9(10),16(17),23(24)-Tetrasubstituted Metallophthalocyanines.

6.2.2. Synthesis of Unsymmetrical Phthalocyanines

Unsymmetrical phthalocyanines are described as macrocycles bearing different substituents on its isoindole units. Hypothetically, unsymmetrical phthalocyanines could be classified as A_3B , $ABAB$, $AABB$, $ABCX$ ($X=A, B$, or C), $ABCD$. One of the most investigated unsymmetrical Pc is the A_3B structure. Unsymmetrical phthalocyanines are of interest for their striking features, and therefore many methods were developed for their syntheses [115]-[119]. Even though variety of synthetic tactics developed to prepare the unsymmetrical phthalocyanines, mixtures of different Pc macrocycles are generally obtained. It is not consequentially surprising that separation of formed phthalocyanine macrocycles is tedious burden. Major synthetic methods to prepare unsymmetrical Pc are briefly discussed below;

i) Statistical Cyclotetramerization

This method is based on the statistical condensation of two differently substituted precursors; phthalonitrile or 1,3-diiminoisoindoline (Figure 6.6). The method is the immensely employed strategy due to its simplicity. In that, stoichiometry plays key role in the favor of formation of certain phthalocyanine structures. Therefore, the symmetrical one is formed as major product from the most abundant precursor [120]. Actually, all forms of phthalocyanine structures are generated during the cyclotetramerization; AAAA, AAAB, AABB, ABAB, ABBB, BBBB. To reduce the number of formed structures, 1/9 ratio (A/B) is privileged. So, isolation of the desired phthalocyanine structure from the phthalocyanine cocktail is required. Column chromatography and plaque chromatography are the most widely used separation techniques for aforementioned isolations.

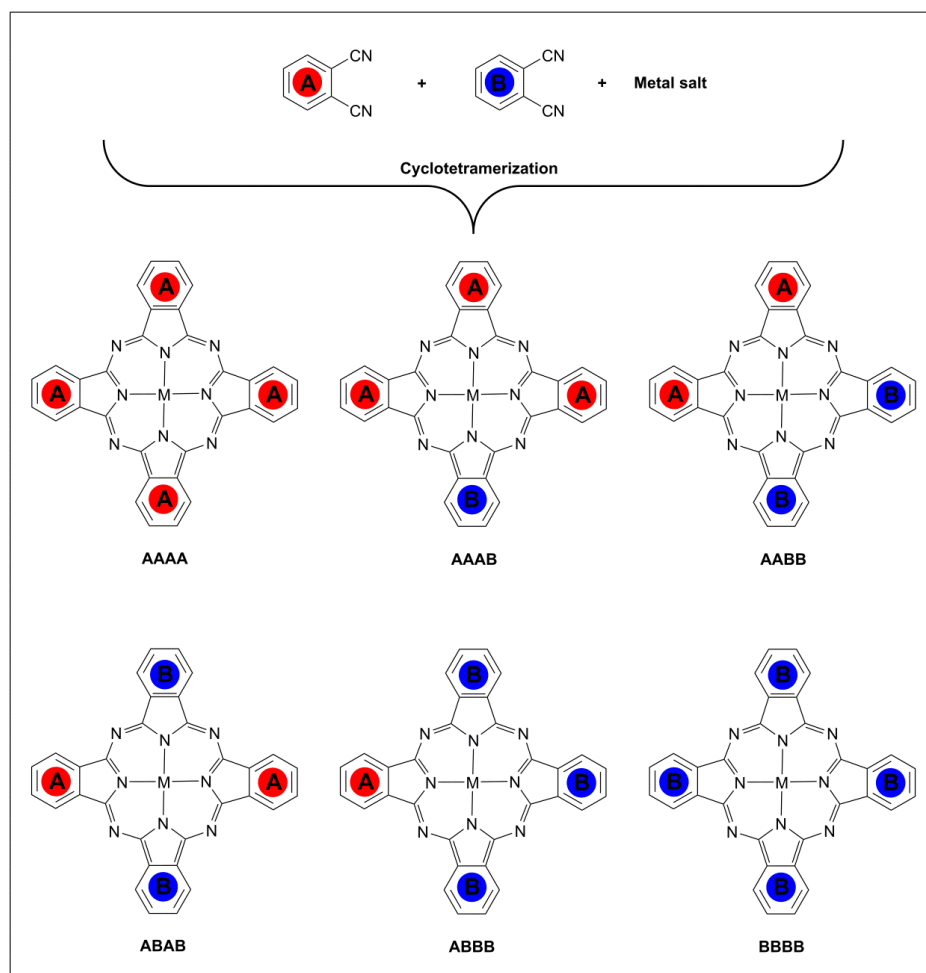


Figure 6.6: Phthalocyanines Structures Formed Upon the Statistical Cyclotetramerization of Two Different Precursors.

ii) cross-condensation reaction for ABAB preparation

This tactic lies on the reaction between two different phthalyl compounds; 1,3,3-trichloroisindolenine and 1,3-diiminoisindoline (Figure 6.7). Particularity of these precursors is that they undergo cross-condensation to generate the ABAB type phthalocyanines [121]. Noteworthy that AABB type structures are avoided as the precursors could not undergo self-condensation. Both metal free and metallo phthalocyanines are synthesized by employing this method.

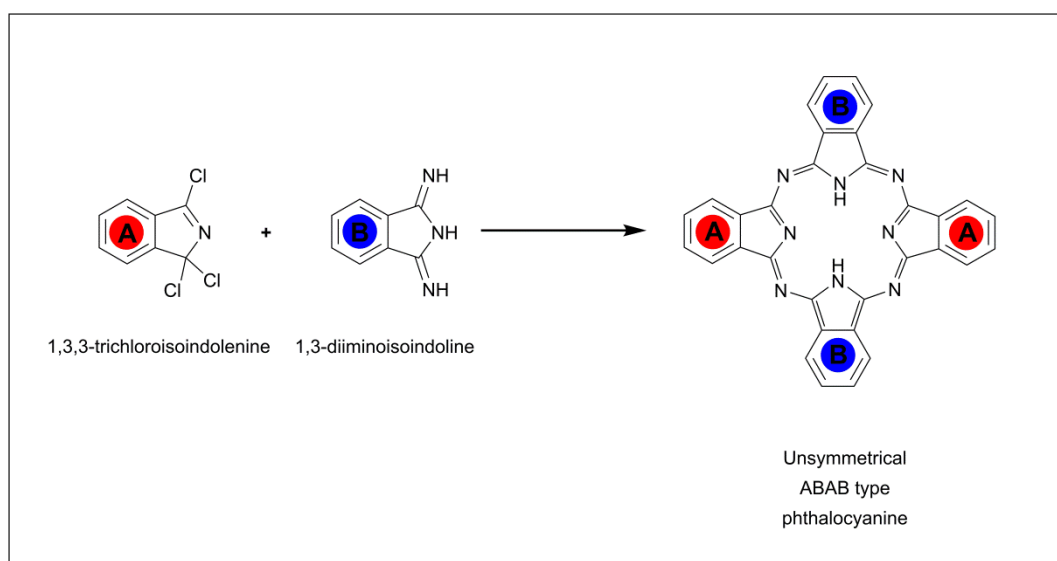


Figure 6.7: Synthesis of Unsymmetrical ABAB Type Phthalocyanines.

iii) ring expansion of subphthalocyanine for A_3B preparation

This method lies on the ring expansion of subphthalocyanines (Figure 6.8). As subphthalocyanines are strained and unstable structures in their nature, they are vulnerable to ring expansion reaction by the attacks of succinimidine or 1,3-diiminoisindoline [122]. Existence of the metal species in the ring expansion reaction increased the yield of target unsymmetrical Pc [123]. It is worth to note that ring expansion of subPc is also possible with phthalonitriles [123]. Disadvantage of this method is formation of mixture of non-desired Pc structures as by-products. Therefore, tedious chromatographic isolation of target Pc is inevitable burden.

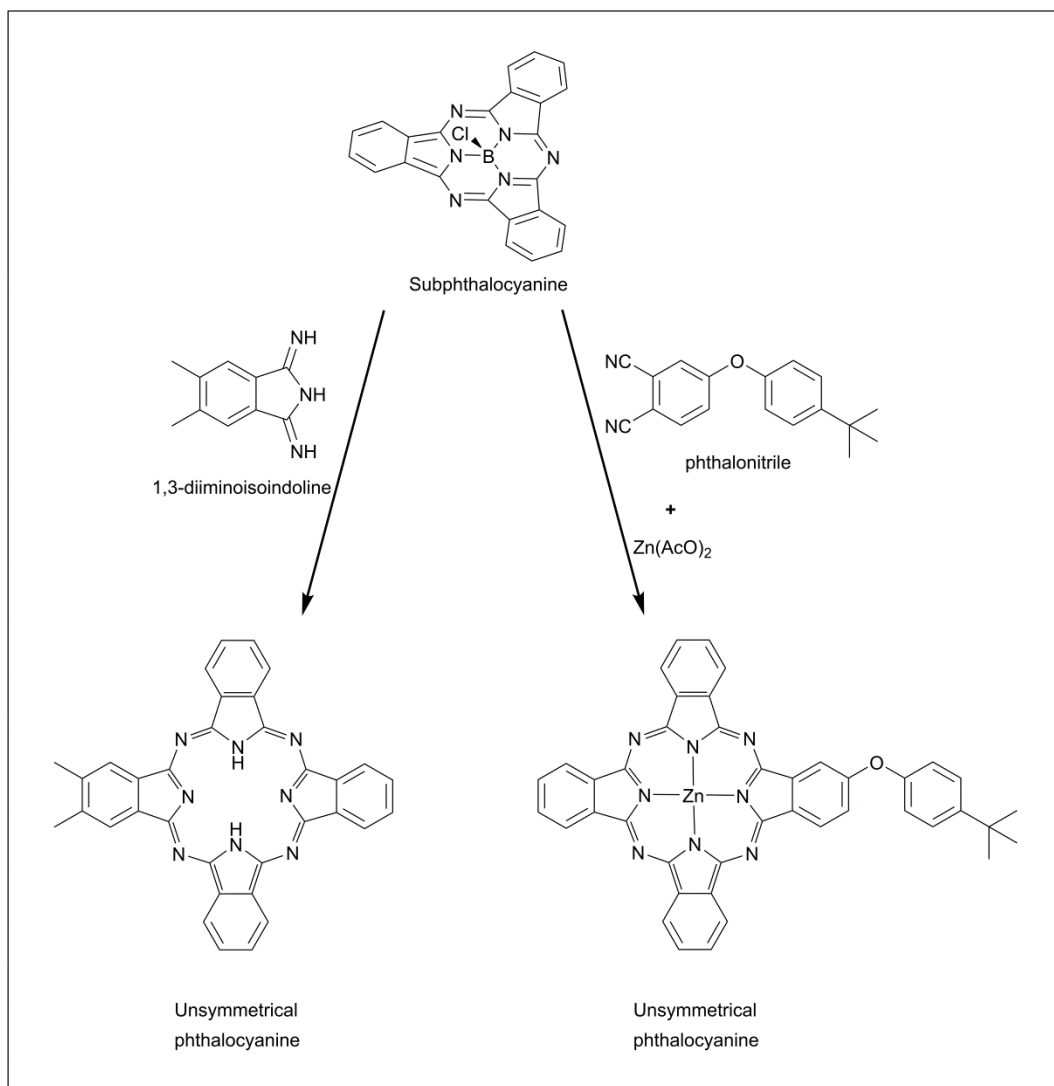


Figure 6.8: Synthesis of Unsymmetrical Pc Through Ring Expansion of Subphthalocyanine.

iv) solid-phase synthesis for A_3B preparation

This method consists in several steps [124]. Initially, phthalonitrile or 1,3-diiminoisoindoline is linked to an insoluble polymer. Then, insoluble polymer linked phthalonitrile is reacted with an excess of differently functionalized soluble phthalonitrile to form A_3B type phthalocyanine macrocycle. Finally, the formed phthalocyanine is cleaved from the polymer support. This strategy is an effective method to obtain A_3B type phthalocyanine structures. However, it needs multiple synthetic manipulations and does not apply to all functional groups.

6.3. Syntheses of Phthalonitriles

In general, functional groups are incorporated into the phthalocyanine macrocycle by modifying the phthalonitrile, the common precursor. Therefore, synthesis of the functionalized phthalonitrile is one of the key task in the synthetic pathway of Pc preparation. Mono-, di-, tri-, and tetra-substituted phthalonitriles could be prepared through a number of ways [125]. Reviewing the all phthalonitrile structures is beyond the scope of this dissertation. Rather, I focus my attention on the appropriate phthalonitrile structures employed as precursors toward the target phthalocyanines.

Alkoxy and aryloxy groups are important classes of substituents widely used for the functionalization of phthalocyanine macrocycles. Because various features such as solubility, liquid crystals, bridging units could be introduced to the phthalocyanine macrocycles via attaching the alkoxy- and aryloxy groups.

Alkylation of phenolic hydrogens, aromatic nucleophilic substitution of nitro groups, aromatic nucleophilic substitution of halogen atoms and Rosenmund-von Braun reactions are the commonly used organic manipulations for the preparation of alkoxy and aryloxy functionalized phthalonitriles [125].

6.3.1. 4,5-Dialkoxy- or 4,5-Diaryloxyphthalonitriles

Syntheses of the 4,5-dialkoxy- or 4,5-diaryloxyphthalonitriles consist several steps [126]-[127]. The preparation starts from the catechol, 1,2-dihydroxybenzene. Firstly, catechol is brominated to yield 1,2-dibromo-4,5-dihydroxybenzene. Secondly, phenolic hydrogens are alkylated to give 1,2-dibromo-4,5-dialkoxybenzene. Finally, bromine atoms are exchanged with cyanide groups via Rosenmund-von Braun reaction to afford the 4,5-dialkoxyphthalonitriles.

Alternatively, catechol is first alkylated to give 1,2-dialkoxybenzene which is subsequently dibrominated to afford 1,2-dibromo-4,5-dialkoxybenzene. As like in the former, cyanation of 1,2-dibromo-4,5-dialkoxybenzene leads to target 4,5-dialkoxyphthalonitriles. The reaction pathways are illustrated in the Figure 6.9.

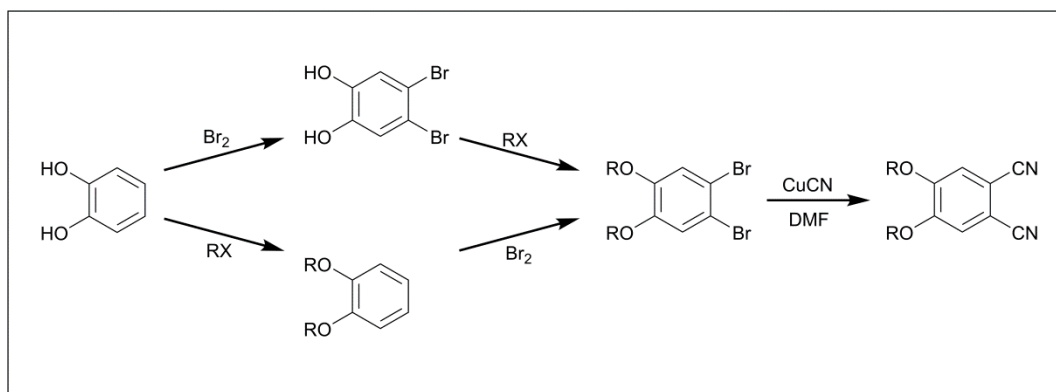


Figure 6.9: Synthetic Pathways for the 4,5-Dialkoxy- or 4,5-Diaryloxyphthalonitriles.

Another alternative is the alkylation of 4,5-dichlorophthalonitrile to obtain the 4,5-dialkoxyphthalonitriles [125]. These pathways are also viable for the synthesis of 3,6-dialkoxy- or 3,6-diaryloxyphthalonitriles [128].

It is worth to note that other 1,2-dibromobenzene structures are also converted to corresponding phthalonitrile with Rosenmund-von Braun reaction.

6.3.2. 4-Alkoxy- or 4-Aryloxyphthalonitriles

Aromatic nucleophilic substitution of nitro groups in 4-nitrophthalonitrile by phenol derivatives or with aliphatic alcohols is an immensely employed method for the preparation of 4-substituted phthalonitriles [121], [125]. The substitution reaction (Figure 6.10) smoothly proceeds in polar aprotic solvents such as DMSO, DMF, acetone, acetonitrile [129], [130]. In majority, K_2CO_3 is a versatile base in terms of primarily basicity, easy usage, and availability as well. However, stronger base such as NaH or LiOH is required for aliphatic alcohols.

The synthetic tactic is also viable for the preparation of 3-substituted-phthalonitriles starting from the 3-nitrophthalonitrile.

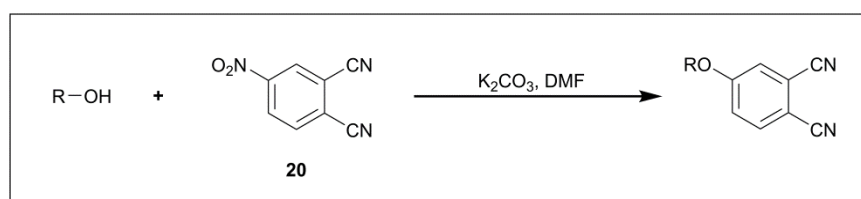


Figure 6.10: Synthetic Pathways for 4-Substituted Phthalonitriles.

One of the most widely used synthetic pathway to prepare 4-substituted phthalonitrile is the modifying 4-nitrophthalonitrile. In the synthetic sequence, 4-nitrophthalonitrile is prepared (Figure 6.11) starting from the commercially available phthalimide [121]. First of all, phthalimide was classically nitrated to obtain 4-nitrophthalimide which subsequently converted to 4-nitrophthalamide. At the final stage, 4-nitrophthalimide is converted to 4-nitrophthalonitrile by treating with SOCl_2 . Indeed, 4-nitrophthalonitrile is now commercially available.

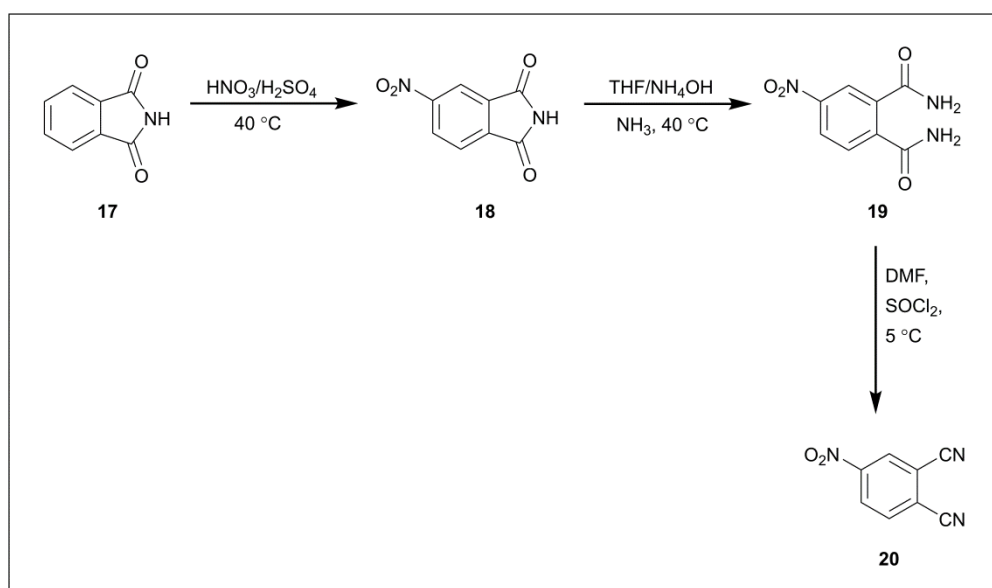


Figure 6.11: Synthetic Pathways for 4-Nitrophthalonitrile.

6.4. Properties of Phthalocyanines

6.4.1. Electronic Structure

Electronic structure of the phthalocyanine macrocycles could be grasped based on the Gouterman's four orbital model [131], primarily known as linear combination of atomic orbitals (LCAO). The electronic absorption spectrum of phthalocyanines displays two main bands; the Q band and B band (or synonymously Soret band, Figure 6.12). The Q band is observed in the region of 600-750 nm and is responsible for the green to blue color of phthalocyanines. Q band is attributed to $\pi \rightarrow \pi^*$ transitions from doubly degenerated HOMO to doubly degenerated LUMO orbital (Figure 6.12) [131], emphatically transitions from the higher-energy molecular

orbitals to LUMO. Actually, Q band is affected to a degree by various parameters such as nature of central metal, oxidation state of central metal, axial ligation, solvents, peripheral substitution, non-peripheral substitution, aggregation and extension of the conjugation [132]. Therefore, analysis of the Q band's shape and position encompasses enormous information about the phthalocyanine structures (Figure 6.12). For instance, metallo phthalocyanines have higher symmetry D_{4h} (all inner nitrogen atoms are equivalent) and therefore only one Q band is observed (Figure 6.12). On the contrary, metal free phthalocyanines have lower symmetry D_{2h} because two inner nitrogen atoms are protonated and two other inner nitrogen atoms are unprotonated. As consequence, LUMO is degenerated that turns out Q band splits to two (Figure 6.12) [132], [133].

The B band is observed around 350 nm and attributed to $\pi \rightarrow \pi^*$ transitions from the lower-energy molecular orbitals to LUMO (Figure 6.12).

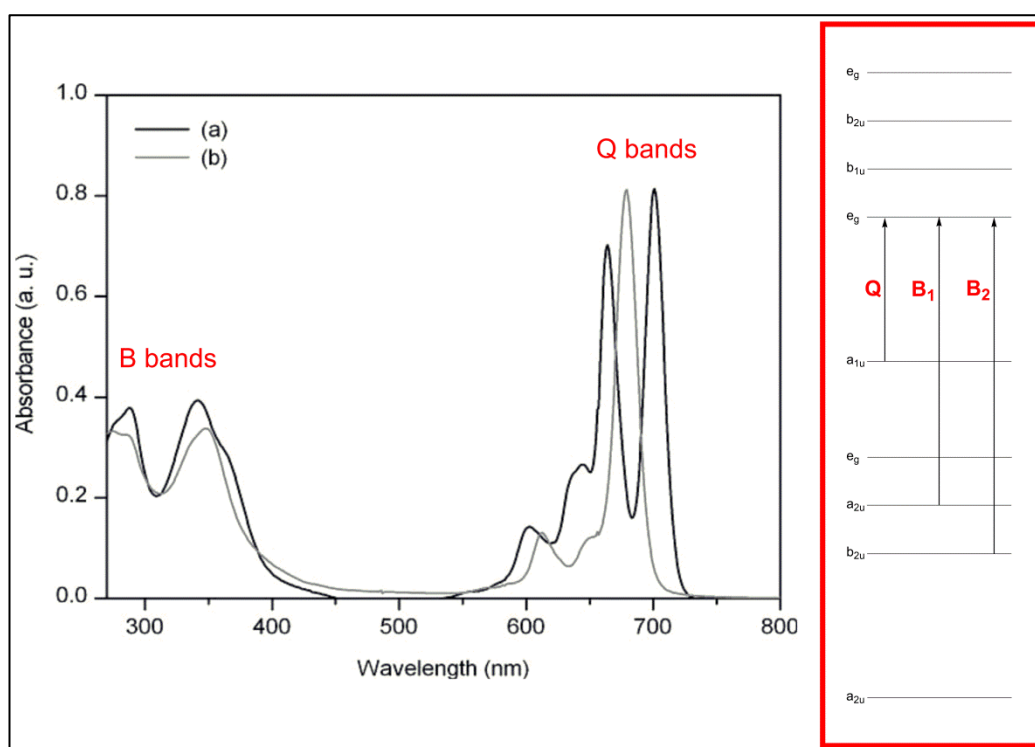


Figure 6.12: Typical UV-vis Spectra for a Phthalocyanine as a) metal free and b) metallated (Left). The Scheme of Energy Levels in Metallated Phthalocyanines with the First Two $\pi \rightarrow \pi^*$ Transitions, the Q- and B-bands Marked (Right). (Taken from Reference 133).

6.4.2. Fluorescence Property

Fluorescence is the emission of light by a material that has absorbed light or other electromagnetic radiation [134]. In most cases, the emitted light has a longer wavelength, and therefore lower energy, than the absorbed radiation. In brief, fluorescence is a property of some molecules which absorb light of one color and emit light of different color [135]. The most striking example of fluorescence occurs when the absorbed radiation is in the ultraviolet region of the spectrum, and thus invisible to the human eye, while the emitted light is in the visible region, which gives the fluorescence substance a distinct color that can only be seen when exposed to UV light [134]. Fluorescent materials cease to glow immediately when the radiation source stops.

Fluorescence is the result of a three-stage process that occurs in certain molecules called fluorophores or fluorescent dyes [136]. The stages are excitation (1), excited-state lifetime (2), and fluorescence emission (3, Figure 6.13). Excitation and emission spectra are depicted in Figure 6.14.

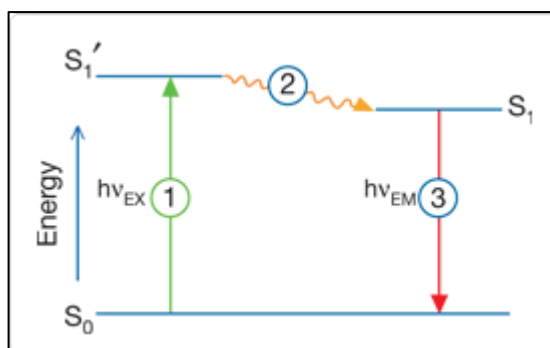


Figure 6.13: Jablonski Diagram of Fluorescence Processes. (Taken from Reference 136).

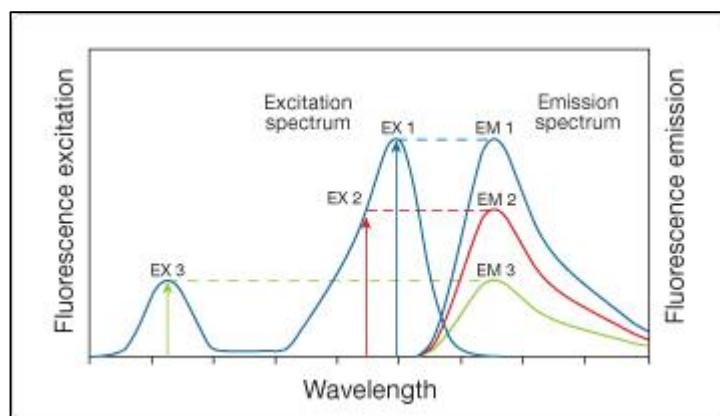


Figure 6.14: Spectrum Profiles for Excitations at Different Wavelengths and Their Corresponding Emissions. (Taken from Reference 136).

Phthalocyanines are well-known fluorophore and their fluorescence property is studied comprehensively [137]. Representative excitation and emission spectra of a phthalocyanine are illustrated in Figure 6.15.

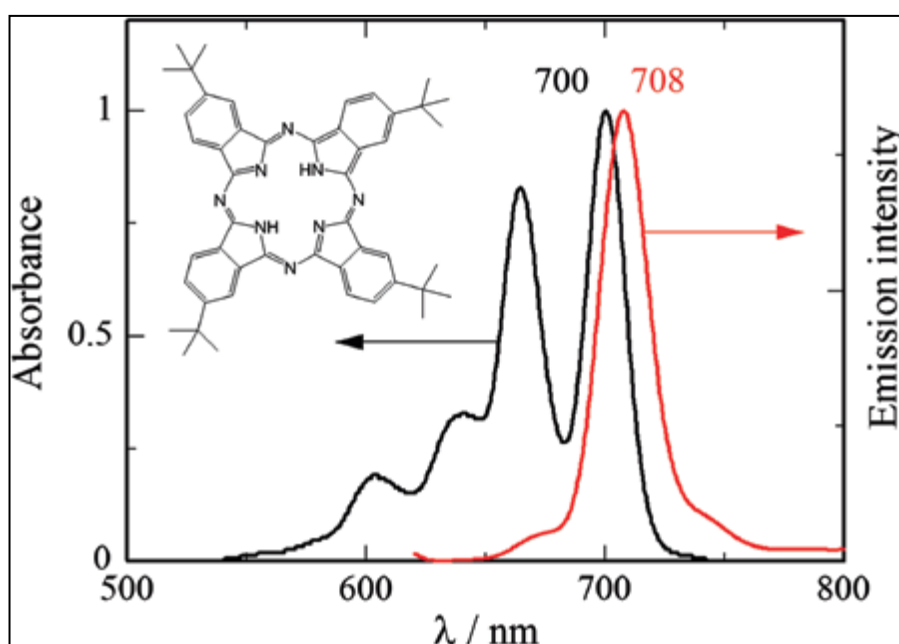


Figure 6.15: Excitation and Emission Spectra of a Phthalocyanine. (Taken from Reference 137).

Nitroxides are well-known quencher for fluorescence. Quenching mechanism is on the basis of electron exchange between the nitroxide species and the excited state fluorophore [59]. When the unpaired spin of a nitroxide interacts with the electrons of fluorophore, the electron spin of the fluorophore in the excited state is exchanged with the electron spin of the nitroxide in the SOMO. Consequently, the

forbidden transitions from the S_1 to T_1 state (ISC) and subsequent T_1 to S_0 state are allowed, resulting in an increase in non-radiative process, and a loss of fluorescence quantum yield. Distance between the nitroxide and the fluorophore play a key role in quenching [59].

6.5. Survey of Nitroxide Functionalized Phthalocyanines

Properties of the phthalocyanine macrocycles could be tailor made by perturbing its well-polarizable 18 π -electron system or incorporation of property targeted substituents either into inner metal or into macrocycle ring. There is vast number of accounts reporting the attachment of various substituents to Pc ring or axial ligation of them toward desired applications. However, majority of those substituents are diamagnetic molecules. On the other side, paramagnetic molecules, namely organic radical units, could add exceptional features to the Pc compounds. Indeed, there are few representative examples of nitroxide radicals functionalized phthalocyanines, as their synthesis are challenging task due to necessity of keeping spin alive.

Nitroxide functionalized phthalocyanines could be discussed in two categories;

- i) axially ligation of nitroxide radicals to the inner metal (Figure 6.16)

To the best of our knowledge, the first nitroxide functionalized Pc compound is phthalocyaninosilicon (IV) covalently linked to two TEMPO radicals [104]. It was synthesized by the reaction of $\text{SiPc}(\text{OH})_2$ with 4-hydroxy-TEMPO in the refluxing toluene. The reaction is basically substitution of hydroxy groups in $\text{SiPc}(\text{OH})_2$ with 4-hydroxy-TEMPO in the presence of CaCl_2 as base. Later, its mono-TEMPO derivative is also prepared with the same synthetic methodology [138]. Another example is phthalocyaninosilicon (IV) covalently linked to one or two PROXYL radicals [139], [140]. Their synthesis is carried out following the same synthetic tactic of TEMPO derivatives. One another report studied the metallo phthalocyanines (M: Mg, Zn) coordinated to amino nitrogen of 4-amino-TEMPO [141].

From the synthetic perspective, relatively high thermal stability of TEMPO and PROXYL radicals pave the way for synthesis of their phthalocyanine derivatives in

refluxing toluene. It needs to be pointed out that 4-hydroxy-TEMPO and 4-amino-TEMPO radicals are now commercially available.

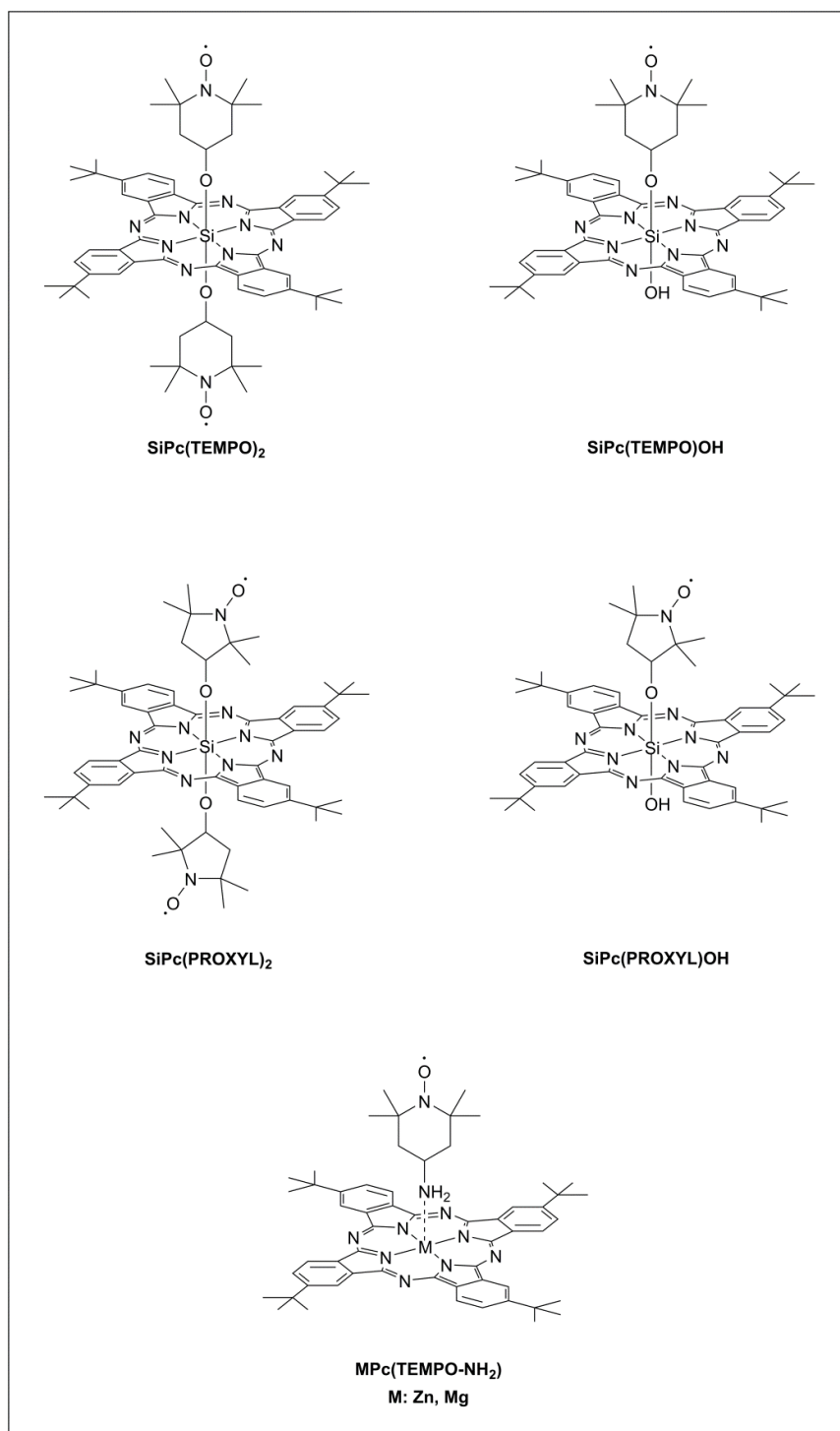


Figure 6.16: Library of Nitroxide Functionalized Phthalocyanines via Axial Ligation of Nitroxides.

In the nitroxides ligated phthalocyanine systems, phthalocyanine macrocycles serve as chromophore and nitroxides do as paramagnetic radical species. Interactions between chromophores and radicals play key role during the quenching of chromophores in excited states by the radicals and for controlling of magnetic properties by photoexcitation. Those originate from the formation of excited multiplet states constituted by the excited triplet chromophore and doublet radicals. These molecules are synthesized with purpose of investigation a phenomenon: photoexcitation control of magnetic interaction between paramagnetic species. Another intention was exploring their singlet oxygen generation mechanism [139]. Aforementioned interactions in the nitroxide ligated phthalocyanines are investigated with rich array of measurements such as electronic absorption, transient absorption, magnetic circular dichroism, fluorescence and time-resolved electron paramagnetic resonance [104], [138]-[143].

Specifically, SiPc(TEMPO)₂ compound was utilized as fluorescence probes for detecting the ascorbic acid in biological milieu. Hydrophobic SiPc(TEMPO)₂ was encapsulated in liposomes for studying them in aqueous solutions of biological systems. In terms of mechanism, radicalic nitroxide fragments (-NO) are protonated upon addition of ascorbic acid and transformed to -NOH. Hence, radical nature is lost, and therefore fluorescence character of phthalocyanine is retrieved [144].

ii) incorporation of radical units into the phthalocyanine ring (Figure 6.17)

Nitroxides attached directly on the phthalocyanine ring systems were first synthesized in 2007 [145]. They are constituted by phthalocyanine ring and PROXYL radical units which are directly fused to the peripheral positions of Pc ring. In the synthetic sequence, firstly PROXYL fused phthalonitrile and its 1,3-diiminoisoindoline analog were prepared. Subsequently, cyclotetramerization of them in the presence of metal salt afforded the corresponding phthalocyanine derivatives. They are characterized with electronic absorption spectroscopy and EPR spectroscopy.

Another nitroxide functionalized phthalocyanine is TEMPO-functionalized zinc phthalocyanine [95]. Four TEMPO radical units are incorporated to peripheral positions of the phthalocyanine ring via ether bond. In the synthetic pathway, TEMPO radicals are first inserted to the phthalonitrile. Then cyclotetramerization of

TEMPO functionalized phthalonitriles in the presence of zinc acetate gave the corresponding phthalocyanine, ZnPc(TEMPO)_4 . It was characterized with electronic absorption spectroscopy, EPR spectroscopy and electrochemical measurements. ZnPc(TEMPO)_4 compound was utilized as electrochemical probes for ascorbic acid [95].

Noteworthy that relatively high thermal stability of TEMPO and PROXYL radicals make possible for synthesis of their phthalocyanine derivatives in refluxing 2-(dimethylamino)ethanol without any precautions. Radical nature of the nitroxides is kept alive during the organic manipulations; phthalonitrile preparation and cyclotetramerization.

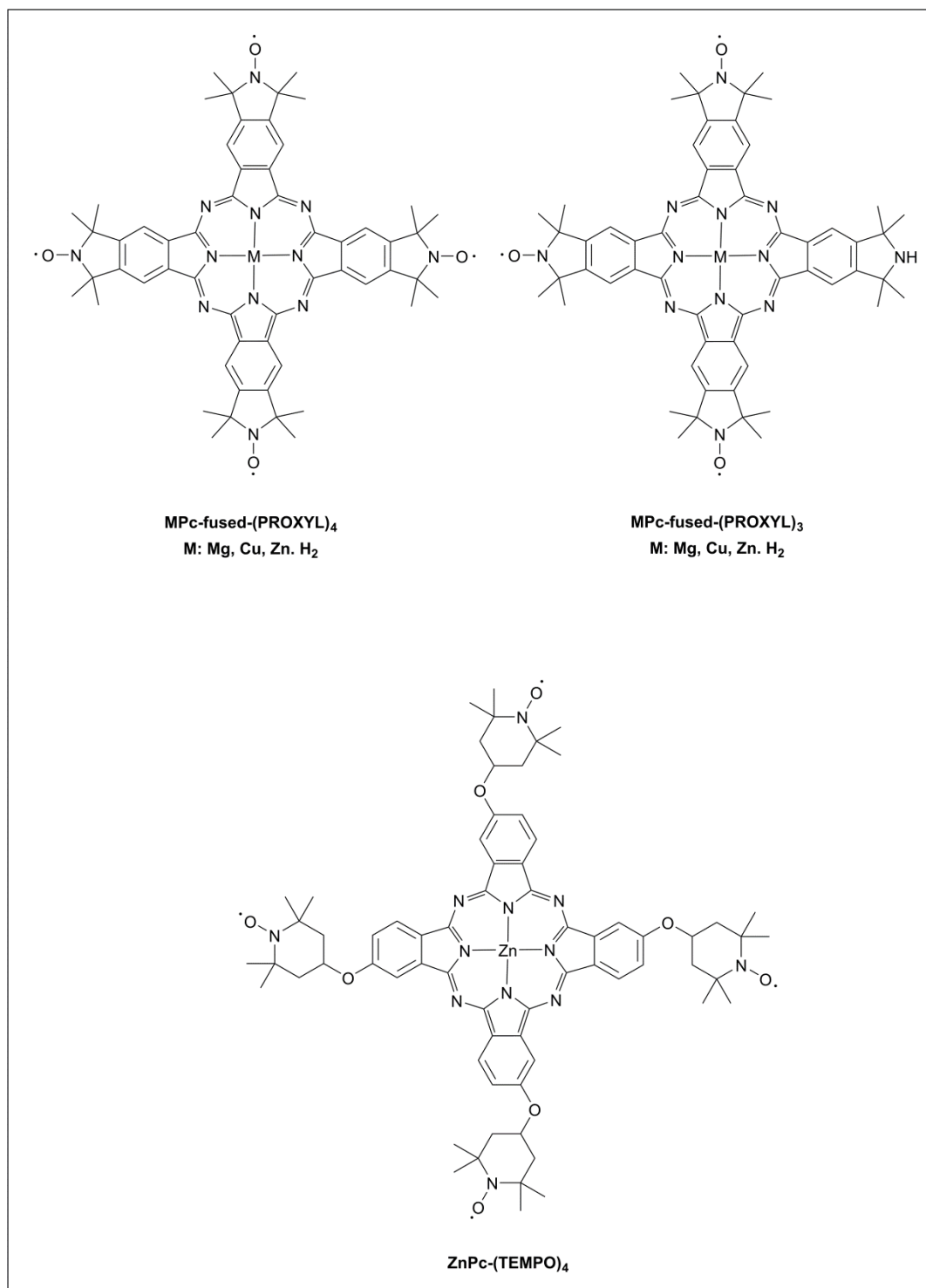


Figure 6.17: Library of Nitroxide Functionalized Phthalocyanines via Incorporation of Radical Units into the Phthalocyanine Ring.

6.6. Scope and Objectives

Survey of nitroxide functionalized phthalocyanines reveals that there are few representative examples of them. In final analysis, nitroxide functionalized phthalocyanines are still in infancy. Therefore, our attention was focused on the synthesis and study of properties of phthalocyanines bearing Ullman radicals, either nitronyl nitroxide or imino nitroxide.

Majority of nitroxide functionalized phthalocyanines are constituted by phthalocyanine ring with silicon atom in the cavity and by TEMPO or PROXYL radicals covalently linked to silicon via ether bonds. Just in one case, PROXYL radical are fused to the phthalocyanine ring. Just in another case, TEMPO radicals are tethered to the phthalocyanine ring via ether bond. However, there is no account reporting the Ullman radicals appended phthalocyanine structures. Therefore, we circumscribed the incorporation of Ullman radicals into the phthalocyanine ring.

Radical moiety linked fluorophores are favored as profluorescent probes. Phthalocyanines are well-known fluorophore. Radical species are also well-known quencher for fluorescence of such compounds as matching of excited triplet states of fluorophore and doublet of radicals. Therefore, we proposed a profluorescent probe constituted by phthalocyanine as fluorophore and Ullman radical as quencher. Upon coordination of Ullman radicals -both nitronyl nitroxides and imino nitroxides- to the Cu^{2+} ions, radical nature of nitroxides would be no longer exist and hence fluorescence character of phthalocyanine is retrieved.

A number of Ullman radical functionalized phthalocyanines are designed by taking into consideration the rich experience of our group on the phthalocyanine chemistry. Metal free phthalocyanines are favored in order to eliminate the interference of metal species in the cavity. First target type is one Ullman radical appended phthalocyanines **37** and **38** (Figure 6.18). They are constituted by one Ullman radical covalently linked to the peripheral position and six neopentoxy substituents on the peripheral positions of the other benzenes. As gender of Ullman radical, both nitronyl nitroxide and imino nitroxide are targeted. Neopentoxy groups are particularly favored in order to increase the solubility of title structures as unsubstituted or less substituted phthalocyanines are insoluble. Indeed, first target type is an A_3B type unsymmetrical phthalocyanines (Figure 6.18).

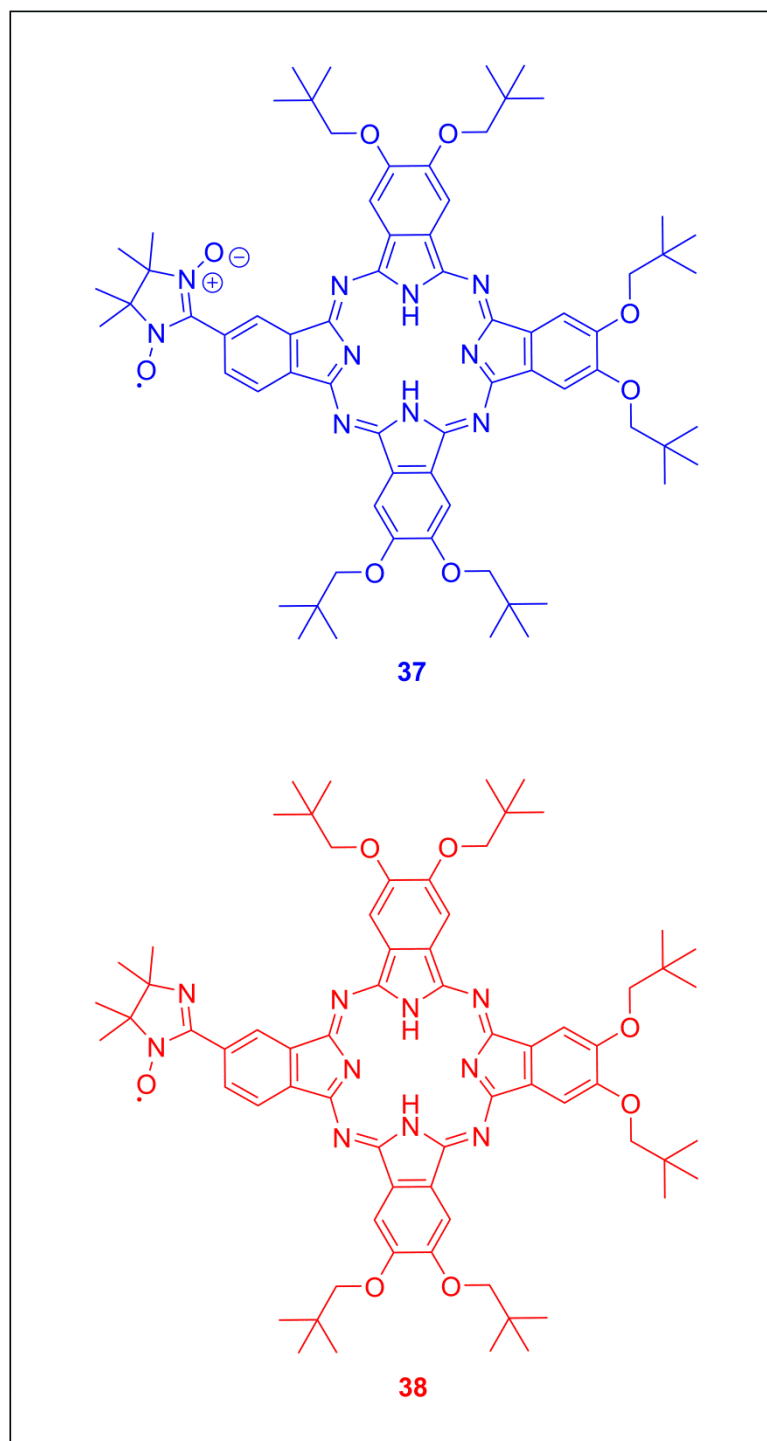


Figure 6.18: One Ullman Radical Linked Phthalocyanines.

Second target type is four Ullman radicals appended phthalocyanines **43** and **44** (Figure 6.19). They are constituted by one Ullman radical covalently linked to the peripheral position of each benzene, in total four Ullman radicals on the phthalocyanine macrocycle. Solubility of this type could be a challenge as they do not contain any solubility enhancing substituents. As gender of Ullman radical, both

nitronyl nitroxide and imino nitroxide are targeted. Actually, second target type is a B₄ type symmetrical phthalocyanines (Figure 6.19).

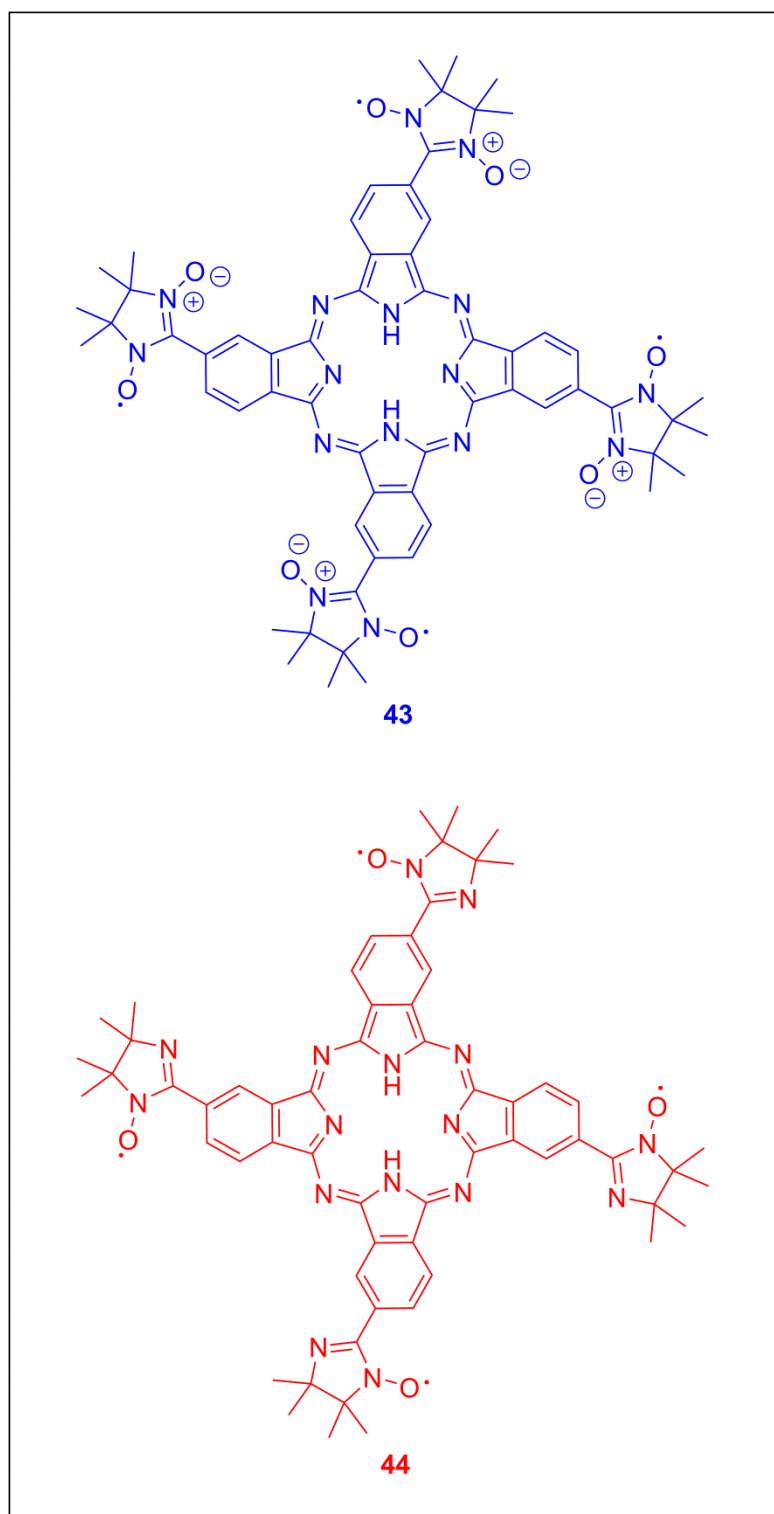


Figure 6.19: Four Ullman Radical Linked Phthalocyanines.

Within the context, the main objectives are;

- i) To synthesize one Ullman radical appended phthalocyanines **37** and **38**,
- ii) To synthesize four Ullman radicals appended phthalocyanines **43** and **44**,
- iii) To investigate Cu^{2+} ions sensing ability of those compounds.

6.7. Synthesis

As stated in Chapter 6.6, target compounds are one Ullman radical appended phthalocyanines **37**, **38** (A_3B type unsymmetrical structures) and four Ullman radicals appended phthalocyanines **43** and **44** (B_4 type symmetrical structures). Toward each type of target compounds, synthetic sequence requires;

- i) preparation of necessary phthalonitrile(s),
- ii) preparation of phthalocyanine aldehyde(s) through cyclotetramerization of phthalonitriles,
- iii) preparation of Ullman radical(s) linked phthalocyanines through Ullman process.

Synthetic studies of target compounds are covered in the following three sub-sections.

6.7.1. Synthesis of Phthalonitriles **25** and **31**

Retrosynthetic analyses of the phthalocyanines **37** and **38** reveals that phthalonitriles **25** and **31** are required. In the cases of **43** and **44**, solely phthalonitrile **31** is necessary. As stated in Chapter 6.2, phthalonitriles, one of the most common precursors, could be converted easily to the corresponding phthalocyanines through cyclotetramerization.

Synthesis of the 4,5-dineopentoxyphthalonitrile **25** was carried out on the basis of Leznoff's procedure [126] with substantial modifications (Figure 6.20). First of all, catechol **21** was brominated to yield 1,2-dibromo-4,5-dihydroxybenzene **22**. Secondly, 1,2-dibromo-4,5-dihydroxybenzene **22** was reacted with neopentyl

tosylate **23** to give 1,2-dibromo-4,5-dineopentoxybenzene **24**. At final stage, bromine atoms of 1,2-dibromo-4,5-dineopentoxybenzene **24** were exchanged with cyanides through Rosenmund-von Braun reaction under microwave irradiation to generate the 4,5-dineopentoxyphthalonitrile **25**. Noteworthy that proceeding the cyanation step under microwave energy reduced the reaction time and lead better purity of the product in comparison to the conventional Rosenmund-von Braun reaction.

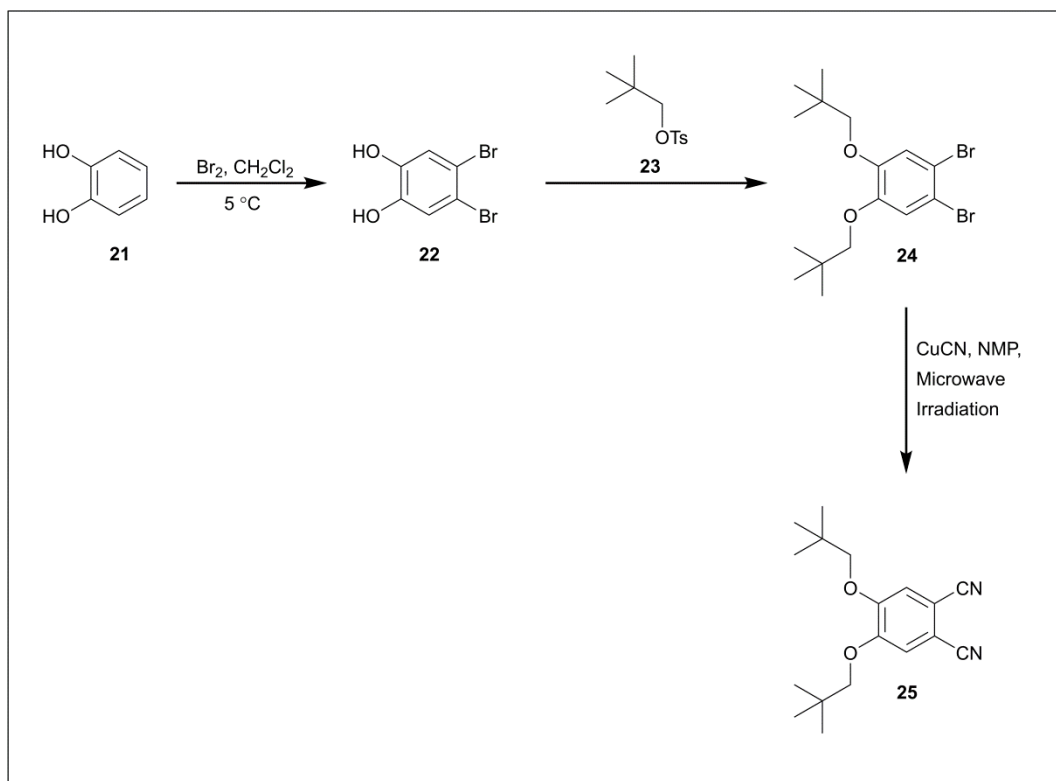


Figure 6.20: Synthetic Pathway for 4,5-Dineopentoxyphthalonitrile **25**.

Formation of the compound **24** was monitored by FT-IR spectrum following the complete disappearance of the --OH stretching of **22**. OH functionality of **22** was transformed into ether bonds of **24** which were clearly assigned in the FT-IR spectra. The transformation was tracked in FT-IR spectra as disappearance of --OH stretchings of **22** and appearance of aromatic aliphatic ether (C-O-C) stretchings of compound **24** at 1248 cm^{-1} and 1017 cm^{-1} (Figure 8.60). Aromatic CH stretching of benzene ring around was not observed. Aliphatic CH stretching of neopentyl groups are observed at 2956 , 2907 , and 1868 cm^{-1} (Figure 8.60). Perfect assignments of the signals in ^1H NMR and ^{13}C NMR (Figure 8.61 and 8.62) demonstrated the identity of

compound **24**. Melting point, FT-IR, ^1H NMR, and ^{13}C NMR analyses demonstrated the identity and as well as the purity of compound **24**.

Formation of 4,5-dineopentoxyphthalonitrile **25** was monitored by FT-IR spectroscopy following appearance of the characteristic --CN stretching of **25**. FT-IR spectrum of **25** displayed CN stretching at 2229 cm^{-1} , aromatic CH stretching of benzene ring at 3129 , 3095 and 3064 cm^{-1} , aliphatic CH stretching of neopentyl groups at 2956 , 2932 , and 2876 cm^{-1} , and stretching of aromatic aliphatic ether (C-O-C) at 1230 and 1090 cm^{-1} (Figure 8.63). Perfect assignments of the signals in ^1H NMR and ^{13}C NMR (Figure 8.64 and 8.65) demonstrated the identity of phthalonitrile **25**. Melting point, FT-IR, ^1H NMR, and ^{13}C NMR analyses demonstrated the identity and as well as the purity of phthalonitrile **25**.

Naturally, synthesis of unsymmetrical phthalocyanine monoaldehyde **34** requires an aldehyde functionalized phthalonitrile as precursor. However, aldehyde group on the phthalonitrile could not survived under the harsh conditions of cyclotetramerization. Therefore, aldehyde group on the corresponding phthalonitrile needs to be protected with a suitable agent. 2,2-dimethylpropan-1,3-diol **29** was purposely favored as protecting agent. Because, in the protected form, it annelated to a 6-membered ring which is more stable than 5-membered ring (formed by ethylene glycol) against to thermal factors [146].

Synthesis of the 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile **31** was carried out on the basis of Hanack's procedure [147] with some optimizations (Figure 6.21). 4-bromobenzaldehyde **26** was first nitrated with classical aromatic nitration to give 4-bromo-3-nitrobenzaldehyde **27** which subsequently converted to the 3,4-dibromobenzaldehyde **28** which is commercially available now in various suppliers. Aldehyde group of 3,4-dibromobenzaldehyde **28** was protected with 2,2-dimethylpropan-1,3-diol **29** to give 1,2-dibromo-4-(5,5-dimethyl-1,3-dioxane-2-yl)benzene **30**. At the final step, 1,2-dibromo-4-(5,5-dimethyl-1,3-dioxane-2-yl)benzene **30** was converted to 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile **31** via Rosenmund-von Braun cyanation under microwave irradiation. Reason behind the protection of **28** is that cyanation via Rosenmund-von Braun takes place at elevated temperatures which may lead to decomposition of aldehyde. To stand on the safe side, aldehyde group was protected prior to cyanation process.

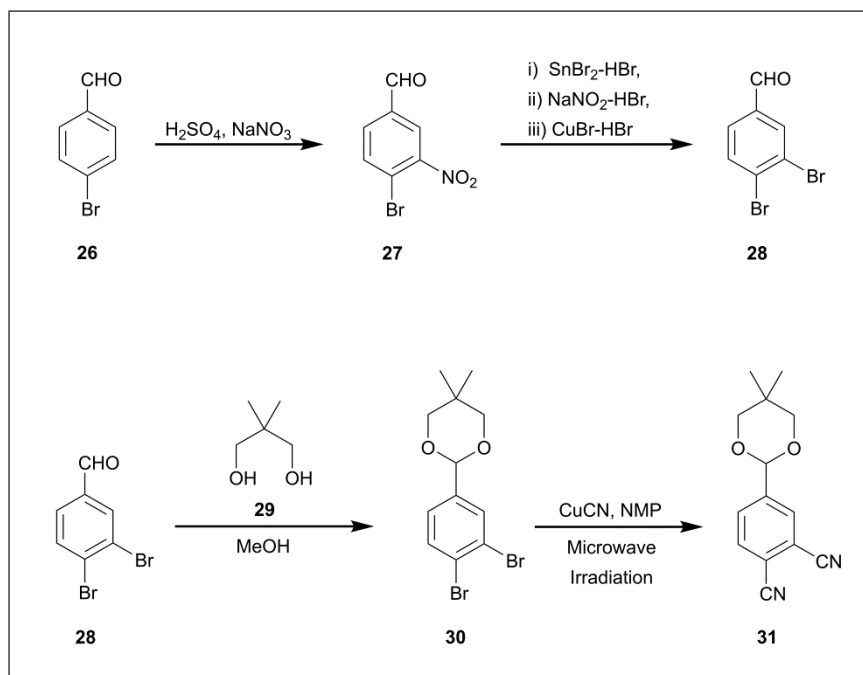


Figure 6.21: Synthetic Pathway for 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile **31**.

Formation of the compound **30** was monitored in FT-IR spectrum following the complete disappearance of the carbonyl stretching of **28** as aldehyde functionality of **28** was transformed into acetal groups in **30**. The transformation was tracked in FT-IR spectra as disappearance of the carbonyl stretchings of **28** and appearance of acetal stretchings of compound **30** at 1376 cm^{-1} (Figure 8.66). FT-IR spectrum of **30** displayed acetal stretching at 1376 cm^{-1} , aromatic CH stretchings of benzene ring at 3096 and 3077 cm^{-1} , aliphatic CH stretchings of methyl groups at 2952 and 2855 cm^{-1} (Figure 8.66). Perfect assignments of the signals in ^1H NMR and ^{13}C NMR (Figure 8.67 and 8.68) demonstrated the identity of compound **30**. Melting point, FT-IR, ^1H NMR, and ^{13}C NMR analyses demonstrated the identity and as well as the purity of compound **30**.

Formation of 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile **31** was monitored by FT-IR spectroscopy following the appearance of the $-\text{CN}$ stretchings of **31**. FT-IR spectrum of **31** displayed CN stretching at 2236 cm^{-1} , aromatic CH stretchings of benzene ring at 3118 , 3085 and 3047 cm^{-1} , aliphatic CH stretchings of methyl groups at 2962 , 2869 , and 2829 cm^{-1} , and acetal stretchings at 1364 cm^{-1} (Figure 8.69). Perfect assignments of the signals in ^1H NMR and ^{13}C NMR (Figure 8.70 and 8.71) demonstrated the identity of phthalonitrile **31**. Melting point, FT-IR,

^1H NMR, and ^{13}C NMR analyses demonstrated the identity and as well as the purity of phthalonitrile **31**.

In conclusion, phthalonitriles **25** and **31** were successfully synthesized with our optimizations on the basis of Leznoff [126] and Hanack protocols [147] respectively. Phthalonitriles **25** and **31** were characterized by melting point, FT-IR, and NMR analyses.

6.7.2. Synthesis of Mono Ullman Radical Linked Phthalocyanines **37** and **38**

Synthetic methodology for **37** and **38** consist on a statistical cyclotetramerization of two different phthalonitriles in different ratio to favor the formation of the unsymmetrical A_3B type phthalocyanine. Ullman route in the method converts aldehyde bearing phthalocyanine **34** to the corresponding radicals. Synthetic pathway requires multi-step organic manipulations which are described briefly as follows;

- i) synthesis of phthalocyanine monoaldehyde (**34**) via statistical cyclotetramerization of phthalonitrile (**25**) and phthalonitrile (**31**),
- ii) condensation of phthalocyanine monoaldehyde (**34**) with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**),
- iii) oxidation of the condensation product to yield the target compounds **37** and **38**.

Statistical cyclotetramerization of phthalonitrile **25** and phthalonitrile **31** afforded symmetrical A_4 type phthalocyanine **32** and unsymmetrical A_3B type phthalocyanine **33** as major products (Figure 6.22) [120]. The reaction was classically carried out by overnight refluxing in pentanol under template effect of metallic lithium to give the unsymmetrical A_3B type **33** in 23% yield and A_4 type **32**. They were isolated through column chromatography on silica gel eluting with dichloromethane-hexane mixture. Phthalocyanines **32** and **33** were characterized with FT-IR and MALDI MS analyses.

FT-IR spectrum of **32** (Figure 8.72) displayed aromatic CH stretching of phthalocyanine ring at 3295 and 3077 cm^{-1} , aliphatic CH stretching of neopentyl groups at 2954 , 2906 , and 2867 cm^{-1} , aromatic aliphatic ether (C-O-C) stretching at

1275, 1260 and 1214 cm^{-1} (Figure 8.72). MALDI-TOF MS analysis (Figure 8.73) shows a peak at m/z of 1204 $[\text{M}+\text{H}]^+$ which is another identity proof of phthalocyanine **32**.

FT-IR spectrum of **33** (Figure 8.74) displayed aromatic CH stretching of phthalocyanine ring at 3296, 3032 and 3005 cm^{-1} , aliphatic CH stretching of neopentyl groups at 2956, 2907, and 2868 cm^{-1} , aromatic aliphatic ether (C-O-C) stretching at 1261 and 1218 cm^{-1} (Figure 8.74). MALDI-TOF MS analysis (Figure 8.75) shows a peak at m/z of 1146 $[\text{M}+\text{H}]^+$ which is another identity proof of phthalocyanine **33**.

Deprotection of phthalocyanine **33** was performed in $\text{F}_3\text{CCOOH}-\text{CH}_2\text{Cl}_2$ mixture to obtain the open aldehyde phthalocyanine **34** in 98% yield (Figure 6.22). It was characterized with FT-IR, NMR, MALDI MS and elemental analyses. FT-IR spectrum of **34** (Figure 8.76) displayed aromatic CH stretching of phthalocyanine ring at 3296 and 3077 cm^{-1} , aliphatic CH stretching of neopentyl groups at 2954, 2907, and 2868 cm^{-1} , carbonyl stretching of aldehyde at 1693 cm^{-1} , and aromatic aliphatic ether (C-O-C) stretching at 1280, 1261 and 1217 cm^{-1} . Perfect assignments of the signals in ^1H NMR and ^{13}C NMR spectra (Figure 8.77 and 8.78) demonstrated the identity and as well as the purity of open aldehyde phthalocyanine **34**. ^1H NMR analysis reveals that open aldehyde phthalocyanine **34** has unsymmetrical structure as the aromatic protons on so-called A isoindole subunits differs from each other, methylene protons of neopentyl groups on A isoindole subunits differs significantly, and methyl protons of neopentyl groups on A isoindole subunits shifts differently as well (Figure 8.77). Same trend was observed in ^{13}C NMR spectrum as methine carbons shifts differently and shifts of methylene carbons vary even small differences (Figure 8.78). MALDI-TOF MS analysis (Figure 8.79) which shows a peak at m/z of 1060 $[\text{M}+\text{H}]^+$ and elemental analysis prove the identity and the purity of the aldehyde group bearing phthalocyanine **34**.

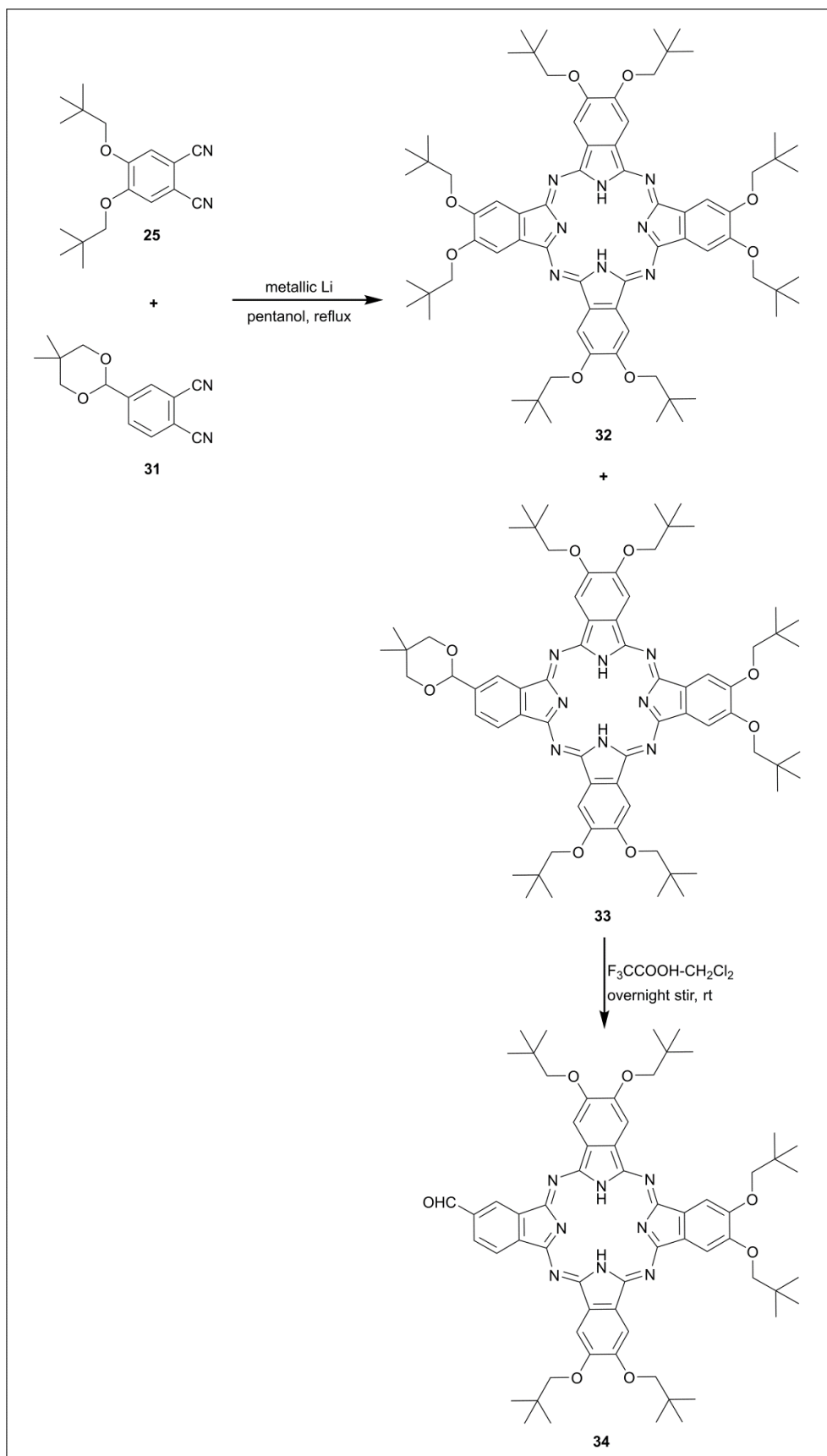


Figure 6.22: Synthetic Pathway for Phthalocyanine Monoaldehyde **34**.

Now, open aldehyde phthalocyanine **34** is in hand to be converted to the Ullman radicals. Condensation step of Ullman process [25] is classically carried out by refluxing the aldehyde and BHA **3** in mostly methanol. Utilization of methanol as solvent is a key parameters because BHA **3** is well soluble in it. However, condensation conditions needs to be optimized specifically for some cases in which the aldehyde is not soluble in methanol. Co-solvent [148] or completely different solvent is required to overcome the solubility obstacle of aldehyde. Besides that, solvent free condensation [26] is also employed. In case of **34**, it is required to optimize the condensation conditions as phthalocyanine monoaldehyde **34** is not soluble in methanol. Optimization experiments were performed according to the conditions tabulated in Table 6.1.

Each reaction was carried out in this manner; phthalocyanine monoaldehyde **34** (10.7 mg, 1 eq.) and BHA **3** (14.8 mg, 10 eq.) and TsOH (1.9 mg, 1 eq.) were stirred in 2 mL of methanol and 4 mL of the other solvent under argon atmosphere at specified temperature. Progress of the reaction was monitored with TLC analysis.

Table 6.1: Optimization of Condensation Conditions.

Entry	Solvent	Temperature	Catalyst	Time (days)	Result
1	(CH ₂ Cl) ₂ -MeOH (2:1)	rt	-	7	No reaction
2	(CH ₂ Cl) ₂ -MeOH (2:1)	rt	TsOH	7	No reaction
3	(CH ₂ Cl) ₂ -MeOH (2:1)	reflux	TsOH	3	No reaction
4	PhMe-MeOH (2:1)	rt	TsOH	7	No reaction
5	PhMe-MeOH (2:1)	reflux	TsOH	3	Little product formed but no completion
6	THF-MeOH (2:1)	rt	-	7	No reaction
7	THF-MeOH (2:1)	rt	TsOH	7	No reaction
8	THF-MeOH (2:1)	50 °C	-	7	No reaction
9	THF-MeOH (2:1)	50 °C	TsOH	7	Little product formed but no completion
10	THF-MeOH (2:1)	reflux	TsOH	2	Product formed, full completion
11	Solvent free	rt	-	7	No reaction
12	Solvent free	rt	TsOH	7	No reaction

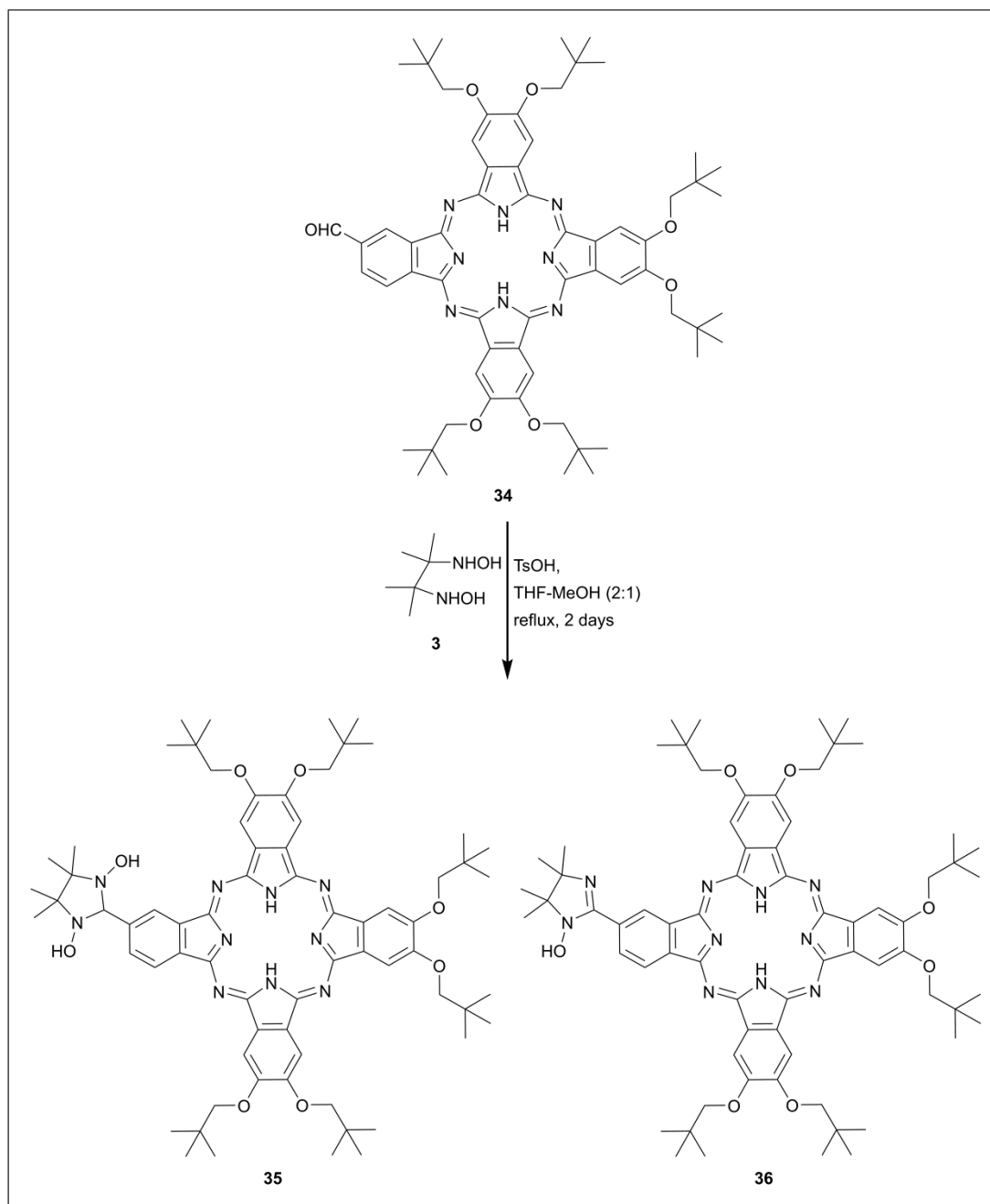


Figure 6.23: Synthetic Pathway for the Condensation Products **35** and **36**.

Upon twelve experiments, the best result was observed in refluxing THF-MeOH (2:1) mixture for two days in the presence of TsOH as catalyst (Figure 6.23). Performing the condensation on the basis of optimized conditions gave solely the 1-hydroxy-2-imidazoline derivative **36** instead of the anticipated 1,3-dihydroxyimidazolidine derivative **35**. The structure of isolated product was confirmed by MALDI-TOF MS (Figure 8.81), m/z 1171 $[M+H]^+$. Obtaining of 1-hydroxy-2-imidazoline derivative **36** was credited to the dehydration [27] of

anticipated product 1,3-dihydroxyimidazolidine derivative **35** at reflux temperature to the isolated product **36**.

Condensation product was characterized with FT-IR and MALDI MS analyses and identified as **36**. FT-IR spectrum of **36** (Figure 8.80) displayed aromatic CH stretchings of phthalocyanine ring at 3296 and 3081 cm^{-1} , aliphatic CH stretchings of neopentyl groups at 2954, 2907, and 2868 cm^{-1} , aromatic aliphatic ether (C-O-C) stretchings at 1279, 1260 and 1215 cm^{-1} and disappearance of carbonyl stretching of aldehyde at 1693 cm^{-1} . MALDI-TOF MS analysis (Figure 8.81) shows a peak at m/z of 1171 $[\text{M}]^+$ which another identity proof of condensation product **36**.

The oxidation step in the Ullman process is important as it generates the radicals. Oxidants commonly utilized in the Ullman process are NaIO_4 , MnO_2 , PbO_2 , and air. Oxidation conditions are also required to be optimized. The most common oxidation methods are described briefly as follows;

- i) Condensation product was dissolved or even suspended in water-immiscible solvent. Saturated NaHCO_3 (aq.) solution was added to the mixture which stirred vigorously. Bi-phasic reaction is performed by adding the aqueous solution of NaIO_4 drop by drop to the mixture [29].
- ii) Condensation product was added to a solvent like CH_2Cl_2 , CHCl_3 or toluene. Heterogeneous reaction was performed by adding the excess of PbO_2 [149].
- iii) Condensation product was added to a solvent like CH_2Cl_2 , CHCl_3 or toluene. Heterogeneous reaction was performed by adding the excess of MnO_2 [150].
- iv) Condensation product was dissolved in any solvent system. NH_4OH (aq.) is added if needed. It is oxidized under air stream in the presence of $\text{Cu}(\text{AcO})_2$ as catalyst.

All of the described methods are examined in order to find best oxidation conditions. The experiments are tabulated in Table 6.2.

Table 6.2: Optimization of Oxidation Conditions.

Entry	Oxidant	Solvent	Time	Result
1	NaIO ₄	CH ₂ Cl ₂ -H ₂ O	3 days	No completion as reaction progressed very slow
2	PbO ₂	CH ₂ Cl ₂	2 days	Reaction completed as condensation product consumed completely
3	MnO ₂	CH ₂ Cl ₂	2 days	Phthalocyanine decomposed
4	Air	THF-MeOH, NH ₄ OH (aq.)	3 days	No completion as reaction progressed very slow, by-products formed

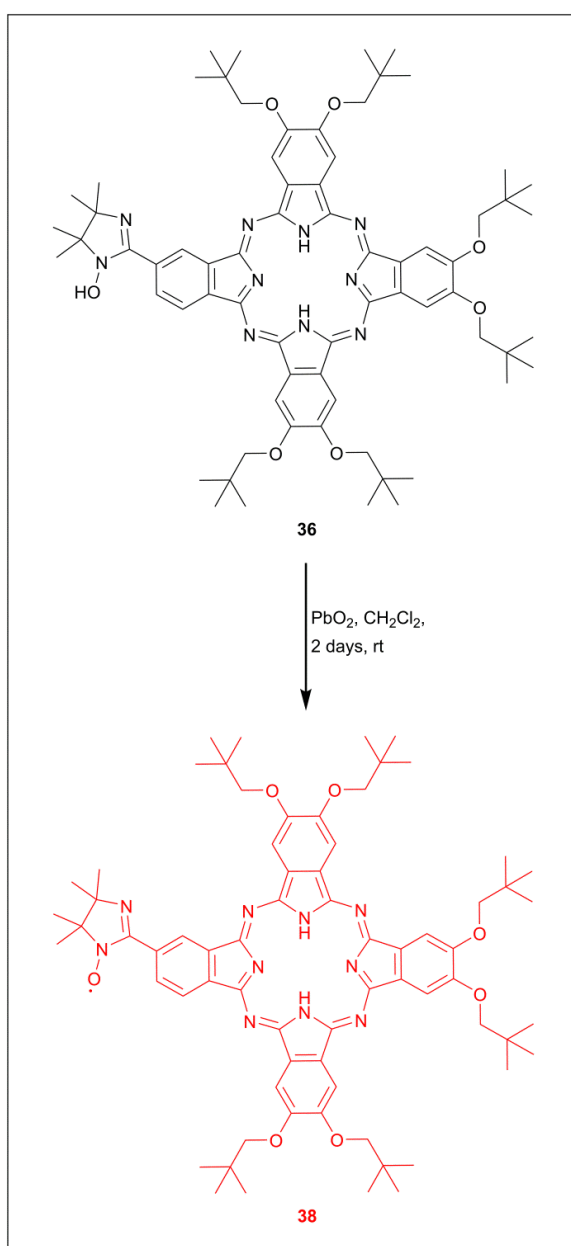


Figure 6.24: Synthetic Pathway for the Monoradical Phthalocyanine **38**.

Best results were observed with PbO₂ as oxidizing in CH₂Cl₂ for two days (Figure 6.24). Oxidation of isolated product 1-hydroxy-2-imidazoline derivative **36** with PbO₂ gave the corresponding imino nitroxide phthalocyanine derivative **38**.

FT-IR spectrum of **38** (Figure 8.82) displayed aromatic CH stretching of phthalocyanine ring at 3296 and 3081 cm⁻¹, aliphatic CH stretching of neopentyl groups at 2955, 2925, and 2867 cm⁻¹, aromatic aliphatic ether (C-O-C) stretching at 1279, 1260 and 1216 cm⁻¹. MALDI-TOF MS analysis of **38** (Figure 8.83) shows a peak at an *m/z* of 1171 [M+H]⁺, which is proof of the formation of **38**, as well as elemental analyses demonstrate its purity.

In conclusion, monoradical phthalocyanine **38** was synthesized through statistical cyclotetramerization of two different phthalonitriles and subsequently Ullman procedure. Monoradical phthalocyanine **38** was characterized unambiguously with a rich array of analyses such as FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, EPR, and magnetic measurements.

6.7.3. Synthesis of Tetra Ullman Radicals Linked Phthalocyanines **43** and **44**

Synthetic methodology for **43** and **44** consist of the cyclotetramerization of phthalonitrile **31** as they are symmetrical phthalocyanines, follows by the Ullman procedure. Synthetic pathway requires multi-step organic manipulations which are described briefly as follows;

- i) synthesis of phthalocyanine tetraaldehyde **40** via cyclotetramerization of phthalonitrile **31**,
- ii) condensation of phthalocyanine tetraaldehyde **40** with 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**3**),
- iii) oxidation of the condensation product to yield the target compounds **43** and **44**.

Phthalonitrile **31** was already prepared as described in Chapter 6.7.1.

Cyclotetramerization of phthalonitrile **31** afforded the phthalocyanine tetra-protected aldehyde **39**. The reaction was classically carried out by 7 hours refluxing in pentanol under template effect of metallic lithium (Figure 6.25).

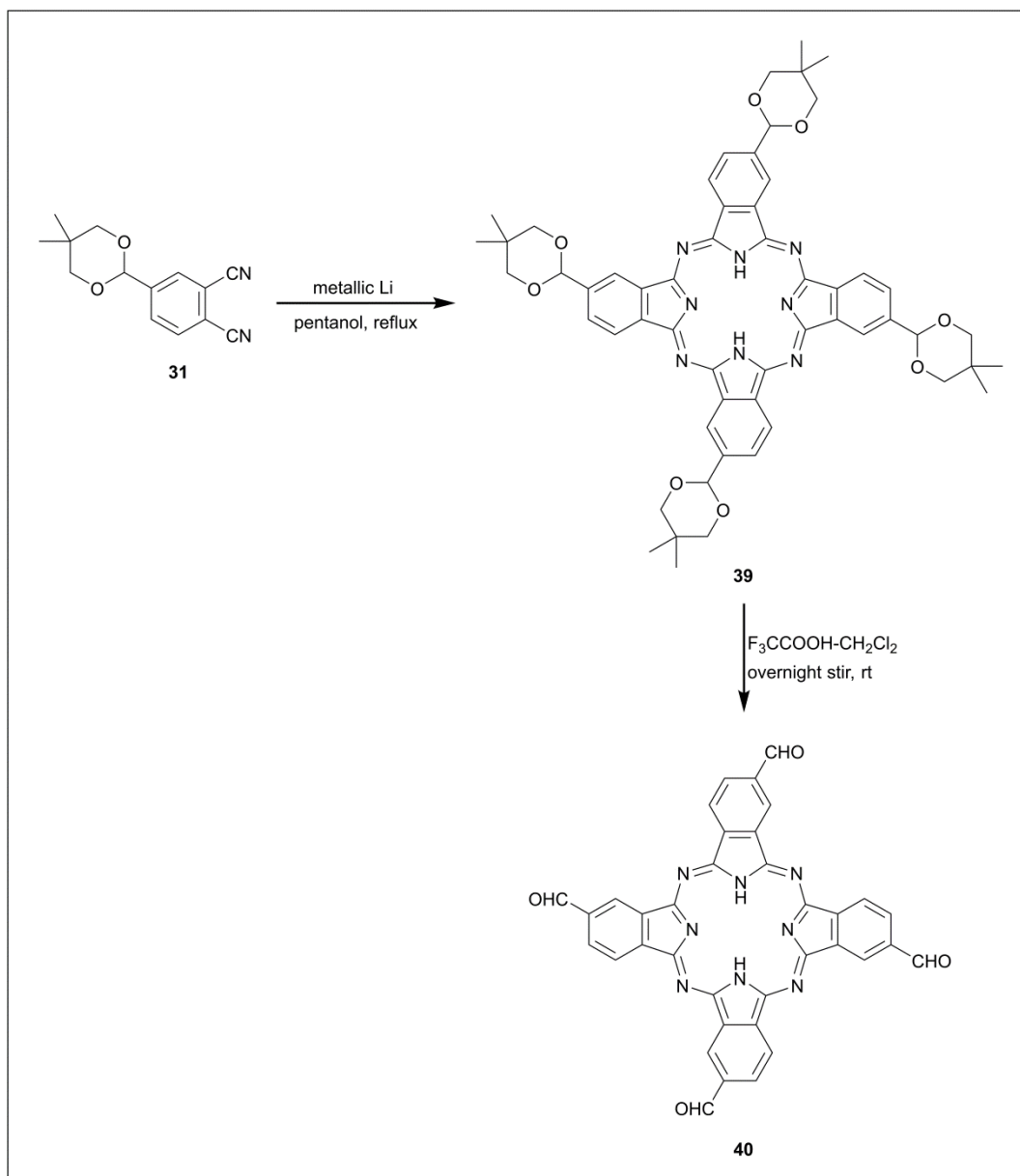
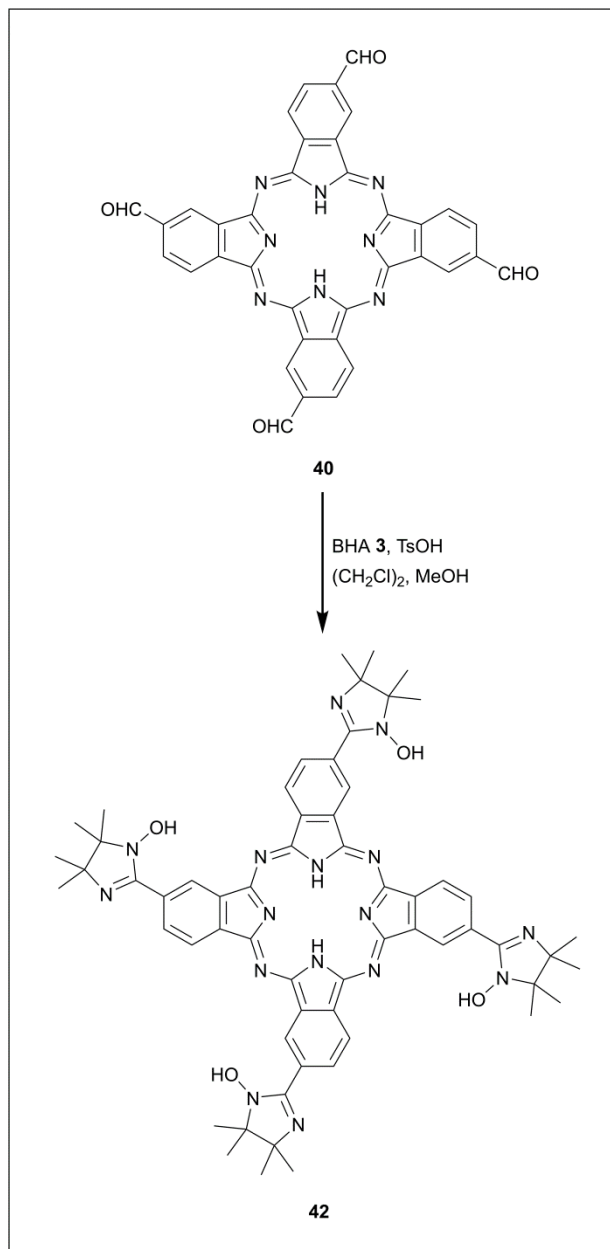


Figure 6.25: Synthetic Pathway for the Phthalocyanine Tetraaldehyde **40**.

FT-IR spectrum of **39** (Figure 8.84) displayed aromatic CH stretching of phthalocyanine ring at 3288 cm^{-1} , aliphatic CH stretching of protecting groups at 2952 , 2924 , and 2851 cm^{-1} , and acetal stretching at 1379 cm^{-1} . MALDI-TOF MS analysis (Figure 8.85) shows a peak at m/z of 971 [M+H]^+ which another identity proof of phthalocyanine **39**.

Deprotection of phthalocyanine **39** was performed in $\text{F}_3\text{CCOOH-CH}_2\text{Cl}_2$ mixture to obtain the phthalocyanine tetraaldehyde **40** in 95% yield (Figure 6.25). It was characterized with FT-IR and MALDI MS analyses. FT-IR spectrum of **40** (Figure 8.86) displayed aromatic CH stretching of phthalocyanine ring at 3286 and

3055 cm^{-1} , CH stretching of aldehyde 2850 cm^{-1} , carbonyl stretching of aldehyde at 1693 cm^{-1} . MALDI-TOF MS analysis (Figure 8.87) which shows a peak at m/z of 626 $[\text{M}]^+$ proves the identity of open tetraaldehyde phthalocyanine **40**.



(Figure 6.26). The final mixture was stirred vigorously under argon atmosphere at room temperature for 14 days (Figure 6.26). It was sonicated for one hour each day and then kept stirring during 14 days. At the end of period, aldehyde was completely consumed (Figure 8.88 and 8.89). The green mixture was added to the 5% ethanol-water mixture and stirred for a while. Formed green precipitates are collected through centrifugation and then washed with water.

Condensation product was characterized with FT-IR and MALDI MS analyses and identified as **42**. FT-IR spectrum of **42** (Figure 8.88) displayed –OH stretching at 3281 cm^{-1} , aliphatic CH stretching at 2923 and 2858 cm^{-1} , and disappearance of carbonyl stretching of aldehyde at 1693 cm^{-1} . MALDI-TOF MS analysis (Figure 8.90) shows a peak at m/z of 1075 [M]^+ which another identity proof of condensation product **42**. MALDI-TOF MS analysis clearly confirms that condensation product **42** is a 1-hydroxy-2-imidazoline derivative which credited to dehydration of 1,3-dihydroxyimidazolidine derivative in solution.

The oxidation step is a tough challenge due to the low solubility of condensation product in most organic solvents. It was performed with NaIO_4 and PbO_2 . Oxidation with NaIO_4 (Figure 6.27) progresses very slowly due to solubility problem of **42** whereas oxidation with PbO_2 does not work. Best solvent combination was determined as mixture of 1,2-dichloroethane, THF, and water. EPR spectrum of **44** have seven-line splitting pattern with the relative intensity of 1:1:2:1:2:1:1 which clearly prove the identity of phthalocyanine tetra-imino nitroxide **44**. MALDI-TOF MS analysis (Figure 8.91) shows a peak at m/z of 1072 [M+H]^+ which another identity proof of phthalocyanine tetra-imino nitroxide **44**. Optimization of oxidation step is in progress. In brief, the synthetic difficulties and isolation of **44** were challenges because of solubility problem.

In conclusion, phthalocyanine tetraaldehyde **40** was synthesized and subsequently converted to condensation product **42** successfully. However, phthalocyanine tetraaldehyde **40** and its derivatives **42** and **44** encountered extremely low solubility in most organic solvents. Oxidation of condensation product **42** with NaIO_4 generated the phthalocyanine tetra-imino nitroxide **44** which characterized with MALDI-TOF MS and EPR analyses. Optimizations are in progress.

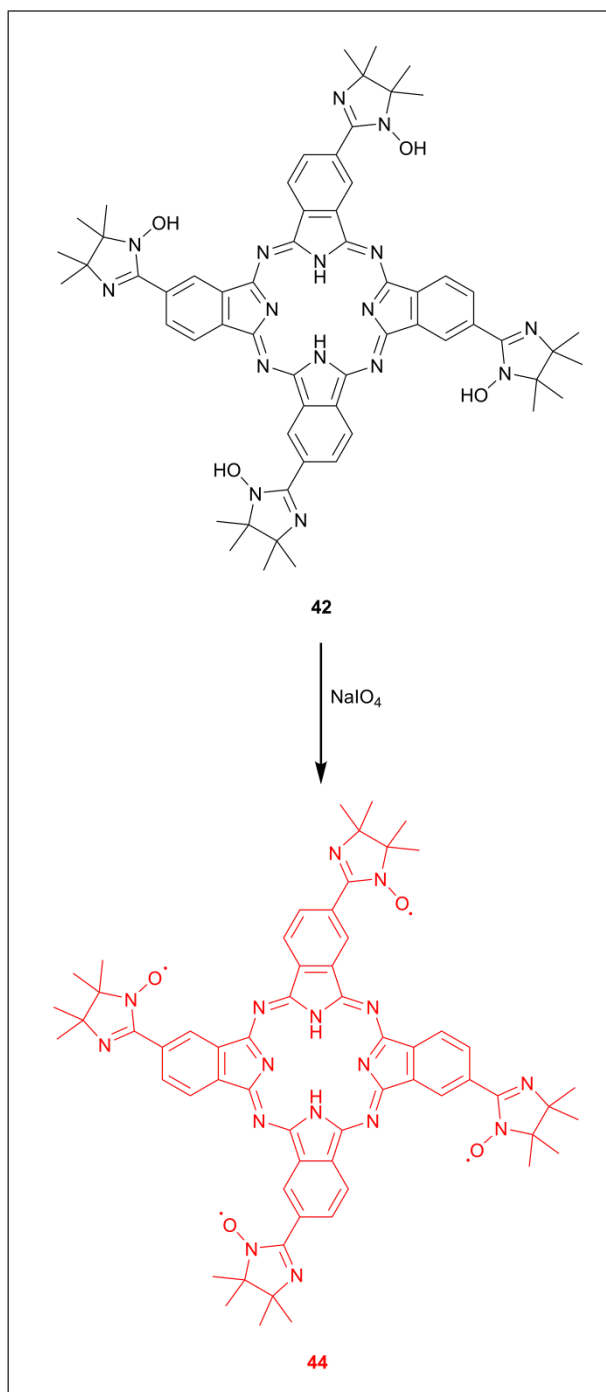


Figure 6.27: Synthetic Pathway for the Phthalocyanine Tetra Imino Nitroxide **44**.

6.8. Absorption Spectroscopy

Electronic structures of phthalocyanine **32** (symmetrical, reference compound) and mono imino nitroxide phthalocyanine **38** (unsymmetrical, target compound) were studied with absorption spectroscopy. **32** and **38** were soluble in dichloromethane in which the Beer–Lambert Law was observed for both compounds

in the range from 10^{-6} to 10^{-5} M (Figure 8.92, 8.93, 8.94 and 8.95). Both of **32** and **38** possess a split Q band, typical of metal free phthalocyanine (Figure 6.28). Symmetrical phthalocyanine **32** has B band absorption at 432 nm and Q band absorptions at 664 nm and 701 nm. Unsymmetrical phthalocyanine **38** have B band at 446 nm and Q bands at 674 nm and 695 nm. The extension of the conjugation, due to the imino nitroxide moiety present in **38**, lead to a 14 nm red shift of the B band in comparison to that of **32** and observed at 446 nm. The low symmetry of **38** leads to a closer Q bands to each other. All of the B and Q bands observed for the **32** and **38** are arised from the $\pi \rightarrow \pi^*$ transitions from the orbitals of phthalocyanine ring.

Typically, imino nitroxide radicals have $n \rightarrow \pi^*$ transitions observed around 450 nm in the spectrum. However, it was overlapped with B band and stayed under.

In conclusion, both of **32** and **38** possess a split Q band which characteristic of metal free phthalocyanines. In case of **38**, extra conjugation by imino nitroxide radical leads a 14 nm red shift of the B band.

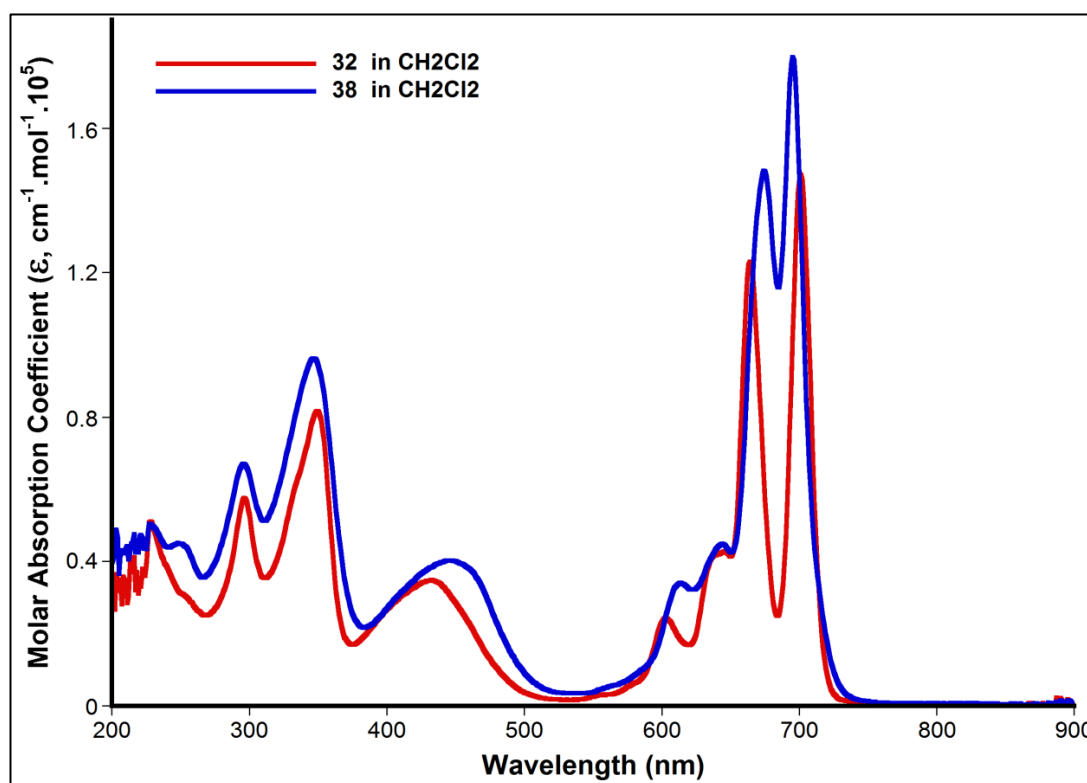


Figure 6.28: UV-Vis Spectra of **32** and **38**.

6.9. Electrochemical Analysis

Electrochemical behavior of phthalocyanine mono imino nitroxide **38** was investigated by cyclic voltammetry. Phthalocyanine **38** showed an irreversible oxidation wave at 1.260 V vs. SCE and a reversible reduction one at -0.886 V (Figure 6.29). Noteworthy that potentials were referenced to ferrocene/ferrocenium couple by taking $E_{1/2}(\text{Fc}/\text{Fc}^+) = 0.480$ V vs. SCE in dichloromethane with 0.1 M $n\text{-Bu}_4\text{NClO}_4$ as supporting electrolyte [151].

Redox characteristics and observed potentials of **38** are in accordance with the literature [31], [92]. In conclusion, electrochemical behavior of phthalocyanine **38** was characterized by cyclic voltammetry.

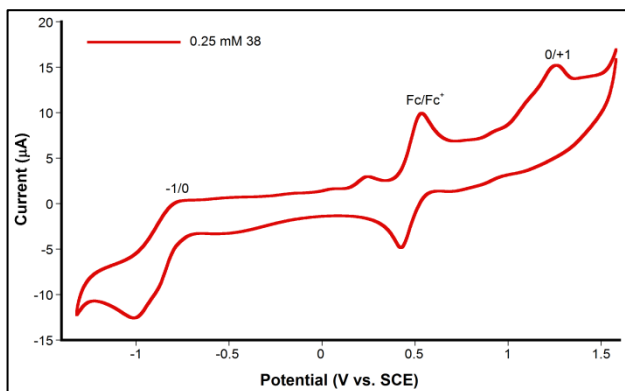


Figure 6.29: Cyclic Voltammogram of Phthalocyanine **38** Recorded at rt in Dichloromethane, 0.1 M $n\text{-Bu}_4\text{NClO}_4$ as Supporting Electrolyte, Scan Rate of 100 mV/s.

6.10. Electron Paramagnetic Resonance Spectroscopy

EPR spectrum of **38** (Figure 6.30) have seven-line splitting pattern with the relative intensity of $1:1:2:1:2:1:1$. The seven-line spectrum reasoned by the interaction of the unpaired electron ($S=1/2$) with two unequivalent ^{14}N nitrogen atoms (nuclear spin $I=1$) in the imidazoline ring. This spectrum was simulated with Jeol IsoSimu computer program. Best fitting parameters are found as $g = 2.0029$, $a_{\text{N1}} = 9.3$ G, $a_{\text{N2}} = 4.2$ G, $\Delta H_{\text{p-p}} = 2.1$ G. Splitting pattern and the parameters clearly proves phthalonitrile **38** as imino nitroxide radical.

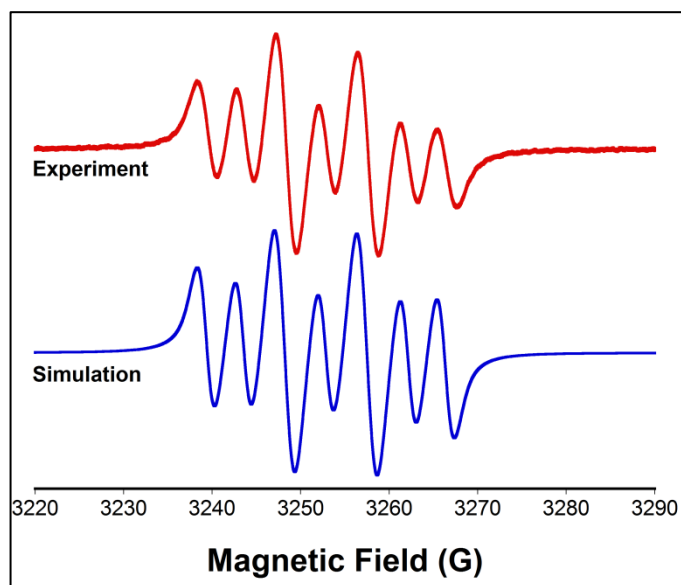


Figure 6.30: EPR Spectra of the Radical **38** at 293 K at 10^{-4} M in Dichloromethane-toluene (1:1) Mixture.

Oxidation of **42** with NaIO_4 generated phthalocyanine tetra-imino nitroxide **44** which is clearly proven by EPR spectra. EPR spectra of **44** from different batches (Figure 6.31 and 6.32) have seven-line splitting pattern with the relative intensity of 1:1:2:1:2:1:1, characteristics of imino nitroxide radicals. EPR analyses of **44** were done regardless of concentration.

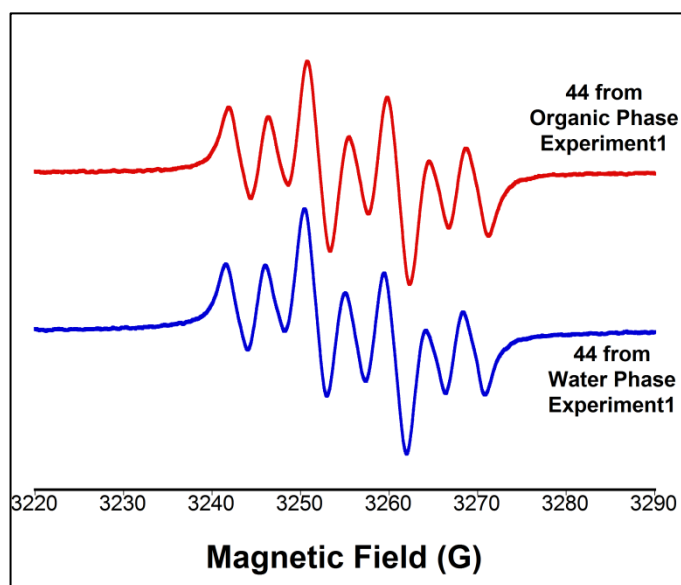


Figure 6.31: EPR Spectra of **44** at 293 K.

EPR spectrum of **44** (Figure 6.32) shows typical imino nitroxide profile with $g = 2.0029$, $a_{N1} = 9.1$ G, $a_{N2} = 4.3$ G and $\Delta H_{p-p} = 2.4$ G.

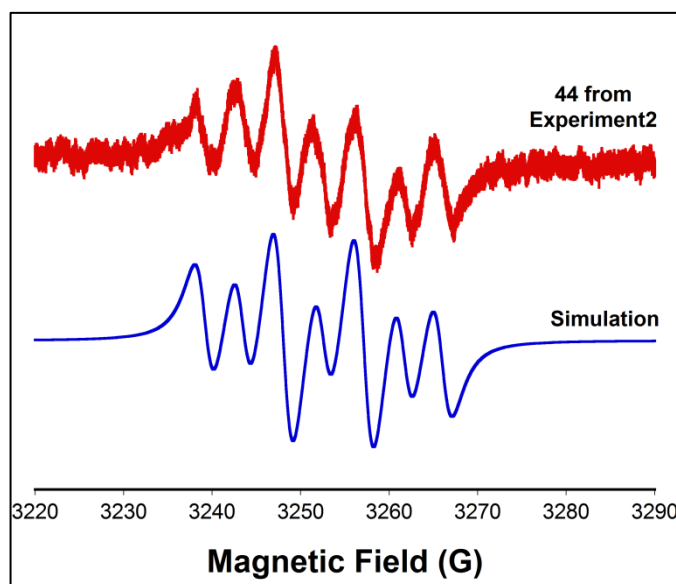


Figure 6.32: EPR Spectrum of **44** at 293 K.

6.11. Magnetic Measurements

Magnetic measurements and analysis are underway.

6.12. X-ray Diffraction Analyses

Crystallizations of phthalonitriles **25**, **31**, and phthalocyanine mono imino nitroxide **38** are in progress. X-ray diffractions and structure determination will be performed upon obtaining suitable crystals.

6.13. Summary and Conclusion

The phthalocyanine bearing one imino nitroxide **38** was successfully synthesized through Ullman process. However, its nitronyl nitroxide analog could not be prepared yet as the anticipated condensation product, 1,3-dihydroxyimidazolidine, dehydrates to the 1-hydroxy-2-imidazoline derivative in our condition. Some works have to be achieved to understand the dehydration

mechanism and to highlight the conditions in which such process occur. From our first observations, the presence of TsOH during the condensation step can promote dehydration process. The phthalocyanine mono imino nitroxide **38** was characterized indubitably by FT-IR, MALDI-TOF, elemental analysis, absorption spectroscopy, cyclic voltammetry and EPR analyses. As far as we know, it is the first time that phthalocyanine bearing an Ullman radical covalently bond on the skeleton was synthesized and characterized. Despite the difficulties encountered in this non trivial synthesis, this first result allows us to hope to obtain soon the molecule **37**, phthalocyanine mono nitronyl nitroxide.

On the other hand, the synthesis of phthalocyanines bearing four Ullman radicals is still a challenge as the condensation product suffers very badly from insolubility. Nevertheless, phthalocyanine tetra imino nitroxide **43** was generated in reaction medium even if not isolated yet and characterized with MALDI-TOF MS and EPR analyses. Optimizations in order to overcome the challenges arisen from insolubility are underway.

6.14. Synthetic Procedures of Phthalonitriles

As stated in the Chapter 6.7.1, phthalonitriles **25** and **31** were synthesized successfully. Procedures for **25** and **31** were optimized on the basis of Leznoff [126] and Hanack protocols [147] respectively.

6.14.1. Synthesis of 1,2-Dibromo-4,5-dineopentoxybenzene **24**

1,2-dibromo-4,5-dihydroxybenzene **22** (1 eq., 0.075 mol, 19.950 g), neopentyl tosylate **23** (2 eq., 0.150 mol, 36.3 g), KOH (4 eq., 0.300 mol, 16.833 g), and tetraheptylammonium bromide (0.4 eq., 0.030 mol, 14.721 g) were charged into 250 mL flask. The mixture was stirred for a while, then hexamethylphosphoramide (HMPA) was added. The solution was heated at 90 °C for one week. The reaction mixture was poured into water (400 mL). It was extracted with CH₂Cl₂ (3 X 400 mL). Organic phase was washed with water (10 X 400 mL) and then dried over Na₂SO₄. Crude product was purified with column chromatography on silica gel eluting with hexane-dichloromethane mixture. Column purification gave 17.052 g of

24 in 56% yield. mp. 47–49 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 2956s, 2907m, 2868m, 1583m, 1497s, 1476s, 1400m, 1364m, 1352m, 1274m, 1248s, 1201s, 1113w, 1046m, 1017s, 923w, 906w, 844m, 766s, 750s. ^1H NMR (500 MHz, CDCl_3): δ 7.02 (s, 2H, aromatic –CH), 3.57 (s, 4H, –CH₂), 1.05 (s, 18H, neopentyl –CH₃) ppm. ^{13}C NMR (125 MHz, CDCl_3): δ 149.58, 117.45, 114.40, 110.13, 79.10, 32.27, 26.70. ppm.

6.14.2. Synthesis of 4,5-Dineopentoxyphthalonitrile **25**

1,2-dibromo-4,5-dineopentoxybenzene **24** (1 eq., 0.040 mol, 16.24 g) was charged into 500 mL flask. CuCN (3 eq., 0.120 mol, 10.748 g) was dissolved in NMP (130 mL), then added to reaction flask. The flask was placed in the cavity and stirred efficiently. Flask content was subjected to microwave irradiation (maximum energy 1000 Watt) at 180 °C for 30 minutes under argon. Reaction mixture was poured into ammonia solution (300 mL, 32% NH_4OH), then stirred for two hours. Formed dark brown precipitate was collected through vacuum filtration and washed with water until filtrate is translucent. Filtrates were combined, then extracted with CH_2Cl_2 (3 X 100 mL). Organic phase was washed with water (10 X 300 mL) and then dried over Na_2SO_4 . Crude product was purified with column chromatography on silica gel eluting with dichloromethane. Column purification gave 8.88 g of **25** in 74% yield. mp. 202–204 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3129w, 3095w, 3064w, 2956s, 2932m, 2876m, 2229s, 1586s, 1562m, 1518s, 1476s, 1406s, 1395s, 1363s, 1286s, 1265s, 1230s, 1214s, 1202s, 1090s, 1040m, 1011s, 990s, 950m, 926s, 884s, 861s. ^1H NMR (500 MHz, CDCl_3): δ 7.08 (s, 2H, aromatic –CH), 3.66 (s, 4H, –CH₂), 1.08 (s, 18H, neopentyl –CH₃) ppm. ^{13}C NMR (125 MHz, CDCl_3): δ 172.64, 152.90, 116.14, 115.35, 108.41, 79.05, 32.25, 26.58 ppm.

6.14.3. Synthesis of 1,2-Dibromo-4-(5,5-dimethyl-1,3-dioxane-2-yl)benzene **30**

3,4-dibromobenzaldehyde **28** (1 eq., 0.040 mol, 10.48 g), 2,2-dimethylpropan-1,3-diol **29** (2 eq., 0.080 mol, 8.32 g), TsOH (5% eq., 0.002 mol, 0.380 g), and toluene (50 mL) were charged into 100 mL flask. It was heated overnight at reflux temperature equipped with Dean-Stark trap. It was cooled to ambient temperature,

and then evaporated to dryness. Residue was dissolved in CH_2Cl_2 (100 mL). Organic phase was washed with saturated NaHCO_3 (aq.) solution (2 X 100 mL), then with water (3 X 100 mL), and finally dried over Na_2SO_4 . Crude product was purified with column chromatography on silica gel eluting with hexane-dichloromethane mixture. Column purification gave 7.795 g white powder of **30** in 56% yield. mp. 65–67 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3096w, 3077w, 2952s, 2855m, 1722m, 1590w, 1557w, 1459s, 1376s, 1335m, 1306s, 1279m, 1229s, 1213s, 1098s, 1035s, 1013s, 992s, 981s, 956s, 930s, 909s, 875s, 811s, 786m, 757w, 736s, 686m, 658s. ^1H NMR (500 MHz, CDCl_3): δ 7.78 (m, 1H, aromatic –CH), 7.62 (m, 1H, aromatic –CH), 7.31 (m, 1H, aromatic –CH), 5.32 (d, J = 2.0 Hz, 1H, aliphatic –CH), 3.76 (d, J = 10.1 Hz, 2H, aliphatic –CH₂), 3.63 (d, J = 10.5 Hz, 2H, aliphatic –CH₂), 1.27 (s, 3H, –CH₃), 0.80 (s, 3H, –CH₃) ppm. ^{13}C NMR (125 MHz, CDCl_3): δ 139.50, 133.60, 131.72, 126.54, 125.21, 124.80, 100.05, 77.75, 30.37, 23.15, 21.97 ppm.

6.14.4. Synthesis of 4-(5,5-Dimethyl-1,3-dioxane-2-yl)-phthalonitrile **31**

1,2-dibromo-4-(5,5-dimethyl-1,3-dioxane-2-yl)benzene **30** (1 eq., 0.020 mol, 6.96 g) was charged in to 250 mL flask. CuCN (4 eq., 0.080 mol, 7.165 g) was dissolved in NMP (180 mL), and then added to the flask. The flask was placed in the cavity and stirred efficiently. Flask content was subjected to microwave irradiation (maximum energy 1000 Watt) at 180 °C for one hour under argon. Reaction mixture was poured into ammonia solution (200 mL, 32% NH_4OH), then stirred for two hours. Formed dark brown precipitate was collected through vacuum filtration and washed with water until filtrate is translucent. Filtrates were combined, then extracted with CH_2Cl_2 (3 X 100 mL). Organic phase was washed with water (10 X 300 mL) and then dried over Na_2SO_4 . Crude product was purified with column chromatography on silica gel eluting with dichloromethane. Column purification gave 2.517 g of **31** in 52% yield. mp. 48–50 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3118w, 3085w, 3047w, 2962m, 2869m, 2829w, 2236s, 1496w, 1473s, 1462s, 1427s, 1395s, 1364s, 1315m, 1286s, 1235m, 1204m, 1216m, 1161w, 1104s, 1094s, 1038s, 1014s, 994s, 976s, 951m, 937w, 919s, 850s, 817s, 783m, 764s, 750s, 716w. ^1H NMR (500 MHz, CDCl_3): δ 7.98 (m, 1H, aromatic –CH), 7.85 (m, 1H, aromatic –CH), 7.81 (m, 1H, aromatic –CH), 5.43 (s, 1H, aliphatic –CH), 3.79 (d, J = 9.9 Hz, 2H, aliphatic

–CH₂), 3.67 (d, *J* = 10.4 Hz, 2H, aliphatic –CH₂), 1.24 (s, 3H, –CH₃), 0.82 (s, 3H, –CH₃) ppm. ¹³C NMR (125 MHz, CDCl₃): δ 144.37, 133.55, 131.70, 131.14, 115.97, 115.87, 115.41, 98.78, 77.77, 30.41, 23.02, 21.86 ppm.

6.15. Synthetic Procedures of Mono Ullman Radical Linked Phthalocyanines

6.15.1. Synthesis of 32 and 33

Metallic lithium was dissolved in pentanol (50 mL) and stirred for 1 hour. Phthalonitrile **25** (6 eq., 0.012 mol, 3.600 g) and phthalonitrile **31** (1 eq., 0.002 mol, 0.484 g) were added to the solution. Final mixture was refluxed overnight. Intense green solution was cooled to ambient temperature. It was precipitated by adding drop by drop into water-ethanol mixture. Formed green precipitate was collected by suction filtration. It was washed with water and then with ethanol, finally dried under air stream to afford 3.800 g crude product as green waxy solid. Crude product was purified with column chromatography on silica gel eluting with dichloromethane-hexane mixture. Column purification gave two major products; 1.680 g of **32** as green waxy solid and 0.527 g of **33** as green powder in 23% yield.

Phthalocyanine **32**: FT-IR (ATR, $\nu_{\max}$, cm⁻¹) : 3295w, 3077w, 2954s, 2906s, 2867m, 1600m, 1491s, 1465s, 1444s, 1419m, 1391s, 1362s, 1325s, 1275s, 1260s, 1211s, 1197s, 1170m, 1098s, 1053s, 1014s, 917m, 866s, 852s, 806s, 748s, 723m, 709s, 693m. MALDI-TOF MS (2,5-dihydroxybenzoic acid): *m/z* for C₇₂H₉₈N₈O₈ [calculated]: 1203, [found]: 1204 [M+H]⁺.

Phthalocyanine **33**: FT-IR (ATR, $\nu_{\max}$, cm⁻¹) : 3296w, 3032w, 2956m, 2914m, 2869m, 1546s, 1534s, 1471s, 1454s, 1408s, 1394s, 1378s, 1340s, 1280m, 1261s, 1218m, 1170s, 1133s, 1096s, 1050m, 1018s, 850s, 799s, 766s, 742s, 647m. MALDI-TOF MS (2,5-dihydroxybenzoic acid): *m/z* for C₆₈H₈₈N₈O₈ [calculated]: 1145, [found]: 1146 [M+H]⁺.

6.15.2. Synthesis of 34

Phthalocyanine **33** (0.46 mmol, 0.527 g) was stirred in F₃CCOOH-CH₂Cl₂ mixture (40 mL-40 mL) at room temperature overnight. Green mixture was poured

into water. Green organic phase was washed with saturated NaHCO_3 (aq.) solution (5 X 100 mL), then with water (10 X 100 mL), finally dried over Na_2SO_4 . Green solution was evaporated to dryness. Crude product was purified with column chromatography on silica gel eluting with dichloromethane-hexane mixture (5:1). Column purification gave 0.477 g of **34** as green powder in 98% yield. FT-IR (ATR, ν_{max} , cm^{-1}) : 3296w, 3077w, 2954s, 2907m, 2868m, 1693s, 1607m, 1583m, 1490s, 1474s, 1450s, 1393s, 1363s, 1342s, 1280m, 1260s, 1235s, 1205s, 1158s, 1132m, 1095s, 1068s, 1049s, 1017s, 921s, 854s, 830s, 739s, 715s, 691s. ^1H NMR (500 MHz, CDCl_3): δ 10.40 (s, 1H, -CHO), 8.93 (s, 1H, aromatic -CH), 8.53 (d, J = 5 Hz, 1H, aromatic -CH), 8.41 (s, 1H, aromatic -CH), 8.29 (s, 1H, aromatic -CH), 8.10 (m, 2H, aromatic -CH), 7.96 (s, 1H, aromatic -CH), 7.56 (m, 2H, aromatic -CH), 4.33 (s, 2H, -CH₂O-), 4.31 (s, 2H, -CH₂O-), 4.20 (s, 2H, -CH₂O-), 4.07 (s, 2H, -CH₂O-), 3.92 (s, 2H, -CH₂O-), 3.90 (s, 2H, -CH₂O-), 1.48 (s, 18H, neopentyl -CH₃), 1.45 (s, 9H, neopentyl -CH₃), 1.41 (s, 9H, neopentyl -CH₃), 1.38 (s, 18H, neopentyl -CH₃), -3.92 (s, 2H, -NH) ppm. ^{13}C NMR (125 MHz, CDCl_3): δ 192.79, 152.66, 152.48, 152.28, 152.22, 151.96, 151.93, 141.99, 137.96, 135.69, 133.20, 133.16, 129.46, 126.93, 126.72, 126.06, 126.01, 123.05, 122.21, 106.08, 105.96, 103.75, 103.54, 102.62, 102.45, 79.14, 78.83, 78.75, 78.49, 78.48, 77.73, 32.76, 32.63, 32.56, 32.53, 27.35, 27.29, 27.19 ppm. MALDI-TOF MS (2,5-dihydroxybenzoic acid): m/z for $\text{C}_{63}\text{H}_{78}\text{N}_8\text{O}_7$ [calculated]: 1059, [found]: 1060 $[\text{M}+\text{H}]^+$. Elemental Analysis for $\text{C}_{63}\text{H}_{78}\text{N}_8\text{O}_7$ [calculated]: C, 71.43; H, 7.42; N, 10.58. [found]: C, 69.81; H, 7.78; N, 9.23.

6.15.3. Synthesis of **38**

Phthalocyanine monoaldehyde **34** (1 eq., 0.075 mmol, 0.079 g), BHA **3** (40 eq., 3 mmol, 0.444 g), and TsOH (6 eq., 0.45 mmol, 0.086 g) were charged into 25 mL flask. THF (10 mL) and MeOH (5 mL) were added to the flask. Reaction solution was refluxed at 70 °C under argon for two days. It was evaporated to dryness. Green residue was dissolved in CH_2Cl_2 (150 mL). Green organic phase was washed firstly with 10% ethanol-water mixture (2 X 100 mL), then with saturated NaHCO_3 (aq.) solution (1 X 100 mL), finally with water (3 X 100 mL). It was dried over Na_2SO_4 , evaporated to dryness, and dried under vacuum to give a green powder. FT-IR and MALDI-TOF MS analyses of the green powder (as crude product) confirmed its

structure as **36**. Crude product of **36** was subjected to PbO₂ oxidation without further purification. FT-IR (ATR, ν_{max} , cm⁻¹) of compound **36**: 3296w, 3081w, 2954s, 2907m, 2868m, 1607m, 1488s, 1474s, 1451s, 1393s, 1363s, 1329s, 1279s, 1260s, 1208s, 1173s, 1096s, 1047s, 1015s, 920s, 855s, 811m, 788m, 742s, 716s, 698s. MALDI-TOF MS (trans-2-[3-(4-tert -butylphenyl)-2-methyl-2-propenylidene]-malononitrile): *m/z* for C₆₉H₉₀N₁₀O₇ [calculated]: 1171, [found]: 1171 [M]⁺.

Monohydroxy condensation product **36** was suspended in CH₂Cl₂ (250 mL) in 1 L flask. PbO₂ (200eq., 3.6 g) was added to flask. The mixture was stirred vigorously at room temperature for 3 days in dark. It was filtered on Celite-plug and washed with CH₂Cl₂. Green solution was evaporated to dryness. Crude product was purified with plaque chromatography on silica gel eluting with dichloromethane-methanol mixture (200:1). Plaque purification gave 0.033 g of **38** as green powder in 38% yield (from aldehyde). FT-IR (ATR, ν_{max} , cm⁻¹): 3296w, 3081w, 2955s, 2925m, 2867m, 1736w, 1608w, 1491s, 1474s, 1451s, 1393s, 1363s, 1329m, 1279s, 1260s, 1209m, 1171s, 1097s, 1049s, 1016s, 920m, 873s, 855s, 796s, 743s, 717s, 698s. MALDI-TOF MS (trans-2-[3-(4-tert -butylphenyl)-2-methyl-2-propenylidene]-malononitrile): *m/z* for C₆₉H₈₉N₁₀O₇ [calculated]: 1170, [found]: 1171 [M+H]⁺. Elemental Analysis for C₆₉H₈₉N₁₀O₇ [calculated]: C, 70.80; H, 7.66; N, 11.97. [found]: C, 71.70; H, 7.98; N, 11.62.

6.16. Synthetic Procedures of Tetra Ullman Radicals Linked Phthalocyanines

6.16.1. Synthesis of 39

Metallic lithium was dissolved in pentanol (10 mL) and stirred at 60 °C for one hour under argon. Phthalonitrile **31** (1 eq., 0.002 mol, 0.484 g) was added to the solution. Final mixture was refluxed 7 hours under argon. Intense green solution was cooled to ambient temperature. It was precipitated by adding drop by drop into water-ethanol mixture. Formed green precipitate was collected by suction filtration. It was washed with water and then with ethanol, finally dried under vacuum to afford 0.267 g green powder of **39** in 55% yield. FT-IR (ATR, ν_{max} , cm⁻¹): 3288w, 2952m, 2924m, 2851m, 1724w, 1617w, 1499m, 1455s, 1420s, 1379s, 1336s, 1307s, 1214s,

1160m, 1092s, 1011s, 978s, 897s, 878s, 858m, 827s, 752s, 740s, 699m. MALDI-TOF MS (2,5-dihydroxybenzoic acid): m/z for $C_{56}H_{58}N_8O_8$ [calculated]: 970, [found]: 971 $[M+H]^+$.

6.16.2. Synthesis of 40

Phthalocyanine **39** (0.268 mmol, 0.260 g) was stirred in $F_3CCOOH-CH_2Cl_2$ mixture (30 mL-50 mL) overnight at room temperature. Green mixture was poured into water. Green organic phase was washed with saturated $NaHCO_3$ (aq.) solution (5 X 100 mL), then with water (10 X 100 mL). Green organic phase was added drop by drop into ethanol. It was precipitated by adding water in small portions. Formed green precipitate was collected through centrifuge, washed with water (3 X 40 mL), finally dried under vacuum. Drying afforded 0.160 g green powder of phthalocyanine tetraaldehyde **40** in 95% yield. FT-IR (ATR, ν_{max} , cm^{-1}) : 3286w, 3055w, 2920m, 2850m, 1693s, 1608s, 1574s, 1502s, 1468s, 1384s, 1338s, 1285s, 1271s, 1164s, 1150s, 1093s, 1006s, 921s, 830s, 813s, 779s, 744s, 723s, 697s, 661w. MALDI-TOF MS (2,5-dihydroxybenzoic acid): m/z for $C_{36}H_{18}N_8O_4$ [calculated]: 626, [found]: 626 $[M]^+$.

6.16.3. Synthesis of 42

Phthalocyanine tetraaldehyde **40** (1 eq., 0.1 mmol, 0.063 g), 1,2-dichloroethane (2 mL) and methanol (2 mL) were charged into a microwave tube. It was sonicated for one hour. BHA **3** (3 eq., 1.2 mmol, 0.180 g) and TsOH (10% eq., 0.04 mmol, 0.0076 g) were added to the tube and sonicated for another hour. Final mixture was stirred efficiently at room temperature under argon for 14 days. It was sonicated for one hour in every day during 14 days. Green mixture was poured into 5% ethanol-water mixture. Formed precipitate was collected through centrifuge, washed with water (3 X 40 mL), finally dried under vacuum. Drying afforded 0.045 g green powder. FT-IR and MALDI-TOF MS analyses of the green powder (as crude product) confirmed its structure as **42**. Crude product of **42** was subjected to oxidation without further purification. FT-IR (ATR, ν_{max} , cm^{-1}) of compound **42**: 3281s, 2923s, 2858s, 1696w, 1594s, 1543s, 1501s, 1449s, 1367s, 1317s, 1235m,

1204s, 1092s, 1012s, 835m, 742s. MALDI-TOF MS (2,5-dihydroxybenzoic acid): m/z for $C_{60}H_{66}N_{16}O_4$ [calculated]: 1075, [found]: 1075 $[M]^+$.

6.16.4. Synthesis of 44

Experiment 1: **42** (1 eq., 0.01 mmol, 0.011 g) was suspended in a solvent mixture; 1,2-dichloroethane (3 mL), THF (3 mL), and H_2O (4 mL). $NaIO_4$ (20 eq., 0.80 mmol, 0.171 g) was dissolved in H_2O (2 mL) and added to the reaction mixture. It was stirred vigorously at room temperature for 7 days. H_2O (20 mL) was added to the mixture and shaken. Phases were separated. Each phase was analyzed in EPR. EPR spectrum of organic phase displayed characteristic imino nitroxide radical. EPR spectrum of water phase did as well.

Experiment 2: **42** (1 eq., 0.01 mmol, 0.011 g) was suspended in a solvent mixture; CH_2Cl_2 (50 mL), and pyridine (20 mL). $NaIO_4$ (20 eq., 0.80 mmol, 0.171 g) was dissolved in H_2O (5 mL) and added to the reaction mixture. It was stirred vigorously at room temperature for 7 days. H_2O (20 mL) was added to the mixture and shaken. Solution was analyzed in EPR. EPR spectrum of organic phase displayed characteristic imino nitroxide radical. MALDI-TOF MS (trans-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidene]-malononitrile): m/z for $C_{60}H_{62}N_{16}O_4$ [calculated]: 1071, [found]: 1072 $[M+H]^+$.

Experiment 3: **42** (1 eq., 0.01 mmol, 0.011 g) was suspended in a solvent mixture; 1,2-dichloroethane (20 mL), CH_2Cl_2 (50 mL), and pyridine (10 mL). PbO_2 (20 eq., 0.80 mmol, 0.192 g) was added to the reaction mixture. It was stirred vigorously at room temperature for 7 days. It was filtered on Celite-plug. Solution was analyzed in EPR. EPR spectrum of solution displayed no peak, emphatically EPR silent.

7. PRE-FORMED RADICAL STRATEGY FOR THE SYNTHESIS OF ULLMAN RADICAL FUNCTIONALIZED PHTHALOCYANINES: ULLMAN RADICALS LINKED PHTHALONITRILES

Synthetic studies within the Chapter 6 utilized Ullman route which generated imino nitroxide derivatives of phthalocyanine. Formation of imino nitroxide adducts were credited to dehydration which took place at reflux temperature of condensation. Subsequent oxidation of dehydrated condensation product, namely 1-hydroxy-2-imidazoline derivative, formed solely the imino nitroxide product. However, nitronyl nitroxide linked phthalocyanines were also designed as target molecules. To that end, pre-formed radical strategy is considered as an alternative route. In the synthetic sequence, radical species will be firstly generated, then formed radical synthons - emphatically radical linked phthalonitriles- will be converted to the target structures of phthalocyanine.

7.1. Survey of Nitroxide Functionalized Phthalonitriles

Functionalization of aromatic compounds with nitroxide radicals was already reported, particularly with TEMPO [152]. However, only one study reported the nitroxide functionalized phthalonitrile [95]. Its preparation is based on the nucleophilic substitution of 4-nitrophthalonitrile (**20**) with 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-oxyl (**101**) as nucleophile. 4-nitrophthalonitrile (**20**) was reacted with **101** in dry DMF at room temperature in the presence of K_2CO_3 as base to give the 4-TEMPO phthalonitrile in 46% yield (Figure 7.1).

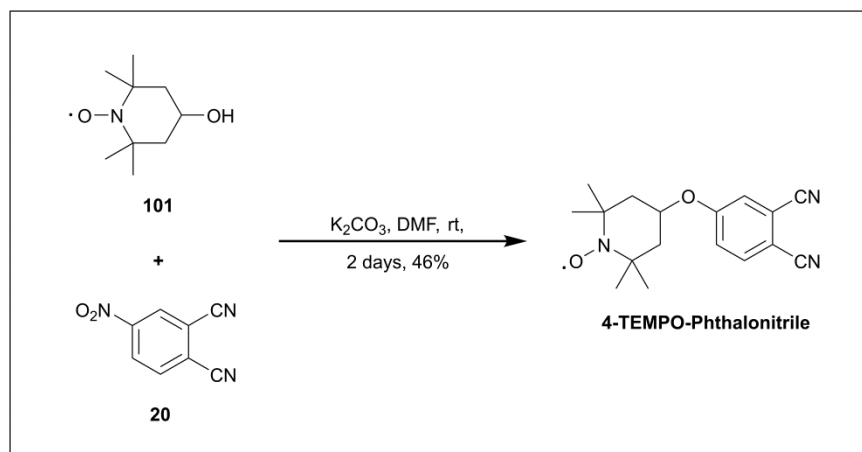


Figure 7.1: Synthesis of Nitroxide Functionalized Phthalonitrile.

7.2. Scope and Objectives

The synthetic studies within the Chapter 6 generated imino nitroxide functionalized phthalocyanines derivatives in good yield but not the nitronyl nitroxide functionalized one. Consequently, to develop an alternative synthetic route for a phthalocyanine bearing nitronyl nitroxide is required. In this way, our attention was circumscribed to the preform radical strategy. A preform radical, the 2-(4-hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**), as already mentioned in Chapter 5, was prepared and utilized as intermediate for the synthesis of Ullman radicals functionalized phthalonitriles. Hydroxy-functionalized nitronyl nitroxide **10** will react with 4-nitrophthalonitrile by nucleophilic aromatic substitution, as the nitro group is a good leaving group. Hence, Ullman radical linked phthalonitriles **46** and **47** (Figure 7.2) could be prepared in that manner. Because, they are considered as key precursors toward the synthesis of Ullman radicals linked phthalocyanine, particularly nitronyl nitroxide one. Cyclotetramerization of the Ullman radical linked phthalonitriles could pave the way for the synthesis of Ullman radicals functionalized phthalocyanine derivatives **48** and **49** (Figure 7.3).

Within the context, main objectives are;

- i) synthesis of nitronyl nitroxide functionalized phthalonitrile (**46**)
- ii) synthesis of imino nitroxide functionalized phthalonitrile (**47**)
- iii) preliminary synthetic studies of nitronyl nitroxide functionalized phthalocyanine (**48**)

iv) preliminary synthetic studies of imino nitroxide functionalized phthalocyanine
(49)

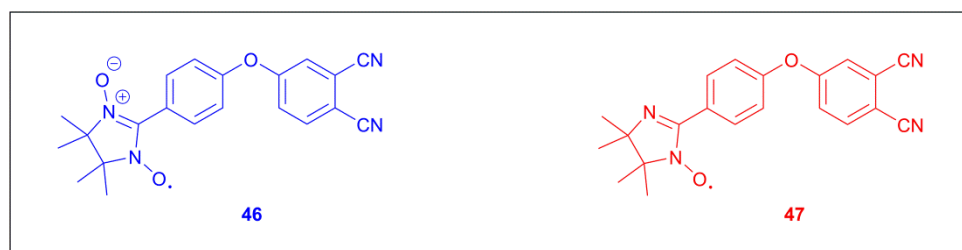


Figure 7.2: Target Phthalonitriles **46** and **47**.

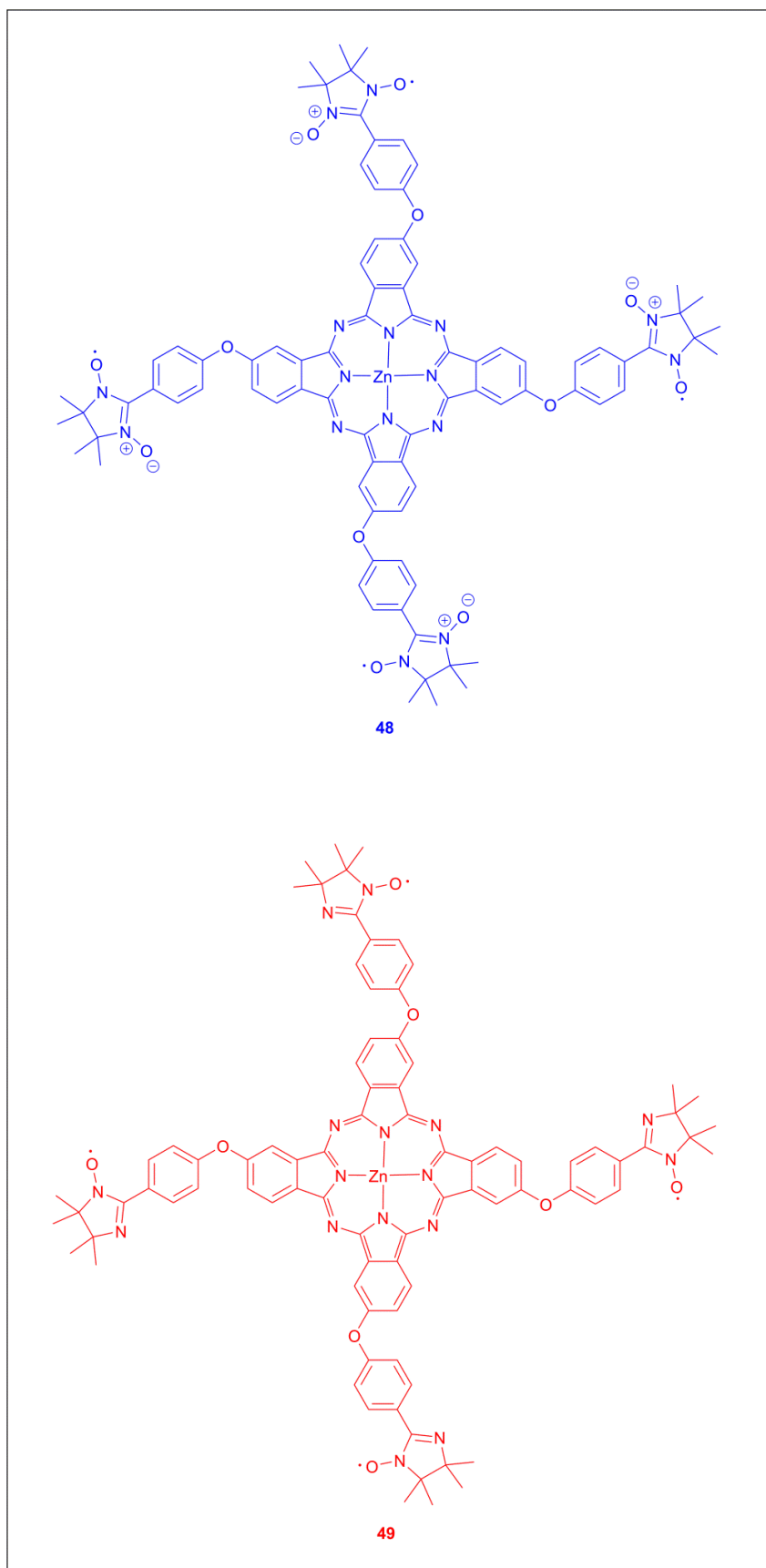


Figure 7.3: Ullman Radicals Linked Phthalocyanines **48** and **49**.

7.3. Synthesis

7.3.1. Synthesis of Ullman Radicals Linked Phthalonitriles **46** and **47**

One of the most widely used synthetic pathway to prepare 4-substituted phthalonitrile is the nucleophilic aromatic substitution of 4-nitrophthalonitrile with many nucleophiles [121], [129], [130]. Same methodology was favored in order to prepare Ullman radicals appended phthalonitriles. 2-(4-Hydroxyphenyl)-2,2,4,4-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**) acts as nucleophile to be exchanged with the nitro group of the 4-nitrophthalonitrile.

Preparation of synthon **10** was already discussed in Chapter 5.3 and 5.10.2.

As already tested during the synthesis of hexa-nitronyl nitroxide cyclotriphosphazene **16**, K_2CO_3 is a cheap and suitable base in terms of primarily basicity. Our first attempts (K_2CO_3 /acetone at 48 °C under microwave irradiation) afforded a mixture of approximately same ratio of **46** and **47** along with lots of impurities. Upon optimizations; the best conditions were determined as K_2CO_3 /DMF at 50 °C under microwave irradiation and give **46** in 57.4% along with 9.7% of **47** (Figure 7.4).

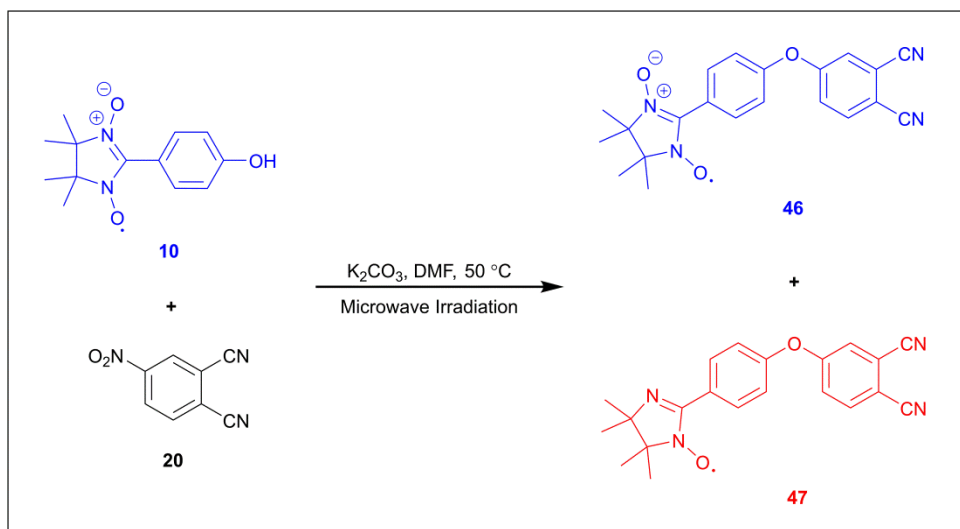


Figure 7.4: Synthetic Pathway to Phthalonitriles **46** and **47**.

Nucleophilic substitution reaction of synthon **10** with 4-nitrophthalonitrile **20** generated not only the nitronyl nitroxide phthalonitrile **46** but also imino nitroxide phthalonitrile **47** (Figure 7.4). The formation of the imino nitroxide phthalonitrile **47**

is credited to self-conversion of nitronyl nitroxide radicals **46** into imino nitroxide ones **47** at relatively high temperature. Indeed, this conversion is even possible at room temperature.

Formed phthalonitriles **46** and **47** were separated through column chromatography. Typically, orange fraction was assigned to imino nitroxide derivative and blue fractions are to nitronyl nitroxide one. For the majority of cases, imino nitroxides are eluted faster than nitronyl nitroxides in the silica-gel column (Figure 7.5).

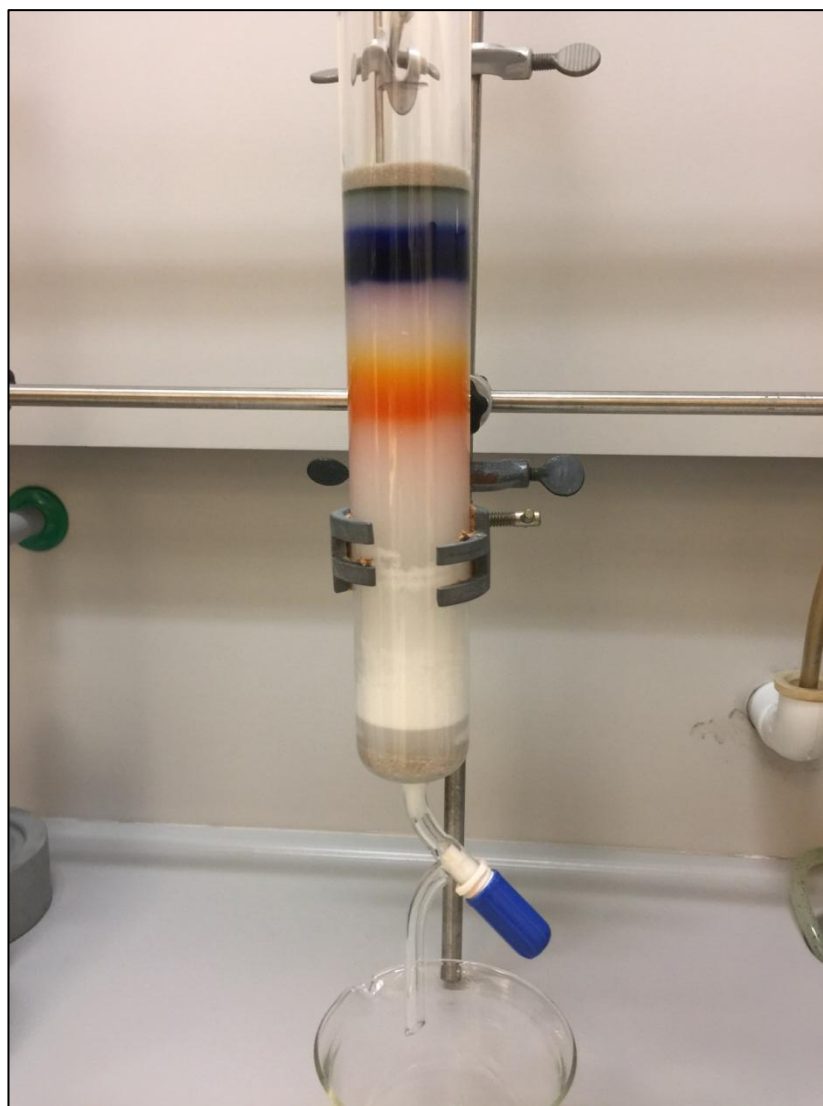


Figure 7.5: Fractions of Phthalonitrile **46** and **47** in Silica-gel Column.

Formation of the phthalonitriles were monitored in FT-IR spectrum following the complete disappearance of the –OH stretching of **10**. OH functionality of **10** was

transformed into ether bonds of phthalonitriles which were clearly assigned in the related FT-IR spectra. Aforementioned transformation was tracked in FT-IR spectra as disappearance of –OH stretching of **10** at 3102 cm^{-1} (Figure 8.36) and appearance of aromatic ether (C-O-C) stretching of phthalonitriles **46** and **47** at 1257 cm^{-1} and 1250 cm^{-1} respectively (Figure 8.96 and 8.98).

FT-IR spectrum of **46** (Figure 8.96) displayed a single signal at 1361 cm^{-1} which attributed to N-O stretchings of nitronyl nitroxide fragment [30]. MALDI-TOF MS analysis of **46** (Figure 8.97) shows a peak at m/z of 374 [M-1] which is another identity proof of the phthalonitrile **46**.

FT-IR spectrum of **47** (Figure 8.98) displayed two signals at 1375 and 1367 cm^{-1} which attributed to N-O stretchings of imino nitroxide fragment [30]. MALDI-TOF MS analysis (Figure 8.99) shows a peak at m/z of 360 [M+H]⁺ which is another identity proof of the phthalonitrile **47**.

In conclusion, the phthalonitriles **46** and **47** were successfully synthesized with our optimizations on the basis of Sener protocol [95]. Both phthalonitriles were characterized unambiguously by melting point analysis, FT-IR, MALDI-TOF MS, elemental analysis, UV-vis, CV, EPR. Magnetic measurements and X-ray analyses are in progress.

7.3.2. Preliminary Synthetic Studies of the Ullman Radicals Linked Symmetrical Phthalocyanines **48** and **49**

Formation of phthalocyanines was performed under the classical cyclotetramerization conditions. Phthalonitrile **46** was refluxed in DMF-DBU mixture at $100\text{ }^{\circ}\text{C}$ in the presence of $\text{Zn}(\text{OAc})_2$ under microwave irradiation (Figure 7.6). Formation of phthalocyanine ring was observed as evidenced by the characteristic green color; however no radical species could be detected by EPR. Possibly, harsh conditions of classical cyclotetramerization lead the decomposition of the radicals. Nevertheless, proceeding the cyclotetramerization around $50\text{ }^{\circ}\text{C}$ would pave the way for the synthesis of nitronyl nitroxide linked phthalocyanines as nitronyl nitroxide character was well-survived at $48\text{ }^{\circ}\text{C}$ during the synthesis of **16** (Chapter 5.3). The cyclotetramerization of phthalonitriles **46** and **47** needs to be performed at low temperature, particularly below $50\text{ }^{\circ}\text{C}$, in order to maintain the integrity of the radical character. Such method for low temperature synthesis of

phthalocyanine was developed by Leznoff [153], [154], and will be tested thereafter to obtain **48** and **49**.

In conclusion, solely preliminary testing of phthalocyanine formation was intended due to time limitation. The classical cyclotetramerization conditions formed the phthalocyanine macrocycle, however lost the radical character. Low temperature synthesis of phthalocyanine is required in order to achieve the synthesis of Ullman radicals linked phthalocyanines **48** and **49**. Such studies are assigned as prospective tasks.

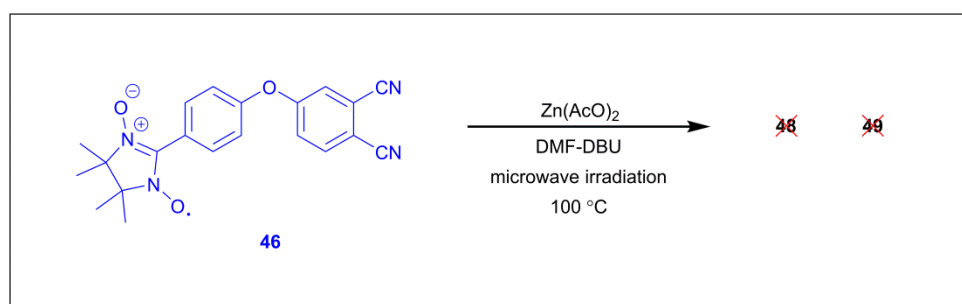


Figure 7.6: Synthetic Pathway to Ullman Radicals Linked Phthalocyanines **48** and **49**.

7.4. Absorption Spectroscopy

Distinguishing features of Ullman radicals are their colors. Typically nitronyl nitroxides are blue, whereas imino nitroxides are orange. Characteristically, the radical nature of nitroxide fragment of Ullman radicals leads to $n \rightarrow \pi^*$ transitions in UV-vis spectrum. Absorption bands of $n \rightarrow \pi^*$ transitions of the phthalonitrile radicals were observed around $\lambda_{\text{max}} \approx 620$ nm for nitronyl nitroxide **46** and $\lambda_{\text{max}} \approx 447$ nm for imino nitroxides **47** (Figure 7.7 and Table 7.1).

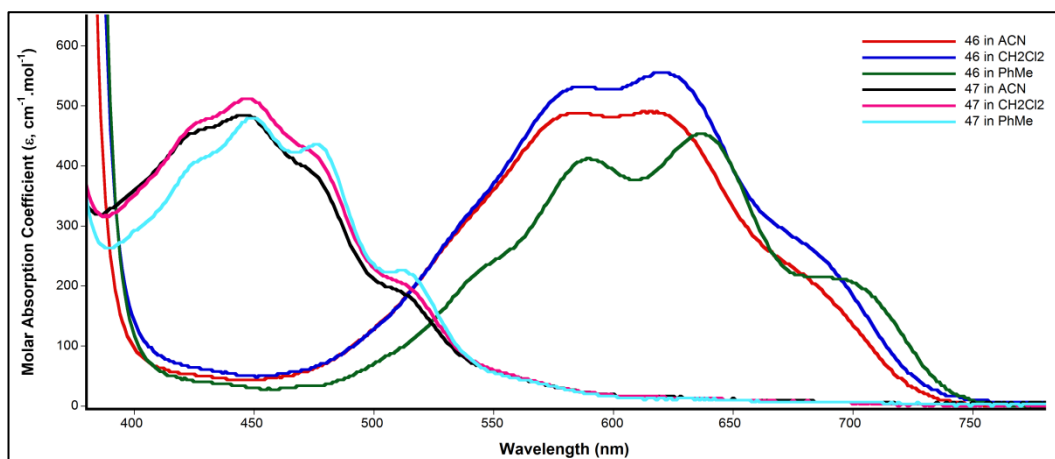


Figure 7.7: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **46** and **47**.

Table 7.1: UV-vis Data for the $n \rightarrow \pi^*$ Transitions of Phthalonitriles **46** and **47** at Room Temperature^a.

Solvent	$\lambda_{\max}$ 46	ϵ 46	$\lambda_{\max}$ 47	ϵ 47
Acetonitrile	615	491	445	484
Dichloromethane	621	555	447	512
Toluene	637	454	449	479

^a $\lambda_{\max}$ in nm, ϵ in $\text{cm}^{-1} \cdot \text{M}^{-1}$

46 and **47** were soluble in numerous solvents including acetonitrile, dichloromethane, and toluene in which the Beer–Lambert Law was observed for both compounds in the range from $5 \cdot 10^{-5}$ to 10^{-3} M (Figure 8.100-8.113). Vibronic components of radical bands were best observed in toluene among the studied solvents (Figure 7.7).

As conclusion, UV-vis spectra proved gender of the phthalonitrile **46** as nitronyl nitroxide and the phthalonitrile **47** as imino nitroxide radicals.

7.5. Electrochemical Analyses

Both nitronyl nitroxides and imino nitroxides are redox-active molecules to be oxidized (p-type redox) to oxo-ammonium cation or reduced (n-type redox) to aminoxyl anion. Redox characteristics of phthalonitrile **46** and **47** were investigated by cyclic voltammetry. Phthalonitrile **46** showed a reversible oxidation wave at 0.765 V vs. SCE and a reversible reduction one at -0.850 V (Figure 7.8). Phthalonitrile **47** showed a quasireversible oxidation wave at 1.265 V vs. SCE and a reversible

reduction one at -0.817 V (Figure 7.9). Redox characteristics and observed potentials of **46** and **47** are in accordance with the literature [31], [52], [92], [99]. In conclusion, electrochemical behavior of phthalonitrile **46** and **47** were characterized by cyclic voltammetry.

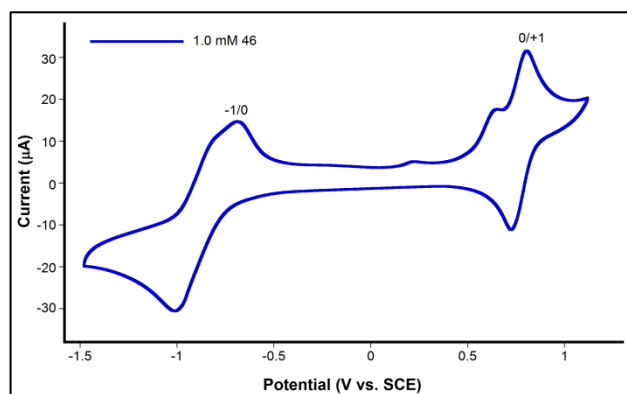


Figure 7.8: Cyclic Voltammogram of the Phthalonitrile **46** Recorded at rt in Acetonitrile, 0.1 M $n\text{-Bu}_4\text{NBF}_4$ as Supporting Electrolyte, Scan Rate of 100 mV/s.

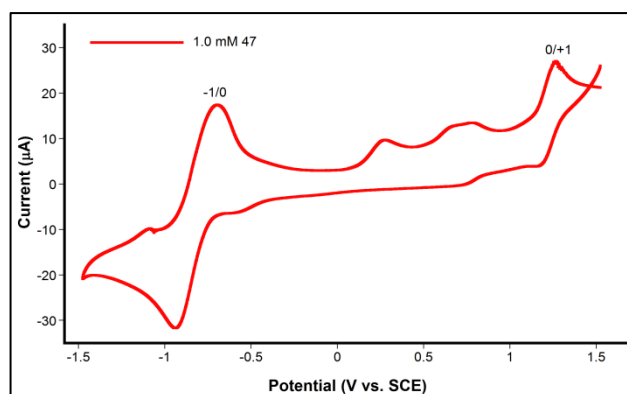


Figure 7.9: Cyclic Voltammogram of the Phthalonitrile **47** Recorded at rt in Acetonitrile, 0.1 M $n\text{-Bu}_4\text{NBF}_4$ as Supporting Electrolyte, Scan Rate of 100 mV/s.

7.6. Electron Paramagnetic Resonance Spectroscopy

EPR spectrum of **46** (Figure 7.10 and 8.114) have five-line splitting pattern with the relative intensity of 1:2:3:2:1. The five-line spectrum reasoned by the interaction of the unpaired electron ($S=1/2$) with two equivalent ^{14}N nitrogen atoms (nuclear spin $I=1$) in the imidazoline ring. This spectrum was simulated with Jeol IsoSimu computer program. Best fitting parameters are found as $g = 2.0034$, $a_{\text{N}} = 7.5$

G, $\Delta H_{p-p} = 2.5$ G. Splitting pattern and the parameters clearly proves phthalonitrile **46** as nitronyl nitroxide radical.

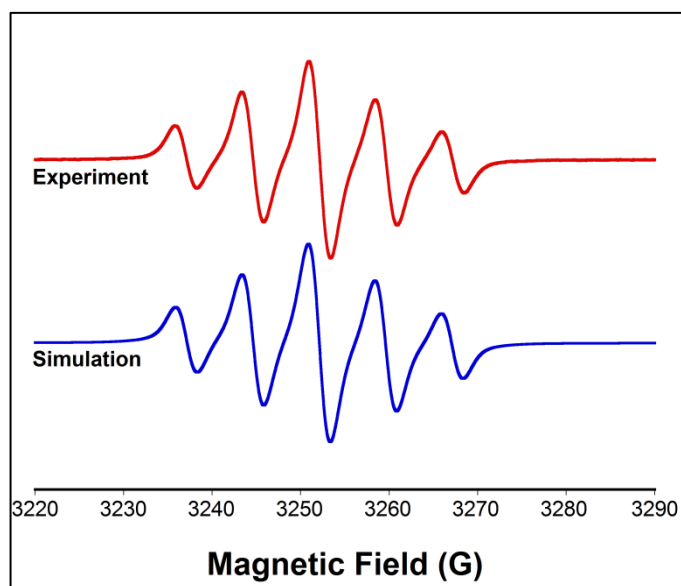


Figure 7.10: EPR spectrum of **46** in dichloromethane–toluene (1:1) solution (10^{-4} M) at 293 K and its simulation.

EPR spectrum of **47** (Figure 7.11 and 8.115) have seven-line splitting pattern with the relative intensity of 1:1:2:1:2:1:1. The seven-line spectrum reasoned by the interaction of the unpaired electron ($S=1/2$) with two unequivalent ^{14}N nitrogen atoms (nuclear spin $I=1$) in the imidazoline ring. This spectrum was simulated with Jeol IsoSimu computer program. Best fitting parameters are found as $g = 2.0028$, $a_{\text{N1}} = 9.2$ G, $a_{\text{N2}} = 4.4$ G, $\Delta H_{p-p} = 2.1$ G. Splitting pattern and the parameters clearly proves phthalonitrile **47** as imino nitroxide radical.

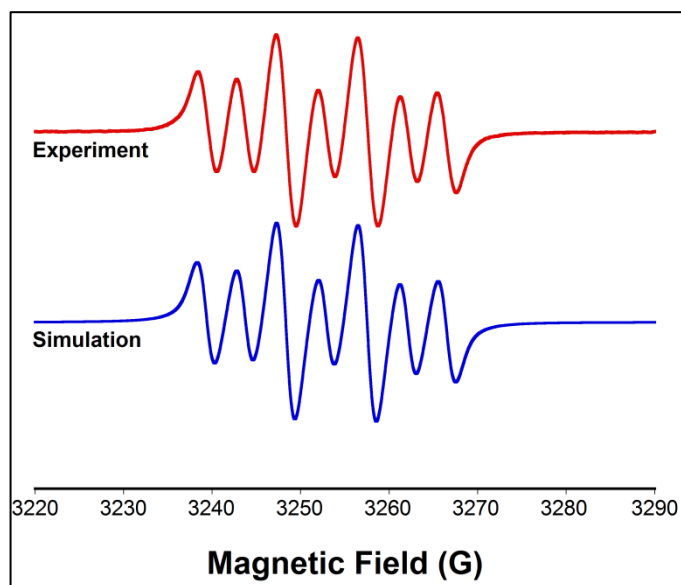


Figure 7.11: EPR spectrum of **47** in dichloromethane–toluene (1:1) solution (10^{-4} M) at 293 K and its simulation.

7.7. Magnetic Measurements

Magnetic measurements and analysis are underway.

7.8. X-ray Diffraction Analyses

Crystallizations of the phthalonitriles **46** and **47** are in progress. X-ray diffractions and structure determination will be performed upon obtaining suitable crystals.

7.9. Summary and Conclusion

Phthalonitriles **46** and **47** were synthesized by nucleophilic aromatic substitution of 4-nitrophthalonitrile (**20**) by 2-(4-hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**). Substitution reaction gave 57.4% of **46**, 9.7% of **47**, and 67.1% in total yield which better than 46% yield reported in previous literature [95]. In conclusion, the phthalonitriles **46** and **47** were successfully synthesized with our optimizations on the basis of Sener protocol [95]. Both phthalonitriles were characterized unambiguously by melting point analysis, FT-IR,

MALDI-TOF MS, elemental analysis, UV-vis, CV, EPR. Magnetic measurements and X-ray analyses are in progress.

In the case of phthalonitrile **46** as precursor, the classical cyclotetramerization conditions formed the phthalocyanine macrocycle, however lost the radical character. As consequence, low temperature synthesis of phthalocyanine is required in order to achieve the synthesis of Ullman radicals linked phthalocyanines **48** and **49**.

7.10. Synthetic Procedures

4-nitrophthalonitrile was purchased commercially. Syntheses of phthalonitriles were performed on the basis of reference procedures [95], [129], [130]. Reaction for syntheses of phthalocyanines **48** and **49** was performed based on the literature procedure [95].

7.10.1. Syntheses of 4-[(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl-2-yl)phenoxy]phthalonitrile (**46**) and 4-[(1-oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl)phenoxy]phthalonitrile (**47**)

4-nitrophthalonitrile (**20**) (1.0 eq., 1.5 mmol, 0.2595 g), 2-(4-Hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**) (1.1 eq., 1.65 mmol, 0.4125 g), and K₂CO₃ (4.4 eq., 4 eq. for each –OH, 6.6 mmol, 0.910 g) were charged into a microwave tube. DMF (10 mL) was added, then purged with argon. The tube was placed in the cavity and stirred efficiently. Tube content was subjected to microwave irradiation (maximum energy 300 Watt) at 50 °C for 2 hours under argon. Reaction mixture was poured into water (200 mL). Blue mixture was extracted with CH₂Cl₂ (150 mL). Blue organic phase was washed with aqueous solution of K₂CO₃ (3x100 mL), then with H₂O (3x100 mL). Resulting blue solution was dried over Na₂SO₄, evaporated to dryness. TLC analysis revealed that crude product contains both phthalonitriles **46** and **47**, which were separated with column chromatography on silica gel eluting with hexane-ethyl acetate mixture. Column purification gave 0.323 g blue powder of **46** in 57.4% yield and 0.052 g brownish-red powder of **47** in 9.7% yield.

Phthalonitrile **46**: mp. 190-192 °C. FT-IR (ATR, ν_{max} , cm⁻¹) : 3094w, 3039w, 2971w, 2937w, 2226m, 1592s, 1574m, 1562s, 1518m, 1491s, 1466s, 1450m, 1418s,

1388s, 1361s, 1308s, 1296s, 1257s, 1217s, 1180s, 1162s, 1129s, 1090m, 1013m, 958s, 917m, 859s, 840s, 822m, 812m, 715m, 696w, 616s. MALDI-TOF MS (*trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile): m/z for $C_{21}H_{19}N_4O_3$ [calculated]: 375, [found]: 374 $[M-1]^+$. Elemental Analysis for $C_{21}H_{19}N_4O_3$ [calculated]: C, 67.19; H, 5.10; N, 14.92. [found]: C, 66.48; H, 5.18; N, 15.13.

Phthalonitrile **47**: mp. 122-124 °C. FT-IR (ATR, ν_{max} , cm^{-1}) : 3107w, 3077w, 3043w, 2981w, 2930w, 2231m, 1593s, 1564s, 1484s, 1423m, 1407m, 1375m, 1367m, 1282s, 1250s, 1208s, 1159s, 1138s, 1090m, 1014m, 951s, 892m, 880s, 854s, 837s, 772m, 747w, 716w, 666s, 625w. MALDI-TOF MS (*trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile): m/z for $C_{21}H_{19}N_4O_2$ [calculated]: 359, [found]: 360 $[M+H]^+$. Elemental Analysis for $C_{21}H_{19}N_4O_2$ [calculated]: C, 70.18; H, 5.33; N, 15.59. [found]: C, 70.36; H, 5.69; N, 15.51.

7.10.2. Syntheses of Phthalocyanines **48** and **49**

4-[(4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl-2-yl)phenoxy]phthalonitrile (**46**) (1.0 eq., 0.1 mmol, 0.0375 g), and $Zn(AcO)_2$ (0.5 eq., 0.05 mmol, 0.0092 g) were charged into a microwave tube. DMF (2 mL) and DBU (2 mL) was added, then purged with argon. The tube was placed in the cavity and stirred efficiently. Tube content was subjected to microwave irradiation (maximum energy 1000 Watt) at 100 °C for one hour under argon. Characteristic green color of phthalocyanine was observed. Sample from the reaction mixture was analyzed with EPR spectroscopy, however it was EPR silent. It was concluded that even phthalocyanine formation was observed, the product was not any of target radical structures **48** and **49**.

8. SPECTRA AND STRUCTURES OF THE COMPOUNDS

Corresponding spectra of the compounds are provided below (Figure 8.1-8.115). Structures of the compounds were again shown in Figure 8.116-8.122.

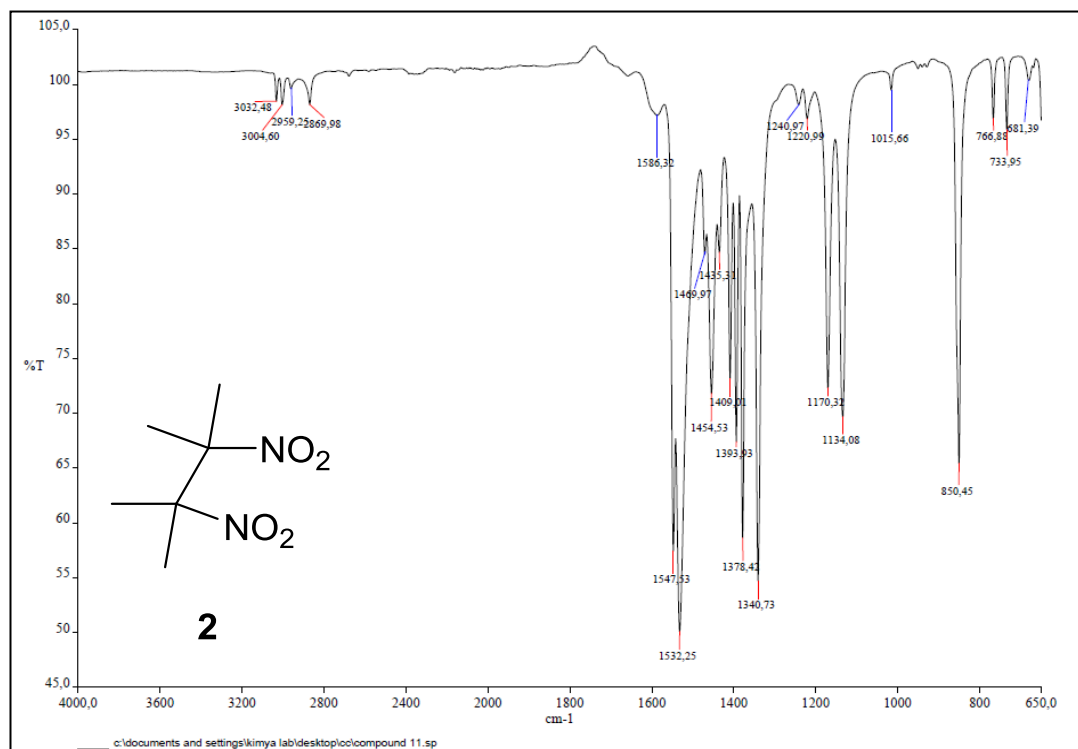


Figure 8.1: FT-IR Spectrum of **2**.

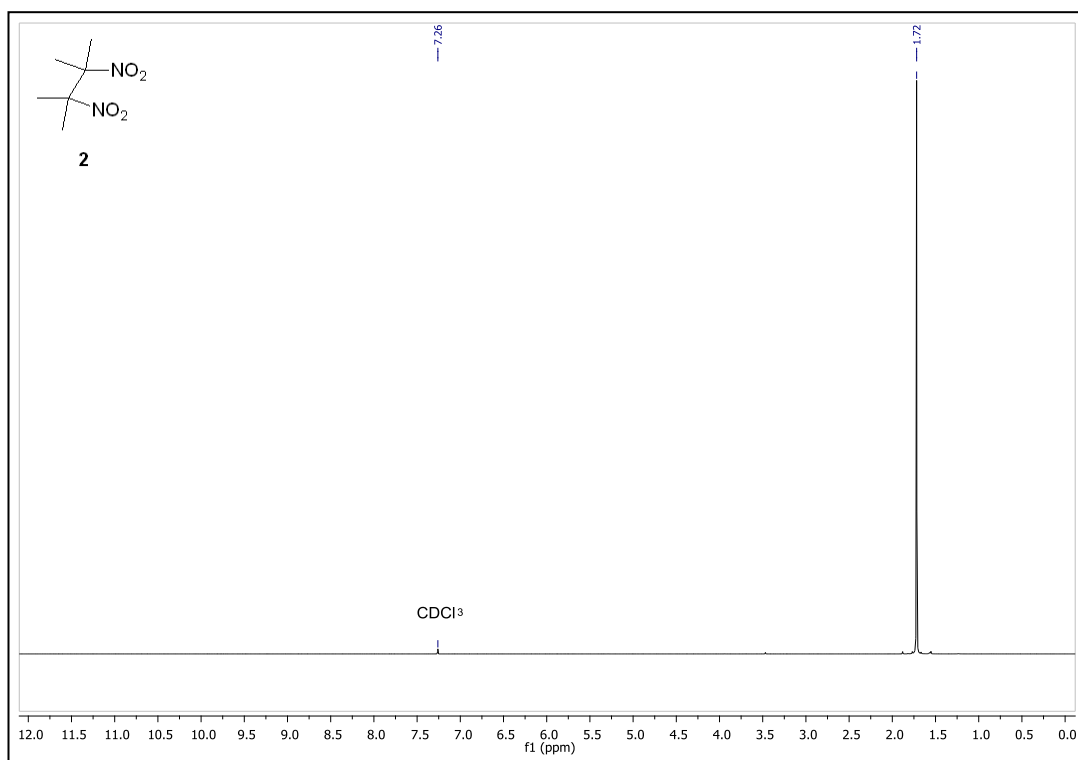


Figure 8.2: ^1H NMR Spectrum of **2** in CDCl_3 (400MHz).

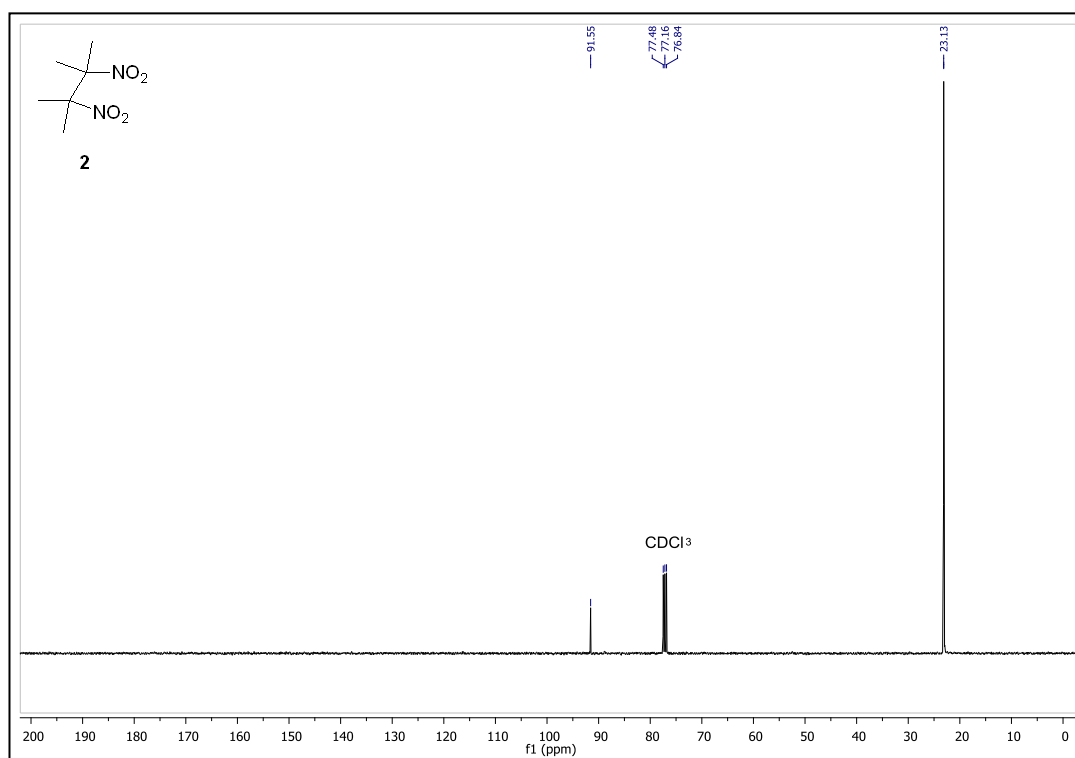


Figure 8.3: ^{13}C NMR Spectrum of **2** in CDCl_3 (100MHz).

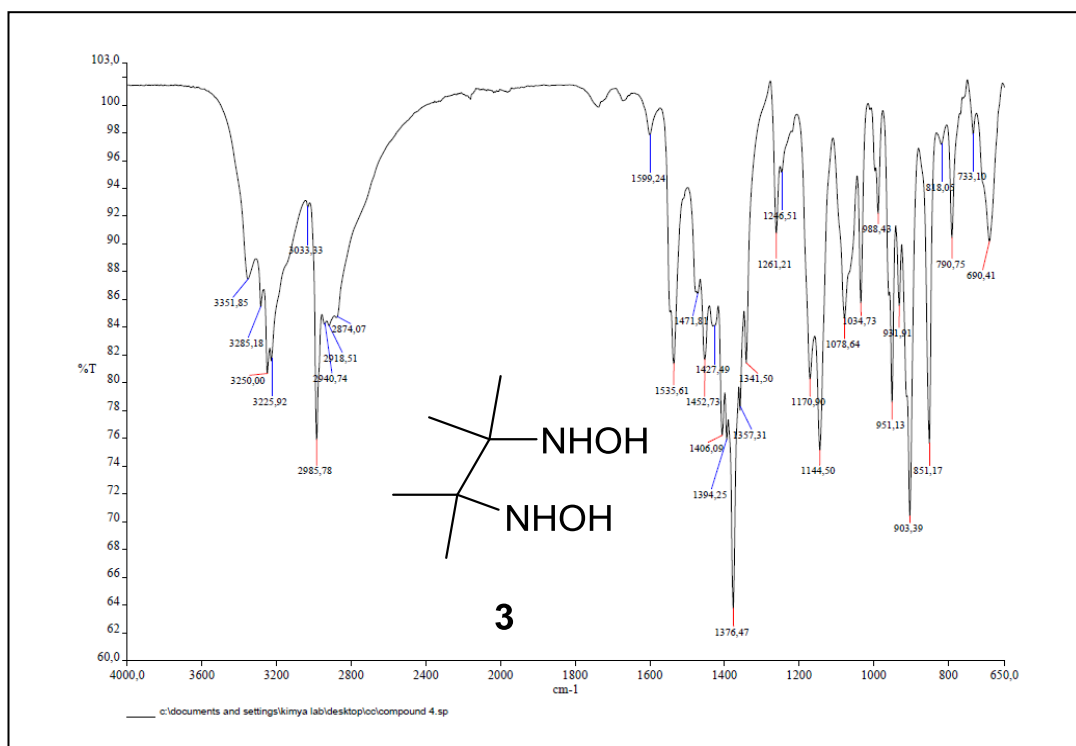


Figure 8.4: FT-IR Spectrum of **3**.

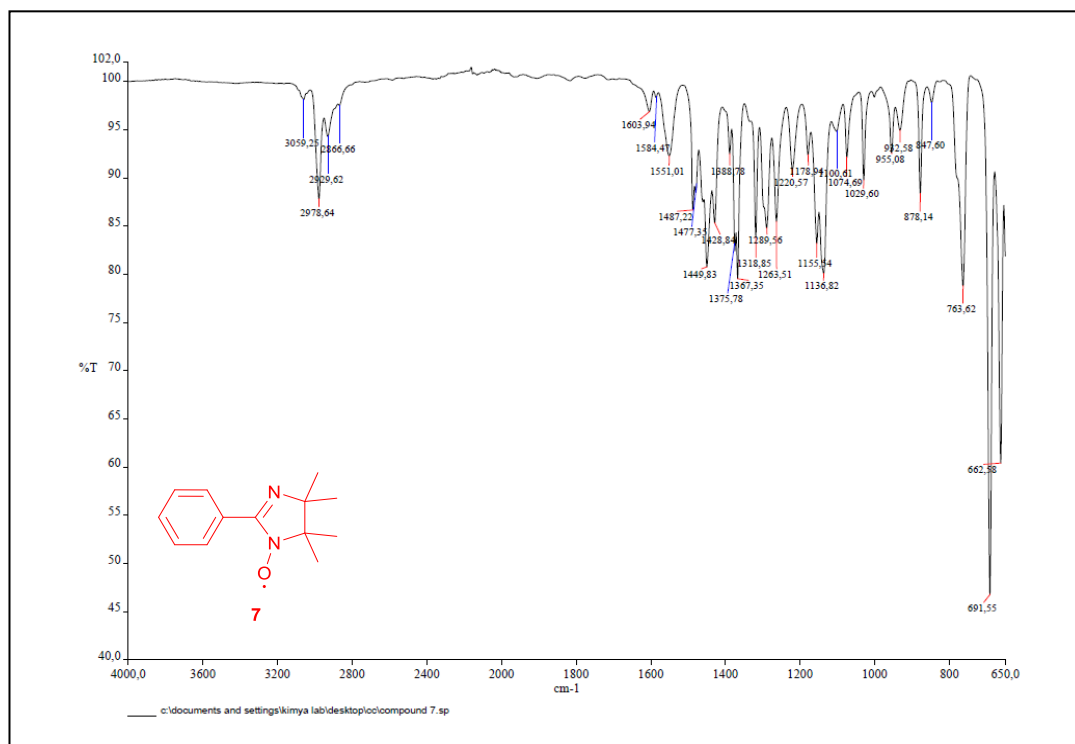


Figure 8.5: FT-IR Spectrum of **7**.

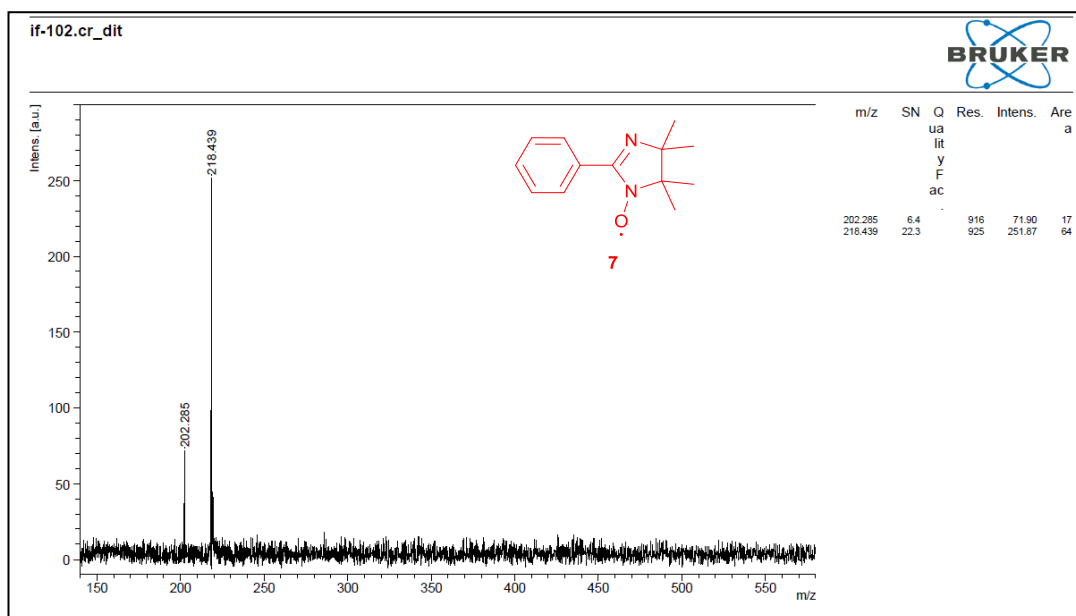


Figure 8.6: MALDI-TOF MS Spectrum of 7.

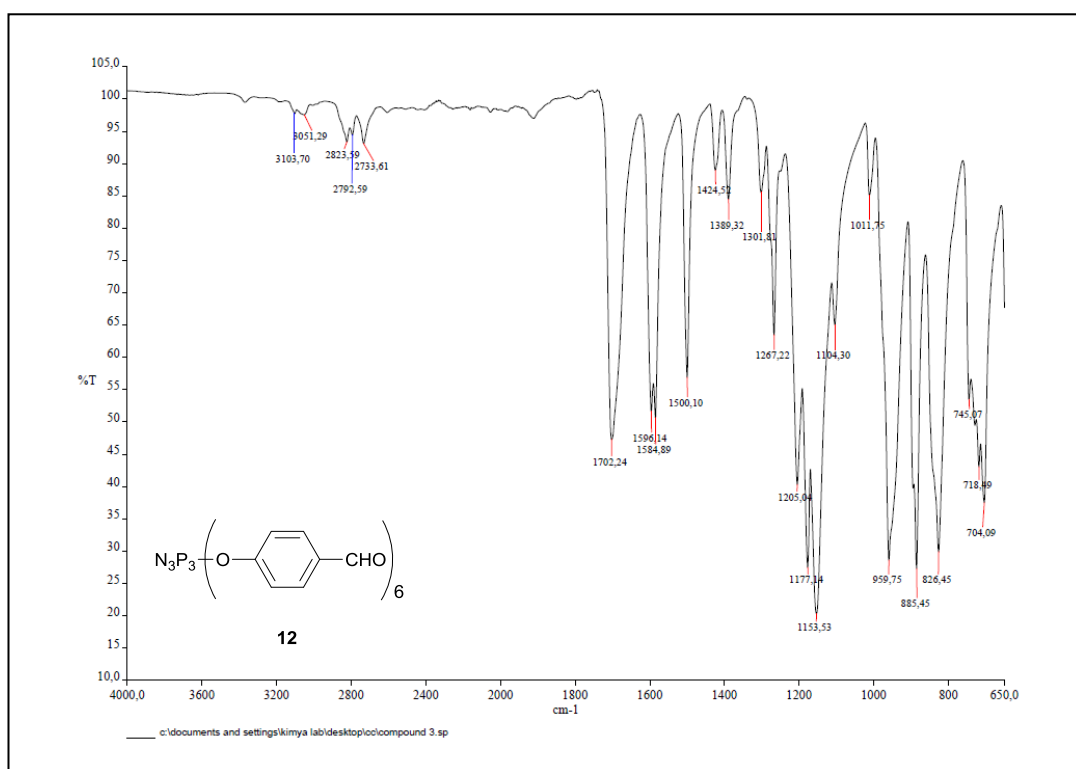


Figure 8.7: FT-IR Spectrum of **12**.

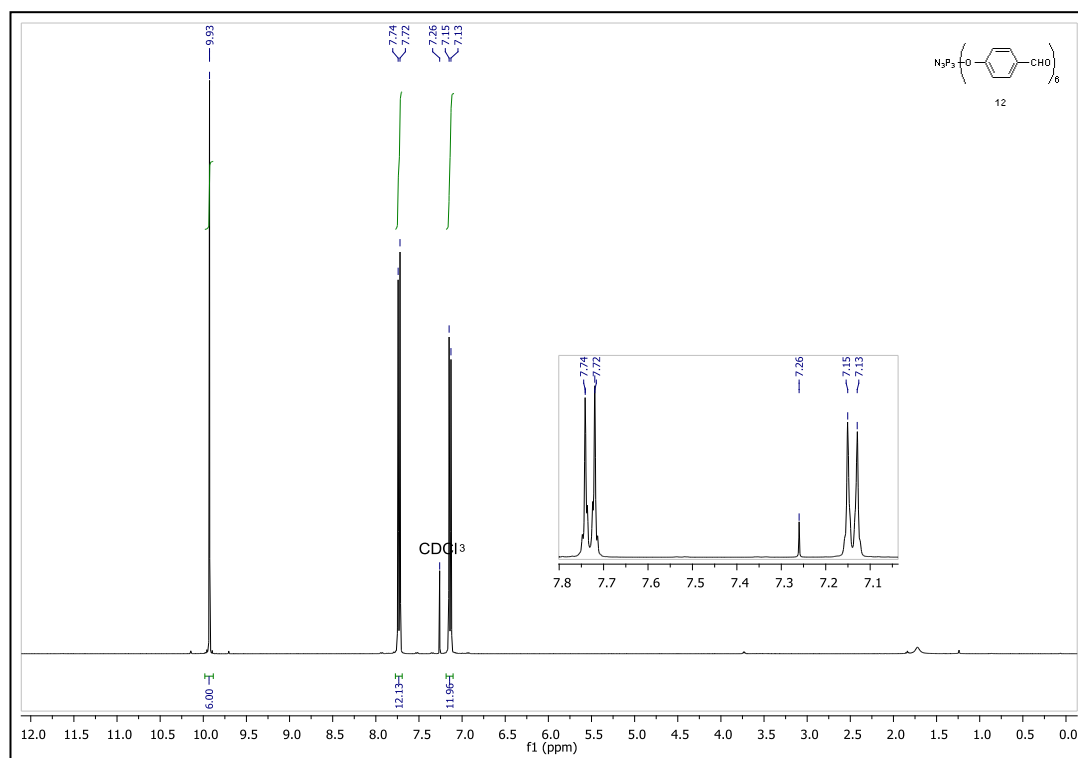


Figure 8.8: ¹H NMR Spectrum of **12** in CDCl₃ (400MHz).

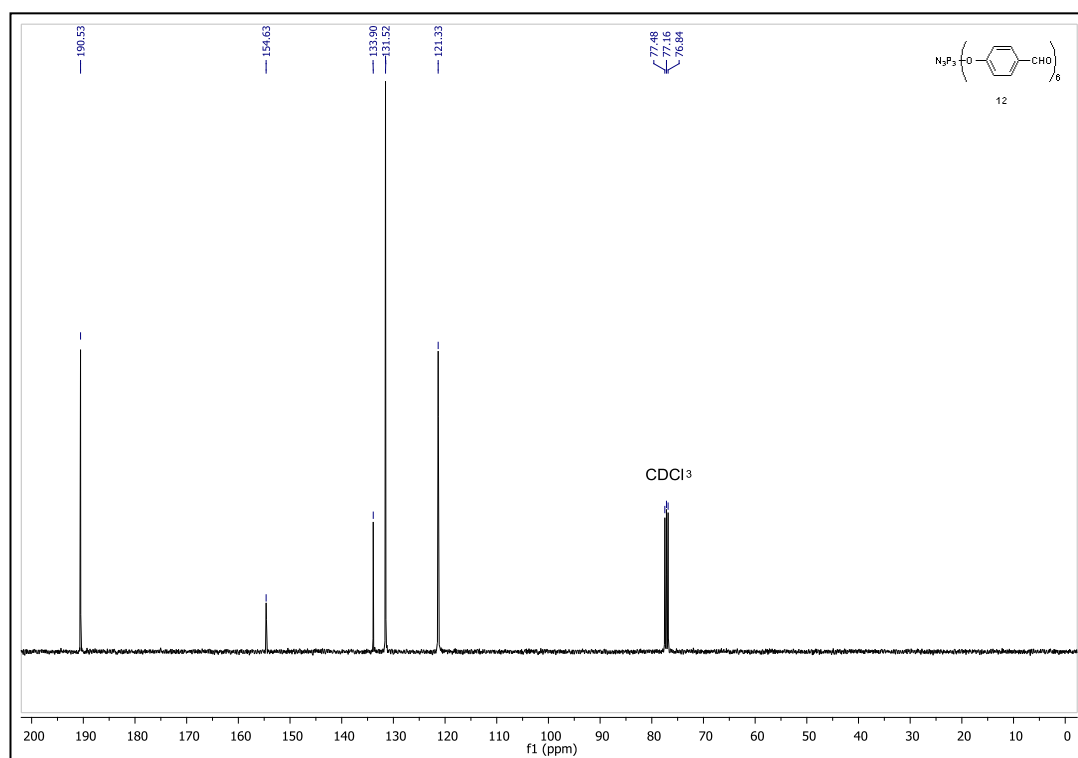


Figure 8.9: ¹³C NMR Spectrum of **12** in CDCl₃ (100MHz).

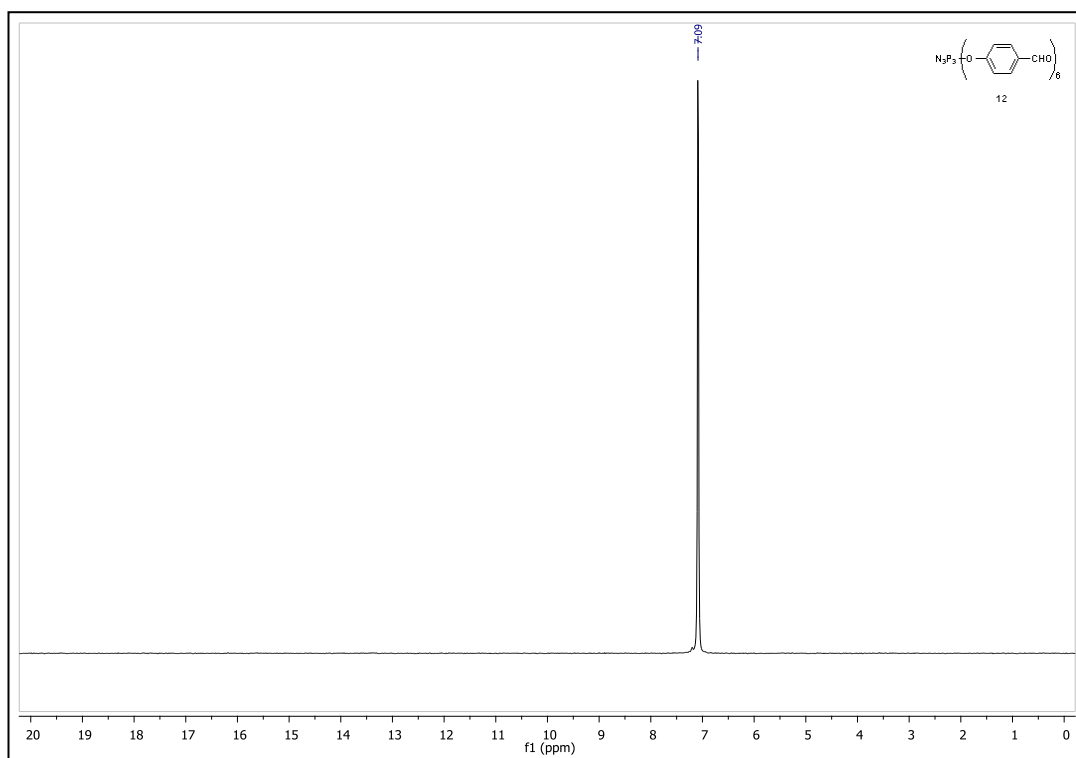


Figure 8.10: ^{31}P NMR Spectrum of **12** in CDCl_3 (162MHz).

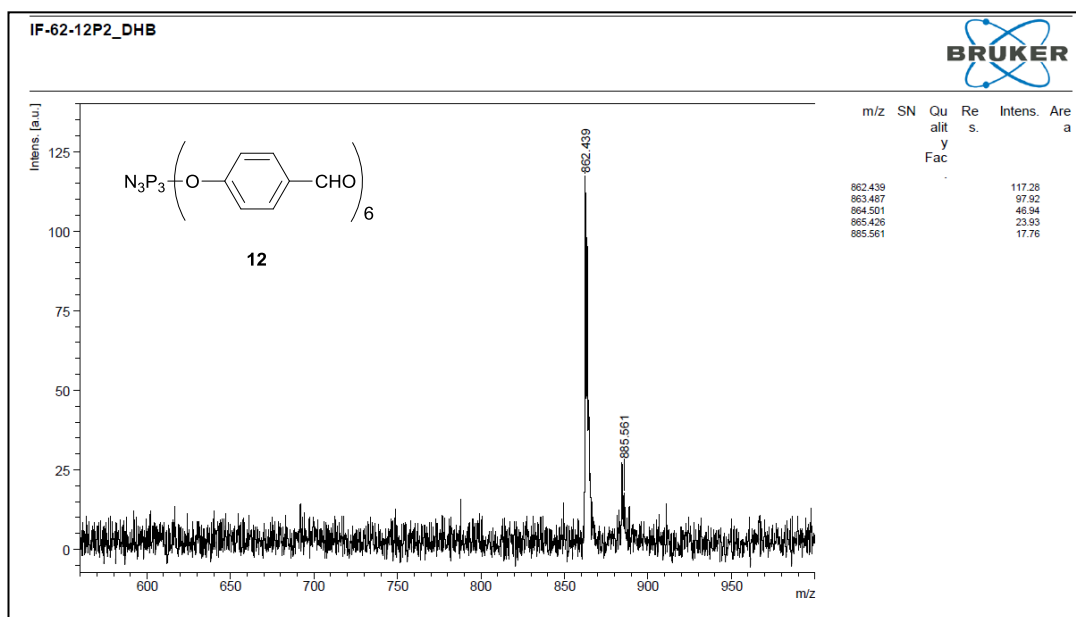


Figure 8.11: MALDI-TOF MS Spectrum of **12**.

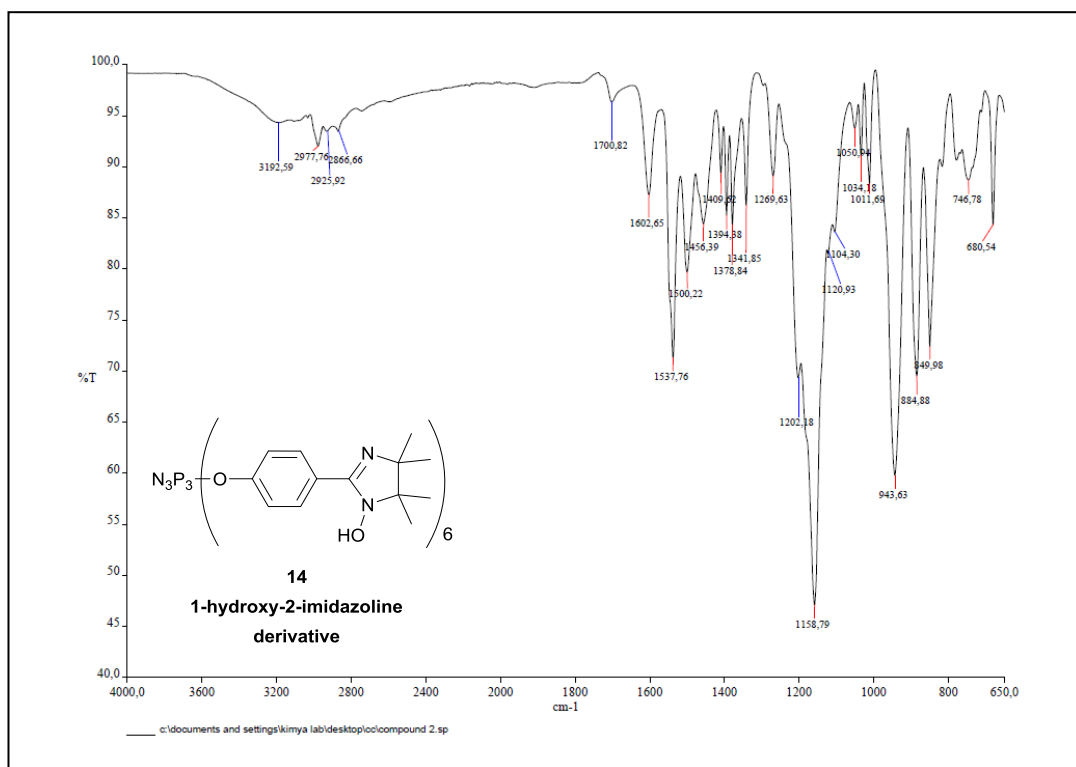


Figure 8.12: FT-IR Spectrum of **14** (Crude Product).

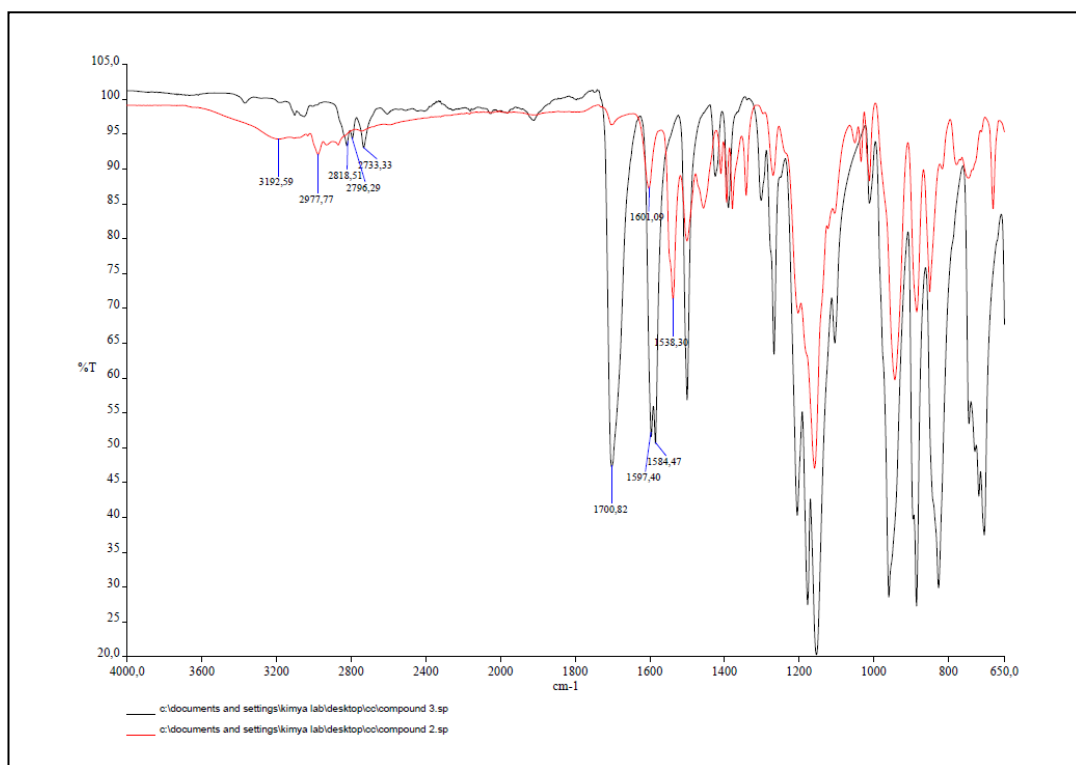


Figure 8.13: Comparison of FT-IR Spectrum of **12** and **14** (Crude Product).

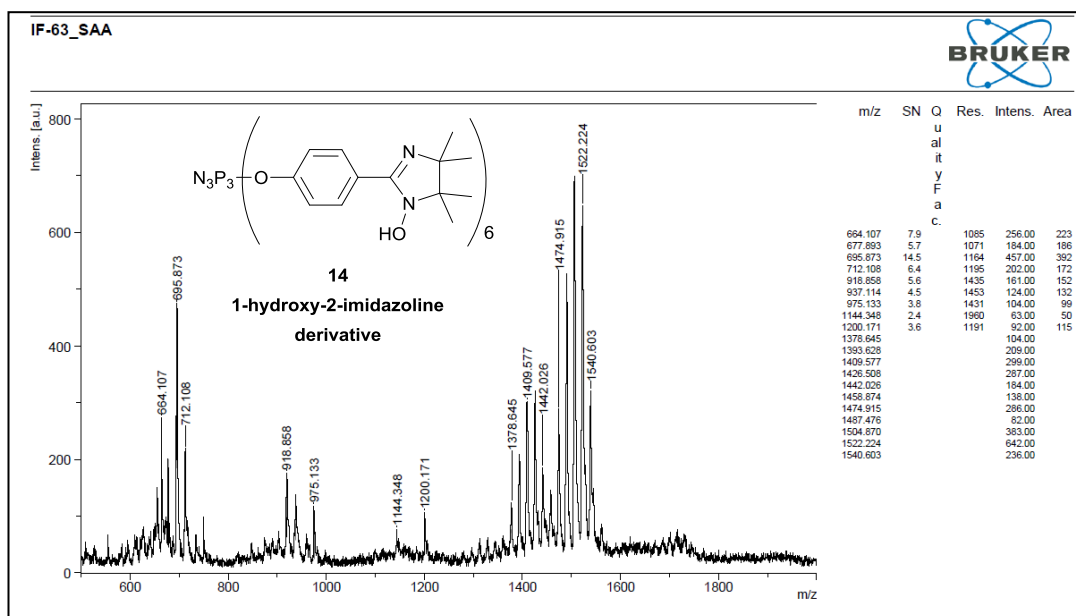


Figure 8.14: MALDI-TOF MS Spectrum of **14** (Crude Product).

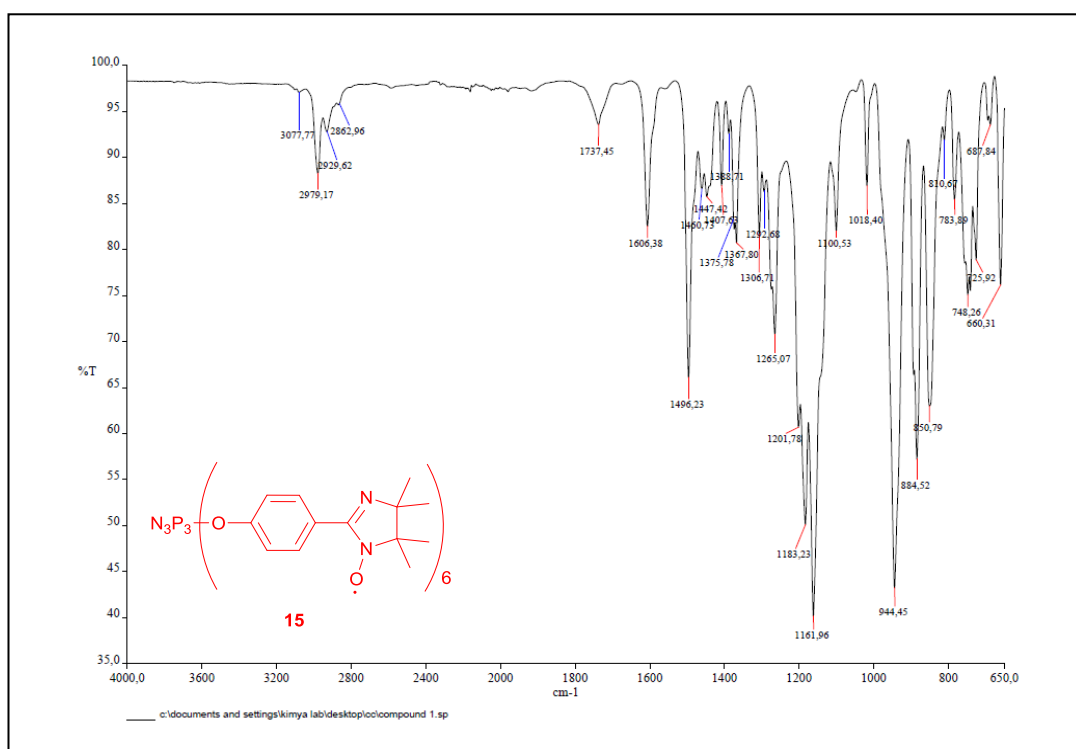


Figure 8.15: FT-IR Spectrum of **15**.

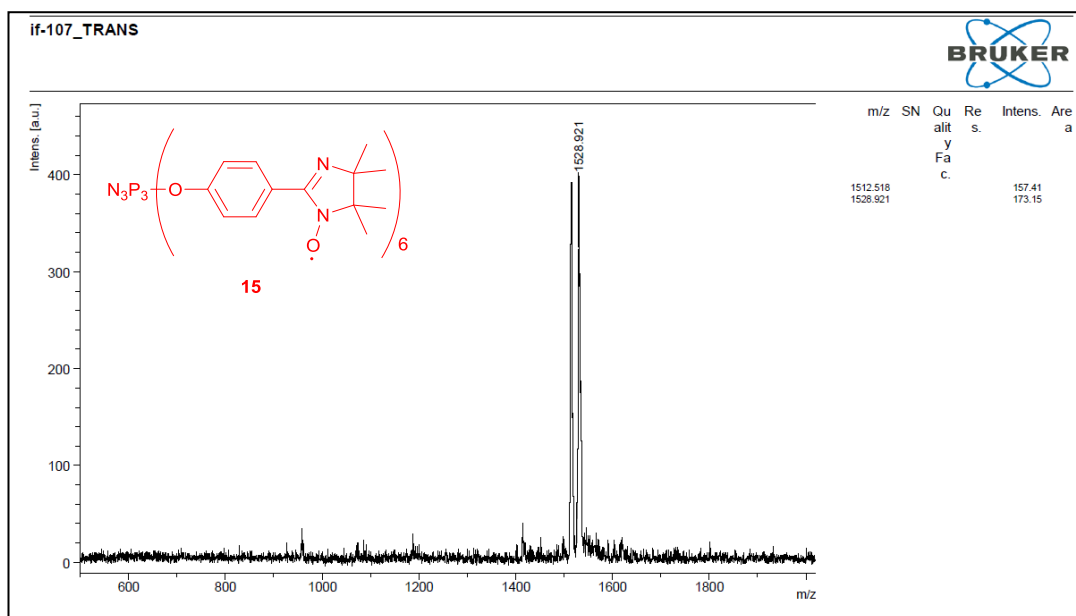


Figure 8.16: MALDI-TOF MS Spectrum of **15**.

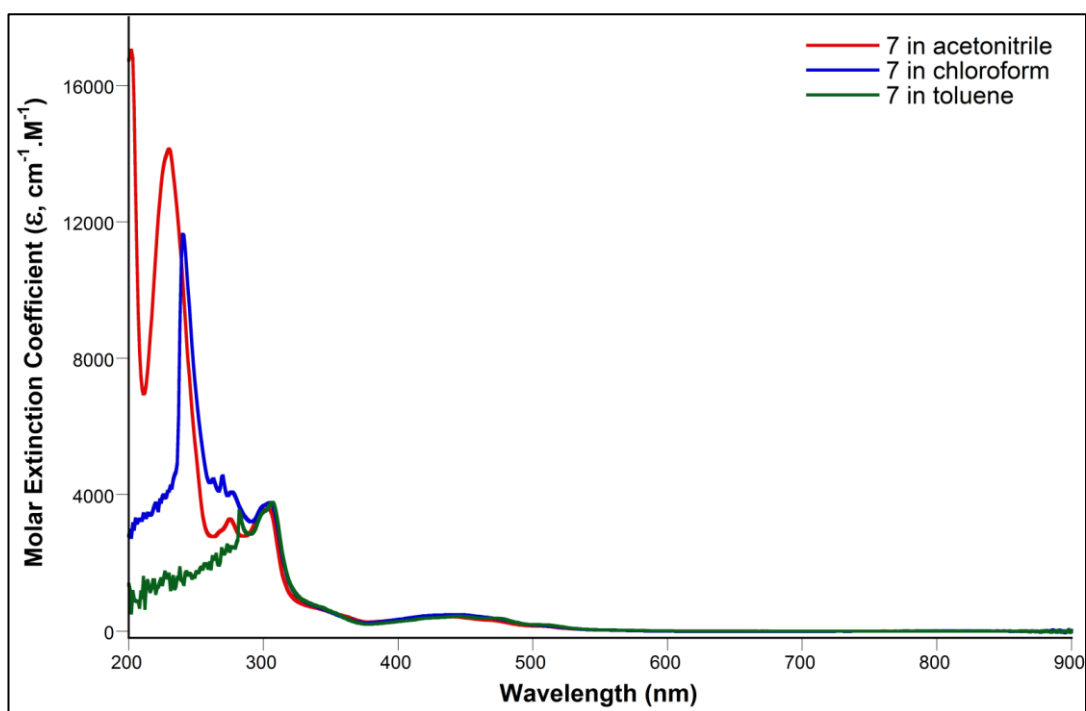


Figure 8.17: UV-Visible Spectra of **7** in Acetonitrile, Chloroform and Toluene.

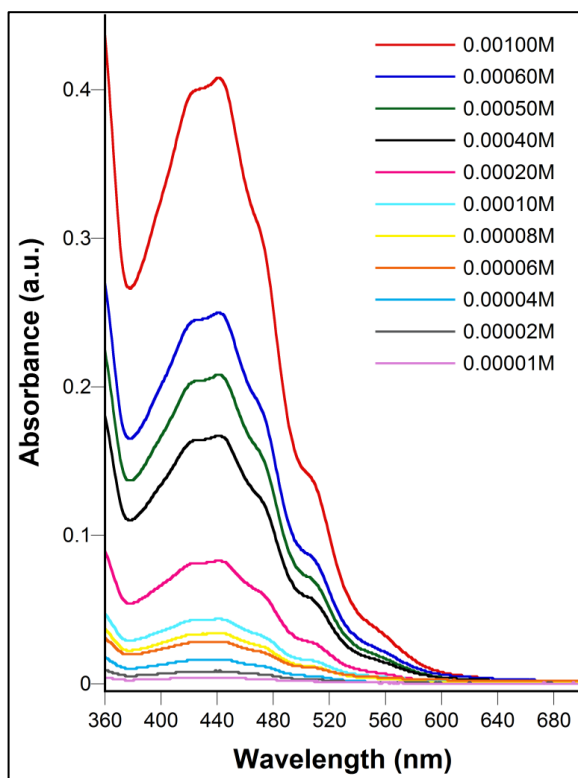


Figure 8.18: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 7 in Acetonitrile.

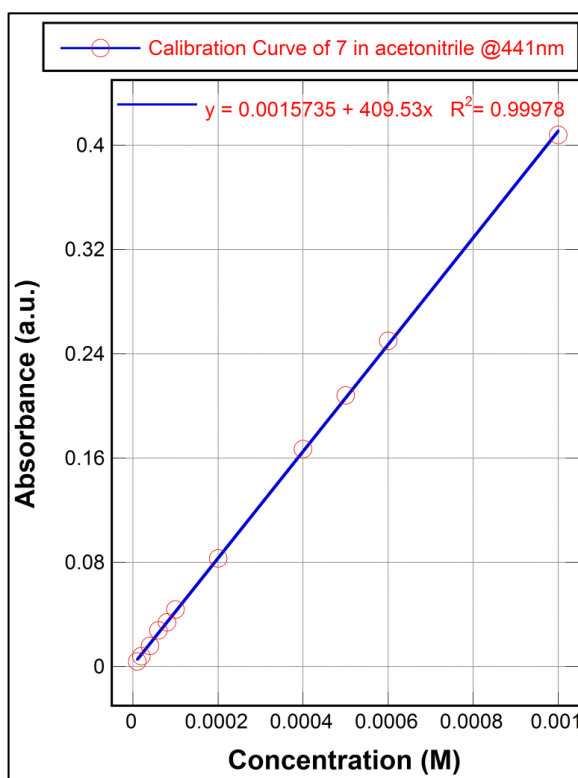


Figure 8.19: Calibration Curve of 7 in Acetonitrile at 441 nm.

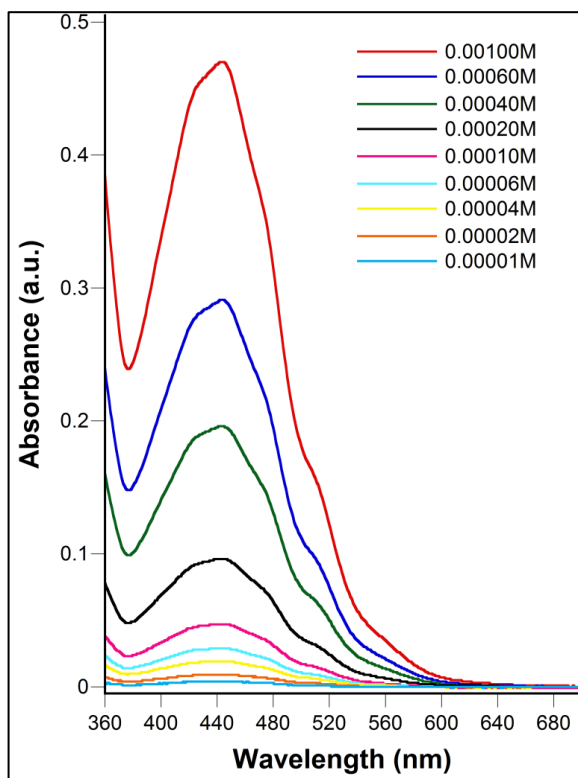


Figure 8.20: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **7** in Chloroform.

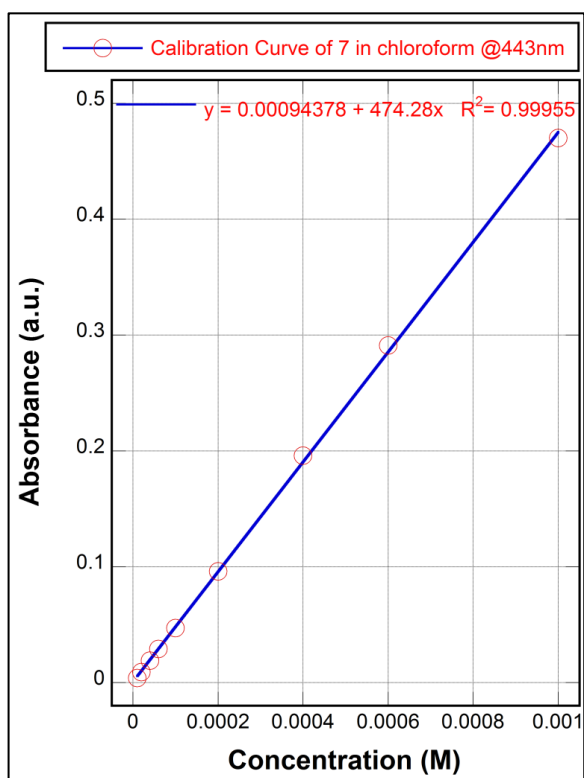


Figure 8.21: Calibration Curve of **7** in Chloroform at 443 nm.

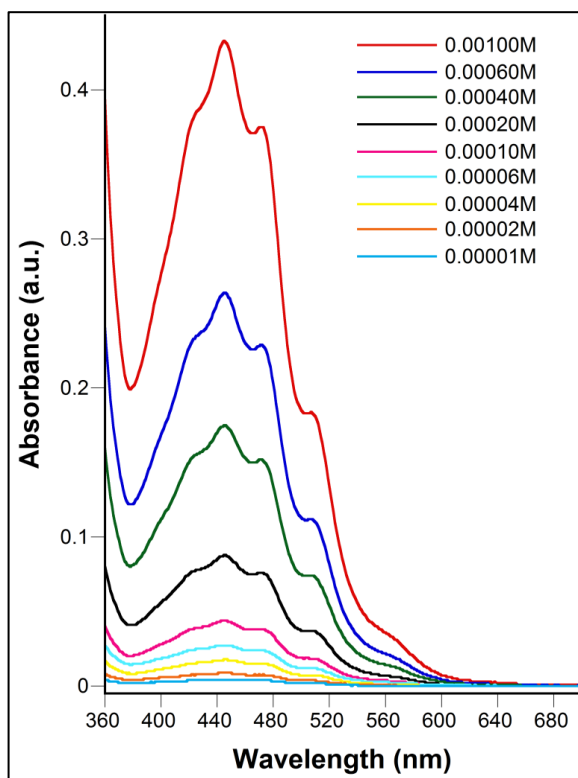


Figure 8.22: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of 7 in Toluene.

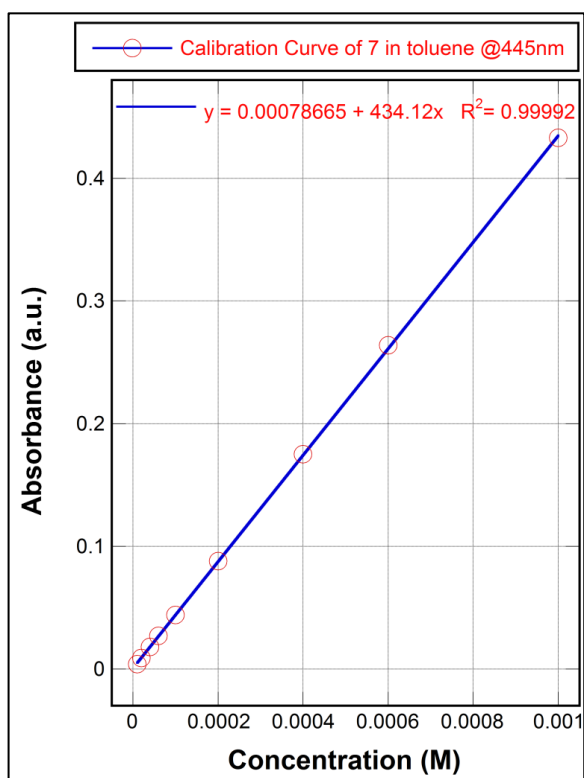


Figure 8.23: Calibration Curve of 7 in Toluene at 445 nm.

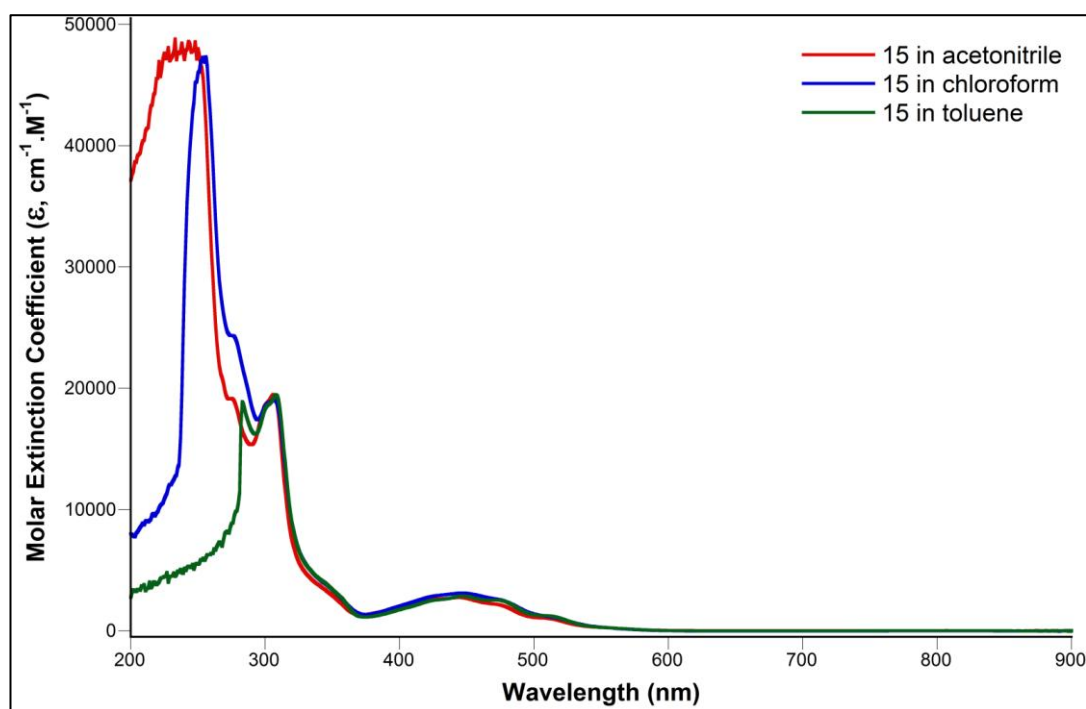


Figure 8.24: UV-Visible Spectra of **15** in Acetonitrile, Chloroform and Toluene.

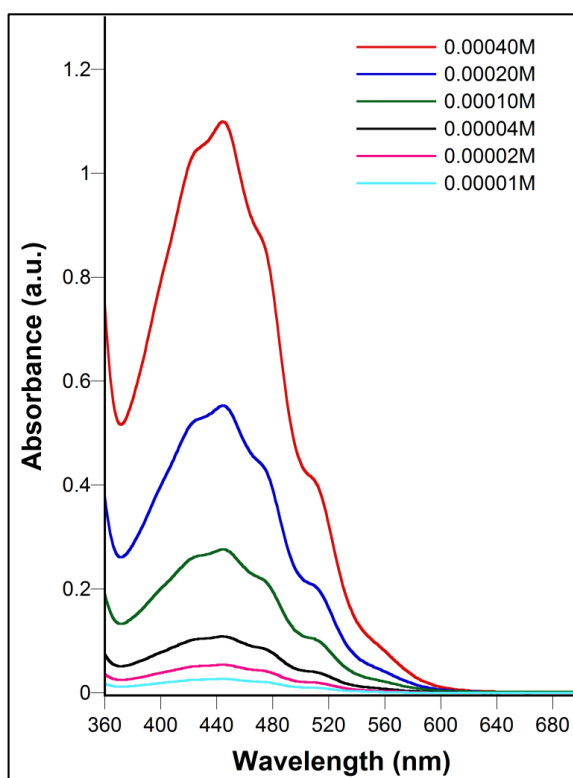


Figure 8.25: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **15** in Acetonitrile.

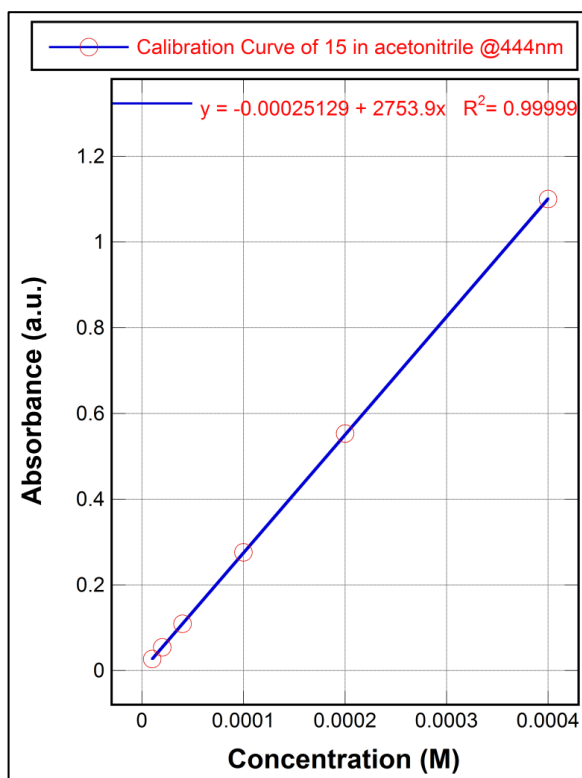


Figure 8.26: Calibration Curve of **15** in Acetonitrile at 444 nm.

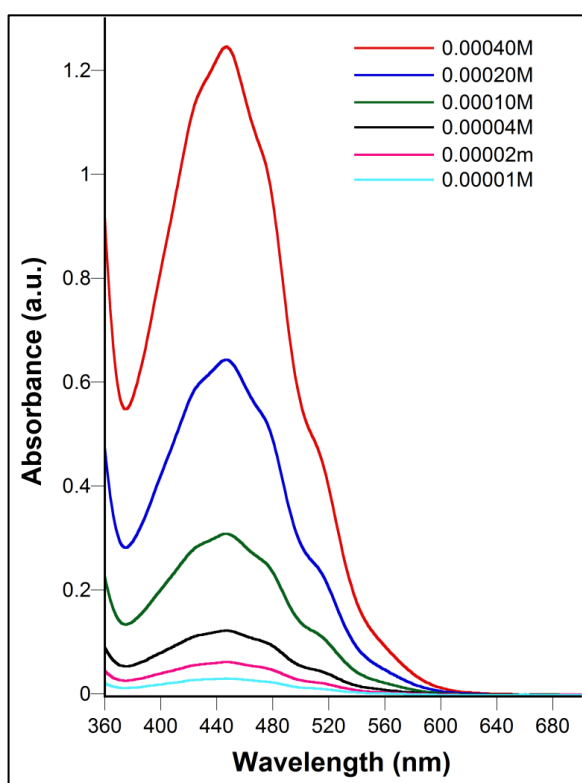


Figure 8.27: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **15** in Chloroform.

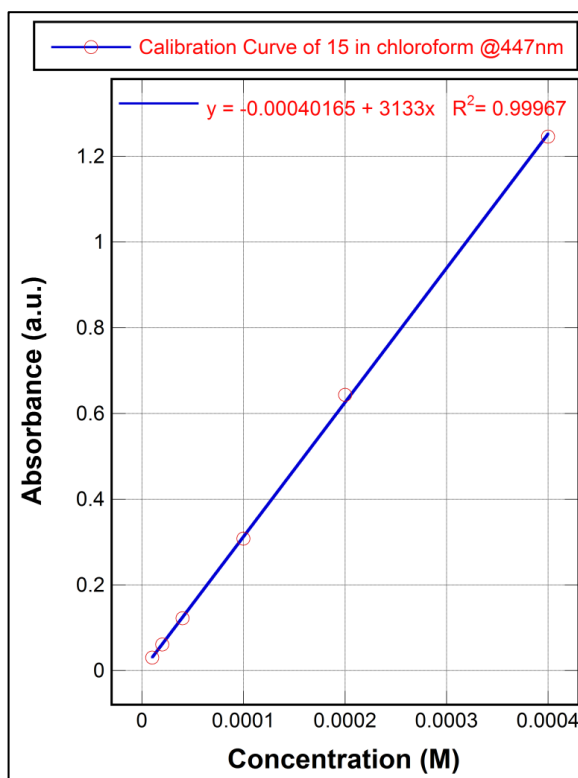


Figure 8.28: Calibration Curve of **15** in Chloroform at 447 nm.

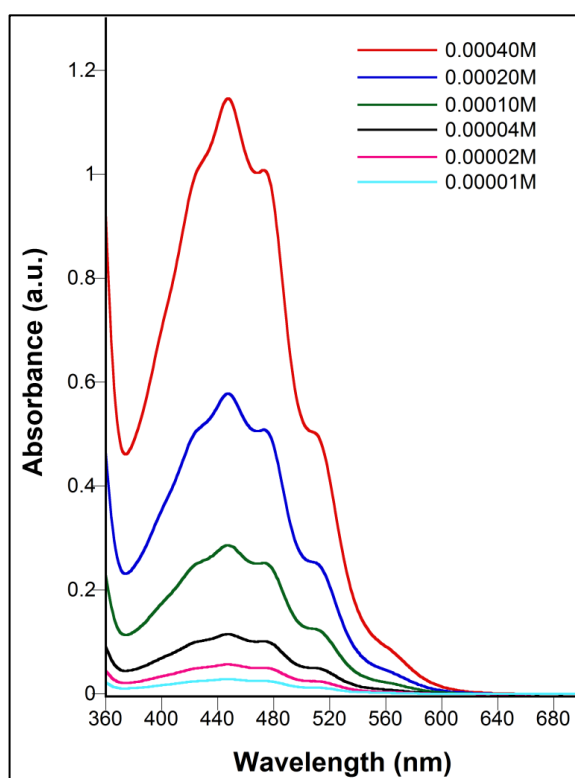


Figure 8.29: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **15** in Toluene.

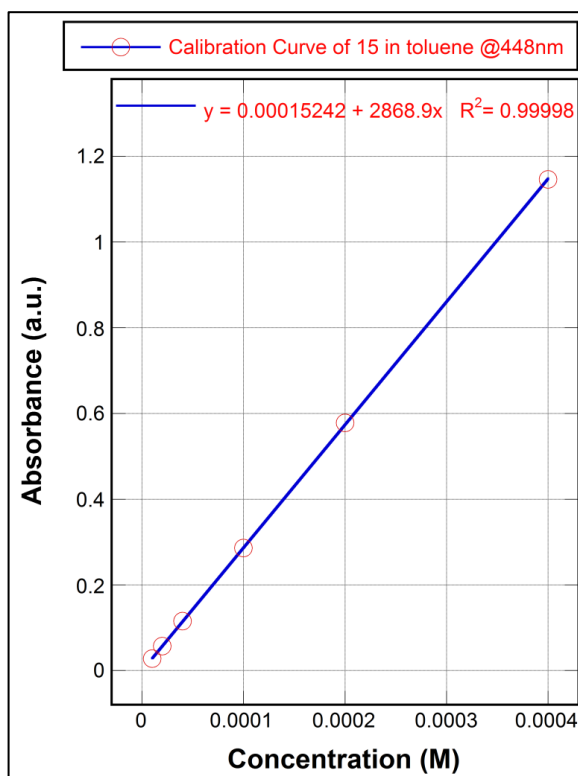


Figure 8.30: Calibration Curve of **15** in Toluene at 448 nm.

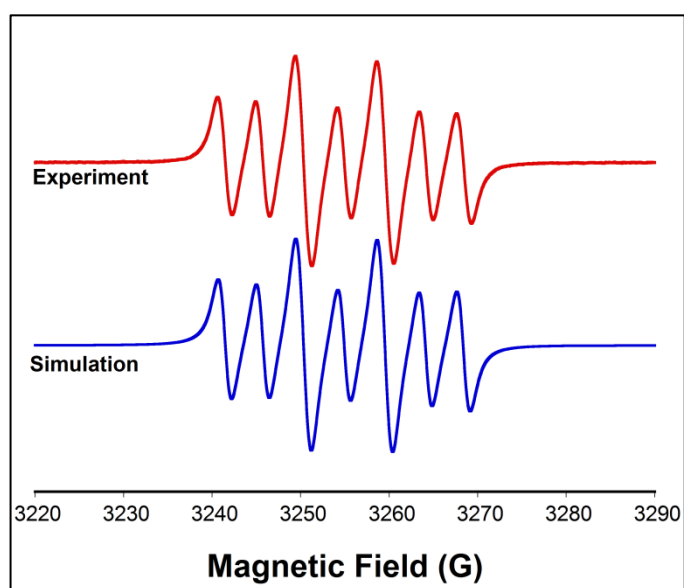


Figure 8.31: X-band EPR Spectrum of 7×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 253 K and Its Simulation (Best Fitting Parameters are $g = 2.0025$, $a_{N1} = 9.2$ G , $a_{N2} = 4.3$ G, and $\Delta H_{p-p} = 1.55$ G).

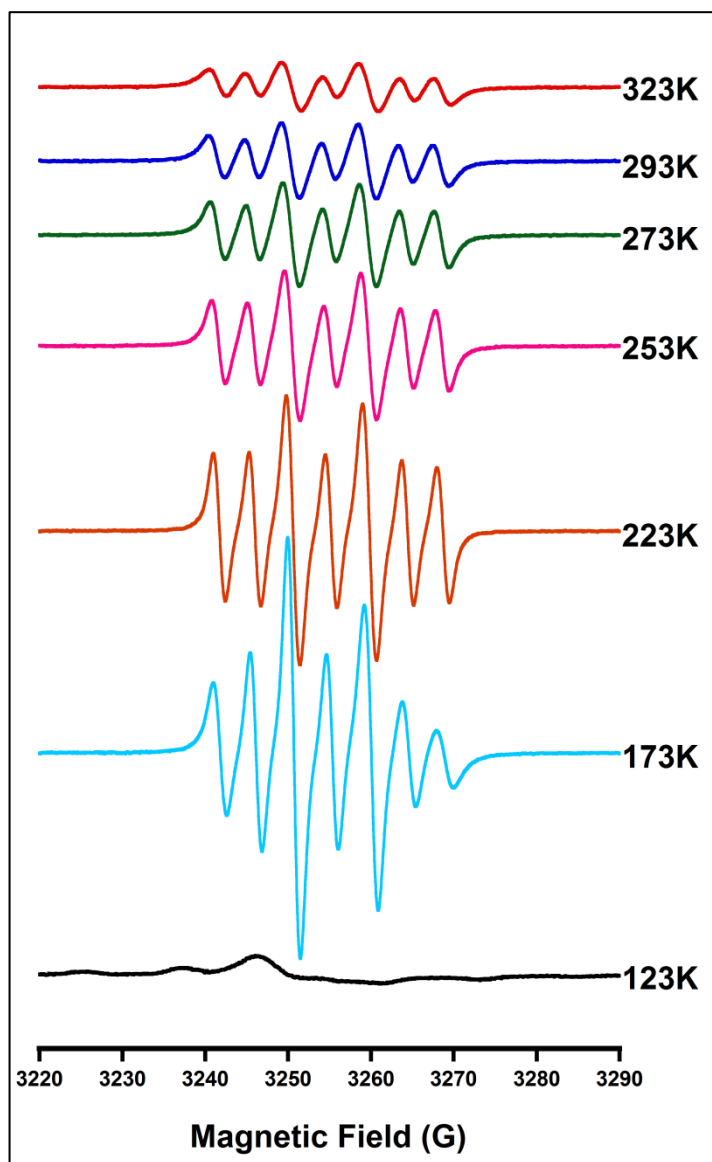


Figure 8.32: X-band EPR Spectra of 7×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

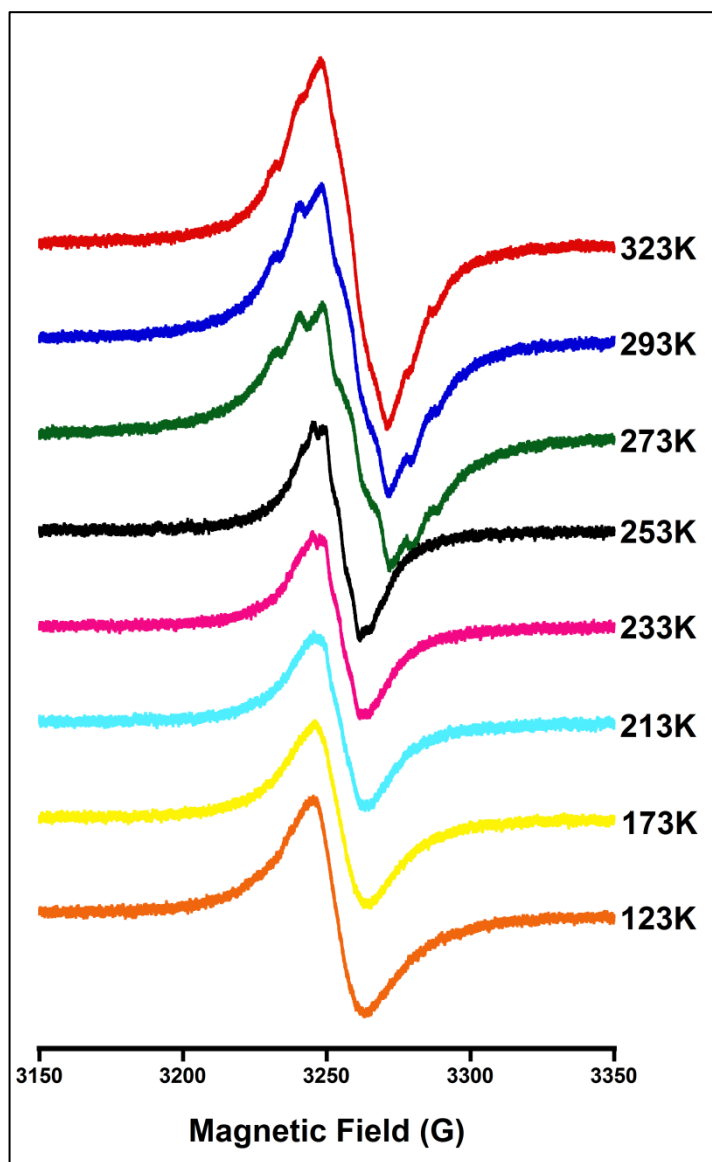


Figure 8.33: X-band EPR Spectra of 15×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

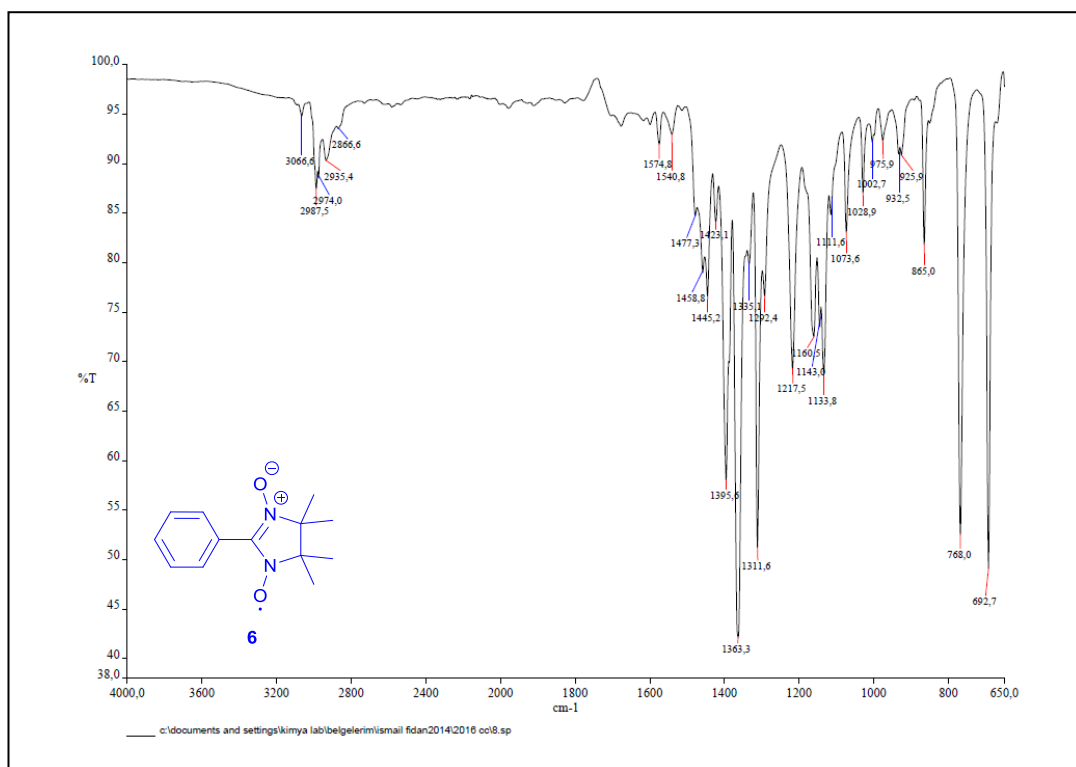


Figure 8.34: FT-IR Spectrum of 6.

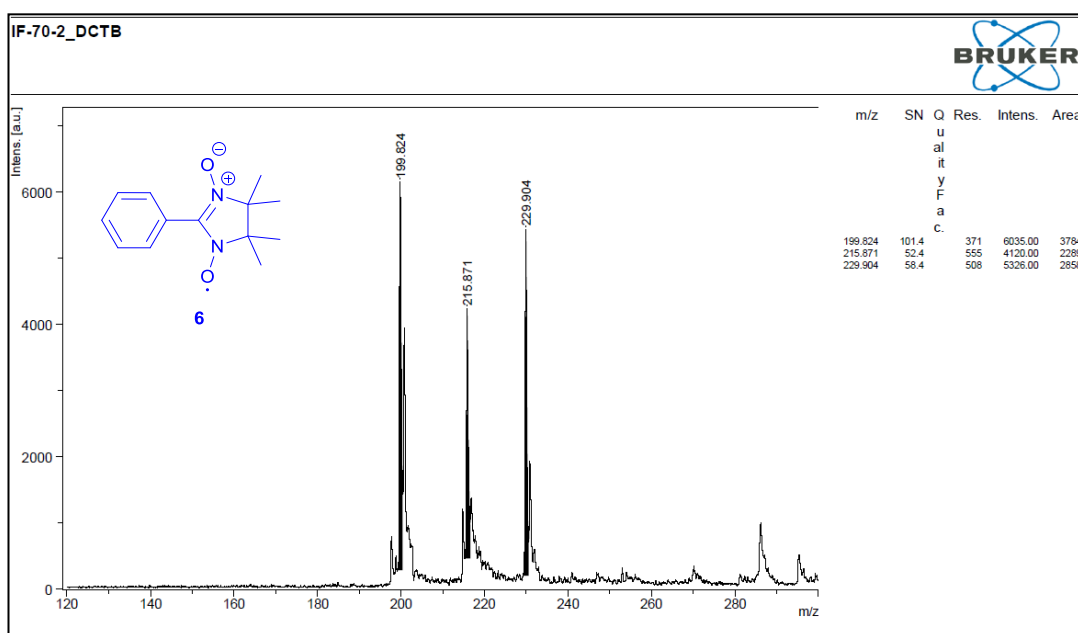


Figure 8.35: MALDI-TOF MS Spectrum of 6.

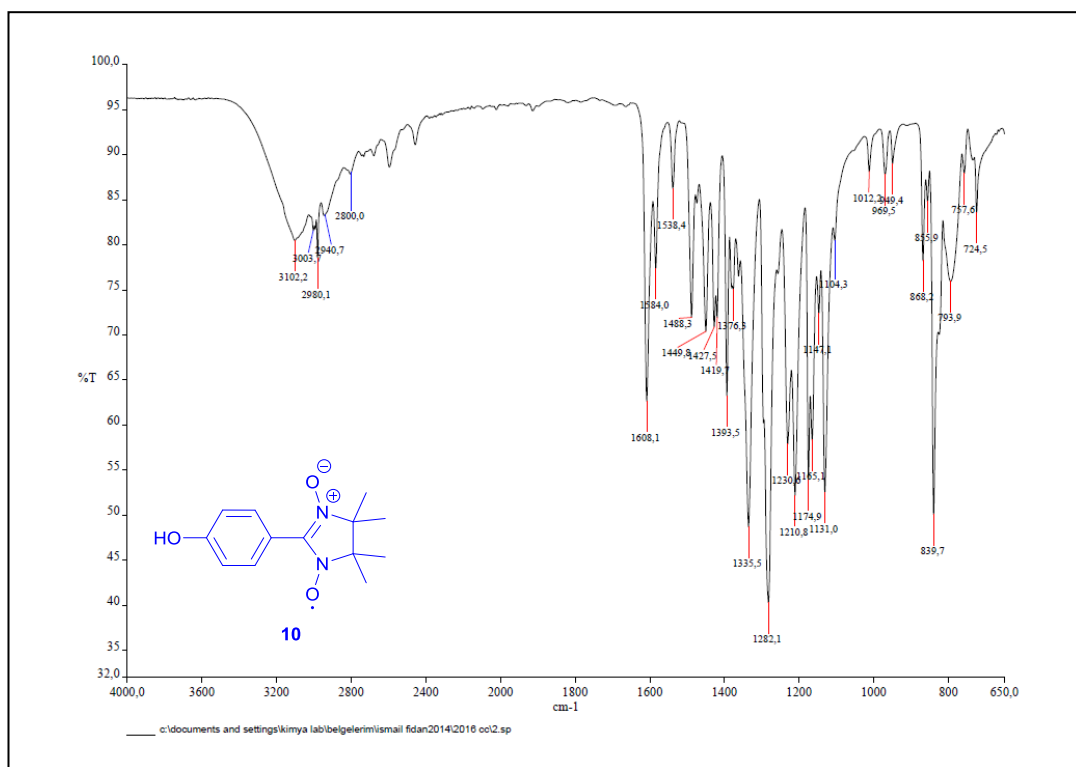


Figure 8.36: FT-IR Spectrum of **10**.

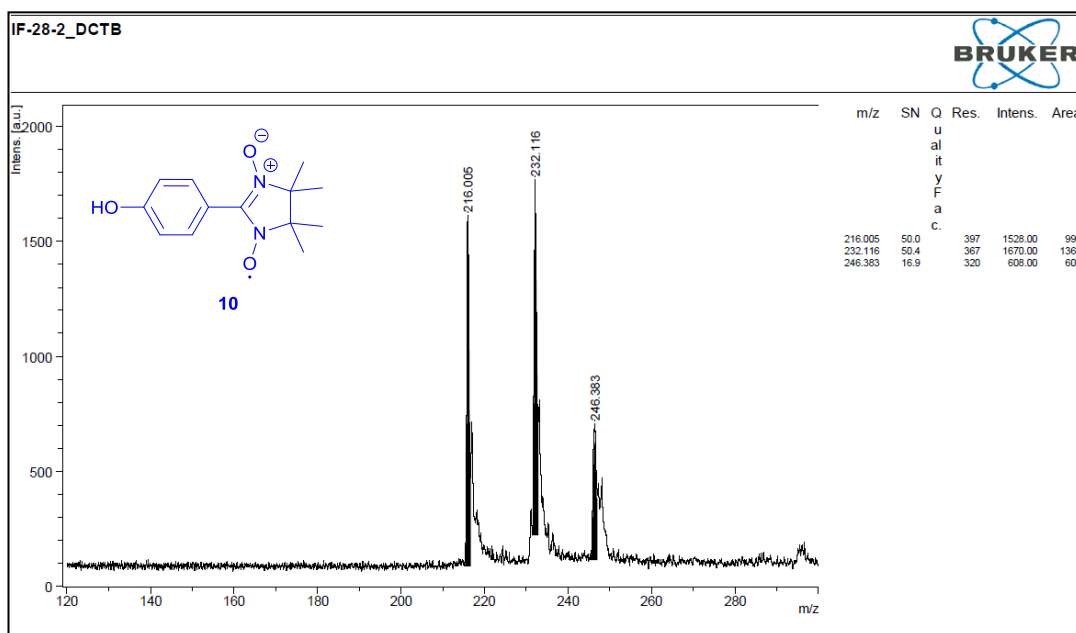


Figure 8.37: MALDI-TOF MS Spectrum of **10**.

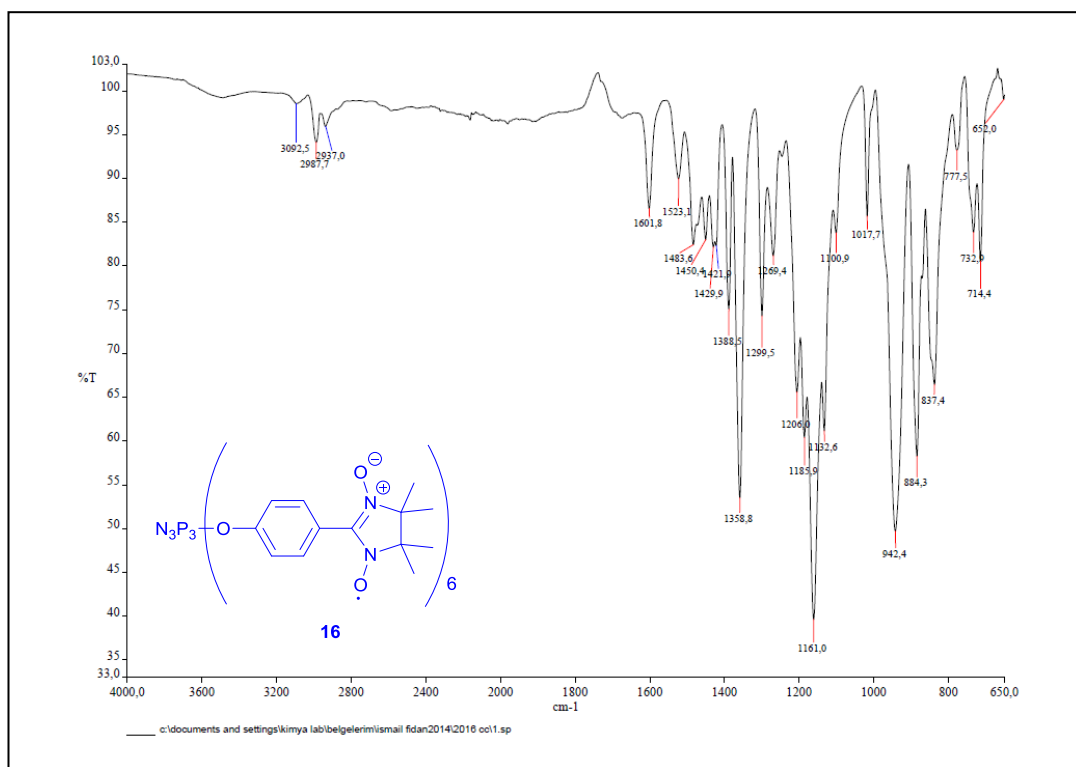


Figure 8.38: FT-IR Spectrum of **16**.

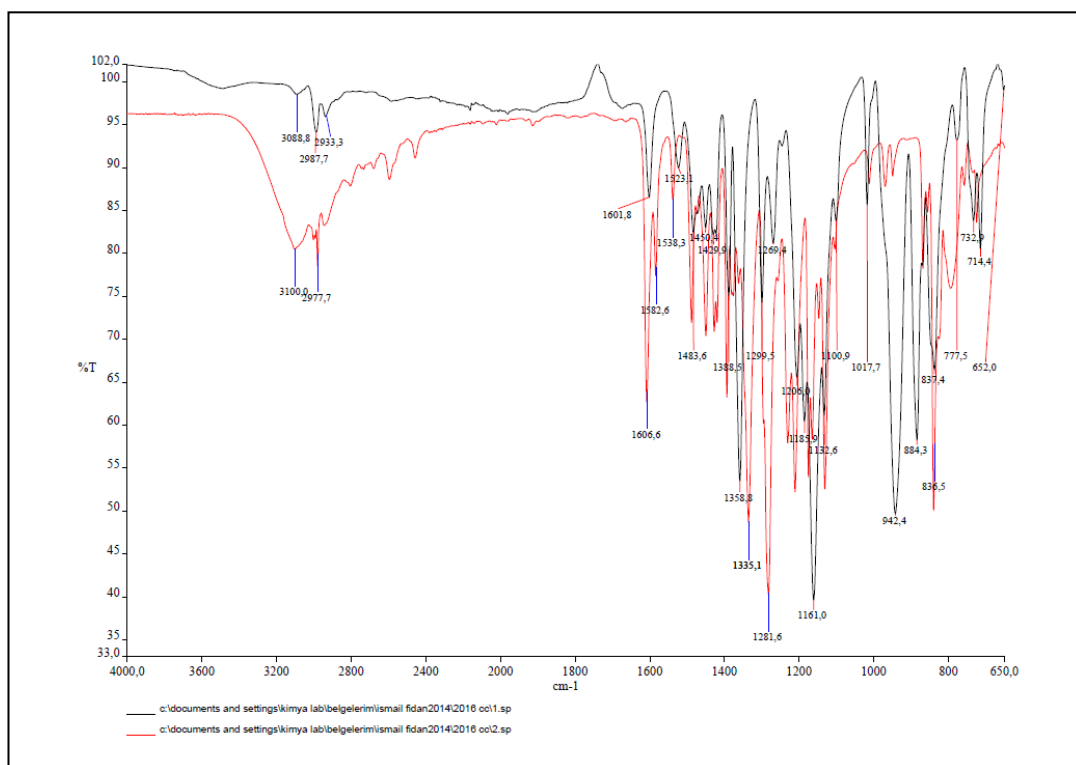


Figure 8.39: Comparison the FT-IR Spectrum of **16** with That of **10**.

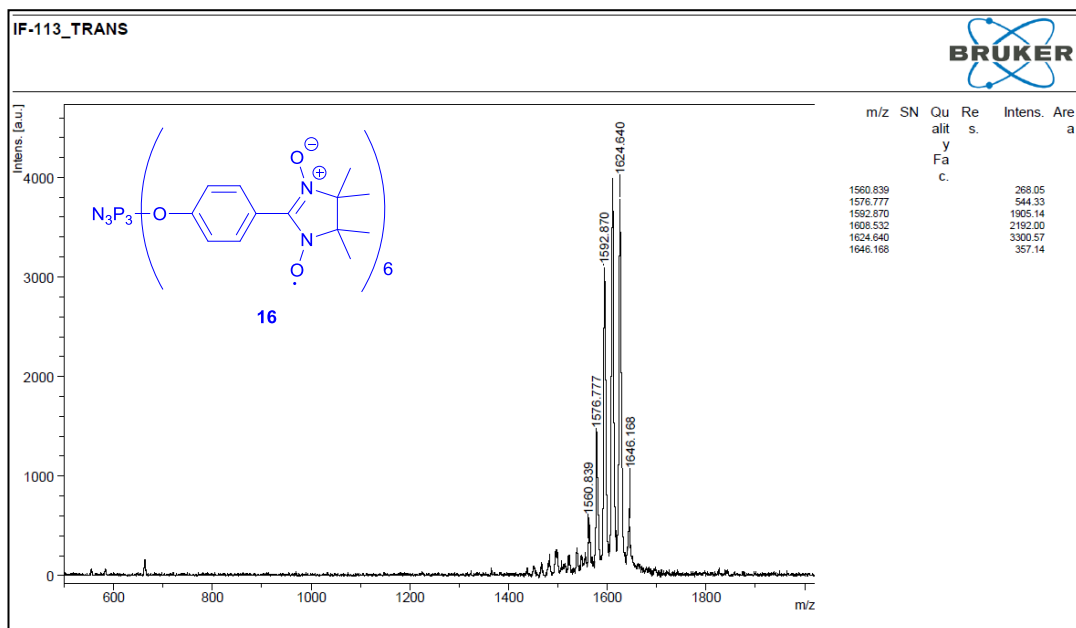


Figure 8.40: MALDI-TOF MS Spectrum of **16**.

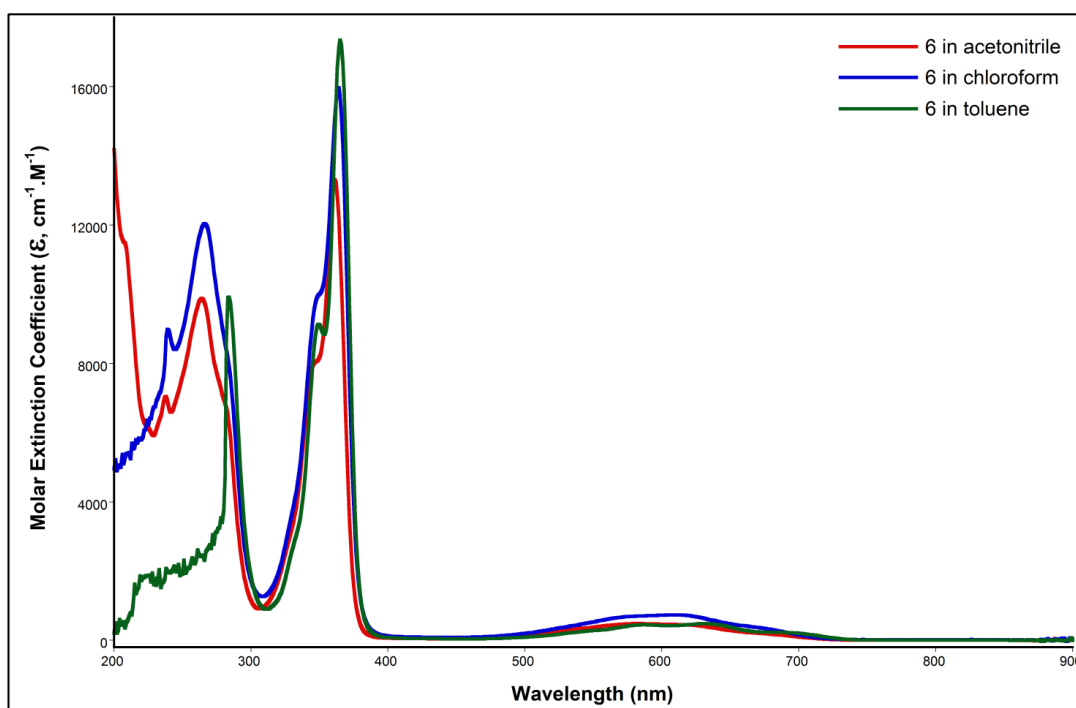


Figure 8.41: UV-vis Spectra of **6** in Acetonitrile, Chloroform and Toluene.

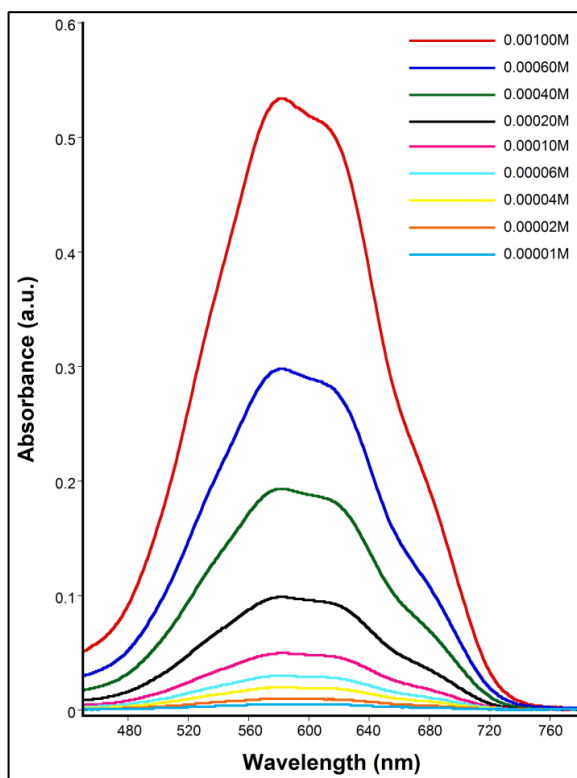


Figure 8.42: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **6** in Acetonitrile.

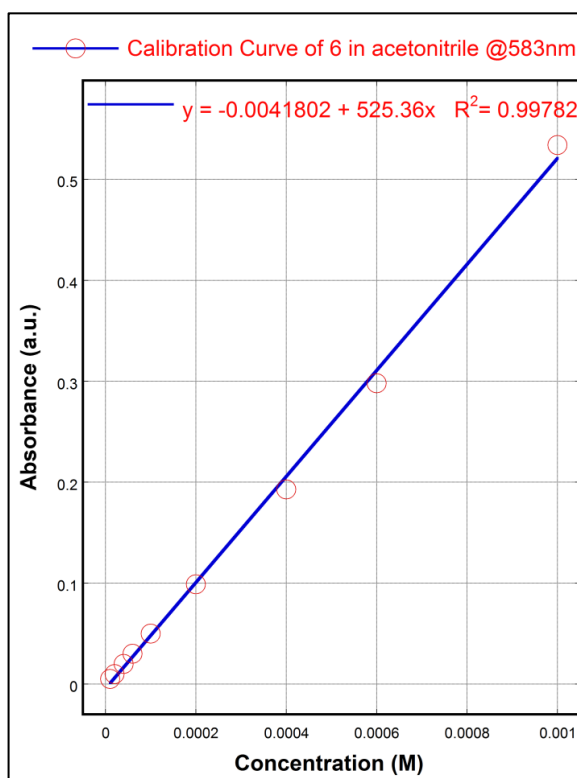


Figure 8.43: Calibration Curve of **6** in Acetonitrile at 583 nm.

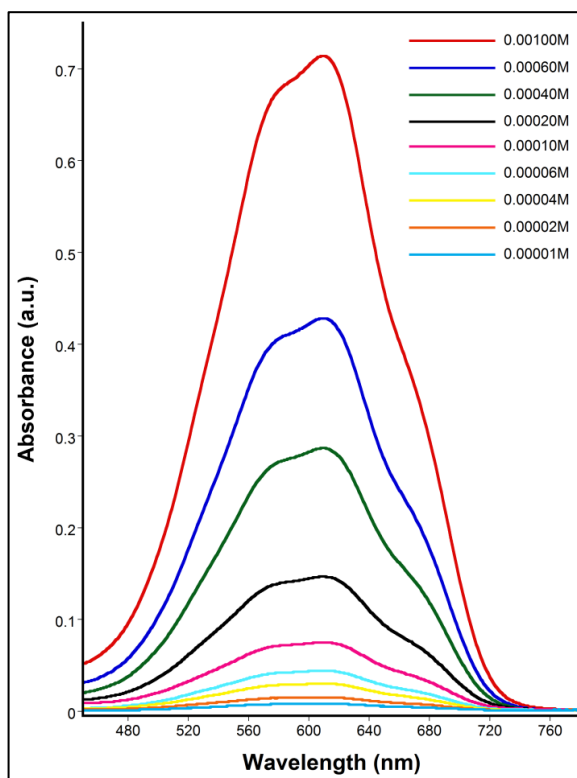


Figure 8.44: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **6** in Chloroform.

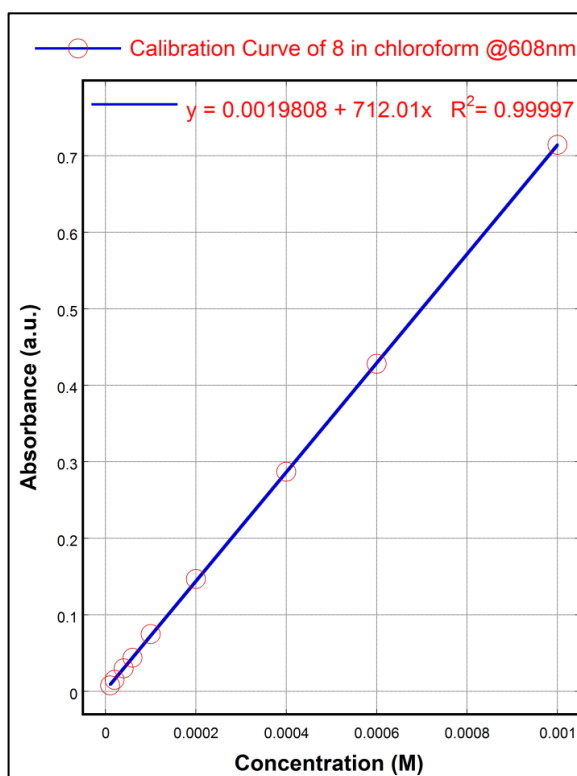


Figure 8.45: Calibration Curve of **6** in Chloroform at 608 nm.

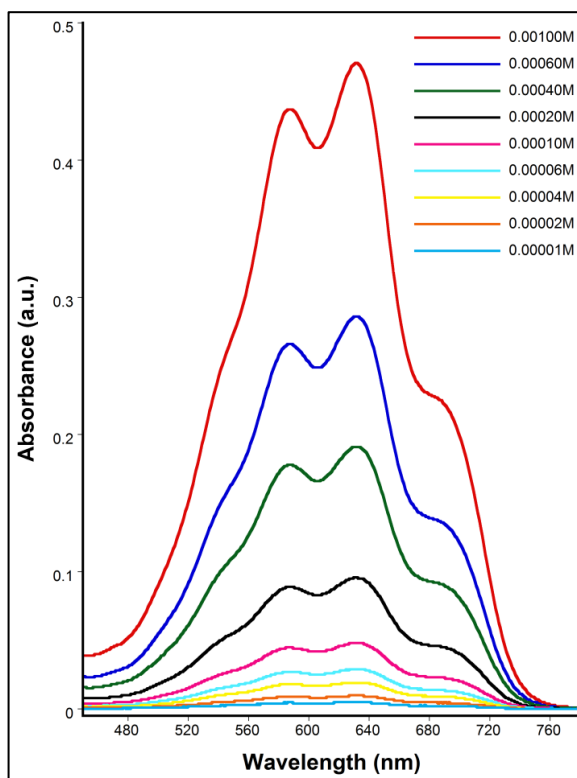


Figure 8.46: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **6** in Toluene.

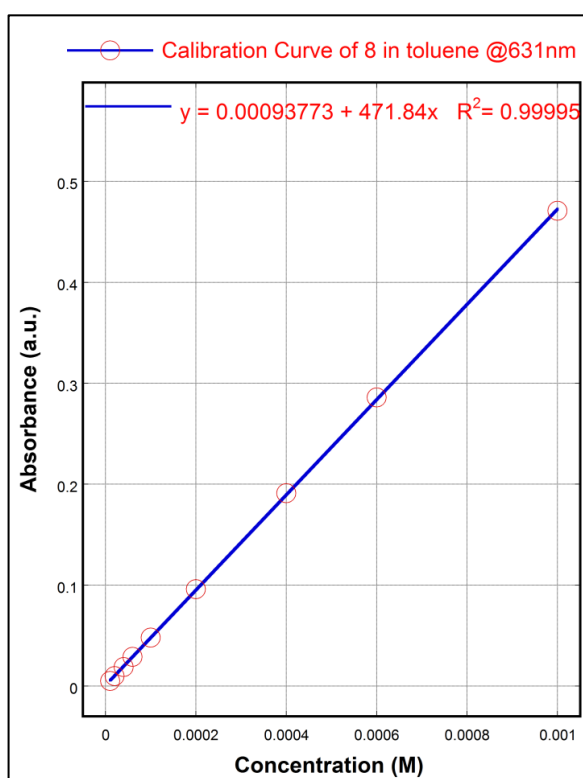


Figure 8.47: Calibration Curve of **6** in Toluene at 631 nm.

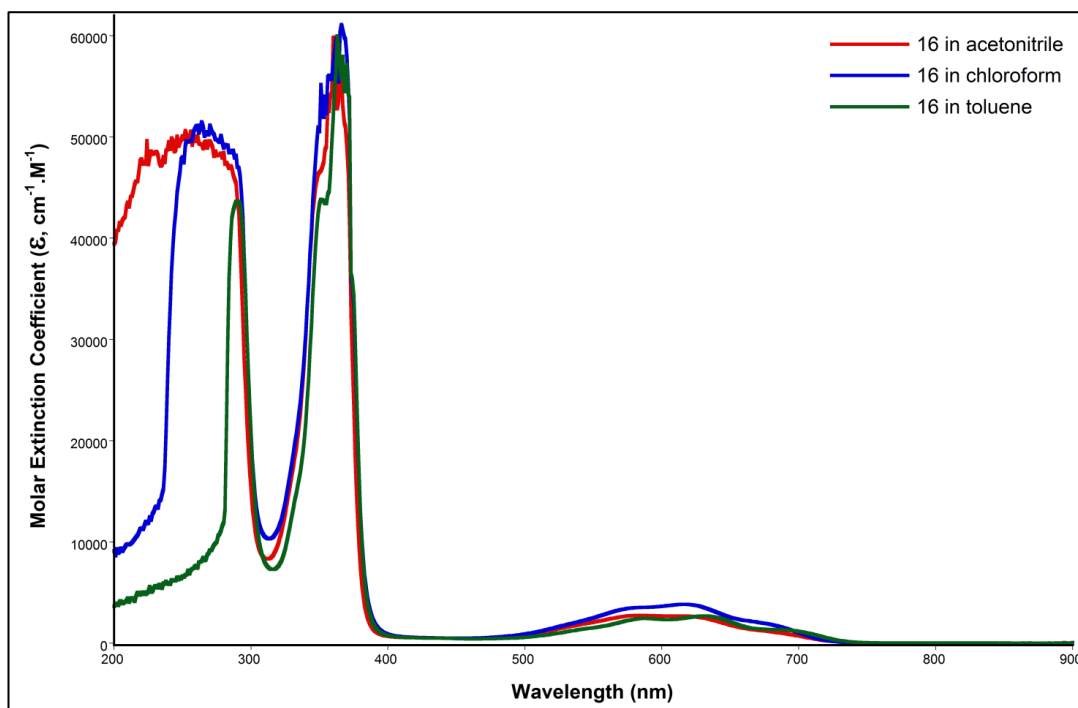


Figure 8.48: UV-vis Spectra of **16** in Acetonitrile, Chloroform and Toluene.

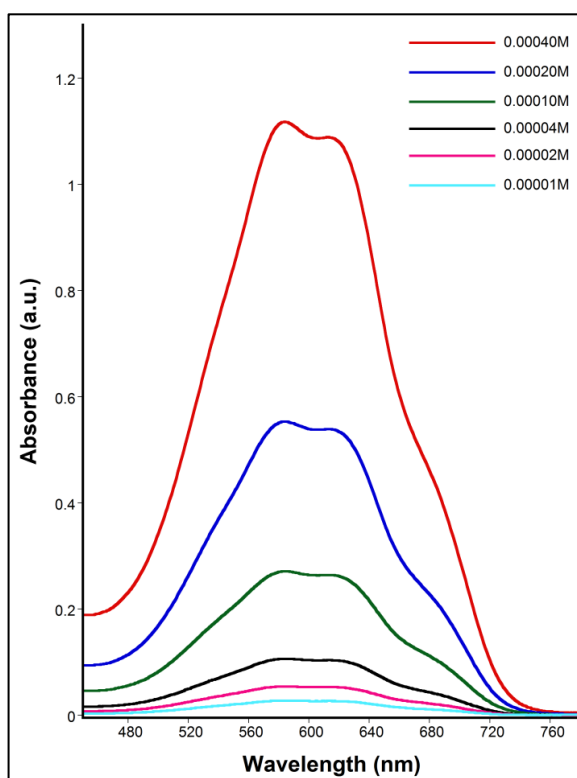


Figure 8.49: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **16** in Acetonitrile.

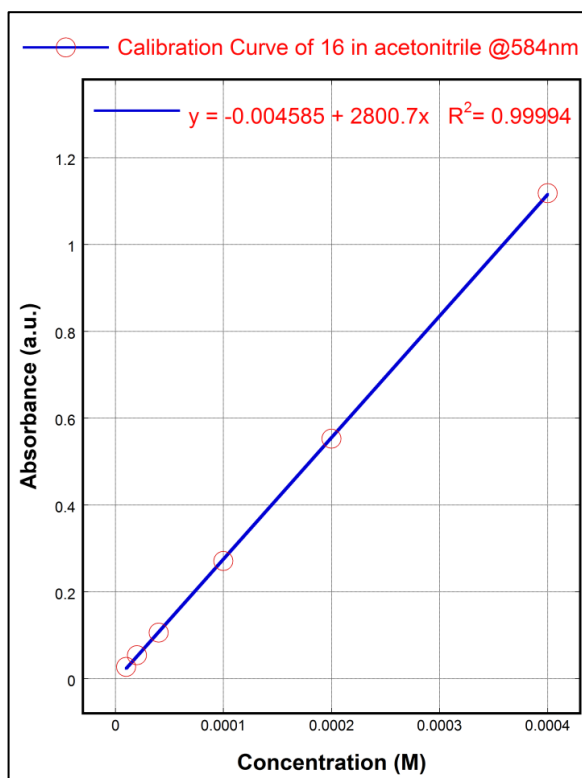


Figure 8.50: Calibration Curve of **16** in Acetonitrile at 584 nm.

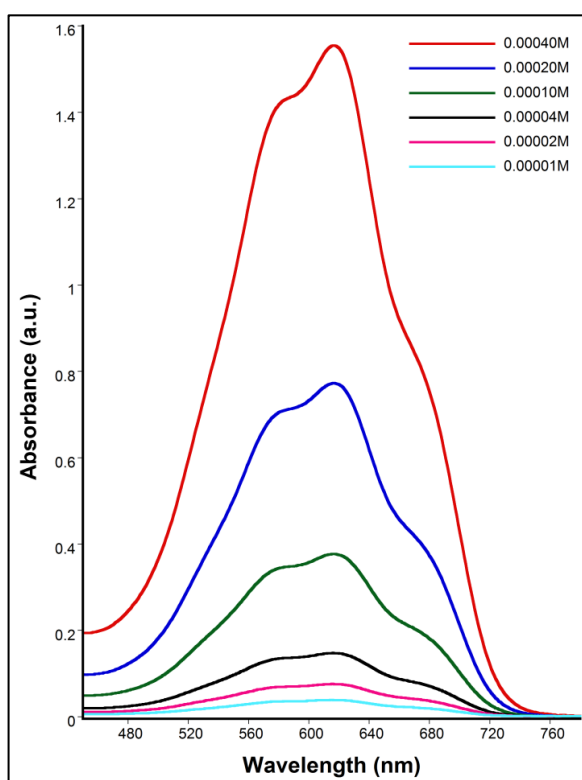


Figure 8.51: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **16** in Chloroform.

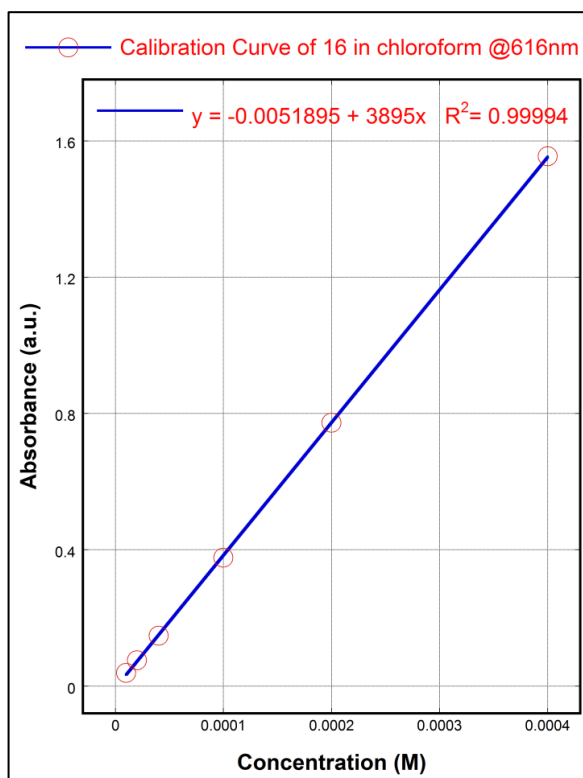


Figure 8.52: Calibration Curve of **16** in Chloroform at 616 nm.

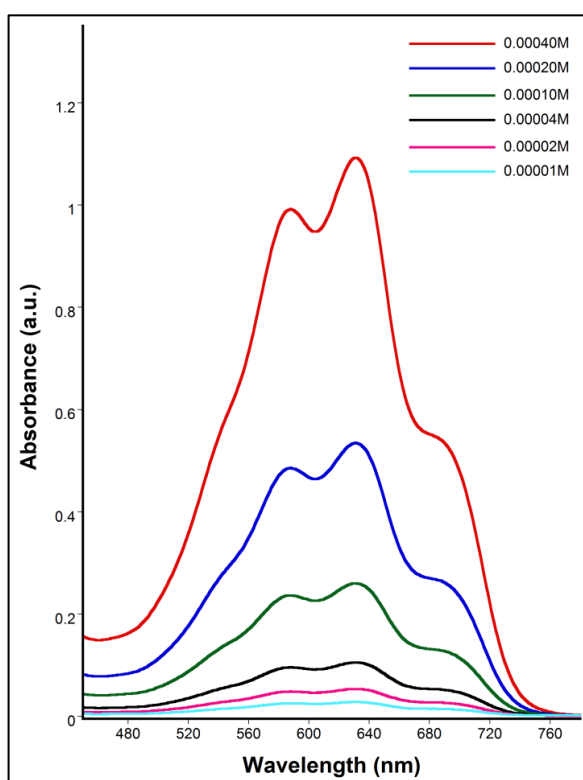


Figure 8.53: UV-vis Spectra for $n \rightarrow \pi^*$ Transitions of **16** in Toluene.

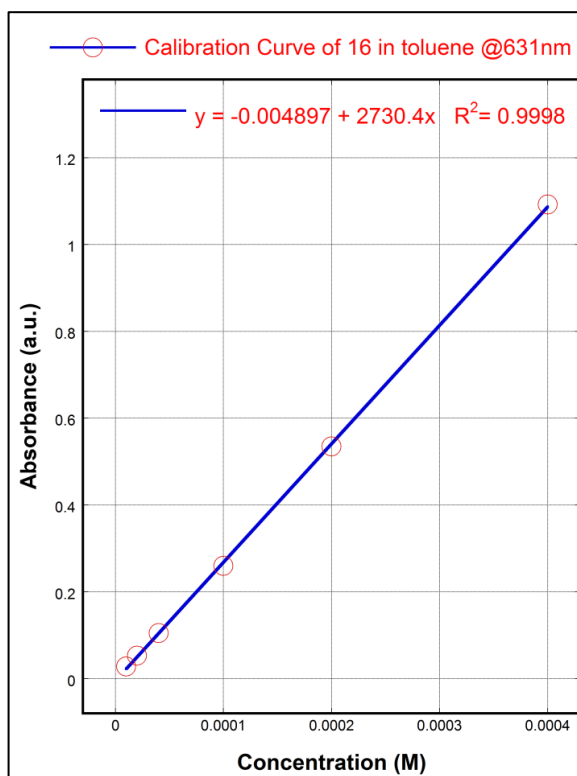


Figure 8.54: Calibration Curve of **16** in Toluene at 631 nm.

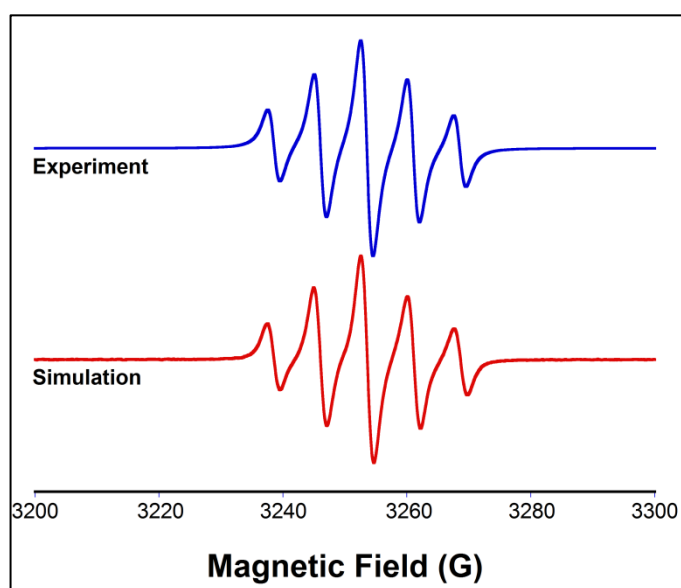


Figure 8.55: X-band EPR Spectrum of **6** 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 293 K and Its Simulation. (Best Fitting Parameters are $g = 2.0031$, $a_N = 7.5$ G, and $\Delta H_{p-p} = 2.0$ G).

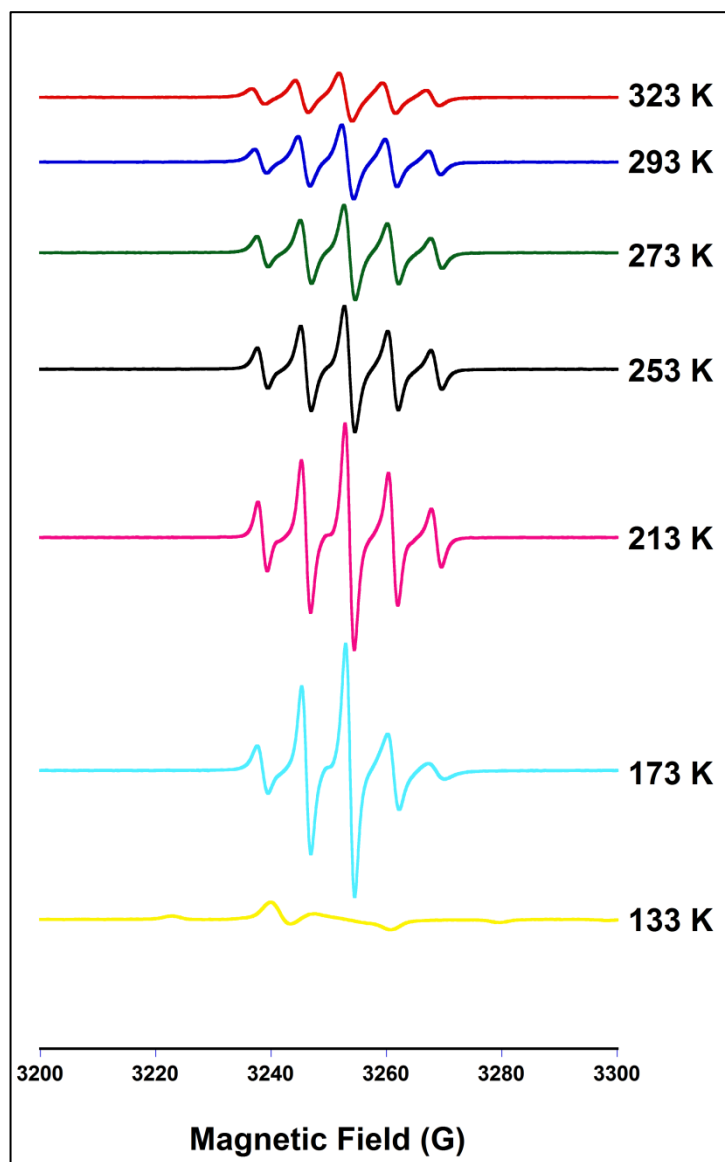


Figure 8.56: X-band EPR Spectra of 6×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

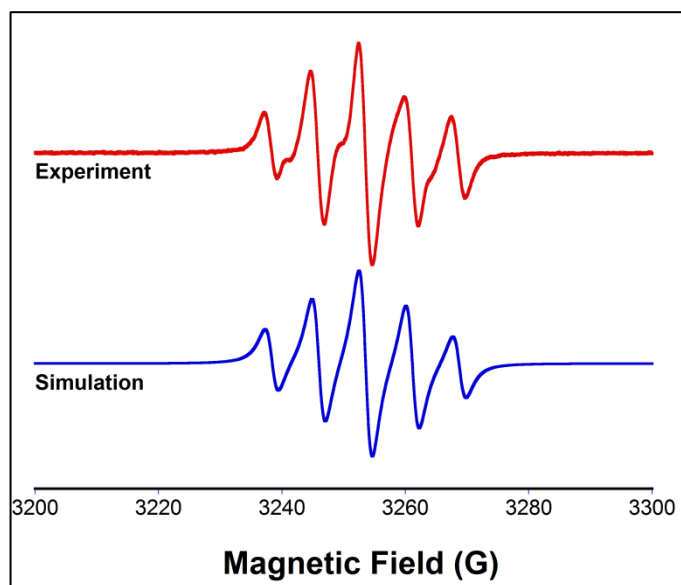


Figure 8.57: X-band EPR Spectrum of 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at 293 K and Its Simulation. (Best Fitting Parameters are $g = 2.0752$, $a_N = 7.6$ G, and $\Delta H_{p-p} = 2.2$ G).

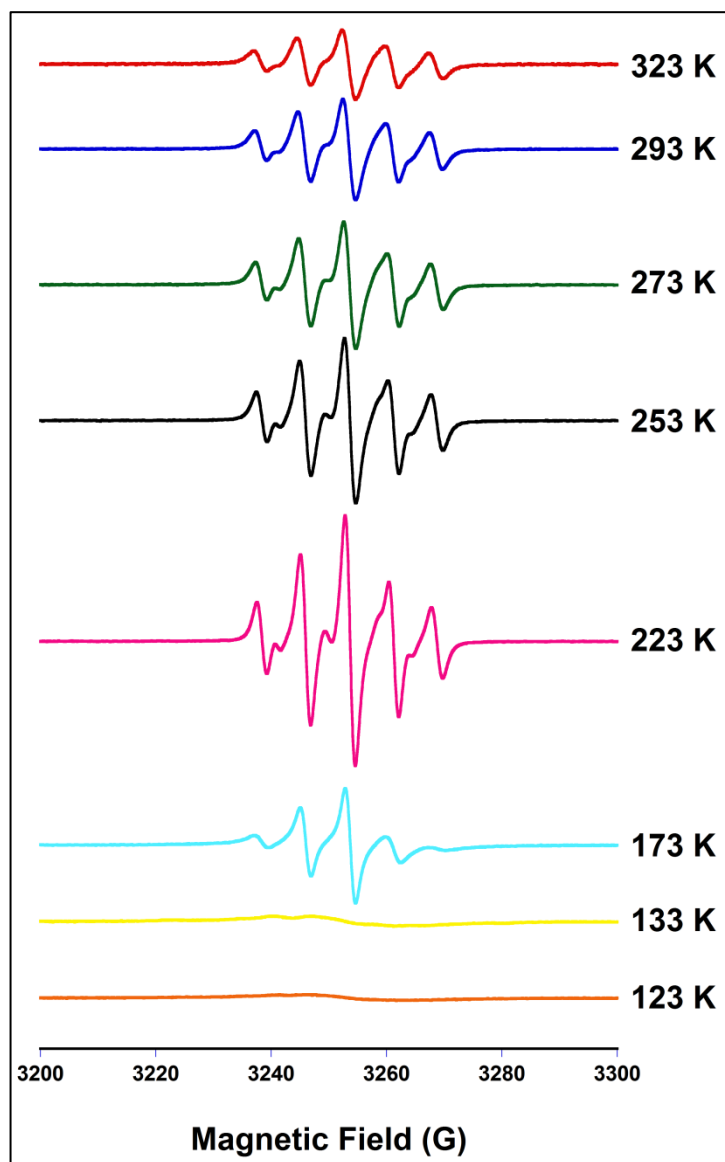


Figure 8.58: X-band EPR Spectrum of $10 \cdot 10^{-4}$ M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

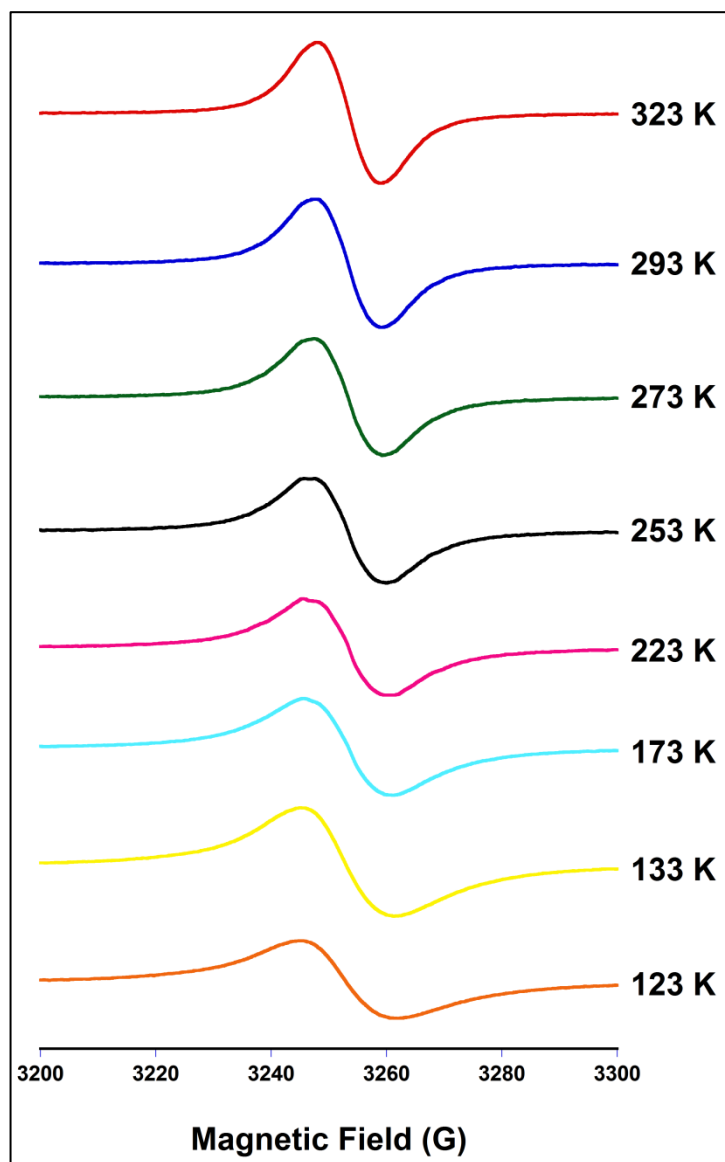


Figure 8.59: X-band EPR Spectra of **16** 10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

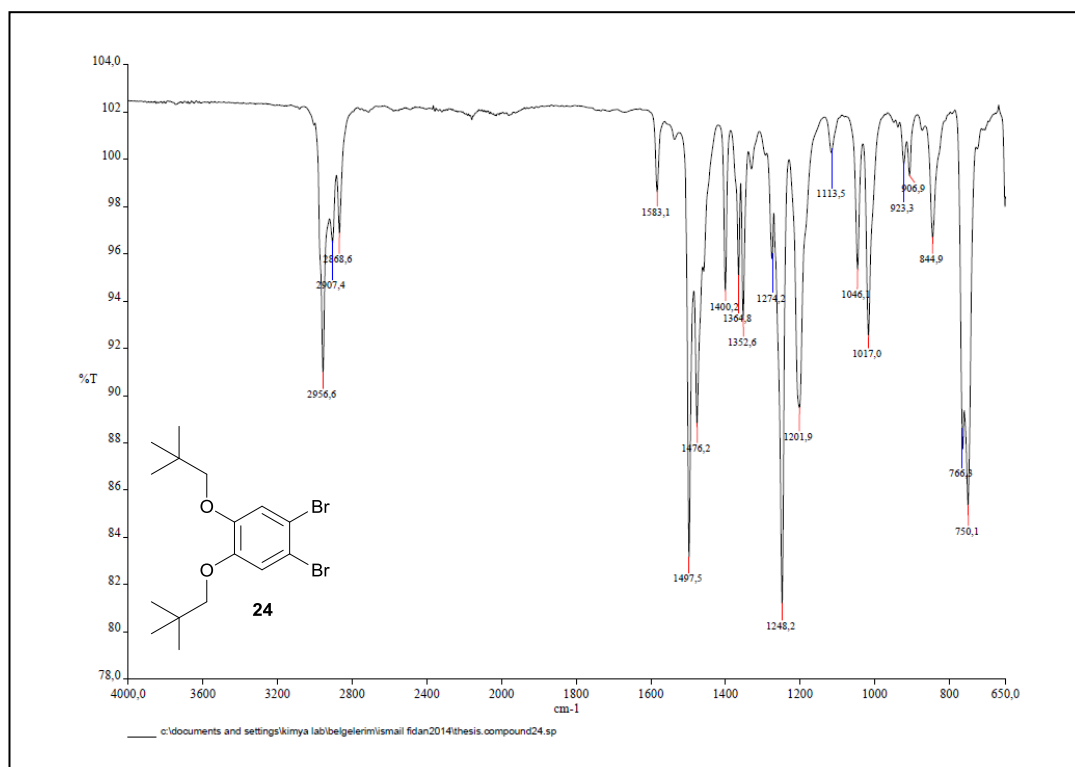


Figure 8.60: FT-IR Spectrum of **24**.

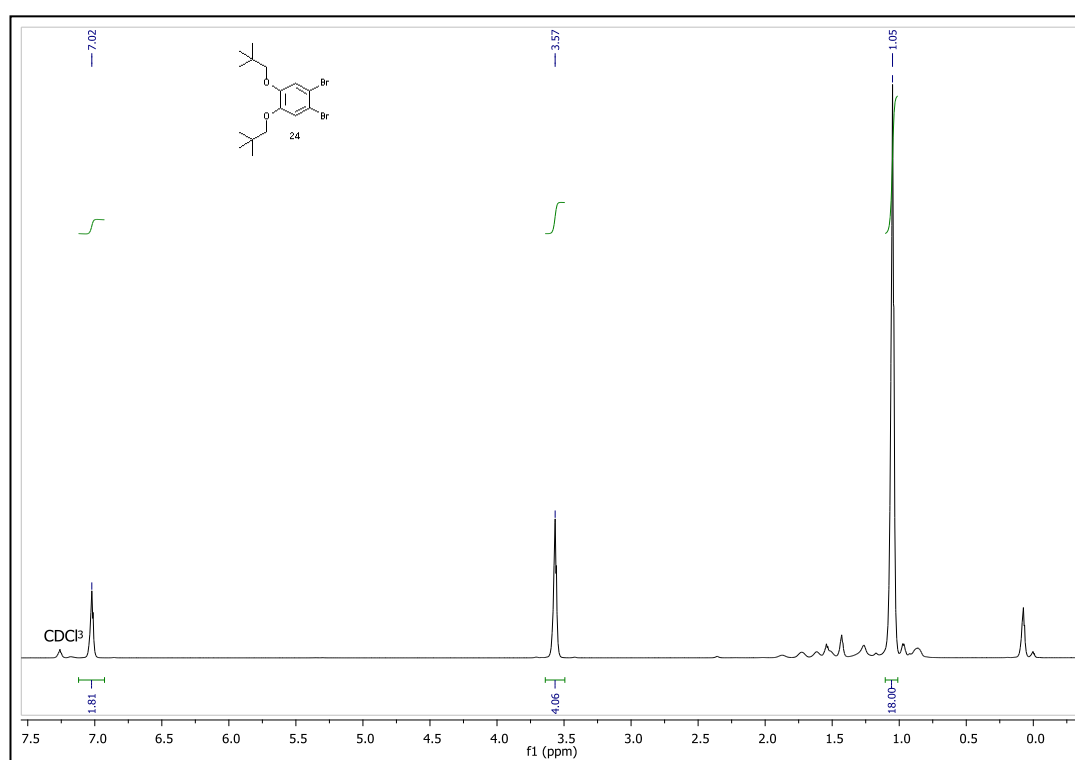


Figure 8.61: ¹H NMR Spectrum of **24** in CDCl₃ (500MHz).

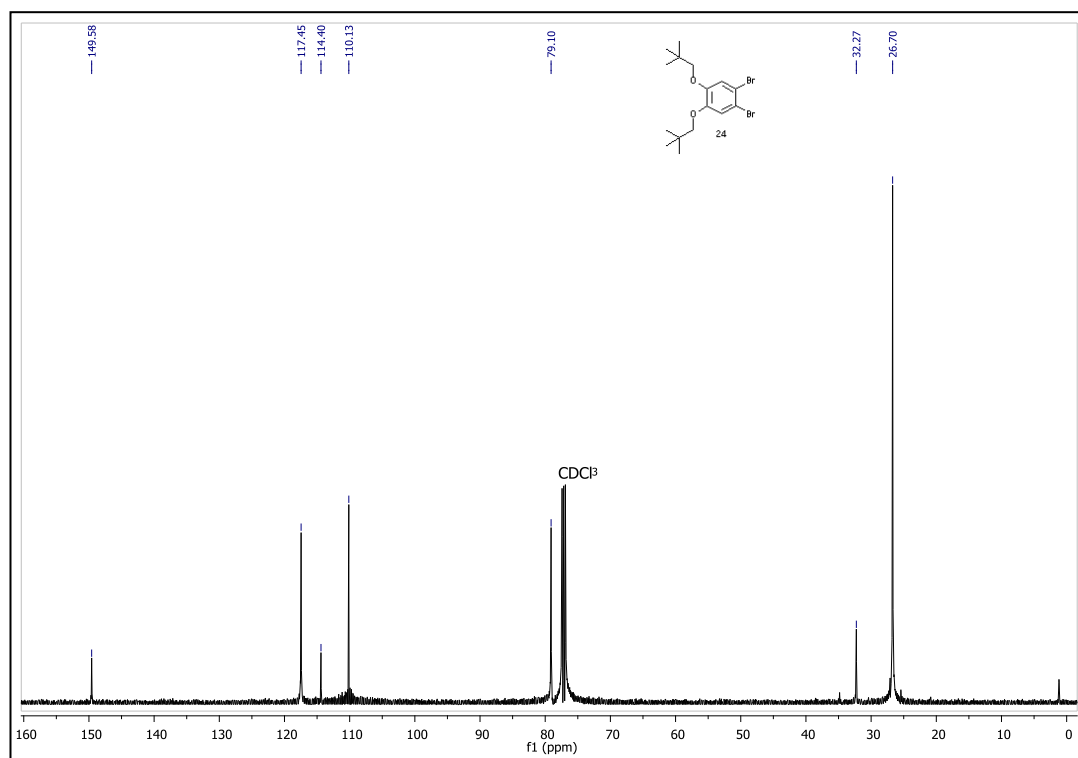


Figure 8.62: ¹³C NMR Spectrum of **24** in CDCl₃ (125MHz).

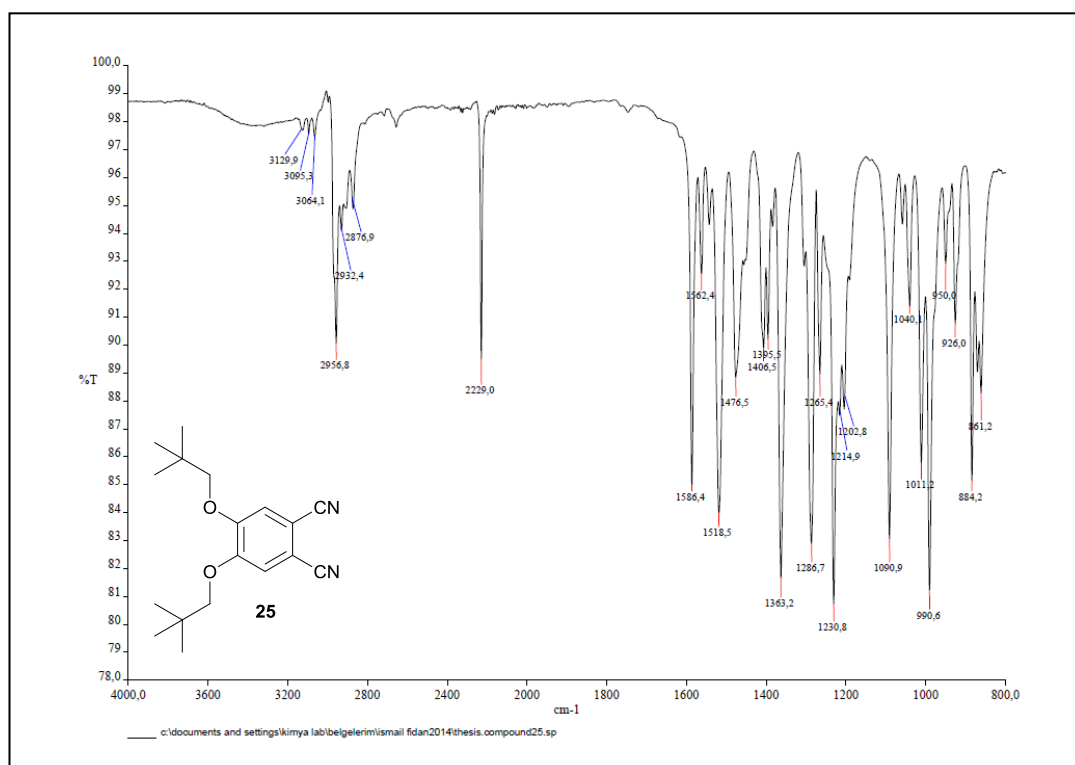


Figure 8.63: FT-IR Spectrum of **25**.

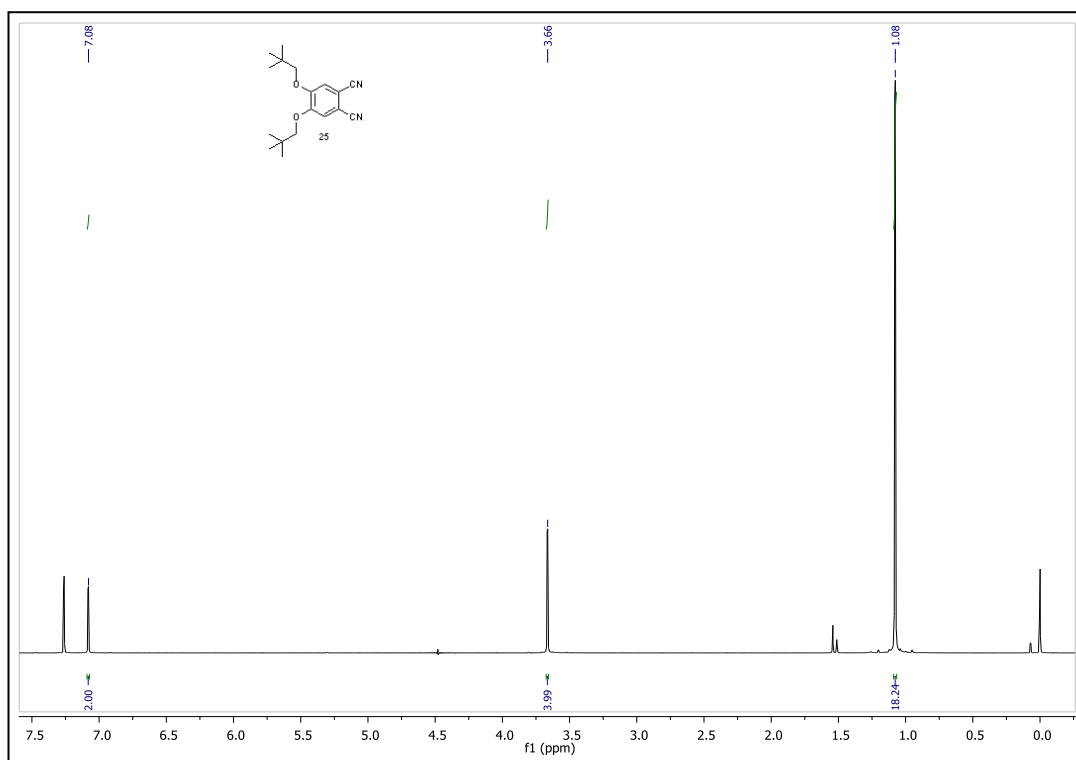


Figure 8.64: ¹H NMR Spectrum of **25** in CDCl₃ (500MHz).

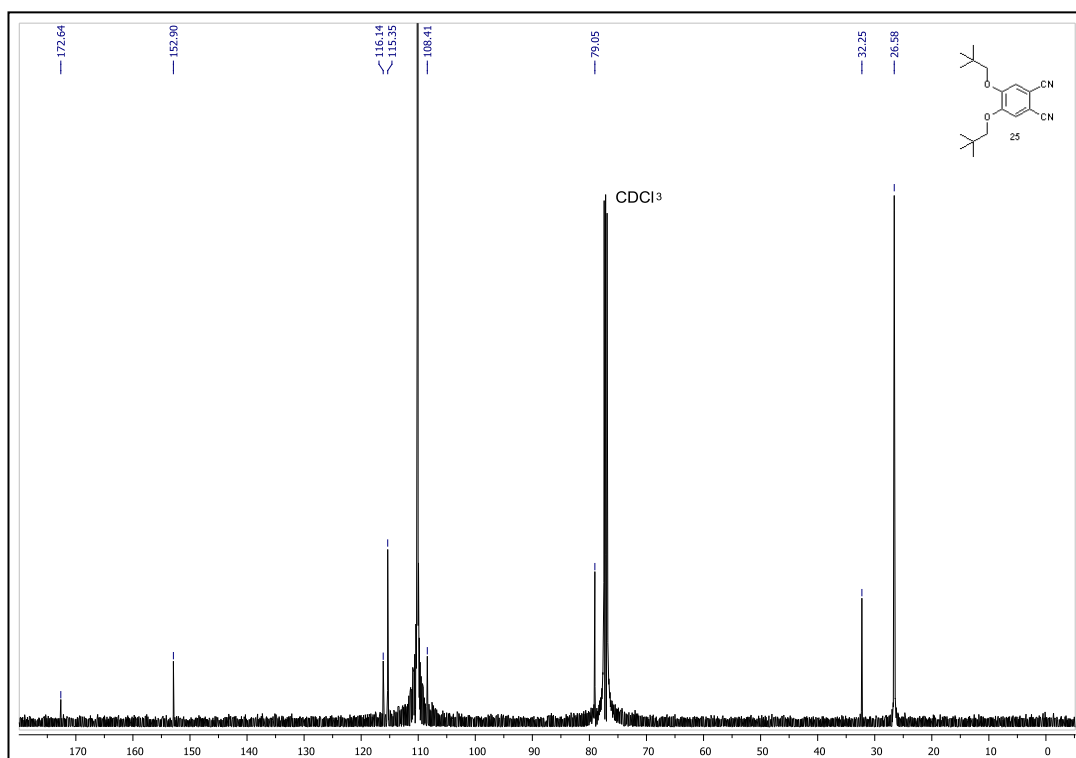


Figure 8.65: ¹³C NMR Spectrum of **25** in CDCl₃ (125MHz).

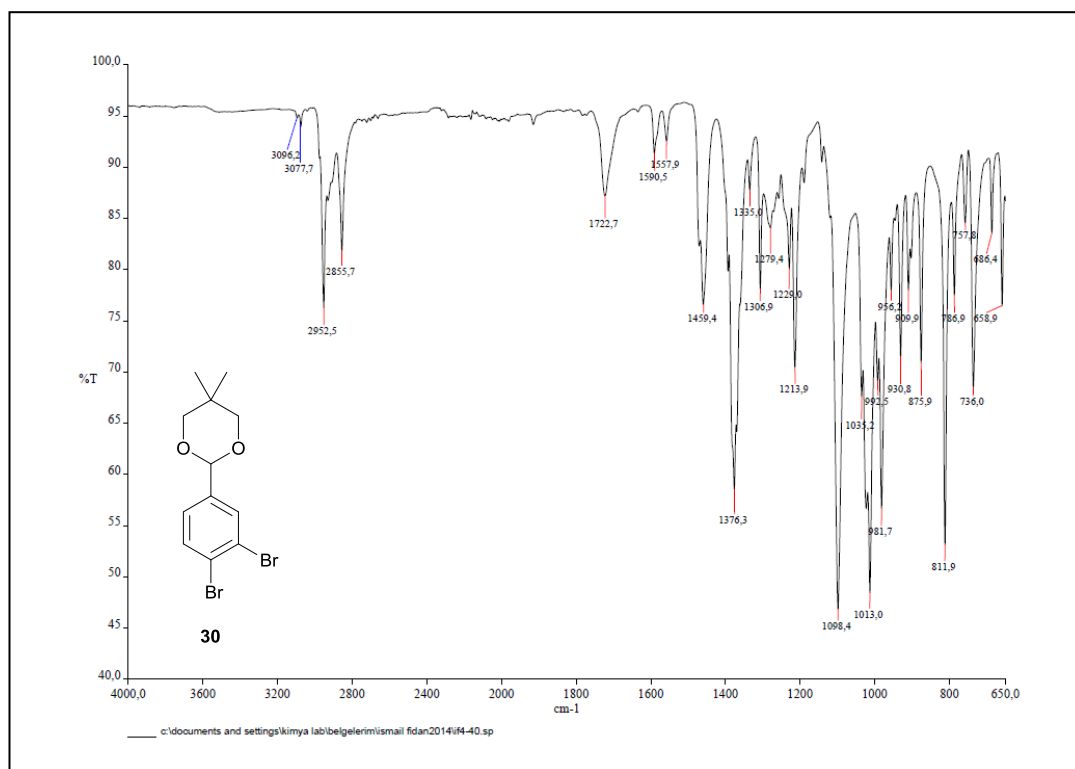


Figure 8.66: FT-IR Spectrum of **30**.

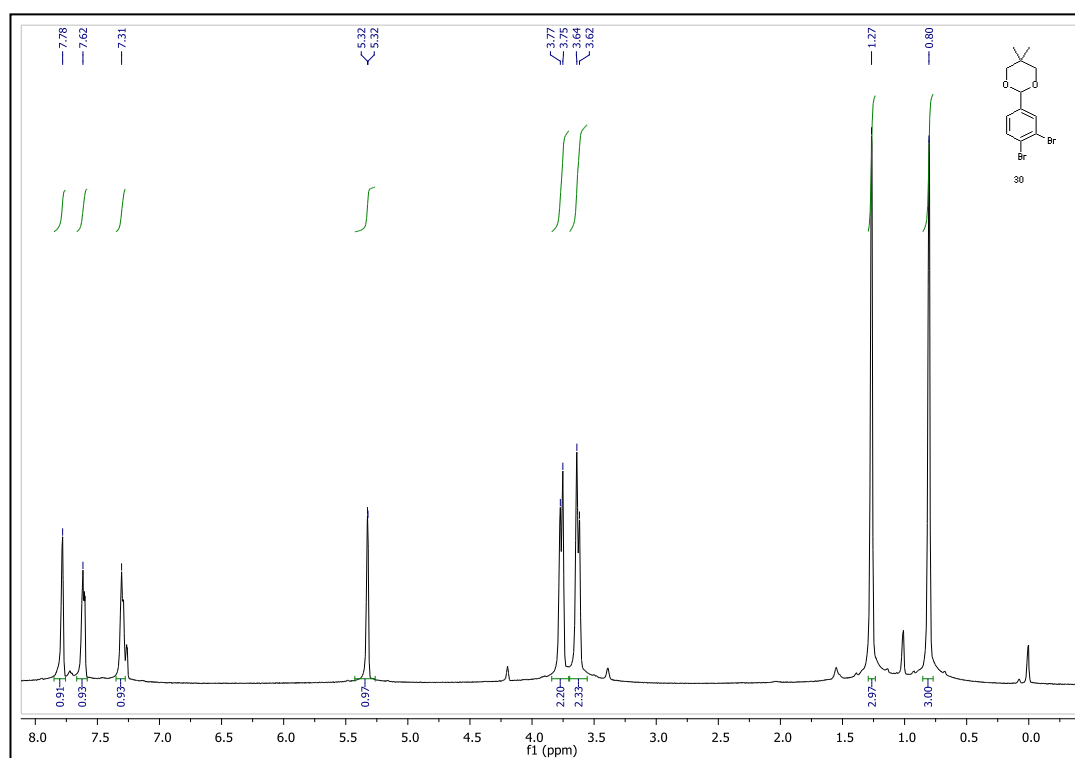


Figure 8.67: ¹H NMR Spectrum of **30** in CDCl₃ (500MHz).

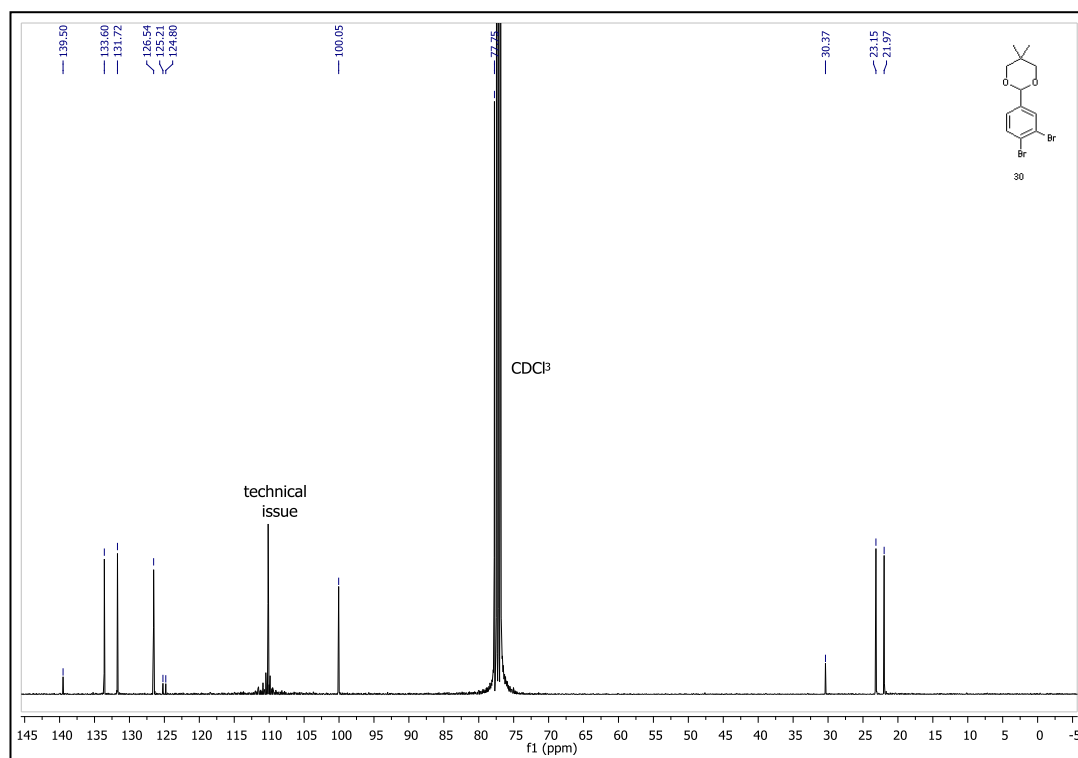


Figure 8.68: ^{13}C NMR Spectrum of **30** in CDCl_3 (125MHz).

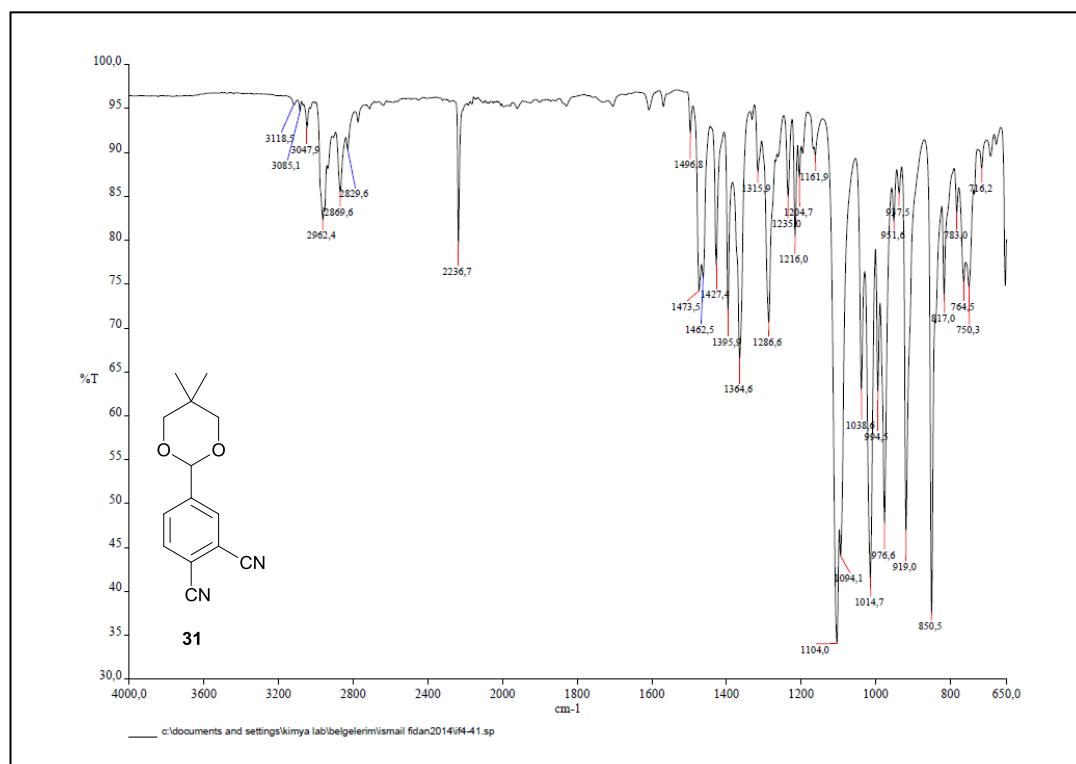


Figure 8.69: FT-IR Spectrum of **31**.

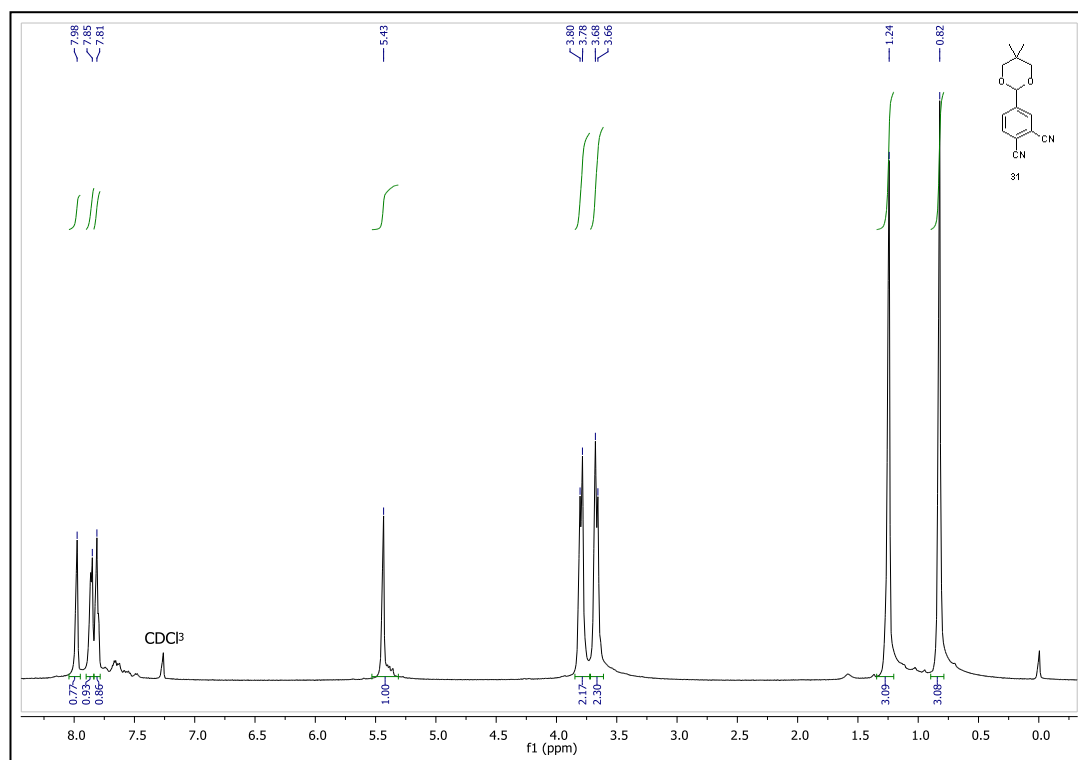


Figure 8.70: ¹H NMR Spectrum of **31** in CDCl₃ (500MHz).

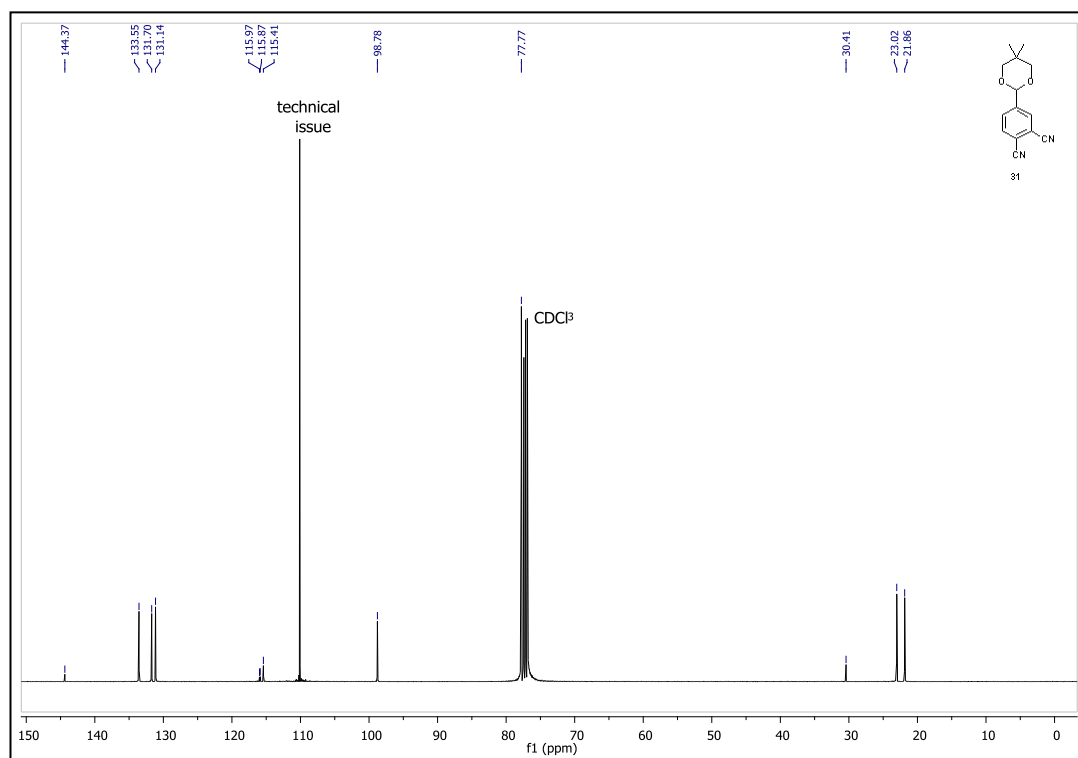


Figure 8.71: ¹³C NMR Spectrum of **31** in CDCl₃ (125MHz).

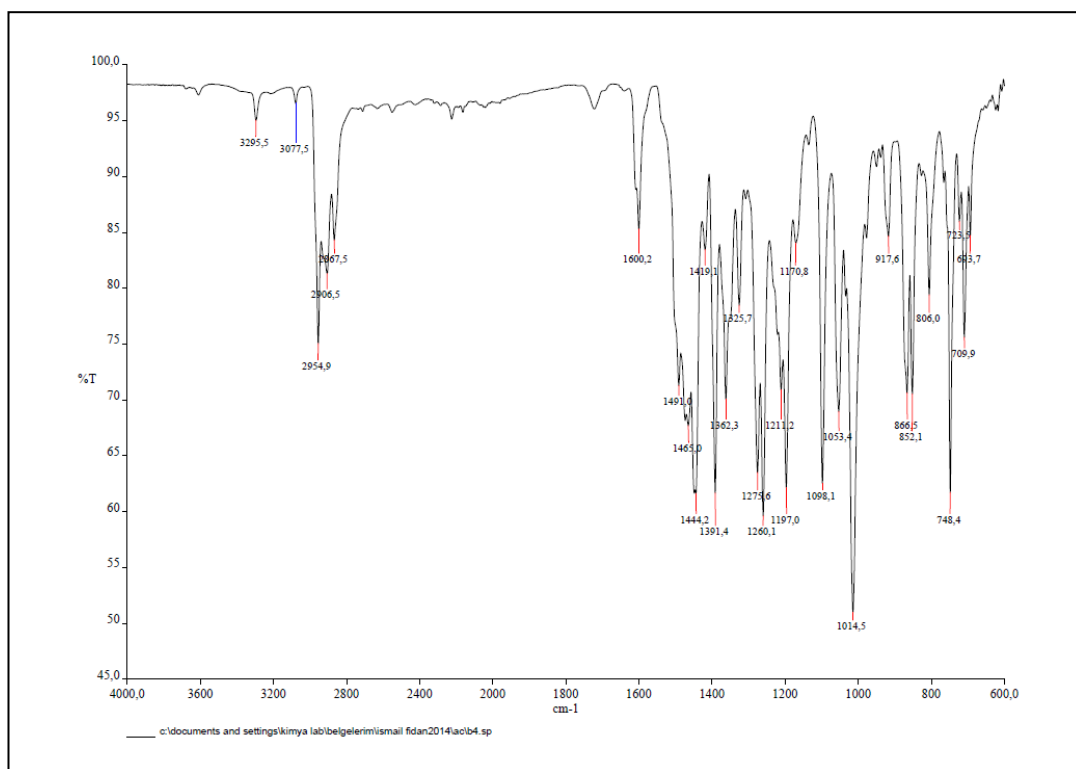


Figure 8.72: FT-IR Spectrum of 32.

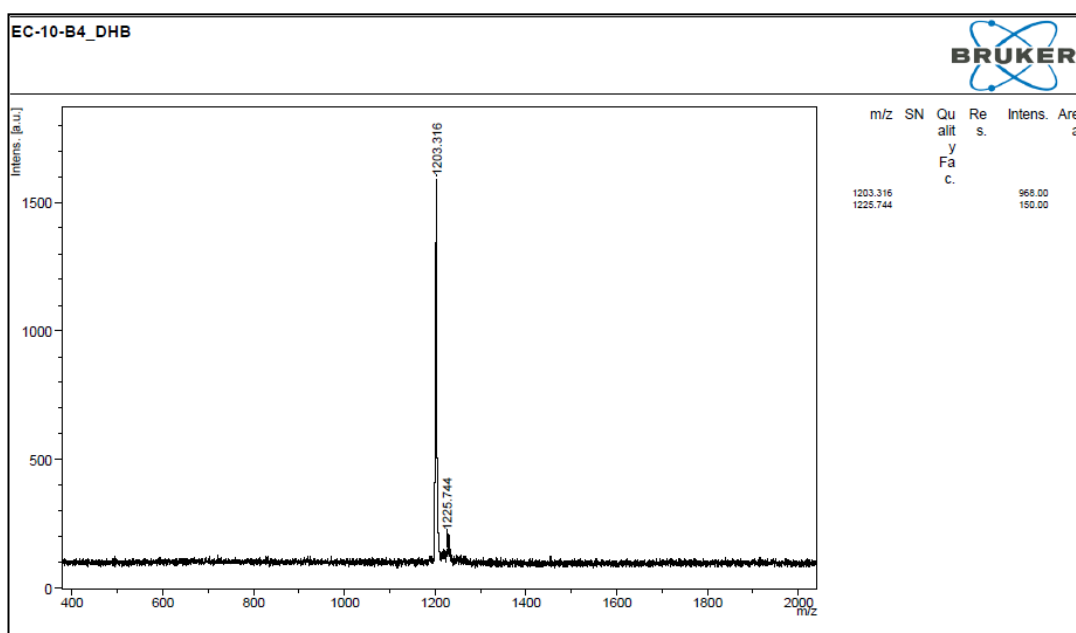


Figure 8.73: MALDI-TOF MS Spectrum of 32.

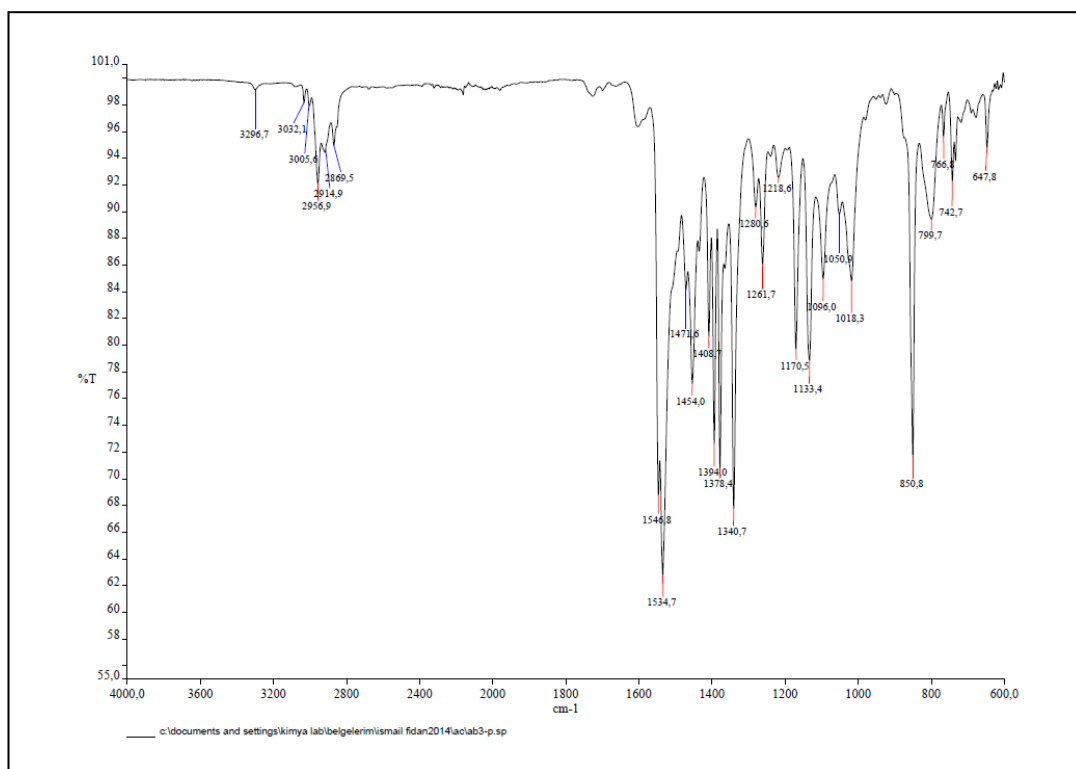


Figure 8.74: FT-IR Spectrum of 33.

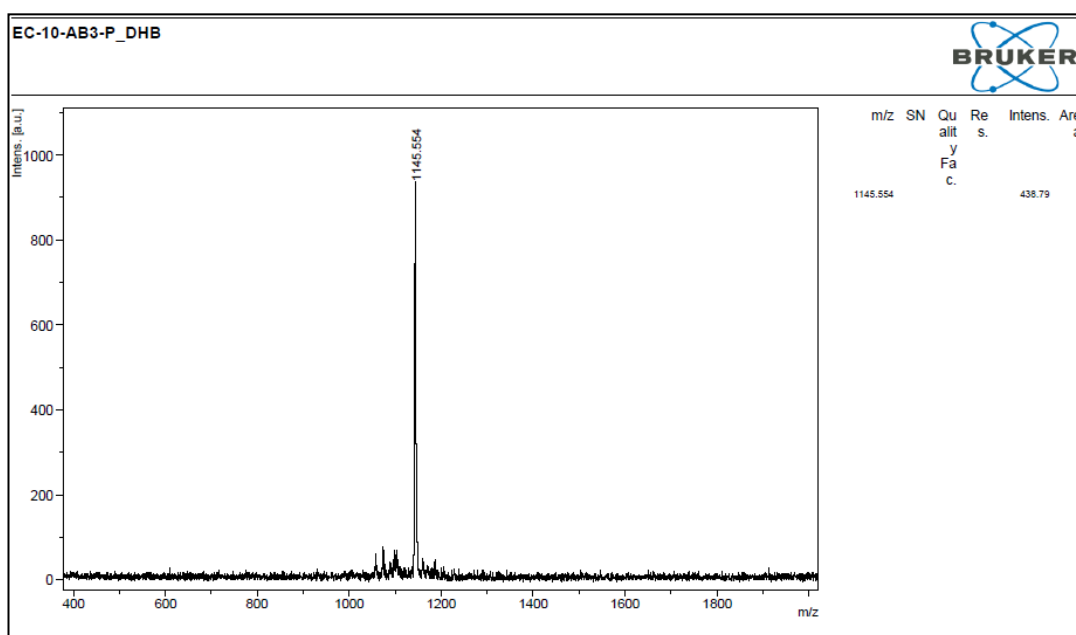


Figure 8.75: MALDI-TOF MS Spectrum of 33.

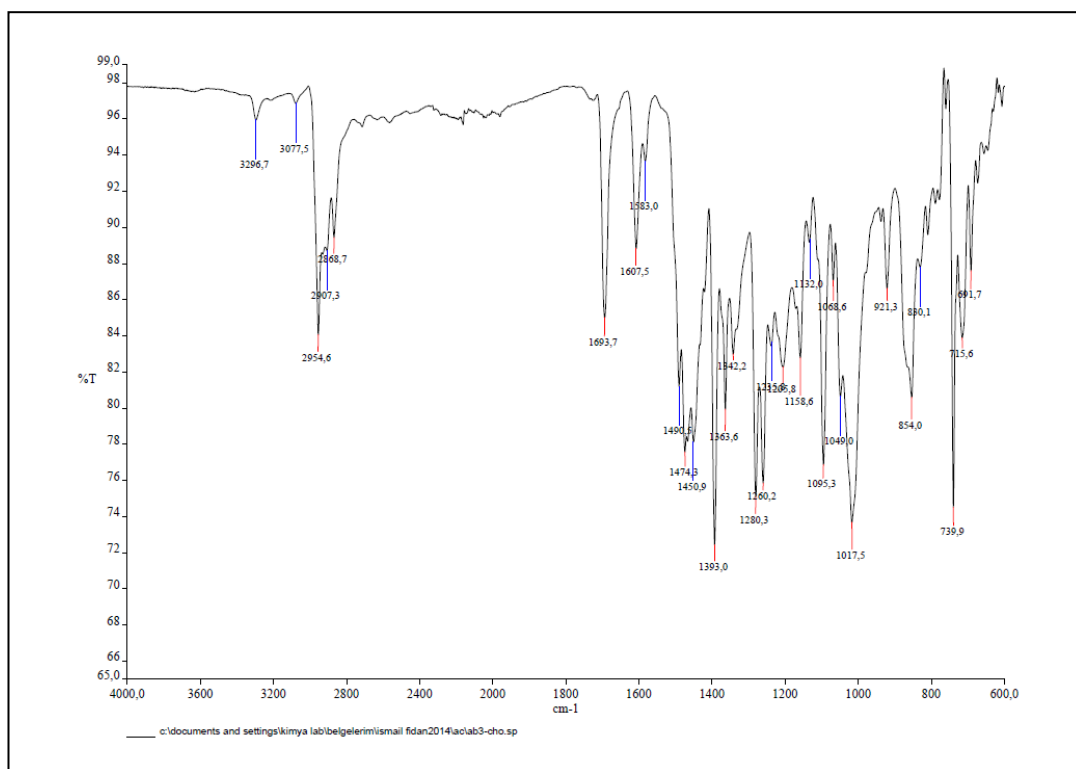


Figure 8.76: FT-IR Spectrum of **34**.

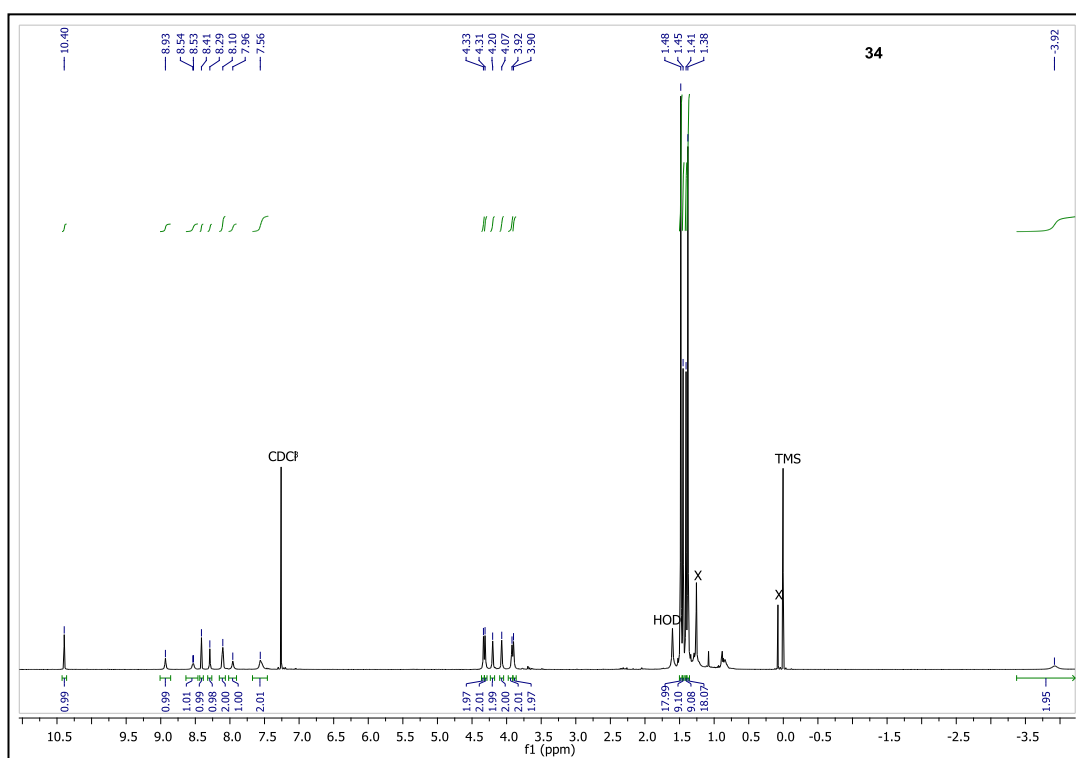


Figure 8.77: ¹H NMR Spectrum of **34** in CDCl₃ (500MHz).

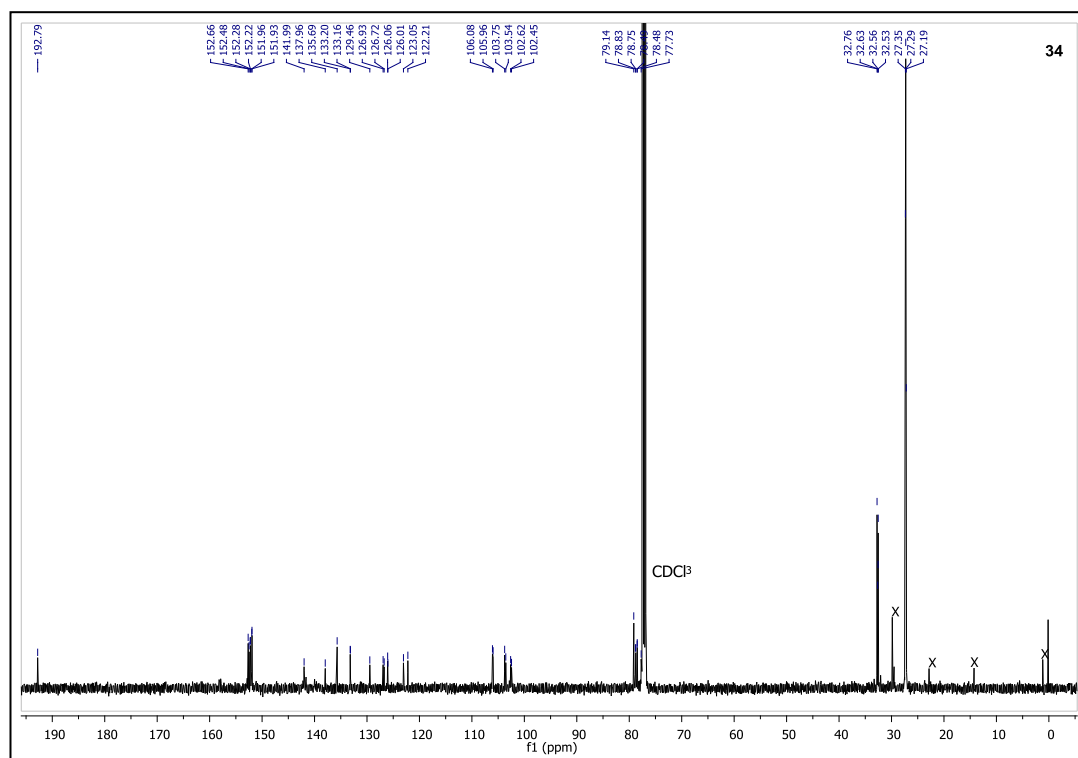


Figure 8.78: ¹³C NMR Spectrum of **34** in CDCl₃ (125MHz).

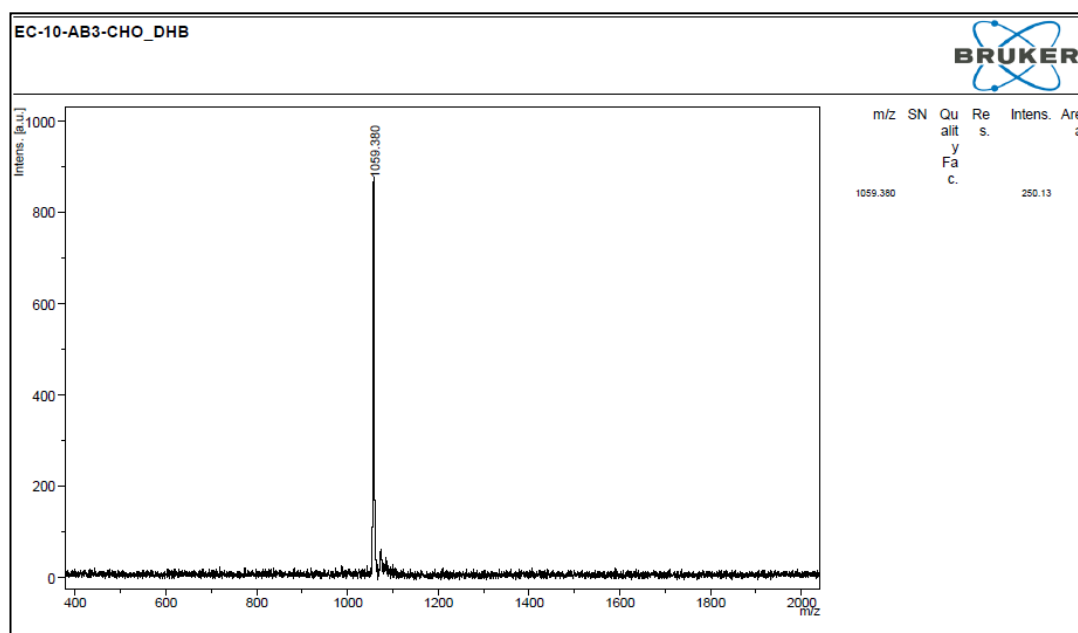


Figure 8.79: MALDI-TOF MS Spectrum of **34**.

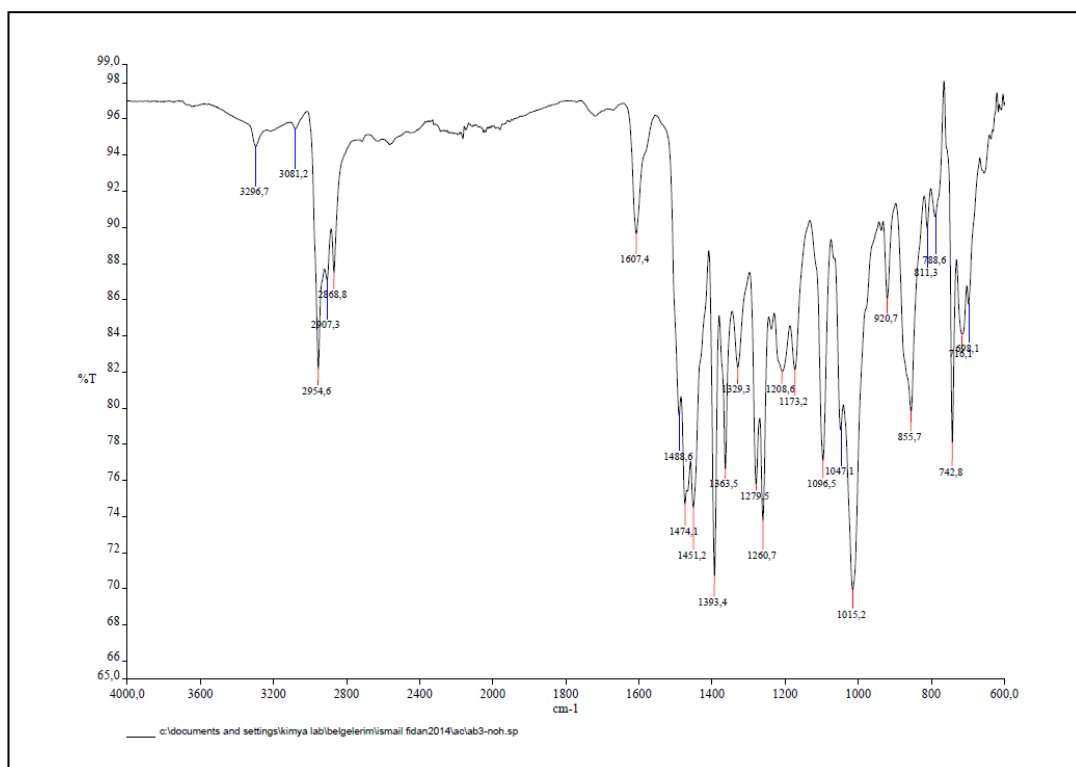


Figure 8.80: FT-IR Spectrum of **36**.

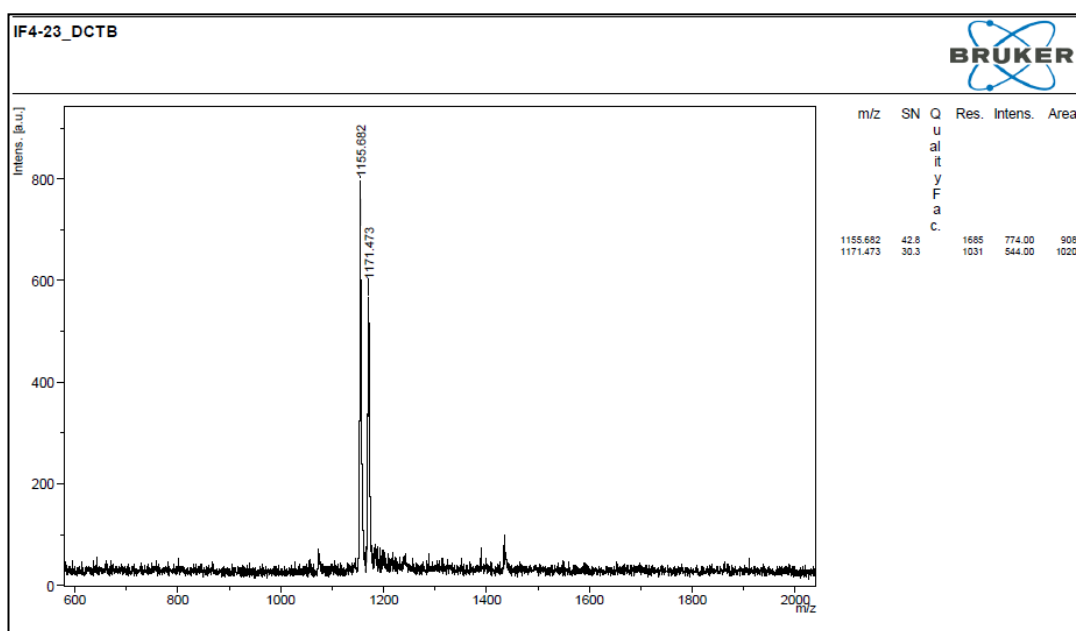


Figure 8.81: MALDI-TOF MS Spectrum of **36**.

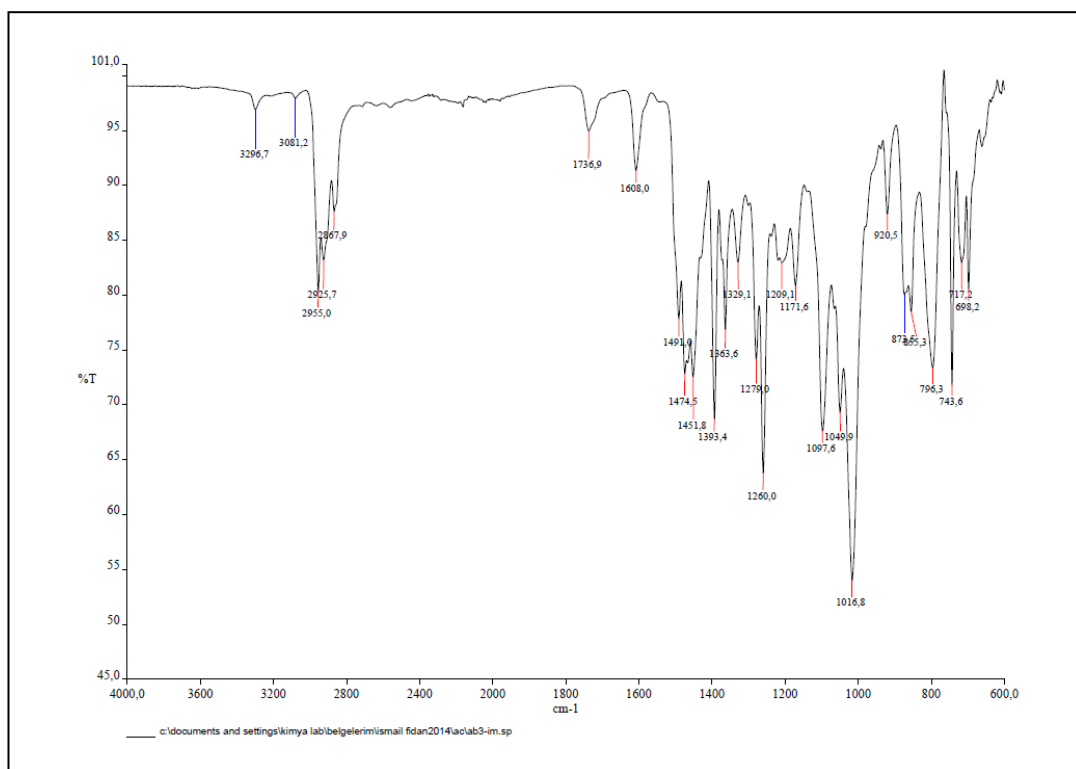


Figure 8.82: FT-IR Spectrum of **38**.

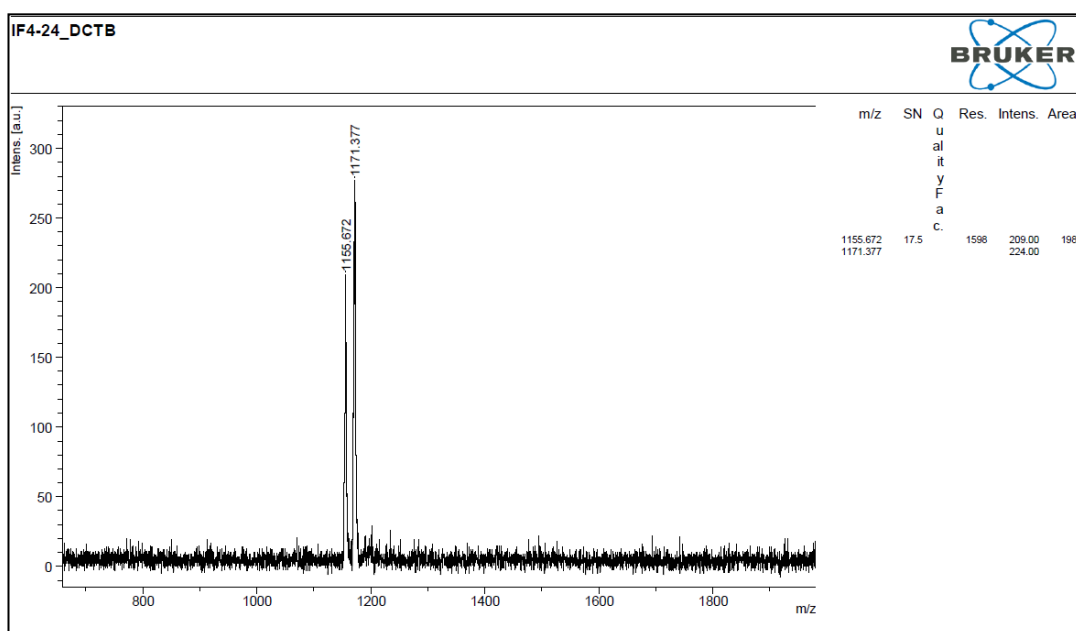


Figure 8.83: MALDI-TOF MS Spectrum of **38**.

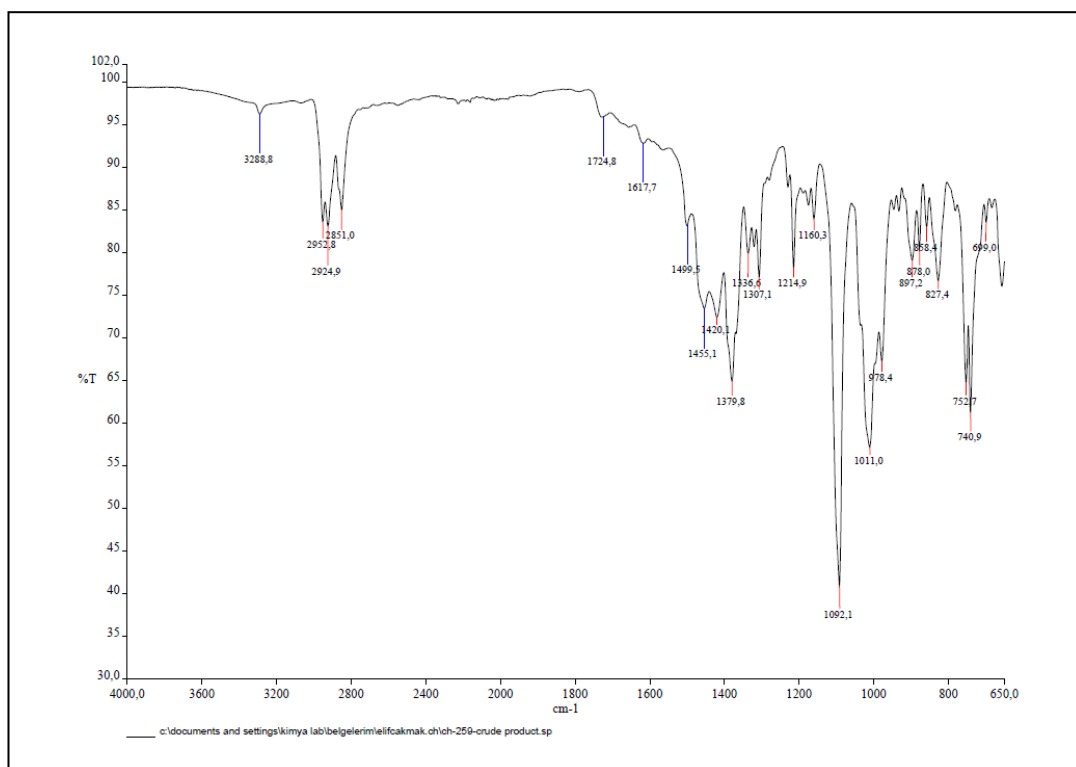


Figure 8.84: FT-IR Spectrum of **39**.

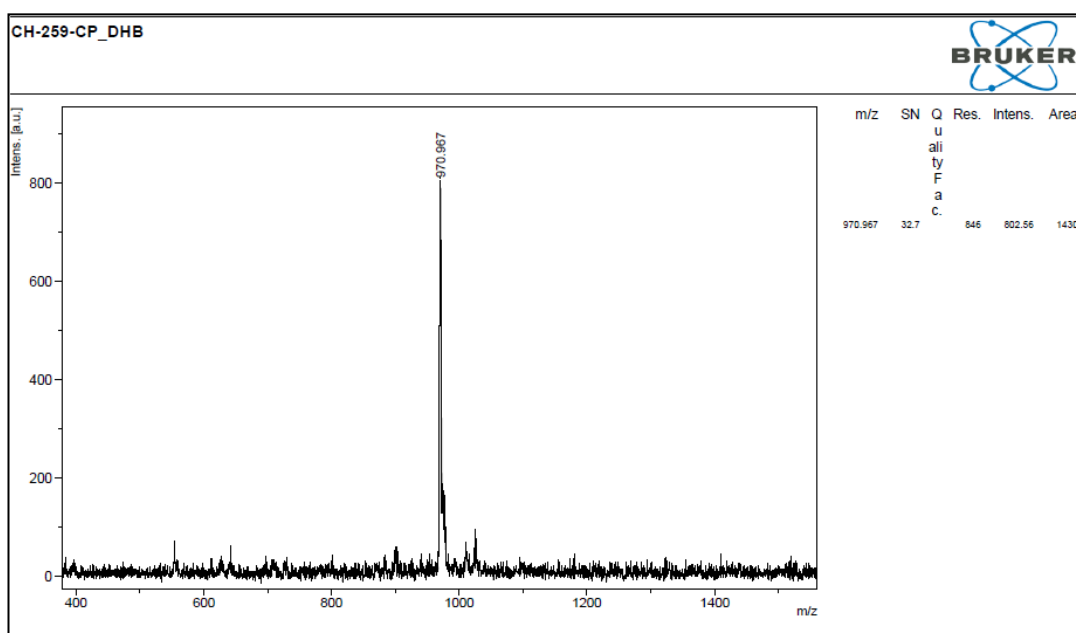


Figure 8.85: MALDI-TOF MS Spectrum of **39**.

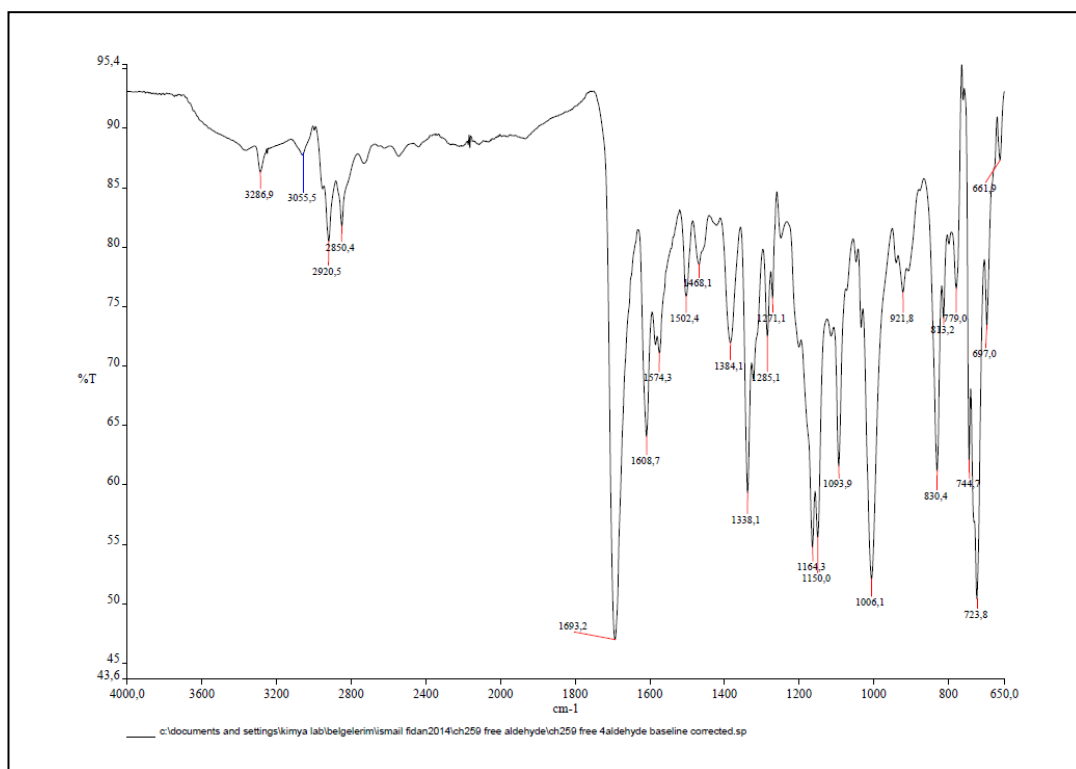


Figure 8.86: FT-IR Spectrum of **40**.

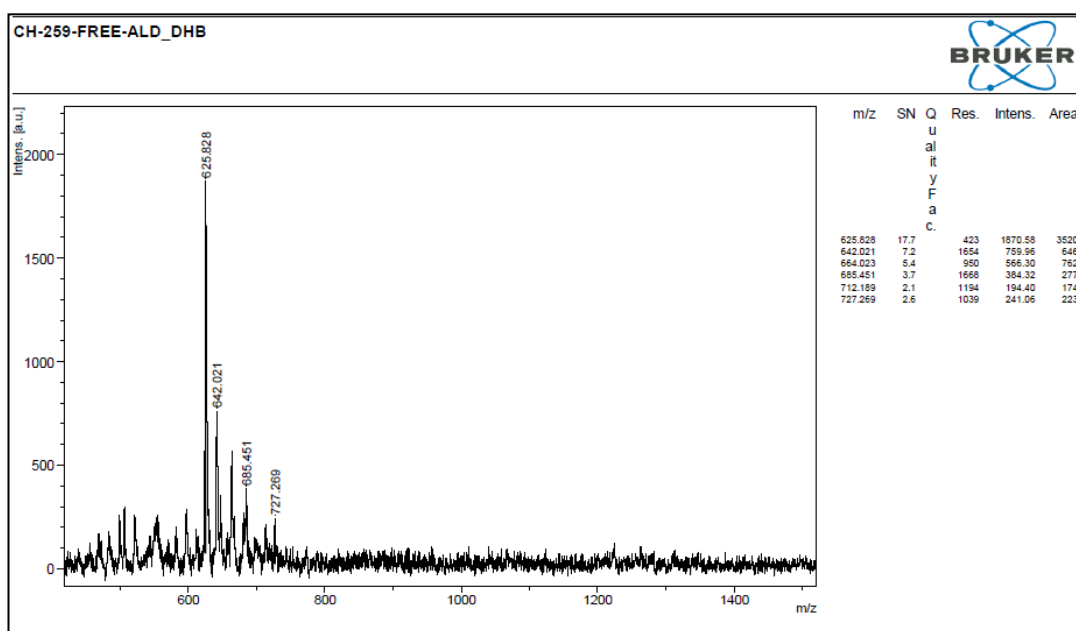


Figure 8.87: MALDI-TOF MS Spectrum of **40**.

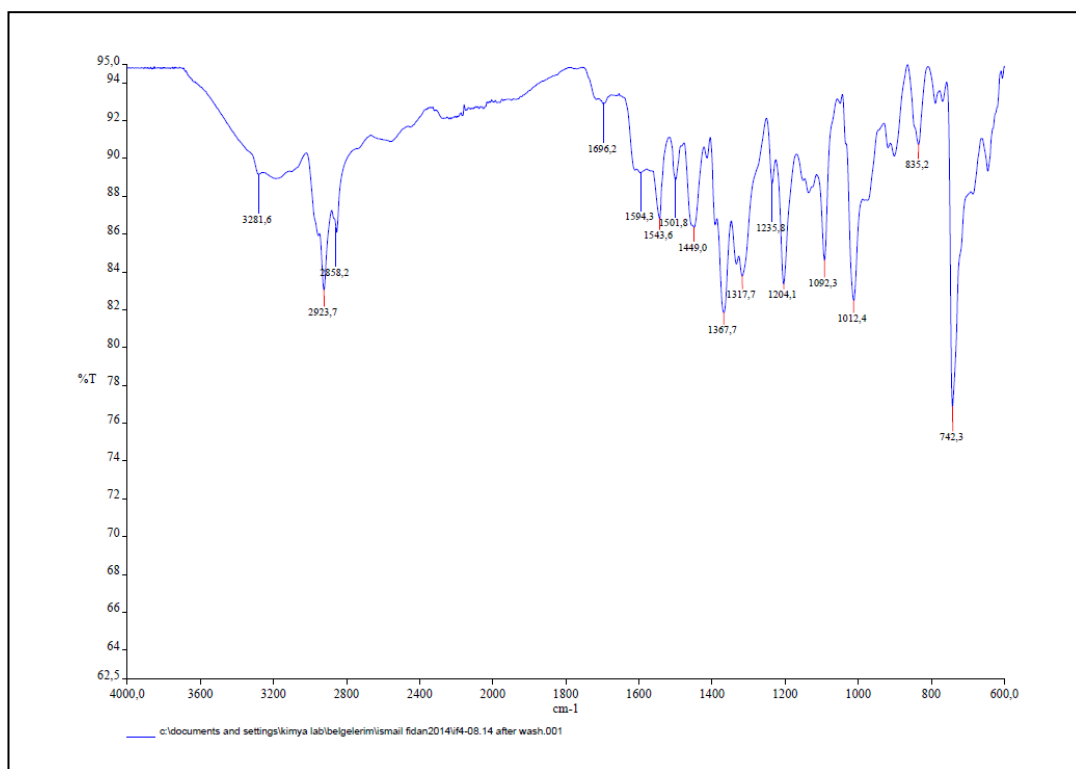


Figure 8.88: FT-IR Spectrum of **42**.

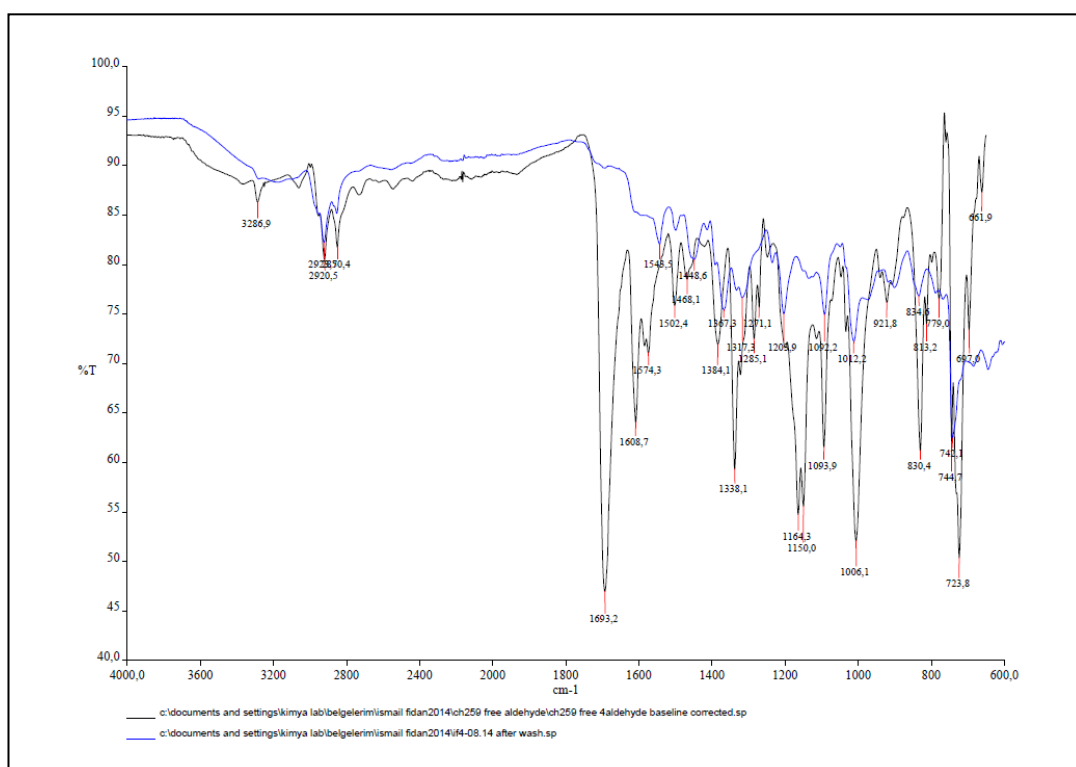


Figure 8.89: FT-IR Spectrum of **40** vs. **42**.

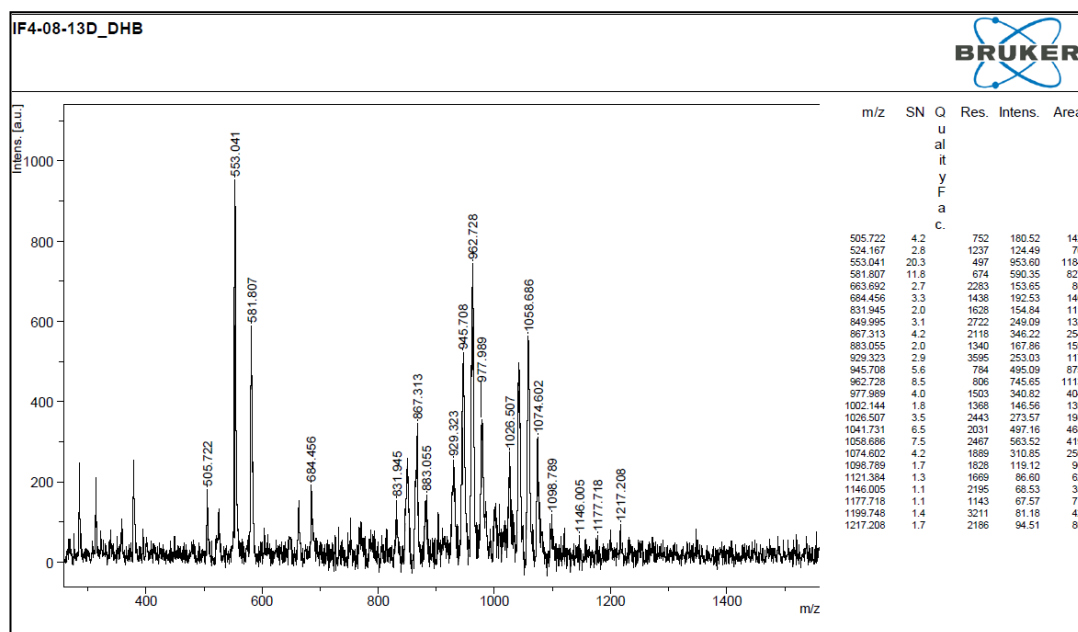


Figure 8.90: MALDI-TOF MS Spectrum of **42**.

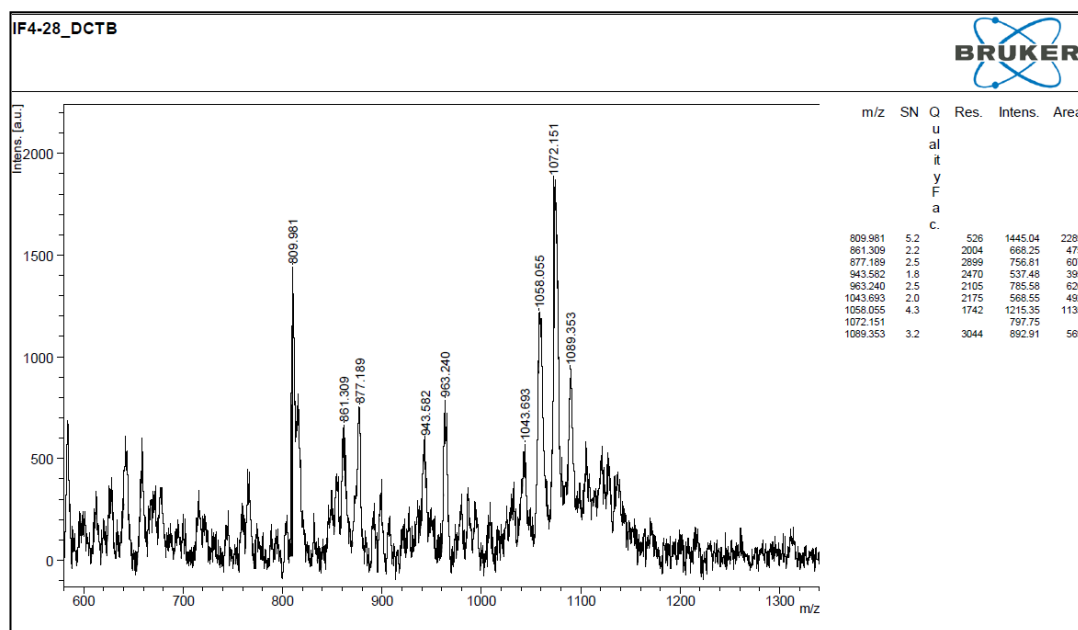


Figure 8.91: MALDI-TOF MS Spectrum of **44**.

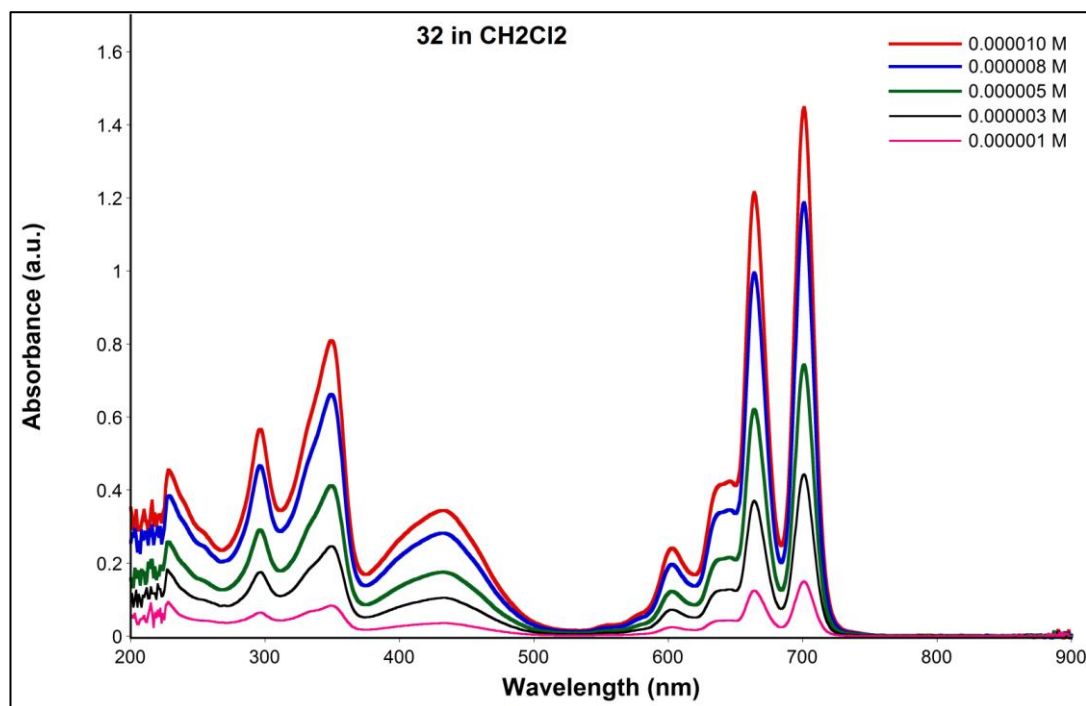


Figure 8.92: UV-Vis Spectra of **32** in Dichloromethane.

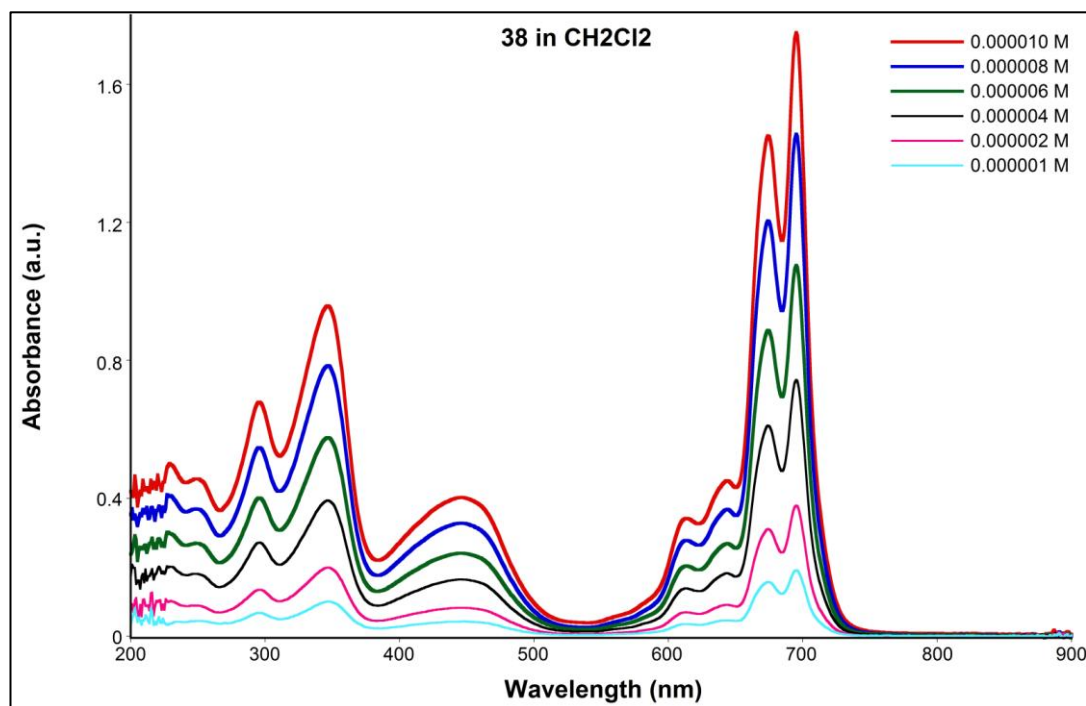


Figure 8.93: UV-Vis Spectra of **38** in Dichloromethane.

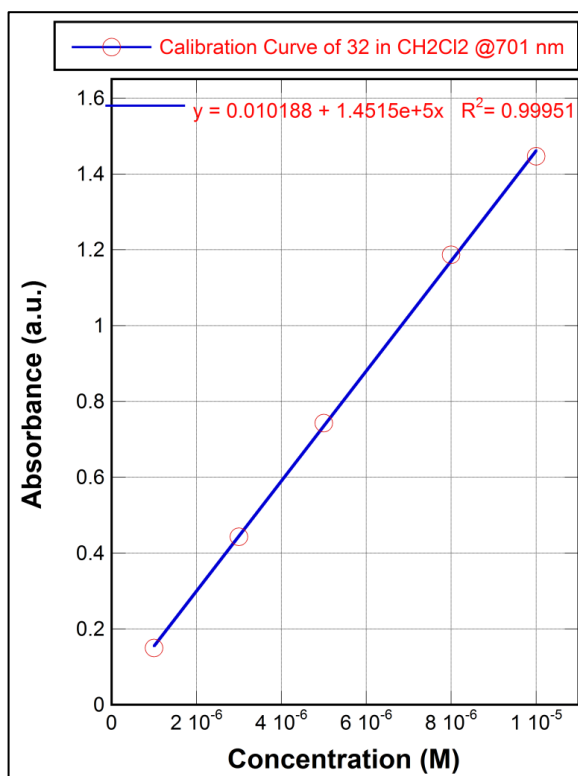


Figure 8.94: Calibration Curve of **32** in Dichloromethane at 701 nm.

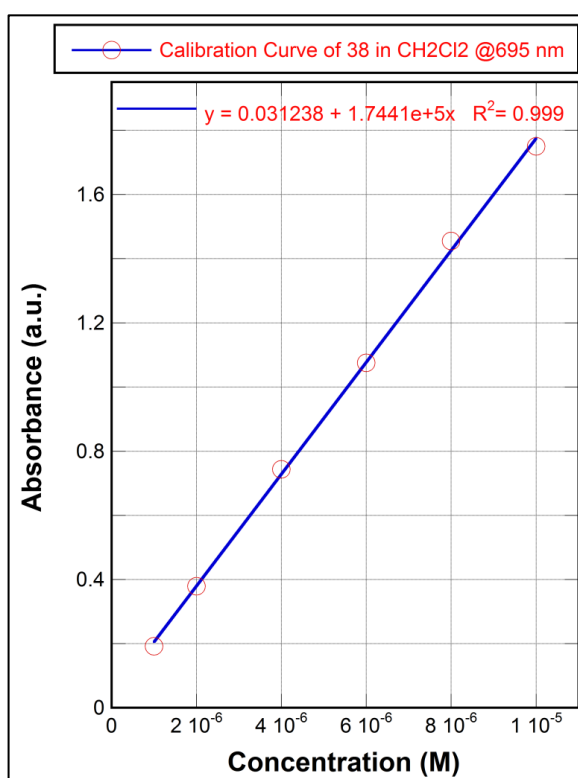


Figure 8.95: Calibration Curve of **38** in Dichloromethane at 695 nm.

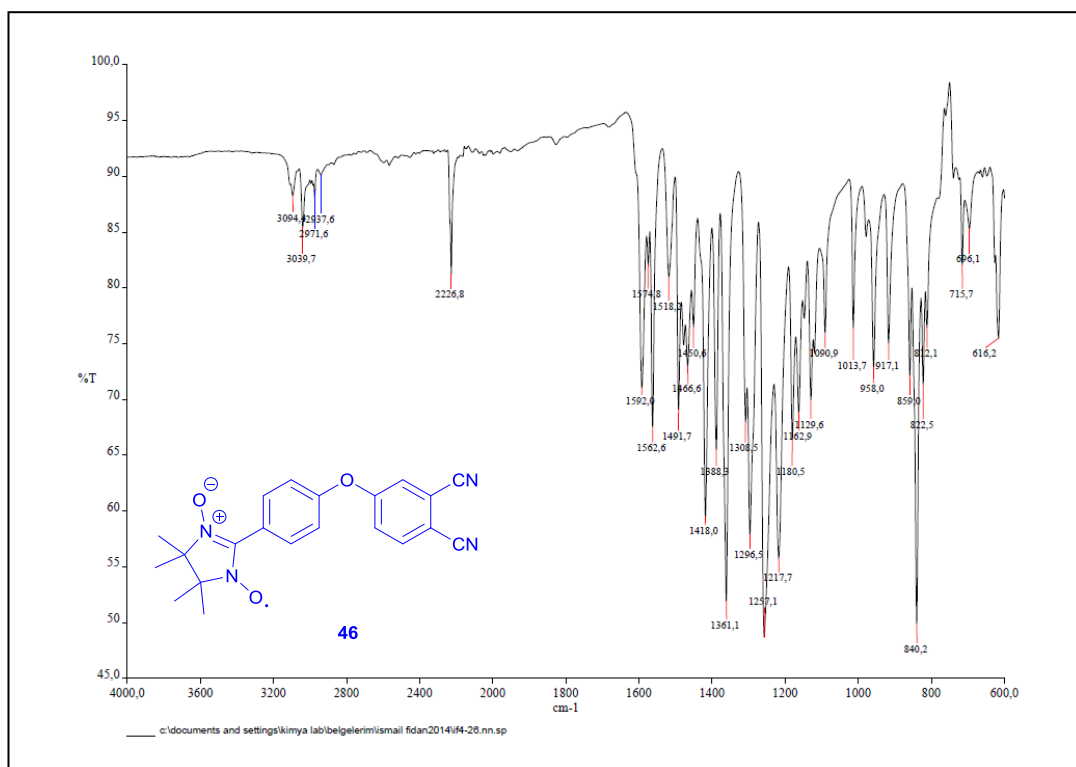


Figure 8.96: FT-IR Spectrum of **46**.

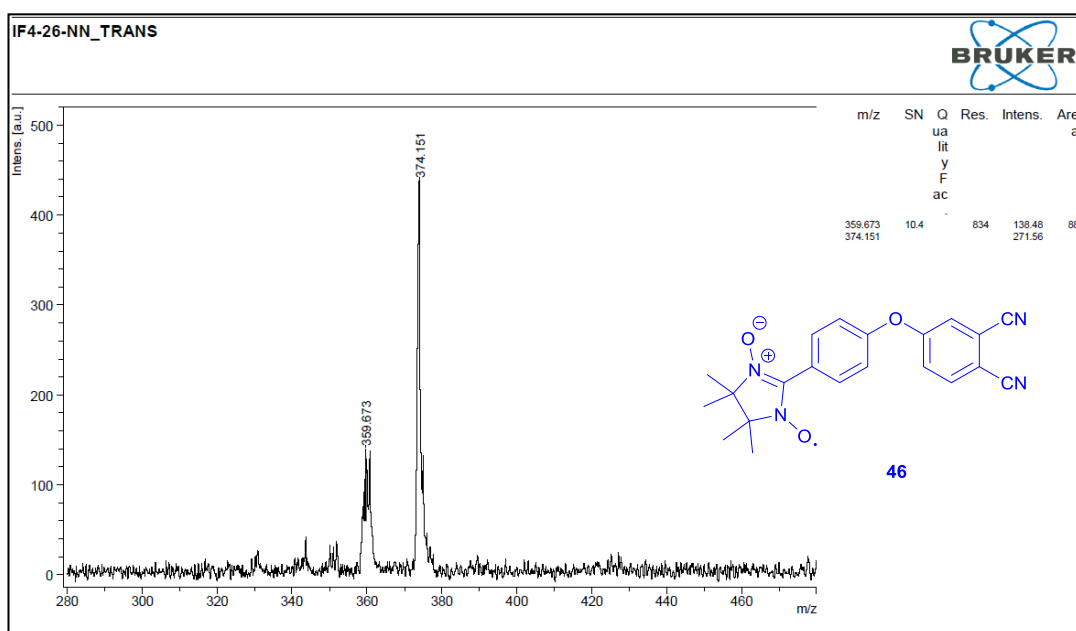


Figure 8.97: MALDI-TOF MS Spectrum of **46**.

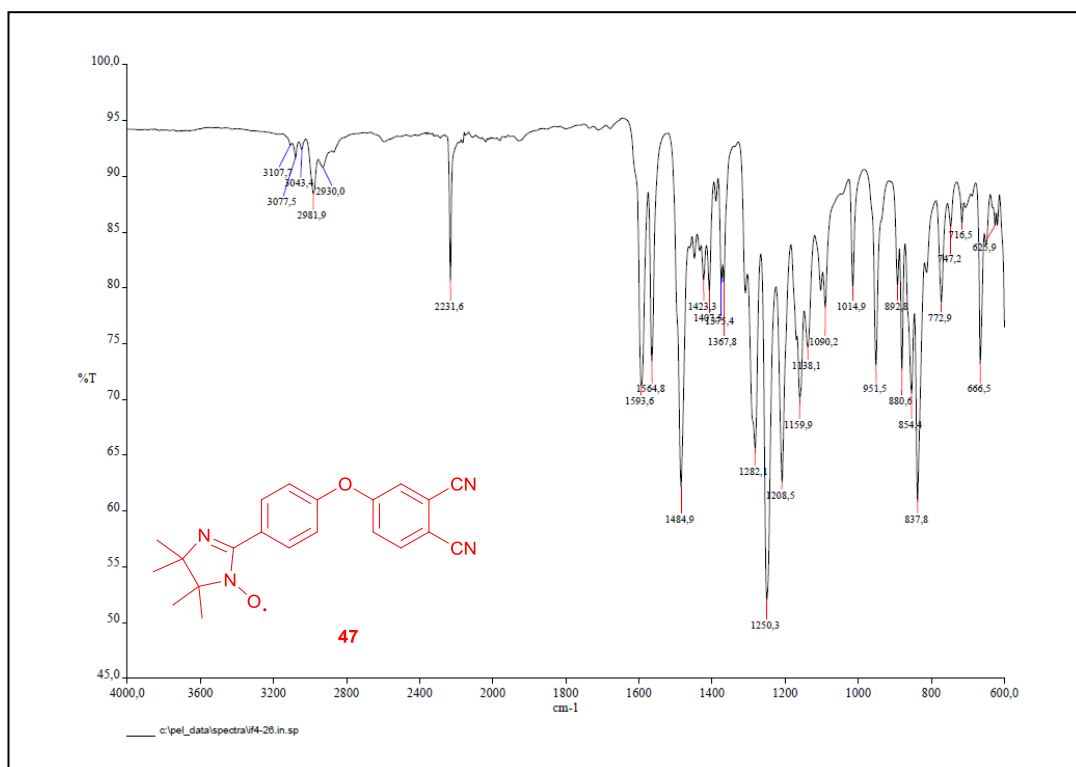


Figure 8.98: FT-IR Spectrum of **47**.

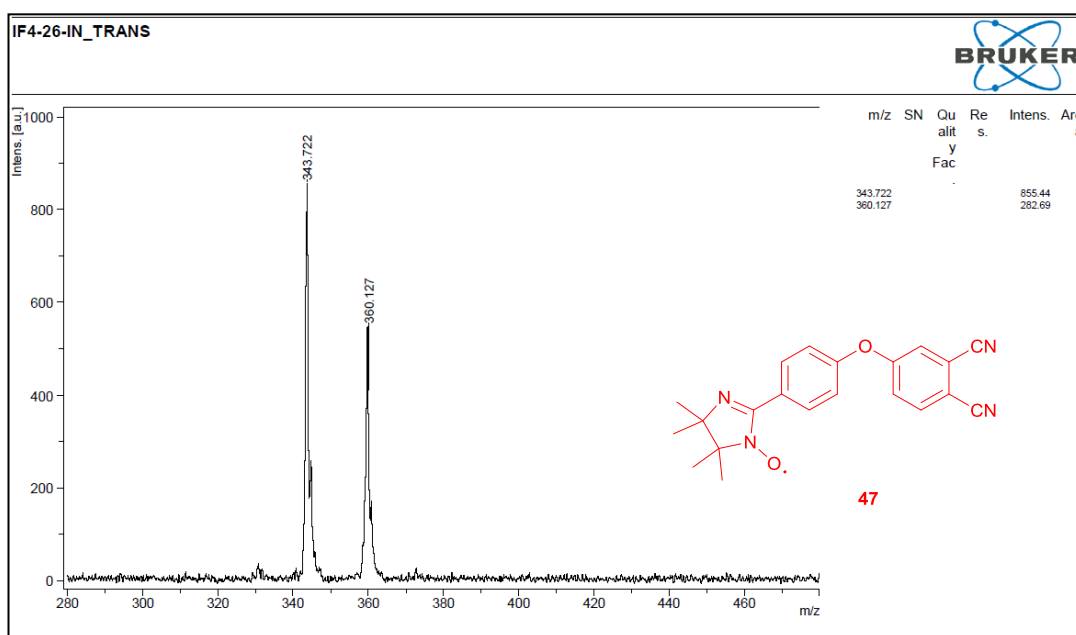


Figure 8.99: MALDI-TOF MS Spectrum of **47**.

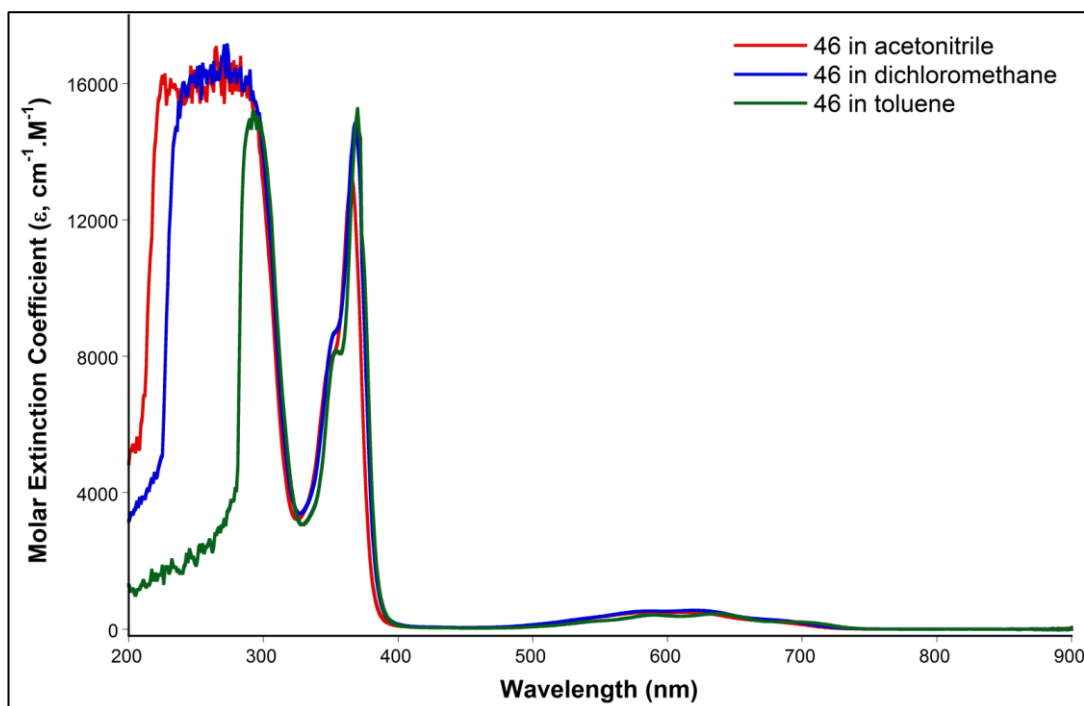


Figure 8.100: UV-vis Spectra of **46** in Acetonitrile, Dichloromethane and Toluene.

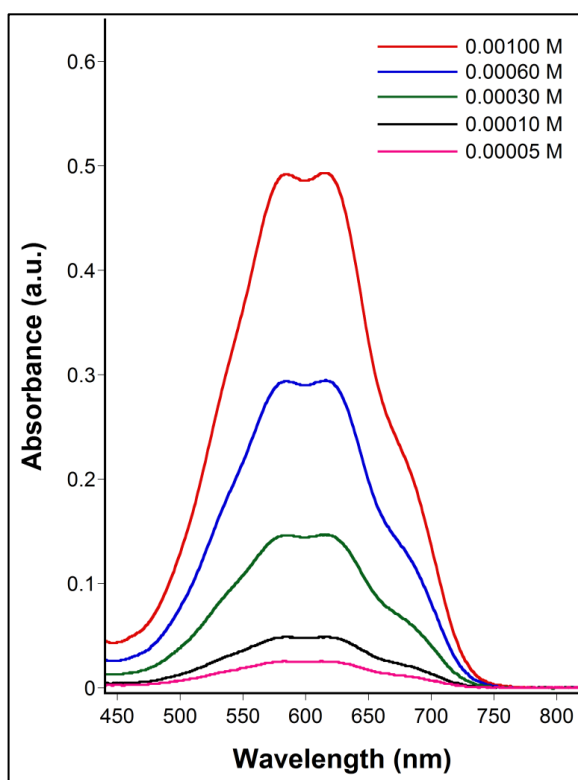


Figure 8.101: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **46** in Acetonitrile.

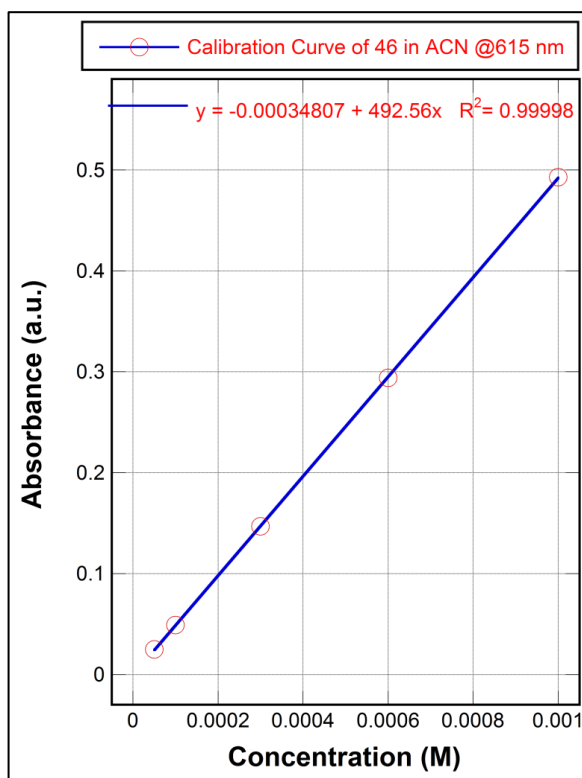


Figure 8.102: Calibration Curve of **46** in Acetonitrile at 615 nm.

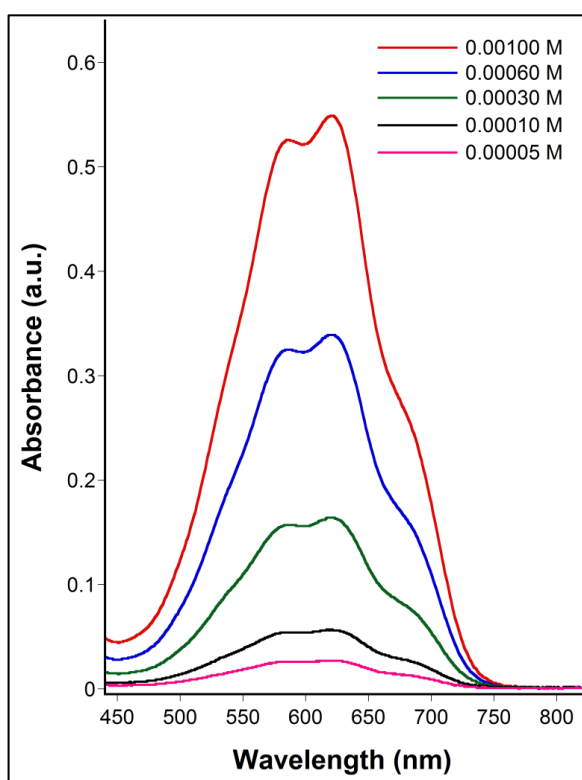


Figure 8.103: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **46** in Dichloromethane.

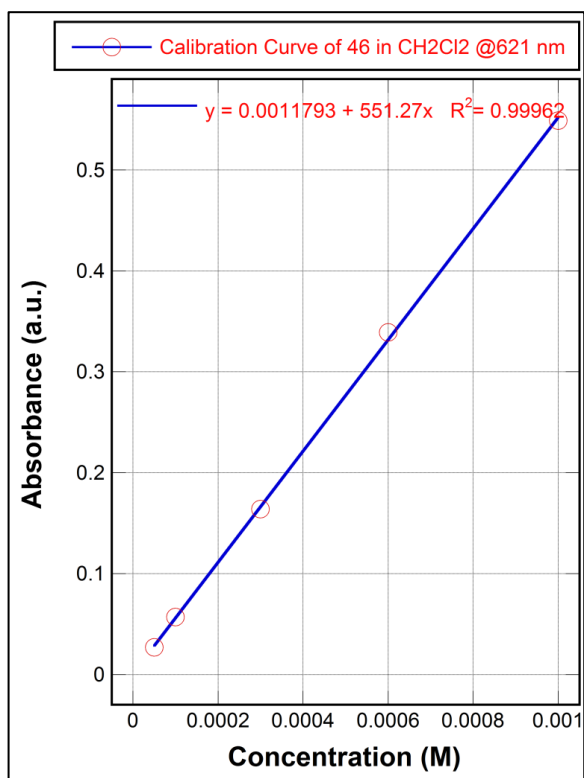


Figure 8.104: Calibration Curve of **46** in Dichloromethane at 621 nm.

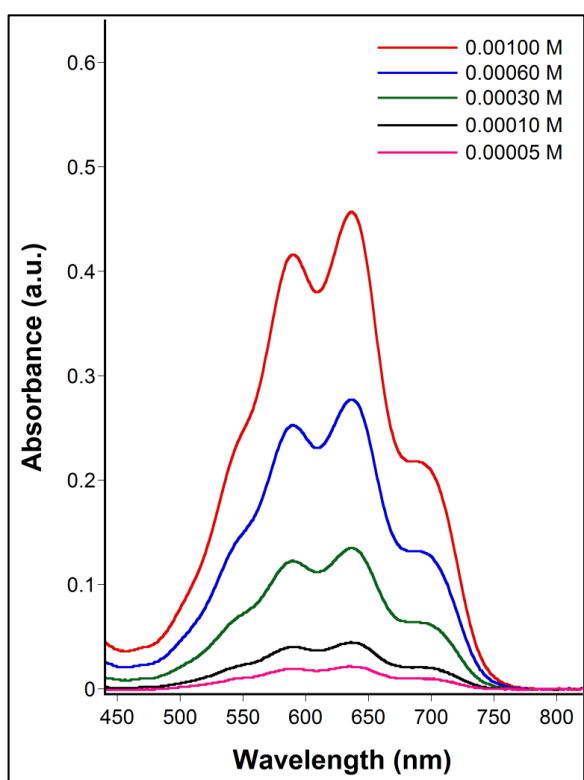


Figure 8.105: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **46** in Toluene.

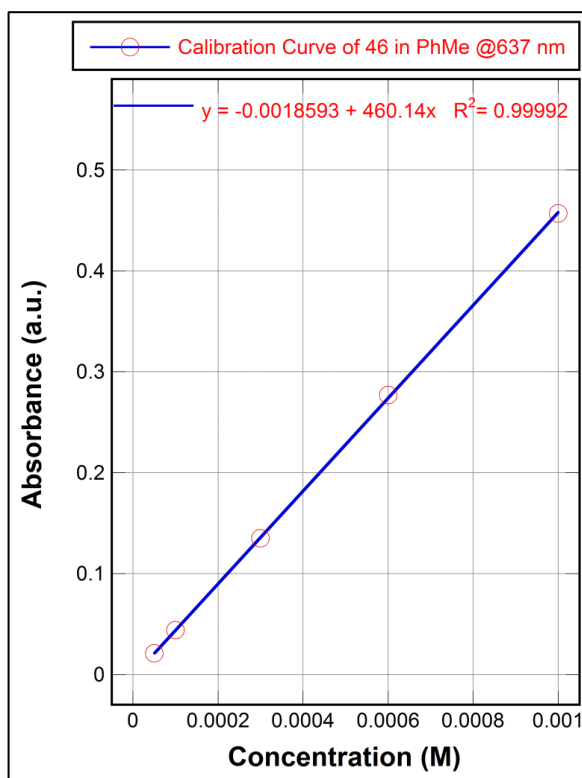


Figure 8.106: Calibration Curve of **46** in Toluene at 637 nm.

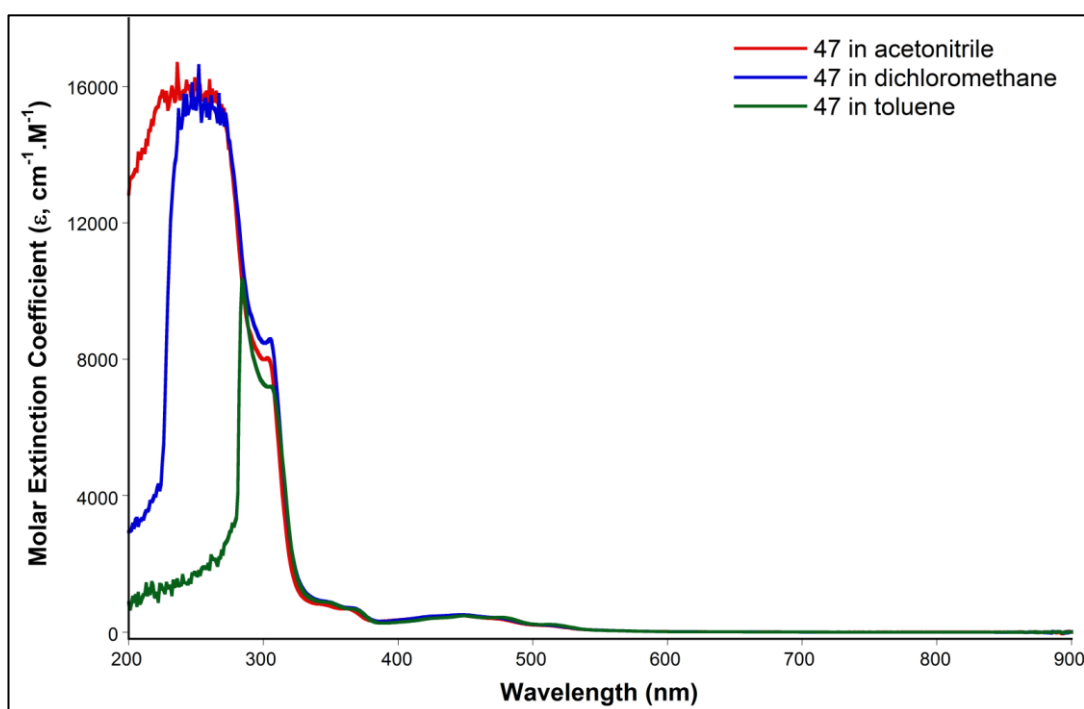


Figure 8.107: UV-vis Spectra of **47** in Acetonitrile, Dichloromethane and Toluene.

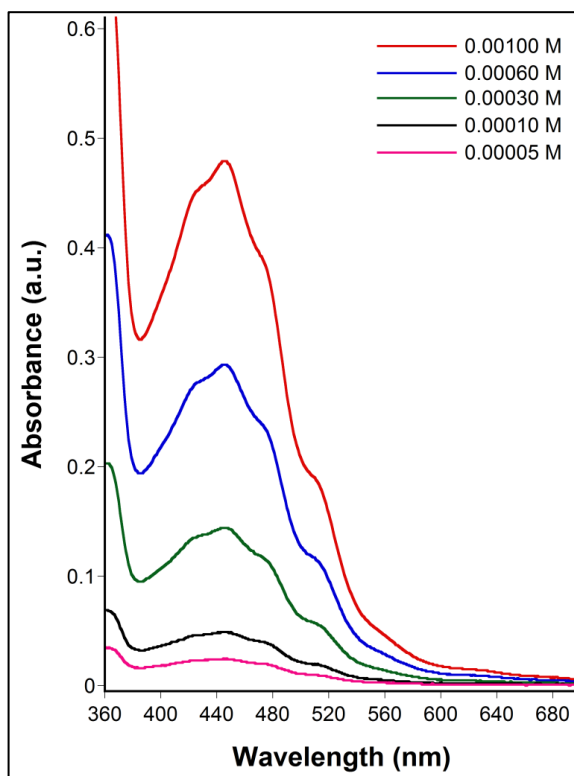


Figure 8.108: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **47** in Acetonitrile.

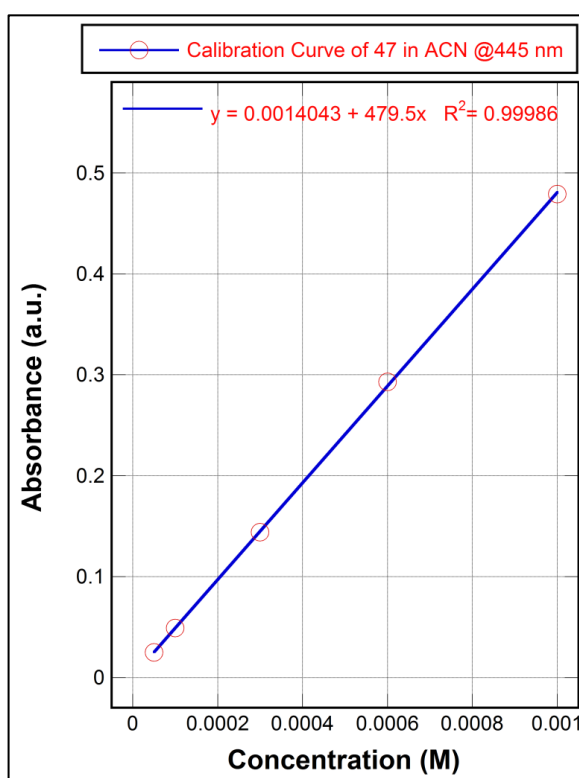


Figure 8.109: Calibration Curve of **47** in Acetonitrile at 445 nm.

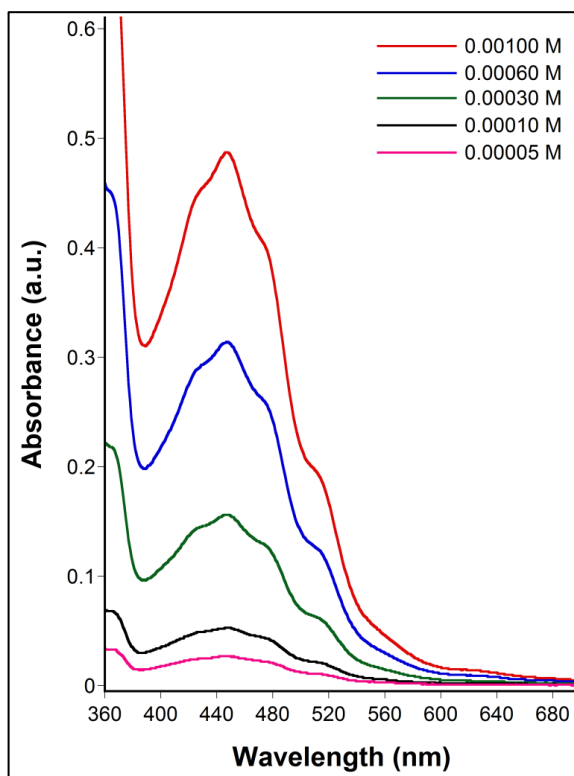


Figure 8.110: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **47** in Dichloromethane.

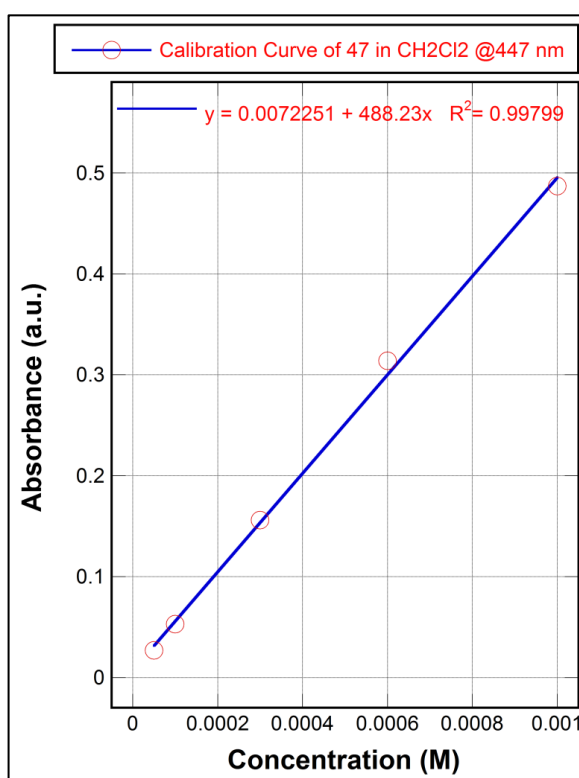


Figure 8.111: Calibration Curve of **47** in Dichloromethane at 447 nm.

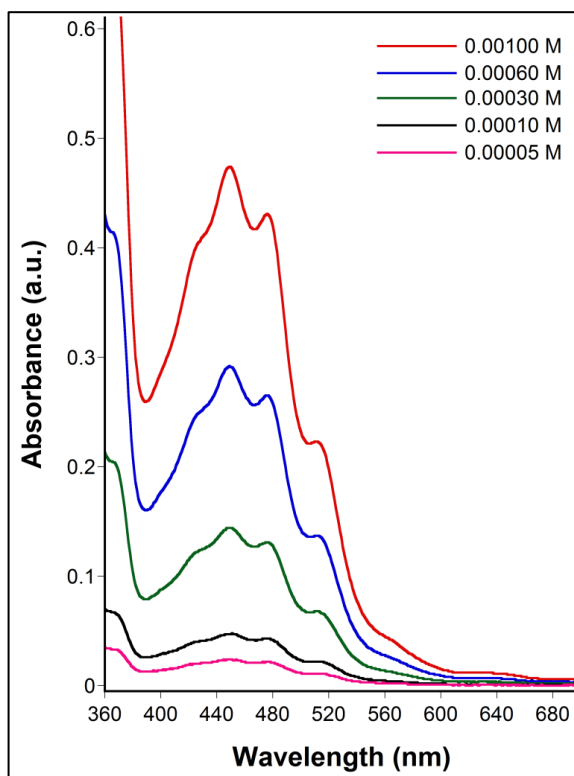


Figure 8.112: UV-Vis Spectra for $n \rightarrow \pi^*$ Transitions of **47** in Toluene.

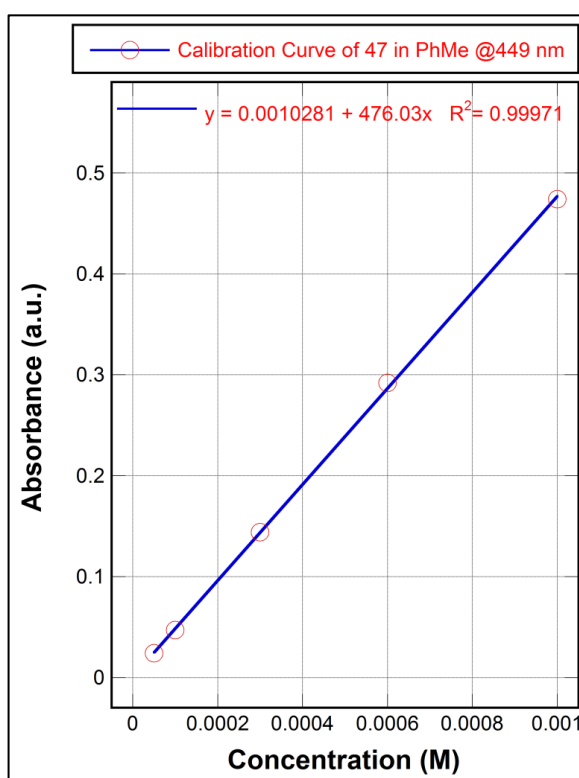


Figure 8.113: Calibration Curve of **47** in Toluene at 631 nm.

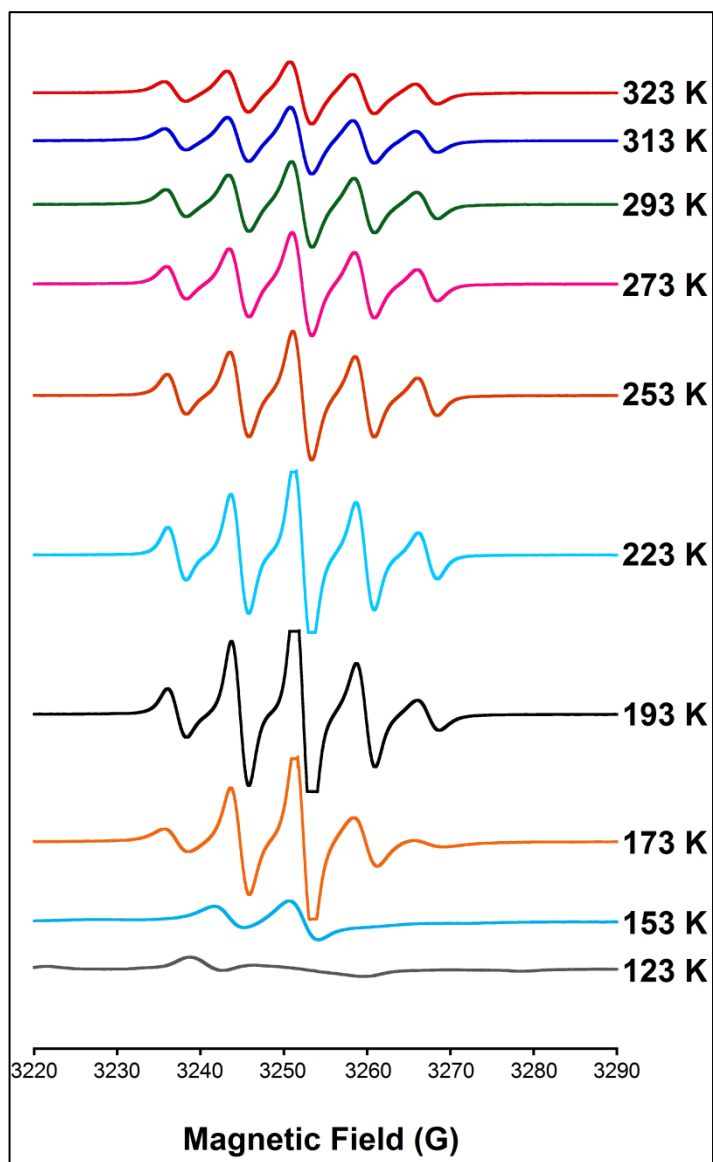


Figure 8.114: X-band EPR Spectra of 46×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

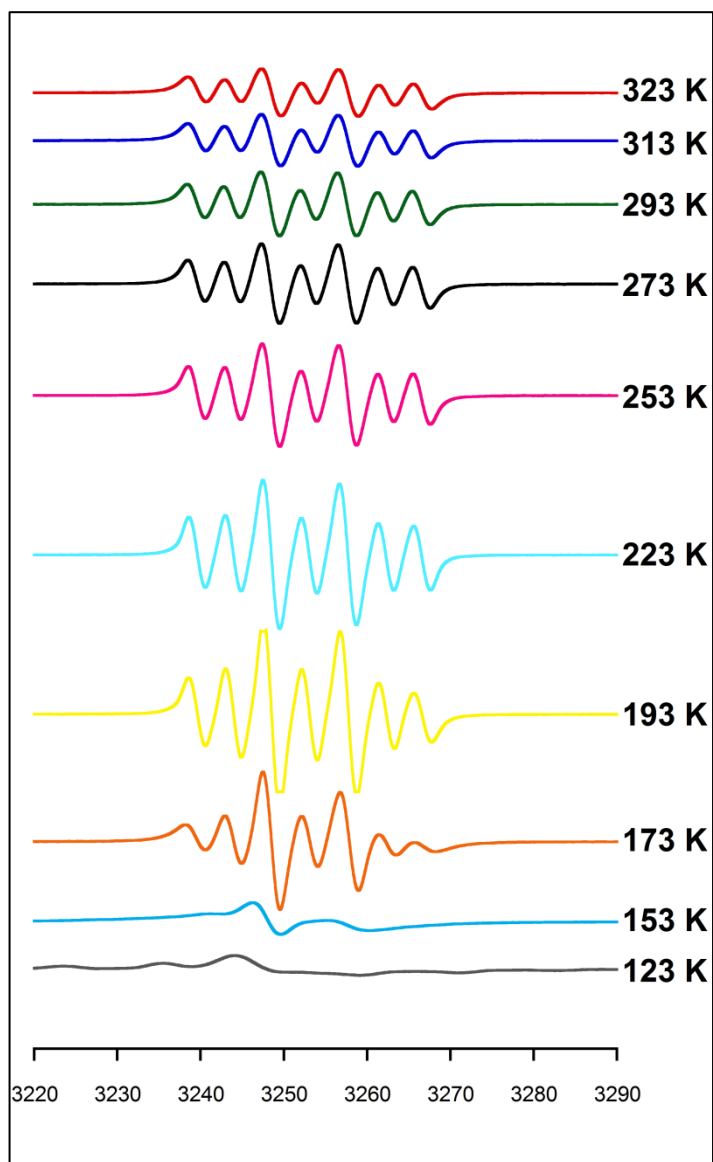


Figure 8.115: X-band EPR Spectra of 47×10^{-4} M in Dichloromethane-Toluene (1:1) Solution at Different Temperature.

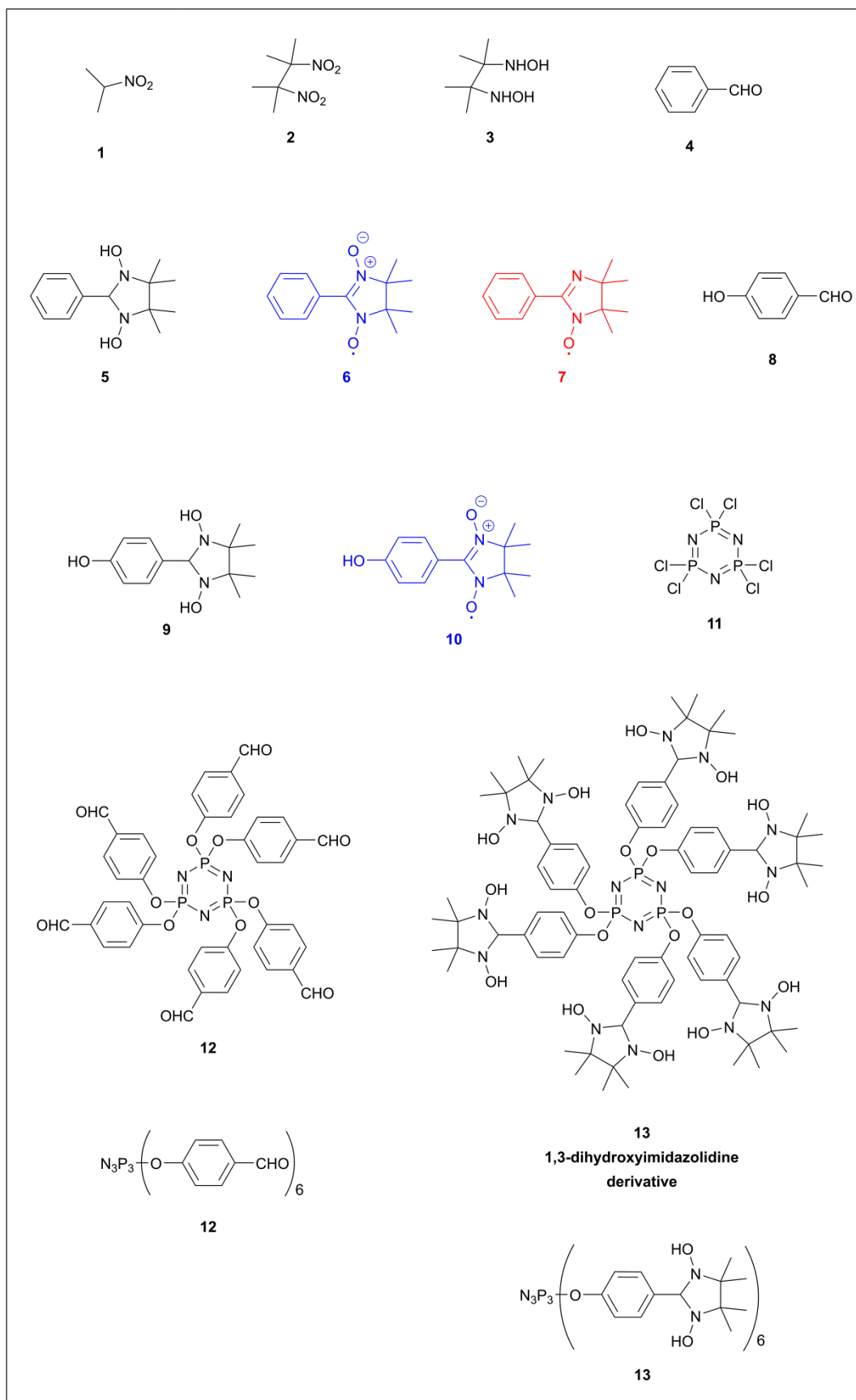
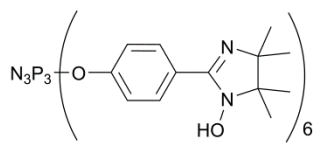
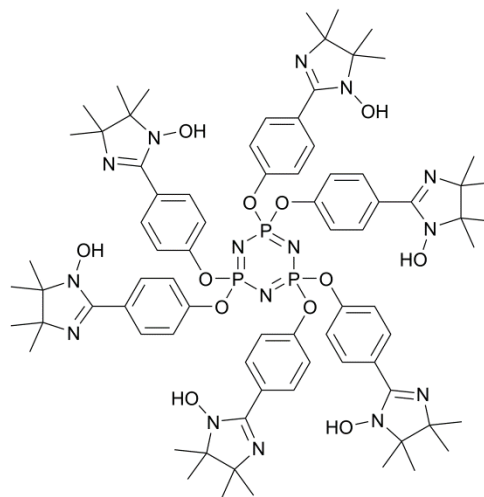


Figure 8.116: Structures of the Compounds.1/7.



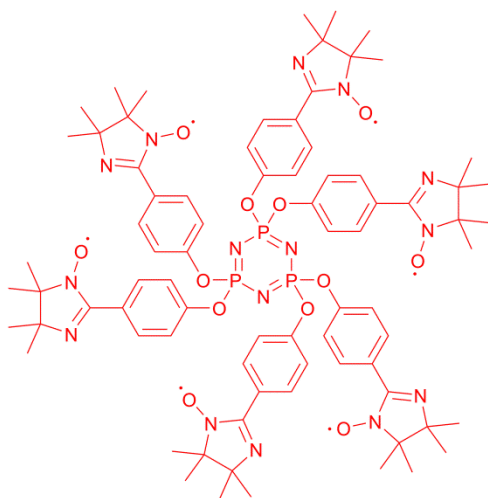
14

1-hydroxy-2-imidazoline
derivative



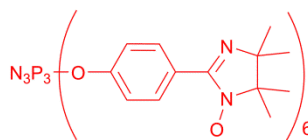
14

1-hydroxy-2-imidazoline
derivative



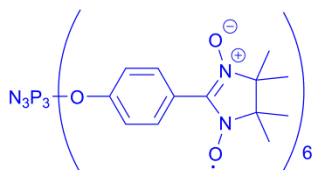
15

target hexaradical



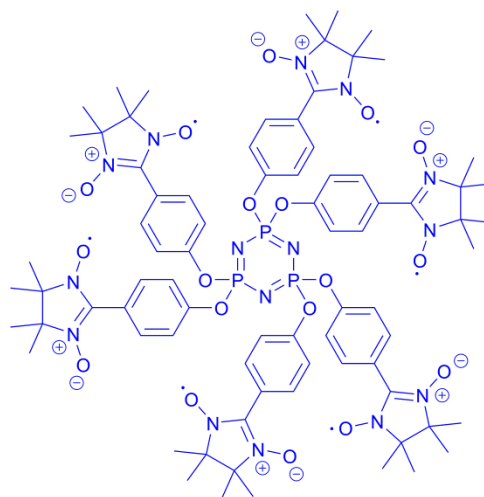
15

target hexaradical



16

target hexaradical



16

target hexaradical

Figure 8.117: Structures of the Compounds.2/7.

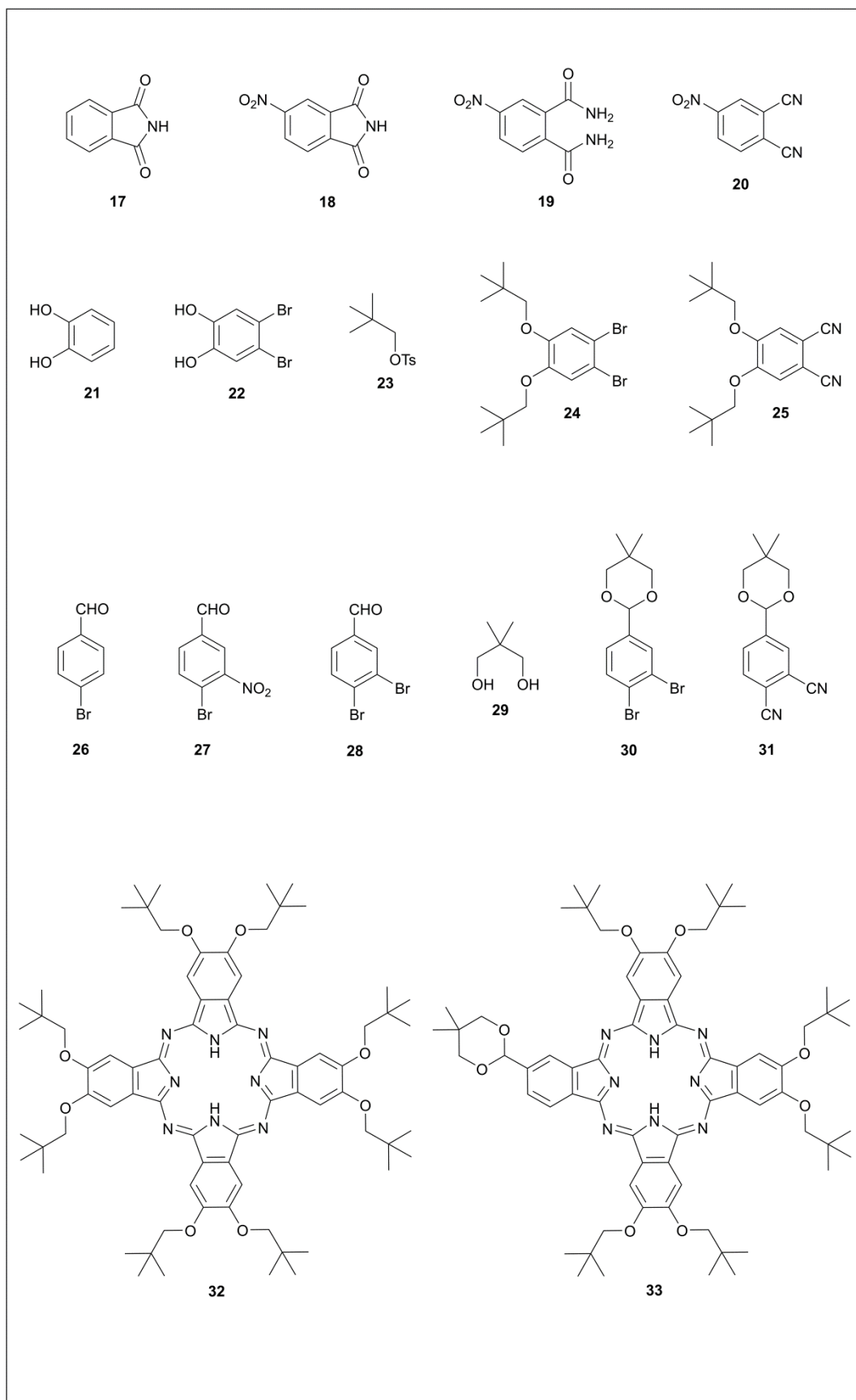


Figure 8.118: Structures of the Compounds.3/7.

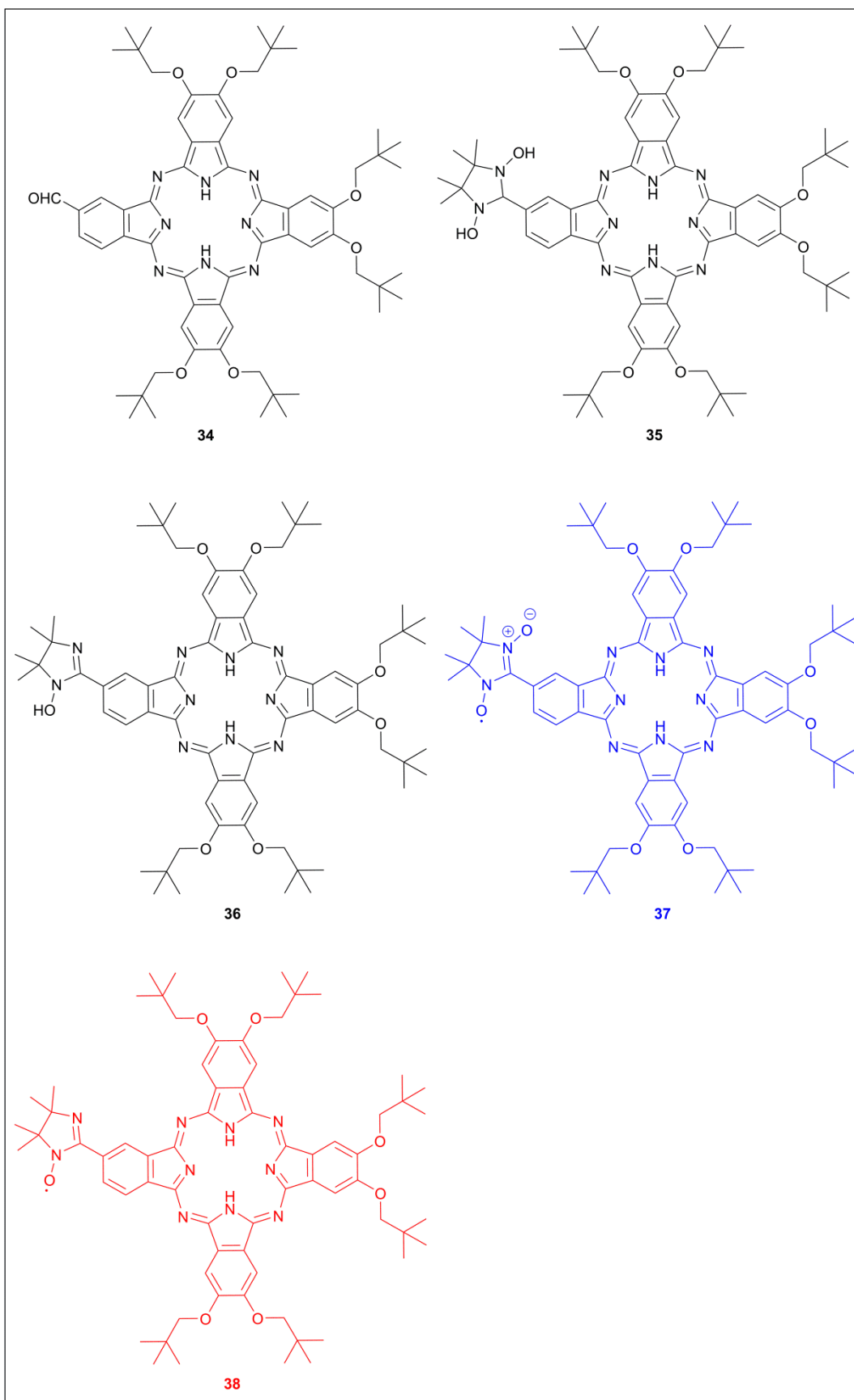


Figure 8.119: Structures of the Compounds.4/7.

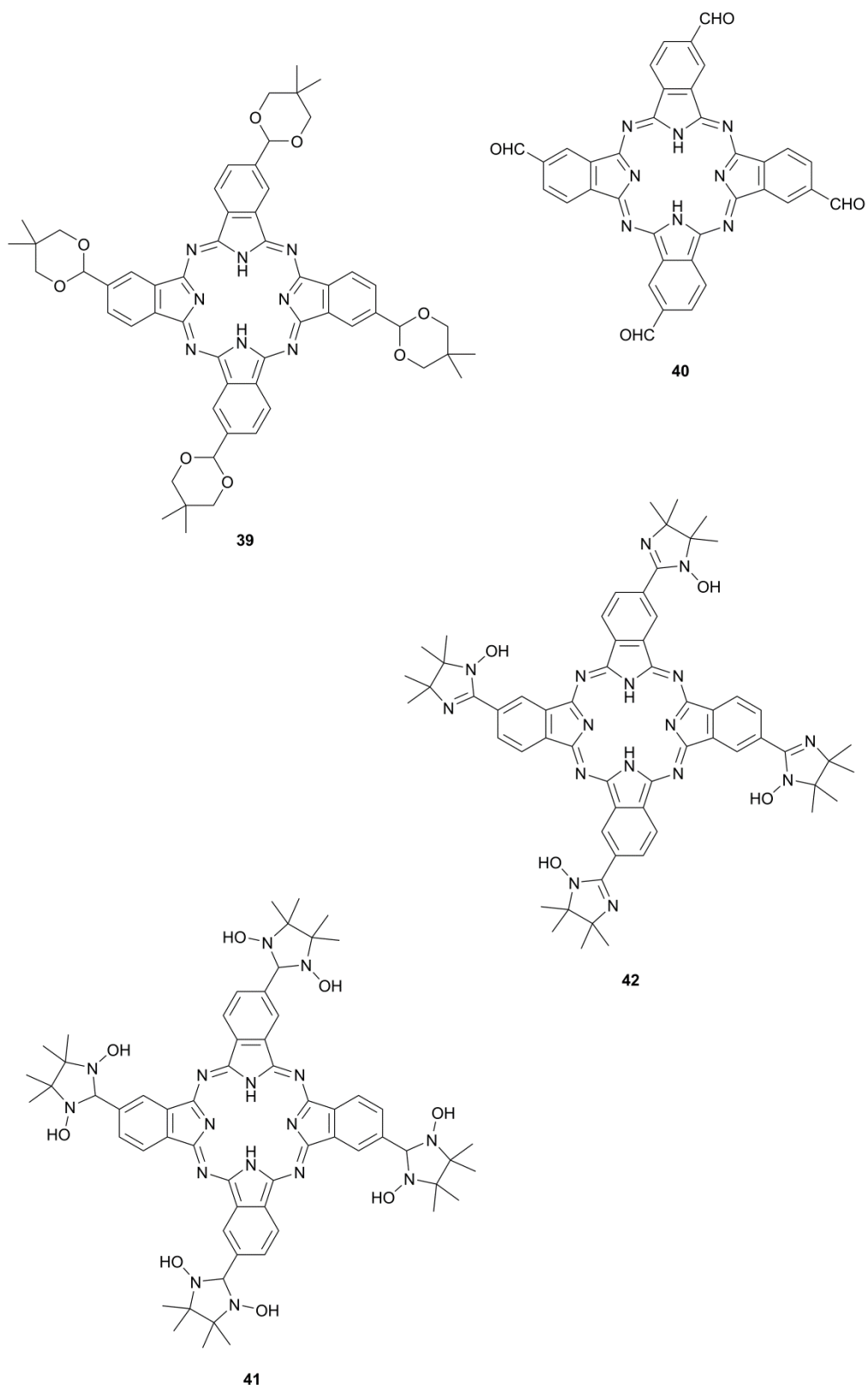
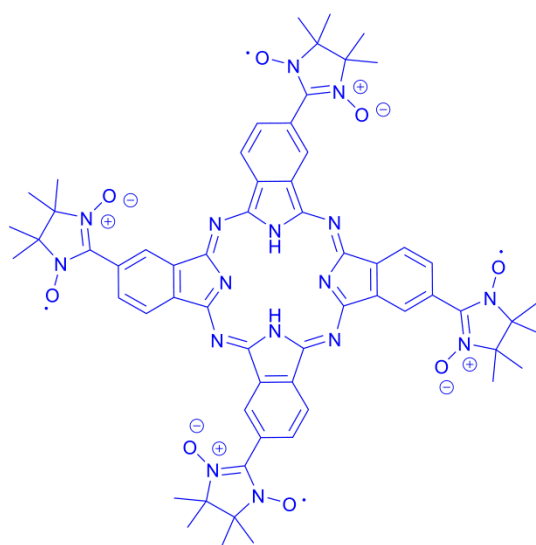
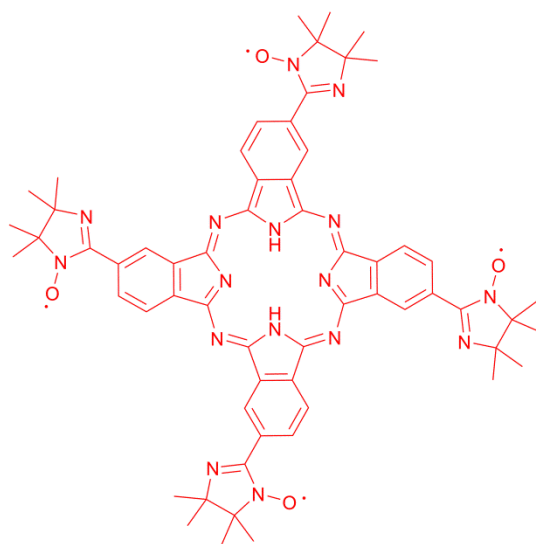


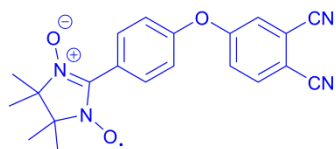
Figure 8.120: Structures of the Compounds.5/7.



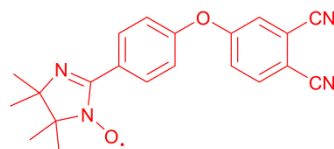
43



44



46



47

Figure 8.121: Structures of the Compounds.6/7.

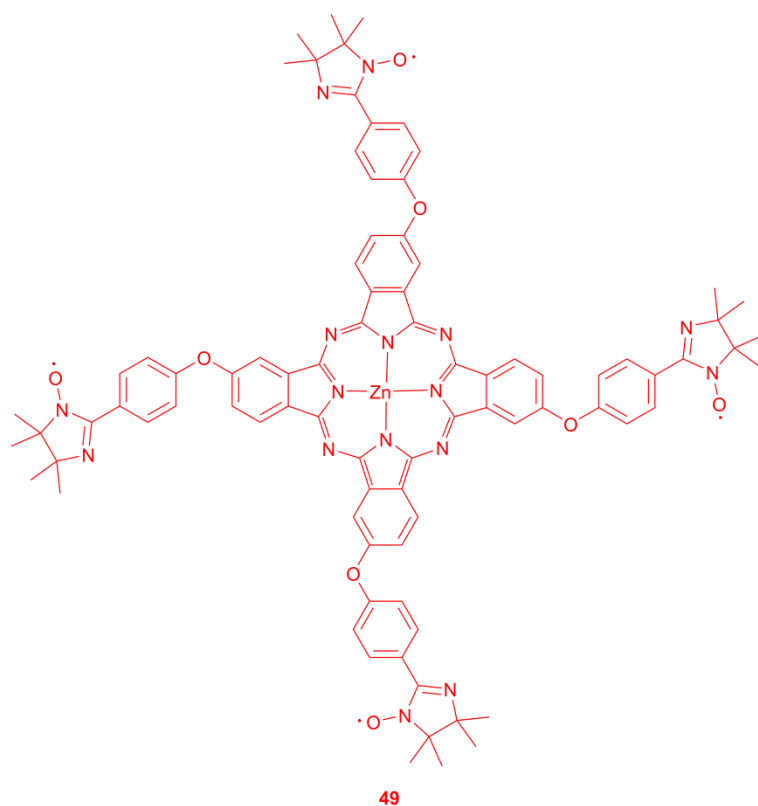
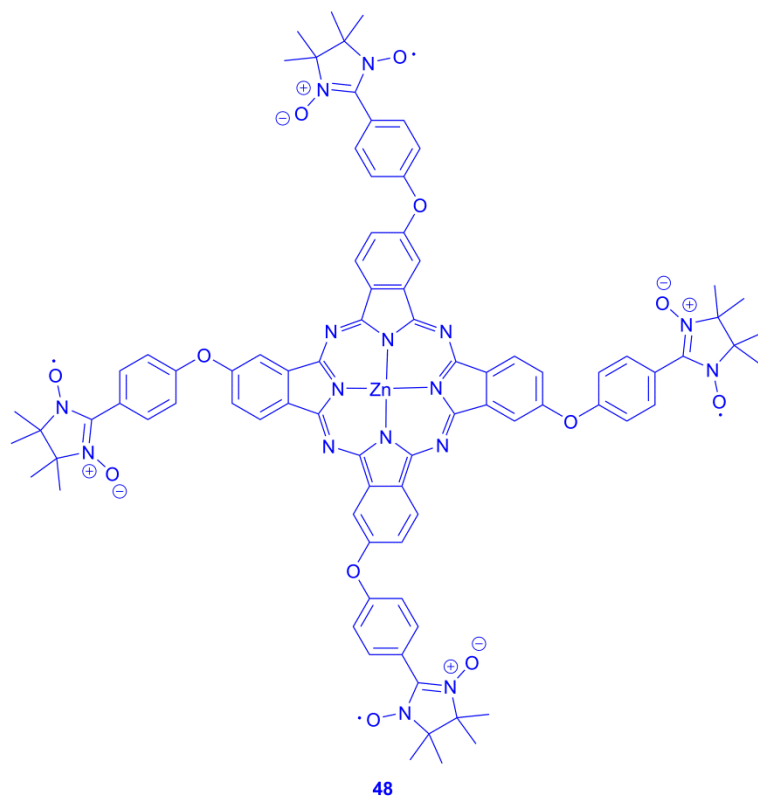


Figure 8.122: Structures of the Compounds.7/7.

9. CONCLUSION

The radical chemistry attracts again considerable attention, as radical groups have emerged as extremely useful active materials involve in numerous applications reported in recent literature, like radical polymer, magnetic devices or flexible batteries for example. Among the radical chemistry, the synthesis of nitronyl and imino nitroxide polyradical is a hard challenge due to the difficulty to control the number and gender of radicals present in the molecule as well as to characterize such molecules in an unequivocal way. In the framework of this thesis, we were interested to synthesis nitronyl and imino nitroxide radical covalently link to the skeleton of cyclotriphosphazene and phthalocyanine platform to obtain polyradical bearing six and four moieties respectively.

The synthesis of cyclotriphosphazene bearing nitronyl and imino nitroxide radical was achieved in good yield following two different synthetic routes that allow to control the number and gender of radical on the molecule. Cyclotriphosphazene bearing imino nitroxide was obtained by the classical Ullman route consisting of the condensation of an adequate aldehyde with 2,3-Bis(hydroxylamino)-2,3-dimethylbutane (**3**) follow by its oxidation whereas cyclotriphosphazene bearing nitronyl nitroxide was synthesis by a so-called “pre-form strategy”. In the pre-form strategy, the radical is first generated on a synthon, the 2-(4-hydroxyphenyl)-4,4,5,5-tetramethyl-2-imidazoline-3-oxide-1-oxyl (**10**) which will then introduced onto the cyclotriphosphazene core by nucleophilic substitution in acetone/ K_2CO_3 . A most important point was to develop two methods of quantification and characterization using UV-vis and electrochemistry which are two easy methods to handle. Especially UV-vis spectroscopy is a routine equipment available in mostly laboratories which requires little raw material. These two methods were proof to be valid for imino or nitroxide radicals indifferently.

The phthalocyanine platform was less easy to undertaken as the multi-step synthesis was less trivial. Consequently, in a first objective, a phthalocyanine bearing one nitronyl and imino nitroxide polyradical was designed to learn how to control the condensation and oxidation step of such macrocycle. Phthalocyanine mono imino nitroxide **38** was obtained and full characterized. For the first time a phthalocyanine bearing an Ullman radical was reported. The condensation step is the key point of

this synthesis as according to the conditions used, dehydration occurs allowing the obtaining of 1-hydroxy-2-imidazoline instead of 1,3-dihydroxyimidazoline is always possible. The synthesis of a symmetric phthalocyanine **44** bearing four radicals is actually being carried out in our laboratory. The synthesis is still not completely under control, due to some solubility problem that lowers the oxidation step, but the phthalocyanine with four imino nitroxide **44** was recently obtained in-situ and characterized by EPR and MALDI-TOF analyses, encouraging us to persevere in this direction.

Moreover, phthalocyanine-base radical will be use thereafter for the sensing of Cu^{2+} ion. Steady-state fluorescence-base preliminary experiments are presented in Figure 9.1, to demonstrate the viability of the strategy presented in the introduction. Under addition of Cu^{2+} ions in acetonitrile solution the fluorescence intensity is magnify by 4.

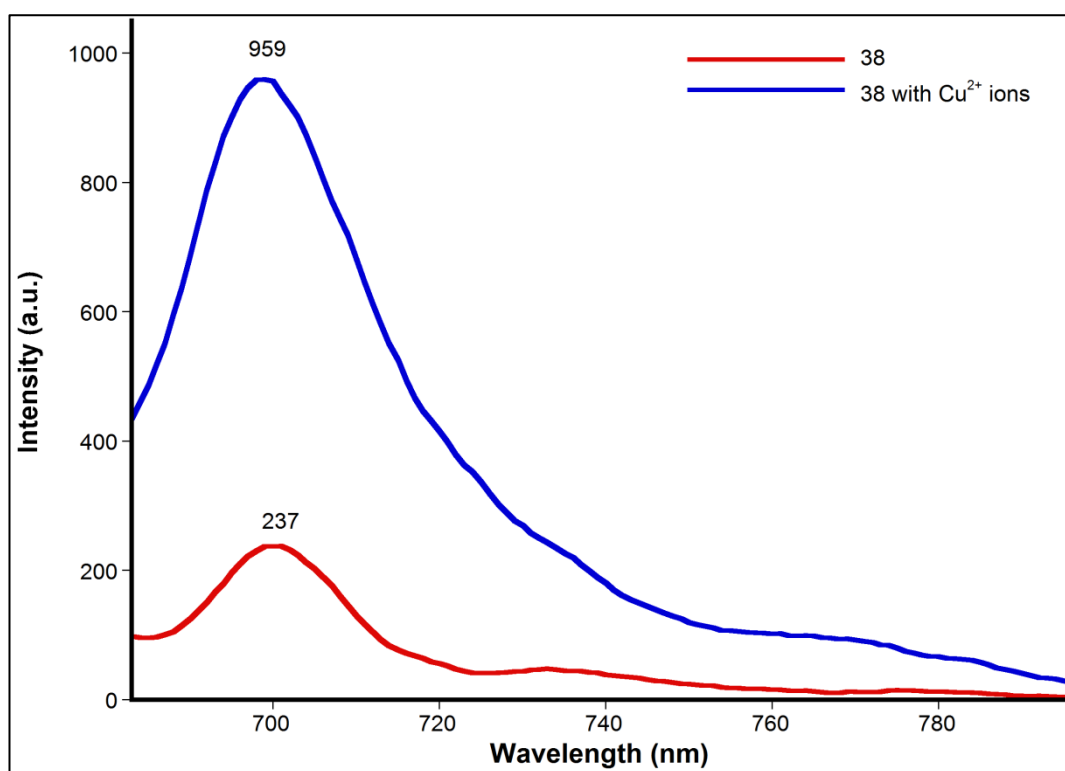


Figure 9.1: Changes in Fluorescent Intensity Upon Addition of Cu^{2+} .

Finally, it could be advantageous to develop an alternative method to synthesize phthalocyanines containing multi Ullman radicals by the “pre-form strategy”. This strategy is based on the incorporation of Ullman radicals onto the

phthalonitriles precursors and the development of a low-temperature cyclotetramerization conditions to preserve the radical character. Such reaction could be advantageous to obtain phthalocyanine bearing nitronyl nitroxide in good yield and by-pass the separation of the nitroxide/imino mixture relative to the Ullman route. Toward that end, nitronyl nitroxide functionalized phthalonitrile **46** and imino nitroxide functionalized phthalonitrile **47** were prepared and fully characterized.

In conclusion, polyradicals chemistry is a rich and promising challenging chemistry that require the understanding of the reactivity, particularly at the level of condensation and oxidation step, the two limiting point to obtain radical in good yield.

REFERENCES

- [1] Griller D., Ingold K. U., (1976), "Persistent Carbon-Centered Radicals", *Accounts of Chemical Research*, 9(1), 13-19.
- [2] Gomberg M., (1900), "An Instance of Trivalent Carbon: Triphenylmethyl", *Journal of the American Chemical Society*, 22(11), 757-771.
- [3] Hicks R. G., (2007), "What's new in stable radical chemistry?", *Organic & Biomolecular Chemistry*, 5, 1321-1338.
- [4] Hicks R. G., (2010), "Stable Radicals : Fundamentals and Applied Aspects of Odd-Electron Compounds", 1st Edition, John Wiley&Sons, West Sussex UK.
- [5] Armet O., Veciana J., Rovira C., Riera J., Castaner J., Molins E., Rius J., Miravittles C., Olivella S., Brichfeus J., (1987), "Inert Carbon Free Radicals. 8. Polychlorotriphenylmethyl Radicals. Synthesis, Structure, and Spin-Density Distribution", *The Journal of Physical Chemistry*, 91(22), 5608-5616.
- [6] Tschitschibabin A. E., (1907), "Über einige phenylierte Derivate des p, p-Ditolyls", *Chemische Berichte*, 40, 1810-1819.
- [7] Allinson G., Bushby R. J., Paillaud J-L., Thornton-Pett M., (1995), "Synthesis of a Derivative of Triangulene; the First Non-Kekule Polynuclear Aromatic", *Journal of the Chemical Society, Perkin Transactions 1*, 385-390.
- [8] Krzystek J., Sienkiewicz A., Pardi L., Brunel L. C., (1997), "DPPH as a Standard for High-Field EPR", *Journal of Magnetic Resonance*, 125, 207-211.
- [9] Kuhn R., Trischmann H., (1963), "Surprisingly Stable Nitrogenous Free Radicals", *Angewandte Chemie International Edition*, 2(3), 155.
- [10] Blatter H. M., Lukaszewski H., (1968), "A New Stable Free Radical", *Tetrahedron Letters*, 9(22), 2701-2705.
- [11] Yan B., Cramen J., McDonald R., Frank N. L., (2011), "Ferromagnetic spin-delocalized electron donors for multifunctional materials: π -conjugated benzotriazinyl radicals", *Chemical Communications*, 47, 3201-3203.
- [12] Constantinides C. P., Koutentis P. A., Loizou G., (2011), "Synthesis of 7-aryl/heteraryl-1,3-diphenyl-1,2,4-benzotriazinyls via palladium catalyzed

Stille and Suzuki-Miyaura reactions”, *Organic & Biomolecular Chemistry*, 9, 3122-3125.

- [13] Constantinides C. P., Koutentis P. A., Krassos H., Rawson J. M., Tasiopoulos A. J., (2011), “Characterization and Magnetic Properties of a “Super Stable” Radical 1,3-Diphenyl-7-trifluoromethyl-1,4-dihydro-1,2,4-benzotriazin-4-yl”, *The Journal of Organic Chemistry*, 76, 2798–2806.
- [14] O’Malley P. J., (2002), “Hybrid Density Functional Studies of Phenoxy Free Radicals Modeling α -Tocopheroxyl”, *The Journal of Physical Chemistry B*, 106, 12331-12335.
- [15] Fremy E., (1845), “Sur un nouvelle serie d’acides forms d’oxygene, de soufre, d’hydrogene et de d’azote”, *Annales de Chimie et de Physique*, Troisieme Serie, 15, 408-488.
- [16] Piloty O., Graf Schwerin B., (1901), “Ueber die Existenz von Derivaten des vierwertigen Stickstoffs. (I. Mittheilung.)”, *Berichte der Deutschen Chemischen Gesellschaft*, 34(2), 1870-1887.
- [17] Lebedev O. L., Kazarnovskii S. N., (1960), “2,2,6,6-tetramethyl-4-piperidone-1-oxyl, (4-oxo-TEMPO)”, *Zhurnal Organicheskoi Khimi*, 30(5), 1631-1635.
- [18] Osiecki J. H., Ullman E. F., (1968), “Studies of Free Radicals. I. α -Nitronyl Nitroxides, a New Class of Stable Radicals”, *Journal of the American Chemical Society*, 90:4, 1078-1079.
- [19] Brough P., Chiarelli R., Pecaut J., Rassat A., Rey P., (2003), “A versatile synthesis of new pyrimidinyl nitronyl nitroxides”, *Chemical Communications*, 2722–2723.
- [20] Brough P., Chiarelli R., Pecaut J., Rassat A., Rey P., (2006), “Pyrimidinyl Nitronyl Nitroxides”, *Chemistry A European Journal*, 12, 5134–5141.
- [21] Dooley B. M., Bowles S. E., Storr T., Frank N. L., (2007), “Synthesis of Neutral Spin-Delocalized Electron Acceptors for Multifunctional Materials”, *Organic Letters*, 9(23), 4781-4783.
- [22] Kusaba Y., Tamura M., Hosokoshi Y., Kinoshita M., Sawa H., Kato R., Kobayashi H., (1997), “Isolation of Crystals of a Planar Nitronyl Nitroxide Radical: 2- Phenylbenzimidazol-1-yl N,N'-dioxide (PBIDO)”, *Journal of Materials Chemistry*, 7(8), 1377-1382.
- [23] Zakrassov A., Shteiman V., Sheynin Y., Tumanskii B., Botoshansky M., Kapon M., Keren A., Kaftory M., Vos T. E., Miller J. S., (2004), “Synthesis, Structural, and Magnetic Characterization of Substituted Benzoimidazole-1-yl N,N'-dioxides”, *Journal of Materials Chemistry*, 14(12), 1827-1837.

- [24] Bowles S. E., Dooley B. M., Benedict J. B., Kaminsky W., Frank N. L., (2009), "The Competing Roles of Topology and Spin Density in the Magnetic Behavior of Spin Delocalized Radicals: Donor-Acceptor Annulated Nitronyl Nitroxides", *Polyhedron*, 28(9-10), 1704-1709.
- [25] Ullman E. F., Osiecki J. H., Boocock D. G. B., Darcy R., (1972), "Studies of Stable Free Radicals. X. Nitronyl Nitroxide Monoradicals and Biradicals as Possible Small Molecule Spin Labels", *Journal of the American Chemical Society*, 94(20), 7049-7059.
- [26] Shimono S., Tamura R., Ikuma N., Takimoto T., Kawame N., Tamada O., Sakai N., Matsuura H., Yamauchi J., (2004), "Preparation and Characterization of New Chiral Nitronyl Nitroxides Bearing a Stereogenic Center in the Imidazolyl Framework", *The Journal of Organic Chemistry*, 69, 475-481.
- [27] Zoppellaro G., Geies A., Enkelmann V., Baumgarten M., (2004), "2,6-Bis(pyrazolyl)pyridine Functionalised with Two Nitronyl Nitroxide and Iminonitroxide Radicals", *European Journal of Organic Chemistry*, 2367-2374.
- [28] Zoppellaro G., Ivanova A., Enkelmann V., Geies A., Baumgarten M., (2003), "Synthesis, magnetic properties and theoretical calculations of novel nitronyl nitroxide and imino nitroxide diradicals grafted on terpyridine moiety", *Polyhedron*, 22, 2099-2110.
- [29] Luneau D., Rey P., (2005), "Magnetism of metal-nitroxide compounds involving bis-chelating imidazole and benzimidazole substituted nitronyl nitroxide free radicals", *Coordination Chemistry Reviews*, 249, 2591-2611.
- [30] Zoppellaro G., (2004), "A Study of Nitronyl and Imino Nitroxide Radicals Attached to Heterocyclic Cores. High Spin Building Blocks Towards Organic Magnets.", Ph.D. Thesis, Johannes Gutenberg-Universität Mainz, Mainz Germany.
- [31] Budnikova Y. G., Gryaznova T. V., Kadirov M. K., Tretyakov E. V., Kholin K. V., Ovcharenko V. I., Sagdeev R. Z., Sinyashin O. G., (2009), "Electrochemistry of Nitronyl and Imino Nitroxides", *Russian Journal of Physical Chemistry A*, 83(11), 1976-1980.
- [32] Web 1, (2016), https://en.wikipedia.org/wiki/Electron_paramagnetic_resonance (Access Date: 27/12/2016).
- [33] Web 2, (2016), <https://www.bruker.com/products/mr/epr/what-is-epr.html> (Access Date: 27/12/2016).

- [34] Gerson F., Huber W., (2003) "Electron Spin Resonance Spectroscopy of Organic Radicals", WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim Germany.
- [35] Ratera I., Veciana J., (2012), "Playing with organic radicals as building blocks for functional molecular materials", *Chemical Society Reviews*, 41, 303-349.
- [36] Bobbitt J. M., Merbouh N., (2005), "Preparation of 4-Acetylamino-2,2,6,6-tetramethylpiperidine-1-oxoammonium tetrafluoroborate, and the Oxidation of Geraniol to Geranial (2,6-Octadienal,3,7-dimethyl-, (2E)-)", *Organic Syntheses*, 82, 80-86.
- [37] Szkurhan A. R., Lukkarila J., Georges M. K., (2010), "Application of Stable Radicals as Mediators in Living-Radical Polymerization", in "Stable Radicals : Fundamentals and Applied Aspects of Odd Electron Compounds", Hicks R. G., Editor, 1st Edition, John Wiley&Sons, West Sussex UK.
- [38] Nam H., Kwon J. E., Choi M-W., Seo J., Shin S., Kim S., Park S. Y., (2016), "Highly Sensitive and Selective Fluorescent Probe for Ascorbic Acid with a Broad Detection Range through Dual-Quenching and Bimodal Action of Nitronyl-Nitroxide", *ACS Sensors*, 1, 392-398.
- [39] Tamura, M., Nakazawa Y., Shiomi D., Nozawa K., Hosokoshi Y., Ishikawa M., Takahashi M., Kinoshita M., (1991), "Bulk ferromagnetism in the β -phase crystal of the *p*-nitrophenyl nitronyl nitroxide radical", *Chemical Physics Letters*, 186 (4-5), 401-404.
- [40] McConnell H. M., (1963), "Ferromagnetism in Solid Free Radicals", *The Journal of Chemical Physics*, 39, 1910.
- [41] Chiarelli R., Novak M. A., Rassat A., Tholence J. L., (1993), "A ferromagnetic transition at 1.48 K in an organic nitroxide", *Nature*, 363, 147-149.
- [42] Luneau D., Rey P., Laugier J., Fries P., Caneschi A., Gatteschi D, Sessoli R., (1991), "N-Bonded Copper(II)-Imino Nitroxide Complexes Exhibiting Large Ferromagnetic Interactions", *Journal of the American Chemical Society*, 113, 1245-1251.
- [43] Inoue K., Hayamizu T., Iwamura H., (1995), "High-Spin Polynitroxide Radicals as Versatile Bridging Ligands for High T_c Transition Metal Complexes", *Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals*, 273, 67-80.
- [44] Mathevet F., Luneau D., (2001), "Interpenetrated 3D Polymeric Metal-Radical Networks Built from a Tetranitroxide Radical and

Bis(hexafluoroacetylacetonato) Manganese(II)", Journal of the American Chemical Society, 123, 7465-7466.

- [45] Nakahara K., Iwasa S., Satoh M., Morioka Y., Iriyama J., Suguro M., Hasegawa E., (2002), "Rechargeable batteries with organic radical cathodes", Chemical Physics Letters, 359, 251-354.
- [46] Janoschka T., Hager M. D., Schubert U. S., (2012), "Powering up the Future: Radical Polymers for Battery Applications", Advanced Materials, 24, 6397-6409.
- [47] Tomlinson E. P., Hay M. E., Boudouris B. W., (2014), "Radical Polymers and Their Application to Organic Electronic Devices", Macromolecules, 47, 6145-6158.
- [48] Nishide H., Oyaizu K., (2008), "Toward Flexible Batteries", Science, 319, 737-738.
- [49] Suga T., Nishide H., (2010), "Rechargeable Batteries Using Robust but Redox Active Organic Radicals", in "Stable Radicals : Fundamentals and Applied Aspects of Odd Electron Compounds", Hicks R. G., Editor, 1st Edition, John Wiley&Sons, West Sussex UK.
- [50] Suga T., Sugita S., Ohshiro H., Oyaizu K., Nishide H., (2011), "p- and n-Type Bipolar Redox-Active Radical Polymer: Toward Totally Organic Polymer-Based Rechargeable Devices with Variable Configuration", Advanced Materials, 23, 751-754.
- [51] Oyaizu K., Sukegawa T., Nishide H., (2011), "Dual Dopable Poly(phenylacetylene) with Nitronyl Nitroxide Pendants for Reversible Ambipolar Charging and Discharging", Chemistry Letters, 40, 184-185.
- [52] Sukegawa T., Kai A., Oyaizu K., Nishide H., (2013), "Synthesis of Pendant Nitronyl Nitroxide Radical-Containing Poly(norbornene)s as Ambipolar Electrode-Active Materials", Macromolecules, 46, 1361-1367.
- [53] Akbey U., Trent Franks W., Linden A., Rydmark M. O., Lange S., Oschkinat H., (2013), "Dynamic Nuclear Polarization Enhanced NMR in the Solid-State", in "Hyperpolarization Methods in NMR Spectroscopy, Volume 338 of the series Topics in Current Chemistry", Kuhn L. T., Editor, Springer-Verlag Berlin Heidelberg, Germany.
- [54] Song C., Hu K.-N., Joo C.-G., Swager T. M., Griffin R. G., (2006), "TOTAPOL: A Biradical Polarizing Agent for Dynamic Nuclear Polarization Experiments in Aqueous Media", Journal of the American Chemical Society, 128, 11385-11390.
- [55] Hu K.-N., Song C., Yu H.-H., Swager T. M., Griffin R. G., (2008), "High-frequency dynamic nuclear polarization using biradicals: A

multifrequency EPR lineshape analysis”, The Journal of Chemical Physics, 128, 052302.

- [56] Munoz-Gomez J-L., Marin-Montesinos I., Lloveras V., Pons M., Vidal-Gancedo J., Veciana J., (2014), “Novel PTM–TEMPO Biradical for Fast Dissolution Dynamic Nuclear Polarization”, Organic Letters, 14, 5402-5405.
- [57] Viennet T., Viegas A., Kuepper A., Arens S., Gelev V., Petrov O, Grossmann T. N., Heise H., Etzkorn M., (2016), “Selective Protein Hyperpolarization in Cell Lysates Using Targeted Dynamic Nuclear Polarization”, Angewandte Chemie International Edition, 55, 10746-10750.
- [58] Web 3, (2017), <https://en.wikipedia.org/wiki/Sensor> (Access Date: 09/01/2017)
- [59] Tansakul C., (2012), “Nitroxides: Profluorescent Sensors and Functionalized Alkoxyamine Initiators for Nitroxide Mediated Radical Polymerization”, Ph.D. Thesis, University of California Santa Cruz, USA.
- [60] Stryer L., Griffith O. H., (1965), “A Spin-Labeled Hapten”, Proceedings of the National Academy of Sciences of the United States of America, 54 (6), 1785-1791.
- [61] Ranchet D., Tommasino J. B., Vittori O., Fabre P. L., (1998), “Solvent Effects on the Electrochemical Behavior of Iron(III) Schiff Base Complex”, Journal of Solution Chemistry, 27(11), 979-91.
- [62] Han H., Wang M., Wang H., (2014), “1-Nitronyl nitroxide pyrene as a new off–on fluorescent chemosensor for Cu²⁺”, New Journal of Chemistry, 38, 914-917.
- [63] Bruker I., (2005), “SADABS”, Bruker AXS Inc., Madison WI USA.
- [64] Bruker I., (2008), “APEX2”, Bruker AXS Inc., Madison WI USA.
- [65] Sheldrick, G., (2008), “A short history of SHELX”, Acta Crystallographica Section A, 64, 112-122.
- [66] Pascal P., (1910), “Recherche Magnétométriques”, Annales de chimie et de physique, 19, 5-70.
- [67] Rose H. (ed. Liebig J.), (1834), “Ueber eine Verbindung des Phosphors mit dem Stickstoff”, Annalen der Pharmacie, 11-12, 129-150.
- [68] Gladstone J. H., Holmes J. D., (1864), “XXVII.-On Chlorophosphuret of Nitrogen, and Its Products of Decomposition”, Journal of the Chemical Society, 17, 225-237.

- [69] Allcock H. R., Kugel, R. L., (1965), "Synthesis of High Polymeric Alkoxy- and Aryloxyphosphonitriles", *Journal of the American Chemical Society*, 87 (18), 4216-4217.
- [70] Allcock H. R., (2012), "Polyphosphazene elastomers, gels, and other soft materials", *Soft Matter*, 8, 7521–7532.
- [71] Stewart F. F., (2015), "Phosphazenes", Allen D. W., Tebby J. C., Loakes D., Editors, "A Specialist Periodical Report-Organophosphorus Chemistry Volume 44", The Royal Society of Chemistry, Cambridge UK.
- [72] Caminade A-M., Hameau A., Majoral J-P., (2016), "The specific functionalization of cyclotriphosphazene for the synthesis of smart dendrimers", *Dalton Transactions*, 45, 1810-1822.
- [73] Yoshida E., Terazono T., (1999), "Synthesis of Model A₅B₁ Heteroarm Star Copolymers Using Living Radical Polymerization Mediated by 2,2,6,6-Tetramethylpiperidine-1-oxyl", *Polymer Journal (Tokyo, Japan)*, 31(7), 621-624.
- [74] Shimono S., Tamura R., Ikuma N., Takahashi H., Sakai N., Yamauchi J., (2004), "Characterization of the Chiral Paramagnetic Multispin System Built on a Cyclotriphosphazene Scaffold", *Chemistry Letters*, 33(7), 932-933.
- [75] Shimono S., Takahashi H., Sakai N., Tamura R., Ikuma N., Yamauchi J., (2005), "Use of Cyclotriphosphazene as a Molecular Scaffold for Building Chiral Multispin Systems", *Molecular Crystals and Liquid Crystals*, 440:1, 37-52.
- [76] Dulog L., Mohler H., (1988), "A λ^5 -cyclotriphosphazene with nitroxyl groups as model for a paramagnetic poly(organo- λ^5 -phosphazene)", *Makromolekulare Chemie*, 189, 2611-2615.
- [77] Sommerlade R., Grutzmacher H., Boulmaaz S., (2001), "Process for the selective oxidation of alcohols using easily separable nitroxyl radicals", *European Patent Applications*, EP 1103537 A1 20010530.
- [78] Badetti E., Lloveras V., Wurst K., Sebastian R. M., Caminade A-M., Majoral J-P., Veciana J., Vidal-Gancedo J., (2013), "Synthesis and Structural Characterization of a Dendrimer Model Compound Based on a Cyclotriphosphazene Core with TEMPO Radicals as Substituents", *Organic Letters*, 15(14), 3490-93.
- [79] Badetti E., Lloveras V., Munoz-Gomez J. L., Sebastian R. M., Caminade A-M., Majoral J-P., Veciana J., Vidal-Gancedo J., (2014), "Radical Dendrimers: A Family of Five Generations of Phosphorus Dendrimers Functionalized with TEMPO Radicals", *Macromolecules*, 47, 7717-24.

- [80] Hirel C., (1999), "Radicaux Libres Nitronyl Nitroxyde Chiraux: Synthese et Proprietes de Coordination", Ph.D. Thesis, Universite Joseph Fourier Grenoble1, Grenoble France.
- [81] Sayre R., (1955), "The Identity of Heilpern's Pinacolylthiourea and the Preparation of Authentic 2-Thiono-4,4,5,5-tetramethylimidazolidine", Journal of the American Chemical Society, 77(24), 6689-6690.
- [82] Lamchen M., Mittag T. W., (1966), "Nitrones. Part IV. Synthesis and Properties of a Monocyclic α -Dinitrone", Journal of the Chemical Society C: Organic, 2300-2303.
- [83] Ovcharenko V., Fokin S., Rey P., (1999), "A Thorough Investigation of the Synthetic Problems of Vic-Bis-Hydroxylamine - the Precursor of Ullman's Nitroxides", Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 334:1, 109-119.
- [84] Hirel C., Vostrikova K. E., Pecaut J., Ovcharenko V. I., Rey P., (2007), "Nitronyl and Imino Nitroxides: Improvement of Ullman's Procedure and Report on a New Efficient Synthetic Route", Chemistry - A European Journal, 7(9), 2007-2014.
- [85] Lescop C., (2000), "Chimie de Coordination de Radicaux Nitroxyde Bisbidentes et Chiraux : Synthèses, caractérisations et propriétés magnétiques", Ph.D. Thesis, Universite Joseph Fourier Grenoble1, Grenoble France.
- [86] Carriedo G. A., Fernandez-Catuxo L., Alonso F. J. G., Elipe P. G., Gonzalez P. A., Sanchez G., (1996), "On the Synthesis of Functionalized Cyclic and Polymeric Aryloxyphosphazenes from Phenols", Journal of Applied Polymer Science, 59, 1879-1885.
- [87] Yuan W., Tang X., Huang X., Zheng S., (2005), "Synthesis, characterization and thermal properties of hexaarmed star-shaped poly(ϵ -caprolactone)-b-poly(D,L-lactide-co-glycolide) initiated with hydroxyl-terminated cyclotriphosphazene", Polymer, 46, 1701-1707.
- [88] Kagit R., Yildirim M., Ozay O., Yesilot S., Ozay H., (2014), "Phosphazene Based Multicentered Naked-Eye Fluorescent Sensor with High Selectivity for Fe^{3+} Ions", Inorganic Chemistry, 53, 2144-2151.
- [89] Bertani R., Chaux F., Gleria M., Metrangolo P., Milani R., Pilati T., Resnati G., Sansotera M., Venza A., (2007), "Supramolecular rods via halogen bonding-based self-assembly of fluorinated phosphazene nanopillars", Inorganica Chimica Acta, 360, 1191-1199.
- [90] Patil B. R., Machakanur S. S., Badiger D. S., Hunoor R. S., Gudasi K. B., Nethaji M., Bligh S. W. A., (2011), "Hexa-arm star shaped hydrazone

derivatives from hexakis(4-formylphenoxy)-cyclotriphosphazene core”, *Journal of Molecular Structure*, 1003, 52-61.

- [91] Nelson J. C., Saven J. G., Moore J. S., Wolynes P. G., (1997), “Solvophobicity Driven Folding of Nonbiological Oligomers”. *Science*, 277(5333), 1793-1796.
- [92] Ravat P., Ito Y., Gorelik E., Enkelmann V., Baumgarten M., (2013), “Tetramethoxypyrene-Based Biradical Donors with Tunable Physical and Magnetic Properties”, *Organic Letters*, 15(17), 4280-4283.
- [93] Vuki M., Shiu K-K., Galik M., O’Mahony A. M., Wang J., (2012), “Simultaneous electrochemical measurement of metal and organic propellant constituents of gunshot residues”, *Analyst*, 137, 3265-3270.
- [94] Onal E., Yerli Y., Cosut B., Pilet G., Ahsen V., Luneau D., Hirel C., (2014), “Nitronyl and imino nitroxide free radicals as precursors of magnetic phthalocyanine and porphyrin building blocks”, *New Journal of Chemistry*, 38, 4440-4447.
- [95] Korkut S. E., Akyuz D., Ozdogan K., Yerli Y., Koca A., Sener M. K., (2016), “TEMPO-functionalized zinc phthalocyanine: synthesis, magnetic properties, and its utility for electrochemical sensing of ascorbic acid”, *Dalton Transactions*, 45, 3086-3092.
- [96] Ullman E. F., Call L., Osiecki J. H., (1970), “Stable Free Radicals. VIII. New Imino, Amidino, and Carbamoyl Nitroxides”, *The Journal of Organic Chemistry*, 35(11), 3623-3631.
- [97] Fidan I., Onal E., Yerli Y., Luneau D., Ahsen V., Hirel C., (2016), “Synthesis and Straightforward Quantification Methods of Imino Nitroxide-Based Hexaradical Architecture on a Cyclotriphosphazene Scaffold”, *Inorganic Chemistry*, 55, 11447-11453.
- [98] Grand A., Rey P., Subra R., Barone V., Minichino C., (1991), “Ab Initio Study of the Nitronyl and Imino Nitroxides. Relation between Electronic Structure and Magnetic Properties in Metal-Nitroxide Complexes”, *The Journal of Physical Chemistry*, 95, 9238-9242.
- [99] Lee J., Lee E., Kim S., Bang G. S., Shultz D. A., Schmidt R. D., Forbes M. D. E., Lee H., (2011), “Nitronyl Nitroxide Radicals as Organic Memory Elements with Both n- and p-Type Properties”, *Angewandte Chemie International Edition*, 123, 4506-4510.
- [100] Furuyama T., Sato T, Kobayashi N., (2015), “A Bottom-up Synthesis of Antiaromatic Expanded Phthalocyanines: Pentabenzotriazasmaragdyrins, i.e. Norcorroles of Superphthalocyanines”, *Journal of the American Chemical Society*, 137, 13788-13791.

- [101] Web 4, (2017), <http://www.phthalocyanines.es/research-lines/selective-synthesis-and-functionalization-of-phthalocyanines/> (Access Date: 10/01/2017).
- [102] Web 5, (2017), <https://en.wikipedia.org/wiki/Phthalocyanine> (Access Date: 10/01/2017).
- [103] Web 6, (2017), <http://www.sigmaaldrich.com/catalog/product/aldrich/423165?lang=en®ion=TR> (Access Date: 22/01/2017).
- [104] Ishii K., Hirose Y., Kobayashi N., (1998), "Selective Population from the Excited Multiplet States to the Triplet Ground State in a Phthalocyanine: A New Concept for Controlling Magnetic Properties by Photoexcitation", *Journal of the American Chemical Society*, 120, 10551-10552.
- [105] Alpugan S., Isci U., Albrieux F., Hirel C., Gurek A. G., Bretonniere Y., Ahsen V., Dumoulin F., (2014), "Expedition selective access to functionalized platforms of A₇B type heteroleptic lanthanide double-decker complexes of phthalocyanine", *Chemical Communications*, 50, 7466-7468.
- [106] Braun A., Tcherniac J., (1907), "Über die Produkte der Einwirkung von Acetanhydrid auf Phthalamid", *Berichte der Deutschen Chemischen Gesellschaft*, 40 (2), 2709–2714.
- [107] De Diesbach H., von der Weid E., (1927), "Quelques sels complexes des o-dinitriles avec le cuivre et la pyridine", *Helvetica Chimica Acta*, 10, 886-888.
- [108] Dandridge A. G., Drescher H. A., Thomas J., (1929), "to Scottish Dyes Ltd.", *British Patent*, 322, 169.
- [109] Gregory P., (2000), "Industrial applications of phthalocyanines", *Journal of Porphyrins and Phthalocyanines*, 4, 432-437.
- [110] Byrne G. T., Linstead R. P., Lowe A. R., (1934), "Phthalocyanines. Part II. The preparation of phthalocyanine and some metallic derivatives from o-cyanobenzamide and phthalimide", *Journal of the Chemical Society*, 1017-1022.
- [111] Tomoda H., Saito S., Ogawa S., Shiraishi S., (1980), "Synthesis of Phthalocyanines From Phthalonitrile With Organic Strong Bases", *Chemistry Letters*, 9, 1277-1280.
- [112] Gurek A. G., Hirel C., (2012), "Recent Developments of Synthetic Techniques for Porphyrins, Phthalocyanines and Related Systems". in : Nyokong T., Ahsen V., Editors, "Photosensitizers in Medicine, Environment and Security", Springer, Dordrecht Netherlands.

- [113] McKeown, N. B., Chambrier I., Cook M. J., (1990), "Synthesis and Characterisation of some 1,4,8,11,15,18,22,25-Octa-alkyl- and 1,4,8,11,15,18-Hexa-alkyl-22,25-bis(carboxypropyl)phthalocyanines", *Journal of the Chemical Society, Perkin Transactions 1*, 1169-1177.
- [114] Zhang Y., Ma P., Zhu P., Zhang X., Gao Y., Qi D., Bian Y., Kobayashi N., Jiang J., (2011), "2,3,9,10,16,17,23,24-Octakis(hexylsulfonyl)phthalocyanines with good n-type semiconducting properties. Synthesis, spectroscopic, and electrochemical characteristics", *Journal of Materials Chemistry*, 21, 6515-6524.
- [115] de la Torre G., Claessens C. G., Torres T., (2000), "Phthalocyanines: The Need for Selective Synthetic Approaches", *European Journal of Organic Chemistry*, 2821-2830.
- [116] de la Torre G., Torres T., (2000), "Synthetic advances in phthalocyanine chemistry", *Journal of Porphyrins and Phthalocyanines*, 6, 274-284.
- [117] Mack J., Kobayashi N., (2011), "Low Symmetry Phthalocyanines and Their Analogues", *Chemical Reviews*, 111, 281-321.
- [118] Wang A., Long L., Zhang C., (2012), "Synthesis of unsymmetrical phthalocyanines: a brief overview", *Tetrahedron*, 68, 2433-2451.
- [119] Nemykin V. N., Dudkin S. V., Dumoulin F., Hirel C., Gurek A. G., Ahsen V., (2014), "Synthetic approaches to asymmetric phthalocyanines and their analogues", *Arkivoc*, i, 142-204.
- [120] Torres T., (2000), "Perspectives in the selective synthesis of phthalocyanines and related compounds", *Journal of Porphyrins and Phthalocyanines*, 4, 325-330.
- [121] Young J. G., Onyebuagu W., (1990), "Synthesis and Characterization of Di-disubstituted Phthalocyanines", *The Journal of Organic Chemistry*, 55, 2155-2159.
- [122] Kobayashi N, Kondo R, Nakajima S., Osa T., (1990), "New route to unsymmetrical phthalocyanine analogs by the use of structurally distorted subphthalocyanines", *Journal of the American Chemical Society*, 112, 9640-9641.
- [123] Weitemeyer A., Kliesch H., Wohrle D., (1995), "Unsymmetrically Substituted Phthalocyanine Derivatives via a Modified Ring Enlargement Reaction of Unsubstituted Subphthalocyanine", *The Journal of Organic Chemistry*, 60, 4900-4904.
- [124] Leznoff C. C., Hall T. W., (1982), "The Synthesis of a Soluble, Unsymmetrical Phthalocyanine on a Polymer Support", *Tetrahedron Letters*, 23(30), 3023-3026.

- [125] Nemykin V. N., Lukyanets E. A., (2010), "Synthesis of substituted phthalocyanines", *Arkivoc*, (i), 136-208.
- [126] Khanamiryan A. K., Bhardwaj N., Leznoff C. C., (2000), "Towards N-alkylated phthalocyanines using 2,3,9,10,16,17,23,24-octaneopentoxyphtalocyanine", *Journal of Porphyrins and Phthalocyanines*, 4, 484-490.
- [127] Liu J-Y., Lo P-C., Fong W-P., Ng D. K. P., (2009), "Effects of the number and position of the substituents on the *in vitro* photodynamic activities of glucosylated zinc(II) phthalocyanines", *Organic & Biomolecular Chemistry*, 7, 1583-1591.
- [128] Durmus M., Ayhan M. M., Gurek A. G., Ahsen V., (2008), "Peripherally alpha(α)-substituted novel phthalocyanines", *Dyes and Pigments*, 77, 570-577.
- [129] Cosimelli B., Roncucci G., Dei D., Fantetti L., Ferroni F., Ricci M., Spinelli D., (2003), "Synthesis and antimycotic activity of new unsymmetrical substituted zinc phthalocyanines", *Tetrahedron*, 59, 10025-10030.
- [130] Seven O., Dindar B., Gultekin B., (2009), "Microwave-Assisted Synthesis of Some Metal-Free Phthalocyanine Derivatives and a Comparison with Conventional Methods of their Synthesis", *Turkish Journal of Chemistry*, 33, 123-134.
- [131] Mack J., Stillman M. I., (2003), "Electronic Structures of Metal Phthalocyanine and Porphyrin Complexes from Analysis of the UV-Visible Absorption and Magnetic Circular Dichroism Spectra and Molecular Orbital Calculations", in "The Porphyrin Handbook: Volume 16/Phthalocyanines: Spectroscopic and Electrochemical Characterization", Kadish K. M., Smith K. M., Guillard R., Editors, Academic Press, San Diego, California USA.
- [132] Nyokong T., Isago H., (2004), "The renaissance in optical spectroscopy of phthalocyanines and other tetraazaporphyrins", *Journal of Porphyrins and Phthalocyanines*, 8, 1083-1090.
- [133] Rio Y., Rodriguez-Morgade M. S., Torres T., (2008), "Modulating the electronic properties of porphyrinoids: a voyage from the violet to the infrared regions of the electromagnetic spectrum", *Organic & Biomolecular Chemistry*, 6, 1877-1894.
- [134] Web 7, (2017), <https://en.wikipedia.org/wiki/Fluorescence> (Access Date: 15/03/2017).
- [135] Web 8, (2017), <https://www.st-andrews.ac.uk/seeinglife/science/imaging/fluorescence/fluorescence.html> (Access Date: 15/03/2017).

- [136] Web 9, (2017), <https://www.thermofisher.com/tr/en/home/references/molecular-probes-the-handbook/introduction-to-fluorescence-techniques.html> (Access Date: 15/03/2017).
- [137] Isago H., (2015), "Optical Spectra of Phthalocyanines and Related Compounds : A Guide for Beginners", Springer, Tokyo Japan.
- [138] Ishii K., Hirose Y., Kobayashi N., (1999), "Electronic Absorption, MCD and Fluorescence Studies on Phthalocyaninatosilicon Covalently Linked to One or Two TEMPO Radicals", *Journal of Porphyrins and Phthalocyanines*, 3, 439–443.
- [139] Ishii K., Takeuchi S., Shimizu S., Kobayashi N., (2004), "A Concept for Controlling Singlet Oxygen ($^1\Delta_g$) Yields Using Nitroxide Radicals: Phthalocyaninatosilicon Covalently Linked to Nitroxide Radicals", *Journal of the American Chemical Society*, 126, 2082-2088.
- [140] Takeuchi S., Ishii K., Kobayashi N., (2004), "Time-Resolved EPR and Transient Absorption Studies on Phthalocyaninatosilicon Covalently Linked to Two PROXYL Radicals", *The Journal of Physical Chemistry A*, 108, 3276-3280.
- [141] Ishii T., Ishizaki T., Kobayashi N., (1999), "Experimental Evidence for a Selection Rule of Intersystem Crossing to the Excited Quartet States: Metallophthalocyanines Coordinated by 4-Amino-TEMPO", *The Journal of Physical Chemistry A*, 103, 6060-6062.
- [142] Ishii K., Hirose Y., Fujitsuka H., Ito O., Kobayashi N., (2001), "Time-Resolved EPR, Fluorescence, and Transient Absorption Studies on Phthalocyaninatosilicon Covalently Linked to One or Two TEMPO Radicals", *Journal of the American Chemical Society*, 123, 702-708.
- [143] Ishii K., Kobayashi N., (2000), "The excited multiplet states of metalloporphyrins and metallophthalocyanines coordinated or linked to nitroxide radicals", *Coordination Chemistry Reviews*, 198, 231–250.
- [144] Ishii K., Kubo K., Sakurada T., Komori K., Sakai Y., (2011), "Phthalocyanine-based fluorescence probes for detecting ascorbic acid: phthalocyaninatosilicon covalently linked to TEMPO radicals", *Chemical Communications*, 47, 4932–4934.
- [145] Barrett A. G. M., Hanson G. R., White A. J. P., Williams D. J., Micallef A. S., (2007), "Synthesis of nitroxide-functionalized phthalocyanines", *Tetrahedron*, 63, 5244–5250.
- [146] Wuts P. G. M., Greene T. W., (2007), "Greene's Protective Groups in Organic Synthesis", 4th Edition, John Wiley & Sons, Hoboken New Jersey USA.

- [147] Schweikart K-H., Hanack M., (2000), "Synthesis of Nickel Phthalocyanines with One Aldehyde Group and Preparation of a Bisvinylene-Phenylene-Bridged Bisphthalocyanine", *European Journal of Organic Chemistry*, 2551-2556.
- [148] Shimizu A., Ito A., Teki Y., (2016), "Photostability enhancement of the pentacene derivative having two nitronyl nitroxide radical substituents", *Chemical Communications*, 52, 2889-2892.
- [149] Zhang J., Zhao M., Cui G., Peng S., (2008), "A class of novel nitronyl nitroxide labeling basic and acidic amino acids: Synthesis, application for preparing ESR optionally labeling peptides, and bioactivity investigations", *Bioorganic & Medicinal Chemistry*, 16, 4019-4028.
- [150] Tretyakov E., Tolstikov S., Mareev A., Medvedeva A., Romanenko G., Stass D., Bogamyakov A., Ovcharenko V., (2009), "New Cascade Syntheses of Nitronyl Nitroxides and a New Synthetic Approach to Imino Nitroxides", *European Journal of Organic Chemistry*, 2548-2561.
- [151] Lakshmi V., Lee W-Z., Ravikanth M., (2014), "Synthesis, structure and spectral and electrochemical properties of 3-pyrrolyl BODIPY-metal dipyrin complexes", *Dalton Transactions*, 43, 16006-16014.
- [152] Zeika O, Li Y., Jockusch S., Parkin G., Sattler A., Sattler W., Turro N. J., (2010). "Synthesis of Polynitroxides Based on Nucleophilic Aromatic Substitution", *Organic Letters*, 12, 3696-3699.
- [153] Leznoff C. C., Hu M., Nolan K. J. M., (1996), "The synthesis of phthalocyanines at room temperature", *Chemical Communications*, 10, 1245-1246.
- [154] Leznoff C. C., D'ascanio A. M., Yildiz S. Z., (2000), "Phthalocyanine formation using metals in primary alcohols at room temperature", *Journal of Porphyrins and Phthalocyanines*, 4, 103-111.

BIOGRAPHY

İsmail Fidan was born in Mezarıřerif in 1981. He was raised in Kırřehir and Tokat. He received Bachelor of Science in Chemistry from the Karadeniz Technical University. He obtained Master of Science in Organic Chemistry from the Yıldız Technical University, under the supervision of Prof. Dr. řeniz Kaban. Then he moved to the Gebze Technical University, Graduate School of Natural and Applied Science, Chemistry Department for his doctoral studies. He is conducting research on the radical chemistry under the supervision of Assist. Prof. Dr. Catherine HIREL.

APPENDICES

Appendix A: Publication Produced From Thesis

Fidan I., Onal E., Yerli Y., Luneau D., Ahsen V., Hirel C., (2016), “Synthesis and Straightforward Quantification Methods of Imino Nitroxide-Based Hexaradical Architecture on a Cyclotriphosphazene Scaffold”, *Inorganic Chemistry*, 55, 11447-11453.

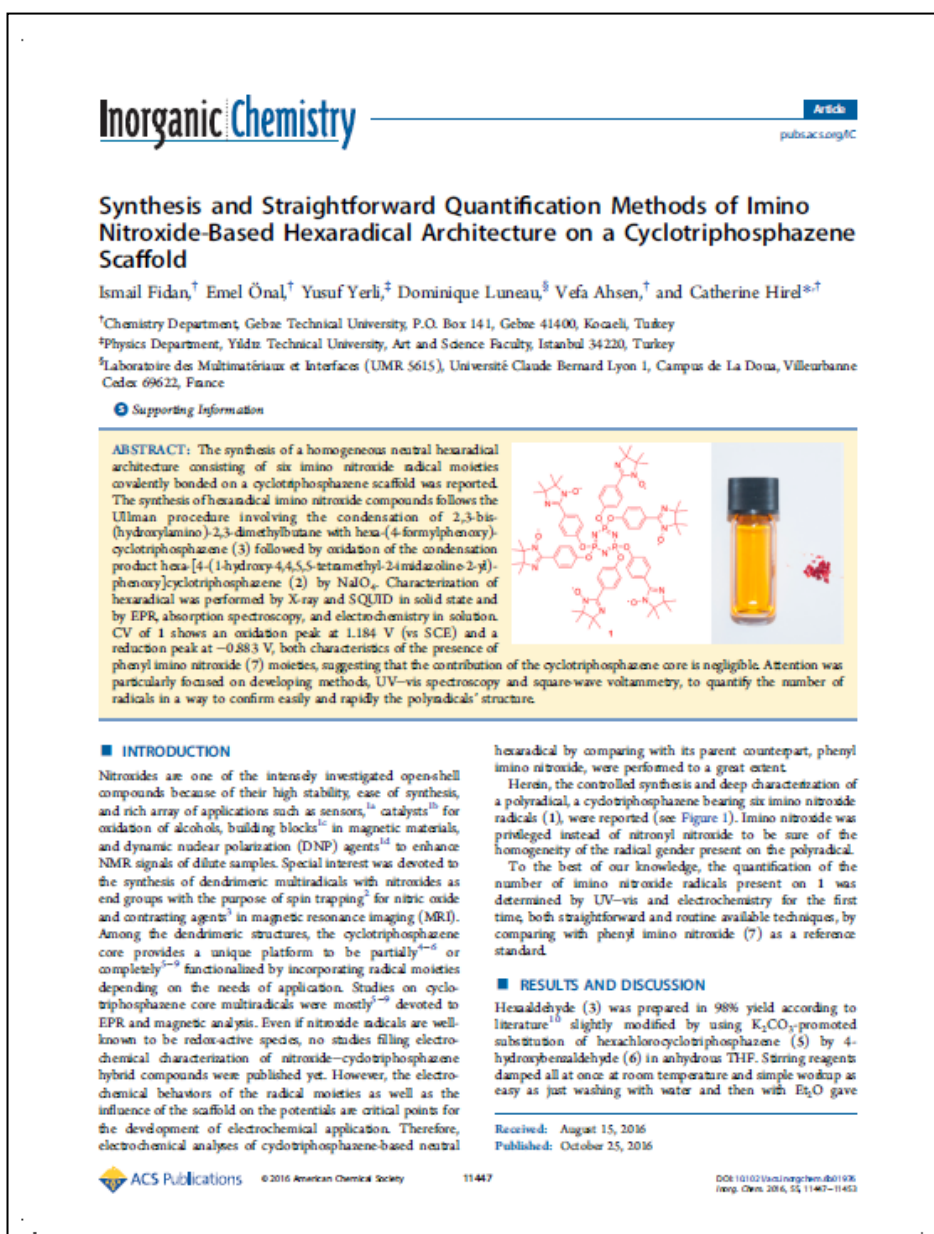


Figure A1.1: Publication in Inorganic Chemistry.

Appendix B: Copyright Permission by American Chemical Society

The screenshot shows a web browser window with the URL <https://s100.copyright.com/AppDispatchServlet>. The page header includes the Copyright Clearance Center logo, the RightsLink logo, and navigation buttons for Home, Create Account, Help, and a mail icon. Below the header, the ACS Publications logo is displayed with the tagline "Most Trusted. Most Cited. Most Read." The main content area lists the following information:

Title: Synthesis and Straightforward Quantification Methods of Imino Nitroxide-Based Hexaradical Architecture on a Cyclotriphosphazene Scaffold
Author: Ismail Fidan, Emel Önal, Yusuf Yerli, et al
Publication: Inorganic Chemistry
Publisher: American Chemical Society
Date: Nov 1, 2016
Copyright © 2016, American Chemical Society

A "LOGIN" button is present next to the title. A text box on the right side of the page states: "If you're a copyright.com user, you can login to RightsLink using your copyright.com credentials. Already a RightsLink user or want to learn more?"

PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms & Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from (COMPLETE REFERENCE CITATION). Copyright (YEAR) American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your request. No additional uses are granted (such as derivative works or other editions). For any other uses, please submit a new request.

At the bottom of the main content area, there are two buttons: "BACK" and "CLOSE WINDOW".

Copyright © 2017 Copyright Clearance Center, Inc. All Rights Reserved. [Privacy statement](#). [Terms and Conditions](#). Comments? We would like to hear from you. E-mail us at customercare@copyright.com

The Windows taskbar at the bottom shows the Start button, a search bar, and several application icons including File Explorer, Edge, and the task view button.

Figure B1.1: Copyright Permission by American Chemical Society.