Synthesis and photochemistry of a few 9,11-annulated dibenzobarrelenes

Thesis submitted to the
Cochin University of Science and Technology
In partial fulfilment of the requirements for the degree of

Doctor of Philosophy
in
Chemistry

In the Faculty of Science
by

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Under the supervision of

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DEPARTMENT OF APPLIED CHEMISTRY
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
KOCHI-682022, KERALA, INDIA

December 2018

Dedicated

To my parents, brothers, sisters, in-laws, nieces, nephews and dawn…

“It's not what you look at that matters, it's what you see.”

Henry David Thoreau

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CERTIFICATE

This is to certify that the thesis entitled "**Synthesis and photochemistry of a few 9,11-annulated dibenzobarrelenes**" is a genuine record of research work carried out by **Mr. Tomson Devassia**, under my supervision, in partial fulfilment of the requirements for the degree of Doctor of Philosophy of Cochin University of Science and Technology, and further that no part thereof has been presented before for the award of any other degree. All the relevant corrections and modifications suggested by the audience and recommended by the doctoral committee of the candidate during the pre-synopsis seminar have been incorporated in the thesis.

Kochi-22
December, 2018

Dr. P. A. Unnikrishnan
(Thesis Supervisor)

DECLARATION

I hereby declare that the work presented in the thesis entitled **"Synthesis and photochemistry of a few 9,11-annulated dibenzobarrelenes"** is the result of genuine research carried out by me under the supervision of **Dr. P. A. Unnikrishnan**, Associate Professor of Organic Chemistry, Department of Applied Chemistry, Cochin University of Science and Technology, Kochi-22, and the same has not been submitted elsewhere for the award of any other degree.

Kochi-22 ***Tomson Devassia***

December, 2018

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Tomson Devassia

PREFACE

Barrelene type systems are well explored and known to undergo photoisomerization to cyclooctatetraene and semibullvalene under direct and sensitized irradiation conditions respectively. In the present investigation, we designed and synthesized several tricyclic barrelenes or annulated dibenzobarrelenes *via* intramolecular Diels-Alder reaction (IMDA). The products were obtained in moderately good yield and the reaction conditions perfected by us satisfied criteria for green approach. A few selected 9,11-annulated dibenzobarrelenes are represented in Figure **1**. Apart from well-established reaction pathways for dibenzobarrelenes, intramolecular photoinduced electron transfer leading to diversion of barrelene photochemistry to hitherto unraveled pathways is a distinct possibility with these dibenzobarrelenes.

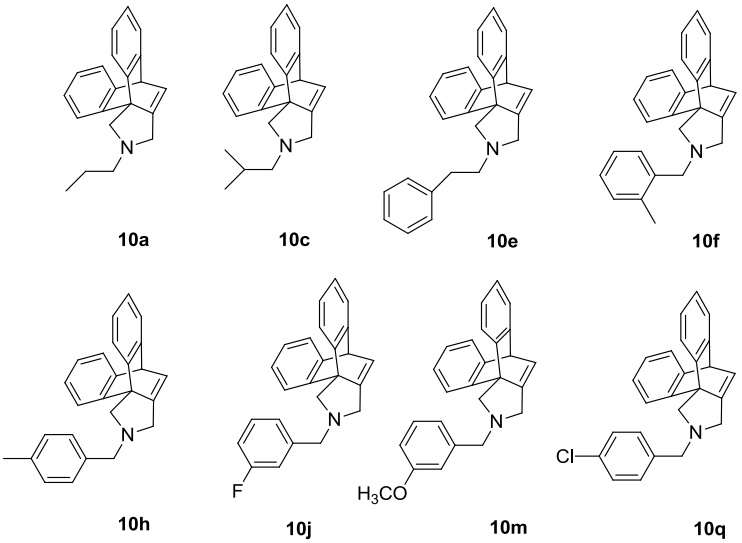
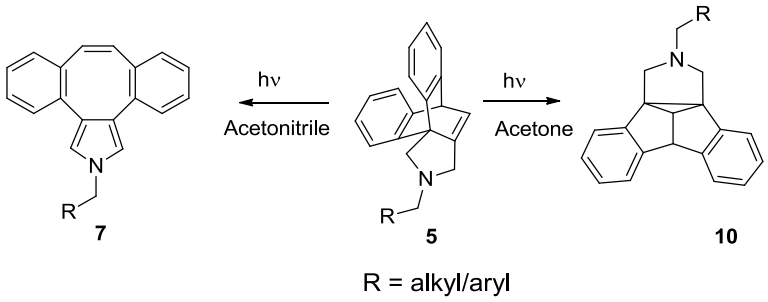


Figure 1. A few novel 9,11-annulated dibenzobarrelenes

Depending on irradiation conditions, annulated barrelenes **10** also gave the corresponding cyclooctatetraene or semibullvalene photoproducts in moderate yields. Anthraquinone was formed as a common product under both direct and sensitized irradiation conditions. General photochemical isomerization of annulated dibenzobarrelenes is depicted in Scheme **1**.



Scheme 1. Photochemical transformations of 9,11-annulated dibenzobarrelenes

Summary of the thesis

The thesis entitled "Synthesis and photochemistry of a few 9,11-annulated dibenzobarrelenes" is divided into four chapters.

Chapter 1: **Introduction to Diels-Alder Reactions and Chemistry of Barrelenes**

Literature survey encompassing the basic fundamentals is included in the introductory chapter. Importance of Diels-Alder reaction and its application in contemporary organic synthesis is well outlined and this chapter briefly delineates a few aspects of barrelenes and use of Diels-Alder reactions in the synthesis of barrelene derivatives as well. It

also describes the effect of bridgehead substituents in controlling the regioselectivity of di-π-methane rearrangement of dibenzobarrelenes.

Chapter 2: **Synthesis and characterization of a few N-alkylaminomethylanthracenes**.

Synthesis of suitably substituted aminomethylanthracenes with acetylene appendage for IMDA reaction is described here. Leuckart-Wallach modification of Leuckart reaction was effectively utilized for the synthesis of anthracene-9-yl-methanamines and further nucleophilic substitution reaction was employed to generate our target compounds. Structure of a few acetylene appended aminomethylanthracenes synthesized by us is given in Figure **2**.

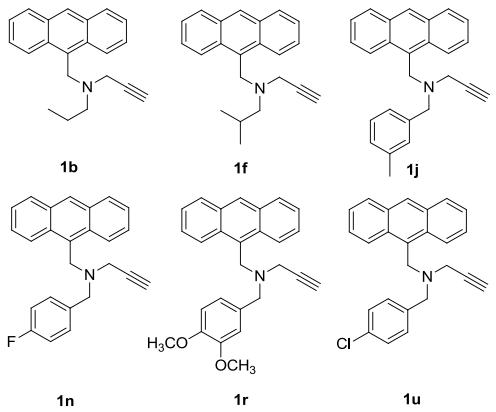


Figure 2

Chapter 3: **Intramolecular Diels-Alder reactions of a few anthracene-*9*-yl-methanamines**.

Intramolecular Diels-Alder reaction (IMDA) was employed for the synthesis of 9,11-annulated dibenzobarrelenes. Brief description of the transformations of suitably substituted alkylaminomethylanthracenes and relevant characterization data are also included in this chapter. We

performed IMDA reaction in solution as well as under solvent free conditions. Solution phase reaction in both polar and nonpolar solvents gave IMDA products in lower yield along with unwanted products such as anthraquinone and intractable polar materials in substantial amounts. Under solvent free conditions, competing electron transfer reactions were effectively suppressed leading to our targets in higher yields. In most cases, required IMDA adducts could be separated by simply washing the reaction mixture with methanol. Thus, solvent free method developed by us provided twin advantages of satisfying the norms for green synthesis and effectively suppressing competing reactions.

Chapter 4: **Photochemical studies of a few 9,11-annulated dibenzobarrelenes**.

This chapter mainly discusses photochemical reactions of annulated dibenzobarrelenes under both direct and sensitized irradiation conditions. Direct irradiation of 9,11-annulated dibenzobarrelenes in acetonitrile led to isomerization to dibenzocyclooctatetraenes and products derived thereof. On the other hand, acetone sensitized initiated highly regioselective rearrangement yielding 8b,8c-annulated semibullvalene as the only product.

Note: The numbers given to various compounds herein correspond to those given in respective chapters. We have reported only the relevant data for the characterization of novel compounds synthesized by us. Relevant references are listed at the end of each chapter.

Chapter 5: Summary and conclusions

List of Abbreviations

C	: centigrade
DCM	: dichloromethane
DMF	: dimethylformamide
DMAD	: dimethyl acetylene dicarboxylate
DBA	: dibenzoyl acetylene
DPM	: di-π-methane rearrangement
d	: doublet
FMO	: frontier molecular orbital
FT IR	: fourier transform infrared
g	: gram
h	: hour
HOMO	: highest occupied molecular orbital
MS	: mass spectrometry
Hz	: hertz
IMDA	: intramolecular Diels-Alder
LUMO	: lowest unoccupied molecular orbital
m	: multiplet
Me	: methyl
mg	: milligram
mL	: millilitre
mp	: melting point
nm	: nanometre
NMR	: nuclear magnetic Resonance
OLED	: organic light emitting diode
Ph	: phenyl
KOH	: potassium hydroxide
NaOH	: sodium hydroxide
ppm	: parts per million
s	: singlet
SN	: nucleophilic substitution
t	: triplet
THF	: tetrahydrofuran
TLC	: thin layer chromatography
TMS	: tetra methyl silane
TS	: transition state

CONTENTS

CHAPTER 1

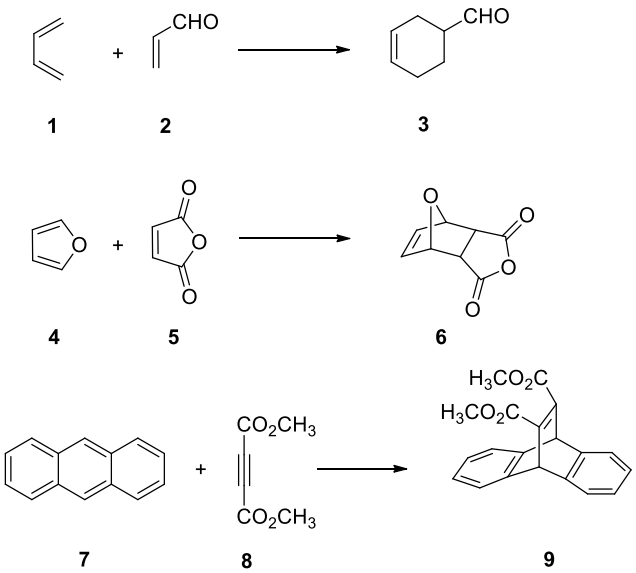
Introduction to Diels-Alder reaction and chemistry of barrelenes

1.1 Abstract

This chapter briefly delineates a few aspects of Diels-Alder reaction with specific emphasis on the synthesis of barrelene derivatives. A general introduction to barrelene photochemistry and the role of bridgehead substituents on controlling regioselectivity of barrelene to semibullvalene rearrangement are also summarized herein.

1.2 Diels-Alder reaction

Cycloaddition reactions belong to the family of pericyclic reactions.[1] Thermal [4+2] cycloaddition reaction between a diene and a dienophile is known as the Diels-Alder reaction, named after its discoverers: Otto Diels and Kurt Alder. They reported the reaction in 1928 and were awarded the Nobel Prize in 1950 for this remarkable reaction.[2] Diels-Alder reaction is employed in the synthesis of monocyclic as well as the polycyclic molecules. A few prototypical examples illustrating several salient features of Diels-Alder reaction are collected in Scheme 1.1.



Scheme 1.1

Synthetic utility of Diels-Alder reaction is reflected by its myriad applications in the synthesis of a variety of bioactive compounds including mono and bicyclic entities.[3,4] Several bicyclic compounds used as therapeutic agents against various diseases have been synthesized using Diels–Alder reaction.[5-7]

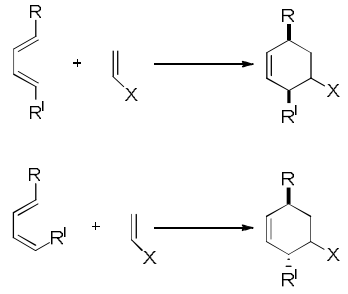
1.3 Classification of Diels-Alder reaction

Depending on the placement of diene and dienophile components, Diels-Alder reaction is classified as *i*) intermolecular Diels-Alder reaction where the reacting components are from two different molecules and *ii*) **i**ntra**m**olecular **D**iels-**A**lder (IMDA) reaction where these two are present in the same molecule.

1.4 Intermolecular Diels-Alder reaction

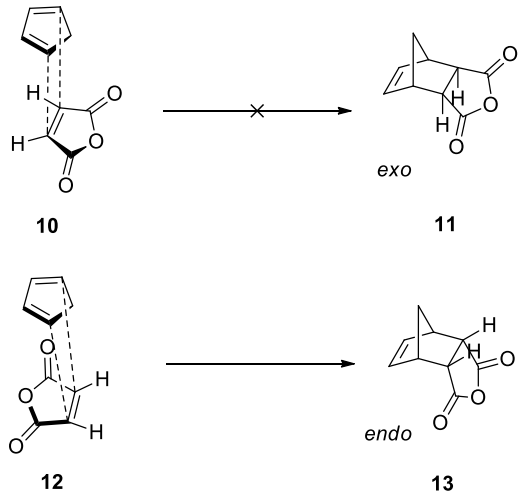
In this version of Diels-Alder reaction, diene and dienophile are two different molecules and under thermal conditions undergo cycloaddition reaction to form six-membered rings containing one or two double bonds. One can tailor different substituents on the diene or dienophile to get product libraries. Many acyclic, cyclic and polycyclic compounds are easily available as dienes and substituted olefins and acetylenes act as dienophiles. [4+2] Cycloaddition reaction of diene and dienophile components containing one or more heteroatoms is termed hetero Diels-Alder reaction.[8]

There are two empirical rules by which one can predict the regio and stereoselectivity of Diels-Alder adduct formation, viz. the *cis principle* and *Alder endo rule* formulated by Alder and Stein.[9] The *cis* principle give a clear cut idea about the stereospecific addition of diene and dienophile through a six membered transition state with permanent *s-cis* conformation of the diene component. It is important to note the retention of stereochemistry of diene and dienophile components in Diels-Alder adduct (Equation 1.1).[10]



(1.1)

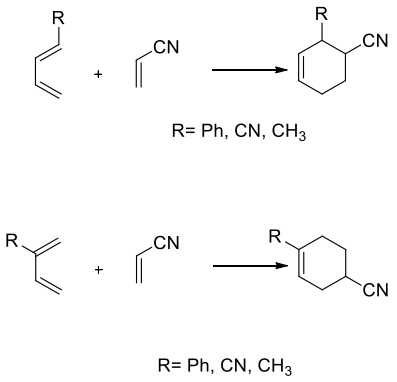
According to Alder *endo* rule thermodynamically unfavorable *endo* product predominates over the more favorable *exo* product. This is owing to the maximum accumulation of HOMO and LUMO in the transition state for *endo* adduct formation enabling secondary orbital interactions more effectively. Intermolecular Diels-Alder reaction of maleic anhydride and cyclopentadiene led to the exclusive formation of *endo* product **13** (Scheme1.2).[11]



10 11 12 13

Scheme 1.2

Regiochemistry of adduct formation in Diels-Alder reaction depends on the substituents in the diene and dienophile components. Reaction between unsymmetrically substituted diene and dienophile may result in the formation of regioisomers. Due to the effects of substituents one of the regioisomer may be formed as the major product.[12,13] Regiochemical modes of addition of diene and dienophile are depicted in the equation 1.2. Both regio and stereoselectivity observed in Diels-Alder reactions can be dependably predicted on the basis of FMO theory.[14]



(1.2)

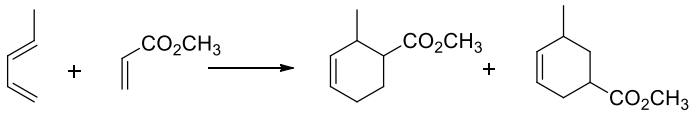
1.4.1 Modifications of Intermolecular Diels-Alder reaction

Several modifications have been developed to improve yield and/ or regioselectivity of Diels-Alder reaction. Different versions include, Lewis acid catalyzed Diels-Alder reactions,[15-21] Diels-Alder reactions in water,[22-34] pressure assisted Diels-Alder reactions,[35-46] enantioselective Diels-Alder reaction,[47] Diels-Alder reaction under solvent free conditions etc.[48]

1.4.2 Lewis acid catalyzed Diels-Alder reaction

Like other organic reactions, Diels-Alder reaction can also be catalyzed by Lewis acids such as $AlCl_3$, BF_3, $SnCl_4$ etc.[49,50] It was first observed by Yates *et al*., that a remarkable increase in the rate of Diels-Alder reaction is achieved in the presence of catalytic amount of $AlCl_3$.[49] Lewis acids not only accelerate the rate of the reaction but also enable reduction in reaction temperature to some extent with no letting down in the reaction rate. Moreover, improved regioselectivity was also observed under Lewis acid catalyzed conditions. Thanks to inherent regio and

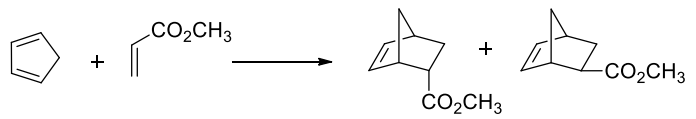
stereoselectivity, Lewis acid catalyzed Diels-Alder reaction received great attention among synthetic chemists. The following schemes (Scheme 1.3 and 1.4) represent the effect of Lewis acids on controlling regio and stereoselectivity of Diels-Alder reactions. As evident from product data presented in Scheme 1.4, best results are obtained under low temperature conditions.



14 **15** **16** **17**

Uncatalyzed	90%	10%
$AlCl_3$ catalyzed	98%	2%

Scheme 1.3



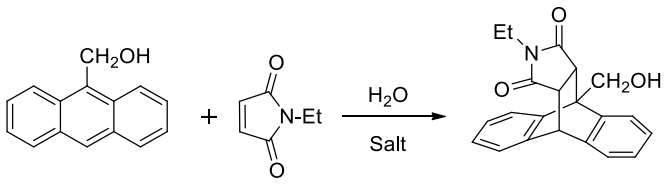
18 **15** **19** **20**

Uncatalyzed, 0 °C	88%	12%
$AlCl_3$, 0 °C	96%	4%
$AlCl_3$, -80 °C	99%	1%

Scheme 1.4

1.4.3 Diels-Alder reaction in water

Rideout and Breslow encountered a remarkable acceleration of Diels-Alder reaction in aqueous medium.[51] It is believed that Diels-Alder reaction is insensitive to solvent polarity, because the six membered transition states involved are largely nonpolar in nature. So the 1000 fold increase in rate in water with respect to that in nonpolar solvents is quite remarkable. Rate enhancement in water is attributed to proximity effect. In water, hydrophobic effects on the diene and dienophile bring them together in a close aggregation enabling higher reaction rates. Scheme 1.5 illustrates typical example for a Diels-Alder reaction performed in water.

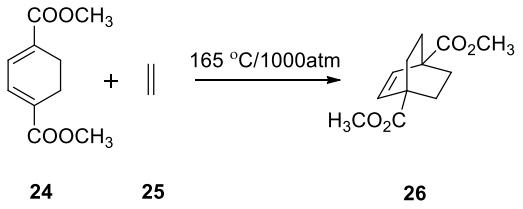


21 **22** **23**

Scheme 1.5

1.4.4 Pressure aided Diels-Alder reaction

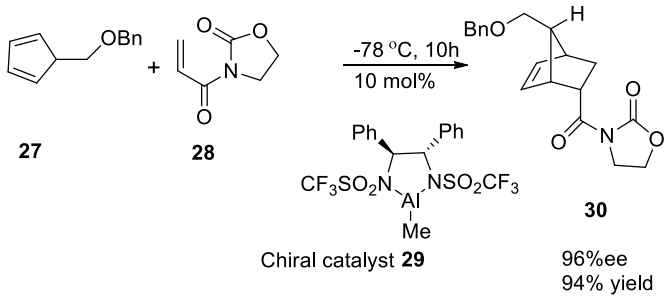
Under pressure Diels-Alder reaction proceeded with high reaction rates and also show remarkable diastereoselectivity.[52] It has been reported that gaseous reactants are convenient precursors for pressure assisted Diels-Alder reaction. For example under high pressure of about 1000 atm, ethylene added to dimethyl cyclohexa-1,3-diene-1,4-dicarboxylate to give corresponding adduct in good yields (Scheme 1.6).



Scheme 1.6

1.4.5 Enantioselective Diels-Alder reaction

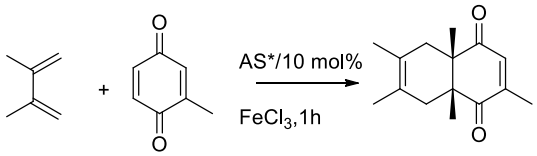
Chiral Diels-Alder adducts were synthesized by the development of enantioselective catalysts.[47] These catalysts incorporating π-electron rich aromatic groups effectively stabilize specific transition state geometries as well as control the stereoselectivity through facial screening. An important example is illustrated in the scheme 1.7.[53-55] The chiral Diels-Alder adduct **30** is obtained with 96% enantiomeric excess which is further utilized in the synthesis of prostaglandins (PGs).



Scheme 1.7

1.4.6 Solvent free Diels-Alder reaction

There are several examples of Diels-Alder reaction performed under solvent free conditions.[48,56,57] Timothy et al. recently reported solvent free Diels-Alder reaction of simple dienes with *p*-benzoquinones catalyzed by $FeCl_3$ on Aerosil silica (Scheme 1.8).[48] They found a substantial increase in the yield of the products and reduction in the reaction time. Scheme 1.8 portrays an example of solvent free Diels-Alder reaction of 2-methyl butadiene with substituted benzoquinone.

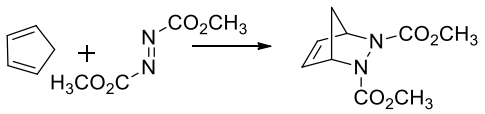


31 **32** **33**
89% yield

Scheme 1.8

1.5 Hetero Diels-Alder reaction

A well-known hetero Diels-Alder reaction[58-65] is the aza Diels-Alder reaction first explored by Libing et al.[63] for the synthesis of aza sugars. Six membered ring containing hetero atoms like N, O, S etc. can be easily made available through hetero Diels-Alder reaction. Many important precursors for natural product synthesis were accessed by means of hetero Diels-Alder reaction. Scheme 1.9 depicts an earlier reported example of hetero Diels-Alder reaction in which hetero atom incorporated norbornene derivative was synthesized from cyclopentadiene and a substituted azo compound.



18 34 35

Scheme 1.9

1.6 Intramolecular Diels-Alder reaction

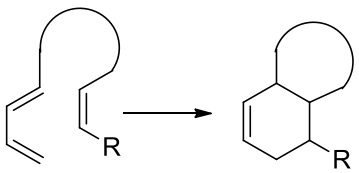
Intramolecular Diels-Alder reaction (IMDA) is one of the most useful synthetic tool widely used for the synthesis of complex polycyclic systems. This reaction remained unexplored for several years after its development by Alder. He obtained a bicyclic compound while carrying out a reaction of 1,4-pentadiene and dimethyl acetylenedicarboxylate (DMAD), formed through an unisolated ene adduct. Intramolecular Diels-Alder reaction is characterized by the presence of a connecting tether between diene and dienophile, i.e. diene and dienophile are part of the same molecule.[66] One can achieve desired regioselectivity and stereoselectivity in the products through selecting the diene or dienophile tether with desired stereochemistry. IMDA reactions are entropically favored and hence proceed under mild conditions and an added advantage is tandem generation of multiple stereocenters in the IMDA adduct. IMDA reaction found tremendous applications in the total synthesis of several natural products.

IMDA reaction provides a simple and better platform for achieving polycyclic skeletons, since the reaction give two rings in one single step. Simultaneous formation of two rings in IMDA reaction comprises the [4+2] cycloadduct and a fused ring, the size of which is dependent on the

length of the tether between diene and dienophile. Generally tethering has two benefits: i) it reduces the energy required to bring the reacting partners (the diene and the dienophile) together and ii) geometric constraints of the tether can directly affect the regio and stereoselectivity of adduct formation.

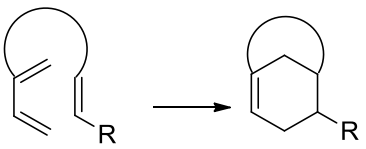
There are two variants of IMDA reaction depending upon the position of the tether bearing dienophile connected to C1 or C2 of the diene. If the tether is attached to the terminus C1 of the diene, it is regarded as the Type 1 and when the tether is connected to the C2 of the diene it is in Type 2. Type 1 IMDA always affords fused product predominantly over the bridged adduct. However, if the tether contains more than nine atoms, bridged products are obtained. In contrast Type 2 IMDA gives only bridged products. Following equations (equation 1.3 and 1.4) represent Type 1 and Type 2 IMDA reactions.

Type 1 IMDA



(1.3)

Type 2 IMDA

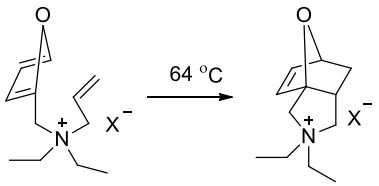


(1.4)

Type 2 IMDA always gives anti-Bredt alkene in which double bond is formed between the bridgehead position and adjacent carbon atom. Both Type 1 and Type 2 IMDA are widely explored in the total synthesis of bioactive compounds.

1.6.1 Effect of solvent polarity on IMDA

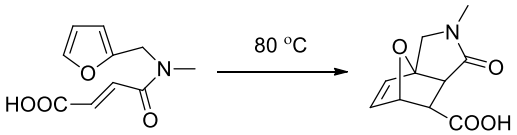
As in the case with intermolecular version, solvent polarity has insignificant effect on IMDA reaction. But a few reports emphasized increased rate of IMDA reaction performed in aqueous medium. This is attributed to the hydrophobic effect felt by the reacting entities. It has been reported that the hydrophobic effect allow the molecule to adopt a coiled conformation that resembles the six membered, highly ordered transition state.[51] The following scheme represents the IMDA reaction of furan derivative (Scheme 1.10). The reaction has been performed under different solvents and it is remarkable to notice the enhanced rate of cyclization in water (6.8). The rate of cyclization in 94% ethanol and acetonitrile are 2.4 and 1 respectively and these results are inferred by means of FMO theory.[67]



36 **37**

Scheme 1.10

Scheme 1.11 describes intramolecular Diels-Alder reaction of furan derivatives in different solvents and table 1.1 indicates the effect of solvent polarity on the rate of cyclization.[68]



38 **39**

Scheme 1.11

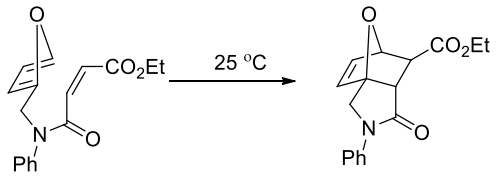
Table 1.1. Effects of solvents in the rates of IMDA cyclization

Solvent	**Temperature** ^{o}C	**K1** (s^{-1})
CH_2Cl_2	25	2.36×10^{-3}
MeCN	25	9.27×10^{-3}
EtOH	25	3.09×10^{-4}
H_2O	25	2.50×10^{-2}

1.6.2 Effect of pressure on IMDA reaction

Intermolecular Diels-Alder reaction possesses large negative volumes of activation and it can hence be accelerated by applying pressure. In contrast IMDA reaction has much lower negative volumes of activation. So pressure has no significant role on IMDA cyclization reaction. For example, IMDA reaction of a furan derivative **40** (Scheme 1.12) proceeded readily at room temperature under milder conditions and application of pressure has no effect on the rate.[69] Volume of activation

for this compound is -25 mL/mol which is less negative than that for a typical intermolecular Diels-Alder reaction i.e. -30 mL/mol.

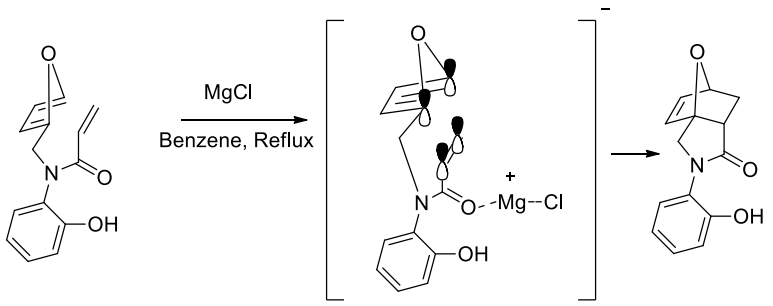


40 **41**

Scheme 1.12

1.6.3 Lewis acid catalyzed IMDA

Like intermolecular Diels-Alder reaction, IMDA also gives positive result towards Lewis acid catalysis. The important thing to notice is that catalyst not only enhances the rate but also control the regio/stereo selectivity. In general the catalyst is complexed with diene or dienophile during the course of the reaction and there is no prerequisite for the diene or dienophile to be complexed with the catalyst in order to bring about the reaction. For Lewis acid catalyzed IMDA reactions, rate enhancement varies from minimal to substantial. It has also been noted that conventional Lewis acids such as BF_3, $AlCl_3$, $TiCl_4$ etc. lead to polymerization of the diene rather than accelerating the rate of IMDA reaction of certain substrates.[70] So, modified catalysts such as menthoxyaluminum dichloride, diethylaluminum chloride, tungsten tetrachloride etc. are employed to reduce the tendency for polymerization and thereby enhance the rate of cyclization. Metal salts MgCl/ZnBr have also been used as efficient catalysts for the cyclization of furan derivative **42** (Scheme 1.13).[71-74]



42 **42'** **43**

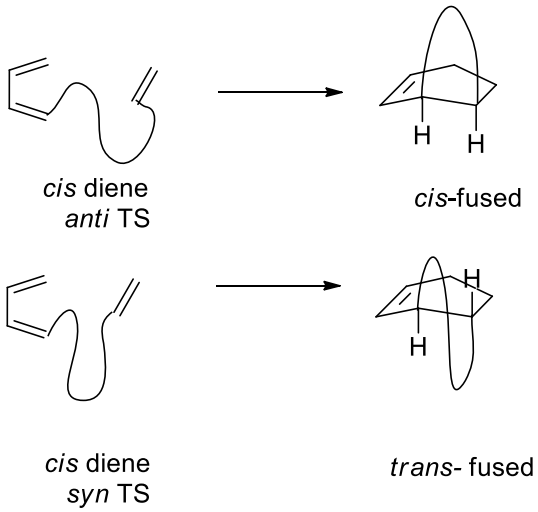
Scheme 1.13

1.6.4 Regioselectivity of IMDA reactions

Generally regiochemistry of intermolecular Diels-Alder reaction rely on substituents attached to the diene and dienophile components. In principle, reaction between unsymmetrically substituted diene and dienophile should afford a mixture of regioisomers. However, depending on the substituents present on these components, one regioisomer is formed as the major product. Similarly Type 1 IMDA reaction also may give two possible regioisomeric products such as fused and bridged products where fused products are favored over bridged products. On the other hand, bridged products are exclusively generated in Type 2 IMDA reactions. Bridged product formation is observed in IMDA reactions where the tether is nine or more atom long. Unlike intermolecular version, the directive influence of groups present in diene or dienophile are ruled out in controlling regioselectivity of IMDA reactions. Here geometrical constraints control regioselectivity.

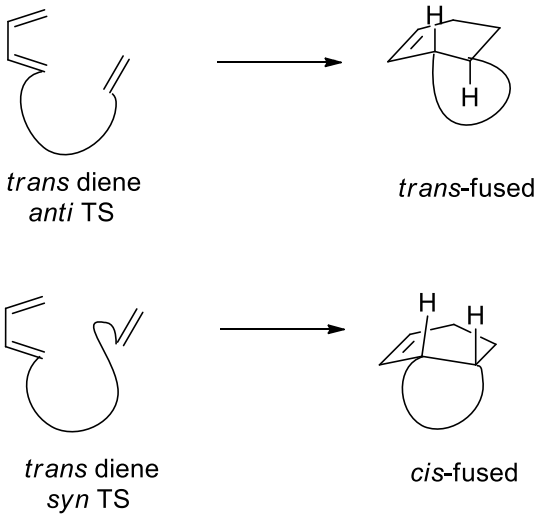
Both fused and bridged products may be obtained as a mixture of stereoisomers. *Syn/anti* selectivity of the transition state (TS) is the major

driving force in determining the stereochemistry of the incipient IMDA adduct. Generally *cis* and *trans* dienes give rise to either *cis* or *trans*-fused products and the actual stereochemistry relies on the orientation of the diene and dienophile in the TS. The *anti* TS of *cis* diene gives *cis*-fused products while *syn* TS gives *trans*-fused products (Equation 1.5).



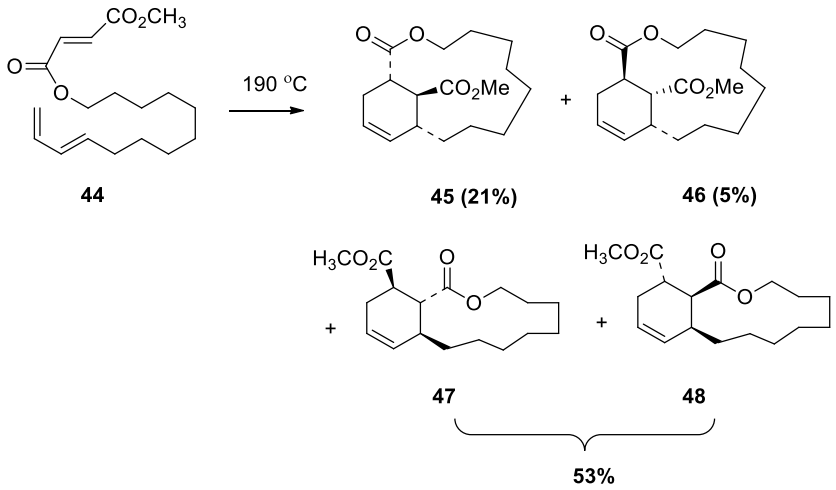
(1.5)

Cis and *trans*-fused products are also possible in the cyclization of *trans* dienes. *Trans* diene may give *cis* and *trans*-fused products via *syn* and *anti* transition state respectively. Equation 1.6 represents the general stereochemical modes of cyclization of the *trans* diene.



(1.6)

However there are limitations in the possibilities particularly due to chain (or tether) length. It has been observed that tether containing one or two atoms preclude the *trans* dienes from IMDA cyclization and the *cis* dienes (with one to four atoms tether) always preferred *anti* transition state resulting in the formation of *cis*-fused products. *Trans* dienes with three to four atoms tether constitute the majority of substrates known to undergo IMDA reaction and always result in a mixture of products via *syn* or *anti* transition state. This follows in the case with *trans* dienes bearing long tether as well. It has been reported that *trans* diene with tether of ten atoms, **44** for example, undergo cyclization giving a total of four products viz, two bridged products via *syn* and *anti* transition state and two possible fused products through *syn* or *anti* transition state (Scheme 1.14).[75] The yields of bridged products were lower in comparison with the corresponding fused products.



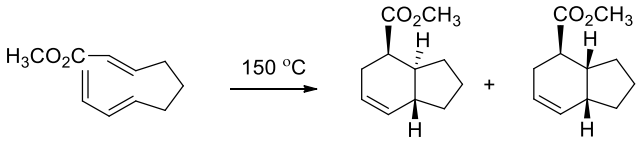
Scheme 1.14

IMDA cyclizations have been mostly performed on *trans* dienes where *cis* and *trans*-fused products are formed via *syn* and *anti* transition state respectively. So it is worth mentioning a few aspects of different *trans* diene systems in the coming sections. The major dienes include:

1. Acyclic diene with all carbon tether
2. Acyclic diene with tether containing heteroatoms
3. Cyclic diene with tether
4. Vinyl aromatics
5. Exocyclic diene with tether
6. Furan derivatives

1.6.5 Acyclic diene with all carbon tether

This kind of dienes with tether containing three or four atoms always give *cis* and *trans*-fused products, out of which *trans*-fused products are the major ones. Explanation for the lack of product selectivity relies on loose adherence to Alder *endo* rule and electronic factors induced by the nature of substituents present on the diene and dienophile connected by a relatively short tether. The example portrayed below is for an uncatalyzed IMDA cyclization in which a mixture of products is formed. The *trans*-fused product **50** is the major isomer with 39% yield along with *cis*-fused product **51** formed in a respectable 26% yield (Scheme 1.15).[70] In the presence of menthoxy $AlCl_2$, a Lewis acid catalyst (at room temperature), the cyclization exhibits dramatic stereoselectivity leading to exclusive formation of *trans*-fused product **50** (72%).[76] The cyclization preferred *anti* TS for exclusive formation of **50**.

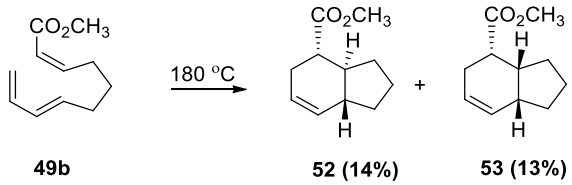


49a **50** **51**

Scheme 1.15

Interestingly, **49b**, a geometrical isomer of **49a** behaved anomalously. Under both catalyzed and uncatalyzed conditions, **49b** underwent cyclization less efficiently. It was also observed that under uncatalyzed conditions, as in the case of **49a**, the *trans*-fused product was formed as the major product. Surprisingly, under Lewis acid catalyzed conditions,

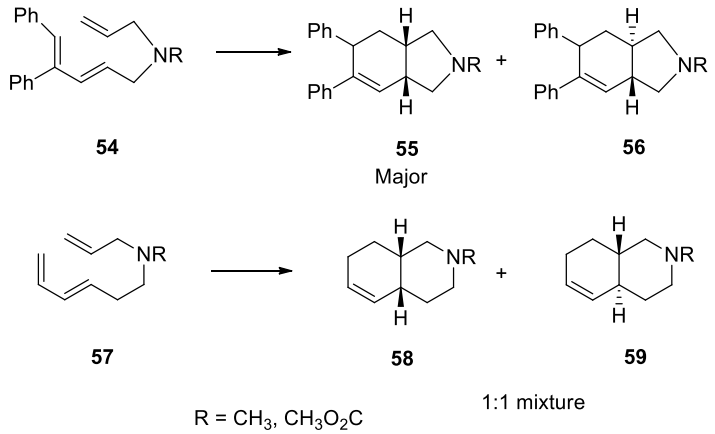
both *cis*- and *trans*-fused products were formed in nearly equal yields (Scheme 1.16).



Scheme 1.16

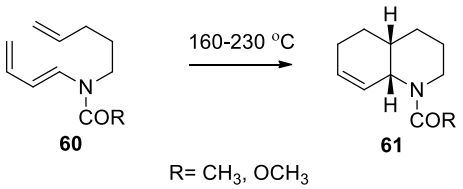
1.6.6 Acyclic diene with tether bearing heteroatoms

Heteroatom inclusion in a tether may affect the stereochemistry due to electronic factors that may apparently drive the selectivity towards either *cis* or *trans* products. Heteroatoms such as nitrogen and oxygen are frequently seen in the tether and are common in the IMDA reactions. In the case of amine **54** when R group is CH_3, the *cis* product predominated over the *trans* product by a factor of five.[77] The structural homolog of the above starting compound i.e. **57** gives a mixture of *cis* and *trans* products in 1:1 ratio indicating the effect of structure (tether length as well as substitution pattern) on controlling stereoselectivity.[78] Both reactions are portrayed in scheme 1.17.



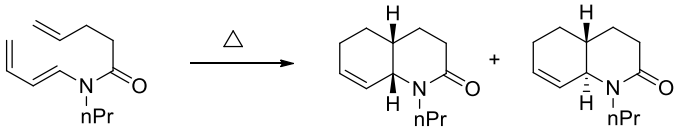
Scheme 1.17

Though acyclic dienes incorporating amine give a mixture of both *cis* and *trans*-fused products, N-acyl dienes such as **60** behaved differently: exclusive formation of *cis*-fused products is observed with these.[79] Secondary orbital interactions are invoked to account for this dramatic change in stereoselectivity (Scheme 1.18).



Scheme 1.18

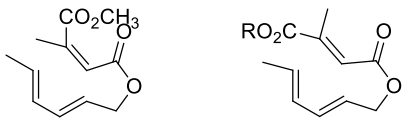
On the other hand, when an amide linkage is part of the tether as in the case of **62**, a mixture of *cis* and *trans*-fused products is formed (Scheme 1.19).[79] There are many examples of acyclic dienes containing nitrogen atom. Covering all the examples of such dienes is beyond the scope of this chapter.



62 63 64

Scheme 1.19

Another important category of the acyclic diene systems are those incorporating ether or ester functional groups. The ether oxygen in the tether has reportedly no influence in driving the stereoselectivity exemplified by a few examples reported in literature. But when it comes to ester group incorporated tether, it has detrimental effect in the selectivity. Isomers of the same compound with ester group attached tether reacts in remarkable way upon IMDA cyclization. Compound **65** (R = CH_3) on IMDA reaction give exclusively the thermodynamically less stable *trans*-fused product; in contrast other isomer **66** on IMDA cyclization yielded a mixture of *cis* and *trans* products (Figure 1.1).[80] The *trans* product is obtained as the major product and the ratio of *trans* product to *cis* is found as 4.6 : 1. In compound **65** when R = H, the reaction becomes thermodynamically controlled and IMDA cyclization give *cis* product exclusively.



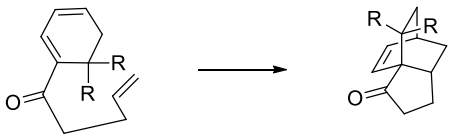
65 **66**

R = H, CH_3

Figure 1.1

1.6.7 Cyclic diene with tether

Cyclic dienes always have *cis* configuration and expected to adopt *anti* transition state to result *cis*-fused products. It does not follow in all cases and by changing the substituents on the substrate altered the stereochemistry of the product. For example the compound **67** upon IMDA cyclization give *cis*-fused product if R = H, and on the other hand if R = CH_3, the cyclization yielded *trans*-fused product via *syn* transition state.[81] This is attributed to the non-bonding interactions between the methyl groups and allylic hydrogen in the transition state. The reaction is represented in the scheme 1.20.



67 **68**

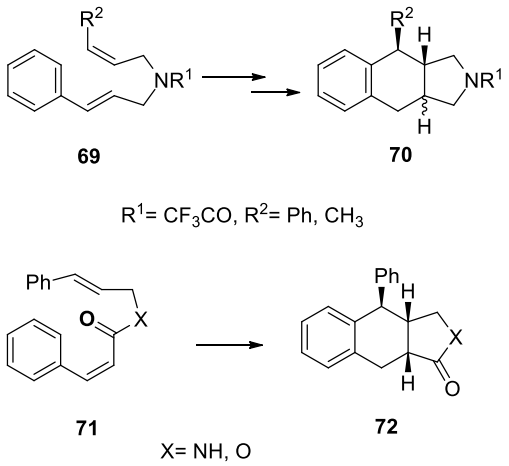
R= H, CH_3

Scheme 1.20

1.6.8 Vinyl aromatics

Like previous cases vinyl aromatic substrates are found selective when appropriate substituents are included in the tether. When bulkier substituents are present in the tether, the cyclization preferred *syn* addition and give *cis*-fused product in a few cases. On the other hand *anti* addition is favored for smaller substituents and give *trans* products and it is important to note that, substituents are part of the tether bearing dienophile. For example an amide **69** in which R^2 is a phenyl group, the IMDA reaction give *cis* products exclusively (Scheme 1.21). Conversely

the cyclization of the same gives *trans*-fused product if R^2 is a methyl group.[82] Another example given is a cinnamic acid derivative and even if it contain a bulkier phenyl group the cyclization followed through *anti* TS and exclusive formation of *cis*-fused product was obtained.[83,84] In this case the cinnamic acid derivative oriented as *cis* diene and preferred the highly crowded *anti* transition state though two phenyl groups are in close proximity. Both reactions are portrayed in the scheme 1.21.

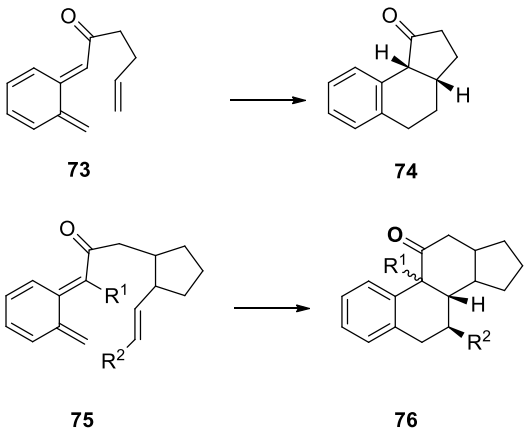


Scheme 1.21

1.6.9 Exocyclic diene with tether (*o*-Quinodimethanes)

These dienes with tether incorporating three carbon atoms prefer *anti* transition state upon cyclization and give only *trans* products unless any substituent effect. The exception to this generalization is presented in the scheme 1.22 in which the IMDA substrate **73** on cyclization yield exclusively the *cis*-fused product via *syn* transition state.[85] In contrast, tether containing four atoms oriented in *anti* transition state irrespective of the substitution on the chain or dienophile afford exclusive *trans*

product. This may be due to the steric factor in the *syn* transition state which controls the stereoselectivity. For example a ketone of type **75** gives *trans* product exclusively upon IMDA cyclization via *anti* transition state.[86] The *anti* selectivity in **75** twisted when R^1 group is a cyano functional group in which the cyclization preferred a *syn* transition state and give only *cis*-fused product exclusively (Scheme 1.22).

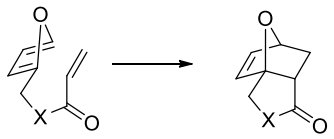


Scheme 1.22

1.6.10 Furan derivatives with tether

It has been observed that, the IMDA reaction of furan appended tether preferred *anti* transition state and resulted in the formation of *trans* products. It is important to note that the *anti* transition state is against the conventional Alder *endo* rule. Thermodynamic control is assumed to be the major driving force in the preferred *anti* selectivity. The reaction scheme 1.23 represents the cyclization of ketone, ester and amide, all are

oriented against the Alder *endo* rule and resulted in the formation of *trans* products.[87]



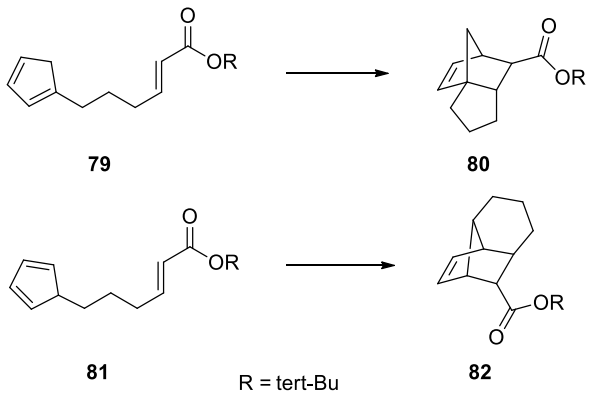
77 **78**

X = CH_2, O, NCH_3

Scheme 1.23

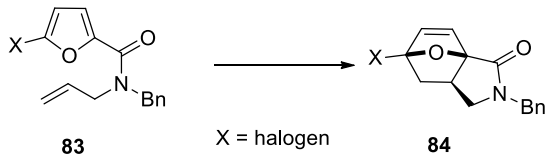
1.7 Applications of IMDA

Over the years, IMDA reactions found more applications in the total synthesis of complex natural products. A few prototypical applications of IMDA in the synthesis of naturally occurring compounds are mentioned here to highlight the importance of IMDA reactions in synthetic organic chemistry. An important feature of IMDA is the simultaneous formation of two rings in a single step which is otherwise difficult to achieve. Stille and Grubbs reported the synthesis of tricyclic systems which are the precursors for certain natural products via IMDA cyclization of cyclopentadiene tethered with an ester dienophile (Scheme 1.24).[88] The reaction proceeded under mild conditions (75 °C) and adducts were obtained in good yields. Both bridged and fused products are accessed by changing position of attachment of the tether to the diene.



Scheme 1.24

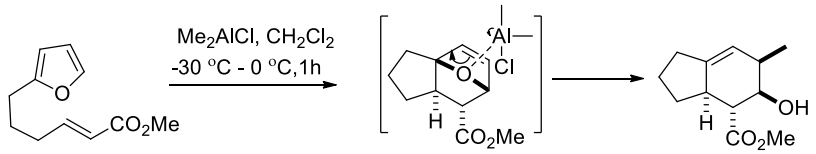
IMDA reactions of furan derivatives, generally abbreviated as IMDAF, are extremely useful synthetic protocols. Adducts formed with furan derivatives are important synthons for complex natural products. Padwa et al. reported that IMDA cyclization of a series of furanyl amides resulted in the formation of the corresponding oxanorbornenes under mild conditions and products are formed in good yields.[89] Scheme 1.25 describes the synthesis of a few functionalized oxanorbornenes from corresponding halo-substituted furans.



Scheme 1.25

In a recent report Riedel et al. highlighted the domino IMDA and nucleophilic ring opening of the ether bridge of furanyl enoates. The

reaction catalyzed by Lewis acids is performed at very low temperatures.[90] The adducts are important due to their potential applications in natural product synthesis. Scheme 1.26 portrays the domino cyclization and nucleophilic ring opening reaction of tethered enoate substituted furan.



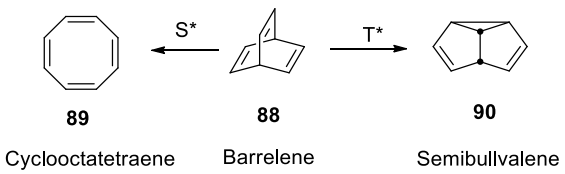
85 86 87

Scheme 1.26

IMDA reaction is now extended to the synthesis of annulated dibenzobarrelenes. Earlier dibenzobarrelene chemistry primarily focused on unraveling structure activity relationships with respect to their singlet and triplet excited state reactions. But in recent years, efforts diverging from the realm of photochemistry are gaining momentum. Dibenzobarrelene adducts formed after IMDA cyclization of certain anthracene appended compounds exhibited excellent fluorescent properties and have potential to find applications as photoluminescent materials.[91,92] Chemical and physical properties of dibenzobarrelenes can be modified by introducing substituents on the barrelene chromophore. The following section mainly focuses on the chemistry of barrelenes and their diverse reactivity and physical properties with subtle references to their synthesis via inter and intramolecular Diels-Alder reaction.

1.8 Chemistry of Barrelenes

Barrelene (C_8H_8) is a bicyclic compound reported by Hine in 1955 and first synthesized by Zimmerman and Paufler in 1960.[93,94] Since then barrelene chemistry emerged as a key branch of photochemistry explored worldwide by scientific community. Multiplicity dependent reactivity of barrelenes attracted much attention because of the product diversity and mechanistic appeal. Singlet and triplet mediated phototransformations of barrelene lead to cyclooctatetraene and semibullvalene respectively. Scheme 1.27 portrays the general photoisomerization of barrelene **88** reported by Zimmerman and Grunewald in 1966.[95]

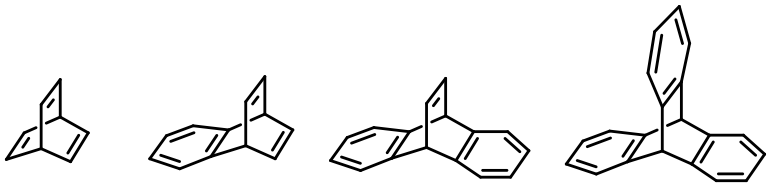


Scheme 1.27

It is clear from the above scheme that cyclooctatetraene, **89** is formed through a singlet mediated pathway and involves [2+2] cycloaddition followed by electrocyclic ring opening of the cycloadduct. Conversely semibullvalene, **90** is obtained via triplet mediated di-π-methane rearrangement (DPM). Since its development, barrelene chemistry is mainly explored for the regiochemical aspects of the di-π-methane rearrangement and cyclooctatetraene formation. Zimmerman encountered the di-π-methane rearrangement in the photoisomerization of barrelene which is shown in scheme 1.27 and later on many experiments were

reported on the general di-π-methane rearrangement. However in this thesis di-π-methane rearrangement and singlet mediated reactions of barrelene derivatives have prime importance.

Barrelene derivatives such as benzobarrelenes, dibenzobarrelenes and triptycenes exhibits structure-controlled definite photophysical and photochemical properties. So it is very important to mention about the behavior of barrelene and its derivatives upon tethering with various substituents as well as their photochemical outcome. Scientists found dramatic results on varying substituents on the barrelene chromophore and here are some reports which are deliberately included to understand the importance of barrelene chemistry. Figure 1.2 gives some idea on the basic skeleton of various barrelene chromophores.



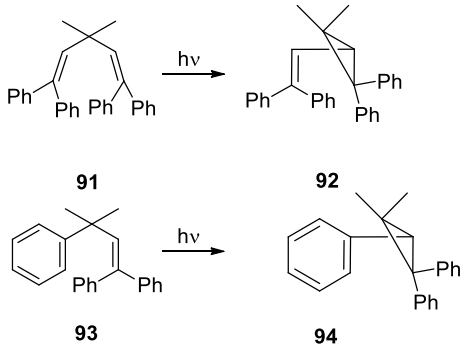
Barrelene Benzobarrelene Dibenzobarrelene Triptycene

Figure 1.2. Basic skeletons of different barrelene derivatives

In the case of bridgehead substituted barrelenes the chemical and physical properties are oddly varied from the expected manner and the following sections briefly delineate those aspects.

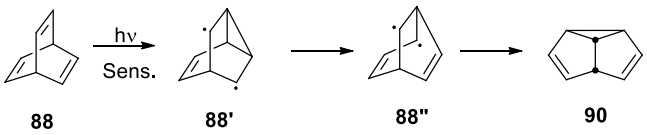
1.9 Important photorearrangements of barrelenes- Multiplicity dependence

The major rearrangement in the photochemistry of barrelenes is di-π-methane rearrangement (DPM) that was, interestingly, a serendipitous discovery encountered while examining barrelene photochemistry. Basic photochemistry of barrelene discovered by Zimmermann in 1966 is outlined in Scheme 1.27. Later in 1967 Zimmerman and Binkely noted the generality of di-π-methane rearrangement in 1,4-dienes (two vinyl moieties bonded to same carbon atom which is sp^3 hybridized) to yield vinyl cyclopropanes (Scheme 1.28) which is obtained after direct irradiation.[96] They initially named reaction as "divinyl methane rearrangement" since two vinyl groups and a sp^3 hybridized carbon atoms are involved. Through a series of experiments, Zimmermann established that divinyl methane rearrangement in open chain systems is singlet mediated while in cyclic systems such as barrelenes, it is triplet mediated. After these initial findings, Zimmerman and co-workers discovered that the same rearrangement occurred when one vinyl group was replaced with an aryl moiety as in **93** (Scheme 1.28). Since then the rearrangement has been known more appropriately as "di-π-methane rearrangement".



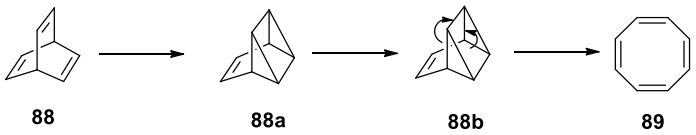
Scheme 1.28

Based on these observations they arrived at a common mechanism for di-π-methane rearrangement, applicable to simple acyclic 1,4-dienes to complex barrelenes. The basic mechanism for semibullvalene formation through di-π-methane rearrangement was illustrated in scheme 1.29. It involves the generation of biradical species which rearranged to give corresponding semibullvalene.



Scheme 1.29

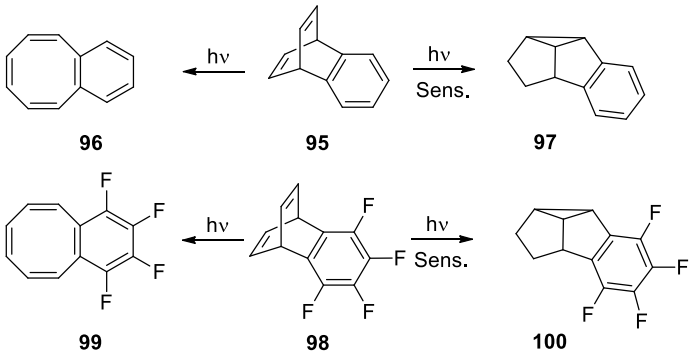
On the other hand cyclooctatetraene is obtained through [2+2] cycloaddition followed by electrocyclic ring opening of the cycloadduct. The mechanism of the rearrangement is given in scheme 1.30. These two photochemical transformations are the major rearrangements of barrelene derivatives.



Scheme 1.30

1.9.1 Isomerization of benzobarrelenes

When it comes to benzobarrelenes the photorearrangement can occur in two possible pathways as expected. Two possible products, benzosemibullvalene is obtained via triplet mediated pathway and benzocyclooctatetraene is perceived through singlet mediated pathway. The following scheme explained the possible photoproducts of benzobarrelene **95** and one of its derivative **98** (Scheme 1.31).[97,98]

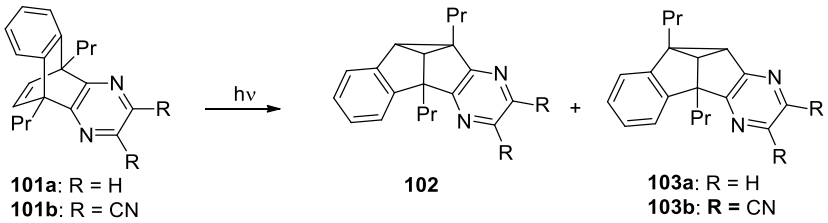


Scheme 1.31

As mentioned earlier, unlike acyclic dienes the cyclic dienes such as barrelenes where free rotation about the π-bonds is restricted preferred triplet mediated pathway during the sensitized photorearrangement. But there are always some notable exceptions to any generalizations. It should be noted that, in cyclic systems, singlet excited state does not

bring about di-π-methane rearrangement because of competition with other pericyclic reactions. Depending on intersystem crossing efficiency, a triplet sensitizer may or may not be needed to bring about the di-π-methane rearrangement in barrelene and its derivatives.

Isomerization of benzopyrazinobarrelenes are also well investigated, here photoisomerization of some benzopyrazinobarrelenes are discussed. These barrelenes are also termed as heteroarene-fused barrelenes and interesting thing is that they do not require any sensitizer for triplet mediated transformations. Irradiation of benzopyrazinobarrelene **101a** in benzene gives both di-π-methane rearrangement products arising through both benzo-vinyl and pyrazino-vinyl bridging possibilities to give **102** and **103** respectively (Scheme 1.32).



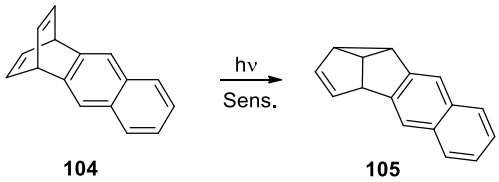
Scheme 1.32

Semibullvalene **103a** is obtained as the major product when R = H (58%). Isomers **102** and **103a** are formed through benzo-vinyl and pyrazino-vinyl bridging respectively. However irradiation of dicyano substituted benzopyrazinobarrelene **101b** affords only **103b** in 100% yield.[99] This is attributed to the stabilization of the pyrazino-vinyl bridging due to pyrazine moiety and cyano group. Photochemistry of several other derivatives of benzopyrazinobarrelenes viz, with *tert*-butyl

groups at bridgehead position, dimethoxybenzopyrazinobarrelene etc. are also well explored.

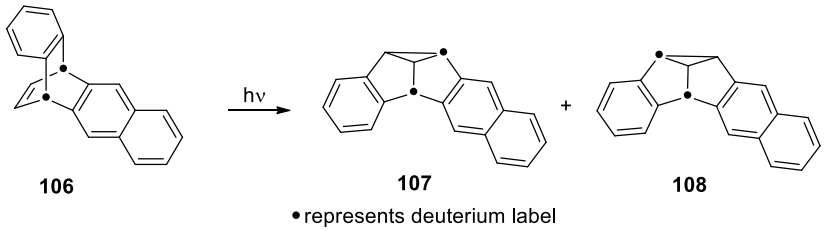
1.9.2 Isomerization of naphthobarrelenes

Naphthobarrelene derivatives are quite different from their parent barrelene. Photoisomerization leads to semibullvalene via di-π-methane pathway under direct irradiation as well as under sensitized conditions. An example for sensitized irradiation is given in the scheme 1.33.[100] Upon sensitized irradiation, naphthobarrelene **104** rearranged through triplet excited state resulting in naphthosemibullvalene **105**.



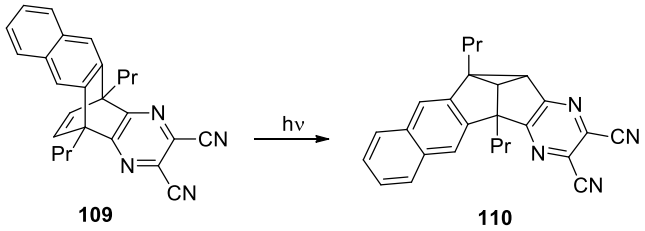
Scheme 1.33

Another example in this category is a benzonaphthobarrelene **106**, which on irradiation in cyclohexane gave semibullvalene product arising through two distinct pathways. Deuterium labels were introduced at the bridge head position to differentiate between the two competing reactions pathways. Deuterium labeled compounds gave two isomers in equal amounts; one isomer is obtained via benzo-vinyl and other through naphtho-vinyl bridging. Scheme 1.34 clearly demonstrated the above transformations. Compound **107** occurred via the benzo-vinyl bridging and compound **108** obtained through the naphtho-vinyl bridging.[101]



Scheme 1.34

Following is an example of photoisomerization of naphtha-pyrazinobarrelene, which is dissimilar from the previous case and afford only one semibullvalene. This naphthopyrazinosemibullvalene was obtained through pyrazino-vinyl bridging. Scheme 1.35 shows the photoisomerization of naphthopyrazinobarrelene **109** which affords semibullvalene **110** exclusively.[102] The rearrangement proceeded through pyrazino-vinyl bridging due to the stabilization effects of cyano and pyrazine moiety. Semibullvalene **110** was formed in very good yield (97%) as in the case of dicyanobenzopyrazinobarrelene **103b** reported earlier.

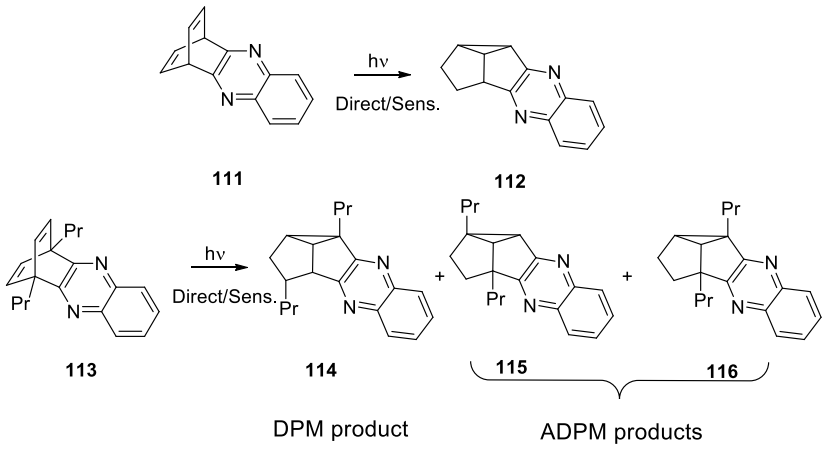


Scheme 1.35

1.9.3 Isomerization of quinoxalinobarrelenes

Photochemical behavior of quinoxalinobarrelene is quite similar to naphthobarrelene and affords corresponding semibullvalene exclusively

under both direct and sensitized irradiation. Photochemical transformation of parent quinoxalinobarrelene is represented in Scheme 1.36. Substituted quinoxalinobarrelenes also follow the same pathway under both direct and sensitized irradiation and may result in the formation of different regioisomers. An example for the phototransformations of bridgehead substituted quinoxalinobarrelene is portrayed in Scheme 1.36. Products **115** and **116** were formed in minor amounts through di-π-methane pathway involving quinoxalino-vinyl bridging.[103] Semibullvalene **114** arising through di-π-methane route involving vinyl-vinyl bridging is formed as the major product.



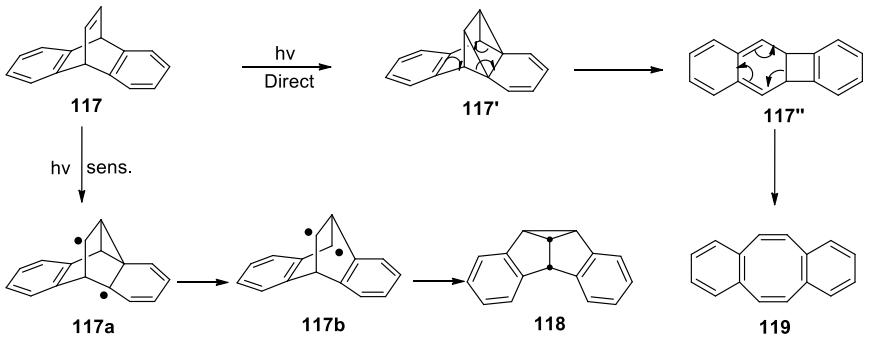
Scheme 1.36

1.9.4 Isomerization of dibenzobarrelenes

The chemistry of dibenzobarrelenes is well-studied and quite remarkable, thanks to the diverse regioselectivity observed therein. Today, dibenzobarrelene chemistry is not restricted to the domain of versatile photochemistry but has attained importance in other aspects

also. Chemistry of dibenzobarrelenes has expanded to many areas: several dibenzobarrelenes shows anti-bacterial activity, some show excellent photochromism, some have found applications in OLED's etc. Since our primary focus is on the photochemistry of dibenzobarrelenes, a few salient features of dibenzobarrelene photochemistry are highlighted in this section along with a brief discussion on other facets of dibenzobarrelene chemistry. Like unsubstituted barrelenes, photolysis of dibenzobarrelene also has the same fate and photoproducts are as expected: dibenzosemibullvalenes and dibenzocyclooctatetraenes.[104] Basic photochemistry of dibenzobarrelene is presented in scheme 1.35.

It is intriguing that both barrelene and dibenzobarrelene photochemistry appeared in the literature in the same year 1966 and the direct irradiation result was reported after two years. Ciganek has reported the sensitized photolysis of dibenzobarrelene **117** and it follows general di-π-methane rearrangement leading to dibenzosemibullvalene **118**.[104] Dibenzosemibullvalene is formed through a triplet mediated pathway as in sensitized photolysis of parent barrelene. In 1968 Friedman and co-workers found the singlet mediated product dibenzocyclooctatetraene **119** after direct irradiation.[105] General mechanism[106,107] for the formation of dibenzosemibullvalene and dibenzocyclooctatetraene are depicted in scheme 1.37.

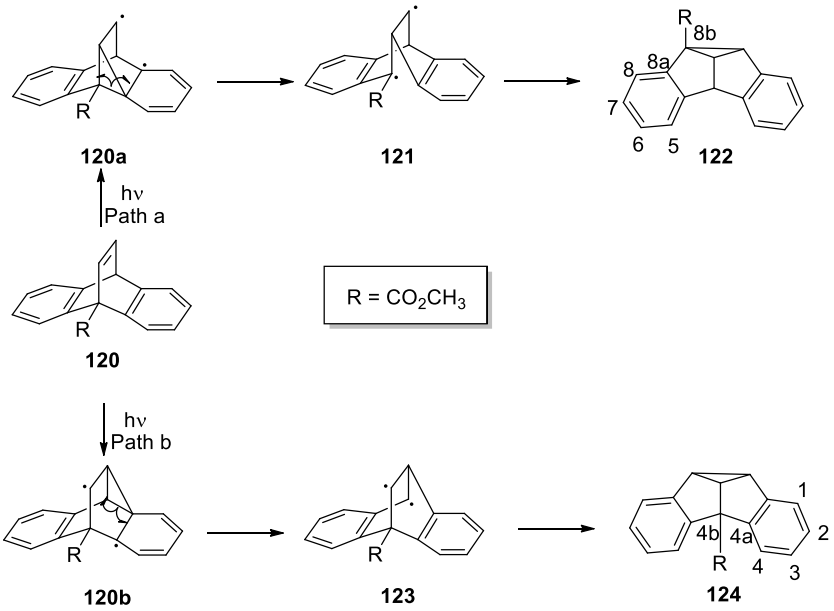


Scheme 1.37

Mechanism of semibullvalene formation involves the generation of a biradical intermediate **117a** through a benzo-vinyl bridging that is subsequently transformed into biradical intermediate **117b**. Radical closure in **117b** completes rearrangement of dibenzobarrelene **117** to dibenzosemibullvalene **118**. Dibenzocyclooctatetraene is generated in the direct irradiation of **117** and mechanism involves an initial [2+2] cycloaddition followed by electrocyclic ring opening of the [2+2] adduct. It has been reported that dibenzocyclooctatetraene formation is also triggered by a triplet mediated tri-π-methane rearrangement.[108-110]

Regioselectivity in di-π-methane rearrangement of bridgehead substituted dibenzobarrelenes was first noticed by Ciganek.[104] When bridgehead position of dibenzobarrelene is substituted with methoxycarbonyl group, acetone sensitized irradiation resulted in the formation of two semibullvalenes viz. 4b and 8b-regioisomers. The following scheme (Scheme 1.38) describes the regioselective product formation of bridgehead substituted dibenzobarrelene **120** upon acetone sensitized irradiation. The mechanism follows pathways analogous to

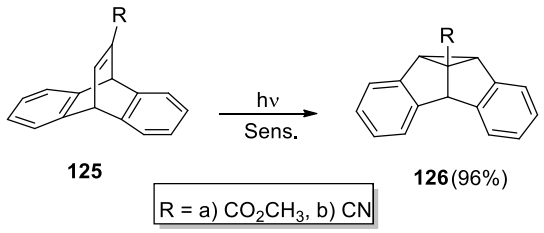
those observed in the sensitized photolysis of dibenzobarrelene, but involving the generation of two biradical intermediates **120a** and **120b**. Two regioisomers (**122** and **124**) are obtained as a result of two different benzo-vinyl bridging possibilities. Among these, the major regioisomer **122** is formed from the more stabilized biradical intermediate. Detailed mechanism of regioselective outcome of the sensitized photolysis of bridgehead substituted dibenzobarrelene is presented in the scheme 1.38. Here the electron withdrawing substituent at the bridgehead position stabilized the biradical intermediate and resulted the formation of 8b-substituted dibenzosemibullvalene as the major product.



Scheme 1.38

Substituents at 11,12-positions (or, the vinylic positions) in dibenzobarrelenes also influence regiochemical outcome of di-π-methane rearrangement in their own way. Electron withdrawing substituents such

as carbomethoxy and cyano at the 11-position of dibenzobarrelenes direct di-π-methane rearrangement in dibenzobarrelenes such as **125a,b** towards the generation of the corresponding dibenzosemibullvalenes **126a,b** (Scheme 1.39).



Scheme 1.39

The photolysis of differently substituted dibenzobarrelenes were extensively studied by George et al.[111-113] and Scheffer et al.[114-123] Their findings led to important information on barrelene-semibullvalene rearrangement. In general, the factors that drive the regioselectivity include,

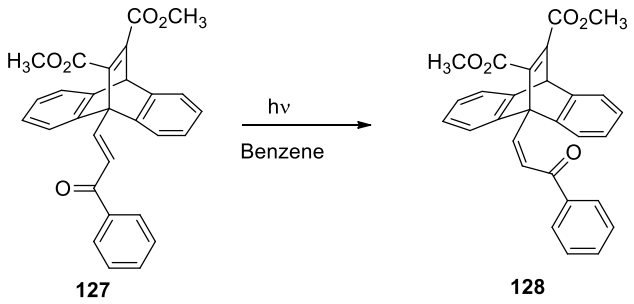
1. Angle strain at the vinylic position (Annulated system)[124]
2. Electronegativity of bridgehead substituents [125-127]
3. Orientation of substituents in the space [127]
4. Van der Waals interactions between bridgehead substituent and aromatic hydrogens [114]

Our group has also made some contributions to the photochemistry of dibenzobarrelenes.[128-130] We took substituent effects to the next level, i.e. beyond controlling regiochemical outcome of barrelene-semibullvalene rearrangement. We have successfully directed barrelene photochemistry to pathways beyond cyclooctatetraene and semibullvalene formation by

appending enone and amine substituents on to the barrelene core. Photochemistry of tethered or 9,11-annulated barrelenes is also a topic of our current interest. A brief outline of our recent findings is included in the following section.

1.9.5 Chemistry of enone appended dibenzobarrelenes

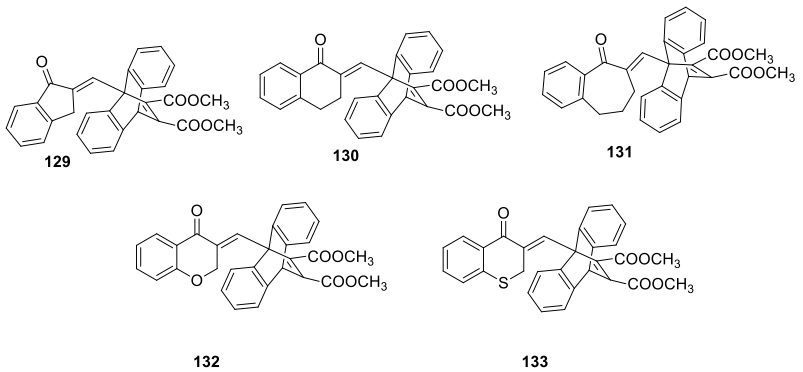
Photochemistry of enones are well investigated and their excited states include singlet S_1 (n, π*); triplet T_1 (n, π*) and T_1 (π, π*) that are close in energy. Vibronic mixing of these excited states and solvent dependence on excited state energies drive diverse reactivity of enones in the photochemical reactions.[131,132] When it is appended to barrelene chromophore, the photochemistry becomes even more complex. Induction of competition between barrelene photochemistry and enone photochemistry is a distinct possibility. In a series of controlled experiments performed in our lab, we observed that *cis-trans* isomerization in enone appended dibenzobarrelenes takes precedence over typical dibenzobarrelene photochemistry.[128,129] Irradiation of the *trans*-isomer enone appended dibenzobarrelene **127** in benzene, for example, gave the *cis*-isomer **128** as the only product (Scheme 1.40). The most common triplet mediated barrelene-semibullvalene rearrangement is not observed in these types of compounds since it contains olefin components which act as triplet quenchers.



127 128

Scheme 1.40

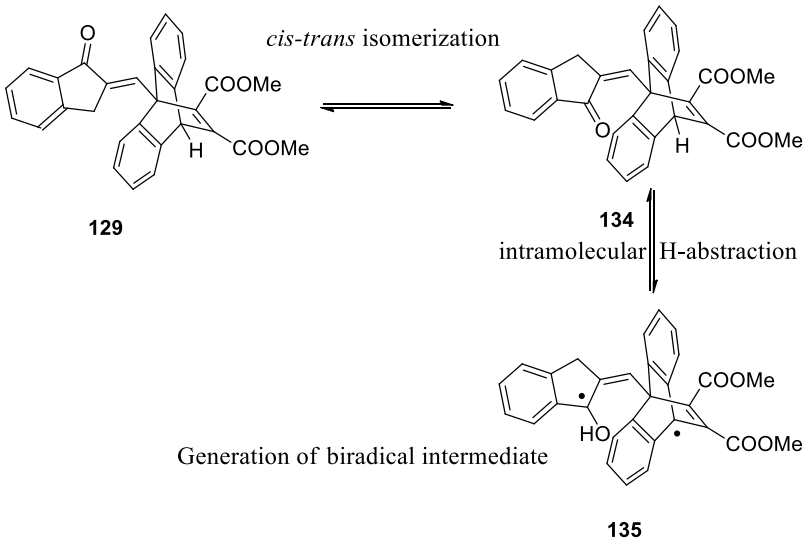
Another striking observation about a few enone appended dibenzobarrelenes is remarkable photochromism exhibited by them in the solid state. Photochromism is attributed to reversible light induced *cis-trans* isomerization followed by intramolecular hydrogen abstraction leading to biradical species.[129] Investigators from our group have synthesized several photochromic barrelenes. A few of the photochromic barrelenes synthesized by our group are listed in Figure 1.3. Scheme 1.41 describes a possible mechanism for photochromic behavior of a selected enone appended dibenzobarrelene **129**.



129 130 131

132 133

Figure 1.3. Enone appended dibenzobarrelenes exhibiting photochromism



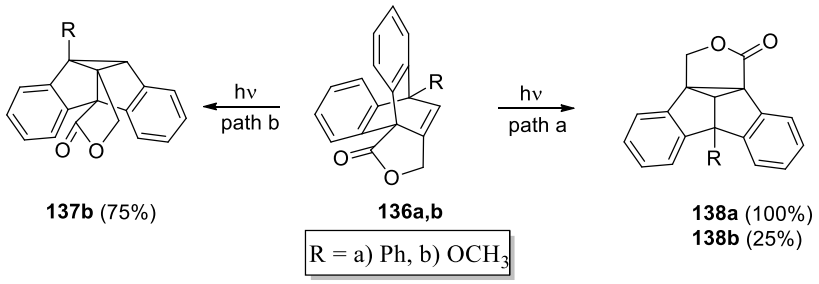
Scheme 1.41

A rare instance of electron transfer mediated retro Diels-Alder reaction in amine-appended dibenzobarrelenes has also been reported from our group.[130]

1.9.6 Chemistry of annulated/tethered dibenzobarrelenes

Several 9,11-anulated barrelenes were synthesized and their photochemistry was examined by our group. In certain instances, dramatic change in the regiochemistry that sweeps away the existing generalizations on regioselectivity principles of di-π-methane rearrangement mentioned earlier was observed with annulated barrelenes.[124] An illustrative example is provided in Scheme 1.42. Earlier reports suggest exclusive generation of the 8b-substituted dibenzosemibullvalene from the corresponding dibenzobarrelene having a phenyl substituent at the bridgehead position.[133] Surprisingly, a hundred and eighty degree turn in regioselectivity was observed with a 9,11-

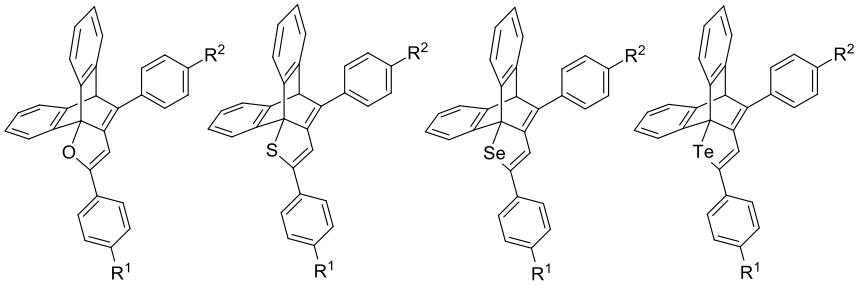
anulated barrelene **136a** which gave the 4b-substituted semibullvalene **138a** in quantitative amounts. Alteration in regioselectivity was observed with a methoxy substituent at the bridgehead position as well. Earlier reports suggest exclusive generation of 4b-substituted dibenzosemibullvalene from a dibenzobarrelene having a methoxy substituent at the bridgehead position. Presence of a cyano, on the other hand favored the formation of the 8b-substituted isomer.[125] In the case of annulated barrelene **136b**, in principle, both methoxy and ester groups are present as bridgehead substituent. In the case of annulated barrelene **136b**, the 8b-substituted isomer was favored 3 to 1 over the 4b-substituted isomer (Scheme 1.42). These results allude to potential influence of other factors in controlling regioselectivity in barrelene to semibullvalene rearrangement.



Scheme 1.42

Research on annulated barrelenes has crossed the barrier of photochemical interest[134] to transcend to more exotic fields including materials chemistry. In a recent report Ishii et al. highlighted remarkable fluorescence property of a few annulated dibenzobarrelene derivatives that might enable their applications in electronic device fabrications.[91,92]

The cherry on the cake here is the relatively simple protocol for the construction of annulated barrelenes: intramolecular Diels-Alder reaction (IMDA) of corresponding anthracene appended enynes. A series of annulated dibenzobarrelenes with group 16 congeners are represented in Figure 1.4. Surprisingly, quenching due to heavy atom effect is absent with these fluorophores and they exhibit high fluorescence quantum yield in both solution and in the solid state



139 **140** **141** **142**

$R^1 = CF_3$

$R^2 = NMe_2$, CN

Figure 1.4. Annulated dibenzobarrelenes with group 16 congeners.

Dibenzobarrelene-based azaacenes are reported to be highly fluorescent and these amorphous azaacenes were processed to OLED's[135] possessing improved device performance (luminance, efficiency and efficacy) compared to that of OLED's devised from iptycene-based azaacenes. So, it is very clear that by altering the substituents on the barrelene chromophore there would be definite change in physical and chemical properties which might have potential applications. Based on these ideas we developed a series of annulated dibenzobarrelenes with a view of investigating their chemical and physical properties.

1.10 Defining the research problem

Barrelenes still hold sheer potential to attract attention of the scientific community. On the basis of a thorough literature review, we realized that photochemistry and photophysics of annulated dibenzobarrelenes remain largely unexplored.[136] Two aspects of barrelene photochemistry appeared attractive to us: i) intramolecular electron transfer in the excited of amine appended barrelenes and ii) the effect of tethers in controlling the regioselectivity of barrelene-semibullvalene rearrangement. 9,11-Annulated barrelenes with amine tethers (Figure 1.5) provide an ideal platform to investigate these twin aspects of barrelene photochemistry in one shot. Keeping the objectives listed in **Section 1.11** in mind, we synthesized and examined several such annulated barrelenes.

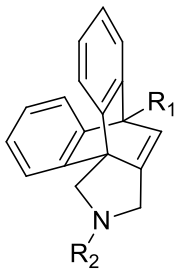


Figure 1.5

Retrosynthetic analysis for our target given in Figure 1.5 offered two possible routes (Figure 1.6). We selected Route **A** where the labile acetylene component is introduced in the last step before IMDA reaction as our method of choice.

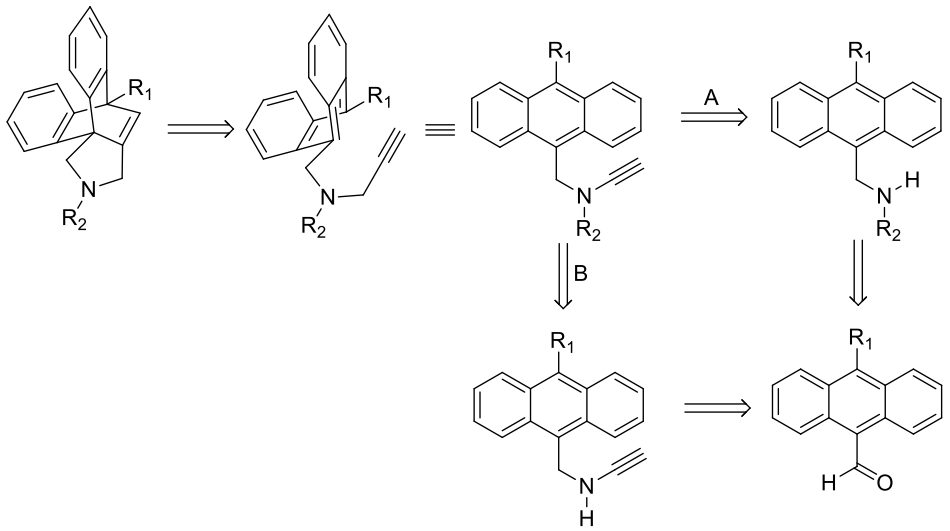


Figure 1.6

1.11 Objectives

- To synthesize a few annulated dibenzobarrelenes via IMDA
- To examine the effect of substituents on the physical and chemical properties of dibenzobarrelenes
- To study the photochemical reactions of different *N*-substituted annulated dibenzobarrelenes
- Characterization of the photoproducts
- To investigate the regiochemical outcome of di-π-methane rearrangement in annulated barrelenes
- To examine the possibility of excited state intramolecular electron transfer reaction in annulated barrelenes

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136. For a detailed discussion on the photochemistry of annulated barrelenes, see Chapter 4 of this thesis.

CHAPTER 2

Synthesis and characterization of a few N-alkylaminomethylanthracenes

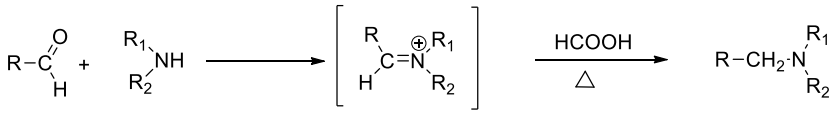
2.1 Abstract

Synthesis of several anthracene-9-yl-methanamines using Leuckart-Wallach modification of Leuckart reaction and their post functionalization are described herein. All new compounds were fully characterized on the basis of their spectral and analytical data.

2.2 Introduction

Amines are a class of compounds of considerable interest due to their importance in various fields of chemistry. Amines participate as single and two electron donors in variety of reactions such as Michael addition reaction[1-5] and various electrochemical,[6-8] photochemical[9-17] and biological redox processes.[18-21] N-Alkylaminomethylanthracenes are well explored in the synthesis of dibenzobarrelene.[22,23] In this chapter emphasis is more on the synthesis of anthracene appended tertiary amines by Leuckart reaction followed by nucleophilic substitutions. Leuckart reaction involves reductive amination of aldehydes or ketones with formic acid or ammonium salts of formic acid and ammonia or primary/secondary amines. The reaction known after Rudolf Leuckart, its founder, was discovered in 1885. Later many modifications were made on Leuckart reaction[24-28] and it can be carried out by using ammonia,

primary and secondary amines with aldehydes or ketones in presence of ammonium formate. The role of formic acid or its derivative in this reaction is to serve as the reducing agent.[29-31] Mechanism of Leuckart reaction is illustrated in Scheme 2.1.[32]



Scheme 2.1

Leuckart reaction has many synthetic applications[33-36] extended to the synthesis of drugs such as amphetamines and methamphetamines.[37,38] Participation of amines as nucleophiles in substitution reaction with both alkyl and aryl halides is also well studied. Nucleophilicity of amines is mainly controlled by the steric factors than the base strength.[39,40] Generally less hindered amines are more favorable for nucleophilic substitution reactions. In the present study tertiary amine appended anthracenes were obtained by N-alkylation of the corresponding 9-alkylaminomethylanthracenes.

2.3 Results and discussion

Anthracene participates as a diene in Diels-Alder reaction. Anthracenes having strategically positioned dienophile components are potential candidates for efficient intramolecular Diels-Alder (IMDA) reactions. In the present investigation, substrates for IMDA reaction were obtained by modified Leuckart reaction (Leuckart-Wallach modification)[25] followed by N-alkylation. Figure 2.1 represents the compounds accessed through this strategy. Compounds **1a-u** possess

ideal structural features (anthracene as diene and acetylene functionality as dienophile) to undergo IMDA reactions.

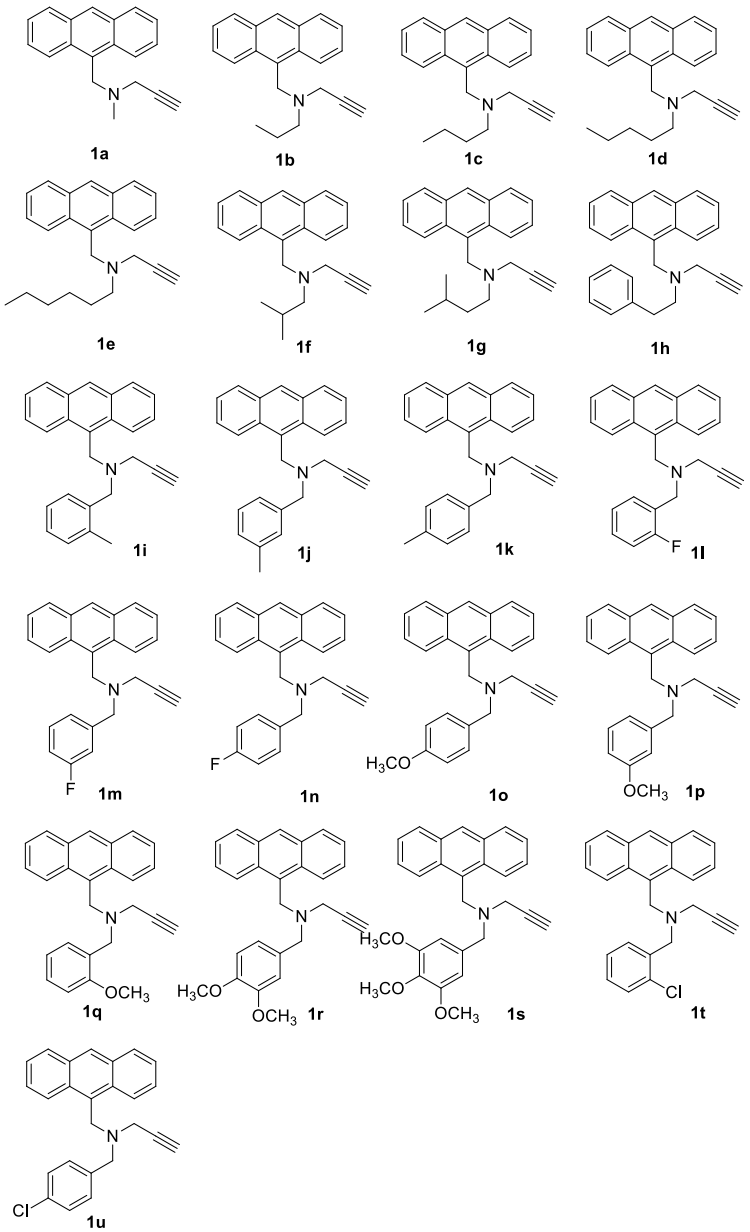


Figure 2.1. Substrates for IMDA reaction

As mentioned earlier, we employed modified Leuckart reaction followed by nucleophilic substitution reaction to carry out the synthesis of the tertiary amines **1b**-**u**. General procedure for the synthesis involves refluxing anthraldehyde **2**, primary amine **3** and ammonium formate in benzene for 3h using a Dean-Stark apparatus fitted with a condenser. Water formed during the condensation reaction was trapped and imine **4** obtained was reduced with sodium borohydride in methanol to get the corresponding secondary amines **5b-u** listed in Figure 2.2. Compound 1**a** was synthesized by a known procedure.[41]

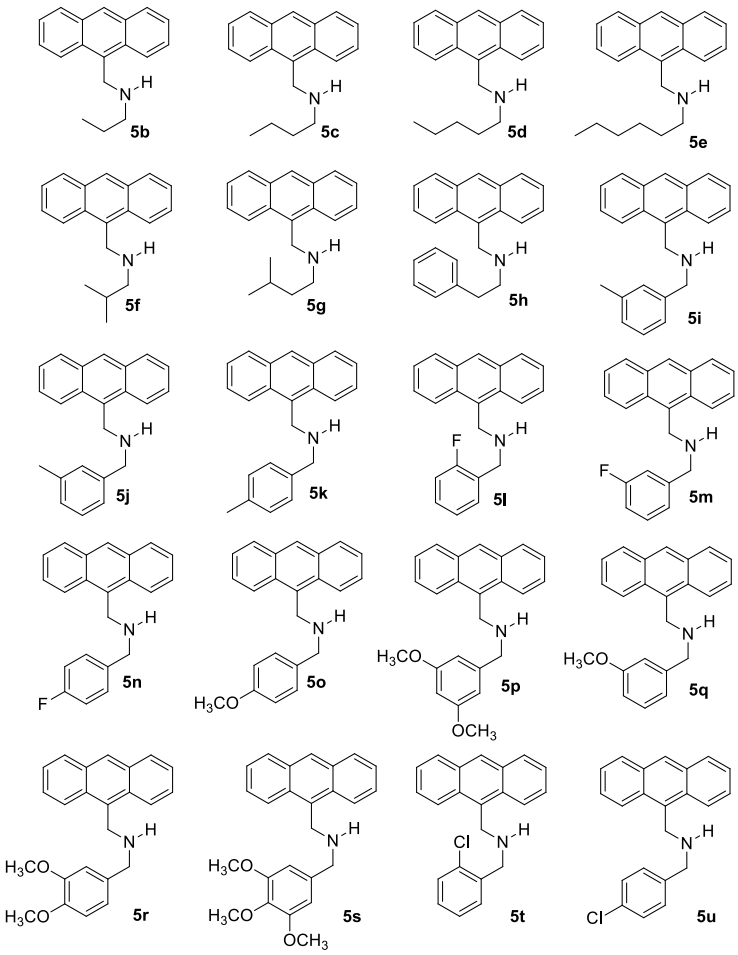
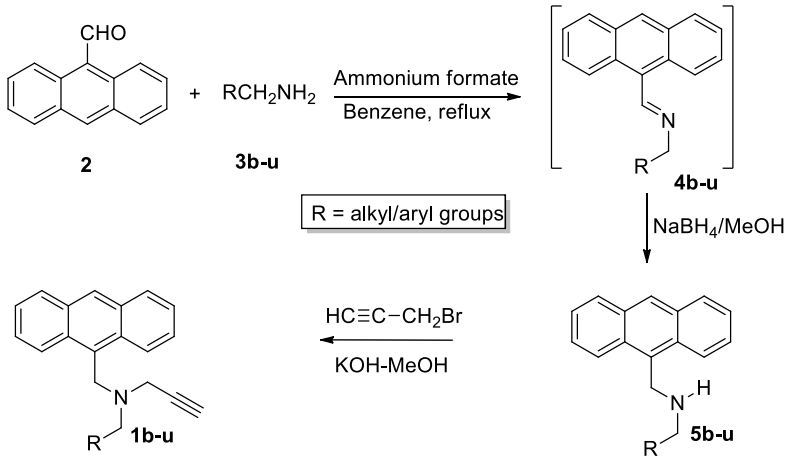


Figure 2.2. Secondary amines **5b-u**

Secondary amines **5b-u** thus obtained were converted to tertiary amines **1b-u** by stirring with propargyl bromide in the presence of KOH in methanol at room temperature. Secondary amines **5v-x** resisted propargylation under these conditions highlighting commanding effect of steric factors in controlling the nucleophilicity of amines. General procedure for the synthesis of **1** is represented in Scheme 2.1.



Scheme 2.1

Using a protocol analogous to that used for the synthesis of **5b-u**, we synthesized amines **5v-x** that suffer from increased steric hindrance around the nucleophilic nitrogen (Figure 2.3).

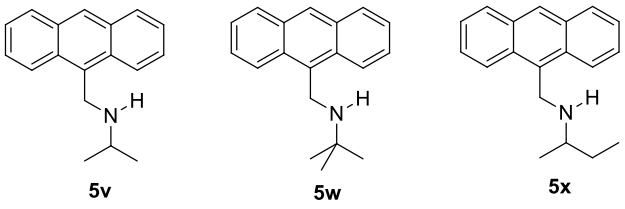
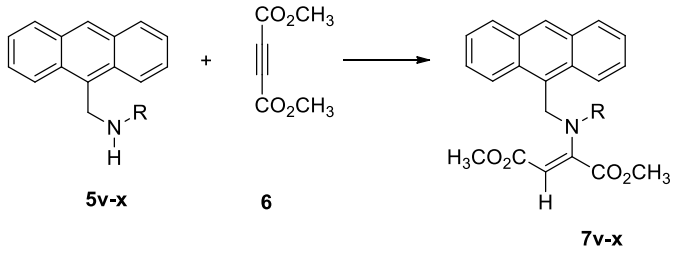


Figure 2.3. Secondary amines **5v-x**

Interestingly, **5v-x** exhibited dichotomous behavior towards nucleophilic substitution and Michael type addition reactions. Though propargylation under both S_N1 (propargyl bromide, KOH, MeOH) and S_N2 conditions (propargyl bromide, KOH, DMF) were unsuccessful on **5v-x**, they underwent facile nucleophilic addition to DMAD to give the corresponding adducts **7v-x** (Scheme 2.2). It appears that approach of

5v-x towards DMAD at Bürgi–Dunitz angle is unhindered while their ability to participate in nucleophilic substitution reactions is heavily compromised by steric factors.



5v-x **6** **7v-x**

Scheme 2.2

2.4 Experimental

2.4.1 General Techniques

All reactions were carried out in oven dried glassware. All the reagents were purchased from *Sigma-Aldrich* or *Alfa-Aesar* and used without further purification. Progress of the reaction and chromatographic separations were monitored by thin layer chromatography (TLC) over dried silica gel TLC plates (Aluminium sheets coated with silica gel, *E. Merck*). Visualisation of TLC plates was achieved by exposure to UV lamp or iodine vapour. Separation and purification of compounds were done by column chromatography using silica gel (*Spectrochem Chemicals*, 60-120 mesh) or alumina (*Spectrochem Chemicals*). Melting points were determined on a *Neolab* melting point apparatus and are uncorrected. Infrared spectra were recorded on *JASCO 4100* FT-IR spectrometer. NMR spectra (^{13}C, ^{1}H) were recorded on a *Bruker Avance III* 400 MHz NMR spectrometer with

TMS as internal standard. Chemical shifts (δ) are reported in parts per million (ppm) downfield of TMS. Unless otherwise mentioned all IR spectra were recorded as KBr pellets and NMR spectra (^{1}H and ^{13}C) were recorded in $CDCl_3$.

2.4.2 Anthraldehyde

Anthraldehyde was purchased from *Sigma-Aldrich* and directly used without further purification.

2.4.3 Primary amines

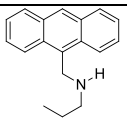
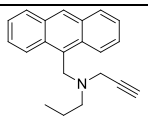
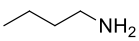
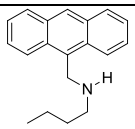
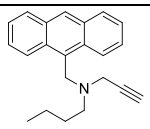
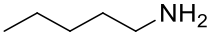
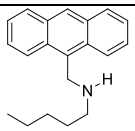
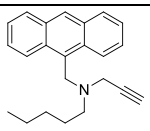
All the amines are purchased either from *Sigma-Aldrich* or *Alfa-Aesar* and directly used without any purification.

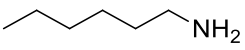
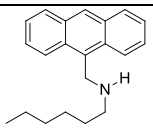
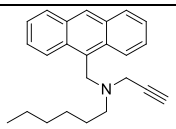
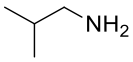
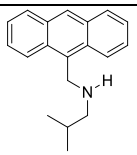
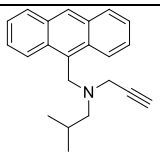
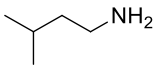
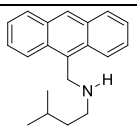
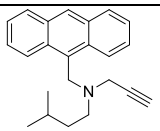
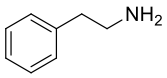
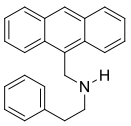
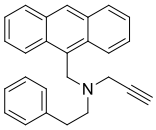
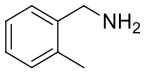
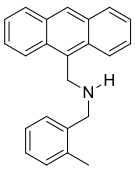
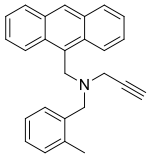
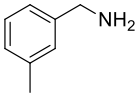
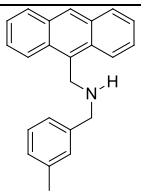
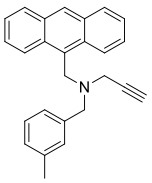
2.4.4 Synthesis of N-alkylaminomethylanthracenes

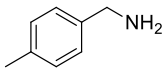
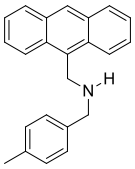
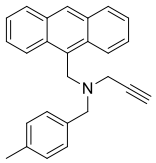
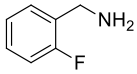
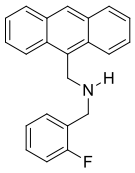
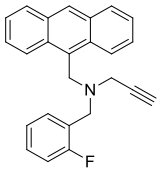
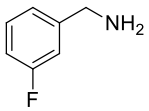
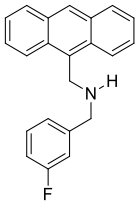
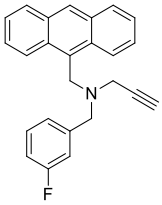
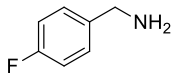
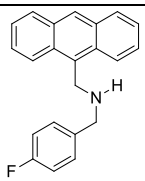
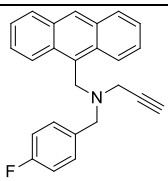
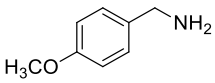
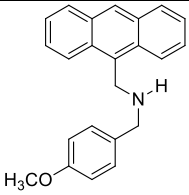
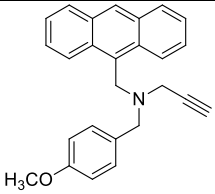
Synthesis of *N*-alkylaminomethylanthracenes was achieved by modified Leuckart reaction using 9-anthraldehyde and corresponding amines. In a 250 mL R. B. flask fitted with Dean and Stark trap, 9-anthraldehyde, primary amines **3b-u** and ammonium formate were taken in a 1:1:1 molar ratio in benzene as solvent. The mixture was refluxed for 3h using an oil bath maintained at 95 °C. Imines **4b-u** obtained thereof were reduced with $NaBH_4$ (1 eqv.) in methanol. The secondary amines **5b-u** were further treated with propargyl bromide (1 eqv.) in presence of KOH/methanol (1 eqv.) at RT to obtain the corresponding tertiary amines **1b-u** while **5v-x** remained unreactive towards propargyl bromide. The reaction mixture was poured into cold water and extracted with dichloromethane. Solvent was removed under reduced pressure and the

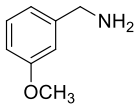
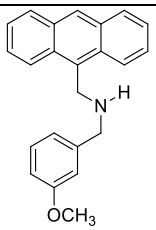
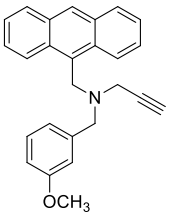
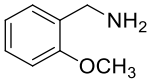
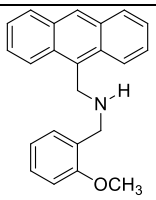
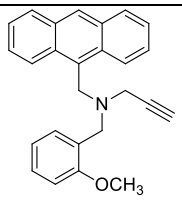
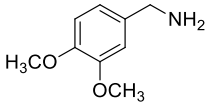
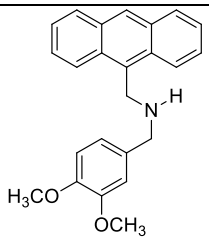
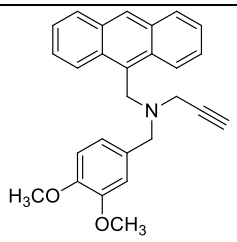
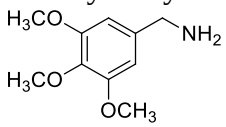
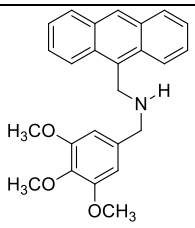
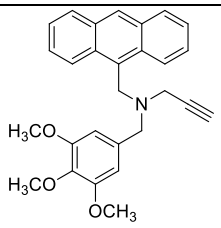
product obtained was purified by column chromatography over silica gel. The product eluted with a mixture (1:19) of dichloromethane and hexane. The list of primary amines **3b-x** and their equivalence in the reaction with 9-anthraldehyde **2** (3.3 g, 16 mmol) and ammonium formate (1.0 g, 16 mmol) and the products obtained are tabulated in Table 2.1. Secondary amines **5b-u** were treated with propargyl bromide (1.42 mL, 16 mmol) and KOH (0.9 g, 16 mmol) dissolved in minimal amount of methanol to give the corresponding tertiary amines **1b-u** in moderately good yields (isolated yields are given in the Table 2.1). Analytically pure samples were obtained by either chromatographic separation or recrystallization from suitable solvents.

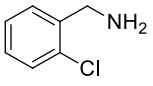
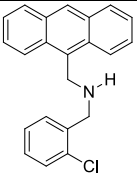
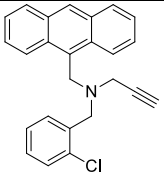
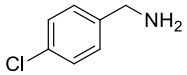
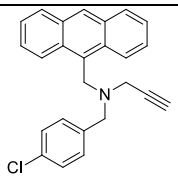
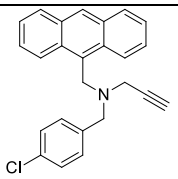
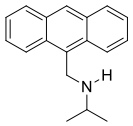
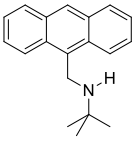
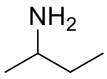
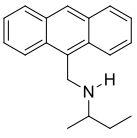
Table 2.1. List of primary amines and corresponding secondary and tertiary amine products

Primary amines (3b-x)	**Secondary amines (5b-x)**	**Tertiary amines (1b-x)**
n-propylamine **3b**, 1.32 mL (16 mmol)	 **5b**, 3.04 g (92%)	 **1b**, 2.75 g (90%)
n-butylamine  **3c**, 1.58 mL, (16 mmol)	 **5c**, 3.10 g (93%)	 **1c**, 2.63 g (84%)
n-pentylamine  **3d**, 1.85 mL, (16 mmol)	 **5d**, 3.15 g (95%)	 **1d**, 2.50 g (79%)

Primary amines (3b-x)	Secondary amines (5b-x)	Tertiary amines (1b-x)
n-hexylamine  **3e**, 2.13 mL (16 mmol)	 **5e**, 2.95 g (89%)	 **1e**, 2.43 g (82%)
isobutylamine  **3f**, 1.58 mL (16 mmol)	 **5f**, 2.98 g (90%)	 **1f**, 2.71 g (90%)
isopentylamine  **3g**, 1.85 mL (16 mmol)	 **5g**, 3.06 g (92%)	 **1g**, 2.79 g (91%)
2-phenylethylamine  **3h**, 2.00 mL (16 mmol)	 **5h**, 3.11 g (94%)	 **1h**, 2.86 g (91%)
2-methylbenzylamine  **3i**, 1.97 mL (16 mmol)	 **5i**, 3.08 g (93%)	 **1i**, 2.76 g (89%)
3-methylbenzylamine  **3j**, 2.02 mL (16 mmol)	 **5j**, 2.85 g (86%)	 1**j**, 2.36 g (82%)

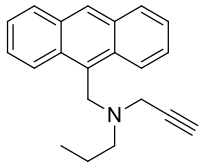
Primary amines (3b-x)	**Secondary amines (5b-x)**	**Tertiary amines (1b-x)**
4-methylbenzylamine 		
3k, 2.03 mL (16 mmol)	**5k**, 3.20 g (96%)	**1k**, 2.96 g (92%)
2-fluorobenzylamine 		
3l, 1.81 mL (16 mmol)	**5l**, 2.75 g (83%)	**1l**, 1.98 g (72%)
3-fluorobenzylamine 		
3m, 1.81 mL (16 mmol)	**5m**, 2.92 g (88%)	**1m**, 2.35 g (80%)
4-fluorobenzylamine 		
3n, 1.81 mL (16 mmol)	**5n**, 3.07g (93%)	**1n**, 2.80 g (91%)
4-methoxybenzylamine 		
3o, 2.06 mL (16 mmol)	**5o**, 3.12 g (94%)	**1o**, 2.81 g (90%)

Primary amines (3b-x)	Secondary amines (5b-x)	Tertiary amines (1b-x)
3-methoxybenzylamine 		
3p, 2. 80 mL (16 mmol)	**5p**, 2.69 g (81%)	**1p**, 1.8 g (66%)
2-methoxybenzylamine 		
3q, 2.06 mL (16 mmol)	**5q**, 2.88 g (87%)	**1q**, 2.4 g (83%)
3,4-dimethoxybenzylamine 		
3r, 2.40 mL (16 mmol)	**5r**, 2.92g (88%)	**1r**, 2.55 g (87%)
3,4,5-trimethoxybenzylamine 		
3s, 2.73 mL (16 mmol)	**5s**, 2.85 g (86%)	**1s**, 2.03 g (71%)

Primary amines (3b-x)	**Secondary amines (5b-x)**	**Tertiary amines (1b-x)**
2-chlorobenzylamine  **3t**, 1.92 mL (16 mmol)	 **5t**, 3.09 g (93%)	 **1t**, 2.89 g (93%)
4-chlorobenzylamine  **3u**, 1.94 mL (16 mmol)	 **5u**, 3.02 g (91%)	 **1u**, 2.94 g (97%)
isopropylamine  **3v**, 1.32 mL (16 mmol)	 **5v**, 3.04 g (92%)	
teritarybutylamine  **3w**, 1.58 mL, (16 mmol)	 **5w**, 3.04 g (92%)	
isobutylamine  **3x**, 1.58 mL, (16 mmol)	 **5x**, 3.04 g (92%)	

2.5 Spectral and analytical data of N-alkylaminomethyl-anthracenes 1b-u

2.5.1 Compound 1b



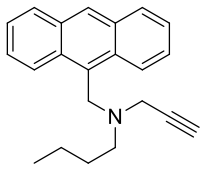
Yield: 90%; m.p: 58 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

^1H NMR: δ 8.58-7.24 (m, 9H), 4.58 (s, 2H), 3.30 (d, 2H, *J* = 1.5Hz), 2.72(t, 2H, *J* = 7Hz), 2.35 (s, 1H), 1.57(q, 2H, *J* = 7Hz), 0.87(t, 3H, *J* = 7Hz).

MS: *m/z* 287.1 (M^+).

Elemental Anal. Calcd for $C_{21}H_{21}N$: C, 87.76; H, 7.36; N, 4.87; Found: C, 87.74; H, 7.32; N, 4.85.

2.5.2 Compound 1c



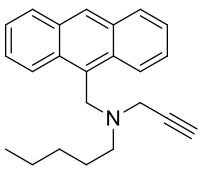
Yield: 84%; m.p: 54 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

^1H NMR: δ 8.58-7.24(m, 9H), 4.58 (s, 2H), 3.31 (d, 2H, *J* = 2Hz), 2.75 (t, 2H, *J* = 7.5Hz), 2.36 (t, 1H, *J* = 2Hz), 1.53 (m, 2H), 1.30 (q, 2H, *J* = 7.5Hz), 0.84 (t, 3H, *J* = 7.5Hz).

MS: *m/z* 301.1(M^+).

Elemental Anal. Calcd for $C_{22}H_{23}N$: C, 87.57; H, 7.99; N, 4.44; Found: C, 87.56; H, 7.97; N: 4.43.

2.5.3 Compound 1d



Yield: 79%; semisolid; IR: 2996, 1620, 700 cm^{-1}

^1H NMR: δ 8.45-7.27 (m, 9H), 4.43 (s, 2H), 3.18 (d, 2H, *J* = 2Hz), 2.61 (t, 2H, *J* = 7.2Hz), 2.21 (t, 1H, *J* = 2Hz), 1.41 (quintet, 2H, *J* = 7.2Hz), 1.12 (m, 4H), 0.71(t, 3H, *J* = 7.2Hz).

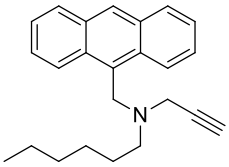
^{13}C NMR: δ 130.4, 130.4, 129.0, 127.8, 126.4, 124.4, 124.2, 123.8, 78.4, 72.36, 52.1, 49.3, 39.5, 28.4, 26.0, 21.4, 13.0.

MS: *m/z* 315.1(M^+).

Elemental Anal. Calcd for $C_{23}H_{25}N$: C, 87.57; H,

7.99; N, 4.44. Found: C, 87.55; H: 7.98; N: 4.43.

2.5.4 Compound 1e



Yield: 82%; semisolid; IR: 3300, 2996, 2100, 1615, 700 cm^{-1}

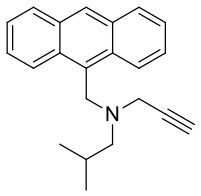
^1H NMR: δ 8.45-7.27 (m, 9H), 4.43 (s, 2H), 3.18 (d, 2H, *J* = 2Hz), 2.60 (t, 2H, *J* = 7.2Hz), 2.21 (t, 1H, *J* = 2Hz), 1.39 (quintet, 2H, *J* = 7.2Hz), 1.12 (m, 6H), 0.70 (t, 3H, *J* = 7.2Hz).

^{13}C NMR: δ 131.6, 131.5, 130.1, 128.9, 127.6, 125.6, 125.3, 124.9, 79.5, 73.5, 53.1, 50.5, 40.7, 31.7, 27.4, 27.0, 22.7, 14.1.

MS: *m/z* 329.1 (M^+).

Elemental Anal. Calcd for $C_{24}H_{27}N$: C, 87.49; H, 8.26; N, 4.25; Found: C; 87.47; H, 8.25; N, 4.24.

2.5.5 Compound 1f



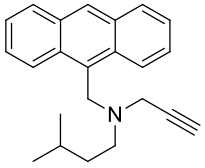
Yield: 90%; mp: 98 °C; IR: 3290, 2996, 2100, 1620, 700 cm^{-1}

^1H NMR: δ 8.59-7.42 (m, 9H), 4.57 (s, 2H), 3.32 (d, 2H, *J* = 2Hz), 2.55 (d, 2H, *J* = 7.6Hz), 2.34 (t, 1H, *J* = 2Hz), 1.80 (septet, 1H, *J* = 6.8Hz), 0.84 (d, 6H, 6.4Hz).

^{13}C NMR: δ 131.5, 131.4, 130.1, 128.8, 127.4, 125.4, 125.3, 124.8, 79.4, 73.3, 61.4, 50.9, 40.5, 25.8, 20.8.

MS: *m/z* 301.1 (M^+). Elemental Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65; Found: C, 87.64; H, 7.67; N, 4.64.

2.5.6 Compound 1g

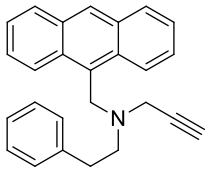


Yield: 91%; mp: 86 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

^1H NMR: δ 8.51-7.35 (m, 9H), 4.50(s, 2H), 3.23 (d, 2H, *J* = 2.4Hz), 2.69 (t, 2H, *J* = 7.6Hz), 2.28 (t, 1H, *J* =

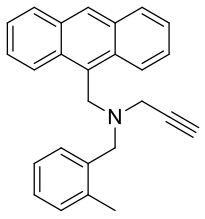
2.4Hz), 1.53 (septet, 1H, *J* = 6.4Hz), 1.35 (q, 2H, *J* = 7.6Hz), 0.84 (d, 6H, *J* = 6.4Hz).
^{13}C NMR: δ 130.4, 130.3, 129.0, 127.8, 127.8, 126.4, 124.4, 124.1, 123.8, 78.3, 72.4, 50.3, 49.4, 39.5, 35.3, 25.0, 21.5.
MS: *m/z* 315.2 (M^+). Elemental Anal. Calcd for $C_{23}H_{25}N$: C, 87.57; H, 7.99; N, 4.44; Found: C, 87.55; H, 7.98; N: 4.43.

2.5.7 Compound 1h



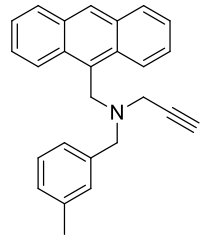
Yield: 91%; mp: 86 °C; IR: 3295, 2996, 2120, 1620, 700 cm^{-1}
^{1}H NMR: δ 8.42-7.07 (m, 14H), 4.53 (s, 2H), 3.28 (d, 2H, *J* = 2.4Hz), 2.99 (t, 2H, *J* = 7.2Hz), 2.77 (t, 2H, *J* = 7.2Hz), 2.29 (t, 1H, *J* = 2.4Hz).
^{13}C NMR: δ 140.3, 131.5, 131.4, 129.6, 128.8, 128.7, 128.2, 127.6, 125.9, 125.6, 125.2, 124.8 79.2, 73.7, 54.8, 50.4, 40.6, 33.9.
MS: *m/z* 349.1 (M^+). Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.33; H, 6.62; N: 4.00.

2.5.8 Compound 1i



Yield: 89%; mp: 96 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}
^{1}H NMR: δ 8.37-7.02 (m, 13H), 4.58 (s, 2H), 3.74 (s, 2H), 3.17 (s, 2H), 2.38 (s, 1H), 2.04 (s, 3H).
^{13}C NMR: δ 138.1, 136.2, 131.5, 131.4, 130.6, 130.3, 129.7, 128.8, 127.6, 127.4, 125.5, 125.4, 125.2, 124.8, 79.5, 74.0, 55.5, 49.2, 41.4, 18.9.
MS: *m/z* 349.1 (M^+).
Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.34; H, 6.62; N: 4.00.

2.5.9 Compound 1j



Yield: 82%; mp: 92 °C; IR: 3300, 2996,2100, 1620, 700 cm^{-1}

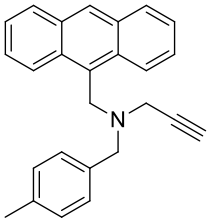
^{1}H NMR: δ 8.47-6.95 (m, 13H), 4.60 (s, 2H), 3.73 (s, 2H), 3.17 (d, 2H, *J* = 2.4Hz), 2.36 (s, 1H), 2.22 (s, 3H).

^{13}C NMR: δ 138.6, 137.7, 131.5, 131.4, 130.1, 129.8, 128.9, 128.0, 127.9, 127.6, 126.3, 125.5, 125.2, 124.8, 79.3, 73.8, 57.4, 49.6, 41.0, 21.3.

MS: *m/z* 349.1 (M^{+}).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.35; H, 6.61; N: 4.00.

2.5.10 Compound 1k



Yield: 92%; mp: 97 °C; IR: 3300, 2996,2100, 1620, 700 cm^{-1}

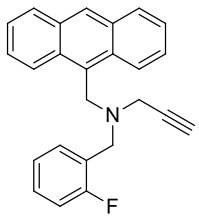
^{1}H NMR: δ 8.47-6.98 (m, 13H), 4.59 (s, 2H), 3.72 (s, 2H), 3.14 (d, 2H, *J* = 2 Hz), 2.34 (t, 1H, *J* = 2Hz), 2.22 (s, 3H).

^{13}C NMR: δ 136.7, 135.6, 131.5, 131.4, 129.9, 129.3, 128.9, 128.9, 127.6, 125.6, 125.2, 124.9, 79.3, 73.8, 57.0, 49.7, 40.7, 21.1.

MS: *m/z* 349.1 (M^{+}).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.34, H, 6.62; N: 4.00.

2.5.11 Compound 1l



Yield: 72%; mp: 88 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

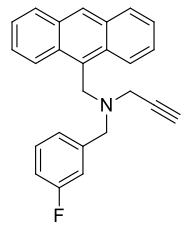
^{1}H NMR: δ 8.54-6.99 (m, 13H), 4.71 (s, 2H), 3.95 (s, 2H), 3.23 (d, 2H, *J* = 2 Hz), 2.46 (t, 1H, *J* = 2Hz).

^{13}C NMR: δ 162.9, 160.5, 131.7, 131.6, 131.5, 131.4, 129.5, 128.9, 128.9, 127.7, 125,6, 125.1, 124.8, 123.8, 123.8, 115.4, 115.2, 79.2, 74.1, 50.3, 50.3, 49.7, 40.8.

MS: *m/z* 353.2 (M^{+}).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.69; N, 3.94.

2.5.12 Compound 1m



Yield: 80%; mp: 80 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

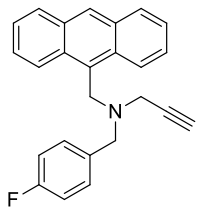
^{1}H NMR: δ 8.46-6.78 (m, 13H), 4.62(s, 2H), 3.71 (s, 2H), 3.18 (d, 2H, *J* = 1.2 Hz), 2.36 (s, 1H).

^{13}C NMR: δ 164.1, 161.6, 141.5, 131.5, 131.4, 129.6, 129.5, 129.0, 127.8, 125.7, 125.0, 124.9, 124.7, 116.0, 115.8, 114.1, 113.9, 78.9, 74.1, 56.4, 56.4, 49.9, 41.0.

MS: *m/z* 353.2 (M^+).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.69; N, 3.94.

2.5.13 Compound 1n



Yield: 91%; mp: 104 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

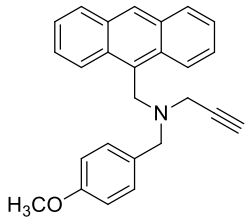
^{1}H NMR: δ 8.45-6.82 (m, 13H), 4.60 (s, 2H), 3.68(s, 2H), 3.14 (s, 2H), 2.35 (s, 1H).

^{13}C NMR: δ 162.2, 159.8, 133.3, 130.4, 130.4, 129.7, 129.6, 128.5, 127.9, 126.7, 124.6, 124.0, 123.8, 114.0, 113.8, 78.0, 72.9, 55.1, 48.7, 39.8.

MS: *m/z* 353.2 (M^+).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.69; N, 3.94.

2.5.14 Compound 1o



Yield: 90%; mp: 76 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

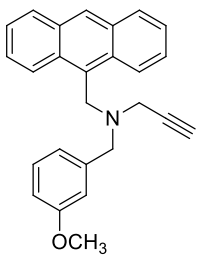
^{1}H NMR: δ 8.54-6.80 (m, 13H), 4.67 (s, 2H), 3.77 (s, 2H), 3.76 (s, 3H) 3.22 (d, 2H, *J* = 2.4 Hz), 2.43 (t, 1H, *J* = 2.4Hz).

^{13}C NMR: δ 158.8, 131.5, 131.4, 130.7, 130.4, 129.9, 128.9, 127.6, 125.6, 125.2, 124.8, 113.6, 79.3, 73.8, 56.6, 55.2, 49.6, 40.7.

MS: *m/z* 365.1 (M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.43; H, 6.33; N, 3.82.

2.5.15 Compound 1p



Yield: 66%; mp: 70 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

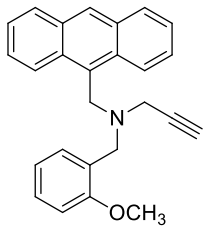
^{1}H NMR: δ 8.57-6.73 (m, 13H), 4.70 (s, 2H), 3.78 (s, 2H), 3.71 (s, 3H) 3.27 (d, 2H, *J* = 2.4 Hz), 2.43 (t, 1H, *J* = 2.4Hz).

^{13}C NMR: δ 159.6, 140.4, 131.5, 131.4, 129.7, 129.1, 128.9, 127.7, 125.6, 125.2, 124.8, 121.5, 114.4, 112.9, 79.3, 73.8, 57.0, 55.0, 49.8, 41.1.

MS: *m/z* 365.1 (M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.44; H, 6.33; N, 3.81.

2.5.16 Compound 1q



Yield: 83%; mp: 72 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

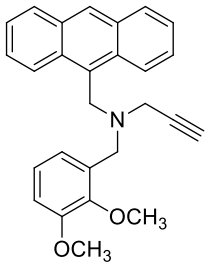
^{1}H NMR: δ 8.59-6.84 (m, 13H), 4.71 (s, 2H), 3.94 (s, 2H), 3.76 (s, 3H) 3.23 (d, 2H, *J* = 2.4 Hz), 2.46 (t, 1H, *J* = 2.4Hz).

^{13}C NMR: δ 158.3, 131.6, 131.4, 131.2, 130.1, 128.8, 128.5, 127.5, 126.6, 125.4, 125.4, 124.7, 120.1, 110.5, 79.8, 73.8, 55.3, 51.8, 49.7, 40.6.

MS: *m/z* 365.1 (M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.44; H, 6.32; N, 3.82.

2.5.17 Compound 1r



Yield: 87%; mp: 106 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

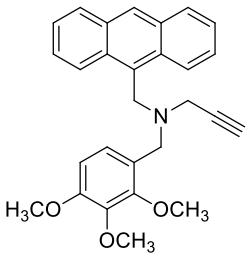
^{1}H NMR: δ 8.48-6.66 (m, 12H), 4.62(s, 2H), 3.76 (s, 3H), 3.66 (s, 5H), 3.21 (d, 2H, *J* = 2 Hz), 2.36 (t, 1H, *J* = 2Hz).

^{13}C NMR: δ 148.8, 148.1, 131.4, 129.9, 128.9, 127.6, 125.5, 125. 2, 124.8, 121.2, 112.2, 110.6, 79.4, 73.7, 56.7, 55.9, 55.6, 49.5, 41.1.

MS: *m/z* 395.1 (M^+).

Elemental Anal. Calcd for $C_{27}H_{25}NO_2$: C, 82.00; H, 6.37; N, 3.54; Found: C, 79.99; H, 6.35; N, 3.52.

2.5.18 Compound 1s



Yield: 71%; mp: 94 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

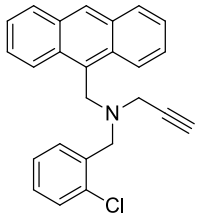
^{1}H NMR: δ 8.56-7.40 (m, 11H), 6.46 (s, 2H), 4.71 (s, 2H), 3.77 (s, 3H), 3.72 (s, 6H), 3.70 (s, 2H), 3.35 (d, 2H, *J* = 2.4 Hz), 2.45 (t, 1H, *J* = 2.4Hz).

^{13}C NMR: δ 152.9, 136.8, 134.7, 131.4, 130.4, 129.8, 129.1, 129.0, 127.7, 126.0, 125.5, 125.1, 124.8, 124.0, 105.7, 79.3, 73.7, 60.7, 57.0, 55.9, 49.6, 41.6.

MS: *m/z* 425.1 (M^+).

Elemental Anal. Calcd for $C_{28}H_{27}NO_3$: C, 79.03; H, 6.40; N, 3.29; Found: C, 79.01; H, 6.38; N, 3.28.

2.5.19 Compound 1t



Yield: 93%; mp: 80 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

^{1}H NMR: δ 8.56-7.16 (m, 13H), 4.73 (s, 2H), 4.01 (s, 2H), 3.25 (d, 2H, *J* = 1.2 Hz), 2.47 (t, 1H, *J* = 1.6Hz).

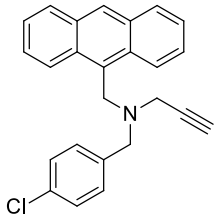
^{13}C NMR: δ 135.9, 134.9, 131.5, 131.4, 129.6, 129.4, 128.8, 128.5, 127.7, 126.5, 125.5, 125.2, 124.8, 79.3, 74.2, 54.5, 49.6, 40.9.

MS: *m/z* 369.1(M^+).

Elemental Anal. Calcd for $C_{25}H_{20}ClN$: C, 81.18; H,

5.45; N, 3.79; Found: C, 81.17; H, 5.44; N, 3.77.

2.5.20 Compound 1u



Yield: 97%; mp: 132 °C; IR: 3300, 2996, 2100, 1620, 700 cm^{-1}

^{1}H NMR: δ 8.53-7.20 (m, 13H), 4.70 (s, 2H), 3.77 (s, 2H), 3.24 (d, 2H, *J* = 2.4 Hz), 2.44 (t, 1H, *J* = 2.4Hz).

^{13}C NMR: δ 138.5, 134.1, 132.7, 132.7, 131.8, 130.7, 130.2, 129.6, 129.0, 127.0, 126.3, 126.2, 80.2, 75.3, 57.4, 51.2, 42.2.

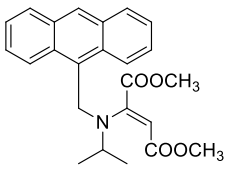
MS: *m/z* 369.1 (M^+).

Elemental Anal. Calcd $C_{25}H_{20}ClN$: C, 81.18; H, 5.45; N, 3.79; Found: C, 81.16; H, 5.44; N, 3.77.

2.6 Reaction of *N*-alkylaminomethylanthracenes 5v-x with DMAD

On refluxing 1:1 mixture of anthracenemethanamines **5** and DMAD, (**6**) in THF, the corresponding 1,4-adducts, **7** arising through nucleophilic addition were obtained. 1,4-Adducts, **7** were formed in moderate to good yields. Products were purified by chromatographic separation using 95:5 mixture of hexane-ethyl acetate as eluent.

2.6.1 Compound 7v



Yield: 88%; mp: 155-158 °C; IR: 2985, 1765, 1760, 1450 1320 cm^{-1}

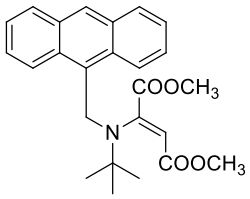
^{1}H NMR: δ 7.47-8.47 (m, 9H, aromatic), 5.23 (s, 2H), 5.10 (s, 1 H), 3.69 (s, 3H), 3.43 (s, 3H), 3.40 (m, 1H), 0.92 (d, 6H, *J* = 7.2 Hz);

^{13}C NMR: δ 168.2, 166.8, 154.1, 131.3, 129.3, 129.0, 126.9, 126.0, 125.1, 123.8, 88.1, 52.9, 51.2, 50.9, 46.6, 19.5.

MS: *m/z* 391 (M^+), 191.

Elemental Anal. Calcd for $C_{24}H_{25}NO_4$; C, 73.64; H, 6.44; N, 3.58; Found: C, 73.61; H, 6.41; N, 3.57.

2.6.2 Compound 7w



Yield: 74%; mp: 162-165 °C; IR: 2954, 1736, 1696, 1577, 1149 cm^{-1}

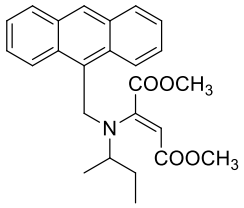
^{1}H NMR: δ 8.44-7.43 (m, 9H, aromatic), 5.33 (s, 2H), 5.28 (s, 1H), 3.50 (s, 3H), 3.35 (s, 3H), 1.36 (s, 9H).

^{13}C NMR: δ 167.0, 166.9, 152.4, 131.3, 130.7, 129.2, 128.4, 126.0, 124.8, 124.4, 109.4, 59.5, 52.1, 51.0, 46.5, 29.1.

MS: *m/z* 405 (M^+), 191.

Elemental Anal. Calcd $C_{25}H_{27}NO_4$: C, 74.05; H, 6.71; N, 3.45; Found: C, 74.04; H, 6.67; N, 3.41.

2.6.3 Compound 7x



Yield: 68%; Semisolid; IR: 2954, 1739, 1694, 1375, 1149 cm^{-1}

^{1}H NMR: δ 8.31-7.30 (m, 9H, aromatic), 5.07 (m, 2H), 4.98 (s, 1H), 3.87 (s, 3H), 3.59 (s, 3H), 1.48 (m, 1H), 1.04 (m, 1H), 0.63 (d, 3H, *J* = 6.8 Hz), 0.40 (t, 3H, *J* =7.2 Hz).

^{13}C NMR: δ 167.1, 165.8, 153.3, 130.3, 130.2, 128.2, 127.9, 125.7, 125.0, 124.1, 122.8, 86.8, 56.5, 51.8, 49.8, 46.0, 25.6, 16.5, 10.4.

MS: *m/z* 405 (M^+), 191.

Elemental Anal. Calcd for $C_{25}H_{27}NO_4$: C, 74.05; H, 6.71; N, 3.45; Found: C, 74.01; H, 6.64; N, 3.41.

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CHAPTER 3

Towards annulated barrelenes: Intramolecular Diels-Alder reactions of a few anthracene-9-yl-methanamines

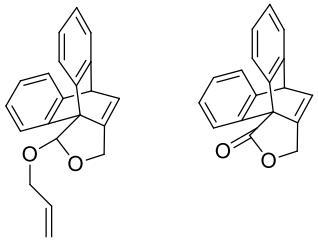
3.1 Abstract

A brief description of the transformation of suitably substituted alkynylaminomethylanthracenes is presented in this chapter. Intramolecular Diels-Alder reaction (IMDA) of these compounds was accomplished under solvent free conditions. Annulated or tethered dibenzobarrelenes obtained thereof in good yields were characterized by spectral and analytical data.

3.2 Introduction

Intramolecular Diels-Alder (IMDA) reaction is an invaluable method for the construction of polycyclic molecules such as present in natural products and other complex polycyclics.[1-20] Synthetic potential of IMDA reactions has been established through enormous number of synthetic strategies with commendable success. IMDA reactions are entropically favored and hence, proceed successfully under relatively mild reaction conditions. Several IMDA reactions could be performed even in the absence of solvent and thereby satisfying green protocols as well.

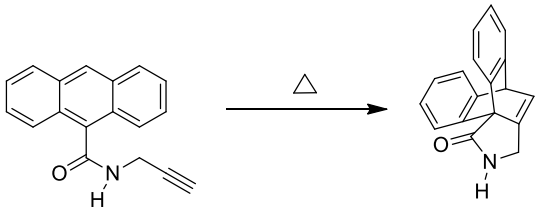
Meek and Dann were the first to report the IMDA cyclization of 9-substituted anthracenes to corresponding acetal **1** and lactone **2** (Figure 3.1).[21,22]



1 **2**

Figure 3.1. IMDA adducts of 9-substituted anthracenes

Ciganek exploited IMDA reaction for the synthesis of a number of 9,11-bridged ethano and ethenoanthracenes (annulated dibenzo-barrelenes) from suitably substituted anthracenes including amide, imine, ester, ether, thioether, acetal and carbinol derivatives (Scheme 3.1).[23]



3 **4**

Scheme 3.1

Recently, we developed simple protocols for the synthesis of several annulated or tethered dibenzobarrelenes. Prototypical examples for annulated/tethered dibenzobarrelenes synthesized by our group are listed in Figure 3.2.[24]

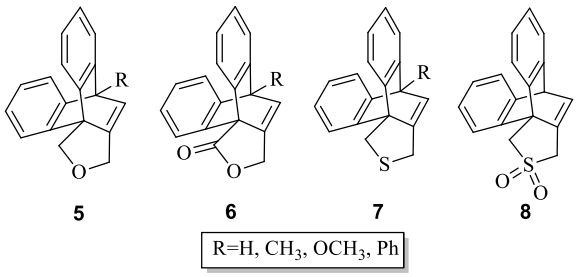


Figure 3.2. Annulated dibenzobarrelenes with various tethers

In the present study, we have effectively utilized IMDA cyclization for the synthesis of a few annulated dibenzobarrelenes containing amine functionality in the tethering unit. Herein we describe the synthesis and characterization of a few annulated dibenzobarrelenes with different N-substituents in the amine tether. N-propargylanthracenemethanamine precursors **9a-r** for IMDA cyclization are presented in the Figure 3.3.

On a closer look, it is evident that **9a-r** possess suitably substituted acetylene part susceptible to undergo IMDA cyclization under thermal conditions. However, with a free amine moiety in these substrates, competitive single electron transfer reaction which is common in intermolecular Diels-Alder reaction between anthracene-methanamines and reactive acetylenes (DMAD, DBA) is a distinct possibility with **9a-r** as well.[25-28]

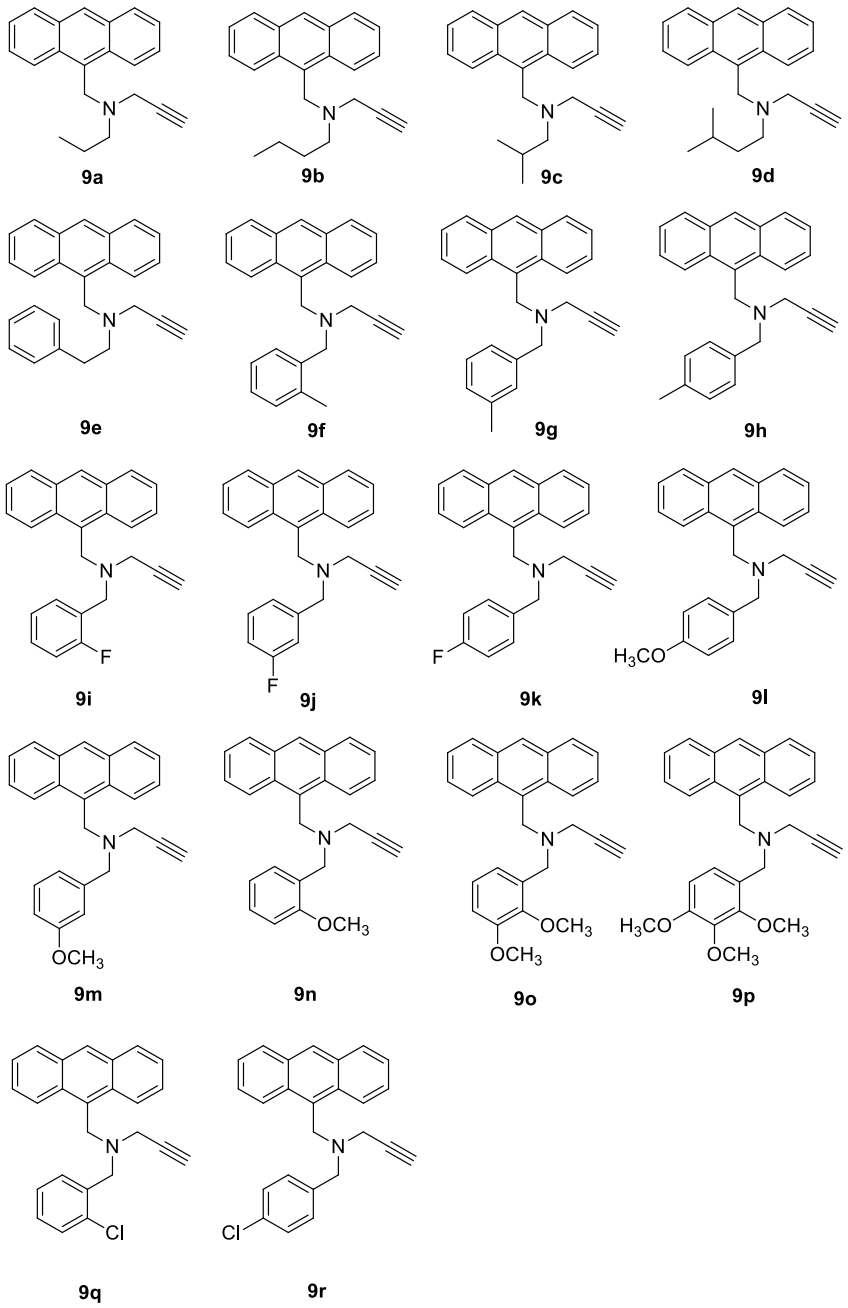
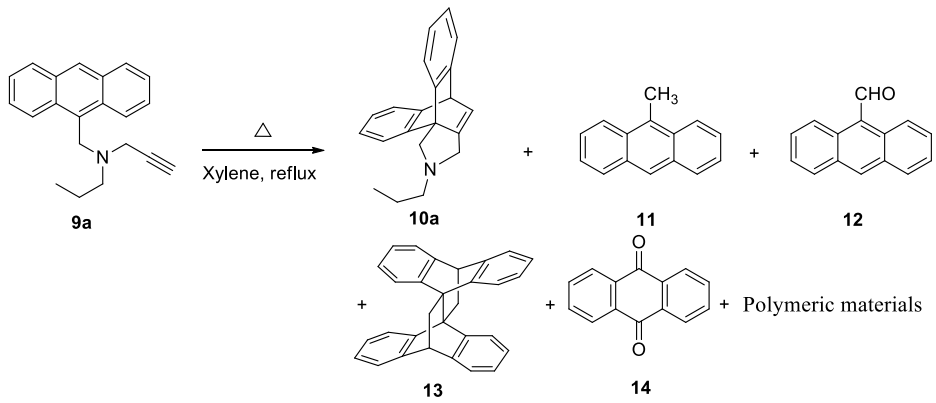


Figure 3.3. Precursors for IMDA reaction

3.3 Results and discussion

We employed IMDA reaction to construct a few tricyclic barrelenes from the corresponding N-propargylated anthracenemethanamines and the transformation is described in the following sections. N-Propargylanthracenemethanamines **9** have an acetylene appendage which can readily undergo IMDA cyclization. We adopted the method perfected in our group for the efficient generation of IMDA adducts **5-8** (refluxing corresponding acetylene appended anthracenes in xylene) as the default synthetic protocol. Unfortunately the amino group present in **9** acted as a minor spoilsport leading to the generation of several single electron transfer mediated products along with the expected IMDA adduct.[29] Though IMDA adduct was formed in major amounts, multitude of side products arising through electron transfer mediated pathways hampered isolation and purification of the required IMDA adducts. Scheme 3.2 describes the IMDA reaction of **9a** under reflux in xylene.



Scheme 3.2

In a typical run, on refluxing **9a** in xylene for 12 h, along with IMDA adduct **10a**, products such as **11**, **12**, **13**, and **14** along with intractable polymeric material in substantial quantities were formed. IMDA adduct was formed in 30 % of yield and other products are in trace amounts and major component is the intractable polymeric material. All the products were isolated by column chromatography over silica gel using a 5:95 mixture of ethyl acetate and hexane. Electron transfer mediated products **11-14** were identified by recording mixture melting point (admixed with authentic samples) and comparing IR spectra with those of authentic samples available with us.[25] IMDA adduct **10a** was identified on the basis of spectral and analytical data.

Earlier reports from our group suggest prominent role for reaction conditions in controlling product distribution in the reaction of amine appended anthracenes.[25,26] Based on this information, we repeated the IMDA reaction of **9** under different conditions. To our pleasant surprise, we observed that neat heating of **9** in a vacuum sealed glass tube for five minutes gave higher yield of **10** and total suppression of unwanted side products such as **11-14** arising through single electron transfer mediated pathways. We adopted this green protocol to synthesize annulated barrelenes **10a-r** listed in Figure 3.4. Isolated yield are given in brackets.

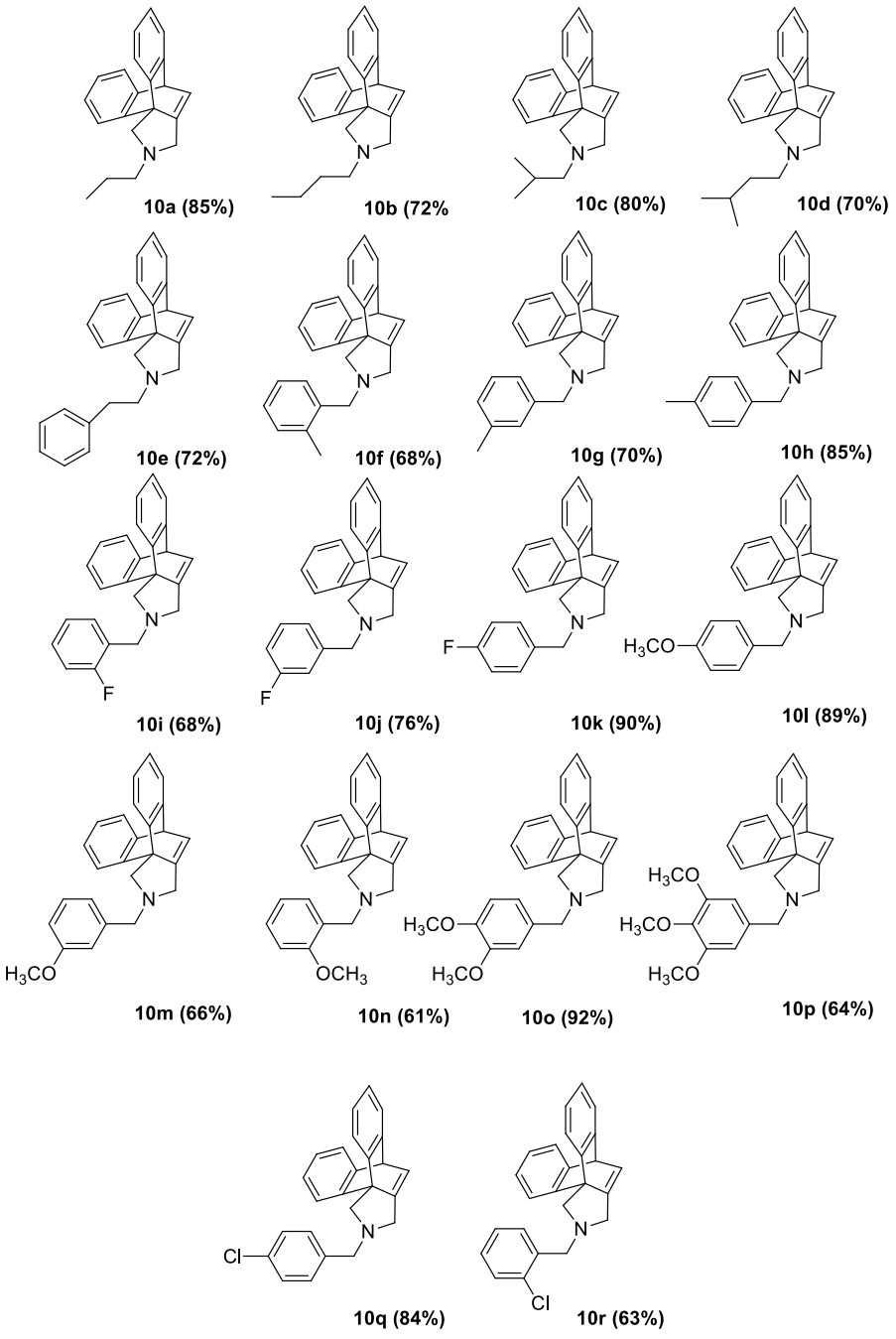


Figure 3.4. IMDA adducts and their isolated yield

We have thus developed a simple and green strategy for the synthesis of annulated barrelenes possessing tethers decorated with a tertiary amine link. Heating the compounds in a sealed tube above its melting point gave the IMDA adducts in high yields. In several cases, cumbersome chromatographic separation could be completely eliminated: washing the product mixture with cold methanol gave annulated barrelenes in high yields. Reduction in reaction time to 5 minutes further enhances the attractiveness of the new protocol. Further brownie points were earned in terms of scalability. Product yield remained unchanged for 100 mg to gram scale reactions (Table 3.1). A scalable, solvent free reaction that does not require chromatographic separations definitely deserve a "green label."

Table 3.1. Scalability of solvent free IMDA reaction of **9a**

9a, Weight in mg	**10a**, Yield (%)
100	92 mg (92%)
250	226 mg (90%)
500	440 mg (88%)
750	650 mg (86%)
1000	850 mg (85%)

3.3.1 Synthesis of 9,11-annulated dibenzobarrelenes

N-Alkylaminomethylanthracene **9** was heated in a Schlenk tube sealed under vacuum for five minutes by immersing in an oil bath preheated to 120 °C. IMDA adduct **10** was isolated from the reaction

mixture by washing with cold methanol or in some cases by column chromatography over silica using a mixture (5:95) of ethyl acetate and hexane. All the target compounds were characterized by ^{1}H and ^{13}C NMR, IR and UV-Vis absorption spectroscopy. IR spectroscopy was particularly helpful in monitoring the success of IMDA reaction. Success of the reaction was revealed by disappearance of vibrational frequencies characteristic of terminal acetylenes (≡CH and C≡C stretching and ≡CH out of plane bending). Disappearance of absorption by anthracene chromophore was also useful in monitoring the success of the reaction,

In the ^{1}H NMR spectrum of **10a**, the vinylic proton appeared as doublet of triplet (J_1 = 5.6 Hz and J_2 = 2 Hz) at δ 6.50 ppm and the bridgehead proton appeared as a doublet (J_1 = 5.6 Hz) at δ 5.02 ppm (Figure 3.5). The vinylic proton appeared as a doublet of triplet due to vicinal coupling (J = 5.6 Hz) with the bridgehead proton appearing at δ 5.02 and allylic coupling (J = 2 Hz) with protons in the pyrrolidine tether appearing at δ 3.21 ppm. The remaining methylene protons of pyrrolidine tether that are α to the bridgehead appeared as a singlet at δ 3.67 ppm. Aromatic protons (8H) appeared multiplet in the δ 7.30-6.80 region. The $A_2M_2X_3$ pattern appearing in the δ 2.70-0.90 region corresponds to the N-propyl component.

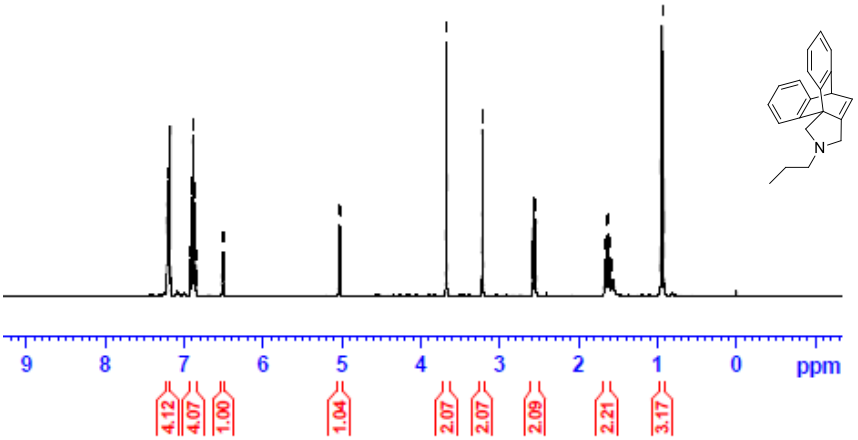


Figure 3.5. ^{1}H NMR spectrum of **10a**

^{13}C NMR spectrum of **10a** (Figure 3.6) is also in agreement with the proposed structure. Signals at δ 155.0-120.1 ppm region are assigned to aromatic and vinylic carbons. As expected, seven aliphatic carbons appeared between δ 60.7-12.0 ppm.

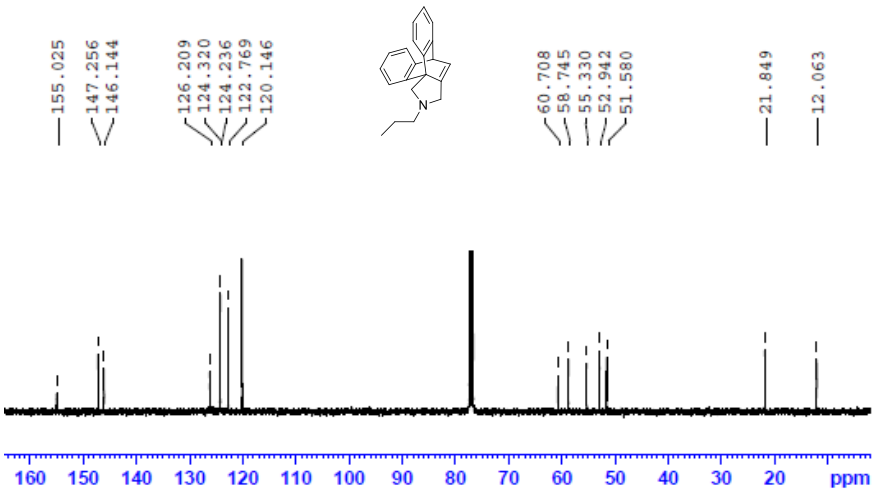


Figure 3.6. ^{13}C NMR spectrum of **10a**

Both ^{1}H and ^{13}C NMR spectra of IMDA adducts **10b-s** exhibited spectral pattern largely similar to that of **10a** but with expected variation in position, intensity and shape of signals attributable to N-substituent present on the pyrrolidine tether.

3.4 Conclusions

We successfully employed neat heating for the synthesis of 9,11-annulated dibenzobarrelenes via IMDA cyclization of corresponding N-propargylated anthracenemethanamines. All the IMDA adducts were formed in good yields and purification was achieved by washing with methanol and in a few cases, by passing through a short plug of silica. Competing electron transfer mediated products generated in solution phase reactions were absent in solvent free runs. Thus we have developed a greener, cleaner, faster and efficient procedure for the generation of our target compounds.

3.5 Experimental

3.5.1 General Techniques

Details are available in Section 2.4.1 of Chapter 2 of this thesis.

3.5.2 General procedure for the Synthesis of 9,11-annulated dibenzobarrelenes 10a-s

3.5.2.1 Solution phase reaction in xylene

N-Propargylanthracenemethanamine **9a** (0.50 g) was refluxed in xylene for 3h. Adduct formation was monitored by TLC and crude product isolated by distillation under reduced pressure. IMDA adduct **10a** was further purified by column chromatography using silica as adsorbent.

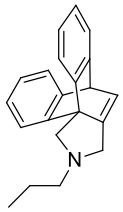
Analytically pure IMDA adduct was eluted by a mixture (5:95) of ethyl acetate and hexane.

3.5.2.2 Solvent free reaction in sealed tubes

Tertiary amines **9a-s** (1.0 g each) were heated in a vacuum sealed Schlenk tube under solvent free conditions for 5 minutes by immersing in an oil bath preheated to 120 °C. The sealed tube was allowed to cool to room temperature and crude product was extracted with dichloromethane. Solvent was removed under reduced pressure and the residue was washed with cold methanol to separate the adducts in pure form. In a few cases, passing of the crude product through a short plug of silica was necessary. A mixture (5:95) of ethyl acetate and hexane was used as the solvent system. Analytical quality materials were generated by recrystallization from suitable solvent systems.

3.6 Spectral and analytical data of IMDA adducts 10a-r

3.6.1 Compound 10a



Yield: 85%; mp: 85 °C; IR: 2962, 1641, 794 cm^{-1}

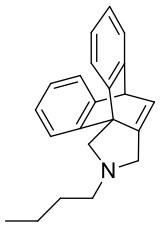
^{1}H NMR: δ 7.21-6.84 (m, 8H), 6.50 (dt, 1H, J_1 = 5.6Hz, J_2 = 2Hz), 5.02 (d, 1H, J = 6Hz), 3.67 (s, 2H), 3.21 (d, 2H, J = 2Hz), 2.55 (q, 2H, J = 7.6Hz), 1.64 (m, 2H), 0.93 (t, 3H, J = 7.6Hz).

^{13}C NMR: δ 155.0, 147.2, 146.1, 126.2, 124.3, 124.2, 122.7, 120.1, 60.7, 58.7, 55.3, 52.9, 51.5, 21.8, 12.0.

MS: *m/z* 287.1(M^+).

Elemental Anal. Calcd for $C_{21}H_{21}N$: C, 87.76; H, 7.36; N, 4.87; Found: C, 87.75; H, 7.35; N, 4.86.

3.6.2 Compound 10b



Yield: 72%; mp: 70 °C; IR: 2962, 1641, 794 cm^{-1}

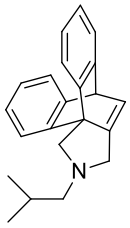
^{1}H NMR: δ 7.27-6.92 (m, 8H), 6.58 (t, 1H, *J*= 6Hz), 5.10 (d, 1H, *J*= 6Hz), 3.74 (s, 2H), 3.28 (s, 2H), 2.66 (t, 2H, *J* = 7.5Hz), 1.66 (m, 2H), 1.43 (m, 2H), 0.98 (t, 3H, *J* = 7.5Hz).

^{13}C NMR: δ 154.9, 147.2, 146.1, 126.2, 124.3, 124.2, 12.8, 120.1, 77.3, 77.0, 76.8, 60.7, 56.6, 55.4, 53.0, 51.5, 30.8, 20.8, 14.1.

MS: *m/z* 301.1(M^+).

Elemental Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65; Found: C, 87.64; H, 7.67; N, 4.64.

3.6.3 Compound 10c



Yield: 80%; mp: 104 °C; IR: 2962, 1641, 794 cm^{-1}

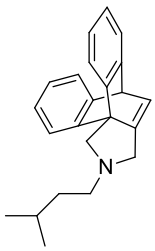
^{1}H NMR: δ 7.20-6.85 (m, 8H), 6.49 (dt, 1H, J_1 = 6Hz, J_2 = 2Hz), 5.02 (d, 1H, *J* = 6Hz), 3.63 (s, 2H), 3.19 (d, 2H, *J* = 2Hz), 2.36 (d, 2H, *J* = 7.6Hz), 1.90 (septet, 1H, *J* = 6.8Hz), 0.94 (d, 6H, *J* = 6.8Hz).

^{13}C NMR: δ 154.0, 146.2, 145.1, 125.0, 123.2, 123.1, 121.7, 119.1, 63.9, 59.7, 54.7, 51.7, 50.5, 26.2, 19.9.

MS: *m/z* 301.1(M^+).

Elemental Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65; Found: C, 87.65; H, 7.67; N, 4.64.

3.6.4 Compound 10d



Yield: 70%; mp: 86 °C; IR: 2962, 1641, 794 cm^{-1}

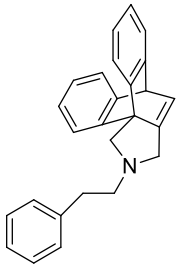
^{1}H NMR: δ 7.20-6.84 (m, 8H), 6.50 (dt, 1H, J_1 = 6Hz, J_2 = 2Hz), 5.02 (d, 1H, *J* = 6Hz), 3.66 (s, 2H), 3.20 (d, 2H, *J* = 2Hz), 2.59 (t, 2H, *J* = 7.6Hz), 1.64 (sep, 1H, *J* = 6.4Hz), 1.51 (q, 2H, *J* = 7.6Hz), 0.89 (d, 6H, *J* = 6.4Hz).

^{13}C NMR: δ 155.0, 147.2, 146.1, 126.1, 124.3, 124.2, 122.7, 120.1, 60.7, 55.4, 55.0, 51.5, 37.6, 26.6, 22.8.

MS: *m/z* 315.1(M^+).

Elemental Anal. Calcd for $C_{23}H_{25}N$: C, 87.57; H, 7.99; N, 4.44; Found: C, 87.55; H, 7.97; N, 4.43.

3.6.5 Compound 10e



Yield: 72%; mp: 120 °C; IR: 2962, 1641, 794 cm^{-1}

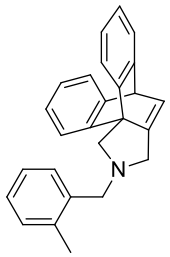
^{1}H NMR: δ 7.26-6.85 (m, 13H), 6.52 (dt, 1H, J_1 = 5.6Hz, J_2 = 2Hz), 5.03 (d, 1H, J = 6Hz), 3.73 (s, 2H), 3.28 (d, 2H, J = 2Hz), 2.94-2.86 (m, 4H).

^{13}C NMR: δ 154.7, 147.2, 146.0, 140.3, 128.7, 128.4, 126.4, 126.1, 124.4, 124.3, 122.8, 120.1, 60.7, 58.4, 55.3, 53.1, 51.5, 35.4.

MS: *m/z* 349.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.35; H, 6.61; N: 4.00.

3.6.6 Compound 10f



Yield: 68%; mp: 118 °C; IR: 2962, 1641, 794 cm^{-1}

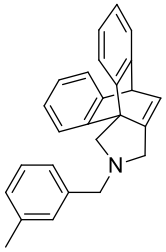
^{1}H NMR: δ 7.33-6.85 (m, 12H), 6.48 (d, 1H, J = 5.6Hz), 5.03 (d, 1H, J = 5.6Hz), 3.76 (s, 2H), 3.67 (s, 2H), 3.23 (s, 2H), 2.32 (s, 3H).

^{13}C NMR: δ 147.2, 146.1, 137.3, 130.3, 129.2, 127.2, 125.7, 124.3, 124.1, 122.7, 120.2, 60.8, 58.6, 54.9, 53.0, 51.5, 19.2.

MS: *m/z* 349.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.34; H, 6.62; N: 3.98.

3.6.7 Compound 10g



Yield: 70%; mp: 95 °C; IR: 2962, 1641, 794 cm^{-1}

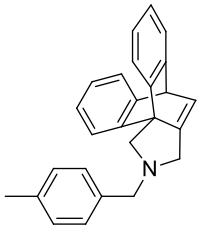
^{1}H NMR: δ 7.21-6.84 (m, 12H), 6.50 (dt, 1H, J_1 = 5.6Hz, J_2 = 2Hz), 5.02 (d, 1H, J = 6Hz), 3.74 (s, 2H), 3.62 (s, 2H), 3.26 (d, 2H, J =2Hz), 2.31 (s, 3H).

^{13}C NMR: δ 155.0, 147.2, 146.1, 138.8, 138.0, 129.4, 128.3, 127.9, 126.4, 125.7, 124.3, 124.2, 122.8, 120.2, 60.9, 60.6, 55.1, 52.8, 51.5, 21.4.

MS: *m/z* 349.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.35; H, 6.61; N: 4.00.

3.6.8 Compound 10h



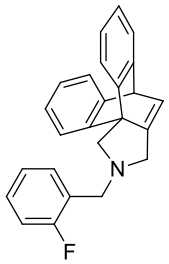
Yield: 85%; mp: 134 °C; IR: 2962, 1641, 794 cm^{-1}

^1H NMR: δ 7.28-6.85 (m, 12H), 6.50 (dt, 1H, J_1 = 6Hz, J_2 = 2Hz), 5.02 (d, 1H, J = 6Hz), 3.74 (s, 2H), 3.61 (s, 2H), 3.26 (d, 2H, J =2Hz), 2.30 (s, 3H).

^{13}C NMR: δ 155.0, 147.2, 146.1, 136.7, 135.8, 129.1, 128.6, 126.3, 124.3, 124.2, 122.7, 120.2, 60.8, 60.3, 55.1, 52.6, 51.5, 21.1. MS: *m/z* 349.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}N$: C, 89.36; H, 6.63; N, 4.01; Found: C, 89.34, H, 6.62; N: 4.00.

3.6.9 Compound 10i



Yield: 68%; mp: 90 °C; IR: 2962, 1641, 794 cm^{-1}

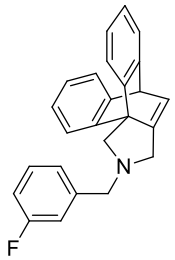
^1H NMR: δ 7.54-6.91 (m, 12H), 6.57 (dt, 1H, J_1 = 6Hz, J_2 = 2Hz), 5.09 (d, 1H, J = 6Hz), 3.94 (s, 2H), 3.77 (s, 2H), 3.36 (d, 2H, J = 1.6Hz).

^{13}C NMR: δ 162.3, 159.9, 154.8, 147.2, 146.0, 131.2, 131.1, 128.8, 128.7, 126.4, 125.3, 124.3, 124.2, 124.1, 124.0, 122.8, 120.2, 116.4, 115.2, 60.8, 54.6, 52.6, 52.3, 52.3, 51.5.

MS: *m/z* 353.1(M^+).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.69; N, 3.94.

3.6.10 Compound 10j



Yield: 76%; mp: 110 °C; IR: 2962, 1641, 794 cm^{-1}

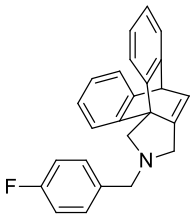
^1H NMR: δ 7.34-6.92 (m, 12H), 6.59 (d, 1H, J = 5.6Hz), 5.11 (d, 1H, J = 5.6Hz), 3.84 (s, 2H), 3.73 (s, 2H), 3.34 (s, 2H).

^{13}C NMR: δ 164.3, 161.9, 147.1, 145.9, 129.9, 129.8, 126.7, 124.4, 124.2, 124.1, 122.8, 120.1, 115.5, 115.3, 114.2, 114.0, 60.8, 60.0, 54.9, 52.8, 51.5.

MS: *m/z* 353.2(M^+).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.95; H, 5.69; N, 3.93.

3.6.11 Compound 10k



Yield: 90%; mp: 126 °C; IR: 2962, 1641, 794 cm^{-1}

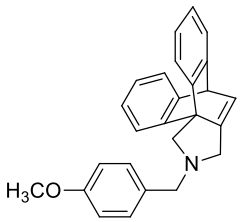
^1H NMR: δ 7.36-6.85 (m, 12H), 6.51 (d, 1H, *J* = 6Hz), 5.03 (d, 1H, *J* = 6Hz), 3.74 (s, 2H), 3.63 (s, 2H), 3.26 (s, 2H).

^{13}C NMR: δ 162.3, 159.8, 153.7, 146.1, 144.9, 129.1, 129.1, 125.5, 123.3, 123.2, 121.8, 119.1, 114.2, 114.0, 59.7, 58.7, 53.9, 52.3, 51.7, 50.5.

MS: *m/z* 353.2(M^+).

Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.68; N, 3.96.

3.6.12 Compound 10l



Yield: 89%; mp: 142 °C; IR: 2962, 1641, 794 cm^{-1}

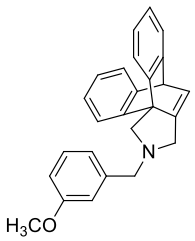
^1H NMR: δ 7.38-6.90 (m, 12H), 6.57 (dt, 1H, J_1 = 5.6Hz, J_2 = 2Hz), 5.02 (d, 1H, *J* = 5.6Hz), 3.83 (s, 3H), 3.79 (s, 2H), 3.68 (s, 2H) 3.30 (d, 2H, *J* = 2Hz).

^{13}C NMR: δ 158.8, 155.0, 147.2, 146.1, 131.0, 129.8, 126.3, 124.3, 124.2, 122.7, 120.2, 113.7, 60.8, 59.9, 55.3, 55.0, 52.6, 51.5.

MS: *m/z* 365.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.43; H, 6.33; N, 3.82.

3.6.13 Compound 10m



Yield: 66%; semisolid; IR: 2962, 1641, 794 cm^{-1}

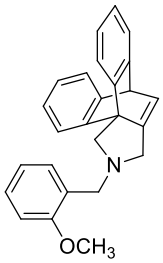
^1H NMR: δ 7.44-6.81 (m, 12H), 6.47 (dt, 1H, J_1 = 5.6Hz, J_2 = 2Hz), 5.00 (d, 1H, *J* = 6Hz), 3.84 (s, 2H), 3.77 (s, 3H), 3.70 (s, 2H) 3.29 (d, 2H, *J* = 2Hz).

^{13}C NMR: δ 156.4, 154.2, 146.2, 145.1, 129.2, 129.0, 126.9, 126.9, 125.6, 125.1, 123.2, 123.1, 121.7, 119.4, 119.2, 119.2, 109.4, 59.8, 54.4, 53.8, 52.3, 51.7, 50.5, 41.0.

MS: *m/z* 365.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.44; H, 6.33; N, 3.81.

3.6.14 Compound 10n



Yield: 61%; semisolid; IR: 2962, 1641, 794 cm^{-1}

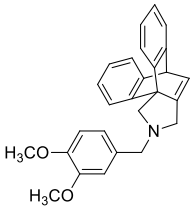
^{1}H NMR: δ 7.19-6.75 (m, 12H), 6.49 (dt, 1H, J_1 = 6Hz, J_2 = 2Hz), 5.01 (d, 1H, J = 6Hz), 3.73 (s, 5H), 3.61 (s, 2H), 3.26 (d, 2H, J = 2Hz).

^{13}C NMR: δ 158.8, 153.9, 146.1, 145.0, 139.5, 128.3, 125.3, 123.3, 123.1, 121.7, 119.8, 119.1, 112.6, 111.9.

MS: *m/z* 365.1(M^+).

Elemental Anal. Calcd for $C_{26}H_{23}NO$: C, 85.45; H, 6.34; N, 3.83; Found: C, 85.44; H, 6.32; N, 3.82.

3.6.15 Compound 10o



Yield: 92%; mp: 142 °C; IR: 2962, 1641, 794 cm^{-1}

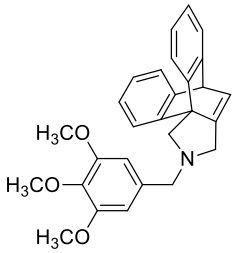
^{1}H NMR: δ 7.28-6.86 (m, 11H), 6.49 (d, 1H, J = 5.6Hz), 5.11 (d, 1H, J = 5.6Hz), 3.91 (s, 6H), 3.78 (s, 2H), 3.65 (s, 2H), 3.77 (s, 2H).

^{13}C NMR: δ 154.9, 149.1, 148.2, 147.2, 146.0, 131.7, 126.4, 124.3, 124.1, 122.8, 120.5, 120.1, 111.5, 110.8, 60.8, 60.2, 55.9, 55.9, 55.2, 52.4, 51.5.

MS: *m/z* 395.1(M^+).

Elemental Anal. Calcd for $C_{27}H_{25}NO_2$: C, 82.00; H, 6.37; N, 3.54; Found: C, 79.99; H, 6.35; N, 3.52.

3.6.16 Compound 10p



Yield: 64%; semisolid; IR: 2962, 1641, 794 $cm.^{-1}$

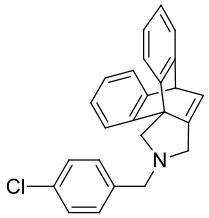
^{1}H NMR: δ 7.22-6.66 (m, 10H), 6.54 (d, 1H, J = 5.6Hz), 5.05 (d, 1H, J = 5.6Hz), 3.82 (s, 6H), 3.81 (s, 3H), 3.71 (s, 2H), 3.33 (s, 2H), 3.31 (s, 2H).

^{13}C NMR: δ 153.8, 152.2, 146.1, 145.0, 135.9, 133.8, 125.5, 123.3, 121.8, 119.1, 104.1, 59.9, 59.8, 59.6, 55.1, 54.2, 51.5, 50.4.

MS: *m/z* 425.1(M^+).

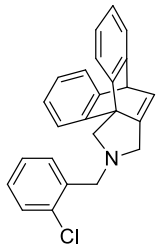
Elemental Anal. Calcd for $C_{28}H_{27}NO_3$: C, 79.03; H, 6.40; N, 3.29; Found: C, 79.01; H, 6.38; N, 3.28.

3.6.17 Compound 10q



Yield: 84%; mp: 132 °C; IR: 2962, 1641, 794 cm.$^{-1}$
^{1}H NMR: δ 7.40-6.92 (m, 12H), 6.58 (dt, 1H, J_1 = 6Hz, J_2 = 1.6Hz), 5.11 (d, 1H, J = 6Hz), 3.81 (s, 2H), 3.69 (s, 2H), 3.30 (d, 2H, J = 1.6Hz).
^{13}C NMR: δ 154.7, 147.1, 145.9, 137.4, 132.8, 129.9, 128.5, 126.5, 124.3, 124.2, 122.8, 120.1, 60.8, 59.8, 55.0, 52.7, 51.5.
MS: *m/z* 369.1(M^+).
Elemental Anal. Calcd for $C_{25}H_{20}ClN$: C, 81.18; H, 5.45; N, 3.79; Found: C, 81.17; H, 5.44; N, 3.77.

3.6.18 Compound 10r



Yield: 63%; semisolid; IR: 2962, 1641, 794 cm^{-1}
^{1}H NMR: δ 7.60-6.92 (m, 12H), 6.57 (d, 1H, J = 5.6Hz), 5.00 (d, 1H, J = 5.6Hz), 3.99 (s, 2H), 3.82 (s, 2H), 3.37 (s, 2H).
^{13}C NMR: δ 155.0, 147.2, 146.0, 136.3, 133.9, 130.4, 129.5, 128.2, 126.8, 126.4, 124.4, 124.2, 122.8, 120.2, 60.9, 56.7, 54.9, 53.0, 51.5.
MS: *m/z* 369.1 (M^+).
Elemental Anal. Calcd for $C_{25}H_{20}ClN$: C, 81.18; H, 5.45; N, 3.79; Found: C, 81.16; H, 5.44; N, 3.77.

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CHAPTER 4

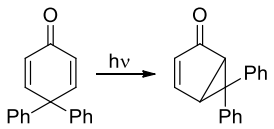
Photochemical transformations of a few 9,11-annulated dibenzobarrelenes

4.1 Abstract

Transformations of a few annulated dibenzobarrelenes possessing methanaminomethyl tethers under direct and acetone sensitized irradiation conditions were examined. Under acid free conditions, we observed that photoinduced electron transfer is competing with typical barrelene photochemistry. We observed contrasting regioselectivity in semibullvalene formation in irradiations carried out in the presence and absence of acid.

4.2 Introduction to photochemistry of barrelenes

Photochemical transformations are well explored due to their synthetic potential and mechanistic appeal. Several reactions that are forbidden in the ground state proceed smoothly in the excited state. This applies to both pericyclic and stepwise processes. Commonly observed phototransformations include rearrangement, fragmentation, addition, hydrogen abstraction, *cis-trans* isomerization etc. Mechanistic aspects of photochemistry gained attention thanks to the seminal work on the mechanism of 4,4-diphenylcyclohexadienone photochemistry reported by Zimmermann and Schuster (Scheme 4.1).[1]



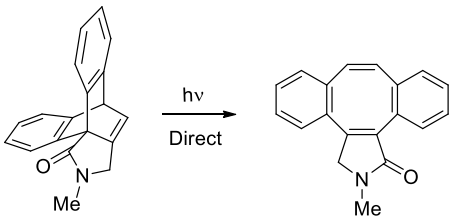
1 **2**

Scheme 4.1

Delineating mechanism of photochemical reactions is much more challenging than that of ground state reactions. A major challenge is identifying the multiplicity of excited state (singlet or triplet) responsible for the observed chemical transformation. Several molecules exhibit (excited) state-selective transformations. Barrelene is archetypal of molecules exhibiting such behavior as explained in Chapter 1 of this thesis.[2] Of late, photochemistry of tricyclic barrelenes has gained renewed interest due to its mechanistic appeal and potential of tricyclic barrelenes for photonic applications.[3-5] A brief discussion on the chemistry of tricyclic barrelenes relevant to our work reported in this chapter is presented in the following section.

4.2.1 Phototransformations of tricyclic dibenzobarrelenes

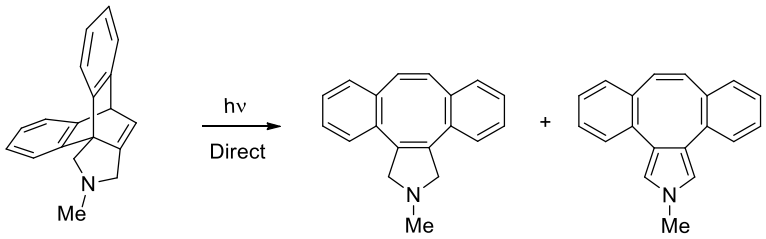
Unlike typical dibenzobarrelenes, annulated barrelenes attracted much less attention. Ciganek reported the photoisomerization of tricyclic or annulated dibenzobarrelenes such as **3** and **5**.[6,7] Much like the dibenzobarrelene congeners, annulated barrelene **3** upon direct irradiation gave the corresponding dibenzocyclooctatetraene **4** in high yields (Scheme 4.2).



3 **4**

Scheme 4.2

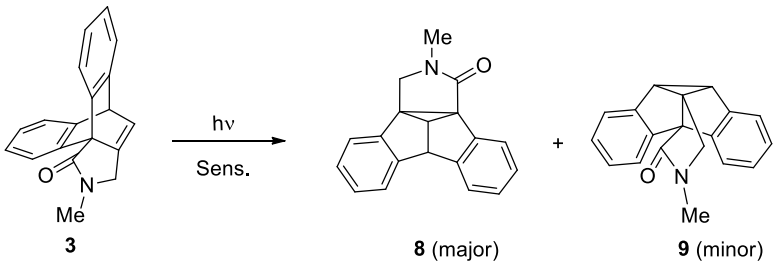
Under direct irradiation conditions, pyrrolidine-bridged dibenzobarrelene **5a** gave two products identified as cyclooctatetraene derivatives **6a** and **7a**. Here, **7a** is a secondary photoproduct formed by aromatization of the primary product **6a** (Scheme 4.3).



5a **6a** **7a**

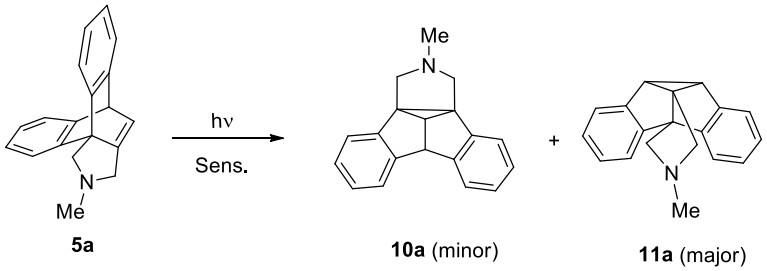
Scheme 4.3

Acetone sensitized irradiation of **3**, on the other hand, gave two isomeric semibullvalene derivatives **8** and **9** analogous to the 8b- and 4b-substituted semibullvalenes formed from bridgehead substituted dibenzobarrelenes (Schemes 4.4).[7]



Scheme 4.4

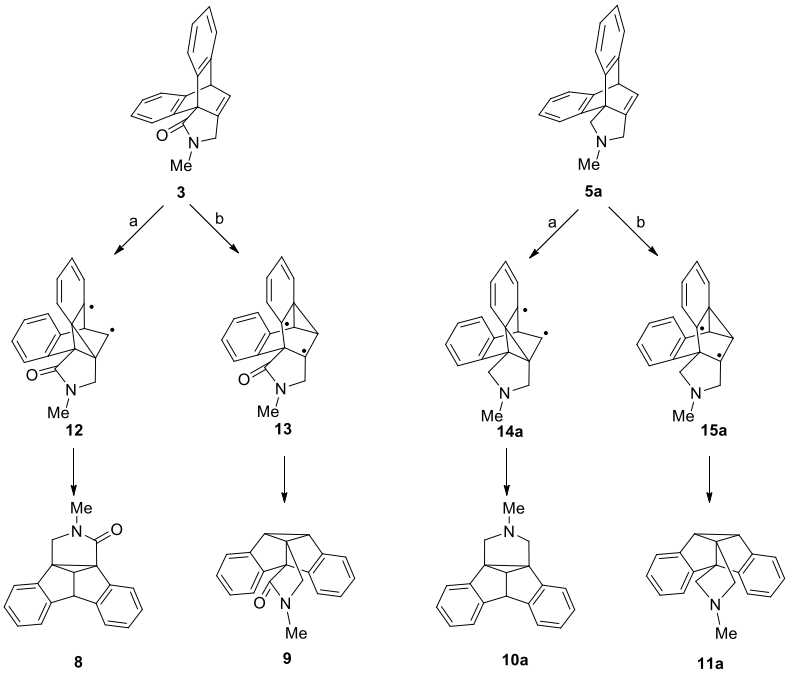
Similarly, acetone sensitized irradiation of **5a** gave isomeric semibullvalene derivatives **10a** and **11a** (Scheme 4.5). Though both **3** and **5a** gave similar products under sensitized irradiation conditions, a major difference is evident in regioselectivity of barrelene-semibullvalene rearrangement. While **3** gave 8b,8d-annulated semibullvalene **8** as the major product, **5a** gave the 4b,8c-annulated semibullvalene **11a** as the major product.[7]



Scheme 4.5

Biradical intermediates formed by two competing benzo-vinyl bridging in **3** and **5a** and the semibullvalene regioisomers formed thereof are collected in scheme 4.6. Ciganek rationalized the observed regioselectivity in the phototransformations of **3** and **5a** on the basis of the stability of biradical intermediates formed by two competing benzo-vinyl bridging paths 'a' and 'b' available for **3** and **5a**. Biradical **12** is the

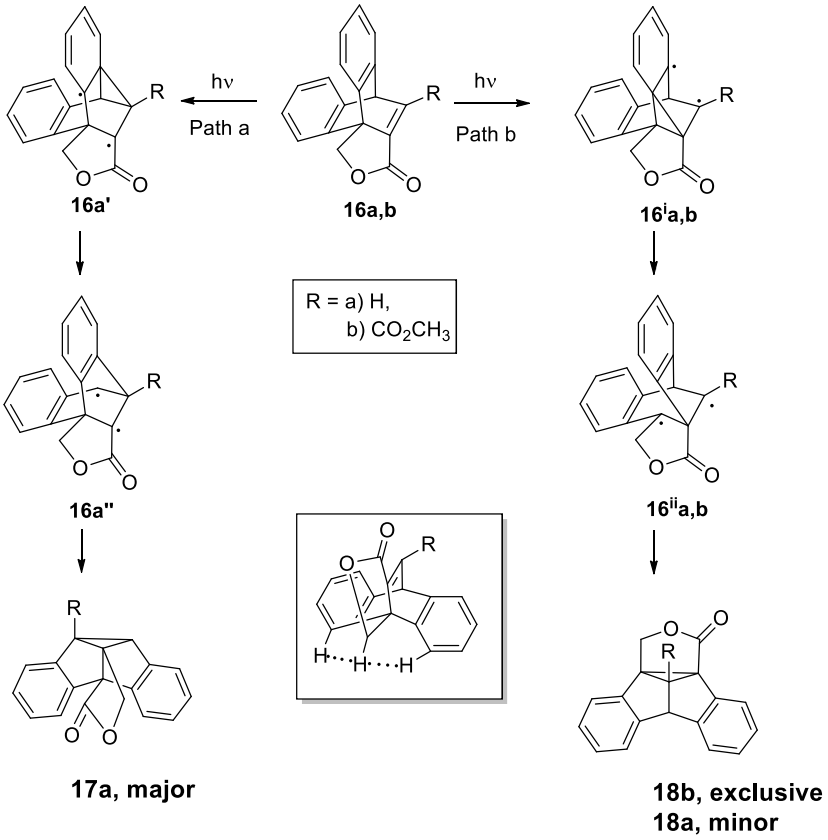
precursor for semibullvalene **8** while **13** is the precursor for **9**. Cyclopropane ring in **12** is stabilized by the electron withdrawing lactam carbonyl while such stabilization is absent in **13**. Consequently, in the case of **3**, path 'a' leading to the more stable biradical intermediate **12** is preferred over path 'b' leading to **13** resulting in preferential generation of semibullvalene **8** over **9**. Similarly, stabilization of incipient radical centers grabs upper hand in controlling regioselectivity observed in the phototransformation of **5a**. Here also, competing benzo-vinyl bridging paths 'a' and 'b' manifest control over regioselectivity. Benzo-vinyl bridging along path 'b' affords a more substituted and hence more stable radical center than the one generated along path 'a.' Hence path 'b' takes predominance over path 'a' in this case leading to preferential generation of semibullvalene **11a**. These observations emphatically underscore the importance of electronic factors in controlling regioselectivity of barrelene-semibullvalene rearrangement. We expect that the extra rigidity imparted to barrelenes upon tethering may exert additional control on the course of the rearrangement; so should the lone pair present on nitrogen in **5**! Since Ciganek ran irradiation experiments of **5** in acidic medium, role of lone pair in controlling regioselectivity was heavily muted if not totally suppressed. So, we decided to examine the photochemistry of **5** under strict exclusion of acid to unravel the effect of nitrogen lone pair in controlling regioselectivity.



Scheme 4.6. Regiochemical course of di-π-methane rearrangement of **3** and **5a**

Decisive influence of electronic factors in controlling regioselectivity in barrelene-semibullvalene rearrangement was further demonstrated by Scheffer and coworkers.[8-16] They showed that annulated dibenzobarrelene **16a,b** exhibited opposing regioselectivity (Scheme 4.7). In the case of **16a**, stabilization of the radical center by the lactone carbonyl is the decisive factor favoring path 'a'. Path 'b' leading to biradical intermediate **16^{i}a** could have generated a more stable cyclopropane ring system. It appears that stabilization of the radical center takes predominance over that of the cyclopropane ring. For **16b**, two factors work in tandem favoring path 'b': both the cyclopropane ring and radical center in **16^{i}b** are stabilized by carbonyl groups. Not surprisingly, **16b** underwent exclusive transformation to give semibullvalene **18** whereas

16a gave semibullvalene **17** as the major product. Relief of unfavourable H···H···H interactions in **16** (shown in inset) is touted as another factor controlling regioselectivity.



Scheme 4.7

Previous investigators from our group have also contributed towards regioselectivity observed in the photochemical transformations of annulated barrelenes such as **19**-**22** (Figure 4.1).[17]

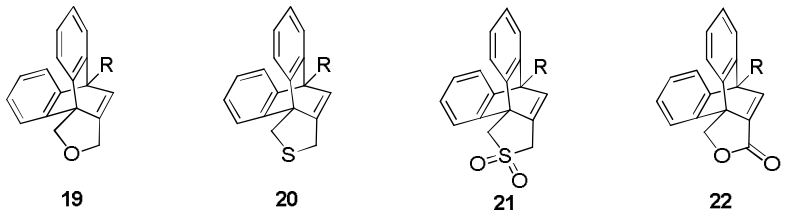


Figure 4.1

Our group focused on unraveling the combined effect of tethers such as ether, sulfane, sulfone and ester, and bridgehead substituents such as methyl, methoxy and phenyl groups in controlling regiochemical preference exhibited by annulated barrelenes.[17] In parallel, we had demonstrated efficient electron transfer mediated quenching of excited state of amine appended dibenzobarrelenes.[18] Based on these findings, we reasoned that annulated barrelenes having methanaminomethyl bridges hold rich potential for mechanistic investigations. Presence of the tether can influence the regiochemical outcome of barrelene-semibullvalene rearrangement. Intramolecular electron transfer in the excited state is a distinct possibility with the proposed molecules. The present investigation is thus a two pronged approach aimed simultaneously at examining intramolecular electron transfer and regiochemical control induced by amine tether on the photochemistry of annulated barrelenes taking **5b-h** listed in the Figure 4.2 as test mules. In the absence of acid, nitrogen lone pair in **5b-h** can efficiently participate in single electron transfer as well as stabilization/destabilization of intermediates involved in di-π-methane rearrangement. Protonation can reduce electron availability on nitrogen and hence full influence of nitrogen present in the methanaminomethyl tether did not manifest in

by Ciganek.[7] We propose to carry out all irradiations in solution under strict exclusion of acid to examine the role of lone pair on nitrogen atom in the tether in controlling the course of photoreaction of **5b-h**. For comparison, we repeated the irradiation **5a** under conditions optimized for **5b-h**.

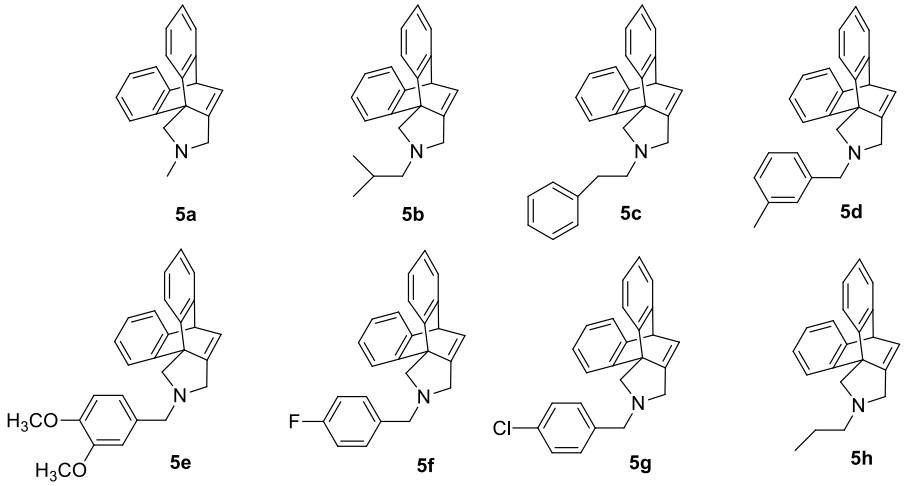
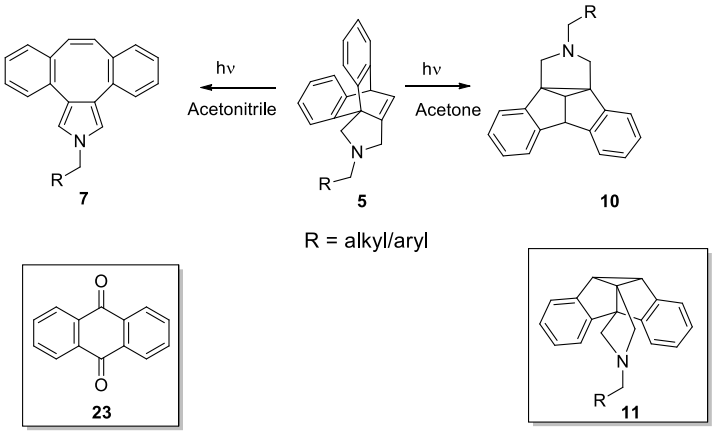


Figure 4.2. 9,11-Methanaminomethyl bridged barrelenes

4.3 Results and discussion

From the large library of methanaminomethyl bridged barrelenes reported in Chapter 3 of this thesis, we selected **5a-h** listed in Figure 4.2 for irradiation experiments. N-substituents in **5** include alkyl (both linear and branched) and appropriately substituted benzyl groups. These substituents are expected to exert steric and electronic effects on the photoisomerization of annulated dibenzobarrelenes under consideration.

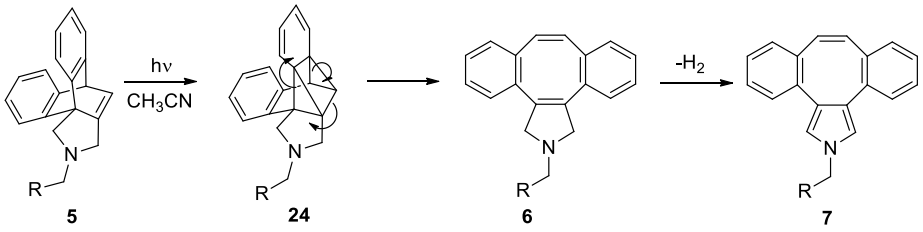
Since irradiation conditions employed by us differ from those employed by Ciganek for **5a**, a direct comparison of our findings with those reported by Ciganek is irrelevant. We too observed multiplicity dependent transformations in the photorearrangement of **5b-h**: under direct irradiation, dibenzocyclooctatetraenes were formed and under triplet sensitization, di-π-methane rearrangement leading to 8b,8c-methaniminomethano bridged dibenzosemibullvalenes in moderate yields was observed. The major difference observed by us is a reversal in regiochemical preference in their di-π-methane rearrangement. What was reported earlier as a minor product was the *only* product formed under the acid-free conditions employed by us. Under both direct and sensitized irradiation conditions, anthraquinone was formed in appreciable quantities suggesting possible intramolecular electron transfer in the excited state.[19,20] General scheme for photochemical isomerization of annulated dibenzobarrelenes **5** under both direct and sensitized irradiation conditions is depicted in Scheme 4.8.



Scheme 4.8

4.3.1 Direct irradiation

Barrelenes **5a-f** showed absorption tail extending beyond 254 nm. Hence, we used an array of 254 nm lamps in a Rayonet Photochemical Reactor (RPR) for direct irradiation experiments. Solution of **5a-f** in acetonitrile (1 mM) taken in quartz tubes was deaerated and then irradiated for 1 h. Workup of the reaction mixture yielded dibenzo[3,4:7,8]cycloocta[1,2-c]pyrroles **7a-f** in moderate yields (20-25%) along with anthraquinone (**23**, 5-10%). Mechanism for the formation of **7** is depicted in Scheme 4.9. Our attempts to isolate **6** were unsuccessful; it underwent facile oxidation under workup to give **7**. All new products were identified on the basis of spectral and analytical data. Compound **7a** was identified by comparing its physical and spectral data with those reported in literature.[7] Structure of photoproducts **7a-f** is collected in the Figure 4.3.



Scheme 4.9

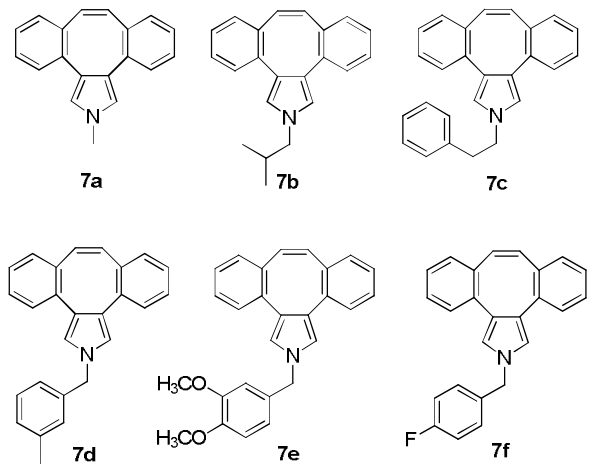


Figure 4.3. Singlet mediated products

^{1}H NMR spectrum of photoproduct **7b** is given in the Figure 4.4. The characteristic vinylic protons of cyclooctatriene appeared at δ 6.64 ppm as a singlet. The eight proton multiplet observed at δ 7.08 ppm corresponds to aromatic protons. The two pyrrole protons appeared as a singlet at δ 6.48 ppm. Methylene protons appeared as a doublet (2H) at δ 3.62 ppm. The one proton multiplet at δ 2.02 ppm is attributable to the methine proton of isopropyl group. Six proton doublet at δ 0.90 ppm corresponds to two methyl groups of isopropyl group.

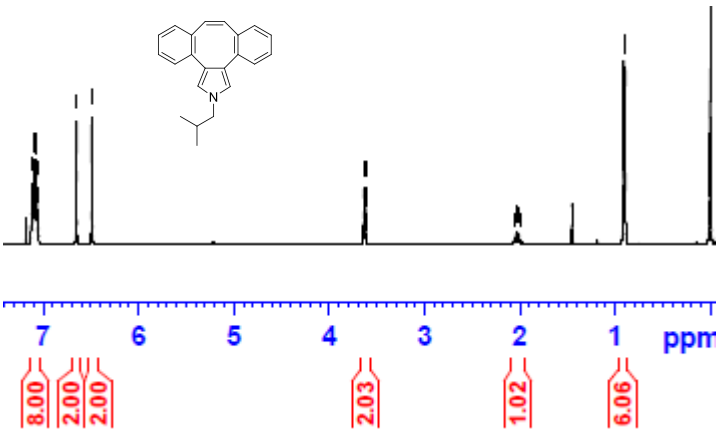


Figure 4.4. ^{1}H NMR spectrum of compound **7b**

Figure 4.5 represents the ^{13}C NMR spectrum of photoproduct **7b**. Signals appearing between δ 136.6 to 118.4 ppm are assigned to the aromatic carbon atoms. The methylene carbon is assigned to a signal at δ 56.6 ppm. Other aliphatic carbon atoms appeared at δ 29.4 ppm and δ 19.1 ppm. Similar spectral patterns were observed for photoproducts **7c-f**.

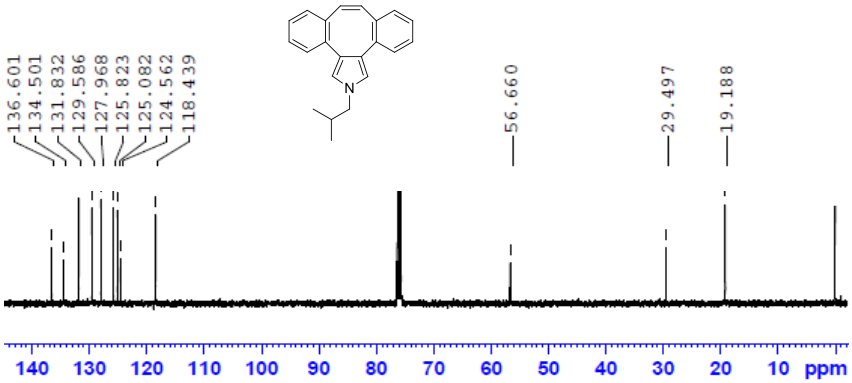
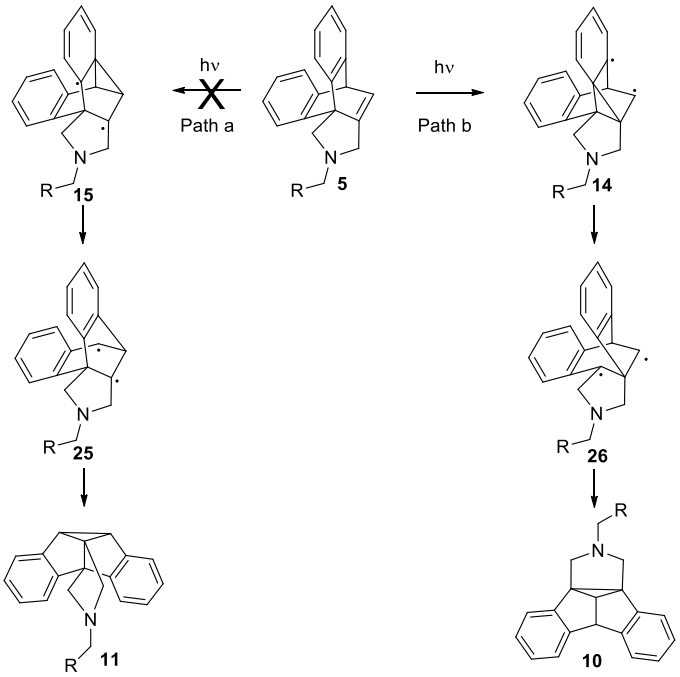


Figure 4.5. ^{13}C NMR spectrum of photoproduct **7b**

4.3.2 Acetone sensitized irradiation experiments

In continuation, we performed sensitized irradiation of five representative annulated dibenzobarrelenes in base-washed quartz tubes using acetone dried over anhydrous potassium carbonate as solvent and sensitizer. Annulated dibenzobarrelenes selected for the sensitized irradiation include **5a**, **5b**, **5f**, **5g** and **5h**. Rayonet photochemical reactor equipped with an array of 254 nm lamps was used to irradiate the respective dibenzobarrelenes of our choice. One millimolar solution of **5** in acetone was irradiated with the output from 254 nm lamps for 1h. Under these conditions, acetone absorbed >98% of lamp output. Though semibullvalene formation was observed under neutral as well as acidic conditions, irradiation under neutral conditions proceeded with a dramatic change in regioselectivity with much lower yield. Unlike previous report, only the 8b,8c-fused regioisomer was formed in non-acidic medium.[7] We attribute the destabilization of proximal radical centers in **25** by the lone pair on nitrogen for diversion of the regiochemistry of barrelene to semibullvalene rearrangement (Scheme 4.10) through the unaffected, albeit less substituted, biradical intermediate **26**. Dramatic changes in the course of reactions induced by subtle changes in structure like these make examination of reaction mechanism exciting. Role of N-substituents in controlling regioselectivity remains uncertain at this stage. Generation of anthraquinone is through a mechanism involving photoinduced electron transfer analogous to that observed for other amine appended barrelenes reported by earlier investigators from our group.[18]



Scheme 4.10

Structure of 8b,8c-fused dibenzosemibullvalenes**10a,b,f,g,h** obtained as triplet mediated products are presented in the Figure 4.6.

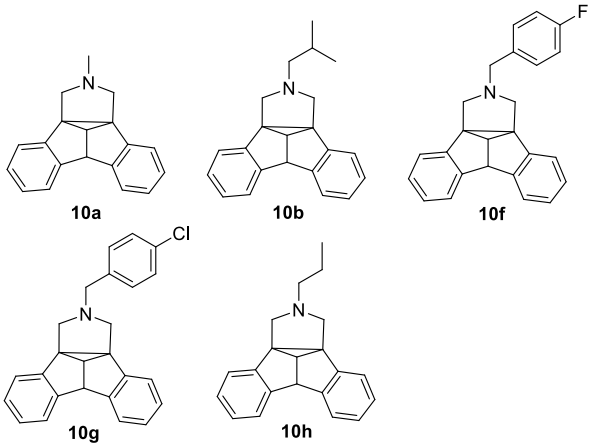


Figure 4.6. Triplet mediated products

^{1}H NMR spectrum (Figure 4.7) of **10h** showed two doublets at δ 4.37 ppm and δ 3.70 ppm assigned to the characteristic methine protons of semibullvalene. Aromatic protons (8 H) appeared as a multiplet in the δ 7.10-6.93 range. Methylene protons of the pyrrolidine bridge appeared as two doublets at δ 3.38 and δ 3.08 ppm. Other aliphatic protons, in the N-propyl group appeared as triplet (2H), multiplet (2H) and triplet (3H) as expected for $A_2M_2X_3$ spin systems.

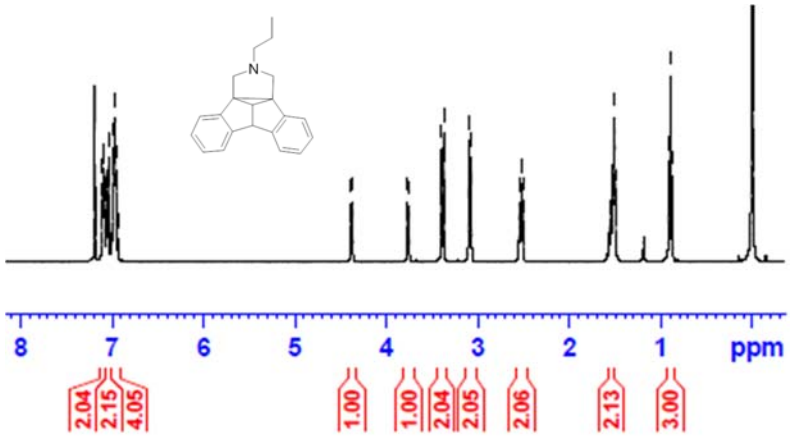


Figure 4.7. ^{1}H NMR spectrum of **10h**

^{13}C NMR spectrum of **10h** is given in Figure 4.8. Signals appearing between δ 147.8 ppm and δ 120.7 ppm are assigned to the aromatic carbons. Methylene carbons of the pyrrolidine ring are observed at δ 57.1 ppm. Signal appearing at δ 56.6 ppm corresponds to the methylene group α to the amine moiety. Signals at δ 52.1 ppm and δ 51.9 ppm are assigned to methine carbons in semibullvalene. The signal at δ 53.5 ppm is assigned to the 8b and 8c carbon atoms of the semibullvalene. Signal at

δ 20.7 ppm corresponds to β-methylene of N-propyl group. Methyl carbon appeared at δ 10.8 ppm.

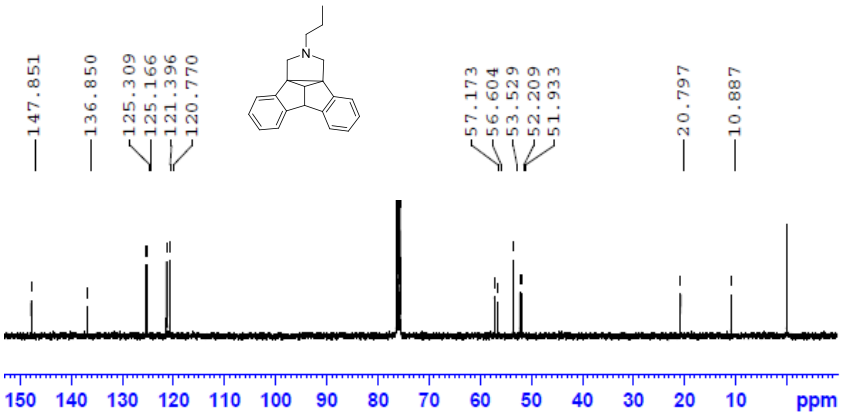


Figure 4.8. ^{13}C NMR spectrum of photoproduct **10h**

4.4 Conclusions

In summary, we examined the photochemistry of several 9,11-annulated dibenzobarrelenes derivatives under both direct and sensitized irradiation conditions. Upon direct irradiation, annulated dibenzobarrelenes **5** gave the expected cyclooctatetraenes **7**. Sensitized irradiation of **5** under strict exclusion of acid lead to exclusive generation of 8b,8c-fused dibenzosemibullvalene **10** which is in contrast with the formation of a mixture of isomers (with **10** as the minor product) when the irradiation was carried out under acidic conditions. Under nonacidic medium, photoinduced electron transfer reduced yield of both cyclooctatetraene and semibullvalene products. All new compounds were identified on the basis of spectral and analytical data. We have also

proposed a plausible mechanism consistent with the regioselectivity observed in the triplet mediated transformations of **5**.

4.5 Experimental

4.5.1 General procedure for direct irradiation

The solvent chosen for irradiation, acetonitrile, was distilled and dried by standard procedures. Acetonitrile was first dried by distillation over P_2O_5, stored overnight over anhydrous potassium carbonate, decanted and distilled prior to use. The substrates for the irradiation, **5a-f** (0.11 mmol) were dissolved in 100 mL of acetonitrile taken in a quartz tube and the solution was degassed by bubbling nitrogen for 30 minutes. The degassed solution was irradiated in a Rayonet photochemical reactor equipped with an array of 254 nm lamps for 1h with incessant purging of nitrogen gas. The crude product obtained after the evaporation of the solvent was purified by column chromatography over silica. The eluent used was a mixture (5:95) of ethyl acetate and hexane. Purified products **7a-f** were identified on the basis of spectral and analytical data. Anthraquinone (5-10%) could be isolated by elution of the column with a mixture (10:90) of ethyl acetate and dichloromethane.

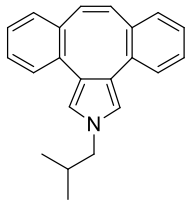
4.5.2 General procedure for sensitized irradiation

Acetone sensitized irradiation of **5(a,b,f,g,h**) was performed using Rayonet photochemical reactor. The solvent, acetone was dried over anhydrous potassium carbonate immediately before irradiation experiments. Barrelenes **5** (0.1 mmol) was dissolved in acetone (100 mL) taken in a quartz tube and the solution was degassed for 30 minutes. The degassed solution was irradiated using 254 nm lamps in a RPR for 1h.

Photoproduct **10** was purified by column chromatography over silica using a mixture (5:95) mixture of ethyl acetate and hexane as eluent. The structure of the photoproduct **10** was confirmed on the basis of spectral and analytical data. Anthraquinone (5-10%) could be isolated by elution of the column with a mixture (10:90) of ethyl acetate and dichloromethane.

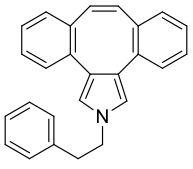
4.6 Spectral and analytical data of irradiation products

4.6.1 Compound 7b



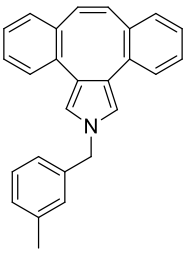
Yield: 21%; mp: 105 °C; IR: 2972, 1627, 794 cm^{-1}
^{1}H NMR: δ 7.11-7.05 (m, 8H), 6.64 (s, 2H), 6.48 (s, 2H), 3.62 (d, 2H, *J* = 6.8Hz), 2.02 (sep, 1H, *J* = 6.8Hz), 0.90 (d, 6H, *J* = 6.4Hz).
^{13}C NMR: δ 136.6, 134.5, 131.8, 129.5, 127.9, 125.8, 125.0, 124.5, 118.4, 56.6, 29.4, 19.1.
MS: *m/z* 299.1(M^+).
Elemental Anal. Calcd for $C_{22}H_{21}N$: C, 88.25; H, 7.07; N, 4.68; Found: C, 88.23; H, 7.06; N, 4.66.

4.6.2 Compound 7c



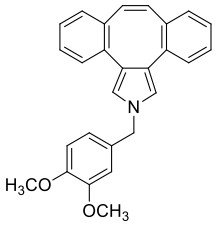
Yield: 20%; mp: 109 °C; IR: 2972, 1627, 794 cm^{-1}
^{1}H NMR: δ 7.25-7.05 (m, 13H), 6.65 (s, 2H), 6.45 (s, 2H), 4.06 (t, 2H, *J* = 7.6Hz), 3.07 (t, 2H, 7.6Hz).
^{13}C NMR: δ 137.2, 136.6, 134.3, 131.8, 129.5, 127.9, 127.7, 127.5, 125.8, 125.7, 125.1, 124.8, 117.9, 52.3, 37.2.
MS: *m/z* 347.1(M^+).
Elemental Anal. Calcd for $C_{26}H_{21}N$: C, 89.88; H, 6.09; N, 4.03; Found: C, 89.87; H, 6.07; N, 4.01.

4.6.3 Compound 7d



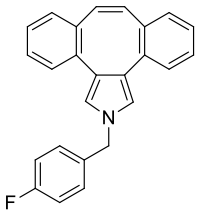
Yield: 23%; mp: 103 °C; IR: 2972, 1627, 794 cm^{-1}
^{1}H NMR: δ 7.20-6.98 (m, 12H), 6.65 (s, 2H), 6.54 (s, 2H), 4.98 (s, 2H), 2.28 (s, 3H).
^{13}C NMR: δ 137.4, 136.5, 136.3, 134.2, 131.8, 129.6, 127.9, 127.9, 127.6, 127.6, 127.3, 125.8, 125.1, 123.6, 118.4, 52.6, 20.4.
MS: *m/z* 347.1(M^{+}).
Elemental Anal. Calcd for $C_{26}H_{21}N$: C, 89.88; H, 6.09; N, 4.03; Found: C, 89.86; H, 6.07; N, 4.02.

4.6.4 Compound 7e



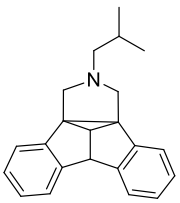
Yield: 25%; mp: 113 °C; IR: 2972, 1622, 800 cm^{-1}
^{1}H NMR: δ 7.17-7.12 (m, 8H), 6.87-6.73 (m, 3H), 6.71 (s, 2H), 6.61 (s, 2H), 5.04 (s, 2H), 3.88 (s, 3H), 3.85 (s, 3H).
^{13}C NMR: δ 149.3, 148.7, 137.6, 135.2, 132.8, 130.5, 129.9, 128.9, 126.8, 126.3, 126.2, 120.0, 119.4, 111.2, 110.7, 55.9, 55.9, 53.3.
MS: *m/z* 393.1(M^{+}).
Elemental Anal. Calcd for $C_{27}H_{23}NO_2$: C, 82.42; H, 5.89; N, 3.56; Found: C, 82.40; H, 5.85; N, 3.55.

4.6.5 Compound 7f



Yield: 24%; mp: 105 °C; IR: 2972, 1627, 794 cm^{-1}
^{1}H NMR: δ 7.18-6.97 (m, 12H), 6.65 (s, 2H), 6.52 (s, 2H), 5.00 (s, 2H).
^{13}C NMR: δ 136.5, 134.1, 131.7, 129.5, 128.2, 128.2, 127.9, 125.8, 125.4, 125.2, 118.2, 114.8, 114.5, 51.8.
MS: *m/z* 351.1(M^{+}).
Elemental Anal. Calcd for $C_{25}H_{18}FN$: C, 85.45; H, 5.16; N, 3.99; Found: C, 85.43; H, 5.14; N, 3.97.

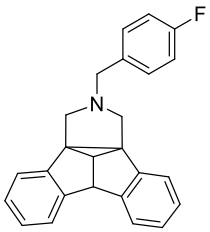
4.6.6 Compound 10b



Yield: 18%; mp: 120 ^{o}C; IR: 2962, 1623, 794 cm^{-1}
^{1}H NMR: δ 7.16-6.99 (m, 8H), 4.43 (d, 1H, *J* = 6Hz), 3.81 (d, 1H, *J* = 5.2Hz), 3.41 (d, 2H, *J* = 8.8Hz), 3.12 (d, 2H, *J* = 8.8Hz), 2.40 (d, 2H, *J* = 7.2Hz), 1.82 (sep, 1H, *J* = 6.4Hz), 0.94 (d, 6H, *J* = 6.4Hz).
^{13}C NMR: δ 147.8, 136.9, 125.2, 125.1, 121.3, 120.7, 63.1, 56.6, 53.6, 52.2, 51.8, 26.2, 19.7.
MS: *m/z* 301.1(M^{+}).

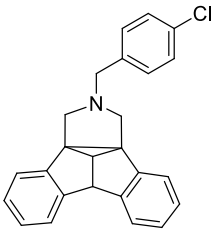
Elemental Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65; Found: C, 87.65; H, 7.67; N, 4.64.

4.6.7 Compound 10f



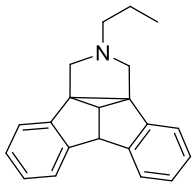
Yield: 16%; mp: 116 °C; IR: 2962, 1641, 794 cm^{-1}
^{1}H NMR: δ 7.29-6.92 (m, 12H), 4.37 (d, 1H, *J* = 6Hz), 3.79 (d, 1H, *J* = 6Hz), 3.72 (s, 2H), 3.30 (d, 2H, *J* = 8.8Hz)), 3.14 (d, 2H, *J* = 9.2Hz)).
^{13}C NMR: δ 147.8, 136.6, 129.0, 128.9, 125.3, 121.3, 120.7, 114.1, 113.9, 57.8, 56.4, 52.9, 52.2, 51.8.
MS: *m/z* 353.2(M^+).
Elemental Anal. Calcd for $C_{25}H_{20}FN$: C, 84.96; H, 5.70; N, 3.96; Found: C, 84.94; H, 5.68; N, 3.96.

4.6.8 Compound 10g



Yield: 22%; mp: 115 °C; IR: 2962, 1641, 794 cm^{-1}
^{1}H NMR: δ 7.34-7.01 (m, 12H), 4.45 (d, 1H, *J* = 6Hz), 3.87 (d, 1H, *J* = 6Hz), 3.80 (s, 2H), 3.38 (d, 2H, *J* = 8.8Hz)), 3.21 (d, 2H, *J* = 9.2Hz)).
^{13}C NMR: δ 148.8, 137.6, 129.8, 128.4, 126.3, 126.2, 122.4, 121.8, 58.9, 57.4, 54.0, 53.2, 52.8.
MS: *m/z* 369.1(M^+).
Elemental Anal. Calcd for $C_{25}H_{20}ClN$: C, 81.18; H, 5.45; N, 3.79; Found: C, 81.17; H, 5.43; N, 3.77.

4.6.8 Compound 10h



Yield: 17%; mp: 116 °C; IR: 2962, 1641, 794 cm^{-1}
^{1}H NMR: δ 7.10-6.93 (m, 8H), 4.37 (d, 1H, *J* = 6Hz), 3.76 (d, 1H, *J* = 6.4Hz), 3.38 (d, 2H, *J* = 9.2Hz), 3.08 (d, 2H, *J* = 9.2Hz), 2.55 (t, 2H, *J* = 7.6Hz), 1.54 (m, 2H), 0.89 (t, 3H, *J* = 7.6Hz).
^{13}C NMR: δ 147.8, 136.8, 125.3, 125.1, 121.3, 120.7, 57.1, 56.6, 53.5, 52.2, 51.9, 20.7, 10.8. MS: *m/z* 287.1(M^+).
Elemental Anal. Calcd for $C_{21}H_{21}N$: C, 87.76; H, 7.36; N, 4.87; Found: C, 87.75; H, 7.35; N, 4.86.

4.7 References

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2. For an exhaustive list of references on barrelene photochemistry, see Chapter 1 of this thesis.
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Summary and Conclusion

The thesis entitled: “Synthesis and photochemistry of a few 9,11-annulated dibenzobarrelenes” describes synthesis of several tricyclic barrelene systems and their photochemical transformations under direct and sensitized conditions. Synthesis of these annulated/tethered barrelenes with tether constituting nitrogen atom was achieved through intramolecular Diels-Alder reaction of suitably substituted anthracenes.

Based on available literature and our own findings on the photochemistry of annulated barrelenes, we designed and synthesized a few amine bridged tricyclic dibenzobarrelenes with various alkyl and benzyl-substituents on nitrogen with a view to examine the role of tethering on controlling regioselectivity of barrelene to semibullvalene rearrangement.

Several N-propargylated anthracenemethanamines were synthesized by reported procedures. These substrates were subjected to intramolecular Diels Alder reaction conditions under solvent free conditions to generate required annulated barrelenes. Competing electron transfer mediated products generated in solution phase reactions were absent in solvent free runs. All annulated barrelenes were formed in good yields and purification was done by washing with methanol and in a few cases, by passing through a short plug of silica. Thus we have developed a greener, cleaner and faster procedure for the generation of our targets.

In principle, annulated barrelenes having amine tether can exhibit singlet mediated transformation to give cyclooctatetraene derivatives or triplet mediated barrelenes-semibullvalene rearrangement. Single electron transfer from nitrogen to barrelene component in its excited state is also a distinct possibility. We observed that under direct irradiation,

cyclooctatetraene was formed in moderate yields along anthraquinone arising through single electron transfer in appreciable quantities. Similarly, under acetone sensitized irradiation, these annulated barrelenes gave the corresponding 8b,8c-fused dibenzosemibullvalenes in moderate yields along with anthraquinone. Interestingly, semibullvalene formation exhibited a high degree of regioselectivity explainable in terms of stabilization/destabilization of intermediates formed in barrelene-semibullvalene rearrangement.

In summary, we synthesized several 9,11-annulated dibenzobarrelenes and examined their photochemistry under both direct and sensitized irradiation conditions. A green protocol was developed for their synthesis. We observed that, along with the expected cyclooctatetraenes and semibullvalenes, anthraquinone arising through single electron transfer mediated pathway is also formed in the irradiation experiments. A plausible mechanism is proposed to account for the high regioselectivity observed in the triplet mediated barrelene-semibullvalene rearrangement of these annulated barrelenes.

Publications:

1. Unusual reactivity of DMAD (Dimethyl Acetylenedicarboxylate) with N-alkyl-9-anthracenemethanamine. **Tomson Devassia**, S. Prathapan, P. A. Unnikrishnan, Chemical Data Collections, 17-18 (2018) 9-12.

2. Synthesis, characterization and crystal structure of heteroatoms substituted annulated dibenzobarrelenes and Hirshfeld studies. **Tomson Devassia**, Eason M. Mathew, Lincy Tom, M. R. P. Kurup, P. A. Unnikrishnan, Under revision in Chemical Data Collections.

3. Synthesis, characterization and transformations of a few anthracene-(9yl)-methanamines, **Tomson Devassia**, Eason M. Mathew, S. Prathapan, P. A. Unnikrishnan MATCON-2016, ISBN 978-93-80095-738.

4. Synthesis and Photochemical Transformations of a few 3,3-Bis(4-chlorophenyl)-5-aryl-2(3*H)*-furanones,, Vidya Raman, Rakesh Natarajan, **Tomson Devassia**, Ligi M. Lalu, *J. Adv. Res. Appl. Chem. Chem. Eng*. 2014.

5. Crystal Structure of "10-Methyl-9,11-annulated dibenzobarrelene", **Tomson Devassia**, Eason M. Mathew, M. Sithambaresan, P. A., Unnikrishnan and M. R. Prathapachandra Kurup, IUCrData (2018). 3, x181102.

6. Synthesis and transformations of a few 9-(pent-4-yn-1-yl)anthracene-type systems, **Tomson Devassia**, Eason M. Mathew, S. Prathapan, P. A. Unnikrishnan, Arkivoc-accepted.

Conference Papers:

1. Unusual reactivity of dimethylacetylene Dicarboxylate (DMAD) with a few anthracene-9-yl-methanamines. **Tomson Devassia**, Prathapan S. and Unnikrishnan P. A. Ctric-2017 (Cochin University of Science and Technology, Kochi).

2. Solvent free green approach in the synthesis of annulated barrelenes. **Tomson Devassia**, Prathapan S. and Unnikrishnan P. A. NTAC-2017 (S. H. College, Thevara, Kochi).

3. Photochemical transformation of a tethered barrelene, Eason M. Mathew and **Tomson Devassia**, CTriC 2013 (Cochin University of Science and Technology, Kochi).