Brigham Young University
BYU ScholarsArchive

All Theses and Dissertations

2008-11-07

Photocycloaddition of Allenes

Crystal Ward
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Biochemistry Commons, and the Chemistry Commons

BYU ScholarsArchive Citation
Ward, Crystal, "Photocycloaddition of Allenes" (2008). *All Theses and Dissertations*. 1580.
https://scholarsarchive.byu.edu/etd/1580

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in All Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.

Photocycloaddition of Allenes

by

Crystal Ward Chatterton

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Chemistry and Biochemistry

Brigham Young University

December 2008

Copyright © 2008 Crystal Ward Chatterton

All Rights Reserved

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Crystal Ward Chatterton

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Steven A. Fleming, Chair
Date	Paul B. Savage
Date	Matthew C. Asplund

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Crystal Ward Chatterton in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date

Steven A. Fleming
Chair, Graduate Committee

Accepted for the Department

Date

David V. Dearden

Accepted for the College

Date

Thomas W. Sederberg

Abstract

Photocycloaddition of Allenes

Crystal Ward Chatterton

Department of Chemistry and Biochemistry

Master of Science

For the past ten years the Fleming research group has been involved in the research of allene compounds. We have explored the synthesis of allenes as well as several reactions involving allenes, such as oxidation and nitrene addition. Recently, we have explored the synthesis and photochemistry of allenic alcohols tethered to silicon. There are literature examples using allenes in synthesis, but very few examples exist using allenes in photochemical cycloaddition reactions. We have found that a diisopropylallenyloxy(cinnamyloxy)silane derivative undergoes [2+2] photochemical cycloaddition to produce a cyclobutylsilane product when irradiated for 60-75 minutes.

Acknowledgements

My sincere thanks to Dr. Steven A. Fleming for his invaluable help and support as a true teacher. He has encouraged me to reach my full potential and he has been available every step of the way to mentor me and to teach me not only how to be successful in chemistry, but also how to succeed in life in general. My thanks also to the other members of the Fleming research group for their help with my research and with my thesis, as well as their love, friendship, and support. I want to acknowledge my husband, Ben Chatterton, for his emotional support and encouragement and for helping me with many of my schemes. Finally, thank you to all the entities who funded this research, namely the Bradshaw Assistantship and the Brigham Young University College of Physical and Mathematical Sciences, especially the Department of Chemistry and Biochemistry.

Table of Contents

List of Figures

List of Tables

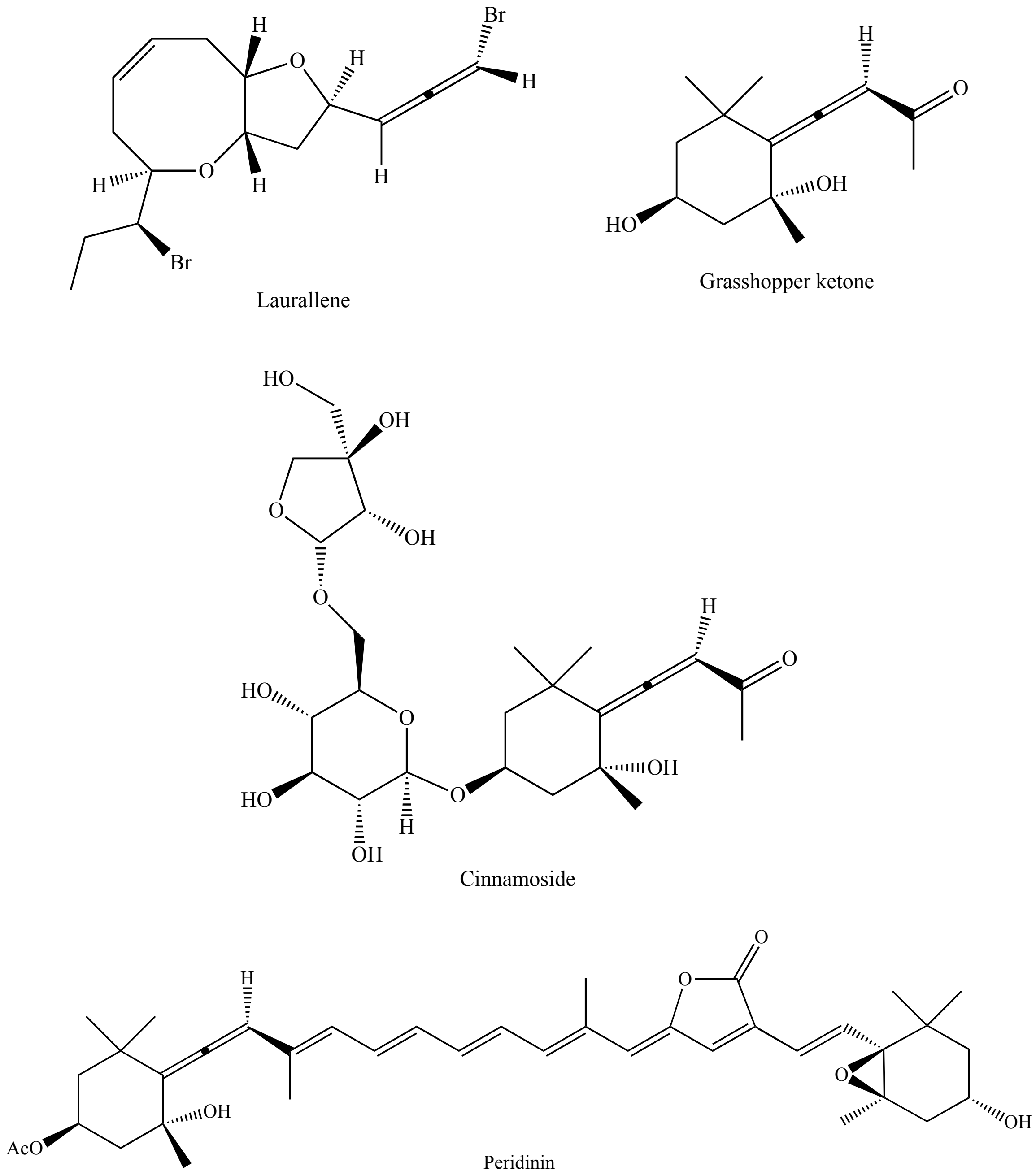
List of Schemes

Background

Allenes are a class of unique compounds with adjacent perpendicular π-orbitals. The allene moiety was originally thought to be very unstable, but it is now known that the two orthogonal π systems of an unsubstituted allene are virtually electronically identical with the π systems of simple alkenes.[1] The introduction of an alkyl group or a heterofunctional group onto the allene causes changes in the orbital energies that play a dominant role in determining the chemoselectivity and reactivity in the reactions of substituted allenes. During the past 15-20 years allenes have taken on an important role in synthetic organic chemistry.[2] Allenes can be transformed into other functional groups, such as olefins, alkynes, and α,β-unsaturated carbonyls. They also participate in a variety of cycloadditions and transition metal-catalyzed cyclization reactions.

I. Natural Products

Today about 150 natural products comprising an allenic or cumulenic structure are known[3]. Once regarded as merely a chemical curiosity, these compounds have now become a very fruitful area of interest to synthetic organic chemists and biochemists. Examples of natural products that contain an allenic moiety include laurallene, cinnamoside, grasshopper ketone, and peridinin (Figure 1). The enantioselective total synthesis of laurallene was published by Crimmins et al.[4] The allenic carotinoid, peridinin, has also been synthesized enantioselectively.[5]



Laurallene

Grasshopper ketone

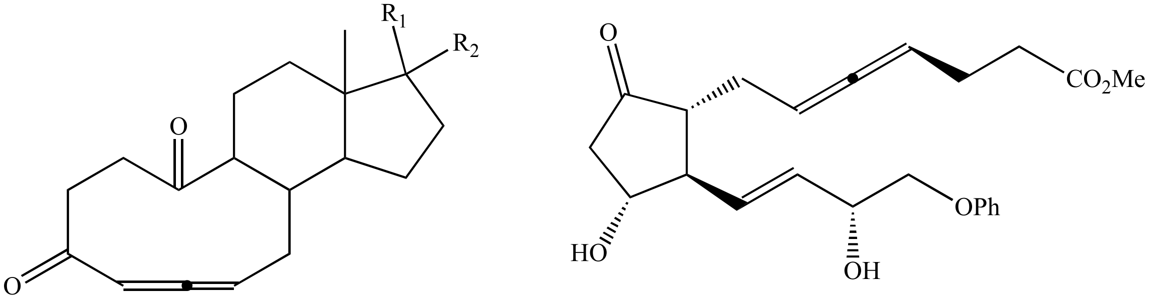
Cinnamoside

Peridinin

Figure 1. Representative natural products with allenic moieties.

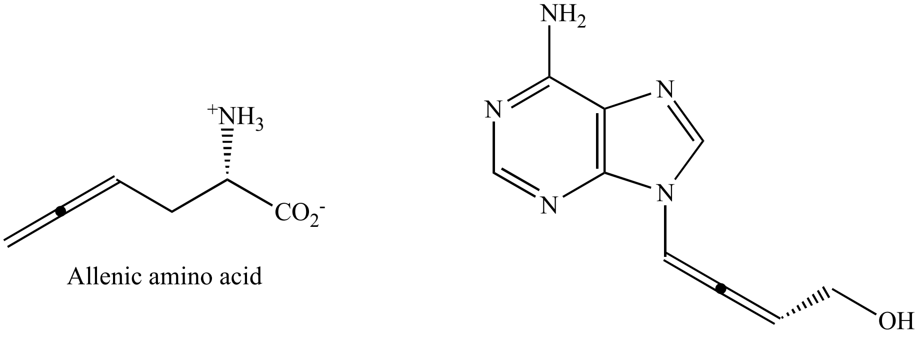
Almost all allenic natural products are chiral and are isolated as enantiomerically pure compounds. A substantial number of these compounds show interesting biological activity. Consequently, efforts have been made during the past 30 years to introduce an allenic moiety into known pharamacologically active compounds in an attempt to fine-tune the properties of these compounds.

Pharmacologically active allenes include allenic steroids, allenic prostaglandins, allenic amino acids, and allenic nucleoside analogues (Figure 2).[3] These compounds often exhibit interesting activities as mechanism-based enzyme inhibitors, cytotoxic agents, or antiviral agents. The development of efficient enantioselective synthetic methods of allenes has been important in establishing allenes as a pharmacologically important class of compounds.



Allenic steroid

Enprostil, an allenic prostaglandin



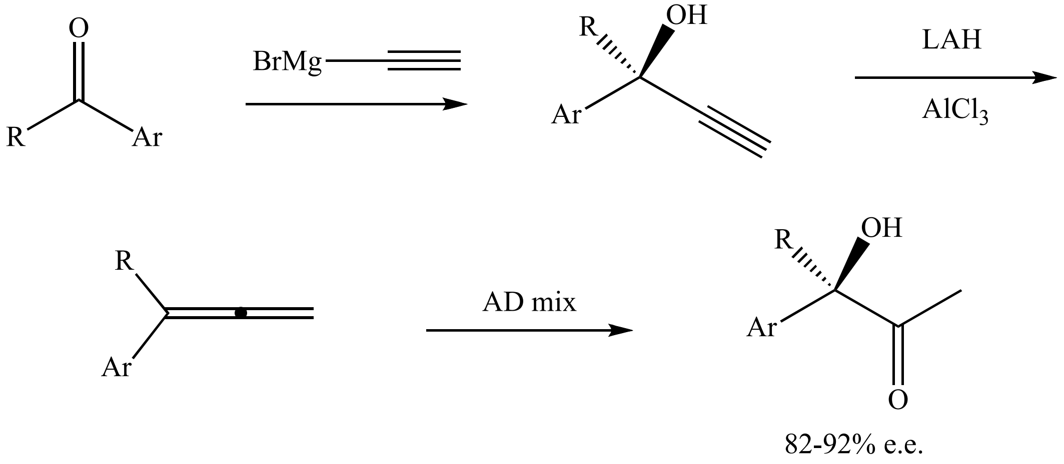
Allenic amino acid

Adenallene, a nucleoside

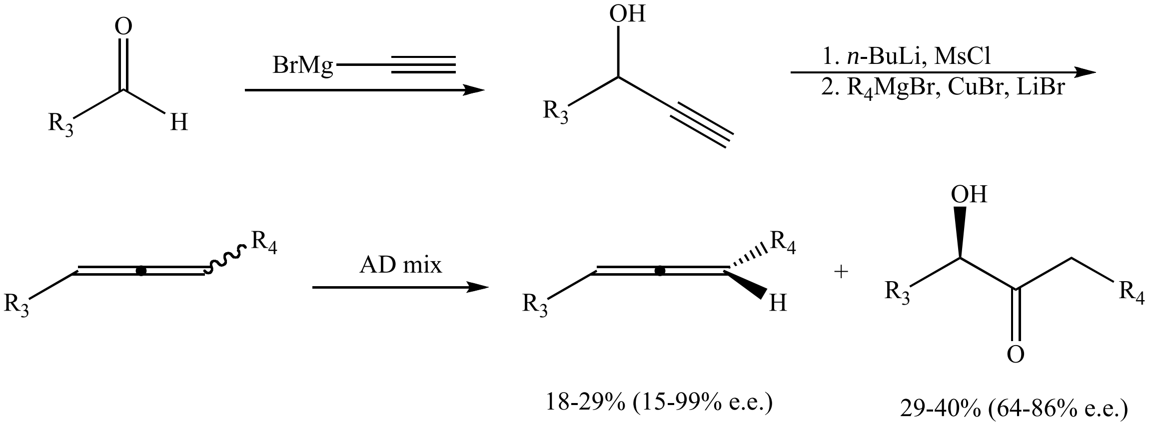
Figure 2. Pharmacologically active allenes.

II. Allene Chemistry in the Fleming Lab

Allenes have been synthesized and studied in the Fleming Lab. The asymmetric dihydroxylation (AD) of 1,1-disubstituted and 1,3-disubstituted allenes has been explored.[6] It was found that chiral α–hydroxy ketones could be effectively synthesized by the AD reaction with monosubstituted and disubstituted allenes in good yield (Scheme 1). It was also determined that AD can be used for kinetic resolution of sterically hindered 1,3-disubstituted allenes (Scheme 2). The recovered allene was found to be nearly pure single enantiomer.

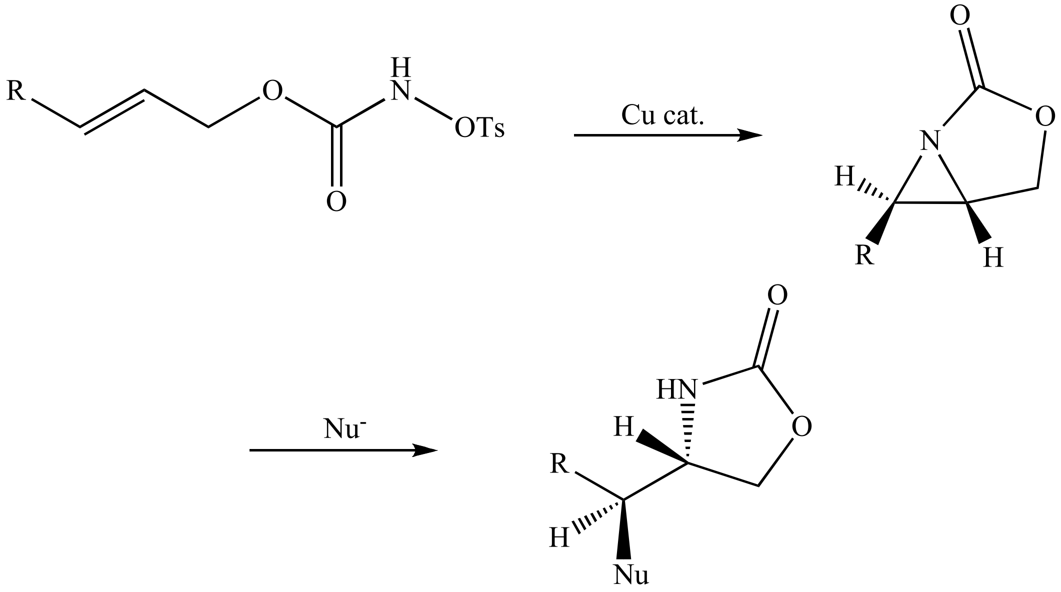


Scheme 1. Synthesis and asymmetric dihydroxylation of terminal allenes.

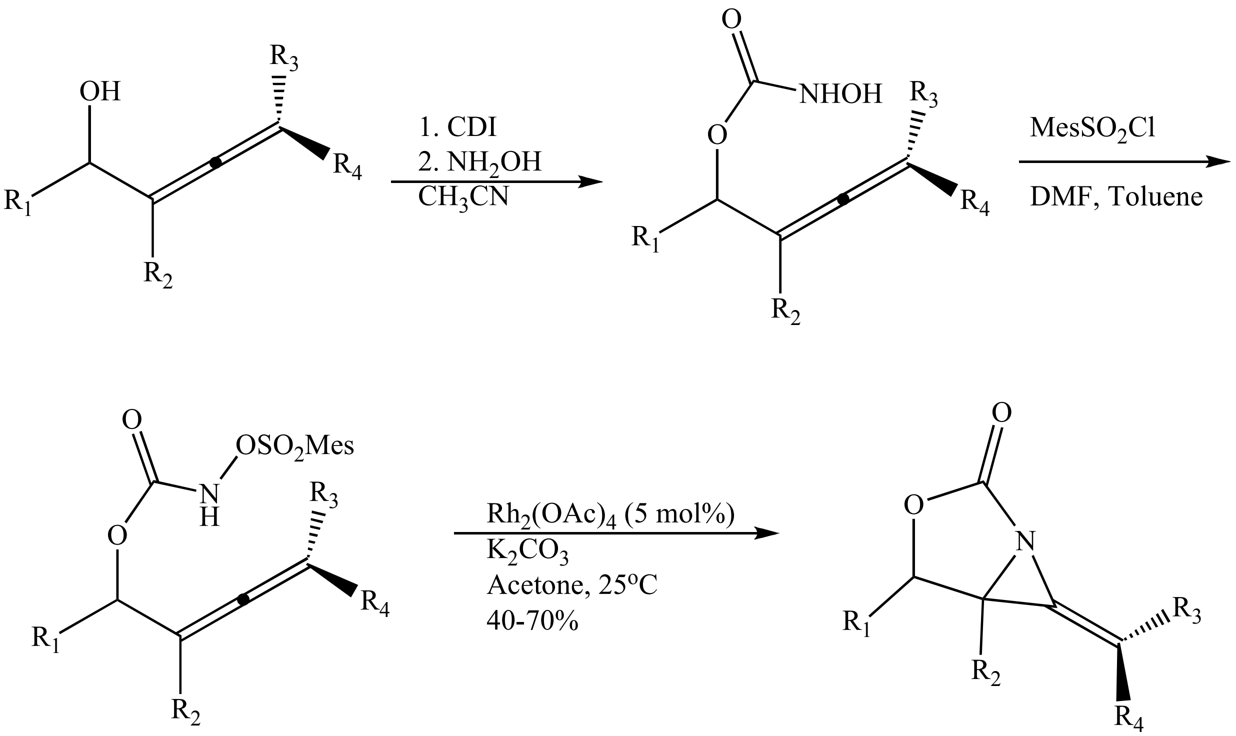


Scheme 2. Synthesis and asymmetric dihydroxylation and kinetic resolution of 1,3-disubstituted allenes.

Work has been carried out in the Fleming Lab on the copper-catalyzed aziridination of alkenes (Scheme 3).[7] This research has been extended to include rhodium-catalyzed aziridination of allenic *N*-mesyloxy carbamates (Scheme 4).[8] Nitrene addition occurs on the interior double bond of the allene leaving an exterior alkene in the final product.



Scheme 3. Copper-catalyzed aziridination of unsaturated *N*-tosyloxy carbamates.



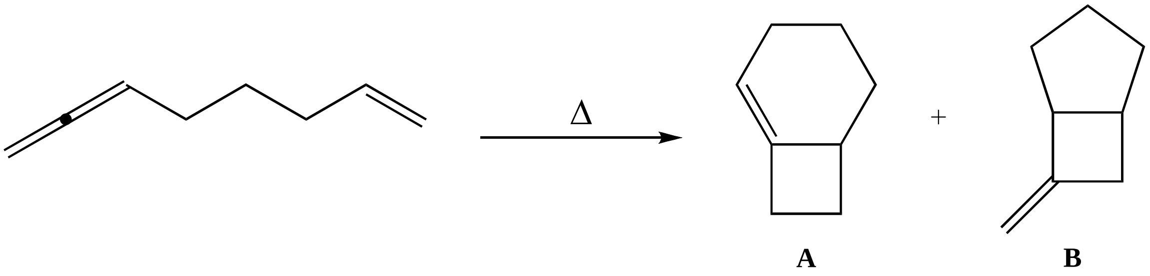
Scheme 4. Synthesis and rhodium-catalyzed aziridination of allenic *N*-mesyloxy carbamates.

III. Thermal Cycloaddition of Allenes

A. Allenenes

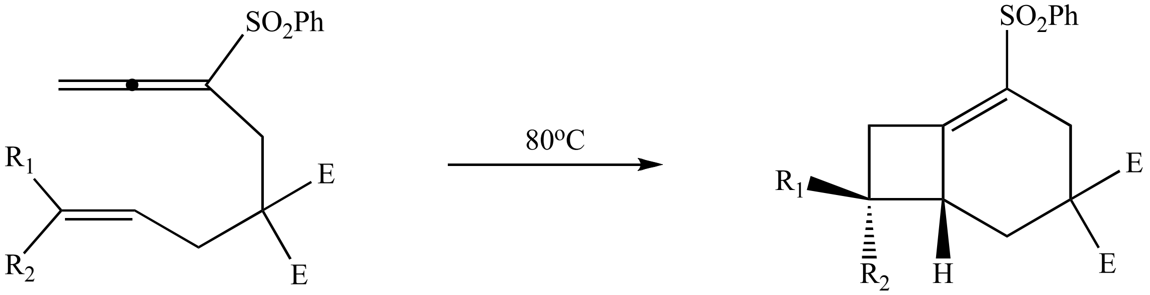
Thermal cycloaddition between carbon-carbon multiple bonds is one powerful approach to construct various cyclic molecules. Cyclobutanes may be easily formed from the [2+2] cycloaddition reaction of two carbon-carbon double bonds. Such cycloadditions are forbidden by Woodward-Hoffman rules. The only logical explanation for the process is a non-concerted mechanism.

This methodology has been extended to include allenes. In 1965 Skattebol et al. observed the unselective formation of cyclic products **A** and **B** from the thermally induced reaction of 1,2,7-octatriene (Scheme 5).[9] This occurs from cycloaddition of the alkene with either the distal or the proximal double bond of the allene in 93% yield.



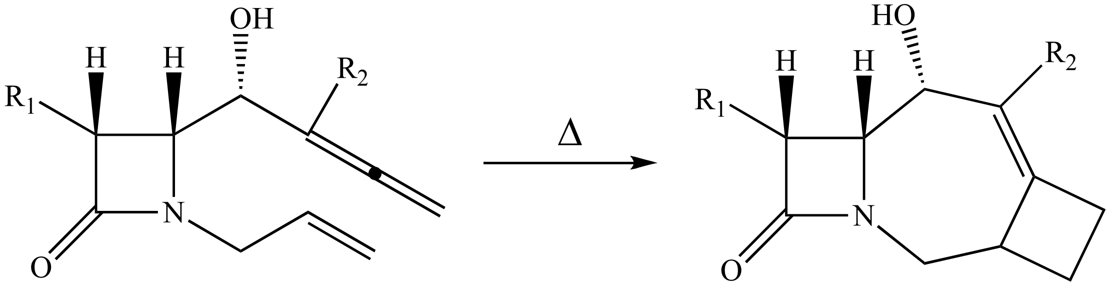
Scheme 5. Unselective cycloaddition of an allenene.

Highly regioselective preparations of distal adducts under thermal conditions have been reported recently. Padwa et al.[10,11] showed how (phenylsulfonyl)allenes can be used as substrates for highly chemo- and stereoselective intramolecular [2+2]-cycloaddition reactions onto unactivated alkenes (Scheme 6). The unsubstituted double bond of the allene was the only one that participated in the cycloaddition in every case and yields were 80-98%.



Scheme 6. Cycloaddition of (phenylsulfonyl)allenenes.

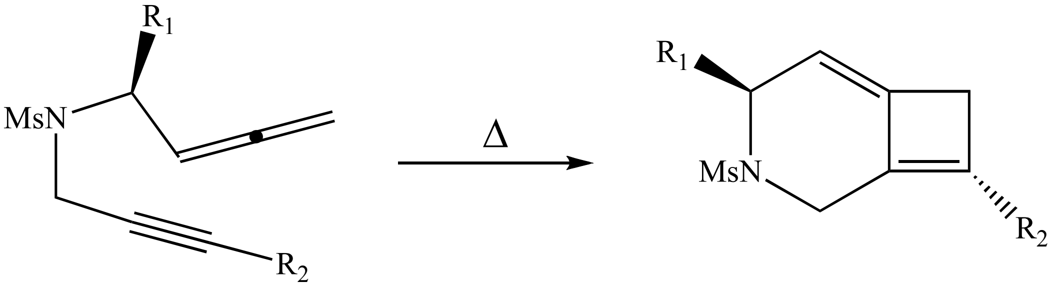
Similar results were found in the cycloaddition reaction of 2-azetidinone-tethered allenenes.[12] Thermolysis of these compounds produced tricyclic ring structures bearing a central seven-membered ring via [2+2] cycloaddition of the alkene with the distal bond of the allene. No traces of the exocyclic methylene regioisomer could be detected (Scheme 7).



Scheme 7. Cycloaddition of 2-azetidinone-tethered allenenes.

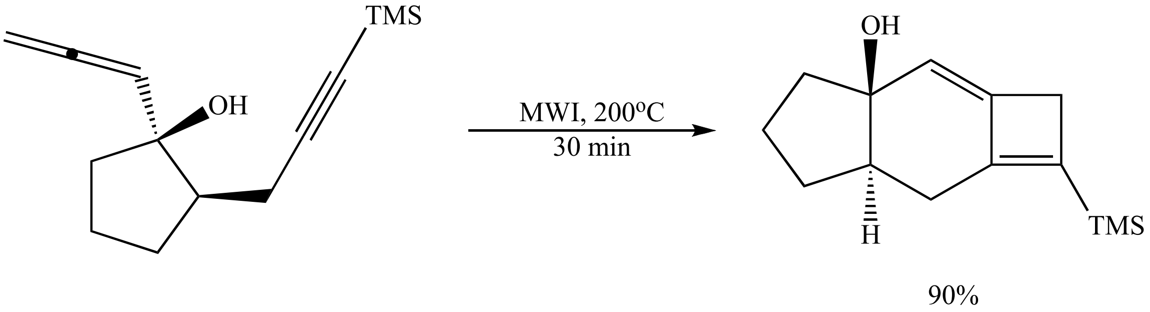
B. Allenynes

Unactivated allenynes can regioselectively undergo thermal intramolecular [2+2] cycloaddition of the distal double bond of the allene moiety in the absence of any catalyst (Scheme 8).[13]



Scheme 8. [2+2] cycloaddition of unactivated allenynes.

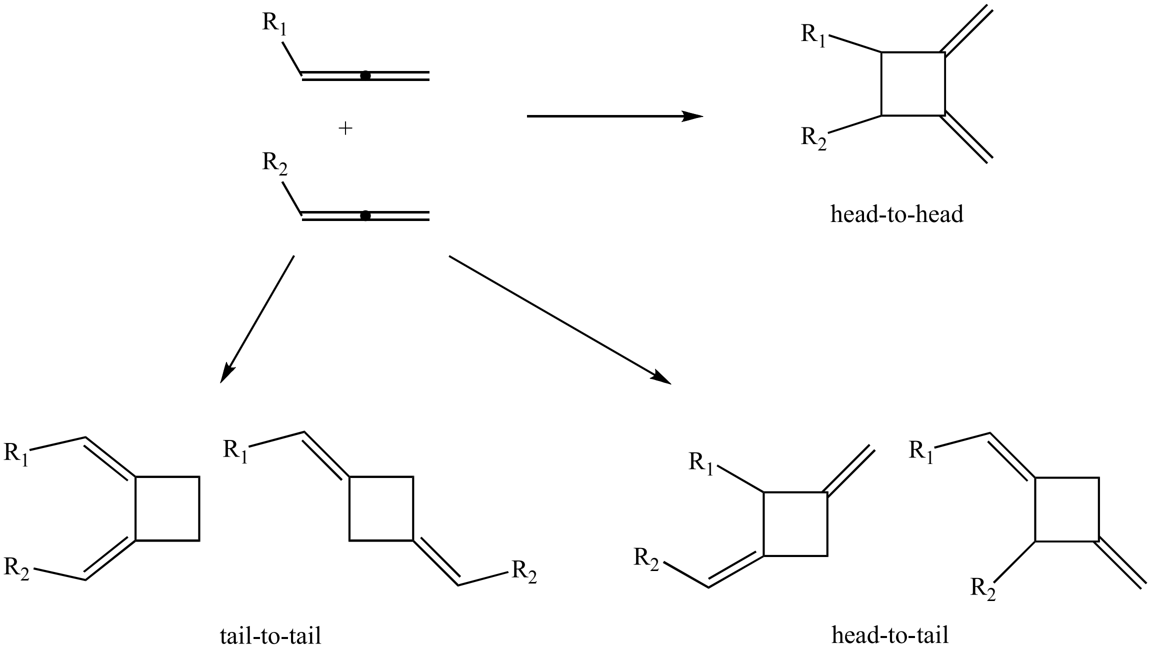
Microwave-assisted [2+2] allenyne cycloaddition reactions have been performed on a variety of 1-allenyl-2-propargyl-substituted cyclopentanol derivatives (Scheme 9, MWI = microwave irradiation).[14] These reactions are used to generate tricyclic 5-6-4 ring systems in nearly quantitative yield and have been used to synthesize the 5-6-4 ring core of sterpurene. Because these reactions occur independent of added catalyst the mechanism is consistent with a thermal intramolecular [2+2] allenyne cycloaddition process. It was found that only the terminal double bond reacts and only allenic systems with the OH and the propargylic moieties in a *cis* orientation were reactive under the conditions described. This is because the geometry allows for better overlap of the terminal p-orbitals of the allenes and acetylene moieties.



Scheme 9. Cycloaddition between an alkyne and an allene.

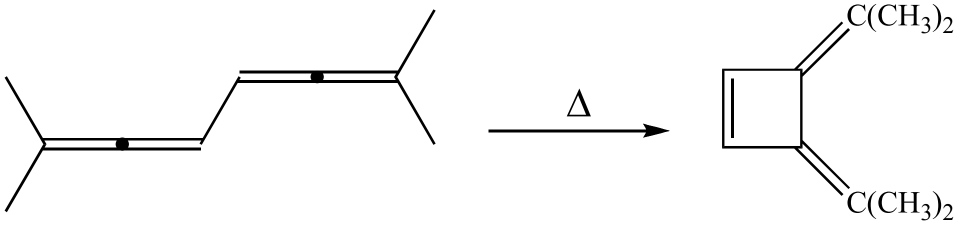
C. Tethered Allenes

In the [2+2] cycloaddition reaction between two allenes the control of regioselectivity (head-to-head, tail-to-tail, head-to-tail) could be a challenge. The a priori results are shown in Scheme 10.



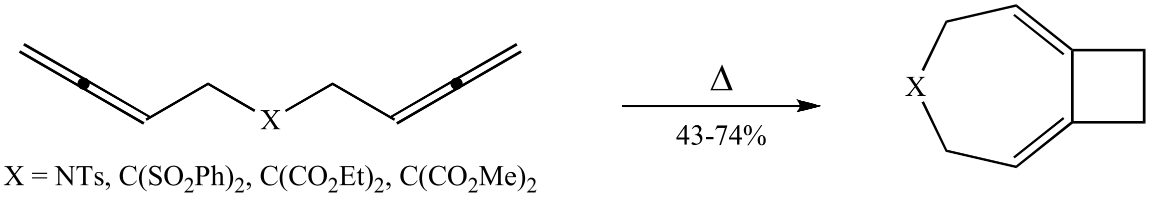
Scheme 10. Intramolecular [2+2] cycloaddition of allenes.

Tethered allenes provide enhanced selectivity. For example, the thermolysis of diallene **1** as reported by Skattebol and Solomon[9] forms head-to-head product **2** in nearly quantitative yield (Scheme 11). In contrast, the tethered allenes shown in Scheme 12[15] with heat and no catalyst exclusively form the tail-to-tail product. A bulkier X group gave higher yields because the bulkier X groups would bring the allenic moieties into closer proximity.



1 **2**

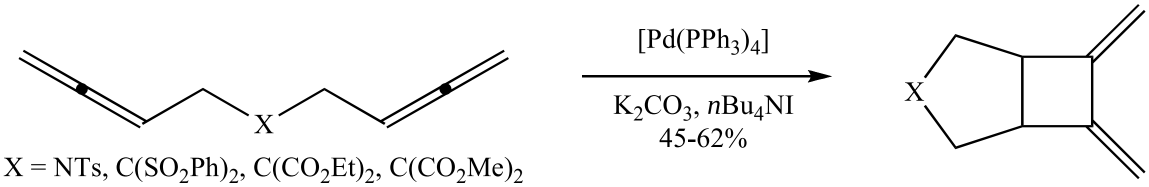
Scheme 11. Head-to-head electrocyclic ring closure.



3

Scheme 12. Tail-to-tail [2+2] cycloaddition.

Heating the tethered allene **3** in the presence of catalytic $[Pd(PPh_3)_4]/K_2CO_3/n\text{Bu}_4NI$ provides an exclusive pathway to the head-to-head product (Scheme 13).



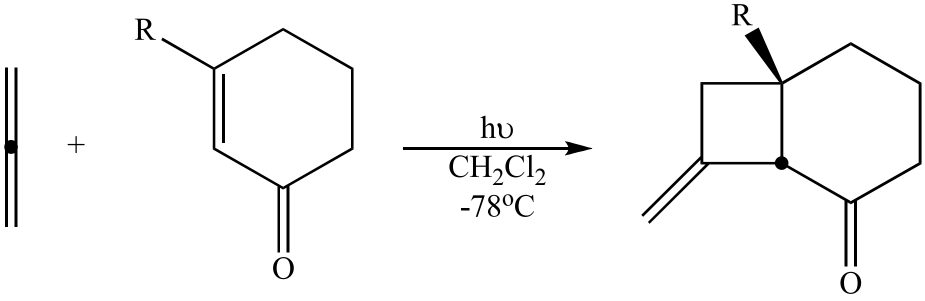
X = NTs, $C(SO_2Ph)_2$, $C(CO_2Et)_2$, $C(CO_2Me)_2$

3

Scheme 13. Head-to-head [2+2] cycloaddition.

IV. Photocycloaddition of Allenes

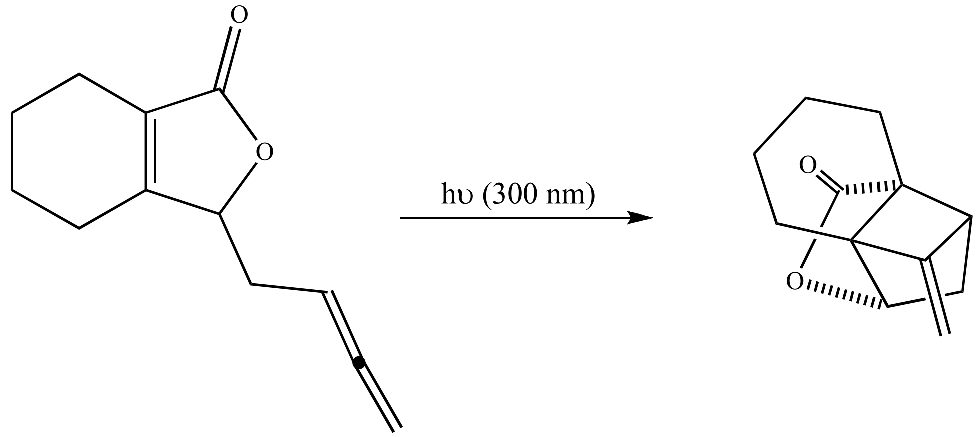
The earliest and most simple photocycloaddition using allene was reported in 1989 by Kakiuchi et al.[16,17] They reported the [2+2] cycloaddition of allene with α,β-unsaturated cyclohexenones to afford methylenecyclobutane bicyclic products **4** in 91% yield (Scheme 14).



4

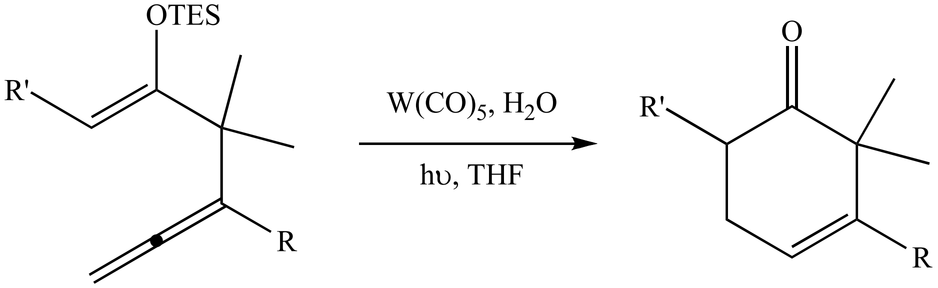
Scheme 14. Photocycloaddition of allene to cyclohexenone.

Intramolecular examples of cycloaddition of allenic moieties with α,β-unsaturated cyclic structures are abundant. Hue et al. used this reaction as a key step in the synthesis of the cyclobutanone core of solanoeclepin A (Scheme 15).[18] The product was formed exclusively from the cycloaddition of the internal allene double bond. This could occur because of the so-called rule of five, which justifies the preference for 5-membered ring formation in intramolecular [2+2]-photocycloaddition.[19] Forming a 5-membered ring involves a stable allylic radical intermediate.



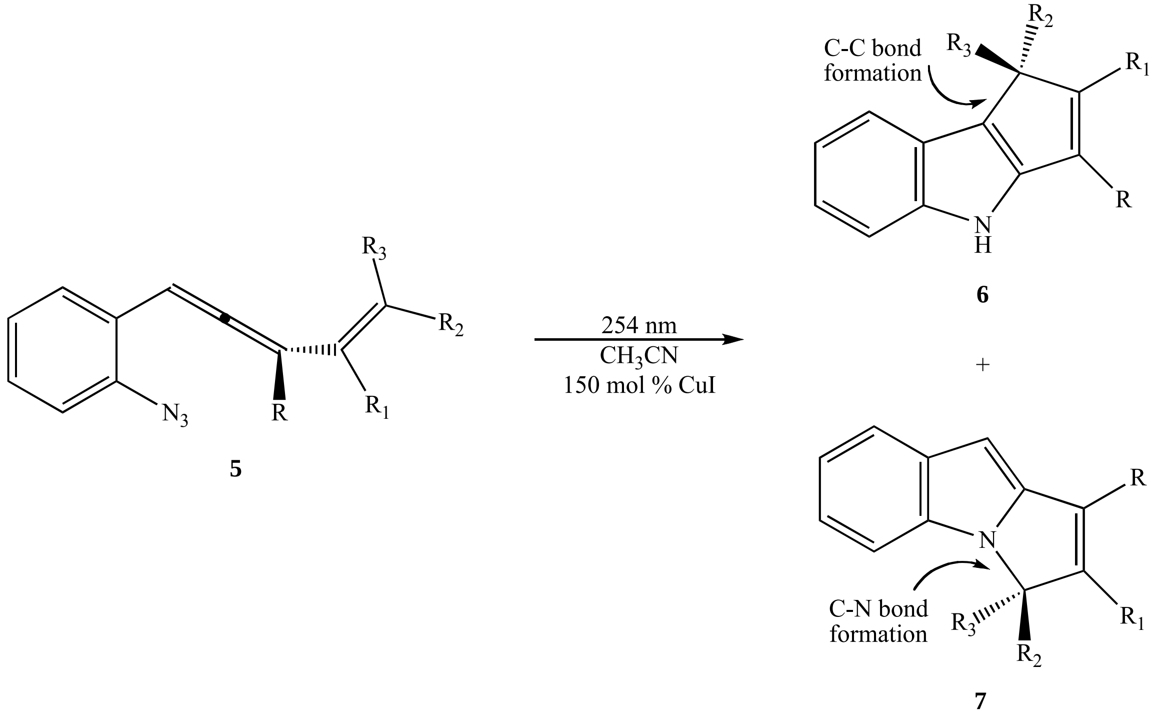
Scheme 15. Intramolecular allene butenolide [2+2] photocycloaddition.

Allenyl silyl enol ethers undergo photocyclization in the presence of catalytic $W(CO)_6$ and water.[20] The $W(CO)_6$ complex effectively coordinates with the allene, allowing for intramolecular nucleophilic attack in a 6-*endo* manner (Scheme 16). The reaction of the same substrate in the absence of water under similar conditions proceeded via a different pathway to give a formal Cope rearrangement product.

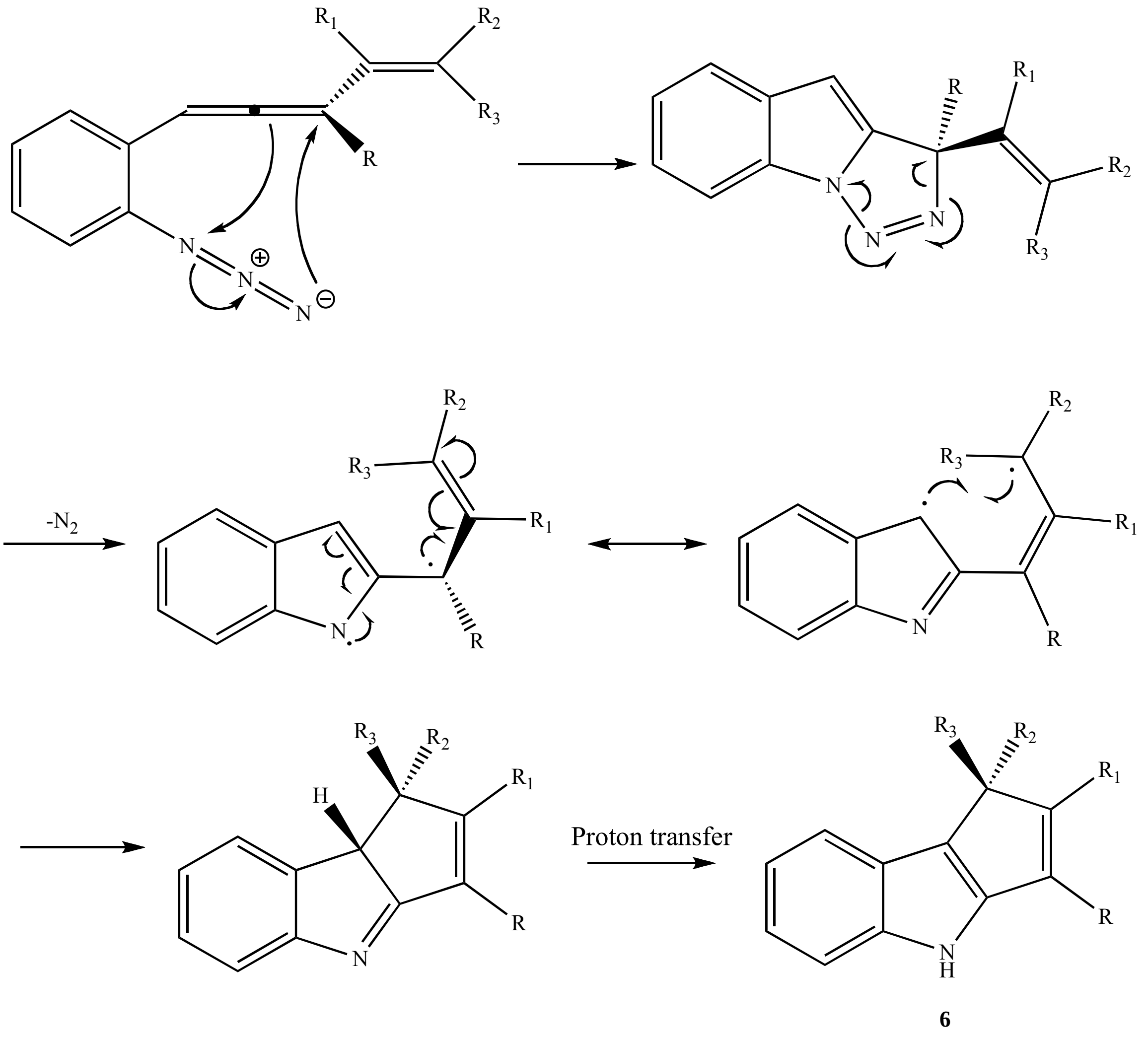


Scheme 16. Selective 6-*endo* cyclization of 5-siloxy-1,2,5-trienes with $W(CO)_5$.

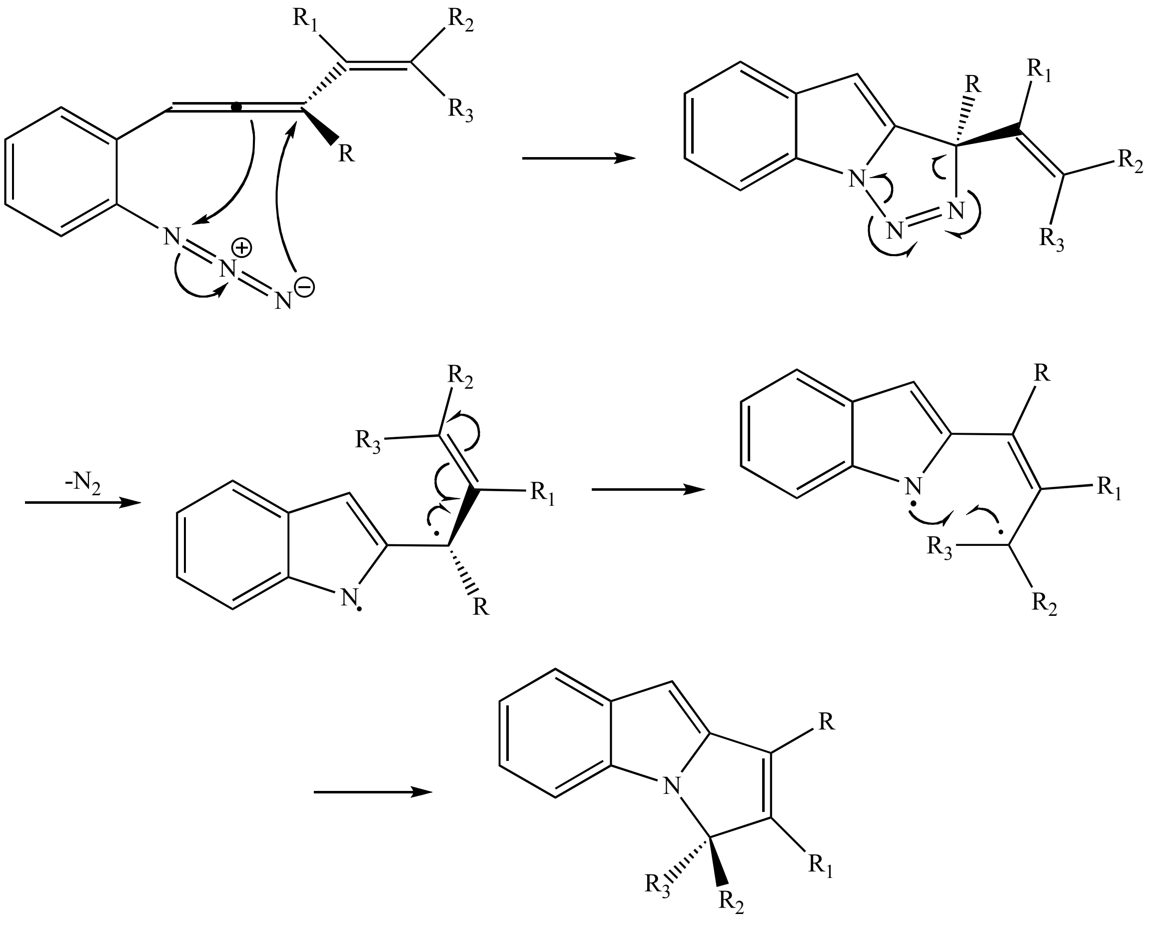
Another example of metal-catalyzed photocycloaddition occurs in the CuI mediated regioselective cycloaddition of allenyl azides. The thermolysis of 2-allenylphenyl has been reported with little regioselectivity during the terminal bond formation in the synthesis of annelated indoles.[21] New studies[22] have revealed that the combination of photochemical initiation and CuI provide enhanced regioselectivity in the formation of the C-C bond of the annelated indole product **6** (Scheme 17). When allenyl azide **5** is irradiated at 254 nm in 150% mol CuI products **6** and **7** were obtained in a 10:1 ratio. When a dark study was performed with CuI the same favorable regioselectivity was observed as in the photochemical studies, but higher concentrations of substrate were necessary to achieve satisfactory results. The mechanisms of formation of **6** and **7** are shown in Scheme 18 and Scheme 19, respectively.



Scheme 17. Irradiation of allenyl azides in the presence of excess CuI.



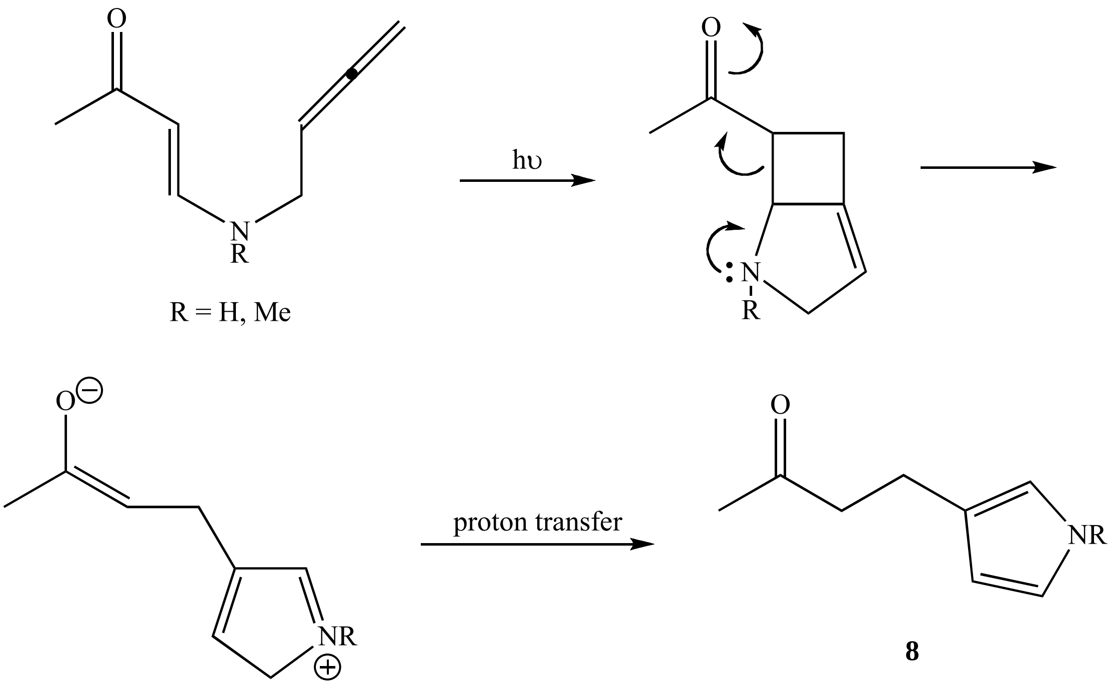
Scheme 18. Formation of product **6**.



7

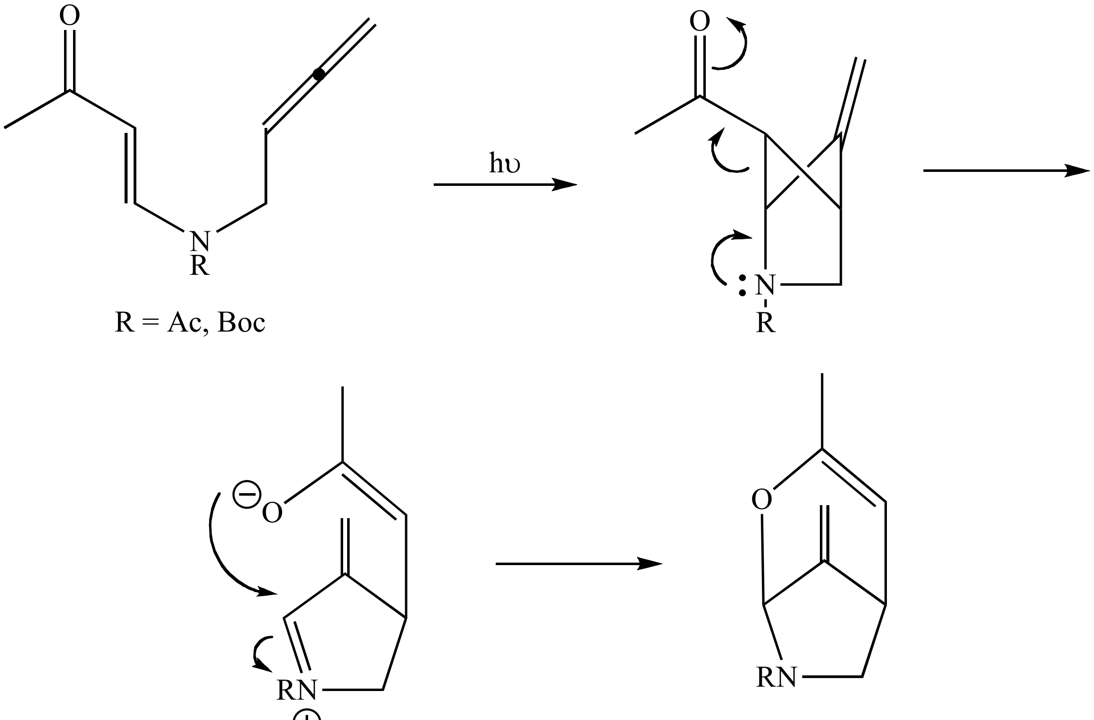
Scheme 19. Formation of product **7**.

Pyrroles can be synthesized from the intramolecular photocycloaddition of vinylogous amides with allenes.[23] When R = H or methyl, parallel cycloaddition to the terminal olefin of the allene occurs, yielding pyrrole **8** (Scheme 20). However, when R = Boc or Ac the crossed photoproduct is observed as an intermediate, yielding product **9** (Scheme 21).



8

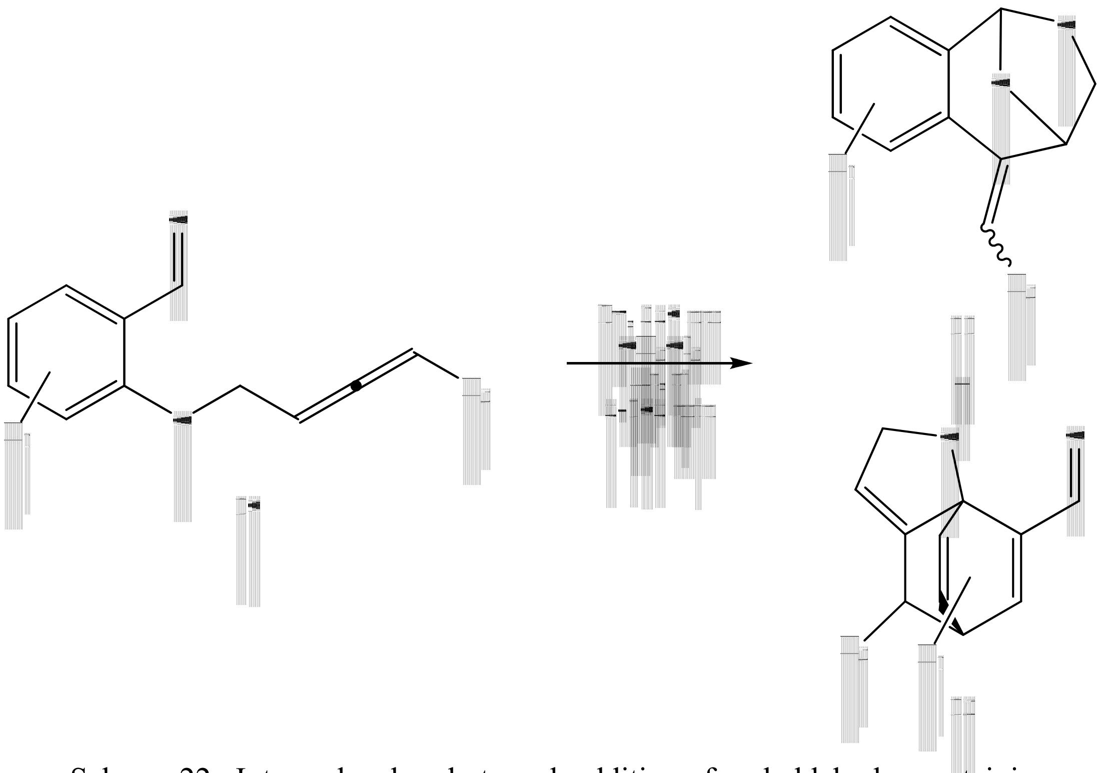
Scheme 20. Synthesis of pyrroles via intramolecular photocycloaddition of vinylogous amides.



9

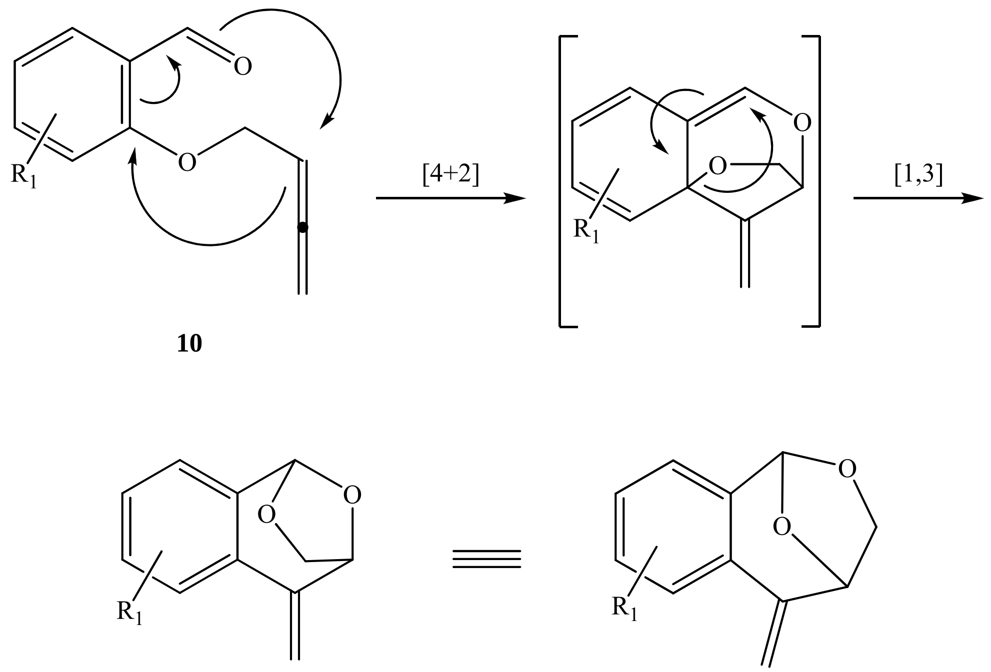
Scheme 21. Photocycloaddition of vinylogous imides.

A recent example of the photocycloaddition of allenes occurs in the intramolecular photocycloaddition of *o*-allenyl-benzaldehyde substrates **10** (Scheme 22).[24]



Scheme 22. Intramolecular photocycloaddition of aryl aldehydes containing allene side chains.

The expected 2-methyleneoxetane (the expected result of a Paterno-Buchi-type reaction) was not formed. Instead, a mixture of 1,3,4-tetrahydro-1,4-epoxy-5-alkylidene-2-benzoxephine **11** (28%) and 2-oxa-tricyclo[5.2.2.0]undeca-4,8,10-triene-9-carbaldahyde **12** (48%) were produced. Electron-donating groups on the arene slightly favor the formation of **12** while electron-withdrawing groups slightly favor the formation of **11**. The mechanisms of formation of products **11** and **12** are shown in Schemes 23 and 24, respectively.



10

11

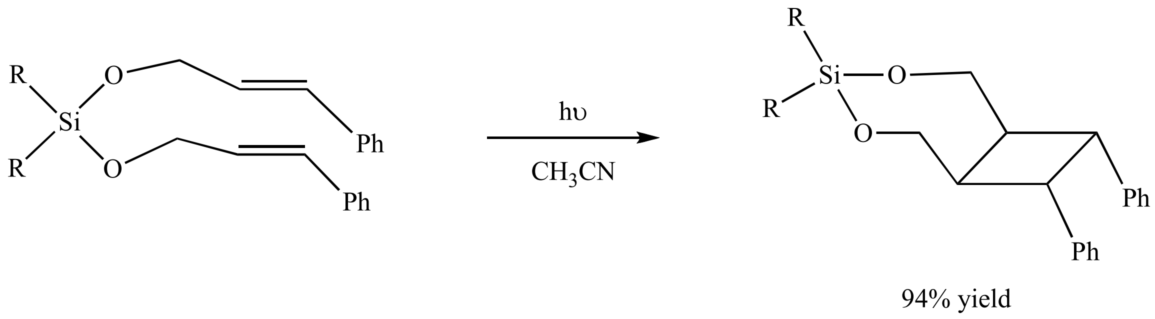
Scheme 23. Formation of product **11**.

Scheme 24. Formation of product **12**.

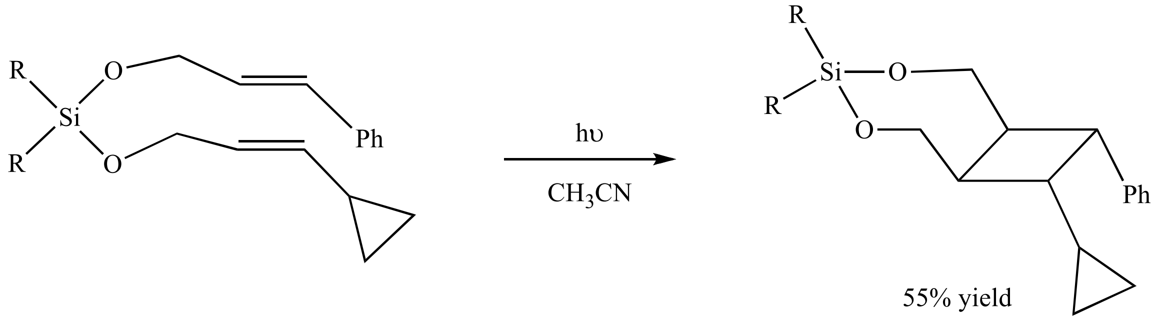
V. Tethered Photocycloaddition of Alkenes

The tethered intramolecular [2+2] photocycloaddition has received much attention as an effective way to preorganize reactant alkenes. This methodology provides a means for controlling the regio- and stereochemistry of the reaction. The use of a temporary tether in the photocycloaddition reaction has the potential for providing the product of an intermolecular cycloaddition with high and predictable selectivity after removal of the temporary tether. The temporary silicon tether has been used in several reactions including radical cyclizations,[25] [4+2] cycloadditions,[26] and disaccharide synthesis.[27]

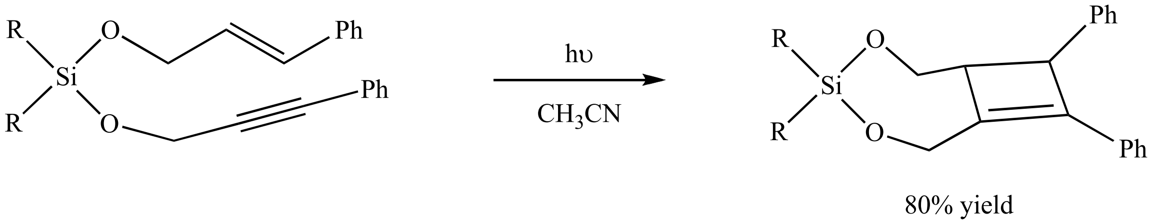
Many examples of diastereoselective formation of cyclobutane derivatives using this tethering technique have been reported by Fleming et al. These examples include photocycloaddition of diisopropylbis(cinnamyloxy)silanes (Scheme 25)[28] and photocycloaddition of various mixed cinnamyloxysilane derivatives (Scheme 26).[29] Synthesis of substituted cyclobutenes was also demonstrated by irradiation of silicon tethered alkenynes (Scheme 27).[30]



Scheme 25. Photocycloaddition of dialkylbis(cinnamyloxy)silanes.

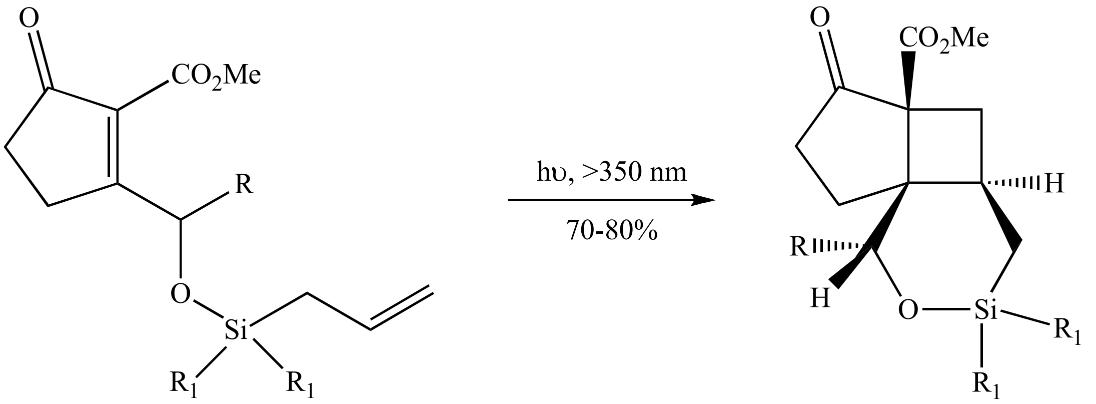


Scheme 26. Photocycloaddition of a mixed cinnamyloxysilane derivative.



Scheme 27. Synthesis of substituted cyclobutenes.

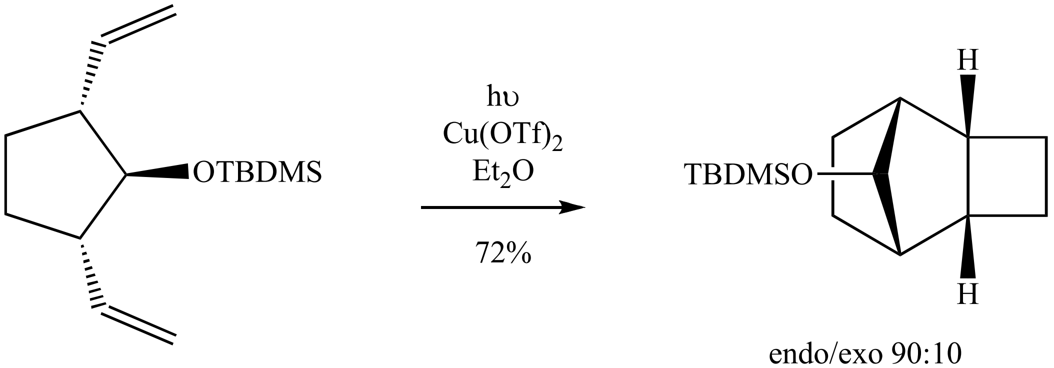
Crimmons and Guise also made use of the silicon tethering technique in enone photochemistry (Scheme 28).[31]



Scheme 28. Tethered photocycloaddition of an alkene and an enone.

VI. Tethered Photocycloaddition of Alkenes Using a Copper Catalyst

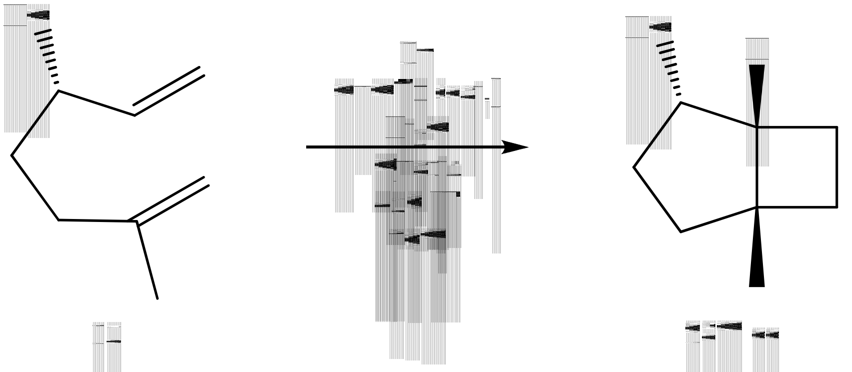
Copper is often used as a catalyst in photochemical [2+2] reactions when neither alkene substrate is a chromophore. Recently Cu(II) was used as a catalyst in the [2+2] photocycloaddition in the synthesis of enantiomerically pure bicyclo[4.2.0]octanes (Scheme 29).[32] It was determined that since Cu-catalyzed photocycloaddition reactions require the coordination of both double bonds to the metal atom only reactions with 1,6-dienes produce the desired bicyclo product.



endo/exo 90:10

Scheme 29. Synthesis of bicyclo[4.2.0]octanes.

Cu(I) can also be used as a catalyst in [2+2] photochemical reactions. In 1992 a stereoselective synthesis of the natural product, grandisol, was described with the key step being the Cu(I)-catalyzed [2+2] photocycloaddition of **13** (Scheme 30).[33]



Scheme 30. Photocycloaddition using Cu(I) as a catalyst.

VII. Summary

We have explored a number of examples of thermal and photochemical allenic cycloadditions. We have also explored cycloadditions of tethered alkenes with and without a copper catalyst. A study of the silyl-tethered photocycloaddition of allenes with and without a copper catalyst seemed promising. The research presented in the next section describes such an investigation.

Results and Discussion

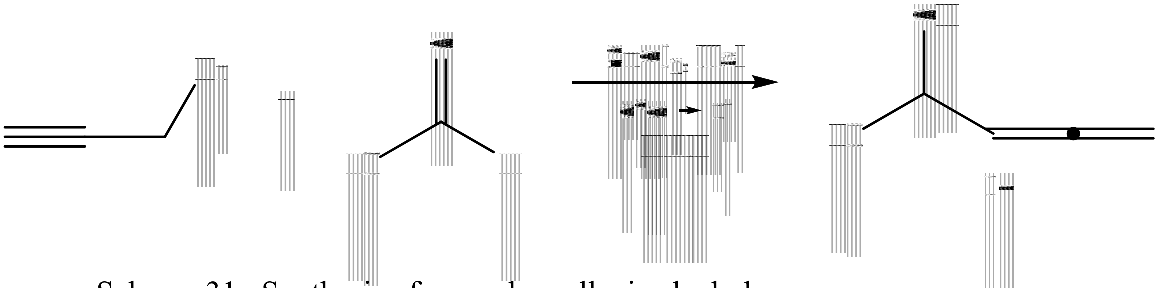
I. Introduction

The thermal cycloaddition of allenes with alkenes, alkynes, and other allenes has been well studied.[8-14] The photocycloaddition of allenes with enones, azides, aromatic rings, and other functional groups has also been studied extensively.[15-23] However, there is a lack of information concerning the photoreactivity of allenes with alkenes, alkynes, and other allenic systems. We have seen examples of the [2+2] photocycloaddition of tethered alkenes to other alkenes and alkynes.[27-29] Research reported here is focused on expanding the utility of the [2+2] photocycloaddition reaction to include tethered allenic systems.

II. Synthesis of Starting Materials

A. Allenols

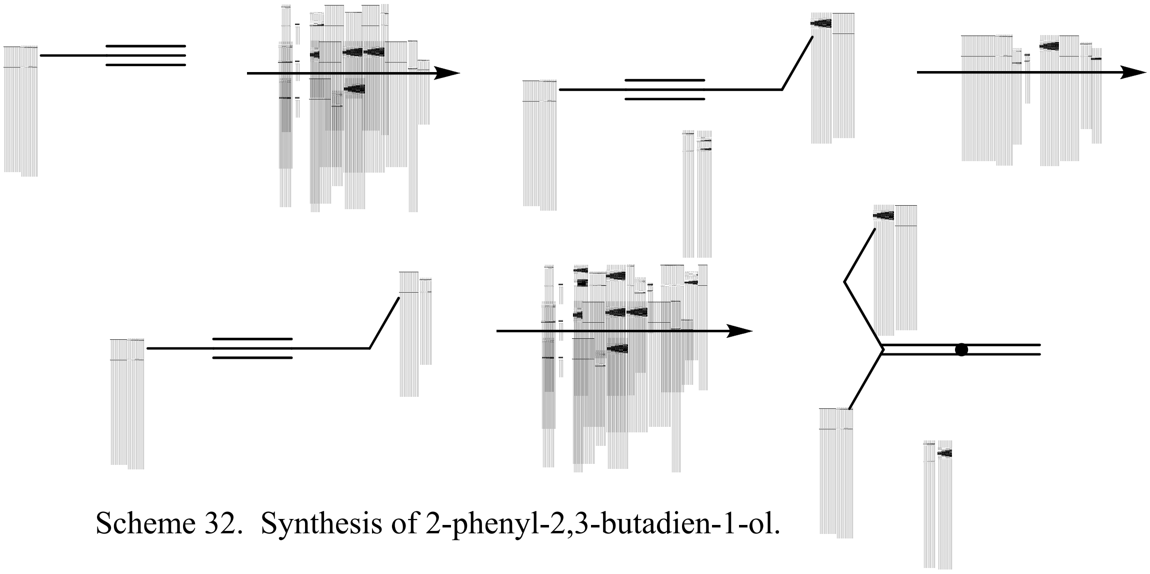
We began our studies by synthesizing various allenols for the purpose of tethering them onto silicon. The first alcohol we synthesized was the secondary allenic alcohol, 1-phenyl-2,3-butadien-1-ol **(14,** Scheme 31). This was done according to the procedure outlined by Mukaiyama and Harada.[34] Stannous chloride and sodium iodide were used to form the allenic alcohol after aqueous work-up from propargyl bromide and benzaldehyde. Propargyl bromide and benzaldehyde were commercially available.



Scheme 31. Synthesis of secondary allenic alcohol.

Because alcohol **14** has a stereocenter it formed a mixture of the *R* and *S* enantiomers. As we will see in the next section, this fact added an unexpected complication to the study. We recognized it would be easier to work with a primary alcohol so that there would be no stereocenter. We also wanted an alcohol that could be a more effective chromophore. Alcohol **14** has a phenyl ring and no further conjugation. Most of the successful [2+2] photocycloadditions have the more conjugated styryl moiety. To that end, we synthesized primary alcohol **16** according to the procedure outlined in Scheme 32.

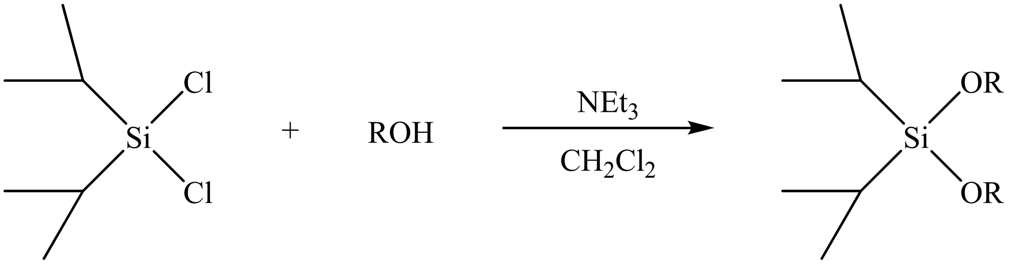
In the first step[35] the commercially available phenylacetylene was deprotonated by *n*-BuLi and then mixed with excess paraformaldehyde, resulting in a nucleophilic addition reaction to form the propargyl alcohol **15**. The second step involved a variation of the Mitsunobu reaction in which the bromide is substituted for the hydroxy group.[36] In the final step of the reaction sequence 3-bromo-1-phenylpropyne was reacted with formaldehyde in the same S_N2'-like pathway as used in the synthesis of the 1-phenyl-2,3-butadien-1-ol (see Scheme 31). The published procedure[37] was modified slightly. This alcohol, 2-phenyl-2,3-butadien-1-ol (**16**), only formed when the reaction was run at room temperature instead of at 0 ºC as published in the paper.



Scheme 32. Synthesis of 2-phenyl-2,3-butadien-1-ol.

B. Silicon Tethering

After synthesizing the allenic alcohols (**14** and **16**) they were tethered onto silicon using the general procedure outlined below (Scheme 33) used by Fleming et al.[27] The commercially available diisopropyldichlorosilane undergoes an S_N2-like substitution in the presence of triethylamine and two equivalents of alcohol.



Scheme 33. Tethering of alcohols onto diisopropyldichlorosilane.

Below are examples of silicon-tethered allenic alcohols that we synthesized according to this basic procedure using alcohols **14** and **16**, respectively (Figure 3).

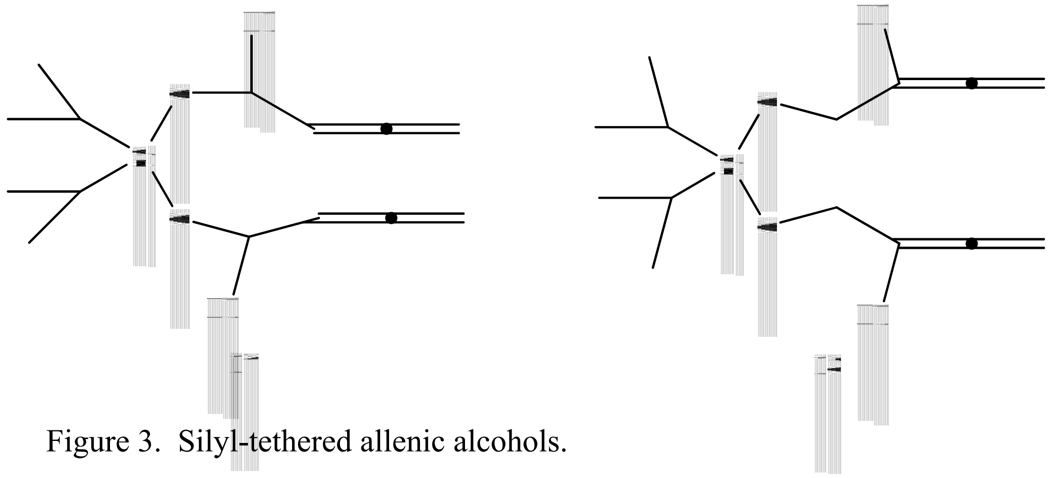
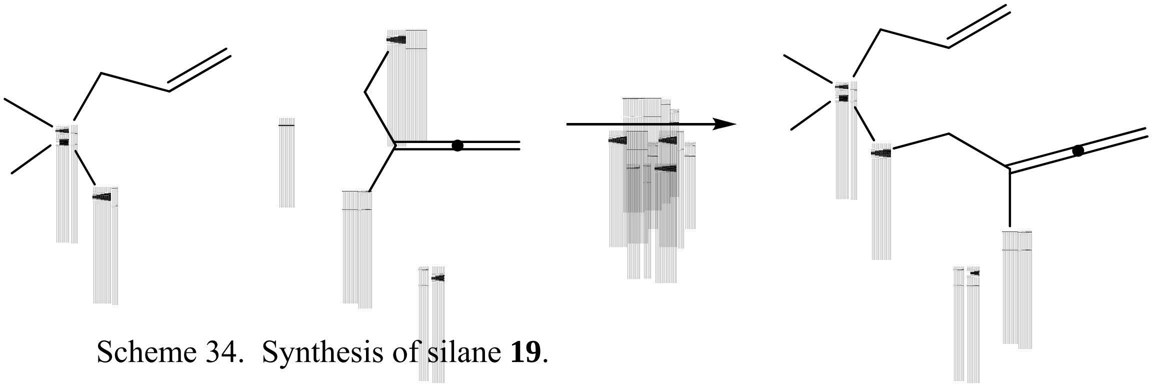


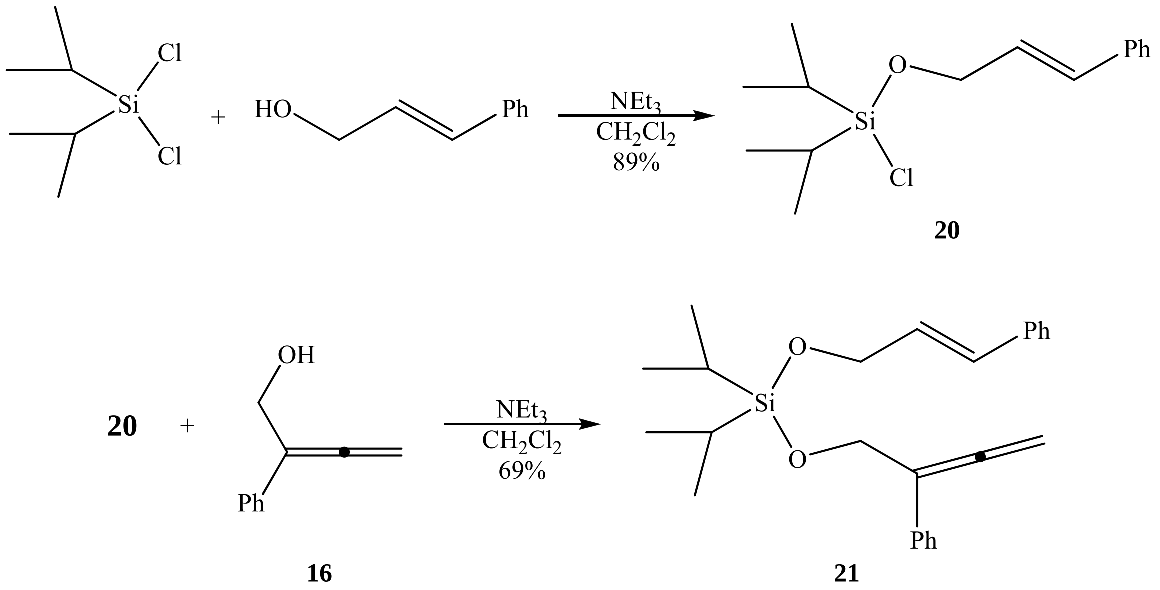
Figure 3. Silyl-tethered allenic alcohols.

Silane **19** was synthesized according to a similar procedure. Allyl(chloro)-dimethylsilane was obtained commercially. One equivalent of alcohol **16** was added with one equivalent allyl(chloro)dimethylsilane and one equivalent of triethylamine to produce silane **19** (Scheme 34).



Scheme 34. Synthesis of silane **19**.

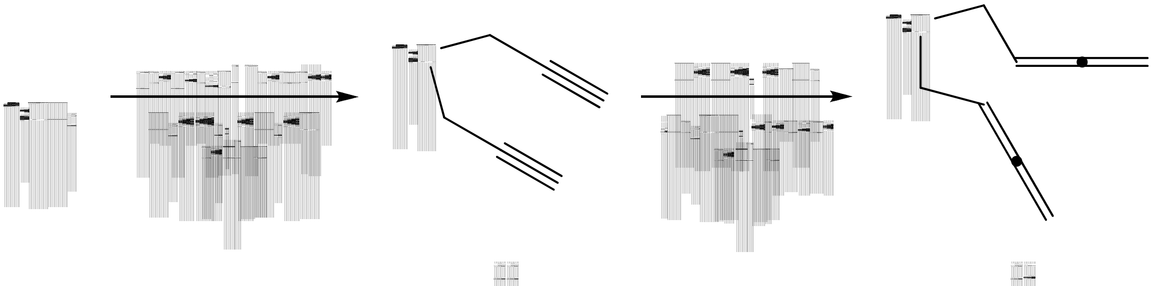
Silane **21** was synthesized according to the procedure of Ward and Fleming.[28] An excess of diisopropyldichlorosilane was mixed with cinnamyl alcohol. The resulting diisopropylchloro(cinnamyloxy)silane (**20**) was isolated by distillation. One equivalent of alcohol **16** was then added to form silane **21** (Scheme 35).



Scheme 35. Synthesis of silane **21**.

C. Amine Tethering

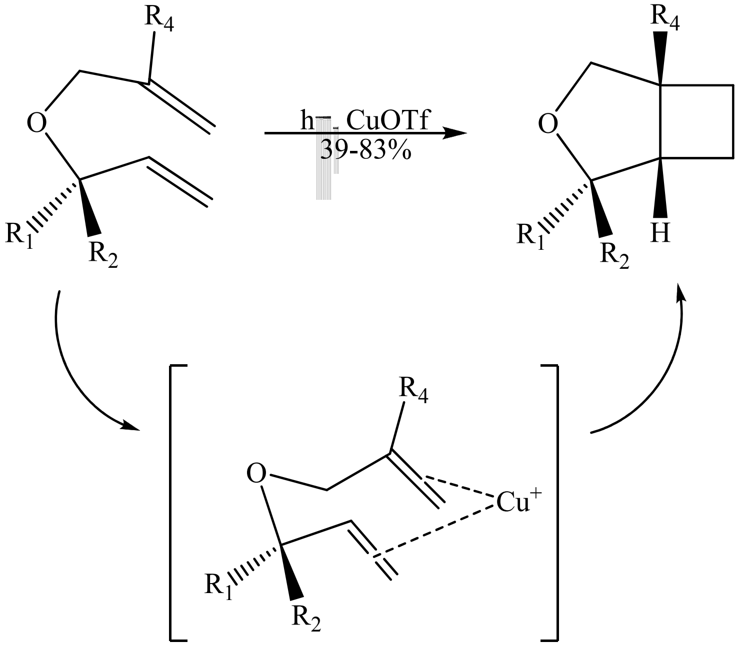
Amine **23** is reported in the literature. Since it is similar to our studies of silyl tethered allenes we synthesized it and studied its photochemistry to see if it would do a [2+2] photocycloaddition. We started with *p*-toluenesulfonamide and reacted it with base and propargyl bromide according to the procedure of Kang et al.[38] to make bis(alkyne) **22**. In the second step the bis(allene)amine was conveniently synthesized via homologation of the corresponding alkynes according to Crabbé et al.[39] (Scheme 36).



Scheme 36. Synthesis of bis(allene)amine.

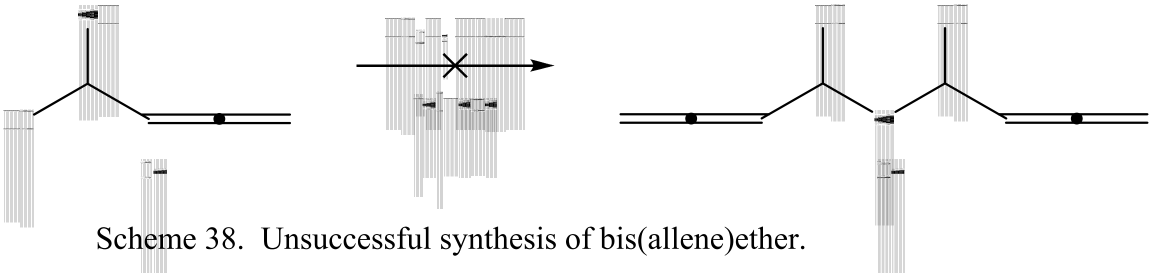
D. Ether Tethering

As will be seen later, silane **17** was irradiated in the presence of Cu. However, it was found that Cu is most often used in conjunction with a 3-atom tether as seen in Scheme 37.[40]



Scheme 37. Copper catalyzed photocycloaddition.

Because copper is most often used in conjunction with a 3-atom tether, it was necessary to make bis(allene)ether **24** instead of using the silicon as a tether. We attempted several routes to this type of bis(allene)ether. For example, we started with the secondary allenol **14** and attempted to make the ether employing a Mitsunobu reaction in which alcohol **14** was added to a solution of triphenylphosphine and DIAD (Scheme 38). However, this attempt (and all others) to synthesize the bis(allene)ether proved unsuccessful. The ether was formed in very low yields in each case. It is possible that the ether is not stable in the conditions used for the attempted purification.



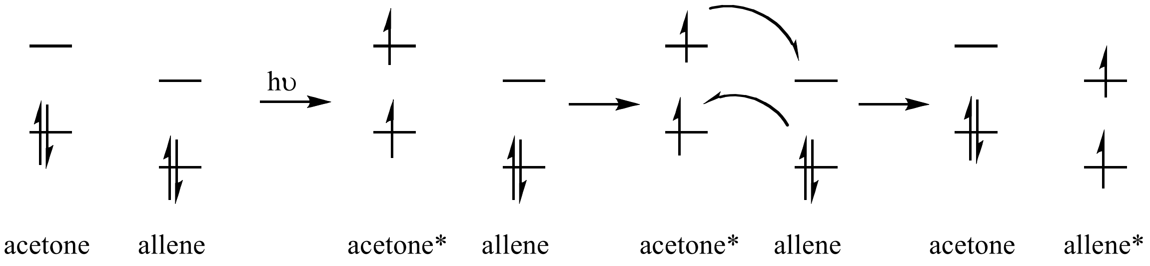
Scheme 38. Unsuccessful synthesis of bis(allene)ether.

III. Irradiation Studies

After synthesizing the silyl-tethered allenes, irradiation studies were performed to see if the allenes could be induced to undergo a [2+2] photocycloaddition. Several studies were performed.

A. Silane 17

Silane **17** was irradiated in acetonitrile using a 450 W Hanovia lamp in quartz. No reaction occurred. We thought it may have been because the direct excitation path of allenes and alkenes involves singlet chemistry, an excited state that is too short-lived for a reaction to occur. In an attempt to excite the molecule to the longer-lived triplet energy state the silane was irradiated in acetone (a common photochemical sensitizer) using the 450 W Hanovia lamp in Pyrex. When exposed to UV light, acetone is excited to a triplet excited state. Energy from the excited acetone is then transferred to the allene, forcing it to a triplet state as acetone returns to its ground state (Scheme 39).



Scheme 39. Triplet sensitization by acetone.

Unfortunately, no reaction was detected using these conditions either. It was determined that since this silane does not contain a chromophore, a catalyst was needed to bring the two allenic moieties into proximity with one another.

As mentioned in the Background Chapter, copper is often used as a catalyst in photochemistry. To this end, both Cu(I) and Cu(II) were used in an attempt at the photocycloaddition of silane **17**. Table 1 summarizes the findings of silane **17** irradiated in ether at 0 ºC by the 450 W Hanovia lamp in Quartz.

Trial	Time	Catalyst (mol eq.)	Results
1	30 min.	$Cu(OTf)_2$ (0.05)	No reaction
2	60 min.	$Cu(OTf)_2$ (0.06)	Polymerization
3	90 min.	$Cu(OTf)_2$ (0.05)	Polymerization
4	30 min.	Cu(OTf) (0.05)	No reaction
5	90 min.	Cu(OTf) (0.05)	Polymerization

Table 1. Irradiation results for silane **17**.

Since alcohol **14** has a stereocenter, diastereomers were formed during the synthesis of silane **17** (see Figure 4). This made irradiation and characterization very difficult. Therefore, silane **18** was synthesized and studied to avoid the problem of diastereomers.

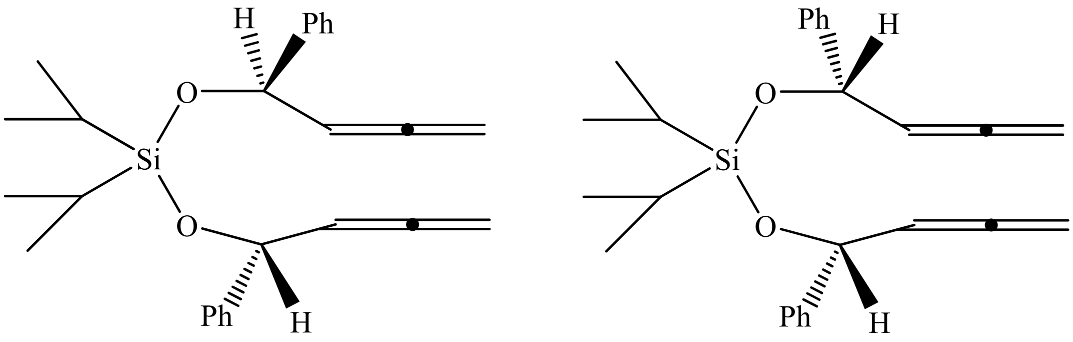


Figure 4. Diastereomers of silane **17** formed using alcohol **14**.

B. Silane 18

The results of the irradiation of silane **18** are summarized in Tables 2 and 3 below. All irradiation trials were carried out in acetonitrile using either the Rayonet or the Hanovia lamps. The Rayonet lamps are monochromatic. The lamps that were used for these trials emit light at a wavelength of 254 nm. The Hanovia lamp is a broad band light source. The light includes 254 nm but also includes wavelengths of 282 nm, 302 nm, 366 nm, and many others with 366 nm being the most intense wavelength. The intensity of light is fairly similar between the Rayonet and the Hanovia lamps.

The Rayonet apparatus is comprised of 16 lamps where the sample is suspended in the middle of the lamps. The light goes through the quartz glass to the sample. In contrast, the Hanovia lamp is placed in a water-cooled jacket with the sample surrounding it. The light goes through the quartz glass then through the water then through quartz again and then to the sample. This may have a small impact on the light.

Hanovia Trials

Trial	Time	Catalyst (mol eq.)	Additional Reagent	Results
1	45 min.	-	-	Degradation
2	30 min.	-	-	Degradation
3	10 min.*	-	methyl acrylate	No reaction
4	12 min.*	-	methyl acrylate	No reaction
5	15 min.	-	TCNE (1.8 eq)	<5% new material
6	30 min.	-	TCNE (4.0 eq)	No reaction
7	60 min.	-	TCNE (3.8 eq)	Degradation
8	40 min.	-	TCNE (3.8 eq)	No reaction
9	15 min.	$Cu(OTf)_2$ (0.2)	TCNE (3.3 eq)	No reaction
10	25 min.	$Cu(OTf)_2$ (0.2)	TCNE (3.3 eq)	No reaction
11	17 min.	$Cu(OTf)_2$ (0.2)	TCNE (3.3 eq)	No reaction

* quartz test tubes, time adjusted for distance from lamp

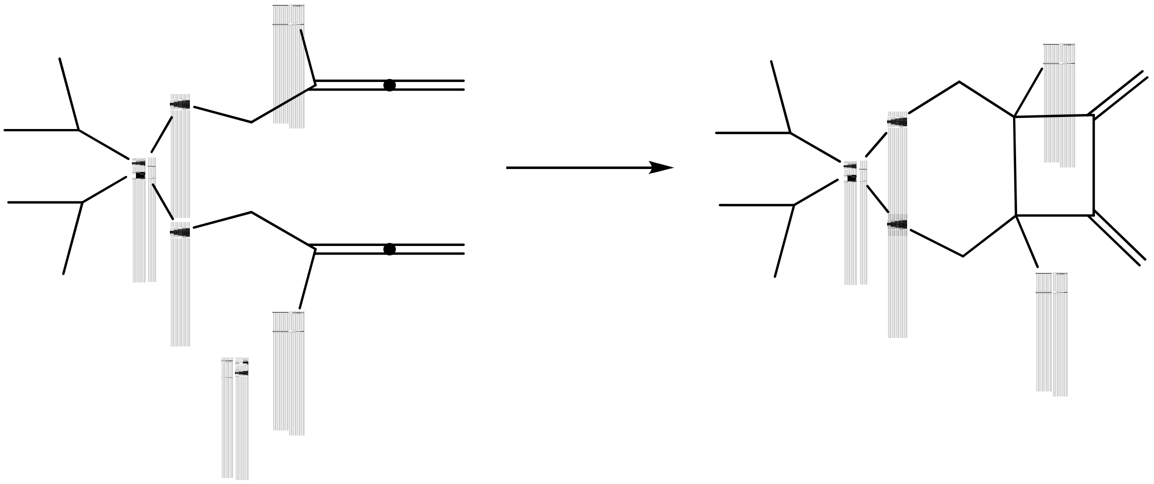
Table 2. Irradiation results for silane **18** in the Hanovia apparatus.

Rayonet Trials

Trial	Time	Catalyst (mol eq.)	Additional Reagent	Results
12	150 min.	-	-	No reaction
13	30 min.	$Cu(OTf)_2$ (0.1)	-	<5% new material
14	22 min.	$Cu(OTf)_2$ (0.1)	-	<5% new material
15	30 min.	$Cu(OTf)_2$ (0.1)	-	No reaction
16	30 min.	$Cu(OTf)_2$ (0.2)	-	No reaction
17	45 min.	$Cu(OTf)_2$ (0.05)	-	No reaction

Table 3. Irradiation results for silane **18** in the Rayonet apparatus.

The desired formation of cyclobutane was never observed with this silane. After several trials without any catalyst or additional reagent we determined that the cyclobutane was most likely forming for a very brief period of time and then decomposing or polymerizing. With this in mind we reasoned that if the two internal double bonds of the two allenes were cycloadding the remaining two exterior double bonds would be in the perfect orientation for a Diels-Alder reaction (see Scheme 40).



Scheme 40. External double bonds involved in Diels-Alder reaction.

Therefore, in trials 3-11 and we added a dienophile (methyl acrylate or tetracyanoethylene) in an effort to capture the cyclobutane product. However, as the table shows, each time a reaction occurred the resulting product was made in such low yield that it was impossible to purify or analyze further. Degradation of the reaction mixture indicated that a reaction occurred since the starting material was consumed. Catching the product before it polymerized or degraded completely presented a challenge.

Copper was used as a catalyst in an effort to increase the coordination between the double bonds of the allene (see Background Chapter). A new product was detected in the NMR from trials 13 and 14. New peaks were found around 4.0 ppm and above 8.0 ppm, indicative of ring formation, but this product was formed in such minimal yield that it was impossible to isolate it from the rest of the solution.

C. Silane 19

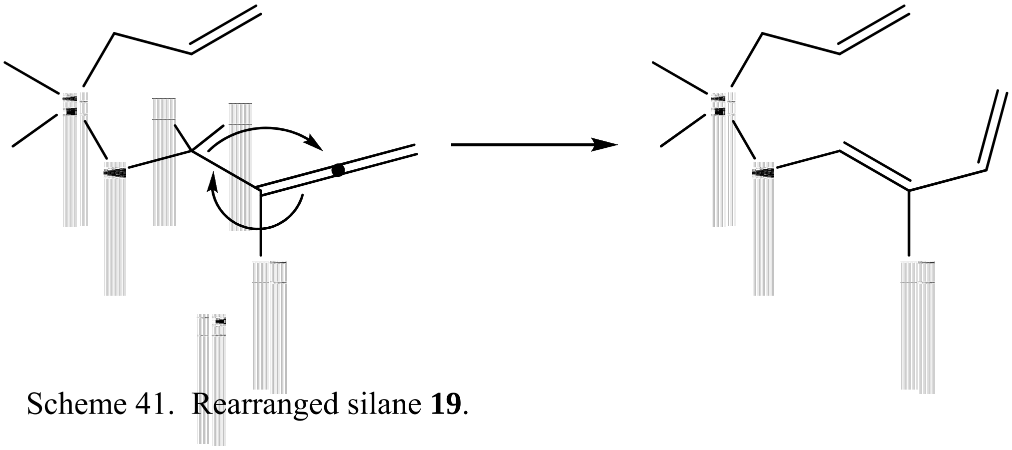
Results from irradiation of silane **19** are summarized in Table 4 below. After no reaction was detected using the Rayonet lamps all trials were done using the Hanovia lamp. All reactions were done in acetonitrile at room temperature.

Trial	Time	Catalyst (mol eq.)	Additional Reagent	Results
1	5 min.	-	-	No reaction
2	5 min.*	-	-	<5% new material
3	20 min.	-	-	<5% new material
4	25 min.	-	-	Polymerization
5	30 min.	-	-	<5% new material
6	5 min.*	$Cu(OTf)_2$ (0.1)	-	<5% new material
7	5 min.*	CuOTf (0.1)	-	<5% new material
8	10 min.	CuOTf (0.1)	-	<5% new material
9	20 min.	CuOTf (0.1)	-	Polymerization
10	10 min.	-	TCNE (2.0 eq)	Polymerization
11	10 min.	-	TCNE (3.3 eq)	Polymerization
12	12 min.	-	TCNE (9.6 eq)	No reaction
13	12 min.	-	TCNE (10.2 eq)	Polymerization
14	12 min.	-	TCNE (3.2 eq)	<5% new material

Table 4. Irradiation results for silane **19**.

Because the allylic side of this silane is not a chromophore, copper was used in an effort to bring the two double bonds into closer proximity with each other. Both Cu(I) and Cu(II) were studied. In some of the trials small amounts of products were detected by NMR, but none of these products were isolated.

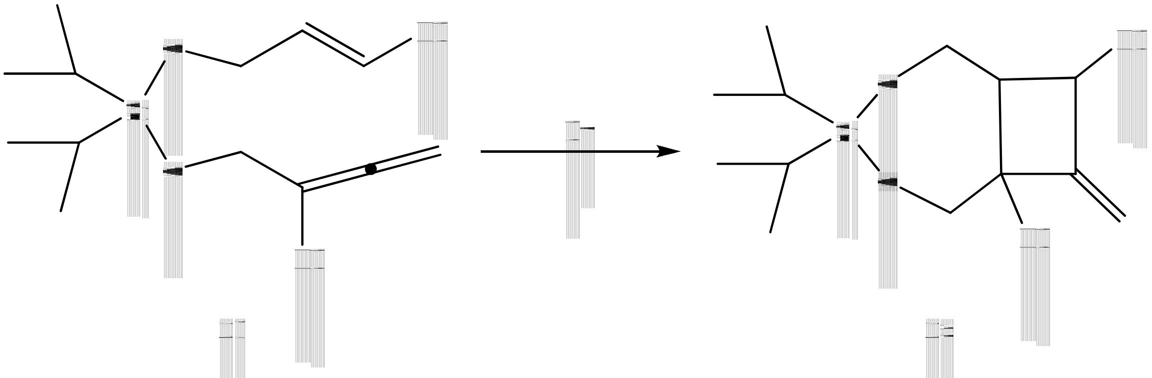
We saw evidence in the crude NMR data that led us to believe that the product being formed was the result of a hydride shift followed by a polymerization of the resulting diene (see Scheme 41). Therefore, TCNE was used in trials 10-14 in an effort to capture the diene that would have been formed as a result of such a rearrangement. As shown by Table 4 the TCNE did not capture the rearranged product and so this study was abandoned.



Scheme 41. Rearranged silane **19**.

D. Silane 21

Silane **21** produced promising results. In the irradiation of this compound using the Rayonet apparatus a new compound was obtained whose NMR data suggest a cycloaddition has occurred (Scheme 42). All irradiation trials were carried out in acetonitrile at room temperature. Because both double bonds are chromophores they efficiently undergo a [2+2] cycloaddition which is shown in Scheme 44. Table 5 indicates that when silane **21** is irradiated for 60-75 minutes product **25** is formed. This occurs in the absence of catalyst.



Scheme 42. Formation of product **25** via [2+2] photocycloaddition.

Trial	Time	Results
1	30 min.	<5% new material
2	60 min.	Formation of product **25**
3	65 min.	Formation of product **25**
4	65 min.	Formation of product **25**
5	75 min.	Formation of product **25**

Table 5. Irradiation results for silane **21**.

Product **25** was detected in the NMR spectrum of the crude reaction solution. All of the starting material peaks disappeared leaving two singlets at 5.01 ppm and 5.23 ppm. These singlets are indicative of the two vinylic protons on the remaining double bond. The rest of the peaks in the NMR spectrum appeared as indistinguishable multiplets located between 3.60 ppm and 4.40 ppm. This is consistent with the predicted NMR for cyclobutane **25**. Data obtained using the LC-MS also indicated that product **25** was formed. The M+1 ion mass was measured as 393.23138 amu (calculated 393.22443 amu).

This product is produced in low yield and has proven impossible to purify. It contains three stereocenters, making purification difficult because of the mixture of diastereomers that exist in the solution. In the future it may be plausible to remove the silicon with NH_4F leaving the product as a diol. This may make the purification of this compound easier because a diol is more stable than a dialkoxysilane on silica gel.

E. Amine Tethered Allene

Amine **23** was irradiated in acetonitrile using the Rayonet. $Cu(OTf)_2$ and Cu(OTf) were used as catalysts in several different trials. None of the irradiation trials produced any reaction.

IV. Conclusion

Many experiments were conducted in the exploration of the photoreactivity of several tethered allenes. Success was achieved in the photocycloaddition of silane **21** as the allene photoadded to the alkene to form a product containing cyclobutane which was detected in the NMR of the crude solution.

Experimental

General Procedures:

All reactions were run under nitrogen atmosphere. Flash chromatography was conducted with silica gel (200-450 mesh) and the indicated eluents. All solvents were dried using the dry solvent system.

Irradiations using the Hanovia apparatus were performed in a Pyrex immersion well around a quartz water-cooled jacket housing a Hanovia 450W lamp. Irradiations using the Rayonet apparatus were performed in a quartz well around a water-cooled cold finger. These studies were performed surrounded by 16 lamps of wavelength 254nm. Solutions were deoxygenated by bubbling dry nitrogen through them for 30-50 minutes.

Nuclear magnetic resonance spectra were obtained in $CDCl_3$ on a Varian VXR 500 MHz Multinuclear FT-NMR Spectrometer and chemical shifts are reported in ppm downfield from TMS. Mass spectrometry data was obtained on a LC-MS spectrometer.

Synthesis of Silane 18

In a flame-dried round-bottom flask were placed 0.5624 g (3.040 mmol) of diisopropyldichlorosilane and 0.8849 g (6.053 mmol) of 2-phenyl-2,3-butadien-1-ol (**16**) in 20 mL dry CH_2Cl_2. The reaction was cooled to $0^{o}C$ and then 0.95 mL (6.8 mmol) triethylamine were added. The reaction was allowed to warm up to room temperature and stirred overnight. It was then concentrated in vacuo, washed with hexane, and filtered. The hexane was evaporated off and the yellow oil was purified by chromatography (0-2% EtOAc in hexane elution). Isolated yield was 0.8962 g (72.9%). The spectral data were as follows: ^{1}H NMR δ 7.20-7.45 (m, 10H), 5.13 (t, 4H), 4.72 (t, 4H), 1.04 (d, 14H); ^{13}C NMR δ 208.69, 134.61, 128.55, 126.92, 126.49, 105.45, 79.08, 62.32, 17.29, 12.37. LC-MS calculated for $C_{26}H_{32}O_2Si$ $[M+H]^+$: 405.22443, found: 405.22170.

Synthesis of Silane 19

In a flame-dried round-bottom flask were placed 0.15 mL (0.99 mmol) of allyl(chloro)dimethylsilane and 0.1545 g (1.057 mmol) of 2-phenyl-2,3-butadien-1-ol (**16**) in 12 mL dry CH_2Cl_2. The reaction was cooled to 0°C and then 0.15 mL (1.078 mmol) triethylamine were added. The reaction was allowed to warm up to room temperature and stirred overnight. It was then concentrated in vacuo, washed with hexane, and filtered. The hexane was evaporated off and the crude solution was purified by chromatography (0-2% EtOAc in hexane elution). Isolated yield was 0.1727 g (71.2%). The spectral data were as follows: ^1H NMR δ 7.14-7.38 (m, 5H), 5.70 (m, 1H), 5.06 (t, 2H), 4.82 (dd, 2H), 4.53 (t, 2H), 1.56 (d, 2H), 0.06 (s, 6H); ^{13}C NMR δ 207.76, 133.28, 132.89, 127.32, 125.82, 125.39, 112.71, 103.94, 77.51, 61.71, 23.45, -3.40. LC-MS calculated for $C_{15}H_{20}OSi$ $[M+H]^+$: 245.13562, found: 245.11519.

Synthesis of Silane 21

To a flame-dried round-bottom flask was added 0.3949 g (2.943 mmol) of cinnamyl alcohol to an excess of diisopropyldichlorosilane (2.1540 g, 11.633mmol) in 20 mL of dry CH_2Cl_2. The reaction was cooled to 0°C and then 0.41 mL (2.9 mmol) triethylamine were added. The reaction was allowed to warm up to room temperature and stirred overnight. It was then concentrated, washed with hexane, filtered, and concentrated. Diisopropylchloro(cinnamyloxy)silane was isolated (0.7372 g, 2.606 mmol, 88.6% yield) by distillation at 0.25 torr and 220°C. It was then placed in another flame-dried round-bottom flask in which 0.3882 g (2.655 mmol) 2-phenyl-2,3-butadien-

1-ol (**16**) was added in 15 mL CH_2Cl_2. The reaction mixture was cooled to 0ºC and 0.37 mL (2.7 mmol) triethylamine was added. The reaction mixture was allowed to warm up to room temperature and stirred overnight. It was then concentrated, washed with hexane, and filtered. The hexane was evaporated off and the crude solution was purified by chromatography (1-4% EtOAc in hexane elution). Isolated yield was 0.7061 g (69.1%). The spectral data were as follows: ^{1}H NMR δ 7.18-7.47 (m, 10H), 6.60 (d, 1H), 6.27 (m, 1H), 5.11 (t, 2H), 4.74 (d, 2H), 4.45 (t, 2H), 1.08 (d, 14H); ^{13}C NMR δ 208.98, 137.42, 134.81, 129.93, 129.14, 129.05, 128.86, 128.71, 127.69, 127.19, 126.74, 105.68, 79.29, 63.85, 62.64, 17.76, 12.65. LC-MS calculated for $C_{25}H_{32}O_2Si$ $[M+H]^+$: 393.22443, found: 393.22467.

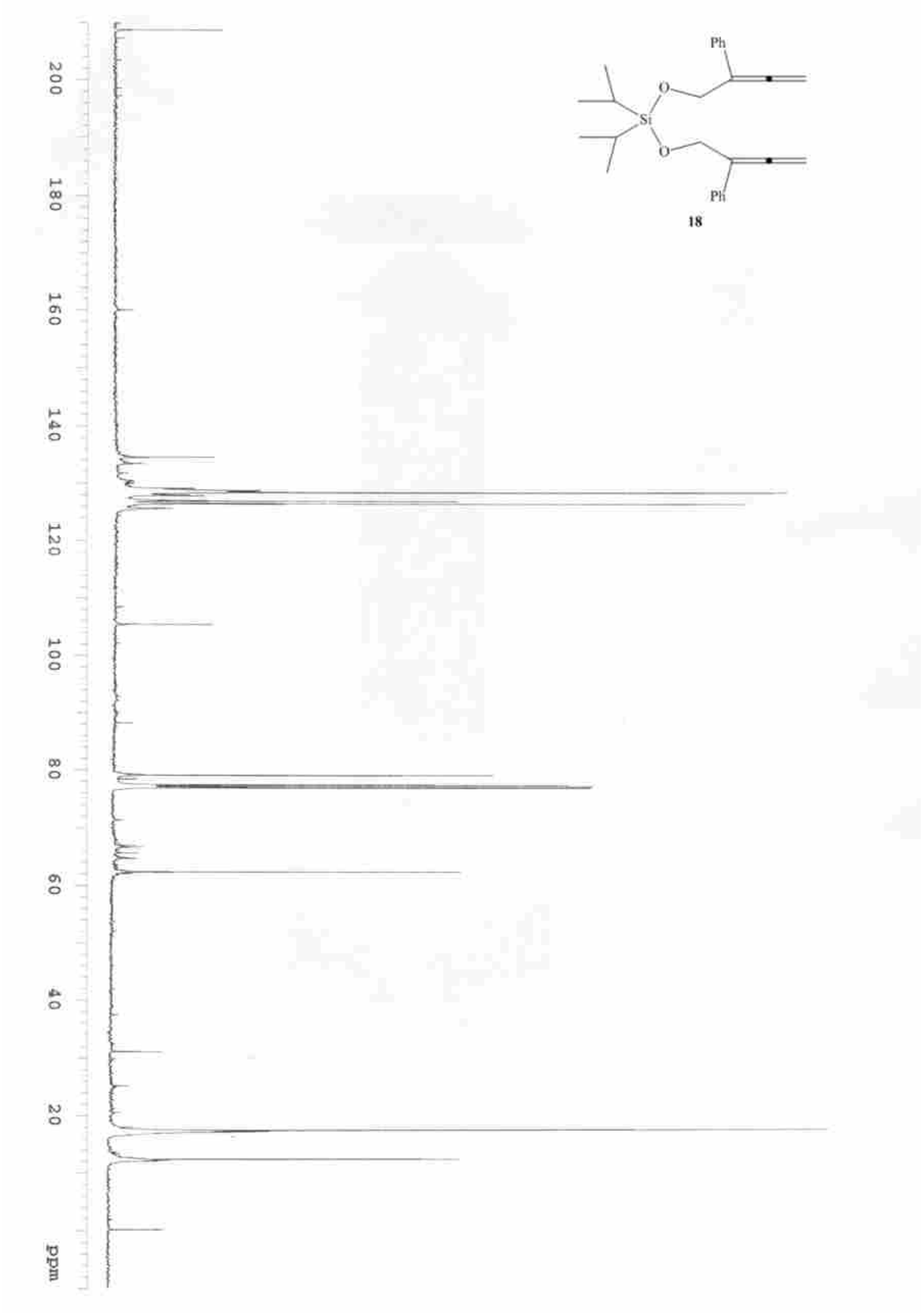
Synthesis of Cyclobutane 25

Into the quartz well of the Rayonet apparatus were placed 0.0642 g (0.1637 mmol) in 60 mL of dry acetonitrile. The lamps were turned on and the solution was left to react for 60-75 minutes. The solution was then concentrated in vacuo. The NMR data was collected from the crude mixture since product **25** was produced in such low yield. LC-MS calculated for $C_{25}H_{32}O_2Si$ $[M+H]^+$: 393.22443, found: 393.23138.

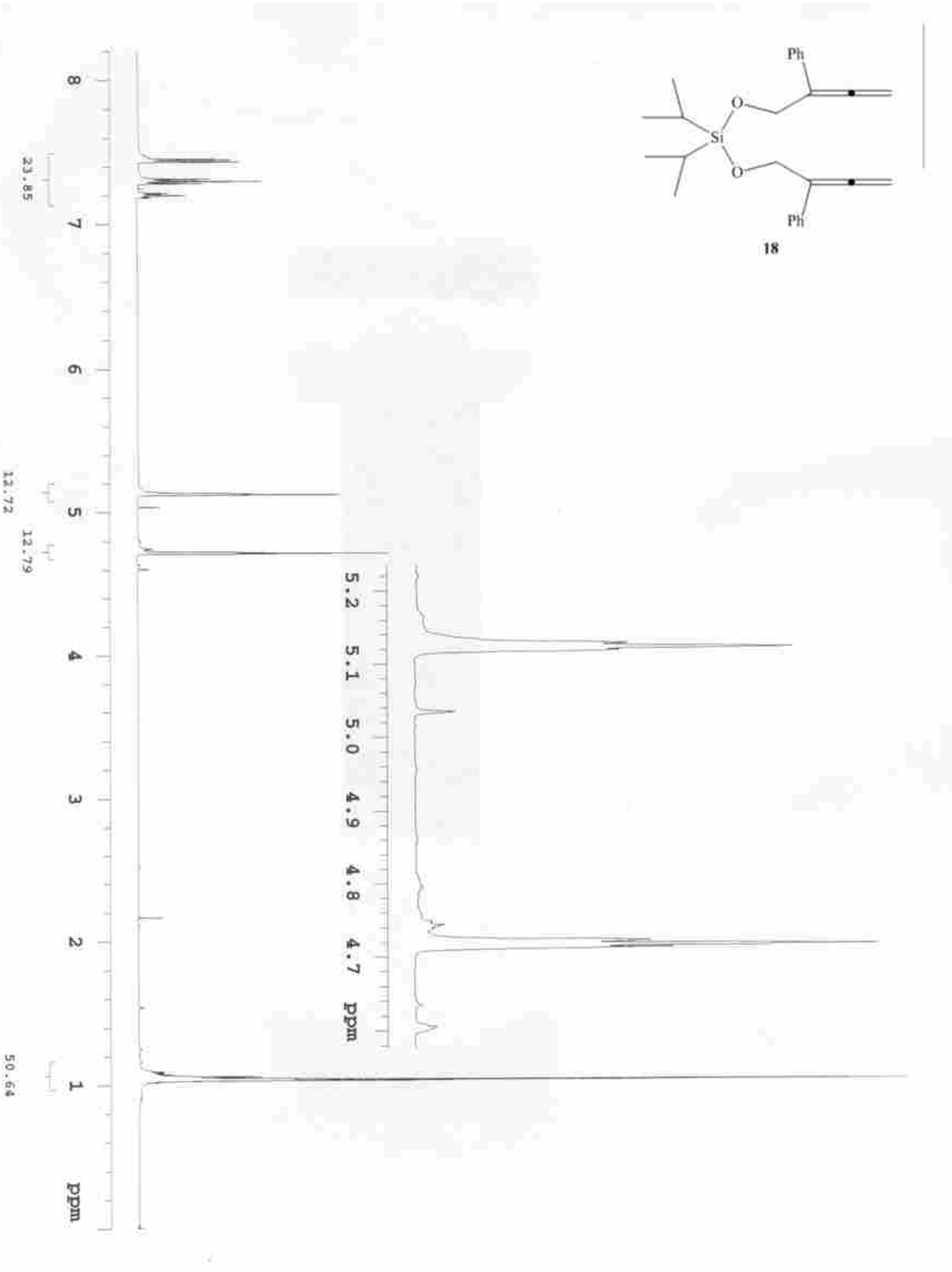
Appendix

NMR Spectra

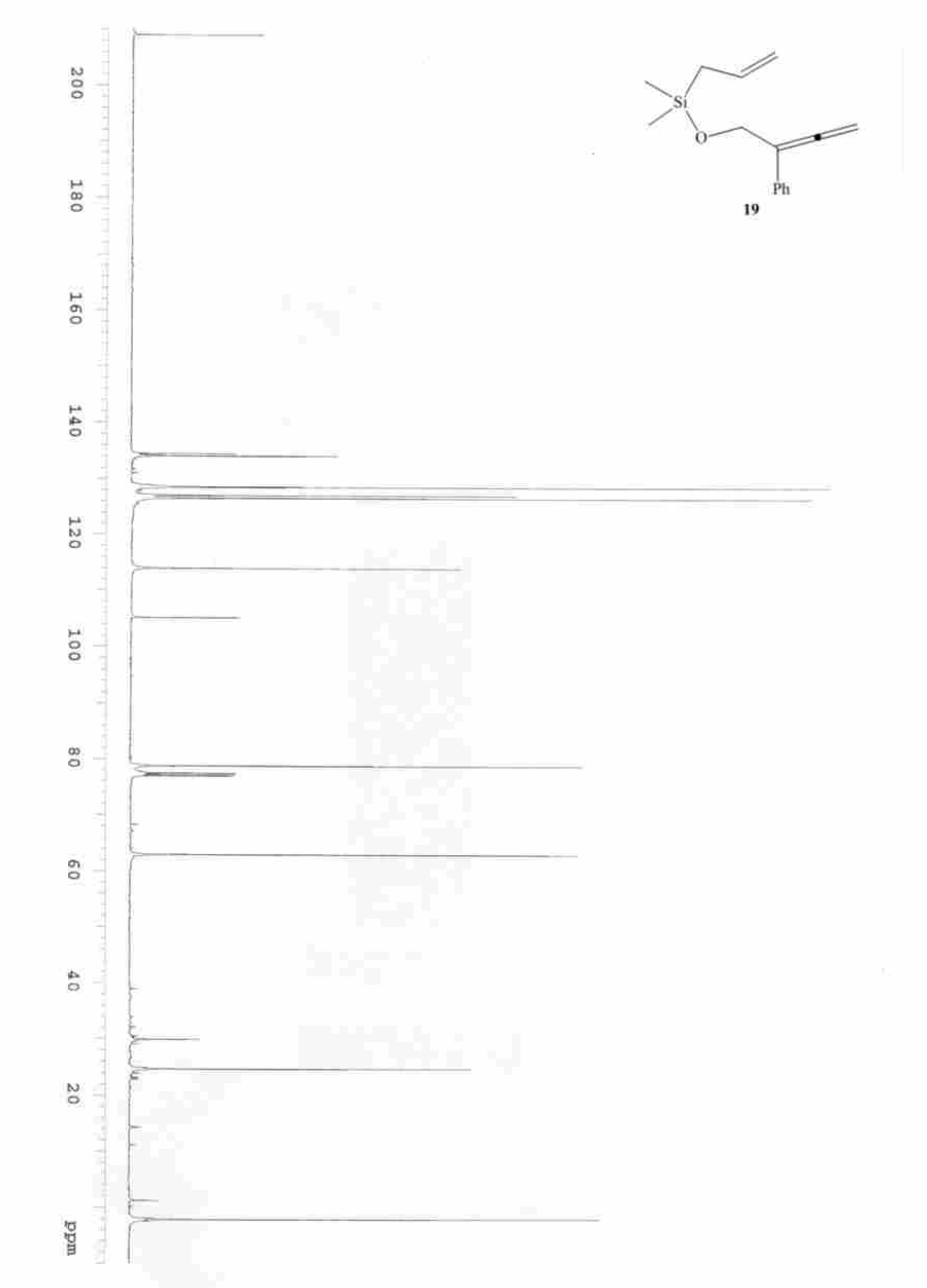
List of Spectra



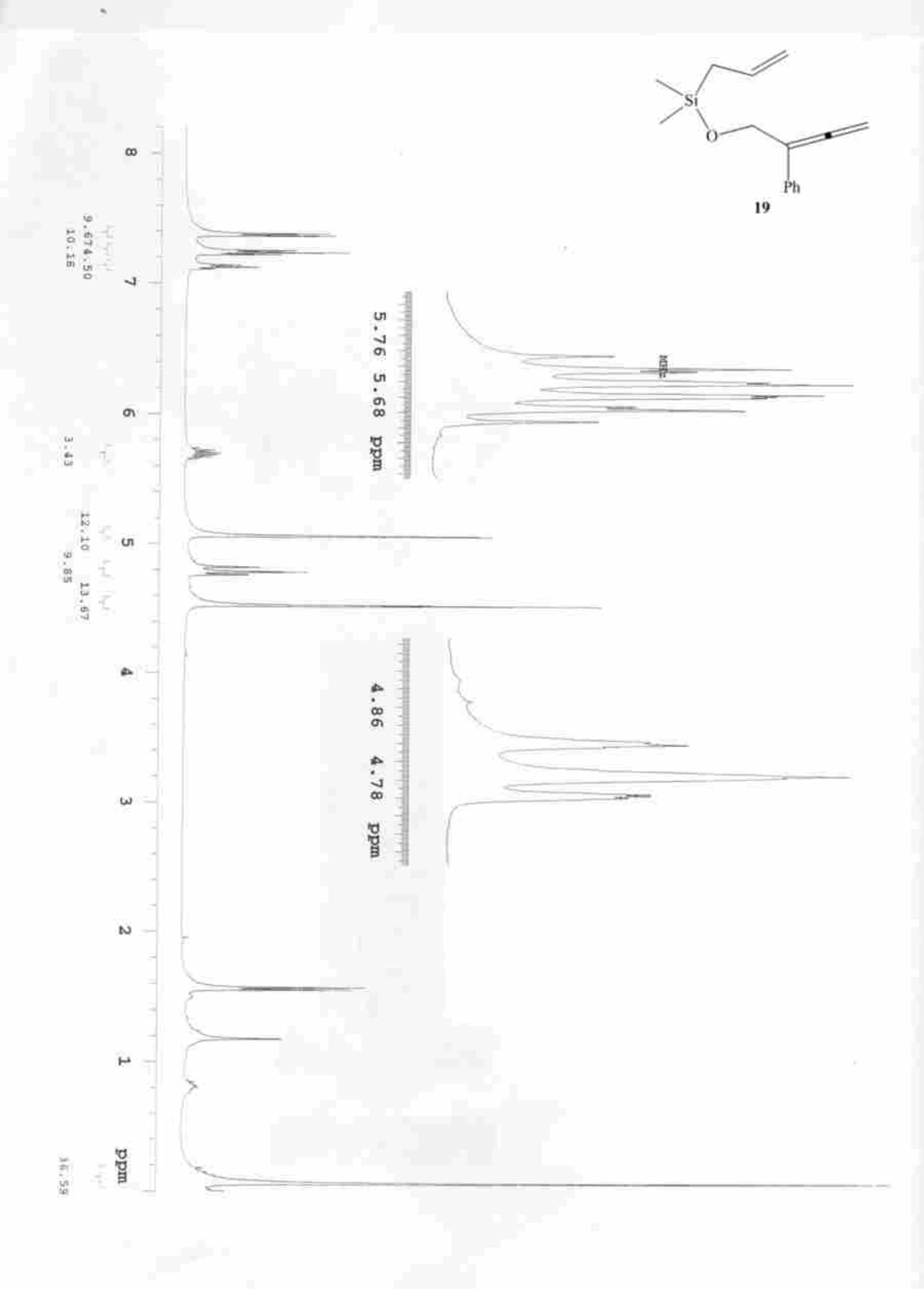
18


8
7
6
5
4
3
2
1
ppm
23.85
12.72
12.79
50.64
5.2
5.1
5.0
4.9
4.8
4.7
ppm
Ph
O
Si
O
Ph

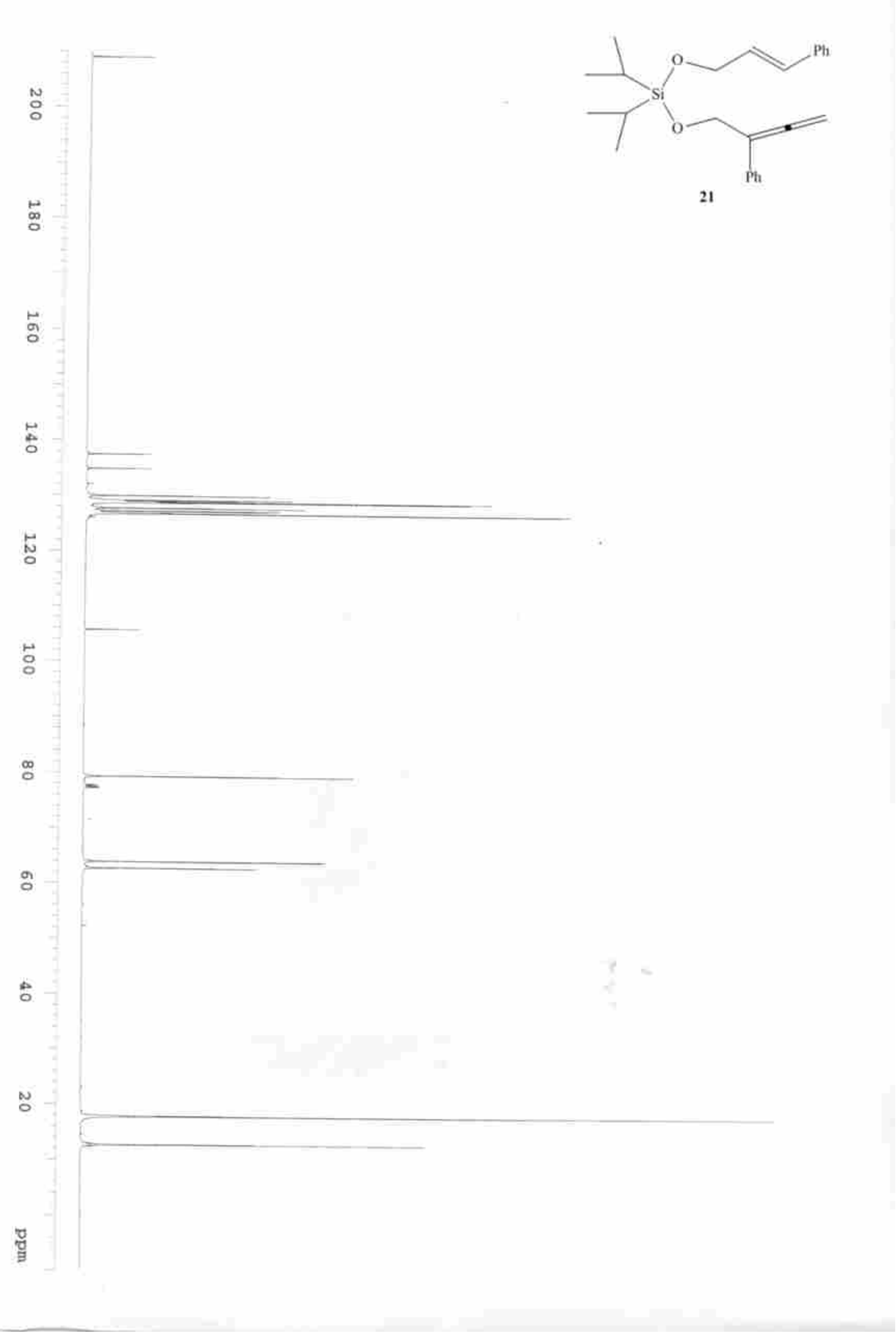
18



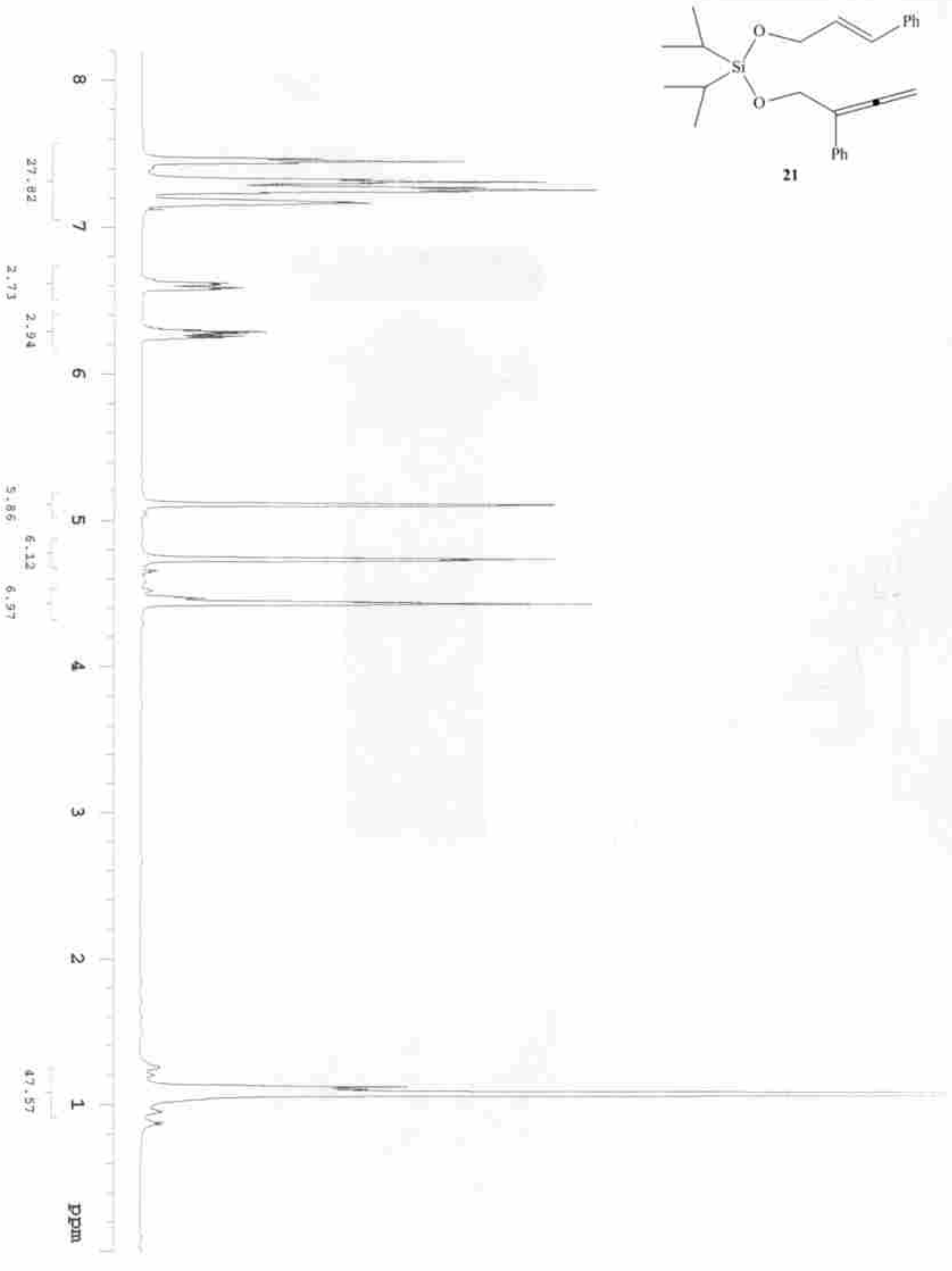
19


Si
O
Ph
8
7
6
5
4
3
2
1
ppm
9.67
4.50
10.16
3.43
12.10
9.85
13.67
16.59
5.76 5.68 ppm
4.86 4.78 ppm

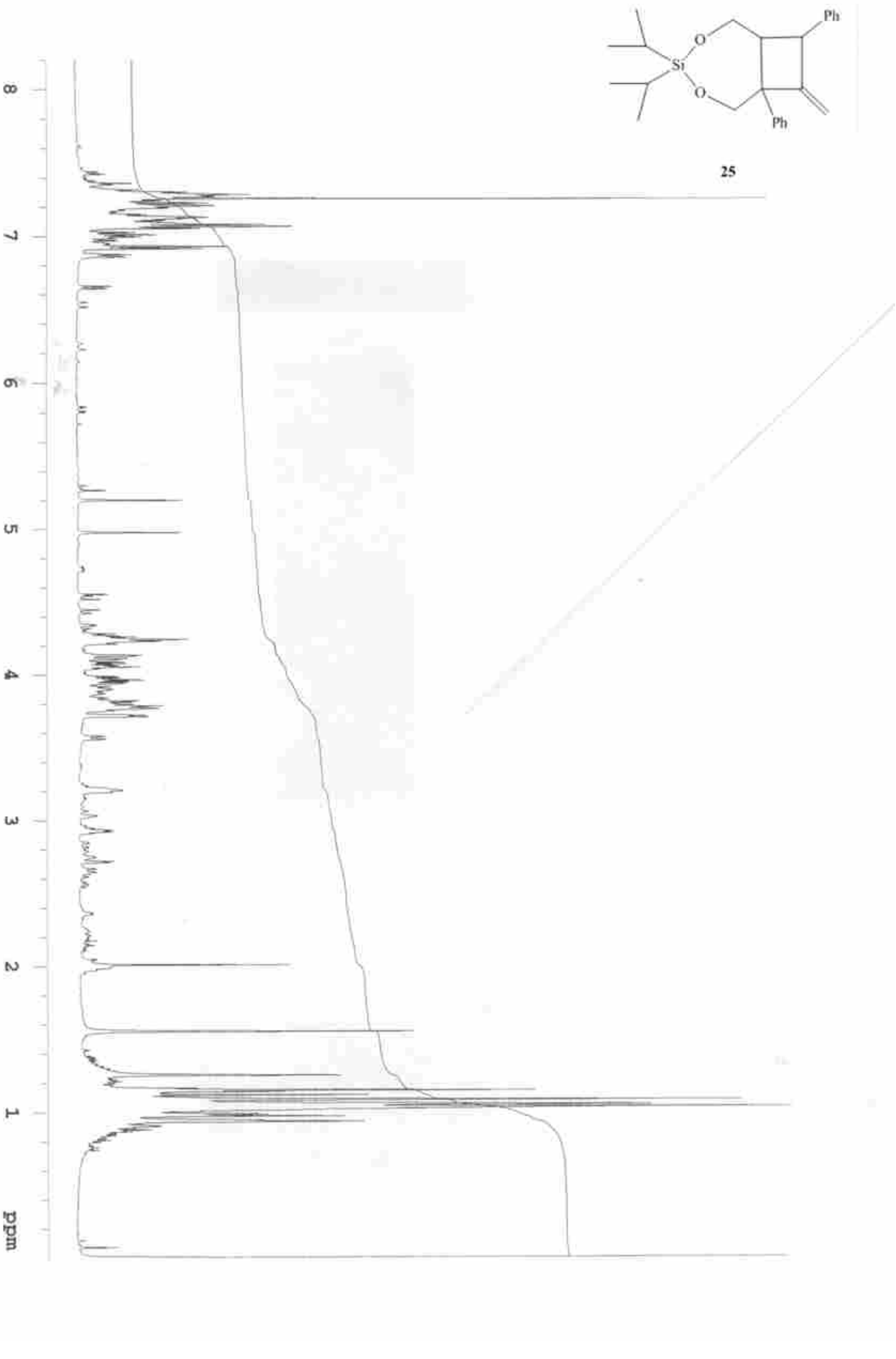
19



21



21



25

References

---

[1] Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805.

[2] Ma, S. *Chem. Rev.* **2005**, *105*, 2829.

[3] Hoffmann-Roder, A.; Krause, N. *Angew. Chem. Int. Ed.* **2004**, *43*, 1196.

[4] Crimmins, M. T.; Tabot, E. A. *J. Am. Chem. Soc.* **2000**, *122*, 5473.

[5] Ito, M. *Pure Appl. Chem.* **1991**, *63*, 13.

[6] Fleming, S. A.; Liu, R.; Redd, J. T. *Tetrahedron Lett.* **2005**, *46*, 8095.

[7] Liu, R.; Herron, S. R.; Fleming, S. A. *J. Org. Chem.* **2007**, *72*, 5587.

[8] Liu, R.; Fleming, S. A. Unpublished results

[9] Skattebol, L.; Solomon, S. *J. Am. Chem. Soc.* **1965**, *87*, 4506.

[10] Padwa, A.; Filipkowski, M. A.; Meske, M.; Watterson, S. H.; Ni, Z. *J. Am. Chem. Soc.* **1993**, *115*, 3776.

[11] Padwa, A.; Meske, M.; Murphree, S. S.; Watterson, S. H.; Ni, Z. *J. Am. Chem. Soc.* **1995**, *117*, 7071.

[12] Alcaide, B.; Almendros, P.; Aragoncillo, C. *Org. Lett.* **2003**, *5*, 3795.

[13] Ohno, H.; Mizutani, T.; Kadoh, Y.; Miyamura, K.; Tanaka, T. *Angew. Chem. Int. Ed.* **2005**, *44*, 5113.

[14] Ovaska, T. V.; Kyne, R. E. *Tetrahedron Lett.* **2008**, *49*, 376.

[15] Jiang, X.; Cheng, X.; Ma, S. *Angew. Chem. Int. Ed.* **2006**, *45*, 8009.

[16] Kakiuchi, K.; Ue, M.; Tsukahara, H.; Shimizu, T.; Miyao, T.; Tobe, Y.; Odaira, Y.; Yasuda, M.; Shima, K. *J. Am. Chem. Soc.* **1989**, *111*, 3707.

[17] Kakiuchi, K.; Nakamura, I.; Matsuo, F.; Nakata, M.; Ogura, M.; Tobe, Y.; Kurosawa, H. *J. Org. Chem.* **1995**, *60*, 3318.

---

[18] Hue, B. T. B.; Dijkink, J.; Kuiper, S.; Larson, K. K.; Guziec, F. S.; Goubitz, K.; Fraanje, J.; Schenk, H.; van Maarseveen, J. H.; Hiemstra, H. *Org. Biomol. Chem.* **2003**, *1*, 4364.

[19] Crimmins, M. T.; Reinhold, T. L. *Org. React.* **1993**, *44*, 297.

[20] Miura, T.; Kiyota, K.; Kusama, H.; Iwasawa, N. *J. Organomet. Chem.* **2007**, *692*, 562.

[21] Feldman, K. S.; Iyer, M. R.; Hester, S. K., *Org. Lett.* **2006**, *8*, 3113.

[22] Feldman, K. S.; Hester, D. K.; Lopez, C. S.; Faza, O. N. *Org. Lett.* **2008**, *10*, 1665.

[23] Winkler, J. D.; Ragains, J. R. *Org. Lett.* **2006**, *8*, 4031.

[24] Birbaum, F.; Neels, A.; Bochet, C. G. *Org. Lett.* **2008**, *10*, 3175.

[25] Hutchinson, J. H.; Daynard, T. S.; Gillard J. W. *Tetrahedron Lett.* **1991**, *32*, 573.

[26] Shea, K. J.; Staab, A. J.; Zandi, K. S. *Tetrahedron Lett.* **1991**, *32*, 2715.

[27] Stork, G.; Kim, G. *J. Am. Chem. Soc.* **1992**, *114*, 1087.

[28] Fleming, S. A.; Ward, S. C. *Tetrahedron Lett.* **1992**, *33*, 1013.

[29] Ward, S. C; Fleming, S. A. *J. Org. Chem.* **1994**, *59*, 6476.

[30] Bradford, C. L.; Fleming, S. A.; Ward, S. C. *Tetrahedron Lett.* **1995**, *36*, 4189.

[31] Crimmins, M. T.; Guise, L. E. *Tetrahedron Lett.* **1994**, *35*, 1657.

[32] Braun, I.; Rudroff, F.; Mihovilovic, M. D.; Bach, T. *Angew. Chem. Int. Ed.* **2006**, *45*, 5541.

[33] Langer, K.; Mattay, J.; Heidbreder, A.; Moller, M. *Liebig. Ann. Chem.* **1992**, *1992*, 257.

[34] Mukaiyama, T.; Harada, T. *Chem. Lett.* **1981**, *10*, 621.

[35] Zachova, H.; Man, S.; Necas, M.; Potacek, M. *Eur. J. Org. Chem.* **2005**, *2005*, 2548.

[36] Cao, X.; Yang, Y.; Wang, X. *J. Chem. Soc., Perkin Trans. 1* **2002**, *22*, 2485.

---

[37] Xu, D.; Li, Z.; Ma, S. *Chem. Eur. J.* **2002**, *8*, 5012.

[38] Kang, S.; Baik, T.; Kulak, A. N.; Ha, Y.; Lim, Y.; Park, J. *J. Am. Chem. Soc.* **2000**, *122*, 11529.

[39] Crabbé, F.; Nassim, B.; Robert-Lopes, M-T. *Org. Synth. Coll.* Vol. VII, 276-277.

[40] Sarkar, N.; Ghosh, S. *Indian J. Chem. B Org* **2006**, *45B*, 2474.