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Arene-alkene meta photocycloadditions and conjugated enyne photorearrangements

Manli Zheng

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**Abstract**
The new advances and synthetic potential of arene-alkene meta photocycloadditions, with the goal of rapid approach to polycyclic molecules, are described. Vinyl cyclohexanecarboxylate has been found to be an efficient alkene moiety to improve the reaction efficiency by reducing formation of polymers during irradiation. Exploration of asymmetric meta photocycloaddition, via chiral auxiliaries, resulted in partial asymmetric induction. Fluorescence studies have led to a better understanding of the reaction mechanism. Intramolecular isotope effect results on meta photocycloaddition remain unexplained.

Conjugated enynes undergo a singlet photorearrangement, resulting in a pseudodegenerate rearrangement. The synthesis of starting materials, characterization of products, studies of the reaction reversibility, and studies of the generality of the rearrangement are described. Two possible mechanisms, 1,2-cyclobutadiene and "carbene" walk, are proposed and discussed.

**Keywords**
Chemistry, Organic

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Arene-alkene \textit{meta} photocycloadditions and conjugated enyne photorearrangements

Zheng, Manli, Ph.D.

University of New Hampshire, 1992
ARENE-ALKENE META PHOTOCYCLOADDITIONS

and

CONJUGATED ENYNE PHOTOREARRANGEMENTS

by

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DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy
in
Chemistry

December, 1992
This dissertation has been examined and approved.

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Oct. 13, 1992
DEDICATION

To My Parents, Minghuan Zheng and Yihua Qu
and
Louis
for Their Love and Support
ACKNOWLEDGEMENT

I would like to thank Dr. Richard P. Johnson for his guidance and support in directing the work that is presented in this thesis. I appreciate all of the knowledge and advice he has given me over the last five years.

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ABSTRACT

ARENE-ALKENE \textit{meta} PHOTOCYCLOADDITIONS AND

CONJUGATED ENYNE PHOTOREARRANGEMENTS

by

Manli Zheng

University of New Hampshire, December, 1992

The new advances and synthetic potential of arene-alkene \textit{meta} photocycloadditions, with the goal of rapid approach to polycyclic molecules, are described. Vinyl cyclohexanecarboxylate has been found to be an efficient alkene moiety to improve the reaction efficiency by reducing formation of polymers during irradiation. Exploration of asymmetric \textit{meta} photocycloaddition, via chiral auxiliaries, resulted in partial asymmetric induction. Fluorescence studies have led to a better understanding of the reaction mechanism. Intramolecular isotope effect results on \textit{meta} photocycloaddition remain unexplained.

Conjugated enynes undergo a singlet photorearrangement, resulting in a pseudodegenerate rearrangement. The synthesis of starting materials, characterization of products, studies of the reaction reversibility, and studies of the generality of the rearrangement are described. Two possible mechanisms, 1,2-cyclobutadiene and "carbene" walk, are proposed and discussed.
CHAPTER ONE

ARENE-ALKENE META PHOTOCYCLOADDITIONS

INTRODUCTION AND HISTORIC BACKGROUND

The field of aromatic photochemistry has been actively investigated during the last three decades. Considerable effort has been devoted to questions related to practical applications in syntheses and chemical technology, ecology, biology, and pharmacy. Photochemical syntheses are particularly valuable, and have received the most attention.

The photochemical reactions of aromatic compounds include: isomerization, photoaddition, photosubstitution, cyclization, photodimerization, as well as other miscellaneous reactions.

1. Ring Isomerization Reactions.

Benzene was long considered photochemically inert. Bryce-Smith's discovery in 1957 that fulvene (1) is formed via irradiation opened a new era in arene photochemical research. Soon afterwards, photochemical isomerizations of benzene (or its derivatives) into Dewar benzenes (3), benzvalenes (2), rearranged benzene derivatives (4), and prismanes were also discovered. Product ratios are strongly dependent on the experimental conditions. Owing to their photochemical and thermal instabilities, it is not always possible to isolate all of these products.
Fulvene (1) was formed via photolysis and can be isolated by gas chromatography. Benzene (2) was formed only by irradiation at long wavelength and can also be isolated by gas chromatography. "Prefulvene" (5) was assumed to be an intermediate in this reaction. (Scheme 2)

Benzene was converted to Dewar benzene (3) upon irradiation at shorter wavelengths in solution. It has been suggested that this forms via a nonpolar 1,4-diradical (5).

Shifts of ring carbon atoms were discovered later. (6 \(\rightarrow\) 7 \(\rightarrow\) 8) It was suggested that benzvalenes (2) are intermediates. These reactions were believed to occur from aromatic singlet states. (Scheme 3) Sensitized rearrangements of the intermediate benzvalenes also are important here.
2. Photocycloadditions.

Photochemical activity in this area was initiated by the report in 1959 that UV irradiation of solutions of maleic anhydride in benzene produced cycloadducts 9 and 10 in a 2:1 ratio. This first example of the photocycloaddition of an arene and an alkene was believed to arise from photochemical [2+2] addition, followed by a second thermal [2+4] addition. (Scheme 4)
The scope of the photocycloadditions of alkenes to arenes has expanded rapidly since then. Benzene and its derivatives are now known to undergo a variety of such processes with a wide range of unsaturated compounds. These reactions have led to the synthesis of many novel compounds and provide versatile routes to carbon skeletons of synthetic interest.

Scheme 5

When benzene is irradiated in the presence of an alkene, a number of processes can take place. The pathways involving bonding between the aromatic ring and the alkene can lead to ortho (1,2-), meta (1,3-), and para (1,4-) cycloadducts, (11-13 in scheme 5), as well as ene addition products. The various factors influencing the modes of cycloaddition have long been subjects of interest. In general, para cycloaddition is a low-efficiency process and occurs only in a limited number of specialized cases. In contrast, both the ortho and meta cycloadditions of alkenes and arenes occur with good chemical and quantum efficiencies. We will consider here the meta cycloaddition as the focus of this research because of this reaction's potential synthetic value and because of the great increase in structural complexity. Starting with readily available materials, the meta cycloaddition leads to three new rings and up to six stereogenic centers in one step. According to Wender, this provides the greatest increase in structural complexity of any
reaction.

Early investigations of the \textit{meta} cycloaddition were conducted in the mid 60's, and have been well reviewed.\textsuperscript{1,2,3} The synthetic value of this reaction has become evident since the 80's, leading to the synthesis of over 15 different classes of natural products.\textsuperscript{3} In principle, the \textit{meta} process can be used for the synthesis of complex 5- and 7- membered rings (16 and 17), bicyclo[3.3.0]- and [3.2.1] octanes (14) and (15),\textsuperscript{2} and other systems. (Scheme 6)

Scheme 6

Synthetic advances in intermolecular and intramolecular \textit{meta} cycloaddition have been extensively studied by Wender and his co-workers.\textsuperscript{3}

Intermolecular \textit{meta} cycloaddition as a route to synthesize modhephene (25) was reported in 1982.\textsuperscript{8} Irradiation of a solution of indan (18) and vinyl acetate (Scheme 7) provided \textit{endo}-cycloadduct 19 as the major product. Deprotonation of the corresponding ketone 20 resulted in generation of a semibullvalene enolate (21 and 22), whose complete alkylation provided 23, which has three of the four methyl groups required for the natural
Cleavage of the vinyl cyclopropane moiety of 23 is accomplished by organocuprate addition to avoid quaternization of a carbon adjacent to the bulky gem-dimethyl group.

Application of the arene-alkene \textit{meta} cycloaddition in the synthesis of (\pm)-\alpha-cedrene\textsuperscript{9} (26), (\pm)-isocomene\textsuperscript{10} (27), (\pm)-decarboxy quadrone\textsuperscript{11} (28) and (\pm)-isoridomyrmecin\textsuperscript{12} (29) have been reported.
One of the limitations of the intermolecular *meta* cycloaddition is low yield, often caused by photopolymerization. Most papers on intermolecular *meta* cycloaddition describe yields no greater than 20%, which limits its effective application.

The enormous potential of this reaction in synthesis was greatly enhanced by discovery of the intramolecular *meta* cycloaddition. This work, largely developed in Wender's laboratories, was based on the recognition that the reaction provides a general and powerful approach to a number of commonly encountered skeletons. In addition to the early syntheses of (±)-α-cedrene (26), and (±)-isocomene (27) during the early 80's, recent applications of intramolecular *meta* cycloaddition include syntheses of (±)-rudmollin\textsuperscript{13} (30), (±)-laurenene\textsuperscript{14} (31), (±)-subergoric acid\textsuperscript{15} (32), and (-)-retigeranic acid\textsuperscript{16,17} (33). These are shown in Scheme 9.
Scheme 10 demonstrates the effectiveness of intramolecular meta cycloaddition in the synthesis of (±)-retigeranic acid (33).\textsuperscript{16,17} Here, the meta photocycloaddition of 34 provides cycloadduct 35 which, in the second photochemical step involving a free radical induced opening of a vinyl cyclopropane, is converted to triquinane 36. Elaboration of the polycyclic compound 37 by intramolecular Diels-Alder cycloaddition, provides the pentacyclic target.
More examples of intramolecular meta cycloadditions were also reported by Morrison,\textsuperscript{18} Cornelisse,\textsuperscript{19} and Ellis-Davies.\textsuperscript{20}

3. Reaction Mechanisms.

During the last three decades, much work has been done to elucidate the characteristics and mechanisms of the meta photocycloaddition of alkenes to arenes.

The UV absorption spectrum of benzene shows maxima centered at 254, 203, and 180 nm, corresponding to electronic excitation from $S_0$ to the $S_1$, $S_2$ and $S_3$ ($\pi$, $\pi^*$) states, respectively.\textsuperscript{7} The $S_0\rightarrow S_1$ and $S_0\rightarrow S_2$ transitions of the benzene chromophore are electric
dipole forbidden and have extinction coefficients of 210 and 7400 dm$^3$mol$^{-1}$cm$^{-1}$, respectively. The $S_0 \rightarrow S_3$ transition is electric dipole allowed and it is very intense ($\varepsilon = 6 \times 10^4$ dm$^3$mol$^{-1}$cm$^{-1}$), but has not been implicated in the excited-state chemistry observed thus far.$^{21}$

The lowest triplet state of benzene is populated by intersystem crossing from the singlet state with a quantum yield of approximately 0.23.$^{21}$

Bryce-Smith and Longuet-Higgins were the first to present a theoretical treatment of the photocycloaddition processes.$^{22,23}$ It has been generally accepted now that the reaction proceeds directly from the $S_1$ state of the arene. Of the many originally proposed reaction pathways, only those depicted (Scheme 11) are still under discussion: (a) a fully concerted, synchronous pathway, where all bonds are formed simultaneously; (b) cyclization of the benzene to a prefulvene species, with or without polar character, followed by addition of the olefin to position 2 and 4 of the prefulvene; and (c) complexation of the olefin with the excited benzene (exciplex formation) or excitation of a ground state complex, followed by bonding of the olefin to $meta$ related positions and subsequent cyclopropane formation.

Scheme 11

Of these mechanisms, currently (c) is considered most probable. Mechanism (a) has
received little attention, since the required extensive bond reorganization is considered unlikely.

Mechanism (b), involving a "prefulvene" diradical or similar species with possible polar character was first proposed by Bryce-Smith et al.\textsuperscript{22,23} However, the course of this reaction was later clarified when the originally assigned product structure was corrected in 1985.\textsuperscript{8} Recent results have indicated that arene substituents, such as methoxy, cyano, and trifluoromethyl, exert powerful directing effects on the mode of photocycloaddition of alkenes to the benzene ring (i.e., \textit{ortho} versus \textit{meta} process)\textsuperscript{25,26,27} and the regio- and stereochemistry of the reactions.\textsuperscript{28,29} In particular, the regiochemistry of the \textit{meta} photocycloaddition is rationalized by the substituents directing the orientation of the addends to provide maximum stabilization of the charge centers developing in the six membered ring on approach to the alkene.\textsuperscript{30} (Scheme 12)

**Scheme 12**

R\textsuperscript{3,5} - cyclization1,3 - cyclization

R = OCH\textsubscript{3}

R = CF\textsubscript{3}, CN

\[ 1,3\text{-cyclization} \quad 3,5\text{-cyclization} \]

Semi-empirical calculations also supported the mechanism that the intermediate is a polar species.\textsuperscript{31}
To prove the possibility of a diradical intermediate Sheridan has independently prepared 39 and 40.\textsuperscript{32} (Scheme 13) Photolysis of each of these compounds gave the same product ratio (43 : 44) observed in the photochemical process. This result provides support to the mechanism that a complex of biradical intermediate 42 is involved in meta cycloaddition.

Scheme 13

Cornelisse and co-workers presented a mechanism in which a zwitterionic intermediate is formed from the excited anisole and alkene.\textsuperscript{33} (Scheme 14) They found that meta photocycloaddition of anisole with cyclopentene gave the endo and exo adducts. The results obtained with the oxa- and dioxa-cyclopentene demonstrated that the presence of one or two oxygen atoms in the five membered ring has a pronounced effect on the
endo/exo ratio. The strong effect was attributed to an electronic interaction between the oxygen atom(s) and the negatively charged allylic moiety in the endo zwitterion. Repulsion between the lone pair electrons on oxygen and the electrons of the allyl anion will render this zwitterion less stable than the endo zwitterion obtained from cyclopentene. Their kinetic study of the meta photocycloaddition of benzene to cyclopentene by fluorescence quenching and quantum yield determination did not exclude the possibility of an intermediate or an exciplex. All attempts to detect the presence of an intermediate or an exciplex with the help of nanosecond laser spectroscopy were unsuccessful.34

The model of preorientation, a sandwich-like arrangement of arene and alkene, was suggested by Mattay.35 (Scheme 15) After a series of recent studies of the electronic influence of electronic properties on the mode of reaction and the regio- and stereoselectivity, a summary was made. In meta cycloadditions, donor substituents are generally found in position 1, whereas acceptor groups are located in position 2 and 4. Unfunctionalized alkenes (especially cyclic alkenes) show a high preference for the formation of endo cycloadducts. In contrast, the stereoselectivity is reversed with olefins that are substituted by strong electron-donating substituents.

In conclusion, the third mechanism, in which a polarized transition state or an
exciplex intermediate is involved, is currently most favored. Although the existence of an exciplex is not conclusively proven in most cases of meta photocycloadditions, the assumption of an exciplex like arrangement of the reactants as a necessary step is the best model to predict the stereochemistry of products. More experimental evidence is needed.
STATEMENT OF THE GOALS

Despite many recent advances in *meta* cycloaddition, there is a continued need for efficient and general approaches to complex polycyclic ring systems. This research seeks to explore the limitations and synthetic potential of the intermolecular arene-alkene *meta* cycloaddition. The initial studies were exploratory and directed towards improving several known syntheses by searching for appropriate substituents on arenes and alkenes. We anticipate the results will form the basis for further experiments and additional applications in synthesis.

Our initial objective was to study asymmetric organic photoreactions. We proposed to explore the asymmetric arene-alkene *meta* cycloaddition by using chiral auxiliaries on arenes and alkenes as asymmetric inductors. Because the *meta* cycloaddition already affords a great increase in structural complexity, asymmetric induction in the same step would greatly benefit natural product synthesis. We hoped to achieve optically active precursors to isoiridomyrmecin (29) and modhephene (25). (Scheme 16)

Another goal was to study the mechanism of arene-alkene *meta* cycloaddition. Although much work on the mechanism has been done, it is still poorly understood. As *meta* cycloaddition occurs with a broad range of arenes and alkenes, more experimental data and other evidence are needed. We proposed to study arene fluorescence quenching by...
alkenes, intramolecular isotope effects, and anticipated that the results would provide more
evidence to elucidate the mechanism of meta photocycloadditions of arenes to alkenes.
Important questions concern the concertedness of the reaction, whether bond formation is
synchronous or asynchronous, and the existence of biradical intermediates or exciplexes.

As this work progressed, we also found a simple means for improving the
efficiency of meta cycloaddition of vinyl esters.
RESULTS AND DISCUSSION


As the introduction indicates, much remains to be understood about arene-alkene
meta cycloaddition. This section will focus on experiments, results, and interpretation. The
contents are in the following order: 1) discovery of new alkenes and arenes, which can
prevent polymer formation and improve reaction efficiencies; 2) introduction of chiral
diestereogenic centers on either alkenes or arenes to achieve maximum asymmetric meta
cycloaddition; and 3) mechanistic discussions based on fluorescence quenching and
isotopic labelling experiments.

2. meta Photocycloaddition of Indan and Hindered Vinyl Esters.

There are several major limitations that prevent the widespread synthetic
applications of meta cycloadditions. One of them is poor yields. Intermolecular meta
cycloadditions are generally characterized by poor yields and the requirement of large
quantities of reagents. For example, photocycloaddition of vinyl acetate to benzene or indan
is generally done with "neat" reagents, which requires large volumes to capture light
efficiently, and proceeds in very low yield. Thus, one important goal would be improving
the reaction efficiency.

In the last decade, intermolecular meta cycloaddition has proven to be of synthetic
value. The synthesis of (±)-modhephene$^8$ (25), (±)-decarboxyquadrone$^{11}$ (28) and (±)-
isoiridomyrmecin$^{12}$ (29) involve vinyl acetate as the alkene moiety. In some cases,
cyclopentenes are used as an alkene moiety. However, all these cycloadditions suffer from
low yields. In one report$^{14}$, irradiation of 82 g of indan and 103 g of vinyl acetate yielded
only 4.2 g of photoadduct.

Vinyl acetate is available commercially. Substituted vinyl esters are generally prepared by transesterification. Two hindered vinyl esters, 45 and 46, were needed in this study and prepared by mercury catalyzed transesterification. (Scheme 17)

Scheme 17

We first repeated previous work on meta cycloadditions of vinyl acetate to benzene and indane. Both reactions proceeded with low yields in hexane at moderate concentration (\( \sim 10^{-2} \text{ M} \)). Extensive polymerization was observed. However, irradiation of vinyl cyclohexanecarboxylate (45) with indan in hexane afforded meta adduct 47a in about 60% isolated yield. (Scheme 18) This reaction was monitored by \(^1\text{H} \) NMR spectroscopy and showed virtually no polymer formation. In one experiment, irradiation of 3.0 g of 45 and 5 g of indan gave 2.8 g of product, characterized as meta adduct, ca. 80% pure. The photoadduct was purified by column chromatography and the structure was identified as endo adduct 47a, (Scheme 18) based upon comparison with known meta cycloadducts.
The $^1$H NMR spectrum of 47a shows no aromatic resonances. Instead, one vinyl proton resonance appears at 5.73 ppm, (dd, $J = 1.9, 5.1$ Hz), while the other one is at 5.11 ppm, (d, $J = 5.2$ Hz). The proton adjacent to the carboxylate group resonates at 5.40 ppm, (dd, $J = 5.9, 8.5$ Hz). The $^{13}$C NMR spectrum displays sixteen resonances. These data indicate that 47a is the meta cycloadduct from indan and vinyl cyclohexanecarboxylate (45). The bulky carboxylate is on the less hindered side to form an endo adduct.

Product stereochemistry follows from NMR coupling constants of the methine adjacent to the ester oxygen. By comparing the dihedral angles shown by molecular models of exo and endo adducts, the dihedral angle of the exo adduct is close to 90°. This agrees with the endo adduct that a dd coupling pattern was observed in the $^1$H NMR spectrum for the proton adjacent to the carboxylate oxygen. Thus, the possibility of an exo adduct is eliminated. If the exo adduct was formed, the $^1$H NMR spectrum would be expected to show a ddd coupling for the exo proton, the one adjacent to the carboxylate group.

Figure 1 shows the relationship between conversion and irradiation time for meta photocycloaddition of vinyl cyclohexanecarboxylate (45) and for vinyl acetate. Throughout the entire irradiation, the sample with 45 looked clear and no polymer formation was observed, while the reaction with vinyl acetate resulted in a large amount of precipitant on the quartz vessel.
This plot shows the remarkable difference in behavior between 45 and vinyl acetate. Vinyl cyclohexanecarboxylate (45) proves to be more substantially efficient than vinyl acetate in the arene-alkene meta cycloaddition. One major adduct 47a was isolated. This indicates that the reaction is regio- and facialselective. Over irradiating the reaction resulted in formation of minor adduct 47a', which is a regioisomer of 47a.

When a similar procedure was used with vinyl adamantanecarboxylate (46), very low reactivity was observed. Irradiation of 46 and indan for thirty hours generated less than 10% of meta adducts. The reason for the low reactivity of this reaction is not clear. One assumption is that the bulky adamantyl group is not geometrically compatible with indan.

**Hydrolysis of Photoadduct 47a in Base**

The ester linkage in cycloadduct 47a can be easily hydrolyzed by KOH in MeOH. (Scheme 19) The resultant polycyclic alcohol 48 was characterized by 1H NMR and is a useful synthon for (±)-modhephene (25) and (±)-decarboxyquadrone (28).
Hydrogenation of Photoadduct 47a

The double bond in the novel complex photoadduct 47a can be easily reduced by hydrogenation, without destroying the cyclopropane ring. The reduced product 49 was purified by chromatography. The $^1$H NMR spectrum indicates that the two vinyl protons in 47a have disappeared and the mass spectrum gave the correct molecular weight of 274. (Scheme 20)

Scheme 20

3. *meta* Cycloaddition of Vinyl Cyclohexanecarboxylate (45) to Different Arenes.

Among intermolecular *meta* cycloadditions, benzene, toluene, indan, anisole and xylenes are the most commonly used arenes. Our initial experimental results on the reactions of benzene and indan with 45 indicated that indan is slightly more reactive than benzene. What influence does the fused ring have on the efficiency of *meta* photocycloaddition? To explore the effect of ring size on *meta* cycloaddition two additional arenes 50a and 50b were studied. (Scheme 21) Each arene was irradiated under the same condition for 12 hours and the conversion versus ring size was plotted. Results are shown in Figure 2. In each case, the *meta* cycloadduct was isolated and characterized.
This data indicates that changing the ring size of indan has only a modest influence on meta cycloaddition reactivity.

Scheme 22 provides the synthesis of 50c, which was not commercially available. This was easily prepared from benzosuberone according to the literature.36

Comparison of the electronic effects of different substituents on arenes in meta cycloadditions was also of interest. Benzene, toluene, and anisole were chosen to react with 45 at 254nm at the same concentration. The extinction coefficient at 254nm of each arene was measured, and the conversions, determined by 1H NMR integrations, are listed in Table 1. The major adducts were isolated by chromatography and characterized. For toluene and o-xylene, the reactions were slow and the methyl group(s) was( were) on the bridge head(s). For anisole, the reaction was fast and two adducts were isolated. A methoxy group was found at the bridge head in both isomers, which were believed to be
regioisomers arising from the substituted alkene.

Table 1

<table>
<thead>
<tr>
<th>Arenes</th>
<th>$\epsilon_{254\text{nm}}$ (cm$^{-1}$mol$^{-1}$)</th>
<th>meta adduct yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) toluene</td>
<td>180</td>
<td>&lt; 15%</td>
</tr>
<tr>
<td>b) o-xylene</td>
<td>~200</td>
<td>~ 15% (54b)</td>
</tr>
<tr>
<td>c) anisole</td>
<td>680</td>
<td>35% (two adducts 54c and 54c')</td>
</tr>
</tbody>
</table>

This table shows that anisole is the most efficient arene with respect to 35% yield among the three for meta cycloadditions. It might be due to the electronic effect of the methoxy group, which enhances the formation of a polar intermediate species, but it also might be due to the larger absorption at 254nm. Further investigation is needed.

4. Asymmetric meta Cycloadditions.

Arene-alkene meta cycloadditions are remarkable reactions, which have proven to have great application potential in synthesis for the rapid assembly of complex ring systems. Asymmetric cycloaddition might be based on the results that we achieved previously about this reaction.

A suitable candidate for asymmetric meta cycloaddition is one that not only carries a chiral group, but also has no absorption in the UV region to compete with arene absorption. It has to be photochemically inert. Chiral groups either on the vinyl ester or the arene will induce asymmetric reaction. We first prepared a chiral vinyl ester 56 and a chiral vinyl ether 58 by transesterification and transetherification, respectively. (Scheme 23)
Later we prepared the racemic chiral indan derivative 59. (Scheme 24)

The significance of using chiral groups as asymmetric inductors is to achieve optically pure adducts photochemically, which is still an area that is poorly understood.

**Asymmetric Induction from Chiral Vinyl Ester 56 and Chiral Vinyl Ether 58**

Photoirradiation of indan with chiral vinyl ester 56 generated *meta* cycloadducts in 20% yield after 20 hours. The product was isolated by chromatography and characterized spectroscopically. The 360 MHz NMR was similar to that of related cycloadducts. This shows a vinyl proton $H_a$ which resonates at 5.74 ppm, an overlapped two sets of dd. The other vinyl proton $H_b$ resonates at 5.53 ppm as a doublet for each diastereomer. Proton $H_c$ on the ring, adjacent to the carboxylate group, is at 5.46 ppm two sets of approximate triplet. Expansion of the $^{13}$C NMR spectrum shows a doublet for each carbon resonance (see the expanded spectrum in Appendix), which provides evidence that two diastereomers
were present. The ratio of these doublets is 1.4 : 1 by resonance intensities. If we assume that each corresponding carbon on each diastereomer has the same relaxation time, \( T_1 \), this provides evidence that the (±)-pinane group induces partial asymmetric meta cycloaddition and the ratio of 1.4:1 corresponds to 17% diastereomeric excess. Although the diastereoselectivity was not very high, this was the first example of asymmetric meta cycloaddition. As the two diastereomers 60a and 60b were inseparable by column chromatography, the absolute configuration of each diastereomer is unknown.

This experiment was repeated several times with the same results. The integration ratio for the carbon resonances varies from 1.2~1.4, depending on which carbon resonance is integrated. Although this reaction gives partial asymmetric induction, it provides a prospect for future research in asymmetric photochemistry.

The (+)-pinane chiral auxiliary could be removed by hydrolysis with KOH in
MeOH, leaving the polycyclic skeleton untouched. (Scheme 25) After removal of the chiral group, the two non-equivalent diastereomers become enantiomers. (Scheme 26) The optical rotation of the mixed alcohol was -0.58 ml dm\(^{-1}\) g\(^{-1}\), which indicates formation of non-equivalent amounts of 61a and 61b. This also supports the fact that asymmetric \textit{meta} cycloaddition occurred. The \(^{1}\text{H} \text{NMR} \) spectrum of the enantiomeric alcohol was identical to that from hydrolysis of 47a. The \(^{13}\text{C} \text{NMR} \) spectrum shows 11 resonances and no doublet on each resonance. (see Appendix)

Scheme 26

\[
\begin{align*}
\text{Achiral} + \begin{array}{c}
\text{R}^* \\
\text{S}^*
\end{array} & \rightarrow \begin{array}{c}
\text{R}^* \\
\text{S}^*
\end{array} \text{ Diastereomers} \\
\text{R}^* & \rightarrow \begin{array}{c}
\text{R} \\
\text{S}
\end{array} \text{ Enantiomers}
\end{align*}
\]

Reaction of chiral vinyl ester 56 and anisole provided two pairs of diastereomers. The reaction conversion reaches 43% after a 19 hours of irradiation, monitored by \(^{1}\text{H} \text{NMR} \). Each pair (62a, 62b versus 62c, 62d) was regioisomers to each other, and they were separable by column chromatography. Among each pair of separated regioisomers, there were two diastereomers that were inseparable. (Scheme 27) Again, \(^{13}\text{C} \text{NMR} \) spectrum of each pair of diastereomers shows doublet for each resonance with a ratio of about 1.05~1.33, which indicates the partial asymmetric induction of (±)-pinane auxiliary in \textit{meta} photocycloaddition.
Enol ethers are functional groups that are often used as the ethylenic component for \textit{meta} cycloaddition. We chose \( \text{1-menthyl} \) as the chiral auxiliary on the vinyl ether for asymmetric \textit{meta} cycloaddition. \( \text{1'-Menthyl vinyl ether (58)} \) was prepared by mercury catalyzed transetherification. Irradiation of 58 and indan, however, showed very low reactivity and no photoadduct was isolable from the crude mixture.

The efforts toward asymmetric \textit{meta} cycloaddition using chiral auxiliaries on alkenes are significant. Although the asymmetric induction is not complete yet, these results show that asymmetric induction in \textit{meta} photocycloaddition is possible. More work is necessary to maximize the diastereoselectivity in order to reach the goal, a single stereoisomer.

\textbf{Asymmetric Induction from 1-Trimethylsilyloxy Indan (59)}

Introduction of a chiral auxiliary on indan is another way to approach an
asymmetric \textit{meta} cycloaddition.

To explore this question, 1-trimethylsilyloxy indan (59) was prepared in racemic form. We expected to observe an enhancement of facial selectivity to \textit{meta} cycloaddition because of the stereogenic centers. The trimethylsilyl group is well-known for its bulkiness, and the ease of removal by reaction with CsF. The stereo- and regiochemical possibilities posed by this reaction are complex. In addition to \pi facial selectivity, two possible regiochemistries arise from the unsymmetric alkene. Each product could be a racemate. The possibilities are shown in Scheme 28. If the reaction is facial selective and the substituents on the alkene tends to stay away from the approaching direction (they always do), only enantiomeric photoadducts will be formed from the racemic 59 and vinyl ester 45; otherwise, diastereomeric photoadducts will result.
Scheme 28  Facile Selective meta Cycloaddition

(R) - 59

1,3 - Addition  
2,4 - Bonding

1,3 - Addition  
2,4 - Bonding

(S) - 59

Enantiomers major

Enantiomers minor

TMSO

(R)  - 59

63a

(S)  - 59

63b

TMSO

(R)  - 59

63c

(S)  - 59

63d

TMSO, H

TMSO
Irradiation of racemic 59 and vinyl cyclohexanecarboxylate (45) for 14 hours gave ca. 10% conversion to cycloadducts. Two photoadducts were separated by column chromatography in a 4:1 ratio. The major adduct was identified, by reference to the spectrum data of 47a, as racemic 63a and 63b, and the minor as racemic 63c and 63d. In one experiment data at lower temperature (-17°C), the reaction yield was increased to 44%, but with no change in regio- and stereoselectivity. These results, which are still exploratory, demonstrate a high degree of facile selectivity, which indicates that experiments with optically active 59 should be successful. To eliminate the possibility of regioisomer formation, the next candidate should be 2-trimethylsilyloxy indan, which has a meso structure with a chiral center. (Scheme 29)

Treatment of the photoadducts with CsF in DMSO for 24 hours should cleave the trimethylsilyl auxiliary to the corresponding alcohols. The cyclopropane rings would remain untouched.

5. Fluorescence Quenching of Reactive Transitions.

How do meta cycloadditions occur and why are reaction efficiencies so different from one case to another? These questions may be answered through fluorescence quenching studies.

When a molecule is photochemically promoted to an excited state, the fate of the excited molecule can be described by a Jablonski diagram.21
Once irradiated, an excited molecule drops back quickly to its lowest vibrational level, which is the first singlet excited state, $S_1$. At this state a molecule can undergo various physical and chemical processes. These processes can be described by three major pathways. The first pathway involves the singlet state molecule falling to the ground state, $S_0$. This process ($S_1 \rightarrow S_0$) results in the loss of energy either in the form of light (fluorescence) or heat (internal conversion). The second pathway is one in which the singlet state molecule interacts or reacts with a ground state molecule (quencher) before the emission occurs. The third pathway is called intersystem crossing. In this case a singlet state molecule crosses over to its triplet state, $T_1$ ($S_1 \rightarrow T_1$). It then falls to the ground state, $S_0$. The latter process ($T_1 \rightarrow S_0$) results in the emission of heat or light (phosphorescence). This is an important process for some molecules, such as ketones.

Information about singlet state reactivity can be obtained from fluorescence quenching studies. For an excited molecule that emits fluorescence, introduction of a quencher molecule will cause a competition between the fluorescence emission and the
bimolecular interaction. As a result, the fluorescence decreases as the quencher concentration increases. The amount of emission reduction is proportional to the increase in the quencher concentration. This relationship is described in the Stern-Volmer Equation.\(^{40}\)

\[
\frac{\Phi^0}{\Phi} = \frac{I^0}{I} = 1 + \frac{k_q}{k_f} [Q]
\]

Equation (1)

\(\Phi^0\): quantum yield in the absence of quencher

\(\Phi\): quantum yield in the presence of quencher

\(I^0\): fluorescence intensity in the absence of quencher

\(I\): fluorescence intensity in the presence of quencher

\(k_q\): quenching rate coefficient

\(k_f\): observed rate coefficient for decay of fluorescence in the absence of quencher

\([Q]\): quencher concentration

If the experimental conditions are kept constant, the ratio of fluorescence intensities equals the ratio of quantum yields in the Stern-Volmer Equation. Theoretically, a plot of \(I^0/I\) versus \([Q]\) will be linear with a slope equal to \(k_q/k_f\). Singlet lifetimes, \(\tau_s\), are known values for different molecules. Singlet lifetime is defined as \(\tau_s = 1/k_f\). Hence quenching rate constants can be determined.

For indan, anisole and o-xylene, measured lifetimes (\(\tau_s\)) equal 29.7, 30, and 32 ns, respectively.\(^{37}\)

In the present work, fluorescence quenching was used to seek an explanation for the difference in reactivity of vinyl esters. The plot in Figure 3 shows results of indan fluorescence quenching by vinyl cyclohexanecarboxylate (45). The slope was measured and \(k_q\) was calculated to be \(3.39 \times 10^9 \text{ L mol}^{-1}\text{s}^{-1}\).
With the same method, other quenching results, calculated from Stern-Volmer plots, are listed in Table 2.

Table 2. Quenching Rate Constants for Some Arenes

<table>
<thead>
<tr>
<th></th>
<th>indan</th>
<th>anisole</th>
<th>o-xylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ ns</td>
<td>29.7</td>
<td>30.0</td>
<td>32.0</td>
</tr>
<tr>
<td>quenching rate constants:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vinyl ester 45 (L mol⁻¹ s⁻¹)</td>
<td>3.39x10⁹</td>
<td>4.35x10⁹</td>
<td>1.36x10⁹</td>
</tr>
<tr>
<td>vinyl acetate (L mol⁻¹ s⁻¹)</td>
<td>3.24x10⁹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cyclopentene (Lmol⁻¹ s⁻¹)</td>
<td></td>
<td>2.57x10⁸</td>
<td>3.25x10⁷</td>
</tr>
</tbody>
</table>

From this table, it can be seen that vinyl acetate and vinyl cyclohexanecarboxylate (45) are both quite efficient for quenching arene singlet energy with $k_q$ near the diffusion controlled value. For each quencher, comparing reactivity with its quenching rate constant shows a good correlation. For example, after 16 hours of irradiation, 30% conversion was accomplished for the meta cycloaddition of anisole and 45, while 18% conversion was observed for meta cycloaddition of o-xylene with 45. In the cases of vinyl acetate and 45,
both quench indan singlet energy with the same efficiency, but they are very different in reaction yields in meta cycloaddition. This is because of polymerization which lowers the efficiency of meta cycloaddition. The results suggest that initiation of oligomer formation is somehow connected to the bimolecular interaction of vinyl acetate and the excited state indan.

No exciplex emission was observed at longer wavelengths in either nonpolar or polar solvents, which suggests that exciplex formation does not occur, or that the exciplex is non-emissive. From our previous regioselectivity studies, it is believed that the development of polarity in the arene ring as the alkene approaches is quite possible. The quenching rate constants for cyclopentene in Table 2 are $2.57 \times 10^8$ and $3.25 \times 10^7$ L mol$^{-1}$ s$^{-1}$ respectively. These results are compatible with Cornelisse's results. Cornelisse determined the fluorescence quenching constants of benzene by cyclopentene in the presence ($8.3 \times 10^7$ L mol$^{-1}$ S$^{-1}$) and absence ($7.9 \times 10^7$ L mol$^{-1}$ S$^{-1}$) of oxygen in 1988 using the Stern-Volmer plots.


One important feature of the meta cycloaddition is that the two adducts can be formed from the cyclopropane ring closure. (Scheme 30). This feature provides a means of probing whether the reaction mechanism is a fully concerted formation of three bonds, or if the intramolecular cyclization occurs subsequent to the alkene addition and involves an intermediate species.
The three mechanisms that have been proposed are: (1) formation of prefulvene from excited benzene, followed by addition of alkene; (2) formation of a biradical or a zwitterion from excited benzene and alkene, followed by closure of the three membered ring; and (3) a fully concerted mechanism. (Scheme 31)

In the second mechanism, one can imagine that the electron cloud of the excited arene becomes polarized upon approach of the alkene. In this early stage, bond formation
between the alkene and the arene takes place if the substituents are in the right position to stabilize the polarized complex. If the bonds become fully formed, the intermediate loses its polarization and presumably attains biradicaloid character. In the second stage of the reaction, substituents can only influence the direction of the closure of the three membered ring.

In order to determine which of the three mechanisms is closest to reality, it is important to know which bond(s) is (are) formed in the primary step and which bond formation is rate determining. We investigated two intramolecular deuterium isotope effects, which could give information about the timing of bond formation.

2-Deuterio anisole (64) was prepared from anisole in BuOK at -77°C followed by addition of D₂O. A mixture of 2-deuterio anisole and cyclopentene in hexane was irradiated at 254 nm and two meta products 65 and 66 were generated in a ratio of 20:1. The meta adducts were isolated by preparative gas chromatography. Deuterium distributions in the adducts were determined by integration of the deuterium NMR spectra. Only labelled deuteriums appear in the deuterium NMR spectrum. The integration ratios are listed in Scheme 32. The deuterium NMR spectra are in Appendix.

Scheme 32

![Scheme 32 Diagram](image)

65a: R₁ = H, R₂ = D
65b: R₁ = D, R₂ = H
66a: R₁ = H, R₂ = D
66b: R₁ = D, R₂ = H

Intramolecular Isotope Effect: 65a : 65b = 1.07 : 1 66a : 66b = 1.08 : 1

The ratios in Scheme 32 indicate that the deuteriums are unevenly distributed in each isomer. It shows the effects of deuterium at the site of addition on the direction of
closure of the three membered ring. If closure of the three membered ring occurs before the bonds are completely formed between the alkene and the arene, an isotope effect would be observed, because the adducts would be formed from an unsymmetrical precursor. However, the experimental results show little isotope effect within experimental error, which suggests the (almost) complete formation of the two addition bonds prior to closure of the three membered ring. This result is in agreement with the recent work of Comelisse on addition of 2-deuterio toluene to cyclopentene. In their work, the deuterium distribution ratios are between 1.0 ~ 1.22. It is believed a polar intermediate or exciplex mechanism is involved.

3-Deuterio-ortho-xylene was prepared from 3-bromo-ortho-xylene via a Grignard reaction which was quenched by D$_2$O. When 3-deuterio-ortho-xylene (67) was irradiated with cyclopentene following the same procedure, two regio products, 68 and 69 were obtained in a ratio of 2:1. Intramolecular deuterium distributions were again determined by deuterium NMR. These are shown in Scheme 33. In this case, a modest isotope effect was observed.

Scheme 33

Analysis of these results remains problematic. In theory, alkene addition to the arene carbon which has a deuterium atom would cause an $\alpha$ secondary isotope effect. As
the hybridization of the carbon changes from sp² to sp³ through the meta cycloaddition, an inverse isotope effect would be expected. This means that the ratio of $^{68}\text{a} : ^{68}\text{b}$ and $^{69}\text{a} : ^{69}\text{b}$ would be less than 1. However, the experimental results conflict with this analysis. A proper explanation of these results from the mechanistic point of view is needed. One thing is clear: since the deuterium distributions are not equal in each adduct, the reaction can't be fully concerted.
CONCLUSIONS

This research has explored the limitations and synthetic potential of arene-alkene meta photocycloadditions, with the goal of providing improved approaches to polycyclic molecules. The reaction efficiency has been significantly improved by using vinyl cyclohexanecarboxylate (45) instead of vinyl acetate. Other influences on reactivity, such as fused ring size and different substitute groups on benzene, have been explored. Modifications of meta adducts provide practical approaches to natural product synthesis. Attempted asymmetric meta cycloaddition by using a chiral auxiliary on an alkene has achieved partial asymmetric induction, which has brought great hope for total asymmetric meta cycloaddition. Introduction of a chiral auxiliary on indan has made the meta cycloaddition facial selective. Fluorescence quenching studies have explained the difference in efficiency between 45 and vinyl acetate. However, the unexpected results of the intramolecular isotope effect experiments are not completely understood. More studies on mechanisms are needed. This work remains substantially incomplete primarily because the focus of research shifted towards studies of a novel reaction of enynes, which is described on the next chapter.
CHAPTER TWO

CONJUGATED ENYNE PHOTOREARRANGEMENT

INTRODUCTION

1. **Electrocyclic Reactions.**

Electrocyclic reactions are really very simple processes. Their studies of them led to formulation of the theory of orbital symmetry conservation during the mid 1960s.\(^{39,40}\) In the course of studies on the synthesis of vitamin B\(_{12}\), Woodward examined an electrocyclic reaction and found that thermal and photochemical activation gave different stereochemical results.\(^{41}\) These observations led to the development of orbital symmetry theory.

The orbital symmetry theory is profoundly simple. In one formulation, the phase relations among molecular orbitals in a fully conjugated system afford a cyclic transition state which is energetically favorable only under certain rotational operations. The consequences can be traced stereochemically. Woodward and Hoffmann have proposed general rules for the preferred or allowed routes for electrocyclic reactions of linear polyenes. When the total number of \(\pi\) electrons in the non-cyclized component equals \(4n\) where \(n\) is an integer, the thermal process will be conrotatory. If the total is \(4n+2\), where \(n\) is an integer, the reaction will be allowed thermally in the disrotatory mode. Photochemical reactions have opposite relationships; these are summarized in Scheme 34.
The thermal and photochemical interconversion of butadiene and cyclobutene have been extensively investigated in the last several decades. The reactions have been explained through orbital symmetry and correlation diagrams, the frontier orbital approach, and Hückel or Möbius transition state aromaticity.

In recent years, quantum mechanical calculations on molecules and chemical reactions have become possible. Theoretical calculations on the butadiene-cyclobutene potential surfaces have been reported at all different levels. Although some of the theoretical studies are still controversial, the empirical stereochemical results have tremendous applications. A variety of experimental work has also been reported in recent years.

In one recent study, Squillacote and co-workers investigated the reaction of 2,3-dimethyl-1,3-butadiene. This diene closes to cyclobutene photochemically in a disrotatory manner at 15 °K in a matrix. Examination of the photochemistry of (E, E)-1,4-dideuterio-2,3-dimethyl-1,3-butadiene showed for the first time that the s-cis conformer undergoes both electrocyclic closure and double bond isomerization in roughly a 1:3 ratio.

The authors postulated an excited-state surface that combines two photochemical events and
includes a concerted nonsynchronous disrotatory closure.

Scheme 35

The thermal chemistry of 2,3-dimethyl-1,3-butadiene has two pathways: a conrotatory cyclobutene closure and reopening with a barrier of 48 kcal/mol and a pathway via an allylmethylene biradical with a barrier of 55 kcal/mol. (Scheme 36)

Scheme 36

The photochemical ring opening of cyclobutenes also has been investigated. Some reactions that contradict orbital symmetry rules were also reported in recent years. In 1990, Leigh and Clark reported cases in which orbital symmetry did not
explain the stereochemical results.\textsuperscript{52} Photochemical ring openings of cis- and trans-3,4-
dimethyl-1,3,4-trimethyl, and 1,2,3,4-tetramethyl cyclobutene proceed
non-stereospecifically upon irradiation at 193 nm and 214 nm. Both "allowed" and
"forbidden" predictions are observed. In these cases, orbital symmetry factors do not play a
role in controlling the stereochemistry. (Scheme 37)

Scheme 37

\begin{align*}
\text{cis} & \quad \xrightarrow{185 \text{ nm pentane}} \quad \text{E, E} + \text{E, Z} + \text{Z, Z} \\
\text{trans} & \quad \xrightarrow{193 \text{ nm pentane}} \quad \text{E, E} + \text{Z, Z} + \text{E, Z} + \text{Z, E} \\
\end{align*}

Carpenter\textsuperscript{53} has predicted that the substituent effects on forbidden processes will be
larger than the analogous substituent effects on allowed reactions.

Houk and co-workers have used ab initio methods to calculate the transition
structures for the disrotatory electrocyclization of butadiene.\textsuperscript{51} The theoretical calculations
show that the unusually large stabilization of the disrotatory transition structure by electron-
acceptor groups is due to the stabilization of the high-lying HOMO by the vacant
substituent orbitals. Donors have a smaller effect on the activation energy. Geometric
constraints may cause the reaction to go through a "forbidden" process. One example
below is the case studied earlier by Miller and co-workers, e.g.:54

Scheme 38

\[ R_1 = \text{Bu, Cl, H, Cl, OMe, Me} \]
\[ R_2 = \text{Bu, Cl, tBu, tBu, tBu, tBu} \]

For a case like this, it is better to consider the reaction products as "expected" rather than "allowed" or "forbidden" since the allowed process is restricted by the molecular structure and then the competition from other pathways becomes significant.

In a similar reaction, 1,3-cyclohexadienes (Scheme 39) interconvert with 1,3,5-hexatriene. In this case, the ring-closing process is generally favored thermally while ring-opening is photochemically favored.55

Another classic example for a six electron system is the Bergman rearrangement,56 in which electrocyclic ring closure and ring opening occur.

Our interest is to apply this reaction to the synthesis of 1,2-cyclobutadiene, which has posed a great challenge among cyclic allenes. In the present work, we drew an analogy from these known electrocyclic reactions to explore a potential synthesis of 1,2-cyclobutadiene.

2. Cyclic Allenes.

Allenes (1,2-propadienes) are the smallest members of the homologous series of
hydrocarbons known as cumulenes. The centrally bonded carbon is sp hybridized. As a consequence, "strain free" allenes prefer linear geometries and cyclic allenes can be substantially strained. As the ring size decreases, the kinetic stability of allenes decreases with the increase of strain. An additional geometric consequence is the twisting of the allene towards planarity.\textsuperscript{57,58}

Calculations have predicted the bond angles of the series of allenes from nine to five membered rings. These are shown in Scheme 40. Bending angles and out-of-plane torsional angles are given for the homologous series.\textsuperscript{59}

Scheme 40

The structures of small ring cumulenes have been studied for some years. Moore and Moser's early experiments\textsuperscript{60} suggested a singlet diradical or a zwitterion as the ground state for 1,2-cyclohexadiene. More recent experimental and computational results provide evidence for a chiral closed shell structure.\textsuperscript{61}(Scheme 41)

Scheme 41

To date, 1,2-cyclohexadiene is the smallest cyclic allene synthesized, although there is some evidence for the existence of 1,2-cyclopentadiene.\textsuperscript{62} Considerable effort towards synthesizing 1,2-cyclopentadiene has been made in our own group, so far without success.

The synthesis and inherent stabilities of several members in the series of 1-phenyl-substituted allenes have been described by Loiselle and Johnson.\textsuperscript{63} Scheme 42 displays the series from ten to six membered rings and data on their kinetic stabilities.
With efforts focused on larger rings, synthesis of 1,2-cyclobutadiene seemed a distant goal. This interesting C₄H₄ isomer is probably too strained to be made by any of the solution phase methods employed to prepare larger rings. Hence, an entirely new approach was required.
STATEMENT OF THE GOALS

For many years, our research group has been interested in both strained molecules and photoreactions. Our theoretical and experimental studies of small cyclic allenes in the ground and excited states have led us to a better understanding about the nature and limitations of chemical bonding in strained $\pi$ systems.

One general goal of this research is to explore the structural limitations of small ring cyclic allenes. 1,2-Cyclobutadiene poses a formidable synthetic challenge. The fundamental questions include: (a) Does 1,2-cyclobutadiene exist? (b) What is the structure? (c) If 1,2-cyclobutadiene exists as a highly reactive intermediate, how can we prove this?

To answer the latter question, we proposed a new electrocyclic rearrangement. By using different substituents on enynes, electrocyclic ring closure and opening would result in the transposition of $R_1$ and $R_2$ as shown in Scheme 43. If an enyne can electrocyclize to a 1,2-cyclobutadiene, then facile thermal opening would be expected as a second step. This process is similar to the Bergman Rearrangement.\textsuperscript{56}

Scheme 43

Our initial goal was to explore the possibility and the generality of this photorearrangement, for which only one previous example is known.\textsuperscript{64} Establishment of a reversible process would provide strong evidence for the existence of 1,2-cyclobutadiene, the smallest possible cyclic allene.

Ab initio calculations on cyclobutadiene are also in progress; results will be outlined
in this chapter.

This chapter also presents the results of exploratory work on the conjugated enyne photorearrangement, including the careful design and synthesis of the starting materials, the photochemistry of conjugated enynes, and the independent synthesis of selected photoproducts.
RESULTS AND DISCUSSIONS

In this section, the photochemistry of a variety of conjugated enynes is described and interpretations of the results are given. It appears most logical to present the results in the following order: (1) synthesis; (2) photorearrangement of alkyl and phenyl 1,3-enynes; (3) extended polyenynes; and (4) discussions of mechanisms. The work on polyenynes can be considered "exploratory". We are interested principally in the gross observable photorearrangement, leaving more subtle mechanistic studies for later work.

1. Synthesis of 2,4-disubstituted-1,3-enynes.

Our initial goal was to synthesize a representative collection of conjugated enynes. Fortunately, these substances are well known and many routes are available. Several of the substrates studied were commercially available. These include enynes 70 and 71 (Scheme 44).

Metal catalyzed coupling provides a general route to synthesize enynes. Starting with commercially available 2-methyl-1-buten-3-yne (72) and iodobenzene, coupling at room temperature in diethylamine with a palladium catalyst gave 2-methyl-4-phenyl-1-buten-3-yne (73) in 73% yield. This compound has been previously described.63

Scheme 44

\[
\begin{align*}
\text{70} & \quad \text{71} \\
\text{72} + \text{PhI} & \xrightarrow{(\text{Ph}_3\text{P})_2\text{PdCl}_2 \text{ Cul, Et}_2\text{NH}} \quad \text{73}
\end{align*}
\]
Similarly, 2-phenyl-1-octen-3-yne 76 was obtained in 55% yield by coupling α-bromostyrene (74) with 1-hexyne (75). This compound has not been reported previously to our knowledge. (Scheme 45)

\[
\begin{align*}
\text{Ph} & \text{Br} + \text{C}_8\text{H}_{17} & \xrightarrow{\text{(Ph}_3\text{P)}_2\text{PdCl}_2, \text{Cul, Et}_2\text{NH, RT}} & \text{Ph} \equiv \equiv\\
74 & 75 & 76
\end{align*}
\]

Our next compound of interest is endiyne 78. Linstrumelle\textsuperscript{60} has reported that vinylidene chloride (77) couples with 2 equivalents of 1-hexyne to give 78. (Scheme 46) However, our present work gave two products, characterized as 78 and the self-coupling product diyne 79. After column chromatography on silica gel, the diyne 79 and endiyne 78 were separated as pure liquids.

\[
\begin{align*}
\text{Cl} & \equiv \equiv + \text{C}_8\text{H}_{17} & \xrightarrow{\text{(Ph}_3\text{P)}_4\text{Pd, Cul, Et}_2\text{NH, RT}} & \equiv \equiv \\
77 & 75 & 78 \text{ (34%)} & 79 \text{ (66%)}
\end{align*}
\]

Using the same palladium coupling reaction, we expected to synthesize dieneyne 81 from 2-bromopropene (80) and 2-methyl-1-buten-3-yne (72). (Scheme 47) This reaction gave 81 as the major product with small amounts of 82. Dieneyne 81 is sensitive to air, and polymerizes at room temperature. The first synthesis of 81 was accomplished in a very different way, reported half a century ago.\textsuperscript{66,67}
Cyclic enyne 87 is another compound of interest for our exploratory investigation. 1-Bromo-cyclooctene (85) is easily prepared from cyclooctene (83). Under the same palladium coupling conditions, 1-hexynyl cyclooctene (87) was obtained in 96% yield. (Scheme 48)

Alkynyl ketones are a different type of compound for this photorearrangement. We proposed and successfully carried out a two step synthesis to obtain methyl ketone 89 and phenyl ketone 91. (Scheme 49) However, both compounds decomposed on an alumina column and distillation could not separate the products from their starting materials.
2. Photochemistry of Conjugated Enynes.

(a) Photorearrangement of 2,4-Dialkyl-1-buten-3-yn

All enyne photorearrangement experiments were performed in dilute solutions of substrate. In two quartz tubes, 50 mg of 70 or 71 were dissolved in 50 mL of spectrophotometric grade hexane. The solutions were purged with nitrogen and irradiated with 254 nm UV light. Although 70 and 71 display $\lambda_{\text{max}}$ at 232 nm, the absorption band extends to longer wavelengths. The reaction mixtures were analyzed by gas chromatography intermittently. At low conversion, a single photoproduct was detected from each reaction. After 37 hours, yields of the new photoproducts reached ~34%. The photoproducts were separated by preparative gas chromatography and characterized by spectroscopy. (Scheme 50)

In each case, the isolated photoproducts displayed spectroscopic properties which were remarkably similar to those of the starting enyne. All data were entirely consistent with the structures of isomeric enynes 92 and 93.

To prove the structure of the photoproduct 93, a four-step independent synthesis of 2-n-butyl-1-penten-3-yn (93) was carried out as shown in Scheme 51. Regioselective synthesis of vinyl bromide 94 was previously reported. Palladium catalyzed coupling of vinyl bromide and trimethylsilyl acetylene afforded 95 in 90% yield. Removal of the trimethylsilyl group by $\text{K}_2\text{CO}_3$/MeOH, followed by methylation at -77°C, gave 93 which was identical with the photoproduct of 71. After several trials of each step, 2-n-butyl-1-penten-3-yn (93) was obtained in a total yield of 43% from 75 to 93.
The 1H and 13C NMR spectra of the independently synthesized 2-n-butyl-1-penten-3-yne (93). (Table 3) were identical with those of the photoproduct. This unambiguously confirmed the photoproduct's structure.
Photostationary State Studies.

With the essential skeletal rearrangement determined, our next concern was whether or not a photoequilibrium was established in this novel rearrangement.
Direct irradiation of 93 in hexane at 254 nm caused a slower rearrangement back to 71, monitored by chromatography. (Scheme 52) However, before the reaction reached equilibrium, the enyne decomposed.

To avoid this problem, a new experiment was designed. A nearly equimolar mixture of 71 and 93 was dissolved in hexane. The solution was irradiated and the relative concentrations of 71 and 93 were determined by gas chromatography at regular intervals. Figure 4 shows the approach to photoequilibrium. Extrapolation to infinity gives a ratio of 93/71 of about 2.0, which indicates that at the photostationary state, there is about twice as much of 93 as 71.

To understand these results, the extinction coefficients of 71 and 93 at 254 nm were accurately measured. The extinction coefficients are listed in Table 4.
From this table, it is clear that 71 absorbs about twice as much light as 93 at 254 nm. If we assume equal quantum efficiencies in each direction, then the observed rate $71 \rightarrow 93$ should be about twice that of $93 \rightarrow 71$. This explains why there is twice as much 93 at the photoequilibrium state. We can conclude at this point that this photorearrangement is reversible and that the photoequilibrium ratio is controlled by the competitive absorption of light by 71 and 93 at 254 nm.

Other Studies.

Exploratory studies on the triplet sensitized irradiation of 71 in benzene and acetone were also performed. The results show that no similar photorearrangement product was formed throughout the entire period of irradiation time and the starting materials were recovered. These experiments exclude the possibility of triplet reactions.

Is there a thermal counterpart to this rearrangement? Vacuum flash thermolysis is a convenient technique for the study of thermal chemistry. By this technique, a sample of 71 was evaporated gradually under vacuum and passed through a heated quartz tube, and then trapped at -78°C. After several runs at different temperatures, it was found that 71 begins to react as the temperature approaches 700°C. The trapped mixture was analyzed by gas chromatography. There was no trace of 93 detected in the mixture of products. Most of the products appear to be fragments derived from 71.

Enyne 95 is an enyne with a bulky trimethylsilyl substituent at C4. Irradiation of 95 results in a similar photorearrangement to give 97. The photoproduct was separated and identified by $^1$H and $^{13}$C NMR spectroscopy. These indicate that the previous enyne photorearrangement 93 applies to 95. (Scheme 53)
3. Photochemistry of Phenyl Substituted-1,3-Enynes 73 and 76

Enynes 73 and 76 both have a phenyl group at C₄ and C₂, respectively. These compounds displayed maximum UV absorptions at 274 nm and 252 nm, respectively. These absorptions are at much longer wavelengths than those of 70 and 71. Thus, the excited state energies of 73 and 76 are substantially lower than those of 70 and 71.

Under the standard irradiation conditions, 73 and 76 failed to rearrange. Instead, 73 proved to be stable in solution after irradiation for more than 60 hours, without significant decomposition or polymerization. In contrast, 76 was very reactive. This compound even easily oligomerized at room temperature. Irradiation of 76 resulted in polymerization. (Scheme 54)

Based on these observations, we have seen that the phenyl groups have a great impact on the photochemical behavior of enynes. The extended conjugation has dramatically changed the enyne chromophores and completely quenched rearrangement. Intersystem crossing more readily occurs in aromatics, but still this does not explain the lack of reactivity of 73.
4. Photochemistry of 7-Methylene-5,8-tridecadiyne (78).

The next question we faced was how general is this conjugated enyne photorearrangement and whether it will occur in a bigger conjugated system, such as an enediyne?

7-Methylene-5,8-tridecadiyne (78) was synthesized in one step as described above. Irradiation of 78 in the usual way yielded a single photoproduct in 40% yield after 16 hours. (Scheme 55) The photoproduct was separated by preparative gas chromatography. It's $^1$H NMR spectrum showed two vinyl protons at 5.43 and 5.32 ppm. The $^{13}$C NMR spectrum showed four sp carbon resonances at 84.3, 75.5, 73.9 and 64.9 ppm, and eight aliphatic carbon resonances. The photoproduct displayed the maximum absorption at 278 nm. These data are consistent with the expected structure of 98.

![Scheme 55](image)

To further prove the structure of the photoproduct, an independent synthesis of 98 was accomplished in three steps. (Scheme 56) Hydrolysis of trimethylsilyl enyne 95 in K$_2$CO$_3$/MeOH gave enyne 96. 1-Bromo-1-hexyne (99) was prepared in situ. Palladium catalyzed coupling of 96 and 99 gave the expected enediyne 98, along with two other coupling products 79 and 100. The final products were separated and characterized by spectroscopy. This synthesis yielded a more complex mixture than anticipated. The $^1$H and $^{13}$C NMR spectra of the independently synthesized 98 were found to be identical to the photoproduct.
The photorearrangement of 98, which is surprisingly clean, largely broadens our horizon for this unprecedented enyne photorearrangement. We can conclude that, like 2,4-dialkyl-1,3-enynes, 7-methylene-5,8-tridecadiyne (78) undergoes a similar photorearrangement.

5. Photochemistry of Dodeca-5,7-diyne (79).

An enyne consists of both alkene and alkyne functional groups, each of which has its own characteristic photoreactions. One fundamental question is the competition of π bond rotation with the presently studied enyne rearrangement.

Dodeca-5,7-diyne (79) is a minor product from synthesis of 78. It is known that 79 undergoes photoreduction in hexane at one of its triple bonds to yield cis and trans conjugated enynes 101 and 102. We took advantage of this reaction as a convenient route to prepare stereoisomeric 1,4-dialkyl conjugated enynes 101 and 102.
Irradiation of 79 in a dilute hexane solution showed that cis 101 and trans 102 enynes are formed in less than 30 minutes in the ratio of 66:34. Two hours later, more than 80% of the starting material was converted, but the product ratio remained constant. Isomers 101 and 102 were readily separable by preparative gas chromatography.

Direct irradiation of pure samples of 101 and 102 separately in hexane resulted only in their own interconversion. The establishment of a photoequilibrium state was observed in each independent case by determining the component ratios on analytical gas chromatography. Extended irradiation gives no evidence of photorearrangement.

The UV spectra of 101 and 102 are very similar to that of 70 and 71, except the former two absorb at slightly longer wavelengths. We are not sure why there is no enyne rearrangement for 101 and 102. One possible reason is that the two adjacent n-butyl groups may add too much steric interaction to the 1,2-cyclobutadiene intermediate (103) that makes ring closure less likely (Scheme 59). In this case, cis and trans photoisomerization becomes the major process.
6. Photochemistry of 1,5-Dimethyl-1,5-hexadiene-3-yne (81).

Can this novel photorearrangement of the four electron system be extended to a six electron system? To answer this question we successfully synthesized symmetric dieneyne 81, with great care.

According to orbital symmetry theory, electrocyclization of 81 under photochemical conditions could form highly strained 1,4-dimethyl-1,2,3-cyclohexatriene (104). (Scheme 60) Based on our previous work,62 this could be trapped by furan to give a Diels-Alder adduct 105.

Scheme 60

![Scheme 60](image)

Photochemical experiments with 81 were carried out with and without the presence of furan. The concentration of furan was 2.2x10^{-2} M (2.5 equivalents relative to 81). The irradiation was monitored by gas chromatography. It was found that both samples generated the same photoproduct 106, not 105. (Scheme 61) The new photoproduct was separated by preparative gas chromatography and characterized by spectroscopy. The \(^1\)H
NMR spectrum showed four vinyl proton resonances at 5.56, 5.45, 5.43 and 5.11 ppm. The $^{13}$C NMR spectrum displayed four vinyl carbon resonances at 140.9, 124.9, 119.5 and 116.5 ppm and two sp resonances at 86.7 and 77.9 ppm. Based on these values, the structure of the new photoproduct was identified as 106.

This photorearrangement result excludes the possibility of the formation of a six membered ring intermediate. Rather, this experimental result adds another example of the conjugated enyne photorearrangement. Four membered ring closure is clearly preferred to that of six membered. Importantly, four membered ring closure and opening may be so fast that furan cannot trap the intermediate.

7. Exploratory Study on 1-Hexynyl-1-cyclooctene (87).

We next studied the ring expansions in the rearrangement of cyclic enynes. Unfortunately, the irradiation of freshly purified 87 always gave polymeric products. No evidence for enyne 108 or 107 was observed. (Scheme 62)

Interestingly, cyclic enyne 87 is thermally unstable. It slowly changed on the bench top even when kept in dilute solution. The product was separated and analyzed by mass and NMR spectroscopy, which all suggested the formation of 109. (See Appendix)

When 87 was treated with m-CPBA in an NMR tube, it afforded the same product,
thus confirming the structure as epoxide 109. (Scheme 63)

A summary of these new photoreactions is given in Table 5.
Table 5 Summary of Conjugated Enyne Photorearrangements

![Chemical structure of enyne photorearrangement]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Cpd #</th>
<th>R₁</th>
<th>R₂</th>
<th>R₃</th>
<th>Rearrangement</th>
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<tr>
<td>1</td>
<td>1</td>
<td>CH₃</td>
<td>C₂H₅</td>
<td>H</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>CH₃</td>
<td>nC₄H₉</td>
<td>H</td>
<td>Yes</td>
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<tr>
<td>3</td>
<td>23</td>
<td>nC₄H₉</td>
<td>CH₃</td>
<td>H</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>nC₄H₉</td>
<td>TMS</td>
<td>H</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>CH₃</td>
<td>Ph</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>Ph</td>
<td>nC₄H₉</td>
<td>H</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>1-Hexynyl</td>
<td>nC₄H₉</td>
<td>H</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>CH₃</td>
<td>-CH₃</td>
<td>H</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>31, 32</td>
<td>H</td>
<td>nC₄H₉</td>
<td>nC₄H₉</td>
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</tr>
<tr>
<td>10</td>
<td>17</td>
<td>R₁=R₃=Cyclooctene, R₂=nC₄H₉</td>
<td></td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

8. Discussion of Mechanisms.

Before discussing the reaction mechanisms, a brief review of known enyne photoreactions is appropriate. In general, the enyne chromophore has been overlooked by the photochemical community. Most previous studies concern only cycloaddition reactions.
The only previous example of an enyne photorearrangement of which we became aware rather late in this project is work by Meier and König. In 1986, they discovered that 1-cycloocten-3-yne (110, $\lambda = 284$ nm) photorearranges to 1-ethynyl cyclohexene (111) in 100% yield, and cyclic dieneyne 112 photorearranges to 2-ethynyl-1,3-cyclohexadiene (113) in 20% yield. Two mechanisms for these enyne photorearrangements were briefly described via 114 and 115 in the same paper for the first time. (Scheme 64)

Scheme 64

![Scheme 64](image-url)
If one examines the skeletal transformation which occurs in these reactions, it is best described in scheme 65. The methylene carbon, labelled G, and its substituents are transported to the other end of the propargyl fragment.

\[
\text{Scheme 65}
\]

Examination of the structures of the photoproducts from each enyne suggests that, in each case, ring closure between the termini of a $\pi$ system and the reverse process in which a $\sigma$ bond is broken to form an acyclic system are necessary. Each step is photoreversible in principle by the rules of orbital symmetry. However, in reality reversibility can be limited by the absorption properties and the relative thermal stability of each enyne isomer. In the photostationary state, the concentrations of isomers are a function of their relative absorption properties (extinction coefficients) of the isomers at the exciting wavelength and their thermodynamic stabilities.

Two fundamental mechanisms need to be considered. The first is one in which a four membered ring is formed and broken; the second requires sequential formation and cleavage of two three-membered rings. These will be described as the 1,2-cyclobutadiene mechanism and the carbene "walk" mechanism, respectively.

(a) 1,2-Cyclobutadiene Mechanism.

Scheme 66 describes the 1,2-cyclobutadiene mechanism.
This mechanism includes the ring closure of the conjugated enyne to a 1,2-cyclobutadiene intermediate, followed by ring opening to a new conjugated enyne. It is simple and logical. The intermediate must be planar or nearly so and is believed to be best represented as diradical 117. Ab initio calculations were performed at the MP3/6-31G* level by Kirchhoff to support this mechanism. Some results are shown in Table 6.

Table 6 shows the relative energies of five interrelated species of formula C₄H₄. Structure 116a represents the ground state acyclic enyne that serves as an energy reference. Cyclic structure 117 is a four membered ring biradical with a planar structure and C₂ᵥ symmetry. Chiral allene 118 represents a structure with C₂ symmetry. It is a non-planar chiral species. The two adjacent real double bonds add much extra strain to the ring and push the two vinyl protons out of plane. The energy is predicted to be >10 kcal/mol more than the diradical species 117, but calculations indicate this is not a true energy minimum. For the intermediate of the 1,2-cyclobutadiene mechanism, it is better to describe the intermediate as biradical 117. However, there is still no experimental evidence to prove the structure of the intermediate.
(b) Carbene "Walk" Mechanism

Scheme 67 describes the carbene "walk" mechanism.

This proposed mechanism includes the formation of two cyclopropenyl carbenes, the equilibrium between the two carbenes, and ring opening. This mechanism is believed less possible because of the following reasons: (a) The photorearrangement is a unique rearrangement and the rearranged enyne is the only photoproduct, while the cyclopropenyl carbene is a highly reactive species that will rearrange or react with solvent instantly to give other products. (b) The interconversion of the two cyclopropenyl carbenes is a very high energy process. The transition state that links the two carbenes will include the forming new bond for the new three-membered ring and the breaking old cyclopropenyl bond. This is an extremely strained state. (c) The existence of the cyclopropenyl species is unknown either at the ground state or the excited state. From our ab initio calculations, cyclopropenyl carbene is 95.5 kcal/mol higher in energy than 1-buten-3-yn, which makes this mechanism really questionable.

(c) Other Mechanisms.

The last option for the mechanism is via a dimeric intermediate, 1,2,5,6-Cyclooctatetraene, which undergoes secondary fragmentation.\textsuperscript{72}
This process can be safely excluded from consideration for the following reasons:

(a) Singlet dimerization of enynes could not occur efficiently in a $10^{-3}$ M solution. For example, photodimerization of trans-stilbene was accomplished at 0.75 M in benzene, and at lower concentrations only cis, trans isomerization occurs.73  
(b) The dimer should be stable enough to be observed. Fragmentation is an unlikely reaction for this substance. No such reaction has been observed in a previous study on 1,2-cyclooctadiene photochemistry. 
(c) The generality of the enyne rearrangement argues for a simpler mechanism. It is very unlikely that a structure such as 78, 81, and 110 could follow such a mechanism.
Conclusions

Conjugated enynes undergo a singlet photoreaction which transposes C-1 of the double bond, thus resulting in a pseudodegenerate rearrangement. The reversibility of this process has been established for a simple acyclic enyne.

Likely mechanisms include electrocyclization to an intermediate 1,2-cyclobutadiene, which thermally ring opens, or closure to a vinylcarbene which rearranges before ring opening. Computational studies support the possibility of a cyclic allene. Both mechanisms lead to identical skeletal transformation.
CHAPTER THREE

EXPERIMENTAL

GENERAL EXPERIMENTAL

CHN Analyses were performed by Ms. Deanna Cardin and Ms. Nancy Cherim at the University of New Hampshire with a Perkin-Elmer 240 B elemental analyzer.

Infrared Spectra were recorded with a Perkin-Elmer Model 283B grating spectrophotometer or a Nicolet MX-1 Fourier transform spectrophotometer. Absorptions were reported in wavenumbers (cm⁻¹), with polystyrene (1601 cm⁻¹) as the calibration.

¹H and ¹³C NMR Spectra were determined with a Bruker AM360 Fourier transform spectrometer operating at 360 MHz. The spectra were determined with CDCl₃ as the solvent and TMS as a reference.

Ultraviolet and Visible Spectra were recorded with a Shimadzu Double-Beam Spectrophotometer Model UV-200S.

Mass Spectra were determined with a Hewlett-Packard 5890A GC and Perkin-Elmer Hitachi RMU-60 mass spectrometer operated by Mr. William Dotchin at the University of New Hampshire.

Analytical Gas Chromatography was performed on a Hewlett-Packard 5790A instrument equipped with a flame ionization detector and an attached model HP 3390A integrator. Unless otherwise indicated, the column was crosslinked methyl silicone (25 m x 0.2 mm x 0.33 µm thickness) at the specified temperature, with helium as the carrier gas.
Preparative Gas Chromatography was accomplished on a Varian Aerography Model 920 instrument, equipped with a glass-linked injector. The column was 15% Carbowax 20 coated on 80/100 Chromosorb W (10' x 0.25") at the indicated temperature.

Thin Layer Chromatography was accomplished on silica gel plates (Sigma T-6145) with a 254 nm fluorescent indicator. The spots were visualized with a short wavelength (254 nm) UV lamp or iodine vapor.

Preparative TLC plates were 20 cm x 20 cm glass plates (Analtech) coated with silica gel GF, 1000 microns (1mm) thick. These plates were oven dried at 85 °C for 24 hours prior to use.

Column Chromatography was accomplished with different sizes of quartz columns packed with silica gel from Davison Chemical (S-704, 60-200 mesh), or Alumina (Aldrich, 150 mesh). Sylvania 2282 green phosphor was added to both for ultraviolet observation.

Photochemical Experiments were performed in either a Rayonet RPR-100 reactor, fitted with 185 or 254 nm UV lamps, or a 450 W Canrad-Hanovia lamp glass sleeve filter. Quartz vessels were employed for all solution phase experiments. Nitrogen was bubbled through the solution prior to or during irradiations. Low temperature irradiations in the Rayonet were performed by passing chilled ethylene glycol through coils in the reaction vessel. A quartz vessel was employed.

Vacuum Flash Thermolysis was performed with a Lindberg 55035 oven. Samples were passed through a horizontal quartz tube packed with quartz chips. The product was collected in a cold trap (-78 °C). The maximum temperature was 1010 °C.

Solvents: The hexane used in the photochemical experiments was spectroquality grade, purchased from Fischer Scientific. Pentane and methylene chloride were HPLC grade from Fischer Scientific, and EM Science, respectively. Tetrahydrofuran was distilled from sodium and benzophenone under nitrogen. Diethylamine was distilled before use.
Reagents:
All starting materials and reagents for synthesis were obtained from either Aldrich or Lancaster. Enynes were purchased from Farchan Laboratories.

Synthesis of Vinyl Cyclohexanecarboxylate (45).\(^7\)

To a three-necked flask, equipped with a thermometer, reflux condenser, and nitrogen inlet tube, were added freshly distilled vinyl acetate (27.0 g, 31.4 mmol), cyclohexanecarboxylic acid (5.0 g, 3.9 mmol), and mercuric acetate (0.3 g, 0.9 mmol). One drop of concentrated H\(_2\)SO\(_4\) was added to the solution and the mixture was refluxed for 3 hours. After cooling, NaOAc·3H\(_2\)O was added to neutralize the solution. The excess vinyl acetate was removed by distillation at atmospheric pressure. (bp. 71-72 °C) Reduced pressure distillation afforded 45 (4.15 g, 67%) as an oil: bp. 28 - 34 °C (0.05 Torr).

\(^1\)H NMR (360 MHz, CDCl\(_3\)) \(\delta\) 7.28 (1H, dd, \(J = 14.0, 6.3\) Hz), 4.87 (1H, dd, \(J = 14.0, 1.5\) Hz), 4.54 (1H, dd, \(J = 6.3, 1.5\) Hz), 2.37 (1H, tt, \(J = 11.0, 3.6\) Hz), 1.93 (2H, m), 1.78 (2H, m), 1.64 (1H, m), 1.48 (2H, m), 1.28 (3H, m). \(^13\)C NMR (360 MHz, CDCl\(_3\)) \(\delta\) 173.07, 141.34, 97.33, 42.83, 28.70, 25.74, 25.30. MS m/e 111, 83, 55, 28, 18. IR (neat) \(\nu_{\text{max}}\) 1750, 1645 cm\(^{-1}\). Anal. Calcd for C\(_9\)H\(_{14}\)O\(_2\): C, 70.10; H, 9.15. Found: C, 69.79; H, 9.24.

Synthesis of Vinyl Adamantanecarboxylate (46).

Vinyl ester 46 was prepared in a manner similar to 45. 1-Adamantanecarboxylic acid (2.0 g, 11.1 mmol) and mercuric acetate (0.2 g, 0.6 mmol), dissolved in vinyl acetate (10.0 g, 116.3 mmol) were refluxed for 5 hours. After work up, vacuum distillation afforded 46 (0.58 g, 25%) as a clear liquid: bp. 30 °C (0.02 Torr).
Synthesis of Vinyl (+)-\(\alpha\)-3-Pinanecarboxylate (56).

A mixture of (+)-\(\alpha\)-3-Pinanecarboxylic acid (5.01 g, 24.2 mmol) and mercuric acetate (0.30 g, 0.9 mmol) dissolved in vinyl acetate (14.2 g, 165.1 mmol) was refluxed overnight. After work up, vacuum distillation afforded 56 (4.42 g, 78%) as an oil: bp. 63-83 °C (0.04 Torr).

\(^1\)H NMR (360 MHz, CDCl\(_3\)) δ 7.32 (1H, dd, J = 14.0, 6.3 Hz), 4.89 (1H, dd, J = 14.0, 1.5 Hz), 4.56 (1H, dd, J = 6.3, 1.5 Hz), 2.74 (1H, dt, J = 10.7, 6.9 Hz), 2.40-1.83 (7H, m), 1.22 (3H, s) 1.15 (3H, d, J = 7.2 Hz), 1.01 (3H, s). 13C NMR (360 MHz, CDCl\(_3\)) δ 174.7, 141.7, 97.3, 47.2, 41.5, 40.5, 39.4, 38.3, 33.2, 30.1, 27.9, 22.9, 22.0. MS m/e 417 (dimer), 237, 209, 165. UV (hexane): \(\lambda_{\text{max}}\) < 200 nm. IR (neat) \(\nu_{\text{max}}\) 1750, 1642 cm\(^{-1}\). Anal. Calcd for C\(_{13}\)H\(_{20}\)O\(_2\): C, 74.96; H, 9.68. Found: C, 74.78; H, 9.85. [\(\alpha\)]\(^{24\text{D}}\) +25.30 (c 11.2, CHCl\(_3\)).

Synthesis of (\(l\))-Menthol Vinyl Ether (58).

(\(l\))-Menthol (0.51 g, 3.2 mmol) and mercuric acetate (74 mg, 0.2 mmol) were dissolved in vinyl ethyl ether (4.62 g, 6.4 mmol). The mixture was refluxed under nitrogen for 20 hours. After it cooled, the mixture was neutralized by K\(_2\)CO\(_3\) and dried over MgSO\(_4\). Distillation removed the excess vinyl ethyl ether at atmospheric pressure. Vacuum
distillation gave 58 (0.32 g, 50%) as a clear oil: bp. 44-45 °C (0.05 Torr).

$^1$H NMR (360 MHz, CDCl$_3$) δ 6.32 (1H, dd, J = 14.1, 6.6 Hz); 4.27 (1H, dd J = 13.1, 1.4 Hz); 3.93 (1H, dd, J = 6.6, 1.4 Hz), 3.52 (1H, dt, J = 10.7, 4.3 Hz), 2.09 (2H, m), 1.66 (2H, m), 1.34 (2H, m), 0.92 (3H, d, J = 6.7 Hz), 0.90 (3H, d, J = 7.2 Hz), 0.78 (3H, d, J = 7.0 Hz), 1.10-0.81 (3H, m). $^{13}$C NMR (360 MHz, CDCl$_3$) δ 151.2, 87.5, 79.7, 47.8, 40.9, 34.4, 31.5, 25.8, 23.5, 22.2, 20.7, 16.1. IR (neat) $\nu_{\text{max}}$ 1650, 1180 cm$^{-1}$.

General Procedure for Photoirradiations and Analysis.

All irradiations were carried out in a Rayonet merry-go-round reactor fitted with sixteen 254 nm lamps. Samples were contained in a quartz tube containing 50 ml of a solution of ~0.13 M arene and ~0.065 M alkene in hexane. Tubes were sealed and purged with nitrogen for 15 minutes before irradiation and rubber septa were covered with aluminum foil to prevent the decomposition caused by UV light. Irradiations were carried out for 20 to 100 hours. After irradiation, the solvent was evaporated by using a rotary evaporator to get a concentrated reaction mixture. The conversions were determined by $^1$H NMR integration, based on vinyl resonances of photoadducts and vinyl esters. Vacuum distillation with care could separate most starting materials from the residues. Residues were further purified by column chromatography on silica gel or using a Chromatron on a silica gel plate (hexane and hexane/10% CH$_2$Cl$_2$). After concentration with a rotary evaporator and vacuum pump, pure photoadduct remained as a viscous liquid.

Photoirradiation of Indan and Vinyl Cyclohexanecarboxylate (45).

A mixture of 45 (0.52 g, 3.2 mmol) and indan (0.85 g, 7.2 mmol) was dissolved
in spectral grade hexane (50 mL). The sample was degassed and irradiated at 254 nm for 12 hours in a quartz tube under the condition described in the general procedure for irradiation. After irradiation, the reaction mixture was concentrated and residue (0.82 g) remained. \(^1\)H NMR spectrum demonstrated that the photoadducts were achieved in 40% yield. Purification of the residue by column chromatography gave pure 45 (0.10 g).

\(^1\)H NMR (360 MHz, CDCl\(_3\)) \(\delta\) 5.73 (1H, dd, \(J = 2.0, 5.1\) Hz), 5.51 (1H, d, \(J = 5.1\) Hz), 5.40 (1H, dd, \(J = 5.9, 8.5\) Hz), 2.15 (1H, m), 1.93 - 1.19 (20H, m). \(^13\)C NMR (360 MHz, CDCl\(_3\)) \(\delta\) 176.0, 137.6, 130.3, 79.5, 67.5, 60.0, 50.8, 43.2, 39.3, 35.4, 34.1, 29.0, 28.8, 27.4, 25.9, 25.5. MS m/e: 272, 162, 144, 83. IR (neat) \(v_{\text{max}}\) 1735, 1595 cm\(^{-1}\). Anal. Calcd for C\(_{18}\)H\(_{24}\)O\(_2\): C, 79.37; H, 8.88. Found: C, 79.53; H, 9.04.

Photoirradiation of 1,2,3,4-Tetrahydronaphthalene (50b) and Vinyl Cyclohexanecarboxylate (45).

The irradiation followed the general procedure. A mixture of 50b (6.80 g, 52.0 mmol) and 45 (4.01 g, 26.0 mmol) in hexane (220 mL) was irradiated at 254 nm for 20 hours. After work up, a viscous residue (4.18 g, 56%) remained. \(^1\)H NMR spectrum indicated a 23% conversion. Purification by column chromatography gave pure 47b.

\(^1\)H NMR (360 MHz, CDCl\(_3\)) \(\delta\) 5.71 (1H, dd, \(J = 2.0, 5.2\) Hz), 5.37 (1H, dd, \(J = 6.3, 8.5\) Hz), 5.32 (1H, d, \(J = 5.3\) Hz), 2.33 (1H, dd, \(J = 8.6, 13.6\) Hz), 2.20 (1H, tt, \(J = 3.5, 10.7\) Hz), 1.93 - 1.22 (21H, m). 2-Dimensional \(^1\)H NMR is in Appendix. \(^13\)C NMR (360 MHz, CDCl\(_3\)) \(\delta\) 176.1, 139.6, 128.9, 56.8, 51.7, 49.9, 43.2, 40.2, 40.1, 29.4, 28.9, 28.8, 26.2, 25.9, 25.5, 21.4, 20.2. MS m/e: 286, 158, 132, 83. IR (neat) \(v_{\text{max}}\) 1732, 1604 cm\(^{-1}\).
Photoirradiation of 1,2-Benz-1,3-cycloheptadiene (50c) and Vinyl Cyclohexanecarboxylate (45).

The irradiation followed the general procedure. A mixture of 50c (0.95 g, 6.5 mmol) and 45 (0.53 g, 3.2 mmol) in hexane (50 mL) was irradiated at 254 nm for 33 hours. After work up, a viscous residue (0.48 g, 49%) remained. $^1$H NMR spectrum indicated a 25% conversion. Purification by column chromatography and preparative TLC gave pure 47b (4 mg).

$^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.76 (1H, dd, $J = 2.0, 5.2$ Hz), 5.33 (1H, dd, $J = 6.4, 8.6$ Hz), 5.27 (1H, d, $J = 5.3$ Hz), 2.32 (1H, dd, $J = 8.7, 13.7$ Hz), 2.21 (1H, tt, $J = 3.5, 11.0$ Hz), 1.98 - 0.84 (23H, m). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 176.1, 139.8, 129.1, 53.2, 43.2, 41.9, 38.1, 34.3, 32.9, 32.2, 31.6, 29.3, 28.9, 26.1, 25.9, 25.5, 22.7, 14.1).

Hydrolysis of meta Adduct 47a.

Adduct 47a (25 mg, 0.09 mmol) was dissolved in 5% KOH/MeOH. The mixture was stirred overnight at room temperature. Water (30 mL) was added and the mixture was extracted with methylene chloride (3 x 10 mL). The combined methylene chloride extracts were dried over MgSO$_4$. After removal of the solvent, 17 mg of a viscous liquid was left. $^1$H NMR spectrum showed a mixture of unreacted 47a and hydrolyzed product 48 in a ratio of about ~50:50. Spectrum data were similar to those described in the literature.8

Hydrogenation of meta Adduct 47a.

Palladium (20 mg, 10% on carbon) was placed in a three-necked flask which was
then purged with nitrogen. Hexane (40 mL) and adduct 47a (0.78 g) were added by syringe. The hydrogen line was turned on to keep a positive pressure while the nitrogen was shut off. The mixture was stirred under hydrogen at 45 °C for three days and the mixture was filtered through a short silica gel column to remove the catalyst. The filtrate was washed with saturated NaHCO₃ (50 mL), 1N HCl (50 mL) and H₂O (3 x 50 mL), respectively. After drying and concentrating, residue 49 (0.73 g, 93% ) remained.

¹H NMR (360 MHz, CDCl₃) δ 5.59 (1H, ddd, J = 9.8, 5.6, 1.7 Hz), 2.35 - 1.23 (25H, m). 2-Dimensional ¹H NMR spectrum is in Appendix. ¹³C NMR (360 MHz, CDCl₃) δ 176.1, 80.9, 61.7, 56.6, 50.2, 45.0, 43.3, 38.4, 35.6, 33.2, 29.7, 29.1, 28.9, 28.6, 27.3, 25.8, 25.5, 25.5. MS m/e 274, 219, 191, 146, 118, 83, 55. IR (neat) νₘₐₓ 1730 cm⁻¹.

**Photoirradiation of o-Xylene and 45.**

o-Xylene (0.67 g, 6.5 mmol) and 45 (0.52 g, 3.2 mmol) were dissolved in spectral grade hexane (50 mL). By the same irradiation and work-up procedure, crude residue (0.54 g, 64%) was obtained after 16 hours of irradiation. ¹H NMR spectrum indicated a 18% conversion. The meta adduct 54d was separated by column chromatography and identified.

¹H NMR (360 MHz, CDCl₃) δ 5.66 (1H, dd, J = 9.8, 5.6, 1.7 Hz), 2.35 - 1.23 (25H, m). 2-Dimensional ¹H NMR spectrum is in Appendix. ¹³C NMR (360 MHz, CDCl₃) δ 176.1, 139.8, 128.1, 56.6, 53.8, 49.2, 43.2, 41.3, 38.9, 28.8, 28.8, 25.8, 25.5, 18.9, 15.3. MS m/e 260, 175, 132, 83, 55.
Photoirradiation of Anisole and 45.

Anisole (0.35 g, 3.2 mmol) and 45 (0.50 g, 3.2 mmol) were dissolved in hexane (50 mL). After 10 hours of irradiation followed by work up, crude residue (0.81 g, 94%) remained, the reaction was 25% completed as indicated by $^1$H NMR spectrum. Two adducts, 54f (major) and 54g (minor), were separated by column chromatography.

54f major: $^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.75 (1H, dd, J = 5.6, 2.3 Hz), 5.65 (1H, ddd, J = 5.4, 2.3, 0.6 Hz), 5.42 (1H, ddd, J = 8.3, 6.3, 1.5 Hz), 3.39 (3H, s); 3.22 (1H, ddd, J = 6.4, 2.0, ~2 Hz), 2.56 (1H, ddd, J = 13.9, 8.4, 6.4 Hz), 2.49 (1H, dd, J = 8.7, 6.2 Hz), 2.25 (1H, ddd, J = 8.7, 2.2, ~1 Hz), 2.20 (1H, tt, J = 10.9, 3.7 Hz), 1.85 - 1.18 (11H, m). 2-Dimensional $^1$H NMR is in Appendix. $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 175.5, 135.2, 129.7, 92.6, 56.4, 50.5, 45.0, 43.1, 40.8, 37.3, 28.8, 28.8, 25.8, 25.4. MS m/e 262, 151, 108, 83, 55, 41. IR (neat) $\nu$ max 1730, 1592, 1130 cm$^{-1}$.

54g minor: $^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.76 (1H, dd, J = 5.8, 2.3 Hz), 5.61 (1H, ddd, J = 5.7, 2.6, ~1.3 Hz), 5.25 (1H ddd, J = 9.1, 8.2, 5.8 Hz), 3.48 (1H, ddd, J = 5.8, 2.5, ~1.4 Hz), 3.36 (3H, s), 2.3 (1H, m), 2.18 (1H, ddd, J = 8.2, 2.4, 1.3 Hz), 1.88 (1H, ddd, J = 8.2, 6.6, 1.5 Hz), 1.36 - 1.23 (12H, m). 2-Dimensional $^1$H NMR is in Appendix.$^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 175.5, 130.3, 129.0, 86.5, 80.6, 56.5, 52.3, 43.1, 35.9, 29.0, 28.9, 27.6, 26.6, 25.7, 25.44 25.4. MS m/e 263 (m+1), 218, 151, 108, 83, 55, 41.

Synthesis of Racemic 1-Trimethylsilyloxy Indan (59).

1-Indanol (1.03 g, 7.5 mmol) was dissolved in THF (30 mL). Et$_3$N (1.52 g, 15.0
mmol) was added to the solution. The system was purged with nitrogen and trimethylsilyl chloride was added through a syringe. The solution was stirred at room temperature for 12 hours. Suction filtration removed the white precipitate. Hexane was added to the filtrate which was washed with water, dilute HCl, and water, respectively. Vacuum distillation afforded 59 (1.31 g, 85%) as a clear liquid: bp. 44-48 °C (0.05 Torr).

$^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 7.32-7.21 (4H, m), 5.25 (1H, t, $J = 6.7$ Hz), 3.03 (1H, m), 2.77 (1H, dd, $J = 15.8$, 8.0 Hz), 2.43 (1H, m), 1.93 (1H, m), 0.22 (9H, s). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 145.3, 142.6, 127.7, 126.5, 124.7, 124.1, 76.2, 36.2, 29.7, 0.3. IR (neat) $\nu_{\text{max}}$ 3070, 1480, 1360, 1175 cm$^{-1}$. Anal. Calcd for C$_{12}$H$_{18}$OSi: C, 69.46; H, 8.74. Found: C, 69.76; H, 8.77.

Photoirradiation of Indan and (+)-Vinyl Pinanecarboxylate (56).

Indan (1.39 g, 12.0 mmol) and (+)-vinyl pinanecarboxylate (56) (0.50 g, 2.4 mmol) were dissolved in hexane (50 mL). The irradiation was carried out at 254 nm UV light. After 19 hours of irradiation, a 20% conversion was achieved by $^1$H NMR. Crude residue (1.04 g) remained. Column chromatography (silica gel, Hexane/CH$_2$Cl$_2$) separated the meta adducts from the starting materials. A mixture of two diastereomeric adducts, 60$^a$ and 60$^b$, was obtained. They were inseparable by column chromatography.

60$^a$ and 60$^b$: $^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.73 (1H, m), 5.53 (1H, d, $J = 5.1$ Hz), 5.45 (1H, dt, $J = 8.3$, 6.5 Hz), 2.58 (1H, m), 2.38 - 0.98 (26H, m). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 177.5 (d), 137.7 (d), 130.3, 79.7 (d), 67.5, 60.0, 50.8 (d), 47.3, 42.0 (d), 40.7 (d), 39.6, 39.3 (d), 38.4, 35.3, 34.1, 33.0 (d), 30.1 (d), 29.0, 27.9, 27.4, 22.9, 22.2 (d). IR (neat) $\nu_{\text{max}}$ 1728, 1590, 1180 cm$^{-1}$. MS m/e 326, 181, 145, 117, 81,
Photoirradiation of Anisole and (+)-Vinyl Pinanecarboxylate (56).

Irradiation of anisole and (+)-vinyl pinanecarboxylate (56) was performed in a similar way. Irradiation of anisole (0.78 g, 7.2 mmol) and 56 (0.5 g, 2.4 mmol) for 19 hours generated four adducts (0.74 g), a 43% conversion was determined by 1H NMR spectrum. They were separated by column chromatography as two pairs of diastereomers, 62a + 62b, and 62c + 62d in an approximately 2 : 1 ratio. The two diastereomers were inseparable and were observed by 13C NMR spectrum.

62a + 62b, major: 1H NMR (360 MHz, CDCl3) δ 5.76 (1H, m), 5.65 (1H, dd, J= 5.7, 2.7 Hz), 5.47 (1H, m), 3.40 (3H, s), 3.24 (1H, m), 2.61 - 1.62 (20H, m). 2-Dimensional 1H NMR is in Appendix. 13C NMR (360 MHz, CDCl3) δ 177.0 (d), 135.2 (d), 129.7 (d), 92.6, 77.6 (d), 56.4, 50.6, 47.2, 45.0 (d), 41.9 (d), 40.7, 39.5, 39.4, 38.3, 37.2, 33.0 (d), 30.0 (d), 27.9, 22.9, 22.2 (d). MS m/e 317, 285, 231, 165, 135, 108. IR (neat) νmax 1730, 1595, 1138 cm⁻¹.

62c + 62d, minor: 1H NMR (360 MHz, CDCl3) δ 5.76 (1H, dd, J = 5.8, 2.2 Hz), 5.63 (1H, m), 5.27 (1H, m), 3.49 (1H, broad), 3.36 (3H, s), 2.58 (1H, m), 2.34 - 0.92 (20H, s). 2-Dimensional 1H NMR is in Appendix. 13C NMR (360 MHz, CDCl3) δ 177.2 (d), 130.4 (d), 129.2 (d), 86.5 (d), 80.8, 56.5, 53.4, 52.4, 47.2, 41.8 (d), 40.7 (d), 39.9 (d), 38.3 (d), 35.9, 33.1 (d), 30.3 (d), 27.9 (d), 26.6, 22.9, 22.1 (d).

Photoirradiation of Racemic 1-Trimethylsilyloxy Indan 59 and 45.

The irradiation followed the general procedure. Racemic 1-trimethylsilyloxy indan
54 (0.50 g, 2.4 mmol) and 45 (1.87 g, 12.1 mmol) were dissolved in hexane (25 mL). After 30 hours of irradiation, a 23% conversion was achieved. Two pairs of meta adducts, 63a and 63b versus 63c and 63d, were separated by column chromatography in approximately a 4:1 ratio.

63a + 63b, major: \(^\text{1H NMR (360 MHz, CDCl}_3, \delta \) \) 5.76 (1H, dd, \( J = 5.1, 2.0 \text{ Hz} \)), 5.55 (1H, d, \( J = 5.3 \text{ Hz} \)), 5.41 (1H, dd, \( J = 8.7, 5.8 \text{ Hz} \)), 4.05 (1H, t, \( J = 5.9 \text{ Hz} \)), 2.59 (1H, dd, \( J = 14.2, 8.8 \text{ Hz} \)), 2.23 - 1.25 (15H, m), 0.10 (9H, s). 2-Dimensional \(^\text{1H NMR} \) is in Appendix. \(^{13}\text{C NMR (360 MHz, CDCl}_3, \delta \) \) 176.0, 136.1, 131.3, 78.8, 70.2, 54.0, 45.4, 43.2, 39.9, 35.6, 35.4, 28.82, 28.79, 24.8, 25.5, 24.7, 0.053. Anal. Calcd for C\(_{21}\)H\(_{32}\)O\(_3\)Si: C, 70.03; H, 9.32. Found: C, 69.96; H, 8.94.

63c + 63d, minor: \(^\text{1H NMR (360 MHz, CDCl}_3, \delta \) \) 5.78 (1H, dd, \( J = 5.4, 2 \text{ Hz} \)), 5.49 (1H, d, \( J = 5.4 \text{ Hz} \)), 5.42 (1H, dd, \( J = 8.6, 5.8 \text{ Hz} \)), 4.03 (1H, t, \( J = 3 \text{ Hz} \)), 2.10 - 0.84 (15H, m), 0.11 (9H, s). 2-Dimensional \(^\text{1H NMR} \) is in Appendix. \(^{13}\text{C NMR (360 MHz, CDCl}_3, \delta \) \) 176.0, 134.8, 131.1, 79.0, 76.8, 71.9, 59.4, 50.2, 43.3, 39.32, 38.0, 35.9, 28.8, 25.9, 25.8, 25.5, 0.11.

**Attempted Deprotection of the TMS group from 63a and 63b.**

Enantiomeric adducts 63a and 63b (22 mg, 0.006 mmol) and CsF (10 mg, 0.006 mmol) were dissolved in freshly distilled dry DMSO (5 mL). The mixture was stirred at room temperature under nitrogen for 24 hours. Water was added to the mixture and the mixture was extracted by ether. After removal of solvent, residue (10 mg, 58%) remained. \(^\text{1H NMR} \) spectrum indicated the vinyl resonances shifted slightly and \(^{13}\text{C NMR} \) shows the TMS disappeared after the reaction.
$^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.98 (1H, dd, $J = 5.1, 1.7$ Hz), 5.54 (1H, d, $J = 5.2$ Hz), 5.39 (1H, dd, $J = 5.9, 8.5$ Hz), 4.08 (1H, broad), 2.63 - 0.84 (18H, m), 0.07 (9H, s).

$^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 175.9, 135.4, 131.8, 78.2, 75.1, 73.4, 69.2, 49.6, 43.1, 40.1, 36.8, 34.8, 28.8, 25.8, 25.7, 25.4, 1.0.

**Deuterium NMR Spectroscopy.**

The deuterium distributions in the *meta* adducts were determined by recording their deuterium NMR spectra and integrating the corresponding resonances. Deuterium NMR spectra were recorded on a Bruker AM 360 spectrometer at 55.283 MHz, using a broadband preamplifier, a sweep width of 773.994 Hz, 80 unlocked scans and a relaxation delay of 3.0 s. Twenty independent spectra of each sample were transformed with frequency domain averaging to obtain maximum accuracy.

**Synthesis of 2-Methyl-4-phenyl-1-buten-3-yne (73)**

This is a modified palladium coupling procedure.$^{75, 76}$ Cuprous iodide (38 mg, 0.2 mmol) was added to a mixture of bis(triphenylphosphine)palladium dichloride (70 mg, 0.1 mmol), bromobenzene (1.54 g, 7.0 mmol), 2-methyl-1-buten-3-yne (0.5 g, 7.6 mmol), and diethylamine (50 mL) under a nitrogen atmosphere in a 100 mL flask, equipped with a magnetic stirring bar. The reaction was monitored by analytical gas chromatography. After being stirred overnight, the solution was dark brown. Diethylamine was removed under reduced pressure using a cold water bath. Ice water was added to the residue. The aqueous phase was extracted with 3 x 20 mL hexane and the combined organic layer was dried over Na$_2$SO$_4$. The solution was run through an alumina column to remove the colored catalyst. After removing the solvent under reduced pressure, vacuum distillation afforded 73 (0.78 g, 73 %) as a clear liquid: bp. 38-45 °C (Torr).
$^1$H NMR (360 MHz, CDCl$_3$), $\delta$: 7.45–7.27 (5H, m), 5.41 (1H, bs), 5.31 (1H, bs), 2.00 (3H, bs). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$: 131.57, 128.27, 128.14, 126.85, 123.25, 121.95, 90.55, 88.36, 23.51. MS m/z: 142, 141, 86, 57, 56, 41. UV (hexane): $\lambda_{\text{max}}$ = 285 nm (21,000 cm$^{-1}$mol$^{-1}$L), $\lambda_{\text{max}}$ = 290 nm (16,000 cm$^{-1}$mol$^{-1}$L).

**Synthesis of 2-Phenyl-1-Octen-3-yne (76)**

A mixture of 1-hexyne (2.02 g, 2.1 mmol), freshly distilled $\alpha$-bromostyrene (3.43 g, 1.9 mmol), cuprous iodide (36 mg, 0.2 mmol), and 100 mL freshly distilled diethylamine was placed into a 250 mL flask. The mixture was stirred under nitrogen for three days at room temperature and the reaction was monitored by TLC with hexane as the eluent. Enyne 76 spot on TLC showed up at the lower part of the plate. (Rf ~ 0.3). A similar workup procedure gave crude 76 (3.12 g, 90%). After column chromatography, pure 76 (1.01 g, 30%) was obtained.

$^1$H NMR (360 MHz, CDCl$_3$), $\delta$: 7.66 (2H, m), 7.38–7.27 (3H, m), 5.86 (1H, d, J = 1Hz), 5.60 (1H, bs), 2.43 (2H, t, J = 7Hz), 1.62 (1H, m), 1.49 (2H, m), 0.96 (3H, t, J = 7Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$: 137.8, 130.9, 128.3, 128.1, 126.1, 119.4, 92.0, 79.7, 30.8, 22.1, 19.1, 13.7. IR (neat) $\nu_{\text{max}}$ 2220, 1600, 1578, 1498 cm$^{-1}$. UV (hexane): $\lambda_{\text{max}}$ = 252 nm (6,700 cm$^{-1}$mol$^{-1}$L). MS m/z: 184, 155, 141, 115.

**Synthesis of 7-Methylene-5,8-tridecadiyne (78).**

Enediyne 78 was prepared by G. Linstrumelle’s approach. 1-Hexyne (4.65 g, 56.7 mmol) was treated with 1,1-dichloroethylene (2.54 g, 25.8 mmol) and
tetrakis(triphenylphosphine)palladium (0.31 g, 0.3 mmol), cuprous iodide (49 mg, 0.3 mmol), and n-butylamine (2.83 g, 38.7 mmol) in benzene (100 mL) at room temperature under nitrogen for three days. Benzene was removed under reduced pressure. Water was added to the residue. The aqueous phase was extracted with 3 x 20 mL pentane. The combined pentane extracts were dried over Na₂SO₄ and passed through a column of alumina. After concentration, residue (1.22 g, 25%) remained. Analytical gas chromatography showed that it was a mixture of the self-coupled 79 and cross-coupled 78 in a ratio of 2 : 1.

The same result was obtained when adding 2 equivalent 1,1-dichloroethylene separately. The mixture of 78 and 79 was separated by column chromatography using silica gel and eluting with pentane.

¹H NMR (360 MHz, CDCl₃), δ: 5.59 (2H, s), 2.31 (4H, t, J = 7Hz), 1.55-1.39 (8H, m), 0.92 (8H, t, J = 7Hz). ¹³C NMR (360 MHz, CDCl₃), δ: 128.5, 113.3, 89.3, 78.8, 30.5, 22.0, 18.9, 13.6. IR (neat) νmax 2225, 1575 cm⁻¹. UV (hexane): λmax=242nm (11,00 cm⁻¹mol⁻¹L⁻¹).

**Synthesis of 2,5-Dimethyl-1,5-hexadiene-3-yne (81).**

2-Bromopropene (1.83 g, 15.1 mmol) was treated with 2-methyl-1-buten-3-yne (1.02 g, 15.1 mmol) and tetrakis(triphenyl)phosphine palladium (175 mg, 0.15 mmol), and cuprous iodide (29 mg, 0.15 mmol) in 50 mL diethylamine. The mixture was stirred under nitrogen at room temperature for two days. After workup, crude 81 (1.21 g, 75%) as a light yellow residue remained. TLC showed one big spot and ¹H NMR spectrum indicated it was 90% pure. This mixture was further purified by column chromatography, using a quartz tube packed with silica gel and pentane. The elution could be monitored by a
254 nm UV lamp. Each fraction was also monitored by analytical gas chromatography to check for purity. One fraction containing 0.25 g of 81 (90%) and 82 (10%) was obtained. As 81 and 82 have similar polarities, their absorption bands overlapped on a silica gel column (hexane). In addition, 81 and 82 are both air sensitive. They were kept in pentane and sealed under nitrogen immediately after coming off the column. Preparative gas chromatography was also used to obtain pure 81 for 1H and 13C NMR spectra.

81: 1H NMR (360 MHz, CDCl₃), δ: 5.31 (2H, bs), 5.24 (2H, bs) 1.92 (6H, bs). 13C NMR (360 MHz, CDCl₃), δ 126.8, 121.8, 89.6, 77.2, 23.5. GC-MS at 5.33 min. m/z: 106, 91, 78, 65. UV (hexane): ƛₘₐₓ=251 nm (1,540 cm⁻¹mol⁻¹L⁻¹), ƛₘₐₓ=263 nm (1,280 cm⁻¹mol⁻¹L⁻¹).

82: GC-MS at 9.5 min. m/e 131 (m+1), 130 (m), 115, 89.

Synthesis of 1-Hexynyl-1-cyclooctene (87).

A similar procedure to that used with 76 was applied to prepare 87. A mixture of 1-bromocyclooctene (3.04 g, 15.9 mmol), 1-hexyne (1.87 g, 19.0 mmol), bis(triphenylphosphine)palladium chloride (0.22 g, 0.3 mmol) and cuprous iodide (0.12 g, 0.6 mmol) in 100 mL diethylamine was stirred for 40 hours. After workup, crude product (2.89 g, 96%) remained. After purification by column chromatography, pure 87 (2.16 g, 71%) was obtained. However, 87 is easily oxidized to epoxide in the air at room temperature, even in solution.

1H NMR (360 MHz, CDCl₃), δ: 5.98 (1H, t, J = 8Hz), 2.31-2.24 (4H, m), 2.15 (2H, bs), 1.59-1.32 (12H, m), 0.92( 3H, m). 13C NMR (360 MHz, CDCl₃), δ 135.8, 124.1, 86.9, 82.9, 31.0, 30.3, 29.8, 28.4, 26.9, 26.4, 25.8, 22.0, 19.0, 13.7. IR (neat) ʋₘₐₓ
2210, 1630 cm\(^{-1}\). MS m/z: 190 (M), 162, 133, 105, 91, 79. UV (hexane): \(\lambda_{\text{max}} = 231\text{nm}\) (6,100 cm\(^{-1}\)mol\(^{-1}\)L).

**Epoxidation of 87.**

In an NMR tube, 87 (12 mg, 0.06 mmol) and m-chloroperoxybenzoic acid (11 mg, 0.06 mmol) were added to CDCl\(_3\). The solution was aged at room temperature for three hours. The \(^1\)H NMR spectrum showed that all of the cyclic enyne 87 had disappeared. The new spectral data of 109 are:

\(^1\)H NMR (360 MHz, CDCl\(_3\)), \(\delta\) 3.03 (1H, dd, J = 10, 4 Hz), 2.20 (2H, \(t\), J = 7Hz), 2.14 (1H, m), 1.70-1.37 (12H, m), 0.91 (3H, \(t\), J = 7Hz). \(^2\)H NMR is in Appendix.\(^{13}\)C NMR (360 MHz, CDCl\(_3\)), \(\delta\) 83.5, 79.6, 63.7, 54.1, 30.8, 30.6, 27.1, 26.4, 26.1, 25.9, 25.2, 21.9, 18.4, 13.6. IR (in CDCl\(_3\)) cm\(^{-1}\): 2935, 2855, 1455, 1260. MS m/z: 206, 177, 149, 121, 91, 79. UV (hexane): \(\lambda_{\text{max}} = 202\text{nm}\) (375 cm\(^{-1}\)mol\(^{-1}\)L).

**Photorearrangement of 2-Methyl-1-octen-3-yne (71).**

A sample of 2-methyl-1-octen-3-yne 71 (50 mg, 0.4 mmol) was dissolved in hexane (50 mL) and placed in a quartz tube. The solution was sealed and purged with nitrogen for 15 minutes before irradiation. Irradiation was carried out in a Rayonet Photoreactor, equipped with 254 nm UV lamps, for periods of 1 to 100 hours. Occasionally, samples were taken by syringe and analyzed by analytical gas chromatography and a new peak was recorded from these samples. Removal of solvent by the rotary evaporator afforded a light yellow residue (60 mg, some solvent in it). The crude mixture was filtered through a small silica gel column and rinsed with hexane. The
photoproduct was separated by preparative gas chromatography, equipped with a carbowax 20M 10% column. The photoproduct was trapped at -77 °C.

\[ ^1H \text{ NMR (360 MHz, CDCl}_3 \] \[ \delta \] 5.21 (1H, d, J = 1.5 Hz), 5.13 (1H, d, J = 1.5 Hz), 2.12 (1H, t, J = 7 Hz), 1.95 (3H, s), 1.51 (2H, m), 1.47 (1H, m), 0.92 (3H, t, J = 7 Hz). \[ ^{13}C \text{ NMR (360 MHz, CDCl}_3 \] \[ \delta \] 132.3, 119.5, 85.3, 80.2, 37.2, 30.3, 22.0, 13.9, 4.2.

Photorearrangements of 70, 78, 81, 95 were performed using the same procedure.

**Attempted Photorearrangement of Phenyl Substituted Enyne 73 and 76.**

Enyne 73 (50 mg, 0.35 mmol) was dissolved in hexane (50 mL) in a quartz tube. The sample was purged with nitrogen before irradiation. After irradiation at 254 nm UV light, no new product was detected by gas chromatography and the starting material was recovered after removal of the solvent.

Under the same conditions, irradiation of enyne 73 gave a polymeric precipitate after irradiation for 5 hours. No starting material remained as shown by GC.

**Photoreduction of Dodeca-5,7-divyne (79).**

Dodeca-5,7-divyne (79) (84 mg, 0.5 mmol) was dissolved in hexane (60 mL) in a quartz tube. The sample was sealed and purged with nitrogen before irradiation. Irradiation was performed in a Rayonet Photoreactor, equipped with 254 nm UV lamps. The reaction was monitored by analytical gas chromatography periodically. After 2 hours of irradiation, GC indicated that more than 80% of the diyne had disappeared and two reduced enynes (cis and trans) were formed in a ratio of 2 : 1. Hexane was removed using a rotary evaporator. The crude mixture was separated by preparative gas chromatography. Photoreduction products 101 (6 mg) and 102 (3 mg) were trapped separately at -77 °C.
Spectral data of 101 and 102 are consistent with the literature.70

**Synthesis of 2-n-Butyl-4-trimethylsilyl-1-buten-3-yne (95).**

Cuprous iodide (0.12 g, 0.6 mmol) was added to a mixture of bis(triphenylphosphine) dichloride (0.21 g, 0.3 mmol), 2-bromo-1-hexene (4.97 g, 30.5 mmol), and trimethylsilyl acetylene (3.29 g, 33.5 mmol) in freshly distilled diethylamine (150 mL). The mixture was stirred under nitrogen at room temperature for 3 hours and monitored by TLC for completion. After work up, crude enyne 95 (3.87 g, 69%) was obtained.

\[ ^1H \text{ NMR (360 MHz, CDCl}_3\] 5.36 (1H, d, J = 2 Hz), 5.24 (1H, dd, J = 3.3, 1.5 Hz), 2.15 (2H, t, J = 7 Hz), 1.5 (2H, m), 1.33 (2H, m), 0.92 (3H, t, J = 7 Hz), 0.20 (9H, s).

\[ ^13C \text{ NMR (360 MHz, CDCl}_3\] 5 131.9, 121.8, 105.8, 93.6, 36.7, 30.1, 22.0, 13.9, -0.013. IR (neat) cm\(^{-1}\): 3095, 2965, 2940, 2880, 2140, 1605, 1462, 1252, 840. MS m/z: 180, 165, 23, 73, 58, 43. UV (hexane): \( \lambda_{\text{max}}=230 \text{ nm (12,000 cm}^{-1}\text{mol}^{-1}\text{L}), \lambda_{\text{max}}=241 \text{ nm (10,000 cm}^{-1}\text{mol}^{-1}\text{L}). \]

Analysis Calcd for C\(_{11}\)H\(_20\)Si: C, 73.25; H, 11.18. Found: C, 72.91; H, 11.33.

**Synthesis of 2-n-Butyl-1-buten-3-yne (96).**

Removal of the trimethylsilyl group was performed by K.S. Y. Lau's method.77 Enyne 95 (2.04 g, crude, 11.4 mmol) was treated with K\(_2\)CO\(_3\) (0.25 g, 1.8 mmol) in MeOH (20 mL). The mixture was stirred under nitrogen at room temperature overnight. Water was added. The aqueous phase was extracted with pentane (3 x 20 mL) and combined pentane extracts were dried over Na\(_2\)SO\(_4\). The solvent was removed using a rotary evaporator with a cold water bath to prevent the evaporation of 96. Crude 96
remained (1.29 g, ~100%).

$^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.47 (1H, d, $J = 1.7$ Hz), 5.37 (1H, dd, $J = 3.0, 1.4$ Hz), 2.16 (2H, t, $J = 7.0$ Hz), 2.88 (1H, s), 1.52 (1H, m), 1.33 (1H, m), 0.92 (3H, t, $J = 7.0$ Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 130.9, 124.2, 82.0, 73.3, 36.5, 30.2, 22.0, 13.8.

**Synthesis of 2-n-Butyl-1-decen-3,5-diyne (98).**

Lithium alkylation of terminal acetylene was performed by W. Beckmann’s method.$^{78}$ A solution of 96 (1.29 g, 11.0 mmol) in fresh distilled dry tetrahydrofuran (50 mL) was cooled to -77 °C while n-BuLi (2.5 M, 6.67 mL, 16.7 mmol) was added dropwise under nitrogen atmosphere. The mixture was stirred for 0.5 hour, and then slowly warmed up to 0 °C. CH$_3$I (1.56 g, 11.0 mmol) and 5 drops of HMTP in 2 mL THF were added dropwise. The mixture was stirred for another 2 hours with the temperature was kept below 15 °C. Ice water was added to quench the reaction and the aqueous solution was extracted with pentane 3 times. The combined pentane extracts were dried over Na$_2$SO$_4$. After removal of the solvent, distillation under reduced pressure afforded pure 98 (0.54 g, 40%) as a clear liquid: bp. 35-65 °C (Torr).

$^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.21 (1H, d, $J = 1.5$ Hz), 5.13 (1H, d, $J = 1.5$ Hz), 2.12 (2H, t, $J = 7.0$ Hz), 1.95 (2H, s), 1.51 (2H, m), 1.47 (2H, m), 0.92 (3H, t, $J = 7.0$ Hz).

$^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 132.3, 119.5, 85.3, 80.4, 37.2, 34.3, 22.05, 13.9, 4.1.

IR (neat) $\nu_{\text{max}}$ 2190, 1596 cm$^{-1}$. MS m/z: 122, 107, 91, 80, 79, 77, 65, 39. UV (hexane): $\lambda_{\text{max}}$ = 221 nm (9,000 cm$^{-1}$mol$^{-1}$L), $\lambda_{\text{max}}$ = 231 nm (7,900 cm$^{-1}$mol$^{-1}$L). Anal. Calcd for C$_{14}$H$_{20}$: C, 88.45; H, 11.55. Found: C, 87.4, 11.95.
Synthesis of 1-Bromo-1-hexyne 99.

Preparation of bromoalkyn followed E. Kloster-Jensen's method79 with slight modification. To a 150 mL three-necked round flask 1-hexyne (4.02 g, 40.8 mmol) was dissolved in freshly distilled dry THF (50 mL). The solution was stirred under nitrogen and cooled to -77 °C. n-BuLi (2.5 M, 19.6 mL, 1.2 eq.) was added dropwise. The mixture was stirred at -77 °C for 0.5 hour. Bromine (6.53 g, 2.1 mL, 40.8 mmol) was added at the -50 to -25 °C over a period of 15 minutes. The addition was discontinued when the solution became yellow. The mixture was stirred under nitrogen below -25 °C for another 2 hours. Ice water was added to the reaction and extracted by pentane (3 x 50 mL). The combined organic phase was dried over Na$_2$SO$_4$ and concentrated. Crude 99 (4.80 g, 65%) remained.

$^1$H NMR (360 MHz, CDCl$_3$) δ 2.21 (2H, t, $J = 7.0$ Hz), 1.55-1.36 (4H, m), 0.92 (3H, t, $J = 7.0$ Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) δ 80.4, 37.0, 30.3, 21.9, 19.4, 13.5.

Synthesis of 2,7-Di-n-butyl-1,7-octadien-3,5-diyne (100).

A mixture of 1-bromo-1-hexyne 99 (167 mg, 0.9 mmol), enyne 96 (0.11 g, 0.9 mmol), bis(triphenylphosphine) dichloride (32.5 mg, 0.05 mmol) and cuprous iodide (mg, 0.05 mmol) was dissolved in diethylamine (10 mL). The mixture was stirred under nitrogen at room temperature overnight. Diethylamine was removed by reduced pressure and the residue was run through a small silica gel column and rinsed with pentane. Crude residue 100 (60 mg, 31%) remained after concentration. TLC showed three spots and preparative TLC separated three bands, which were identified by NMR and mass spectra as dodeca-5,7-diyne (79), 2,7-n-butyl-1,7-octadien-3,5-diyne (100), and 2-n-butyl-1-decen-3,5-diyne (98), respectively. The ratio of 79 : 100 : 98 = 7 : 2 : 1, was determined by
analytical gas chromatography.

100: $^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 5.43 (1H, d, $J = 1.4$ Hz), 5.33 (1H, d, $J = 1.4$ Hz), 2.34 (2H, t, $J = 7.0$ Hz), 2.15 (2H, t, $J = 7.6$ Hz), 1.58-1.26 (8H, m), 0.92 (3H, t, 7.0 Hz), 0.91 (3H, t, $J = 7.0$ Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 130.9, 124.2, 82.0, 73.4, 36.5, 30.2, 22.0, 13.8. IR (CDCl$_3$) $v_{\text{max}}$ 2870, 1795, 1602 cm$^{-1}$. MS m/z: 376 (dimer), 229, 209, 137, 136. UV (hexane) $\lambda_{\text{max}}$ = 249 nm (5,000 cm$^{-1}$ mol$^{-1}$L), $\lambda_{\text{max}}$ = 262 nm (5,200 cm$^{-1}$ mol$^{-1}$L), $\lambda_{\text{max}}$ = 278 nm (5,000 cm$^{-1}$ mol$^{-1}$L).

98: $^1$H NMR (360 MHz, CDCl$_3$), $\delta$ 5.47 (2H, d, $J = 1.6$ Hz), 5.37 (2H, dd, $J = 3.0$, 1.4 Hz), 2.18 (4H, t, $J = 7.0$ Hz), 1.53 (4H, m), 1.32 (4H, m), 0.92 (6H, t, $J = 7.0$ Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 131.0, 123.6, 84.3, 75.5, 73.9, 65.0, 36.6, 30.3, 30.2, 22.0, 21.9, 19.2, 13.8 13.5. IR (CDCl$_3$) $v_{\text{max}}$ 2255, 1795, 1468 cm$^{-1}$. MS m/z: 214 (m), 172, 157, 130, 115, 91. UV (hexane) $\lambda_{\text{max}}$ = 270 nm (8,700 cm$^{-1}$ mol$^{-1}$L), $\lambda_{\text{max}}$ = 287 nm (13,400 cm$^{-1}$ mol$^{-1}$L), $\lambda_{\text{max}}$ = 305 nm (11,000 cm$^{-1}$ mol$^{-1}$L). Anal. Calcd for C$_{14}$H$_{20}$: C, 89.66; H, 10.34. Found: C, 88.54; H, 10.65.

79: $^1$H NMR (360 MHz, CDCl$_3$) $\delta$ 2.26 (4H, t, $J = 7$ Hz), 1.55-1.39 (8H, m), 0.92 (6H, t, $J = 7$ Hz). $^{13}$C NMR (360 MHz, CDCl$_3$) $\delta$ 77.5, 61.2, 3.47 21.9, 18.9, 13.5.
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72 We thank Professor Weisman, G. R. for this suggestion.
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APPENDIX
$65a : 65b = 1.07 : 1$