

AN ABSTRACT OF THE THESIS OF

Gerald G. Moy for the degree of Doctor of Philosophy  
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Title: THERMAL REACTIONS OF SOME SELECTED OLEFINS: 1. CLAISEN  
REARRANGEMENT OF 2-ISOPROPYL-1-METHYL-2-PROPENYL VINYL  
ETHER. 2. ELECTROCYCLIC REACTION OF cis,cis-1,4-DI(1-  
CYCLOHEXENYL)-1,3-BUTADIENE. 3. ELECTROCYCLIC REACTIONS OF  
cis-2-PHENYL-1,3,5-HEXATRIENE AND cis-2-PHENYL-1,3-HEXADIENE-  
5-YNE.

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Abstract approved: \_\_\_\_\_

Dr. Elliot N. Marvell

As part of a continuing effort to understand structure-reactivity relationships of thermal reactions, four polyenes have been synthesized and the results of their thermal reactions determined.

The Claisen rearrangement of 2-isopropyl-1-methyl-2-propenyl vinyl ether, prepared from ethyl acetoacetate via a three step synthesis, occurs at 180°C giving a 40:60 mixture of E- and Z-4-isopropyl-4-hexenal, respectively.

Hydrogenation of 1,4-di(1-cyclohexenyl)-1,3-butadiyne over Lindlar catalyst occurs slowly at room temperature giving tricyclo-(10.4.0.0<sup>6,11</sup>)hexadeca-1,3,5-triene in good yield. The product presumably arises from the facile electrocyclization of cis,cis-1,4-di(1-cyclohexenyl)-1,3-butadiene which is not entirely unexpected by analogy to other eight pi-electron systems. Due to the slow rate of hydrogenation, this intermediate was not isolated.

The Wittig reaction of 2-phenyl-2-propenyltriphenylphosphorane and propynal gives a 30:70 mixture of cis- and trans-2-phenyl-1,3-hexadien-5-yne, respectively. Pyrolysis of the above mixture in a flow apparatus (300° C; 15 sec) gave biphenyl as the sole isolable product presumably through the electrocyclization of the cis isomer followed by a hydrogen shift.

Partial reduction of the above dienyne mixture gives a 1:2 mixture of cis- and trans-2-phenyl-1,3,5-hexatriene. Owing to their thermal instabilities and air sensitivities, the isomers could not be separated. The rate of electrocyclization of cis-2-phenyl-1,3,5-hexatriene ( $k = 4.42 \times 10^{-5} \text{ sec}^{-1}$ ;  $\pm 0.12 \times 10^{-5} \text{ sec}^{-1}$ , 95% conf.; 76.4°C) was determined from a solution of the isomeric mixture in hexadecane by observing the formation of a cyclized product ( $\text{uv}_{\text{max}} = 302 \text{ nm}$ ). Assuming the electrocyclization occurs without significant buildup of intermediates and without by-product formation, the rate is 290 times faster than the unsubstituted triene.

Thermal Reactions of Some Selected Olefins

1. Claisen Rearrangement of 2-Isopropyl-1-methyl-2-propenyl Vinyl Ether
2. Electrocyclic Reaction of cis, cis-1,4-Di(1-cyclohexenyl)-1,3-butadiene
3. Electrocyclic Reactions of cis-2-Phenyl-1,3,5-hexatriene and cis-2-Phenyl-1,3-hexadien-5-yne

by

Gerald George Moy

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Redacted for privacy

\_\_\_\_\_  
Professor of Chemistry

in charge of major

Redacted for privacy

\_\_\_\_\_  
Chairman of Department of Chemistry

Redacted for privacy

\_\_\_\_\_  
Dean of Graduate School

Date thesis is presented March 11, 1977

Typed by Sheri Bearse for Gerald George Moy

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To Dorothy and George

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## THERMAL REACTIONS OF SOME SELECTED OLEFINS

1. CLAISEN REARRANGEMENT OF 2-ISOPROPYL-1-METHYL-2-PROPENYL VINYL ETHER
2. ELECTROCYCLIC REACTION OF cis,cis-1,4-DI(1-CYCLOHEXENYL)-1,3-BUTADIENE
3. ELECTROCYCLIC REACTIONS OF cis-2-PHENYL-1,3,5-HEXATRIENE AND cis-2-PHENYL-1,3-HEXADIENE-5-YNE

### INTRODUCTION

Although the application of molecular orbital theory to explain a wide variety of chemical and spectroscopic phenomena has been recognized for some time, it was not until 1965 that its applicability to concerted reactions was revealed in a series of papers by Professors Woodward and Hoffmann.

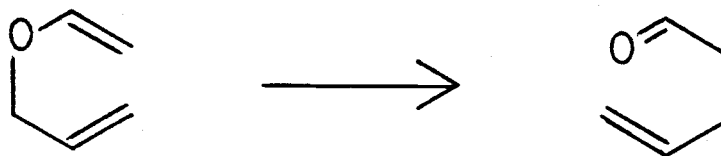
Concerted reactions are those in which a reactant is transformed usually with heat or light to a product without intervention of an intermediate. Bond formation and bond breakage occur synchronously. The stereochemical consequences of these transformations have been predicted with remarkable success by the "Woodward-Hoffmann Rules". However, the exact nature of the transition states of these reactions (especially energetics and structure-reactivity relationships) is only qualitatively suggested by the terms "allowed" and "disallowed".

In this work we have attempted to probe the transition states of three thermally induced pericyclic reactions and have attempted to correlate our results with theoretical calculations which have been developed as an alternative to the Woodward-Hoffmann approach.

PART 1. THE CLAISEN REARRANGEMENT OF 2-ISOPROPYL-1-METHYL-2-PROPENYL  
VINYL ETHER

I. Introduction

The thermally induced rearrangement of a vinyl allyl ether to form an unsaturated carbonyl compound was first observed by Claisen in 1912 (1). The corresponding rearrangement of the all carbon analog was identified in the studies of substituted 1,5-hexadienes by Cope (2) some thirty years later. Other analogs involving nitrogen or sulfur are now known but their synthetic applications have been limited (3).



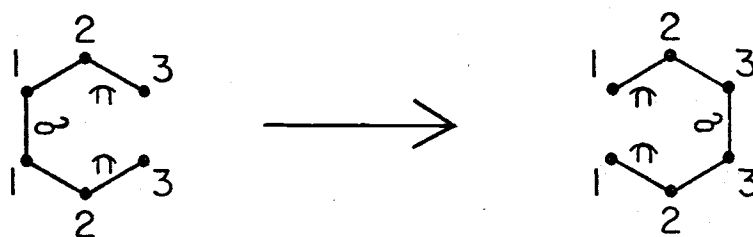
The Claisen rearrangements of vinyl and aryl allylic ethers have been extensively studied and exploited for their synthetic value. Since the subject has been adequately reviewed (3,4,5), only a short discussion of the mechanism and stereochemistry will be presented.

II. Mechanism and Stereochemistry

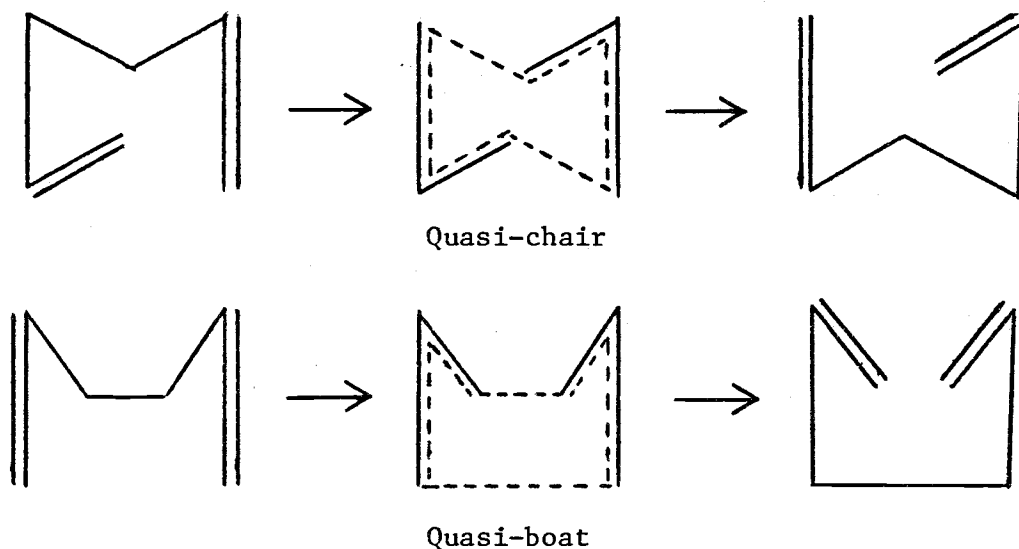
Experimental evidence derived from labeling techniques, stereochemical probes, kinetic analyses, inter- and intra-molecular "crossing" experiments supports the view of a concerted mechanism in which simultaneous bond-making and -breaking occur with the relocation of the unsaturated bonds (3). Kinetic studies have shown the

rearrangement to have activation parameters consistent with a concerted cyclic process with a highly ordered transition state (6).

With the application of concepts developed by Woodward and Hoffmann (7), the Claisen rearrangement was recognized to fall within the general category of (3,3)sigmatropic migrations. As shown below, the sigma bond may be considered as migrating across the pi orbitals.

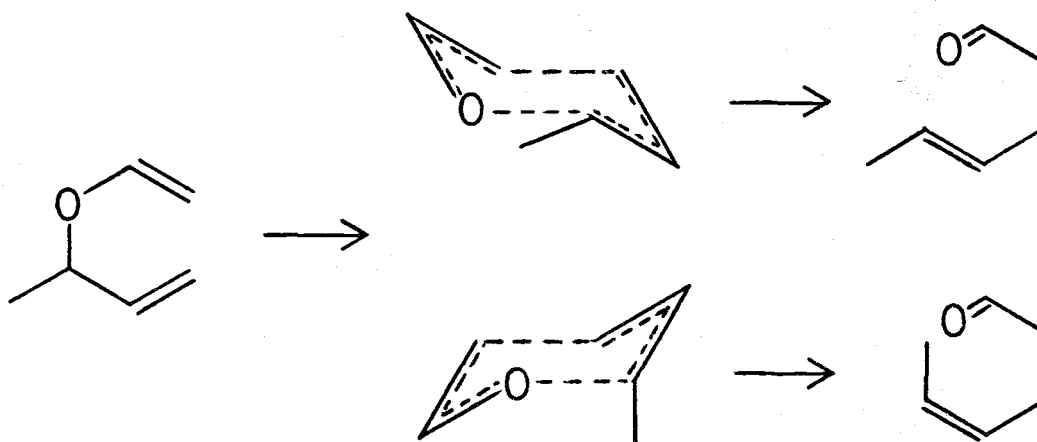


The prediction based on the conservation of orbital symmetry for thermal (3,3)sigmatropic migrations, is that the process can occur in a suprafacial manner. Other allowed processes are also predicted but are of much higher energy due to loss of overlap. Two transition state conformations are possible, the quasi-chair and the quasi-boat, which are analogous to the conformations of cyclohexane.



Although cases are known where additional geometric requirements lead to the quasi-boat form (8,9,10), the preferred transition state is the quasi-chair conformation. This has been unambiguously demonstrated in the Cope rearrangement of meso- and d,1-3,4-dimethyl-1,5-hexadienes by Doering and Roth (11). Their results showed that the quasi-chair transition state is at least  $5.7 \text{ kcal mole}^{-1}$  more stable than the quasi-boat for their system at  $225^\circ$ . From studies of 1,5-hexadiene-1,3,4,6- $d_4$ , Goldstein (12) has shown that the quasi-chair transition state has an enthalpy of activation of about  $11 \text{ kcal mole}^{-1}$  lower than the quasi-boat form. Numerous calculations (13,14,15) have confirmed the quasi-chair transition state preference.

One question which arises in connection with the quasi-chair transition state is whether a substituent will prefer an axial or equatorial position. As shown below, the axial and equatorial conformations of the quasi-chair transition state produce cis- and trans-products, respectively. Although general predictions of the



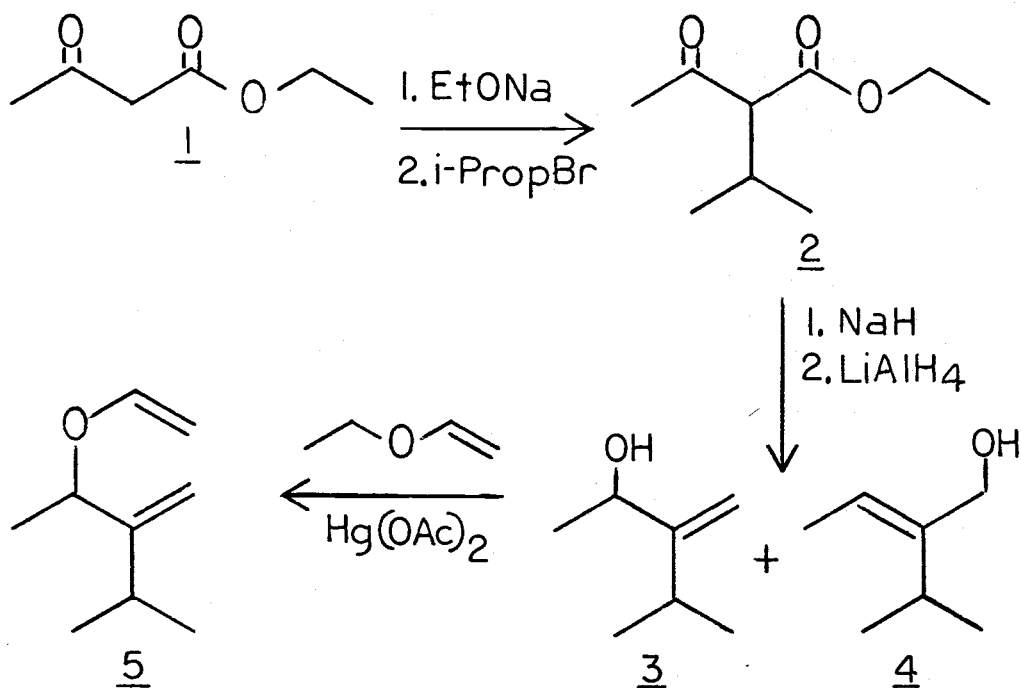
cis:trans ratios of products from the rearrangement of simple allyl vinyl ethers are in qualitative agreement with conformational preferences of the corresponding cyclohexanes, quantitative predictions or descriptions of the transition state as a cyclohexane will probably exceed the limits of the analogy. Since two of the  $sp^2$ -carbons are maintained in both the reactants and products, the  $sp^2$ -character of these carbon atoms will alter the bond lengths and angles in the transition state. Coupled with the effects of the oxygen atom, substituents in the transition state should possess different conformational free-energies than those observed for the corresponding cyclohexanes.

This study of the Claisen rearrangement of 2-isopropyl-1-methyl-2-propenyl vinyl ether establishes a limit to the cyclohexane model. The experimental observations confirm that quantitative predictions must be cautiously approached.

### III. Synthesis of 2-Isopropyl-1-methyl-2-propenyl Vinyl Ether (5)

The synthetic route required the preparation of the properly substituted allyl alcohol 3 which then could be converted into the desired ether 5 by the transesterification procedure of Watanabe and Conlon (16). The scheme used is that shown below.

Ethyl acetoacetate 1 was alkylated by treatment with sodium ethoxide and then 2-bromopropane by the general procedure of Marvel and Hager (17) to give ethyl  $\alpha$ -isopropylacetoacetate 2. The boiling point was consistent with that reported in the literature (18). The ir spectrum showed the ketone and ester bands at 1720 and 1740  $cm^{-1}$ .



The nmr spectrum showed the isopropyl methyl groups at 0.97  $\delta$  as a pair of doublets and the hydrogen of the isopropyl at 2.47  $\delta$  as a multiplet. The methine hydrogen adjacent to the carbonyl groups appeared as a doublet at 3.11  $\delta$ . The remainder of the spectrum as consistent with the assigned structure.

The reduction of 2 was effected by consecutive treatment with sodium hydride and lithium aluminum hydride by the procedure of Marshall and Litsas (19). The reaction gave a 30:70 mixture of E-2-isopropyl-2-buten-1-ol 4 and 3-isopropyl-3-buten-2-ol 3 in a combined yield of 45%. The products 3 and 4 may be rationalized as arising from the two possible enolates generated by initial treatment with sodium hydride. The isomers were distilled and then were separated by preparative glc. The assignment of stereochemistry to 4 was based



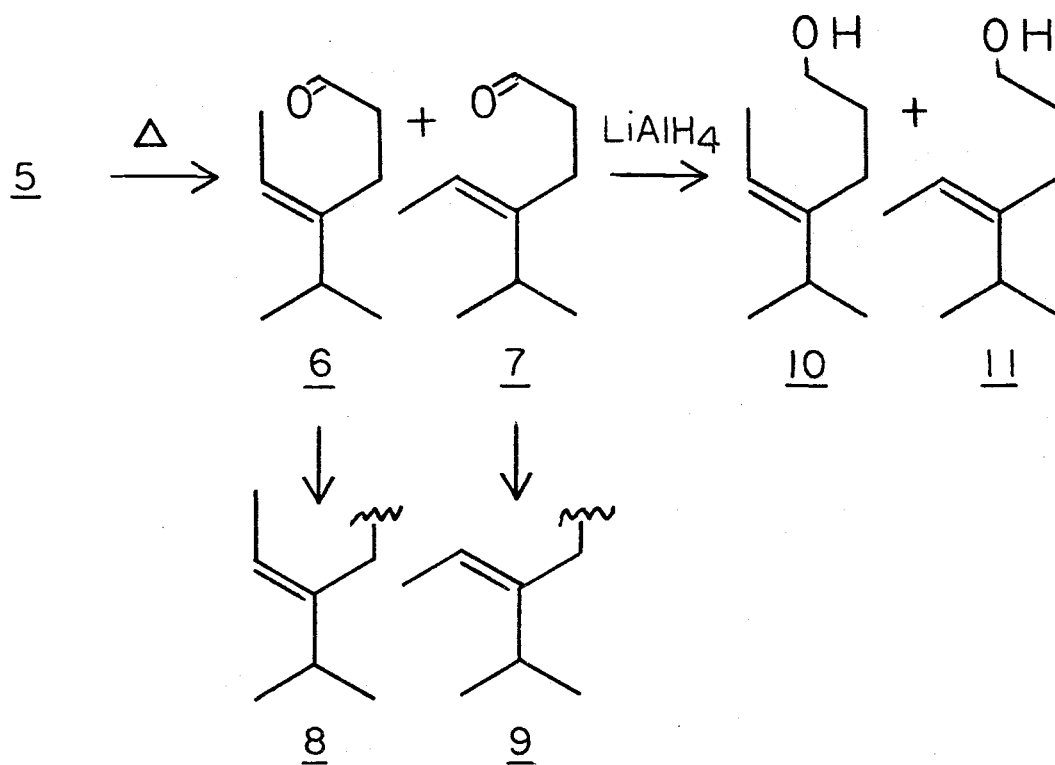
on product studies conducted in the original paper. The nmr and ir spectra were consistent with these assigned structures.

The alcohol 3 was converted into 2-isopropyl-1-methyl-2-propenyl vinyl ether 5 by transesterification with ethyl vinyl ether. The process is catalyzed by mercuric acetate and ethyl vinyl ether is used as the solvent to assure a favorable equilibrium for the formation of product. Initial reactions in which all reagents were mixed at once showed only about 5% conversion to 5 by glc. When the mercuric acetate and ethyl vinyl ether were allowed to stir at room temperature for 12 hrs prior to the addition of 3, glc showed a conversion to 5 of 99%. A possible explanation is that 3 complexes with the mercuric acetate in competition with ethyl vinyl ether. Isolation of 5 was accomplished by preparative glc on a 20% SE 30 column. The ether 5 has an ir spectrum which showed no bands over  $3100\text{ cm}^{-1}$  but showed characteristic vinyl ether bands at 1095, 1190 and  $1650\text{ cm}^{-1}$ . The nmr spectrum showed the isopropyl methyl groups as a doublet at  $1.05\ \delta$  and the isopropyl hydrogen as a septet at  $2.31\ \delta$ . The other methyl group appeared as a doublet at  $1.29\ \delta$  and the allylic hydrogen appeared as a quartet at  $4.27\ \delta$ . The vinylic region integrated to five hydrogens and showed the expected splitting patterns for a vinyl group and a gem-disubstituted alkenyl group. The mass spectrum gave a parent peak at 140 amu.

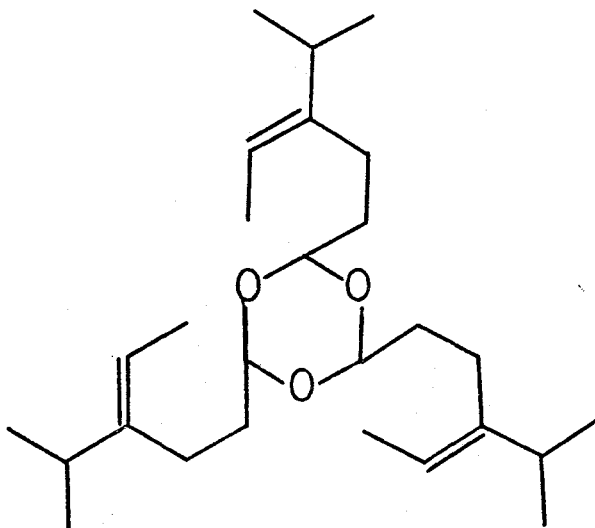
#### IV. Claisen Rearrangement of 2-Isopropyl-1-methyl-2-propenyl Vinyl Ether (5)

The rearrangement of 5 was conducted in sealed glass ampoules which were washed with 5% ammonium hydroxide and dried thoroughly

prior to use. Dilute solutions of 5 in spectral grade cyclohexane were heated at  $180^\circ \pm 2^\circ$  for 30 min. The nmr spectrum of the pyrolysis solution showed a somewhat broadened aldehydic signal and a multiplet in the vinyl region in a ratio of 1:1. The remainder of the spectrum was obscured by cyclohexane. The glc analysis showed the disappearance of 5 and the appearance of two peaks in a ratio of 40:60 which have been shown to be E- and Z-4-isopropyl-4-hexenal 6 and 7, respectively. However, isolation of these compounds by preparative glc gave new products 8 and 9 which had neither aldehydic proton absorptions in their nmr spectra nor carbonyl absorptions in their ir spectra. Evidence that they are isomers was given by the mass spectra



which showed identical fragmentation patterns with both showing parent peaks at 140 amu. The stereochemistries of the double bonds in 8 and 9 are the same as 6 and 7 based on comparisons with the nmr spectra of the alcohols 10 and 11, respectively. Although the nmr integration is not entirely consistent with this possibility, cyclic trimers as shown for 8 are suspected although their formation is usually acid catalyzed.



Due to this complication, the aldehydes 6 and 7 were immediately reduced by treatment with lithium aluminum hydride to yield the corresponding alcohols, E- and Z-4-isopropyl-4-hexen-1-ol 10 and 11 in a ratio of 40:60, respectively. The isomers were collected pure by preparative glc using a 5% OV-17 column.

The stereochemical assignments were based on previously observed downfield shifts for the tertiary isopropyl hydrogens of cis alkenes

The nmr spectra of cis- and trans-4-methyl-2-pentene 12 and 13 illustrate this effect. The data in Table 1 shows that the tertiary isopropyl proton (c) of 12 is considerably downfield from that of 13 which is in a normal position for a tertiary allylic proton. The

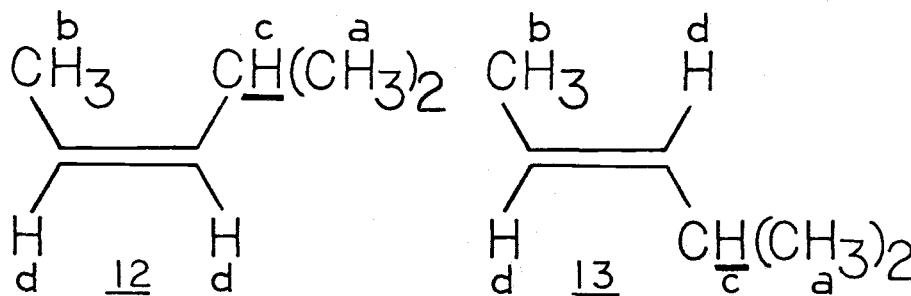


Table 1. NMR Chemical Shifts and Coupling Patterns of cis- and trans-4-Methyl-2-pentenes (Ref. 20)

Assignment	Chemical Shift ( $\delta$ )		Coupling Pattern	
	<u>12</u>	<u>13</u>	<u>12</u>	<u>13</u>
a	0.95	0.95	d	d
b	1.60	1.62	d	d
<u>c</u>	<u>2.60</u>	<u>2.20</u>	<u>septet</u>	<u>m</u>
d	5.35	5.35	m	m

deshielding effect may be attributed to diamagnetic anisotropic effects of the olefin in conjunction with a restricted rotation of the isopropyl group. The coupling pattern is also indicative of restricted rotation since the coupling constant between  $H_c$  and  $H_d$  is near zero instead of the 4-10 Hz when normal populations of syn and anti conformations contribute to the nmr average. These contentions are supported by the nmr spectrum of 4 which showed a chemical shift for the tertiary isopropyl

proton of 2.82  $\delta$  with a clear symmetrical coupling constant of 7 Hz. Although only five peaks were observable, their relative intensities allow a septet assignment.

The isopropyl hydrogen of 11 appears in the nmr as a clear septet at 2.87  $\delta$  while that of 10 appears at about 2.15  $\delta$  but is obscured due to methylene absorption in that region. The remainder of the nmr spectra of 10 and 11 were nearly identical. Both showed hydroxyl bands for monomeric and polymeric association in their ir spectra. The mass spectra gave parent peaks at 142 amu and identical fragmentation patterns although intensities varied slightly between them.

With the establishment of the structures for 10 and 11, the Claisen rearrangement products 6 and 7 can be assigned with some confidence. The ratios of 10:11 and of 6:7 were both determined to be 40:60 by triangulation of their glc traces.

## V. Discussion

### A. Quantitative Predictions Based on Ground State Preferences

The similarities between the cis:trans ratio in products from the Cope and Claisen rearrangements and the ratio of axial:equatorial conformations of the corresponding substituted cyclohexanes were noted by Perrin and Faulkner (21). They presented a table of observed values of  $-RT \ln(k_{\text{trans}}/k_{\text{cis}}) = \Delta\Delta G^\ddagger$  for a number of Cope and Claisen rearrangements. The values of  $k_{\text{trans}}/k_{\text{cis}}$  were obtained from the ratios of the trans- and cis-products observed. The values of the differences of the free-energies of activation were noted to be in general agreement with values of the free-energy change for the conversion of

a substituent from the equatorial to the axial position of correspondingly substituted cyclohexanes.

In a subsequent paper, Faulkner and Petersen (22) claimed that it was possible to predict quantitatively the cis:trans ratios in simple examples of the Claisen rearrangement. Their data are given as entries 1-4 in Table 2. Their predictions were calculated only on the basis of the recommended values of the free-energy change between conformations of  $R_2$ -substituted cyclohexanes  $\Delta G^\circ$ , by using cis:trans =

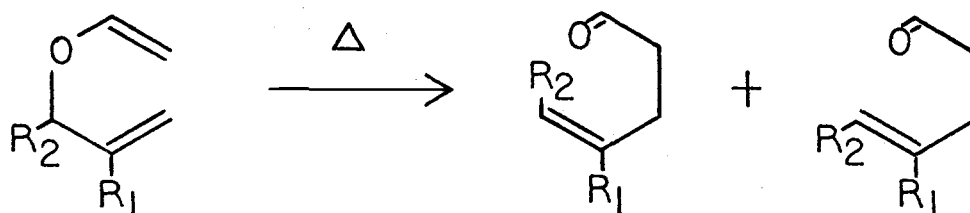


Table 2. Observed and Predicted cis:trans Ratios for Claisen Rearrangement Products.

Entry	$R_1$	$R_2$	Temp. ( $^\circ\text{C}$ )	<u>Cis:trans</u> Ratio	Predicted
1	Me	Et	110	10:90	9:91
2	Me	Et	205	14:86	14:86
3	Me	i-Pr	110	7:93	6:94
4	Et	Et	110	10:90	9:91
5	i-Pr	Me	180	40:60	13:87

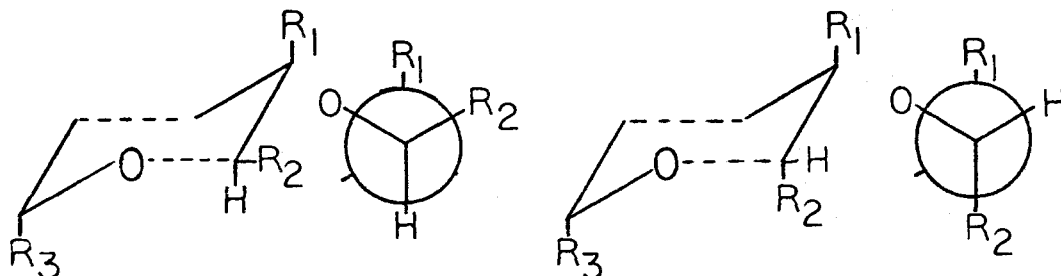
exp ( $\Delta G^\circ/RT$ ). The presence of  $R_1$  was ignored. Entry 5 of Table 2 is the result of this study. The predicted ratio was calculated by the prescribed method by using  $-1.71 \text{ kcal mole}^{-1}$  for the free-energy

change for the conversion of the axial conformer to the equatorial conformer in methylcyclohexane. Since the rearrangement was performed at  $180^\circ$ , the predicted ratio of products is calculated to be 13:87 which clearly deviates from the observed value of 40:60.

### B. Transition State Considerations

Before these results can be explained, it is necessary to examine the two proposed transition state geometries. Both resemble cyclohexane but differ in their predictions of the steric interactions in the transition state.

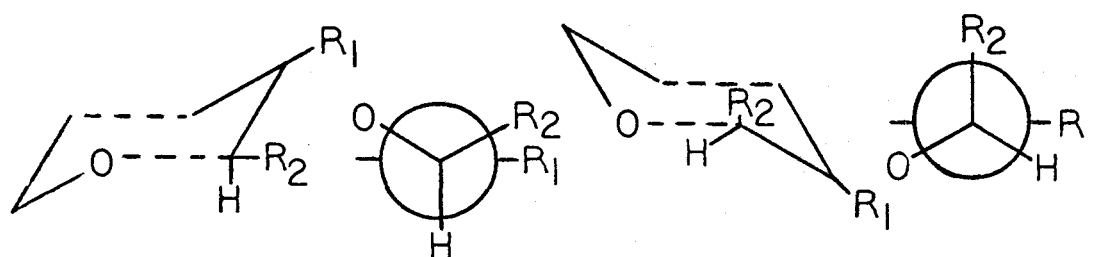
Implicit in the above calculations was that the  $R_1$  and  $R_2$  substituents did not interact. To account for this, Faulkner and Petersen proposed a transition state model as shown below which they termed "cyclohexane-like". All carbon atoms are assumed to be  $sp^3$  hybridized and the  $R_1$  substituent is assumed to occupy an axial position. As shown in the accompanying Newman projections, the steric interactions of  $R_1$  and  $R_2$  are minimized owing to a gauche relationship for the transition state which leads to the trans product.



Trans Product Transition State

Cis Product Transition State

In contrast, the more generally accepted "chair" model proposed by Marvell (23) shown below assumes that two carbon atoms are fully  $sp^2$  hybridized in the transition state. The nearly eclipsed arrangement of  $R_1$  and  $R_2$  in the "chair" transition state which leads to the trans product should result in steric interactions of approximately 1 kcal mole<sup>-1</sup> based on the heats of formation of appropriately substituted cis- and trans-alkenes.



Trans Product Transition State

Cis Product Transition State

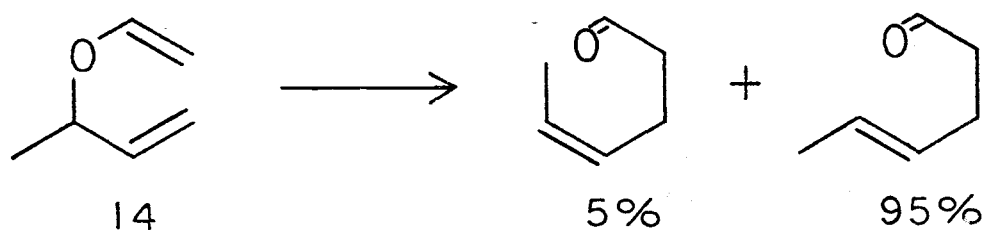
It is interesting to note that a similar dichotomy exists in the MINDO/2 calculations of the transition state for the Cope rearrangement (15,24).

### C. 1,3-Diaxial Interactions

To understand why there is no apparent steric interaction between  $R_1$  and  $R_2$  and why the results of this study deviate from a seemingly perfect correlation with conformational preferences of substituted cyclohexanes, it is only necessary to examine the basic assumption of Faulkner's method. The assumption is that the 1,3-diaxial interactions in the transition state of the Claisen rearrangement are comparable to the 1,3-diaxial interactions in  $R_2$  substituted cyclohexanes.



This assumption is clearly shown to be invalid from the data of Frey and Montague (25) for the rearrangement of 1-methylallyl vinyl ether 14. The cis product comprises only 5% of the total and corresponds to a difference in the free-energies of activation in favor of the equatorial methyl of  $2.4 \text{ kcal mole}^{-1}$ . The result is at variance



with the prediction of Faulkner and Petersen which would have calculated the difference to favor the equatorial methyl as  $1.71 \text{ kcal mole}^{-1}$  based on the conformational preference for the equatorial methyl in methylcyclohexane. The difference may be due to a flattened geometry as in tetrahydropyran (25) or due to electronic effects such as electron pair participation or contribution of ionic character to the two "halves" of the transition state due to differences in electronegativities. It should be noted that the equatorial methyl preference for the analogous 3-methyl-1,5-hexadiene rearrangement (27) was determined to be  $1.5 \pm 0.3 \text{ kcal mole}^{-1}$ .

Therefore, the effect of the  $R_1$  substituent is to compensate for the additional trans preference not represented in the cyclohexane system. The additional trans preference which might be estimated from the above example at about  $0.7 \text{ kcal mole}^{-1}$  approximately balances the steric interaction of  $R_1$  and  $R_2$  and results in a value for the

difference in free-energies of activation which is coincidentally similar to the conformational free-energy change in  $R_2$  substituted cyclohexanes.

The results obtained by Faulkner and Petersen can, therefore, be qualitatively accounted for by the "chair" model although the results of entries 1 and 4 of Table 2 are somewhat anomalous. The "chair" model would have predicted that the increased steric interaction on going from a methyl-ethyl to an ethyl-ethyl interaction in the transition state which leads to the trans product, should have resulted in a higher proportion of the cis product. That the two cases gave identical cis:trans ratios leaves unexplained about  $0.7 \text{ kcal mole}^{-1}$  in additional steric interaction based on the difference between the heats of formation of cis- and trans-2-pentene and cis- and trans-3-hexene (28).

#### D. Qualitative Predictions Based on the "Chair" Model

In contrast to the above, the results of this study are incorrectly predicted by the "cyclohexane-like" model. Consistent with the "chair" model the results can be interpreted by known preferences of the Claisen transition state and appropriate steric considerations.

The difference between the free-energy of activation for the equatorial methyl in the transition states of 14 and that of this study 5 can be calculated from the amounts of cis- and trans-product formed in each reaction to be  $2.4$  and  $0.37 \text{ kcal mole}^{-1}$ , respectively. The difference of about  $2 \text{ kcal mole}^{-1}$  between the two results can partially be accounted for by assuming the methyl-isopropyl repulsion in 5 is about  $1 \text{ kcal mole}^{-1}$  based on the heats of formation of cis-

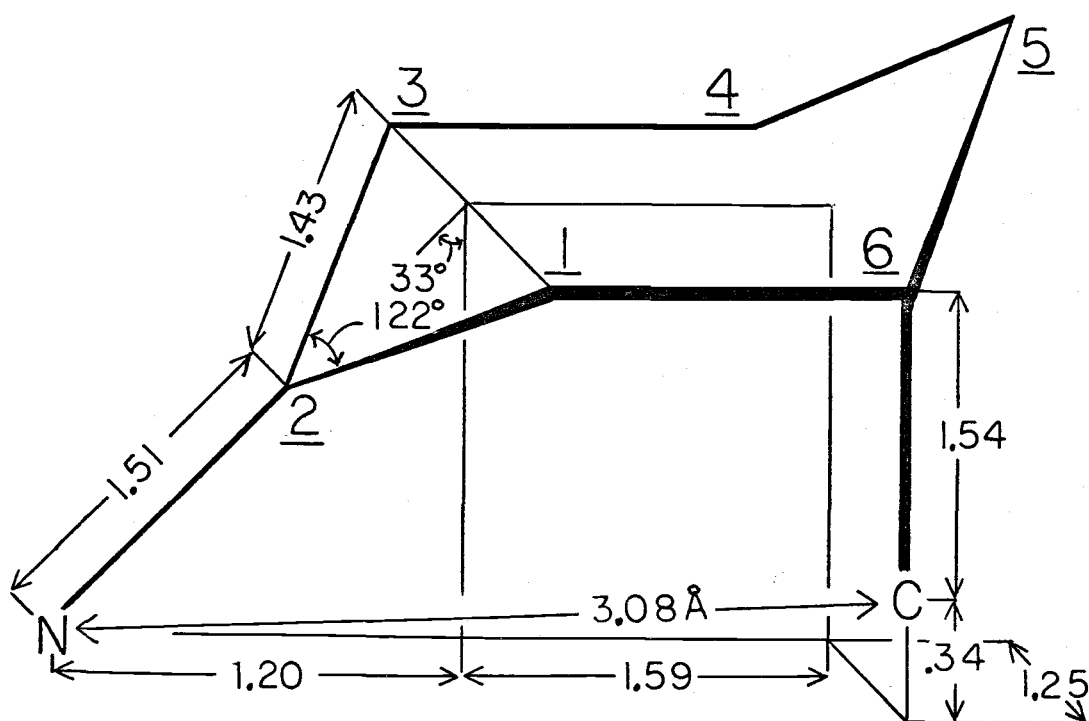
and trans-4-methyl-2-pentenes (28). The remaining 1 kcal mole<sup>-1</sup> might be attributed to an entropy effect. In reference to entries 1 and 2 in Table 2, the difference between the entropies of activation for the two transition states does appear to be negligible. However, the limited data (29) which is available suggests that entropy is a factor. In this case the problem of explaining the additional 1 kcal mole<sup>-1</sup> is compounded by the fact that the standard entropy of cis-4-methyl-2-pentene is 1.21 cal deg<sup>-1</sup> mole<sup>-1</sup> greater than the trans isomer in the gas phase. The standard entropies would have to be corrected for the liquid phase and temperature to be thermodynamically rigorous but the basic issue is the reliability of quantitative predictions of cis:trans ratios. Clearly, even if adequate data were available, the correlation of the ground state thermodynamic values with those of the transition state will be far from ideal.

Qualitatively, the effect of the isopropyl group in 5 in producing greater amounts of the cis isomer than that observed in the rearrangement of 14, can be predicted. Prudent use of ground state values may refine these predictions but the apparent sensitivity of the Claisen transition state to alterations of substituents precludes more exact calculations.

#### E. Another Possible Interaction

Another point of distinction between the "chair" model and the "cyclohexane-like" model is the possibility of a 1,3-diaxial interaction between R<sub>2</sub> and R<sub>3</sub> especially if R<sub>3</sub> is large. For the case when R<sub>3</sub> is dimethylamino in the dimethylacetamide dimethylacetal variant (30) of the Claisen rearrangement, the internuclear distance between

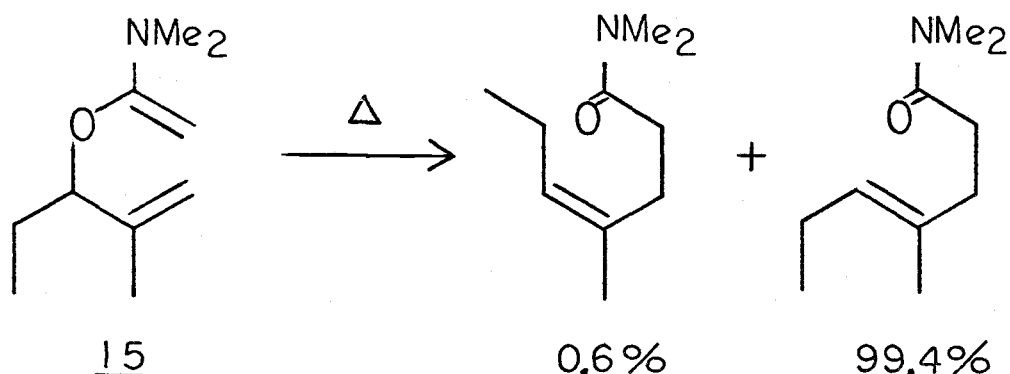
the nitrogen atom and an axial carbon atom was calculated as shown below using dimensions given by Dewar (15) in a MINDO/2 study of the Cope rearrangement. Despite the trigonal geometry at the apices of the system, the internuclear distance is calculated to be 3.08 Å. If the nitrogen is placed in an axial position the internuclear distance decreases to 2.04 Å. The sum of the covalent carbon-hydrogen distance



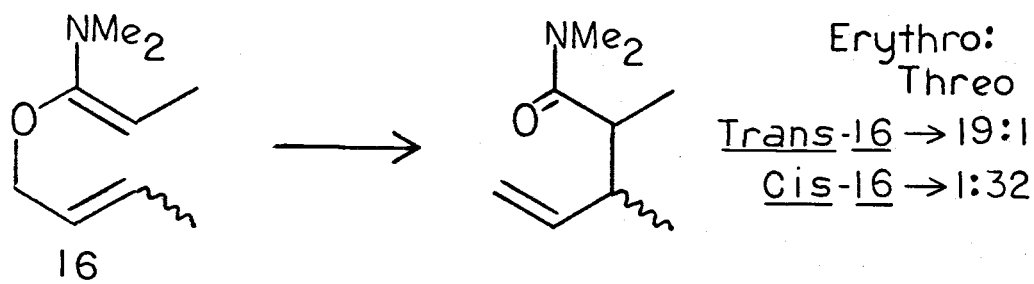
and the van der Waals radii of nitrogen and hydrogen is calculated to be 3.77 Å. Although the effect in the "chair" model would be expected to be small, the steric interaction in the "cyclohexane-like" model would be substantial. Recent MINDO/2 calculations of the Cope rearrangement transition state based on the cyclohexyl diradical by McIver (24) show a deviation of the apical hydrogen of 20° toward the axial positions. Although Dewar's calculations were based on the minimization

of energy in two allylic radicals, the reason for the difference between the two calculations is uncertain. However, the angle between carbons 1,2 and 3(4,5 and 6) was calculated in both studies to be near  $120^\circ$ . As with pyramidal nitrogen compounds, carbon 2 should have a low barrier to inversion and it seems likely that a substituent could easily be converted from a psuedo-axial to a psuedo-equatorial position if 1,3-diaxial repulsions became significant.

Experimental results presented by Faulkner (22) for the rearrangement of 1-substituted vinyl ethers support the existence of large 1,3-diaxial interactions between  $R_2$  and  $R_3$ . The N,N-dimethylamino analogue of the vinyl ether 15 given in Table 2 as Entries 1 and 2, rearranged at  $140^\circ$  to give the corresponding cis- and trans-amides in a ratio of 0.6:99.4, respectively. The substitution of the N,N-dimethylamino group for a hydrogen results in an increased equatorial preference of the ethyl group in the transition state of  $2.4 \text{ kcal mole}^{-1}$  which Faulkner attributed wholly to increased 1,3-diaxial interactions.

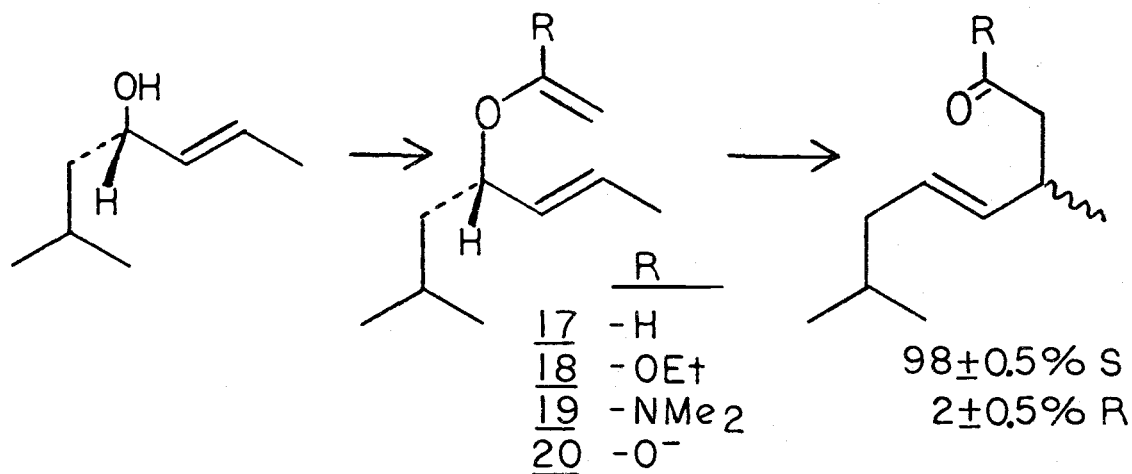


However, experimental evidence is accumulating which indicates that this effect is small or negligible. The results obtained by Sucrow and Richter (31) for the rearrangement of cis- and trans-2-butenyl 1-(N,N-dimethylamino)-1-propenyl ethers 16 resemble the ratio obtained from the rearrangement of 14. The free-energy preference is calculated to be 2.4 kcal mole<sup>-1</sup> for trans-15 while that of the cis-isomer is calculated to be 2.8 kcal mole<sup>-1</sup> which is a more modest



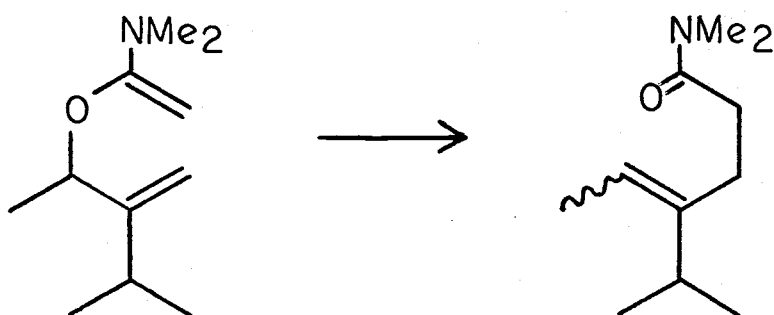
0.4 kcal mole<sup>-1</sup> higher than that of the unsubstituted analogous ether.

The transfer of chirality in the rearrangement of the vinyl ether of (S)-(-)-(E)-6-methylhept-2-en-4-ol 17 and three other 1-substituted vinyl ethers 18, 19, and 20 failed to show increased formation of



the (S)-isomer (32). However, differences of less than 0.5 kcal mole<sup>-1</sup> between the axial and equatorial transition states may be undetectable since the isomer ratio is a logarithmic function of the free-energy.

The best estimates of these interactions will be obtained when the free-energies of the transition states are similar. It would be desirable to experiment further with the N,N-dimethylaminovinyl ether of alcohol 3 since this system would be sensitive to changes in free-energies and the steric interaction could more properly be assessed.



## VI. Summary

The claim of quantitative predictions of the cis:trans ratios for the Claisen rearrangement have been shown to be invalid when based purely on 1,3-diaxial interactions of the corresponding cyclohexanes. Qualitative predictions based on free-energy differences determined from cis:trans ratios for the Claisen rearrangement do correlate within the series but cannot be extended to the Cope rearrangement. The "cyclohexane-like" transition state does not appear to be likely due to the results obtained from this experiment.

Calculations of the internuclear distances have shown that the "chair" model of the transition state can exhibit some steric interaction when substituted in the 1-position on the vinyl group although the existence or magnitude of this interaction has not been experimentally established.



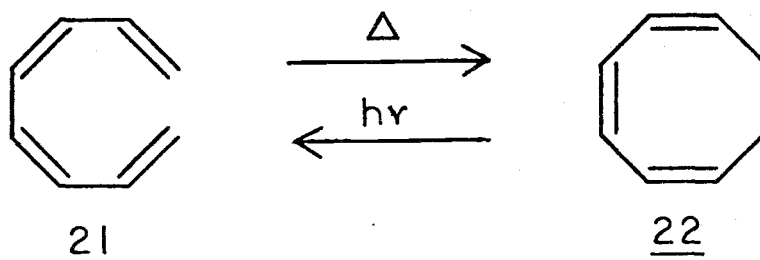
PART 2. ELECTROCYCLIC REACTION OF cis, cis-1,4-DI(1-CYCLOHEXENYL)-  
1,3-BUTADIENE

I. Introduction

The prediction of the Woodward-Hoffmann rules for the electrocyclic reaction of an 8 pi-electron system is that the process should occur in a conrotatory manner. This prediction has been confirmed in studies of C-1 and C-8 substituted octatetraenes (33). These systems have remarkably high rates of closure relative to 6 pi-electron systems. The steric and electronic effects of substituents on the transition states of 8 pi-electron cyclization are largely undetermined due to the kinetic instabilities of these compounds which cyclize rapidly at room temperature. One attempt to synthesize a stable 8 pi-electron system will be presented in this discussion.

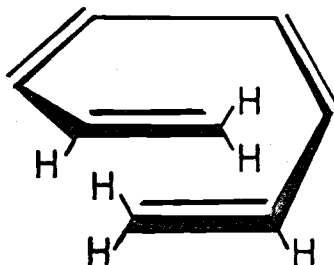
II. Expectations on the Stability of cis, cis-1,4-Di(1-cyclohexenyl)-1,3-butadiene (33)

The cyclization of cis, cis-1,3,5,7-octatetraene 21 was recognized to occur quickly at room temperature to give all-cis-1,3,5-cyclooctatriene 22 (34). Goldfarb and Lindquist (35) determined the rate of this process by photolysis of 22 which they showed gave only the cis, cis-octatetraene 21. The thermal reversion to 22 could then be observed



and the rate constant was determined to be  $3 \times 10^{-2} \text{ sec}^{-1}$  ( $t_{1/2} = 23$  sec) at  $25^\circ$ .

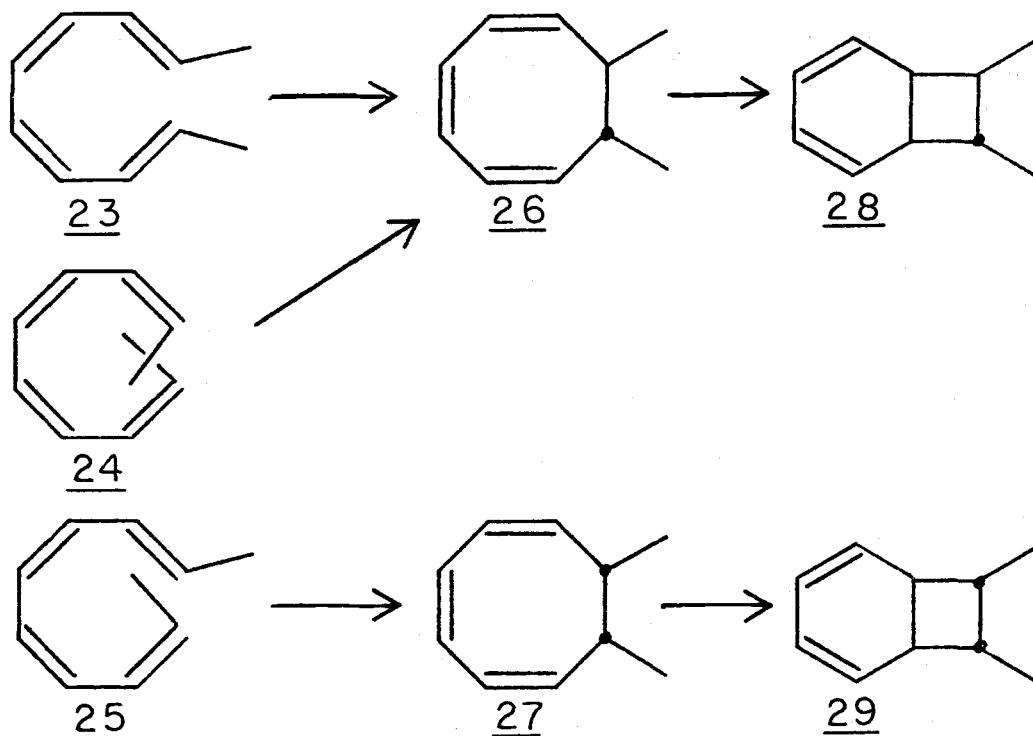
The rate of cyclization of 21 is about  $10^9$  times faster than the corresponding reaction of cis-hexatriene. The difference in enthalpies of activation between the two is about 13 kcal/mole. This difference may be rationalized by considering the transition state geometries for conrotatory and disrotatory processes. With the use of models, it is seen that cis, cis-octatetraene can be rotated into a helical conformation that will allow p-orbital overlap with little angle strain or steric interference of the terminal hydrogen.



In contrast, the cis-hexatriene cyclization occurs via a disrotatory mode and is expected to be accompanied by both angle distortion and steric interference.

Huisgen, *et al.*, (36,37) isolated the isomeric 2,cis-4,cis-6,8-decatetraenes 23, 24, and 25, and reported their rates of cyclization to the corresponding cyclooctatrienes 26 and 27. Although the rate of 23 was essentially unchanged from that of the unsubstituted compound 21, the cis isomer 25 was  $10^{-2}$  times slower and the cis, cis isomer 24 was  $10^{-4}$  times slower. The calculated effect of each cis-terminal methyl group is to increase the enthalpy of activation by

about  $3 \text{ kcal mole}^{-1}$ . The lower rates for the cis substituted octatetraenes can readily be explained by steric interactions in the helical transition state.

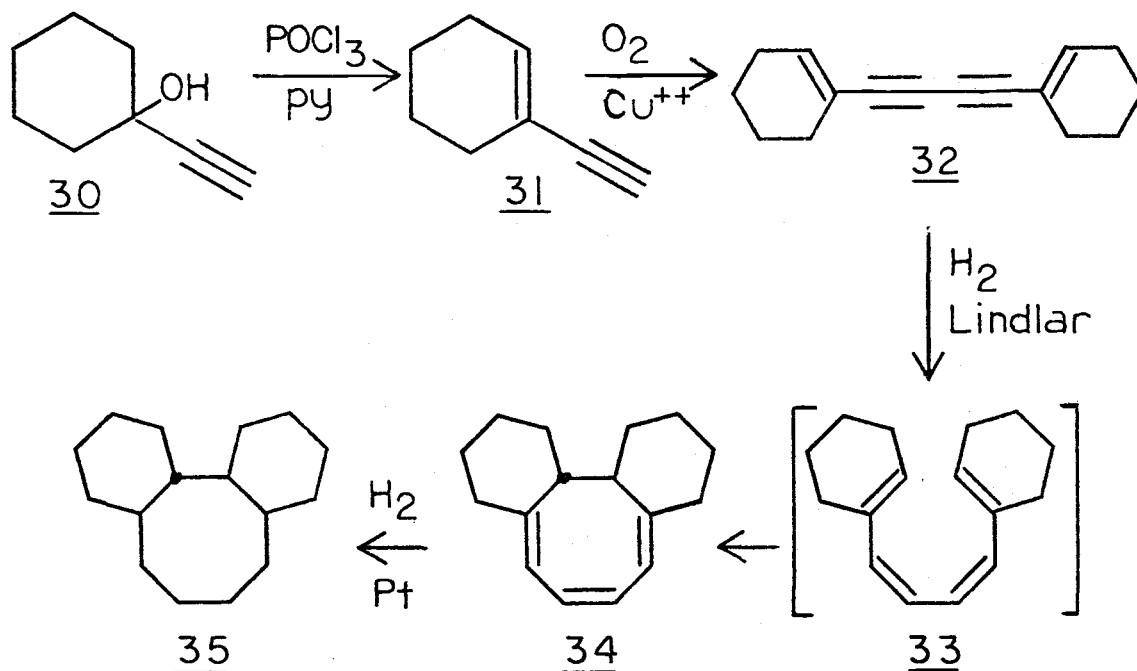


Although the effect of the methyl substituents on the rate of 23 was negligible, the rate of closure of cis, cis-1,4-di(1-cyclohexenyl)-1,3-butadiene 33 could conceivably be retarded by the steric hindrance of the two fused-cyclohexyl moieties on the terminal double bonds. The effect of C-2 and C-7 alkyl substituents is presently unknown for 8 pi-electron systems but is usually mildly rate enhancing on the corresponding C-2 and C-5 positions in 6 pi-electron cyclizations (38). However, this substitution is advantageous in that it will prevent the formation of further 6 pi-electron cyclization products such as 28 and 29 which are commonly observed in these systems (39-42).

Another problem which is avoided is one related to the relative thermodynamic stabilities of the tetraene and cyclotriene. A study of 1,8-diphenyl-trans-1, cis-3, cis-5, trans-7-octatetraene (43,44) was complicated by an equilibrium which favored the open-chaired isomer due to conjugation of the phenyl groups with the unsaturated system in the tetraene and steric interference of the phenyl groups in the cyclotriene. A rough calculation indicates that this is not expected to be a factor in this study. If it is assumed that the basic conversion of a pi bond to form a sigma bond and a ring is given by the  $-14.5 \text{ kcal mole}^{-1}$  for the conversion of cis-1,3-5-hexatriene to form 1,3-cyclohexadiene (45), the energy difference for the electrocyclic reaction of 33 is this value plus the difference in strain energy between cyclooctatriene and 1,3-cyclohexadiene ( $+4.1 \text{ kcal mole}^{-1}$ ) (46) and twice the energy difference between ethylidene-cyclohexane and 1-ethylcyclohexene ( $+0.8 \text{ kcal mole}^{-1}$ ) (47), and, therefore, is exothermic by  $8.8 \text{ kcal mole}^{-1}$ .

### III. Synthesis and Cyclization of 1,4-Di(1-cyclohexenyl)-1,3-butadiene (33)

A direct route to the desired tetraene 33 was provided by the acetylenic reactions of Jones, et al., (48,49). Commercially available 1-ethynylcyclohexanol 30 was dehydrated with phosphorous oxychloride in pyridine to give good yields of 1-ethynylcyclohexene 31. This method has been found to be of general applicability for the conversion of tertiary acetylenic and secondary benzylic alcohols into the corresponding unsaturated hydrocarbons. The acetylenic



coupling of 31 by aerial oxidation in the presence of cuprous ammonium chloride gave 1,4-di(1-cyclohexenyl)-1,3-butadiyne 32 as a white solid m.p. 63.5-64.5°. The ir and nmr spectra of 32 were similar to those of 31 except for the disappearance of the acetylenic hydrogen signal in the ir at 3315  $\text{cm}^{-1}$  and in the nmr at 2.68  $\delta$ . Reduction of 32 in the presence of Lindlar catalyst and a trace of quinoline gave 68% tricyclo(10.4.0.0<sup>6,11</sup>)hexadeca-1,3,5-triene 34, 18% of an unknown material presumed to be 1,4-di(1-cyclohexenyl)-cis-cis-1, trans-3-butadiene and 14% unreacted starting material. Pure 34 was isolated by preparative glc and gave a nmr spectrum which showed a broad twelve proton multiplet at 1.49  $\delta$  and a four proton multiplet at 2.15  $\delta$ . These protons were assigned to the cyclohexyl methylene hydrogens. The tertiary hydrogens appeared as a two proton

multiplet at 2.67  $\delta$  and the olefinic protons appeared as a four proton multiplet between 5.59  $\delta$  and 5.65  $\delta$ . The ir spectrum showed olefinic bands at 1645  $\text{cm}^{-1}$ , 1620  $\text{cm}^{-1}$ , and 1600  $\text{cm}^{-1}$  with cis stereochemistry indicated by a sharp band at 717  $\text{cm}^{-1}$ . The uv spectrum showed maxima at 244 nm ( $\epsilon = 4,870$ ), 252 nm ( $\epsilon = 4,600$ ) and 269 nm ( $\epsilon = 4,530$ ) with strong end absorption at 208 nm ( $\epsilon = 13,400$ ). The mass spectrum showed a parent peak (214 amu) with a relative intensity of 70.1%. A sample of pure 34 was reduced over Adam's catalyst to give the saturated hydrocarbon 35 which showed only aliphatic hydrogens in its nmr spectrum as a broad multiplet from 0.8  $\delta$  to 2.0  $\delta$  and only carbon-hydrogen bands in its ir spectrum at 2920  $\text{cm}^{-1}$ , 2852  $\text{cm}^{-1}$  and 1448  $\text{cm}^{-1}$ . The mass spectrum of 35 verified that three moles of hydrogen were added by showing a parent peak (220 amu) with a relative intensity of 44%.

To assure the cyclization was not occurring during the purification procedure, an aliquot of the Lindlar reduction solution was immediately hydrogenated over Adam's catalyst. Another aliquot was refluxed for two hours in carbon tetrachloride and then reduced. Both samples showed the same ratio of 35 by glc analysis. Although this experiment confirmed that the rate of cyclization of 33 was significant at room temperature, neither the determination of a minimum rate of cyclization nor the low temperature hydrogenation of 33 were feasible due to the extremely slow rate of hydrogenation which for 34 required about 18 hours to go to completion.

#### IV. Summary

The synthesis of an 8 pi-electron system in which the rate of cyclization could be measured conveniently was unsuccessful due to facile closure to tricyclo(10.4.0.0<sup>6,11</sup>)hexadeca-1,3,5-triene.

Although the electronic effects of alkyl substituents in the C-2 and C-7 positions are unknown, the steric effects of the fused-cyclohexyl groups appears to be minimal.

PART 3. ELECTROCYCLIC REACTIONS OF cis-2-PHENYL-1,3,5-HEXATRIENE AND  
cis-2-PHENYL-1,3-HEXADIEN-5-YNE

I. Introduction

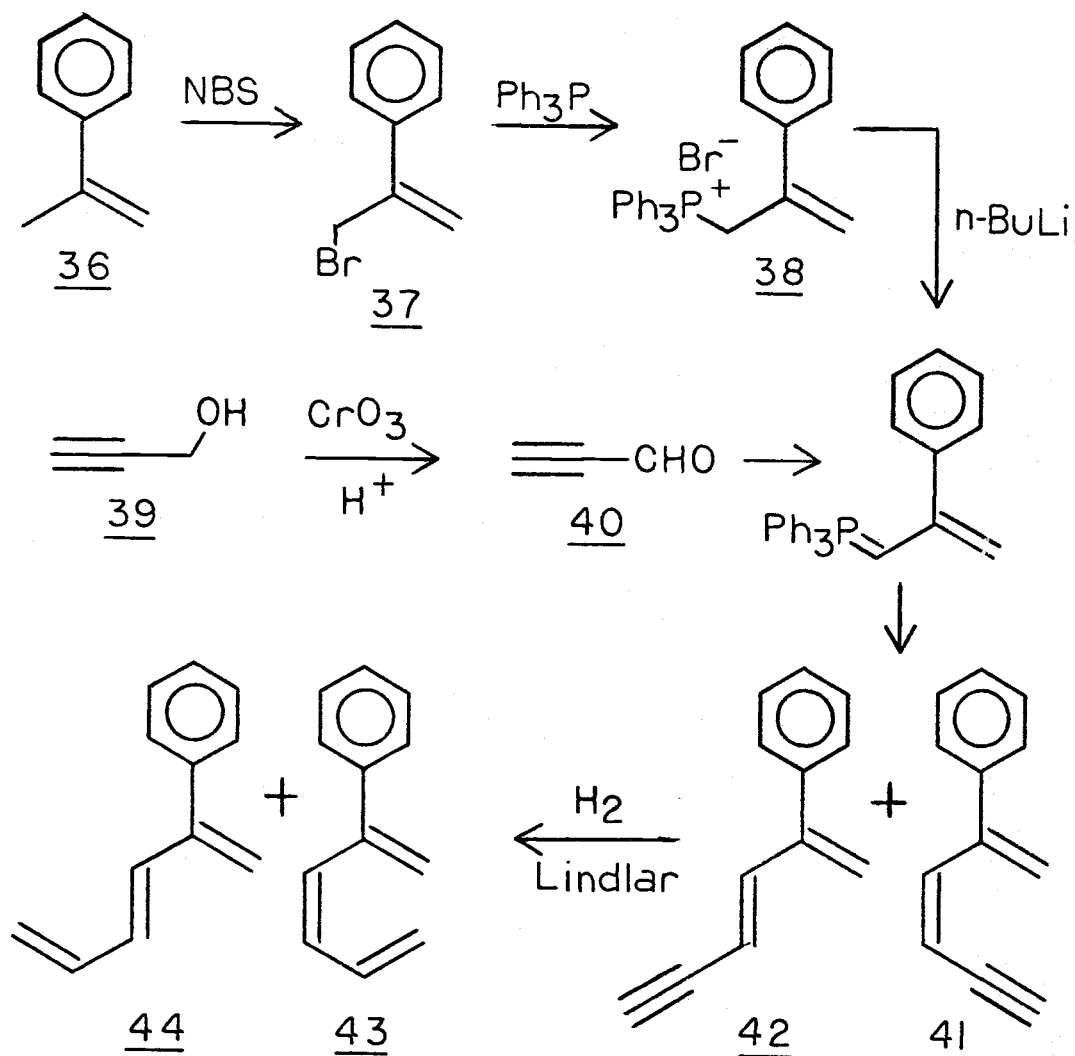
The thermal cyclization of cis-1,3,5-hexatriene is the simplest case of a Woodward-Hoffmann (50) concerted, disrotatory reaction. Ample experimental evidence (51-54) has verified the predicted stereochemical outcome. Recent interest has been directed towards energetics and structure-reactivity relationships as a method of gaining insight into the nature of the transition state. Since there was some evidence that it would have an extraordinarily enhanced rate of cyclization, the isolation of cis-2-phenyl-1,3,5-hexatriene became the object of a number of synthetic routes. However, the isolation of an intermediate cis-2-phenyl-1,3-hexadien-5-yne proved interesting in itself since it also undergoes cyclization albeit at a higher temperature.

II. Synthesis of cis-2-Phenyl-1,3-hexadiene-5-yne (41) and cis-2-Phenyl-1,3,5-hexatriene (43)

The synthetic route as shown below fulfilled the two requirements of generating cis stereochemistry at the central double bond and of forming the triene at a low temperature to prevent the expected facile cyclization from occurring. Two other synthetic approaches which possess these features will be presented later in the discussion.

The key step in the synthesis of cis-2-phenyl-1,3,5-hexatriene 43 was the Wittig reaction between 2-phenyl-2-propenyltriphenylphosphonium bromide 38 and propynal 40. Although stabilized Wittig





reagents have been generally thought to yield only the trans isomer, we have found that in the reaction with propanal and propynal, 2-phenyl-2-propenyltriphenylphosphonium bromide yielded large amounts of the cis isomer as well as the trans isomer.

The reaction of  $\alpha$ -methylstyrene 36 with N-bromosuccinimide to yield the allylic bromination product 3-bromo-2-phenyl-1-propene 37 proceeded rapidly after the reaction was initiated by heating. The

extremely lachrymatory product distilled at the expected temperature (55) and gave an nmr spectrum consistent with its structure.

The phosphonium salt was formed smoothly at room temperature from a stirred solution of 37 and triphenylphosphine. White crystals of 2-phenyl-2-propenyltriphenylphosphonium bromide 38 were collected and recrystallized. The nmr spectrum of the product showed two methylene protons as a doublet at 5.24  $\delta$  ( $J = 15$  Hz) and the olefinic protons as two overlapping doublets centered at 5.50  $\delta$ . The melting point of the solid matched the literature value (56).

The acetylenic aldehyde, 2-propynal 40 was prepared by chromium trioxide oxidation of 2-propynol 39 under reduced pressure which allowed the aldehyde to be removed as it was formed. The product had a boiling point which agreed with that reported earlier (57), and gave a simple nmr spectrum of two singlets at 3.67  $\delta$  and 9.29  $\delta$ .

The Wittig reagent was prepared by the reaction of 38 with an ethereal solution of n-butyllithium. Treatment of the ylid with freshly distilled propynal gave a 30:70 mixture of cis- and trans-2-phenyl-1,3-hexadien-5-yne 41 and 42. The mixture of isomers could not be resolved by glc but the presence of the trans isomer was not expected to be a problem since it cannot cyclize. The mixture gave a uv spectrum with maxima at 242 nm, 259 nm, and 270 nm with extinction coefficients on the order of 20,000. The ir spectrum showed terminal acetylenic bands at 3300  $\text{cm}^{-1}$  and 2100  $\text{cm}^{-1}$ . The nmr spectrum showed the acetylenic hydrogens of the cis- and trans-isomers as a pair of doublets centered at 2.91  $\delta$ , three olefinic hydrogens as a series of peaks between 5.16  $\delta$  and 5.92  $\delta$  and the aromatic

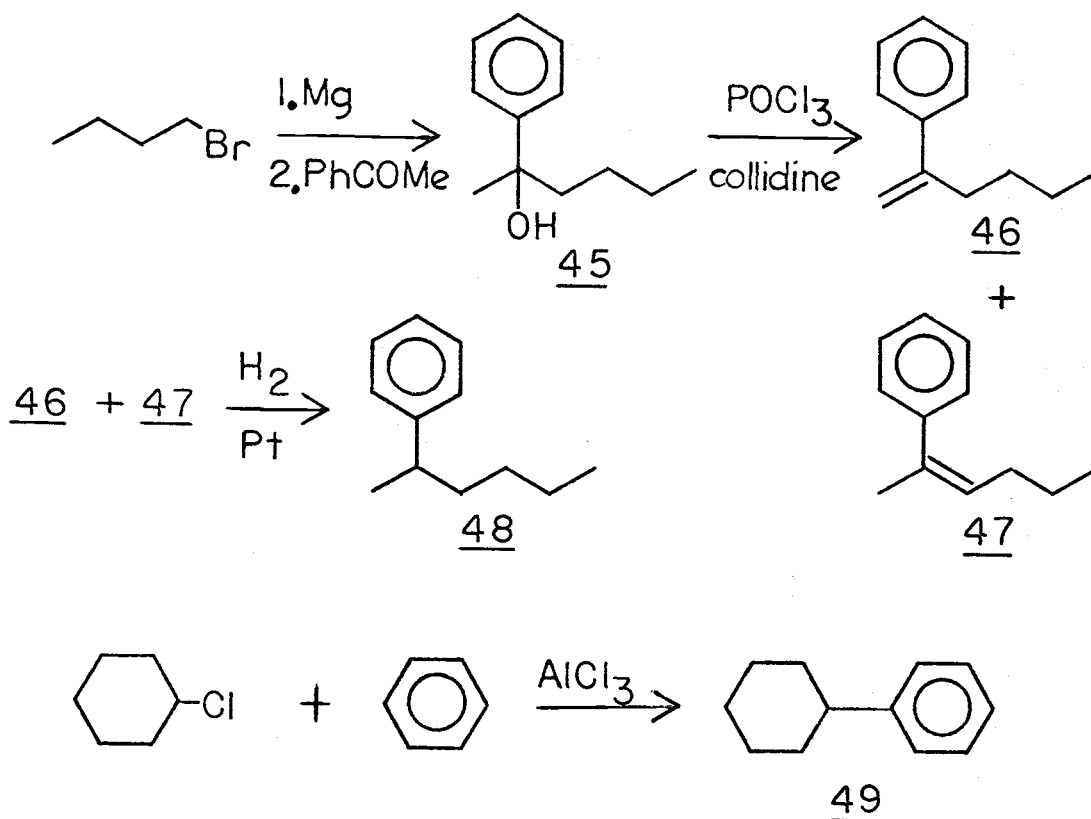
hydrogens as a singlet at 7.26  $\delta$ . The resonance for the remaining olefinic proton clearly separated in the spectrum into two sections which were assigned to the cis- and trans-isomers. A doublet ( $J = 11$  Hz) at 6.47  $\delta$  integrated to 0.3 hydrogen and was assigned to the cis isomer. A doublet ( $J = 16$  Hz) at 6.87  $\delta$  integrated to 0.7 hydrogen and was assigned to the trans isomer. Interestingly, the mass spectrum showed that the parent peak at 154 amu was the base peak and the peak corresponding to the loss of a hydrogen had about 70% relative intensity with the remaining fragmentations being much less notable. A small dimer peak at 308 amu was also observed. The compound was sensitive to air and rapidly formed a red oil on exposure to the atmosphere. Even with precautions to exclude oxygen, decomposition occurred when the substance was stored neat. However, dilute ethereal solutions stored cold were reasonably stable for periods of about a week.

The mixture of the dienyne isomers 41 and 42 was hydrogenated over Lindlar catalyst to yield three products of which 63% was trans-2-phenyl-1,3,5-hexatriene 44, 27% was cis-2-phenyl-1,3,5-hexatriene 43 and 10% was an unknown component. Preparative glc was used to collect small samples of 44 which showed a uv spectrum with maxima at 273.5 nm, 263 nm, and 254 nm previously reported for the trans triene (56). However, 43 cyclized under the column conditions and only the cyclized product 1-phenyl-1,3-cyclohexadiene was obtained. To confirm the presence of 43, two samples of the reaction mixture were hydrogenated over platinum oxide. One of the samples was heated in a sealed tube for 30 min at 150° prior to the hydrogenation. The

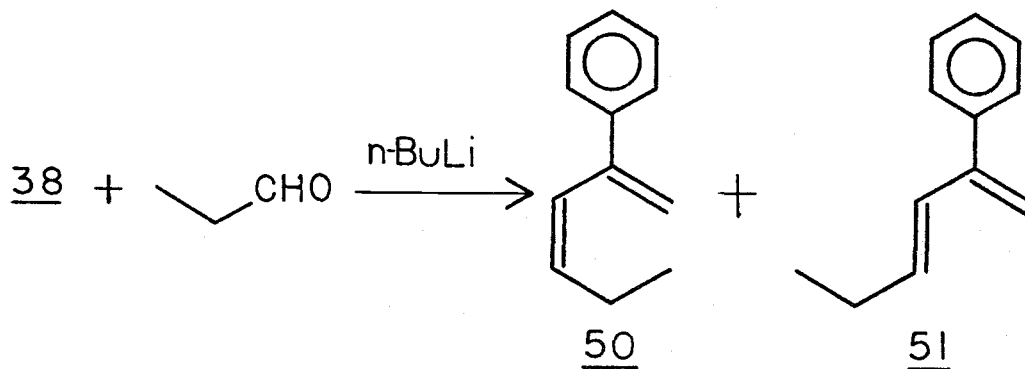
unheated sample gave only 2-phenylhexane 48 as verified by comparison with an authentic sample with no detectable amounts of cyclized material. The heated sample gave 56% 2-phenylhexane 48 and 42% phenylcyclohexane 49 which were identified by glc comparison with authentic samples. The above results confirm that although 43 was stable at room temperature, the rate of cyclization of 43 was quite rapid at higher temperatures.

The authentic samples of 2-phenylhexane 48 and phenylcyclohexane 49 were synthesized by unambiguous methods. A Grignard reaction was used to prepare 2-phenyl-2-hexanol 45 from acetophenone and n-butylbromide. Elimination with phosphorous oxychloride in collidine gave a good yield of a mixture of 2-phenyl-1-hexene 46 and 2-phenyl-2-hexene 47 with the thermodynamically less stable isomer as the major product. This result is in contrast to an earlier report (58) that 45 was resistant to dehydration and then gave only 47. A mixture of 46 and 47 was hydrogenated over platinum to give 2-phenylhexane 48 which had a boiling point consistent with that reported in the literature (59). The ir spectrum showed aromatic bands at  $764\text{ cm}^{-1}$  and  $702\text{ cm}^{-1}$ . The nmr spectrum showed aliphatic hydrogens from  $0.84\ \delta$  to  $1.7\ \delta$ , a benzylic hydrogen as a sextet ( $J = 7\text{ Hz}$ ) at  $2.62\ \delta$  and aromatic hydrogens as a singlet at  $7.1\ \delta$ .

Phenylcyclohexane 49 was prepared by the Friedel-Crafts reaction of chlorocyclohexane and benzene. The boiling point observed was identical to that reported (60). The ir spectrum and nmr spectrum were compatible with its assigned structure.



To provide spectral correlations, *cis*- and *trans*-2-phenyl-1,3-hexadiene 50 and 51 were synthesized by the Wittig reaction of the available phosphonium salt 38 and propanal. Again, *n*-butyllithium

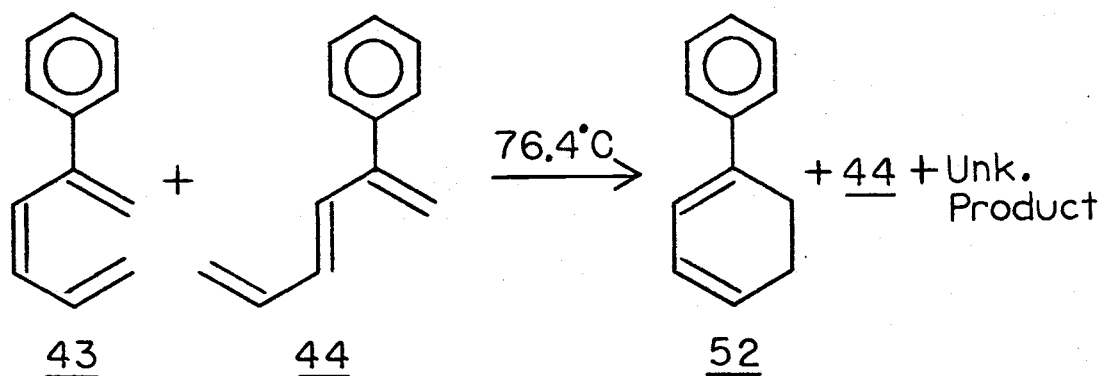


was used as the base and a 40:60 mixture of 50 and 51 was obtained. The isomers could not be separated by glc techniques. The uv

spectrum of the mixture showed a maximum at 220 nm and a shoulder at 240 nm with extinction coefficients of about 16,000. The ir spectrum showed a trans double bond at  $965\text{ cm}^{-1}$  and aromatic bands at  $760\text{ cm}^{-1}$  and  $698\text{ cm}^{-1}$ . The nmr spectrum showed two superimposed triplets ( $J = 7\text{ Hz}$ ) centered at  $0.98\ \delta$  assigned to the methyl groups of the isomers and a multiplet centered at  $2.10\ \delta$  assigned to the methylene hydrogens. The vinylic region showed a pair of overlapping AB patterns ( $J = 2\text{ Hz}$ ) assigned to the geminal vinylic hydrogens. Slightly downfield from these geminal protons was a multiplet centered about  $5.65\ \delta$  which integrated to one hydrogen. Irradiation of the protons at  $2.10\ \delta$  simplified this multiplet to a pair of overlapping doublets with coupling constants of 12 Hz and 16 Hz characteristic of cis and trans coupling constants for vicinal olefinic protons. Coupled to them were a pair of doublets ( $J = 12\text{ Hz}$  and  $J = 16\text{ Hz}$ ) farther downfield at  $6.08\ \delta$  and  $6.25\ \delta$  with relative integrations of 0.4 and 0.6 hydrogens, respectively. These doublets were assigned to cis and trans hydrogens of the C-3 carbon and their identification proved useful in the analysis of the nmr spectra of other compounds. The mass spectrum of 50 and 51 showed a parent peak at 158 amu with a relative intensity of 54%. Other significant peaks included those that correspond to losses of a methyl or ethyl at 143 amu and 131 amu with relative intensities of 100% and 84%, respectively.

### III. Kinetic Study of the Electrocyclization of *cis*-2-Phenyl-1,3,5-hexatriene (43)

Although only the uv spectrum of the thermal rearrangement product of 43 was obtained, the presence of phenylcyclohexane 49 in the reduction mixture establishes that cyclization is occurring. Since the isomeric cyclic diene 2-phenyl-1,3-cyclohexadiene has been reported (61) to give a uv maximum at 276 nm, the thermal rearrangement of 43 in this experiment to give 1-phenyl-1,3-cyclohexadiene 52



appears to be reasonable based on the identical uv maxima at 302 nm observed for the product and that reported (56) for 1-phenyl-1,3-cyclohexadiene.

The trienes 43 and 44 did not show absorption above 300 nm but an impurity present at the ten percent level showed a uv maximum at 284 nm which tailed to about 305 nm. Consequently, the formation of 52 was monitored using the ultraviolet absorbance at 320 nm. The reaction was conducted in a thermostated quartz cell at 76.4°C.

If the absorbance of 52 is proportional to its concentration, the rate may be calculated from the first-order rate equation expressed in terms of the formation of product (62):

$$k = -1/t \ln[1 - (A - A_0)/(A_\infty - A_0)]$$

where  $A$  = absorbance at time  $t$

$A_0$  = initial absorbance at  $t = 0$

$A_\infty$  = absorbance at infinite time

The absorbance data obtained showed an apparent logarithmic increase during the initial stages of the reaction but after twenty-six hours the absorbance was still increasing. An attempt to correlate the data by the Guggenheim method (63) failed to produce a linear relationship. However, the increase in absorbance with time was linear after about seventeen hours (four half-lives of 43) and it was assumed this represented a concurrent reaction which formed an unidentified product which superimposed its uv absorbance on that of 52. The linearity of the process indicates a slow rate of formation of the additional product. A slow decomposition of the trans triene 44 to give a product with a large extinction coefficient is a possible explanation since there is some indication of the instability of the trans isomer from the hydrogenation experiments with 43 and 44.

Fortunately, the linearity of the process allowed its effect to be subtracted from the original absorbance values. A least-squares fit to the experimental absorbance values after 16.75 hours to 26 hours (correlation coefficient = 0.98) gave an intercept of 1.04 which was used for the value of the absorbance at infinite time  $A_\infty$ . Experimental data for the initial seven hours of the reaction were corrected and the rate constant was calculated at each data point. Some justification for this procedure can be derived from the precision of the



results. The values for these calculations are listed in Table 3. The average rate was determined to be  $4.42 \times 10^{-5} \text{ sec}^{-1}$  ( $\pm 0.12 \times 10^{-5} \text{ sec}^{-1}$ ; 95% confidence). The relative rate to that of cis-1,3,5-hexatriene was calculated from the parameters given by Steiner (64) for its cyclization. The cyclization of 43 is calculated to be 290 times faster than the unsubstituted triene.

Table 3. Tabulation of Calculations and Rate Constants of the Electrocyclic Reaction of cis-2-Phenyl-1,3,5-hexatriene at 76.4°C

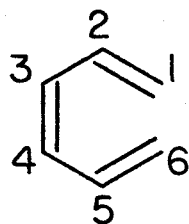
Time (min)	Absorbance	Absorbance (corrected)	Rate Constant, $k \times 10^5 \text{ (sec}^{-1}\text{)}$
0	0.242	0.242	-
25	0.302	0.298	4.85
35	0.328	0.323	5.09
45	0.343	0.336	4.64
55	0.359	0.351	4.45
70	0.386	0.376	4.38
90	0.422	0.409	4.35
105	0.443	0.427	4.19
120	0.472	0.454	4.29
145	0.502	0.480	4.07
165	0.540	0.515	4.23
195	0.581	0.552	4.20
240	0.645	0.609	4.28
280	0.698	0.656	4.35
300	0.720	0.675	4.35
330	0.750	0.701	4.32
360	0.781	0.727	4.33
385	0.810	0.753	4.42
420	0.852	0.789	4.59

$$\bar{k} = 4.42 \times 10^{-5} \text{ sec}^{-1} \text{ (95\% confidence = } \pm 0.12 \times 10^{-5} \text{ sec}^{-1}\text{)}$$

#### IV. Discussion

##### A. Electrocyclic Reactions of Substituted cis-2-Phenyl-1,3,5-hexatrienes

Triene electrocyclizations have been known for over a decade. They have been the topic of two recent doctoral theses (56,65) from this laboratory and the tables of approximately twenty-five substituted cis-1,3,5-hexatrienes presented therein will not be reproduced here. Only the preliminary interpretations will be reiterated which may be summarized in terms of the positions of substituents on the triene system.



Substitution of alkyl groups on position 1 and 6 have almost no effect on the rate of cyclization if they are trans. Cis groups at these positions result in pronounced rate retardations that are attributed to steric interactions in the transition states.

Substitution of radical stabilizing groups such as  $-\text{CO}_2\text{Et}$  and  $-\text{CON}(\text{Me})_2$  which are also electron-attracting, on positions 2 and 5 result in marked rate enhancements but the phenyl substituent appears to be an anomaly.

Alkyl substitutions on positions 3 and 4 display modest rate enhancements. Substitution of a vinyl group at the 3 position has been shown to produce a significant rate enhancement (66).

These observations, respectively, have been interpreted by the following rationalizations.

In the transition state, the carbons at positions 1 and 6 do not possess appreciable p-orbital character which would permit stabilization by resonance.

The carbons 2 and 5 appear to have isolated p-orbital character which are readily stabilized by resonance interactions. The effects of the phenyl group at these positions will be discussed in the following section but it appears that the situation at these carbons is not fully understood.

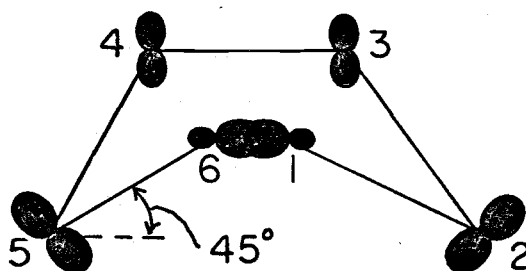
The substituent effect at carbons 3 and 4 has been interpreted in terms of an inductive effect in which the alkyl substituent introduces electron density remote from the reaction center and in terms of raising the ground state energies. The effect of the vinyl group at the 3 position which produced a significantly higher rate enhancement than alkyl substituents, has additionally been suggested to be the result of vinyl participation in the pi-system of the transition state (66).

#### B. Calculated Transition States

Marvell (67) has proposed a transition state described in terms of two sets of coordinates with three parameters each. The parameters included rotations about the bond between the 1 and 2 (5 and 6) carbons and about the bond between the 2 and 3 (4 and 5) carbons. The other parameter described changes in hybridization at carbon 1 (6).

Energies calculated were those of the pi-system, the forming sigma bond and the nonbonded interactions. The preferred transition state

was found on the disrotatory mode of closure. Consistent with the experimental observations, rehybridization at the 1 and 6 carbons was found to be well advanced while the double bond between carbons 3 and 4 was essentially intact. The angle of rotation about the bonds between carbons 1 and 2 and carbons 5 and 6 was found to be  $135^\circ$ . The proposed transition state is shown below.



A MINDO/2 study of the hexatriene-cyclohexadiene reaction carried out by Kormornicki and McIver (68) gave a transition state similar to the one shown above. Their internuclear distance between carbons 1 and 6 was calculated to be  $2.06 \text{ \AA}$  compared to Marvell's calculation of  $2.0 \text{ \AA}$ . Their dihedral angle between carbons 1,2,3, and 4 was  $42^\circ$  compared to Marvell's angle of  $45^\circ$ .

Both calculations predict that the p-orbitals at carbons 2 and 5 are to a large extent isolated from the remaining pi-system due to their tilted orientation. The pseudo-biradical character of the transition state should then be stabilized by placing radical stabilizing groups at the 2 and 5 positions.

### C. Mechanistic Implications

The substitution of a phenyl group at the 2 position produces a rate enhancement which is 290 times faster than the unsubstituted

cis-hexatriene. Since the rate was measured at only one temperature only the difference in free-energies of activation can be calculated. For the purposes of this discussion, entropy differences will be assumed to be negligible. The difference in the enthalpies of activation will, therefore, be assumed to be 3.9 kcal mole<sup>-1</sup>.

In view of the calculated transition states and the known radical stabilizing ability of the phenyl group (69) of ca. 12.5 kcal mole<sup>-1</sup>, the rate enhancement observed is below expectations. The substitution of such groups as carbethoxy and N,N-dimethylcarboxamide at the 2 position resulted in rate enhancements of as much as three orders of magnitude (70-72). The radical stabilizing effect of the carbethoxy group is known to be ca. 4.5 kcal mole<sup>-1</sup>, so that by comparison the phenyl would again be predicted to produce a substantial increase in rate.

At this point a number of possible explanations can be advanced. Further experimental work will be needed to differentiate the correct one and based on presently available evidence no final judgements can be passed.

The first simply assumes that the results obtained for the carbethoxy and N,N-dimethylcarboxamido groups are abnormally high. The effects could be due to the electronegativity of these groups or due to carbonyl participation in the electrocyclization transition state. If the results of this study are then taken as a measure of the radical character at the 2 carbon, the p-orbital would not appear to be as isolated as was previously calculated. Recent calculations (73) on the conformational preferences of cis-2-methyl-1,3,5-hexatriene

have shown that torsion about the central double bond of as much as  $19^\circ$  is not as unfavorable as one might have guessed. The p-orbitals on carbons 3 and 4 may also undergo torsional changes which would allow better overlap with the p-orbitals on carbons 2 and 5. There is some experimental evidence that the central double bond of cis-1,3,5-hexatriene possesses a  $10^\circ$  torsion angle but there is some uncertainty in the experimental value (74).

A second explanation is that advocated by Delphey (65) to account for the relative rate of cyclization of 1.5 observed for 1-( $\alpha$ -styryl)-2-vinyl-cyclohexene. The low rate of ring closure was explained in terms of the inability of the phenyl group to achieve coplanarity with the 1, 2, and 3 carbon plane. He presented uv data for a series of substituted biphenyls, styrenes and cyclohexenes and demonstrated that even for simple systems the phenyl ring may be twisted from coplanarity. Pertinent to this discussion is the data obtained for  $\alpha$ -methylstyrene in which the phenyl ring has been calculated to be twisted by an angle of  $33^\circ$  (75,76). In the transition state, the phenyl group may be in a similar environment in which the ortho-hydrogens would interact with a  $sp^2$  center on one side and a  $sp^3$  center on the other corresponding to the 3 and 1 carbons. A SCF calculation on the destabilizing effect of rotating a phenyl group out of coplanarity with a benzylic radical (77) would predict that at  $33^\circ$  the destabilization would be about  $6 \text{ kcal mole}^{-1}$ . This leaves about  $6.5 \text{ kcal mole}^{-1}$  of stabilization energy of which 60% was effective in stabilizing the p-orbital on the 2 carbon. This is, of course,

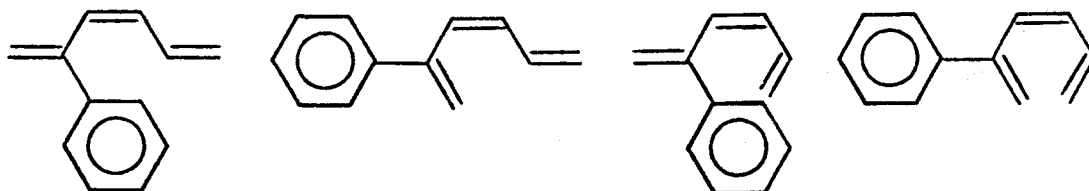
assuming that there has been no change in the ground state energy of the reactant. The ground state energy changes form the basis of the last argument.

The conformational calculations of hexatrienes cited earlier (73) also revealed that the substitution of a methyl group at the 2 position of cis-1,3,5-hexatriene raised the ground state energy by about 2.1 kcal mole<sup>-1</sup>. If the previous data (78,79) for alkyl groups substituted at the 2 position are accurate, the free-energy of activation is lowered by about 1 kcal mole<sup>-1</sup>. The rate enhancement can, therefore, be more than adequately accounted for purely on the rise in ground state energy, and the radical stabilizing effect of the alkyl substituent (estimated from the n-propyl and isopropyl radicals (80) at ca. 3.5 kcal mole<sup>-1</sup>) need not be invoked.

A similar analysis for the 2-phenyl triene can be approximated by the substitution of the phenyl group for the methyl group in that system. A methyl group stabilizes a double bond by 2.4 kcal mole<sup>-1</sup> determined from the heats of formation of 2- and 3-methyl-1-pentenes (81) and at a maximum, the phenyl group stabilizes a double bond by 3.0 kcal mole<sup>-1</sup> determined from the heats of hydrogenation of 1,2- and 1,4-dihydronaphthalenes (82). With this difference in stabilization, the ground state of cis-2-phenylhexatriene is raised only 1.5 kcal mole<sup>-1</sup> over the unsubstituted triene, but additional steric interactions still need to be considered.

The steric interactions due to the methyl group have already been included in the calculation and it can be assumed that these would be similar for the phenyl group. However, the interaction of the

ortho-hydrogens of the phenyl group lead to further destabilizations of the ground state. Of the possible conformations shown below, the second would appear to have the fewest nonbonded interactions. The



interactions of the ortho-hydrogens with the olefinic hydrogens are similar to the arrangement in biphenyl in which the steric interactions of ortho-hydrogens causes a  $20^\circ$  rotation (75). The additional steric interaction may be estimated from biphenyl (83) to be  $1.4 \text{ kcal mole}^{-1}$ . The ground state of the 2-phenyl isomer is then  $2.9 \text{ kcal mole}^{-1}$  higher than the unsubstituted triene and could explain a considerable portion of the rate enhancement.

Spangler (66) suggested a similar ground state effect to explain the enhanced rates of cyclization for 3-substituted hexatrienes. However, the conformation calculations (73) show that cis-3-methyl-1,3,5-hexatriene is  $1.04 \text{ kcal mole}^{-1}$  more stable than the parent triene.

#### V. Summary of the Electrocyclization of cis-2-Phenyl-1,3,5-hexatriene (43)

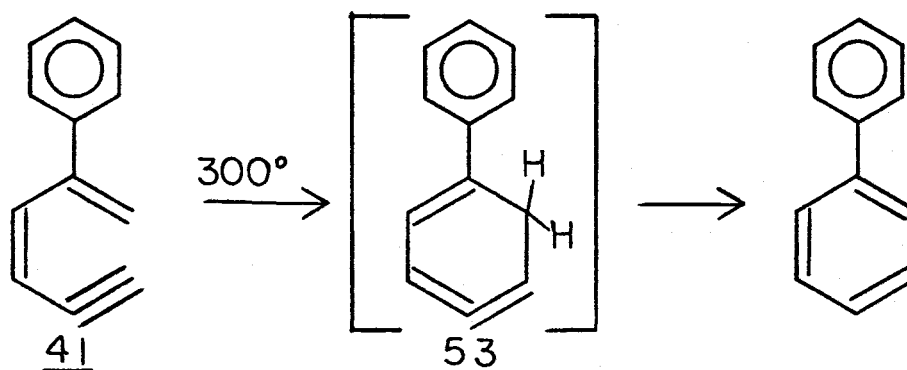
The result that cis-2-phenyl-1,3,5-hexatriene undergoes electrocyclization at a relative rate of 290 times that of cis-1,3,5-hexatriene can be rationalized by any one of the three theories presented. It is probable that the reality of the situation may be some combina-



tion of effects. Further experimentation with other substituents at the 2 position is needed. Future substituents should have small steric bulk, radical stabilizing ability and neutral electronegativity.

#### VI. Electrocyclic Reaction of *cis*-2-Phenyl-1,3-hexadiene-5-yne (41)

The electrocyclic reaction of *cis*-2-phenyl-1,3-hexadiene-5-yne 41 proceeded in a flow apparatus (84) at 300° with a contact time of 15 seconds to yield biphenyl as the major product. The initial cyclization product 5-phenyl-1,2,4-cyclohexatriene 53 presumably undergoes a rapid hydrogen shift. The *trans*-isomer 42 present in the pyrolyzed

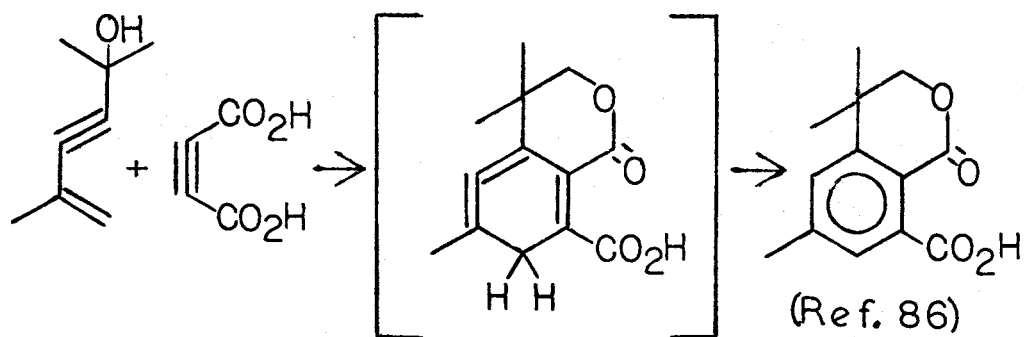


material did not appear to react since the ratio of 41:42 in the starting material was approximately the ratio of biphenyl:dienyne in the product mixture.

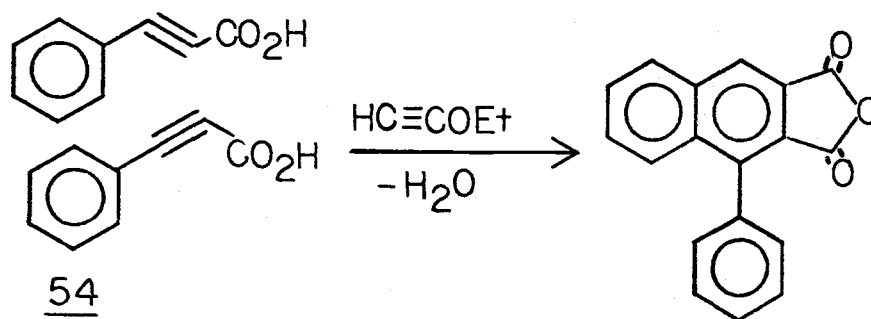
Although intermediates such as 53 have been produced as intermediates in related Diels-Alder reactions, this is one of the few cases of dienyne electrocyclizations which have been reported (126,127).

Vinyl acetylenes have long been used as partners for acetylenes in the formation of benzene rings. In his first review in 1944, Alder (85), described such reactions as extensions of the diene

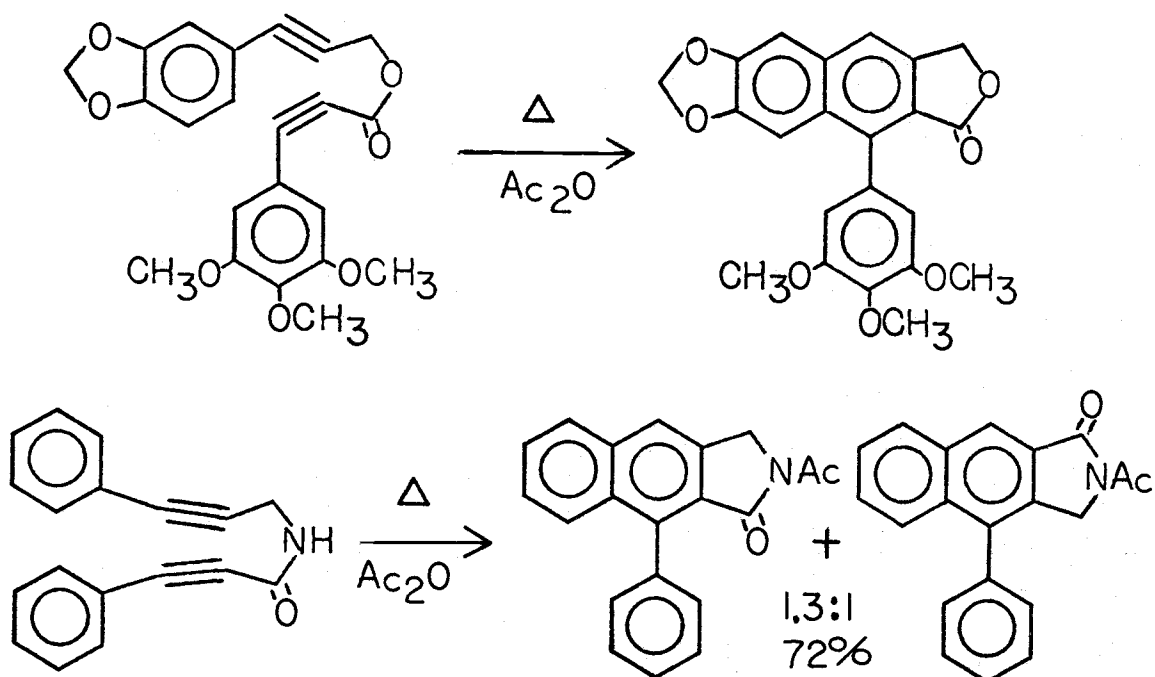
synthesis although they involve not only cycloaddition but also hydrogen migration.



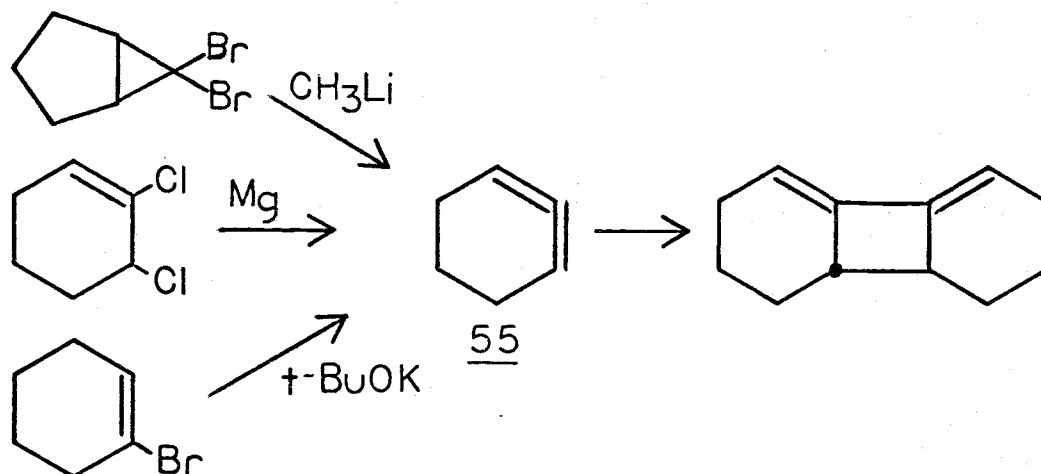
For a long time it has been known that phenylpropionic acid 54 leads to naphthalene derivatives (87). This reaction is especially smooth when anhydride is formed first.



Substituted symmetric or mixed anhydrides of phenylpropionic acids have been cyclized similarly (88,89) as have esters (90,91) and amides (92).

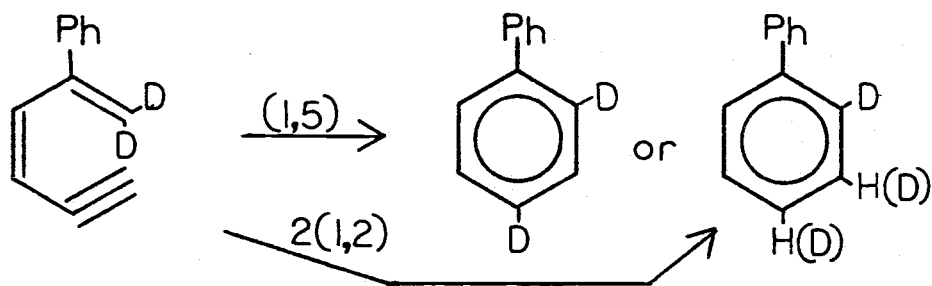


A similarly strained cyclic allene is 1,2-cyclohexadiene 55 which has been generated from 6,6-dibromobicyclo(3.1.0)hexane by treatment with methyl lithium (93), from 1,6-dichlorocyclohexene with magnesium (94) and from 1-bromocyclohexene with potassium *t*-butoxide (95). Since only a disallowed (1,3) hydrogen shift is possible, 55



undergoes a (2 + 2) cycloaddition dimerization. In the presence of 1,3-cyclohexadiene, 55 gives both the (4 + 2) and (2 + 2) cycloaddition products in a ratio of 3:1 respectively (94).

Since no dimerization products were observed in the pyrolysis of 41, the chemical behavior of 53 is, therefore, related to the Diels-Alder intermediates in which the hydrogen shift is facile. However, the nature of the hydrogen shift is uncertain. An allowed (1,5)-hydrogen shift is a possibility but the strained geometry of the intermediate suggests the possibility of two (1,2)-hydrogen shifts. Further studies with deuterium labeled compounds should provide insight into the mechanism of the aromatization.



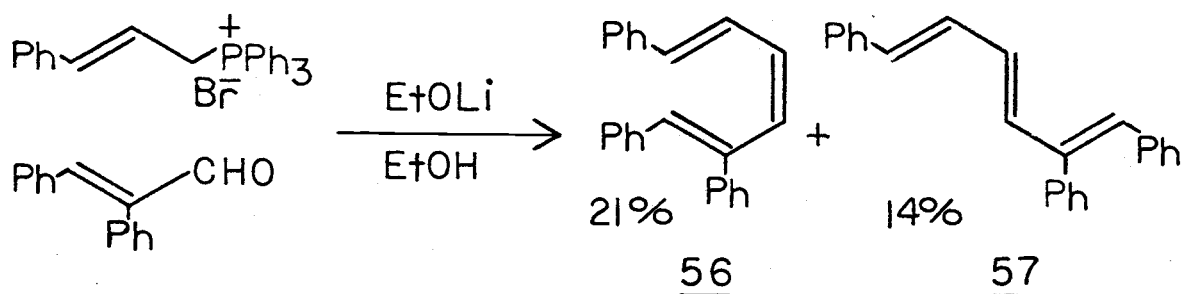
#### VII. Summary of the Electrocyclization of *cis*-2-Phenyl-1,3-hexadiene-5-yne (41)

A new electrocyclization reaction of a *cis*-dienyne to give apparently quantitative yields of the corresponding substituted benzene has been discovered. Although details of the reaction have not been determined, the reaction appears to involve a six pi-electron electrocyclization which is followed by a rapid hydrogen shift.

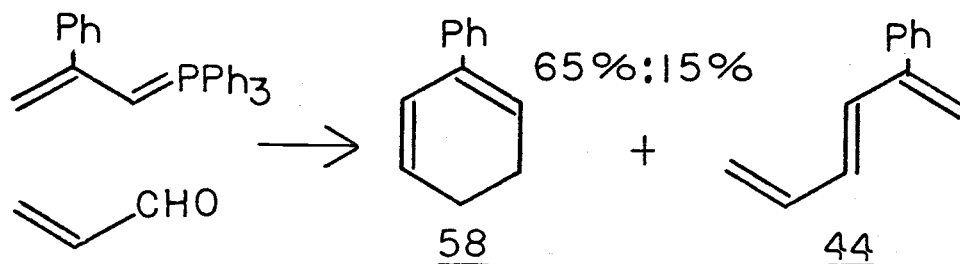
VIII. Other Attempts to Synthesize *cis*-2-Phenyl-1,3,5-hexatriene (43)

A. An Abnormal Wittig Reaction of 2-Phenyl-2-propenyltriphenylphosphorane and Acrolein

Encouraged by the success of Padwa (96,97) in the preparation of the two isomeric 1,2,6-triphenyl-1,3,5-hexatrienes 56 and 57 in which the *cis* isomer predominated, Cleary (56) and Delphey (65) attempted a similar synthesis of 43 by employing Schlosser's salt-free modifica-



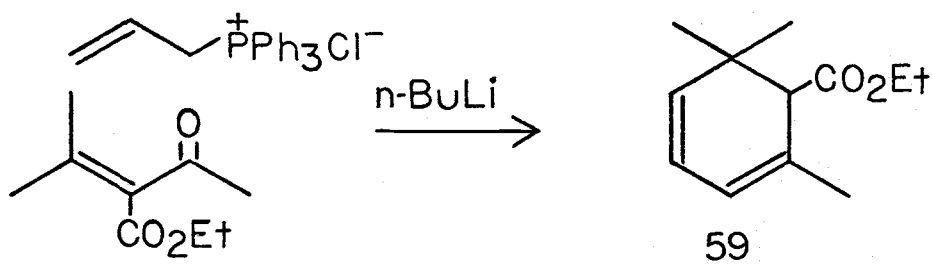
tion (98) which was reported to be more favorable for *cis* olefin formation. They obtained a small amount of the *trans* isomer 44 and an abnormal cyclized product, 2-phenyl-1,3-cyclohexadiene 58. None of the *cis* isomer could be identified in the reaction mixture. Since the *cis* isomer may have been responsible for this product through



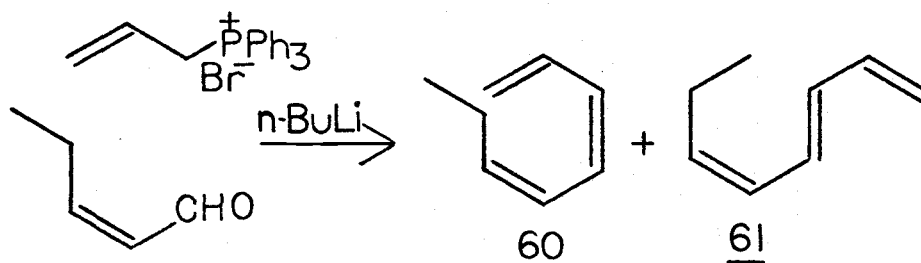
cyclization followed by rearrangement, Cleary synthesized 1-phenyl-1,3-cyclohexadiene 52 by the method of Grisdale (99) and showed it to

be stable to the reaction conditions. This confirmed that 58 was being formed directly from the reaction.

Buchi (100) first noted abnormal cyclized products of this type 59 in the reaction of  $\alpha,\beta$ -unsaturated ketones with allylidetriphenylphosphoranes and noted that their formation was favored by salt-free



conditions. A recent report (101) in which an allyl ylid was successfully reacted with 2-pentenal to give a mixture of trienes 60 and 61 under normal Wittig conditions, prompted a reexamination of this



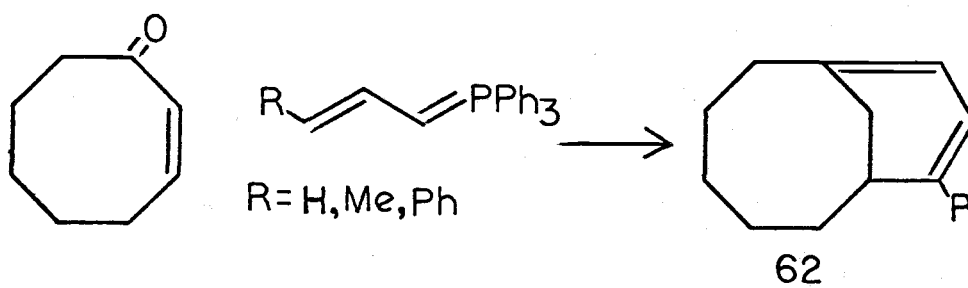
reaction to determine if the salt-free conditions were responsible for the formation of the abnormal product.

The ylids were generated with either  $n$ -butyllithium or in liquid ammonia by the procedure of Jaenicke and Seferiadis (101). Addition of freshly distilled acrolein followed by the normal work-up procedures gave 44 and 58 in a ratio of about 1:4. At this point the

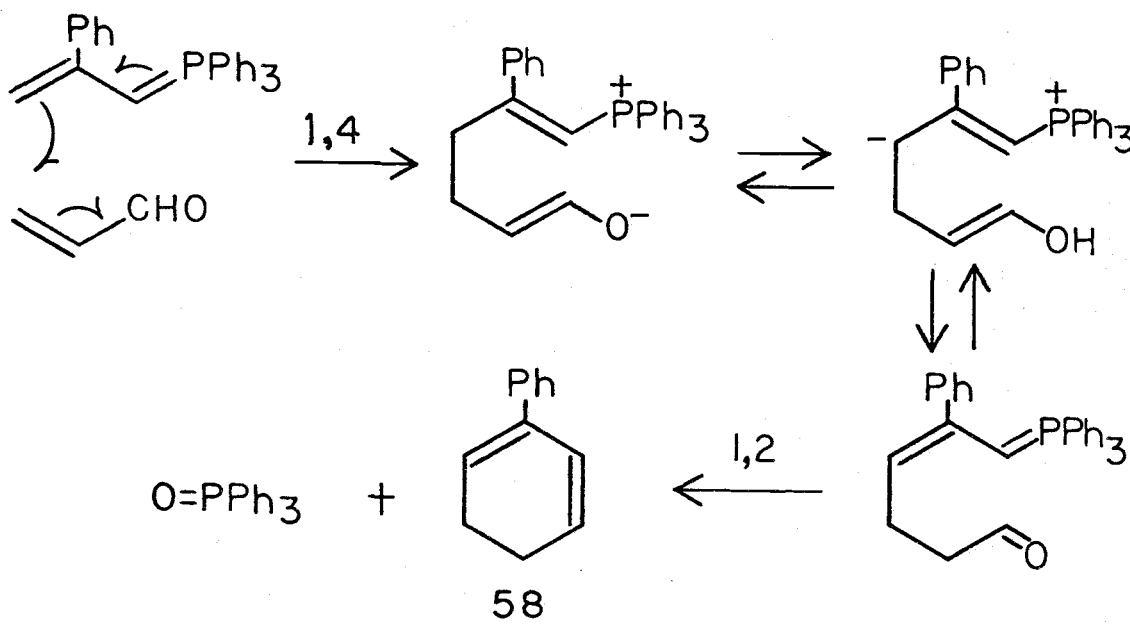
approach was abandoned but the successful reactions of propanal and propynal raises some interesting mechanistic questions.

### 1. Discussion

Dauben (102) has shown that the abnormal product 62 obtained from the reaction of 2-cyclooctenone and substituted allylidetriphenylphosphoranes, was not the result of triene cyclization.

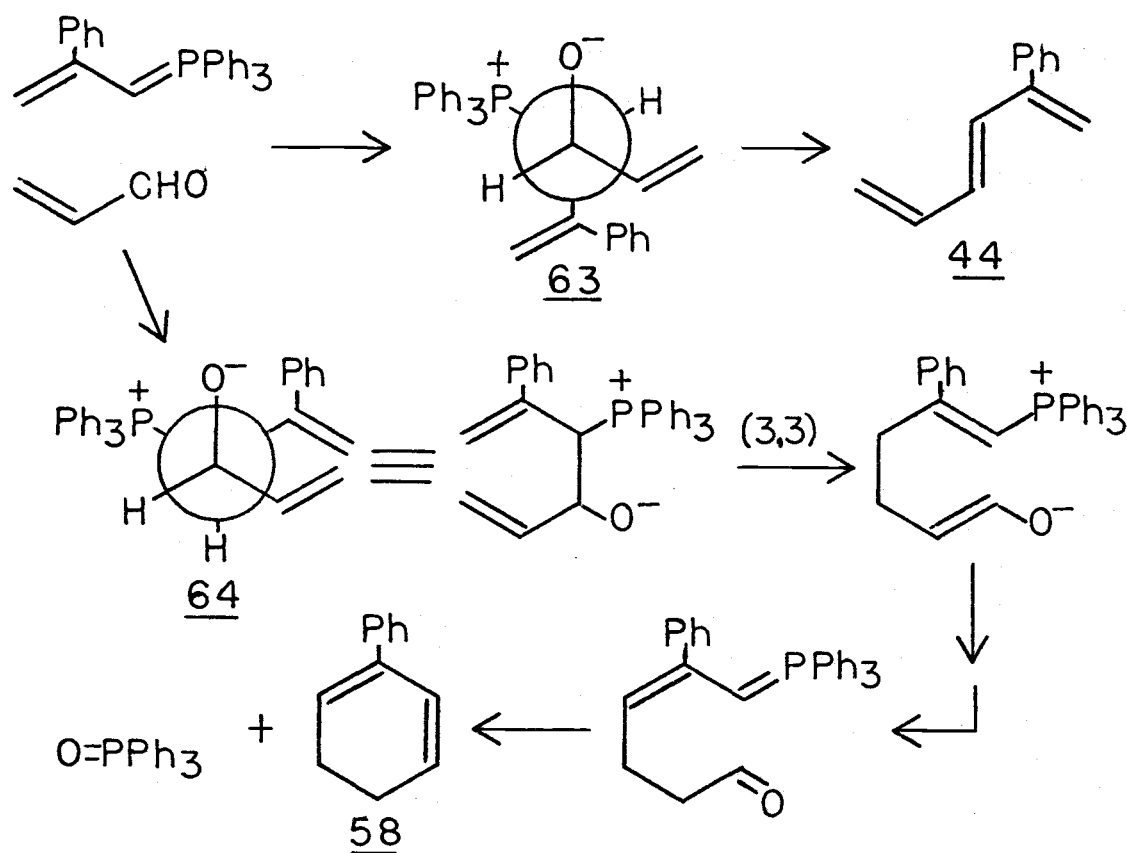


According to the mechanism which Dauben proposed, the formation of 58 occurs with the initial conjugate addition of both ylid and acrolein as shown below. A proton transfer and a tautomeric shift



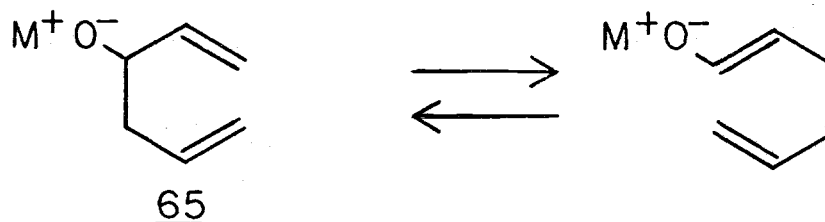
regenerates the ylid and carbonyl which then undergo an intramolecular Wittig reaction.

An alternative mechanism proposed by Cleary (56) involves the normal 1,2-addition of the aldehyde and ylid to give the diastereomeric betaines 63 and 64. Betaine 63 decomposes to give the trans triene 44 but betaine 64 undergoes a rapid Cope rearrangement before triphenylphosphine oxide can be eliminated. The reaction then proceeds as the last two steps of the previous mechanism.

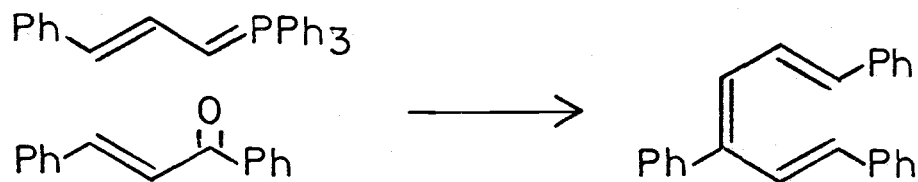


The rate of the Cope rearrangement has been shown to be significantly accelerated by ionic substituents. A rate enhancement of  $10^{10} - 10^{17}$  for the oxy-Cope rearrangement has been observed for metal alkoxides 65 over that of the corresponding alcohols (103).





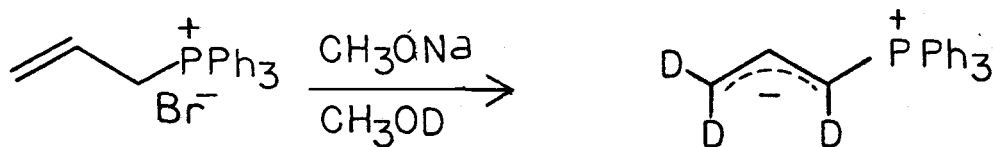
According to Dauben's mechanism, an increased tendency for the unsaturated carbonyl to undergo 1,4-addition (Michael acceptors) should be favorable for the formation of cyclized product. Since  $\alpha,\beta$ -unsaturated ketones are known to be more susceptible to conjugate addition than the corresponding aldehydes, they may be expected to produce greater amounts of cyclized products. Indeed, the "normal" reactions of  $\alpha,\beta$ -unsaturated ketones and allylidenetriphenylphosphoranes are to give the cyclohexadiene products. Only one case in which the expected Wittig products were obtained has been reported (104).



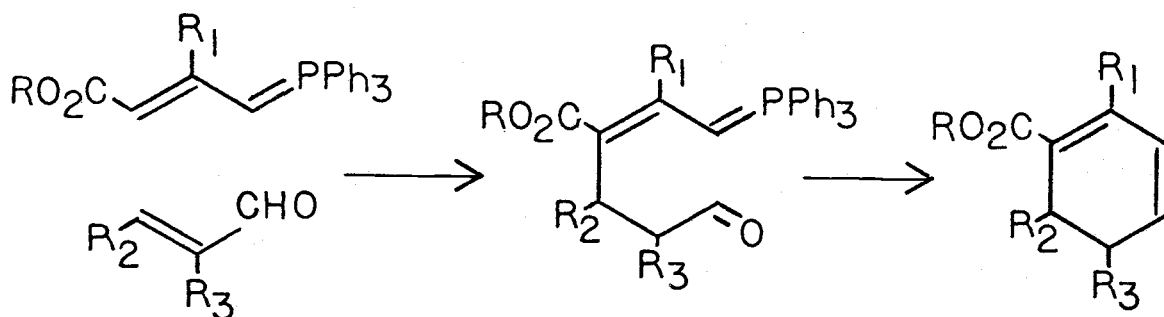
As described earlier, the reaction of propynal with 2-phenyl-2-propenyltriphenylphosphorane yielded the expected dienyne products. The difference in reaction between propynal and acrolein is better

explained by the known lower tendency of propynal to undergo 1,4-addition rather than invoking a lower rate of the Cope rearrangement for the erythro-propynal betaine since the rate of the Cope rearrangement of 1-hexen-5-yne is known to be comparable with that of 1,5-hexadiene (3).

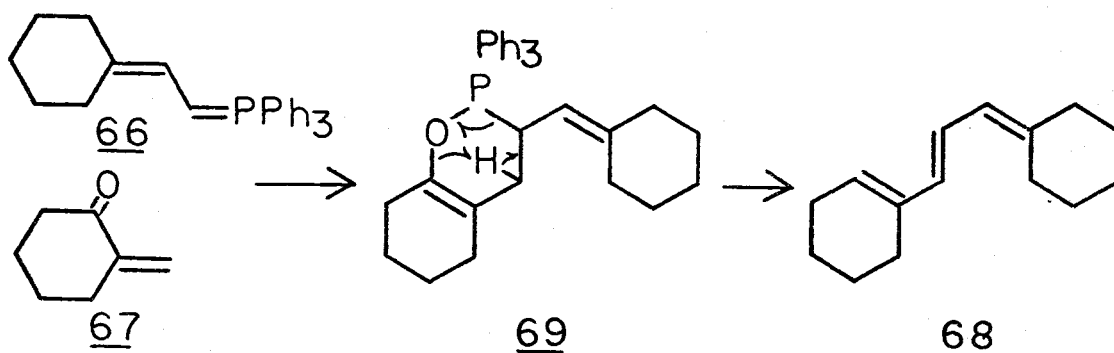
The 1,4-addition required by Dauben's mechanism also requires that the anionic character of the  $\gamma$ -carbon of the ylid be sufficient to provide a major reaction pathway. Some anionic character at the  $\gamma$ -carbon of allyltriphenylphosphorane has been demonstrated by Schweizer and coworkers (105). The ylid of allylphosphonium bromide was generated by sodium methoxide in deuterio-methanol. The Wittig adducts obtained were shown to contain deuterium in positions which corresponded to the  $\alpha$ - and  $\gamma$ -carbons of the ylid although incorporation at the  $\gamma$ -carbon was incomplete. It is interesting that the



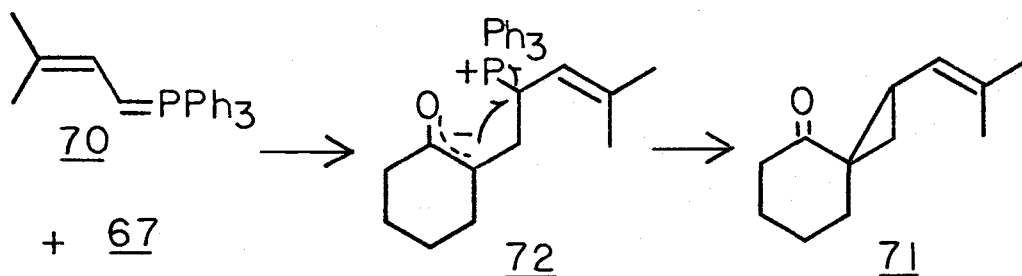
only other cases of  $\alpha,\beta$ -unsaturated aldehydes yielding abnormal Wittig adducts have been with allylidenephosphoranes with anion stabilizing groups ( $-\text{COOR}$ ,  $-\text{CONR}_2$ ,  $-\text{CN}$ ) in the C-3 position (106). In some of these reactions the trans triene was also isolated.



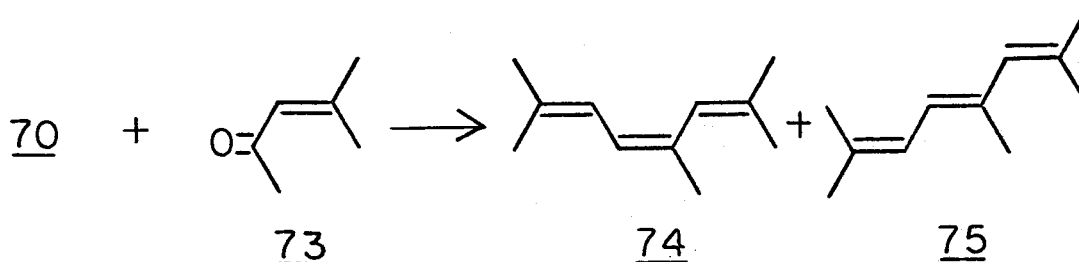
The 1,2-addition to the aldehyde carbonyl has been firmly established in reactions with other carbanion-type reagents such as Grignards and enolates. The trans-triene 44, however, may be the result of another process proposed by Inhoffen (107). A  $\gamma$ -disubstituted allylidene phosphorane 66 which blocks the proton transfer in the cyclization process gave an unusual reaction with 2-methylene-cyclohexanone 67 which is known to be a rather reactive Michael acceptor. The triene 68 isolated from the reaction was postulated to be the result of the rearrangement of the intermediate 69 formed by the 1,4-addition to the carbonyl by the  $\alpha$ -carbon of the ylid.



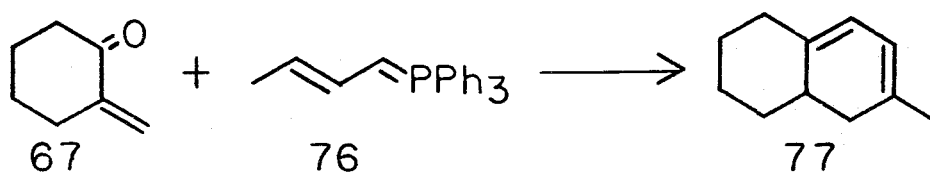
However, the extension of this mechanism to other systems must be only tentative. Dauben (108) treated a similar  $\gamma$ -disubstituted ylid 70 with 67 and obtained the cyclopropane 71 which can be envisioned as a displacement of triphenylphosphorous by the enolate of intermediate 72. When 70 is treated with mesityl oxide 73 the normal



1,2-addition occurs to give the isomeric trienes 74 and 75. The



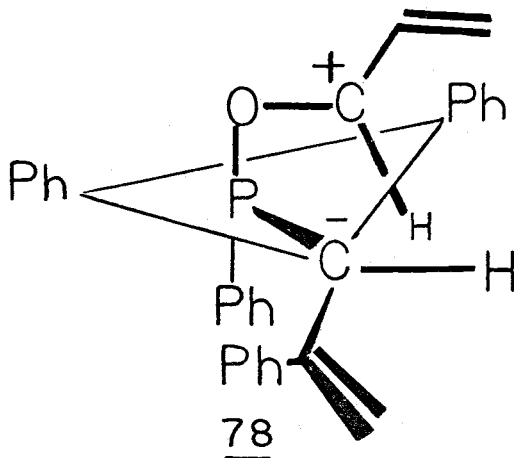
reaction of 2-butenyltriphenylphosphorane 76 with 67 gave only the cyclized diene 77. This result verifies the necessity for the



presence of at least one hydrogen at C-2 of the ylid in the cyclization mechanism but does little to help distinguish between the two

mechanisms. It should be noted that crossed-addition products such as 71 have not been isolated from any of these reactions in which cyclized diene products were obtained. A few cases of cyclopropane formation have been reported for the reaction of simple methylene-triphenylphosphoranes with unsaturated carbonyl compounds (109,110). If one assumes that the trans trienes observed in some of these reactions are the result of competitive 1,2-addition, the absence of the cis isomer in the acrolein reaction cannot be explained since the formation of cis isomers with propanal and propynal demonstrate the kinetic viability for cis isomer formation.

Another possible mechanism is that postulated by Schneider (111) to explain the cis:trans ratios of products from reactions of non-stabilized ylids with aldehydes. Schneider assumed the carbonyl oxygen coordinates with phosphorous in the initial step to give the trigonal-bipyramidal complex 78 in which the oxygen is bonded to an apical position and the ylid carbon occupies an equatorial position. The bulk of the aldehyde is directed upwards and the aldehydic hydrogen is directed downward into the equatorial plane between the least sterically crowded groups. As shown for the reaction of 2-phenyl-2-propenyltriphenylphosphorane with acrolein, a clockwise rotation about the  $C^+ - O$  bond gives the threo-intermediate which decomposes to give trans triene. The counter-clockwise rotation results in the proximity of the reactive terminus where bond formation occurs preferentially to the C-1 positions. Propynal fails to undergo this reaction due to steric and electronic effects and gives the



cis triene instead. Again, proton transfer and normal Wittig addition complete the sequence to give 2-phenyl-1,3-cyclohexadiene 58. Schneider points out that the betaine intermediate could not be detected in nonpolar solvents even at  $-30^\circ$  but has been intercepted in the presence of dissolved salts or polar solvents (98) which may be a result of competition for coordination sites on phosphorous. The isolation of a crystalline ylid-ketone adduct which had the proposed oxaphosphetane structure (112) indicates that the steric requirements of the complex are not as severe as expected.

Although this mechanism contradicts the generally accepted notion of the betaine intermediate in the Wittig reaction, its virtue is that it explains most of the experimental data concerning the formation of abnormal cyclized products. It may be especially important for the Wittig reaction of ketones in which the steric requirements are greater than with aldehydes. The susceptibility of unsaturated ketones to form cyclized products can be accounted for by noting that in the intermediate oxaphosphetane, either rotation of the

O - C<sup>+</sup> bond will result in steric interactions which increases the P - O - C<sup>+</sup> bond angle and increases the C<sup>-</sup> to C<sup>+</sup> distance. Coupled with known differences in electrophilicity between the carbonyl carbon of a ketone and that of an aldehyde, these effects results in exclusive addition at the terminal ends of the system.

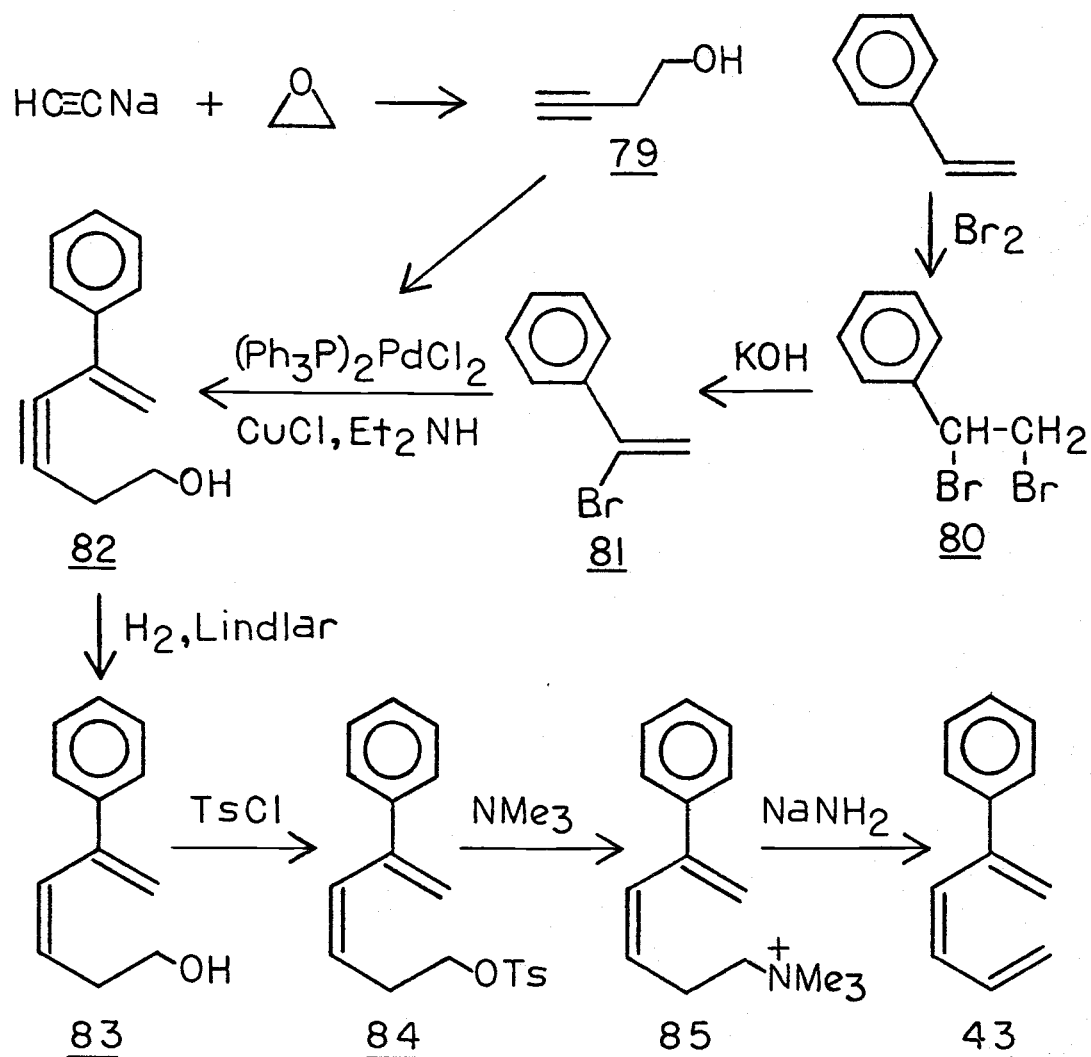
## 2. Conclusions

The results obtained from the reactions of propanal, acrolein and propynal with 2-phenyl-2-propenyltriphenylphosphorane are consistent with the initial formation of a oxaphosphetane intermediate since the sensitivity of the reaction to both ylid and unsaturated carbonyl is preserved and the formation of trans triene is accounted for. However, the existence of the complex and its importance in nonstabilized ylid reactions is for the moment speculative at best.

### B. A Potentially Successful Route to cis-2-Phenyl-1,3,5-hexatriene

Another synthetic approach to cis-2-phenyl-1,3,5-hexatriene 43, shown below, was a modification of the scheme used by Platt (113) in the synthesis of cis-1-phenyl-1,3,5-hexatriene. The procedure generates the cis double bond by the semi-hydrogenation of an acetylenic alcohol which is then converted to triene at low temperature by the Hoffmann elimination.

The reaction of ethylene oxide and sodium acetylide in liquid ammonia was used to prepare 3-butyne-1-ol 79. The boiling point was in agreement with that reported by Henne and Greenlee (114). The nmr spectrum of 79 shows the acetylenic proton as a triplet at 2.01  $\delta$ , the methylene protons adjacent to the triple bond as a doublet of



triplets at 2.40  $\delta$  and the oxygen-bearing methylene protons as a triplet at 3.71  $\delta$ . The variable hydroxyl proton appeared as a broad singlet at 4.26  $\delta$ .

The other molecule needed for the coupling was 1-bromo-1-phenylethene **81**. Styrene was converted to 1,2-dibromo-1-phenylethane **80** by the addition of bromine. The product was recrystallized from 10:1 ethanol:chloroform to give **80** as a crystalline white solid with a



melting point identical to that reported in the literature (115) and a nmr spectrum consistent with its assigned structure.

The elimination of hydrogen bromide from 80 was accomplished with alcoholic potassium hydroxide to give 81 which showed an nmr spectrum with the characteristic geminal vinylic protons as finely split (1.5 Hz) doublets at 5.61 and 5.93  $\delta$ . The aromatic region showed a pair of multiplets in a relative ratio of 2:3.

The coupling reaction of 79 and 81 in diethylamine, catalyzed by bis(triphenylphosphine)palladium dichloride (116) and cuprous iodide, was complicated by a slow reaction rate and the instability of the product, 5-phenyl-5-hexen-3-yn-1-ol 82. When the reaction was performed at room temperature as prescribed (117), no conversion to 82 was observed. When the reaction temperature was raised to 55°, the rate of the decomposition of 82 to form a dark orange viscous oil was too rapid to allow appreciable concentrations of 82 to develop. After a number of additional experiments, it was found that optimum yields of 82 could be obtained with a molar excess of 81, a reaction temperature of 45° and a reaction time of 48 hrs. The purification of 82 by distillation at reduced pressure was unsuccessful due to rapid polymerization at temperatures over 100°. Therefore, column chromatography was employed but the material obtained was shown to contain polymeric material as well as 82. Pure 82 was obtained by evaporative distillation on a kugelrohr apparatus at about 100° and  $5 \times 10^{-4}$  mm. The uv spectrum of 82 showed a maximum at 256 nm ( $\epsilon = 8,400$ ) in 95% ethanol. The ir spectrum showed a hydroxyl band at  $3380 \text{ cm}^{-1}$  and an acetylenic band at  $2230 \text{ cm}^{-1}$ . The nmr spectrum was consistent

with the assigned structure and was easily assigned from the nmr spectra of 79 and 81 since the loss of the acetylenic proton between them simplified one coupling pattern and did not affect the relative chemical shifts of the remaining protons.

The semi-reduction of 82 over Lindlar catalyst showed only moderate selectivity which is in accord with hydrogenations of similar systems (118). The reduction was found to be very sensitive to the purity of 82 and would proceed only if 82 were distilled immediately prior to its use. The progress of the reduction was monitored by glc and was terminated when the relative amounts of 82 and over-hydrogenated product were 17% and 11%, respectively. The content of cis-5-phenyl-3,5-hexadien-1-ol 83 was 60% at that point. Pure 83 as isolated by preparative glc and showed a uv maximum at 244 nm ( $\epsilon = 9,200$ ) which is quite reasonable since a maximum at 240 nm ( $\epsilon = 11,000$ ) was observed for 2-phenyl-1,3-hexadiene. The ir spectrum of 83 showed a hydroxyl band at  $3340\text{ cm}^{-1}$  but lacked the acetylenic absorption observed in the spectrum of 82. The cis stereochemistry was confirmed by the nmr spectrum which showed a one proton doublet ( $J = 12\text{ Hz}$ ) at  $6.23\ \delta$ .

Although the tosylate 84 was not isolated, the infrared spectrum of a mixture of 83 and p-toluenesulfonyl chloride in s-collidine showed the disappearance of the hydroxyl band and the appearance of bands at  $1330\text{ cm}^{-1}$  and  $1185\text{ cm}^{-1}$  characteristic of the sulphonate ester. After the mixture had been washed with water, addition of anhydrous trimethylamine failed to produce the corresponding quaternary trimethylammonium salt 85. Only three attempts to prepare 85

were performed since each attempt had to begin with the coupling of 79 and 81 due to the instabilities of intermediate compounds 82, 83, 84. The reason for the failure of 85 to react properly with trimethylamine is presently uncertain. However, Platt reported that this reaction gave quantitative yields with a nearly identical substrate.

This reaction sequence appears to be a potentially useful route to cis-2-phenyl-1,3,5-hexatriene and could be adapted for the synthesis of other 2-substituted and 2,4-disubstituted analogs. However, the instabilities of the intermediates require the use of tedious procedures and result in low yields and the process is not recommended if other pathways are available.

## EXPERIMENTAL

All melting points are corrected and all boiling points are uncorrected. The infrared spectra were run on a Perkin-Elmer model 621 grating infrared spectrophotometer. The ultraviolet spectra and the kinetic study were run on a Cary model 15 ultraviolet-visible spectrophotometer. All nuclear magnetic resonance spectra were run on a Varian model HA-100 instrument except where indicated in which case a Varian model EM-360 instrument was used. All mass spectra were run on a Varian model MAT-CH7 mass spectrometer interfaced to a SYSTEM 150 data processor.

### I. Ethyl $\alpha$ -Isopropylacetoacetate (2)

This compound was synthesized by the method of Marvel and Hager (17). The reaction was carried out under nitrogen and rigorously dry conditions. To 500 ml of absolute ethanol distilled directly from magnesium was added 23 g (1.0 mol) of metallic sodium cut into small pieces. After all the sodium was dissolved, 130 g (1.0 mol) of ethyl acetoacetate was added and the solution was heated at reflux for 1 hr. To the boiling solution 135 g (1.1 mol) of 2-bromopropane was added dropwise over a period of 2 hrs. The mixture was refluxed with stirring for 21 hrs and then cooled and filtered to remove precipitated sodium bromide. The salt was washed with 25 ml of absolute ethanol and the washings were added to the main solution. Ethanol was removed on a rotary evaporator and the product was isolated by reduced pressure distillation, b.p. 81-82° (8 mm) [lit. (18) b.p. 93-94° (18 mm)]; ir (neat)  $\text{cm}^{-1}$  1040, 1140, 1225, 1280, 1370,

1460, 1625, 1720 (C=O), 1740 ( $-\text{CO}_2^-$ ), 2900, 2980, 3000; nmr ( $\text{CCl}_4$ )  $\delta$  0.97 (pair of d, 6 H,  $J = 7$  Hz, isopropyl  $\text{CH}_3^-$ ), 1.32 (t, 3 H,  $J = 7$  Hz,  $\text{CH}_3^-$ ), 2.18 (s, 3 H,  $\text{CH}_3\text{C}=\text{O}$ ), 2.47 (m, 1 H, isopropyl CH), 3.11 (d, 1 H,  $J = 9$  Hz,  $\text{C}=\text{OCHC}=\text{O}$ ), 4.20 (q, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{O}$ ); 62 g (36%).

II. 3-Isopropyl-3-buten-2-ol (3) and E-2-Isopropyl-2-buten-1-ol (4)

The method of Marshall and Litsas was used (19). A solution of 30.5 g (0.18 mol) of ethyl  $\alpha$ -isopropylacetoacetate in 75 ml of dry tetrahydrofuran was added dropwise to 5.0 g (0.21 mol) of sodium hydride (from 8.8 g of 57% oil dispersion) in 400 ml of dry tetrahydrofuran and the mixture was heated at reflux for 1 hr and treated with 8.0 g (0.21 mol) of lithium aluminum hydride in portions. The mixture was heated at reflux for 4 hrs. The solution was allowed to cool and 40 ml of dry ethyl acetate was cautiously added to destroy any excess lithium aluminum hydride. The solution was stirred at 40-45° for 1 hr and then cooled. To the solution was added 100 ml of saturated aqueous ammonium chloride. The solution was filtered and the precipitate was washed with 100 ml of diethyl ether. The filtrate was washed twice with 150 ml portions of diethyl ether and the combined ether fractions were extracted with three 200 ml portions of water and then dried over anhydrous magnesium sulfate. The ether was removed on a rotary evaporator and reduced pressure spinning band distillation was used to isolate a 30:70 mixture of E-2-isopropyl-2-buten-1-ol and 3-isopropyl-3-buten-2-ol, b.p. 60-62° (20 mm) 9.2 g (45%). Preparative gas chromatography (2% SE 30 on Chromosorb W 40/60

mesh, 1/4 in. X 8 ft.) was used to isolate the pure isomers which had the following properties:

3-Isopropyl-3-buten-2-ol (3) had ir (neat)  $\text{cm}^{-1}$  905 ( $=\text{CH}_2$ ), 1648 (C=C), 2960, 3090, 3350; nmr ( $\text{CCl}_4$ )  $\delta$  1.07 (pair of d, 6 H,  $J = 7$  Hz, isopropyl  $\text{CH}_3$ ), 1.29 (d, 3 H,  $J = 6.5$  Hz,  $\text{CH}_3$ ), 2.24 (m, 1 H,  $J = 7$  Hz, isopropyl CH), 3.29 (s, 1 H, OH), 4.13 (q, 1 H,  $J = 6.5$  Hz, CH-O), 4.87 (s, 1 H,  $=\text{CH}_2$ ), 5.00 (s, 1 H,  $=\text{CH}_2$ ); Anal. Calc'd for  $\text{C}_7\text{H}_{14}\text{O}$ : C, 73.63; H, 12.36. Found: C, 73.34; H, 12.29.

E-2-Isopropyl-2-buten-1-ol (4) had ir (neat)  $\text{cm}^{-1}$  980, 1105, 1467, 1652, 2872, 2935, 2970, 3335; nmr ( $\text{CCl}_4$ )  $\delta$  1.03 (d, 6 H,  $J = 7$  Hz, isopropyl  $\text{CH}_3$ ), 1.63 (d, 3 H,  $J = 7$  Hz,  $\text{CH}_3\text{-C=}$ ), 2.82 (m, 1 H,  $J = 7$  Hz, isopropyl CH), 3.16 (s, 1 H, OH), 3.98 (s, 2 H,  $\text{CH}_2\text{O}$ ), 5.43 (q, 1 H,  $J = 7$  Hz, HC=C).

### III. 2-Isopropyl-1-methyl-2-propenyl Vinyl Ether (5)

The method of Wantanabe and Conlon was used in this synthesis (16). A mixture of 11.4 g (0.16 mol) of ethyl vinyl ether and 1.0 g (3.1 mmol) of mercuric acetate was stirred for 12 hrs and 0.296 g (2.60 mol) of 3-isopropyl-3-buten-2-ol was added. The solution was heated to reflux and the progress of the reaction was followed by gas-liquid chromatography on a 20% SE 30 on Chromosorb W 45/60 mesh, 1/4 in. X 6 ft. column. After 5 1/2 hrs the ratio of product peak to alcohol peak was greater than 99:1 and the reaction was terminated by cooling and adding five drops of glacial acetic acid. The solution was stirred for 10 mins and 15 ml of cold pentane was added. The solution was washed three times with 6 ml portions of cold 5%

aqueous potassium hydroxide solution and then dried over anhydrous potassium carbonate. The product was concentrated on a rotary evaporator and isolated by preparative gas-liquid chromatography using the forementioned column, 0.084 g (23%); ir ( $\text{CCl}_4$ )  $\text{cm}^{-1}$  1190, 1306, 1365, 1455, 1604, 1650, 2865, 2958, 3065; nmr ( $\text{CCl}_4$ )  $\delta$  1.05 (d, 6 H, isopropyl  $\text{CH}_3$ ), 1.29 (d, 3 H,  $\text{CH}_3$ ), 2.31 (septet, 1 H, isopropyl CH), 3.88 (d, 1 H,  $J = 6$  Hz,  $\text{HC}=\underline{\text{CH}}_2$ ), 4.19 (d, 1 H,  $J = 14$  Hz,  $\text{HC}=\underline{\text{CH}}_2$ ), 4.27 (q, 1 H,  $-\text{CH}-\text{O}$ ), 4.91 (s, 1 H,  $\text{C}-\text{CH}_2$ ), 4.98 (s, 1 H,  $\text{C}=\text{CH}_2$ ), 6.18 (pair of d, 1 H,  $J = 6$  Hz,  $J' = 14$  Hz,  $\underline{\text{HC}}-\text{CH}_2$ ); mass spectrum  $m/e$  (rel. intensity) 140(5), 125(6), 122(11), 97(32), 55(100).

#### IV. Claisen Rearrangement of 2-Isopropyl-1-methyl-2-propenyl Vinyl Ether (5)

A 30 mg (0.21 mmol) sample of 2-isopropyl-1-methyl-2-propenyl vinyl ether and 1 ml of spectral grade cyclohexane were sealed in a glass ampoule which was washed with 5% ammonium hydroxide solution, dried at  $120^\circ\text{C}$  for 2 days and flamed out just prior to use. The ampoule was fully immersed in an oil bath at  $180 \pm 2^\circ\text{C}$  for 30 min, cooled and opened. The contents were immediately analyzed by nmr which showed a finely split singlet at  $9.70 \delta$  and a complex multiplet centered around  $4.2 \delta$  in a ratio of 1:1 with the remainder of the spectrum obscured by solvent. Gas-liquid chromatography using a 20% SE 30 on Chromosorb W 45/60 mesh, 1/4 in. X 6 ft. column, was performed and the material was shown to contain two products 8 and 9 in a ratio of 40:60 and none of the starting ether. Preparative gas chromatography was used to isolate the products in 5.4 mg and 7.4 mg yields (43%). Identification of the compounds was complicated by

apparent trimerization of the aldehydes when they were concentrated. Spectral data were obtained but no structures can be assigned at this time.

V. Reduction and Identification of E- and Z-4-Isopropyl-4-hexenal (6) and (7)

A solution of 84.4 mg (0.603 mmol) of 2-isopropyl-1-methyl-2-propenyl vinyl ether and 2 ml of spectral grade cyclohexane were placed in a sealed tube and heated as previously described. After the ampoule was cooled, it was opened. The solution was slowly added to a suspension of 7.6 mg (0.20 mmol) of lithium aluminum hydride in 2 ml of anhydrous diethyl ether. After the addition the reaction was stirred for 30 mins and 1 ml of water was cautiously added followed by 5 ml of 10% aqueous sulfuric acid. The aqueous layer was washed three times with 2 ml portions of ether and the combined ether fractions were washed with 5 ml of water and then with 5 ml of saturated aqueous sodium bicarbonate. After the solution was dried with anhydrous magnesium sulfate, the solvents were removed on a rotary evaporator and the products were isolated by preparative gas-liquid chromatography using a 5% OV-17 on Chromosorb W 45/60 mesh, 1/4 in X 9 ft. column in yields of 10 mg and 15 mg (34%) of E and Z-4-isopropyl-4-hexen-1-ols respectively. The isomers had the following spectral properties:

E-4-Isopropyl-4-hexen-1-ol 10 had ir (CCl<sub>4</sub>) cm<sup>-1</sup> 1062, 1252, 1289, 1383, 1423, 1468, 2895, 2960, 3360, 3640; nmr (CCl<sub>4</sub>) δ 1.99 (d, 6 H, J = 7 Hz, isopropyl CH<sub>3</sub>), 1.59 (d, 3 H, J = 6 Hz, CH<sub>3</sub>-C=C), 1.77



(m, 2 H), 2.15 (m, 3 H), 3.56 (t, 2 H, CH<sub>2</sub>-O), 3.68 (s, 1 H, OH), 5.24 (q, 1 H, J = 6 Hz, HC=C; mass spectrum m/e (rel. intensity) 142(29), 124(2), 109(36), 98(22), 55(100).

Z-4-Isopropyl-4-hexen-1-ol 11 had ir (CCl<sub>4</sub>) cm<sup>-1</sup> 1035, 1060, 1105, 1362, 1469, 2879, 2984, 3341, 3640; nmr (CCl<sub>4</sub>) δ 1.99 (d, 6 H, J = 7 Hz, isopropyl CH<sub>3</sub>), 1.58 (d, 3 H, J = 6 Hz, CH<sub>3</sub>-C=C), 1.68 (m, 2 H), 2.10 (m, 2 H), 2.87 (septet, 1 H, J = 7 Hz, isopropyl CH), 3.58 (t, 2 H, CH<sub>2</sub>-O), 4.41 (s, 1 H, OH), 5.17 (q, 1 H, J = 6 Hz, HC=C); mass spectrum m/e (rel. intensity) 142(18), 124(2), 109(23), 98(18), 55(100).

#### IV. 1-Ethynylcyclohexene (31)

The procedure of Hamlet, Henbest, and Jones was employed (48). A solution of 114 g (0.74 mol) of phosphorous oxychloride in 75 ml of dry pyridine was added slowly to a solution of 124 g (1.00 mol) of 1-ethynylcyclohexanol in 175 ml of dry pyridine, in a flask fitted with a stirrer and reflux condenser. The solution was then heated at 100°C for 1 hr after which it was poured over ice. The product was extracted with pentane and dried over anhydrous calcium chloride. The pentane was removed on a rotary evaporator and the product isolated by distillation, b.p. 61-63°C (34 mm) [lit. (48). b.p. 53-56°C (43 mm)], 78.2 g (74%), uv max (hexane) 223 nm (ε = 12,200) [lit. (48) uv mas (95% ethanol) 223.5 nm (ε = 10,500)]; ir (neat) cm<sup>-1</sup> 3315 (≡C-H), 3015 (=C-H), 2930, 2095 (C≡C), 1642 (C=C), 1436; nmr (CCl<sub>4</sub>) δ 1.49 (m, 4 H, -CH<sub>2</sub>-), 1.98 (m, 4 H, -CH<sub>2</sub>-C=C), 2.68 (s, 1 H, ≡C-H), 6.09 (m, 1 H, H-C=C).

VII. 1,4-Di(1-cyclohexenyl)-1,3-butadiyne (32)

The procedure of Bowden, Heilbron, Jones, and Sargent was used (49). In a 1 liter flask fitted with a mechanical stirrer was placed 30 g (0.30 mol) cuprous chloride, 48 g (0.90 mol) ammonium chloride and 1 ml of concentrated hydrochloric acid in 200 ml of water. A solution of 10.6 g (0.10 mol) of 1-ethynylcyclohexene in 50 ml of methanol was slowly added with stirring at 55°C. After the addition, air was bubbled through the solution for 2 hrs during which a lime-green precipitate was formed. The solution was filtered and the precipitate was washed with 100 ml of 1 N hydrochloric acid and then with two 100 ml portions of hexane. The filtrate was extracted twice with 100 ml portions of hexane and the combined hexane fractions were dried over anhydrous magnesium sulfate. After the hexane was removed on a rotary evaporator, the product spontaneously crystallized and was filtered and dried to yield 9.97 g (95%). Sublimation gave the pure product, m.p. 63.5-64.5°C [lit. (119) m.p. 62.5-63°C] uv max (hexane) 310 ( $\epsilon = 18,200$ ), 291 ( $\epsilon = 23,300$ ), 274 ( $\epsilon = 15,500$ ), 259 ( $\epsilon = 7,560$ ), 246 ( $\epsilon = 26,000$ ), 236 ( $\epsilon = 31,000$ ) nm; ir (CCl<sub>4</sub>) cm<sup>-1</sup> 3150 (H-C=C), 2920 (C≡C), 1638 (C=C); nmr (CCl<sub>4</sub>)  $\delta$  1.71 (m, 8 H, -CH<sub>2</sub>-), 2.19 (m, 8 H, -CH<sub>2</sub>-C=C), 6.20 (m, 2 H, H-C=C).

VIII. Tricyclo(10.4.0.0<sup>6,11</sup>)hexadeca-1,3,5-triene (34)

The procedure of Marvell and Tashiro was used (118). A solution of 0.387 g (1.84 mmol) of 1,4-di(1-cyclohexenyl)-1,3-butadiyne, 40 mg of Lindlar catalyst (120) and 0.01 ml of synthetic quinoline in 3 ml of hexane was hydrogenated for 3 hrs at ambient temperature.

The solution was filtered and the hexane was removed on a rotary evaporator. Analysis by gas chromatography using a 4% SE 30 on Chrom G 4 ft. X 1/4 in. column gave:

<u>Peak</u>	<u>Retention Time (min)</u>	<u>Rel. Area (%)</u>	<u>Assignment</u>
1	1.2	68	Product
2	1.9	18	<u>trans</u> isomer
3	3.8	14	Starting Material

Reduced pressure spinning band distillation was used to concentrate the product which was collected between 190-195°C (0.09 mm). Pure product was isolated by preparative gas chromatography using a 5% OV-17 on Chrom. G 45/60 6 ft. X 1/4 in. column; uv max (hexane) 208 ( $\epsilon = 13,400$ ), 244 ( $\epsilon = 4,870$ ), 252.5 ( $\epsilon = 4,590$ ), 269 ( $\epsilon = 4,530$ ) nm; ir (neat)  $\text{cm}^{-1}$  3005 (H-C=C), 2920, 2850, 1645 (C=C), 1620, 1600, 1440; nmr ( $\text{CCl}_4$ )  $\delta$  1.56 (m, 12 H,  $-\text{CH}_2-$ ), 2.15 (m, 4 H,  $-\text{CH}_2-\text{C}=\text{C}$ ), 2.67 (m, 2 H,  $-\text{CH}-\text{C}=\text{C}$ ), 5.59 (s, 2 H, H-C=C), 5.65 (s, 2 H, H-C=C); mass spectrum m/e (rel. intensity) 214(70), 91(100); Anal. Calc'd for  $\text{C}_{16}\text{H}_{22}$ : C, 89.65; H, 10.35. Found: C, 89.81; H, 10.16.

#### IX. Tricyclo(10.4.0.0<sup>6,11</sup>)hexadecane (35)

A mixture of 0.396 g (18.5 mmol) tricyclo(10.4.0.0<sup>6,11</sup>)hexadeca-1,3,5-triene and 101 mg of Adam's catalyst ( $\text{PtO}_2$ ) in 5 ml of hexane was hydrogenated at ambient temperature for 18 hrs. The solution was filtered to remove the catalyst and the hexane was removed by rotary evaporation to yield the product which was 95% pure

by gas chromatography; ir ( $\text{CCl}_4$ )  $\text{cm}^{-1}$  2920, 2852, 1448; nmr ( $\text{CCl}_4$ )  $\delta$  0.9-2.1 broad multiplet; mass spectrum m/e (rel. intensity) 220(44), 98(100).

X. 3-Bromo-2-phenyl-1-propene (37)

The method of S. F. Reed (55) was used. A mixture of 97 g (0.83 mol) of freshly distilled  $\alpha$ -methylstyrene, 89 g (0.79 mol) of N-bromo-succinimide (recrystallized from glacial acetic acid) and 50 ml of carbontetrachloride was placed in a 1 liter round-bottomed flask equipped with a magnetic stirrer and an efficient condenser. The mixture was heated to reflux to initiate the reaction. After 5 mins the vigorous reaction had subsided and the mixture was allowed to cool to room temperature. The mixture was filtered under a hood.

(CAUTION: PRODUCT IS AN EXTREME LACHRYMATOR) The filtrate was distilled, giving 66.5 g (43%) of 3-bromo-2-phenyl-1-propene, b.p. 77-86°/2.25 mm, [lit. (55) b.p. 66-67°/0.9 mm]; nmr ( $\text{CCl}_4$ )  $\delta$  4.32 (s, 2 H,  $-\text{CH}_2\text{Br}$ ), 5.40 (s, 1 H,  $=\text{CH}_2$ ), 5.51 (s, 1 H,  $=\text{CH}_2$ ), 7.36 (m, 5 H, aromatic).

XI. 2-Phenyl-2-propenyltriphenylphosphonium Bromide (38)

The procedure described by Schlosser and Christmann was employed (98). A mixture of 66.5 g (0.338 mol) of 3-bromo-2-phenyl-1-propene, 104 g (0.396 mol) of triphenylphosphine and 500 ml of benzene was stirred for 72 hrs at ambient temperature. The product was isolated by filtration and recrystallized from chloroform-pentane solution. The product was dried under vacuum to give 106 g (67.9%) m.p. 224-226°

[lit. (56) m.p. 224-225°]; nmr ( $\text{CDCl}_3$ )  $\delta$  5.24 (d, 2 H,  $J = 15$  Hz, P- $\text{CH}_2$ -), 5.46 (s, 1 H,  $=\text{CH}_2$ ), 5.51 (s, 1 H,  $=\text{CH}_2$ ), 7.1-7.4 (m, 5 H, Ph-C), 7.5-7.9 (m, 15 H,  $\text{Ph}_3$ -P).

## XII. 2-Propynal (40)

The procedure of Sauer was used (57). A 1 liter three-necked round-bottomed flask was fitted with a stirrer, an additional funnel, a fine capillary for the introduction of nitrogen and an exit tube attached through a manometer to a series of three traps. In the flask were placed 37 g (0.67 mol) of propargyl alcohol and a cooled solution of 45 ml of concentrated sulfuric acid and 66 ml of water. The flask and the first trap were cooled with ice-salt baths to  $-15^\circ\text{C}$ . The second and third traps were cooled to  $-78^\circ\text{C}$  with acetone-Dry Ice baths. The pressure was reduced to 50 mm and the nitrogen flow and stirrer were started. A cooled solution of 70 g (0.70 mol) of chromium trioxide in 133 ml of water and 45 ml of concentrated sulfuric acid was added dropwise through the addition funnel over a 2 hr period while the reaction temperature was maintained between  $2^\circ$ - $10^\circ\text{C}$ . After the addition was completed, the flask was allowed to warm to room temperature while the pressure was gradually reduced to 15 mm. The trapped product was separated from the aqueous layer which was saturated with sodium chloride. (CAUTION: PRODUCT IS A LACHRYMATOR AND MAY POLYMERIZE EXPLOSIVELY OR DECOMPOSE IN THE PRESENCE OF BASE, ESPECIALLY PYRIDINE). The crude product was dried over anhydrous magnesium sulfate and distilled to yield pure 2-propynal, b.p.  $55$ - $56^\circ$  [lit. (57)  $54$ - $57^\circ$ ], 7.8 g (22%); nmr (EM360) ( $\text{CCl}_4$ )  $\delta$  3.67 (s, 1 H  $\equiv\text{C-H}$ ) 9.29 (s, 1 H,  $-\text{CHO}$ ).

XIII. Cis- and trans-2-phenyl-1,3-hexadien-5-yne (41) and 42)

The procedure of Bohlmann and Inhoffen was used (104). Under anhydrous conditions with a nitrogen atmosphere maintained throughout the reaction and work-up, 17 g (37 mmol) of 2-phenyl-2-propenyltriphenylphosphonium bromide and 250 ml of dry ether were placed in a 500 ml round-bottomed flask equipped with a condenser, an additional funnel and a magnetic stirrer. Slowly, 18.5 ml (37 mmol) of 2 M n-butyllithium in ether was added. To the clear red solution, 2.4 g (45 mmol) of freshly distilled propynal in 100 ml of dry ether was added dropwise. The mixture was hydrolyzed with 150 ml of ice water and the ether layer was separated and dried over anhydrous magnesium sulfate. The ether was removed by rotary evaporation and the product was isolated by evaporative distillation (about  $75^{\circ}/5 \times 10^{-4}$  mm) on a kugelrohr apparatus to give 1.66 g (29%) of a 3:7 mixture of cis- and trans-2-phenyl-1,3-hexadien-5-yne. The product was unstable but was stored for limited periods (1 week) as a dilute ether solution. The mixture had: uv max (cyclohexane) 242 ( $\epsilon = 21,000$ ), 259 ( $\epsilon = 19,000$ ), 270 ( $\epsilon = 15,000$ ) nm; ir (neat)  $\text{cm}^{-1}$  3300, 3092, 3060, 3014, 2100, 1612, 1601, 1587, 1577, 1495, 1445, 1076, 1029, 961, 903, 776, 704; nmr ( $\text{CCl}_4$ )  $\delta$  2.91 (pair of d, 1 H,  $\text{HC}\equiv$ ), 5.16-5.92 (m, 3 H,  $\text{H}_2\text{C}=\text{,}=\text{CH}-\text{C}\equiv$ ), 6.47 (d, 0.3 H,  $J = 11$  Hz,  $=\text{CH}-\text{CPh}$ , cis), 6.87 (d, 0.7 H,  $J = 16$  Hz,  $=\text{CH}-\text{CPh}$ , trans), 7.26 (s, 5 H, Ph); mass spectrum m/e (rel. intensity) 154(100), 153(71), 152(45), 308(8).

XIV. Cis- and trans-2-phenyl-1,3,5-hexatriene (43) and (44)

The procedure of Marvell and Tashiro was employed (118). A freshly distilled sample, 1.0 g (6.5 mmol), of a 3:7 mixture of cis-

and trans-2-phenyl-1,3-hexadien-5-yne in 5 ml of spectral grade hexane was added to a prehydrogenated solution of 0.5 g Lindlar catalyst and 0.03 ml of synthetic quinoline in 20 ml of spectral grade hexane. The progress of the hydrogenation was monitored by glc analysis (20% SE 30 on Chromosorb G 0.25 in. X 6 ft. column; T = 160°; He flow = 60 ml/min). After 136 ml of hydrogen was consumed, the rate of the reaction was slowed markedly. Glc analysis showed two major products and one minor product that had uv spectra (hexane) as follows:

<u>Peak</u>	<u>Retention Time (min)</u>	<u>Relative Area (%)</u>	<u>UV max (nm)</u>
1	5.4	63	273.5
			263
			254
			244
2	9.0	10	284
3	10.3	27	302

A 10 ml aliquot of the reaction solution was hydrogenated over 0.15 g of Adam's catalyst (PtO<sub>2</sub>) to give 2-phenylhexane that was identified by comparison with an authentic sample and by its uv spectrum which had: uv max (cyclohexane) 205 nm ( $\epsilon$  is large) and 261 nm (largest of fine structure;  $\epsilon$  is moderate). A minor product that did not absorb in the uv range was also obtained.

A 1 ml aliquot of the reaction solution and 1 ml of methylcyclohexane were placed in a pyrex ampoule, degassed and sealed. The ampoule was heated for 30 mins at 150° and the contents was hydrogenated over Adam's catalyst (PtO<sub>2</sub>) for 18 hrs. Glc analysis gave:

<u>Peak</u>	<u>Retention Time (min)</u>	<u>Relative Area (%)</u>	<u>Assignment</u> *
1	3.8	56	2-phenylhexane
2	5.7	1	
3	6.7	42	phenylcyclohexane
4	9.1	1	

\* Assignments were made by comparison with authentic samples.

#### XV. 2-Phenyl-2-hexanol (45)

The method of Crawford, Saeger, and Warneke was used (58). In a 1 liter round-bottomed flask was placed 12.6 g (0.52 mol) of magnesium turnings and 250 ml of anhydrous ether. A solution of 68 g (0.50 mol) of n-butyl bromide in 75 ml of anhydrous ether was added dropwise. After the addition was completed, a solution of 58 g (0.48 mol) of acetophenone in 50 ml of anhydrous ether was slowly added and the mixture was allowed to stir for 30 mins. The magnesium salts were hydrolyzed by the addition of 250 ml of saturated ammonium chloride solution. The aqueous layer was separated and washed with two 50 ml portions of ether. The ethereal solutions were dried over anhydrous magnesium sulfate and the ether was removed by rotary evaporation. The crude product was distilled to give 50 g (58%) of product, b.p. 104-105°/4 mm [lit. (58) 123-124°/9 mm]; ir (neat)  $\text{cm}^{-1}$  3410 (broad), 3094, 3062, 3029, 2960, 2875, 1601, 786, 701; nmr ( $\text{CCl}_4$ )  $\delta$  0.8-1.3 (m, 7 H,  $\text{CH}_2\text{CH}_2\text{CH}_3$ ), 1.46 (s, 3 H,  $\text{CH}_3\text{COH}$ ), 1.60 (m, 2 H,  $\text{CH}_2\text{COH}$ ), 3.3 (s, 1 H, OH), 7.2 (m, 5 H, Ph).



XVI. 2-Phenyl-1-hexene (46) and 2-Phenyl-2-hexene (47)

In a 250 ml round-bottomed flask were placed 42 g (0.27 mol) of phosphorous oxychloride and 50 ml of s-collidine (2,4,6-trimethylpyridine). The solution was cooled to 0° and a solution of 25 g (0.14 mol) of 2-phenyl-2-hexanol in 50 ml of s-collidine was added, dropwise, to maintain the temperature below 10°. After the addition was completed, the reaction temperature was maintained below 10° for 30 mins, raised to 125° for 1 hr and then allowed to come to room temperature. The reaction mixture was poured over ice and the product extracted with pentane. The pentane solution was washed with two 50 ml portions of 0.1 N hydrochloric acid solution and was dried over anhydrous magnesium sulfate. The pentane was removed by rotary evaporation and the residue was distilled to yield 14 g (62%) of a 6:4 mixture of 2-phenyl-1-hexene and 2-phenyl-2-hexene, b.p. 57-65°/1.5 mm. The isomers were separated by spinning band distillation to give 3.9 g (18%) of 2-phenyl-1-hexene, b.p. 35-37°/0.35 mm [lit. (121) 89-90°/10 mm]; uv max (cyclohexane) 239 nm ( $\epsilon = 9,300$ ); ir (neat)  $\text{cm}^{-1}$  3096, 3075, 3046, 900, 782; nmr ( $\text{CCl}_4$ )  $\delta$  0.82 (t, 3 H,  $J = 7$  Hz,  $\text{CH}_3$ ), 1.3-1.6 (m, 4 H,  $\text{CH}_2\text{CH}_2$ ), 2.42 (t, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{C}=\text{}$ ), 4.99 (d, 1 H,  $J = 2$  Hz,  $\text{H}_2\text{C}=\text{}$ ), 5.21 (d, 1 H,  $J = 2$  Hz,  $\text{H}_2\text{C}=\text{}$ ), 7.1-7.4 (m, 5 H, Ph).

After the distillation temperature was stabilized at 47°/0.45 mm, the distillation was stopped and the material in the still pot was collected to give 1.6 g (7%) of 2-phenyl-2-hexene [lit. (58) b.p. 223-226°]; uv max (cyclohexane) 245 nm ( $\epsilon = 9,200$ ); nmr ( $\text{CCl}_4$ )  $\delta$

0.91 (t, 3 H,  $J = 7$  Hz,  $\text{CH}_3\text{CH}_2$ ), 1.40 (sextet, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{CH}_3$ ), 1.92 (s, 3 H,  $\text{CH}_3\text{C}=\text{}$ ), 2.09 (q, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{C}=\text{}$ ), 5.74 (t, 1 H,  $J = 7$  Hz,  $\text{HC}=\text{}$ ), 7.0-7.4 (m, 5 H, Ph).

#### XVII. 2-Phenylhexane (48)

A solution of 1.4 g (8.8 mmol) of a 3:1 mixture of 2-phenyl-1-hexene and 2-phenyl-2-hexene in 25 ml of spectral grade cyclohexane was hydrogenated over Adam's catalyst ( $\text{PtO}_2$ ) to give 1.32 g (93%) of 2-phenylhexane, b.p. 67-68°/3.25 mm [lit. (59) b.p. 100°/5 mm]: ir (neat)  $\text{cm}^{-1}$  3015, 2965, 2932, 2878, 2862, 1495, 1452, 1378, 764, 702; nmr ( $\text{CCl}_4$ )  $\delta$  0.84 (t, 3 H,  $J = 6$  Hz,  $\text{CH}_3\text{-CH}_2$ ), 1.19 (d, 3 H,  $J = 7$  Hz,  $\text{CH}_3\text{-CH}$ ), 1.1-1.4 (m, 4 H), 1.4-1.7 (m, 2 H,  $\text{CH}_2\text{-CH}$ ), 2.62 (sextet, 1 H,  $J = 7$  Hz, CH), 7.1 (s, 5 H, Ph).

#### XVIII. Phenylcyclohexane (49)

The method of Kursanoff was employed (60). A solution of 15.0 g (0.126 mol) of chlorocyclohexane in 75 ml (0.84 mol) of thiophene-free benzene was placed in a 250 ml erlenmeyer flask and cooled to 0°. In portions, 1.0 g (7.5 mmol) of anhydrous aluminum chloride were added. After the vigorous reaction had subsided, the mixture was allowed to warm to room temperature and 100 ml of water and 100 ml of ether were added. The ether layer was washed with 50 ml of water and then with 50 ml of saturated sodium chloride solution. The solution was dried over anhydrous magnesium sulfate and the ether and most of the unreacted benzene were removed by rotary evaporation. The crude product was distilled to give 16.1 g (80%) of phenylcyclohexane, b.p. 239-241° [lit. (60) 239°]; ir (neat)  $\text{cm}^{-1}$  3060, 3025, 1601, 1490,

1448, 820, 755, 700; nmr ( $\text{CCl}_4$ )  $\delta$  1.2-1.6 (m, 6 H), 1.6-2.0 (m, 4 H), 2.45 (m, 1 H, CH-Ph), 7.13 (s, 5 H, Ph).

XIX. Cis- and trans-2-phenyl-1,3-hexadiene (50) and (51)

To a suspension of 9.18 g (20.0 mmol) of 2-phenyl-2-propenyl-triphenylphosphonium bromide in 150 ml of dry ether was added dropwise, 10 ml (20 mmol) of 2 M n-butyllithium in ether. To the clear red solution of ylid was added a solution of 1.74 g (30.0 mmol) of freshly distilled propanal in 50 ml of dry ether. The reaction mixture was hydrolyzed with 100 ml of saturated ammonium chloride solution and the ether layer was separated, washed with 50 ml of water and then dried (anhydrous magnesium sulfate). After the ether was removed by rotary evaporation, 25 ml of pentane was added and the cold solution was filtered. The pentane was removed by rotary evaporation to give 2.01 g (96% product by glc) (61%) of a 2:3 mixture of cis- and trans-2-phenyl-1,3-hexadiene; uv max (cyclohexane) 220 nm ( $\epsilon = 16,000$ ), sh 240 nm ( $\epsilon = 11,000$ ); ir (neat)  $\text{cm}^{-1}$  3080, 3059, 3024, 3008, 2964, 3008, 2964, 2930, 2875, 1590, 1490, 1442, 965, 888, 760, 698; nmr ( $\text{CCl}_4$ )  $\delta$  0.98 (pair of t, 3 H,  $J = 7$  Hz,  $\text{CH}_3$ ), 2.10 (m, 2 H,  $\text{CH}_2$ ), 4.98-5.46 (m, 2 H,  $\text{H}_2\text{C}=\text{}$ ), 5.51-5.79 (m, 1 H,  $=\text{CH}-\text{CH}_2$ ), 6.08 (d, 0.34 H,  $J = 12$  Hz,  $=\text{CH}-\text{CPh}$ , cis), 6.25 (d, 0.66 H,  $J = 16$  Hz,  $=\text{CH}-\text{CPh}$ , trans), 7.21 (s, 5 H, Ph); mass spectrum  $m/e$  (rel. intensity) 158(54), 142(100), 129(84).

XX. Kinetic Study of the Electrocyclic Reaction of *cis*-2-Phenyl-1,3,5-hexatriene (43)

A solution of 8.5  $\mu$ l of 32:68 *cis*- and *trans*-2-phenyl-1,3,5-hexatriene in 7.5 ml of olefin-free hexadecane was placed in a thermostated quartz cell at 76.4°C. The progress of the reaction was followed for about 26 hrs by observing the formation of 1-phenyl-1,3-cyclohexadiene at 320 nm [lit. (99) uv max (cyclohexane) 302 nm ( $\epsilon = 13,800$ )]. The absorbance of product was superimposed on the absorbance of another product resulting from a slow process which could be observed independently after about 17 hrs (4 half-lives of the *cis*-2-phenyl-1,3,5-hexatriene reaction). A least-squares fit to the data points after 16.75 hrs (correlation coefficient = 0.98) gave an intercept of 1.04 which was used for  $A_{\infty}$  and a slope of  $1.495 \times 10^{-4} \text{ min}^{-1}$  which was used to correct the original absorbance values. The rate constants were calculated from the expression,  $k = -1/t \text{ (sec)} \ln[1 - (A_{\infty} - A_0)/(A_{\infty} - A_0)]$ . The results are given in Table 3.

XXI. Electrocyclic Reaction of *cis*-2-Phenyl-1,3-hexadien-5-yne (41)

The pyrolysis apparatus described by Fleming (84) was adapted for high boiling compounds by fitting a 20 cm glass column packed with glass beads to the top of the pyrolysis column. The top of the column was closed with a rubber septum through which samples were injected. Immediately below was a side arm through which the carrier gas, pre-pure nitrogen was introduced. The column was wrapped with heating tape and heated to 340°. The pyrolysis column temperature was 300° and the flow rate of the carrier gas was adjusted to give a contact

time of 15 sec. A 115 mg sample of freshly distilled 3:7 cis- and trans-2-phenyl-1,3-hexadien-5-yne was injected on the column over a 30 min period. Considerable polymerization and aerosol formation was observed. The system was allowed to cool and the Dry Ice-acetone traps were rinsed with small aliquots of ether. The ether was removed under reduced pressure to give 42 mg (36%) of a mixture of 58% 2-phenyl-1,3-hexadien-5-yne and 42% biphenyl by glc (20% SE 30 on Chromosob G). The biphenyl which gave an identical retention time and peak shape as that of an authentic sample was collected, m.p. 73-74° [lit. (121) 71°]; uv max (cyclohexane) 247 nm [lit. (123) 246 nm].

XXII. Reaction of Acrolein with the Ammonia Generated Ylid of 2-Phenyl-2-propenyltriphenylphosphonium Bromide

The method of Jaenicke and Seferiadis was used (101). A solution of 4.5 g (80 mmol) of freshly distilled acrolein in 50 ml of acetonitrile was slowly added to a suspension of 24.9 g (54 mmol) of 2-phenyl-2-propenyltriphenylphosphonium bromide in 200 ml of liquid ammonia at -50°. After the addition was completed, the mixture was stirred for 4 hrs and 100 ml of ether was added. The ammonia was evaporated by allowing the solution to come to room temperature. An additional 100 ml of ether was added and the solution was filtered to remove precipitated material. The ether was removed by rotary evaporation and the residue was taken up in pentane. The solution was cooled and filtered to remove precipitated triphenylphosphine oxide. Gas-liquid chromatography with a 20% SE 30 column gave two pairs of overlapping components in a ratio of about 1:4 and a trace of unreacted acrolein. The nmr of this solution showed vinylic signals in the range of

5.8-6.4  $\delta$ . The ultraviolet spectrum (hexane) showed strong absorptions at 273 nm, 261 nm, 251 nm, and 238 nm. One aliquot of this solution was heated in a sealed tube at 150° for 3 hrs and another was refluxed for 6 hrs. In neither case was absorption at 302 nm observed.

XXIII. Reaction of Acrolein with the n-Butyllithium Generated Ylid of 2-Phenyl-2-propenyltriphenylphosphonium Bromide

The method of Jaenicke and Seferiadis was used (101). Under anhydrous conditions with a nitrogen atmosphere, 10 ml (20 mmol) of 2 M n-butyllithium in ether was slowly added to a suspension of 9.2 g (20 mmol) of 2-phenyl-2-propenyltriphenylphosphonium bromide in 100 ml of dry ether. To the clear red solution was then added a solution of 1.7 g (30 mmol) of freshly distilled acrolein in 50 ml of dry ether. After the addition was completed, the mixture was stirred for 1 hr and then hydrolyzed with 100 ml of ice water. The ether layer was separated, washed with 50 ml of ice water and then dried over anhydrous sodium sulfate. The ether was removed on a rotary evaporator to give about 0.5 ml of a red-orange liquid which was taken up in 10 ml of pentane and cooled. After the precipitated triphenylphosphine oxide was removed by filtration, the ultraviolet spectrum (hexane) showed maxima at 272 nm, 251 nm, and 221 nm with shoulders at 251 nm and 236 nm. Gas-liquid chromatography with a 20% SE 30 column gave two pairs of overlapping components in a ratio of 1:4 and unreacted acrolein. Preparative glc (20% SE 30 on Chromosorb G at 135°; He flow - 80 ml/min) was used to collect the products. The minor product

pair gave a uv triplet at 251 nm, 262 nm, and 271 nm. The major product pair was partially resolved into separate components to give a uv spectrum with maxima at 281 nm, 234 nm, and 228 nm and a second uv spectrum with maxima at 224 nm and 302 nm. The mixture was shown by comparison with an authentic sample, not to contain 1-phenyl-1,3-cyclohexadiene.

XXIV. 3-Butyn-1-ol (79)

The method of Henne and Greenlee was used (114). In a 5 liter flask equipped with an acetone-Dry Ice condenser, a Hirschberg stirrer and a gas inlet tube long enough to be submerged in the liquid was placed 2.5 liters of liquid ammonia. A flow of acetylene was started and after 5 mins the stirrer was started. In small pieces about 0.5 cm on an edge, 92 g (4 mol) of sodium was slowly added to prevent the sodium from depleting the acetylene and giving a blue color to the solution. To the freshly formed sodium acetylide was added 229 g (5.2 mol) of ethylene oxide and the mixture was stirred overnight. After the insulation around the flask was removed, 500 ml of ether was added and the ammonia was allowed to evaporate. Powdered ammonium chloride, 100 g, was added and then 75 ml of 9 M sulfuric acid solution was added. The aqueous layer was separated and washed with two 100 ml portions of ether. The ether solutions were combined and washed with 100 ml of saturated sodium chloride solution. The solution was dried over anhydrous magnesium sulfate and the ether was removed by rotary evaporation. The crude product was distilled to give 131 g (47%) of a clear liquid, b.p. 54-56°/52 mm [lit. (114)

128.9<sup>o</sup>]; nmr (CCl<sub>4</sub>) δ 2.01 (t, 1 H, J = 2.5 Hz, HC≡), 2.40 (d of t, 2 H, J = 2.5 Hz, J' = 7 Hz, CH<sub>2</sub>C≡), 3.71 (t, 2 H, J = 7 Hz, CH<sub>2</sub>O), 4.26 (s, 1 H, OH).

XXV. 1,2-Dibromo-1-phenylethane (80)

The method of Glaser was employed (124). To a solution of 56 g (0.54 mol) of styrene in 50 ml of chloroform was added 86.5 g (0.54 mol) of bromine over a 2 hr period at 0°. The precipitated product was removed by filtration and was recrystallized from a 10:1 solution of ethanol:chloroform to give 94 g (66%) of white crystals; m.p. 71-71.5° [lit. (115) 72-73°]; nmr (CCl<sub>4</sub>) δ 3.99 (d, 1 H, J = 10 Hz, CH<sub>2</sub>Br), 4.01 (d, 1 H, J = 6 Hz, CH<sub>2</sub>Br), 5.08 (d of d, 1 H, J = 6 Hz, J' = 10 Hz, CHBr), 7.33 (s, 5 H, Ph).

XXVI. 1-Bromo-1-phenylethene (81)

The method of Glaser was used (124). A solution of 190 g (0.72 mol) of 1,2-dibromo-1-phenylethane in 200 ml of absolute ethanol was added to a solution of 50 g (1.1 mol) of potassium hydroxide in 200 ml of absolute ethanol. The reaction mixture was heated at 55° for 30 mins, cooled and poured into 2 liters of water. The aqueous layer was separated and washed with three 100 ml portions of ether. The combined organic solutions was washed with 100 ml of water and then dried over anhydrous magnesium sulfate. (CAUTION: PRODUCT IS A LACHRYMATOR) After the solvent was removed by rotary evaporation, the residue was distilled to give 90 g (68%) of a pale yellow oil, b.p. 77.5-78.5°/7 mm [lit. (125) b.p. 71°/8 mm]; nmr (EM-360) (CCl<sub>4</sub>) δ



5.61 (d, 1 H,  $J = 1.5$  Hz,  $=\text{CH}_2$ ), 5.93 (d, 1 H,  $J = 1.5$  Hz,  $=\text{CH}_2$ ),  
7.1 (m, 3 H, Ph), 7.4 (m, 2 H, Ph).

XXVII. 5-Phenyl-5-hexen-3-yn-1-ol (82)

The procedure of Sonogashira, Tohda, and Hagihara was employed (117). In a flask flushed with nitrogen were placed 7.3 g (81 mmol) of 1-bromo-1-phenylethene, 2.4 g (34 mmol) of 3-butyn-1-ol, 144 mg of bis(triphenylphosphine)palladium dichloride and 200 ml of diethylamine. Cuprous iodide, 76 mg (0.40 mmol) was added and the solution was stirred magnetically at  $45^\circ$  for 48 hrs. After removal of diethylamine under reduced pressure, 25 ml of benzene and 25 ml of water were added. The concentrated benzene extract was chromatographed on a Silica gel Woelm column with a series of eluents starting with pentane and gradually converting to pure ether. After removal of solvents under reduced pressure, 3.5 g (60%) of a light orange crude product was obtained. Evaporative distillation at about  $100^\circ/5 \times 10^{-4}$  mm on a kugelrohr apparatus was used to obtain a light yellow oil (~ 0.5 g) with the remainder of the material forming a dark orange polymer. The product had: uv max (95% ethanol) 256 nm ( $\epsilon = 8,400$ ); ir (neat)  $\text{cm}^{-1}$  3380 (broad), 3064, 3034, 2975, 2880, 2230, 1595, 1580, 1490, 1443, 1050, 892, 772, 708; nmr ( $\text{CCl}_4$ )  $\delta$  2.59 (t, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{C}\equiv$ ), 2.79 (s, 1 H, OH), 3.73 (t, 2 H,  $J = 7$  Hz,  $\text{CH}_2\text{CO}$ ), 5.56 (s, 1 H,  $\text{H}_2\text{C}=\text{}$ ), 5.81 (s, 1 H,  $\text{H}_2\text{C}=\text{}$ ), 7.26 (m, 3 H, Ph), 7.58 (m, 2 H, Ph).

XXVIII. Cis-5-phenyl-3,5-hexadien-1-ol (83)

The general procedure of Marvell and Tashiro was employed (118). A solution of 0.50 g (2.9 mmol) of 5-phenyl-5-hexen-3-yn-1-ol, 0.25 g of Lindlar catalyst and 0.05  $\mu$ l of synthetic quinoline in 5 ml of ethylacetate was hydrogenated for 8 hrs at ambient temperature. The solution was filtered and the ethylacetate was removed on a rotary evaporator. The hydrogenation was monitored by glc (20% SE 30 Chromosorb G, 0.25 in. X 8 ft. column; T = 170°; He flow = 60 ml/min) and was terminated when glc analysis gave the following:

<u>Peak</u>	<u>Retention Time (min)</u>	<u>Relative Area (%)</u> *	<u>Assignment</u>
1	9.3	11	
2	10.9	60	<u>cis-5-phenyl-3,5-hexadien-1-ol</u>
3	13.9	17	5-phenyl-5-hexen-3-yn-1-ol
4	16.8	5	
5	20.0	6	

\* The areas were determined by triangulation.

Preparative glc was used to obtain pure product: uv max (cyclohexane) 244 nm ( $\epsilon = 9,200$ ); ir (neat)  $\text{cm}^{-1}$  3340, 3080, 3060, 3020, 1495, 1445, 1050, 900; nmr ( $\text{CCl}_3\text{D}$ )  $\delta$  1.77 (m, 2 H,  $\text{CH}_2\text{C}=\text{}$ ), 3.53 (m, 2 H,  $\text{CH}_2\text{O}$ ), 5.0-5.6 (m, 2 H,  $\text{CH}_2=\text{}$ ), 5.6-5.9 (m, 1 H,  $=\text{CHCH}_2$ ), 6.23 (d, 1 H, J = 12 Hz,  $=\text{CHCPh}$ ), 7.23 (m, 5 H, Ph).

## BIBLIOGRAPHY

1. D. S. Tarbell, Org. React., 2, 2 (1944).
2. A. C. Cope and E. M. Hardy, J. Amer. Chem. Soc., 62, 441 (1940).
3. S. J. Rhoads and N. R. Raulins, Org. React., 22, 1 (1975).
4. H. J. Hansen and H. Schmid, Tetrahedron, 30, 1959 (1974).
5. A. Jefferson and F. Scheimann, Quart. Rev., Chem. Soc., 22, 391 (1968).
6. S. J. Rhoads in "Molecular Rearrangements," Vol. I, P. de Mayo, Ed., Interscience, New York, NY, 1963, Chapter 11.
7. R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry," Academic Press, New York, NY, 1970, pp 114-140.
8. R. B. Woodward and T. J. Katz, Tetrahedron, 5, 70 (1959).
9. E. Vogel, Angew. Chem. Int. Ed. Eng., 2, 1 (1963).
10. W. v. E. Doering and W. R. Roth, ibid., 2, 115 (1963).
11. W. v. E. Doering and W. R. Roth, Tetrahedron, 18, 67 (1962).
12. M. J. Goldstein and M. Benzon, J. Amer. Chem. Soc., 94, 7147 (1972).
13. K. Fukui and H. Fujimoto, Tetrahedron Lett., 251 (1966).
14. J. A. Hirsh in "Topic in Stereochemistry", Vol. 1, N. L. Allinger and E. L. Eliel, Ed., Interscience, New York, NY, 1967, p. 199.
15. A. Brown, M. J. S. Dewar and W. Schoeller, J. Amer. Chem. Soc., 92, 5516 (1970).
16. W. H. Watanabe and L. E. Conlon, ibid., 70, 2828 (1957).
17. C. S. Marvel and F. D. Hager in "Organic Synthesis," Coll. Vol. I, H. Gilman, Ed., John Wiley and Sons, New York, NY, 1941, pp 248-249.
18. V. N. Kulakov, A. M. Likosherstov and N. K. Kochetkov, Zh. Obsch. Khim., 37, 146 (1967).
19. J. A. Marshall and S. B. Litsas, J. Org. Chem., 37, 2110 (1971).
20. C. J. Pouchert and J. R. Campbell, "The Aldrich Library of NMR Spectra," Vol. I, Aldrich Chemical Company, Milwaukee, WI., 1974, p. 24.

21. C. L. Perrin and D. J. Faulkner, Tetrahedron Lett., 2873 (1969).
22. D. J. Faulkner and M. R. Peterson, J. Amer. Chem. Soc., 95, 553 (1973).
23. E. N. Marvell and J. L. Stephenson, J. Org. Chem., 25, 676 (1960).
24. A. Komornicki and J. W. McIver, J. Amer. Chem. Soc., 98, 4553 (1976).
25. H. M. Frey and D. C. Montague, Trans. Faraday Soc., 64, 2369 (1968).
26. J. B. Lambert, Accounts Chem. Res., 4, 87 (1971).
27. H. M. Frey and R. K. Solly, Trans. Faraday Soc., 64, 1858 (1968).
28. J. D. Cox and G. Pilcher, "Thermochemistry of Organic and Organometallic Compounds," Academic Press, New York, NY, 1970, pp 150-151.
29. American Petroleum Institute, "Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds," Carnegie Press, Pittsburgh, PA., 1953, p. 476.
30. A. E. Wick, D. Felix, K. Steen and A. Eschenmoser, Helv. Chim. Acta., 47, 2425 (1964).
31. W. Sucrow and W. Richter, Chem. Ber., 104, 3679 (1971).
32. K. N. Chan, J. P. De Noble, A. C. Specian and G. Saucy, J. Org. Chem., 41, 3497 (1976).
33. E. N. Marvell and J. Seubert, J. Amer. Chem. Soc., 89, 3377 (1967).
34. W. Ziegenbein, Chem. Ber., 98, 1427 (1965).
35. T. D. Goldfarb and L. Lindquist, J. Amer. Chem. Soc., 89, 4588 (1967).
36. R. Huisgen, A. Dahmen and H. Huber, ibid., 89, 7130 (1967).
37. R. Huisgen, A. Dahmen and H. Huber, Tetrahedron Lett., 1461 (1969).
38. C. W. Spangler, T. P. Johdahl and B. Spangler, J. Org. Chem., 38, 2478 (1973).
39. A. C. Cope, A. C. Haven, F. L. Ramp and E. R. Trumbull, J. Amer. Chem. Soc., 74, 4867 (1952).
40. T. S. Cantrell, Tetrahedron Lett., 54, 5635 (1968).

41. R. Huisgen and G. Boche, Angew. Chem. Int. Ed. Engl., 5, 585 (1966).
42. H. Hoever, Tetrahedron Lett., 6, 255 (1962).
43. E. N. Marvell and J. Seubert, ibid., 17, 1333 (1969).
44. E. N. Marvell, Oregon State University, Department of Chemistry, Personal communication, Corvallis, OR, January, 1977.
45. S. W. Benson and H. E. O'Neal, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand., No. 21, 1970.
46. S. W. Benson, F. R. Cruichshank, D. M. Golden, G. R. Haugen, H. E. O'Neal, A. S. Rodgers, R. Shaw and R. Walsh, Chem. Rev., 69, 279 (1969).
47. J. D. Cox and G. Pilcher, "Thermochemistry of Organic and Organometallic Compounds," Academic Press, New York, NY, 1970, pp 160-161.
48. J. C. Hamlett, H. B. Henbest and E. R. H. Jones, J. Chem. Soc., 2652 (1951).
49. K. Bowden, I. Heilbron, E. R. H. Jones and K. H. Sargent, ibid., 1579 (1947).
50. R. B. Woodward and R. Hoffman, "The Conservation of Orbital Symmetry," Academic Press, New York, NY, 1970, pp 38-64.
51. E. N. Marvell, G. Caple, B. Schatz, and W. Pippin, Tetrahedron, 29, 378 (1973).
52. E. N. Marvell, G. Caple and B. Schatz, Tetrahedron Lett., 385 (1965).
53. E. Vogel, W. Grimme and E. Dinne, ibid., 391 (1965).
54. D. S. Glass, J. W. H. Wattney and S. Winstein, ibid., 377 (1965).
55. S. F. Reed, J. Org. Chem., 30, 3258 (1965).
56. M. F. Cleary, Ph.D. Thesis, June 1975, Oregon State University, Corvallis, OR, 105 numb. leaves.
57. J. C. Sauer in "Organic Synthesis," Coll. Vol. IV, N. Rabjohn, Ed., John Wiley and Sons, New York, NY, 1963, pp 813-815.
58. H. M. Crawford, M. E. Saeger and F. E. Warneke, J. Amer. Chem. Soc., 64, 2862 (1942).
59. P. A. Levens and R. E. Marker, J. Biol. Chem., 93, 749 (1931).
60. N. Kursanoff, Ann. Chem., 318, 309 (1901).

61. E. A. Braude and O. H. Wheeler, J. Chem. Soc., 39, 320 (1955).
62. A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," 2nd. Ed., John Wiley and Sons, New York, NY, 1961.
63. E. A. Guggenheim, Phil. Mag., 2, 538 (1926).
64. H. Steiner and K. E. Lewis, J. Chem. Soc., 3080 (1964).
65. C. E. Delphey, Ph.D. Thesis, June 1977, Oregon State University, Corvallis, OR, 134 numb. leaves.
66. C. Spangler, Tetrahedron, 32, 2681 (1976).
67. E. N. Marvell, ibid., 29, 3791 (1973).
68. A. Komornicki and J. W. McIver, J. Amer. Chem. Soc., 96, 5798 (1974).
69. K. W. Egger, D. M. Golden and S. W. Benson, ibid., 86, 5420 (1964).
70. H. M. Prinzbach and E. Druckery, Tetrahedron Lett., 2959 (1965).
71. H. M. Prinzbach, H. Hagemann, J. H. Hartenstein and R. Kitzing, Chem. Ber., 98, 2201 (1965).
72. see H. Prinzbach and R. Kaiser, footnote 7 in Ref. 70.
73. J. C. Tai and N. L. Allinger, J. Amer. Chem. Soc., 98, 7928 (1976).
74. M. Traetteberg, Acta. Chem. Scand., 20, 1726 (1966).
75. H. Suzuki, Bull. Chem. Soc. Japan, 33, 619 (1960).
76. G. Favini and M. Simonetta, Theoret. Chim. Acta., 1, 294 (1960).
77. M. Shanshal, Molec. Phys., 23, 441 (1972).
78. K. W. Egger, Helv. Chim. Acta., 51, 422 (1968).
79. E. N. Marvell, G. Caple, C. Delphey, J. Platt, N. Polstron and J. Tashiro, Tetrahedron, 29, 3797 (1973).
80. S. W. Benson, "Thermochemical Kinetics," John Wiley and Sons, New York, NY, 1968, p 204.
81. American Petroleum Institute, "Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds," Carnegie Press, Pittsburgh, PA, 1953, p. 716.

82. R. B. Williams, J. Amer. Chem. Soc., 52, 5060 (1930).
83. P. George, Chem. Rev., 75, 85 (1975).
84. M. P. Fleming, Master's Thesis, June 1972, Oregon State University, Corvallis, OR, 53 numb. leaves.
85. K. Alder, "Neuere Methoden der preparativen organischen Chemie," Vol. 1, Verlag Chemie, Weinheim, 1944, p. 251.
86. A. W. Johnson, J. Chem. Soc., 715 (1945).
87. F. G. Badder, G. E. M. Moussa and M. T. Omar, J. Chem. Soc., C, 110 (1968).
88. F. G. Badder, L. S. Es-Assal and N. A. Doss, J. Chem. Soc., 1027, (1959).
89. A. D. Campbell and M. R. Grimmet, Australian J. Chem., 61, 854 (1963).
90. L. H. Klemm, D. H. Lee, K. W. Gopinath and C. E. Kloffenstein, J. Org. Chem., 31, 2376 (1966).
91. L. H. Klemm, D. H. Lee, K. W. Gopinath, F. W. Kelly, E. Trod and T. M. McGuire, Tetrahedron, 22, 1797 (1966).
92. L. H. Klemm, T. M. McGuire and K. W. Gopinath, J. Org. Chem., 41, 2571 (1976).
93. W. R. Moore and W. R. Moser, ibid., 35, 908 (1970).
94. A. T. Bottini, L. L. Hilton and J. Plott, Tetrahedron, 31, 1997, (1975).
95. G. Witting and P. Fritz, Angew. Chem., 78, 905 (1965).
96. A. Padwa and S. Clough, J. Amer. Chem. Soc., 92, 5803 (1970).
97. A. Padwa, L. Brodsky and S. Clough, ibid., 94, 6767 (1972).
98. M. Schlosser and K. Christmann, Ann. Chem., 708, 1 (1967).
99. P. J. Grisdale, T. H. Regan, J. C. Doty, J. Figueras and J. L. R. Williams, J. Org. Chem., 33, 1116 (1968).
100. G. Buchi and H. Wuest, Helv. Chim. Acta., 54, 1767 (1971).
101. L. Jaenicke and K. Seferiadis, Chem. Ber., 108, 225 (1975).
102. W. G. Dauben and J. Ipakschi, J. Amer. Chem. Soc., 95, 5088 (1973).

103. D. A. Evans and A. M. Golob, ibid., 97, 4765 (1975).
104. F. Bohlman and E. Inhoffen, Chem. Ber., 89, 2191 (1956).
105. E. E. Schweizer, E. T. Shaffer, C. T. Hughes and C. J. Berninger, J. Org. Chem., 31, 2907 (1966).
106. F. Bohlmann and C. Zdero, Chem. Ber., 106, 3779 (1963).
107. H. H. Inhoffen, K. Bruckner, G. F. Domagk and H. M. Erdmann, ibid., 88, 1415 (1955).
108. W. G. Dauben, D. J. Hart, J. Ipaktschi and A. P. Kozikowski, Tetrahedron Lett., 4425 (1973).
109. J. P. Freeman, J. Org. Chem., 31, 538 (1966).
110. P. A. Grieco and R. S. Finkelhor, Tetrahedron Lett., 3781 (1972).
111. W. P. Schneider, Chem. Comm., 785 (1969).
112. G. H. Birum and C. H. Matthews, J. Org. Chem., 32, 3554 (1967).
113. J. L. Platt, Ph.D. Thesis, June 1970, Oregon State University, Corvallis, OR, 155 numb. leaves.
114. A. L. Henne and K. W. Greenlee, J. Amer. Chem. Soc., 67, 484 (1945).
115. W. Taylor, J. Chem. Soc., 343 (1937).
116. J. Chatt and F. G. Mann, ibid., 1622 (1939).
117. K. Sonogashira, Y. Tohda and N. Hagihara, Tetrahedron Lett., 50, 4467 (1975).
118. E. N. Marvel and J. Tashiro, J. Org. Chem., 30, 3991 (1965).
119. R. Kuhn and K. Wallenfels, Chem. Ber., 1889 (1938).
120. H. Lindlar and R. Dubuis, Org. Syn., 46, 89 (1966).
121. G. B. Bulter and T. W. Brooks, J. Org. Chem., 28, 2699 (1963).
122. G. M. Bennet and E. E. Turner, J. Chem. Soc., 1057 (1914).
123. R. M. Silverstein, G. C. Bassler and T. C. Morill, "Spectrometric Identification of Organic Compounds," 3rd. Ed., Wiley, New York, NY, 1974, p. 251.
124. C. Glaser, Ann. Chem., 159, 137 (1870).
125. C. Dufraisse, Ann. Chim. (Paris), 17, 164 (1922).



126. H. Hopf and H. Musso, Angew. Chem. Int. Ed., 8, 680 (1969).
127. H. Hopf, Tetrahedron Lett., 1107 (1970).