Portland State University

PDXScholar

Dissertations and Theses

Dissertations and Theses

1972

On the mechanism of the Diels-Alder reaction-- dimerization of trans-phenylbutadiene

Michael Ward McNicholas

Portland State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/open_access_etds

Part of the [Inorganic Chemistry Commons](#), [Materials Chemistry Commons](#), and the [Physical Chemistry Commons](#)

Let us know how access to this document benefits you.

Recommended Citation

McNicholas, Michael Ward, "On the mechanism of the Diels-Alder reaction--dimerization of trans-phenylbutadiene" (1972). *Dissertations and Theses*. Paper 972.

<https://doi.org/10.15760/etd.972>

This Thesis is brought to you for free and open access. It has been accepted for inclusion in Dissertations and Theses by an authorized administrator of PDXScholar. Please contact us if we can make this document more accessible: pdxscholar@pdx.edu.

AN ABSTRACT OF THE THESIS OF Michael Ward McNicholas for the Master of Arts in Chemistry presented August 31, 1972.

Title: On The Mechanism of the Diels-Alder Reaction -- Dimerization of trans-Phenylbutadiene.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Raymond P. Lutz

Philip G. Roberti

Alfred S. Levinson

The Diels-Alder dimerization of trans-1-substituted butadienes is expected to yield a cyclohexene adduct with the substituents in the 3 and 4 positions cis to one another. This prediction is based on past observations of other Diels-Alder additions. The cis-isomer is the only one consistent with a two-stage mechanism proposed by Woodward and Katz.

In the case of trans-phenylbutadiene, the expected adduct is cis-3-phenyl-4-(trans-styryl)cyclohexene. Alder, Haydn and Vogt, however, reported that the corresponding trans-isomer is the dimer-

ization product. There is reason to believe that the observation of the trans-isomer may have been the result of product isomerization during purification. In view of the unexpected nature of the product and its implications with respect to the Diels-Alder mechanism, the dimerization reaction was reinvestigated.

trans-Phenylbutadiene was heated at 130° for six hours. Analysis by thin layer chromatography on silica gel impregnated with silver nitrate revealed two major components as well as several minor ones. The two major components were isolated by column chromatography on silica gel impregnated with silver nitrate. They were present in roughly equal proportions. One of them was purified and found to be identical with cis-3-phenyl-4-(trans-styryl)cyclohexene prepared by an independent method. The second major component, not yet isolated in pure form, is probably the corresponding trans-isomer on the basis of IR and NMR spectra as well as the fact that the trans-isomer was found by Alder et al.

An evaluation of the significance of this reaction with respect to the Diels-Alder mechanism will have to await positive identification of the second component as well as a more careful determination of its relative proportion to the cis-isomer.

ON THE MECHANISM OF THE DIELS-ALDER REACTION --
DIMERIZATION OF TRANS-PHENYLBUTADIENE

by

MICHAEL WARD McNICHOLAS

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF ARTS
in
CHEMISTRY

Portland State University
1972

TO THE OFFICE OF GRADUATE STUDIES:

The members of the Committee approve the thesis of Michael
Ward McNicholas presented August 31, 1972.

Raymond P. Lutz, Chairman

Philip C. Roberti

Alfred S. Levinson

APPROVED:

Gary L. Gard, Chairman
Department of Chemistry

David T. Clark, Dean of Graduate Studies

ACKNOWLEDGEMENTS

I am forever grateful to Dr. Raymond P. Lutz for his guidance and assistance throughout this research project. His friendship and instruction have been of immeasurable value.

I would also like to express my gratitude to the entire chemistry faculty for their advice and encouragement. Contact with them has made these years pleasant ones.

Finally, to my wife, Mimi, for her help as well as her patience and understanding.

This thesis is dedicated to
my Mother

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGMENTS	iii
LIST OF FIGURES	vi
INTRODUCTION	1
RESULTS AND DISCUSSION	16
GENERAL LABORATORY PROCEDURES AND INSTRUMENTATION . . .	28
EXPERIMENTAL	29
<u>trans</u> -Phenylbutadiene (Grignard Method)	29
<u>trans</u> -Phenylbutadiene (Modified Wittig Method) . . .	30
Dimerization of <u>trans</u> -Phenylbutadiene	32
<u>cis</u> -3-Phenyl-4-formylcyclohexene	34
<u>cis</u> -3-Phenyl-4-(<u>trans</u> -styryl)cyclohexene	35
Preparation of <u>trans</u> -Phenylbutadiene Dimer Mixture (Undistilled) for Chromatography	37
Thin Layer Chromatography on Silica Gel Impregnated with Silver Nitrate	37
Analysis of <u>trans</u> -Phenylbutadiene Dimer Mixture with Commercial Liquid Chromatograph	38
Column Chromatography on Silica Gel Impregnated with Silver Nitrate	39
Dry Column Chromatography on Silica Gel Impregnated with Silver Nitrate	42
Attempted Preparative Scale Layer Chromatography on Silica Gel Impregnated with Silver Nitrate	44
<u>cis</u> -3-Phenyl-4-carboxycyclohexene	44
Oxidation of <u>trans</u> -Phenylbutadiene Dimer Mixture . .	45
Oxidation of <u>cis</u> -3-Phenyl-4-(<u>trans</u> -styryl)cyclohexene	47
Oxidation of <u>cis</u> -3-Phenyl-4-carboxycyclohexene . . .	48
Thermal Stability of <u>cis</u> -3-Phenyl-4-(<u>trans</u> -styryl)- cyclohexene	49

BIBLIOGRAPHY	51-52
------------------------	-------

LIST OF FIGURES

FIGURES		Page
1	NMR Spectrum of <u>cis</u> -3-phenyl-4-(<u>trans</u> -styryl)-cyclohexene	19
2	IR Spectrum of <u>cis</u> -3-phenyl-4-(<u>trans</u> -styryl)-cyclohexene	20
3a	Liquid chromatogram of crude <u>trans</u> -phenylbutadiene dimerization mixture. (Sample load 8 μ g)	22
3b	Liquid chromatogram of crude <u>trans</u> -phenylbutadiene dimerization mixture. (Sample load 100 μ g)	23
4	Thin layer chromatogram of crude <u>trans</u> -phenylbutadiene dimerization mixture	24

INTRODUCTION

The reversible thermal addition of a conjugated diene (I) to an olefin (II, referred to as the dienophile) to yield a cyclohexene adduct (III) was extensively investigated by Diels and Alder (1).

This reaction -- universally known as the Diels-Alder reaction -- provided the synthetic organic chemist with one of the simplest known routes to cyclic compounds and proved of such value that it won for Diels and Alder the Nobel prize in chemistry in 1950.

Although ethylene and simple olefins can be used as dienophiles, it is found that electron-donating substituents [e.g. $\text{N}(\text{CH}_3)_2$, OCH_3 , CH_3] in the diene and electron-withdrawing substituents [e.g. CN , CO_2CH_3 , CHO , NO] in the dienophile promote the reaction.

Because of rotation about the single bond between the two conjugated double bonds of open chain dienes, these molecules can occur in two conformations. With butadiene and its simple alkyl derivatives, the transoid form (IV) usually predominates in the conformer equilibrium (2) because of the steric repulsion between terminal hydrogens in the cisoid form (V). There is strong evidence which suggests that it is only the cisoid conformer that is capable of taking part in the

Diels-Alder reaction. This is shown by the fact that 1-substituted

butadienes can be used almost without exception provided the substituent R is in the trans-arrangement (VI), while the cis-form (VII) generally undergoes a Diels-Alder reaction only with a poor yield (3).

Carbon-hetero double bonds may also act as dienophiles to give rise to heterocyclic adducts (4). Some examples of these are $N \equiv C-$, $-N = C-$, $-N = N-$, $O = N$, and $-C = O$ compounds.

The active unsaturated portion of the dienophile, and that of the diene, may be involved in rings, giving rise to polycyclic adducts. An example of this can be seen in the addition of anthracene to maleic anhydride.

in a multicenter mechanism involving a transition state (XIII) having a steric configuration similar to that of the product molecule. This view proposes that we are dealing with a one-step reaction, whose energy profile contains only one activation barrier.

XIII

Reaction Coordinate

In the other proposal, the new σ bonds are said to form in two successive reaction steps, where one of the bonds is formed in the rate determining step. The energy profile of the two-step reaction, which contains two transition states, includes a biradical intermediate (XIV).

XIV

It was recognized very early that the steric arrangement of substituents both in the diene and in the dienophile is preserved in the adduct, and this observation was formulated by Alder and Stein as the "cis" principle (6). This is illustrated in the reaction of maleic acid with butadiene to yield the cis-isomer XV but not XVI.

The "cis" principle applies also to substituents in the diene components. In the addition of maleic anhydride to trans,trans-1,4-diphenylbutadiene, the adduct (XVII) has the phenyl groups cis to each other (7).

The only known exception to this rule was reported by Hendrickson (8). The addition of cis- and trans- β -sulfoacrylic acid ($\text{HO}_3\text{S}-\text{CH}=\text{CH}-\text{CO}_2\text{H}$) to cyclopentadiene leads to the same adduct, in which the substituents of the dienophile are trans to each other, but according to the author it requires further corroboration.

The almost universal strict adherence to this rule can be readily rationalized by the synchronous formation of the bonds between the two components in a one-step mechanism, but does not, in principle, rule out a two-step mechanism. If the formation of the second bond is much faster than rotation about bond ab in the intermediate (XVIII), the two-step mechanism should also lead to stereospecificity.

XVIII

Another interesting feature relating to the stereochemistry of the Diels-Alder reaction is observed whenever two modes of combination leading to different configurations of the product are possible. If we assume the reactants come together in a "sandwich-like" preorienta-

tion, the dienophile is added in such a way as to give a maximum accumulation of unsaturated centers in the transition state. An example of this is found in the addition of maleic anhydride to cyclopentadiene (10). This addition leads almost exclusively to the endo adduct (XIX) rather than the exo compound (XX), which is formed in yields of less than 1.5%.

Similarly, the reactions of cyclopentadiene with cyclopentene (11) and cyclopropene (12) give preferential or exclusive formation of the endo adduct. The endo-addition rule is not as hard and fast as the cis-rule, however, and many exceptions are known (13, 14).

In general, substituent effects can be more readily explained by a two-step mechanism than a one-step. Where more than one product is possible, the observed adduct is usually the one predicted on the basis of the most stable diradical intermediate. This is exemplified by

the dimerization of trans-piperylene. Viewing this as a two-step process, the addition would lead initially to the intermediate XXI (the most stable diradical), and from there to the observed major product.

If the dimerization occurred by simultaneous formation of both new bonds of the adduct, there is no apparent reason why the two substituents of the adduct should be on adjacent carbon atoms.

Another example is found in the dimerization of acrolein. Viewing this once again as a two-step process, the addition would lead initially to the intermediate XXII, and from there to the observed product XXIII (15). If the reaction went through a symmetrical one-

step process, polar forces in the complex XXIV should favor formation of XXV, whereas only XXIII is formed.

Another effect of substituents that can be better explained by the two-step mechanism is their effect on reaction rates. Conjugative substituents in either the diene or dienophile are found to accelerate reaction. During the initial bond formation of a two-step process, electrons are delocalized away from each of the original unsaturated centers, leaving on either side electrons which are less stabilized. The presence of any group which stabilizes these partially freed electrons will facilitate the initial bond-forming process.

On the other hand, a concerted one-step mechanism could not be used to rationalize these substituent effects. For, if two electrons from each partner must be simultaneously delocalized to participate in two simultaneous bond-forming processes, groups capable of conjugation would make the reaction much more difficult, due to the demands they would make upon these electrons.

In explaining substituent effects in terms of a two-step mechanism, it must also be recognized that these explanations apply equally well to an unsymmetrical one-step process.

In an attempt to incorporate the diverse characteristics of the one- and two-step mechanisms, Woodward and Katz put forth a proposal based upon their work with α - and β -1-hydroxydicyclopentadiene (16).

In this work they found that α -1-hydroxydicyclopentadiene XXVI, when heated at 140° , yields an equilibrium mixture of XXVI and syn-8-hydroxydicyclopentadiene (XXVII) with an equilibrium constant of approximately 1. When either alcohol was heated at 140° , it was converted into the

same equilibrium mixture of XXVI and XXVII. It was also observed that complete stereochemical integrity was maintained, with only syn-8-hydroxydicyclopentadiene and no anti-8-hydroxydicyclopentadiene (XXIX) being formed. Similarly, β -1-hydroxydicyclopentadiene (XXVIII) was converted to anti-8-hydroxydicyclopentadiene (XXIX) when it was heated at 140° , with the equilibrium lying strongly in favor of XXIX. Once again,

stereochemical integrity was maintained with only anti-8-hydroxydicyclopentadiene and no syn-8-hydroxydicyclopentadiene being formed. The observed stereochemical specificity showed that this reaction did not

involve dissociation into the fragments cyclopentadiene and cyclopentadienol, but was intramolecular. To account for these results, Woodward and Katz proposed that only the bond between C-3a and C-4 was broken and a new bond between C-2 and C-6 was formed while the bond between C-7 and C-7a remained intact.

The intramolecular rearrangement observed by Woodward and Katz is a special case of the Cope rearrangement (17), where a six-atom unit (e.g. XXX) with double bonds at the end groups undergoes thermal rearrangement to XXXI, but it possesses an additional significance in

that the compound undergoing isomerization is a Diels-Alder adduct, which usually cleaves into two addends.

Woodward and Katz presumed that in the dissociation of XXVI to two addend molecules, the cleavage of the bond between C-3a and C-4 took place relatively readily. At a higher energy, the second bond (between

C-7 and C-7a) ruptured to yield the products. They then proposed that all reverse Diels-Alder reactions proceeded in a similar manner and, on the basis of the principle of microscopic reversibility, assumed that forward Diels-Alder reactions in general must proceed through a two-stage mechanism where one of the new bonds is fully established while the other is in the process of formation. The diene and the dienophile approach one another in parallel planes, perpendicular to the direction of the bond about to be formed; in the rate-determining step, only one bond, i.e. that between a and b, is formed (cf. XXXIIb); "thus as electrons at c, d, and e are progressively freed of their involvement with their former partners at a and b, attractive electrostatic, electrodynamic, and even to some extent exchange forces" between the centers at e, d, and c are assumed to be responsible for the observed *cis* addition because they should prevent rotation about C-C single bonds. At

this point it should be mentioned that the Woodward-Katz rearrangement appears to be confined to adducts in which both components possess diene character. The conversion of 8-ketodicyclopentadiene to the corresponding 1-ketodicyclopentadiene (18) is another example of this rearrangement. Yet another example is found in the thermal rearrangement of optically active methacrolein dimer (XXXIII), labeled with deuterium at the aldehyde hydrogen, to yield XXXIV with retention of optical activity (19).

The dimer (XXXIII) also undergoes the reverse Diels-Alder reaction at slightly higher activation energy than the Cope rearrangement.

The proposal of Woodward and Katz does account for the diverse characteristics of the one- and two-step mechanisms. It encompasses within it the requirements for stereochemical rigidity (cis addition) in the transition state while allowing the same substituent effects which would be predicted using the two-step mechanism.

According to this proposal, secondary attractive forces account for the principle of maximum accumulation of unsaturated centers. The predicted transition state for the dimerization of trans-1- substituted butadienes should have structure XXXV leading to the cis-isomer XXXVI. (Note that the initial configuration of the product has the potential

for undergoing the degenerate Cope rearrangement.)

The trans-isomer (XXXVIII) would arise through the alternative

transition state XXXVII.

The previously mentioned work of Nazarov, et al. (5) with trans-piperylene fits reasonably well into Woodward and Katz's scheme. It was found that 90% of the total quantity of the dimers existed in the form VIIIa and VIIIb, with the cis isomer (VIIIa) predominating by a

ratio of 7:1.

With these facts in mind, the dimerization of trans-phenylbutadiene to yield the trans-isomer (XXXIX), reported by Alder, Haydn and Vogt (20), is very surprising. It is in direct contrast to the proposal of

Woodward and Katz and it contradicts the principle of maximum accumulation of unsaturated centers. There is, however, reason to doubt the validity of Alder's results. After running the reaction at a temperature of 150°, the distillation of the oily dimerization products was carried out at temperatures ranging as high as 230°. At temperatures that high, there is a possibility of thermal isomerization resulting in products which might not be the same as the kinetically controlled products. It is conceivable that the isomer isolated by Alder and his colleagues was not the kinetically controlled product. It was the purpose of this research to repeat the work of Alder, Hayden and Vogt at considerably lower temperatures to avoid, as much as possible, the occurrence of thermal isomerization of the product.

It was found, in fact, as is described in detail in the next section, that trans-phenylbutadiene dimerizes to yield two main components in roughly comparable amounts, one of which was isolated in pure form and characterized as cis-3-phenyl-4-(trans-styryl)cyclohexene. Evidence points to the suggestion that the second major component is the trans-isomer, although it has not yet been isolated in pure form.

RESULTS AND DISCUSSION

trans-Phenylbutadiene was prepared according to the method of Grummitt and Becker (21). Pure trans-phenylbutadiene, $\geq 99.5\%$ (by vpc),

was obtained after two fractional distillations, b.p. 36-41° (0.2-0.3 mm). The purity was ascertained by gas chromatographic analysis on an 8 ft. x 1/8 in. column of diethyleneglycol succinate (Lac 728) polyesters operated at 125° and on an 8 ft. x 1/8 in., 5% XE-60 (cyanosilicone) column operated at 125°. Durkin (22) was able to separate the cis- and trans-isomers on the column of diethyleneglycol succinate (Lac 728).

The trans-phenylbutadiene was heated with a trace of hydroquinone for six hours at 130°. It was then fractionally distilled (0.08 mm) with the temperature never exceeding 160°. The temperatures were intentionally kept low, in contrast to the procedures of Alder and colleagues (20) where the dimerization was run at 150° and the distillation at 227-230° (16 mm), to avoid as much as possible the occurrence of thermal isomerization of the product. Two main fractions were obtained; fraction 1, 14.1 g., b.p. 147-158° (0.08 mm) and fraction 2, 27 g, b.p. 158-

160° (0.08 mm) for a total yield of 85%. As will be discussed below, both fractions were actually mixtures with two major components although analysis by vpc showed only one main peak whose area was 98% of the total peak areas. A small portion of fraction 1 was dissolved in methanol and crystallized by cooling in dry ice. The dry ice was allowed to evaporate slowly overnight and some solid remained at room temperature. The solid was used to seed both fractions and they were stored in a refrigerator. This method proved successful in solidifying almost all of fraction 2 and a large percentage of fraction 1. When brought to room temperature, both fractions slowly remelted.

Fraction 2 was filtered with vacuum suction through a sintered glass funnel at 0° to separate a solid (mp 34-38°) from the oil. This solid was recrystallized 3 times from methanol to yield a compound (Isomer A) having mp 42.8-43.0°. Attempts to repeat the above procedure with fraction 1 proved unsuccessful. The solid remaining after filtration at 0° became an oil at room temperature. Efforts to remove impurities by dissolving the oil in methanol and crystallizing isomer A from solution also proved ineffective.

The NMR spectrum of isomer A (Fig. 1) was consistent with the structure XL (no stereochemistry implied). Assignments are summarized below where combined relative areas are given for overlapping peaks.

<u>Chemical Shift</u> <u>δ ppm</u>	<u>Relative</u> <u>Areas</u>	<u>Assignment</u>
7.1	10.6	aromatic protons
6.1	4.0	protons at C-7 and C-8
5.7		protons at C-1 and C-2
3.1	1.0	proton at C-3

<u>Chemical Shift</u> <u>δ ppm</u>	<u>Relative</u> <u>Areas</u>	<u>Assignment</u>
2.0	5.3	protons at C-6 and C-4
1.75		protons at C-5

The IR spectrum of isomer A (Fig. 2) had characteristic absorptions at 962 (trans CH=CH), 690 (cis CH=CH) and 1595 cm^{-1} (phenyl).

The ultraviolet spectrum had λ_{max} 252 m μ (Heptane, ϵ 19,200), indicative of a trans-styryl group (23).

XL

To determine which of the two isomers had been isolated (i.e., cis- or trans-3-phenyl-4-(trans-styryl)cyclohexene), the cis-isomer was synthesized by an independent method. This was accomplished by first making cis-3-phenyl-4-formylcyclohexene (XLI) from trans-phenylbutadiene and acrolein (24).^{*} This was followed by a modified Wittig (24) reaction using triethylphosphite and benzyl chloride. The solid obtained

* Alder assigned the cis stereochemistry to this aldehyde on the basis of oxidation to the carboxylic acid with silver oxide followed by reduction to the cyclohexane derivative of known stereochemistry.

Figure 1. NMR spectrum (CCl_4) of cis-3-phenyl-4-(trans-styryl)cyclohexene. (Isomer A).

Figure 2. IR spectrum (CCl₄, 35 mg/ml) of *cis*-3-phenyl-4-(*trans*-styryl)cyclohexene. (Isomer A).

was recrystallized several times from methanol to yield a compound (XLII, mp 41.2-42.2°) whose NMR and IR spectra corresponded to those of isomer A. A mixture of the two solids had mp 42.0-42.9°. On this basis, isomer A was assigned the structure of cis-3-phenyl-4-(trans-styryl)cyclohexene (XLII), where the trans-styryl configuration was established by IR and UV, as mentioned previously. This aspect of the product's stereochemistry was not reported by Alder.

A sample of the trans-phenylbutadiene was dimerized again under the same conditions as before. However, this time it was not distilled in order to avoid possible product isomerization at distillation temperatures. A portion of this crude reaction mixture was analyzed by Waters Associates, using one of their commercial liquid chromatographs. Their analysis indicated one major component with about seven minor ones (Fig. 3a and 3b). This was followed by analysis with thin-layer chromatography using 10% silver nitrate impregnated silica gel

Figure 3a. Liquid chromatogram of crude trans-phenylbutadiene dimerization mixture. Column: 2 ft. x 2.3 mm ID Corasil II (spherical particles consisting of a solid glass core with a double layer of porous silica). Sample load, 8 μg. RI refers to refractive index monitor. UV refers to ultraviolet monitor.

Figure 3b. Liquid chromatogram of crude trans-phenylbutadiene dimerization mixture. Column: 2 ft. x 2.3 mm ID Corasil II (spherical particles consisting of a solid glass core with a double layer of porous silica). Sample load, 100 μ g. RI refers to refractive index monitor. UV refers to ultraviolet monitor.

Figure 4. Thin layer chromatogram of crude trans-phenylbutadiene dimerization mixture on silica gel impregnated with 10% silver nitrate. Development in chloroform.

as the adsorbent. It was possible to detect 6 separate components (Fig. 4) of which two were predominant. Separation of these two major components was accomplished with column chromatography on 10% silver nitrate impregnated silica gel. Although the separation was not complete because of overlapping, it was possible to recover most of these two components uncontaminated by one another (on the basis of TLC). Of the two isomers, which existed in a ratio of approximately 1:1, the slow moving one was a solid at room temperature. Recrystallization from methanol yielded a compound (mp 42.0-42.2°) whose IR spectrum corresponded to that of isomer A. The other component, labeled isomer B, remained an oil at room temperature. It was suspected of being the trans-isomer on the basis of the similarity of IR and NMR spectra with isomer A. It remains yet to be purified and fully characterized. Numerous attempts to recrystallize it were unsuccessful.

The structural assignment for the trans-phenylbutadiene dimerization product made by Alder, Haydn and Vogt was based on potassium permanganate oxidation to a tricarboxylic acid of known stereochemistry (20). Both the cis- and trans-3-phenyl-4-carboxycyclohexene (XLIII and XLIV) were known to oxidize to different triacids as shown below.

Alder's oxidation of the distilled trans-phenylbutadiene dimerization mixture gave, after several recrystallizations from acetonitrile, a triacid having mp 194-195° (no yield reported). Hence he assigned the trans configuration to the substituents on the ring of the dimer.

Attempts were made to repeat Alder's procedures for oxidizing the dimerization products in hopes that the oxidation product of the cis-isomer could be isolated to further substantiate the structural assignment made in this study. It was possible to isolate a solid from the oxidation of the distilled dimerization mixture, but the purified product (mp 187°d) obtained after repeated recrystallizations from acetonitrile represented less than 10% yield.

Oxidation of the pure cis-3-phenyl-4-(trans-styryl)cyclohexene resulted in the recovery of a solid (mp 165.5°-167.0°d) representing less than 5% yield. The oxidation of cis-3-phenyl-4-carboxycyclohexene (XLIII) for comparison purposes also proved unsuccessful. A white solid (mp 172-175°d) was obtained representing less than a 5% yield. Most of the oxidation product from these two compounds was recovered as a brown oil. The melting points of the isolated solids varied with the rate the temperature was elevated. Reproduction of melting points was very difficult.

There is some reason to believe the poor results obtained above were due to the fact that the oxidations were done with potassium permanganate. Although the compounds are not similar, it is known that permanganate is of little value in the oxidation of the ortho-substituted benzene derivatives, as its use results in low yields of not over 10-20% with formation of a complex mixture of oxidation products

(5). Better results may be obtained by using 20% dilute nitric acid in phthalic acid or through ozonization (5).

The possibility that the trans-3-phenyl-4-(trans-styryl)cyclohexene characterized by Alder, and probably present in our mixture, was the result of thermal isomerization was explored next. A sample of the cis-isomer was heated for 6 hours at 130° and analyzed. Its IR spectrum showed no change. A TLC comparison on silver nitrate impregnated silica gel showed it to be identical with the starting material. The sample, which was a yellow oil at 130°, solidified at room temperature (mp 40-42°, yellow color).

Another sample of the cis-isomer was heated at 200° for 1 hour. IR and TLC analysis showed no change from the starting material.

It appears from these results that the other isomer present (probably trans-3-phenyl-4-(trans-styryl)cyclohexene) is a kinetically controlled product.

To summarize the results of this work, the dimerization of trans-phenylbutadiene yields a number of components of which two are predominant. Of these two major components, one has been isolated and purified, and identified as cis-3-phenyl-4-(trans-styryl)cyclohexene. The other is probably trans-3-phenyl-4-(trans-styryl)cyclohexene, since this was the isomer identified by Alder, Haydn and Vogt.

An evaluation of the significance of this reaction with respect to the proposal of Woodward and Katz will have to await the positive identification of the second major component and a more careful determination of its relative proportion to the cis-isomer.

GENERAL LABORATORY PROCEDURES AND INSTRUMENTATION

Melting points were determined on a Thomas-Hoover capillary melting point apparatus.

Infrared spectra were obtained on a Perkin-Elmer 467 Grating Infrared Spectrophotometer and a Perkin-Elmer 700 Infrared Spectrophotometer. The positions of peaks were calibrated with the 6.24μ band of polystyrene. Samples were run neat between sodium chloride plates or in solution.

Ultraviolet spectra were measured on a Cary Model 14 Recording Spectrophotometer.

Nuclear magnetic resonance (NMR) spectra were recorded on a Varian Associates A-60 Spectrometer. Tetramethylsilane (TMS) was used as an internal standard.

Vapor phase chromatography (vpc) was carried out on Hewlett-Packard 5750B Flame Ionization Research Chromatograph. The two columns used were 8 ft. x 1/8 in OD. Column A was 20% diethyleneglycol succinate (on 80-100 mesh Chromosorb W, acid washed and silanized). Column B was 5% XE-60 (cyanosilicone, 80-100 mesh Chromosorb W, acid washed and silanized).

Elemental analysis was performed by Scandinavian Microanalytical Laboratories, Herlev, Denmark.

Volatile solvents were evaporated at water-pump pressure on a rotary evaporater.

EXPERIMENTAL

trans-Phenylbutadiene (Grignard Method). This compound was prepared following the procedure of Grumitt and Becker (21). In a 1-liter, three-necked flask equipped with magnetic stirrer, thermometer, nitrogen inlet, and addition funnel with pressure equalizing arm was placed 0.52 mole of methylmagnesium bromide in 340 ml of absolute ether (1.5 N). By means of an ice bath, the temperature was kept between 0-10° and a solution of 66 g (0.50 mole) of redistilled cinnamaldehyde was added with stirring over 1½ hours. Throughout the addition, a constant flow of nitrogen was passed over the solution.

The contents of this flask were immediately transferred to a 500-ml addition funnel, and the flask was washed twice with ether to transfer any remaining adduct. The addition funnel was then connected to a 2-liter, three-necked flask equipped with a reflux condenser and a Hershberg nichrome wire stirrer. To the flask was added 175 ml of 30% sulfuric acid. Without cooling but with efficient stirring of 1800 r.p.m., (Fisher dyna-mix stirrer, 18:1 gear ratio), the ether solution of the cinnamaldehyde-methylmagnesium bromide adduct was added at a rate that did not exceed the capacity of the condenser. Heat was then applied to maintain gentle reflux. Total time for this step was 20 minutes.

The mixture was immediately placed in a 1-liter separatory funnel, the lower aqueous layer discarded, and the ether layer washed successively with 50 ml of water, a mixture of 50 ml of 5% sodium hydroxide

and 50 ml of saturated ammonium chloride solution, and finally with 50 ml of water. The air in the funnel was displaced with nitrogen before each washing. When the second wash was added, 0.3 g of phenyl- β -naphthylamine, a polymerization inhibitor, was dissolved in the ether layer.

The washed solution was dried over 20 g of anhydrous sodium sulfate for 20 minutes, and then over potassium carbonate for 15 hours. The ether solution was concentrated by stripping on the rotary evaporator and then under vacuum to give 72.6 g of crude oil.

The above preparation was repeated using the same procedures with 0.475 mole of methylmagnesium bromide and 63.0 g (0.475 mole) of cinnamaldehyde to give 69.6 g of crude oil.

The residues from both preparations were combined and vacuum distilled through a 30-cm Vigreux column to yield 89.1 g (70.1%) of the crude product. This was distilled again through the Vigreux column to yield 77.6 g (61%) of trans-phenylbutadiene boiling 36-41° (.2-.3 mm). Composition of the product was 99.5% trans isomer and 0.5% suspected cis (22) by vpc analysis (Column A and B, 125°).

An attempt to repeat this synthesis at a later date gave a much lower yield (33%). A yellow precipitate formed during the addition of cinnamaldehyde which was not observed in the earlier synthesis. There appears to be a susceptibility toward polymerization that warrants greater use of inhibitors throughout the preparation.

trans-Phenylbutadiene (Modified Wittig Method). This compound was prepared according to the procedure of Maercker (26). In a 2-liter three-necked flask equipped with a reflux condenser, nitrogen

inlet, and magnetic stirrer was placed 100 g (0.28 mole) of methyl triphenylphosphonium bromide and 350 ml of absolute ether. A constant flow of nitrogen was passed over this mixture. Through a septum, 168 ml of 15% n-butyllithium in hexane (0.28 M) was injected with a syringe over a 1½ hour period. The suspension turned yellow immediately and after 25 minutes an orange color was noted. When all the n-butyllithium had been added, 50 ml of absolute ether was injected into the solution. This was followed with 37 g (0.28 mole) of re-distilled cinnamaldehyde added through an addition funnel. As the cinnamaldehyde was added, a gummy precipitate began to form. This effectively froze the stirring bar and necessitated manual stirring. This was done with a glass rod attached to a crescent-shaped teflon base. After adding an additional 150 ml of absolute ether, the almost colorless mixture was left at room temperature for one hour with occasional swirling. It was then placed in a constant temperature oil bath at 65° and refluxed for 5 hours. It was then removed and pressure filtered with nitrogen. The precipitate was washed three times with ether and the solid left in the reaction flask was rinsed liberally with ether. The combined ether washings were extracted with 225 ml of 40% sodium bisulfite solution and twice with water. The ethereal solution was then dried over anhydrous magnesium sulfate with a trace of hydroquinone. The ether solution was then concentrated by vacuum stripping and distilled through a 30-cm Vigreux column. Four fractions were obtained; 2.58 g, bp 28-35° (0.08 mm), 3.36 g, bp 35-38° (0.08 mm), 2.79 g, bp 38-48° (0.08 mm) and 3.09 g, bp 48-55° (0.08 mm). Total yield 11.8 g (32%). Analysis by vpc (Column A, 130°)

showed less than 90% trans-phenylbutadiene in all four fractions. Of the remaining impurities, most was assumed to be the cis-isomer (22).

Dimerization of trans-Phenylbutadiene. In a 25-ml round-bottom flask was placed 10.0 g (0.076 mole) trans-phenylbutadiene and 0.1 g hydroquinone. The flask was put into a constant temperature oil bath at 130°. The progress of the reaction was followed by removing small amounts of the mixture and analyzing them with NMR. After seven hours the reaction appeared complete and the flask was removed from the oil bath and stored over night in the freezer.

The reaction mixture, which remained an oil in the freezer, was removed and distilled through a 30-cm Vigreux column connected to an air-cooled condenser with a cow attached. The column was wrapped with heating tape to help bring the high boiling material over. In addition to a forerun of 0.5 g, bp 26.5-145° (0.1 mm), two main fractions were obtained; 4.9 g bp 145-161° (0.1 mm) and 1.7 g, bp 161° (0.1 mm). Total yield, 6.6 g (66%), showed one main peak whose area was 98% of the total peak areas with vpc analysis (column B, 212°). Separation of the two main isomers was not accomplished.

The above procedure was repeated using 48.3 g (0.37 mole) of trans-phenylbutadiene. After a forerun of 3.4 g, bp 26-147° (0.08 mm), two main fractions were obtained; 14.1 g, bp 147-158° (0.08 mm) and 27 g, bp 158-160° (0.08 mm). Total yield, 41.1 g (85%).

The two main fractions from the second preparation above were stored in the freezer. A small amount of the first fraction (147-158° (0.08 mm)) was removed and dissolved in methanol. It was then solidified in a dry ice bath. The dry ice was allowed to evaporate and when the

sample returned to room temperature, some remained as a solid. This solid was used to seed the two fractions. Although crystallization did occur in both fractions while being stored in the freezer, they were transferred to a refrigerator to reduce viscosity and enhance further crystallization. This proved effective as almost all of the fraction boiling at 158-160° became solid and a large percentage of the 147-158° fraction did likewise. When they were removed to room temperature, the crystals slowly remelted.

The samples were returned to the refrigerator and after solidification appeared complete, the 158-160° fraction was transferred to a sintered glass pressure filter which had been cooled to 0°. The filter was kept over night at 0°.

It was then packed in ice and 20 lbs. of nitrogen pressure was applied. This proved to be ineffectual as the oil remained with the solid. The sample was then filtered with vacuum suction and in this manner most of the oil was separated from the solid. Throughout the filtration, the filter was kept packed in ice and the sample was continually pressed down with a spatula.

The 147-158° fraction was subjected to this same procedure. The two fractions were kept at 0° and under vacuum suction for 3 days. They were then brought to room temperature with the resulting melt of much of the solid. They were then brought back down to 0° and a small amount of solid from the 158-160° fraction was removed and dissolved in a minimum of warm methanol. Upon cooling, the sample came out of solution as an oil. It was heated again and brought back into solution. By continually agitating the solution while cooling, the sample eventu-

ally came out as a solid, mp 40-41.5°.

The remainder of the 158-160° fraction was then recrystallized from methanol. As with the previous recrystallization, getting the sample to come out as a solid rather than an oil proved to be a problem. The solid (Isomer A) was filtered and dried under vacuum to yield 1.34 g, mp 42.1-42.5°. This sample was recrystallized again from methanol to yield 0.76 g, mp 42.8-43°. Anal. Calcd. for $C_{20}H_{20}$: C, 92.26; H, 7.74. Found: C, 91.99; H, 7.63. The nmr spectrum (cf. Fig 1.) and IR spectrum (cf. Fig 2.) were consistent with the expected dimer. U.V. analysis, λ_{max} 252 m μ (heptane, ϵ 19,200), was also consistent with the expected dimer.

Attempts to crystallize the 147-158° fraction from methanol proved unsuccessful. Although a solid existed at 0°, it was contaminated by impurities and became gummy at room temperature.

cis-3-Phenyl-4-formylcyclohexene. This compound was prepared by the method of Alder, Vagt and Vogt (24). In a 100-ml round bottom flask with a thermometer well was placed 9.22 g (0.017 mole) trans-phenylbutadiene with a trace of hydroquinone. To this was added 4.06 g (0.072 mole) of redistilled acrolein (bp 52-53°). The mixture was put into a constant temperature bath at 100° with a small condenser attached to the flask. During the first hour, the pot temperature remained at 80° and some solid was observed forming in the condenser. Over a period of 2½ hours, the pot temperature rose to 95°. The mixture was removed from the oil bath and allowed to come to room temperature. It was then distilled through a 5-inch Vigreux column connected to a condenser with a cow attached. After a small forerun, two main

fractions were obtained; 5.16 g, bp 80-95° (0.08 mm) and 3.67 g, bp 95° (0.09 mm). Total yield 8.83 g (63%).

cis-3-Phenyl-4-(trans-styryl)cyclohexene (Wittig Synthesis).

This compound was prepared by the method of Kosolapoff (25). In a 50-ml round bottom flask, 8.3 g (0.05 mole) of triethyl phosphite and 6.3 g (0.05 mole) of benzyl chloride were combined and a reflux condenser attached. This mixture was heated gently and when the internal temperature reached 130°, ethyl chloride began to boil off. The mixture was refluxed for 1 hour and then set aside and allowed to cool.

In a 250 ml round bottom flask was placed 100 ml of dry dimethoxyethane (molecular sieves). To this was added 0.05 mole sodium hydride (2.1 g of 57% mineral oil dispersion). The slurry was cooled to 18° and the diethyl benzylphosphonate from above was added with stirring. This was followed by the dropwise addition of 8.83 g (0.045 mole) cis-3-phenyl-4-formylcyclohexene. After the addition was complete, a reflux condenser with a calcium chloride drying tube was attached to the flask and it was heated slowly with a mantle. Evolution of gas began at 25° and at 50°, a copious evolution of gas was observed. At 65°, a precipitate appeared. The mixture was heated to 85° and refluxed for 2 hours.

The mixture was then cooled to room temperature and a brown, gummy precipitate was observed. The mixture was taken up in a large excess of water and a brown oil came to the top. The aqueous portion was separated and washed with four 50-ml portions of ether. The ether extracts were combined with the oil and dried over anhydrous magnesium sulfate. The dried solution was filtered and stripped on the rotary

evaporater. It was then dried under vacuum to give 12.5 g (98%) of a brown oil. This undoubtedly was contaminated by the mineral oil from the sodium hydride dispersion.

After 2 weeks storage in the refrigerator, this oil solidified. A small amount was removed and recrystallized from methanol to give a yellowish solid mp 40.9-41.8°.

The rest of the sample was dissolved in hot methanol. The solution was cooled and Norite was added. It was then brought back to boiling in a water bath. At this point, the bottom of the flask broke and the methanol solution went into the water. The resulting mixture was then filtered and the Norite was washed with chloroform. The 2 phase mixture was then stripped of the chloroform and most of the methanol and extracted three times with a total of 350 ml pentane. The combined pentane extracts were dried over anhydrous magnesium sulfate, filtered and the pentane was stripped on the rotary evaporater. The brown oil remaining was dried under vacuum to yield 4.79 grams.

The remaining aqueous solution after pentane extractions was extracted three times with ether and the combined extracts were dried over anhydrous magnesium sulfate. The ether was stripped and the remaining oil was dried under vacuum to give 0.53 g of a brown oil.

The aqueous solution was extracted three more times with chloroform, the extracts were combined, dried over anhydrous magnesium sulfate, and the dried solution was stripped on the rotary evaporater. After drying under vacuum, there remained 0.51 g of a brown oil. The sample recovered from the pentane extractions (4.79 g) was recrystallized from methanol to yield 2.26 g, mp 40.1-41.1°. A small portion of this

sample was recrystallized twice from methanol; mp 41.2-42.2°; mixture mp with isomer A (mp 42.8-43°) from the dimerization of trans-phenylbutadiene, 42-42.9°. The NMR and IR spectra of this compound were identical to those of isomer A.

Preparation of trans-Phenylbutadiene Dimer Mixture (Undistilled) for Chromatography. In a 50-ml round bottom flask was placed 22 g (0.17 mole) trans-phenylbutadiene and 0.1 g hydroquinone. The flask was then placed in a constant temperature bath at 130° and the progress of the reaction followed by NMR. After 6 hours, the flask was removed from the oil bath and fitted with a 5-inch Vigreux column connected to a condenser. It was then returned to the oil bath and the unreacted trans-phenylbutadiene was vacuum distilled (approx 0.1 mm), with the oil bath never exceeding 100°. The flask was then removed and placed in the freezer for future analysis.

Thin Layer Chromatography on Silica Gel Impregnated with Silver Nitrate. A slurry was prepared by stirring 32.7 g of TLC silica gel (Merk, HF₂₅₄) into a solution of 3.63 g silver nitrate in 50-ml of water. Additional water was added to make the slurry thin enough for dipping 25 x 75 mm microscope slides. The plates were dipped and then air dried. Before use they were activated by heating at 110° for one hour. After developing, the plates were dried and then sprayed with a 0.1% solution of 2,7-dichlorofluorescein in a 50:50 mixture of ethanol: water. They were then observed under long wavelength ultraviolet light.

Tests with a series of different solvents showed chloroform to be the most effective in separating the dimerization mixture into different components.

The analysis was repeated using 5 x 20 cm plates to enhance the separation. To apply a layer of slurry to the plates, three to five plates were placed in a row with the edges in alignment. They were secured by taping both ends of the plates to a large glass supporting plate. The slurry was then poured over the first plate and drawn over the rest of the plates with a glass rod. The thickness of the film was dependent upon the layers of tape used. All of this work was done with both ends secured with two layers of tape.

Development of the dimerization mixture with chloroform on 5 x 20 cm plates, followed by spraying with 2,7-dichlorofluorescein and observation under U.V. light, showed six separate components, of which two were predominant. When the solid obtained from the previous work up of the dimerization (isomer A, mp 42.8-43°) was developed along with the crude dimerization mixture, it was found to have moved a distance identical to the lowest of the two predominant components. The R_f value for the upper component was 0.43. The R_f value for the lower component was 0.32. These values varied with each development.

Analysis of *trans*-Phenylbutadiene Dimer Mixture with Commercial Liquid Chromatograph. A sample of the crude product from the dimerization of *trans*-phenylbutadiene was sent to Waters Associates Inc., Framingham, Mass., for analysis on a Waters' ALC 202/401 dual detector liquid chromatograph. These analytical separations were done with a 2-foot by 2.3 mm I.D. column of Corasil II with a surface area of 15 m²/g. The mobile phase was isooctane: chloroform (3:1) with a flow rate of 0.71 ml/min and the chart speed was 12 in/hr. The solvents were redistilled in glass prior to use. The two detectors, an 8 μ l 10 mm

path length ultraviolet photometer set at 254 nm and a 10 μ l differential refractometer, were in series.

The sample was run at two different sample loads, 8 μ g (cf. Fig. 3a) and 100 μ g (cf. Fig. 3b) and separated into about eight peaks. At the 8 μ g sample load a small peak (1.47-ml) on the front of the major peak (1.96-ml) was observed. Separation of the two major isomers was not accomplished.

Column Chromatography on Silica Gel Impregnated with Silver Nitrate.

(Run #1). The adsorbent was prepared according to the method of DeVries (27). A 200 g portion of silica gel (Woelm, activity grade 1) was suspended in 400-ml of 50% silver nitrate solution. The mixture was heated at 100° for 30 minutes and then cooled. It was filtered through a buchner funnel and dried for 20 hours at 110°. Using this procedure, DeVries had obtained 0.3-0.4 g of silver nitrate per gram of adsorbent. The dried adsorbent was placed in a ball mill and ground for 2 hours. Sixty grams of this powder was then combined with 30 grams of a filter aid (Celite 535) and slurried with 350-ml of hexane. This was then boiled for 5 minutes and allowed to cool. Seventy-five grams of this slurry was placed in a column (19 mm ID x 60 cm) and protected from light by wrapping with aluminum foil. The crude dimerization mixture (628 mg) was dissolved in chloroform and applied to the column. It was then eluted with chloroform at a rate of 0.3-ml per minute and collected in 10-ml fractions. During the separation, a rupture developed in the column. The progress of the separation was followed by spotting silica gel coated sheets (Eastman Chromgram, Type K 301R) with each of the fractions and developing in an iodine chamber. Strong positive tests were

obtained for that portion coming out between 200 ml and 280 ml. TLC analysis showed no detectable separation of the two major components as they both were present in all of the 9 fractions.

The 9 fractions above were combined and the chloroform was stripped off on the rotary evaporater leaving 518 mg (83% recovery).

(Run #2). The recovered sample from above was reapplied to another column prepared in the same manner with the exception that the adsorbent was slurried with chloroform rather than hexane. This variation proved ineffectual in separating the components.

(Run #3). Eighty-two grams of silica gel (Woelm, activity grade 1) was slurried with a solution of silver nitrate (9.1 g) in 100 ml of water. It was put into a drying oven at 110° for 30 hours to drive off the water. It was then removed and allowed to stand in the hood at room temperature for 48 hours to partially deactivate before being ground for 25 minutes in the ball mill.

A column (19 mm ID x 60 cm) was prepared by inserting a glass wool plug and covering this with a layer of sand. It was then filled to two-thirds of its capacity with chloroform (spectral) and 70 g of the adsorbent was added slowly through a funnel. It was then covered with a layer of sand and wrapped with aluminum foil to protect it from the light. A sample of the crude dimerization mixture (509 mg) was dissolved in a minimum of chloroform and applied to the column. This was followed by elution with chloroform (spectra grade) at a rate of 0.5 ml per minute. As in Run 1, the progress of the separation was followed by spotting each 10 ml fraction on silica gel coated sheets and developing in an iodine chamber. That portion collected between

300-ml and 720-ml showed positive iodine tests. TLC studies showed that the majority of the two predominant components existed in the fractions between 420 ml and 670 ml, with the fractions 42 through 58 containing the fast moving component and fractions 63 through 67 containing the slower moving component. Fractions 59 through 62 were a mixture of the two. Fractions 42 through 58 were combined, stripped of the chloroform and dried under vacuum to yield 132 mg (26% recovery) of the faster moving component. Fractions 63 through 67 were also combined, stripped of the chloroform and dried under vacuum to yield 116 mg (23% recovery) of the slower moving component.

The slower moving component, which became a solid upon drying, was recrystallized from methanol to give 63 mg (54% recovery) mp 42-42.2°. IR analysis showed this to be identical to both isomer A (mp 42.8-43°) and the Wittig cis-isomer (mp 41.2-42.2°). TLC analysis of these three compounds showed them to have identical R_f values.

The faster moving component (isomer B) remained an oil after drying. It was dissolved in methanol, solidified in a dry ice bath and slowly brought to room temperature by letting the dry ice evaporate. Although a few crystals did remain, most of the sample was an oil. Numerous attempts to crystallize isomer B were unsuccessful. NMR of crude isomer B (CCl_4): δ 7.1 (doublet, C_6H_5), 5.9 (multiple peaks, $\text{CH} = \text{CH}$), 3.5 (broad multiplet, $\text{C}_6\text{H}_5\text{CH}$), 2.7 (broad multiplet, $\text{C}_6\text{H}_5\text{CH} = \text{CHCH}$), 2.2 (broad multiplet, allylic CH_2), 1.7 ppm (broad multiplet, CH_2). IR of crude isomer B (CCl_4): 6.1 (weak, $\text{C} = \text{C}$), 10.3 (trans- $\text{CH} = \text{CH}$), and 14.5 μ ($\text{C}_6\text{H}_5\text{R}$).

(Run #4). Five hundred grams of silica gel (Woelm, activity grade 1) was added to a solution of silver nitrate (55.5 g) in 250-ml of water and mixed well. This mixture was placed in the oven at 110° and dried for 24 hours and then removed to the hood for 36 hours to partially deactivate. It was noted from the very beginning that some reduction of the silver had occurred by the grey color of the mixture. The mixture was ground in the ball mill for 90 minutes just before use. Three hundred and ten grams of this silver nitrate impregnated silica gel was used to pack a column (3-cm OD x 135-cm) following the same procedure used in Run 3. A portion of the crude dimer (2.71 g) was dissolved in a minimum of chloroform and placed on the column. This was eluted with chloroform at a rate of 1-ml per minute and collected in 20-ml fractions. That portion collected between 220-ml and 580-ml showed positive iodine vapor tests. TLC analysis showed no effective separation of the two major components which came out between 300-ml and 580-ml. Earlier fractions contained the fastest moving impurities. That portion containing the two major components was stripped on the rotary evaporater to yield 2.03 g.

(Run #5). A new column was prepared using silver nitrate impregnated silica gel made following the same procedure above (300 g silica gel-33.3 g silver nitrate). To this column 1.04 g of the sample recovered above was applied. This was eluted with chloroform at a rate of 0.5-ml per minute and collected in 10-ml fractions. As previously experienced, separation was not achieved.

Dry Column Chromatography on Silica Gel Impregnated with Silver Nitrate. (Run #1). Forty grams of silica gel (Woelm dry-column grade,

0.5% inorganic fluorescent indicator) was slurried with a solution of silver nitrate (4.4 g) in a 50-ml of water. This was then placed in an oven at 110° for 24 hours to drive the water off. A nylon column (1 in. flat width) was packed, first by inserting a glass wool plug and then punching holes in the bottom with a hypodermic needle. It was then filled with the dried silver nitrate impregnated silica gel. The crude dimerization mixture (259-mg) was dissolved in a minimum of chloroform and applied to the column (sand covered the silica gel). It was eluted with chloroform until the solvent reached the bottom of the column. The column was then placed in the hood and slit to expose it for drying. After drying for 24 hours, the column was sprayed with 2,7-dichlorofluorescein and viewed under long wave ultraviolet light. Fluorescence was observed 1 in. from the top of the column in a single band. There was no separation of the crude mixture. It appeared that the adsorbent was too active and, therefore, it was repeated using a less active adsorbent.

(Run #2).. One hundred grams of silica gel (Woelm dry column grade, 0.5% inorganic fluorescent indicator) was slurried with an aqueous solution of silver nitrate (11.1 g) and put in the oven at 110° for 24 hours to drive off the water. After drying, it was removed and placed in the hood for 48 hours to decrease its activity. A nylon column (1 in. flat width) was prepared as in Run 1, using 70 g of the silver nitrate impregnated silica gel. The crude dimerization mixture (277-mg) was dissolved in a minimum of chloroform and applied to the column. It was eluted with chloroform and when the solvent reached the bottom of the column it was allowed to drain into

a flask. In this way, a three-fold excess of chloroform was used to bring the sample further down the column and enhance the separation. After elution, it was removed to the hood, slit to expose the adsorbent for drying, and left over night. The dried column was then sprayed with 2,7-dichlorofluorescein and exposed to long wave ultraviolet light. Fluorescence was observed in a band approximately 4 in. from the top of the column but there was no separation of components.

Attempted Preparative Scale Layer Chromatography on Silica Gel Impregnated with Silver Nitrate. A 20-cm x 20-cm plate was bordered with labeling tape rising 5-mm from the surface. A slurry of 10% silver nitrate impregnated silica gel (E. Merk, PF₂₅₄) was poured over the plate and a smooth surface was obtained by picking the plate up and dropping it a number of times from a height of 2-3 in. The plate was set in the hood and when the slurry had dried sufficiently, the tape was removed. It was placed in the oven at 100° for 2 hours to activate the adsorbent. The plate was removed from the oven and cooled. It was prepared for sample application by making a small groove 2-cm from the bottom across the width of the plate. A sample of the crude dimerization mixture (891-mg) was dissolved in a minimum of chloroform and applied along this groove. It was placed in a developing tank and developed twice with chloroform. Upon drying and spraying with indicator, ultraviolet light showed no separation of the two main components. Approximate R_f value was 0.33.

cis-3-Phenyl-4-carboxycyclohexene. This compound was prepared according to the method of Alder, Vagt and Vogt (24). In a 50-ml erlenmeyer flask were placed 5.0 g (0.038 mole) of trans-phenylbutadiene and 2.94 g (0.041 mole) of acrylic acid. To this mixture was

added a trace of hydroquinone and the flask was put into a constant temperature bath at 40°. After 5 days, crystallization was observed. The flask was removed from the bath and the sides and bottom were scratched with a glass stirring rod to induce further crystallization. This resulted in almost complete crystallization and the mixture was left to stand at room temperature for 7 days. It was then stored in the freezer for 3 weeks until it could be worked up.

The acid was recrystallized from an ethylacetate-petroleum ether mixture. The resulting crystals were dried under vacuum to yield 3.53 g (46%), m.p. 115.5-118.5° (lit. (24) m.p. 122°).

Oxidation of trans-Phenylbutadiene Dimer Mixture. A sample of the distilled dimerization mixture (7.5 g, bp 158-160°(0.08-mm)) was dissolved in 200-ml of acetone and to this was added 2 g of sodium bicarbonate. The solution was cooled to 0° in an ice bath and potassium permanganate (35 g, 0.22 mole) was added slowly with magnetic stirring. After 4 hours stirring at 0°, it was removed and a spot test was made on filter paper to see if any permanganate remained. The test was positive so methanol was added to reduce the excess permanganate. When a positive spot test was observed after the addition of 55-ml of methanol, the solution was returned to the ice bath and left overnight. After 15 hours a spot test revealed the absence of any permanganate. The mixture was then brought to room temperature and the liquid was filtered off the muddy manganese dioxide precipitate. The manganese dioxide was washed several times with water and then it was removed from the filter, heated to 70° in 200-ml of water and filtered again. The combined filtrates were stripped to

half their original volume on the rotary evaporater where a gummy, yellow precipitate was observed starting to come out of solution. This mixture was acidified with dilute hydrochloric acid until a white precipitate appeared. This was filtered and the filtrate was acidified again resulting in more precipitation. This also was filtered and combined with the previously obtained solid to yield 2.75 g, m.p. 100-130°.

The remaining filtrate was acidified again but no further precipitation was observed. It was returned to the rotary evaporater and stripped until another white precipitate came out of solution. This was filtered and dried to yield 2.05 g, m.p. 100-180°d.

The filtrate remaining was stripped to dryness on the rotary evaporater. There remained a solid-oil mixture which was washed with acetone and filtered with suction. The filtrate was stripped on the rotary evaporater and dried under vacuum to yield 4.77 g of a yellow oil.

The yellow oil was washed several times with chloroform, leaving behind a brownish solid (2.24 g, m.p. 130-160°d). This material was recrystallized from an excess of acetonitrile to yield 0.58 g (26% recovery) of a white solid melting at 183-186°d. A portion of this sample was recrystallized 3 times from acetonitrile to give a white solid m.p. 187°.

A 1.63 g portion of the sample melting at 100-180° was dissolved in acetone and filtered with suction to remove any insoluble inorganic salts. The filtrate was stripped on the rotary evaporater and dried under vacuum. It was then recrystallized from an excess

of hot acetonitrile and filtered with suction. This sample was then dried under vacuum to yield 0.39 g (24% recovery) of a white solid m.p. 162-169°. A portion of this sample was recrystallized four times from acetonitrile to give a white solid m.p. 180-182°d.

Oxidation of *cis*-3-Phenyl-4-(*trans*-styryl)cyclohexene. A portion of *cis*-3-phenyl-4-(*trans*-styryl)cyclohexene (0.9 g, 0.003 mole) was dissolved in 25-ml of acetone and a trace of sodium bicarbonate was added. This mixture was cooled to 0° in an ice bath and potassium permanganate (4.1 g, 0.0026 mole) was added slowly with magnetic stirring. The mixture was allowed to stir at 0° for 13 hours with occasional small additions of water not totaling over 10-ml. It was then brought to room temperature and 2-ml of methanol was added. It was then warmed in a water bath for 20 minutes. A spot test revealed the absence of any unreacted permanganate.

The mixture was filtered with suction and the manganese dioxide filter cake was washed 4 times with boiling water. The filter cake was mixed with water, boiled, and then filtered again. The combined filtrates were stripped on the rotary evaporater to a volume equal to the original reaction mixture. The solution was acidified with dilute hydrochloric acid and the resulting precipitate was filtered with suction and dried to yield a white solid (0.239 g, m.p. 118-125° with some solid remaining at 220°).

The remaining filtrate was stripped to 1/3 its original volume and filtered with suction to yield a grey solid (0.103 g, m.p. 110-120° with some solid remaining at 220°).

The small amount of filtrate left was stripped to dryness leaving a brown solid. This was washed several times with boiling ace-

tonitrile. The combined washings were stripped until crystals appeared. The acetonitrile solution was then warmed until the crystals went back into solution. The solution was cooled to room temperature, stored at 0° for 24 hours, and filtered with suction to yield 0.105 g (m.p. 176-180°, with some solid remaining at 220°). A second crop yielded 0.118 g and the remaining filtrate was stripped of acetonitrile and dried under vacuum to yield 0.476 g of a brown oil.

A portion of the first crop (44-mg) was refluxed in a minimum of acetonitrile and the insoluble impurities were filtered. The filtrate was cooled in ice and filtered with suction to yield 11-mg (m.p. 165.5-167° d).

Oxidation of *cis*-3-Phenyl-4-carboxycyclohexene. A sample of *cis*-3-phenyl-4-carboxycyclohexene (1.0 g, 0.0050 mole) was dissolved in 40-ml of acetone and sodium bicarbonate (0.5 g) was added. This mixture was placed in an ice bath and stirred with magnetic stirring. Potassium permanganate (3.5 g, 0.022 mole) was slowly added and the mixture was left in the ice bath with the occasional addition of small portions of water. After 13 hours, 4-ml of methanol was added and a spot test revealed the absence of any permanganate. The mixture was brought to room temperature, filtered with suction, and the manganese dioxide filter cake was washed with hot water. The filter cake was boiled in water and filtered. The combined filtrates, after first being acidified with concentrated hydrochloric acid, were stripped on the rotary evaporater to remove most of the water and reduce the volume to that of the original reaction mixture. The remaining mixture was cooled to 0° and filtered with suction. The gummy solid obtained

was recrystallized from acetonitrile to yield 17-mg (m.p. 163-170°d, with some solid remaining at 220°).

A second crop yielded 46-mg (m.p. 160-170°d, with some solid remaining at 220°).

These two crops were combined and recrystallized from acetonitrile to yield 16-mg (m.p. 172.5-175°d).

The filtrate remaining from the filtration of the acidified oxidation mixture was stripped to dryness on the rotary evaporater. The residue left was washed several times with boiling acetonitrile and these washings were combined with the mother liquor from the above recrystallization. This solution was stripped to one-half of its original volume and cooled to 0°. The resulting crystals weighed 46-mg (m.p. 161-164°d).

A second crop was obtained weighing 15-mg and the filtrate remaining was vacuum stripped to yield 818-mg of a brown oil.

The melting points of the isolated solids varied with the rate the temperature was elevated. Reproduction of melting points was very difficult.

Thermal Stability of *cis*-3-Phenyl-4-(*trans*-styryl)cyclohexene.

A sample of *cis*-3-phenyl-4-(*trans*-styryl)cyclohexene (33-mg, m.p. 42.8-43°) was placed in a glass tube and put into a constant temperature bath at 130° for 6 hours. TLC analysis showed no change in the compound and the IR spectrum was identical to the original *cis*-isomer. The sample, which was a yellow oil after heating, solidified again at room temperature (m.p. 40-42°).

Another sample of the *cis*-3-phenyl-4-(*trans*-styryl)cyclohexene (26-mg) was placed in a glass tube and put into a constant temperature

bath at 200° for 1 hour. TLC analysis showed no change. When a pure sample of the cis-isomer was analyzed along with it, identical R_f values were obtained. An IR spectrum showed it to be identical to the pure cis-isomer.

BIBLIOGRAPHY

1. (a) O. Diels and K. Alder, Liebigs Ann. Chem., 460, 98 (1928).
(b) For reviews see M.C. Kloetzel, Org. Reactions, 4, 1 (1948)
and J.G. Martin and R.K. Hill, Chem. Rev. 61, 537 (1961).
2. J. Gresser, A. Rajbenbach and M. Szwarc, J. Am. Chem. Soc., 82,
5820 (1960).
3. (a) I.I. Guseninov and G.S. Vasil'ev, Russ. Chem. Rev., 32, 20
(1963); (b) D. Craig, J. Am. Chem. Soc., 72, 1678 (1950).
4. J. Hammer: 1-4 Cycloaddition Reactions, Academic Press, New York,
N.Y., 1967.
5. I.N. Nazarov, N.V. Kužnetsov and A.I. Kuznetsova, J. Gen. Chem.
(USSR) 25, 291 (1955) (Engl. translation).
6. K. Alder and G. Stein, Angew. Chem., 50, 510 (1937).
7. K. Alder and M. Schumacher, Liebigs Ann. Chem., 571, 87 (1951).
8. J.B. Hendrickson, J. Am. Chem. Soc., 84, 653 (1962).
9. L.K. Montgomery, K. Schueller and P.D. Bartlett, J. Am. Chem.
Soc., 86, 622 (1964); P.D. Bartlett and L.K. Montgomery, ibid.
86, 628 (1964).
10. H. Stockmann, J. Org. Chem., 26, 2025 (1961).
11. S.J. Cristol, W.K. Seifert and S.B. Soloway, J. Am. Chem. Soc.,
82, 2351 (1960).
12. K.B. Wiberg and W.J. Bartley, ibid., 6375 (1960).
13. R.B. Woodward and M. Baer, ibid., 70, 1161 (1948).
14. J.A. Berson, Z. Hamlet and W.A. Mueller, ibid., 84, 297 (1962).
15. K. Alder and E. Ruden, Chem. Ber., 74, 920 (1941).
16. R.B. Woodward and T.J. Katz, Tetrahedron, 5, 70 (1959).
17. E.G. Foster, A.C. Cope and F. Daniels, J. Am. Chem. Soc., 69, 1893
(1947).

18. R.C. Cookson, J. Hudec and R.O. Williams, Tetrahedron Lett., 1960, 29.
19. R.P. Lutz and J.D. Roberts, J. Am. Chem. Soc., 83, 2198 (1961).
20. K. Alder, J. Haydn and W. Vogt, Chem. Ber., 86, 1302 (1953).
21. O. Grummitt and E.I. Becker, Org. Synthesis, 30, 75 (1950).
22. H.L. Durkin, Ph.D. Thesis, Case Western Reserve University, Cleveland, Ohio (1968).
23. C.G. Overberger, D. Tanner and E.M. Pearce, J. Am. Chem. Soc., 80, 4566 (1958).
24. K. Alder, H. Vagt and W. Vogt, Liebigs Ann. Chem., 565, 135 (1949).
25. G.M. Kosolapoff, Org. Reactions, 6, 276 (1951).
26. A. Maercker, Org. Reactions, 14, 270 (1965).
27. B. DeVries, J. Am. Oil Chem. Soc., 40, 184 (1963).