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PROBLEMS IN KINETICS AND CONFORMATIONAL
ANALYSIS.

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PROBLEMS IN KINETICS AND CONFORMATIONAL ANALYSIS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of the Ohio State University

By

John David Rawn, B.S., M.Sc.

The Ohio State University
1971

Approved by

[Signature]
Adviser
Department of Chemistry
PLEASE NOTE:

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DEDICATION

To Margie

Et lux in tenebris lucet
ACKNOWLEDGMENT

The author wishes to express his gratitude to Dr. Robert Ouellette for his patience during the course of this work. Few indeed are the men who combine his skill in research with superlative teaching ability.
VITA

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CHAPTER I

CONFORMATIONAL PREFERENCE OF THE METHYL GROUP IN BICYCLIC HYDROCARBONS

Introduction

Conformational analysis of cyclohexane and its derivatives is a well documented subject. However, data on bicyclic systems which incorporate the cyclohexane ring in one form or another is somewhat less abundant. The systems to be discussed here are bicyclo[2.2.1]heptane, bicyclo[3.2.1]octane, and bicyclo[2.2.2]octane, whose skeletons provide interesting extensions of the cyclohexane molecule.

Comparison of the Bicyclic and Cyclohexane Systems

Cyclohexane is known to exist in two readily interconvertible forms: the so-called chair and boat conformations. The difference in energy between the two conformations is approximately 5.3 Kcal/mole, the chair form being the more stable. The chair forms are converted into


each other by internal rotation. In the process of chair conversion all equatorial bonds become axial and all axial bonds become equatorial. At room temperature chair inversion occurs very rapidly. A monosubstituted cyclohexane may exist either in the chair conformation having the substituent axial, or in the one having it equatorial. The barrier for monosubstituted cyclohexanes is of the same order of magnitude as in cyclohexane itself. Therefore the rate of interconversion is still very rapid. However, by sufficiently cooling a monosubstituted cyclohexane the rate of interconversion is slowed to such an extent that the equatorial and axial hydrogens may be clearly differentiated by nuclear magnetic resonance experiments. For a substituent larger than hydrogen the distance from the C-1 axial position to the syn-axial hydrogens at C-3 and C-5 is less than the distance from the C-1 equatorial hydrogens at C-2 and C-6. (For example, if the axial substituent is carbon the former distance is 2.55 Å and the latter is 2.8 Å.) Hence an axial substituent will experience a larger van der Waals repulsion from the syn-axial 3 and 5 hydrogens than an equatorial substituent will experience from the equatorial protons at C-2 and C-6. Thus, a monosubstituted cyclohexane is more stable in the conformation in which the substituent is equatorial than in the conformation in which the substituent is axial. The equilibrium constant, K, for axial-equatorial


interconversion will be greater than one (Fig. 1).

![Diagram of chair-chair interconversion of a monosubstituted cyclohexane]

Fig. 1 Chair-chair Interconversion of a Monosubstituted Cyclohexane

The interaction between the axial substituent and the syn-axial hydrogens in cyclohexane derivatives is the same type as that encountered in the gauche conformation of butane. For example, in methylcyclohexane there are two syn-axial methyl-hydrogen interactions. Therefore the enthalpy difference between the equatorial and axial conformations should be twice the gauche-anti enthalpy difference in butane (0.8-0.9 Kcal/mole). This is in good agreement with the experimentally observed values.

The negative free energy difference, \( \Delta G_X^0 \), corresponding to the conformational equilibrium constants for a large number of substituents have been determined. The free energy differences relevant to this discussion are given in Table 1.

The conformational free energy values obtained in the series of monosubstituted cyclohexanes all assume that the cyclohexane ring exists in an "ideal" chair form. However, the ring in the case of poly-

---

Table 1. Conformational Free Energies of Substituents in Cyclohexane

<table>
<thead>
<tr>
<th>Group</th>
<th>$\Delta G_X^o$ (Kcal/mole)</th>
<th>Temp $^\circ$ C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$CH$_3$ a</td>
<td>1.2</td>
<td>25</td>
</tr>
<tr>
<td>NO$_2$ a</td>
<td>1.1</td>
<td>100</td>
</tr>
<tr>
<td>CH$_3$ b</td>
<td>1.75-1.95</td>
<td>25-300</td>
</tr>
<tr>
<td>CN c</td>
<td>0.1</td>
<td>25</td>
</tr>
<tr>
<td>OH b</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

b. see ref. 3, pp. 441-442.
c. see ref. 3, p. 44.

Substituted cyclohexanes may undergo various distortions from ideal chair or boat forms. It thus seems likely that even monosubstituted cyclohexanes may be distorted from ideal chair forms particularly when the substituent in question has a large steric bulk. If this is indeed the case, then a more rigid skeleton where the magnitude of such distortions should be smaller might provide a more suitable model for the evaluation of non-bonded interactions. One such system is bicyclo[2.2.1]heptane.

In contrast to cyclohexane, the bicyclo[2.2.1]heptane system is relatively rigid. This rigidity and the concomitant limitations on

the orientation which functional groups may assume provide one
with a useful model for the evaluation of non-bonded interactions.
Variation of the bicyclic skeleton should yield non-bonded inter­
actions directly as a function of distance. The following consider­
atations are qualitative in nature. However the arguments and general
conclusions are unaltered by more detailed calculations (vide infra)
and hence provide one with a convenient method of analysis.

Examination of models of bicyclo[2.2.1]heptane, (Fig. 2.),

![Fig. 2. Bicyclo[2.2.1]heptane](image)

indicates that a substituent on the endo-2 position should experience
steric repulsion from the endo-6 position. As a first approximation,
this interaction should be about one-half that of an axial substituent
in cyclohexane since this interaction is also similar to that
encountered in gauche-butane. However, the axial substituents in
cyclohexane are parallel to each other (if one makes the peraaps
unjustified assumption that the chair is ideal) whereas the endo
substituents in bicyclo[2.2.1]heptane are inclined somewhat towards
each other due to the strain introduced by the 7-methylene bridge. This
suggests that an endo 2,6 interaction in bicyclo[2.2.1]heptane is
somewhat greater than the corresponding 1,3 diaxial interaction in

Soc., 1957, 2909.
cyclohexane.

A substituent in the 2-exo position of bicyclo[2.2.1]heptane encounters steric repulsion from the 7-syn-hydrogen. This interaction should be less than a 1,3 diaxial interaction. The distance from a 2-exo-methyl to the 7-syn-hydrogen is 2.7 Å. The distance from a 2-endo-methyl carbon to the 6-endo-hydrogen is 2.5 Å. The angle between the plane defined by the substituent carbon, C-2, and C-1 with the plane defined by C-2, C-1, and C-7 is approximately 80°. Thus the repulsion from the 7-syn-hydrogen should be less than gauche-butane interaction where the dihedral angle is less than 60°.

The structure of the parent hydrocarbon, bicyclo[2.2.1]heptane, has been determined by gas phase electron diffraction. This data is listed in Table 2.

Table 2. Bond Lengths and Bond Angles in Bicyclo[2.2.1]heptane

<table>
<thead>
<tr>
<th>Bond Length</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-C2</td>
<td>1.53 ± 0.01 Å</td>
</tr>
<tr>
<td>C2-C3</td>
<td>1.53 ± 0.02 Å</td>
</tr>
<tr>
<td>C1-C7</td>
<td>1.56 ± 0.01 Å</td>
</tr>
<tr>
<td>C1-C7-C4</td>
<td>93.2 ± 1.5°</td>
</tr>
<tr>
<td>C(3 sp-H)</td>
<td>113.0 ± 1.5°</td>
</tr>
<tr>
<td>C(sp3)-H (Av)</td>
<td>1.11 ± 0.01 Å</td>
</tr>
</tbody>
</table>

a. θ is the angle between the planes defined by C-1, C-2, C-3, C-4 and C-1, C-4, C-5, C-6.

In addition to the aforementioned interactions two more must be considered. The first is the interaction of the 2-endo substituent with the 5-endo-hydrogen. This interaction should be intermediate between the 2,6-endo interaction and that of the 7-syn-hydrogen, 2-exo substituent. The second interaction is between the bridgehead hydrogen and the 2-substituent. For an endo substituent the bridgehead hydrogen is at a dihedral angle of $85^\circ$ and for an exo substituent the dihedral angle is $35^\circ$. Hence, the result of this interaction is to favor the endo substituent over the exo by a small amount.

Since the sum of the interactions for the endo substituent appears to be greater than the sum of the interactions experienced by the exo substituent, one qualitatively expects the exo epimer to be favored. Hence the exo/endo equilibrium constant should be greater than unity with its magnitude dependent upon the steric bulk of the substituent.

A substituent in the 2-exo position of bicyclo[2.2.1]hept-5-ene experiences the same interactions as it does in the saturated analog. However, a C-2-endo substituent no longer encounters repulsion due to the endo-5 and -6 hydrogens. The C-5 vinyl hydrogen is $3.2\ A$ from a 2-endo group and should therefore exert little steric influence. The $\pi$-electron cloud which is perpendicular to the plane defined by C-1, C-4, C-5 and C-6 and which extends below it causes an interaction which is dependent upon the electrostatic properties of the substituent at C-2.
The conformational preferences of several groups have been determined in the norbornane system. Cope has equilibrated exo and endo -5-carbomethoxybicyclo[2.2.1]hept-2-ene in methanolic sodium methoxide. The equilibrium constant was determined by gas-liquid partition chromatography (glpc). The exo/endo ratio is approximately 0.94 and is independent of temperature. The 2-carbomethoxybicyclo[2.2.1]heptane was also equilibrated and the exo/endo ratio found to be 2.35, independent of temperature. Berson determined the optical rotation of a mixture of exo and endo compounds. The exo/endo ratio was found to be 1.4.

The equilibrium constant for the unsaturated carbomethoxy compound was also determined by saponification of the equilibrated esters followed by iodolactonization. A value of 1.15 for the exo/endo ratio was found in a gravimetric determination of the iodolactone.

The equilibrium constant for the exo and endo-5-acetylbicyclo-[2.2.1]hept-2-ene was obtained in methanolic sodium methoxide. An exo/endo ratio of 2.21 was obtained by glpc analysis of the equilibrium mixture. Similarly, an exo/endo ratio of 3.25 was obtained for the acetylbicyclo[2.2.1]heptane.


Ouellette and Booth have obtained the equilibrium constant of exo and endo-5-carbomethoxybicyclo[2.2.1]hept-2-ene and found an exo/endo ratio of 1.09 (at 100°C). The same authors equilibrated exo and endo-5-nitrobicyclo[2.2.1]hept-2-ene and found an exo/endo ratio of 1.81 (also at 100°C). In the case of exo and endo-5-cyano-bicyclo[2.2.1]hept-2-ene they found an exo/endo ratio of 0.81. The equilibrium constant for 2-nitrobicyclo[2.2.1]heptane was determined in sodium methoxide and the exo/endo ratio found to be 6.5. The equilibrium constant for 2-methylbicyclo[2.2.1]heptane was determined in the gas phase over a palladium catalyst and the exo/endo ratio found to be 2.2. The subject of the equilibration of bicyclic alcohols and the problems associated with such studies has been discussed by Wilcox.

Most other studies in which equilibration of bicyclic compounds has been employed have not been for the purpose of determining thermodynamic parameters. The primary objective has been either to enrich a reaction mixture in one epimer or to observe an isomerization of interest. It is not likely that the isomer ratios reported are true equilibrium values. For example, Roberts treated

Table 3. Equilibrium Constants for Bicyclic Compounds

<table>
<thead>
<tr>
<th>Compound</th>
<th>T (°C)</th>
<th>$K_{exo/endo}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-carbomethoxybicyclo[2.2.1]hept-2-ene</td>
<td>100</td>
<td>1.09</td>
</tr>
<tr>
<td>5-nitrobicyclo[2.2.1]hept-2-ene</td>
<td>100</td>
<td>1.81</td>
</tr>
<tr>
<td>2-nitrobicyclo[2.2.1]heptane</td>
<td>100</td>
<td>6.50</td>
</tr>
<tr>
<td>2-carbomethoxybicyclo[2.2.1]heptane</td>
<td>100</td>
<td>2.35</td>
</tr>
<tr>
<td>2-methylbicyclo[2.2.1]heptane</td>
<td>300</td>
<td>2.20</td>
</tr>
<tr>
<td>bicyclo[2.2.1]heptane-2-ol</td>
<td>100</td>
<td>4.0</td>
</tr>
</tbody>
</table>

a. Ref. 15  
b. Ref. 16  
c. Ref. 17

Table 4. Thermodynamic Parameters of Bicyclic Compounds

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Delta G^o$ (Kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-carbomethoxybicyclo[2.2.1]hept-2-ene</td>
<td>0.05</td>
</tr>
<tr>
<td>5-nitrobicyclo[2.2.1]hept-2-ene</td>
<td>0.41</td>
</tr>
<tr>
<td>2-nitrobicyclo[2.2.1]heptane</td>
<td>1.38</td>
</tr>
<tr>
<td>2-methylbicyclo[2.2.1]heptane</td>
<td>0.89</td>
</tr>
<tr>
<td>2-carbomethoxybicyclo[2.2.1]heptane</td>
<td>0.63</td>
</tr>
<tr>
<td>bicyclo[2.2.1]heptane-2-ol</td>
<td>1.02</td>
</tr>
</tbody>
</table>
bicyclo[2.2.1]hept-2-ene-5-ols with sodium and fluorenone in refluxing toluene and obtained 14% of the exo isomer in the recovered product. The isomerization of 2,3-dimethylbicyclo[2.2.1]heptane over a palladium catalyst in the gas phase has been reported. No attempt was made to obtain equilibrium constants in the resulting mixture. The results of studies in the bicyclo[2.2.1]heptane system are summarized in Tables 3 and 4.

The Bicyclo[3.2.1]octane System

The bicyclo[3.2.1]octane molecule (Fig. 3) represents a further extension of the cyclohexane system. This molecule is unique in that

![Bicyclo[3.2.1]octane](image)

Fig. 3. Bicyclo[3.2.1]octane

it incorporates a cyclohexane ring, a cycloheptane ring, and a cyclopentane ring system. Due to the presence of a three carbon bridging unit the bicyclo[3.2.1]octane molecule is more flexible than the bicyclo[2.2.1]heptane molecule discussed above. This


flexibility, apparent in molecular models, involves a change in conformation at carbon atoms 2, 3 and 4. The type of ring conversion possible is analogous to the chair-boat interconversion in cyclohexane. This type of ring conversion forms the less energetically favored boat conformation of the cyclohexane ring, but the more favored chair conformation of the cycloheptane moiety (Fig. 4).

Fig. 4. "Chair-Boat" Interconversion in Bicyclo[3.2.1]octane

The energy barriers for the interconversion of the chair and boat forms of cyclohexane and cycloheptane as a function of a pseudorotation coordinate have been calculated. For the ideal chair-boat interconversion the energies of activation are 12.7 and 8.5 Kcal/mole for cyclohexane and cycloheptane respectively. On the basis of the facts, and neglecting any additional hindrance caused by the ethylene bridge, the equilibrium represented in Figure 4 should be rapid at ambient temperatures. However, the barriers do not indicate the populations of the two conformers since the former quantity is a kinetic parameter and the latter a thermodynamic function. Nevertheless a qualitative estimation of the relative

energies of the two conformers of bicyclo[3.2.1]octane can be made
by considering the contributions of the six and seven membered
rings incorporated in the molecule, neglecting again the influence
of the ethylene bridge. The energy difference between the chair and
boat forms of cyclohexane and cycloheptane are 6.9 and 2.5 Kcal/
mole respectively. Therefore the conformation depicted on the
left in Figure 4 should be more stable than the alternate conformer
by 4.4 Kcal/mole. This conclusion is consistent with an earlier
contention that the bicyclo[3.2.1]octane system is fixed in the
chair cyclohexane conformation. This conclusion is based on the
fact that the infrared carbonyl absorption of bicyclo[3.2.1]octan-
2-one at 1715 cm⁻¹ is characteristic of a six membered ring.
However, it is not clear that this is a valid criterion for
ascertaining the conformation of the ketone, to say nothing of its
temperity in predicting the conformation of the parent hydrocarbon
which has no sp² hybridized atoms.

Numerical calculations utilizing computer techniques support
the "chair" conformation as the one having the lowest energy.
Table 5 records the bond lengths and bond angles calculated for the
chair conformation. It has more recently been calculated that the

89, 582 (1967).
23. N. A. Allinger, M. T. Tribble, M. A. Miller, and D. H.
Table 5. Bond Lengths and Bond Angles in Bicyclo[3.2.1]octane

<table>
<thead>
<tr>
<th>Bond Lengths (Å)</th>
<th>Bond Angles (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁-C₂</td>
<td>1.536</td>
</tr>
<tr>
<td>C₂-C₃</td>
<td>1.550</td>
</tr>
<tr>
<td>C₁-C₇</td>
<td>1.543</td>
</tr>
<tr>
<td>C₆-C₇</td>
<td>1.548</td>
</tr>
<tr>
<td>C₁-C₈</td>
<td>1.530</td>
</tr>
<tr>
<td>C₃-C₈</td>
<td>2.939</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

conformer of bicyclo[3.2.1]octane having the chair form of the cyclohexane ring is 6.75 Kcal/mole more stable than the conformer containing the boat form. The situation is thus reminiscent of cyclohexane where chair-boat interconversion is also very rapid, but where the equilibrium lies overwhelmingly on the side of the chair conformation.

There are five nonequivalent carbon atoms in the bicyclo[3.2.1]-octane system, four of which may possess conformational isomers (C-7, C-3, C-6, and C-8). Isomerization at the 2 and 3 positions is investigated in this research.
The Bicyclo[2.2.2]octane System

The bicyclo[2.2.2]octane molecule (Fig. 5) is another system which might be expected to yield information on the magnitude of nonbonded interactions. Since this molecule has a high degree of symmetry, there is no exo or endo type of isomerization, and since the molecule is rigid no chair-boat isomerism is possible either. Hence investigation of the conformational preference of a single substituent in the parent hydrocarbon is not possible. One must either observe cis-trans isomerization of two substituents or else modify the parent hydrocarbon to make the exo and endo positions nonequivalent. Such investigations have been carried out on the 2-substituted bicyclo[2.2.2]oct-5-ene system. The results of these studies give the following order of conformational preference: nitro > carbomethoxy > acetyl > cyano; the free energy differences are 0.58, 0.55, 0.54, and 0.38 Kcal/mole respectively.


Calculations of Conformational Energies

In recent years calculations of relative conformational energies of a large number of molecules have been made by biochemists and organic chemists. Among the molecules whose energies have been calculated are those of interest in this study. Namely, bicyclo[2.2.1]heptane, bicyclo[3.2.1]octane, and bicyclo[2.2.2]octane. One parameter of particular interest which is common to all of these molecules is the strain energy. The strain energy has been defined as the energy by which the molecule in question differs from that of an n-alkane having the same molecular formula which is taken to be unstrained. (It is of interest to note that according to this definition cyclohexane is not strain free.

but has a strain energy of 1.75 Kcal/mole.)

The strain energies of bicyclic ring systems investigated in this study have been calculated. The results are summarized in Table 7. The calculated strain energies of the bicyclo[x.y.z]octanes are in agreement with experimentally determined results obtained by acid catalyzed isomerization of the parent hydrocarbon. The experimental facts are listed in Table 7.

The conformation of the bicyclo[3.2.1]octane molecule has been previously discussed and the conclusion reached that the "chair" form predominates. In the case of bicyclo[2.2.2]octane no such chair-boat interconversions are possible. Recent calculations indicate that bicyclo[2.2.2]octane exists essentially in the totally

Table 6. Calculated Strain Energies of Bicyclic Hydrocarbons

<table>
<thead>
<tr>
<th>Compound</th>
<th>Strain Energy (Kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bicyclo[2.2.1]heptane</td>
<td>17.95</td>
</tr>
<tr>
<td>bicyclo[2.2.2]octane</td>
<td>11.69</td>
</tr>
<tr>
<td>bicyclo[3.2.1]octane</td>
<td>8.50</td>
</tr>
</tbody>
</table>

Table 7. Relative Enthalpies of Bicyclo[x.y.z]octanes

<table>
<thead>
<tr>
<th>Compound</th>
<th>Relative Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>bicyclo[3.2.1]octane</td>
<td>0.0</td>
</tr>
<tr>
<td>bicyclo[2.2.2]octane</td>
<td>0.06</td>
</tr>
<tr>
<td>bicyclo[3.3.0]octane</td>
<td>1.89</td>
</tr>
</tbody>
</table>

symmetrical state with a difference in energy between the eclipsed and twist forms of no more than 0.1 Kcal/mole. This implies that eclipsed substituents will be subjected to large van der Waals repulsions and are not likely to be nearly as stable as trans substituents.

The procedure to be used in the calculation of equilibrium constants will be to calculate the strain energy for each epimer and then compare their energies. The difference in energy between two epimers is taken to be the enthalpy difference between epimers in the equilibration process. The accuracy of the calculations may be ascertained from the degree to which the calculated values correspond to the experimentally determined enthalpy differences.


Discussion
Calculation of Conformational Energies

The model upon which the calculation of the energies of the bicyclic molecules of interest in this study is based upon that of the "strained molecule". "Strain-free" molecules have structures and energies taken to be "normal". Compounds whose structures differ significantly from these values are observed to have higher energies and are said to be "strained". Molecular geometries may be defined by four types of structural parameters, viz., bond lengths $r$, bond angles $\theta$, torsion angles $\phi$, and nonbonded distances $d$. Strain energy, $E_s$, may be thought of as the sum of these four components.

$$E_s = E_r(r) + E_y(\theta) + E_\phi(\phi) + E_{nb}(d)$$

Here $E_y$ and $E_r$, respectively, the total energies of bond-angle ("Baeyer strain") and bond length deformations, may be computed using Hooke's law; $E_\phi$, the torsional eclipsing energy ("Pitzer strain"), by a simple cosine law. The nonbonded interaction energy, $E_{nb}$, is given by the van der Waals interactions in the molecule. Since relations between isomeric molecules are of interest in this study only relative energy differences are required. Hence the energies of a series of isomers are calculated and the differences in their relative potential energies are approximated to an enthalpy difference which in turn can be related to a conformational free
energy (neglecting, for a moment, entropy considerations). This free energy can then be used to calculate equilibrium constants for a series of compounds.

Potential Functions

There are three general types of potential functions which are considered as contributing to the energies of strained molecules. They are the harmonic potentials, the torsional potentials, and the nonbonded potentials.

The simplest functions in the force field treat small deformations in bond angles and bond lengths and are assumed to have harmonic restoring forces. Hooke's law then holds and the energies are expressed as sums of terms each proportional to the square of the deformation:

\[ E_r = \sum \frac{1}{2} k_r (r-r_0)^2 \]

\[ E_\theta = \sum \frac{1}{2} k_\theta (\theta-\theta_0)^2 \]

where the sums are over all bond lengths and angles, respectively, and \( r_0 \) and \( \theta_0 \) represent strain-free lengths and angles. The force constants \( k_r \) and \( k_\theta \) are calculated from available data. There are limitations in the results of calculations of \( E_\theta \) when the harmonic potential function is used. For molecules containing bond angles which differ from the normal tetrahedral angle the calculated energy is too high. Allinger has used a specialized function to account for the differences between experimental and calculated
values of $E_s$ which may reasonably be attributed to $E_0$ terms. A second approach recently developed by Allinger involves cross terms of the type $\Delta \theta \Delta r$ which have the opposite sign of the $(\Delta r)^2$ and $(\Delta \theta)^2$ terms. The cross terms take cognizance of the inter-relationship which must exist between bending bond angles which are already "stretched" and stretching bonds whose bond angles are already "bent". Neither of the computer programs associated with these approaches was available for this work and therefore it is recognized that all of the calculated strain energies are too high. Furthermore calculated differences in strain energies between pairs of isomers will be greater than the experimental values.

The most general potential function used for the torsional energy for a three fold barrier is given by

$$E_\phi = \frac{1}{2} \sum V_0 (1 + \cos 3\phi)$$

where $\phi$ is the dihedral angle and $V_0$ is the barrier height. The barrier height is assumed to be the value of the destabilization attendant upon eclipsing a pair of bonds.

The function used to describe the nonbonded interactions is empirical. The functions used consist of two terms, one for repulsive forces acting at short distances and one for attractive forces acting at somewhat greater distances. One of the most commonly used functions is the Lennard-Jones equation:

$$E_{nb} = a/r^{12} - b/r^6$$

The repulsive term is the one involving $r^{12}$ and the attractive term
is proportional to \( r \).

The procedure used in calculating \( E_s \) is to vary the values of \( E_r \), \( E_\theta \), \( E_\phi \), and \( E_{nb} \) until the minimum value of \( E_s \) is obtained. This involves an enormous number of calculations in a large molecule and requires the use of computers.\(^3^9\) The results of these calculation for methyl substituted bicyclic hydrocarbons are listed in Table 8. The data in Table 8 shows that the greater part of the strain associated with molecules in the substituted bicyclo[2.2.1]heptane series comes from the angle strain, \( E_\theta \). This is not surprising since the \( \text{C}_1-\text{C}_7-\text{C}_4 \) bond angle is 93.3° which is considerably distorted from the tetrahedral angle. It should be noted that the calculated bond angle in the more sophisticated approach of Allinger is 93.0°. The bond angle as determined by gas phase electron diffraction in the parent hydrocarbon is 93.2°. While both Allinger's approach and this work give reasonable bond angles, the energies of the minimized geometries are different. This is expected since the calculated values of \( E_\theta \) in Table 8 are obtained using a simple harmonic function. The \( E_\theta \) term for the angle \( \text{C}_1-\text{C}_7-\text{C}_4 \) is 4.5 Kcal/mole. The total strain energy for bicyclo[2.2.1]heptane is calculated by Allinger to be 17.95 Kcal/mole. It appears likely that the \( E_\theta \) term which accounts for 75% of the total energy in the calculations reported in this study is too large by approximately 5.7 Kcal/mole. The calculated \( E_\theta \) is larger than an estimated "real" value by a factor of 1.45.

\(^{39}\) The computer program used in this study was written by D. Baron.
<table>
<thead>
<tr>
<th>Compound</th>
<th>( E_r )</th>
<th>( E_\theta )</th>
<th>( E_\phi )</th>
<th>( E_{mb} )</th>
<th>( E_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>exo-2-methylbicyclo[2.2.1]heptane</td>
<td>0.80</td>
<td>17.64</td>
<td>4.93</td>
<td>0.36</td>
<td>23.73</td>
</tr>
<tr>
<td>endo-2-methylbicyclo[2.2.1]heptane</td>
<td>0.83</td>
<td>18.60</td>
<td>4.90</td>
<td>0.65</td>
<td>24.97</td>
</tr>
<tr>
<td>exo-endo-2,3-dimethylbicyclo[2.2.1]heptane</td>
<td>0.99</td>
<td>19.27</td>
<td>5.35</td>
<td>0.09</td>
<td>25.69</td>
</tr>
<tr>
<td>exo,exo-2,3-dimethylbicyclo[2.2.1]heptane</td>
<td>1.26</td>
<td>19.25</td>
<td>4.83</td>
<td>0.79</td>
<td>26.13</td>
</tr>
<tr>
<td>endo,endo-2,3-dimethylbicyclo[2.2.1]heptane</td>
<td>1.48</td>
<td>22.27</td>
<td>4.30</td>
<td>1.48</td>
<td>29.31</td>
</tr>
<tr>
<td>1-methyl-exo-2-methylbicyclo[2.2.1]heptane</td>
<td>0.97</td>
<td>17.93</td>
<td>4.87</td>
<td>-0.99</td>
<td>22.77</td>
</tr>
<tr>
<td>1-methyl-endo-2-methylbicyclo[2.2.1]heptane</td>
<td>0.96</td>
<td>18.66</td>
<td>5.07</td>
<td>-0.88</td>
<td>23.81</td>
</tr>
</tbody>
</table>
Experimental Equilibrium Constants

Methyl Substituted Bicyclo[2.2.1]heptanes

The experimental equilibrium constants determined over a 5% palladium on carbon catalyst in the gas phase at 300 °C in sealed tubes are listed, along with free energy and enthalpy differences, in Table 9. The enthalpy changes were calculated assuming the entropy difference between isomeric pairs of compounds is due only to symmetry differences and entropy of mixing terms. In general the entropy of a reaction may be written as \( \Delta S_{\text{obs}} = \Delta S_{\text{chem}} + \Delta S_{\text{sym}} + \Delta S_{\text{mixing}} \). Here it is assumed that there is no significant entropy difference associated with structural differences, i.e. \( \Delta S_{\text{chem}} = 0 \).

With one notable exception (vide infra) the experimental results agree with chemical intuition. That is, groups prefer to be in the exo position where they encounter small interactions with the syn-7-hydrogen rather than in the endo position where they encounter severe interactions with the endo-6-hydrogen and to a lesser degree with the endo-5-hydrogen. In addition eclipsed methyl groups are at higher energy than methyl groups at a dihedral angle of 120 °.

Consider first 2-exo and 2-endo-methylbicyclo[2.2.1]heptane. The experimental value for the conformational preference of a methyl group is -0.89 Kcal/mole. This is in reasonable agreement with the calculated value of -1.24 Kcal/mole. The ratio of calculated to experimental values is 1.4. This is similar to the
<table>
<thead>
<tr>
<th>Equilibrated Compound</th>
<th>Equilibrium Constant</th>
<th>$^{\circ}$AG</th>
<th>$^{\circ}$AH</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-methylbicyclo[2.2.1]heptane</td>
<td>$K_{\text{exo/endo}} = 2.2$</td>
<td>-0.89</td>
<td>-0.89</td>
</tr>
<tr>
<td>2,3-dimethylbicyclo[2.2.1]heptane</td>
<td>$K_{\text{trans/diexo}} = 3.6$</td>
<td>-1.45</td>
<td>-0.66</td>
</tr>
<tr>
<td></td>
<td>$K_{\text{diexo/diendeo}} = 6.9$</td>
<td>-2.19</td>
<td>-2.19</td>
</tr>
<tr>
<td></td>
<td>$K_{\text{trans/diendeo}} = 24.7$</td>
<td>-3.63</td>
<td>-2.84</td>
</tr>
<tr>
<td>1,2-dimethylbicyclo[2.2.1]heptane</td>
<td>$K_{\text{endo/exo}} = 7.2$</td>
<td>2.23</td>
<td>2.23</td>
</tr>
</tbody>
</table>
ratio previously mentioned as reflecting the inadequacy of the bending function used to calculate $E_g$. The calculations show that the -1.24 Kcal/mole term can be associated with a decrease in $E_g$ of -0.96 Kcal/mole and a decrease in the van der Waals repulsion of -0.29 Kcal/mole. Examination of molecular models reveals that substituents in the endo-2 and -3 positions are somewhat inclined toward endo substituents in the 5 and 6 positions. The distortion in bond angle caused by the interaction of the 2 and 6-endo substituents presumably gives rise to the increase in bond angle strain, $E_g$, as well as accounting for the increase in van der Waals repulsion, $E_{nb}$.

![Molecular model diagram](image)

**Fig. 6.** $\text{C}_\text{methyl}-\text{C}_2-\text{C}_3$ Bond Angles in exo and endo-2-methylbicyclo[2.2.1]heptane

It is interesting to note that the $\text{C}_\text{methyl}-\text{C}_2-\text{C}_3$ bond angles are 113.1° and 113.8°, respectively, in the exo and endo cases. This accounts for a difference in $E_g$ of 0.09 Kcal/mole. However, the $\text{C}_{\text{endo}-2}-\text{C}_2-\text{C}_1$ bond angles are 110.3° and 115.3°, respectively, in the exo and endo compounds. And this bond angle distortion accounts for a difference of 0.51 Kcal/mole between the two isomers.

Consider next the 2,3-dimethylbicyclo[2.2.1]heptanes. If -0.89 Kcal/mole is taken as the stabilization gained from moving a methyl
group to the exo position from the endo position, then one might naively expect that, other things being equal, displacing two methyl groups from endo to exo positions would give a decrease in energy of -1.78 Kcal/mole. This simple prediction is based on the identity of dihedral angles between two methyl groups in the diexo and diendo compounds. The observed value of -2.19 Kcal/mole, while somewhat greater than predicted on such a simple basis, is nevertheless in reasonable accord with a more detailed picture of the bicyclo[2.2.1]heptane ring system. The distance between the endo-2-methyl and the endo-3-methyl groups is less than the distance between the exo-2-methyl and the exo-3-methyl. Therefore substituents at these positions will experience greater mutual repulsion when both are endo than when they are both exo (Fig. 7).

![Fig. 7. C\textsubscript{methyl}-C\textsubscript{2}-C\textsubscript{3} Bond Angles in diexo and diendo Compounds](image)

The difference between the simple prediction of -1.78 Kcal/mole and the experimentally observed value of -2.19 Kcal/mole, although small, is probably a reflection of this factor. Indeed the calculated C\textsubscript{methyl}-C\textsubscript{2}-C\textsubscript{3} bond angles in energy minimized structures are 116.2° and 117.3°, respectively, in the diexo and diendo compounds. This
accounts for a total of 1.46 Kcal/mole destabilization in the diexo compound and a 2.02 Kcal/mole destabilization in the diendo compound. The difference in $E_y$ between the two isomers due to distortion of these angles is 0.56 Kcal/mole.

Once again it is noted that the energy difference of the minimized structure is a factor of 1.45 larger than the observed energy difference. Thus the inadequacies of the model for calculating $E_y$ appear to be reflected in a constant manner in these structurally related compounds.

The other two equilibria of the 2,3-dimethylbicyclo[2.2.1]-heptanes are less amenable to such simple considerations. There are no longer cancelling eclipsing interactions but rather an interplay of eclipsing interactions and interactions with the 7-syn-hydrogen and the 5 and 6-endo-hydrogens. All of the factors are associated with the conversion of a methyl group from the endo to the exo position. The stabilization gained in going from diexo-2,3-dimethylbicyclo[2.2.1]heptane is -0.66 Kcal/mole. It is thus clear that the eclipsing interaction is more energetically unfavorable than an endo-2,6 interaction. Using -0.89 Kcal/mole as the factor which is associated with an endo to exo conversion, the energy of the eclipsing interaction may be calculated as 1.55 Kcal/mole. The significance of this value will be discussed later when compared to values for an eclipsing interaction derived from equilibrium constants in other systems. The calculated value predicts that the trans isomer will be more stable than the diexo
isomer by 1.0 Kcal/mole. This value is a factor of 1.5 larger than the observed stabilization. The origin of the difference between the calculated and observed values has been previously discussed.

The case of 1,2-dimethylbicyclo[2.2.1]heptane is not readily explained. It represents the only case where a methyl group prefers to be endo rather than exo. The observed stabilization is -2.23 Kcal/mole. The calculated enthalpy predicts a destabilization of the endo position of 0.96 Kcal/mole. This is by far the greatest divergence of calculated and experimental values. It is at the moment something of an enigma.

The equilibrium constant was determined by integration of peak areas of the glpc of the equilibrium mixture. The compound was obtained from hydrogenation of 1-methyl-2-methylenebicyclo[2.2.1]-heptane to give a mixture containing 88% of one isomer and 12% of the other. On the basis of the result of the hydrogenation of 2-methylenebicyclo[2.2.1]heptane which gives 66% of the endo isomer, the major peak was assigned as the endo isomer. After equilibration for three months over 5% palladium on carbon catalyst at a temperature of 300 °C, the glpc of the mixture showed that the minor peak, initially assigned as the exo isomer, had decreased in size.

An estimation of the free energy difference between exo and endo-1,2-dimethylbicyclo[2.2.1]heptane can be made on the basis of the dihedral angle between the two methyl groups. In the exo isomer this
dihedral angle is 35°. Calculation of the conformational energies of the gauche and methyl-methyl eclipsed conformations of butane yields values of 0.8 and 4.5 Kcal/mole, respectively. Subtracting 1.9 Kcal/mole from 4.5 Kcal/mole to account for the pairs of eclipsed hydrogen atoms gives 2.6 Kcal/mole as an estimate of the methyl-methyl eclipsing interaction in a strain-free system. The methyl-methyl interaction at a 60° dihedral angle, i.e. the gauche interaction, is 0.8 Kcal/mole. Thus at a 35° angle in a strain-free system, the interaction is approximately 1.6 Kcal/mole. However, in the strained bicyclo[2.2.1]heptane system the methyl-methyl eclipsing interaction is in the order of 1.5 to 1.9 Kcal/mole. Using an intermediate value of 1.7 Kcal/mole for a dihedral angle of 0°, one may estimate the interaction at 35° to be 0.9 Kcal/mole. In considering the 0.89 Kcal/mole energy difference between exo and endo-2-methylbicyclo[2.2.1]heptane it is estimated that exo and endo-1,2-dimethylbicyclo[2.2.1]heptane are of equal energy. Although the estimate is not quantitative, it is sufficiently well based to indicate that something may have gone awry in the observation that the endo isomer is 2.23 Kcal/mole more stable than the exo isomer. Taking into account the 0.89 Kcal/mole energy difference between exo and endo-2-methylbicyclo[2.2.1]-heptane, it would be necessary to assert that a 3.1 Kcal/mole destabilization prevails between two methyl groups at a dihedral angle of 35°, an interaction which is greater than an eclipsing interaction. Such a conclusion is unacceptable.
If the assignment of the exo and endo-1,2-dimethylbicyclo-
[2.2.1]heptane glpc peaks is reversed, a reversal in opposition
to the chemistry of hydrogenation, the results are equally
difficult to interpret. It would then be necessary for one to
contend that the 1-methyl group increases the stability of the exo-
methyl group by 1.3 Kcal/mole. This conclusion is not acceptable.

At present the only alternative explanation that seems
plausible is the possibility that the starting compound rearranges
on the catalyst to give a compound with the same glpc retention
time as the starting material. The glpc peak areas would then be
meaningless.

The Bicyclo[3.2.1]octane System

The experimental equilibrium constants and corresponding free
energy differences for the methyl substituted bicyclo[3.2.1]octanes
studied are listed in Table 10.

A methyl group in the 2 position of bicyclo[3.2.1]octane may
occupy either an exo position or an endo position. The exo position
is axial in the six membered ring moiety of the bicyclic molecule
and the endo position is equatorial. In the axial position the methyl
group encounters an interaction with the C-8 methylene group and
with the axial C-4 hydrogen which are as a first approximation
roughly equivalent to a 1,3-diaxial interaction in cyclohexane.
However, due to the bridging of the C-1 and C-5 atoms by the C_{6}-C_{7}
ethylene bridge, the C-8 methylene group is moved over the
Table 10. Equilibrium Constants and Free Energies in Kcal/mole for n-methylbicyclo[3.2.1]octanes

| Compound                        | Equilibrium Constant | $\Delta G^o$ | \(a\) |
|--------------------------------|----------------------|--------------|
| 2-methylbicyclo[3.2.1]octane   |                      | $K_{exo/endo}$ = 4.0 | -1.57 |
| 3-methylbicyclo[3.2.1]octane   |                      | $K_{endo/exo}$ = 350  | -6.54 |

\(a\) Since there are no symmetry corrections, and since $\Delta S_{mixing} = 0$, $\Delta G^o = \Delta H^o$

\(b\) endo = equatorial, exo = axial.

\(c\) endo = axial, exo = equatorial.

cyclohexane chair and the distance between the C-8 methylene and the substituent in the 2-axial position is less than in cyclohexane. In the equatorial position this 1,3-diaxial interaction is relieved. However a new interaction is encountered in the equatorial position which is similar to a gauche 1,2-diequatorial dimethyl interaction.

In the cyclohexane ring system the difference between axial and equatorial methyl groups is 1.8 Kcal/mole. The gauche methyl-interaction in butane is 0.8 Kcal/mole. These two interactions provide a reasonable basis for interpreting the data for the 2-methylbicyclo[3.2.1]octanes. The gauche interaction of the equatorial methyl group with the C-7 methylene group increases the energy of the methyl group 0.8 Kcal/mole above the energy of
equatorial cyclohexane. Thus the energy of the axial isomer of 2-methylbicyclo[3.2.1]octane is $1.5 + 0.8 - 1.8 = 0.5$ Kcal/mole above that of axial methylcyclohexane. The 0.5 Kcal/mole must reflect the decreased distance between the C-8 methylene and the axial methyl group in the bicyclic ring system. The relative energies of the various possible conformations of the cyclic and bicyclic ring systems is represented schematically in Fig. 8.

![Fig. 8. Relative Energies of methylcyclohexanes and 2-methylbicyclo[3.2.1]octanes](image)

Even qualitative considerations based on a cyclohexane model indicate that the endo-3-methylbicyclo[3.2.1]octane will be very unstable since it is not only axial but in a diaxial relationship with both of the methylene groups at C-6 and C-7. Molecular models indicate that the methyl hydrogens lie within the van der Waals radius of the hydrogens in the ethylene bridge. The chair cyclohexane moiety is no doubt badly deformed in this conformation. The energy of the axial conformation may be estimated as being twice the 1,3-diaxial methyl-methyl interaction of 3.5 Kcal/mole plus the conformational preference of a methyl group in cyclohexane. Thus the endo isomer is expected to be 8.8 Kcal/mole less stable than the exo isomer. If the conformation were changed from the chair to the boat conformation of bicyclo[3.2.1]octane, this
high energy interaction would be relieved. The boat conformation of bicyclo[3.2.1]octane has been calculated to be 6.75 Kcal/mole less stable than the chair conformation, an energy difference very similar to the one observed in this equilibrium. The various possible conformations of this system are illustrated in Fig. 9.

Fig 9. Possible Conformations of 3-methylbicyclo[3.2.1]octane

In the equatorial position of a boat conformation the endo-3-methyl group can exist with virtually no destabilizing interactions. The total strain energy of the 3-exo-methylbicyclo[3.2.1]octane will be the same as the strain energy of the parent hydrocarbon since both isomers would contain equatorial methyl groups. Thus the observed energy difference is the chair-boat energy difference.

The Bicyclo[2.2.2]octane System

The equilibrium constant, $K_{cis/trans}$, for 2,3-dimethylbicyclo[2.2.2]octane is 15.7 corresponding to a free energy difference of 3.12 Kcal/mole. Due to symmetry a methyl group encounters the same interactions with the bridgehead hydrogen and the bridging ethylene groups whether it is cis or trans to its neighboring methyl group. Therefore the equilibrium constant must be solely a reflection of
the repulsion due to the eclipsing methyl groups.

The methyl-methyl eclipsing interaction in 2,3-dimethyl-
bicyclo[2.2.2]octane is significantly larger than the 1.5 Kcal/mole found in exo-exo-dimethylbicyclo[2.2.1]heptane and 1.9 Kcal/mole observed in endo-endo-dimethylbicyclo[2.2.1]heptane. The observed value of 3.12 Kcal/mole is also larger than the "strain free" eclipsing interaction in n-butane of 2.6 Kcal/mole. All of these values can be explained in terms of simple models. The internal bond angles of bicyclo[2.2.1]heptane are decreased below the tetrahedral value. Thus the substituents at the 2 and 3 positions are moved apart (cf. Fig. 6) leading to a decreased methyl-methyl interaction. In butane those distortions of idealized structures which must occur are, in effect, already built into the bicyclo-
[2.2.1]heptane ring. In bicyclo[2.2.2]octane the bond angles are more nearly tetrahedral and comparable to an idealized butane structure. However, while butane may become distorted by a number of means requiring relatively little energy, the bridged bicyclo-
[2.2.2]octane ring system is more restricted and distortions which would decrease the eclipsing interaction require considerable energy. Therefore it is not surprising that the methyl-methyl eclipsing interaction is greater than in butane.

The 1,2-dimethylcyclopentane System

The free energy difference between cis and trans-1,2-dimethyl-
cyclopentane is 1.77 Kcal/mole, the trans isomer being the more stable. The symmetry correction is -R ln 2. However it is cancelled by an entropy of mixing of +R ln 2. Therefore the enthalpy difference is also 1.77 Kcal/mole. This value is in good agreement with the reported value of 1.71. If cyclopentane were planar the 1.77 Kcal/mole would be equal to a methyl-methyl eclipsing interaction. In a planar cyclopentane molecule transfer of a methyl group from one side of the ring to the other would involve no differences in environment and would be solely a reflection of an eclipsing interaction. But cyclopentane is known to be non-planar. Likely conformations for 1,2-dimethylcyclopentanes are given in Fig. 10.

![Fig. 10. Conformations of cis and trans-1,2-dimethylcyclopentane](image)

In the cis isomer the dihedral angle between methyl groups is approximately 30°. In the trans isomer the dihedral angle between methyl groups is near 90°. There is a resemblance between these structures and the 1,2-dimethylbicyclo[2.2.1]heptanes which contain similar dihedral angles.

The 1.77 Kcal/mole difference in energy is the result of changing a methyl group from equatorial to axial and simultaneously
increasing the methyl-methyl interaction. Earlier in the discussion of 1,2-dimethylbicyclo[2.2.1]heptane it was suggested that an interaction of 0.9 Kcal/mole is reasonable for two methyl groups at a 35° dihedral angle. Therefore one can estimate that the greater part of the 1.77 Kcal/mole energy difference is due to a methyl-methyl interaction. A rough estimate for the equatorial-axial methyl interaction of 0.8 Kcal/mole can then be obtained.
CHAPTER II

THE OXIDATION OF TRANS-PROPENYBENZENE WITH SODIUM PALLADIUM CHLORIDE

Introduction

Palladium chloride reacts with olefins to give carbonyl compounds as products. The oxidation of ethylene to acetaldehyde by platinum group metals was known as early as 1894. Today the reaction is the basis of the commercial production of acetaldehyde in the so-called Wacker process. In the commercial process the elemental palladium formed during the course of the reaction is reoxidized to Pd(II) by Cu(II) which in turn is reduced to Cu(I). The palladium is insensitive to air oxidation, however cuprous ion is very labile in that respect and is rapidly oxidized to Cu(II). The net result, summarized below, is the Pd(II) catalyzed air oxidation of ethylene to acetaldehyde.


Several investigators have studied the kinetics of this reaction. The reaction is first order in ethylene and first order in palladium. Henry regarded the initial rapid uptake of ethylene beyond that required to obtain a saturated solution as evidence for the formation of a pi complex between the olefin and palladium. Moiseev has obtained evidence for the formation of $\text{Pd(Cl)}_3(C_4H_8)^-$ and $\text{Pd(Cl)}_2(\text{H}_2\text{O})(C_4H_8)$ complexes in the oxidation of butenes. The observation that ethylene d-4 yields acetaldehyde d-4 is unequivocal evidence for an internal hydride transfer during the course of the reaction.

The reaction is strongly inhibited by chloride ions, having second order chloride inhibition. It also displays first order...

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inhibition in hydrogen ions. The reaction obeys the rate law given below.

\[
\frac{-d(C_2H_4)}{dt} = \frac{kK_1K_2K_3(PdCl_4^-)(C_2H_4)}{(Cl)^2(H^+)} \tag{5}
\]

The following mechanism, proposed by Henry, accounts for all of the experimental facts. It may be seen that the pre-equilibria lead to the inhibition terms, and that the rate determining step involves collapse of the pi complex to a sigma bonded organo-palladium intermediate. It is also clear that the reactive species in Henry's mechanism, namely Pd(Cl)_2(OH)(C_2H_4), is derived from Pd(Cl)_2(H_2O)_2 and that other ordering of these equilibria are possible.

\[
PdCl_4^- + C_2H_4 \rightleftharpoons K_1 Pd(Cl)_3(C_2H_4)^- + Cl^- \tag{6}
\]

\[
Pd(Cl)_3(C_2H_4)^- + H_2O \rightleftharpoons K_2 Pd(Cl)_2(H_2O)(C_2H_4) + Cl^- \tag{7}
\]

\[
Pd(Cl)_2(H_2O)(C_2H_4) \overset{K_3}{\rightleftharpoons} Pd(Cl)_2(OH)(C_2H_4)^+ + H^+ \tag{8}
\]

\[
Pd(Cl)_2(OH)(C_2H_4)^- \overset{\text{slow}}{\rightarrow} \text{HO-CH}_2-\text{CH}_2-Pd- \tag{9}
\]

\[
\text{HO-CH}_2-\text{CH}_2-Pd- \overset{\text{fast}}{\rightarrow} \text{CH}_3\text{CHO} + \text{Pd}^0 + 2 \text{HCl} + 2 \text{Cl}^- \tag{10}
\]

Evidently there is no carbonium ion intermediate formed since no glycol products are formed. Furthermore when the relative rates of a number of olefins were studied \(^{45b}\) it was found that the ordering was ethylene > trans-2-butene = propylene > cis-2-butene = 1-butene but that the rates differed by a factor of only six. This implies that the addition of palladium to the double bond is non-polar.
in character and further diminishes the likelihood that the reaction proceeds via a carbonium ion intermediate. The ordering of rates is, however, parallel to the order of \( \pi \) complexation of metals with olefins.

Evidence that the \( \pi \) complex of Equation (9) does not lead directly to product, but rather rearranges to a \( \sigma \)-bonded intermediate which decomposes to product in a fast step is to be found in the kinetic isotope effect. Since the reaction involves a hydride transfer, if the \( \pi \) complex were involved in the step leading to product a large primary isotope effect would be observed. Since, however, \( \frac{k_H}{k_D} = 1.07 \) the hydride shift must occur in a fast step and not via a path leading directly from \( \pi \) complex to product. The pathway thus followed is illustrated in Figures 11 and 12.

Fig. 11. Rearrangement of \( \pi \) complex to \( \sigma \)-bonded intermediate

Fig. 12. Decomposition of \( \sigma \)-bonded intermediate to product
Pd(II) has a d⁸ electronic configuration and forms diamagnetic, low spin, square-planar complexes. Hybridization of the 4dₓ²₋ᵧ², 5s, 5pₓ and 5pᵧ orbitals on the metal imposes a square planar geometry on the coordination of this palladium oxidation state. In the solid state palladium chloride is an infinite polymer with chloride bridges maintaining the four coordinate square planar configuration. In aqueous solution these bridges break up to give mononuclear complexes in which water and/or other ligands complete the coordination sphere of the metal. The nature of the Pd(II) species present in solution will be discussed in greater detail below.

Pd(II) readily forms complexes with ligands such as amines, phosphines, halides, and unsaturated organic moieties such as olefins. Henry has determined the complexation constant for ethylene with aqueous sodium palladium chloride to be 17.4 in solutions greater than 0.2 M in added chloride ion. The bonding in such metal-olefin complexes is believed to consist of a sigma bond formed between one of the dsp² hybrid orbitals on palladium with a filled pi molecular orbital of the olefin. An additional inter-

action of considerable importance is a π type backbonding of a filled metal d_{xy} or d_{yz} orbital with a vacant antibonding π**, molecular orbital of the alkene.

The oxidation of a number of more complex olefins has been studied. It has been observed that trans-propenylbenzene is oxidized by palladium chloride to give only phenylacetone and that the palladium chloride forms a complex with the olefin, that styrene is oxidized to give 25% acetophenone and 75% phenylacetaldehyde, and that m-nitrostyrene gives only m-nitroacetophenone. No kinetic data was obtained in any of these cases. Ouellette and Levin found that one of the products in the oxidation of phenylcyclopropane with sodium palladium chloride was phenylacetone which was an oxidation product of trans-propenylbenzene arising from the palladium catalyzed ring opening of the cyclopropane ring. Again no kinetic studies were undertaken. The somewhat surprising non-Markownikoff products in the oxidations, plus the paucity of kinetic and mechanistic data in these olefins, prompted this study.


Product Studies

The only product observed in the reaction of trans-propenylbenzene with sodium palladium chloride is phenylaceton. This product was identified by the nuclear magnetic resonance (nmr) spectrum of the reaction mixture; an identification made facile since the aliphatic protons of phenylaceton appear in a unique area of the nmr spectrum. The observed resonances, a three proton singlet at $\tau 8.1$ and a two proton singlet at $\tau 6.5$, correspond to those of an authentic sample of phenylaceton. The other possible oxidation product, propiophenone, also has a unique nmr spectrum. Its aliphatic resonances, a three proton triplet at $\tau 8.8$ and a two proton quartet at $\tau 7.2$, identify it unambiguously. In addition to spectroscopic evidence, gas-liquid partition chromatography (glpc) of the reaction mixture shows only two compounds: trans-propenylbenzene and phenylaceton as verified by comparison with the retention times of authentic samples under the same conditions.

The anti-Markownikoff oxidation of trans-propenylbenzene to give phenylaceton has been noted by other workers. As yet no explanation has been advanced.
A number of mechanisms are possible which explain the observed products of the reaction. One might postulate attack by palladium to give an intermediate related to the carbonium ion corresponding to Markownikoff addition. An initial Markownikoff intermediate could then rearrange to product by migration of hydroxide, loss of palladium,

\[
\begin{align*}
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
+ \quad \text{Na}_2\text{PdCl}_4 & \quad \rightarrow \quad \text{Ph}^+ \quad \text{H}_2\text{O} \quad \text{Ph} \quad \text{Pd} \\
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
\text{several steps} & \quad \rightarrow \quad \text{Ph} \quad \text{Ph} \quad \text{Pd} \\
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
\text{OH} & \quad \text{OH} \\
\end{align*}
\]

and the eventual formation of the observed product.

Alternatively, attack by Pd(II) could proceed by non-Markownikoff addition of palladium with the formation of the carbonium ion related to 5. A 1,2 hydride shift would then result in the formation of the observed product.

\[
\begin{align*}
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
+ \quad \text{Na}_2\text{PdCl}_4 & \quad \rightarrow \quad \text{Ph} \quad \text{Ph} \quad \text{Pd} \\
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
\text{H}_2\text{O} & \quad \text{H}_2\text{O} \\
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
\text{Ph} & \quad \text{Ph} \quad \text{Pd} \\
\text{OH} & \quad \text{OH} \\
\end{align*}
\]
The most definite proof of the intermediate (either \( \mathcal{L} \) or \( \mathcal{Z} \)) would be its actual isolation. However, the instability of organopalladium compounds has been well established. But a number of workers have succeeded in generating organopalladium compounds as transient intermediates. The method most commonly employed has been to make the corresponding organomercuric chloride and then exchange it with palladium chloride. Since such a process has been shown to give organopalladium compounds, at least transiently, one would expect the organomercuric alcohol to give the desired palladium intermediates. Hence the mechanism of the reaction can be at least partially elucidated by formation of the oxymercury derivative of \( \mathcal{L} \) followed by displacement by \( \text{Pd}(\text{II}) \). On the basis of data published by Brown the reaction was expected to give the

\[
\begin{align*}
\text{1} & \xrightarrow{\text{1)HgOAc}_2} \text{HgOAc}_2 \quad \text{2)NaCl} \\
\text{HgCl} & + \\
\text{7} & \quad \text{8}
\end{align*}
\]

\[
\begin{align*}
\text{7} + \text{8} & \xrightarrow{\text{Pd(II)}} \\
\text{4} & \quad \text{2}
\end{align*}
\]

---


Markownikoff addition product \( I \). However, the major product observed is not \( I \), but \( \delta \) which corresponds to anti-Markownikoff addition. (This result has been observed before\(^{56}\) and is somewhat surprising since reactions of mercuric ion are known\(^{57}\) to have large rho's. On this basis the benzyl carbonium ion is expected.)

Treatment of \( \delta \) with sodium palladium chloride should give phenylacetone if the migrating species is hydride. Propiophenone would be formed if there is a hydroxide shift. No propiophenone is formed thus eliminating the postulate of a hydroxide shift.

\[
\begin{array}{c}
\text{HgCl} \\
\downarrow \\
\text{Pd(II)}
\end{array}
\begin{array}{c}
\text{Ph} \\
\downarrow \\
\text{Ac}
\end{array}
\]

\( \delta \)

This leaves the mechanism in which initial attack by Pd(II) is followed by a 1,2 hydride shift as the most likely possibility.

The Pd(II) oxidation of olefins has been previously demonstrated\(^{42,43,45,53,54}\) to involve such hydride shifts. Furthermore, since there are many examples of hydride shifts in the literature\(^{58}\), such a pathway seems reasonable. Whether or not the metal assists in the migration of hydride is an unresolved question.

\[
\begin{array}{c}
\text{Ph} \\
\downarrow \\
\text{Ac}
\end{array}
\]

---

Substituent Effects in the Oxidation of trans-Propenylbenzene

The formation of phenylacetone in the oxidation of trans-propenylbenzene implicates the formation of 6 which is derived from 7 during the course of the reaction. It was of interest to determine the effect of substituents on the rate of reaction since such information should shed light on the electronic character of the intermediate. If a full-fledged carbonium ion is formed, then the reaction should display a large substituent effect. Conversely, a small substituent effect would imply that there is little polar character in the transition state. Furthermore a large substituent effect might be expected to lead to different products for strongly electron donating groups such as para-methoxy.

In fact, the reaction is rather insensitive to substituents. The relative rates for the substituents studied is given in Table 11.

Table 11.
Effect of Substituents in the Oxidation of trans-Propenylbenzene

<table>
<thead>
<tr>
<th>Substituent</th>
<th>Relative Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>para- H</td>
<td>1.05</td>
</tr>
<tr>
<td>para-fluoro</td>
<td>2.0</td>
</tr>
<tr>
<td>para-methyl</td>
<td>3.1</td>
</tr>
<tr>
<td>para-methoxy</td>
<td>6.0</td>
</tr>
</tbody>
</table>
If a plot of the log of the observed rate constant versus the substituent constant, \( \sigma^+ \), is made, a straight line is obtained with a slope, \( \rho \), of -0.80 (Figure 13). This value of \( \rho \) is quite small and suggests that the reaction indeed proceeds through a relatively nonpolar transition state. The small rate change in going from ethylene to 2-butene has previously been cited as evidence for a nonpolar transition state. The results in this case are in agreement with that conclusion.

The non-Markownikoff addition of Pd(II) persists regardless of the substituent. In the cases of para-fluoro and para-methyl-trans-propenylbenzene the only observed product is the corresponding arylacetone. When the substituent is para-methoxy, the product is 92\% para-methoxyphenylacetone, and 8\% para-methoxypropiophenone. The products in all cases are uniquely characterized by the aliphatic region of their nmr spectra. Thus, para-fluorophenylacetone has a three proton singlet corresponding to a methyl group at \( \tau 7.9 \) and a two proton singlet corresponding to the methylene at \( \tau 6.4 \). The spectrum of para-methylphenylacetone likewise has two singlets in the aliphatic region corresponding to the methyl and methylene protons. These resonances appear at \( \tau 8.0 \) and \( \tau 6.5 \) respectively. The nmr spectrum of the reaction mixture of the products of para-methoxy-trans-propenylbenzene contained a three proton singlet at \( \tau 8.1 \) and a two proton singlet at \( \tau 6.7 \) corresponding to para-methoxyphenylacetone. It also contains a three proton triplet centered at \( \tau 8.9 \) and a two proton quartet at \( \tau 7.3 \) corresponding to the methyl and methylene resonances of para-methoxypropiophenone.
Fig. 13. Substituent Effects in the Oxidation of trans-Propenylbenzene with Pd(II)
The product ratios were determined by integration of the appropriate resonances in the nmr spectrum and confirmed by integration of the peak areas obtained by glpc of the reaction mixture.

The marked preference for anti-Markownikoff addition even when strongly electron donating groups are present, suggests that palladium complexation with the olefin, or alternatively with the benzene ring, is more important in determining the product than the electronic character of the transition state.

In connection with the novel anti-Markownikoff addition it is interesting to note the product in the oxidation of the isomeric olefin, allylbenzene. Reaction of allylbenzene with sodium palladium chloride leads to phenylacetone and trans-propenylbenzene. Apparently Markownikoff attack prevails in the case of allylbenzene, although it could be argued that the primary process is isomerization to the conjugated olefin followed by anti-Markownikoff addition. If this path is followed, one must seek the reason for the dramatic change produced upon going to the conjugated olefin. One possibility is that the palladium attacks the benzene ring, perhaps at the para position. Classical resonance structures for the ion thus formed include one resonance hybrid in which the positive charge resides on
Although purely speculative, such a mechanism would account for a small \( \rho \), if the charge were sufficiently delocalized, as well as being consistent with the products observed both in the oxidation of trans-propenylbenzene and in the oxidation of allylbenzene.
Kinetic Studies

Previous kinetic studies of the oxidation of phenylcyclopropane established a convenient solvent system for studying the kinetics of the reaction. In order to have homogeneous conditions for studying the kinetics a mixed solvent of 2:1 glyme-water (v/v) was employed. This corresponds to 70 mole per cent water.

The method of analysis chosen was spectrophotometric determination of $\text{PdCl}_4^-$ which has an absorption at 480 nm in the visible region of the spectrum. Since the rate of disappearance of Pd(II) is the same as the rate of appearance of phenylacetone, this method of analysis is preferred over glpc or nmr analysis since it is more facile experimentally.

Typical kinetic runs were done at an olefin concentration of about $5 \times 10^{-3}$ M and palladium concentrations of $2.5 \times 10^{-3}$ M. However, in order to determine the order of the reaction, the olefin concentration was varied by a factor of two and the palladium concentration varied by a factor of three. In addition to these reactants, sodium perchlorate was present at a concentration of 1 M in all runs in order to maintain a reasonably constant ionic strength. As the reaction proceeds, there is a considerable change in ionic strength of the medium and it seemed desirable to minimize the effect of this change by including a large excess of a non-interacting electrolyte. Several kinetic runs were made at concentrations of sodium chloride of $10^{-2}$ M to $3 \times 10^{-2}$ M to test for chloride inhibition. The motivation for studying the effect of
added chloride ion came from the kinetic results of olefin oxidation by Pd(II) discussed previously. It will be recalled that Henry observed an inverse second order dependence on the chloride ion concentration. Since Levin observed the same phenomenon, a search for similar behavior was undertaken in the present system. Kinetic runs were also made with added perchloric acid at a concentration of \(3.5 \times 10^{-2}\) M since Henry also observed first order inhibition in hydrogen ions.

The approach taken to fitting the experimental data to a rate law was guided by the results of the previous studies of Pd(II) oxidation. It will be recalled that Henry established the following rate law for the oxidation of ethylene.

\[
\frac{dx}{dt} = \frac{kK_1K_2K_0 [\text{PdCl}_4^{2-}][\text{C}_2\text{H}_4]}{[\text{Cl}^-][\text{H}^+]} \quad (5)
\]

It was shown in previous work involving the oxidation of phenylcyclopropane that Henry's rate law did not give constant rate constants in that system. The rate law which does give reasonably constant rate constants is, however, closely related to (5). Henry's rate law indicates that the reacting species in the olefin oxidation is derived from \(\text{Pd(Cl)}_2(\text{H}_2\text{O})(\text{OH})^-\). A modified form of Henry's rate law then involves this species whose concentration is related to the stability constants for the various species present in solution. The stability constants for the Pd(II) species in 2:1 glyme-water have been determined, and when they are related to the total Pd(II) concentration, the correct rate law is obtained.
\[
\frac{dx}{dt} = \frac{k_3k_4K_3[B_0-x][A_0-x]}{[H^+][[Cl^-]^2 + K_4[Cl^-] + K_3k_4]}
\]  

(6)

Where \( A_0 = \) initial conc. of olefin in moles/liter

\( B_0 = \) initial conc. of \( \text{Pd(II)} \) in moles/liter

\( x = \) instantaneous conc. of product in moles/liter

\([H^+] = 2x\)

Derivation and Integration of Rate Law

All of the rate laws to be derived below make use of the basic relationships given in equations (7) - (9).

\[
[B_0-x] \approx [\text{PdCl}_4^{2-}] + [\text{PdCl}_3(\text{H}_2\text{O})^-] + [\text{Pd(Cl)}_2(\text{H}_2\text{O})_2]
\]  

(7)

\[
K_4 = \frac{[\text{PdCl}_3(\text{H}_2\text{O})^-][\text{Cl}^-]}{[\text{PdCl}_4^{2-}]}
\]  

(8)

\[
K_3 = \frac{[\text{PdCl}_2(\text{H}_2\text{O})_2][\text{Cl}^-]}{[\text{PdCl}_3(\text{H}_2\text{O})^-]}
\]  

(9)

In each of the rate laws to be derived, a reacting species is assumed and equations (7) - (9) are used to obtain an expression for that species in terms of the initial conc. of substrate, \( A_0 \), the initial concentration of metal, \( B_0 \), the concentration of added chloride, \( C \), the equilibrium constants, and the reaction variable \( x \). The expression for the mechanism involving \( \text{Pd(Cl)}_2(\text{H}_2\text{O})(\text{OH})^- \) will be derived in detail. The other rate laws are obtained in the same way.

Equation (7) is rearranged, making use of (8) and (9) so that it contains only terms involving \( \text{Pd(Cl)}_2(\text{H}_2\text{O})_2 \), the equilibrium constants
K₃ and K₄, and the instantaneous chloride ion concentration. This gives equation (10) which is solved for Pd(Cl)₂(H₂O)₂ to give (11).

\[ [B₀-x] = \frac{[\text{PdCl}_2 \text{H}_2\text{O})_2][\text{Cl}^-]^2}{K₃K₄} + \frac{[\text{PdCl}_2 \text{H}_2\text{O})_2][\text{Cl}^-]}{K₃} + \frac{[\text{PdCl}_2 \text{H}_2\text{O})_2]}{1} \]

(10)

\[ [\text{PdCl}_2 \text{H}_2\text{O})_2] = \frac{K₃K₄[B₀-x]}{[\text{Cl}^-]^2 + K₄[\text{Cl}^-] + K₃K₄} \]

(11)

If the species [Pd(Cl)₂(H₂O)(OH)]⁻ is to be considered, the expression (12) must be used.

\[ \frac{[\text{Pd(Cl)}_2 \text{H}_2\text{O}) (\text{OH})][\text{H}^+]}{[\text{Pd(Cl)}_2 \text{H}_2\text{O})_2]} = K₅ \]

(12)

Solving for Pd(Cl)₂(H₂O)(OH)⁻ and substitution of (11) yields (13).

\[ [\text{PdCl}_2 \text{H}_2\text{O}) (\text{OH})⁻] = \frac{K₃K₄K₅[B₀-x]}{[\text{H}^+][[\text{Cl}^-]^2 + K₄[\text{Cl}^-] + K₃K₄]} \]

(13)

In order to complete the derivation, it is only necessary to substitute (13) into the rate law (14). The rate law obtained is (6).
\[
\frac{dx}{dt} = k [\text{Pd(Cl)}_2(\text{H}_2\text{O})(\text{OH})^-]
\]  \hspace{1cm} (14)

\[
\frac{dx}{dt} = \frac{kK_3K_4K_5[B_0-x][A_0-x]}{[H^+][[\text{Cl}^-]^2 + K_4[\text{Cl}^-] + K_3K_4]}
\]  \hspace{1cm} (15)

In like manner, the following additional rate laws are obtained.

Reacting species = Pd(\text{Cl})_2(\text{H}_2\text{O})_2

\[
\frac{dx}{dt} = \frac{kK_3K_4[B_0-x][A_0-x]}{[\text{Cl}^-]^2 + K_4[\text{Cl}^-] + K_3K_4}
\]

Reacting species = PdCl_3(\text{H}_2\text{O})^-

\[
\frac{dx}{dt} = \frac{kK_4[B_0-x][A_0-x][\text{Cl}^-]}{[\text{Cl}^-]^2 + K_4[\text{Cl}^-] + K_3K_4}
\]

Reacting species = PdCl_3(\text{OH})^-

\[
\frac{dx}{dt} = \frac{kK_4K_5[B_0-x][A_0-x][\text{Cl}^-]}{[H^+][[\text{Cl}^-]^2 + K_4[\text{Cl}^-] + K_3K_4]}
\]

Reacting species = Pd(\text{Cl})_3(\text{H}_2\text{O})_3^+

\[
\frac{dx}{dt} = \frac{kK_3K_4[B_0-x][A_0-x]}{K_2K_3K_4 + K_3K_4[\text{Cl}^-] + K_4[\text{Cl}^-]^2 + [\text{Cl}^-]^3}
\]

In the following discussion, only PdCl_2(\text{H}_2\text{O})(\text{OH})^- will be considered. The same types of considerations will apply to the above species and the final integrated rate laws for all species will be listed below.

In order to convert equation (6) into an expression which can be subjected to experimental verification one additional modification is
required. It is seen that the unintegrated rate law (6) contains terms involving the instantaneous chloride ion concentration. The chloride concentration at any time is given by (16).

\[ [\text{Cl}^-] = C + 4x + (\text{Cl}^-)_{\text{ion}} \]  

(16)

Where \( C \) = amount of chloride added initially

\[ 4x = \text{amount of chloride formed for each } x \text{ of product formed} \]

\( (\text{Cl}^-)_{\text{ion}} = \text{chloride ion formed in hydrolysis equilibria, i.e.} \)

\( (\text{Cl}^-)_{\text{ion}} = [\text{PdCl}_3(\text{H}_2\text{O})] + 2[\text{PdCl}_2(\text{H}_2\text{O})_2] + \ldots \)

Thus, for every equivalent of Pd metal which is formed, four equivalents of chloride ion result. This decreases the total concentration of Pd(II) present, thus shifting the position of the various ionization equilibria. The amount of chloride added is a constant, whereas the amount of chloride formed due to ionization, equation (16), is a continuously changing parameter. In order to simplify the situation, the assumption is made that only the \( \text{Pd(Cl)}_3(\text{H}_2\text{O})^- \) and \( \text{Pd(Cl)}_2(\text{H}_2\text{O})_2 \) terms contribute significantly to chloride formed by ionization. This simplification seems reasonable on the basis of the stability constants for the various Pd(II) species in solution which indicate that nearly all Pd(II) is accounted for by these terms. The various equilibrium constants in water\(^{59} \) are given in Table 12.

Table 12. Equilibrium Constants for Possible Pd(II) Species

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$K_4^a$</th>
<th>$K_3$</th>
<th>$K_2$</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$4.16 \times 10^{-2}$</td>
<td>$4.54 \times 10^{-3}$</td>
<td>$4.54 \times 10^{-4}$</td>
<td>$4.16 \times 10^{-5}$</td>
</tr>
<tr>
<td>2:1 glyme-water</td>
<td>$2.10 \times 10^{-2}$</td>
<td>$2.10 \times 10^{-3}$</td>
<td>$2.10 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

a. $K_n = \frac{[\text{PdCl}_{(n-1)}][\text{Cl}^-]}{\text{PdCl}_n}$

b. Only $K_4$ was determined in 2:1 glyme-water. Since it was very close to Weed's values it was felt that $K_3$ and $K_4$ would also parallel Weed's values.

In order to obtain an expression for the instantaneous chloride concentration equations (7) and (16) are recast so that they contain only Pd(Cl)$_3$(H$_2$O) terms. Equations (8) and (9) are also employed and the equations obtained are (17) and (18). Solving each of these expressions for Pd(Cl)$_2$(H$_2$O) gives (19) and (20). When these two equations are equated and rearranged, (21), a cubic equation expressing the instantaneous chloride concentration, is obtained.

$$[\text{Cl}^-] = C + 4x + [\text{Pd(Cl)}_3(\text{H}_2\text{O})^-] + 2[\text{Pd(Cl)}_2(\text{H}_2\text{O})_2]$$  \hspace{1cm} (16)

$$[B_0-x] = [\text{PdCl}_4^-] + [\text{Pd(Cl)}_3(\text{H}_2\text{O})^-] + [\text{Pd(Cl)}_2(\text{H}_2\text{O})_2]$$  \hspace{1cm} (7)

$$[\text{Cl}^-] = C + 4x + [\text{Pd(Cl)}_3(\text{H}_2\text{O})^-] + 2K_3[\text{Pd(Cl)}_3(\text{H}_2\text{O})^-][\text{Cl}^-]$$  \hspace{1cm} (17)

$$[B_0-x] = \frac{[\text{Pd(Cl)}_3(\text{H}_2\text{O})^-]}{K_4} + [\text{Pd(Cl)}_3(\text{H}_2\text{O})^-] + K_3\frac{[\text{Pd(Cl)}_3(\text{H}_2\text{O})^-]}{[\text{Cl}^-]}$$  \hspace{1cm} (18)
\[
[PdCl_3(H_2O)^-] = \frac{[Cl^-]([Cl^-] - C - 4x)}{([Cl^-] + 2K_3)} \tag{19}
\]

\[
[PdCl_3(H_2O)^-] = K_4\frac{[Cl^-][B_0-x]}{([Cl^-]^2 + K_4[Cl^-] + K_3K_4)} \tag{20}
\]

\[
[Cl^-]^3 + (K_4 - C - 4x)[Cl^-]^2 + [K_3K_4 - K_4(C+4x) - K_4[B_0-x]][Cl^-] \\
- K_3K_4(C+4x) + 2K_3K_4[B_0-x] = 0 \tag{21}
\]

Rigorous integration of the rate law (6) would involve substituting an analytical expression for the solution of the cubic equation (21) for the instantaneous chloride ion concentration. The resulting form of the cubic equation would be very difficult to integrate. Furthermore, since there are three solutions to the cubic equation one would have to choose that particular analytical expression corresponding to the physically acceptable root. Therefore an approximation for the total chloride concentration was sought.

The approach taken to finding such an approximation was to calculate values for the chloride concentration by solving the cubic equation (21) for various values of the reaction variable, \( x \). Since the coefficients of the cubic equation involve \( B_0 \), and \( C \), this process must be repeated for each kinetic run. In order to do this a computer program was written which solved the equation when given \( B_0, C \) and the \( K \)'s for specified values of \( x \). The program then obtained a least squares fit between the total chloride ion concentration and \( x \), assuming a linear relationship. The results were
Table 13: Least Squares Parameters for Approximation $[\text{Cl}^-] = ax + b$

<table>
<thead>
<tr>
<th>$B_0 \times 10^2$</th>
<th>$C \times 10^1$</th>
<th>$a$</th>
<th>$b \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.0</td>
<td>3.147</td>
<td>3.09</td>
</tr>
<tr>
<td>5.0</td>
<td>0.0</td>
<td>3.267</td>
<td>2.30</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0</td>
<td>3.450</td>
<td>1.39</td>
</tr>
<tr>
<td>2.5</td>
<td>0.1</td>
<td>3.544</td>
<td>2.15</td>
</tr>
<tr>
<td>2.5</td>
<td>0.2</td>
<td>3.615</td>
<td>2.97</td>
</tr>
<tr>
<td>2.5</td>
<td>0.3</td>
<td>3.668</td>
<td>3.83</td>
</tr>
</tbody>
</table>
excellent straight lines with all correlation coefficients
0.9993 or higher. The chloride ion variable in (6) can therefore
be replaced with the linear relationship (22) where \( a \) and \( b \) are

\[
[\text{Cl}^-] = (ax + b) \tag{22}
\]

the slope and intercept of the least squares line calculated
by the computer. Substitution of the approximation (22) into the
rate law (6) gives equation (23).

\[
\frac{dx}{dt} = \frac{kK_3K_4K_5[B_0-x][A_0-x]}{2x[(ax+b)^2 + K_4(ax+b) + K_3K_4]} \tag{23}
\]

This expression can be integrated to give the final form of the
rate law (24). The details of the integration and the rate laws
for other reactive species are discussed in detail in the appendix.

\[
kK_3K_4K_5t = \frac{2}{(B_0-A_0)} \left\{ (QB_0 + RB_0^2 + a^2B_0^3\ln[B_0-x] \right. \\
- (QA_0 + RA_0^2 + a^2A_0^3\ln[A_0-x] + [R(B_0-A_0) + a^2(B_0^2-A_0^2)]x + (a^2/2)(B_0-A_0)x^2 \right\} \tag{24}
\]

A summary of the empirical constants for seven kinetic runs
of interest is given in Table 13. The rate constants obtained from
plots of equation (24) versus time, as well as the rate constants
for other reactive species, are summarized in Table 14.
Table 14. Summary of Rate Constants for Reactive Species Considered

<table>
<thead>
<tr>
<th>$A_0 \times 10^2$</th>
<th>$B_0 \times 10^2$</th>
<th>$C \times 10^2$</th>
<th>$\text{PdCl}_2(H_2O)(OH)$</th>
<th>$\text{PdCl}_3(H_2O)$</th>
<th>$\text{PdCl}_2(H_2O)_2$</th>
<th>$\text{PdCl}(H_2O)_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>6.65</td>
<td>-</td>
<td>0.8</td>
<td>1.0</td>
<td>2.6</td>
<td>7.2</td>
</tr>
<tr>
<td>2.5</td>
<td>4.41</td>
<td>-</td>
<td>1.0</td>
<td>3.6</td>
<td>5.3</td>
<td>6.4</td>
</tr>
<tr>
<td>5.0</td>
<td>2.24</td>
<td>-</td>
<td>1.3</td>
<td>3.3</td>
<td>5.2</td>
<td>1.8</td>
</tr>
<tr>
<td>5.0</td>
<td>2.29</td>
<td>1.0</td>
<td>0.9</td>
<td>2.5</td>
<td>4.0</td>
<td>1.4</td>
</tr>
<tr>
<td>5.0</td>
<td>2.27</td>
<td>2.0</td>
<td>1.2</td>
<td>2.7</td>
<td>5.1</td>
<td>2.5</td>
</tr>
<tr>
<td>5.0</td>
<td>2.27</td>
<td>3.0</td>
<td>0.8</td>
<td>2.3</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>5.0</td>
<td>2.38</td>
<td>-</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

a) Relative rates incorporating equilibrium constants, i.e. $k' = kK_3K_4K_5$

b) $\times 10^2$

c) $\times 10^2$

d) $\times 10^4$

e) $\times 10^4$

f) 0.035 M perchloric acid added
The rate constants in Table 14 for the reactive species PdCl₂(H₂O)(OH) agree within 14%. None of the other possible reactive species give constant rate constants. Hence one may conclude that the reactive species in the reaction is, indeed, PdCl₂(H₂O)(OH). While acceptable, a standard deviation of 14% is somewhat greater than one would like to achieve. Unfortunately it is quite likely that such an error is very nearly unavoidable. Part of the error must come from the experimental method used. Since Beer's Law does not apply to systems in which multiple equilibria prevail, it was necessary to add 2 M NaCl to the aliquots removed from the reaction mixture for analysis. This addition of chloride forces the equilibria entirely to the species PdCl₄⁻ which was analyzed by its absorption at 480 nm. When 2 M NaCl is added to a kinetic sample an emulsion is formed necessitating extraction of the organic material with ether. In the process of extraction it is inevitable that some Pd(II) will be lost. It also seems probable that the form of the rate law itself contributes somewhat to the error, since any error in measuring the reaction variable $x$ is multiplied many times in a rate law of such complexity. Changes in the ionic strength of the medium might also contribute to small errors. Even though 1 M sodium perchlorate solutions were employed, the ionic strength could change by as much as 20%. The rate law takes no cognizance of changes in ionic strength. Although it does not seem possible to analyze the relative contribution of these factors, their cumulative effect might readily account for the observed standard deviation.
CHAPTER III
EXPERIMENTAL

Synthesis of 1,2-dimethylbicyclo[2.2.1]heptane

Conversion of norbornanone to exo-2-methyl-endo-norborneol, I

To an ethereal solution of excess methylmagnesium iodide was added dropwise, with stirring, and ethereal solution of 12.0 g (0.1 mole) of 2-norbornanone. The resulting solution was stirred 12 hr after which it was poured onto an ice-water slurry, extracted three times with ether, the ether washed successively with saturated sodium bicarbonate solution and water, and the ether carefully removed on a fractionating column. The remaining oil was then distilled under reduced pressure on a 15 cm Vigreux column to give 8.3 g of exo-2-methyl-endo-norborneol, I, bp 70-72°/10 mm; reported bp 72-73°/11 mm.

Preparation of 1-methyl-exo-2-acetoxynorborneane, II

To a solution of 15 g of I in 50 ml of glacial acetic acid was added five drops of con sulfuric acid. The reaction mixture was heated for 6 hr on a steam bath, cooled, and diluted with water to a volume of 500 ml. The sulfuric acid was neutralized with sodium bicarbonate, and

the mixture was extracted seven times with ether. The ether layer was washed with water and brine solution and dried over anhydrous magnesium sulfate. The solvent was carefully removed on a fractionating column and the residual oil distilled to give 17 g of 1-methyl-exo-2-acetoxy-3-norbornane, \( \text{bp} \ 70-72^\circ / 10 \text{mm} \); reported \( \text{bp} \ 75-77^\circ / 12 \text{mm} \).

**Preparation of 1-methyl-2-exo-norborneol, III**

To a stirred suspension of 4.0 g of lithium aluminum hydride in 250 ml of anhydrous ether was added dropwise, with stirring, a solution of 17 g of II in 75 ml of dry ether. The mixture was stirred at room temperature for 24 hr. The lithium aluminum hydride was hydrolyzed by adding dropwise 16 ml of a 15% solution of aqueous sodium hydroxide. The resulting mixture was stirred for 8 hr. The ether was filtered with a sintered glass funnel and the ether removed under a fractionating column. The remaining oil was not further purified but was used immediately in the next step.

**Preparation of 1-methyl-2-norbornanone, IV.**

To a stirred, ice cold solution of 10 g of III in 150 ml of acetone (freshly distilled from potassium permanganate) was added dropwise a solution of Jones reagent. The addition was continued until the green reaction mixture turned orange. The reaction was then stirred for 10 min, diluted to 100 ml with water, salted heavily, and extracted with seven 110 ml portions of ether. The ether solution was dried with anhydrous magnesium sulfate, filtered and the solvent removed on a fractionating column. The remaining oil was then distilled on a 15 cm Vigreux column to give 6.5 g of 1-methyl-2-
norbornanone, \( IV \), bp 60-62\(^{\circ}\)/15 mm; reported \( 60-62\^{\circ} /15 \) mm.

Preparation of 1-methyl-2-methylenenorbornane, \( V \), via the Wittig \( 61, 62 \) Reaction

To a vigorously stirring suspension of 36 g (0.1 mole) of methyl-triphenylphosphonium bromide in 150 ml of anhydrous ether under a dry nitrogen atmosphere was added 50 ml of n-butyllithium (22\% by weight) in hexane. To the resulting yellow mixture was added 8.8 g (0.08 mole) of \( IV \), and the reaction mixture, under nitrogen, was refluxed for 68 hr. After cooling, the mixture was poured into water and extracted with ether. The extract was dried over anhydrous magnesium sulfate, filtered, and the ether removed on a fractionating column. The residue was distilled on a spinning band column to give 3 g of 1-methyl-2-methylenenorbornane, \( V \), bp 125-135 \( 61^{\circ} \), reported bp 124-132 \( 62^{\circ} \); and reported bp 130-135 \( 62^{\circ} \). An exact molecular weight was obtained: m/e calcd 122.1095444 , obs 122.1096966.

Preparation of 1,2-dimethylbicyclo[2.2.1]heptane, \( VI \)

To a suspension of 8.0 g of \( V \) in 95\% ethanol was added 100 mg of 5\% Pd on carbon catalyst and the mixture hydrogenated on a Parr hydrogenation apparatus. After the hydrogenation was complete the catalyst was remove by filtration and the solvent removed on a

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fractionating column. The product, 1,2-dimethylbicyclo[2.2.1]heptane, was then purified by preparative glpc on a 10' x 1/4" SF 96 column at a temperature of 150 °. An exact molecular weight was obtained: m/e calcd 124.1251936, obs 124.1250679. The purified hydrocarbon was separated into two peaks by analytical glpc on a 25' x 1/8" 25% silver nitrate, satd ethylene glycol, column on 60/80 Chromsorb W at 0 °. The mixture was 88% endo and 12% exo. The assignment was made by analogy with 2-methylenebicyclo[2.2.1]heptane in which hydrogenation of the exocyclic double bond gives 67% endo and 33% exo-2-methylbicyclo[2.2.1]heptane.

Synthesis of 2,3-dimethylbicyclo[2.2.1]heptane

Conversion of 3-methylnorcammphane-2-methanol, VII, to 2-methyl-3-acetoxy-methylnorbornane, VIII.

To a vigorously stirring, ice cooled, ethereal solution of 14 g (0.1 mole) of VII and 1.1 equivalents of pyridine was added dropwise 7.8 ml (0.11 mole) of acetyl chloride. After the addition was complete the reaction was stored in the freezer for 12 hr. It was then poured onto an ice-water slurry and extracted three times with ether. The combined ether extracts were successively washed with dilute hydrochloric acid solution, saturated sodium bicarbonate, and water, the ether layer dried over anhydrous magnesium sulfate and the solvent removed by distillation on a 15 cm Vigreux column. The product was distilled under reduced pressure to give 13 g of 2-methyl-3-acetoxy-methylnorbornane, VIII, bp 90-93 °/10 mm; reported 89.5-92 °/ 7 mm.
Preparation of 2-methylene-3-methylnorbornane, IX

A pyrolysis column packed with glass beads was heated to 450 °C with a flow of nitrogen through the column at the rate of 300 ml/min and VII was added dropwise to it at a rate of 0.2 ml/min. The condensate was collected in a receiver cooled to -78 °C in an isopropyl alcohol-dry ice bath. After the addition was complete the column was allowed to cool, then rinsed with ether and the washings added to the condensate. The ether solution was washed successively with saturated salt solution, a saturated sodium bicarbonate solution until the aqueous phase was basic, and finally with salt solution until neutral. The ether layer was dried over anhydrous magnesium sulfate, filtered, and the ether distilled. The remaining liquid was distilled under reduced pressure to yield 6 g of 2-methylene-3-methylnorbornane, IX, bp 47-50 °C/25 mm; reported bp 47-52 °C/28 mm. 63

Preparation of 2,3-dimethylnorbornane, X

A suspension of 6 g of IX in 95% ethanol with 100 mg of 5% Pd on carbon catalyst was hydrogenated on a Parr hydrogenation apparatus. After the hydrogenation was complete the catalyst was removed by filtration and the solvent removed by distillation. The remaining liquid was then distilled at atmospheric pressure on a 15 cm Vigreux column to give 5.5 g of 2,3-dimethylbicyclo[2.2.1]heptane, bp 130-140 °C/760 mm; reported bp 130-145 °C/760 mm. The mixture was analyzed

by glpc and found to be 40% exo-endo, 40% endo-endo, and 10% exo-exo.

**Synthesis of trans-2,3-dimethylbicyclo[2.2.2]octane**

**Preparation of 3-methylbicyclo[2.2.2]oct-5-en-2-ylmethanal, XI**

A mixture of 25 g (0.31 mole) of 1,3-cyclohexadiene and 22 g (0.31 mole) of crotonaldehyde was heated in a bomb at 190° for 24 hr. The Diels-Alder adduct was distilled under reduced pressure to give 10 g of 3-methylbicyclo[2.2.2]oct-5-en-2-ylmethanal, XI, bp 81-85°/10 mm; reported bp 88-90°/12 mm.

**Preparation of 2,3-dimethylbicyclo[2.2.2]oct-5-ene, XII**

A 25 ml flask, equipped with a reflux condenser and mechanical stirrer, containing 250 ml of ethylene glycol, 10 g (0.066 mole) of XI, and 10 g (0.2 mole) of 95% hydrazine hydrate was refluxed for 30 min at 130° after which a concentrated solution of 11.2 g (0.2 mole) of aqueous potassium hydroxide was slowly added. The reflux condenser was replaced with a 10 cm Vigreux column and the water and excess hydrazine removed. The condenser was then replaced and the reaction refluxed for two hr at 190°. The flask was then cooled, water added, and the product extracted three times with ether. The combined ether extracts were dried over anhydrous magnesium sulfate, filtered, and the solvent removed on a flash evaporator. The remaining oil was

then distilled on a 15 cm Vigreux column to give 6 g of 2,3-dimethyl-
bicyclo[2.2.2]oct-5-one, XII, bp 160-165 °/760 mm; reported bp 160-
162 °/753 mm. An exact molecular weight was obtained: m/e calcd 136.1251936, obs 136.1250627.

Preparation of trans-2,3-dimethylbicyclo[2.2.2]octane

A 5 g sample of XIII was dissolved in 95% ethanol, 100 mg of 5% Pd on carbon catalyst was added, and the suspension hydrogenated on a Parr hydrogenation apparatus. After the hydrogenation was completed, the catalyst was removed by filtration and the solvent removed by distillation. The product, trans-2,3-dimethylbicyclo[2.2.2]octane was then purified by preparative glpc on a 10' x 1/4" SF 96 column at 130 °. An exact molecular weight was obtained: m/e calcd 138.1408428, obs 138.14102993.

Synthesis of 2-methylbicyclo[3.2.1]octane

Preparation of 2-methylenebicyclo[3.2.1]octane, XV

To a vigorously stirring suspension of 12.1 g (0.034 mole) of triphenylmethylphosphonium bromide in anhydrous ether, under a dry nitrogen atmosphere, was added 160 ml of n-butyllithium (22% by weight) in hexane. to the resulting yellow solution was added

dropwise a hexane solution of 5 g (0.034 mole) of bicyclo[3.2.1]-octan-2-one (available from Aldrich Chemical Co.). The mixture was refluxed 24 hr, cooled, and poured onto an ice-water slurry. The aqueous layer was extracted three times with ether, and the combined extracts dried over anhydrous magnesium sulfate. The solution was filtered and the solvent removed under a fractionating column. The remaining oil, which contained 25% starting material, was purified by preparative glpc on a 10 x 1/4" 20% carbowax on 60/80 Chromsorb W column at 140° to give 2 g of 2-methylenebicyclo[3.2.1]octane, XV. An exact molecular weight was obtained: m/e calcd 122.1095444, obs 122.1096006.

Preparation of 2-methylbicyclo 3.2.1]octane, XVI

A suspension of 2 g of XV in 10 ml of 95% ethanol to which 100 mg of 5% Pd on carbon catalyst had been added was hydrogenated on a Parr hydrogenation apparatus. After the uptake of hydrogen was completed, the catalyst was filtered and the solvent removed by distillation. The product, 2-methylbicyclo[3.2.1]octane, was purified by preparative glpc under the same conditions as described for XV. An exact molecular weight was obtained: m/e calcd 124.1251936, obs 124.249679. The purified material was then separated into two peaks by analytical glpc on a 10% apiezon J on 60/80 Chromsorb W at 100° and a flow rate of 15 ml/min. The mixture was 90% endo and 10% exo.
Synthesis of 3-methylbicyclo[3.2.1]octane

Preparation of 3,4-dibromobicyclo[3.2.1]oct-2-ene, XVII

A dried 300 ml, three-neck flask was equipped with a dropping funnel, a condenser, and a mechanical stirrer. To this apparatus was added 135 g (1.20 mole) of potassium t-butoxide and 58.4 g (0.06 mole) of norbornene dissolved in pentane. Bromoform, 105 ml (0.06 mole) was added dropwise with stirring. The temperature was maintained at 0 ° with an ice-water slurry and an atmosphere of dry nitrogen was maintained. After all bromoform had been added the reaction was stirred for an additional two hours. Then it was poured into water. The pentane layer was removed and the aqueous layer extracted with pentane and the combined pentane extracts dried over anhydrous magnesium sulfate. The pentane was filtered and removed by distillation. The remaining reddish liquid was distilled under reduced pressure with a 15 cm Vigreux column to give 40 g of 3,4-dibromobicyclo[3.2.1]oct-2-ene, XVII, bp 90-95 °/1.4 mm; reported bp 104 °/1.0 mm. The nmr spectrum was identical with that reported in the literature.

Preparation of 3-bromobicyclo[3.2.1]oct-2-ene, XVIII

To a vigorously stirring suspension of 2.4 g (0.05 mole) of lithium aluminum hydride in 150 ml of anhydrous ether was added dropwise with stirring 30.5 g (0.15 mole) of XVII. The resultant mixture

was stirred for 36 hr and then 10 ml of 15% aqueous sodium hydroxide was added dropwise. The solution was then stirred for an additional 12 hr, the ether filtered, dried over anhydrous magnesium sulfate, and distilled. The remaining oil was distilled under reduced pressure to give 11.5 g of 3-bromobicyclo[3.2.1]oct-2-ene, XVIII, bp 50-52°C/1.2 mm; reported  bp 63°C/3.2 mm.

Preparation of 3-methylbicyclo[3.2.1]oct-2-ene, XIX

To a stirred ethereal solution of 25 g (0.07 mole) of cuprous iodide at 0°C under a dry nitrogen atmosphere was added 30 ml (0.07 mole) of ethereal methyllithium. The resulting solution was stirred for 1 hr at 0°C and then 3.0 g (0.016 mole) of XVIII was added and the resulting suspension was stirred for 8 hr and the solution then was poured onto ice and extracted with ether. The ether solution was dried over anhydrous magnesium sulfate, and the ether removed by distillation. The nmr of the remaining oil exhibited resonances at 3.88 corresponding to XVIII and at 4.48 corresponding to XIX. The product was then isolated by preparative glpc to give 1.2 g of 3-methylbicyclo[3.2.1]oct-2-ene, XIX. The nmr showed a vinyl doublet at 4.48 corresponding to the methyl group. An exact molecular weight

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was obtained: m/e calcd 122.1095444, obs 122.1095966.

Preparation of 3-methylbicyclo[3.2.1]octane, XX

A suspension of 1.0 g of XIX in 95% ethanol to which 100 mg of 5% Pd on carbon catalyst had been added was hydrogenated on a Parr hydrogenation apparatus. After the reaction was complete the catalyst was removed by filtration and the solvent removed by distillation. The product, XX, was then purified by preparative glpc on a 10′ x 1/4″ SE 30 column at 130°. The nmr spectrum exhibited no resonances in the low field portion of the spectrum indicating the complete absence of olefin, an observation confirmed by glpc retention times of starting material and product. In addition the nmr showed a doublet at τ9.5 due to the methyl group. The purified material was separated into two peaks on a 100′ squalene capillary column at 50°. The peaks were assigned on the basis of the thermodynamic stability of the equilibrated mixture to be 86% endo and 14% exo-3-methylbicyclo[3.2.1]-octane.

trans-Propenylbenzene

The trans-propenylbenzene used in all kinetic runs was obtained 99% pure from Chemical Samples Co. It was used without further purification.

para-Methoxy-trans-propenylbenzene

para-Methoxypropenylbenzene was available from Aldrich Chemical Co. The trans isomer was obtained from a mixture of cis and trans by
preparative glpc on a Varian Aerograph A 90 P instrument equipped with a 10' x 1/4" SF 96 on 60/80 Chromsorb W column at 130 ° with a flow rate of 15 ml/min.

**para-Methyl-trans-pro phenylbenzene**

A sample of 10 g (0.06 moles) of α-ethyl-para-methylbenzyl alcohol was dissolved in 50 ml of anhydrous pyridine and cooled to 0 ° in an ice-water slurry. To this vigorously stirring solution was added dropwise 20 ml (0.12 moles) of phosphorous oxychloride. The reaction was stirred for 12 hr at 0 °, poured onto ice and extracted with three portions of ether. The combined ether extracts were washed successively with dilute hydrochloric acid, saturated sodium bicarbonate solution, and water. The solvent was removed by flash evaporation and the remaining oil distilled under reduced pressure to give 5.4 g of para-methylpro phenylbenzene, bp 70-75 °/5 mm; reported bp 70-75 °/5 mm. The trans isomer was obtained by preparative glpc as described above.

**para-Fluoro-trans-pro phenylbenzene**

para-Fluoro-trans-propenylbenzene was prepared by the procedure described above. The trans isomer was isolated by glpc again using the same conditions as described above, bp 90-95 °/15 mm; reported bp 99 °/17 mm.

---


Preparation of 2-hydroxy-1-phenyl-1-propylmercuric chloride

A mixture of 1.18 g (0.010 mole) of trans-propenylbenzene and 3.18 g (0.010 mole) of mercuric acetate, 50 ml of acetone, and 50 ml of water was heated at 50 °C in an oil bath. The initially bright yellow solution became colorless after five hours after which the reaction was heated for an additional thirty hours. The reaction was cooled to room temperature. To the cooled reaction mixture was added a solution of 0.8 g (0.02 mole) of sodium hydroxide and 0.11 g (0.02 mole) of solid sodium chloride. The solvent was removed by a rotary evaporator and the remaining material wased with acetone. The acetone solution was filtered and the solvent removed on a rotary evaporator leaving a clear viscous oil. This oil was dried in a vacuum oven for 48 hours. A sample was dissolved in pyridine and its nmr spectrum taken. The product exhibited resonances at approximately $\tau 9.0$ (3 proton quartet), $\tau 4.7$ (1 proton quartet), and $\tau 5.4$ (1 proton multiplet). These resonances are approximate because no internal standard was used in the pyridine solution.

Conversion of 2-hydroxy-1-phenyl-1-propylmercuric chloride to phenylacetone

A solution of 2 g (0.005 mole) of the mercury adduct in 50 ml of 2:1 glyme-water was heated for one hour at 78.5 °C with 1.6 g (0.005 mole) of sodium palladium chloride. The reaction was cooled and the product extracted with ether. The ethereal solution was dried

over anhydrous magnesium sulfate, filtered, and the solvent removed on a rotary evaporator to give phenylacetone. The product was identified by comparison of its glpc retention time with that of an authentic sample.

Preparation of Solutions

Glyme

Reagent grade glyme was refluxed with calcium hydride for 48 hr and then distilled through a 15 cm Vigreux column. Only that portion of the glyme boiling at 85°C was retained.

Water

Only double distilled water obtained from the Ohio State University Lab Stores was used in solvent prepared for kinetic runs.

2:1 Glyme-Water Solutions, 1.0 M in Sodium Perchlorate

A 500 ml volumetric flask was twice filled to the mark with glyme and the glyme poured into a clean, dry, reagent bottle. To this bottle was added 500 ml of water. Since the heat of mixing is substantial, it was necessary to let the glyme-water solution stand for several hours before using. After the solution had reached room temperature a portion was poured into a 1 liter volumetric flask into which 122.4 g of sodium perchlorate had been added. Several hours were required for all of the solid to dissolve after which the flask was diluted to the mark.
Preparations of Solutions for Kinetics and Kinetic Technique

A clean, dry, two-necked flask equipped with a serum stopper was charged with the appropriate amount of olefin. Into this flask was pipetted 50 ml of 2:1 glyme-water. The appropriate amount of sodium palladium chloride was then added and allowed to stand until all of the palladium salt had dissolved, i.e. about five minutes. A 2 ml aliquot of solution was then removed to determine the initial concentration spectrophotometrically. The flask was then fitted with a reflux condenser and immersed in a constant temperature bath at 75.8\degree as measured by a National Bureau of Standards thermometer.

Samples were removed for analysis by means of a 2 ml syringe inserted into the flask via the serum stopper.

In those cases where chloride was added to the solution the technique employed was the same as above except for the fact that the olefin-glyme-water solution was allowed to stand from 12 to 36 hr so that all of the added sodium chloride would dissolve. The palladium salt was then added and the kinetic run started.

Nmr Analysis

The products of the kinetic studies were identified by their nmr spectra obtained on a Varian HA 100 instrument. All spectra were taken in carbon tetrachloride. Since the nmr spectra provided an unambiguous means of identifying all products, further method of analysis were not deemed necessary.
Spectrophotometric Analysis

The kinetics of the reactions studied were obtained by following the disappearance of Pd(II) by monitoring the absorbance of Pd(II) at 480 nm. Each aliquot removed from the reaction vessel was pipetted into a separatory funnel, diluted with 2.0 M sodium chloride solution, and the organic material extracted with ether. The aqueous layer was then drained into a 25 ml volumetric flask which was diluted to the mark with more sodium chloride solution.

Spectrophotometric measurements were obtained on a Beckmann DU spectrophotometer equipped with a Beckmann DU Power Supply. Matched Beckmann 1.0 cm Vydac cells were employed.

Numerical Computations

All calculations were performed on an IBM 360 Model 75 computer. Computer time was supplied by The Ohio State University Computer Center.
APPENDIX

Integration of the Rate Law for $\text{Pd}(\text{Cl})_2(\text{H}_2\text{O})(\text{OH})$

Integration of (23) is based on the method of partial fractions. The denominator of this expression can be written as the sum of two terms. Using (25) in (19) gives (26). First consider the integration of the first term in (26). To facilitate integration the substitutions (27) are made.

\[
\frac{1}{(A_0-x)(B_0-x)} = \frac{1}{(B_0-A_0)} \frac{1}{(A_0-x)} - \frac{1}{(B_0-x)}
\]  

(25)

The inverse relation (27) is also needed.

\[
\begin{align*}
  u &= B_0-x \\
  u' &= A_0-x \\
  du &= -dx \\
  du' &= -dx
\end{align*}
\]  

(27)

Substituting the transformations (28) into the first term of (26)

\[
\begin{align*}
  x &= B_0-u \\
  x &= A_0-u
\end{align*}
\]  

(28)

and collecting coefficients of the same power of $u$ gives (31).

The integration is now straightforward since it has been reduced to a series of polynomial integrations. Integration of (31) and use of the inverse relation (28) gives equation (32). This expression can be simplified by dropping all of the constant terms. This may be done since the integrated rate expression is a linear function of $t$ with slope $k$. Hence, dropping the constant terms affects only the intercept $\beta_2$. 

\[ kK_3K_4K_5t = \frac{2}{(B_0 - A_0)} \int \frac{[x][\frac{(ax+b)^2}{(B_0-x)} + K_4(ax+b) + K_3K_4]}{(B_0-x)} \, dx + \int \frac{[x][\frac{(ax+b)^2}{(A_0-x)} + K_4(ax+b) + K_3K_4]}{(A_0-x)} \, dx \]  

(26)

\[ \int \frac{[x][\frac{(ax+b)^2}{(B_0-x)} + K_4(ax+b) + K_3K_4]}{(B_0-x)} \, dx = \int \frac{-(Qx + Bx^2 + a^2x^3)}{(B_0-x)} \, dx \]  

(29)

where: \( Q = K_3K_4 + K_4b + b^2 \)

\[ R = K_4a + 2ab \]

\[ = \int \frac{\left[ Q(B_0-u) + R(B_0-u)^2 + a^2(B_0-u)^3 \right]}{u} \, du \]

\[ = \int \frac{(QB_0 + RB_0^2 + a^2B_0^3)}{u} \, du - \int \frac{(+ 2RB_0 + 3a^2B_0^2)}{u} \, du \]

\[ + \int \frac{(R + 3a^2B_0)u^2}{u} \, du - \int \frac{a^2u^3}{u} \, du \]  

(31)
\[ = (Q B_0 + R B_0 + a^2 B_0^3) \ln(B_0-x) - (Q + 2R B_0 + 3a B_0)(B_0-x) \]

\[ + \frac{1}{2}(R + 3a^2 B_0)(B_0-x)^2 - (a^2/3)(B_0-x)^3 \]

\[ \int \frac{-[x][ax+b]^2 + K_4[ax+b] + K_4 K_4}{(B_0-x)} \, dx = (Q B_0 + R B_0 + a^2 B_0^3) \ln(B_0-x) + (Q + R B_0 + a^2 B_0^2)x \]

\[ + (R + a^2 B_0)(x^2/2) + (a^2 x^3/3) \]  \hspace{1cm} (33)

\[ \int \frac{[x][ax+b]^2 + K_4[ax+b] + K_4 K_4}{(A_0-x)} \, dx = -(Q A_0 + R A_0 + a^2 A_0^3) \ln(A_0-x) - (Q + R B_0 + a^2 B_0^2)x \]

\[ - (R + a^2 A_0)(x^2/2) - (a^2 x^3/3) \]  \hspace{1cm} (34)

\[ k K_3 K_4 K_5 t = \frac{2}{(B_0-A_0)} \left[ (Q B_0 + R B_0 + a^2 B_0^3) \ln(B_0-x) - (Q A_0 + R A_0 + a^2 A_0^3) \ln(A_0-x) \right. \]

\[ + \left[ R(B_0-A_0) + a^2(B_0-A_0^2)x + (a^2/2)(B_0-A_0)x^2 \right] \]  \hspace{1cm} (24)
of the line and is therefore of no consequence in obtaining the rate constant. Dropping the constants and rearranging leads to equation (33).

The second term in equation (26) is next considered. Except for the minus sign the functional forms of the first and second terms are the same. The result is that the integrated form of the second term can be obtained from (33) by replacing each $B_0$ by an $A_0$ and multiplying the result by $(-1)$. When this is done and the two integrated expressions are combined, rearranged and the necessary cancellation carried out, the integrated rate law (24) is obtained.

The integration of the rate laws derived from Pd(Cl)$_3$ species is somewhat more difficult. It can be seen from the form of these rate laws that there is an additional term in the numerator. This eventually necessitates a separation of the expression into three partial fractions instead of two. Moreover, the coefficients are no longer simply related and the expressions become more involved. Algebraic manipulation shows that there is much cancellation in spite of the formidable appearance of the integrated expressions initially. The coefficients for the expansion into partial fractions are given in equation (35). Table 6 gives the integrated rate laws corresponding to each of the reactive species considered. The definitions below together with the relations in (35) lead to the considerable simplifications of these expressions in Table 6.

$$\frac{1}{(A_0-x)(B_0-x)(ax+b)} = \frac{D}{A_0-x} + \frac{F}{B_0-x} + \frac{F}{ax+b} \quad (35)$$
where \[ D = \frac{-1}{(A_0-B_0)(aA_0+b)} \]
\[ E = \frac{1}{(A_0-B_0)(aB_0+b)} \]
\[ F = \frac{a^2}{(aA_0+b)(aB_0+b)} \]

Definitions for use in Table 16:

\[ Q = K_3K_4 + bK_4 + b^2 \]
\[ R = AK_4 + 2ab \]
\[ S_B = Q + RB_0 + a^2B_0^2 \]
\[ S_A = Q + RA_0 + a^2B_0^2 \]
\[ T = (Q - Rb/a + b^2) \]
\[ RR = K_2K_3K_4 + bK_3K_4 + K_4b^2 + b^3 \]
\[ SS = 3ab^2 + 2aK_4 + aK_3K_4 \]
\[ TT = 3ab^2 + 2aK_4 + aK_3K_4 \]
\[ U_B = RR + (SS)B_0 + (TT)B_0^2 + a^3B_0^3 \]
\[ U_A = RR + (SS)A_0 + (TT)A_0^2 + a^3A_0^3 \]
\[ V = (TT)(B_0-A_0) + a^3(B_0^2-A_0^2) \]
Table 15. Integrated Rate Laws for Other Reactive Species

<table>
<thead>
<tr>
<th>Reactive Species</th>
<th>Integrated Rate Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{PdCl}_3(\text{H}_2\text{O})$</td>
<td>$\left{ -DS_B \ln(B_0-x) - ES_A \ln(A_0-x) + (FT/a) \ln(x+b/a) \right} = kK_4t$</td>
</tr>
<tr>
<td>$\text{PdCl}_3(\text{OH})$</td>
<td>$2\left{ -DB_0S_B \ln(B_0-x) - EA_0S_A \ln(A_0-x) - (bFT/a^2) \ln(x+b/a) \right} = kK_4K_5't$</td>
</tr>
<tr>
<td>$\text{PdCl}_2(\text{H}_2\text{O})_2$</td>
<td>$\frac{1}{(B_0-A_0)} \left{ S_B \ln(B_0-x) - S_A \ln(A_0-x) + a^2(B_0-A_0)x \right} = kK_3K_4t$</td>
</tr>
<tr>
<td>$\text{PdCl}(\text{H}_2\text{O})_3$</td>
<td>$\frac{1}{(B_0-A_0)} \left{ U_B \ln(B_0-x) - U_A \ln(A_0-x) + Vx + (a^3/2)(B_0-A_0)x^2 \right} = kK_2K_3K_4t$</td>
</tr>
</tbody>
</table>

$$K_2 = \frac{[\text{PdCl}(\text{H}_2\text{O})_3][\text{Cl}^-]}{[\text{PdCl}_2(\text{H}_2\text{O})_2]}$$

$$K_5' = \frac{[\text{PdCl}_3(\text{OH})][\text{H}^+]}{[\text{PdCl}_3(\text{H}_2\text{O})]}$$
Integration of Rate Law for "Added Acid"

The rate constant for the reaction in which the acid inhibition was tested by adding 0.035 M perchloric acid was obtained by integration of the following rate law.

\[
\frac{dx}{dt} = \frac{kK_3K_4K_5 [B_0-x][A_0-x]}{([H^+] + [H^+]_{\text{added}}) [Cl^-]^2 + k_3K_4} \quad (36)
\]

Since \([H^+]_{\text{added}}\) is a constant and since the approximation for the instantaneous chloride concentration is still valid, (36) may be rewritten as

\[
\frac{dx}{dt} = \frac{kK_3K_4K_5 [B_0-x][A_0-x]}{(2x+d)((ax+b)^2 + K_4(ax+b) + K_3K_4)} \quad (37)
\]

Where \([H^+] = 2x\), and added acid = d

Equation (37) is seen to be identical to (23) except for the constant, d, in the denominator. Consequently the integration involves two integrals. The solution of the first is equation (24). The second, involving terms in \(A_0\) and \(B_0\) is given in (38) and (39).

\[
\int \left( \frac{[ax+b]^2 + K_4(ax+b) + K_3K_4}{[B_0-x]} \right) dx = \frac{1}{2}a^2(B_0-x)^2 - (2a^2 B_0R)(B_0-x) + S_B \log(B_0-x) \quad (38)
\]
\[
\int \left( [ax+b]^2 + K_4 [ax+b] + K_3 K_4 \right) dx = \frac{-\frac{1}{2}a (A_0-x)^2 + \left(2a^2 A_0 + R\right)(A_0-x)}{[A_0-x]} - S_A \log(A_0-x)
\]

When (24), (38), and (39) are combined and \(d\) set equal to 0.035 (40), the integrated rate law for acid inhibition when the reactive species is \(\text{Pd(Cl)}_2(\text{H}_2\text{O})(\text{OH})^-\), is obtained.

\[
k K_3 K_4 K_5 t = \frac{2}{(B_0 - A_0)} [QB_0 + RB_0 + a B_0 \ln(B_0-x)]^2 + a B_0 \ln(B_0-x) + [R(B_0-A_0) + a (B_0 - A_0)] x + (a^2/2) [B_0 - A_0]^2 x^2
\]

\[
+ \frac{d}{(B_0-A_0)} \left[ \frac{1}{2}a (B_0-x)^2 - (2a B_0 + R)(B_0-x) + S_B \log(B_0-x) \right] = \frac{1}{2}a (A_0-x)^2 + \left(2a^2 A_0 + R\right)(A_0-x) - S_A \log(A_0-x)
\]
REFERENCES


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39. See p. 22.


