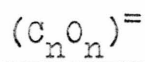


A STUDY OF THE CYCLIC SERIES



A THESIS

presented to the Department of Chemistry of  
Washington and Lee University  
as a completion of honors work under the department.

BY

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on

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VITA

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## INTRODUCTION

When the synthesis of squaric acid ( $C_4O_4H_2$ ) was first published in 1959, the authors referred to the compound as a new cyclobutadieno-acid derivative.<sup>1</sup> Of immediate importance to the experimenters was the indicated resonance stabilization of the anion ( $C_4O_4$ )<sup>-</sup>. Others became interested in this compound and proposed that the anions of the cyclic series ( $C_nO_n$ )<sup>-</sup> would be symmetrical, electron-delocalized anions.<sup>2</sup>

Much work had already been done on the study of cyclobutadiene derivatives with the primary interest being the stabilization of these derivatives through resonant stabilization.<sup>3,4,5</sup> According to Hueckel's Rule of resonant energy, completely filled molecular orbitals are peculiarly stable just as filled atomic orbitals are stable (ie. noble gases). Since there are only four pi electrons in cyclobutadiene, one must predict a triplet ground state which violates the Pauli Exclusion Principle and which does not demonstrate delocalization energy.<sup>3</sup> Cyclobutadiene derivatives inductively stabilize the ring by withdrawing the excess pi electrons from the ring. The delocalization energies for many of these derivatives have been calculated by LCAO molecular orbital calculations.<sup>3</sup>

To determine delocalization energies, one uses the equation for the average energy of a molecular orbital,

which is derived from the Schrödinger wave equation  $H\Psi = E\Psi$ .<sup>6,7</sup> This average energy equation,  $E = \frac{\int \Psi H \Psi d\tau}{\int \Psi^2 d\tau}$  (I), is then minimized to determine the ground state energy (ie. most stable electron distribution). The wave function of each LCAO molecular orbital can be set up in the form  $\Psi_j = C_{j1}\phi_1 + C_{j2}\phi_2 + \dots + C_{jn}\phi_n$  or  $\Psi_j = \sum_{r=1}^n C_{jr} \phi_r$  (II) where  $\Psi_j$  is for molecular orbital and  $\phi_r$  is the wave function of the atomic orbital and  $C_{jr}$  are the weighting coefficients. Thus, substituting equation II into equation I, the equation for average energy of the molecular orbital becomes

$$E = \frac{\int (\sum_r C_r \phi_r) H (\sum_r C_r \phi_r) d\tau}{\int (\sum_r C_r \phi_r)^2 d\tau}$$

$$E = \frac{\sum_r \sum_s C_r C_s \int \phi_r H \phi_s d\tau}{\sum_r \sum_s C_r C_s \int \phi_r \phi_s d\tau}$$

For convenience the following symbols are introduced

$$H_{rs} \equiv \int \phi_r H \phi_s d\tau$$

$$S_{rs} \equiv \int \phi_r \phi_s d\tau$$

Thus we have

$$E = \frac{\sum_r \sum_s C_r C_s H_{rs}}{\sum_r \sum_s C_r C_s S_{rs}} \quad \text{or} \quad E = \frac{\sum_r \sum_s C_r C_s H_{rs}}{\sum_r \sum_s C_r C_s S_{rs}} \quad \text{(III)}$$

The average energy can then be minimized by differentiating equation III with respect to coefficient  $C_t$

$$E \sum_s C_s S_{ts} + E \sum_r C_r S_{rt} = \sum_s C_s H_{ts} + \sum_r C_r H_{rt}$$

which can be reduced to  $E \sum_r C_r S_{rt} = \sum_r C_r H_{rt}$

where  $S_{rs} = S_{sr}$  and  $H_{rs} = H_{sr}$ .

If we have  $n$  atomic orbitals we can minimize the average energy with respect to each coefficient and thus obtain  $n$  simultaneous equations in the form of

$$C_1 (H_{11} - S_{11} \epsilon) + C_2 (H_{12} - S_{12} \epsilon) + \dots + C_n (H_{1n} - S_{1n} \epsilon) = 0$$

The coulombic integral refers to the term  $H_{rr}$ . This term represents the energy of an electron in one  $2p$  orbital. The symbol  $\alpha_0$  represents this energy for a  $2p$  carbon orbital, and  $\alpha_0 + h_x \beta_0$  represents the energy for a  $2p$  heteroatom orbital. The term  $H_{rs}$  where  $r \neq s$  is called the bond integral or resonance integral. This is the energy of interaction of two atomic orbitals and thus for nonbonded atoms  $H_{rs} = 0$  and for bonded atoms  $H_{rs} = \beta$ . Thus, to get proper resonance integrals the two bonding  $2p$  orbitals must have the same nodal plane. There is a proportionality factor times  $\beta_0$  for bonds other than c-c of benzene. Also, in setting up the simultaneous equations it matters whether there is transannular interaction in the smaller ring systems.

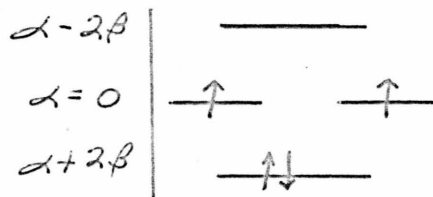
The term  $S_{rs}$  is the overlap integral. Since the molecular orbitals are normalized,  $S_{rr} = 1$ ; and  $S_{rs}$  is assumed to be equal to zero.

The  $n$  simultaneous equations are set up in a secular determinant which is set equal to zero. From this determinant  $n$  energy values are generated as an algebraic sum of a coulombic integral and some fraction of a bond integral. If energy  $\alpha$ , the energy of an electron in one  $2p$  orbital, is assumed to be zero energy, a series of energy levels above and below  $\alpha$  can be set up. A matrix such as the following

would be suitable for cyclobutadiene, where  $x = \frac{(\alpha - E)}{\beta}$ .

$$\begin{array}{|c|c|c|c|}
 \hline
 X & 1 & 0 & 1 \\
 \hline
 1 & X & 1 & 0 \\
 \hline
 0 & 1 & X & 1 \\
 \hline
 1 & 0 & 1 & X \\
 \hline
 \end{array} = 0$$

This matrix generates the values for  $x=2,0,0,-2$ , which indicates the energy levels to be  $\alpha+2\beta$ ,  $\alpha$ ,  $\alpha$ , and  $\alpha-2\beta$ . Since  $\beta$  and  $\alpha$  are negative values, the energy diagram for cyclobutadiene is



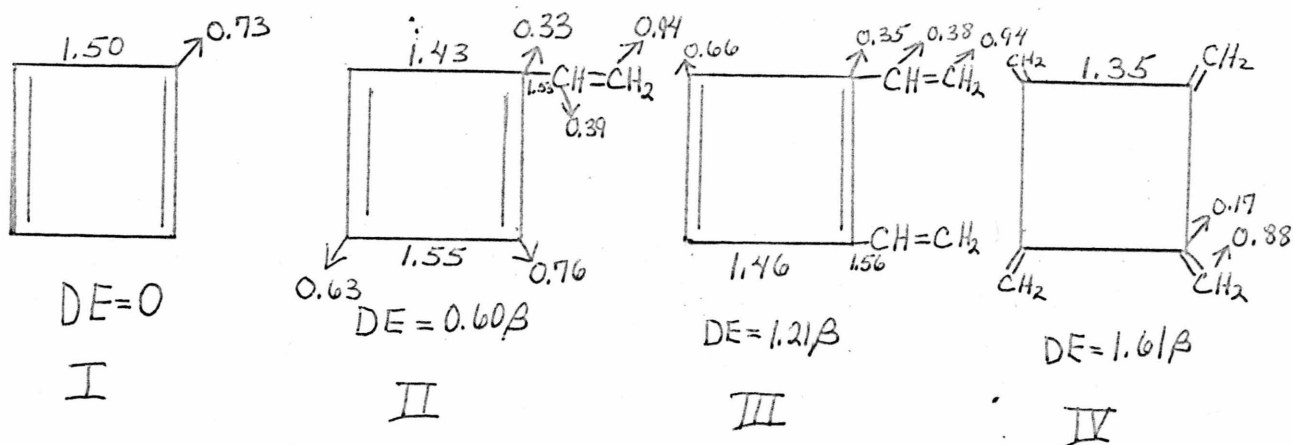
The calculated value for two pi electrons in an ethylene bond is  $E_{\pi} = 2\alpha + 2\beta$ .<sup>6</sup> Therefore, the energy of two isolated ethylene bonds is  $4\alpha + 4\beta$ . The  $E_{\pi}$  of cyclobutadiene equals  $2(\alpha + 2\beta) + 2\alpha$  or  $4\alpha + 4\beta$ . Thus the delocalization energy for cyclobutadiene is zero.

The weighting coefficients can be calculated once the values of  $x$  for the determinant have been generated. The coefficients then are used to calculate the bond order ( $P_{rs}$ ) by adding the products of the number of electrons in a particular orbital ( $n_j$ ), and weighting coefficients ( $C_{rj}$ ) for each atomic orbital that has been linearly combined into the molecular orbital (ie.  $P_{rs} = \sum_j n_j C_{rj} C_{sj}$ ). From this value the free valence of atom  $r$  ( $F_r$ ) can be calculated by subtracting the total energy of an atom used for



bonding  $\sum P_{rs}$  from the maximum available energy of the atom ( $N_{Max}$ ). Thus  $F_r = N_{Max} - \sum P_{rs}$ .

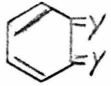
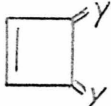
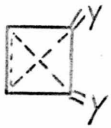

The calculated delocalization energies, bond orders, and free valences for three of the cyclobutadiene derivatives are as follows.



The substantial delocalization energies of II - IV are explainable by the rather high free valence values on the  $\beta$  carbons of vinyl groups in II and III and on the methylene carbons of IV. This high free valence value indicates a pile up of electrons outside the ring, thus bringing the ring pi electron number closer to Hueckel's magic number of 2. The bond orders in the ring of II in comparison to III also indicate a lessening of pi electrons within the ring.

The resonant stability of the cyclopropenyl cation and cyclopentadienyl anion can also be calculated in a similar manner.<sup>3</sup>

Robert West et al determined that the dissociation constants for the cyclic series ( $C_nO_nH_2$ ) declined as the ring size increased (ie.  $C_4O_4H_2 > C_5O_5H_2 > C_6O_6H_2$ ).<sup>2</sup> The calculated dissociation constants were: squaric acid -  $pK_1 \approx 1$ ,  $pK_2 = 2.2$ ; croconic acid -  $pK_1 = 2.17$ ,  $pK_2 = 4.0$ ; and rhodizonic acid -  $pK_1 = 3.15$ ,  $pK_2 = 4.9$ . The strong acidity of squaric acid indicates a more stable anion than the anions of croconic or rhodizonic. Preliminary LCAO molecular orbital calculations of delocalization energy, considering only adjacent atom interaction, determined that although total delocalization energy increases as ring size increases from  $(C_3O_3)^-$  to  $(C_6O_6)^-$ , delocalization energy per atom decreases in the same sequence. LCAO calculations were then carried out on the series.<sup>5</sup>

		DE ( $\beta$ )	
		$\gamma = CH_2$	$\gamma = O$
I)	$\gamma = CHCH = \gamma$	0.47	0.20
II)	$\gamma = CHCH = CHCH = \gamma$	0.99	0.89
III		1.95	1.58
IV		1.21	1.24
V		1.42	1.99
VI		0.96	1.36

Oxygen has a greater withdrawing effect than the methylene group because of increased electronegativity of the oxygen atom over the carbon atom. Thus the coulombic integral of oxygen is greater than that of carbon as expressed by the equation

$$\alpha_{\text{oxygen}} = \alpha_{\text{carbon of benzene}} + h_{\text{oxygen}} + \beta_{\text{benzene}}$$

Since the effective nuclear charge is quite important in determining the coulombic integral, the coulombic integral will vary in magnitude in the same manner as electronegativity does across the periodic table. Thus  $h_x$  is proportional to the difference between the electronegativity of the heteroatom and the electronegativity of carbon. The matrix for the calculation of methylenecyclopropene delocalization energy is

X	1	1	0
1	X	1	0
1	1	X	1
0	0	1	X

$$= 0 = X^4 - 4X^2 + 2X + 1$$

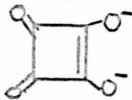
and the matrix that would be used for cyclopropenone is

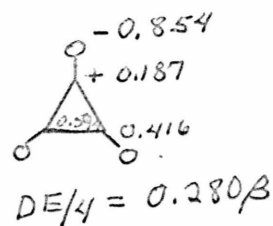
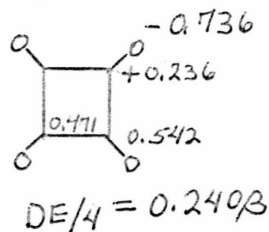
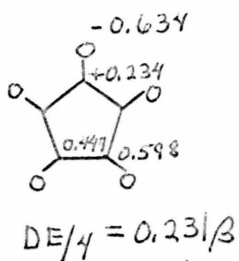
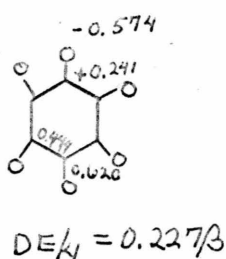
X	1	1	0
1	X	1	0
1	1	X	$\sqrt{2}$
0	0	$\sqrt{2}$	$X+2$

$$= 0 = X^4 + 2X^3 - 5X^2 - 4X + 6$$

where  $X = \frac{(\alpha - E)}{\beta}$ . Since the bond integral is indirectly related to bond length and since the ketone bond is shorter than the carbon to carbon bond of benzene,  $\beta_{C=O} = \sqrt{2} \beta_{C-C \text{ Benzene}}$  in the cyclopropenone matrix.

In the above series compounds I and II have greater resonance for the methylene groups rather than for the ketonic groups, since there is more spreading of the electrons in the methylene derivatives. The ketonic functions of the six-membered ring (III) tend to reduce the number of electrons operating over the centers to below six pi electrons. The excessive withdrawal of the ketonic group, as indicated by its coulombic integral of  $(\alpha_0 + 2\beta - \epsilon)$ , does not allow complete stabilization. The ketonic groups on the four (IV) and three (VI) membered rings stabilize the system by reducing the number of pi electrons involved in the ring. For figure V the authors have included cross-ring interaction considerations in their calculation of delocalized energy. The cross-ring interaction does increase the stability of the system.

The preliminary molecular orbital calculations of Robert West et al<sup>2</sup> were completed in 1963 by the same authors.<sup>8</sup> Localized structures such as  were the structures for which the delocalization energies were calculated. Thus both the coulombic integrals and the bond integrals were different for the  $C=O$  and  $C-O^{\ominus}$  groups. Delocalization energy per number of pi electrons, pi bond orders and atomic charge densities were calculated.



The three membered ring is significantly more stable than the other three members of the series, but angle strain was neglected in these calculations. The c-c bond lengths decrease in size as ring size increases, and c-o bond order increases as ring size increases.

Once having studied the proposed aromaticity of the cyclic series  $(C_nO_n)^{\ominus}$ , the problem involved the preparation and further study of the electronics of this ring system. As an introduction, the rhodizonate  $(C_6O_6)^{\ominus}$  and Croconate  $(C_5O_5)^{\ominus}$  anions were synthesized. Having this background work, several procedures have now been proposed for the synthesis of the squarate anion  $(C_4O_4)^{\ominus}$ . It is proposed that through the synthesis of squaric acid a procedure applicable to the unknown trigonalate anion  $(C_3O_3)^{\ominus}$  can also be developed.

Since the entire series of anions has not been synthesized, a complete study of the energy considerations of the series has not been completed. Developing methods of synthesizing these compounds, however, has lead to extensive and valuable knowledge about their electronic structures which will aid in the preparation of the desired trigonalate anion  $(C_3O_3)^{\ominus}$ .

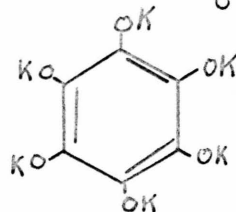
## HISTORICAL

### Hexahydroxybenzene

In 1834, Justus Liebig reported the preparation of Kohlenoxydkalium (potassium hexacarbonyl) from the self-condensation of carbon monoxide in the presence of potassium metal.<sup>9</sup> Although there was much difficulty in determining the empirical formula of this salt due to its rapid oxidation, Liebig finally determined the composition to be  $(C_7O_7K$  or  $C_7O_7K_2)$ .

B.C. Brodie disagreed with Liebig's analysis and stated that the composition was  $(C_2O_2K_2)$ .<sup>10</sup> He used the already known reaction of  $CO + KOH \rightarrow C_2O_2HK$  to support his analysis.

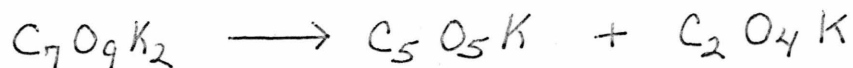
The first to agree with the present day analysis of hexahydroxybenzene were R. Nietzki and Th. Benckiser in 1885.<sup>11</sup> Their empirical formula was  $C_6O_6K_6$ , and they proposed the structure



From this point on, the primary interest in hexahydroxybenzene was its violent oxidation to members of the cyclic series  $(C_nO_n)^{\pm}$ .

Rhodizonic Acid, Croconic Acid, and Related Derivatives

Croconic acid was the first member of the studied cyclic series  $(C_nO_n)^-$  to be isolated. In determining the empirical formula of the potassium salt of hexahydroxybenzene, Justus Liebig supported his formula with his equation for the formation of potassium croconate from the condensation product of carbon monoxide and potassium.<sup>9</sup> The equation was



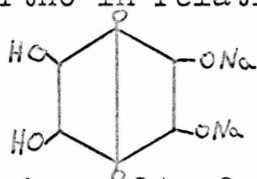
Once again B.C. Brodie disagreed with Liebig and proposed the accurate formula for dipotassium croconate  $(C_5O_5K_2)$ .<sup>10</sup> He also stated that he did not isolate the potassium oxalate but rather a compound of formula  $2(KHO)$ . At this time he warned of the extreme drive for the oxidation of the hexapotassium salt of hexahydroxybenzene, and noted the formation of dipotassium rhodizonate upon addition of water or anhydrous alcohol to the hexapotassium salt. He stated that the ease with which the croconate anion is formed from the rhodizonate salt makes it extremely difficult to determine the proper empirical formula of rhodizonic acid. His formula for the rhodizonate anion was  $C_{10}O_8K_6$ .

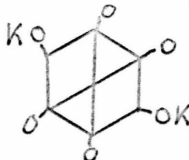
Triquinyl, which was prepared by oxidation of hexahydroxybenzene, is another often used source of the rhodizonate anion. Either chlorine<sup>12</sup> or nitric acid<sup>13</sup> can be used as the oxidizing agent for this transformation, and triquinyl was given the structure

Sulfurous acid will then reduce the triquinyl to rhodizonic acid<sup>13</sup>, or the self-reduction of triquinyl in water with simultaneous oxidation of another molecule of triquinyl will form rhodizonic acid and carbon dioxide.<sup>11</sup>

Disodium tetrahydroxy-p-benzoquinone can also be synthesized from the self-condensation of glyoxal in the presence of a sodium sulfite solution.<sup>14,15,16</sup> Later, in 1942, it was found that the saturated ring of inositol could be oxidized with nitric acid to both tetrahydroxy-p-benzoquinone and rhodizonic acid.<sup>17</sup>

The tetrahydroxy-p-benzoquinone was first prepared by air oxidation of hexahydroxybenzene in the presence of sodium carbonate.<sup>11</sup> Since the two free alcohol groups of disodium tetrahydroxy-p-benzoquinone were not easily oxidized by air, Nietzki and Benckiser felt that the alcohol groups must be ortho in relation to each other. ie.

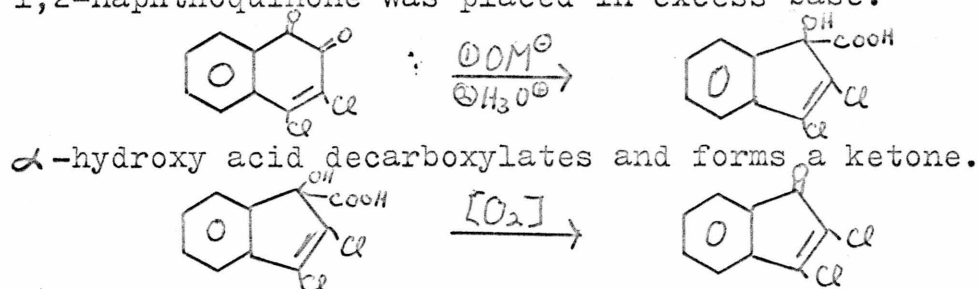


The dipotassium salt of tetrahydroxy-p-benzoquinone in the presence of potassium hydroxide was then oxidized by air to form dipotassium rhodizonate, which was properly analyzed as  $C_6K_2O_6$ .<sup>11</sup> The structure of this salt was determined to be . Hydrochloric acid

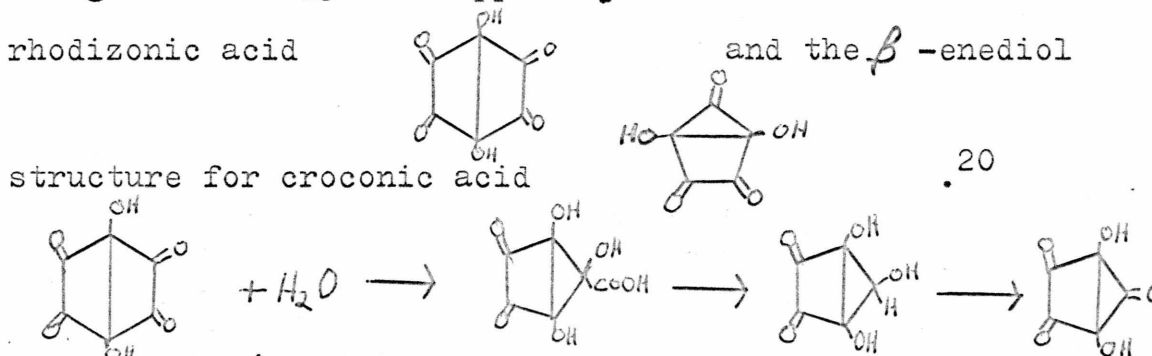
was then used to isolate rhodizonic acid, which was very easily oxidized.



When Th. Zincke and C. Fröhlich published their paper on the reaction of 3,4-dichloro-1,2-naphthoquinone, R. Nietzki took special note of dipotassium rhodizonate in excess potassium carbonate. Zincke and Fröhlich indicated an alpha hydroxy carboxylic acid formation when 3,4-dichloro-1,2-naphthoquinone was placed in excess base.<sup>19</sup> This



Nietzki proposed that when the intense red-yellow color of dipotassium rhodizonate in excess potassium carbonate became yellow, croconic acid hydride ( $C_5H_4O_5$ ) was formed. This intermediate was isolated by warming dipotassium rhodizonate in a dilute potassium carbonate solution until the solution turned light yellow. The barium salt of the croconate hydride precipitated out. This proposed mechanism for the formation of croconic acid from rhodizonic acid was still being used in 1938 to support  $\gamma$ -enediol structure for rhodizonic acid and the  $\beta$ -enediol

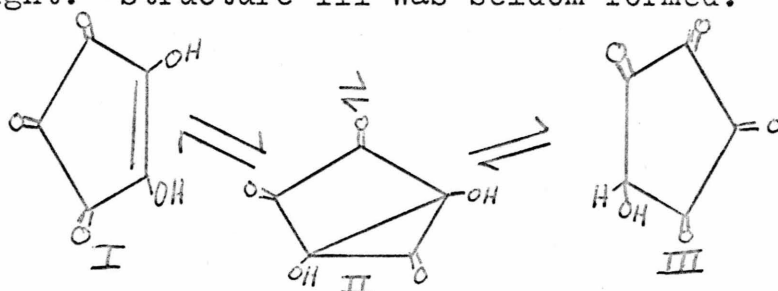


would not titrate with iodine, thus indicating the  $\beta$ -enediol instead of the  $\alpha$ -enediol.<sup>20b</sup>

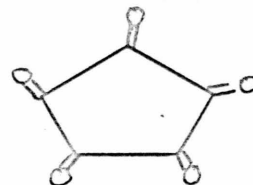
The acidities of the two alcohol groups for both rhodizonic and croconic acids were almost equally strong, as shown by the small difference in their disassociation constants. The small difference in the  $pK$ 's indicated a weak interaction between the alcohol groups and thus the  $\gamma$ -enediol structure for rhodizonic acid and  $\beta$ -enediol structure for croconic acid.<sup>20</sup>

In 1948, Georges Carpeni suggested that it was resonance that caused the weak interaction between the hydroxyl groups of rhodizonic acid.<sup>21</sup> Thus the greater the resonance the less the hydroxyl interaction and the smaller the difference in  $pK$  values. This resonance and not the  $\beta$ -enediol structure was the reason for the similar acidities of the alcohol groups of croconic acid.

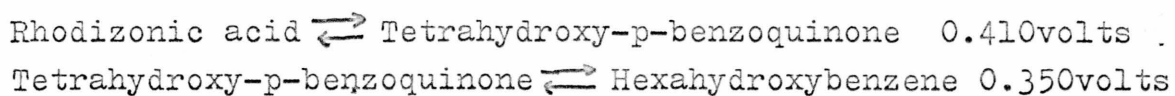
The same year a three way equilibrium was proposed for croconic acid.<sup>22</sup> Structure I would react with iodine, and structure II was present after the acid was delocalized with light. Structure III was seldom formed.

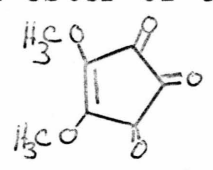


Leuconic acid, the pentaketone, was found to react with sodium carbonate to form sodium mesoxalate and glyoxal<sup>23</sup> which it was felt may support the structure

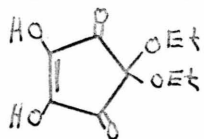


In further support of the equal redox potentials of the two alcohol groups in rhodizonic acid, it was found that there are two bivalent steps in going from rhodizonic acid to hexahydroxybenzene.<sup>24</sup> There was little evidence of semiquinone formation. The redox potentials are

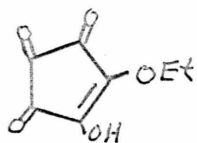


In 1939, the molecular weight determination of the dimethyl ester of croconic acid once again confirmed the formula .<sup>25</sup> The dimethyl ester was found to

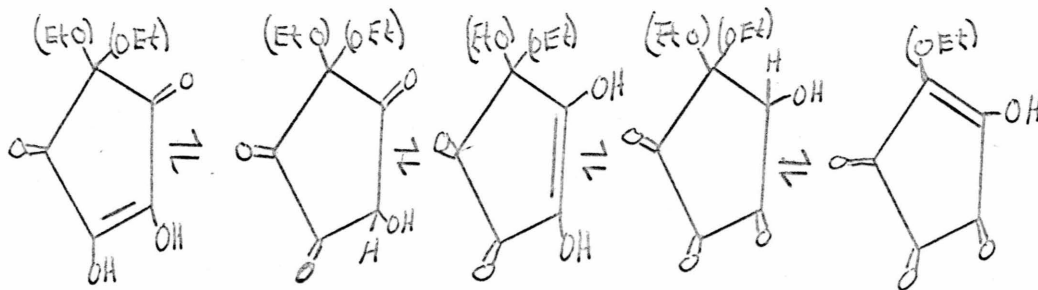
be stable except it was easily hydrolyzed in water or even atmospheric moisture. Croconic acid reacted with alcoholic hydrogen chloride, which yielded diethyl acetal.



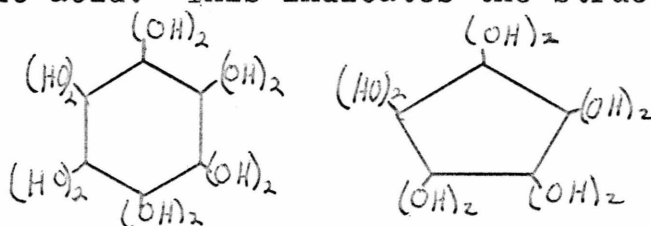
With long boiling in benzene, a tautomeric rearrangement occurs and forms ethyl hemiacetal of croconic acid.



The mechanism for this rearrangement is



Since neither leuconic acid nor triquinyl absorbed in the region from 1500 to 2000  $\text{cm}^{-1}$ , unhydrated carbonyl groups were unlikely for either compound.<sup>26</sup> There is a strong band for both in the region of 3500  $\text{cm}^{-1}$  and other bands characteristic of secondary alcohols. In the region above 1000  $\text{cm}^{-1}$  the spectra of chloral hydrate is similar to that of triquinyl and leuconic acid. This indicates the structures



At about this time the analytical chemists became interested in the rhodizonate salt in the detection of the cations - barium, strontium, and calcium.<sup>27</sup> The instability of the indicator (ie. sodium rhodizonate) to light made it difficult to obtain accurate results.<sup>28</sup> The sulfate anion can also be determined volumetrically in the absence of the phosphate ion.<sup>29,30</sup>

In 1953, potassium croconate was used to determine barium ion to a sensitivity of  $5 \times 10^{-4} \text{M}$ , calcium ion to a sensitivity of  $2 \times 10^{-3} \text{M}$ , strontium ion to a sensitivity of  $4 \times 10^{-3} \text{M}$ , and magnesium ion to a sensitivity of  $1 \times 10^{-3} \text{M}$ .<sup>31</sup> Ethylene diaminetetracetate was used to complex the heavy metal ions that would interfere.

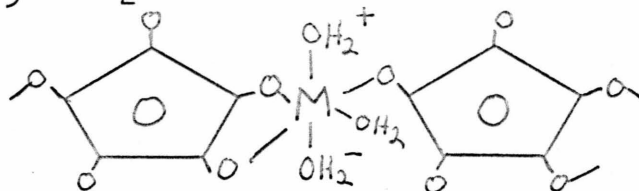
The Russian chemists then became quite interested in turbidimetric determinations for lead ion and sulfuric acid vapors with rhodizonate anion as a complexing agent.<sup>32,33</sup>

Spectrometric determinations of Indium (III) and Gallium (III) were also successful with tetrahydroxy-p-benzoquinone as the indicator.<sup>34</sup>

The absorption curves of croconic acid which were taken in the pH range of 0.6~1.2 do not indicate an isosbestic point.<sup>35</sup> This indicates an equilibrium of three components in this pH region, if Beer's Law has not been deviated from.

A symmetrical structure for the dianions of croconic acid,  $(C_5O_5)^{=}$ , and rhodizonic acid,  $(C_6O_6)^{=}$ , is strongly indicated by their respective Raman and infrared spectra.<sup>2</sup> The five lines observed for the croconate anion in the Raman spectrum agree with the spectrum for a  $D_{5h}$  symmetric structure, except for lacking one depolarized line. Any structure in which all the oxygens are not equivalent would have at least nineteen Raman-active fundamental nodes. The infrared spectra of both anions lack the usual carbonyl peak, but they have a broad band centered near  $1500\text{ cm}^{-1}$  which indicates a similarity to the carboxylate anion.

Unlike ferrocene, the croconate anion does not form sandwich complexes.<sup>36</sup> The croconate ion bonds to divalent transition metals through oxygen. The anion acts both as a monodentate and a bidentate ligand. The complex's formula is  $MC_5O_5 \cdot 3H_2O$  in the structure



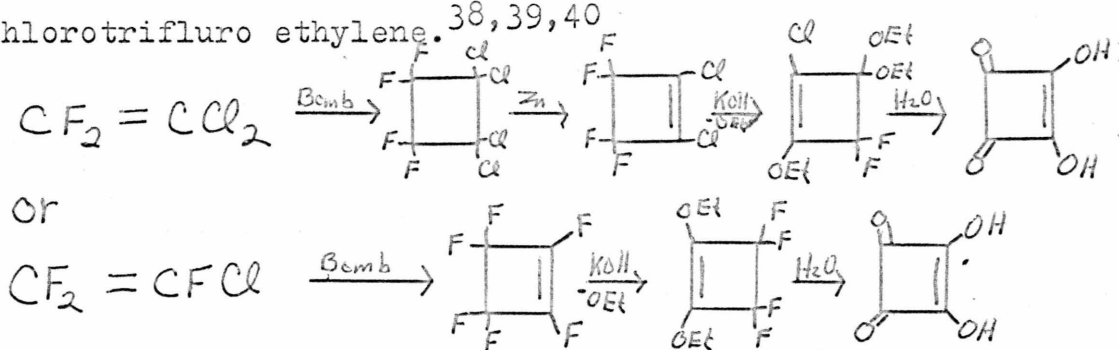
The infrared spectrum of the complex indicates non-coordinated  $\text{C}=\text{O}$  at  $1725 \text{ cm}^{-1}$  and a mixture of  $\text{C}-\text{O}$  and  $\text{C}-\text{C}$  stretching from  $1300$  to  $1700 \text{ cm}^{-1}$ . The complexes of croconate with trivalent metals do not have as constant a formula as the divalent metal complexes. There is a cross linkage between the chains through the hydroxyl group. There is also both coordinated and non-coordinated  $\text{C}=\text{O}$  indicated by infrared spectrum. Both the divalent and trivalent metal complexes should be high-spin complexes; yet the trivalent complex may be a little less paramagnetic than the divalent complex due to antiferromagnetic spin-pairing between the metal atoms.

#### Squaric Acid

In 1959, Sidney Cohen, John R. Lacher, and Joseph D. Park reported the synthesis of dioxocyclobutanediol - squaric acid ( $\text{C}_4\text{O}_4\text{H}_2$ ).<sup>1</sup> The infrared spectrum of the potassium salt indicates that all four oxygen atoms are equivalent. The carbonyl peak of the solid, free acid is not observed at  $1820 \text{ cm}^{-1}$ ; and a broad, intense band occurs from  $1560$ - $1480 \text{ cm}^{-1}$ , which indicate the breathing vibration of  $\text{C}-\text{O}$  of the anion. The  $\text{C}=\text{C}$  absorption also vanishes in the spectrum of the anion. The infrared red of the acid indicated strong hydrogen bonding and both  $\text{C}=\text{O}$  at  $1700$ - $1800 \text{ cm}^{-1}$  and  $\text{C}=\text{C}$  at  $1540$ - $1780 \text{ cm}^{-1}$ . The strong hydrogen bonding also explains the high decomposition

point of  $293^{\circ}$  C. The acid also tests positive for ketoenol by ferric chloride test, and tests positive for alcohol with ceric nitrate test. Unsaturation is also indicated by decoloration of bromine water and permanganate. The carbonyl groups of the acid do not give a phenylhydrazine test.

Squaric acid was prepared from a high pressure self-condensation of 1,2-dichloro-3,4-difluoro ethylene<sup>37</sup> or of chlorotrifluoro ethylene.<sup>38,39,40</sup>



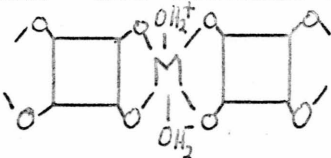
The hydrolysis of the halo or alkoxy derivatives of cyclobutene yield squaric acid due to the high resonance energy of the system.<sup>41,42</sup> Squaric acid is so stable that 50% sulfuric acid at  $100^{\circ}$  C can be used to hydrolyze the diether.

The Raman spectrum of the squarate anion indicated a planar symmetrical structure of  $D_{4h}$  symmetry.<sup>43</sup> Eight lines were observed in the spectrum with one weak line due to an overtone, thus confirming  $D_{4h}$  symmetry with 7 Raman active fundamentals. There are also 4 infrared active fundamentals, as would be expected for a molecule of  $D_{4h}$  symmetry. The Urey-Bradley Force Constant for c-c bond in squarate anion

is less than that for benzene, but it is much greater than for a single bond. The squarate anion force constant approximates the value calculated for ferrocene. Thus the squarate's force constant indicates aromaticity.

Nitric acid oxidizes squaric acid to octahydroxycyclobutane.<sup>42</sup> The structure of this compound is related to the completely hydrated carbonyl groups of triquinyl and leuconic acid. The infrared spectra also agree with the spectra of hydrated triquinyl and leuconic acid.

The absence of a sharp band above  $1600\text{ cm}^{-1}$  in the infrared spectra of divalent transition metal complexes with the squarate anion indicates that all the oxygens are coordinated.<sup>44</sup> Since there still were only four infrared active fundamentals, the  $D_{4h}$  symmetry was not lost in

complexation. The formula is  $MC_4D_4 \cdot 2H_2O$  with the structure . The trivalent metals form

a complex with a formula of  $MC_4O_4(OH)(H_2O)_3$ . Unlike the croconate complex with trivalent metal ions, the carbonyl peak is absent in the infrared absorption. This may indicate the symmetrical cancellation of the carbonyl group. Like the croconate complex, the squarate complex is paramagnetic.

Perchlorocyclobutenone is synthesized from 1-ethoxy pentachloro 1,3-butadiene.<sup>45,46</sup> This chlorocyclicketone can then be hydrolyzed to squaric acid.



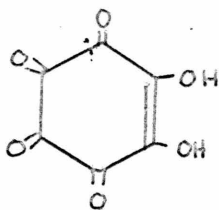
X-ray crystal analysis of the structure of dipotassium squarate-monohydrate indicates that the anions are packed in stacks with the planes of the anions parallel.<sup>47</sup> The anion still has  $D_{4h}$  symmetry. The four carbons are planar and equidistant ( $1.457 \text{ \AA}$ ) and the four oxygen's are planar and equidistant ( $1.259 \text{ \AA}$ ). The anions are  $3.237 \text{ \AA}$  apart which indicates some attraction between the anions because a neutral aromatic molecule is usually  $3.4 \text{ \AA}$  apart.

## DISCUSSION

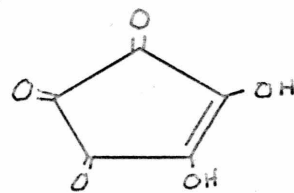
This investigation involves the preparation and structures of compounds of the cyclic series  $(C_nO_n)^{\pm}$ .

The study was centered around four principle compounds and their derivatives. They are the salts of

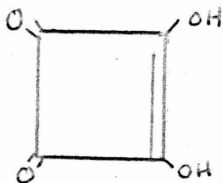
rhodizonic acid,



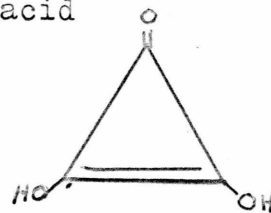
croconic acid,



squaric acid,

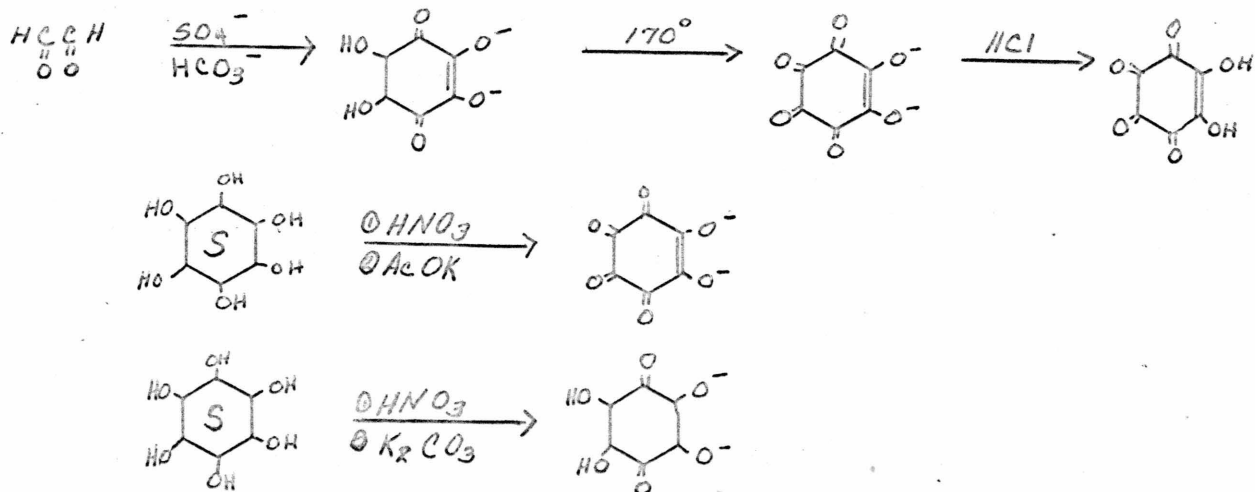


and trigonallic acid

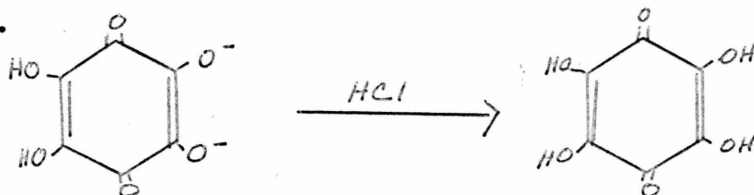


Not only were these compounds studied separately, but their chemistries were studied and compared in the hope of finding a synthesis for trigonallic acid.

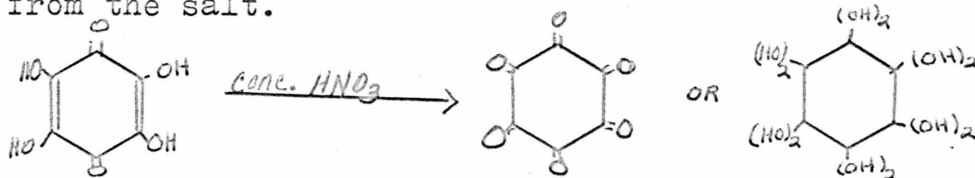
### Rhodizonic Acid and Its Derivatives



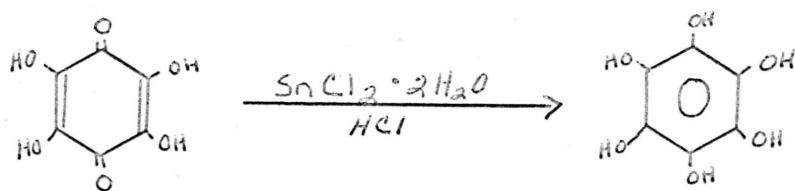
Rhodizonic acid was prepared through the disodium salt of tetrahydroxy-p-benzoquinone from the self-condensation of glyoxal.<sup>15</sup> Both the rhodizionate and the tetrahydroxy-p-benzoquinone salts were also synthesized by the oxidation of mesoinositol.<sup>17</sup> The salt of tetrahydroxy-p-benzoquinone was heated at 170° C for 24 hours to be oxidized to disodium rhodizionate, and from this was obtained the acid dihydrate. A poor yield of the acid dihydrate was obtained since a non-homogeneous solvent, dioxane and pentane, had to be used in its recrystallization. The tetrahydroxy-p-benzoquinone was found to react best when used immediately after preparation, for it was easily oxidized on standing. A pine oil smell was noticed after oxidation. The rhodizionate salt and acid were best stored under nitrogen atmosphere in brown bottles.



This immediate use of the tetrahydroxy-p-benzoquinone salt was even more important in forming the tetrahydroxy compound from the salt.



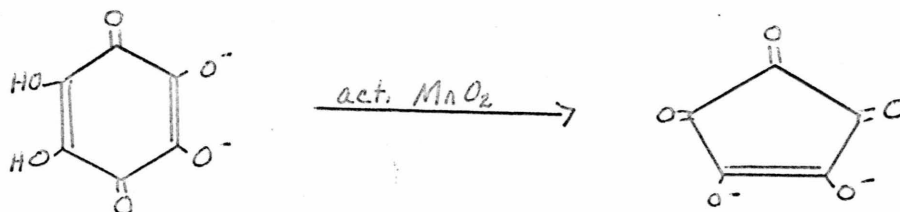
Triquinyl was also prepared from tetrahydroxy-p-benzoquinone. Triquinyl was reacted with BaCl<sub>2</sub>, PbCl<sub>2</sub>, KCl, and NaCl to form the corresponding salts of rhodizonic acid.



To be certain that tetrahydroxy-p-benzoquinone and its salts were the actual compounds present in the previously mentioned reactions, the tetrahydroxy-p-benzoquinone obtained was reacted with stannous chloride dihydrate to form hexahydroxybenzene. The hexaacetate derivative was run on the hexahydroxybenzene to verify the compound.

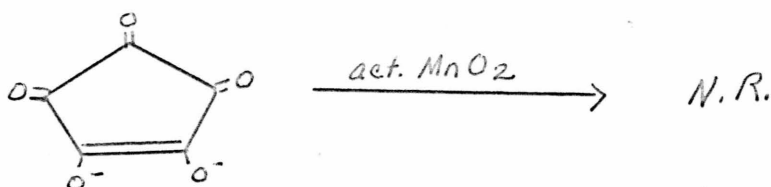
Infrared curves were run of the rhodizonate anion, tetrahydroxy-p-benzoquinone and its anion, and triquinyl.

#### Croconic Acid



Another use of the disodium tetrahydroxy-p-benzoquinone was the preparation of barium croconate.<sup>15</sup> Activated manganese dioxide was used in this oxidation. The salt of the acid was also converted to the acid trihydrate.

#### Squaric Acid



The first attempt to synthesize squaric acid was unsuccessful. This attempt was a parallel of the preparation of croconic acid from disodium tetrahydroxy-p-benzoquinone.<sup>15</sup> It was felt that the oxidation of disodium croconate was unsuccessful because the activated manganese dioxide was not a strong enough oxidizing agent to convert from a five-membered ring to a ring-strained four-membered system. Thus, the starting material, croconic acid, was returned as proven by a mixed melting point of the anhydrous acids.

Another synthesis was undertaken to prepare squaric acid under ordinary conditions of pressure and temperature.<sup>48</sup> The devised plan entailed the formation of hexaethyl 1,1,2,2,3,4-cyclobutane hexacarboxylate from the condensation of diethyl acetylene dicarboxylate and tetraethyl ethane tetracarboxylate in the presence of sodium ethoxide. This ester was then hydrolyzed by hydrochloric acid and heated to 1,2,3,4-cyclobutane tetracarboxylic acid. Then it was proposed to titrate the acid with silver bromide to form the 1,2,3,4-tetrabromocyclobutane. Heat and dilithium carbonate would react with this brominated ring to form the tetrahydroxy ring, 1,2,3,4-tetrahydroxycyclobutane. From this compound squaric acid could be prepared with the use of sulfur dioxide.

During the preparation of diethyl acetylene dicarboxylate, the extreme irritations of the skin which it causes became quite apparent. Thus, in the formation and reaction of it

with tetraethyl ethane tetracarboxylate, strict care should be observed in its handling.

The white precipitate which was formed in the reaction of diethyl acetylene dicarboxylate and tetraethyl ethane tetracarboxylate was hydrolyzed immediately.

A precipitate, melting from 187 to 188° C, was obtained from this hydrolysis. The literature stated that the melting point should have been from 210 to 213° C. Several isomers of 1,2,3,4-cyclobutane tetracarboxylic acid are possible, such as trans, trans, trans, -cis, cis, cis, or cis, trans, cis. The higher melting isomer may have been isolated and reported in the literature, whereas the lower melting isomer may have been isolated now. The three degree literature melting point range also indicated impurities, perhaps the impurity of some lower melting isomer, mixed in the higher melting isomer.

Neutral equivalents were taken, and they proved decarboxylation to have been unlikely, thus eliminating the possibilities of the tricarboxylic or dicarboxylic cyclobutanes.

To further identify the isolated precipitate, pH titrations were run on this acid. The results indicated two titratable hydrogens, for there was one large peak and one moderate-sized peak.

Realizing that the ring may have been hydrolyzed, a mixed melting point was taken with succinic acid. Since there was no melting point depression, the conclusion

was that succinic acid had been isolated. The di-(p-nitrobenzyl) succinate derivative confirmed this.

Reconsidering the synthesis, it was decided that either the reduced pressure concentration used to induce crystallization of the cyclobutane tetracarboxylic acid had hydrolyzed the ring twice or else hexaethyl cyclobutane hexacarboxylate had not been the white precipitate obtained from the reaction of diethyl acetylene dicarboxylate and tetraethyl ethane tetracarboxylate.

The necessity to isolate the hexaethyl ester was apparent and proved that this ester had not been formed.

Having decided that the four carbon member of this series could not be approached through a reaction at ordinary conditions due to the high energy of activation that it was decided must be needed, the tetramethyl ester of cis,trans, cis-1,2,3,4-cyclobutane tetracarboxylic acid was prepared through the ultra-violet light excitation of dimethyl fumarate.<sup>49</sup>

Both piperidine<sup>50</sup> and bromine were used to convert dimethyl maleate to its thermodynamically-stabler isomer dimethyl fumarate. Methylene chloride worked better than acetone as the solvent that was used to make a thin layer on the walls of the container of the fumarate ester in preparation for excitation. Both hydrolysis and saponification were used to convert the ester to the tetra-acid derivative of cyclobutane. In reduced pressure

distilling of hydrochloric acid after hydrolysis is complete, care should be taken not to steam distill too much of the cis, trans, cis 1,2,3,4-cyclobutane tetracarboxylic acid. The reduced pressure distillation should be stopped when a white oil can be seen to condense near the bulb of the thermometer. After filtration it often is best to reduce pressure distill further, and more tetra-acid can be isolated. Since this tetra-acid derivative of cyclobutane is insoluble in ether, acidification of the salt solution is best performed with sulfuric acid. Sulfuric acid is better than hydrochloric acid since sodium sulfate is soluble in sulfuric acid but sodium chloride is insoluble in hydrochloric acid. Thus the inorganic salt will not be isolated with the organic acid if sulfuric acid is used. A mixed melting point of cis, trans, cis 1,2,3,4-cyclobutane tetracarboxylic acid and fumaric acid was taken. Since the tetra-acid derivative decomposes at 235-240° C and fumaric acid slowly decomposes at approximately 300° C, the decomposition of the mixture at 225-230° C indicated the ring had not been broken in conversion from ester to acid. Both the mixture and fumaric acid melting point tubes had rings of sublimed fumarate about half way up the tube. The titration curve of the tetra-acid is similar to that of fumaric (ie. NE for tetra-acid = 56.7 and NE for fumaric = 56.7), but its pk values are approximately  $pk_1 \approx 3.75$  and  $pk_2 \approx 6.05$ , which are higher than fumaric's ( $pk_1 = 3.03$  and  $pk_2 = 4.44$ ).



One must remember that not only are the acid groups 1,4 and 2,3 trans to each other, but 1,2 and 3,4 are in the cis position. Thus the greater difference in pk values of the tetra-acid than the difference in pk values for fumaric may be due to cis hydrogen bonding of maleic-type acids. The acidity of these acid groups is important, for although previous literature states that methyl-lithium reacts like Grignard reagents<sup>51</sup>, Grignard reagents do not form methyl ketones from carboxylic acid groups as methyl-lithium does.<sup>52</sup> The magnesium has a greater affinity for the carboxylate anion than does lithium. Thus magnesium complexes with the dissociated acid and precipitates out, which increases the dissociation of the acid. The lithium cannot form as stable a complex with the anion nor is the lithium carbonate complex believed to be insoluble. The lithium must substitute for the hydroxy group, rather than react with the carboxylate anion.

To study further the electronics of the tetra-acid derivative of cyclobutane, the potassium permanganate test for unsaturation was run on the tetra-acid and fumaric acid. The tetra-acid remained purple on one drop, and fumaric acid showed unsaturation by remaining cherry-brown on fifty drops of potassium permanganate solution. The tetra-acid derivative tested  $S_2$  solubility; whereas fumaric acid tests  $A_1$  solubility. Infrared curves were run on cis, trans, cis-1,2,3,4-cyclobutane tetracarboxylic acid, fumaric acid,

the salts of the two acids and the methyl esters of the two acids. Although the fumaric acid curve did not indicate a conjugated trans system, the methyl ester did have a peak at  $1665\text{ cm}^{-1}$  for conjugated  $\text{c}=\text{c}-\overset{\text{!}}{\text{c}}=\text{o}$ . The methyl ester of cyclobutane carboxylic acid derivative did not indicate unsaturation or conjugation to the  $\text{c}=\text{o}$  bond. The cyclobutane derivatives, though, did have several peaks that were not found in the non-cyclic compounds. The peaks are  $1225\text{ cm}^{-1}$ ,  $845\text{ cm}^{-1}$ ,  $820\text{ cm}^{-1}$ , and  $595\text{ cm}^{-1}$ . These peaks may indicate ring vibrational fundamentals. Several peaks of the tetramethyl derivative that are not in the methyl fumarate curve do match up to peaks of polystyrene. The peaks are  $1375\text{ cm}^{-1}$ ,  $1055\text{ cm}^{-1}$ ,  $955\text{ cm}^{-1}$ ,  $940\text{ cm}^{-1}$ ,  $840\text{ cm}^{-1}$ , and  $735\text{ cm}^{-1}$ . These peaks may indicate that some linear polymerization had also occurred during the ultra-violet light excitation. Several peaks of the cyclic compounds made definite shifts in relation to the corresponding peak of the related non-cyclic compound. A further study of these curves may indicate more about the cyclic electronic arrangement.

To transform this acid to the tetra-bromo derivative by a procedure successful for the cyclobutane carboxylic acid,<sup>53</sup> the tetra-silver salt would have to be formed as an intermediate. To obtain quantitative results in the reaction of the tetra-silver salt, it must be perfectly dry. Thus, as an alternative procedure, the Schmidt reaction

with sodium oxide and sulfuric acid could be run on the tetra basic acid to form the tetra-amine cyclobutane, by a procedure used for cis and trans 1,2-cyclobutane dicarboxylic acid.<sup>54</sup>

Instead of using lithium carbonate and heat to convert the tetrabromo to the tetrahydroxy derivative, sodium nitrite in perchloric acid would have to be used to convert the tetra-amine to the tetrahydroxy derivative.<sup>55</sup> However, recently a procedure for the conversion of the carboxylic acid group through a methyl ketone derivative to an alcoholic derivative of cyclopropane has been published.<sup>52</sup> This procedure predicted a better yield than either the amine or bromo conversion to hydroxy derivatives.

An acid such as nitric acid, which oxidized inositol to rhodizonic acid, or perhaps a method similar to the oppenauer oxidation<sup>56</sup> could be used to form squaric acid. The drive toward the formation of the stable anion should enhance the reaction.

The tetrahydroxy derivative of cyclobutane is also being approached through the ultra-violet light excitation of vinylene carbonate.<sup>57</sup> The use of acetone as a sensitizer has been suggested. An ultra-violet light absorption curve must be run on the vinylene carbonate because the compound is believed to be polymerizing into a chain rather than dimerizing into a ring. The infrared curve of the polymer does not indicate any carbonyl groups to be present, but

there appears to be much OH stretching. If the ultra-violet spectrum is run, a filter can be used to restrict the incident wave length to the proper region for c=c absorption and exclude the c=o absorption. The linear polymer may have a structure similar to polyvinyl alcohol, for this would indicate a loss of carbon dioxide which is possible if the c=o bond is excited. A shorter period of excitation may help; but both starting material and polymer (but no tetrahydrocyclobutane) have been isolated upon shorter periods of excitation.

#### Trigonallic Acid

Trigonallic acid, which has never been synthesized, was approached through the cyclopropane tricarboxylic acid derivative by a method related to the cyclobutane tetracarboxylic acid derivative for squaric acid.

Tetraethyl 1,2,3-cyclopropane tetracarboxylate has been prepared by the condensation of sodium malonate and diethyl dl-dibromosuccinate.<sup>58</sup> The bromination of diethyl maleate was used to obtain this ethyl ester of dibromosuccinic acid. Although about half of the bromination product was the diethyl meso-dibromosuccinate, this isomer of the desired dl-dibromosuccinate is a solid whereas the dl-isomer was a liquid. Thus filtration easily separated the isomers. The condensation went smoothly, and the ester was easily isolated by reduced pressure distillation.

Hydrolysis was attempted, and a yellow oil was isolated after the reduced pressure distillation of the hydrolyzing acid. The tetra-acid cyclopropane was reported as a solid, but neither porcelain plate nor sublimation could isolate a solid. The hydrolysis had taken several hours for all of the organic layer to become soluble in the acid layer (ie. for hydrolysis to be completed). There were two possibilities: (1) the excessive period of hydrolysis required for the ethyl ester may have cleaved the ring; or (2) the acid had been steam distilled during reduced pressure distillation. The first possibility was decided upon; and the procedure was attempted with dimethyl maleate, for it was felt that methyl esters generally are easier to hydrolyze. The attempt to brominate this ester merely formed dimethyl fumarate as proven by a mixed melting point. The literature states that if the reaction is carried out in the dark isomerization will not occur<sup>59</sup>, but the addition of bromine was carried out with a towel around the flask and then the flask was stored in the dark.

Bromination of maleic anhydride was attempted, but a very poor yield of  $\alpha, \alpha'$ -dibromosuccinic anhydride was isolated.

Since the final product after the condensation of the proposed diethyl dl-dibromosuccinate had a refractive index and a density almost the same as for diethyl fumarate, the boiling points were compared. Diethyl fumarate boils at

218.4° C <sup>60</sup>, but the proposed tetraethyl 1,1,2,3-trans-cyclopropane tetracarboxylate distilled at 150-155° C at 0.7 mm Hg (ie.  $\approx$  340° C atmospheric pressure). This final product does not decolorize potassium permanganate solution. When one considers the proposed diethyl dl-dibromosuccinate, it gives a beilstein test for bromine and its boiling point was 137-138° C at 11 mm Hg (ie. 270° C atmospheric pressure). Infrared curves were run on the proposed dimethyl dl-dibromosuccinate, diethyl dl-dibromosuccinate, and 1,1,2,3-trans tetraethyl cyclopropane tetracarboxylate. The dimethyl dl-dibromosuccinate curve was identical to a known dimethyl fumarate curve. A known dimethyl maleate curve was also run and had a peak at 1625 cm<sup>-1</sup>, which indicated unsaturation in conjugation to the ester carbonyl. Neither the diethyl dl-dibromosuccinate curve nor the curve of the tetraethyl derivative of cyclopropane indicated the unsaturation. Bromine was also indicated in the dibromosuccinate curve. With this data in mind, and having recently discovered that the tetra-acid cyclobutane derivative was being steam distilled during its isolation, the diethyl dl-dibromosuccinate method was returned to. The tetraethyl ester derivative of cyclopropane has been isolated again, but neither hydrolysis nor saponification were attempted until further study of this compound through other spectrometric methods can be carried out.

## EXPERIMENTAL

### I. RHODIZONIC ACID

#### A. Dipotassium Rhodizonate

Ten grams of anhydrous meso-inosital was reacted with 25 ml of concentrated nitric acid. The reaction was stirred continuously for three hours in a water bath at 64° C. A brown gas evolved after 15 minutes. The solution was then diluted with 100 ml of water, potassium acetate added until one drop produced permanent yellow color, and aerated for one hour in the dark. The salt was filtered, dried, and stored. The yield was 2.5 grams. The sample was kept in the dark and under nitrogen to prevent oxidation.

#### B. Dipotassium Salt of Tetrahydroxy-p-benzoquinone

The procedure is the same as for dipotassium rhodizonate, but potassium carbonate is used instead of potassium acetate. The yield was 1.0 grams.

#### C. Disodium Salt of Tetrahydroxy-p-benzoquinone

A solution of 240 g of anhydrous sodium sulfite and 90 g of sodium bicarbonate in 1800 ml of water was heated to 45° C. A three-liter, three-necked flask (with one neck

connected to an aspirator, one for an air hose, and one for a thermometer) was used. After adding 360 g of 30 per cent aqueous solution of glyoxal, air was run through without heating. After one hour, the solution was heated to 90° C and then the aeration was stopped. Next, the solution was heated to boiling and then cooled to room temperature overnight. The precipitate was filtered and placed in a vacuum desiccator in the dark. The yield was 9.0 grams.

Note: If this salt begins to smell like pine oil, it most likely has oxidized.

D. Disodium Rhodizonate

One gram of disodium salt of tetrahydroxy-p-benzoquinone was heated in an oven at 170° C for 24 hours. The solid was oxidized to disodium rhodizonate. The yield was approximately one gram.

E. Rhodizonic Acid Dihydrate

The one gram of disodium rhodizonate was suspended in 20 ml of warm 2.5-N hydrochloric acid and 0.1 g of decolorizing carbon. The solution was cooled and concentrated in a vacuum at 35° C. The solution was filtered and the precipitate was added to 20 ml of dioxane at 80° C. The solution was stirred for five minutes and then filtered. The filtrate was cooled to 20° C and pentane was added until



turbidity. The solution was concentrated to a thick curd and the precipitate was isolated as the acid dihydrate. A very poor yield of 0.04 grams was obtained.

F. Tetrahydroxy-p-benzoquinone

Five grams of crude disodium salt of tetrahydroxy-p-benzoquinone was dissolved in 104 ml of 2.5-N hydrochloric acid. Glistening blue-black crystals were filtered from the solution and bottled as tetrahydroxy-p-benzoquinone. The yield was 3.0 grams.

Note: Crude means reacted immediately after filtered.

G. Hexahydroxybenzene

Ten grams of stannous chloride dihydrate was added to a solution of 1 g of tetrahydroxy-p-benzoquinone in 20 ml of 2.4-N hydrochloric acid. When the red color disappeared and grayish crystals formed, 25 ml of 12-N hydrochloric acid was added. The solution, which was stirred constantly, was heated to boiling. Then the solution was removed from the hot plate and 60 ml of 12-N hydrochloric acid was added to it. The solution was cooled in the refrigerator overnight. The filtered precipitate was dissolved in 45 ml of 2.4-N hydrochloric acid with 0.3 g of stannous chloride dihydrate and 0.1 g of decolorizing carbon. The solution was filtered while hot, and 100 ml of 12-N hydrochloric

acid was added to it. The solution was cooled in the refrigerator overnight. The precipitate was collected by filtration under nitrogen, washed with 10 ml of cold 1(ethanol) : 1(2N HCl), and dried in a vacuum desiccator. The hexaacetate derivative was run and the derivative's melting point was 203-204° C. The yield was 0.6 grams.

#### H. Triquinyl

One gram of tetrahydroxy-p-benzoquinone was added to 10 ml of concentrated nitric acid in 2.5 ml of water at 10° C. (The addition should be slow.) After five minutes of stirring, 3 ml of water were added, and the solution was cooled on ice for three hours. The white precipitate was collected, washed with ice water and acetone-ether mixture, and dried in air. The melting point was 96-97° C (decomposition). The literature melting point is 99-100° C (decomposition) after one recrystallization. The yield was 0.9 grams.

#### I. Infrared Curves

Infrared curves were run of the rhodizonate anion, tetrahydroxy-p-benzoquinone and its anion, and triquinyl.

## II. CROCONIC ACID

### A. Activated Manganese Dioxide

Two hundred and fifty grams of manganese carbonate was heated at 300-310° C for 13 hours. The solid was cooled and added to 400 ml of water with 80 ml of concentrated nitric acid until carbon dioxide no longer was evolved. The solution was allowed to sit for 45 minutes. Then the solution was filtered, washed with water, and the precipitate was dried at 150-160° C for 24 hours. The manganese dioxide can be reactivated by heating at 150-160° C for 24 hours.

### B. Barium Croconate

Eight grams of crude disodium tetrahydroxy-p-benzoquinone and 22 g of active manganese dioxide were stirred into a solution of 16 g of sodium hydroxide in 480 ml of water. After five minutes the solution was heated to reflux for 45 minutes. One should watch for bumping. After reflux, the solution was filtered and the manganese dioxide was washed with 320 ml of hot water. The combined filtrates were added to 84 ml of concentrated hydrochloric acid. A solution of 20 g of barium chloride dihydrate in 60 ml of water was added to the filtrates. The yellow precipitate was then filtered and air dried. The yield was 7.5 grams.

C. Sodium Croconate

Six grams of barium croconate was added slowly to 50 ml of 10 per cent aqueous solution of anhydrous sodium carbonate. The solution was boiled for five minutes, filtered, and washed with hot water. Seven milliliters of glacial acetic acid was added to the combined filtrates. The sodium croconate precipitate was isolated by filtration. A good yield was obtained by adding 95 per cent ethanol to the filtrate. The total yield was 4.9 grams.

D. Anhydrous Croconic Acid

One gram of barium croconate was added to 4 ml of sulfuric acid at 60° C. The solution was stirred. The barium sulfate precipitate was filtered and washed with 2 ml of hot water. The combined filtrate and wash were evaporated to dryness. The residue was redissolved in 1 ml of ethanol and 3 ml of dioxane. This solution was concentrated by evaporation until a precipitate formed upon cooling. Benzene was then added to the warmed solution until turbidity. The solution was then left in the refrigerator overnight. The precipitate was filtered and then heated at 120° C for four hours. Decomposition took place from 148-150° C. The yield was 0.2 grams.

### III. SQUARIC ACID

#### A. First Attempted Synthesis

3.5 grams of disodium croconate and 4.5 grams of re-activated manganese dioxide was stirred into a solution of 4.0 grams of sodium hydroxide in 90 ml of water. The rest of the procedure was the same as for barium croconate. Four grams of dibarium croconate was isolated as proven by conversion to the anhydrous acid by the same procedure as for the barium croconate. The acids showed no melting point depression.

#### B. Diethyl Acetylene Dicarboxylate

Five grams of monopotassium salt of acetylene dicarboxylic acid was added to 24 ml of water and 6 ml of concentrated sulfuric acid. The solution was extracted with five 10 ml portions of ether. The ether was stripped from the solution, and an oily phase was left. When cooled, 3.9 g of precipitate formed. The solid was dissolved in 15 ml of absolute ethanol. The solution was saturated with hydrochloric gas. The solution was then extracted with five 10 ml portions of dichloromethane. The extract was washed with 5 per cent sodium bicarbonate until carbon dioxide was no longer evolved. The dichloromethane was removed by reduced pressure. The product was distilled at 25 mm Hg pressure at 120-130° C. The yield was 1.2 grams.

More runs were made with proportionately larger quantities.<sup>61</sup>

C. Tetraethyl Ethane Tetracarboxylate

A solution of 4.6 g of sodium in 110 ml of absolute ethanol was added to 32 g of chilled malonic ester. Approximately 300 ml of ether was added, and then 25.4 g of iodine dissolved in ether was added to the solution. The solution was washed with water. The ether layer was then washed with dilute sodium thiosulfate until the layer became colorless. The oil was solidified overnight. The solid was then recrystallized from an ethanol-water pair. The melting point was 74-74° C after recrystallization. The literature stated that the melting point should be 76° C. The yield was 20 grams.<sup>62</sup>

D. Attempted Synthesis of Hexaethyl 1,1,2,2,3,4-Cyclobutane Hexacarboxylate

A solution of 6 g of diethyl acetylene dicarboxylate and 10 g of tetraethyl 1,1,2,2-ethane tetracarboxylate in 3 ml of absolute ethanol was warmed to 45° C under anhydrous, stirred conditions. Three tenths of a gram of sodium dissolved in 4.2 ml of absolute ethanol was added to the solution dropwise and with rapid stirring. The solution turned brown and was refluxed 3 hours with stirring. The solution was poured into 20 ml of 3-N hydrochloric acid. It was then extracted with ether. The ether was stripped,

and the residue was added to 40 ml of 80 per cent ethanol. The solution was left overnight in the refrigerator. The melting point of the isolated product was 75-76° C. The reported melting point was 78° C.<sup>63</sup> The yield was 4.8 grams. A later mixed melting point with tetraethyl ethane tetracarboxylate gave no melting point depression.

E. Attempted Synthesis of 1,2,3,4-Cyclobutane Tetracarboxylic Acid

A solution of 4.8 g of the proposed hexaethyl 1,1,2,2,3,4-cyclobutane hexacarboxylate in 48 ml of concentrated hydrochloric acid was refluxed for two days. Care should be taken to use a long column, for hydrochloric gas can escape. The refluxed solution was concentrated, and a precipitate was isolated that melted at 187-188° C. The neutral equivalent was found to be 55.7. A mixed melting point was taken with succinic acid, and there was no melting point depression. A titration curve was run with 0.1-N sodium hydroxide. The titration curve indicated two titratable hydrogens. The conclusion was that succinic acid was the isolated precipitate. The di-(p-nitrobenzyl) succinate derivative confirmed this.<sup>60</sup>

F. Dimethyl Maleate

Sixty grams of maleic anhydride was added to 100 ml of methanol and 5 ml of concentrated sulfuric acid. This mixture was refluxed for  $3\frac{1}{2}$  hours on a steam bath. Approximately 60 ml of excess methanol was distilled off. Then a little water and solid sodium carbonate was added to the pot residue to neutralize the sulfuric acid. The solution was extracted with ether and dried over sodium sulphate. Approximately 60 grams was distilled at  $204-210^{\circ}$  C.<sup>64</sup> The ethyl ester was made by a similar procedure except absolute ethanol instead of methanol was used.

G. Diethyl Fumarate

The 60 grams of methyl maleate was isomerized with 16 ml of piperidine. The reaction was very exothermic, so precautions had to be taken to collect the methyl fumarate that sublimes. The white crystals were dissolved in ether and then washed with 5 per cent hydrochloric acid to remove the piperidine. The ether was then distilled off, and then the solid was recrystallized with ethanol. The melting point was  $102-103^{\circ}$  C, which was the melting point stated by the literature.<sup>60</sup> The yield was 12.0 grams.



H. Tetramethyl cis,trans,cis 1,2,3,4-Cyclobutane  
Tetracarboxylate

Ten grams of dimethyl fumarate was dissolved in just enough (approximately 20 ml) methylene chloride to completely dissolve the ester. The methylene chloride evaporates faster than the suggested acetone.<sup>49</sup> With swirling the sample vessel on top of a steam bath, a thin layer of dimethyl fumarate was deposited. This was then excited by the mercury vapor arc ultra-violet light (Hanovia) for 24 hours. The reaction vessel was kept satisfactorily cooled from 20-23° C throughout the reaction by running water through the jacket. The water pressure will vary and must be checked. The reaction vessel was also placed in a large beaker of water. After the excitation, 30 ml of benzene was added to the reaction vessel to wash the crystals out of the vessel into a buchner funnel to be filtered. The solid was washed with 30 ml portions of benzene until the solid that remained in the buchner funnel melted from 144-145° C. 5.15 grams of unreacted methyl fumarate was reisolated from the benzene wash solution. The yield of the tetramethyl ester derivative of cyclobutane was 4.2 grams.

I. Cis,trans,cis 1,2,3,4-Cyclobutanetetracarboxylic Acid

1. Hydrolysis

The 1.05 grams of tetramethyl ester was added to 80ml of concentrated hydrochloric acid. The solution was refluxed for  $\frac{1}{2}$  hour and then the solution was reduced pressure distilled. After 58 ml of hydrochloric acid had been reduced pressure distilled, a white oil was noticed near the thermometer. The solution was filtered; and 0.1 grams of acid, which decomposed at 225-230° C, was isolated. The reduced pressure distillation was continued on the filtrate until steam distillation of the acid was indicated again ( $\approx$  11 ml more distillate). Another 0.25 g of the tetra-acid was isolated. The melting point was 230-232° C (decomposition). This continued until total yield was 0.53 grams.

2. Saponification

The 2.81 grams of tetramethyl ester was mixed with 80 ml of 25 per cent sodium hydroxide. The solution was refluxed for three hours. The solution was foamy and still had solid on top of the foam after the reflux. This solid was filtered, and 0.80 grams was isolated. Concentrated sulfuric acid (3.0 ml) was added to 0.2 grams of the precipitate. A white solid formed upon evolution of heat, and the solution was filtered. The 0.16 grams of precipitate melted from 229-232° C (decomposition).

3. Mixed Melting Points

Mixed melting points were taken with fumaric acid for both isolated acids and both gave melting point depressions. A mixed melting point of the two isolated acids did not give a melting point depression. The tetra-acid cyclobutane derivative was titrated with 0.0895-N sodium hydroxide. The neutral equivalent was 56.7.

J. Attempted Synthesis of Cis,trans,cis 1,2,3,4-Tetrahydroxy Cyclobutane\*

Vinylene carbonate (1.0 ml) was dissolved in 12 ml of acetone. The solution was excited for 24 hours with cooling. A brown precipitate (0.05 grams), which would not dissolve in acetonitrile as the literature stated, was filtered from the solution.<sup>57</sup> The crystal was reported to sublime at 150° C and decompose at 320° C. This isolated precipitate did neither. The distillation of acetone from the filtrate only reisolated vinylene carbonate. The attempt to hydrolyze the adduct with 0.7 ml of 1-N sodium hydroxide by heating for 20 minutes caused no change. Excitations for periods of 12 and 5 hours had no better results.

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\* The author wishes to express thanks to B.B. Bernard who made several of these runs.

K. Infrared Curves

Infrared curves were run on dimethyl maleate, dimethyl fumarate, tetramethyl cis,trans,cis 1,2,3,4-cyclobutane tetracarboxylate, fumaric acid, cis,trans,cis 1,2,3,4-cyclobutane tetracarboxylic acid, disodium fumarate, tetrasodium cis,trans,cis 1,2,3,4-cyclobutane tetracarboxylate, and the polymer from vinylene carbonate excitation.

L. Attempted Synthesis of Methyl Lithium

1.72 grams of lithium metal was cut into 23 pieces and was added to 30 ml of anhydrous ether.<sup>65</sup> 16 grams of methyl oxide in 30 ml of anhydrous ether was added slowly to the lithium ether mixture. The solution was refluxed on steam bath for 12 hours under anhydrous conditions. The solution turned yellow in the beginning and then the yellow disappeared as a gray precipitate formed. The ether layer did not appear to have lowered very much during reflux. At the end of the reflux most of the lithium metal was reisolated and weighed. The weight was 1.69 grams. When weighing the lithium metal after the reaction, the ether in the weighing flask turned yellow. The methyl lithium is the reagent necessary to convert the tetra-acid to the tetramethyl ketone.

IV. TRIGONALIC ACID

A. Dry Bromine

An equal portion of concentrated sulfuric acid was used to wash the bromine in a separatory funnel.

B. Diethyl dl-Dibromosuccinate

Dry bromine (46.5 grams) was added dropwise to a solution of 50 grams of diethyl maleate and 250 ml of anhydrous ether. The reaction vessel was protected from direct sunlight with a towel. There was no apparent immediate reaction, so the solution was refluxed for 3 hours. The solution had turned golden yellow. The solution was washed with dilute sulphurous acid and then neutralized with dilute sodium carbonate. The ether layer was dried over magnesium sulfate and then filtered. The ether was distilled off. The solid was filtered and was identified as the meso-isomer which melted at 57-58° C. The liquid distilled at 137-138° C at 11 mm Hg, which was the reported boiling point of this dibromo ester.<sup>58</sup> The yield was 20 grams.

C. Attempted Synthesis of Dimethyl dl-Dibromosuccinate

This was run exactly as the synthesis of diethyl dl-dibromosuccinate, but dimethyl maleate was used instead of diethyl maleate. After reflux the solution was still cherry red, so it was placed in the dark for 24 hours. A white solid precipitated out that melted from 100-102° C. The mixed melting point with dimethyl fumarate gave no melting point depression.

D. dl, dl' Dibromosuccinic Anhydride

The 13.1 ml of dry bromine was added dropwise to the 25 grams of molten maleic anhydride at 98° C. After the addition, the solution was washed with sulphurous acid and then neutralized with sodium carbonate. The solution was extracted with ether. The ether was distilled off and very little oil was left. The oil crystallized when stirred vigorously and was found to melt at 30-32° C. The literature melting point was 32° C.<sup>66</sup> The yield was an insignificant amount.

E. Tetraethyl 1,1,2,3-Cyclopropane Tetracarboxylate

A 40 ml solution of absolute ethanol and 2.5 grams of sodium was added to 17.5 grams of ethyl malonate. The solution was cooled by an ice-salt bath to below 5° C and

was stirred mechanically. The 18 grams of diethyl dl-dibromosuccinate was added dropwise, keeping the temperature below 5° C. The solution turned yellow as the dibromosuccinate was added. After the addition was complete, the red-brown solution was refluxed on a steam bath for one hour. The stirring was continued throughout the reflux. The solution was cooled and then extracted with 150 ml of ether. The ether layer was dried over magnesium sulfate and then the solution was filtered. The ether was distilled, and a precipitate formed. The precipitate was filtered and the solid isolated melted at 75-76° C. A mixed melting point with tetraethyl ethane tetracarboxylate showed no melting point depression. The filtrate was then set up for reduced pressure distillation. Once having reduced the pressure to 0.7 mm Hg, more precipitate was formed. Although this precipitate will distill over at 138-145° C at 0.7 mm Hg pressure, the precipitate in the pot caused much bumping. Thus it was better to filter again and then to reduce pressure distill. There were two fractions. The first fraction distilled at 37-40° C at 65 mm Hg pressure and was concluded to be ethanol by its physical constants and infrared spectrum. The second fraction distilled at 150-155° C at 0.7 mm Hg pressure, which was proposed to be the tetraethyl ester derivative of cyclopropane. The reported boiling point was 187° at 11 mm Hg pressure.<sup>58</sup> The refractive index is

1.443 and density is 1.01. The yield was 15.2 grams.

F. Infrared Curves

Infrared curves were run on diethyl dl-dibromosuccinate, the precipitate that was isolated from the attempted preparation of dimethyl dl-dibromosuccinate, and tetraethyl 1,1,2,3-cyclopropane tetracarboxylate.



## SUMMARY

The Baeyer-Villiger oxidation of the cyclic carboxylic acid derivatives seems to be the most direct path for the formation of the hydroxy cyclic derivatives. The thorough study of the resonance of the series  $(C_nO_n)^=$  strongly indicates that the hydroxy derivatives should be easily oxidized to the desired anions.

For the researchers who will follow, there are several steps that should be taken. The clean-up for the synthesis of 1,2,3,4-cyclobutane tetracarboxylic acid should be as directed in this paper. The methyl lithium can possibly be prepared by cutting the lithium into smaller pieces, perhaps ribbons could be made. The entire preparation should be under a nitrogen atmosphere. The study of vinylene carbonate should be continued by running an ultra-violet light spectrum so that a filter can be used during the excitation. A less concentrated solution of vinylene carbonate in the acetone may allow dimerization to occur rather than linear polymerization. The proposed diethyl dl-dibromosuccinate must be studied further. Perhaps a nuclear magnetic resonance spectrum could better determine the structure of the compound. A carbene synthesis (ie. ethyl chloroacetate and diethyl fumarate in the presence of sodium amide) may be a better approach to the three-membered ring.<sup>67</sup> Although it has been

suggested that the three-membered ring can be formed through methyl diazoacetate and methyl fumarate,<sup>68</sup> other literature has warned of the explosiveness of diazo compounds.<sup>69</sup>

LITERATURE CITED

1. S. Cohen, J. Lacher, and J. Park, J. Am. Chem. Soc., 81, 3480 (1959).
2. R. West, H. Niu, D. Powell, and M. Evans, J. Am. Chem. Soc., 82, 6204 (1960).
3. J. Roberts, A. Streitwieser, Jr., and C. Regan, J. Am. Chem. Soc., 74, 4579 (1952).
4. L. Skattebol and J. Roberts, J. Am. Chem. Soc., 80, 4087 (1958).
5. E. Smutny, M. Caserio, and J. Roberts, J. Am. Chem. Soc., 82, 1793 (1960).
6. Molecular Orbital Theory for Organic Chemists, A. Streitwieser, Jr., John Wiley and Sons, New York, New York, 1961, Chapters 2 and 4.
7. Advanced Concepts in Physical Chemistry, E. Kaufman, McGraw-Hill, New York, New York, 1966, Chapter 6.
8. R. West and D. Powell, J. Am. Chem. Soc., 85, 2577, (1963).
9. J. Liebin, Ann., 11, 182 (1834).
10. B. Brodie, J. Chem. Soc., XII, 269 (1860).
11. R. Nietzki and T. Benckiser, Ber., 18, 1833 (1885).
12. J. Lerch, Ann., 124, 34 (1862).
13. R. Nietzki and T. Benckiser, Ber., 18, 1833 (1885).
14. B. Homolka, Ber, 54, 1395 (1921).
15. A. Fatiadi, H. Isbell, and W. Sager, J. Research Natl. Bureau Stand., 67A, 153 (1963).
16. Organic Syntheses, v.42, John Wiley and Sons, New York, New York, 1962, pp. 66 and 90.
17. P. Preisler and L. Berger, J. Am. Chem. Soc., 64, 67-9 (1942).

18. R. Nietzki, Ber. 20, 1617 (1887).
19. T. Zincke and C. Fröhlich, Ber., 20, 1265 (1887).
20. a.G. Carpéni, Compt. Rend., 206, 432 (1938).  
b.G. Carpéni, Compt. Rend., 206, 601 (1938).
21. G. Carpéni, J. Chim. Phys., 45, 128-36 (1948).
22. Y. Hirata, K. Inukai, and T. Tsujiucki, J. Chem. Soc. (Japan), 69, 63-4 (1948).
23. B. Homolka, Ber., 55B, 1310-1 (1922).
24. P. Preisler, L. Berger, and E. Hill, J. Am. Chem. Soc., 69, 326-9 (1947).
25. R. Malachowski and S. Prebendowski, Ber., 71B, 2241 (1939).
26. W. Person and D. Williams, J. Phys. Chem., 61, 1017, (1957).
27. F. Feigl, Z. Angew. Chem., 39, 393-8 (1926).
28. A. Friedrich and S. Rapoport, Mikrochemi, 14, 41-8 (1933).
29. R. Roshal, J. Applied Chem. (U.S.S.R.), 6, 951-62 (1933).
30. C. Miller, J. Chem. Soc., 1940, 401-6.
31. J. Faucherre, Bull. Soc. Chim. France, 1953, 900-2.
32. N. Stepanyuk, A. Bulycheva, and P. Melnikova, Sb. Nauchn. Rabot. Inst., 1962, 97.
33. B. Andronov, T. Sergeeva, T. Gaeva, and A. Yudina, Sb. Nauchn. Rabot. Inst., 1962, 89.
34. P. Sokellaridis, Compt. Rend., 255, 940 (1962).
35. K. Yamada, N. Mizuno, and Y. Hirata, Bull. Chem. Soc. (Japan), 31, 543 (1958).

36. R. West and H. Niu, J. Am. Chem. Soc., 85, 2587, (1963).
37. J. Park, C. Snow, J. Lacher, J. Am. Chem. Soc., 73, 2342 (1951).
38. J. Park, M. Sharrah, and J. Lacher, J. Am. Chem. Soc., 71, 2337 (1949).
39. J. Park, S. Cohen, and J. Lacher, J. Am. Chem. Soc., 84, 2919-22 (1962).
40. S. Cohen, Univ. Microfilms (Ann Arbor, Mich.), LC Card No. Mic 60-1062, 109 (1960).
41. J. Park and S. Cohen, Patent US 3,059,030, (1963).
42. R. West, H. Niu, and M. Ito, J. Am. Chem. Soc., 85, 2584 (1963).
43. M. Ito and R. West, J. Am. Chem. Soc., 85, 2580 (1963).
44. R. West and H. Niu, J. Am. Chem. Soc., 85, 2589 (1963).
45. G. Maahs, Angew Chem., 75(20), 982 (1963).
46. G. Maahs, Ann., 686, 55-63 (1965).
47. W. MacIntyre and M. Werkema, J. Chem. Phys., 40(12), 3563-8 (1964).
48. E. Reid and M. Sack, J. Am. Chem. Soc., 73, 1985 (1951).
49. G. Griffin, A. Velluro, and K. Furukawa, J. Am. Chem. Soc., 83, 2725 (1961).
50. G. Clemo and S. Graham, J. Chem. Soc., 132, 213 (1930).
51. Chemistry of Organic Compounds, C. Noller, W.B. Saunders Co., Philadelphia, Penn., Third Edition, 1965.
52. C. DePuy, Accounts of Chemical Research, 1, 33, (1968).
53. J. Cason and R. Way, J. Org. Chem., 14, 33 (1949).
54. E. Buchman, A. Reims, T. Skei, and M. Schlatter, J. Am. Chem. Soc., 64, 2696 (1942).

55. J. Roberts and R. Mazur, J. Am. Chem. Soc., 73, 2519, (1951).
56. Organic Reactions, V.VI, John Wiley and Sons, New York, New York, 1951, Chapter 5.
57. W. Hartmann and R. Steinmetz, Ber., 100, 217-222 (1967).
58. H. Raymond and W. Perkin, J. Chem. Soc., 125-2, 1822 (1924).
59. O. Grummitt, J. Chem. Ed., 18, 447 (1941).
60. Identification of Organic Compounds, N. Cheronis and J. Entrikin, Interscience Publishers, New York, New York, 1963.
61. S. Rukemann and F. Beddow, J. Chem. Soc., 77, 1121 (1900).
62. C. Bischoff and C. Roch, Ber., 17, 2781 (1884).
63. E. Reid and M. Sack, J. Am. Chem. Soc., 73, 1985-8 (1951).
64. G. Clemo and S. Graham, J. Chem. Soc., 132, 215 (1930).
65. H. Gilman, E. Zoellner, and W. Selby, J. Am. Chem. Soc., 55, 1253 (1933).
66. M. Bogert and J. Ritter, J. Am. Chem. Soc., 47, 530 (1925).
67. M. Mousseron, R. Fraisse, R. Jacquier, and G. Bonavent, Compt. Rend., 248, 1465 (1959).
68. E. Buchner and H. Witter, Ann., 273, 239 (1893).
69. Organic Syntheses, Coll. Vol. IV, John Wiley and Sons, New York, New York, 1963, p.424.