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著者

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STUDIES ON STRUCTURE AND SYNTHESIS OF $\beta$-DICARBONYLS

By

Hisanobu Ogoshi

1969

Department of Synthetic Chemistry
Faculty of Engineering
Kyoto University
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I should like to express my warmest gratitude to Professor Zen-ichi Yoshida who served as my research advisor during the course of this work. His kindly guidance and enthusiastic interest are sincerely appreciated. I am also indebted to Dr. Kazuo Nakamoto for permitting me to stay at Illinois Institute of Technology and for giving me the big chance to study the theory of vibrational spectrum. The author further wishes to express his sincere thanks to Dr. Robert Adams Condrate, Dr. Masaru Hojo, Dr. Shigeo Yoneda, Mr. Takao Tokumitsu and Mr. Yasutaka Shimizu who gave me suggestive discussions. The author's great thanks are due to Professor Yoshimasa Takezaki and Dr. Kenji Kanasaki for their continuous encouragement to him. Finally, I am very grateful to Mrs. Sadae Furukawa and Miss Keiko Mori for their typing this thesis and shall never forget their kindness.
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Introduction

Since the importance of the hydrogen bond in the chemical bond was recognized by Pauling, the phenomena of hydrogen bonding have been given considerable attention by chemists and physicists for almost forty years.\textsuperscript{1-3} Even though so many works have been published to elucidate the nature of hydrogen bond, we are still lacking a great deal of the quantitative understanding. Further, the importance of the hydrogen bond associated with the energy transfer and the replication process will be increased in the field of the molecular biology and biochemistry.

In a last decade, the rapid progress in spectrophotometers enables us to approach to the micro-structure and dynamic properties of the hydrogen bond. Moreover, the development of large scale computer has offered facilities for mathematical treatment such as molecular orbital calculation and normal coordinate analysis.

Among recent physico-chemical methods, vibrational spectra have provided as the most powerful tools for the elucidation of the nature of the hydrogen bond. It should be noted, however, that previous vibrational studies have concentrated on the stretching band in the higher frequency region, and rather little information is reported for the lower frequency \textit{vibrations} such as O-H······O and bending of O-H······O.
Further, the lower frequency appears in the region of far infrared, where one can not perform a correct assignment any more as in higher region according to the concept of the group vibrations. Consequently, the theoretical analysis of the vibrational spectra can be made in aid of normal coordinate analysis. This permits one to calculate the force constants which represent the magnitude of inter-atomic forces in molecule. If the force constants relating to O-H·····0 system are obtained for a series of compounds, they can serve as a measure of the relative strength of the hydrogen bond.

Extensive investigations on tautomeric equilibrium of β-dicarbonyls have been carried out by organic and physical chemists. Nevertheless, there have never been reported for the comprehensive and conclusive works on intramolecular hydrogen bond itself of the enol form of β-dicarbonyls involving π-conjugative systems. Quasi aromatic properties of the chelate ring is of particular interest in view of structural chemistry and its reactivity. It is still pending problem whether the participation of vacant 2p-orbital of hydrogen can construct 6π-electrons system or not, as has been proposed by Shigorin.\(^2\) Therefore, even though phenomena are familiar to us, attractive and challengeable problems to be solved have been accumulated in modern chemistry.

Chapter I is concerned with the study on the linear hydrogen
bond of acidic carbonate ion. Normal coordinate analysis has been carried out to analyse theoretically vibrational spectra using Urey-Bradley force field. It has been established that the resultant force constants in connection with the hydrogen bonding are correlated with the distance of $0\cdots\cdots0$. A nature of bend type hydrogen bond associated with $\pi$-conjugative system such as acetylacetone is quite different from that of linear hydrogen bond as has been introduced in the first chapter. Thus, in Chapter II, the author studies the theoretical treatment of the vibrational spectra of the enol form of $\beta$-diketones. The chemical shifts of enol proton of enol are correlated with the chelated carbonyl stretching vibrations. This chapter includes the first observation of intramolecularly hydrogen bond stretching mode which is theoretically determined by the potential energy distribution.

Chapter III deals with the studies on the electronic effect of 3-substituents on the chelate ring of 2,4-pentanedione (acetylacetone). It has been proposed that the participation of vacant 2p-orbital of hydrogen atom is not necessary to explain electronic effect of substituents.

The marked $p_n-d_\pi$ conjugative stabilization of sulfur directly linked to the chelate ring and easier synthetic pathway with sulfur nucleophile are presented in Chapter IV. In Chapter V, the first successful nucleophilic substitution reaction of trivalent metal
acetylacetonates has been reported. The reaction mechanism is interpreted considering the effect of solvents and substituents.

Chapter VI treats with cyclopropyl conjugation with the chelate ring in comparison with the corresponding iso-propyl substituted β-diketones at the both ground and electronically excited states. Its effect on the copper complexes of β-diketones is discussed in the same chapter.

In Chapter VII, the molecular orbital calculation of enolation of β-dicarbonyls in Hückel and Self-Consistent Field approximation has carried out in order to study the electronic structure which is strongly perturbed by intramolecular hydrogen bond.

In Chapter VIII, the theory of normal coordinate analysis is briefly introduced. Its application has been demonstrated for two highly enolized 3-substituted-2,4-pentanedione. Resultant force constants show good agreement with the results of nmr spectra.
References

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   W. A. Benjamin, Inc., N. Y. 1968
Chapter 1

Normal Coordinate Analysis of Hydrogen Bonded Compounds.

The Acid carbonate Ion*1

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*1 Published in J. Chem. Phys., 43, 1177 (1965)
1.1 Summary

The infrared spectra of potassium acid carbonate and its deuterated analog have been obtained from 4000 to 160 cm⁻¹. The Raman spectrum of the latter has also been obtained in the crystalline state. A normal coordinate analysis has been carried out to estimate the force constants as well as to make theoretical band assignments. The infrared bands of the non-deuterated compound at 2620, 1405, and 248 cm⁻¹ have been assigned to the O-H stretching, O-H······0 in-plane bending, and O······H stretching coupled with C=O bending modes, respectively. The corresponding force constants are: O-H stretching, 3.20, O-H······0 bending, 0.22, and O······H stretching, 0.76 mdyn/Å. Plots of these force constants versus O-H······0 distances for three compounds thus far investigated yield a linear relationship for each force constant.

1.2 Introduction

In previous papers of this series, we have reported normal coordinate analyses of acetic (and formic) acid dimer¹ and of the acid maleate ion²; the O-H······0 bond of the former is relatively long (2.74 Å), whereas that of the latter is extremely short (2.44 Å). It is, therefore, of particular interest to carry out a normal coordinate analysis of a hydrogen-bonded compound which has an O-H······0 bond of intermediate length, and to investigate the variation of force constants.
as a function of the O-H······O distance. According to the results of an x-ray analysis, the acid carbonate ion in KHCO₃ is dimerized through O-H······O bonds 2.61 Å long, to form a ring structure similar to that of acetic acid dimer. Therefore, crystalline potassium acid carbonate serves as an ideal compound for this study.

The infrared spectra of KHCO₃ and KDCO₃ have been studied by Tarte, Ryskin, and Novak et al. Among these, the last investigators have made the most complete band assignments in the NaCl region. However, no infrared spectra have yet been obtained below 600 cm⁻¹ where the O······H stretching and ring deformation modes may appear. The Raman spectrum of crystalline KHCO₃ has been obtained by Couture-Mathieu. No Raman data, however, are yet available for crystalline KDCO₃.

In this paper, we report the infrared spectra of KHCO₃ and KDCO₃ from 4000 to 160 cm⁻¹ and the Raman spectrum of the latter in the crystalline state. We also describe the results of a normal coordinate analysis of the acid carbonate ion, and discuss the force constants of the O-H······O system in connection with our previous papers.
1.3 Experimental

Preparation of Compounds

Potassium acid carbonate (KHCO₃) was purchased from Fisher Scientific Company, Chicago, and recrystallized from aqueous solution by passing in CO₂ gas below 70°C. KDCO₃ was obtained by dissolving crystalline K₂CO₃ in D₂O and passing in CO₂ gas. Both compounds were dried in an atmosphere of CO₂.

Spectral Measurements

The infrared spectra were obtained by using a Perkin-Elmer Model 21 infrared spectrophotometer (4000-650 cm⁻¹), a Beckman Model IR 7 infrared spectrophotometer equipped with CsI optics (700-250 cm⁻¹), and a Perkin-Elmer Model 301 far-infrared spectrophotometer (320-160 cm⁻¹). The KBr-disk method was employed for the range between 4000 and 650 cm⁻¹, whereas the Nujol mull technique was used with CsI and polyethylene windows for the ranges between 700 and 250 cm⁻¹ and between 320 and 160 cm⁻¹, respectively.

The Raman spectrum of KDCO₃ was obtained by using a Cary Model 81 Raman spectrometer with a single crystal of KDCO₃ of approximately 10 x 7 x 2 mm. The 10 Raman lines listed in Table II were observed in the region 2000 to 200 cm⁻¹.
Procedure of Calculation

As noted above, the X-ray analysis of crystalline KHCO$_3$ definitely indicates that the HCO$_3^-$ ion is dimerized through the O-H······O bonds to form a ring structure such as shown in Fig. 1. Therefore, the procedure of calculation used for acetic acid dimer$^1$ can be used with slight modification. Although the molecular model shown in Fig. 1 has C$_{2h}$ symmetry, the spectra obtained in the crystalline state should rather be interpreted on the basis of C$_1$ symmetry, since the site symmetry of the (HCO$_3$)$_2^{2-}$ion is known to be C$_1$.$^6$ Under C$_1$ symmetry, the 9A$^g$ and 3B$^g$ vibrations of the C$_{2h}$ model are grouped into the A$^g$ species, and the 4A$_u$ and 8B$_u$ vibrations are grouped into the A$_u$ species. Nevertheless, we adopted the C$_{2h}$ model in our calculation, because errors due to neglect of the effect of crystal environment on internal vibrations are within the tolerances required for meaningful interpretation of force constants in this paper.

We have calculated only the in-plane vibrations (9A$_g$ + 8B$_u$) because most out-of-plane bending vibrations are expected to appear below 200 cm$^{-1}$ except the O-H······O and CO$_3$ skeletal bending modes, which can be identified on an empirical basis. The G-matrix elements were evaluated using the molecular parameters obtained from X-ray analysis$^3$: C=O$_3$, 1.28 Å; C-O$_1$, 1.33 Å; C······O$_2$, 1.32 Å; O$_1$-H······O$_2$, 2.61 Å; the O-H$_1$ distance was estimated to be 1.05 Å by using the relationship, "O-H distance
versus O-H·········O distance" developed by Lippincott and Schroeder. All the angles were taken as 120°, except ω, which was taken as 180°. The F-matrix elements were expressed by using the modified Urey-Bradley force field described in our previous paper.

Table I lists the best set of force constants obtained for the \((\text{HCO}_3)^2^-\) ion. In Table II the calculated frequencies obtained by using this set of force constants are compared with those observed for \(\text{KHCO}_3\) and \(\text{KDCO}_3\). The agreement with observed frequencies is quite satisfactory, the maximum deviation being 5.0% (for ν₁ of \(\text{KHCO}_3\)), and the average deviation for 32 observed frequencies being 1.9%. Table II also gives the theoretical band assignments obtained from the calculation of potential-energy distribution in each normal vibration.

1.4 Results and Discussion

Frequencies and Band Assignments

Figure 2 illustrates the infrared spectra of crystalline \(\text{KHCO}_3\) and \(\text{KDCO}_3\) from 3500 to 160 cm\(^{-1}\). These spectra are similar in general features, but different in fine detail from those published by previous investigators. For example, Novak et al. reported four bands at 3070, 2940, 2720, and 2620 cm\(^{-1}\) for \(\text{KHCO}_3\), and assigned the former two bands to the combinations between O-H·········O bending and C-O stretching, and the latter two bands to the O-H stretching modes. We have observed only two distinct bands at 2920 and 2620 cm\(^{-1}\), and have assigned
the former to the same combination band (O–H⋯⋯O bend plus C=O stretch), and the latter to the O–H stretching band (ν\textsubscript{10}). The latter frequency is in good agreement with that predicted from the correlation diagram, "O–H stretching frequency versus O–H⋯⋯O distance",\textsuperscript{10} which gives a frequency of \(\sim 2600 \text{ cm}^{-1}\) for a distance of 2.61 Å. The O–H stretching force constant was adjusted to minimize the errors of ν\textsubscript{1} and ν\textsubscript{10} of KHCO\textsubscript{3} and KDCO\textsubscript{3}, as seen in Table II. As in the case of the 2920 cm\textsuperscript{-1} band of KHCO\textsubscript{3}, the infrared band at 2240 cm\textsuperscript{-1} of KDCO\textsubscript{3} is assigned to a combination band.

Crystalline KHCO\textsubscript{3} exhibits two strong bands of almost equal intensity at 1650 and 1618 cm\textsuperscript{-1}. Novak et al.\textsuperscript{6} previously assigned the former to the C=O stretching and the latter to the overtone of the out-of-plane bending mode of the CO\textsubscript{3} skeleton at 830 cm\textsuperscript{-1}. However, our calculation gives a better agreement for the Raman-active C=O stretching mode (ν\textsubscript{2}) if the band at 1618 cm\textsuperscript{-1} is assigned to the C=O stretching mode (ν\textsubscript{11}). Although the infrared spectrum of KDCO\textsubscript{3} exhibits three bands (1652, 1615, and 1585 cm\textsuperscript{-1}) in this region, the strongest band at 1615 cm\textsuperscript{-1} is assigned to the fundamental for the same reason.

Previously, Novak et al.\textsuperscript{6} assigned the infrared bands at 1405 and 1367 cm\textsuperscript{-1} of KHCO\textsubscript{3} to the coupled vibrations between the O–H⋯⋯O in-plane bending and the C=O stretching modes. Calculation of potential energy distribution indicates that the
former ($v_{12}$) is an almost pure O-H⋯O bending mode whereas the latter ($v_{13}$) consists of C-O stretching (38 %), C—O stretching (32 %) and O-H⋯O bending (30 %) modes. Upon deuteration, $v_{12}$ is shifted to 1050 cm$^{-1}$ whereas $v_{13}$ is shifted to a slightly higher frequency (1392 cm$^{-1}$). Because of the shift of O-H⋯O in-plane bending band to a lower frequency, $v_{13}$ of KDCO$_3$ consists of C-O stretching (60 %) and C—O stretching (40%). Corresponding to these infrared active modes, the Raman spectrum of KDCO$_3$ exhibits two lines at 1448 and 1284 cm$^{-1}$; the former is the pure O-H⋯O bending ($v_3$), whereas the latter is a coupled vibration between C—O and C-O stretching modes ($v_4$). Upon deuteration, the former is shifted to 1054 cm$^{-1}$ whereas the latter stays at almost the same frequency as before.

The infrared spectrum of KHCO$_3$ exhibits two bands at 1001 and 988 cm$^{-1}$. The former is the C-O stretching coupled with the C—O stretching mode ($v_{14}$), whereas the latter is the O-H⋯O out-of-plane bending mode which was not calculated in this paper. The latter assignment is supported by the correlation diagram, 
"O-H⋯O out-of-plane bending frequency versus O-H⋯O distance",$^{11}$ which predicts a frequency of $\sim$965 cm$^{-1}$ for a distance of 2.61 Å. Upon deuteration, this band is shifted to $\sim$665 cm$^{-1}$, which is partly hidden by a band at 688 cm$^{-1}$ ($v_{15}$). However, $v_{14}$ of KHCO$_3$ is shifted only slightly to a lower frequency (985 cm$^{-1}$) as predicted from the calculation. The Raman-active mode corre-
sponding to $\nu_{14}$ is $\nu_{5}$ which appears strongly near 1025 cm$^{-1}$ in both the compounds. However, the Raman lines corresponding to the O-H-O and O-D-O out-of-plane bending modes were not observed.

The bands at 830 cm$^{-1}$ in the infrared spectra of both the compounds are definitely due to the out-of-plane bending mode of the CO$_3$ skeleton. This band is always observed between 880 and 800 cm$^{-1}$ in a number of metal carbonates. The corresponding Raman lines appear near 830 cm$^{-1}$ in both the compounds.

The bands at 698 and 655 cm$^{-1}$ in the infrared spectrum of KHCO$_3$ are assigned to the C=O in-plane bending coupled with the O-H stretching ($\nu_{15}$) and the O$_2$CO bending ($\nu_{16}$) modes, respectively. As expected, these frequencies do not change appreciably upon deuteration. The corresponding Raman lines were observed at 676 (\nu$\nu_{6}$) and 635 (\nu$\nu_{7}$) cm$^{-1}$ for KHCO$_3$, and at 666 (\nu$\nu_{6}$) and 616 (\nu$\nu_{7}$) cm$^{-1}$ for KDCO$_3$. According to the potential-energy distribution, \nu$\nu_{6}$ is mainly the O$_2$CO bending mode, and \nu$\nu_{7}$ the C=O in-plane bending mode in KHCO$_3$.

As is seen in Fig. 2, neither of the compounds exhibit any distinct bands between 600 and 300 cm$^{-1}$. By extending our measurements down to 160 cm$^{-1}$, we observed only two bands at 248 and 186 cm$^{-1}$ for both the compounds. The potential-energy distribution indicates that the former is the O-H stretching coupled with the C=O bending mode (\nu$\nu_{17}$). However, the latter does not correspond to any calculated frequency. It may be one of the out-of-
plane ring-deformation modes which were not calculated in this paper. It has been shown previously\textsuperscript{1,2} that the O······H stretching frequency of the O-H······O system is little sensitive to deuteration. In the present case, the contribution of the C=O stretching to $v_{17}$ may further enhance this trend.

The Raman active mode corresponding to $v_{17}$ is $v_8$, which was predicted at 257 cm$^{-1}$ for both the compounds. However, no Raman lines were observed in this region, probably because they are too weak. It is interesting to note that, different from $v_{17}$, this mode is the O······H stretching coupled with $0_1CO_2$ bending vibration according to the potential-energy distribution.

Finally, the Raman line at 134 cm$^{-1}$ reported for KHCO$_3$ is in good agreement with the calculated frequency of $v_9$, which is an in-plane ring-deformation mode.

**Force Constants**

Thus far we have carried out normal-coordinate analyses of acetic acid dimer,\textsuperscript{1} the acid carbonate ion, and the acid maleate ion,\textsuperscript{2} all of which have different O-H······O distances. The O-H and O······H stretching and the O-H······O in-plane bending-force constants obtained from these analyses have been plotted against the O-H······O distance, as is shown in Fig. 3. It is seen that a good linear relationship is obtained for each force constant. Such a diagram will be highly useful in predicting the Urey-Bradley force constants of other hydrogen-bonded systems.
If the straight lines for the O-H and O······H stretching force constants are extrapolated to an O-H······O distance of 3.00 Å, the diagram predicts about 7.5 and 0 mdyn/Å, respectively, for these force constants. An example of such an extremely weak hydrogen bond is seen in crystalline LiOH.H₂O, in which the hydroxyl groups form O-H······OH type hydrogen bonds of 2.99 Å. The hydroxyl O-H stretching frequency of this compound is reported to be 3547 cm⁻¹. This frequency corresponds to a force constant of ~ 7.10 mdyn/Å, if the OH group in this compound is treated as a diatomic molecule. It seems, therefore, that such a linear relationship between O-H stretching force constant and O-H······O distance holds over a wide range of O-H······O distances. This result should be contrasted to the plot of "O-H stretching frequency versus O-H······O distance", in which the linear relationship breaks down beyond an O-H······O distance of 2.75 Å.

As is seen in Table I, we have used three different CO stretching force constants in our calculations: K(C=O₃), 7.50; K(C=O₂), 5.50 and K(C=O₁), 4.00 mdyn/Å. On the other hand, the reported X-ray distances are: C=O₃, 1.28 Å; C=O₂, 1.32 Å and C=O₁, 1.33 Å. We feel that the latter two values should differ more appreciably than those reported since the O₁ atom is much more strongly bonded to the hydrogen atom than is the O₂ atom. Although we used the values reported by X-ray analysis in this paper, we found that small variations in these values do not
cause any significant changes in our results. It is interesting to note that the average value of these three CO stretching force constants used here is 5.66 mdyn/A, which is close to 5.46 mdyn/A obtained for the CO stretching force constant of the free CO$_3^{2-}$ ion in the Urey-Bradley field. The average value of the three bending force constants around the C atom is 0.44 mdyn/A, which is also close to that obtained for the free CO$_3^{2-}$ ion (0.44 mdyn/A). Although $F(O_2 \cdots O_3)$ used here is almost the same as that for the free CO$_3^{2-}$ ion (1.742 mdyn/A), $F(O_1 \cdots O_3)$ is smaller than $F(O_2 \cdots O_3)$, possibly because the negative charge on the O$_1$ atom is less than that on the O$_2$ atom. $F(O_1 \cdots O_2)$ is considerably smaller than $F(O_2 \cdots O_3)$ because negative charges on the O$_1$ and O$_2$ atoms are much less than that on the O$_3$ atom.

Finally, it is interesting to note that the two stretching-stretching ($\rho_1$ and $\rho_2$) and the two bending-bending ($l_1$ and $l_2$) interaction force constants used here are 75-80 % larger than those used for acetic acid dimer. This result seems to suggest the presence of stronger vibrational interactions and, consequently, of stronger bonding in potassium acid carbonate than in acetic acid dimer. However, the other two bending-bending interaction constants ($l_3$ and $l_4$) used here have the same absolute values (0.08 and 0.04 mdyn/A) as those used for acetic acid dimer, and differ only in sign. A more detailed discussion of the significance of the absolute value and sign of these interaction constants
will be made after more calculations have been carried out on similar systems.

Table I. Force constants of (HCO₃)₂⁻ ion in millidynes per angstrom.

<table>
<thead>
<tr>
<th></th>
<th>Stretching</th>
<th>Bending</th>
<th>Repulsive</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>K(0-H)=3.20</td>
<td>H(0-C–0)=0.66</td>
<td>F(01–C–O₂)=0.21</td>
</tr>
<tr>
<td></td>
<td>K(C-O)=4.00</td>
<td>H(0-C=O)=0.30</td>
<td>F(0₂–C–O₃)=1.16</td>
</tr>
<tr>
<td></td>
<td>K(C=C=O)=5.50</td>
<td>H(0=C=O)=0.40</td>
<td>F(0₂–C–O₃)=1.74</td>
</tr>
<tr>
<td></td>
<td>K(C=O)=7.50</td>
<td>H(C-O-H)=0.092</td>
<td>F(C–O₂–H₁)=0.29</td>
</tr>
<tr>
<td></td>
<td>K(0–H)=0.76</td>
<td>H(C–O–H)=0.042</td>
<td>F(C–O₂–H₁')=0.01</td>
</tr>
<tr>
<td></td>
<td>H(O-H–O)=0.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stretching-stretching interaction

Bending-bending interaction

ρ₁=0.175
ρ₂=−0.715

₁₁=1₂=−0.11
₁₃=−0.08
₁₄=0.04

Fig. 1. Molecular model and internal coordinates of (HCO₃)₂⁻ ion.
Table II. Comparison of calculated and observed frequencies of \((\text{HCO})_3^2^-\) and \((\text{DCO})_3^2^-\) ions in cm\(^{-1}\).

<table>
<thead>
<tr>
<th>((\text{HCO})_3^2^-)</th>
<th>((\text{DCO})_3^2^-)</th>
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<tr>
<td><strong>Obs.</strong></td>
<td><strong>Calc.</strong></td>
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<tr>
<td>(A^v \nu_1)</td>
<td>2590 (\text{s})</td>
</tr>
<tr>
<td>(\nu_2)</td>
<td>1682 (\text{m})</td>
</tr>
<tr>
<td>(\nu_3)</td>
<td>1448 (\text{w})</td>
</tr>
<tr>
<td>(\nu_4)</td>
<td>1283 (\text{s})</td>
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<td>(\nu_5)</td>
<td>1029 (\text{s})</td>
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<td>(\nu_6)</td>
<td>676 (\text{w})</td>
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<td>(\nu_7)</td>
<td>635 (\text{s})</td>
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<td>(\nu_8)</td>
<td>134 (\text{d})</td>
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<td>(\nu_9)</td>
<td>832 (\text{w})</td>
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<td>(B^v \nu_{10})</td>
<td>2620 (\text{w})</td>
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<td>(\nu_{16})</td>
<td>655 (\text{m})</td>
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<tr>
<td>(\nu_{17})</td>
<td>248 (\text{w})</td>
</tr>
<tr>
<td>(\nu_{18})</td>
<td>988 (\text{m})</td>
</tr>
<tr>
<td>(\nu_{19})</td>
<td>830 (\text{m})</td>
</tr>
</tbody>
</table>

\(^a\) \(s\), strong; \(m\), medium; \(w\), weak.
\(^b\) Band assignments are given for the \((\text{HCO})_3^+\) ion; \(\nu\), stretching; \(\delta\), in-plane bending; \(\nu\), out-of-plane bending.

\(^c\) Reference 8.
\(^d\) Reference 7.
Fig. 2. Infrared spectra of KHCO₃ (1) and KD₃CO₃ (2).
Fig. 3. Plot of O-H···O force constants against O-H···O distance.
References

Chapter 2

Normal Coordinate Analysis of Hydrogen Bonded Compounds.
The Enol-Forms of Acetylacetone and Hexafluoroacetylacetone.

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*1 Published in J. Chem. Phys., 45, 3113 (1966)
2.1 Summary

The infrared spectra of the enol forms of acetylacetone, hexafluoroacetylacetone, and their deutero analogs have been measured from 4000 to 70 cm⁻¹. Normal-coordinate analyses have been carried out to estimate the force constants as well as to make theoretical band assignments. The bands at 2750, 1460, 945, and 230 cm⁻¹ of nondeuterated acetylacetone have been assigned to the vibrations originating in the O-H·······O system. The corresponding force constants are: O-H stretching, 4.00; O-H·······O in-plane bending, 0.05; OH·······O stretching, 0.30 mdyn/A. Similar calculations have also been carried out for hexafluoroacetylacetone and its deutero analog. The effect of the substituent on the chelate ring has been discussed by comparing the results obtained for these two molecules.

2.2 Introduction

In previous papers of this series, we have reported the results of normal-coordinate analyses of several hydrogen-bonded compounds containing straight hydrogen bonds.¹ It has also been shown that the O-H stretching force constant decreases and the 0·······H stretching force constant increases almost linearly as the 0·······H·······0 distance decreases.² It is, therefore, of particular interest to calculate the force constants of bent O-H·······0 bonds, and to compare them with those of straight O-H·······0 bonds to see
the differences between these two types.

Among a number of compounds containing bent $\text{O-H-\ldots-O}$ bonds, the enol form of acetylacetone serves as an ideal compound for normal-coordinate analysis because of its relatively simple and planar structure. It is well known that acetylacetone exists as a mixture of the enol and keto forms in solution as well as in the gaseous phase. In solution, the percentage of the enol form increases as the polarity of the solvent decreases: 45 % in 10 vol % methylcyanide solution, and 90 % in 10 vol % hexane solution. In the gaseous phase, the percentage of the enol form increases as the temperature decreases: $\sim 60 \%$ at $230^\circ C$ and $\sim 95 \%$ at $60^\circ C$. Since the enol form is of interest to us, we have measured the spectra in hexane solution as well as in the gaseous phase at $80^\circ C$, where the vapor pressure is sufficient to give clear spectra.

The infrared spectrum of acetylacetone has already been reported by Rasmussen et al., Smith, Bellamy and Beecher, and Bratoz et al. in organic solvents, and by Mecke and Funke in organic solvents as well as in the gaseous phase. However, most of these measurements were carried out in the NaCl region, and the band assignments were made only on an empirical basis. Furthermore, no spectra have been reported for the deutero analogs except the $d_2$ species. We have, therefore, obtained the infrared spectra of the $d_0$, $d_2$, $d_6$, and $d_8$ species from 4000 to $70 \text{ cm}^{-1}$.
and have carried out normal-coordinate analysis on all the isotopic species. (The structures of these deuto analogs are shown in Fig. 2.)

In order further to confirm the results obtained for acetylacetone and also to study the effect of the substituent group on the O–H⋯O system, we have studied the infrared spectra of hexafluoroacetylacetone and its d$_2$ analog in the vapor phase. Similar to acetylacetone, this compound also exists as a mixture of the enol and keto forms. Under the same physical conditions, however, the enol form is more predominant in hexafluoroacetylacetone than in acetylacetone. Since hexafluoroacetylacetone is much more volatile than acetylacetone, the vapor spectrum of the former was easily obtained even at room temperature. It should be mentioned that no complete infrared spectra (4000 to 70 cm$^{-1}$) of hexafluoroacetylacetone and its d$_2$ analog have been reported previously. However, the Raman spectrum of the nondeuterated species has been reported by Shigorin and Shevendina.

2.3 Experimental

Preparation of Compounds

Acetylacetone, CH$_3$COCH$_2$COCH$_3$, was obtained from Eastman Organic Chemicals and purified by distillation under nitrogen atmosphere. Acetylacetone–d$_2$ was prepared by refluxing one volume of acetylacetone with five volumes of D$_2$O, followed by extraction with absolute ethyl ether. This procedure was repeated...
several times to ensure complete deuteration. Acetylacetone-d₈ was prepared according to the method of Manyik et al.¹¹ from acetone-d₆ and acetic anhydride-d₆ (both purchased from Merck, Sharp & Dohme, Ltd., of Canada). Acetylacetone-d₆ was prepared by refluxing acetylacetone-d₈ with H₂O for 14 h.

Hexafluoroacetylacetone (purchased from Pierce Chemical Company, Rockford, Illinois) was dried over P₂O₅ overnight, and purified by distillation. Hexafluoroacetylacetone-d₂ was prepared by dissolving hexafluoroacetylacetone in D₂O, followed by dehydration with P₂O₅.¹²

Spectral Measurements

The infrared spectra in the gaseous phase were measured on a Perkin-Elmer Model 21 infrared spectrophotometer (4000 -650 cm⁻¹), a Beckman Model IR 12 infrared spectrophotometer (700-300 cm⁻¹) and a Beckman Model IR 11 far-infrared spectrophotometer (350-70 cm⁻¹). A gas cell equipped with an electrical heater was used to obtain the spectra of acetylacetone and its deuterated analogs in the vapor phase. The temperature was kept at 80°C, where the enol percentage was estimated to be 95% from the intensity of the 1623-cm⁻¹ band. However, the spectra below 350 cm⁻¹ were difficult to obtain even under these conditions. We have, therefore, obtained them in 5% (volume) hexane solution. It has been confirmed that these solutions give spectra almost identical with those of the vapor in the region above 350 cm⁻¹.
It was not necessary to use the heated cell for hexafluoroacetylacetone because the vapor pressure was sufficiently high at room temperature. The window materials used were KBr (4000–400 cm\(^{-1}\)) and polyethylene (400–70 cm\(^{-1}\)).

2.4 Procedure of Calculation

Figure 1 illustrates the molecular model and the internal coordinates used for normal-coordinate analysis. To simplify the calculation, we have assumed that the methyl and trifluoromethyl groups are single atoms having masses of 15.035 and 69.006, respectively. Since the symmetry of this model is \(C_s\), its 21 (3 x 9-6) normal vibrations are grouped into 15 \(A'\) (in-plane) and 6\(A''\) (out-of-plane) vibrations. In this paper, we have calculated only the 15 in-plane vibrations using the 21 internal coordinates shown in Fig. 1. As a first step, the \(G\) and \(F\) matrices were constructed using these 21 internal coordinates. These matrices were reduced to 17th order through a coordinate transformation, which removed four redundancies (concerned with the sum of the angles around each C atom and one concerned with the six angles in the ring). However, the 17th-order \(A'\) matrices thus obtained still included two redundancies which were complicated functions of bond distances and angles and which could not be removed easily from the calculation. Therefore, we solved the 17th-order secular equation of the form \(|GF-E\lambda|=0\) using an IBM 7094 computer. The fact that two "zero frequencies" were obtained provided a good
Table I lists the symmetry coordinates used for our calculation. The G-matrix elements of acetylacetone were evaluated using the following molecular dimensions: \( Z = 1.10 \, \text{Å}, \, d_3 = d_3' = 1.51 \, \text{Å}, \)
\( d_2 = 1.38 \, \text{Å}, \, d_2' = 1.46 \, \text{Å}, \, d_1 = 1.33 \, \text{Å}, \, d_1' = 1.26 \, \text{Å}, \)
\( r = 1.18 \, \text{Å}, \, r' = 1.34 \, \text{Å}, \, \alpha_1 = \alpha_2 = \alpha_3 = \alpha_1' = \alpha_2' = \alpha_3' = \delta = \delta_1 = \delta_1' = 120^\circ, \, \beta = \beta' = 102^\circ, \)
\( \theta = 156^\circ. \) These values are almost the same as those obtained from X-ray analysis of the enol form of dibenzoylmethane. \(^{13}\) The G-matrix elements for hexafluoroacetylacetone were estimated from the same molecular parameters as used above except \( d_3 = d_3' = 1.54 \, \text{Å}. \)

The F-matrix elements were expressed by using the simple Urey-Bradley force field. \(^{14}\) Most force constants were transferred from benzene \(^{15}\) and acetone, \(^{16}\) and were adjusted to fit all the isotopic species of acetylacetone or hexafluoroacetylacetone. Table II lists the best set of force constants thus obtained. Table III compares the observed frequencies with those calculated. The agreement is quite satisfactory; the average deviation for 59 observed frequencies of acetylacetone is 1.9 %, and the maximum deviation is 6.6 % for \( v_{11} \) of the \( d_6 \) species. For hexafluoroacetylacetone, the average deviation for 30 observed frequencies is 1.5 %, and the maximum deviation is 5.0 % for \( v_9 \) of the \( d_2 \) species. In order to make theoretical band assignments, we have calculated the L matrix and the potential-energy distribution \(^{17}\) for each normal vibration in each symmetry coordinate. The last
column of Table III gives the theoretical band assignments of the nondeuterated species thus obtained. In the same table, the frequencies of all other isotopic species were rearranged so that the frequencies listed in the same row correspond approximately to the vibrational mode of the nondeuterated species listed in the last column. In the following, we discuss mainly the results obtained for the nondeuterated species. However, the results obtained for deuterated species are quoted whenever necessary to substantiate the band assignments for the nondeuterated species.

2.5 Results and Discussion

Acetylacetone

Figures 2 and 3 illustrate the infrared spectra of the enol form of acetylacetone and its three deutero analogs in the vapor phase and in hexane solution, respectively. A comparison of the $d_0$ and $d_2$ spectra is useful in confirming the vibrations due to the $O-H \cdots 0$ and the central ($\gamma$) C-H groups while a comparison of the $d_0$ and $d_6$ spectra is helpful in locating all the vibrations of the CH$_3$ groups.

Two weak bands at 3020 and 2960 cm$^{-1}$ of $d_0$ are definitely due to the C-H stretching modes of the CH$_3$ groups. The C-H stretching mode ($v_1$) of the $\gamma$-CH group is weak, and probably hidden under these peaks. In the $d_8$ compound, all these bands are
shifted to the region around 2200 cm\(^{-1}\). As is seen in Fig.2, it is extremely difficult to define the center of the O-H stretching band \(v_2\) because it is broad and weak. However, the \(d_2\) compound exhibits a relatively sharp O-D stretching band at 2020 cm\(^{-1}\). If the same force constant is assumed for both the O-H and O-D bonds, the O-H stretching frequency is estimated to be \(\sim 2773\) cm\(^{-1}\) from the calculations.

The strong and broad bands at \(\sim 1615\) cm\(^{-1}\) of \(d_0\) and \(d_6\) are interpreted as the superposition of the C=O stretching \(v_3\) and the C=C stretching coupled with the C-H in-plane bending mode \(v_4\). It is interesting to note that this single band is separated into two peaks in the \(d_2\) and \(d_8\) compounds. In accordance with this observation, our calculations provide two different frequencies which are in good agreement with those observed (Table III). This separation is due to the fact that \(v_4\) is shifted to a lower frequency in the \(d_2\) and \(d_8\) compounds because the contribution of the C-H in-plane bending mode to the C=C stretching mode decreases markedly upon deuteration of the \(\gamma\)-CH hydrogen.

The spectra between 1500 and 1300 cm\(^{-1}\) are complicated because the C-O stretching \(v_6\), O-H······O in-plane bending \(v_5\), and two CH\(_3\) deformation modes (degenerate and symmetric) are expected to appear in this region. The spectra of the \(d_2\), \(d_6\), and \(d_8\) compounds are extremely useful in distinguishing these
modes. In the $d_0$ compound, the shoulder band at $\sim 1460 \text{ cm}^{-1}$ is assigned to the $O-H\cdots\cdots O$ in-plane bending mode ($\nu_5$) since it is shifted to $\sim 1070 \text{ cm}^{-1}$ in the $d_2$ and $d_8$ compounds. The next band at $1432 \text{ cm}^{-1}$ of $d_0$ is interpreted as a superposition of the $C=O$ stretching and the $CH_3$ degenerate deformation modes, and the band at $1368 \text{ cm}^{-1}$ is assigned to the $CH_3$ symmetric deformation mode. The spectra of the $d_6$ and $d_8$ compounds are simple since no $CH_3$ deformation band appears in this region.

The band at $1250 \text{ cm}^{-1}$ of $d_0$ is assigned to the $C-C$ stretching coupled with the $C=C$ stretching mode ($\nu_7$), and appears strongly in all the compounds studied. The next band at $1170 \text{ cm}^{-1}$ is assigned to the $C-H$ in-plane bending ($\nu_8$) overlapped with the $CH_3$ rocking mode. The fact that the $d_6$ compound exhibits a relatively strong band at $1180 \text{ cm}^{-1}$ supports this assignment. The bands at 945 and 908 cm$^{-1}$ of $d_0$ are assigned to the $OH$ out-of-plane bending and one of the $C-CH_3$ stretching modes ($\nu_9$), respectively. It is interesting to note that the latter is shifted to a higher frequency in $d_2$ and $d_8$ because in couples with the $C-D$ in-plane bending mode ($\nu_8$, $\sim 870 \text{ cm}^{-1}$). The strong bands at 764 and 757 cm$^{-1}$ of $d_0$ and $d_6$, respectively, are definitely due to the $C-H$ out-of-plane bending mode, and are shifted to $560-530 \text{ cm}^{-1}$ in $d_2$ and $d_8$.

A doublet band at $640 \text{ cm}^{-1}$ of $d_0$ is assigned to an out-of-plane ring deformation mode and seems to correspond to a band at
620 cm\(^{-1}\) of bis (acetylacetonato) Cu(II).\(^{18}\) The frequency of this mode decreases gradually as more deuterium is substituted. The same trend is also seen for the bands at 515 cm\(^{-1}\) (\(\nu_{11}\)) and at 364 cm\(^{-1}\) (\(\nu_{13}\)) of \(d_0\), both of which are assigned to the in-plane ring deformations. A band at 388 (\(\nu_{12}\)) and a weak shoulder at 320 cm\(^{-1}\) (\(\nu_{14}\)) of \(d_0\) are assigned to the C-CH\(_3\) bending modes, and are shifted very slightly to lower frequencies upon deuteration of the CH\(_3\) hydrogens. The lowest frequency band observed in the hexane solution of \(d_0\) is at 230 cm\(^{-1}\) (Fig. 3). According to the potential-energy distribution, this band is due to the O⋯⋯⋯⋯H stretching coupled with the OH⋯⋯⋯⋯O bending and C-CH\(_3\) bending modes (\(\nu_{15}\)). Since the hydrogen motion in this mode is very small, it is only slightly sensitive to deuteration.

Hexafluoroacetylacetone

Figure 4 illustrates the infrared spectra of hexafluoroacetylacetone (\(d_0\)) and its deuterio analog (\(d_2\)) in the vapor phase. The sharp band at 3140 cm\(^{-1}\) is clearly due to the C-H stretching mode (\(\nu_1\)). However, the center of the O-H stretching band is not obvious in the \(d_0\) spectrum. Since the \(d_2\) spectrum exhibits a sharp O-D stretching band at 2240 cm\(^{-1}\), it is possible to estimate the O-H stretching frequency (\(\sim 3032\) cm\(^{-1}\)) assuming the same force constant for both the O-H and O-D bonds.
The sharp strong bands at 1690 and 1636 cm\(^{-1}\) of \(d_0\) are assigned to the C=O stretching (\(v_3\)) and the C=C stretching coupled with the C-H in-plane bending mode (\(v_4\)), respectively. As has been discussed previously, they are accidentally overlapped in the case of acetylacetone. This overlapping disappears in hexafluoroacetylacetone because electron-withdrawing inductive effect of the CF\(_3\) group causes a shift of the C=O stretching to a higher frequency (1690 cm\(^{-1}\)).

The band at 1448 cm\(^{-1}\) is interpreted as a superposition of the C-O stretching (\(v_6\)) and the O-H······O in-plane bending modes (\(v_5\)), although they are separated into two bands in acetylacetone. Five bands at 1368, 1320, 1270, 1185, and 1090 cm\(^{-1}\) of \(d_0\) and those at 1362, 1310, 1232, 1185, and 1040 cm\(^{-1}\) of \(d_2\) are assigned to the stretching vibrations of the CF\(_3\) groups. In hexafluoroacetone, they are observed between 1344 and 1200 cm\(^{-1}\). The band at 1225 cm\(^{-1}\) of \(d_0\) is assigned to the C-C stretching coupled with the C=C stretching mode (\(v_7\)). The corresponding band of acetylacetone is clearly seen at 1250 cm\(^{-1}\) in the absence of the CF\(_3\) group vibrations in this region. The shoulder band at 1108 cm\(^{-1}\) of \(d_0\) is assigned to the C-H in-plane bending mode (\(v_8\)), and is shifted to 880 cm\(^{-1}\) in \(d_2\).

The band at 913 cm\(^{-1}\) is assigned to the O-H······O out-of-plane bending mode and is shifted to 634 cm\(^{-1}\) upon deuteration. The bands at 855 (shoulder), 740, and 816 cm\(^{-1}\) of \(d_0\) are assigned to
the C-CF$_3$ stretching modes ($v_9$ and $v_{10}$) and one of the CF$_3$ group deformation modes. All these vibrations are only slightly shifted upon deuteration. The strong band at 647 cm$^{-1}$ of d$_0$ is assigned to an out-of-plane ring deformation mode which corresponds to the band at 640 cm$^{-1}$ in acetylacetone. In d$_2$, this band is assumed to be overlapped by the 0-D·····0 out-of-plane bending mode.

The strong band at 573 cm$^{-1}$ is assigned to another deformation mode of the CF$_3$ group. Two medium intensity bands at 522 and 324 cm$^{-1}$ of d$_0$ are attributed to the in-plane ring deformation modes, $v_{11}$ and $v_{13}$, respectively. Also two weak bands at 438 and 145 cm$^{-1}$ are assigned to the C-CF$_3$ in-plane bending modes, $v_{12}$ and $v_{14}$, respectively. The bands at 255 and 240 cm$^{-1}$ are tentatively assigned to the CF$_3$ rocking modes$^{19}$ which are not calculated in this paper. As is seen in Fig. 4, the strong band at 240 cm$^{-1}$ has a shoulder at ~228 cm$^{-1}$, which correspond to the band at 230 cm$^{-1}$ ($v_{15}$) of acetylacetone. Two bands at 106 and 90 cm$^{-1}$ of d$_0$ may be due to the torsional modes of the CF$_3$ groups. This mode is reported to appear at 84 cm$^{-1}$ in CF$_3$CF=CF$_2$.  

**Force Constants**

Table II lists the best sets of force constants obtained for the enol forms of acetylacetone and hexafluoroacetylacetone. Among these force constants, the stretching force constants are most sensitive to the changes in bond strength. Therefore, the values of these
values of these force constants for the two molecules are compared in Fig. 5. It is possible to explain the differences in these force constants on the basis of the differences in electronic effect between the CF$_3$ and CH$_3$ groups. As a first approximation, we assume that the inductive effect of these groups is more important than the mesomeric effect. To discuss the inductive effect of the substituent group on the chelate ring, we may consider the effects of two CF$_3$ or CH$_3$ groups separately. In hexafluoroacetylacetone, the strong electron-withdrawing property of the CF$_3$ group (see Fig. 5) will increase the double-bond character of the C=O$_2$ bond, resulting in a considerable decrease in the charge density of the lone-pair electron on the O$_2$ atom. On the other hand, it will weaken the C-C bond as has already been demonstrated by the normal-coordinate analyses of C$_2$H$_6$ and C$_2$F$_6$. Since the CH$_3$ group is rather slightly electron donating, its effects on the chelate ring may occur in the opposite direction to those described above. Therefore, the C=O stretching force constant is larger and the C-C stretching force constant is smaller in hexafluoroacetylacetone than in acetylacetone.

The effect of the second substituent group can be explained similarly. Relative to the CH$_3$ group, the CF$_3$ group will strengthen both the C=C and C-O$_1$ bonds. Thus their force constants are larger in hexafluoroacetylacetone than in acetyl-
acetone. According to our calculations, however, the O-H and O⋯⋯H stretching force constants of the former are larger and smaller, respectively, than those of the latter. This result can only be interpreted if we assume that the strength of the O⋯⋯H bond in these compounds is mainly determined by the basicity of the O atom (charge density of the lone-pair electron). Since the O atom of acetylacetone is more basic than that of hexafluoroacetylacetone, the former forms a stronger O⋯⋯H bond and a weaker O-H bond than the latter.

Burdett and Rogers plotted the C=O stretching frequencies of hexafluoroacetylacetone, trifluoroacetylacetone, acetylacetone, and dibenzoylmethane against the chemical shifts of the OH protons, and noted considerable deviations from a linear relationship for the former two compounds. However, they assigned the bands at 1633 and 1600 cm\(^{-1}\) of hexa- and trifluoroacetylacetones, respectively, to the C=O stretching modes. Figure 6 shows that a good linear relationship exists if the higher frequency bands at 1690 and 1655 cm\(^{-1}\) of these compounds are assigned to the C=O stretching modes. It is concluded, therefore, that the lower the C=O stretching frequency, the stronger the O⋯⋯H bond and the lower the magnetic field of the proton resonance, since the H atom is less shielded. Thus, the results shown in Fig. 6 are interpreted to indicate that the strength of the O-H⋯⋯O bond will decrease in the order: dibenzoylmethane > acetylacet-
Recently, Kondo et al.\textsuperscript{23} have noted that the magnetic field of the proton resonance becomes higher as the acidity of the enol form increases in the above order of \(\beta\)-diketones. This result again seems to support our interpretation that the basicity of the \(O_2\) atom rather than the acidity of the \(O-H\) bond determines the magnitude of the electron shielding around the \(H\) atom.

We have previously shown\textsuperscript{2} that the \(O-H\) stretching force constant decreases and the \(O\cdots\cdots\cdots H\) stretching force constant increases almost linearly as the \(O\cdots\cdots\cdots O\) distance of the straight hydrogen bond decreases. These relationships predict \(\sim 2.0\) and \(1.0\) mdyn/Å for a distance of 2.5 Å which is found in acetylacetone and hexafluoroacetylacetone. It is evident, therefore, that they are not applicable to bent hydrogen bonds. As has been pointed out by Schneider\textsuperscript{24} the hydrogen bond is the strongest when the \(O-H\) bond is collinear with the direction of the lone-pair orbital of the \(O_2\) atom. This condition is satisfied in the three hydrogen-bonded compounds studied thus far, acetic acid dimer, the acid carbonate ion, and the acid maleate ion, all of which contain linear hydrogen bonds of various \(O-H\cdots\cdots\cdots O\) length.\textsuperscript{2} It is evident that this condition cannot be met in intramolecular hydrogen-bonded compounds such as acetylacetone and hexafluoroacetylacetone. Aside from the collinearity of the \(O-H\cdots\cdots\cdots O\) bond, the direction of the lone-pair orbital of the \(O_2\) atom (120°
from the C=O bond) deviates by 18° from that of the O---H bond obtained from X-ray analysis (C-O-H angle, 102°). Therefore, it is not surprising to find large deviations of the O-H and O---H stretching force constants of the bent hydrogen bonds from the linear relationships obtained for straight hydrogen bonds.

Table I. Symmetry coordinates for in-plane vibrations.

<table>
<thead>
<tr>
<th>Symmetry coordinate</th>
<th>Vibration mode</th>
</tr>
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<tbody>
<tr>
<td>$S_1 = \Delta Z$</td>
<td>$\nu$ (C-H)</td>
</tr>
<tr>
<td>$S_2 = \Delta r$</td>
<td>$\nu$ (O-H)</td>
</tr>
<tr>
<td>$S_3 = \Delta \delta$</td>
<td>$\nu$ (C=O)</td>
</tr>
<tr>
<td>$S_4 = \Delta \delta'$</td>
<td>$\nu$ (C=C)</td>
</tr>
<tr>
<td>$S_5 = (1/\theta) (2 \Delta \phi - \Delta \delta - \Delta \delta')$</td>
<td>$\delta$ (O-H)</td>
</tr>
<tr>
<td>$S_6 = \Delta \delta$</td>
<td>$\nu$ (C-O)</td>
</tr>
<tr>
<td>$S_7 = \Delta \delta'$</td>
<td>$\nu$ (C-C)</td>
</tr>
<tr>
<td>$S_8 = \Delta \delta$</td>
<td>$\nu$ (C-H)</td>
</tr>
<tr>
<td>$S_9 = \Delta \delta'$</td>
<td>$\nu$ (C-R')</td>
</tr>
<tr>
<td>$S_{10} = \Delta \delta$</td>
<td>$\nu$ (C-R)</td>
</tr>
<tr>
<td>$S_{11} = (1/\theta) (2 \Delta \phi - \Delta \alpha_1 - \Delta \alpha_1')$</td>
<td>Ring def</td>
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<td>$\delta$ (C-R)</td>
</tr>
<tr>
<td>$S_{13} = (1/\sqrt{2}) (\Delta \beta - \Delta \beta')$</td>
<td>Ring def</td>
</tr>
<tr>
<td>$S_{14} = \Delta \alpha_2' - \Delta \alpha_2'$</td>
<td>$\delta$ (C-R')</td>
</tr>
<tr>
<td>$S_{15} = \Delta \alpha_1'$</td>
<td>$\nu$ (O---H)</td>
</tr>
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<td>$S_{16} = (1/\theta) (\Delta \alpha_1 + \Delta \alpha_1' + \Delta \beta - \Delta \beta' - \Delta \Theta)$</td>
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</tr>
<tr>
<td>$S_{17} = (1/\sqrt{2}) (\Delta \alpha_1 - \Delta \alpha_1')$</td>
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</table>

a These coordinates are not normalized.

$\nu$, stretching; $\delta$, bending.
Table II. Urey-Bradley force constants of acetylacetone and hexafluoroacetylacetone (in millidynes per angstrom).

<table>
<thead>
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<th>Stretching</th>
<th>Bending</th>
<th>Repulsive</th>
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<td>R,R'=CF₃</td>
<td>R,R'=CH₃</td>
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<tr>
<td>K(C-O)</td>
<td>5.800</td>
<td>6.100</td>
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<tr>
<td>K(O=O)</td>
<td>8.820</td>
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<tr>
<td>H(O=O···C=O)</td>
<td>0.185</td>
<td>0.500</td>
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<td>H(R-C=C)</td>
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* Asterisks indicates shoulder, and parentheses indicate overlap.

* Band assignments are given for the IR components. \(v_s\), \(v_a\), \(v_m\), and \(\nu\) denote symmetric deformation, asymmetric deformation, rocking, and out-of-plane bending modes, respectively.
Fig. 4. Infrared spectra of enol forms of hexafluoroacetylacetone and its deutero analog in the vapor phase.
Fig. 5. Comparison of stretching force constants of acetylacetone and hexafluoroacetylacetone (millidynes per angstrom).

Fig. 6. Plot of proton chemical shift against C=O stretching frequency.
Fig. 1. Molecular model and internal coordinates of enol from of \( \beta \)-diketones.

Fig. 3. Infrared spectra of enol forms of acetylacetone and its deutero analogs in hexane solution.
Fig. 2. Infrared spectra of enol forms of acetylacetone and its deuterated analogs in the vapor phase.
References


Chapter 3

Intramolecular Hydrogen Bond in Enol-Form of 3-Substituted-2,4-pentanedione.*1

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3.1 Summary

Spectroscopic characteristics of highly enolized tautomers of 3-substituted-2,4-pentanediones have been studied with infrared and nuclear magnetic resonance methods. The linear relationship between the chemical shifts of enolic proton and the chelated carbonyl stretching vibrations has been established for the various 3-substituted-2,4-pentanediones. The stronger electron-withdrawing resonance effect of the substituent at 3-position results in the lower magnetic field shift of the enolic proton and the lower frequency shift of the chelated carbonyl stretching. The synthesis and structure in tautomeric equilibrium of new 3-substituted-2,4-pentanediones are described.

3.2 Introduction

Forsen and Nilsson\textsuperscript{1-4} have extensively investigated enolized \(\beta\)-triketones using nmr and infrared spectroscopies and found the good linear relationship between the chemical shifts of enolic proton and the carbonyl stretching vibration. On the other hand, Burdett and Rogers\textsuperscript{5} have found that this correlation is not kept for the system of \(\beta\)-diketones. However, the correct band assignments to carbonyl stretching according to the normal coordinate analysis give the similar linear relationship for the \(\beta\)-diketone system as pointed out by Ogoshi and Nakamoto.\textsuperscript{6} Of the spectra of \(\beta\)-diketones, the nmr spectra have been already reported for
acetylacetone, 5,7 3-methyl-5,7 3-chloro-, 7-formyl-4 (in chloroform and dimethylsulfoxide), and 3-acetyl-2,4-pentanediene. 8 Infrared spectroscopic study on 3-cyano-2,4-pentanediene by Wierzchowsky and Shugar 9 has shown that it completely enolizes both in the crystalline state and carbon tetrachloride solution. For 3-chloro-2,4-pentanediene and 2,4-pentanediene, Mecke and Funke 10 have reported the infrared spectra from 4000 to 400 cm⁻¹ with the empirical band assignment. In order further to confirm the results obtained for the above mentioned diketones and to study systematically the effect of the substituents on the intramolecular hydrogen bonding, we have investigated the nmr and infrared spectra of 3-substituted-2,4-pentanedienses including those of which spectra have never been reported. The structural form of new compounds in tautomeric equilibrium will be discussed in this paper.

3.3 Experimental

Preparation of Compounds

3-Nitro-2,4-pentanediene (VII). Bis-(3-nitro-2,4-pentanediene)–Cu(II) was prepared according to the method of Collman et al. 11 The finely pulverized powder of the complex (15.0g) suspended in 150 ml. of chloroform was shaken with 150 g. of EDTA di-ammonium dissolved in 150 ml. of water, until the green color of the chloroform layer disappeared. The chloroform solution was
washed with a small amount of water and dried over anhydrous sodium sulfate. After removing chloroform, distillation gave 12.2 g. (87.7 %) of diketone as a pale yellow liquid; bp 72.5-73.0° (8 mm.).

Anal. Cald. for C_5H_7O_N: C, 41.39 %; H, 4.86 %; N, 9.65 %.

Found C, 41.39 %; H, 4.99 %; N, 9.75 %.

3-Carboxymethoxy-2,4-pentanedione (XI). (methyl diacetylacetate). The procedure was slight modification of the method reported by Spassow, using methyl acetoacetate in stead of ethyl acetoacetate. The product was purified by precipitation as violet copper (II) chelate with aqueous copper (II) acetate and subsequent contact of the chloroform solution of the complex with the aqueous EDTA diammonium. The colorless liquid was distilled at 94.0-94.5° (24 mm). The total yield was 21 % based on methylacetoacetate.

Anal. Cal. for C_7H_10O_4: C, 53.17 %; H, 6.23 %; Found C, 53.38 %; H, 6.31 %.

3-Methylthio-2,4-pentanedione (IX). A solution of methylmercaptane (7.5 g.) in methanol (20 ml.) was dropwisely added to the stirred mixture of 3-chloro-2,4-pentandione (II) (19.0 g.) and pyridine (12.0 g.) at 0°. The reaction mixture was further stirred for 2 hr at room temperature. After methanol was removed under vacuum, pyridine hydrochloride crystalized from the solution was filtered off. Carbon tetrachloride (100 ml.) was added to
the filtrates.

The carbon tetrachloride solution was separated from solid material, washed with water, and dried over sodium sulfate overnight. The distillation gave the pale yellow liquid (4.6 g.), bp 75.0-75.7° (16 mm). The copper (II) chelate was gradually decomposed upon standing.

Anal. Cald. for C₆H₁₀O₂S: C, 49.31 %; H, 6.85 %; S, 21.92 %.
Found C, 49.45 %; H, 6.80 %; S, 22.21 %.

The remaining materials were prepared according to the well established methods listed in Table I. Acetylacetone was commercially available and purified by distillation under nitrogen atmosphere.

Spectral measurements

Proton magnetic resonance spectra in carbon tetrachloride solution were recorded on a Jeolco JNM SH-60 spectrometer. Concentration was changed from ca. 20 % to ca. 1 % at 25°C. Values of chemical shift are reported in δ(ppm) from internal tetramethylsilane. A Jasco DS-402G spectrophotometer was used to obtain the infrared spectra (4000-800 cm⁻¹) in carbon tetrachloride at 25°C.

3.4 Result and Discussion

It has been known that β-diketone exists as a mixture of the enol (e) and the keto form (k), of which ratio in tautomeric equilibrium is influenced by some factors such as temperature
and solvents.

\[
\begin{align*}
X= & \text{H (I), Cl(II), } \text{CH=CH-CH}_3 \text{(III), CH=CH-C}_2\text{H}_5 \text{(IV),}
\text{CH}_2=\text{CH=CH}_2 \text{(V), CN(VI), NO}_2 \text{(VII), SCN(VIII), SCH}_3 \text{(IX),}
\text{COCH}_3 \text{(X), COOCH}_3 \text{(XI), COOC}_2\text{H}_5 \text{(XII), CHO(XIII).}
\end{align*}
\]

Table 1 lists frequencies of carbonyl stretching, chemical shifts, and the percentages of enol form in carbon tetrachloride. Collman et al.\(^{11}\) have reported that hydrolysis of bis-(3-nitro-2,4-pentanedioato)-Cu(II) with acid yields intractable oily material. We followed the same procedure as they tried and separated the white crystal confirming as nitroacetone; mp 46.3°C (lit.\(^{20}\) mp 46.5°C). The alternative method, that is, the exchange of metal ion with proton using the aqueous EDTA diammonium proved to be useful method to isolate free ligand without decomposition.

Figure 1 shows the infrared spectra of VII in the carbon tetrachloride solution. A medium shoulder band at around 1600 cm\(^{-1}\) is assigned to the overlapping band of the C=O stretching and the C=C stretching. The two strong absorptions at
at 1526 and 1351 cm\(^{-1}\) are assigned to the asymmetric and the symmetric stretching of nitro group, respectively. Another strong and sharp band at 825 cm\(^{-1}\) seems to be the C-NO\(_2\) stretching mode. As is seen in Table I, the nmr spectrum of VII in carbon tetrachloride shows the presence of an enolic proton at -6.95 ppm and two methyl groups attached to the chelate ring as a singlet at 7.54 ppm.

In the enol form of VII, one may suppose the different forms as shown below.

![Diagram of molecular structures](image)

The chelate ring of (A) or (A') is the same as that of acetylacetone, whereas the oxygen of nitro group can act as a proton acceptor to form another type of the chelate ring (B). As
a matter of fact, ir and nmr data suggest that the tautomeric equilibrium is remarkably shifted to increase the enol tautomer by the substitution with the nitro group, and the presence of singlet methyl proton might be an evidence that the enolic form (A) or (A') is more stable than (B). Kluiber\textsuperscript{21} reported that VIII prepared by the reaction of copper chelate of acetylacetone with thiocyanogen in the absence of sodium bicarbonate has infrared absorptions at 2208, 1739, and 1588 cm\textsuperscript{-1}. The observed absorption at 1739 cm\textsuperscript{-1} suggested the existence of the keto form to some extent. However, our careful investigation indicates that VIII is entirely enolized in the carbon tetrachloride solution and also crystalline state based on nmr and infrared spectra (Table 1 and Figure 1). The nmr spectrum of VIII shows the two singlet peaks at 7.50 and -7.10 ppm which are assigned to six protons of methyl and one proton of enol. Moreover, the carbonyl stretching of the keto form appeared at around 1700 cm\textsuperscript{-1} has never been observed in the infrared spectrum. The X-ray crystallographic studies\textsuperscript{22,23} have suggested that the planar chelate ring is proved to be essentially asymmetric structure about the position of proton between two oxygens. If that is true, there must be observed two different kinds of chemical shifts of the methyl groups jointed to the chelate ring. It has, however, been known that the chemical shifts of two methyl groups are usually observed as the averaged singlet
peak except for the metal complexes of some acetylacetonate. As has been pointed out by Forsen, many different enolic forms are possible in some $\beta$-triketones. Thus we can represent three types of enol forms as shown below. The interconversion between A and A' as well as B and B' can occur by a movement of enolic hydrogen along the hydrogen bond. Since the alkoxy oxygen acts as a weaker base, the enolic form C seems to be less favorable compared with A (or A') and B (or B'). The nmr spectrum of XI shows three singlet peaks at 7.65 ppm (6H), 6.25 ppm (3H) and -7.97 ppm (1H) assigned to the two methyl groups attached to
chelate ring, the methyl of methoxy and enolic proton respectively as is seen in Figure 2. It is convinced that the enol form A (or A') is the most stable among them, otherwise the chemical shifts of different methyl groups must exhibit at least more than three peaks in this region. The nmr spectrum of XII in Figure 3 can be similarly explained to support the exclusive existence of the enol form corresponding to A or (A'). On the other hand, the three chelate species are distinguished for 3-formyl-2,4-pentanodione XIII from the nmr spectra in chloroform-dimethylsulfoxide solution. Thus it is shown that the enol form corresponding to the form A (or A') amounts to about 80 %, whereas the rest of about 20 % are the two internal isomers B and B'.

M. E. McEwntee et al.\textsuperscript{14} and G. B. Payne\textsuperscript{15} have suggested that 3-propenyl-(III) and 3-butenyl-2,4-pentanodione (IV) are highly enolized. However, no available spectra of nmr has never been reported so far. In the infrared spectrum of III the C=C stretching has not been detected, since the conjugation of C=C of the alkenyl group with the chelate ring decreases the frequencies of C=C and causes a eventual overlapping with the strong C=O stretching at 1607 cm\textsuperscript{-1}. The strong absorption at 970 cm\textsuperscript{-1} is assigned to the wagging mode of trans C-H of olefinic group. This suggests that III exists only in the trans form about the propenyl group (Figure 4). As shown in Figure 4, the nmr spec-
trum indicates that III are highly enolized (ca. 93 %) in carbon tetrachloride. On the contrary, the substitution of allyl group at the 3-position increases the percentage of the keto tautomer (49 %) in the comparable order to that (61 %) of 3-n-propyl derivative. It should be noted that the π-π conjugation of a substituent double bond with the chelate ring significantly enhances the stability of the chelate ring, but seems to give small effect on the strength of hydrogen bonding, since the chemical shift of enol proton is not so much different from that of 3-allyl derivative (V). The chemical shift of enol proton of V appears at -6.60 ppm. as a singlet in carbon tetrachloride.

Figure 5 illustrates infrared spectra of III and V from 1800 to 1500 cm\(^{-1}\). The strong absorption at 1731 and 1705 cm\(^{-1}\) in V are assigned to the carbonyl stretching vibrations of the keto form, whereas the strength of those bands at around 1700 cm\(^{-1}\) extremely decreases in III. The hydrogen-bonded carbonyl stretching of III and V give the strong absorptions at 1607 and 1606 cm\(^{-1}\), respectively. Moreover, the sharp band at 1640 cm\(^{-1}\) of V is possibly assigned to the C=C stretching of allyl group. The comparison of the both spectra seems to support our above interpretation again. The sulfur atom has an electron donating resonance ability using its 3p orbital (non-bonding electron) as well as an electron accepting resonance ability using its 3d orbital (or the hybrid orbital including 3d orbital). It is,
therefore, of particular interest to investigate the effect of substituents containing sulfur atom on chelate ring and its tautomeric equilibrium.

However, no preparative method has been reported as concerns carbon-sulfur bond formation at 3-position of 2,4-pentanedione except 3-thiocyano-18 and 3-(o-nitrophenylthio)-derivatives.27 We have succeeded in the first nucleophilic substitution of 3-chloro-2,4-pentanedione (γ-chloroacetylacetone) by the reaction with methylmercaptane in the presence of pyridine. The nmr and ir spectra of the obtained 3-methylthio-2,4-pentanedione (IX) are shown in Figures 6 and 7, respectively. The high enol percentage of IX is confirmed by both nmr spectra and infrared. As shown in Figure 6 three absorptions were observed at -7.08, 7.67 and 7.86 ppm attributed to the enolic proton (1H), the methylthio group (3H), and two methyl groups of chelate ring (6H) respectively. The percentage of enol form of IX is estimated to be above 98 %. The strong and broad band at 1576 cm⁻¹ is characteristic of the carbonyl stretching vibration strongly perturbed with hydrogen bond as is seen in Fig. 7. The weak shoulder band at 1696 cm⁻¹ is assigned to the carbonyl stretching of the keto form to reveal the existence of the trace of the keto tautomer. The substitution of alkylthio group increases markedly the enol ratio and results in the downfield shift of enolic proton. These facts strongly indicate that sulfur atom act
as an electron acceptor. This seems to be rather anormalous, since the S atom is usually able to conjugate through 3p orbital and consequently shows the electron donor character. The effect of sulfur will be possibly explained if we suppose the utilization of the 3d orbital of sulfur (or the hybrid orbital involving its 3s, 3p, and 3d orbitals) to accept π electrons through conjugation with the chelate ring.

The coplanarity of the substituent double bond with the chelate ring become an important factor to evaluate the effect of the substituents such as 3-alkenyl, 3-carboalkoxy, 3-nitro-, 3-acetyl, and 3-formyl derivatives on chelate ring. As one may suppose that the situation of molecular configuration is similar to 1-substituted-2,6-dimethylbenzene, there might be expected steric hindrance between the substituent and the two methyl group of chelate ring to some extent. Unfortunately a precise discussion on the coplanarity seems to be rather difficult in this stage.

Table 2 lists the observed frequencies of various double bonds of substituents and those of aliphatic (non-conjugated and conjugated) and aromatic systems as a reference. The bands of our compounds are shifted towards lower frequencies due to the conjugation with chelate ring. This tendency seems to suggest that molecular configuration permits considerable interaction between the substituent and ring, even if the steric hindrance
inhibits complete coplanarity of the substituent with the ring.

As has been reported by Burdett and Rogers, the chemical shift of the O-H proton of some \( \beta \)-diketones are influenced by the concentration. Therefore, we have examined the dependencies of the concentration and used the values \( \tau^o_{O-H} \) obtained by extrapolation of observed value \( \tau_{O-H} \) to zero concentration to evaluate the strength of hydrogen bonding. Figure 8 illustrates the plot of \( \tau^o_{O-H} \) against the concentration. Among them, the chemical shifts of the O-H of I and VI are slightly shifted to the downfield on the dilution in carbon tetrachloride. The rest of them show no appreciable changes in the chemical shifts upon the dilution. It is of another interest that the enol proton of 3-substituted derivatives exhibits much sharper peak than that of acetylacetone in carbon tetrachloride at room temperature. This general observation may be explained by the absence of ethylenic proton on the 3-position, which is able to be easily exchanged with the enolic proton in high frequency.

The C=O stretching vibrations exhibit the strong and rather broad bands at around 1550-1630 cm\(^{-1}\) which are separated into the two bands upon deutration of the enolic proton. This strong band has been interpreted as the superposition of the C=O stretching and the C=C stretching.\(^5,9\)

Figure 9 shows that the linear relationship exists in the plot of \( \tau^o_{O-H} \) against the C=O stretching. It is concluded,
therefore, that the stronger hydrogen bond results in the lower frequency of the C=O stretching and the lower magnetic field of proton resonance of O–H, since the H atom is less shielded or the electron charge distribution is presumably deformed in the direction to give the lower magnetic field. Thus, it can be most likely explained the effect of the substituents on the strength of intramolecular hydrogen bond decreases in the order: \(-\text{CHO}\) \(\geq\) \(-\text{CO}_2\text{R}\) \(\geq\) \(-\text{COCH}_3\) \(\geq\) \(-\text{SCN}\) \(\geq\) \(-\text{NO}_2\) \(\geq\) \(-\text{CN}\) \(\geq\) \(-\text{CH=CH-R}\) \(\geq\) \(\text{H}\) \(\geq\) \(\text{Cl}\). This trend can only be interpreted if we assume that (electron-withdrawing) resonance effect of the substituent on hydrogen bond is more important than the inductive effect. The resonance effect through chelate ring causes migration of the \(\pi\)-electron from the –OH to the substituent group, resulting in decrease of the diamagnetic shielding of the enolic hydrogen nucleus by its own electrons. The resultant reduction of the charge density on the O–H oxygen bring the enolic proton to the closer proximity of the carbonyl oxygen to form stronger hydrogen bond and, therefore, the C=O stretching is shifted towards lower frequency region. It seems to suggest that ionic resonance form (b) contributes to a large part of the observed effects of the substituents. In contrast, it is particularly interesting to compare with the series; dibenzoylmethane, benzoylacetone, trifluoroacetylacetone, and hexafluoroacetylacetone, where the inductive effect give more profound influence on the chelate
We obtain the value 0.037 (ppm/cm$^{-1}$) as the slope of the plot in Figure 9 and 0.044 for the latter case. Relatively small difference between the two values seems to indicate that substitution on the different position of chelate ring does not make so much difference in the slope of the plot, that is, the order of these values may be intrinsic to this type of chelate ring aside from the kinds of electronic effects of a substituent.
Table 1. The carbonyl stretching and the proton chemical shifts of the enol form of 3-substituted-2,4-pentanediones.

<table>
<thead>
<tr>
<th>Substituent</th>
<th>$\nu$(C=O) (cm$^{-1}$)</th>
<th>Chemical Shift (ppm)</th>
<th>Others**</th>
<th>Enol (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I H</td>
<td>1613</td>
<td>-5.84 7.98</td>
<td>H(4.54s)</td>
<td>96</td>
</tr>
<tr>
<td>II Cl</td>
<td>1618</td>
<td>-5.55 7.70</td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>III -CH$_n$-CH$_n$-CH$_3$</td>
<td>1607</td>
<td>-6.61 7.85 H$_n$(4.09m), H$_n$(4.50m), 93 CH$_3$(8.20d; J=5.8cps)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV -CH$_m$-CH$_m$-CH$_2$-CH$_3$</td>
<td>1603</td>
<td>-6.60 8.00 H$_m$(3.50m), H$_m$(4.20m), 93 CH$_2$(7.90m) CH$_3$(9.10t; J=7.5cps)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V -CH$_b$-CH$_b$</td>
<td>1606</td>
<td>-6.60 7.90</td>
<td>$\dagger$</td>
<td>49</td>
</tr>
<tr>
<td>VI -CN</td>
<td>1598</td>
<td>-6.90 7.58</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>VII –NO$_2$</td>
<td>1595</td>
<td>-6.95 7.54</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>VIII -SCN</td>
<td>1580</td>
<td>-7.10 7.48</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>IX -SCH$_3$</td>
<td>1575</td>
<td>-7.08 7.67 CH$_3$(7.86s)</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>X -COCH$_3$</td>
<td>1580</td>
<td>-7.40 7.81 CH$_3$(7.65s)</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>XI -COOCH$_2$</td>
<td>1555</td>
<td>-7.97 7.65 CH$_3$(6.25s)</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>XII -COOCH$_2$-CH$_3$</td>
<td>1560</td>
<td>-8.10 7.74 CH$_2$(5.75q; J=7.5), CH$_3$(8.67t; J=7.0)</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>XIII -CHO$^*$</td>
<td>1550</td>
<td>-8.51 7.55 H(0.03s)</td>
<td></td>
<td>98</td>
</tr>
</tbody>
</table>

* The values of chemical shifts are listed here for only enolic form A.
** s, d, t, and q in the parentheses denote singlet, doublet, triplet, and quartet. CH$_3^a$ and CH$_3^b$ indicate two methyl attached to the chelate ring.
$\dagger$ Assignment is difficult, because of complex splitting pattern.
Table 2. The observed frequencies of the stretching vibration of the 
C=O, C=C and NO₂

<table>
<thead>
<tr>
<th>Substituent</th>
<th>Obs. Frequencies. a</th>
<th>Ref. 28</th>
</tr>
</thead>
<tbody>
<tr>
<td>-C-CH₃</td>
<td>1680 (cm⁻¹)</td>
<td>V(C=O)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aliphatic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>conjugated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>conjugated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>conjugated</td>
</tr>
<tr>
<td>-C-O-C₂H₅</td>
<td>1710</td>
<td>V(C=O)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aliphatic</td>
</tr>
<tr>
<td>-C-O-CH₃</td>
<td>1720</td>
<td>V(C=O)</td>
</tr>
<tr>
<td>-C-H</td>
<td>1677</td>
<td>V(C=O)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aliphatic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>conjugated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aromatic</td>
</tr>
<tr>
<td>-NO₂</td>
<td></td>
<td>V₃(NO₂)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aliphatic</td>
</tr>
<tr>
<td></td>
<td>1530</td>
<td>V₃(NO₂)</td>
</tr>
<tr>
<td></td>
<td>1350</td>
<td>V₃(NO₂)</td>
</tr>
<tr>
<td>-CH₂-CH-CH₃</td>
<td>1607</td>
<td>V(C=C)</td>
</tr>
<tr>
<td>-CH₂-CH₂-CH₂</td>
<td>1640</td>
<td>mono olefine</td>
</tr>
</tbody>
</table>

(a) V₃ and V₃ as denote the symmetric stretching and antisymmetric 
stretching of the NO₂ respectively. Observed frequencies were 
calibrated from the polyethylene film.
Fig. 1 Infrared spectra of 3-nitro-2,4-pentanedione and 3-thiocyanato-2,4-pentanedione.
Fig. 2 NMR spectrum of 3-carbomethoxy-2,4-pentanedione
Fig. 3 NMR spectrum of 3-carboethoxy-2,4-pentanedione
Fig. 4. NMR spectrum of 3-propenyl-2,4-pentanedione
Fig. 5 Infrared spectra of 3-propenyl-2,4-pentanedione (III) and 3-allyl-2,4-pentanedione (V) from 1800 to 1500 cm$^{-1}$.
Fig. 6 NMR spectrum of 3-methylthio-2,4-pentanedione
Fig. 7 Infrared spectrum of 3-methylthio-2,4-pentanedione
Fig. 8 Chemical shift ($\tau_{OH}$) of the OH proton as a function of the concentration of 3-substituted-2,4-pentane- 
diones in carbon tetrachloride
Fig. 9 Plot of chemical shift ($\tau^{0}_{OH}$) of OH proton at infinite dilution against C=O stretching frequency.
References


Chapter 4

Synthesis and Structural Elucidation of α-Alkylthio- and α-Phenylthio-β-dicarbonyls.*1

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*1 Presented in part at the 21 Annual Meeting of the Chemical Society of Japan at Osaka, April, 1968.
4.1 Summary

Various α-alkylthio- and α-phenylthio- β-dicarbonyls have been prepared by the reaction of α-chloro-β-dicarbonyls with mercaptans in the presence of pyridine or piperidine and their structures have been established. It was found that an introduction of alkylthio and phenylthio group into α-position of β-dicarbonyls resulted in marked shift of the tautomeric equilibrium to enol side. The enhanced stability of the chelate ring involving strong hydrogen bonding is explained in terms of the electron withdrawing resonance effect of divalent sulfur atom from the chelate ring through $\pi-\pi$ conjugation.

4.2 Introduction

Several works in which α-hydrogen of the active methylene group have been substituted with alkylthio or phenylthio groups by the usual electrophilic substitution have been reported. Thus, α-alkylthio and α-aryltio-β-dicarbonyls have been prepared by the reaction of β-dicarbonyls with α-chloroethylsulfenyl chloride, vinylsulfenyl chloride, acetylsulfenyl chloride, o-nitrobenzenesulfenyl chloride, 2,4-dinitrobenzenesulfenyl chloride. However, no precise structural studies and behavior at tautomeric equilibrium are known for these compounds. In another synthetic approach to form the C-S linkage at the α-position, nucleophilic substitution was proposed as the possible course of the reaction of
diethyl bromomalonate with ethylmercaptan by Waygand. The latter reaction are of particular interest to us because they proved easier alternative synthetic pathway for α-alkylthio and α-phenylthio-β-dicarboxyls.

Further, there have been several discussions on the subject that the conjugation of the sulfur atom directly attached to an adjacent double bond involves the 3p or 3d orbitals of sulfur. However, systematic work has not been done for α-alkylthio- and α-phenylthio-β-dicarboxyls so far.

Such work has been indicated here as an example by which resolve questions regarding the conjugative interaction of sulfur with intramolecularly hydrogen bonded chelate rings and its effect on the tautomeric equilibria.

4.3 Experimental

Melting points were determined on Kyoto Electronic Co., apparatus and were uncorrected. Infrared spectra were measured on Jasco DG-402G spectrophotometers in carbon tetrachloride solution calibrated by polystyrene film. The nmr spectra were recorded on Jeolco JNM-C-60H spectrophotometers using TMS as an internal reference. The ultraviolet spectra were determined in n-heptane on Hitachi Model EPS-3T spectrophotometer.

Starting Materials

3-Chloro-2,4-pentanedione was prepared by the method of
Suzuki. Ethyl and methyl α-chloro acetoacetate were prepared by chlorination of the corresponding ketoesters with sulfonyl chloride. 10 1-Phenyl-2-chloro-3-butanedione was prepared from benzoylaceton and sulfonyl chloride following the method of Stenner. 11 1-3-Diphenyl-2-chloro-propanedione was prepared from benzoylaceton and sulfonyl chloride. 12 All mercaptans obtained from commercial source were dried and distilled before their uses.

General Procedure for Method A.
(represented by (I))

To the solution of 7.0 g (0.057 mole) of 3-chloro-2,4-pentanedione and 3.5 g (0.057 mole) of ethylmercaptan was slowly added 5.0 g (0.063 mole) of pyridine under vigorous stirring at room temperature for 30 min., followed by further stirring for 6 hr. Precipitated pyridine hydrochloride was filtered off and washed with three portions of 20 ml of ethylether. Combined filtrates was washed with 30 ml of water five times and dried over anhydrous sodium sulfate. A solvent was removed under reduced pressure using rotary evaporator. Crude product was purified by distillation. Four compounds, (VI), (VII), (VIII), and (XI) were recrystallized from n-hexane. (IX) and (XIII) were recrystallized from benzene-methanol mixture to give needle crystals.

-80-
General Procedure for Method B
(represented by (II))

A solution of 13.4 g of (0.10 mole) of 3-chloro-2,4-pentanedione, 10 g (0.12 mole) of pyridine, and 8.4 g (0.11 mole) of iso-propylmercaptan in 15 ml of carbon tetrachloride was refluxed under vigorous stirring for 10 hr. Subsequent procedure was identical with method A.

General Procedure for Method C
(represented by (III))

To a solution of 37.4 g (0.28 mole) of tert-butylmercaptan and 37.5 g (0.28 mole) of 3-chloro-2,4-pentanedione cooled at 0°C was added dropwise 23.0 g (0.27 mole) of piperidine in 20 ml of chloroform for 10 min. After exothermic reaction ceased, the reaction mixture was added by 100 ml of methyl alcohol followed by further stirring for 5 hr at room temperature. Successive treatment was identical with method A. (X) and (XIV) were recrystallized from ether solution.

4.4 Results and Discussion

Our first attempts to prepare α-alkythio and α-phenylthio-β-dicarbonyls have been done through the reaction of relatively stable α-chloro-β-dicarbonyls with various mercaptans in the presence of pyridine or piperidine. The results are listed in Table I. The reaction conditions were varied depending on the reactivity of mercaptans. When α-chloro-β-dicarbonyls were
treated with the thiophenol or ethyl mercaptan in the presence of pyridine, an exothermic reaction occurred

\[
\text{RCOCHClCOR'} + \text{R''SH} \rightarrow \text{RCOCHCOR'}^{SR''} \]

pyridine

or piperidine

beta-dicarbonyls: \(\text{CH}_3\text{COCH}_2\text{COCH}_3\), \(\text{CH}_3\text{COCH}_2\text{CO}_2\text{C}_2\text{H}_5\), \(\text{CH}_3\text{COCH}_2\text{CO}_2\text{CH}_3\), \(\text{C}_6\text{H}_5\text{COCH}_2\text{COCH}_3\), \(\text{C}_6\text{H}_5\text{COCH}_2\text{CO}_2\text{CH}_3\)

mercaptans: alkyl mercaptan, \(\text{C}_6\text{H}_5\text{SH}\), \(\text{HSCH}_2\text{CH}_2\text{SH}\), \(\text{HSCH}_2\text{COOH}\)

with the immediate precipitation of pyridinium hydrochloride even at room temperature. However, more drastic conditions were required as the size of the alkyl group on the mercaptan was increased. Higher temperature and longer reaction periods were necessary to effect a reaction with i-propyl mercaptan. For the reaction with t-butyl mercaptan or n-butyl mercaptan using pyridine in carbon tetrachloride, only small amounts of the hydrochloride salt were found after refluxing for 24 hours. On the other hand, the use of piperidine accelerated the reactions without warming. As a matter of fact, these reactions can be effectively controlled by preferring the choice of the basicity of the amine and acidity of the mercaptan.

The structure and tautomeric ratio were determined from analyses and spectroscopic properties. The chemical shifts of
synthesized α-alkylthio- and α-phenylthio-β-dicarboxyls in carbon tetrachloride solution are listed in Table II. In the nmr spectra, the chemical shifts of enol proton appeared at lower magnetic field, in the region −6∼−8 ppm for β-diketones and −2∼−4 ppm for β-ketoesters are ascribed to intramolecularly hydrogen bonded proton. The highly enolized structures except for 1,3-diphenyl-2-phenylthio-1,3-propanedione (VII) and 1,3-diphenyl-2-methylthio-1,3-propanedione (VIII) are confirmed by the absence of signals of −CHX− together with intensity ratios of the enol proton to the protons of R and R' group.

Table III lists UV spectra in n-heptane and the prominent vibrational frequencies of the chelate ring with the tentative assignments according to normal coordinate analyses. A weak and broad absorption at around 2600 cm⁻¹ for β-diketones and a band at 2700−2900 cm⁻¹ for β-ketoesters are assigned to strongly hydrogen bonded O−H stretching vibrations. A strong and broad absorption at 1580−1560 cm⁻¹ in β-diketones is attributed to the C=O stretching vibration strongly perturbed by hydrogen bonding and superimposed with the C=C stretching vibration. This composite band is shifted by about 60−80 cm⁻¹ toward lower frequency region compared with the original β-diketones.

Two strong absorptions at 1640−1620 and 1590−1670 cm⁻¹ can be assigned to the C=O and the C=C stretching for the chelate ring of β-ketoesters respectively. Since ν(C=O)
and $\nu(C=\text{C})$ appear at 1655 and 1632 cm$^{-1}$ in ethyl acetoacetate, it indicates that a stronger intramolecular hydrogen bond and more delocalization of $\pi$-electrons in the chelate ring are formed by substitution with an alkylthio or phenylthio group. These trends are consistent with what we observed in the nmr spectra. For $\alpha$-substituted $\beta$-ketoesters, very weak absorption at 1720 cm$^{-1}$ due to free carbonyl stretching indicates the existence of trace amounts of the keto form which could not be observed in the nmr spectrum.

Reactions of 3-chloro-2,4-pentanedione or ethyl $\alpha$-chloro acetoacetate with dithioethyleneglycol afforded respectively (IX) and (XIII) as colorless crystals in moderate yields. These two compounds exhibit the characteristic infrared spectra of chelation as are shown in Table III. The keto forms are excluded by the absence of $\nu(C=\text{O})$ due to the free carbonyl stretching. The singlet enol proton and identical signals of $R$ or $R'$ belonged to the different chelate rings suggest the dienolic structure consisted of the two equivalent chelate rings as shown in Figure 1. (VII) and (VIII) were confirmed to be complete keto form both in crystals and non polar solvents by the appearance of chemical shift of $-\text{CH-}$ and three strong absorptions at around 1720 cm$^{-1}$ due to free carbonyl stretchings. It is presumed that a strong steric interaction between the sulfur atom and the two phenyls attached to the chelate ring destabilize chelate ring resulting
in considerable loss of coplanarity of two phenyl rings to chelate ring and giving more stable keto tautomer. In contrast, in case of l-phenyl-2-phenylthio-1,3-butanedione (VI) one phenyl ring attached to chelate ring can permit (VI) to form enol structure, even if there is an interaction between sulfur atom and phenyl ring to some extent. Its nmr spectrum is demonstrated in Fig. 2.

Ultraviolet spectra showed characteristic absorption at 280-300 μm for β-diketones\(^{19}\) and about 250 μm for β-ketoesters\(^{20}\) as shown in Table III. These bands are assigned to the first \(\pi \rightarrow \pi^*\) transition of chelate ring involving the intramolecular hydrogen bond. α-Alkylthio-β-diketones exhibits absorption at around 230 μm (ε=1,500 -2,000) which has not been observed in other α-substituted β-diketones such as nitro, cyano, acetyl and chloro.\(^{21}\) At the present time, it can not determined whether this band is attributed to the excitation of non-bonding electrons of sulfur to the higher level involving 3d orbitals of sulfur and chelate ring without presice molecular orbital calculations and these are currently being made in our laboratory.

It is of interest to compare the ratio of tautomers in the α-substituted-β-ketoesters with those of their non substituted β-ketoesters.\(^{22}\) By contrast with β-diketones, it is noteworthy that α-thio substituted β-ketoesters (XI), (XII), and (XIII) cause surprising shift of tautomeric equilibrium to the enol side relative to parent β-ketoesters. Figure 3 shows the nmr spectra
of α-phenylthio-β-ketoesters.

Furthermore, similar treatment of α-chloro-β-dicarbonyls with thioglycolic acid gave 3-carboxymethylthio-2,4-pentanediine (X) and methyl α-carboxymethylthio-acetoacetate (XIV). Figure 4 shows the nmr spectra of (X) and (XIV) in CDCl₃ with TMS as an internal standard. Broadened singlets at τ 0.18 for (X) and τ 1.22 for (XIV) are assigned to carboxy proton according to the dependency of their chemical shifts upon dilution. On the contrary, sharp singlets at τ -7.62 of (X) and τ -3.52 of (XVI) assigned to enolic proton are slightly sensitive to dilution. This fact indicates that the strong intramolecular hydrogen bond results in slower inter and intramolecular proton exchange compared with carboxy proton. Figure 5 shows the dependencies of two proton signals on dilution.

The infrared spectra of (X) exhibited a strong band at 2960 cm⁻¹ and 1700 cm⁻¹ owing to bonded O-H and the carbonyl stretching of carboxy group respectively as is seen in Figure 6. The broad and strong absorption at 1570 cm⁻¹ shows a good evidence to support the chelate ring structure. The infrared spectrum of (XIV) in Figure 7 is akin to that of (X).

It is also noticed that this reaction route is able to extend to prepare 3-acetyltio-2,4-pentanediine (XV) by using 3-chloro-2,4-pentanediine and thioacetic acid in stead of 2,4-pentanediine and acetylsulfenylchloride.¹
Complete enolization of (XV) was confirmed by proton signals at 7.86, 7.67, and -7.29 with intensity ratios of 6:3:1 in Fig. 8.

In comparison with the parent \( \beta \)-dicarbonyls, chemical shift of enol proton resonates at lower magnetic field and the C=O stretching shifts toward lower frequency region as increasing the strength of hydrogen bond. Accordingly, it is clearly indicated that substitution with alkylthio or phenylthio group results in formation of stronger hydrogen bond and more delocalization of \( \pi \)-electrons in chelate ring.

In connection with the effect of \( \alpha \)-substituents on tautomeric equilibria and hydrogen bonding, the few works have been reported to give rather vague conclusions. We have suggested that the major effect of \( \alpha \)-substituents may be attributed to mesomeric effect and electron-withdrawing group such as nitro, acetyl, and cyano will increase delocalization of electrons in the chelate ring and the strength of the hydrogen bonding. As has been pointed out by Baker and Harris, sulfur in thioesters directly attached to the carbonyl participates in resonance interaction in the ground state through its 3d orbitals. Thus it may be analogously considered that the sulfur atom directly attached to
the α-position of β-dicarbonyls behaves as an electron-withdrawing substituent through π-δ conjugation rather than electron-releasing at ground state. This leads to reasonable conclusion that the decrease of electron density on the enol oxygen favors shift of the proton at the equilibrium position closer to the oxygen of carbonyl, forming a stronger hydrogen bond. High enolization can be also explained by the decrease of the electron density on methylene carbon to cause easier proton releasing relative to the parent β-dicarbonyls.
Table 1  Synthesized α-Alkylthio- and α-Phenylthio-α-dicarbonyls, RCOCHCOR'  

<table>
<thead>
<tr>
<th>Compound</th>
<th>R</th>
<th>R'</th>
<th>X</th>
<th>yield%</th>
<th>bp(°C)</th>
<th>Formula</th>
<th>C</th>
<th>H</th>
<th>S</th>
<th>Method of Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CH₃</td>
<td>CH₃</td>
<td>SC₂H₅</td>
<td>84</td>
<td>95(20)</td>
<td>C₇H₁₂O₂S</td>
<td>52.45</td>
<td>7.55</td>
<td>20.00</td>
<td>52.47 7.70 19.93 A</td>
</tr>
<tr>
<td>II</td>
<td>CH₃</td>
<td>CH₃</td>
<td>S(t-C₃H₇)</td>
<td>46</td>
<td>87-88(8)</td>
<td>C₄H₁₀O₂S</td>
<td>55.10</td>
<td>8.10</td>
<td>18.36</td>
<td>55.31 8.14 18.10 B</td>
</tr>
<tr>
<td>III</td>
<td>CH₃</td>
<td>CH₃</td>
<td>S(t-C₃H₇)</td>
<td>63</td>
<td>68-70(7)</td>
<td>C₉H₁₇O₂S</td>
<td>57.60</td>
<td>8.56</td>
<td>17.01</td>
<td>57.65 8.84 16.71 C</td>
</tr>
<tr>
<td>IV</td>
<td>CH₃</td>
<td>CH₃</td>
<td>S(t-C₃H₇)</td>
<td>44</td>
<td>80-81(9)</td>
<td>C₉H₁₈O₂S</td>
<td>57.40</td>
<td>8.56</td>
<td>17.01</td>
<td>57.70 8.69 17.25 C</td>
</tr>
<tr>
<td>V</td>
<td>CH₃</td>
<td>CH₃</td>
<td>SC₂H₅</td>
<td>81</td>
<td>142-143(12)</td>
<td>C₁₁H₁₄O₂S</td>
<td>63.19</td>
<td>6.08</td>
<td>15.54</td>
<td>63.46 5.81 15.40 A</td>
</tr>
<tr>
<td>VI</td>
<td>C₆H₅</td>
<td>CH₃</td>
<td>SC₂H₅</td>
<td>40</td>
<td>63</td>
<td>C₁₉H₁₄O₂S</td>
<td>71.08</td>
<td>5.21</td>
<td>11.85</td>
<td>71.45 5.27 11.95 A</td>
</tr>
<tr>
<td>VII</td>
<td>C₆H₅</td>
<td>C₆H₅</td>
<td>SC₂H₅</td>
<td>32</td>
<td>63-65</td>
<td>C₂₁H₁₆O₂S</td>
<td>75.87</td>
<td>4.85</td>
<td>9.64</td>
<td>75.87 4.84 9.60 A</td>
</tr>
<tr>
<td>VIII</td>
<td>C₆H₅</td>
<td>C₆H₅</td>
<td>SC₂H₅</td>
<td>36</td>
<td>88</td>
<td>C₁₆H₁₄O₂S</td>
<td>71.08</td>
<td>5.22</td>
<td>11.85</td>
<td>70.84 5.19 11.71 A</td>
</tr>
<tr>
<td>IX</td>
<td>CH₃</td>
<td>CH₃</td>
<td>SC₂CH₂₂H₂</td>
<td>83</td>
<td>126-128b</td>
<td>C₁₂H₁₈O₂S</td>
<td>49.85</td>
<td>6.32</td>
<td>22.09</td>
<td>49.51 6.42 21.82 A</td>
</tr>
<tr>
<td>X</td>
<td>CH₃</td>
<td>CH₃</td>
<td>SCH₂COON</td>
<td>45</td>
<td>86</td>
<td>C₁₄H₁₀O₅S</td>
<td>44.20</td>
<td>5.26</td>
<td>16.86</td>
<td>43.93 5.28 16.61 C</td>
</tr>
<tr>
<td>XI</td>
<td>CH₃</td>
<td>OCH₃</td>
<td>SC₂H₅</td>
<td>45</td>
<td>35b</td>
<td>C₁₁H₁₄O₃S</td>
<td>58.91</td>
<td>5.39</td>
<td>14.30</td>
<td>58.82 5.27 14.16 A</td>
</tr>
<tr>
<td>XII</td>
<td>CH₃</td>
<td>OCH₃</td>
<td>SC₂H₅</td>
<td>53</td>
<td>165(19)</td>
<td>C₁₂H₁₄O₃S</td>
<td>60.48</td>
<td>5.92</td>
<td>13.46</td>
<td>60.46 5.94 13.78 A</td>
</tr>
<tr>
<td>XIII</td>
<td>CH₃</td>
<td>OCH₃</td>
<td>SCH₂CH₂₂H₂</td>
<td>65</td>
<td>104b</td>
<td>C₁₄H₂₂O₆S</td>
<td>48.00</td>
<td>6.29</td>
<td>18.30</td>
<td>48.06 6.41 18.10 A</td>
</tr>
<tr>
<td>XIV</td>
<td>CH₃</td>
<td>OCH₃</td>
<td>SCH₂COON</td>
<td>38</td>
<td>82</td>
<td>C₁₉H₁₀O₅S</td>
<td>41.05</td>
<td>4.85</td>
<td>15.55</td>
<td>40.78 4.87 15.27 C</td>
</tr>
</tbody>
</table>

a) yields based on α-dicarbonyl  
b) melting points.
Table II: Nuclear Magnetic Resonance Spectra

<table>
<thead>
<tr>
<th>Compound</th>
<th>R</th>
<th>R'</th>
<th>CH</th>
<th>R''</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>7.60 s  (CH₃)</td>
<td>-6.96 s</td>
<td>7.80 t  (-SCCH₂), 7.50 m  (-SCH₂C)</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>7.70 s  (CH₃)</td>
<td>-7.17 s</td>
<td>8.80 d  (-SC(CH₂)₂), 7.70-7.50 m  (-SCH)</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>7.72 s  (CH₃)</td>
<td>-7.30 s</td>
<td>8.80 s  (-SC(CH₃)₂)</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>7.71 s  (CH₃)</td>
<td>-7.17 s</td>
<td>8.60 s  (-SCCH₂OH₂C), 7.41 t  (-SCH₂⁻), 8.90 t  (-SCCCCH₂)</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>7.72 s  (CH₃)</td>
<td>-7.33 s</td>
<td>2.90 s  (-SC₆H₅)</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>2.94 s  (-C₆H₅)</td>
<td>7.70 s  (CH₃)</td>
<td>-7.75 s</td>
<td>3.11-3.15 m  (-C₆H₅)</td>
</tr>
<tr>
<td>VII</td>
<td>2.30 s  (two C₆H₅)</td>
<td>-6.52 s</td>
<td>7.90 m  (-SC₆H₅), 4.37 s  (-CH⁻)</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>2.40 s  (two C₆H₅)</td>
<td>-6.52 s</td>
<td>7.95 s  (-SCH₂), 4.66 s  (-CH⁻)</td>
<td></td>
</tr>
<tr>
<td>IX</td>
<td>7.65 s  (CH₃)</td>
<td>-6.52 s</td>
<td>7.74 s  (-SCCH₂S⁻)</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>7.57 s  (CH₃)</td>
<td>-7.20 s</td>
<td>6.76 s  (-SC₆H₅C≡), 0.18 s  (COOH)</td>
<td></td>
</tr>
<tr>
<td>XI</td>
<td>7.78 s  (CH₃)</td>
<td>6.45 s  (OCH₃)</td>
<td>-3.66 s</td>
<td>3.16-3.20 m  (-SC₆H₅)</td>
</tr>
<tr>
<td>XII</td>
<td>7.80 s  (CH₃)</td>
<td>6.20 q  (-OCH₂CO), -3.73 s</td>
<td>3.18-3.19 m  (-SC₆H₅)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.90 t  (-OCH₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XIII</td>
<td>7.74 s  (CH₃)</td>
<td>8.69 t  (-OCH₃), -2.95 s</td>
<td>7.48 s  (-SC₆H₅C≡), 5.88 q  (-OCH₃)</td>
<td></td>
</tr>
<tr>
<td>XIV</td>
<td>7.64 s  (CH₃)</td>
<td>6.39 s  (-OCH₃)</td>
<td>-3.52 s</td>
<td>6.74 s  (-SC₆H₅CO), 1.22 s  (COOH)</td>
</tr>
</tbody>
</table>

a) Measured from TMS as an internal reference in CCl₄.  b) s, d, t, and q denote singlet, doublet, triplet, quartet, and multiplet, respectively.
### Table III: IR and UV spectra for α-alkylthio- and α-phenylthio-3-dicarboxyls

<table>
<thead>
<tr>
<th>Compound</th>
<th>IR Spectra (cm⁻¹)</th>
<th>UV Spectra(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>𝜈(O–H)</td>
<td>𝜈(C=O)</td>
</tr>
<tr>
<td>I</td>
<td>2590</td>
<td>1578c</td>
</tr>
<tr>
<td>II</td>
<td>2596</td>
<td>1585c</td>
</tr>
<tr>
<td>III</td>
<td>2600</td>
<td>1565c</td>
</tr>
<tr>
<td>IV</td>
<td>2600</td>
<td>1575c</td>
</tr>
<tr>
<td>V</td>
<td>2580</td>
<td>1572e</td>
</tr>
<tr>
<td>VI</td>
<td>2510</td>
<td>1525c</td>
</tr>
<tr>
<td>VII</td>
<td>1710, 1679, 1663</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>1709, 1671, 1659</td>
<td></td>
</tr>
<tr>
<td>IX</td>
<td>2570</td>
<td>1575</td>
</tr>
<tr>
<td>X</td>
<td>f</td>
<td>1570</td>
</tr>
<tr>
<td>XI</td>
<td>2780</td>
<td>1624</td>
</tr>
<tr>
<td>XII</td>
<td>2780</td>
<td>1625</td>
</tr>
<tr>
<td>XIII</td>
<td>2880</td>
<td>1638</td>
</tr>
<tr>
<td>XIV</td>
<td>f</td>
<td>1619</td>
</tr>
</tbody>
</table>

- a) measured in CC1₄
- b) measured in n-heptane
- c) overlapped with 𝜈(C=O) and 𝜈(C=C)
- d) 𝜈(C=O) for ketones
- e) measured in CHCl₃
- f) difficult assignment due to the superimposition of 𝜈(OH) of the COOH.
Figure 1 The NMR spectra of ethylenebis-(3-thio-2,4-pentane-dione) (IX) and ethylenebis-(ethyl α-thioacetate-acetate) (XIII)
Fig. 2 The nmr spectrum of 3-phenylthio-1-phenyl-1,3-butanedione.
Fig. 3. NMR spectra of Ethyl and "ethyl 3-phenylthio acetoacetate
Figure 4  The NMR spectra of 3-carboxymethylthio-2,4-pentanedione (X) and methyl α-carboxymethylthioacetate (XIV)
Fig. 5 The dependencies of chemical shifts of the -COOH and O-H of (X) on dilution.
Fig. 6  The infrared spectrum of 3-carboxymethylthio-2,4-pentanedione
Fig. 7 The infrared of methyl α-carboxymethylthioacetacetate
Fig. 8. Nmr spectrum of 3-acetylthio-2,4-pentanedione
References


22. J. B. Conant and A. F. Thompson have reported that the enol percentages of ethyl and methyl acetoacetate are 7.6 and 6.7 in liquid respectively, J. Am. Chem. Soc., 54, 4309 (1953). Reexamined values in CCl₄ solution from NMR showed 22.0 % and 24.2 %.


Chapter 5

The Reaction of Metal(III) Chelates of 3-Bromo-2,4-Pentanediione with Thiophenoles*1

5.1 Summary 103
5.2 Introduction 103
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5.4 Results 107
5.5 Discussion 111

*1 Presented before at the Annual Meeting of the Chemical Society of Japan held at Tokyo, April, 1969.
5.1 Summary

Although extensive works on electrophilic substitution reaction of acetylacetonates have been reported by many workers, successful cases of nucleophilic displacement at the central carbon of the chelate ring have never been found. We have succeeded in the first nucleophilic reaction of metal (III) acetylacetonate chelate ring by the reaction of tris-(3-bromo-2,4-pentanediono)-aluminum (III), -cobalt(III), and -chromium(III) with arylmercaptans, leading to yield tris-(3-arylthio-2,4-pentanediono)-metal (III) chelates. The proposed structures were confirmed by spectroscopic evidences and analyses.

The reaction in stronger proton acceptor such as acetone, methylalcohol, and diethylether was extremely depressed in comparison with the system in weaker proton acceptor such as benzene and methylenedichloride. The reaction behavior is qualitatively discussed in terms of the solvent effect, the substituent effect of nucleophiles and metals.

5.2 Introduction

It has been of great interest that trivalent metal chelate of acetylacetone undergo quasi-aromatic electrophilic substitution with a various reagents. The first direct substitution was the bromination of chromium(III) acetylacetonate by the action of bromine in chloroform. Since Djoidjevic reported
nitration of copper (II) acetylacetonate,\(^2\) it has invoked the attention of chemists to this field concerning with new aromatic system. Extensive works on electrophilic substitution have been reported by Collman and his co-workers.\(^3\)

\[\begin{align*}
\text{H}_3\text{C} & \quad \text{O} \quad \text{Cr}/3 \\
\text{H} & \quad \text{Cr}/3 \\
\text{H}_3\text{C} & \quad \text{O} \\
\text{H} & \quad \text{Cu}/2 \\
\text{H}_3\text{C} & \quad \text{O} \\
\text{H} & \quad \text{M}/3 \\
\text{H}_3\text{C} & \quad \text{O}
\end{align*}\]

\[\begin{align*}
\text{Br}^+ & \quad \text{O} \quad \text{Br}/3 \\
\text{Br} & \quad \text{Cr}/3 \\
\text{O}_2\text{N} & \quad \text{O}_2\text{N} \\
\text{Cu}/2 & \quad \text{O}_2\text{N} \\
\text{X}^+ & \quad \text{X} + \text{H}^+
\end{align*}\]

\(X=\text{I, Br, Cl, SCN, SAr, SC1, NO}_2, \text{COCH}_3, \text{CHO, CH}_2\text{Cl}\)

However, successful nucleophilic substitution have never been found anywhere. The treatment of tris-(3-bromo-2,4-pentanediono)-chromium(III) with azide, acetate, cyano, and iodo anion resulted in recovery of the starting material. In addition, the reaction of brominated chelate with sodium ethoxide in cold ethanol caused decomposition of metal chelate.\(^4\)

Collman et al have reported that the treatment of tris-
(2,4-pentanediono)-chromium(III) with sulfur nucleophile such as phenylsulfenyl chloride can afford tris-(3-phenylthio-2,4-pentanediono)-chromium(III) among his wide investigations.\(^5\)

\[
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{H} \\
\text{C} \quad \text{C} \quad \text{O} \\
\text{Cr/3} \\
\text{CH}_3
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{C} \quad \text{O} \\
\text{H-C=C(}\text{Cr/3} \quad \text{Q} \quad \text{SCl}
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\downarrow \\
\text{CH}_3
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{S} \\
\text{C} \quad \text{O} \\
\text{Cr/3} \\
\text{CH}_3
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{C} \quad \text{C} \quad \text{O} \\
\text{HCl}
\end{array}
\end{align*}
\]

(4)

To the contrary, we have found an alternative nucleophilic pathway to prepare the above compound in milder condition using tris-(3-bromo-2,4-pentanediono)-metal (III) complexes and arylmercaptans in methylenedichloride at \(-5^\circ - -20^\circ\). This is the first instance of the successful nucleophilic displacement to the central carbon atom of acetylacetonates.

\[
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{Br} \\
\text{M/3} \quad \text{O} \\
\text{CH}_3
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\downarrow \\
\text{RSH}
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\text{CH}_3 \\
\text{S} \\
\text{C} \quad \text{O} \\
\text{M/3} \\
\text{CH}_3
\end{array}
\end{align*}
\begin{align*}
\begin{array}{c}
\downarrow \\
\text{HBr}
\end{array}
\end{align*}
\]

(5)

\[
M = \text{Al(III), Co(III), Cr(III)}
\]

\[
R = \text{C}_6\text{H}_5, \text{p-CH}_3\text{C}_6\text{H}_4, \text{p-NO}_2\text{C}_6\text{H}_4
\]
5.3 Experimental

Starting materials; Acetylacetone was commercially available and distilled under nitrogen stream before use. Aluminum (III), cobalt(III), and chromium(III) acetylacetonates were prepared according to the authentic method. These chelates were halogenated by means of N-halosuccinimides followed by chromatography on silicagel. Commercial thiophenols were purified by distillation or recrystallization.

5.3.1 Tris-(3-phenylthio-2,4-pentanediono)-aluminum(III), (1a);
Solution of tris-(3-bromo-2,4-pentanediono)-aluminum (1.0 g) in 60 ml. of methylenedichloride was kept at -20°C with dry ice-acetone. To this solution was slowly added a solution of thionphenol in 10 ml. of methylenedichloride under stirring. After two hours, the solution was treated with aqueous sodium bicarbonate and washed with water three times. A white powder (0.26g.) was obtained from recrystallization from the mixture of water-ethanol.

5.3.2 Tris-(3-phenylthio-2,4-pentanediono)-cobalt(III)(2a);
To a solution of tris-(3-bromo-2,4-pentanediono)-cobalt(III) (0.5g) in 40 ml. of methylenedichloride was dropwisely added a thiophenol (0.3g) in 10 ml of methylenedichloride at -20°C. After two hours at -20°C, 0.3g of pyridine was added to the solution at once. The reaction mixture was chromatographed on Florisil with benzene. A green solution was collected and
condensed to small portions under vacuum. Recrystallization from ethanol-water yielded a fine green crystals (0.3 g).

5.3.3 Tris-(3-phenylthio-2,4-pentanediono)-chromium(III), (3a); A solution of thiopenol (0.6 g) in 50 ml. of methylenechloride was slowly added to a solution of tris(3-bromo-2,4-pentanediono)-chromium(III) in 100 ml. of methylenedichloride at -5°C. The treatment similar to the method of (5.3.2) gave 0.52 g of reddish brown crystals. As an minor product, (2,4-pentanediono)-bis-(3-phenylthio-2,4-pentanediono)-chromium(III) was separated by thin layer chromatography, confirmed by infrared spectrum. Another metal(III) chelates were prepared according to the above described methods respectively.

Spectral measurements; Proton magnetic resonances of cobalt(III) and aluminium(III) chelates were measured on Japan Electron Laboratory, Model JNM C-60H in carbontetrachloride with TMS as an internal reference. Infrared spectra were recorded on Japan Spectroscopy Co., Model DS-402G grating spectrophotometer in KBr pellet. Hitachi Model EPS-3T spectrophotometer was used to study electronic spectra in methylenedichloride.

5.4 Results

Table 1 lists yields, physical properties and elementary analyses of products resulted from the reaction of brominated
acetylacetonates and arylmercaptans. Compound (3a) was obtainable in the yield of 32.7 % from the reaction of chromium(III) acetylacetonate with phenylsulfonylchloride. Alternative nucleophilic courses are possible to give corresponding compound (3a) by the reaction of tris-(3-bromo-2,4-pentanediono)-metal(III) with sulfur nucleophiles at low temperature. Eight complexes in Table 1 have never been reported anywhere except for (3a).

Nuclear magnetic resonance spectra

As is shown in Table 2, chemical shifts and ratio of integration for cobalt(III) and aluminum(III) complexes represent clear evidences to indicate the displacement of bromine with arylthio group. Furthermore, singlet signal of methyl group attached to the chelate ring does support that complexes are constructed with one species of ligands as is seen in Figure 1. Otherwise, chemical shift of methyl in the mixed ligand will be splitted into the two peaks because of their different magnetic field.\(^{10,11,12}\) The methyl protons of aluminum(III) complexes resonates at lower magnetic field by 0.18-0.24 ppm than those of cobalt(III) complexes in Figure 2. It is not clear the reason why difference due to the electronic field caused by central metal charge\(^{13}\) or the induced magnetic field of ring current of the chelates. Proton magnetic resonance of chromium (III) complexes are not measurable owing to paramagnetism of unpaired d-electron of chromium(III) ion. Hence the structure
of chromium(III) chelates were determined based on infrared and ultraviolet spectra.

**Infrared spectra**

Upon displacement of bromine with arylthio group, a few new absorptions appeared at 1494, 1481 and 1468 cm\(^{-1}\) assigned to skeletal stretching vibration of phenyl ring. In addition to those bands, another bands at 1086, 1073, 1059 and 1046 cm\(^{-1}\) are probably assigned to C-H in-plane bending vibration of phenyl ring and the C-S stretching vibration. The C-H out-of-plane bending of monosubstituted phenyl ring showed at 806 and 742 cm\(^{-1}\). The latter one was disappeared on introduction of p-CH\(_3\) and p-NO\(_2\). Since new band at 708 cm\(^{-1}\) was not so sensitive to the para substituents, it is likely to be assigned to the stretching vibrational mode of S-C (central carbon atom of chelate).\(^{14}\) The chelates substituted with p-nitrophenylthio group revealed asymmetric stretching vibration of NO\(_2\) at 1510 cm\(^{-1}\) and two absorptions at around 850 cm\(^{-1}\) which are possibly assigned to \(\pi(C-H)\) and \(\nu(C-N)\). p-Methyl phenylthio group would be characterized by the new absorption at 755 cm\(^{-1}\) due to the rocking vibration of methyl group. Infrared spectra of chromium(III) chelates in the region from 1800-400 cm\(^{-1}\) are demonstrated in Figure 2.
Ultraviolet spectra

The ultraviolet spectra and characteristic infrared spectra are listed in Table 3. Non substituted chelates exhibit strong absorption at 288, 258 and 336\textmu m for aluminum(III), cobalt(III) and chromium(III) chelate respectively. Similar strong absorption due to chelate ring is observed for each arylthio substituted chelate. As is seen in Table 3, another strong absorption at 252(1a), 254(1b) and 340(1c) are assigned to the local excitation band $\pi-\pi^*$ transition of para substituted phenyl ring in aluminum(III) chelates. Unfortunately, accidental overlapping of absorption related to the chelate ring and the arylthio group occurred in the cases of (2a), (2b) and (3c) with increases of the strength of absorption.

Reactivity of halogens

In order to elucidate the reaction mechanism, the reaction of tris-(3-chloro-2,4-pentanediono)-cobalt(III) with thiophenol was carried out under the same condition as the case of (6.3.2). The starting material was recovered from the resultant reaction mixture. Even though temperature was raised up to room temperature, trace of (2a) was detected by means of thin layer chromatography. On the other hand, treatment of tris-(3-iodo-2,4-pentanediono)cobalt(III) with thiophenol yielded (2a) to the same extent as the brominated chelates. Consequently, reactivity of halogens are shown in the following order I, Br $\gg$ Cl. The bond
C-X breaking step seems to be significant kinetically.

Effects of oxygen and light

As is well known facts, mercaptans can undergo radical reaction in the presence of oxygen or under irradiation of light. To assure the these effects, the reaction of cobalt (III) chelates with thiophenol was carried out in the dark place under nitrogen stream. As a matter of fact, the significant acceleration or depression of the reaction was not observed within experimental error. Radical reaction scheme is probably less possible.

Effect of solvents

Metal(III) acetylacetonates used to be soluble in usual organic solvents. A solvent effect on the reaction involving metal chelates has never been taken into consideration. Various solvents such as acetone, diethylether, methylalcohol and dimethylsulfoxide were used in order to study the effect of solvent on the reaction. Reaction proceeds effectively in benzene as well as in methylenechloride. To the contrary, it is worthy of notice that the reaction in stronger proton acceptor such as acetone, methanol, ether and dimethylsulfoxide was entirely inhibited. Therefore, it must be mentioned that the effect of solvent is considerably larger than in the electrophilic displacement reaction. An addition of amine such as pyridine and piperidine to accelerate nucleophilic displacement resulted in a failure.
to initiate the reaction under the same condition as (5.3.2.).

Effect of substituents in arylthio group

To avoid difficulties to separate the mixed ligands chelate resulted from competitive reaction of different nucleophiles to a tri-halogenated metal(III) chelate, mono brominated chelate, (3-bromo-2,4-pentanediono)-bis-(2,4-pentanediono)-cobalt(III) was used to investigate the effect of substituents in arylthio group on the reaction. A competitive nucleophilic displacement of p-nitro and p-methyl thiophenol to mono brominated cobalt (III) chelate showed the presence of the exclusive product substituted with p-methylphenylthio group which was clearly proved by NMR spectra of the product. It is, therefore, concluded that the nucleophilicity of sulfur is enhanced by the electron donating substituent and lowered by the electron attracting one. This trend is surprisingly similar to the nucleophilic substitution of thiophenols toward 2,4-dinitrochlorobenzene. 16

![Chemical structure](image-url)
5.5 Discussion

Despite of extensive works on the electrophilic reaction, there have never been reported quantitative reaction kinetics and mechanisms from the standpoint of the quasi aromatic ring of metal chelates except for the mechanisms of bromination by Kluiber.\textsuperscript{17} It was suggested that the consequent of the electron shift from chelate ring to the metal will reduce the tendency towards electrophilic substitution. On the contrary to expectation, only electrophilic substitutions have been developed and successful as has been reported.

An insignificant effect of oxygen and light seems to exclude radical mechanism to explain the reaction scheme in this system. It is reasonably assumed from the effect of solvent that weakly polarized sulfur nucleophiles might participate in the center of reaction rather than completely ionized species.\textsuperscript{18} The sequence of reactivity of leaving halogens would be explained in terms of polarizability of halogens rather than their electronegativities. Moreover, the great polarizability of sulfur atom enables sulfur nucleophile to form the C-S bond easily. Thus both polarizability of attacking sulfur nucleophile and leaving halogen seems to play kinetically important role on the transition state. The presence of strong proton acceptor may break the plausible four centered intermediate to form favorable intermolecular hydrogen bond of $\text{-SH} \cdots \text{O <}$
It is of particular interest to discuss about the effect of metals on the reaction. In case of chromium(III) complexes, reaction temperature was raised up to -5°C to initiate reaction. Therefore, the reactivity of chromium(III) complex is lower than that of cobalt(III) complex judging from the severity of condition. On the other hand, in electrophilic substitution such as acylation, chromium(III) chelates were found to be more reactive than that of cobalt(III).

It can be considered that charge transfer from metal to ligand or ligand to metal may be possible through d-orbitals of metal to interpret the electronic effect of metal. However, it is rather difficult to attribute the electronic effect to d-electron of metal generally, because aluminum(III) chelate showed potential reactivity to sulfur nucleophile under the same condition as cobalt(III) and chromium(III) complexes, even though aluminum possesses no available d-electrons.

In nucleophilic displacement, it should be noticed that there are two kinds of reaction sites, that is, the central
carbon atom and metal. An attack of nucleophile to metal possibly leads exchange of ligands followed by the decomposition of the chelate ring at higher temperature. Especially strongly ionized nucleophiles may have the trend to decomposition. This fact has been observed in the reaction of bis-(3-chloro-2,4-pentanediono)-copper(II) chelate with thiophenol resulted in ready decomposition to give copper sulfide.
<table>
<thead>
<tr>
<th>Metal</th>
<th>R</th>
<th>Yield(%)</th>
<th>m.p.(°C)</th>
<th>Cal.</th>
<th>Found</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>C</td>
</tr>
<tr>
<td>Al(III)</td>
<td>C₆H₅</td>
<td>23</td>
<td>65-67</td>
<td>5.13</td>
<td>61.11</td>
</tr>
<tr>
<td>Al(III)</td>
<td>p-CH₃C₆H₄</td>
<td>53.5</td>
<td>162-164</td>
<td>5.69</td>
<td>62.60</td>
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<tr>
<td>Al(III)</td>
<td>p-NO₂C₆H₄</td>
<td>18.6</td>
<td>135-137</td>
<td>3.86</td>
<td>50.58</td>
</tr>
<tr>
<td>Co(III)</td>
<td>C₆H₅</td>
<td>45.3</td>
<td>104-106</td>
<td>4.89</td>
<td>58.24</td>
</tr>
<tr>
<td>Co(III)</td>
<td>p-CH₃C₆H₄</td>
<td>44.8</td>
<td>170-171</td>
<td>5.44</td>
<td>59.83</td>
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<tr>
<td>Co(III)</td>
<td>p-NO₂C₆H₄</td>
<td>43.5</td>
<td>163-165</td>
<td>3.61</td>
<td>47.38</td>
</tr>
<tr>
<td>Cr(III)</td>
<td>C₆H₅</td>
<td>90</td>
<td>105-107</td>
<td>4.94</td>
<td>58.84</td>
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<tr>
<td>Cr(III)</td>
<td>p-CH₃C₆H₄</td>
<td>68.6</td>
<td>100-102</td>
<td>5.49</td>
<td>60.41</td>
</tr>
<tr>
<td>Cr(III)</td>
<td>p-NO₂C₆H₄</td>
<td>88.6</td>
<td>148-150</td>
<td>3.74</td>
<td>49.01</td>
</tr>
</tbody>
</table>

* Based on chelate

** The sample was found to contain 0.36 mole % of CH₂Cl₂ as impurity determined from the n.m.r. spectrum.
Table 2 The NMR spectra of Al(III) and Co(III) chelates

<table>
<thead>
<tr>
<th>Metal</th>
<th>R</th>
<th>CH$_3$</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(III)</td>
<td>C$_6$H$_5$</td>
<td>7.63(s, 18H)</td>
<td>2.90-3.05(m, 15H)</td>
</tr>
<tr>
<td>Al(III)</td>
<td>p-CH$_3$C$_6$H$_4$</td>
<td>7.64(s, 18H)</td>
<td>3.05(s, 12H) 7.76(s, 9H)</td>
</tr>
<tr>
<td>Al(III)</td>
<td>p-NO$_2$C$_6$H$_4$</td>
<td>7.63(s, 18H)</td>
<td>2.01(d, 6H) 2.82(d, 6H)</td>
</tr>
<tr>
<td>Co(III)</td>
<td>C$_6$H$_5$</td>
<td>7.46(s, 18H)</td>
<td>2.92-3.05(m, 15H)</td>
</tr>
<tr>
<td>Co(III)</td>
<td>p-CH$_3$C$_6$H$_4$</td>
<td>7.50(s, 18H)</td>
<td>3.06(s, 12H) 7.77(s, 9H)</td>
</tr>
<tr>
<td>Co(III)</td>
<td>p-NO$_2$C$_6$H$_4$</td>
<td>7.40(s, 18H)</td>
<td>1.90(d, 6H) 2.75(d, 6H)</td>
</tr>
</tbody>
</table>

* Measured in CCl$_4$ using TMS as an internal standard s, d, and m denote singlet, doublet and multiplet respectively.
### Table 3 The IR and UV spectra of metal (III) chelates

<table>
<thead>
<tr>
<th>Metal</th>
<th>R</th>
<th>IR (in KBr, cm$^{-1}$)</th>
<th>UV (in CH$_2$Cl$_2$, μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>v(C=C)</td>
<td>η(CH)</td>
</tr>
<tr>
<td>Al(III)</td>
<td>C$_6$H$_5$</td>
<td>1480</td>
<td>805</td>
</tr>
<tr>
<td>Al(III)</td>
<td>p-CH$_3$C$_6$H$_4$</td>
<td>1495</td>
<td>808</td>
</tr>
<tr>
<td>Al(III)</td>
<td>p-NO$_2$C$_6$H$_4$</td>
<td>1478</td>
<td>842</td>
</tr>
<tr>
<td>Co(III)</td>
<td>C$_6$H$_5$</td>
<td>1482</td>
<td>805</td>
</tr>
<tr>
<td>Co(III)</td>
<td>p-CH$_3$C$_6$H$_4$</td>
<td>1495</td>
<td>807</td>
</tr>
<tr>
<td>Co(III)</td>
<td>p-NO$_2$C$_6$H$_4$</td>
<td>1477</td>
<td>842</td>
</tr>
<tr>
<td>Cr(III)</td>
<td>C$_6$H$_5$</td>
<td>1481</td>
<td>806</td>
</tr>
<tr>
<td>Cr(III)</td>
<td>p-CH$_3$C$_6$H$_4$</td>
<td>1495</td>
<td>806</td>
</tr>
<tr>
<td>Cr(III)</td>
<td>p-NO$_2$C$_6$H$_4$</td>
<td>1477</td>
<td>841</td>
</tr>
</tbody>
</table>

* Showed only characteristic bands and calibrated by polystyrene film.
Figure 1 The NMR spectra of tris-(3-arylthio-2,4-pentanediono) aluminum(III)
Figure 2 The NMR spectra of tris-(3-arylthio-2,4-pentanediono) cobalt (III)
Figure 3 The IR spectra of tris-(3-arylthio-2,4-pentanediono) chromium (III)
References


Chapter 6

Cyclopropyl Conjugation with the Chelate Ring of β-dicarbonyls*1

| 6.1  | Summary  | 124 |
| 6.2  | Introduction  | 124 |
| 6.3  | Experimental  | 125 |
| 6.4  | Results and Discussion  | 126 |

*1 Presented before at the Annual Meeting of the Chemical Society of Japan at Tokyo, April 1969.
6.1 Summary

\( \pi \)-Conjugative effect of cyclopropyl ring on the chelate ring of \( \beta \)-diketones at the both ground and excited state has been studied by means of spectroscopic methods. The changes in spectra have been compared on the substitution of isopropyl group with cyclopropyl ring. Proton magnetic resonance and infrared spectra indicate that there is appreciable conjugative effect at the ground state. The bathochromic shift of \( \pi - \pi^* \) transition band of the chelate ring suggests more stabilization of the excited state rather than the ground state. Conformational preference of cyclopropyl ring in the chelate ring of \( \beta \)-diketones become more important at the excited state. Cyclopropyl conjugation in metal chelate of \( \beta \)-diketone appears to be considerably small in comparison with free ligand.

6.2 Introduction

Problems of \( \pi \)-conjugative interaction of cyclopropyl ring with adjacent unsaturated bond have been a great deals of chemist.\(^1\) It has been of particular interest that conformational preference of cyclopropyl reflects on the overlapping of p-orbital of adjacent double bond.\(^2,3\) Even though so many works have been reported, a large number of them is concerned with electronic spectra with less care of the ground state.\(^4-7\) The cyclopropyl conjugation at the ground state have recently
been investigated by the techniques of proton magnetic resonance, infrared, electron diffraction, and solvolysis reaction.

The system of enolic structure of β-diketones present the proper example in order to study rather weak conjugative effect of cyclopropane ring, since π-electron system associated with intramolecular hydrogen bond enable to give information about both ground and excited state. Several new cyclopropyl substituted β-diketones have been reported in the present paper.

6.3 Experimental

1-Cyclopropyl-3-isopropyl-1,3-propanedione (II); Essential procedure were followed according to the method to prepare asymmetric β-diketone reported by Linn and Hauser.

A solution of 8.04 g (0.096 mole) of cyclopropylmethylketone in 100 ml of ethylether was slowly added to suspension of 7.0 g (0.18 mole) of finely pulverized sodium amide under vigorous stirring for 30 min. To reaction mixture was dropwisely added 32.0 g (0.27 mole) of ethyl iso-butyrate followed by further stirring for 3 hr at room temperature. A gelatinous mixture was poured into ice-water and nutrilized by 6N-HCl. β-Diketone was separated by treatment of aqueous copper acetate in the form of bis-(1-cyclopropyl-3-isopropyl-1,3-propanediono)
-copper(II). Copper chelate recrystallized from chloroform was
hydrolized by 6N-HCl. β-Diketone was recovered by extraction
with ether. Extract was washed with water and dried over anhy-
drous sodium sulfate. Distillation at reduced pressure afforded
6.5 g of a colorless liquid, 54.0-55.5°C/6mm, 44% yield based
on ketone.

1,3-dicyclopentyl-1,3-propanedione (III), 1-cyclopentyl-3-(2-
thenoyl-1,3-propandione (IX), 1-cyclopentyl-3-(2-furyl-1,3-propane-
dione (VII), and 1-cyclopentyl-3-trifloromethyl-1,3-propnedione
(XI) were prepared using corresponding ketone and ester. In
case of (XI), ether extract was refluxed with P_2O_5 for 5 hr.
Its elementary analysis was doubtful because of the action of
fluorine, however structural identification was supported by
nmr spectrum. Colorless liquid was separated by distillation.

Spectral Measurements

Spectrophotometers used in this work were stated in the
previous chapter. Infrared spectra were measured in carbon
tetrachloride. Measurement of ultraviolet and visible spectra
were carried out in n-hexane for β-diketones and in methylene-
chloride for copper chelates respectively

6.4 Results and Discussion

Table 1 lists yield, physical properties and elementary
analysis of newly synthetized cyclopropyl substituted β-diketone.
The synthetic pathway of 1,3-diketones

\[
\begin{align*}
\text{NaNH}_2 & \quad \text{in (C}_2\text{H}_5\text{)}_2\text{O} \\
\begin{array}{c}
\text{R}_1\text{-C-CH}_3 \\
\text{0}
\end{array} & + & \begin{array}{c}
\text{R}_2\text{-COC}_2\text{H}_5 \\
\text{0}
\end{array} & \rightarrow & \begin{array}{c}
\text{R}_1\text{-C-CH}_2\text{-C-CH}_2\text{-R}_2 \\
\text{0} & & \text{0}
\end{array}
\end{align*}
\]

\( R_1 = \text{cyclopropyl, isopropyl} \)

\( R_2 = \text{cyclopropyl, isopropyl, phenyl, 2-furyl, 2-thenoyl, trifluoromethyl} \)

Cannon and Whidden have already synthetized cyclopropyl substituted \( \beta \)-diketones such as 1-cyclopropyl-1,3-butanedione and 1-cyclopropyl-3-phenyl-1,3-propanedione, however they have never mentioned about available spectroscopic data. Their nmr spectra in carbon tetrachloride are shown in Figure 1 - Figure 4. No cleavage of cyclopropane ring has been proved by the spectroscopic evidences and the elementary analyses. As has been explained by Hammond et al., substitution of bulky groups at 1- and 3-positions increases the percentage of enol tautomer owing to repulsive interaction between two substituents. Similar high enolization has been proved by the nmr spectra. The enolization of cyclopropyl substituted \( \beta \)-diketones are not different from corresponding isopropyl substituted \( \beta \)-diketone. All of them showed more than 90 % of enol structure estimated from the ratio of integration of the \(-\text{CH}_2-\) proton of keto form and the \(-\text{CH}=-\) of enol form.
Chemical shifts of β-diketones are summarized in Table 2. Two chemical shifts, \(-\text{CH}=\) and \(\text{O-H}\cdots\text{O}\), characteristic of the chelate ring were noticed to evaluate the changes in π-conjugative system and the strength of intramolecular hydrogen bond. The proton chemical shifts of the \(-\text{CH}=\) resonate slightly at lower magnetic field compared with corresponding iso-propyl substituted β-diketones. Similar trend have been observed in cyclopropyl substituted olefinic esters, where the \(-\text{CH}=\) proton of trans conformer appeared at lower magnetic field than cis conformer. However, it is rather hard to show whether a cyclopropyl ring exist in s-trans or s-cis to the C=C bond of the chelate ring.

As has been reported by Jarret et al, the enolic proton resonates at quite lower magnetic field. The position of chemical represents a measure of the strength of hydrogen bond in accord with a shift of carbonyl stretching vibration in infrared spectra. Substitution of iso-propyl with cyclopropyl indicates an appreciable down field shift for 3-isopropyl, 3-thenoyl and 3-trifluoro series. On the other hand, slight up field shift are observed in 3-phenyl and 3-fruyl substituted ones. As is seen in Table 3, the C=O stretching shifted appreciably to lower frequency region for former group and for the latter case, the shift was only few wave numbers on substitution with cyclopropyl group. Strictly speaking, the indication
by the C=O stretching is rather vague because of its superimposition with the C=C stretching. There exist possible interconvertible enol isomers (A) and (B) for asymmetric β-diketones, even though its potential barrier between two isomers seems to be very small. In nmr spectrum, it is impossible to distinguish whether (A) or (B) is predominant structure at equilibrium. Averaged chemical shifts of (A) and (B) used to be measured owing to rapid interconversion. If one enol structure is more stable than the other, the nmr spectrum belonged to the former would be reflected on the averaged spectrum. According to this consideration, it is explainable that cyclopropyl substitution exhibit different effect on hydrogen bonding. Electron supplying cyclopropyl adjacent to carbonyl in A form enhances the electron density on the oxygen of carbonyl increasing the strength of hydrogen bond whereas it in B form close to enol increases the electron density on the oxygen of enol resulted in weaker hydrogen bond due to less proton releasing.

\[ \text{H} \]

\[ \text{C} \]

\[ \text{C} \]

\[ \text{H} \]

\[ \text{O} \]

\[ \text{H} \]

\[ \text{R} \]

\[ \text{H} \]

\[ \text{O} \]
Conformational studies on cyclopropyl carbonyls by electron diffraction\textsuperscript{14} have suggested that s-cis rotational isomer is preferential rather than s-trans conformer at the ground state. This is evidently supported by vibrational spectrum of cyclopropanecarboxylic acid chloride.\textsuperscript{12} It has been proposed that s-trans rotational isomer is the lower energy conformer on the basis of analysis of nmr spectra of vinylcyclopropane. These results lead us to suppose that one of two cyclopropyl ring of 1,3-dicarbonyl-1,3-propanedione (III) is placed in s-cis configuration to the carbonyl and the other one is s-trans to perform maximum overlap with p-orbitals of the chelate ring recognized from Walsh's model.\textsuperscript{23}

The electronic spectra of \(\beta\)-diketones are given in Table 3.

Cyclopropyl substitution cause the bathochromic shift of the \(\pi-\pi^*\) transition of the chelate ring which are smaller than that of olefinic esters. Among them, \(\beta\)-diketones containing heterocyclic group and strong electronegative group show somewhat larger shift than those of iso-propyl and aryl substituted
β-diketones. Charge separation of former at the excited state become more significant on substitution with cyclopropyl compared with the latter cases. It is concluded that cyclopropyl ring seems to interact more effectively with π-electron system of the chelate ring at the electronically excited state than the ground state, since the change in electronic spectra are related to the energy difference between the ground and excited states. Cyclopropyl conjugation with metal chelate interest us for its quasi-aromatic ring in comparison with phenylcyclopropane. However, substitution with cyclopropyl has never shown such appreciable changes at both ground and excited states as are seen in metal free chelate. Table 4 and 5 list ultraviolet and visible spectra of metal chelates respectively.

Although band (I) at around 250 μm assigned to σ(ligand) → d_σ (metal) transition reveals very small shift to lower wavelength, it is rather difficult to interpret the electronic effect of cyclopropyl group on the bonding of metal and ligand without precise molecular orbital calculation. Band(II) appeared at 290-340 μm due to π→π* transition of chelate ring does not show significant changes which represent less interaction between cyclopropyl group and the chelate ring as is seen in phenylcyclopropane. Broad absorptions in the visible region seem to be less accurate to discuss, because the positions of maximum absorption are hard to be determined. The chelated C=O stretching vibration appeared at 1580 cm^{-1} was not
<table>
<thead>
<tr>
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<th>R_2</th>
<th>Yield(%)</th>
<th>bp(°C/mm)</th>
<th>Calcd, %</th>
<th>Found, %</th>
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</tbody>
</table>

* base on ketone
Table 2 The nmr spectra of β-diketones

<table>
<thead>
<tr>
<th></th>
<th>R&lt;sub&gt;1&lt;/sub&gt;</th>
<th>R&lt;sub&gt;2&lt;/sub&gt;</th>
<th>(\tau_{CH})</th>
<th>(\tau_{OH})</th>
<th>(\text{-CH(CH}_3\text{)}_2) or</th>
<th>R&lt;sub&gt;1&lt;/sub&gt;</th>
<th>R&lt;sub&gt;2&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I)</td>
<td>-CH(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-CH(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>4.56</td>
<td>-5.34</td>
<td>7.56(2H, m), 8.84(8H, d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(II)</td>
<td>-CH(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td>4.49</td>
<td>-5.66</td>
<td>7.62(1H, m), 8.85(6H, d)</td>
<td>8.40(1H, m), 9.10(4H, m)</td>
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</tr>
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<td>(III)</td>
<td></td>
<td></td>
<td>4.35</td>
<td>-5.76</td>
<td>8.45(1H, m), 9.02(8H, m)</td>
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<tr>
<td>(IV)</td>
<td></td>
<td></td>
<td>3.93</td>
<td>-6.32</td>
<td>2.20(2H, m), 2.60(3H, m)</td>
<td>7.44(1H, m), 8.80(6H, d)</td>
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<tr>
<td>(V)</td>
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<td></td>
<td>3.84</td>
<td>-6.27</td>
<td>2.25(2H, m), 2.65(3H, m)</td>
<td>8.16(1H, m), 8.94(4H, m)</td>
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<td>(VI)</td>
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<td>4.00</td>
<td>-5.37</td>
<td>3.50(1H, m), 2.94(1H, d)</td>
<td>8.80(6H, d), 7.47(1H, m)</td>
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</tr>
<tr>
<td>(VII)</td>
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<td></td>
<td>3.93</td>
<td>-5.29</td>
<td>3.50(1H, m), 3.03(1H, d)</td>
<td>8.29(1H, m), 8.90(4H, m)</td>
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</tr>
<tr>
<td>(VIII)</td>
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<td>4.10</td>
<td>-5.77</td>
<td>2.95(1H, m), 2.45(2H, m)</td>
<td>7.50(1H, m), 8.80(6H, d)</td>
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<tr>
<td>(IX)</td>
<td></td>
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<td>3.96</td>
<td>-6.00</td>
<td>2.98(1H, m), 2.50(2H, m)</td>
<td>8.34(1H, m), 8.92(4H, m)</td>
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<tr>
<td>(X)</td>
<td>CF&lt;sub&gt;3&lt;/sub&gt;</td>
<td>-CH(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>4.12</td>
<td>-3.53</td>
<td>7.45(1H, m), 8.78(6H, d)</td>
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<tr>
<td>(XI)</td>
<td>CF&lt;sub&gt;3&lt;/sub&gt;</td>
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<td>3.98</td>
<td>-4.69</td>
<td>8.22(1H, m), 8.80(4H, m)</td>
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Table 3 The ultraviolet spectra of copper(II) chelate of β-diketones

<table>
<thead>
<tr>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$\lambda_{\text{max}}$ (log $\varepsilon$) (m$\mu$)</th>
<th>$\nu$(C=O) cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>273.5 (4.13)</td>
<td>1613</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>277.0 (4.12)</td>
<td>1610</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>284.0 (4.11)</td>
<td>1584</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>307.0 (4.42)</td>
<td>1573</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>315.0 (4.23)</td>
<td>1571</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{O}$</td>
<td>310.0 (4.36)</td>
<td>1610</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{O}$</td>
<td>323.5 (4.43)</td>
<td>1607</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{S}$</td>
<td>318.0 (4.26)</td>
<td>1605</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{S}$</td>
<td>331.0 (4.25)</td>
<td>1582</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CF}_3$</td>
<td>282.5 (3.84)</td>
<td>1612</td>
</tr>
<tr>
<td>$\text{-CH(CH}_3\text{_2)}$</td>
<td>$\text{-CF}_3$</td>
<td>295.5 (3.85)</td>
<td>1598</td>
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</table>
Table 4  UV spectra of copper (II) chelates of 1,3-diketones

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_{\text{max}} ) (log ( e ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I)</td>
<td></td>
</tr>
<tr>
<td>( R_1 )</td>
<td>( R_2 )</td>
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<tr>
<td>251.1 (4.08)</td>
<td>299.9 (4.36)</td>
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<tr>
<td>249.1 (4.29)</td>
<td>298.5 (4.49)</td>
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<tr>
<td>248.2 (4.36)</td>
<td>300.0 (4.59)</td>
</tr>
<tr>
<td>261.5 (4.45)</td>
<td>325.4 (4.57)</td>
</tr>
<tr>
<td>258.5 (4.37)</td>
<td>327.4 (4.55)</td>
</tr>
<tr>
<td>336.2 (4.59)</td>
<td></td>
</tr>
<tr>
<td>336.5 (4.76)</td>
<td></td>
</tr>
<tr>
<td>266.5 (4.29)</td>
<td>340.5 (4.57)</td>
</tr>
<tr>
<td>265.8 (4.22)</td>
<td>341.0 (4.54)</td>
</tr>
</tbody>
</table>

* measured in methylenedichloride
Table 5 Visible Spectra of Copper (II) Chelate

<table>
<thead>
<tr>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( \lambda_{\text{max}} ) (log ( \varepsilon ))</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>555 (1.606)</td>
<td>663 (1.696)</td>
</tr>
<tr>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>554 (1.626)</td>
<td>664 (1.698)</td>
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<tr>
<td>( \text{C}_6\text{H}_5^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>550 (1.636)</td>
<td>660 (1.680)</td>
</tr>
<tr>
<td>( \text{C}_6\text{H}_5^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>550 (1.542)</td>
<td>658 (1.628)</td>
</tr>
<tr>
<td>( 2\text{-C}_4\text{H}_3\text{O}^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>545 (1.540)</td>
<td>655 (1.660)</td>
</tr>
<tr>
<td>( 2\text{-C}_4\text{H}_3\text{O}^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>552 (1.552)</td>
<td>658 (1.618)</td>
</tr>
<tr>
<td>( 2\text{-C}_4\text{H}_3\text{S}^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>550 (1.765)</td>
<td>656 (1.716)</td>
</tr>
<tr>
<td>( 2\text{-C}_4\text{H}_3\text{S}^-)</td>
<td>(-\text{CH(} \text{CH}_3 \text{)}_2)</td>
<td>553 (1.700)</td>
<td>658 (1.700)</td>
</tr>
</tbody>
</table>

* measured in methylenedichloride
Fig. 1 The nmr spectrum of 1,3-dicyclopentyl-1,5-propanedione
Fig. 2 The nmr spectrum of 1-cyclopropyl-3-trifluoromethyl-1,3-propanedione
Fig. 3. The nmr spectrum of 1-cyclopropyl-(2-furyl)-1,3-propanedione.
Fig. 4 The 1H NMR spectrum of 1-cyclopropyl-(2-thienyl)-1,3-propanedione
References

10. O. Bastlausen and A. de Meijere, Angew. Chem. 78, 142 (1966).
12. J. E. Katon, W. R. Feairheller, Jr., and J. T. Miller Jr.,
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Chapter 7

Molecular Orbital Calculations in Hückel and SCF Approximation; The Enolate Ion*1

7.1 Summary
7.2 Introduction
7.3 The procedure of Calculations
7.4 Results and Discussion

7.1 Summary

Simple molecular orbital calculation of the enolate ion of 3-substituted-2,4-pentanediones has been made for the purpose of evaluating the electronic effect of 3-substituents. The decrease of electron density on the enol oxygen results in the shift of the enol proton toward the lower magnetic field in the nmr spectra.

The π-electron structure of β-dicarbonyls such as acetylacetone, benzoylacetonc, dibenzoylmethane and β-keto esters have been investigated in the semiempirical SCF-LCAO-MO approximation. The comparison of the bond order and electron density showed relatively good agreement with observed infrared spectra.

7.2 Introduction

Several investigations on the electronic structure of enolate ion have been reported. Although there are somewhat difference, the electronic structure and π-π* transition absorption have been reasonably explained. As far concerned with intramolecular hydrogen bond, the most important problem is whether vacant 2p-orbital of hydrogen perpendicular to the chelate ring, can participate in π-electron system of the chelate ring. Preliminary extended Hückel MO treatment by Morokuma et al suggested the less possibility of the participation of 2p-orbital perpendicular to the chelate ring. To the
contrary, Shigorin\textsuperscript{5} has stated that construction of quasi aromatic ring can be performed by taking account of $2p\pi$-orbital of hydrogen associated with hydrogen bonding using SCF-LCAO-MO calculation.\textsuperscript{6} This conclusion seems to give us easier understanding to peculiar phenomena of the chelate ring. However, the validity of the MO calculation is still suspicious because of the high promotion energy from $1s$ orbital to $2p$ orbital of hydrogen atom. Therefore, more advanced treatment will be required to describe the nature of hydrogen bond of the complex molecule.

Since intramolecular hydrogen bond is strongly associated with the $\pi$-electron system, molecular orbital calculation in Hückel and Self consistent field approximation have been carried out in order to interpret the properties of enolate ion of $\beta$-dicarbonyls neglecting hydrogen bonded system.

7.3 The Procedure of Calculations

A. Hückel Molecular Orbital Calculation

A semi-empirical molecular orbital (MO-LCAO) method has been used neglecting overlap integral.\textsuperscript{7} In Hückel method the normalized molecular orbitals are of the LCAO form.

$$
\phi_i = \sum_p c_{ip} x_p
$$

\textsuperscript{(1)}
where the summation index \( p \) extends over all the atoms in \( \pi \)-electron system. The coefficient, \( c_{ip} \), and orbital energy \( \varepsilon_i \) are determined by diagonalization the \( H \) matrix, with elements defined as

\[
H_{pq} = \chi_{p}^{\text{eff}} \chi_{q} \int \text{d} \tau
\]  

\( (2) \)

The coulomb integrals \( H_{pp} = \alpha_p \) and the resonance integrals, \( H_{pq} = \beta_{pq} \), are determined empirically. Although there are some uncertainties in choice of parameters, a set of parameters proposed by Pallman and Pullman is used in this work. The parameters including hetero atom are evaluated according to Streitwieser. The hyperconjugative effect of methyl has been considered in the present work.

\[
\begin{align*}
\alpha &= 0 = \alpha_C + 1.2 \beta_{CC} \\
\alpha_{-0-} &= \alpha_C + 2 \beta_{CC} \\
\beta_{C=0} &= 2 \beta_{CC} \\
\beta_{-0-} &= 0.9 \beta_{CC}
\end{align*}
\]

B. SCF-LCAO-MO

The calculation involved the iteration of the solutions of the eigenvalue problem of the matrix \( F \),

\[
F_{i,i}^{(1)} = -I_i + 1/2 \sum_{i,j} (P_{i,j}^{(0)} I_i - E_i) + \sum_{i,j} (P_{i,j}^{(0)} - Z_j) \gamma_i,j \quad \ldots
\]

\( i \neq j \)  

\[
\ldots \ldots (3)
\]
\[ F_{i,j} = \beta_{i,j} - \frac{1}{2} P_{i,j}^{(0)} \gamma_{i,j} \]

The index is the same as that used by Pople. The Coulomb integrals have been evaluated according to approximation proposed by Mataga and Nishimoto.

\[ \gamma_{i,j} = e^2 / (R_{i,j} + a_{i,j}) \quad (4) \]

The molecular dimension in this calculation were quoted from crystallographic result by Williams. The constants \( a_{i,j} \) are defined by the following expression.

\[ \gamma_{i,i} = e^2 / a_{i,j} = I_i - E_i \quad (5) \]

\[ e^2 / a_{i,j} = 1/2(I_i - E_i + I_j - E_j) \quad (6) \]

\( I_i \) and \( E_i \) indicate the ionization potential and electron affinity of the \( i \)-th atom in valence state respectively.

The parameters used in this work are

\[ \begin{align*}
I_0 &= 17.70 \text{ eV} \quad E_0 = 2.47 \text{ eV} \quad \beta_{\text{C-C}} = -2.56 \text{ eV} \\
I_{\text{O-O}} &= 27.60 \text{ eV} \quad E_{\text{O-O}} = 4.94 \text{ eV} \quad \beta_{\text{C=O}} = -2.39 \text{ eV} \\
I_{\text{C-C}} &= 11.16 \text{ eV} \quad E_{\text{C-C}} = 0.03 \text{ eV} \quad \beta_{\text{C-O}} = -1.33 \text{ eV}
\end{align*} \]

All calculations have been carried out using a digital computer Model KDC-II at Kyoto University. The iteration were continued until the difference of each coefficient of atomic orbital at \( i \) th step and that of \( i + 1 \) the step converged within 0.001.
7.4 Results and Discussion

The Hückel MO calculations have been carried out for acetylacetone, 3-chloro, 3-propenyl, 3-cyano, 3-nitro and 3-acetyl-2, 4-pentanedione.

Figure 1 demonstrates the plot of the chemical shift of enolic proton against the π-electron charge density on enolic oxygen. The linear relationship between them indicates that the lower electron density on the enolic oxygen causes the lower magnetic field shift of the enolic proton. A contribution of ionic structure of enol form at the ground state seems to have profound effect on the intramolecular hydrogen bond. Although an alternative explanation using vacant 2p-orbitals of hydrogen may be possible in the same way as in mono substituted benzene, this concept is not necessary to interpret this system. One may suppose that the expansion to 2p-orbital in Lithium must be much easier than that of hydrogen atom. However, recent report has suggested that the contribution of 2p\(^n\)-orbital of Lithium in acetylacetonate is proved to be negligible by vibrational spectra.\(^{13}\)

Figure 2 and 3 illustrate the π-electron charge density and bond order resulted from self consistent field approximation. Comparison of bond order of \(\text{C}=\text{C}\) and \(\text{C}=\text{O}\) with the stretching vibration shows parallelism as is seen in Table 1. Two vibrations are obviously distinguished for \(\beta\)-keto ester. However, two
vibrations are superimposed in the spectra of the enol structure of \( \beta \)-dicarbonyls which used to be splitted into two absorptions upon deuteriation of enol proton. These frequencies must be interpreted with the both bond orders of \( C=C \), and \( C=O \), because the superimposition of the two bands gives rather vague measure to evaluate the results of calculation. Delocalization of \( \pi \)-electron appears to have some relation with the strength of hydrogen bond owing to the resultant electronic effect and the deformation of the structure of the chelate ring whose molecular dimension is fixed in calculations. More advanced calculation involving \( \sigma \)-orbitals should be required to do elaborate discussions.

<table>
<thead>
<tr>
<th>Bond order</th>
<th>Obs. freq. (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P(\text{C}=\text{O}) )</td>
<td>( P(\text{C}=\text{C}) )</td>
</tr>
<tr>
<td>( \beta )-keto ester</td>
<td>0.894</td>
</tr>
<tr>
<td>acetylacetone</td>
<td>0.803</td>
</tr>
<tr>
<td>benzoylacetone</td>
<td>0.802</td>
</tr>
<tr>
<td>dibenzoylmethane</td>
<td>0.766</td>
</tr>
</tbody>
</table>
Fig. 1 Correlation of chemical shifts of enol proton with electron densities at enol oxygen
Figure 2 Charge density (in parenthesis) and bond-order of enolate ion of acetylacetone and $\beta$-ketoester
Figure 3 Charge density (in parenthesis) and bond-order of enolate ion of benzoylacetone and dibenzoylmethane
References

Chapter 8

The Theory and Application of Normal Coordinate Analysis.*1
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c1 Presented before at the General Discussion on Molecular Structure held at Tokyo, Oct., 1968.

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Introduction

Chemists have studied the vibrational spectra of the complex molecules to obtain information about their chemical structures. They have assigned the observed frequencies to a particular group frequency and related the differences in group frequencies between structurally connected molecules to difference in chemical structure. An empirical method is reasonable, only if the vibrational mode of particular group is less coupled with the motion of the rest of the molecule.

Therefore, they have unconsciously made band assignments of the observed frequencies according to the concept of the group frequency.

However, theory indicates that all atoms of molecule in normal vibration perform their harmonic oscillations. Consequently a pure isolated vibration, that is just as diatomic vibration, can not be expected for polyatomic molecules.

Invalidity of empirical approach can be shown in the cases: (1) In cyclic molecules, some vibrations couple with another vibrations as a result of the trigonometric requirements of a ring structure. (2) Generally, vibrational coupling can happen when two groups vibrations show the close frequencies to each
other. The strong coupling is usually observed in the stretching vibrations of adjacent bonds which consist of atoms of similar masses and are of approximately equal strength.

Extreme care must be paid in interpreting the observed frequencies owing to the vibrational coupling. Empirical approach can not assure chemist whether the observed differences are attributed to the changes in chemical bonding or resultant coupling.

Thus the theoretical analysis of vibrational spectra can be handled by normal coordinate analysis which gives a set of force constants to express the inter-atomic forces in a molecule. One may interpret the chemical structure of a molecule in terms of a set of force constants. A brief description of the theoretical treatment of normal vibration (normal coordinate analysis) and the outline of program to execute this calculation.

8.1. Normal vibrations and Normal coordinates

In diatomic molecule, vibration occurs along the line connected with two nuclei. Complicated vibration seems to be expected in polyatomic molecule because each atom vibrates as a harmonic oscillation.

The kinetic energy of $N$-atom is given by

$$2T = \sum_{N} m_{N} \left[ \left( \frac{d\Delta x_{N}}{dt} \right)^{2} + \left( \frac{d\Delta y_{N}}{dt} \right)^{2} + \left( \frac{d\Delta z_{N}}{dt} \right)^{2} \right]$$

(1)
where \( \Delta x_N, \Delta y_N, \) and \( \Delta z_N \) represent small displacement of the N-th atom from its equilibrium position along the x, y, and z axes, respectively.

The cartitian coordinates are transfered its mass-weighted coordinates \( q_1, q_2, \) and \( q_3. \)

\[
\begin{align*}
q_1 &= \sqrt{m_1} \cdot \Delta x_1 \\
q_2 &= \sqrt{m_1} \cdot \Delta y_1 \\
q_3 &= \sqrt{m_1} \cdot z_1 \\
\end{align*}
\]

The kinetic energy will be expressed in

\[
2T = \sum_{i=1}^{3N} q_i^2 
\]

For potential energy, it may be expanded in a Taylor's series as

\[
V(q_1, q_2, \cdots, q_{3N}) = V_o + \sum_{i=1}^{3N} \left( \frac{\partial V}{\partial q_i} \right)_o \cdot q_i \\
+ \frac{1}{2} \sum_{i,j} \left( \frac{\partial^2 V}{\partial q_i \partial q_j} \right)_o q_i q_j + \cdots 
\]

The \( \left( \frac{\partial V}{\partial q_i} \right)_o \) equals to zero since \( V \) must be a minimum at \( q_i = 0. \)

\[
V = \frac{1}{2} \sum_{i,j} \left( \frac{\partial^2 V}{\partial q_i \partial q_j} \right)_o q_i \cdot q_j = \frac{1}{2} \sum_{i,j} b_{ij} q_i \cdot q_j + \cdots 
\]

Substitution of the expressions for kinetic and potential energies into Newton's equation of motion,
\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) + \frac{\partial V}{\partial q_i} = 0 \quad i = 1, 2, \ldots, 3N, \tag{6}
\]
yields a set of 3N simultaneous linear differential equations,

\[ q''_i + \sum_j b_{ij} q_j = 0 \quad j = 1, 2, \ldots, 3N \tag{7} \]

A solution is

\[ q_i = q_i \cdot \sin \left( \sqrt{b_{ij}} t + \delta_i \right) \tag{8} \]

Generally speaking, the coordinates must be transformed into a new set of coordinates which are termed normal coordinates. They are defined by

\[ Q_k = \sum_{i=1}^{3N} \lambda_{ki} q_i \quad k = 1, 2, \ldots, 3N \tag{9} \]

which \( \lambda_{ki} \) are chosen so that the kinetic and potential energy may be expressed by the relations,

\[ 2T = \sum \dot{Q}_k^2 \tag{10} \]

\[ 2V = \sum \lambda_k \cdot Q_k^2 \tag{11} \]

From equation (6), the following equation is given;

\[ Q_k'' + \lambda_k Q_k = 0 \tag{12} \]
Solution of (12) gives

\[ Q_k = Q_k^0 \sin(\sqrt{\lambda_k} kt + \delta_k) \]  
(13)

which yield the frequency which is called as normal vibration.

\[ \nu_k = \frac{1}{2\pi} \cdot \sqrt{\lambda_k} \]  
(14)

8.2 The Application of Wilson's Method to Normal Coordinate Analysis.

The Wilson's GF matrix method considerably simplifies the solution of the secular equation. A brief procedure of this method is summarized as following.\(^1\)

1. Selection of internal coordinates
2. Expression of the potential energy in terms of internal coordinates
3. The B matrix defined by molecular configuration
5. Application of the group theory to deduce the matrix into the small block matrices
6. Calculation of eigen values and eigen vectors of GF matrix.
7. Determination of frequencies from eigen values and vibrational modes from eigen vectors.

8.3 Urey-Bradley Force Field

The two familiar potential fields are the general force field
(GVF) and the Urey-Bradley force field (UBF). The potential energy expression for the GVF field is given by

\[
2V = \sum_i f_{ri} (\Delta r_i)^2 + \sum_{i,j} f_{rij} (\Delta r_i)(\Delta r_j) + \sum_{i,j} f_{aij} (r_{ij})^2
\]

\[+ \sum_{i,j,k} f_{r_{ijk}} (\Delta r_i)(\Delta r_j)(\Delta r_k)\]

\[+ \sum_{i,j,k,l} f_{r_{ijkl}} (r_{ij})^2 (r_{kl})^2 (\Delta r_{ijkl})^2\]  

where \(f_{ri}\) and \(f_{aij}\) denote the stretching force constant of the bond, whose length is \(r_i\) and the bending force constant of the \(\alpha_{ij}\) angle, respectively. \(f_{r_{ij}}\), \(f_{r_{ijk}}\) and \(f_{r_{ijkl}}\) indicate the interaction force constants between stretching and stretching coordinates, between stretching and bending coordinate, and between bending and bending coordinate.

In UBF field, the repulsion between the non-bonded atoms is taken account into the potential. The general expression of the UBF is expressed by

\[
2V = \sum_i \left[K_i (\Delta r_i)^2 + 2K_i' r_i^3 (\Delta r_i)\right] + \sum_{i,j} \left[H_{ij} (r_{ij} \Delta \alpha_{ij})^2\right]
\]

\[+ 2H'_{ij} r_{ij} (r_{ij} \Delta \alpha_{ij}) + \sum_{i,j} \left[F_{ij} (\Delta q_{ij})^2 + 2F'_{ij} q_{ij} (\Delta q_{ij})\right]\]  

\[K_i, H_{ij}, \text{ and } F_{ij} \text{ represent stretching, bending and repulsive force constants, respectively. } q_{ij} \text{ is the distance between the two non-bonded atoms } i \text{ and } j. \text{ Geometrical restriction is related by}\]

\[q_{ij} = (r_i^2 + r_j^2 - 2r_i r_j \cos \alpha)^{1/2}\]
8.4 Principle of Normal Coordinate Analysis

The number of normal vibrations for \( N \)-atom molecule is 
\( 3N-6 \) for non-linear molecule and \( 3N-5 \) for linear molecule. Among 
normal vibrations, infra and Raman active species are determined 
by the selection rule using the group theory.

The kinetic energy is expressed by \( 3N \) cartesian coordinates.

\[
T = \frac{1}{2} m_1 \dot{x}_1^2 + \frac{1}{2} m_1 \dot{y}_1^2 + \frac{1}{2} m_1 \dot{z}_1^2 + \cdots + \frac{1}{2} m_N \dot{x}_N^2 + \frac{1}{2} m_N \dot{y}_N^2 + \frac{1}{2} m_N \dot{z}_N^2
\]

\[
\cdots\cdots (18)
\]

Above equation is simplified using matrix and vectors.

\[
\begin{pmatrix}
  x_1 \\
  y_1 \\
  z_1 \\
  \vdots \\
  x_N \\
  y_N \\
  z_N \\
\end{pmatrix}
= \begin{pmatrix}
  m_1 & 0 \\
  m_1 & 0 \\
  m_1 & 0 \\
  \vdots & \vdots \\
  m_N & 0 \\
  m_N & 0 \\
  m_N & 0 \\
\end{pmatrix}
\cdot
\begin{pmatrix}
  \ddot{x}_1 \\
  \ddot{y}_1 \\
  \ddot{z}_1 \\
  \vdots \\
  \ddot{x}_N \\
  \ddot{y}_N \\
  \ddot{z}_N \\
\end{pmatrix}
\]

\[
2T = \mathbf{x} \cdot \mathbf{M} \ddot{\mathbf{x}}
\]

The potential energy is given using the internal coordinates

\[
V = \frac{1}{2} \mathbf{R} \cdot \mathbf{F} \cdot \mathbf{R}^T
\]

\[
\cdots\cdots (20)
\]
where

$$\mathbf{R} = \begin{pmatrix} \Delta r_1 \\ \Delta r_2 \\ \vdots \\ \Delta r_n \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & \cdots & \cdots & f_{nn} \end{pmatrix}$$

\(\tilde{R}\) denotes its transpose.

The coordinates are transformed to express two energy matrices in the common coordinates.

$$\mathbf{X} = \mathbf{U} \mathbf{q}$$

$$\mathbf{R} = \mathbf{U}^T \mathbf{R} \mathbf{q} \quad (21)$$

In common coordinate, two energy matrices are defined by

$$2\mathbf{T} = \tilde{\mathbf{q}} \mathbf{G}^{-1} \mathbf{q}$$

$$2\mathbf{V} = \tilde{\mathbf{q}} \mathbf{F} \mathbf{q} \quad \cdots \quad (22)$$

The transformation matrix is correlated by

$$\mathbf{G}^{-1} = \tilde{\mathbf{U}} \mathbf{M} \mathbf{U} \quad \cdots \quad (23)$$

$$\mathbf{F} = \tilde{\mathbf{U}} \mathbf{F} \mathbf{U}$$

In order to determine the modes of normal vibrations, it is necessary to calculate the L matrix, defined by

$$\mathbf{q} = \mathbf{L} \mathbf{Q}$$

If the L matrix is obtainable, (23) are transformed into

$$\tilde{\mathbf{L}} \mathbf{G}^{-1} \mathbf{L} = \mathbf{E} \quad \cdots \quad (24)$$

$$\tilde{\mathbf{L}} \mathbf{F} \mathbf{L} = \mathbf{\Lambda} \quad \cdots \quad (25)$$
E is the unit matrix. Inverse matrix of (24) is written by
\[
((L^{-1}G^{-1})(L))^{-1} = (L^{-1})(LG^{-1})^{-1} = (L^{-1})(G^{-1})^{-1}(L)^{-1}
\]
\[L^{-1}G(L)^{-1} = E \quad \text{-----------------------------}(26)\]

The multiplication of (25) by (26) gives
\[L^{-1}G(L)^{-1}(L)FL = EA = A\]
\[L^{-1}GFL = A \quad \text{----------}(27)\]

(27) multiplied by L from left hand yields
\[LL^{-1}GFL = GFL = LA\]
\[\text{----------}(28)\]

Therefore, this problem is attributed to solve the secular equation
\[|GF - E \lambda| = 0 \quad \text{----------}(29)\]

Consequently the potential energy is expressed by
\[V = \frac{1}{2} \vec{Q} LFL \vec{Q} = \frac{1}{2} \vec{Q} \Lambda \vec{Q} \quad \text{----------}(30)\]

The relation between internal coordinate R and normal coordinates Q is shown by the following equations.
\[
\begin{align*}
R_1 &= L_{11}Q_1 + L_{12}Q_2 + \cdots + L_{1N}Q_N \\
R_2 &= L_{21}Q_1 + L_{22}Q_2 + \cdots + L_{2N}Q_N \\
&\vdots \\
R_i &= L_{i1}Q_1 + L_{i2}Q_2 + \cdots + L_{iN}Q_N \\
\end{align*}
\]
\[\text{----------}(31)\]

A particular frequency is expressed by
\[
\lambda_a = \sum_{i,j} \bar{a}_{ij} F_{ij} L_{ia} L_{ja} = \sum_{i,j} F_{ij} L_{ia} L_{ja} \quad \text{----------}(32)\]
$F_{ijL_iL_j}$ indicates the distribution of the potential energy in each internal coordinate. 4

8.5 Application of Normal Coordinate Analysis

It is of great interest to compare the electronic effect of sulfur and chlorine at 3-position on the enol form of 2,4-pentanediol, because both atomic weights are not different so much. Therefore, vibrational spectra of 3-methylthio- (I) and 3-chloro-2,4-pentanediol (II) can tell us the difference in their electronic effect.

The whole procedures have been followed as described in Chapter II. The infrared spectra of (I), (II), and their deutero analogs are shown in Fig. 1 and Fig. 2. The set of force constants are listed in Table 1, 2 and 3. Table 4 illustrates band assignments according to the potential energy distributions. The comparison of stretching force constants of (I) and (II) is demonstrated in Fig. 3.

As is seen in Table 4, the two frequencies $\nu_1$ and $\nu_2$ are easily explained by high percentages of contribution of coordinates $S_1$ and $S_2$. However, it is evidently indicated that the rest of thirteen frequencies consist of more than two vibrational modes expressed in internal coordinates. For instance, hydrogen bonded stretching contribute to $\nu_{11}$, 452 cm$^{-1}$ and $\nu_{14}$, 225 cm$^{-1}$ which vibrational modes are schematically expressed as follow
Comparison of the force constants of (I) and (II) shows a fair agreement with the result of nmr spectra. (I) forms more stronger hydrogen bond than that of (II).
Table 1  Force Constants of 3-chloro- and 3-methylthio-2,4-pentanedione. (in millidynes per angstrom).

<table>
<thead>
<tr>
<th></th>
<th>(X=\text{S})</th>
<th>(X=\text{Cl})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K(\text{C-O}))</td>
<td>6.300</td>
<td>5.100</td>
</tr>
<tr>
<td>(K(\text{C}=\text{O}))</td>
<td>8.000</td>
<td>8.300</td>
</tr>
<tr>
<td>(K(\text{C}=\text{C}))</td>
<td>4.800</td>
<td>5.000</td>
</tr>
<tr>
<td>(K(\text{C-C}))</td>
<td>4.600</td>
<td>4.700</td>
</tr>
<tr>
<td>(K(\text{C}-\text{R}))</td>
<td>3.800</td>
<td>4.000</td>
</tr>
<tr>
<td>(K(\text{C}-\text{R'}))</td>
<td>4.000</td>
<td>4.100</td>
</tr>
<tr>
<td>(K(\text{O-H}))</td>
<td>3.500</td>
<td>3.950</td>
</tr>
<tr>
<td>(K(\text{O} \cdots \text{H}))</td>
<td>0.400</td>
<td>0.300</td>
</tr>
<tr>
<td>(K(\text{C-X}))</td>
<td>2.500</td>
<td>2.150</td>
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</table>

Table II

Table II

<table>
<thead>
<tr>
<th></th>
<th>(X=\text{S})</th>
<th>(X=\text{Cl})</th>
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<tr>
<td>(\text{H}(\text{C}=\text{C}-\text{O}_1))</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>(\text{H}(\text{R}-\text{C}=\text{C}))</td>
<td>0.250</td>
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<td>(\text{H}(\text{R}-\text{C}-\text{O}_1))</td>
<td>0.330</td>
<td>0.300</td>
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<tr>
<td>(\text{H}(\text{O}_2=\text{C}-\text{C}))</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>(\text{H}(\text{R}'-\text{C}-\text{C}))</td>
<td>0.230</td>
<td>0.230</td>
</tr>
<tr>
<td>(\text{H}(\text{R}'-\text{C}=\text{O}_2))</td>
<td>0.180</td>
<td>0.200</td>
</tr>
<tr>
<td>(\text{H}(\text{C}=\text{C}-\text{C}))</td>
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<td>0.310</td>
</tr>
<tr>
<td>(\text{H}(\text{C}=\text{C}-\text{X}))</td>
<td>0.290</td>
<td>0.280</td>
</tr>
<tr>
<td>(\text{H}(\text{C}-\text{C}-\text{X}))</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>(\text{H}(\text{C}-\text{O}_1-\text{H}))</td>
<td>0.560</td>
<td>0.530</td>
</tr>
<tr>
<td>(\text{H}(\text{C}=\text{O}_2-\text{H}))</td>
<td>0.220</td>
<td>0.200</td>
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<tr>
<td>(\text{H}(\text{O}<em>1-\text{H}</em>\nu \cdots \text{O}_2))</td>
<td>0.050</td>
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</table>
Table III

<table>
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<tr>
<th></th>
<th>X=S</th>
<th>X=Cl</th>
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<tbody>
<tr>
<td>F(O₁···C)</td>
<td>0.350</td>
<td>0.300</td>
</tr>
<tr>
<td>F(R···C)</td>
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<td>0.250</td>
</tr>
<tr>
<td>F(R···O₁)</td>
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<td>0.350</td>
</tr>
<tr>
<td>F(O₂···C)</td>
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<td>0.350</td>
</tr>
<tr>
<td>F(R···C)</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>F(R'···O₂)</td>
<td>0.150</td>
<td>0.160</td>
</tr>
<tr>
<td>F(C···C)</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>F(C···X)</td>
<td>0.360</td>
<td>0.330</td>
</tr>
<tr>
<td>F(C···X)</td>
<td>0.350</td>
<td>0.330</td>
</tr>
<tr>
<td>F(C···H)</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>F(H···C)</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>F(O₁···O₂)</td>
<td>0.010</td>
<td>0.010</td>
</tr>
</tbody>
</table>
Table 4

Comparisons of observed and calculated frequencies of 3-methylthio-2,4-pentanedione

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Calc. (A')</th>
<th>P.E.D. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2975</td>
<td>v₁ 2744</td>
<td>s₁(100)</td>
</tr>
<tr>
<td>2925</td>
<td>v₂ 1593</td>
<td>s₂(73)</td>
</tr>
<tr>
<td>2915</td>
<td>v₃ 1554</td>
<td>s₃(29), s₆(14)</td>
</tr>
<tr>
<td>2580</td>
<td>v₄ 1480</td>
<td>s₄(28), s₈(21)</td>
</tr>
<tr>
<td>1576</td>
<td>v₅ 1404</td>
<td>s₅(55), s₃(30)</td>
</tr>
<tr>
<td>1410</td>
<td>v₆ 1217</td>
<td>s₆(42), s₃(29)</td>
</tr>
<tr>
<td>1369</td>
<td>v₇ 904</td>
<td>s₇(58), s₈(16), s₉(30)</td>
</tr>
<tr>
<td>1314</td>
<td>v₈ 897</td>
<td>s₈(50), s₇(31)</td>
</tr>
<tr>
<td>1255</td>
<td>v₉ 630</td>
<td>s₉(34), s₁₁(32)</td>
</tr>
<tr>
<td>1060</td>
<td>v₁₀ 568</td>
<td>s₁₀(53),</td>
</tr>
<tr>
<td>1017</td>
<td>v₁₁ 439</td>
<td>s₁₁(40), s₁₄(23)</td>
</tr>
<tr>
<td>992</td>
<td>v₁₂ 383</td>
<td>s₁₂(36), s₁₁(41)</td>
</tr>
<tr>
<td>966</td>
<td>v₁₃ 291</td>
<td>s₁₃(37), s₁₂(26)</td>
</tr>
<tr>
<td>905</td>
<td>v₁₄ 220</td>
<td>s₁₄(35), s₁₃(25)</td>
</tr>
<tr>
<td>701</td>
<td>v₁₅ 202</td>
<td>s₁₅(40), s₁₃(45)</td>
</tr>
</tbody>
</table>
Fig. 1. Infrared spectra of 3-methylthio-2,4-pentanedione (I) and deuter analog.
Fig. 2. Infrared spectra of 3-chloro-2,4-pentanedione (II) and deutero analog.
Fig. 3  Comparison of stretching force constants

References


Appendix

Flow Diagram of Computational Calculations

It has been recognized that the high speed digital computer facilitates the tedious and complicated calculations in the field of the chemistry. They include the solution of secular equation in quantum chemistry and normal coordinate analysis, and the coupling problem in nmr spectrum. Especially, the analysis of three dimensional Fourier Series by computer affords a considerably powerful tool to elucidate the molecular structure. Furthermore, complicated reaction rate expressed in linear differential is also solved using Runge-Kutta-Gill method in computer.

In this work, programs have been developed to carry out molecular orbital calculations and normal coordinate analysis. Normal vibrations can be calculated by three main programs; G-program is intended to construct the G elements and sort into the groups according to the molecular symmetry. F-program provides the F elements based on Urey-Bradly force field. Final program is used in order to solve higher order secular equation giving eigenvalue and eigenvector, from which the frequencies and potential energy are obtained. The brief flow diagram of the third program is shown in Figure 1. A flow diagram illustrated in Figure 2 represents the program for SCF-LCAO-MO calculation, where the result of Hückel MO calculation is given at the first step of interactive calculation. All statements in program are
written according to the FORTRAN IV system.

READ: Number of molecules
to be calculated (NUM)

dimension of matrix (N)
READ: Name of molecule
READ: Elements of A matrix $A(i,j)$
READ: Number of calculations (NEC)
READ: Control card

READ: set of force constants

* Subroutine FMAT *
$A^*F*A$

* Subroutine HDIAG *
to solve $|GF-E| = 0$

WRITE frequencies

STOP

(NUM-KCAL)

NEC-NC

PRINT
Potential Energy

0

1

* Subroutine *
PTENL

IP

Fig. 1. Block diagram to obtain frequencies and potential energy distribution.
Fig. 2. Block diagram for Hückel and SCF-LCAO-MO