1970

The conformations of cycloheptanesemidione and related systems

Robert Gustav Keske
Iowa State University

Recommended Citation

Keske, Robert Gustav, "The conformations of cycloheptanesemidione and related systems " (1970). *Retrospective Theses and Dissertations*. 4331.
https://lib.dr.iastate.edu/rtd/4331

71-7292

KESKE, Robert Gustav, 1945-
THE CONFORMATIONS OF CYCLOHEPTANESEMIDIONE
AND RELATED SYSTEMS.

Iowa State University, Ph.D., 1970
Chemistry, organic

University Microfilms, Inc., Ann Arbor, Michigan

THE CONFORMATIONS OF CYCLOHEPTANESEMIDIONE AND RELATED SYSTEMS

by

Robert Gustav Keske

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Organic Chemistry

Approved:

In Charge of Major Work

Head of Major Department

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1970

TABLE OF CONTENTS

INTRODUCTION

Semidiones

Semidiones (1-6), which are the vinylog of the paramagnetic superoxide ion, $O_2^{\overline{\cdot}}$, have been studied in great detail over the past decade. The first aryl substituted semidione was studied in 1963 by Dehl and Fraenkel (7), and the following year Russell and Strom (8) studied aliphatic semidiones. During this time, a wealth of data has been accumulated for numerous systems.

Semidiones can be generated by numerous methods. Basic oxidation of ketones having an α-methylene group, hydrolysis and oxidation of bis(trimethylsiloxy)alkenes or esters of α-hydroxy ketones, and even the acyloin condensation (9) are some of the methods which can serve to generate these radicals. In general, once formed, most semidiones are then stable for hours at room temperature.

The interpretation of the esr spectra of semidiones has led to numerous conclusions concerning assignments of long-range hyperfine splittings in bicyclic compounds (10-16), assignments of configuration in steroids and decalones (17-20), and conformational assignments (11, 14, 21) in mono- and bicyclic systems. These and other applications have recently been reviewed (5, 22, 23).

This particular work was undertaken in order to study cycloheptanesemidione and related systems. Our attention was first focussed on the determination of the conformation of cycloheptanesemidione. This work was then extended to the determinations of conformations of bicyclic molecules, which contained the cycloheptanesemidione moiety. Next, an examination of the geometrical and structural dependence of long-range hyperfine splittings of bi- and polycyclicsemidiones, which again contained the seven-membered ring, was undertaken. Finally, the use of Extended Huckel calculations as a basis for prediction of hyperfine splitting constants in semidiones, was examined.

CYCLOHEPTANESEMIDIONE

Relatively few conformational studies have been performed on the cycloheptene type ring system. Allinger and Szkrybalo (24) have concluded from dipole moment studies that 1,2-benzocyclohepten-5-one exists mainly in the chair form. Later calculations by Allinger et al. (25) suggest that the boat form of cycloheptene would be more stable than the chair form.

Nmr studies on substituted cycloheptenes and benzocycloheptenes have shown that one (26-27) or more (28-30) conformations are present in solution, with the chair form predominating in some cases and the boat form in others.

Russell, Underwood, and Lini (21) have demonstrated that cyclohexanesemidione and cyclohexene have similar conformations with similar barriers for ring inversion. In their studies they also obtained the esr spectrum of cycloheptanesemidione (I) by generation of the radical from the corresponding α-hydroxy ketone. Application of the reactions of Scheme I to diethyl pimelate gave a clean, strong, well resolved signal of semidione I. When the solution was cooled to -10°, the resolution improved and additional lines were apparent in the spectrum (Figure 1). The spectrum consists of a 6.60 gauss (G) triplet assigned to the α-axial protons, a 2.05 G triplet due to two of the β-protons, a 0.28 G quintet due to the two α-equatorial protons and the other two β-protons, and finally a 0.54 G doublet from one of the γ-pro-

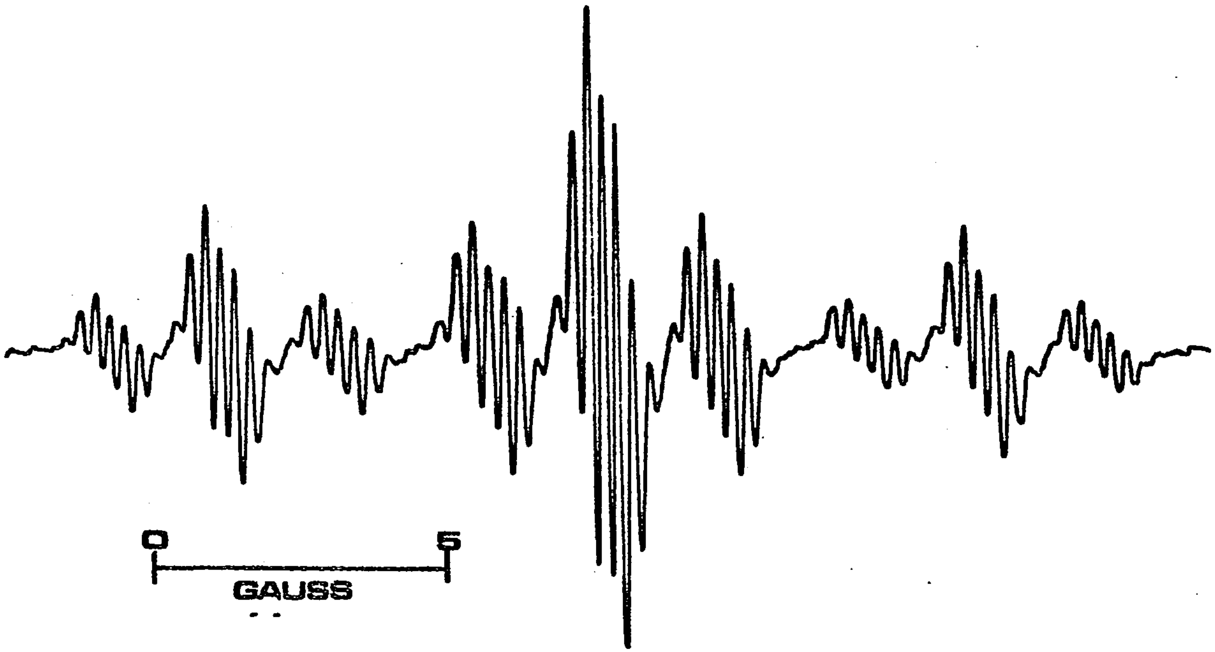
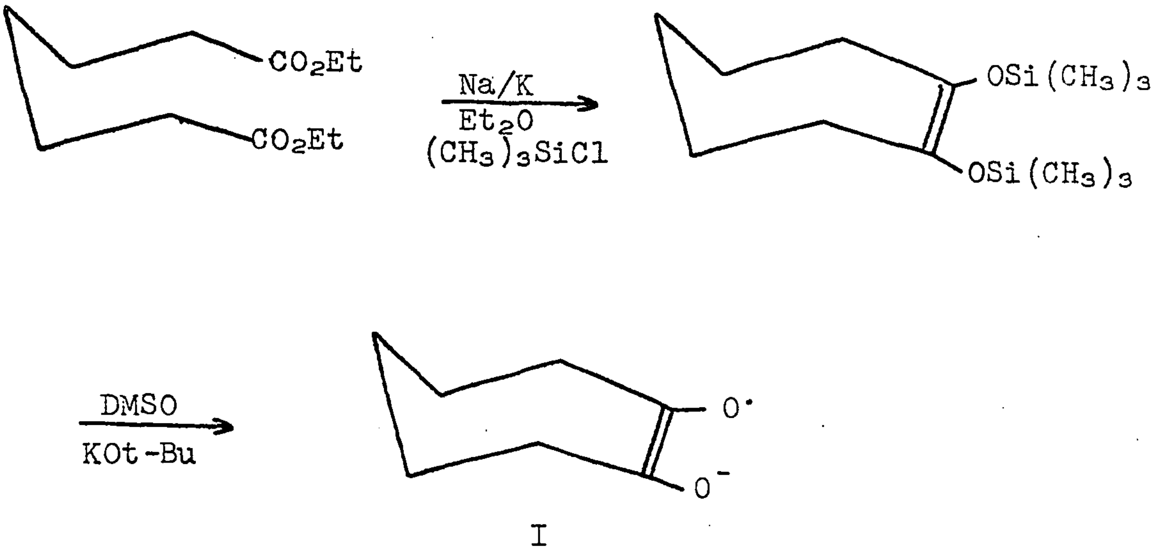


Figure 1. The first derivative esr spectrum of cycloheptanesemidione (I) in DMSO at -10°.

Scheme I



tons. These assignments were confirmed by preparing I in DMSO-d_6 (Figure 2), and observing the exchange of the α-protons for deuteriums.

By simultaneous solution of the Heller-McConnell equations, $a^{H_{ax}} = \rho_c B\cos^2\theta_{ax}$ and $a^{H_{eq}} = \rho_c B\cos^2\theta_{eq}$, two solutions are obtained for the dihedral angles of the α-hydrogens, $\theta_{ax} = -19°$ and $\theta_{ax} = -39°$. The first solution is identical with the value of $\theta_{ax} = -19°$ obtained by a measurement for cycloheptene using nmr spectroscopy (31). Thus the conformation of cycloheptanesemidione is similar to cycloheptene. The magnetic nonequivalence of the α-protons demands a single populated conformation, which is "frozen" with respect to the esr time scale. The doublet splitting from the γ-position, and hence the nonequivalence of the γ-hydrogens eliminates the twist boat from

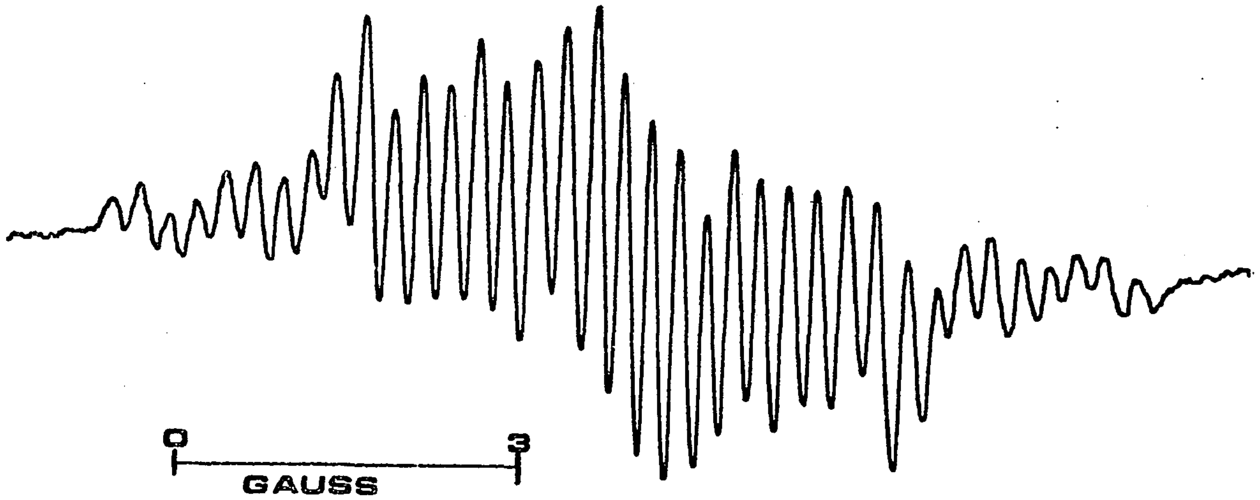
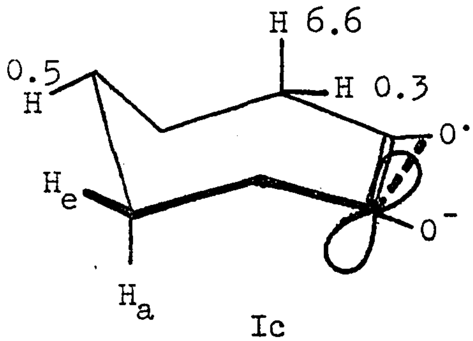
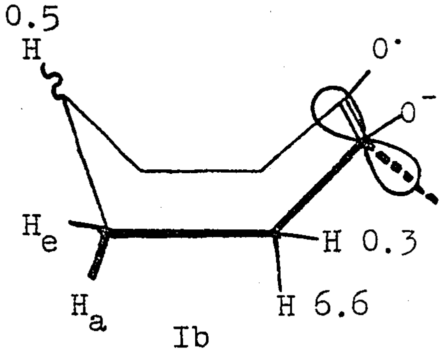


Figure 2. The first derivative esr spectrum of cycloheptanesemidione (I) in DMSO-d_6 at 5° showing complete exchange of the α-protons.

consideration. The magnitude of the α-hyperfine interactions are consistent with either the chair (Ic) or the boat (Ib) conformation.



Ic



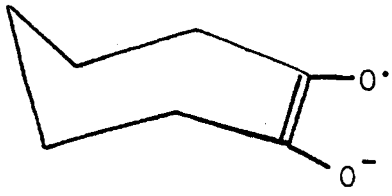
Ib

It was hoped that the preparation of a number of methyl-substituted cycloheptanesemidiones (Chart I) would help solve the problem. These substituted compounds were prepared from the commercially available glutaric acids using the reactions outlined in Scheme 2 and Scheme 1. The observed hfsc for cycloheptanesemidione and the methyl derivatives are listed in Table I.

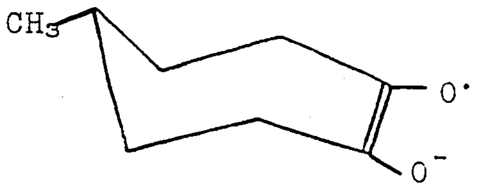
The spectrum of γ-methylcycloheptanesemidione II is shown in Figure 3. Since the analysis gives hfsc quite close to those of the parent compound except for the removal of the doublet splitting, and since the methyl group would presumably occupy the equatorial position, the assignment of the γ-hfsc must be to an equatorial proton whether the conformation is Ic or Ib.

The spectrum of γ,γ-dimethylcycloheptanesemidione is shown in Figure 4. The compound was prepared for two reasons.

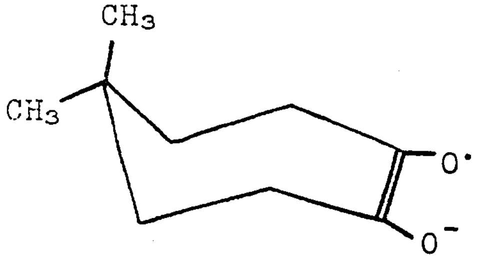
Chart I



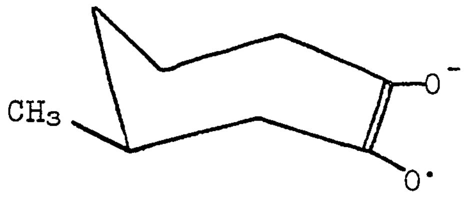
I



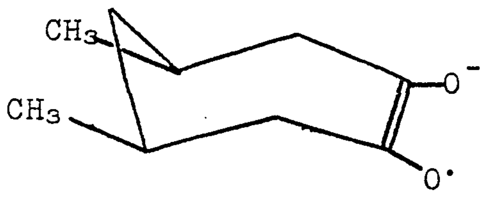
II



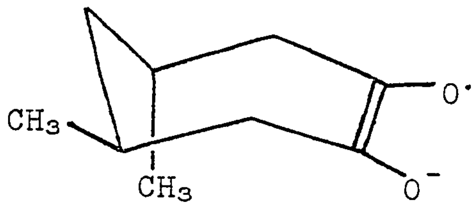
III



IV



V



VI

Table 1. Hyperfine splitting constants[a] and assignments for substituted cycloheptane-semidiones at 25° in DMSO.

Substituent	$H_{\alpha,\alpha'}$	$H_{\beta,\beta'}$	H_{γ}
None (I)	6.60 (2), 0.28 (2)	2.05 (2), 0.28 (2)	0.54 (1)
I in DMSO-d_6	1.00 (2D),----	2.05 (2), 0.28 (2),	0.54 (1)
γ-methyl (II)	6.62 (2), 0.29 (2)	1.88 (2), 0.29 (2)	----
γ,γ -dimethyl (III)	6.90 (2), 0.29 (2)	1.85 (2), 0.29 (2)	----
β-methyl (IV)	6.60 (2), 0.32 (2)	2.15 (1), 0.32 (2)	~0.32 (1)
IV in DMSO-d_6	1.00 (2D),----	2.15 (1), 0.28 (2)	0.40 (1)
<u>cis</u>-β,β'-dimethyl (V)	6.50 (2), 0.32 (2)	---- 0.32 (2)	0.32 (1)
<u>trans</u>-β,β'-dimethyl (VI)	6.81 (1) 7.25 (1)[b], 0.33 (2)	0.66 (1), 0.33 (1)	0.33 (1)
VI in DMSO-d_6	1.05 (2D),----	0.66 (1), 0.33 (1)	0.33 (1)

[a] In gauss.

[b] The nonequivalence is caused by a loss of symmetry due to the methyl groups.

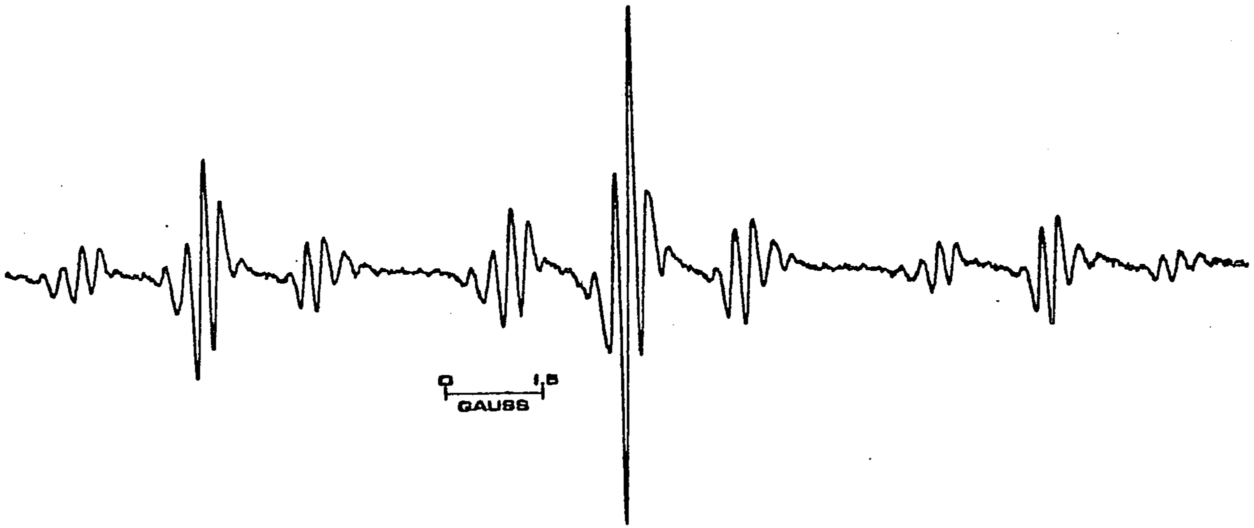


Figure 3. The first derivative esr spectrum of γ-methylcycloheptanesemidione (II) in DMSO.

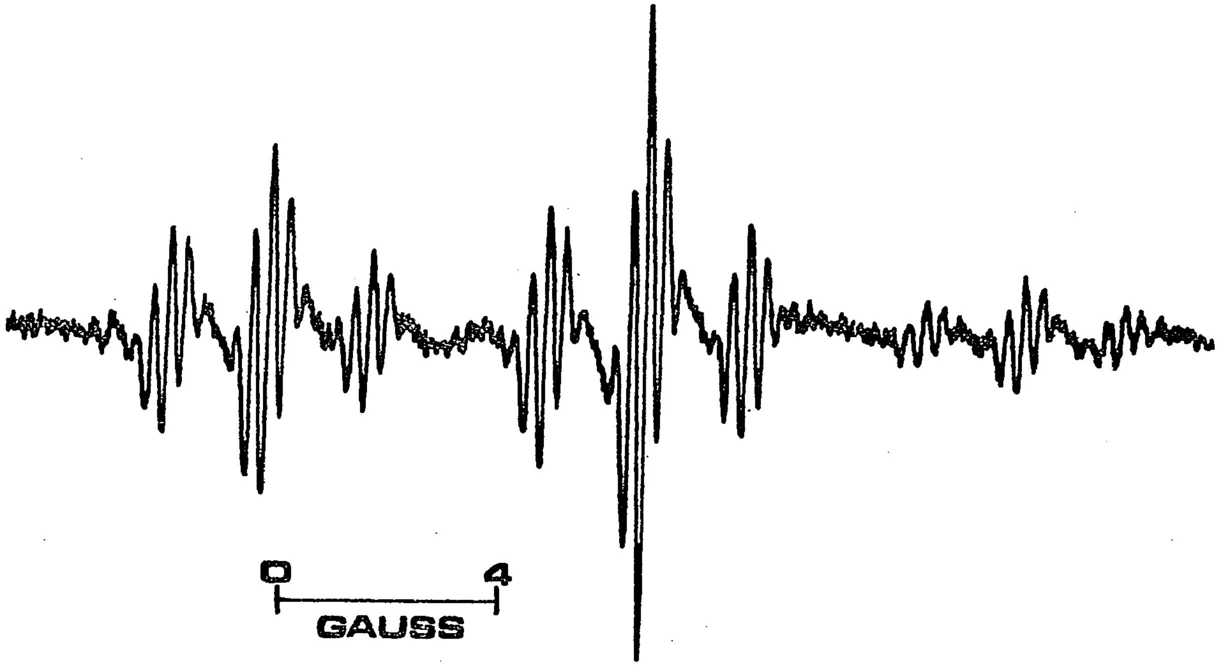
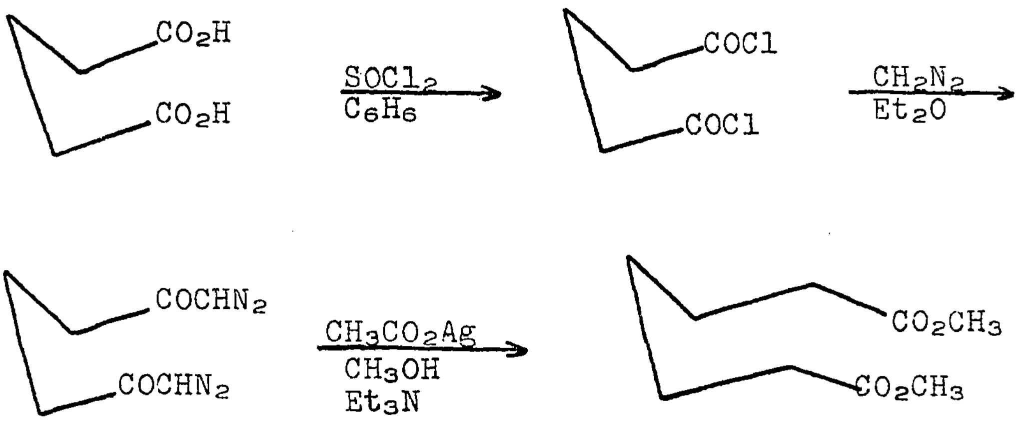


Figure 4. The first derivative esr spectrum of γ,γ-dimethylcycloheptanesemidione (III) in DMSO. The radical concentration is slowly decreasing.

Scheme II



First, to see if the introduction of an axial methyl group would have an appreciable effect on the geometry of the molecule, and secondly, the axial methyl might also raise the ground state energy of the molecule by the axial-axial interactions and hence lower the energy of activation for ring inversion. As seen by the hfsc (Table I), the geometry underwent little change since calculations predict (32) that even a small change in geometry would have a large effect on the hfsc. In addition, the ring remained conformationally frozen.

It has been demonstrated in numerous systems that the hfsc of a methylene hydrogen atom with a trans-coplanar (zigzag) arrangement of bonds to the p_z orbital of the carbonyl carbon, is much larger than the hfsc of the other methylene hydrogen atom (23). For Ic the β-equatorial hydrogen atoms have the desired trans arrangement of bonds while for Ib the β-axial hydrogen possesses the proper geometry. Experimentally, the β-hydrogens of I with the zig-zag arrangement have a hfsc of 2.05 G while the other β-hydrogens have a hfsc of only 0.28 G. Introduction of a β-methyl (in IV) and cis-β,β′-dimethyl (in V) substituents into cycloheptanesemidione gave spectra in which, respectfully, one (Figures 5 and 6) and two (Figure 7) of the 2.05 G hfsc were lost by methyl substitution. Since one or two of the β-methyl groups would occupy an equatorial position in either Ic or Ib, it follows that the β-hydrogens with the 2.05 G hfsc are equatorial hydrogens and that the conformation of cycloheptanesemidione is most likely Ic, the chair structure.

A possibility exists that equatorial substituents in Ib might greatly reduce the magnitude of the β-hfsc of axial hydrogens from 2 G to 0.3 G. Trans-β,β′-dimethylcycloheptanesemidione (VI), whose spectra are given in Figures 8 and 9, completely eliminates this possibility unless it is also postulated that an axial-β-substituent increases the equatorial β-hydrogen hfsc from 0.3 to 0.66 G.

On the other hand, the result observed for the trans-β,β′-dimethyl semidione is in perfect agreement with a prediction based on structure Ic. The equatorial methyl would remove one of the 2.05 G hfsc of the parent semidione while the axial methyl would reduce the magnitude of the zig-zag equatorial β-hydrogen by a factor of two-threefold using VII (10) and VIII (33-34) as models.

Considering the γ-position, a further possibility of

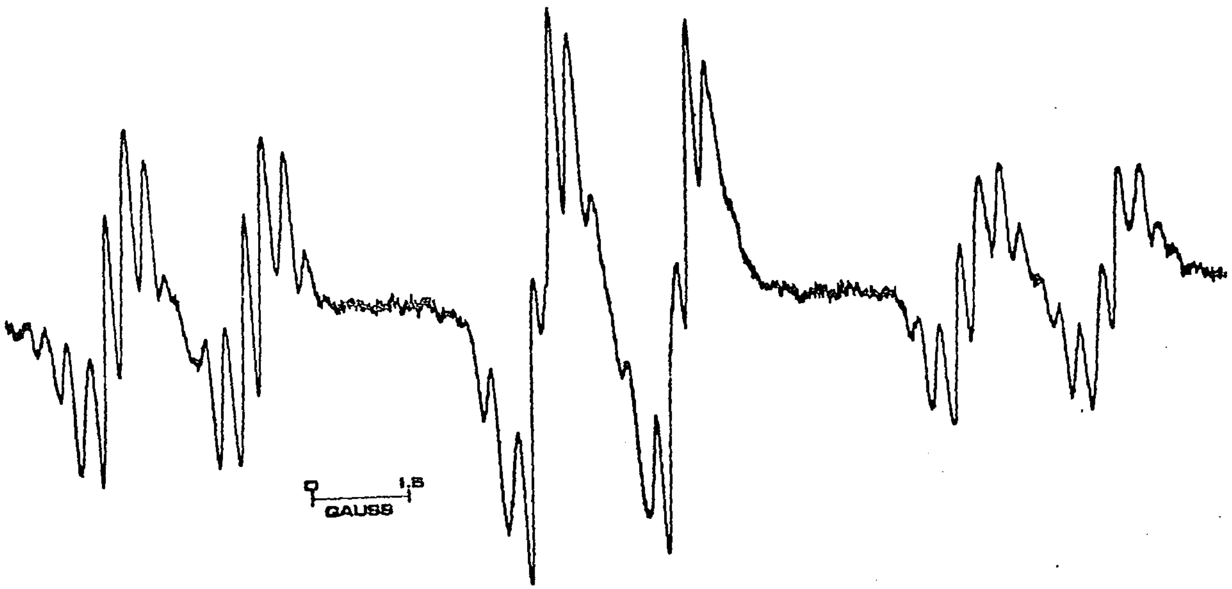


Figure 5. The first derivative esr spectrum of β-methylcycloheptanesemidione (IV) in DMSO.

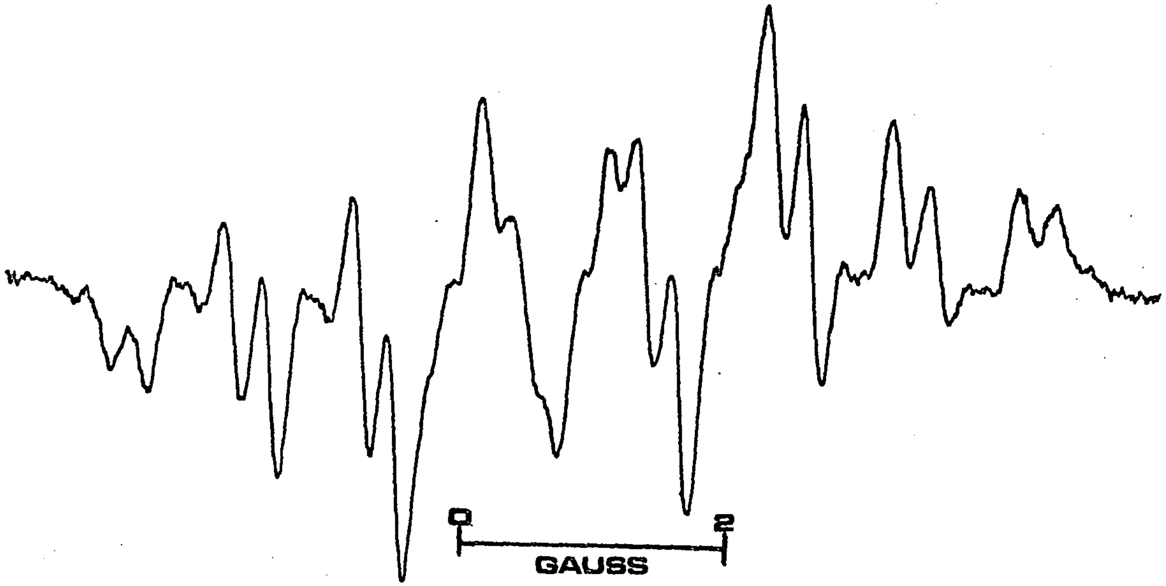


Figure 6. The first derivative esr spectrum of β-methylcycloheptanesemidione (IV) in DMSO-d_6 showing exchange of the α-protons.

Figure 7. The first derivative esr spectrum of *cis*-β,β'-dimethylcycloheptanesemidione (V) in DMSO. A small amount of VI is present as an impurity.

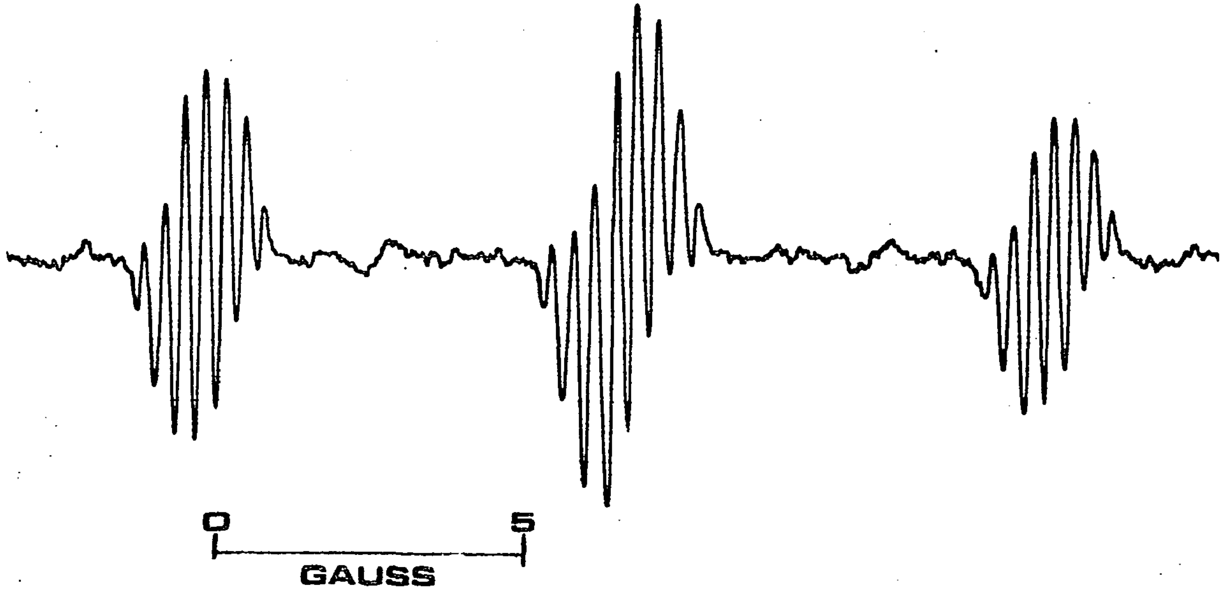


Figure 8. The first derivative esr spectrum of *trans*-β,β'-dimethylcycloheptanesemidione (VI) in DMSO.

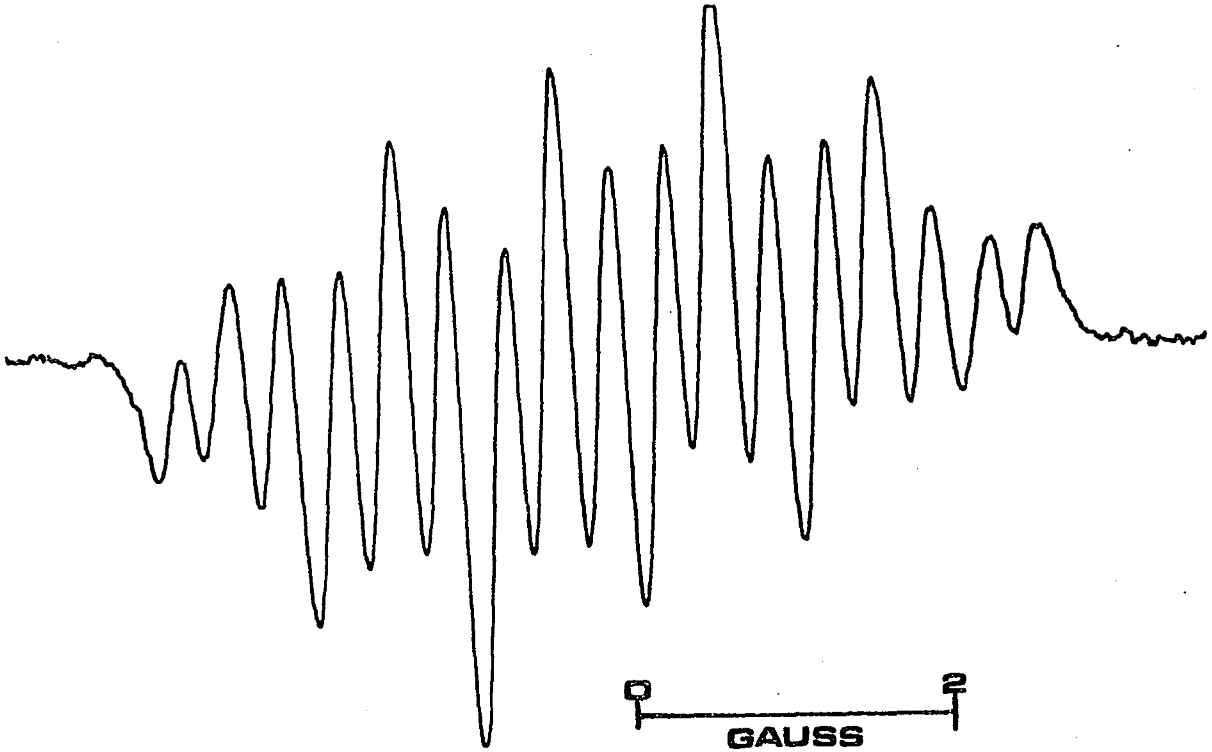
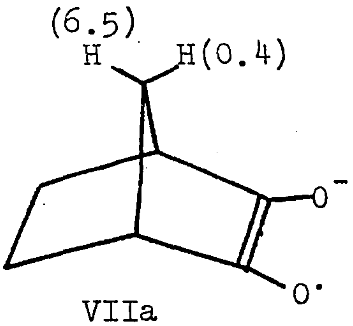
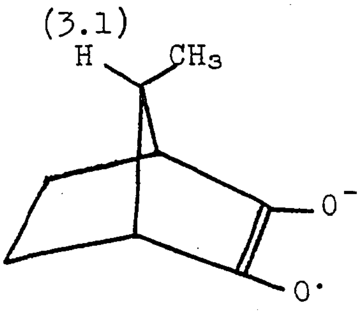


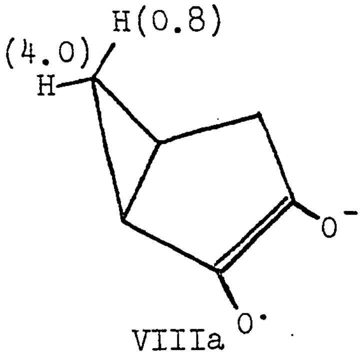
Figure 9. The first derivative esr spectrum of *trans*-β,β'-dimethylcycloheptanesemidione in DMSO-d_6 showing exchange of the α-protons.



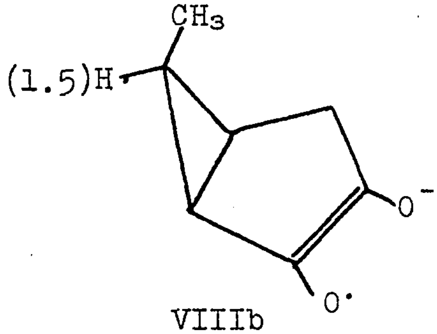
VIIa



VIIb



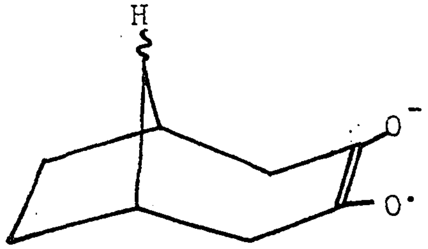
VIIIa



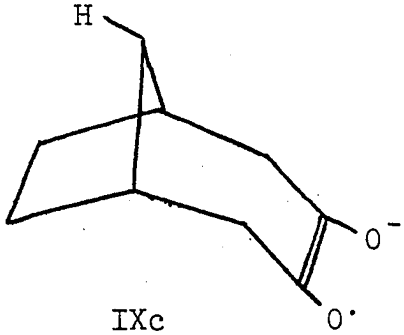
VIIIb

assigning the β-hfsc, and therefore the conformation, without the perturbations of alkyl substitution, was apparent. The chair conformation has the γ-equatorial hydrogen in a $2\frac{1}{2}$ V zig-zag arrangement and this proton would be the cause of the doublet splitting. For the boat form, splitting from either γ-hydrogen was possible, and in fact both hydrogens are seen in some of the polycyclic compounds. It was of interest to determine which hydrogen causes the doublet hfsc in the boat.

A model compound which has the seven-membered ring in the boat form was sought. The bicyclo[4.2.1]non-3-ene system seemed a likely candidate. The olefinic bond would occupy the least hindered side of the molecule, and comparing the structure to the bicyclo[2.2.1]heptane system, the <u>exo</u> side



IXb



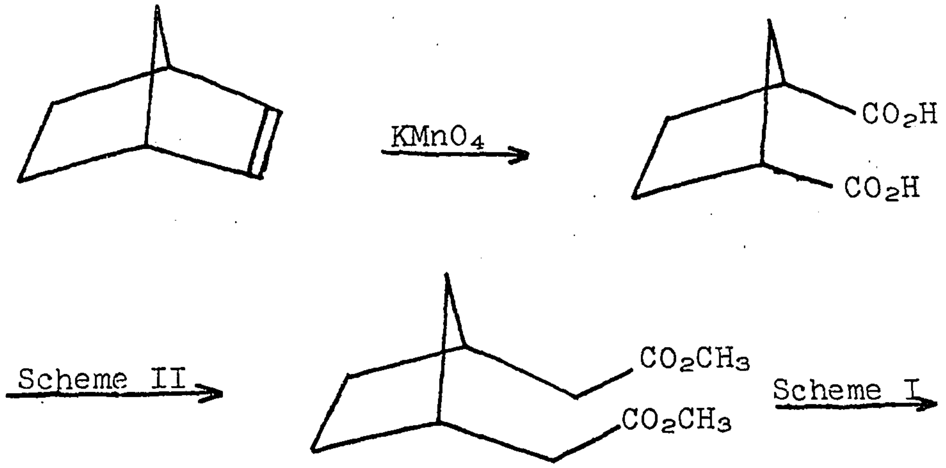
IXc

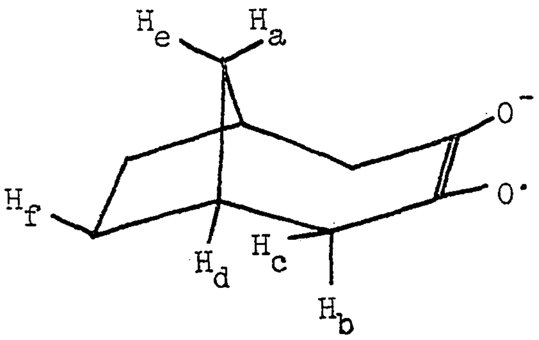
would be the least hindered one, and the conformation would therefore be IXb. The preparation of semidione IX is given in Scheme III. Norbornene was oxidized with potassium permanganate to *cis*-1,3-cyclopentanedicarboxylic acid, which was chain extended by the reactions of Scheme II, and converted to the semidione using Scheme I.

The analysis of the spectrum, Figure 10, gives a large triplet of 9.85 G, a smaller triplet of 1.56 G, two more small triplets of 0.53 and 0.25 G, and one doublet splitting of 0.54 G. The magnitude of this doublet confirms the conformational assignment to IXb when it is compared to the doublet splittings in X and XI which had been previously prepared by Whittle (14). In X, which has the seven-membered ring locked in the boat form, the doublet is only 0.40 G, whereas in XI, the seven-membered ring is in the chair and a 2.40 G is observed.

To determine which hydrogen, H_a or H_e, in IX was giving the doublet, IX was prepared with deuterium in the 9-position according to the reactions in Scheme IV. Norbornene was brominated to give 2,7-dibromobicyclo[2.2.1]heptane, which on

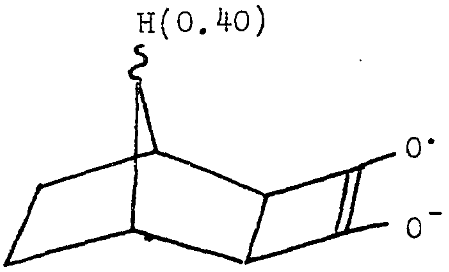
Scheme III



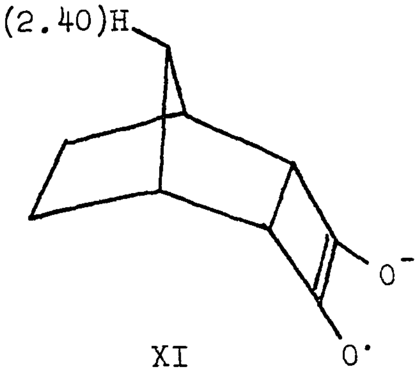


IX

a^H=9.85 (2H) H_b
1.56 (2H) H_c
0.53 (2H) H_d or H_f
0.25 (2H) H_f or H_d
0.54 (1H) H_e or H_a



X



XI

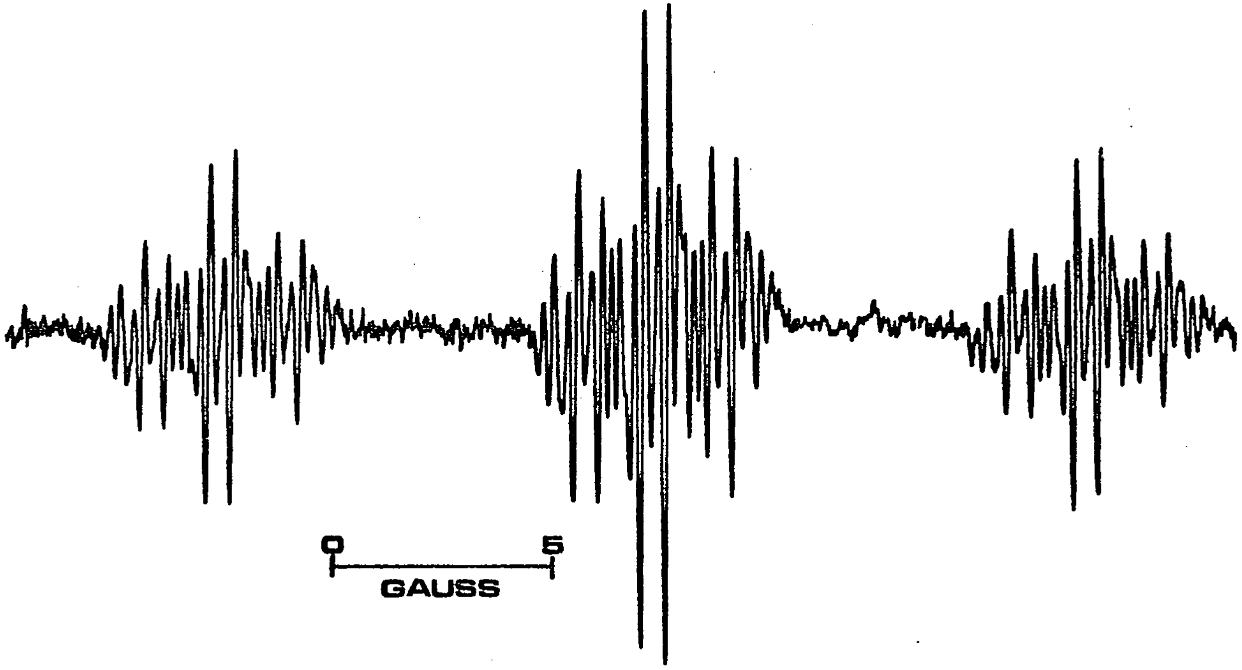
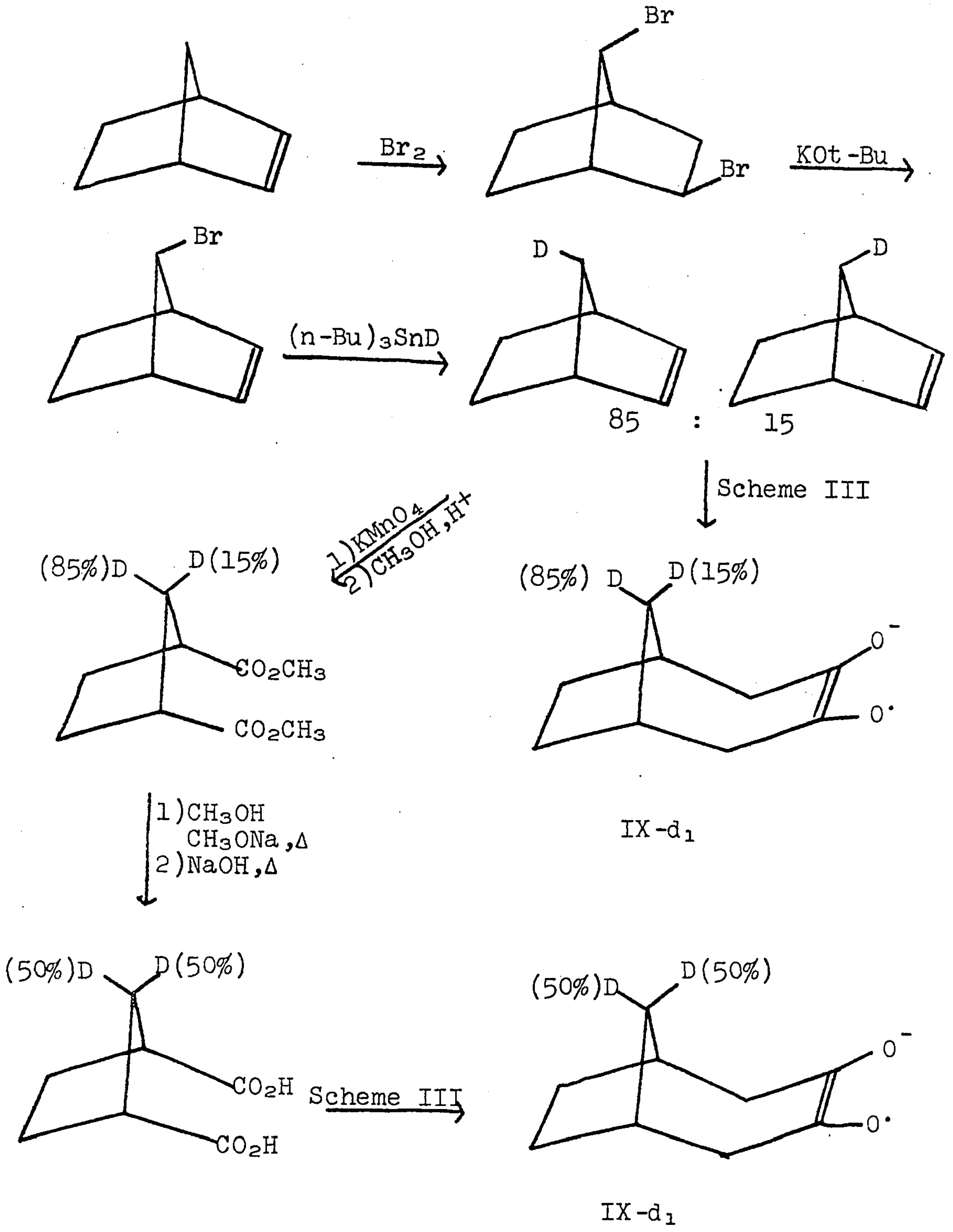


Figure 10. The first derivative esr spectrum of bicyclo[4.2.1]nonane-3,4-semidione (IX) in DMSO.

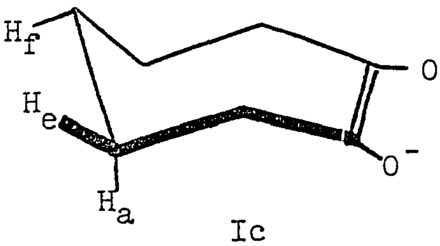
Scheme IV



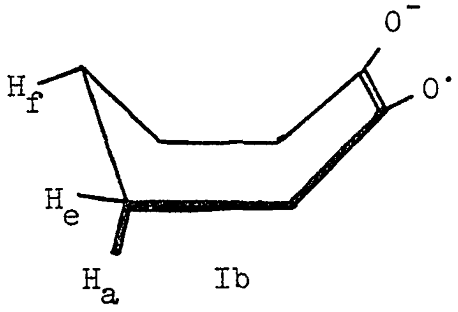
Br
Br$_2$
Br
KOt-Bu
Br
(n-Bu)$_3$SnD
D
D
85 : 15
Scheme III
1)KMnO$_4$
2)CH$_3$OH,H$^+$
(85%)D
D(15%)
CO$_2$CH$_3$
CO$_2$CH$_3$
(85%) D
D(15%)
O$^-$
O$\cdot$
IX-d$_1$
1)CH$_3$OH
CH$_3$ONa,Δ
2)NaOH,Δ
(50%)D
D(50%)
CO$_2$H
CO$_2$H
Scheme III
(50%)D
D(50%)
O$^-$
O$\cdot$
IX-d$_1$

treatment with potassium t-butoxide gave anti-7-bromobicyclo[2.2.1]heptene. Reacting the bromide with tri-n-butyltindeuteride (15,35,36) gave a mixture of anti-7-deuteriobicyclo[2.2.1]heptene and syn-7-deuteriobicyclo[2.2.1]heptene in the ratio of 85:15 (15). Using Scheme III, IX was prepared with deuterium in the 9-position anti:syn of 85:15. In addition, the isomers were also equilibrated (Scheme IV) to give a 1:1 mixture of deuterated material. The center portion of the spectrum of IX is compared to the analogous portions of the spectra of IX with the different deuterium distributions in Figure 11. As more and more of the anti-9-hydrogen is replaced, the doublet splitting is removed and must be assigned to H_e, which is the equatorial proton in the γ-position of the boat conformation.

Whether or not the boat or chair conformation of cycloheptanesemidione was predominant, the γ-equatorial hydrogen would be the one causing the doublet splitting. This was confirmed by γ-methylcycloheptanesemidione II, where the doublet splitting was removed upon introduction of the methyl group. In Ic, the chair form, the large β-splitting would be



Ic



Ib

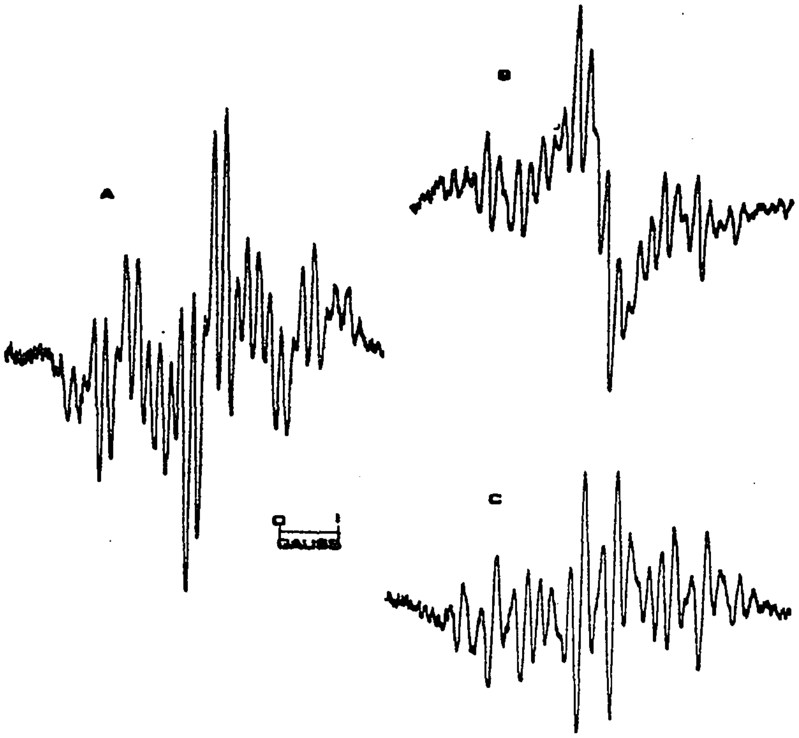
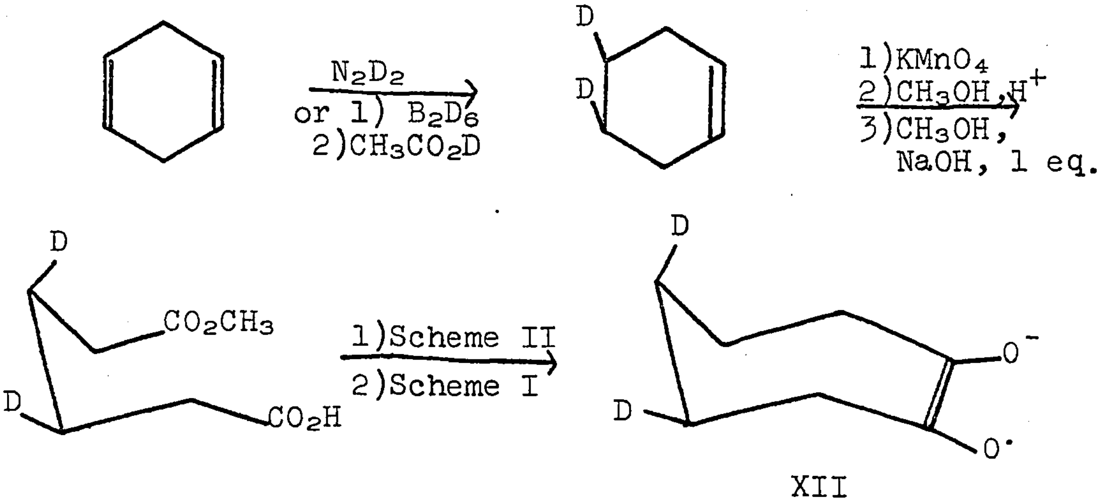


Figure 11. The first derivative esr spectra of the center group of the large triplet of bicyclo[4.2.1]-nonane-3,4-semidione: (A) 85/15 deuterated IX-d$_1$; (B) 50/50 deuterated IX-d$_1$; (C) undeuterated IX.

from H_e which is *trans* with respect to H_f, whereas in the boat form Ib, the large β-hfsc would be from H_a, which is *cis* with respect to H_f. Introduction of *cis* deuteriums into the molecule at this position would permit an indisputable assignment of splittings at the β-position and hopefully confirm the conclusion reached in the examination of the methyl-substituted cycloheptanesemidiones.

Introduction of the *cis*-deuteriums was accomplished by the reactions in Scheme V. Reaction of 1,4-cyclohexadiene with either deuterodiimide, or deuterodiborane followed by reaction with acetic acid-d would add the deuteriums *cis* (37,38) and give the *cis*-4,5-dideuterocyclohexene. Oxidation with potassium permanganate to adipic acid, esterfication to to dimethyl adipate, followed by basic hydrolysis with one equivalent of sodium hydroxide gave the monoacid-ester. Chain

Scheme V



XII

extension with Scheme II and closure to the semidione (Scheme I) gave the desired product XII. The spectrum of XII, Figure 12, starting with deuterodiimide was identical to the spectrum obtained when deuterodiborane was used to begin the reaction sequence.

For the analysis of the spectrum, which shows two different radicals, it was easiest to consider the possible radicals and their predicted splitting constants. If the chair from was present, radicals $XIIc_1$ and $XIIc_2$ (Chart II) would be seen; if however, the boat form was present, $XIIb_1$ and $XIIb_2$ would be seen. The two important possibilities are $XIIc_2$ and $XIIb_2$ which would still have both 2.05 G splittings, and therefore have lines which were not overlapping with the lines of the other radical. The center of the outside sets from the 2.05 G triplet are marked with arrows (Figure 12). This set analyzes for a 1:3:3:1 quartet due to three equivalent hydrogens and hence the radical seen is $XIIc_2$ and not $XIIb_2$ (which would also show a 0.54 G doublet). This confirms the result obtained from the analyses of the alkyl-substituted cycloheptanesemidiones, namely that the chair form and not the boat form is the predominant conformation in solution.

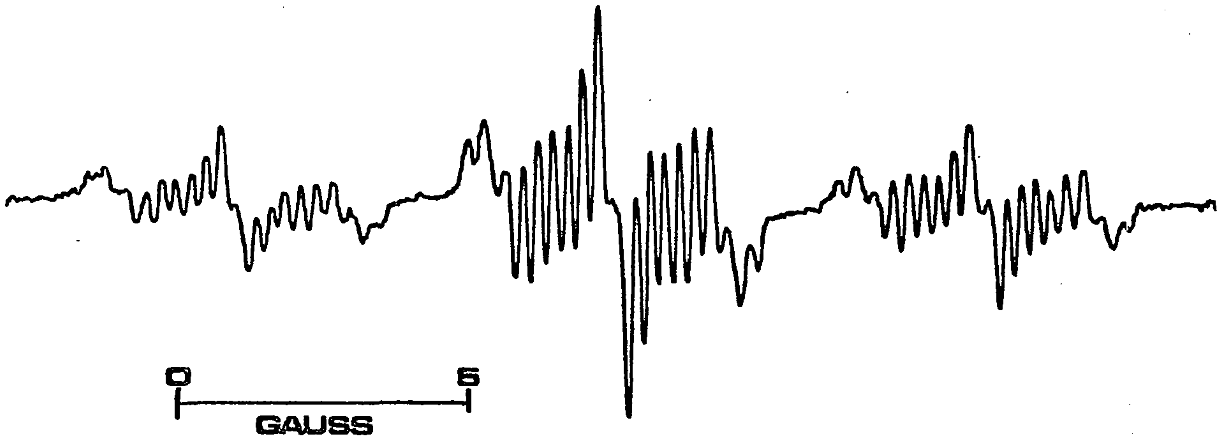
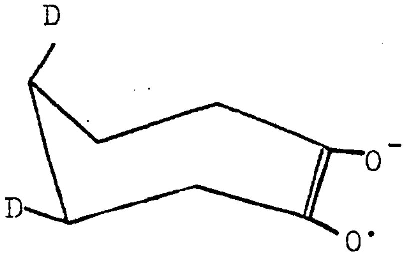


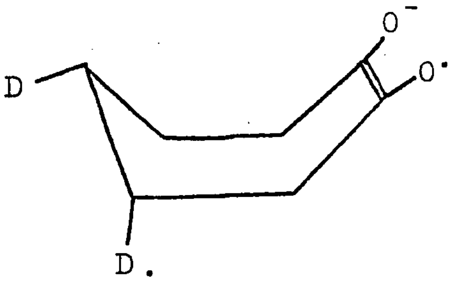
Figure 12. The first derivative esr spectrum of *cis*-4,5-dideuterocycloheptanesemidione (XII) in DMSO at 0°.

Chart II



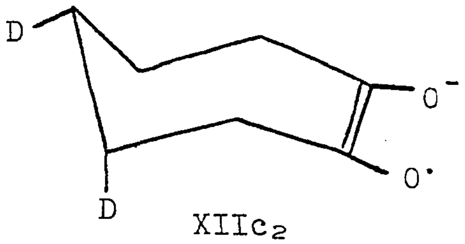
XIIc$_1$

a^H=6.60 (2H)
2.05 (1H)
0.28 (4H)
0.32 (1D)
0.54 (1H)



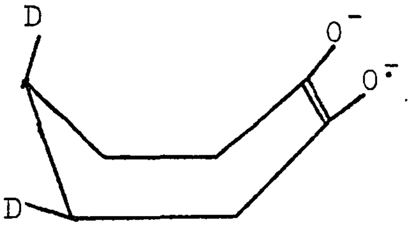
XIIb$_1$

a^H=6.60 (2H)
2.05 (2H)
0.28 (4H)
0.32 (1D)



XIIc$_2$

a^H=6.60 (2H)
2.05 (2H)
0.28 (3H)

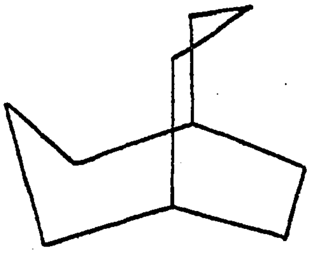


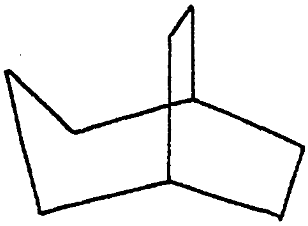
XIIb$_2$

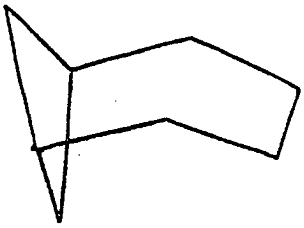
a^H=6.60 (2H)
2.05 (2H)
0.28 (3H)
0.54 (1H)

CONFORMATIONAL INTERCONVERSIONS AND PREFERENCES OF THE CYCLOHEPTANESEMIDIONE RING IN BICYCLIC COMPOUNDS

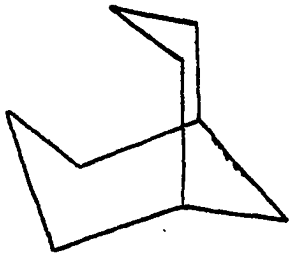
Although cycloheptanesemidione is conformationally frozen with respect to the esr time scale, the possibility of lowering the energy of activation for ring flip still existed. The manner in which this could be done, would be to make a bicyclic compound wherein the steric interactions raise the ground-state energy of the seven-membered ring. Three systems in which this could occur were bicyclo[3.3.2]decane (XIII), bicyclo[3.2.2]-nonane (XIV), and bicyclo[4.1.1]octane (XV). However, the main attractions of these systems were the conformational preferences that they would show and their relationship to the saturated and unsaturated hydrocarbons.


XIII

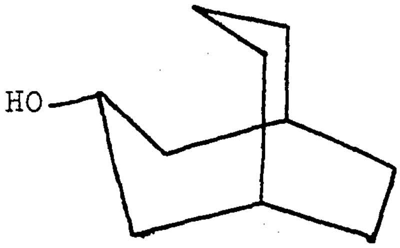

XIV


XV

It has been shown that bicyclo[3.3.1]nonane exists in the conformation (XVI) where both six-membered rings are in the chair form (39-44). On the basis of chemical shift data in a recent nmr study, Doyle and Parker (45) have assigned an analogous conformation (XVII) to bicyclo[3.3.2]nonan-3-ol. An assignment of conformation to bicyclo[3.3.2]decane-9,10-semidione



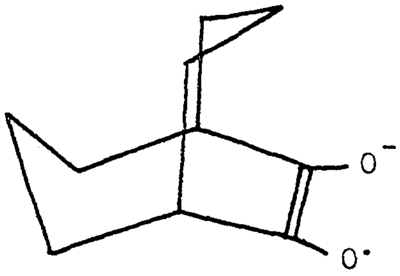
XVI



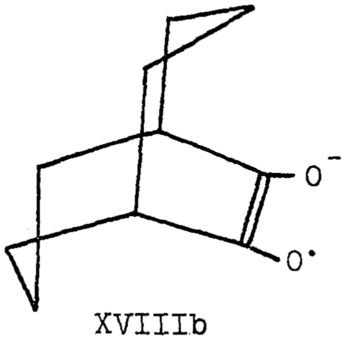
XVII

(XVIII) would allow assignment of conformation to the parent olefin.

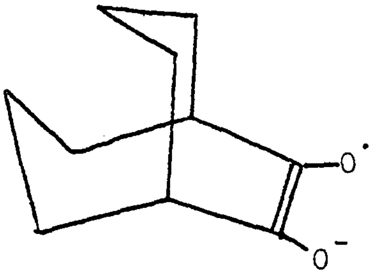
The bicyclo[3.3.2]decane system is especially interesting in that three distinct conformations are possible. The esr spectra of semidiones in these conformations would be quite distinctive and would allow an unambiguous assignment of conformation. The β-hydrogens which have a *trans*-coplanar arrangement of bonds to the carbon p_z orbital of the π-system, have large hyperfine splittings, 1.8 to 2.8 G, when the seven-membered ring is in the chair form (see p. 58). However, when the seven-membered ring is a boat, the splittings are 0.5 G or less. Thus XVIIIa would have two splittings of $\sim$2 G, XVIIIb would not show any large hfsc, and XVIIIc would have four large



XVIIIa



XVIIIb



XVIIIc

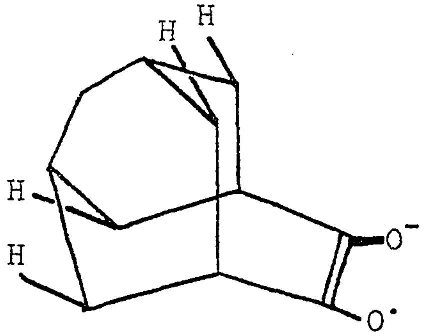
hfsc's.* In addition, XVIIIa would be the only form which could have hydrogens which are different from all the others in the molecule, and hence be the only one with doublet splittings.

XVIII was prepared by the synthetic sequence shown in Scheme VI. The room-temperature and low-temperature spectra of XVIII are shown in Figure 13. The room-temperature spectrum gave the following analysis: a^H (2H) 2.36 G, a^H (2H) 0.54 G, and a^H (3 or 5H) 0.1 G. At low temperature the smaller triplet split into a doublet of doublets, a^H 0.42 and 0.77 G. Thus conformation XVIIIa is required both from the doublet splittings and from the number of β-hydrogens with a <u>trans</u>-coplanar arrangement of bonds leading to a^H ~2 G.

The temperature dependent spectra of this system, Figures 13 and 14, do present one problem. There are two possible explanations of them, and neither is wholly consistent with previous results. Considering the room temperature

---

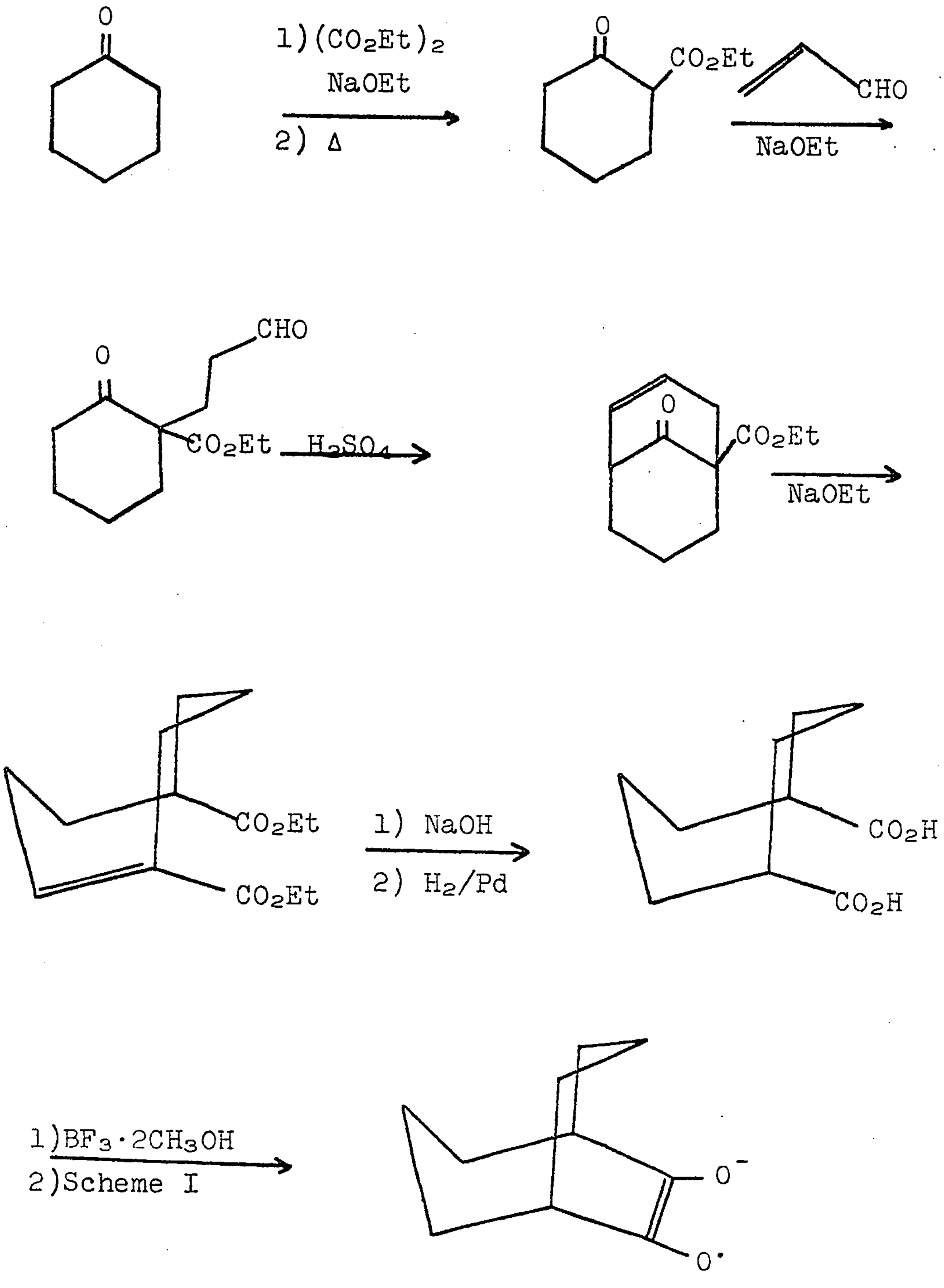
*Dr. R. S. Givens has prepared semidione XIX wherein the geometry is locked in that of XVIIIc and his results are in total agreement with our predictions.



XIX

a^H=2.26 (4H)

Scheme VI



XVIII

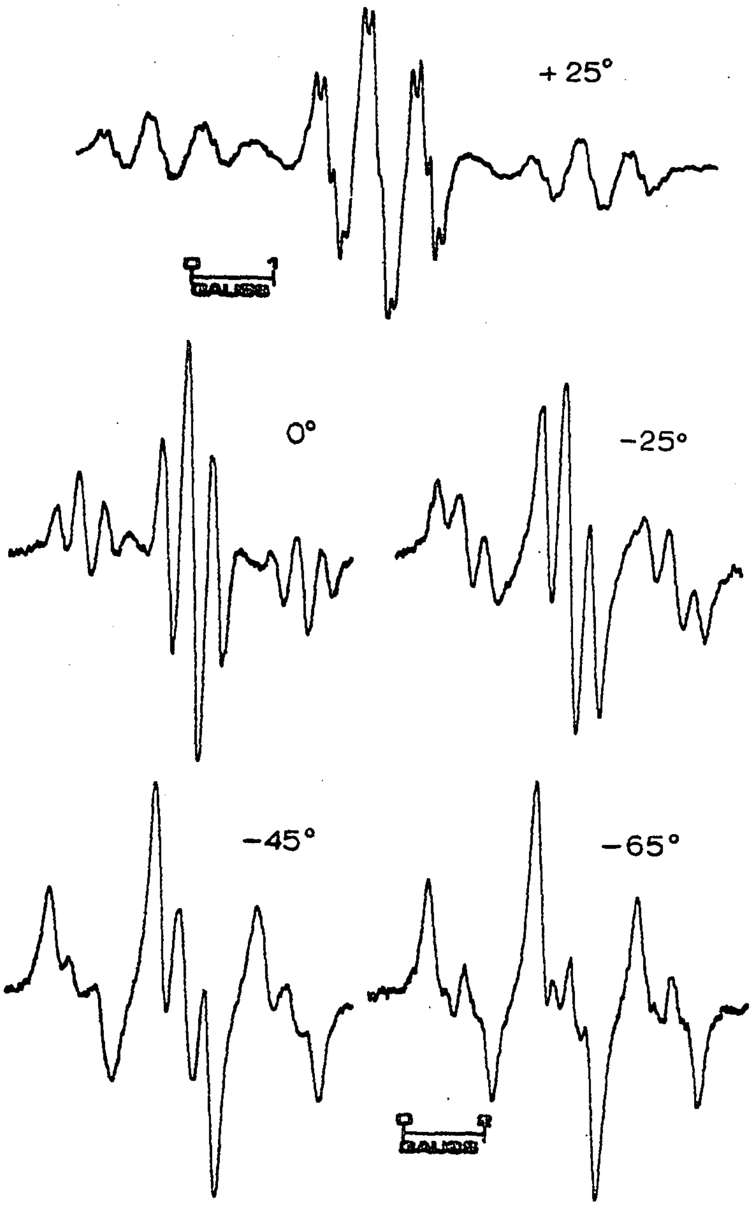


Figure 13. The room-temperature and low-temperature first derivative esr spectra of bicyclo[3.3.2]decane-9,10-semidione (XVIII) in 80/20 DMF-DMSO.

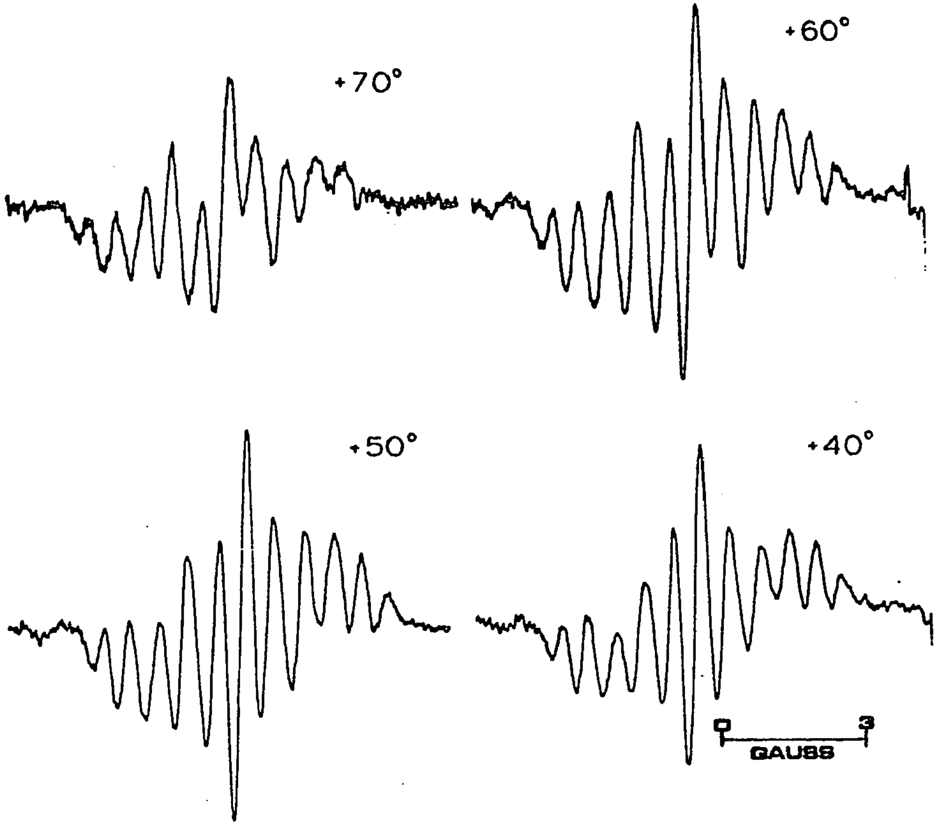
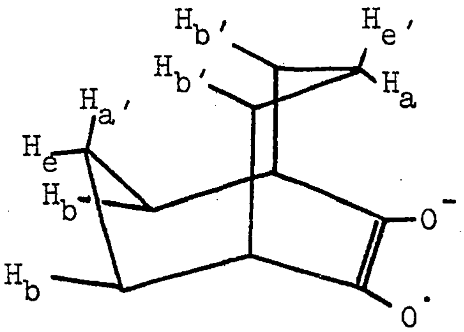
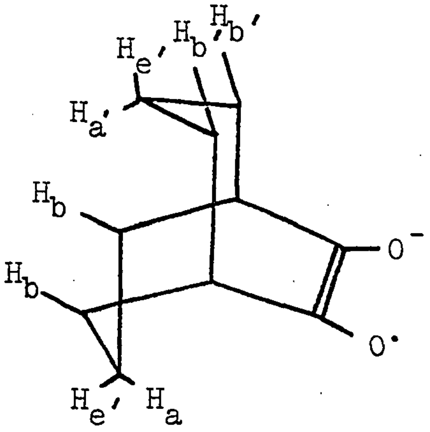


Figure 14. The high-temperature first derivative esr spectra of bicyclo-[3.3.2]decane-9,10-semidione (XVIII) in DMSO.

spectrum, if a small doublet of 0.1 G is present, then the system must be conformationally frozen. The 0.55 G triplet is then due to two protons (H_e and $H_{e'}$) which are fortuitously magnetically equivalent, and which become non-equivalent as the temperature is lowered due to some slight structural change. The additional lines, which appear between the large triplet lines, in the high temperature spectrum must then be caused by an additional frozen conformation of XVIII. The other possible explanation is that the apparent doublet splitting is caused by potassium, which has a nuclear spin of 3/2, and would give lines with these intensities if an even number of protons with the same hfsc were also present. The temperature dependence would then be caused by conformational interchange at a rate such that broadening was seen by the esr time scale. This then means that the 0.55 G triplet (from H_e and H_a or $H_{e'}$ and $H_{a'}$) coalesces and gives a doublet of doublets, with the more reasonable assignment being the γ-equatorial proton (H_e) of the chair and the γ-axial proton (H_a) of the boat, or less likely $H_{e'}$ and $H_{a'}$. The additional lines in the high temperature spectrum are then caused by the 2.36 G triplet from H_b at slow exchange becoming a 1.18 G quintet from H_b and $H_{b'}$ at rapid exchange. The latter explanation is less likely on two points: first, potassium splittings have never been seen in similar systems, and secondly, the assignment of the γ-hfsc to H_a in the boat section is contrary to the results of the bicyclo[4.2.1]nonane





system or the assignment of the other γ-hfsc to $H_{a'}$ in the chair part is contrary to the assignment in cycloheptane semidione itself. In either case, the assignment of the predominant conformation to XVIIIa remains unchanged, and this conformation then seems likely for the parent olefin.

In relating the conformation of XVIII to the conformation of the parent saturated hydrocarbon, it was considered worthwhile to determine the relative preferences of the saturated and unsaturated seven-membered rings for the chair form. If the seven-membered ring with a semidione group did not have as great a preference for the chair as the saturated ring, it would be quite possible for XVIII and the parent olefin to be in conformation XVIIIa, while the conformation of the saturated hydrocarbon is XVIIIc, as was proposed for XVII. This question would appear to be answered by the determination of the conformations of XX and XXI, where two possibilities exist, XXa and XXIa, or XXb and XXIb. The temperature dependent spectra of XX, Figures 15 and 16, were

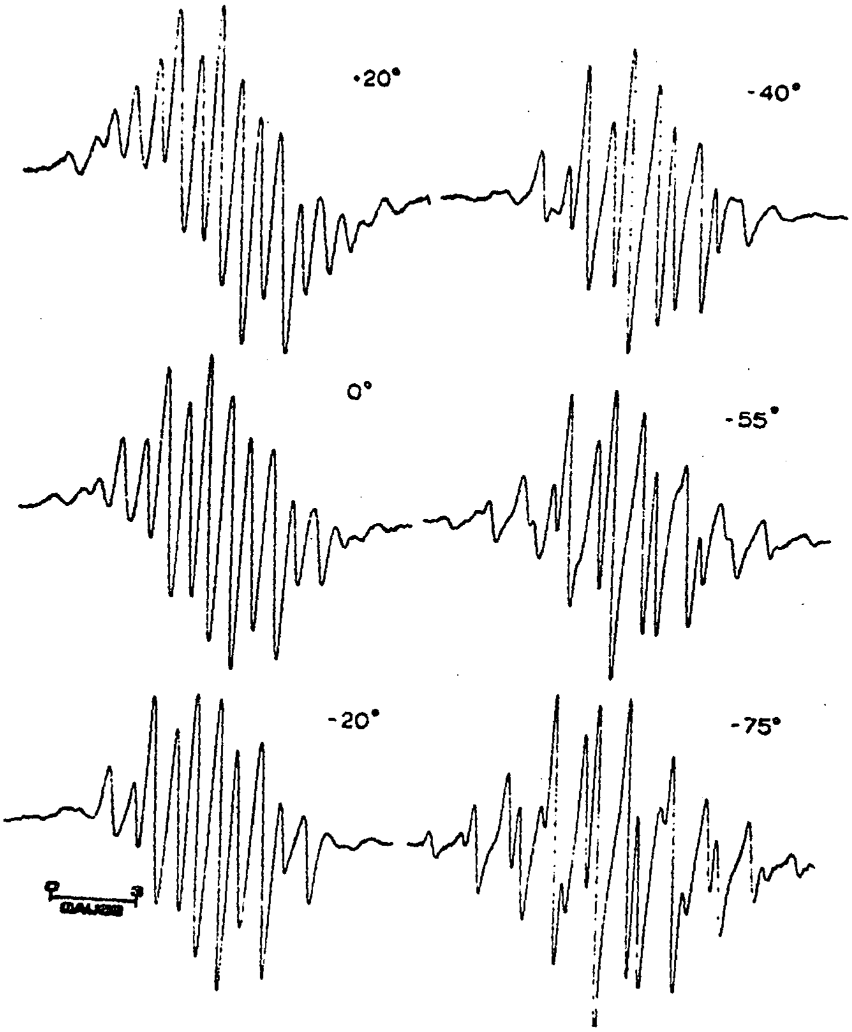


Figure 15. Low-temperature first derivative esr spectra of bicyclo[3.2.2]nonane-6,7-semidione (XX) in 80/20 DMF-DMSO.

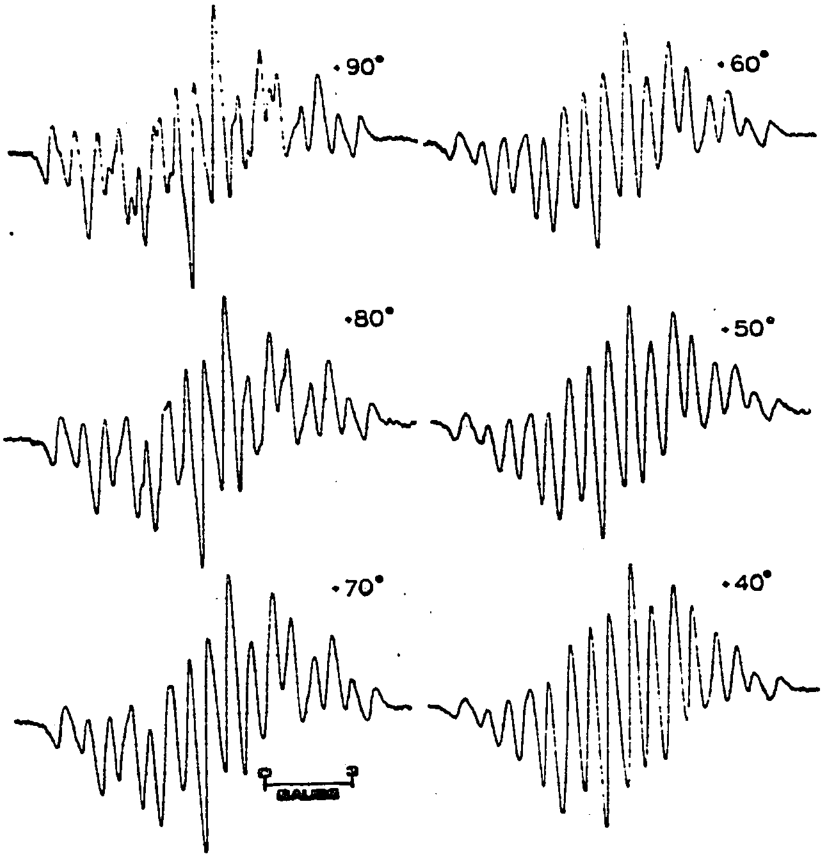
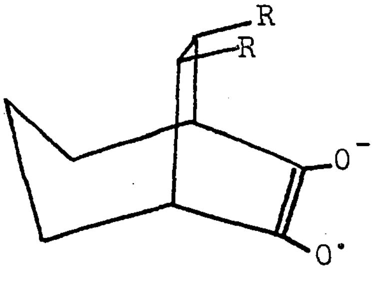
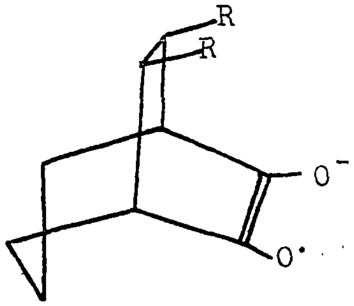


Figure 16. High-temperature esr spectra of bicyclo[3.2.2]-nonane-6,7-semidione (XX) in DMSO.



XXa, R=H
XXIa, R=CH_3

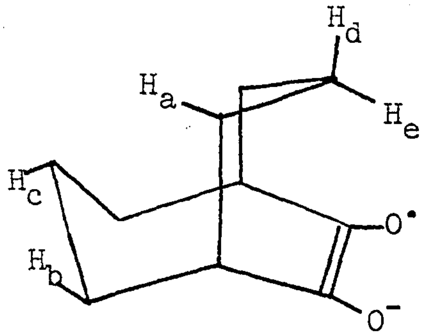


XXb, R=H
XXIb, R=CH_3

determined between -75 and 100°. This system possesses a small energy of activation for interconversion as does the bicyclo[3.2.2]nona-6,8-diene system, (46). Thus, at high temperature the two forms are rapidly interconverting and the hfsc are population averaged, with a^H (2 H) 1.95, a^H (2 H) 1.55, a^H (2 H) 1.40, and a^H (1 H) 0.80 G. As the temperature is lowered, the large triplet, from the flexible portion of the molecule, coalesces, and at -65°, when ring inversion has been slowed, increases to 2.75 G. The magnitude of this splitting indicates that the spectrum is due to XXa where the seven-membered ring with the semidione group is in the chair form. The behavior and results for XXI parallel those of XX and are shown in Chart III, with the temperature dependent spectra of Figures 17 and 18.

The syntheses of XX and XXI are shown in Scheme VII. The reactions are all straightforward, however in both cases the diesters could not be obtained pure, and an alternative preparation of XX was done in order to demonstrate that the

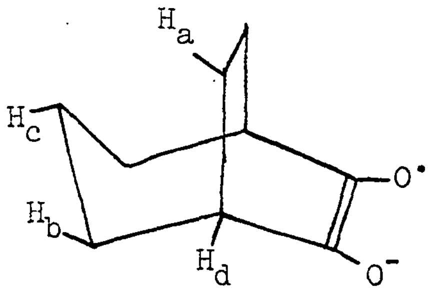
Chart III



XVIII

·H. T. a^H=1.18 (4H) H_a, H_b
0.54 (2H) H_c, H_d or H_e

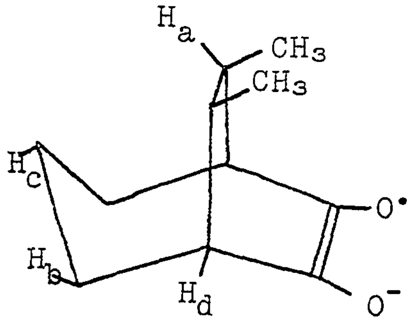
L. T. a^H=2.36 (2H) H_b
0.77 (1H) H_c
0.42 (1H) H_d or H_e



XX

·H. T. a^H=1.95 (2H) H_b
1.55 (2H) H_a
1.40 (2H) H_d
0.80 (1H) H_c

L. T. a^H=2.75 (2H) H_b
1.55 (4H) H_a, H_d
1.12 (1H) H_c

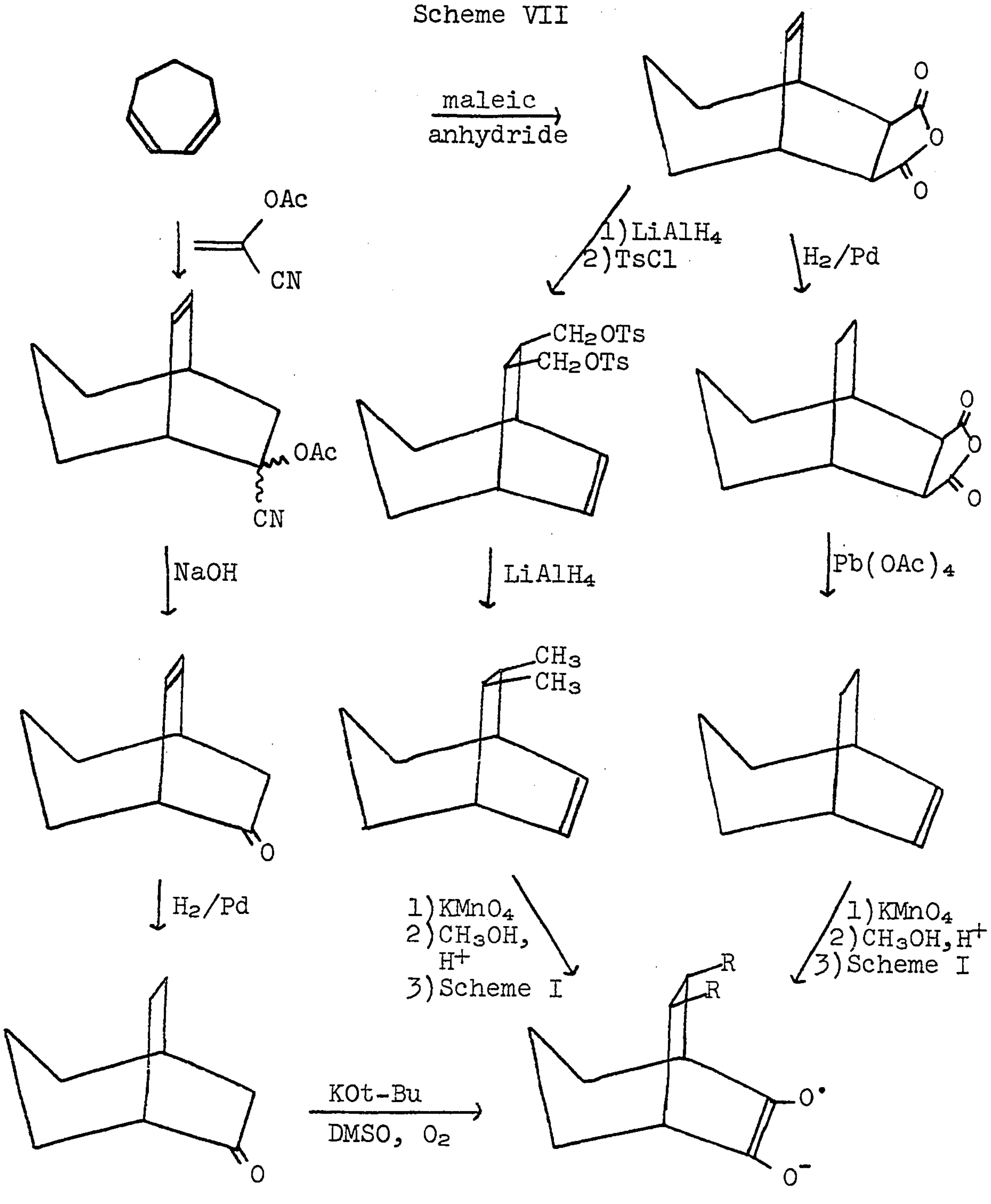


XXI

·H. T. a^H=1.50 (4H) H_b, H_d
0.75 (3H) H_c, H_a
0.10 (6H) CH_3's

L. T. a^H=2.85 (2H) H_b
1.55 (2H) H_d
0.80 (2H) H_a
0.90 (1H) H_c

Scheme VII



XX, R=H
XXI, R=CH_3

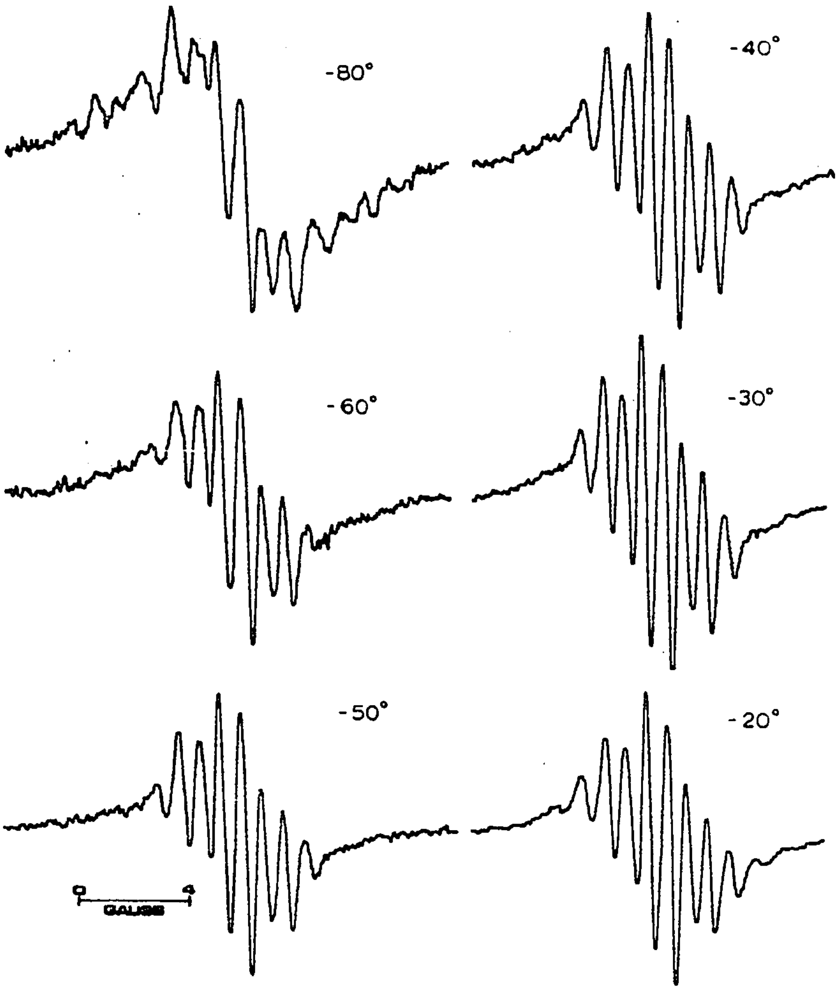


Figure 17. Low-temperature first derivative esr spectra of *endo,endo*-8,9-dimethylbicyclo[3.2.2]nonane-6,7-*semidione* (XXI) in 80/20 DMF-DMSO.

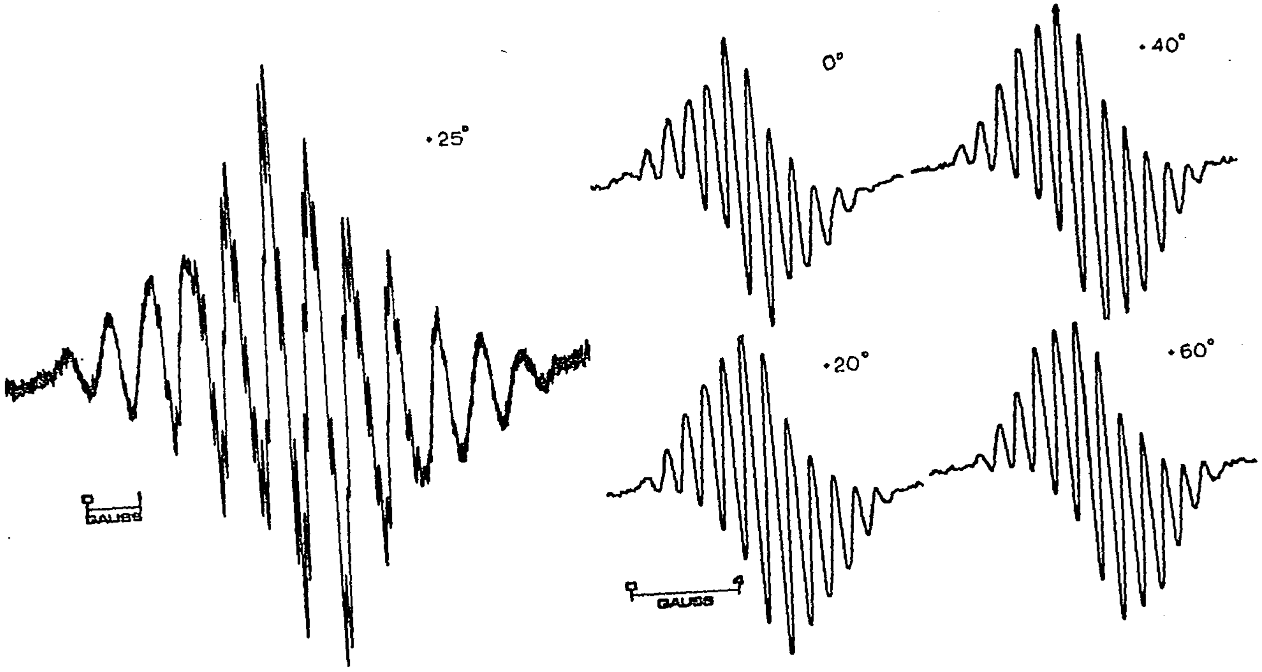


Figure 18. The high-temperature first derivative esr spectra of *endo,endo*-8,9-dimethylbicyclo[3.2.2]nonane-6,7-semidione (XXI) in DMSO.

semidione obtained from the diester was as formulated. The signal from the ketone, although weaker, was identical to the one obtained from the diester and both are shown in Figure 19.

The results indicate that the seven-membered ring containing the semidione group prefers the chair conformation to a slightly greater extent than does the saturated seven-membered ring, at least at -75°. Relating this to XVIII, it would seem that XVIII would have a greater preference for conformation XVIIIc than would the parent hydrocarbon. Since XVIII does not assume the conformation XVIIIc it would be unlikely for the saturated parent system to do so. The instability of XVIIIc must then be due to the (unfavorable) "saddle" conformation of the eight-membered ring, which is contrary to the suggestion of Dale et al. (47). Thus conformation XVIIIa is established as the conformation of XVIII and as the most likely conformation of the parent hydrocarbon and olefin.

The last conformationally mobile system to be considered was XV. Bicyclo[4.1.1]octane-3,4-semidione XXII was prepared according to the reactions outlined in Scheme VIII. Initially the main spectrum shown in Figure 20 was assigned to this semidione. However when semidione XXIII, bicyclo[3.1.1]heptane-2,3-semidione, was prepared, the spectrum (Figure 21) was identical to that in Figure 20. The spectrum in Figure 20 shows the presence of an additional radical. When the

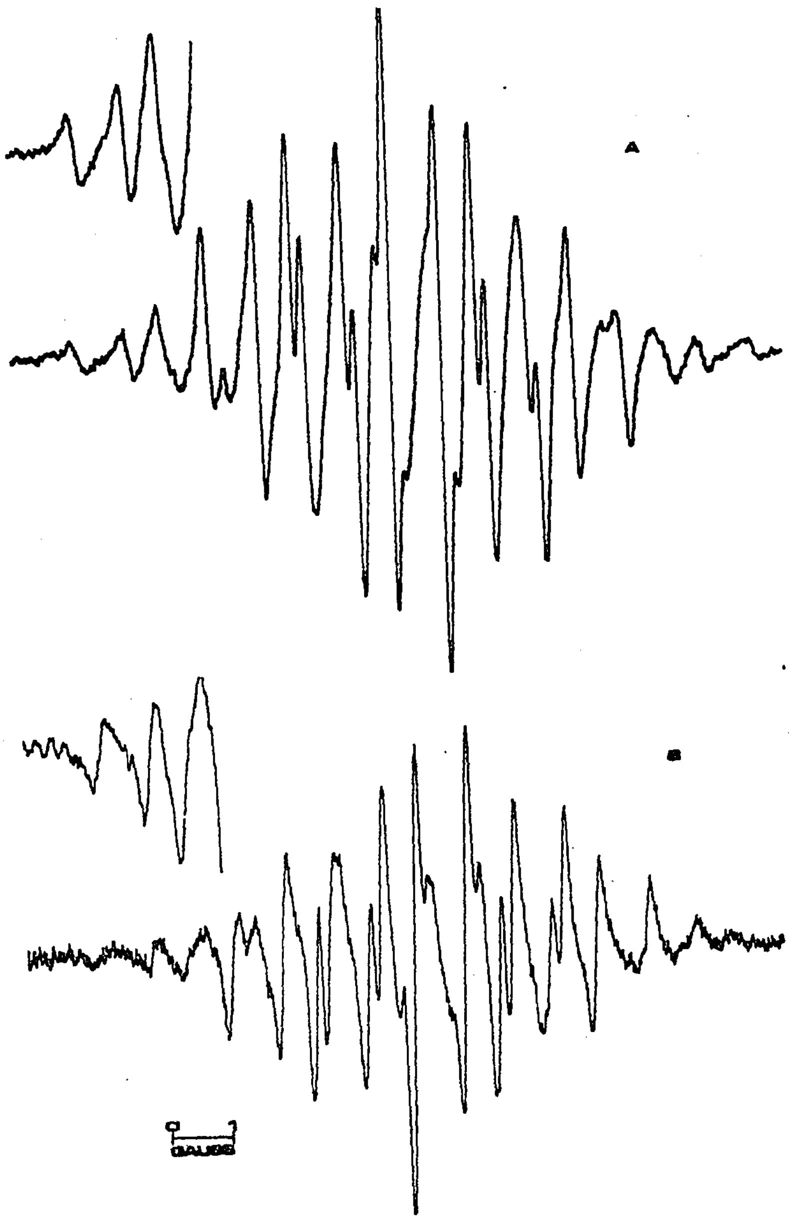
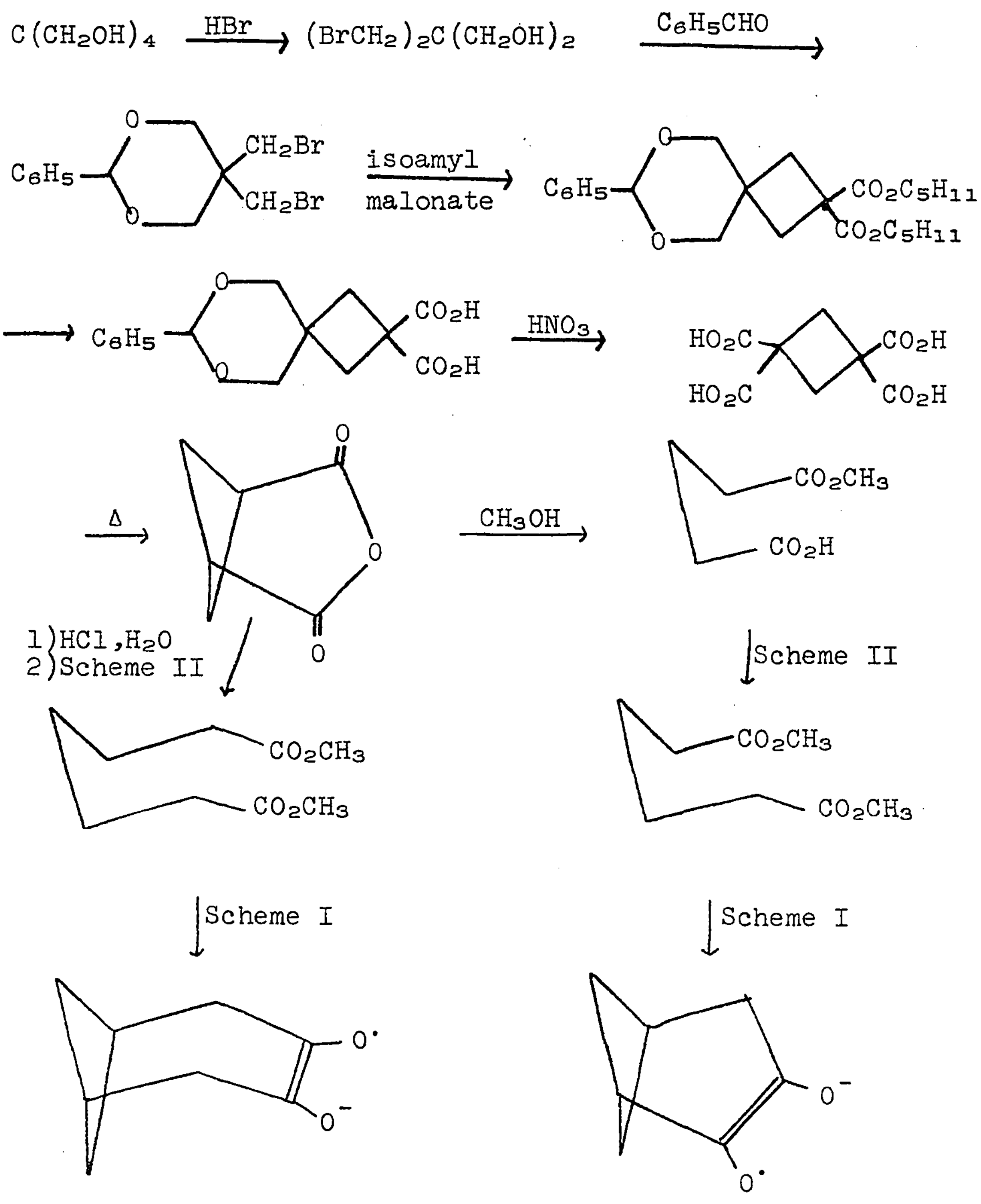


Figure 19. The first derivative esr spectra of bicyclo-[3.2.2]nonane-6,7-semidione (XX) in DMSO. Prepared from (A) the diester and (B) the ketone.

Scheme VIII



XXII

XXIII

Figure 20. The first derivative esr spectra of two radicals, the stronger being bicyclo[3.1.1]heptane-2,3-semidione (XXIII) and the weaker being bicyclo[4.1.1]octane-3,4-semidione (XXII) in DMSO.

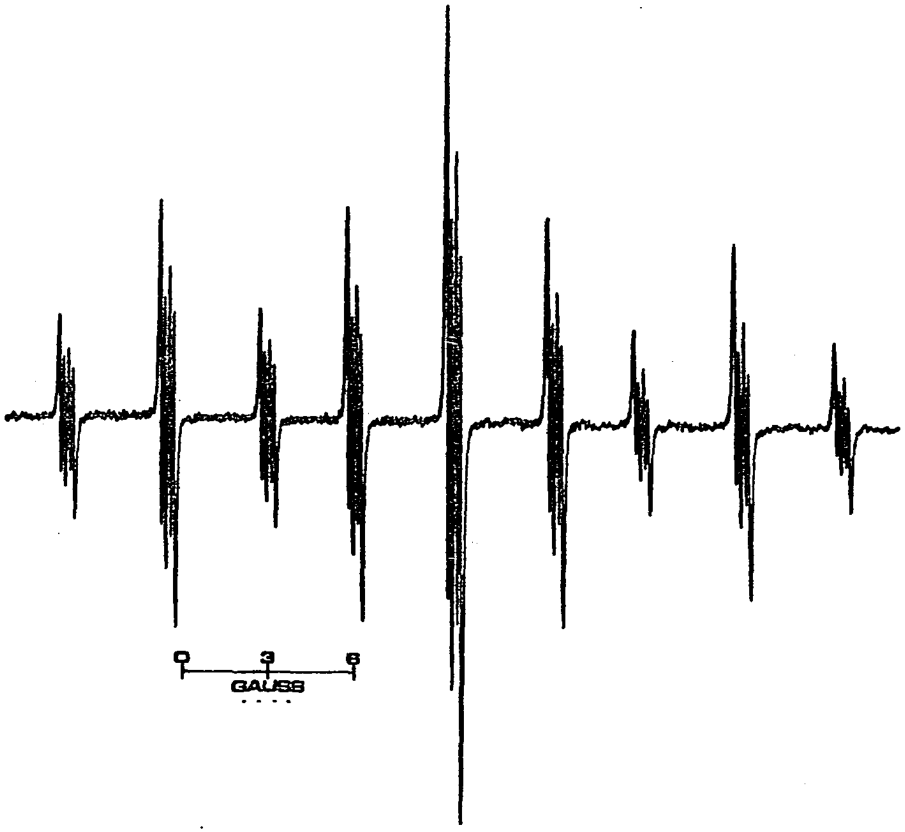
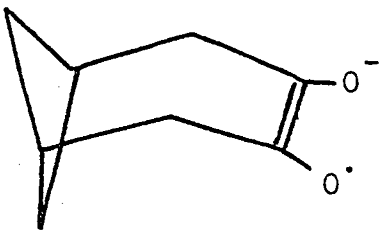
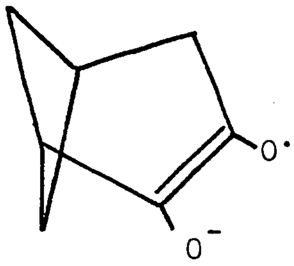


Figure 21. The first derivative esr spectrum of bicyclo[3.1.1]heptane-2,3-semidione (XXIII) in DMSO.


XXII


XXIII

diester precurser of XXII was checked by glpc, a small impurity was present in an amount less than 1%, but with a retention time identical to that of the diester precurser of XXIII. Repurifying of the diester by glpc and generation of the semidione gave the spectrum shown in Figure 22. This spectrum was identical to the spectrum of the "impurity" radical in Figure 20, and therefore is the correct spectrum of XXII. Semidione XXII was examined between +60° and -80°. Below 0° a mixture of 80% DMF and 20% DMSO was employed as the solvent. In this temperature range, the spectrum did not appreciably change, and it must be concluded from the equivalence of the various sets of protons (Chart IV) that the spectrum is the result of a very rapid ring inversion.

A second radical was obtained from XXII whose identity is unknown. Upon exposure to oxygen, the signal due to XXII disappeared and another signal formed over a period of 4 hr. This new signal is shown in Figure 23 and analyzes for a^H=4.85 (4H), 0.40 (4H), and 0.20 (2H).

The same behavior is also exhibited by the 7,7-dimethyl

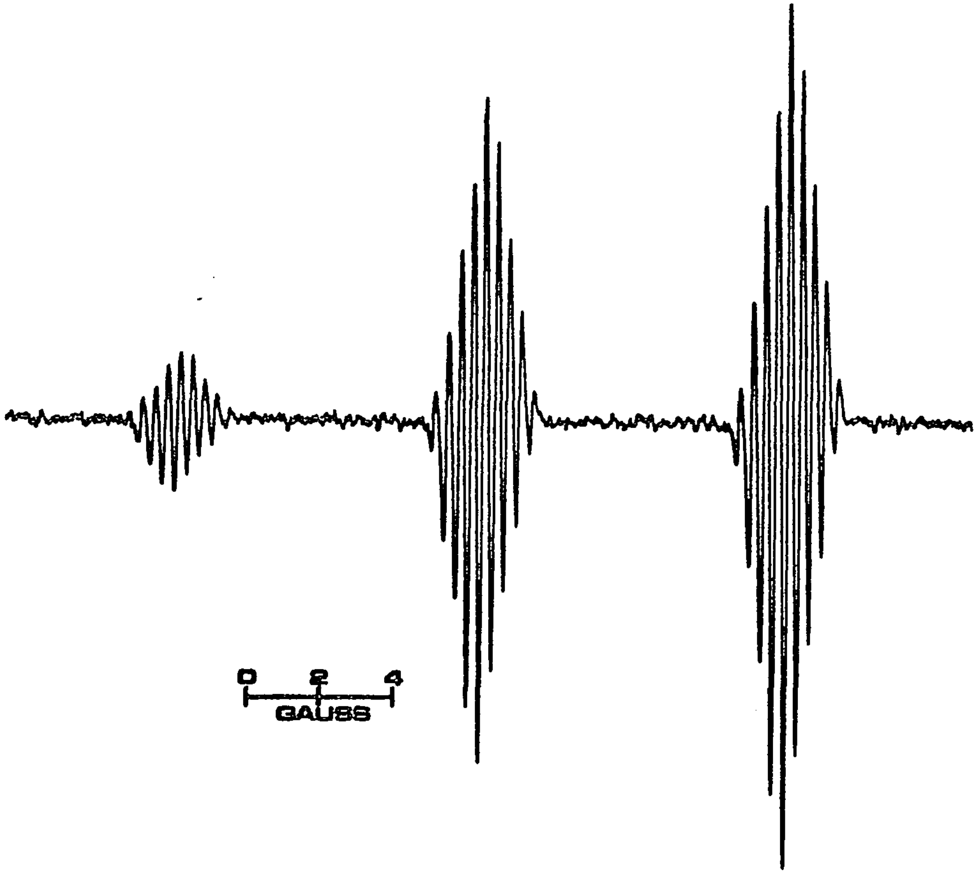
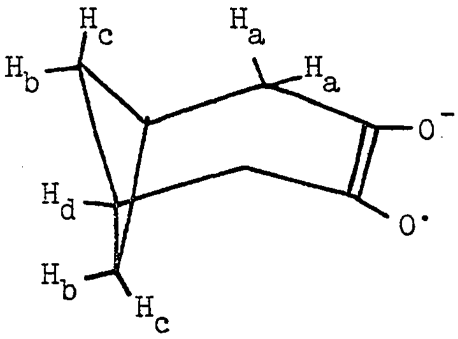


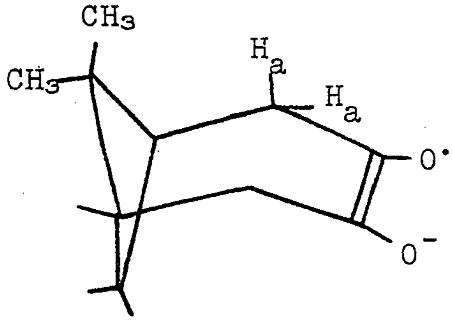
Figure 22. The first derivative esr spectrum of bicyclo[4.1.1]octane-3,4-semidione (XXII) in DMSO. Only the first three parts of the large quintet are shown.

Chart IV



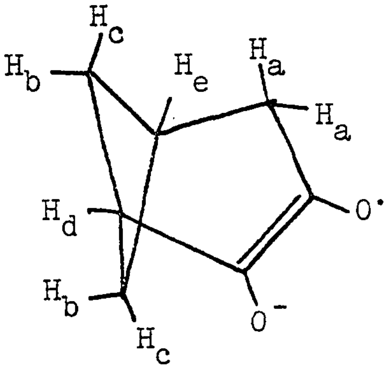
XXII

a^H=8.40 (4H) H_a
0.67 (2H) H_b
0.33 (4H) H_c, H_d



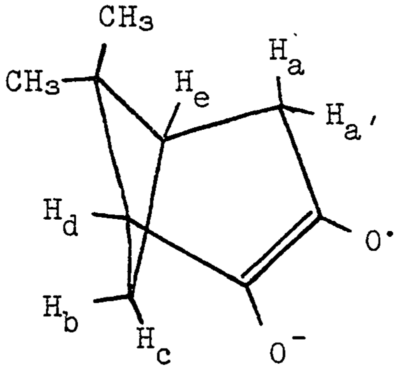
XXIV

a^H=8.65 (4H) H_a



XXIII

a^H=10.05 (2H) H_a
3.52 (2H) H_b
0.33 (1H) H_d or H_e
0.18 (1H) H_e or H_d



XXV

a^H=9.95 (1H) H_a or $H_{a'}$
9.30 (1H) $H_{a'}$ or H_a
3.90 (1H) H_b
0.33 (5H) CH_3, H_d, H_e

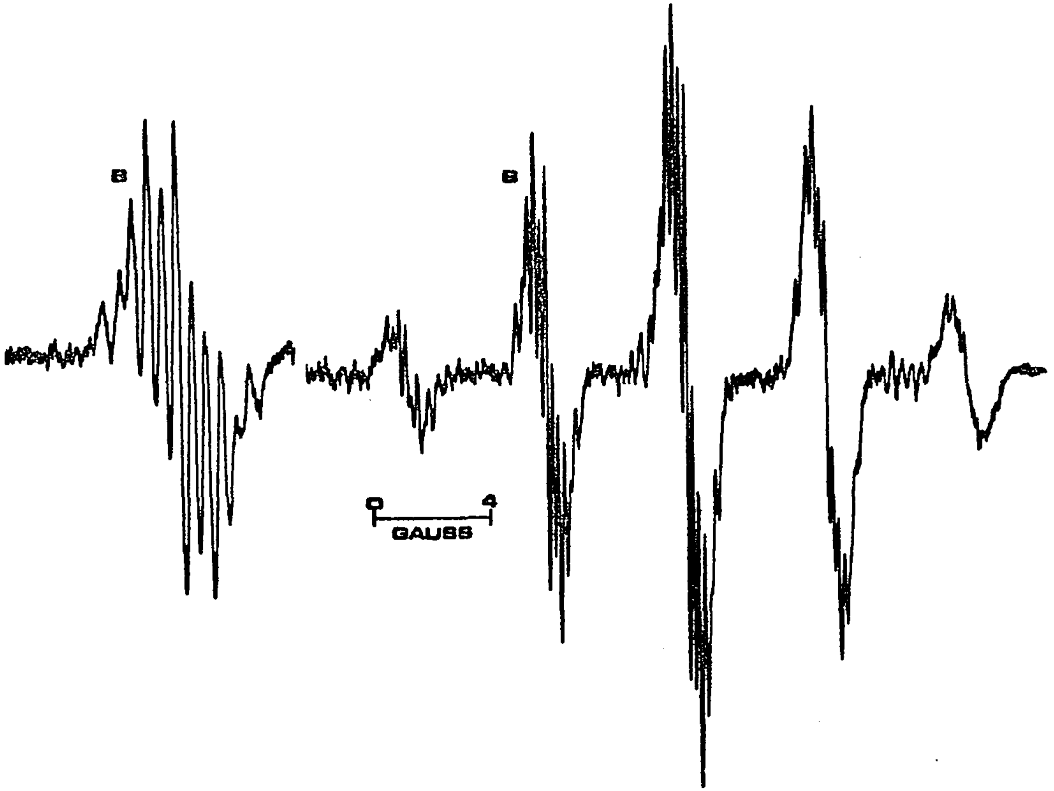
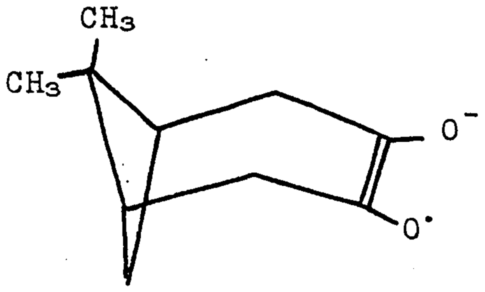
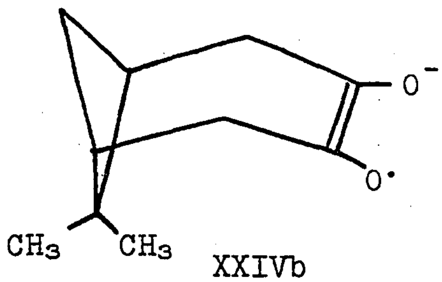


Figure 23. The first derivative esr spectrum of the unknown radical formed from XXII on exposure to oxygen.

derivative of XXII, (XXIV) whose spectrum is shown in Figure



XXIVa



XXIVb

24. At first glance it would seem that XXIV should show some conformational preference. However, in each case, XXIVa and XXIVb, there is one axial methyl group and one equatorial methyl group. The spectrum, which was run in DME, is poorly resolved and shows only the major hfsc. Both XXIV and XXV (Figure 25) were prepared according to Scheme IX, in order to compare them to the parent systems. Semidione XXV had previously been prepared by Dr. Chang (12). In each case, the dimethyl substituted compound compares well with the parent semidione.

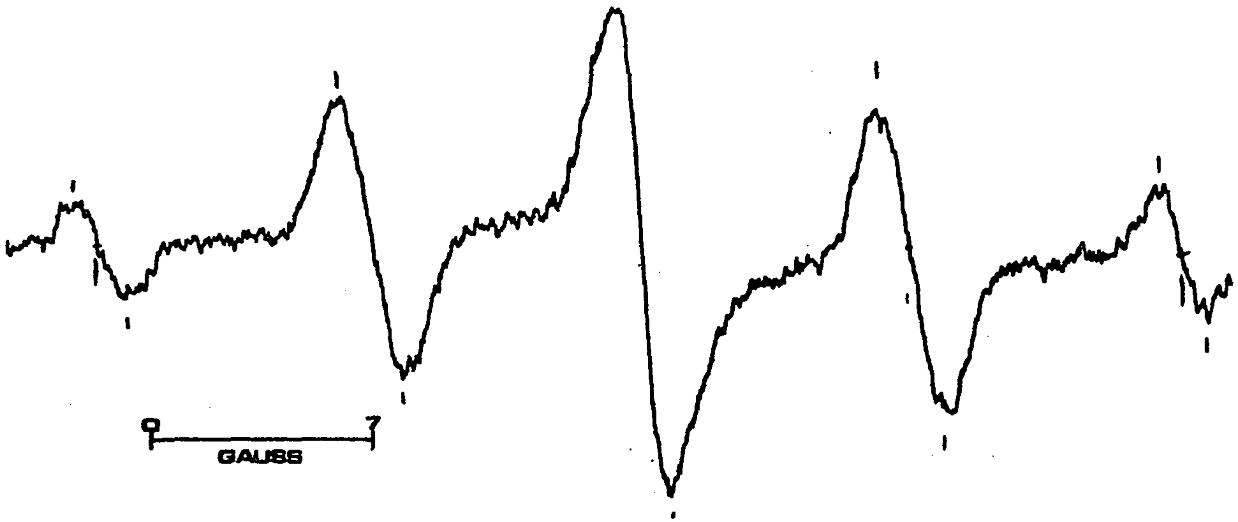


Figure 24. The first derivative esr spectrum of 7,7-dimethylbicyclo[4.1.1]-octane-3,4-semidione (XXIV) in DME.

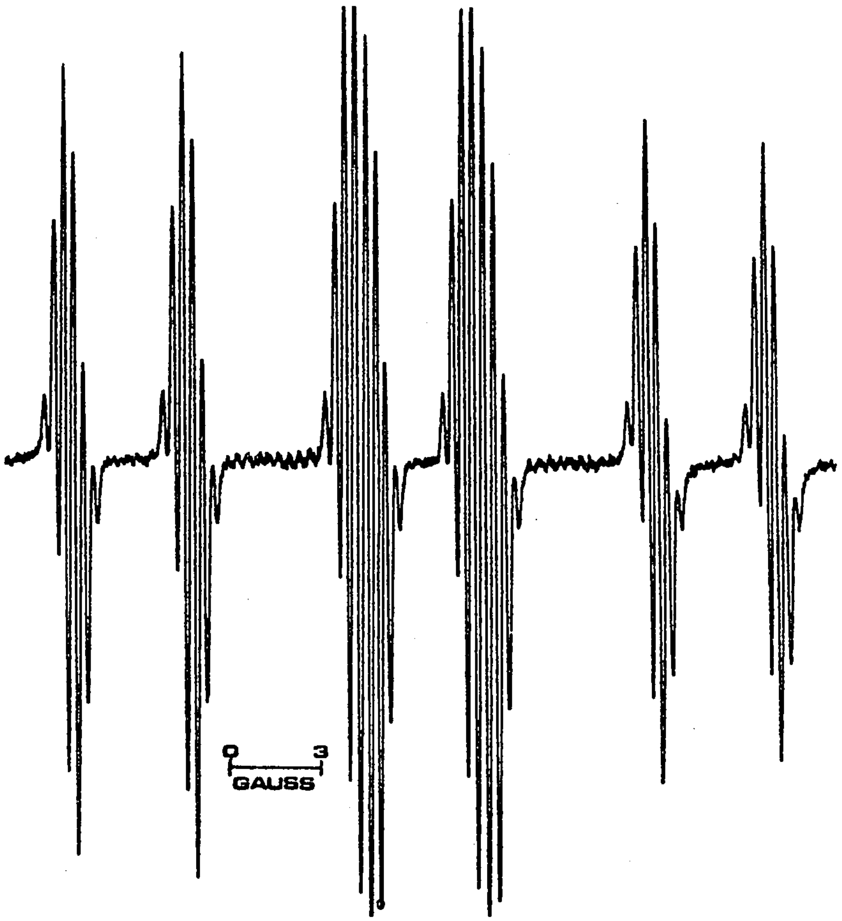
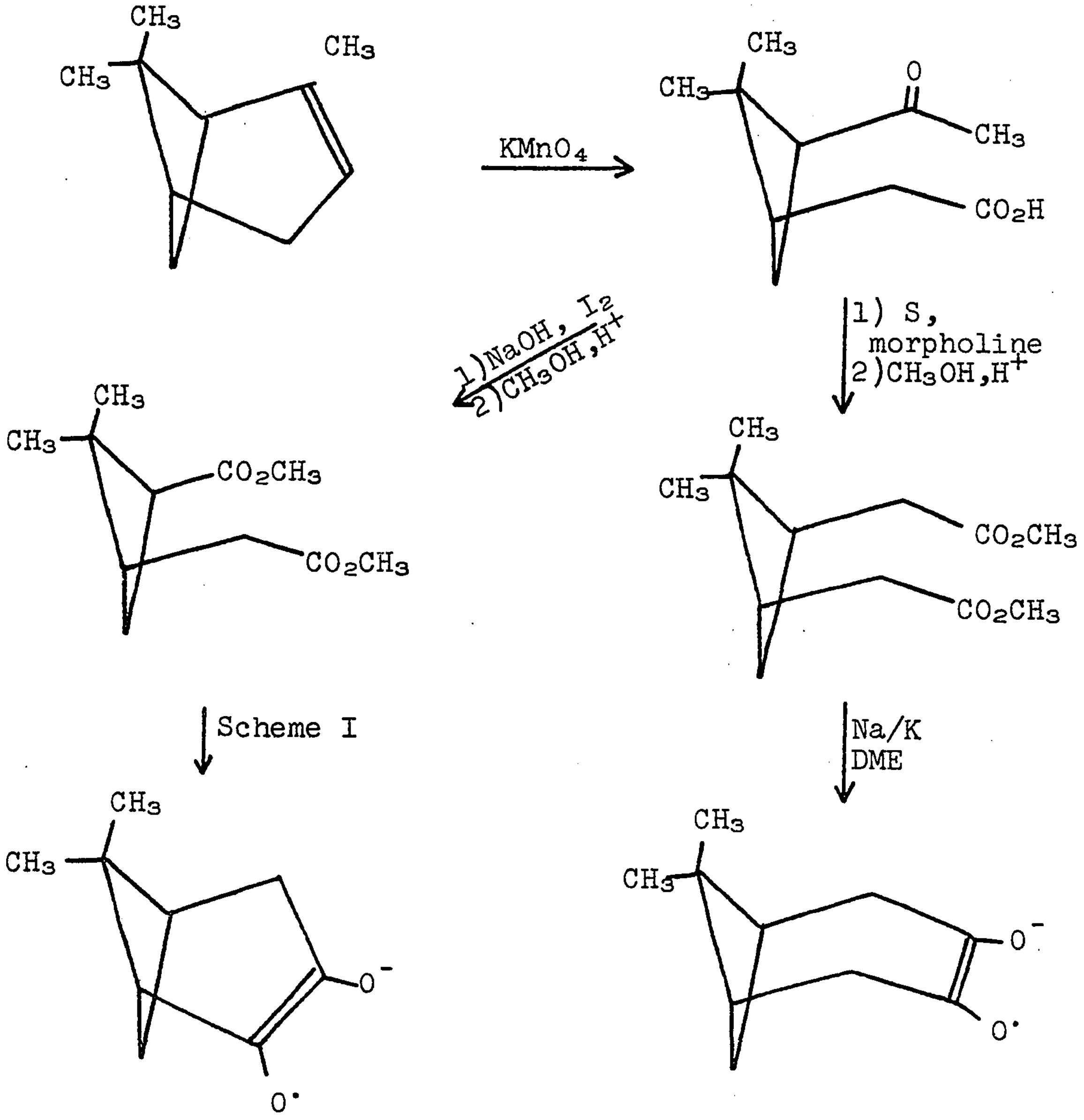


Figure 25. The first derivative esr spectrum of 6,6-dimethylbicyclo[3.1.1]heptane-2,3-semidione (XXV) in DMSO.

Scheme IX

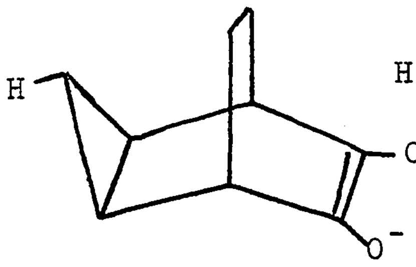


XXV

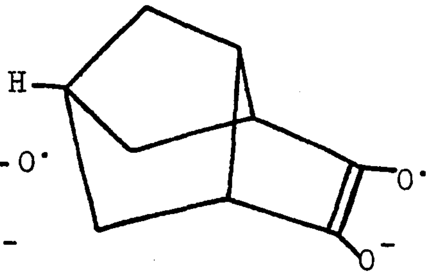
XXIV

LONG RANGE HYPERFINE SPLITTING CONSTANTS IN BI- AND POLYCYCLIC SEMIDIONES CONTAINING THE SEVEN-MEMBERED RING

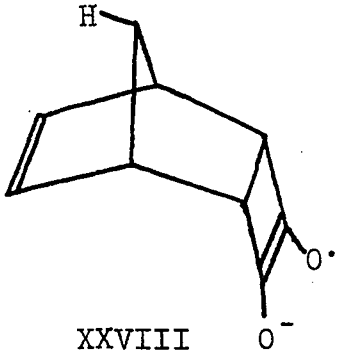
In the examples discussed so far, the γ-hydrogen in the chair form of the seven-membered ring has had hfsc's ranging from 0.32 G in V to 1.12 G in XX. Other semidiones have been made where the γ-hydrogen hfsc has been much larger: 1.98 G in XXVI (15), 2.60 G in XXVII (12), and 2.70 G in XXVIII (14). The β-hydrogens of the chair form have shown different behavior. When the β-hydrogen is a methylene hydrogen and has a <u>trans</u>-coplanar (zig-zag) arrangement of bonds to the π-system, the hfsc's have been in a fairly constant range, 1.8-2.8 G. For example, the hfsc in the parent system, I-IV, have been 1.85-2.15 G; in XVIII, 2.26 G; in XIX, 2.26 G; in XX, 2.75 G; and in XXVII, 2.34 G.



XXVI

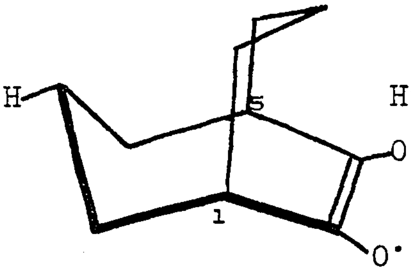


XXVII

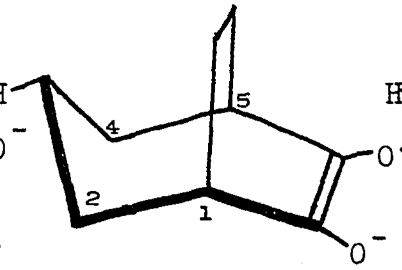


XXVIII

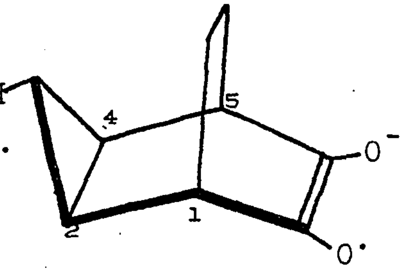
Our attentions were first turned to the behavior of the γ-hydrogen. Considering the series XVIII to XX to XXVI, a possible trend can be visualized. In going from XVIII to XX, the carbons in the zig-zag arrangement (bold line) have



XVIII



XX

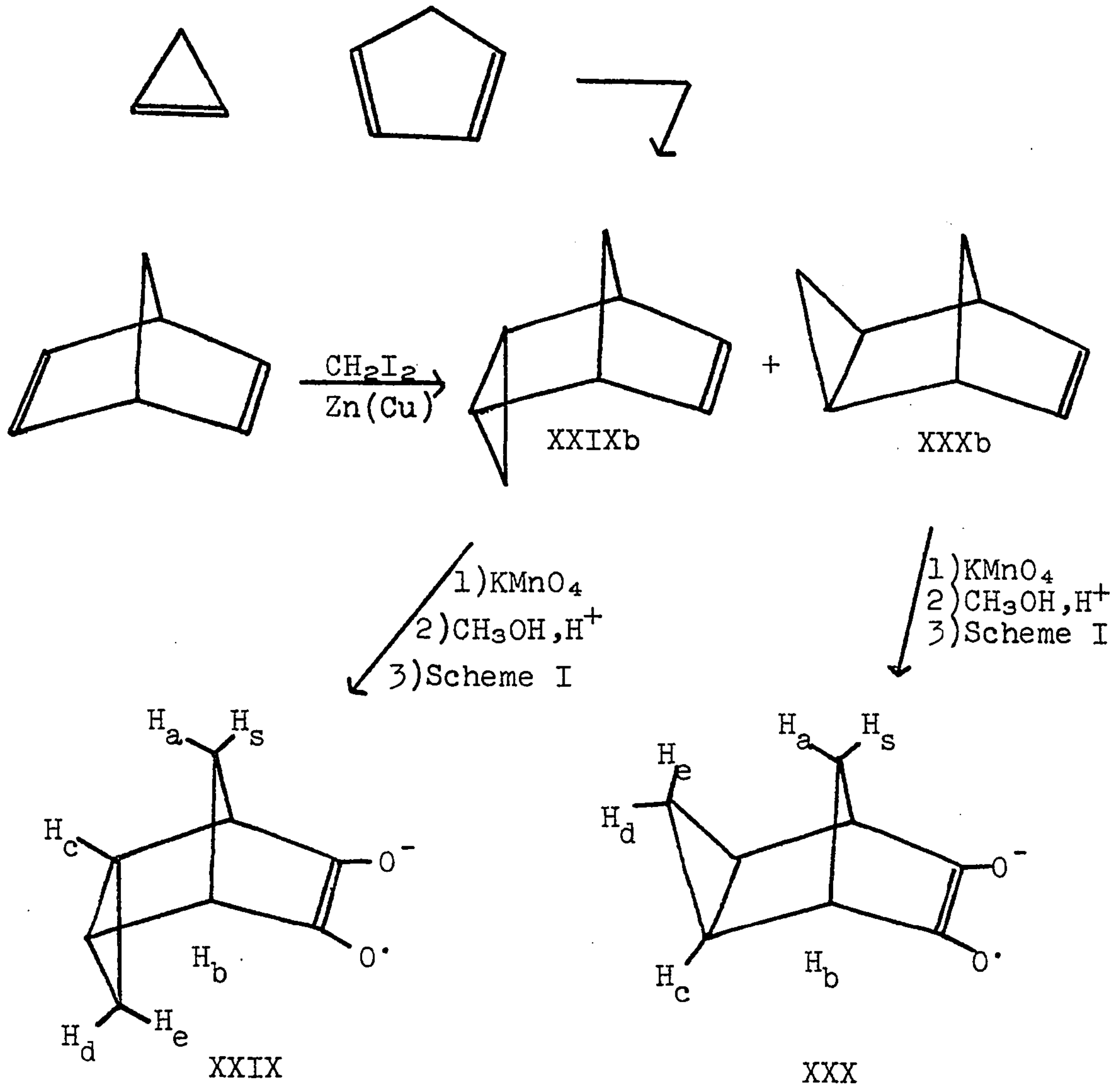


XXVI

been brought closer to being coplanar, mainly by the decrease in the C_1-C_5 distance, caused by decreasing the number of bridging carbons from three to two. Associated with this change in geometry is an increase in the γ-hfsc from 0.7 to 1.12 G. The coplanarity becomes even better in XXVI, where the C_2-C_4 distance has been lowered and the hfsc increases to 1.98 G. If this is a true trend, another increase in the γ-hfsc would be expected if the C_1-C_5 distance in XXVI was again decreased, for example, by replacing the ethano bridge by a methano bridge.

In reference to the synthesis of this compound, it has been reported that the Simmons-Smith reaction between norbornadiene and methylene iodide gives only an exo addition product (48). When this reaction was run (Scheme X) two products, XXIXb and XXXb, were obtained in the ratio of 1:3 respectively. The Diels-Alder reaction of cyclopentadiene and cyclopropene is reported (49) to give only endo-tricyclo-[3.2.1.$0^{2,4}$]oct-6-ene (XXIXb). Comparison of this product to the two products of the Simmons-Smith reaction establishes the

Scheme X



a^H =7.78 (1H) H_a
1.37 (1H) H_s
0.47 (1H) H_d or H_e
0.15 (1H) H_e or H_d
2.88 (2H) H_b
0.34 (2H) H_c

a^H=7.61 (1H) H_a
3.45 (1H) H_d
1.05 (1H) H_s
0.20 (1H) H_e
0.98 (2H) H_b
0.40 (2H) H_c

minor product as being the endo-addition product, and hence the other olefin (XXXb) must be the exo addition product. Utilizing the Schemes already discussed, semidiones XXIX and XXX were generated (Figures 26 and 27). The assignments of splitting constants are shown and were confirmed by comparison with the values of bicyclo[2.2.1]heptane-2,3-semidiones (15).

The largest splittings (7.78 and 7.61 G) in each semidione are assigned to the 8-anti protons, and the 1.37 G (in XXIX) and 1.05 G (in XXX) splittings are due to the 8-syn protons. In both cases, these values are larger than the corresponding hfsc of bicyclo[2.2.1]heptane-2,3-semidione (15). This enhancement parallels that seen in the benzobicyclo[2.2.1]heptane-2,3-semidione system (15). One very startling fact about these two systems is the great difference between the hfsc of H_b. With an endo-cyclopropane ring its value is slightly enhanced (2.88 vs. 2.49 G) over the parent system. However, with an exo-cyclopropane ring, the hfsc has greatly decreased until it is only 0.98 G. Just why this happens is unknown, but it presumably involves a change in the molecular orbitals rather than a geometrical change in this part of the molecule (this will be discussed in more detail in the next section). The most noteworthy fact about XXX is that the γ-hfsc, as predicted, has increased to 3.45 G, larger than any previous γ-splitting.

We now sought to make a molecule in which the γ-hfsc

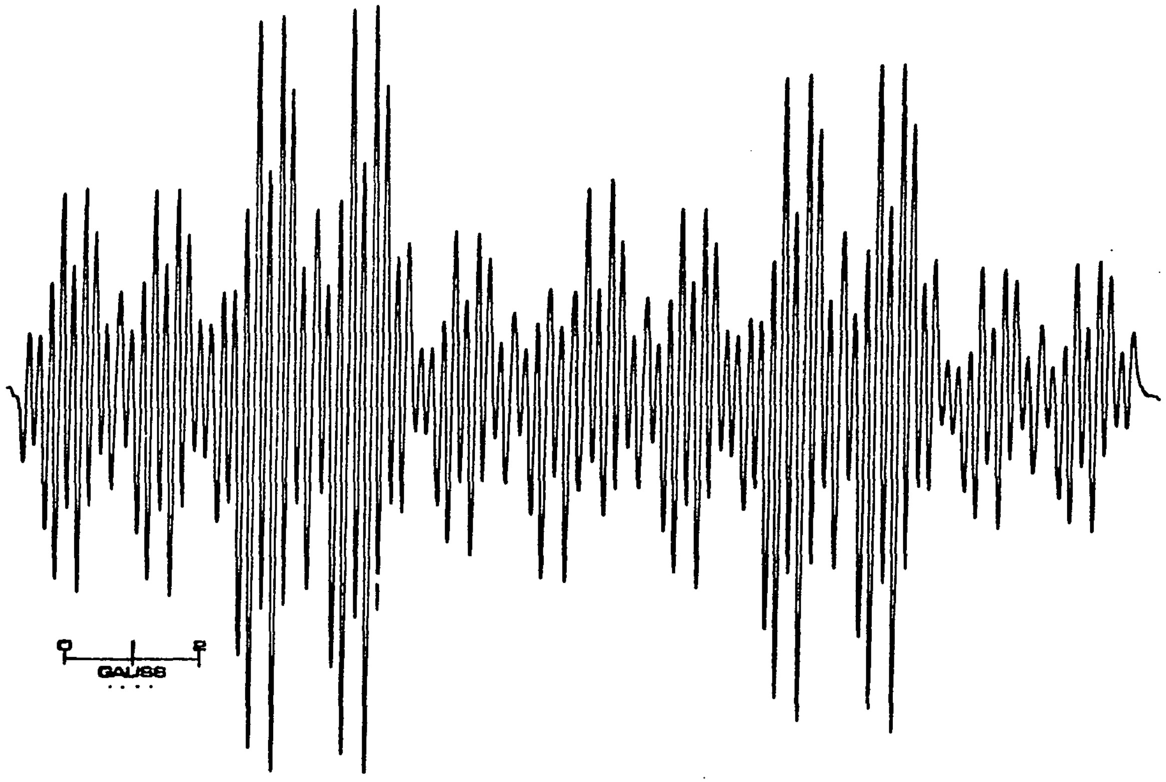


Figure 26. The first derivative esr spectrum of endo-tricyclo[3.2.1.$0^{2,4}$]-octane-6,7-semidione (XXIX) in DMSO.

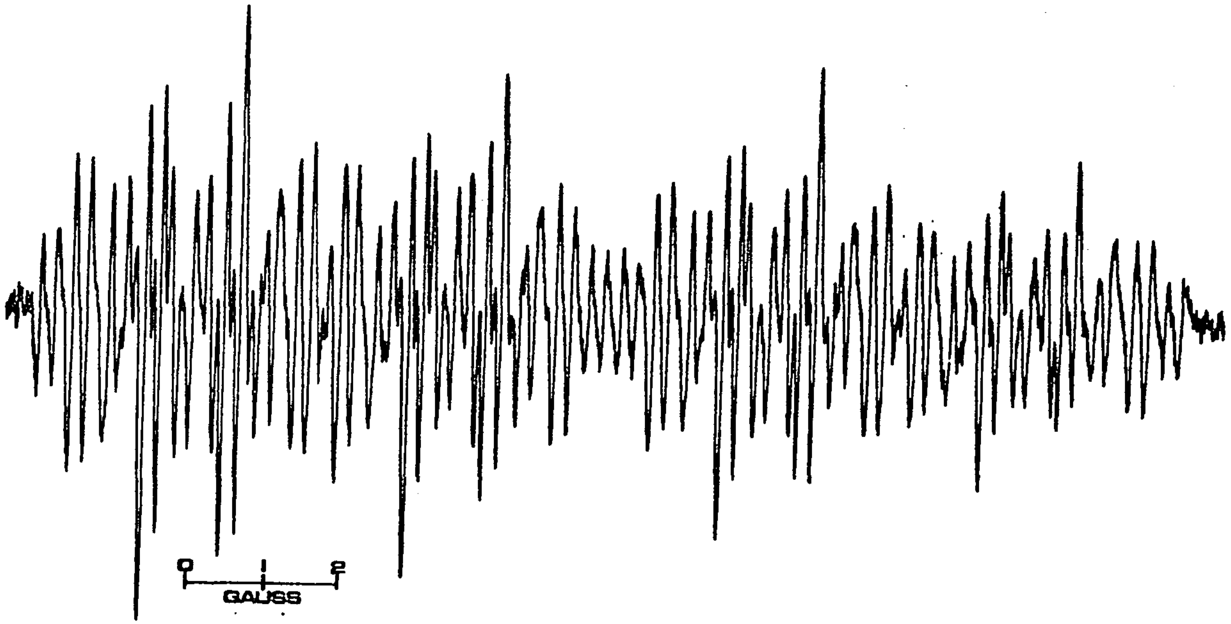
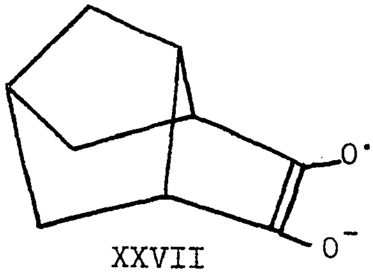


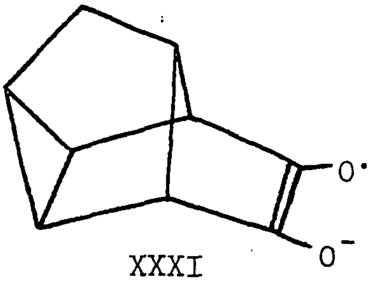
Figure 27. The first derivative esr spectrum of *exo*-tricyclo[3.2.1.0^{2,4}]octane-6,7-semidione (XXX) in DMSO.

would become even larger. Examining the relationship between XX, with a γ-hfsc of 1.12 G, and XXVII, with a γ-hfsc of 2.60 G, the change in the hfsc seemed larger than would be expected by the zig-zag carbons simply becoming more coplanar. An increase in the γ-hfsc by a factor of 2.3 occurred here whereas in going from XXVI to XXX, the increase was by a factor of 1.7, in going from XX to XXVI the factor was 1.8, and in going from XVIII to XX the factor was 1.6. In considering the structures of XX and XXVII, not one but two geometrical changes have been made. In addition to becoming more coplanar, the bond angles made by the zig-zag carbons have decreased, i.e. the zig-zag has become, so to speak, "sharper."

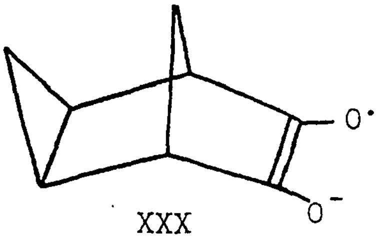
To ascertain if this second change was having any real effect on the γ-hfsc, semidione XXXI was prepared. If the



XXVII



XXXI



XXX

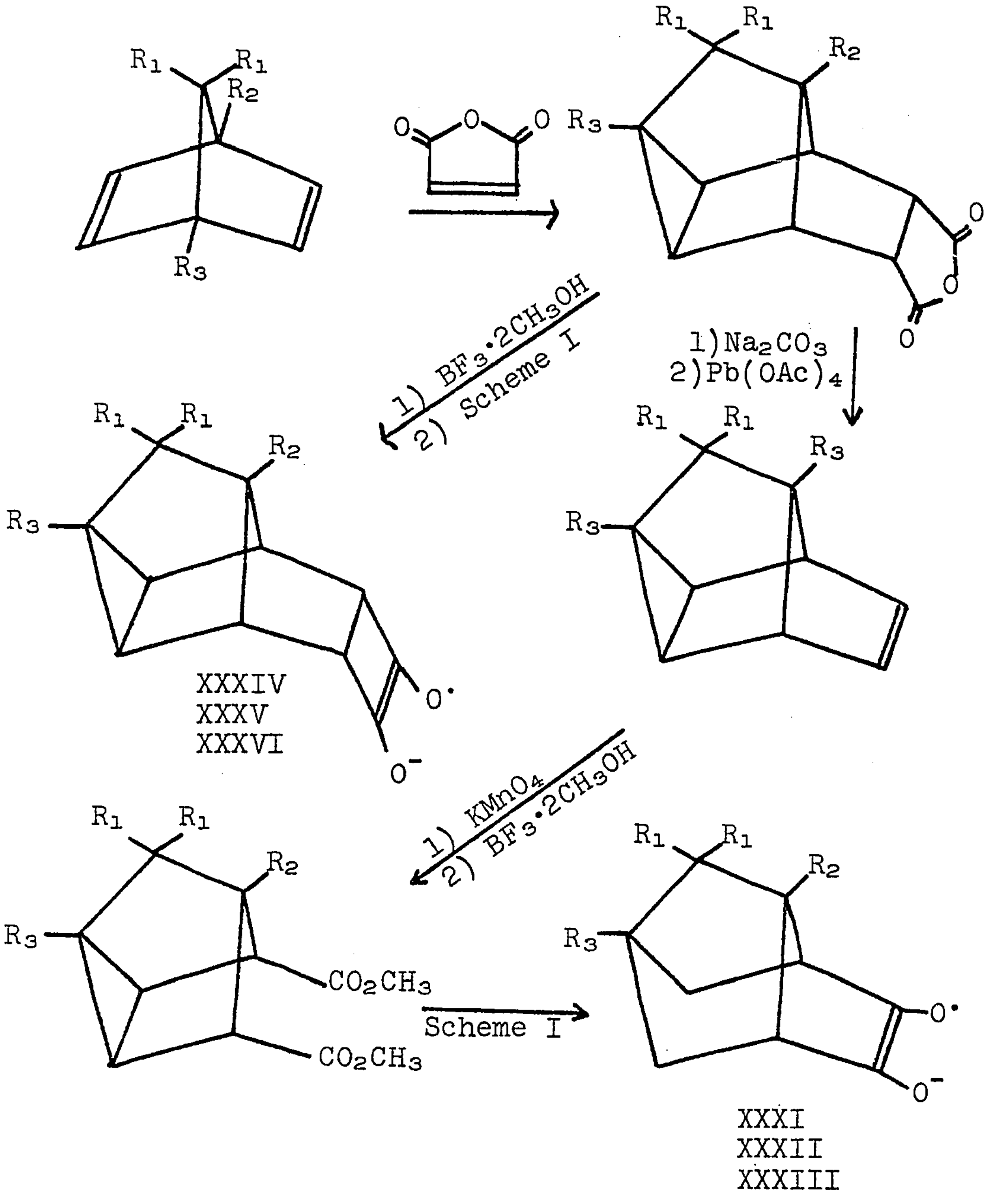
splitting depended only on coplanarity, the γ-hfsc of XXXI would be about the same as that of XXX. This would represent an increase over that of XXVII by a factor of only 1.3. If both coplanarity and the bond angles were important, the γ-hfsc of XXXI would be larger than that of XXX and would be larger than that of XXVII, by a factor of 1.6-1.8, based on our other models.

The syntheses of XXXI and the trimethyl derivatives XXXII and XXXIII are shown in Scheme XI. This route also allowed the preparation of semidiones XXXIV, XXXV, and XXXVI, which definitely establish the assignment of splitting of the γ-hfsc in the seven-membered ring chair form. The spectra of these semidiones are shown in Figures 28 to 33 and their analyses and assignments are in Charts V and VI.

The most striking feature in the spectrum of XXXI, Figure 28, is the large doublet splitting of 4.81 G. This hfsc is larger than the γ-hfsc in XXVII by the predicted factor of 1.8, and since it is also larger than the γ-hfsc of XXX, it confirms the hypothesis that the magnitude of this splitting depends not only on the coplanarity of the zig-zag system, but also on the bond angles between these carbons, namely, the smaller the angles, the larger the splitting constant.

The synthetic route (Scheme XI) also gave the two trimethyl derivatives of this system. A definite assignment of the methyl positions in these isomers, comes from the nmr spectra of the two tricyclic isomers. In the parent system, the C_4 proton is centered at δ 2.58 ppm and the three cyclopropyl protons are in the range of 1.6-1.15 ppm. The one trimethyl isomer, which was obtained pure, showed three protons in the range of 1.65-1.0 ppm. These must be the three cyclopropyl protons and hence the isomer is the 4,7,7-tri-

Scheme XI



XXXII, XXXV $R_1=R_2=CH_3$, $R_3=H$

XXXIII, XXXVI $R_1=R_3=CH_3$, $R_2=H$

XXXI, XXXIV $R_1=R_2=R_3=H$

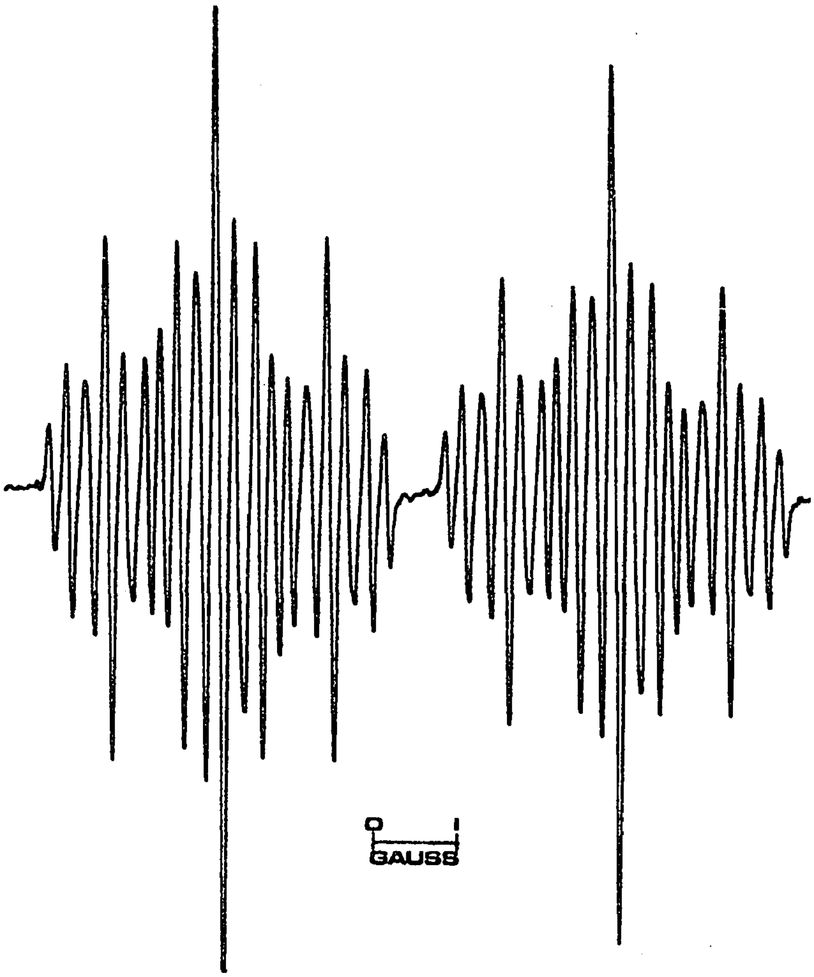


Figure 28. The first derivative esr spectrum of tetracyclo$[4.3.0.0^{2,4}.0^{3,7}]$nonane-8,9-semidione (XXXI) in DMSO.

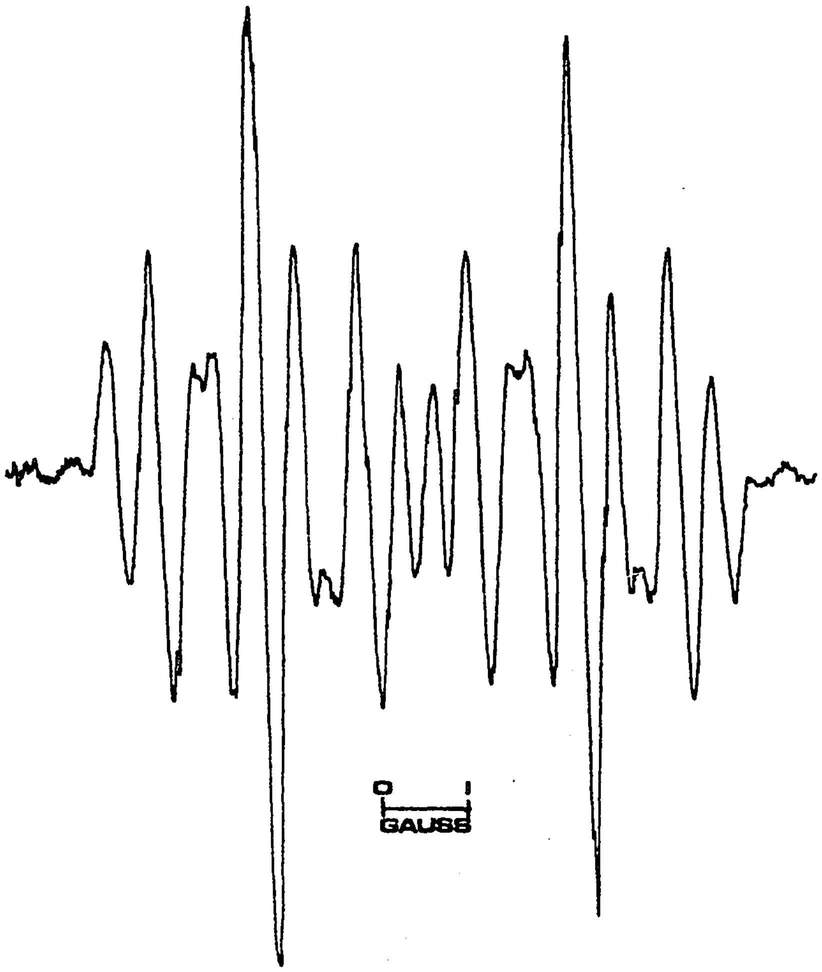


Figure 29. The first derivative esr spectrum of 5,5,6-trimethyltetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]nonane-8,9-semidione (XXXII) in DMSO.

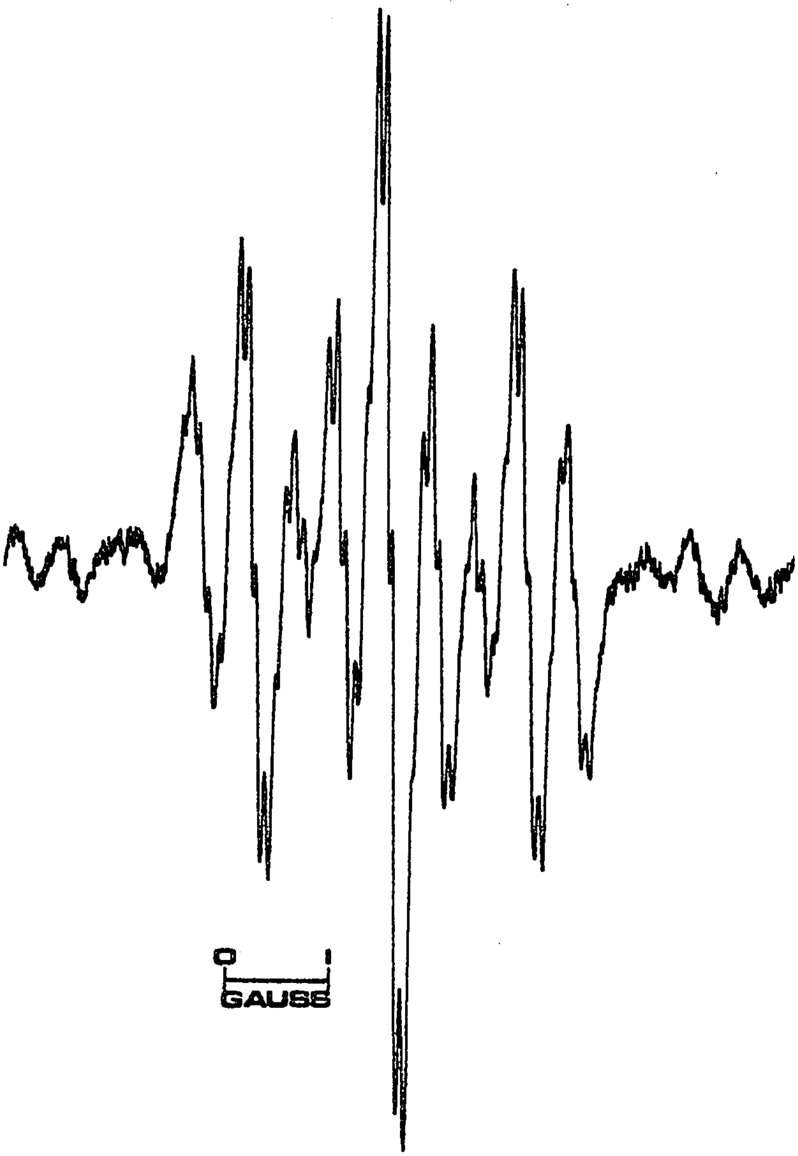


Figure 30. The first derivative esr spectrum of 4,5,5-trimethyltetracyclo[$4.3.0.0^{2,4}.0^{3,7}$]nonane-8,9-semidione (XXXIII) in DMSO.

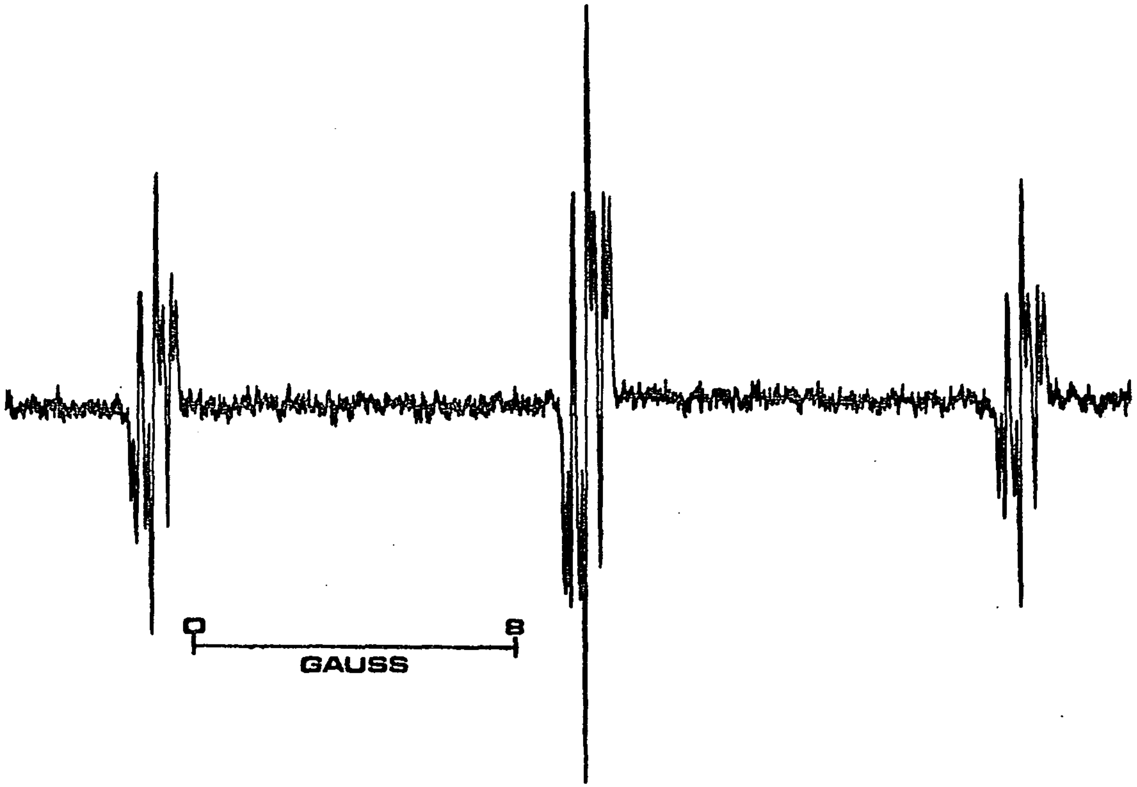


Figure 31. The first derivative esr spectrum of pentacyclo[5.4.0.0^{2,5}.0^{8,10}.0^{9,11}]undecane-3,4-semidione (XXXIV) in DMSO.

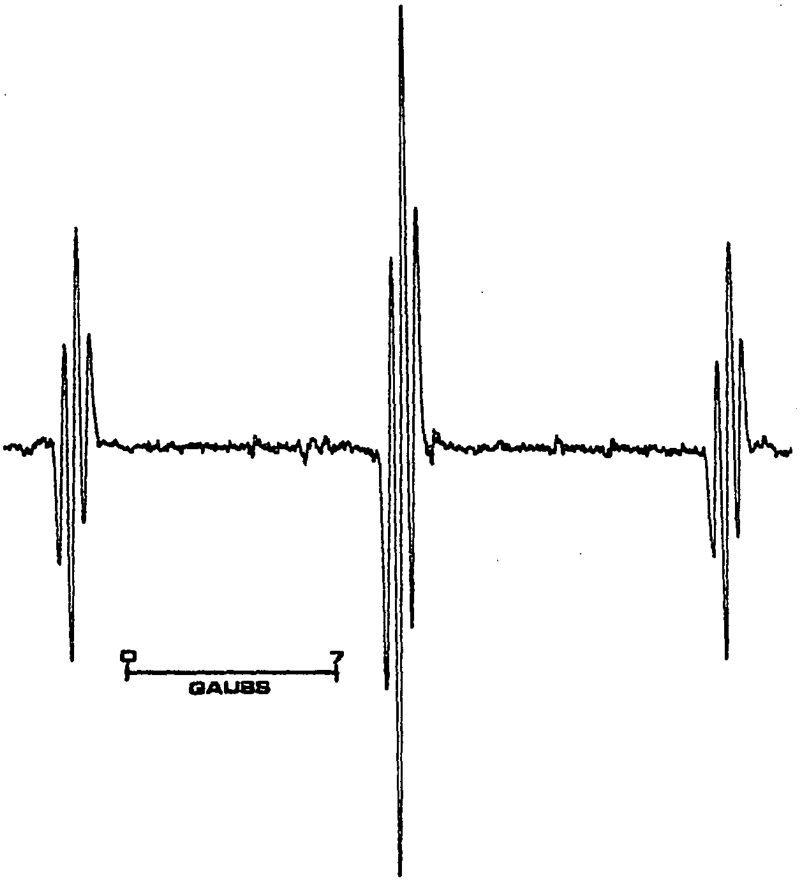


Figure 32. The first derivative esr spectrum of 7,8,8-trimethylpentacyclo[5.4.0.$0^{2,5}$.$0^{6,10}$.$0^{9,11}$]undecane-3,4-semidione (XXXV) in DMSO.

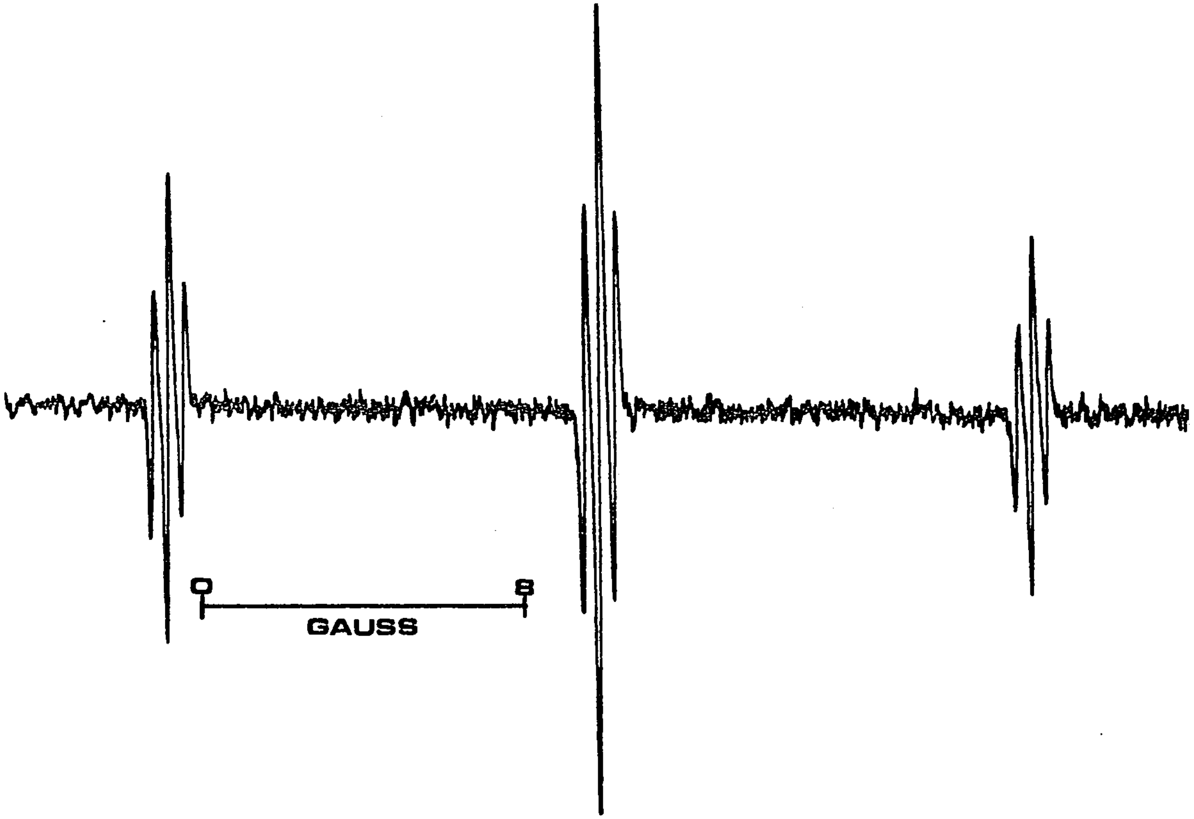
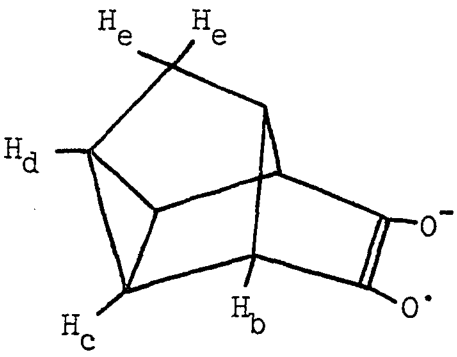


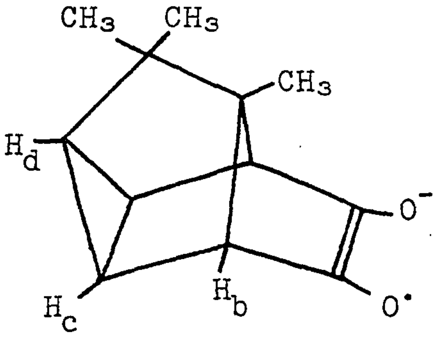
Figure 33. The first derivative esr spectrum of 8,8,9-trimethylpentacyclo-[$5.4.0.0^{2,5}.0^{3,10}.0^{9,11}$]undecane-3,4-semidione (XXXVI) in DMSO.

Chart V



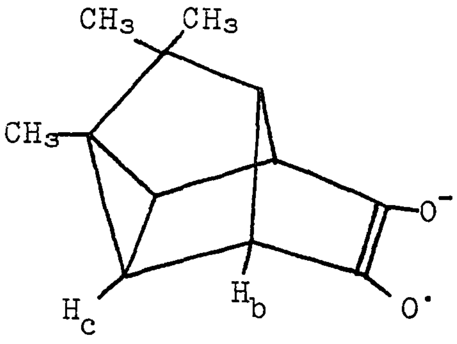
XXXI

a^H=4.81 (1H) H_d
1.33 (2H) H_b
0.48 (2H) H_c
0.21 (2H) H_e



XXXII

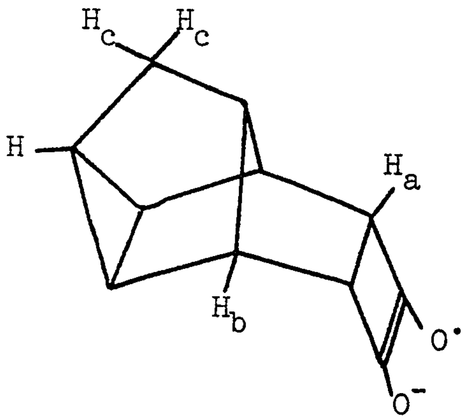
a^H=3.74 (1H) H_d
1.20 (2H) H_b
0.50 (2H) H_c
0.07 (≥3H) CH_3's



XXXIII

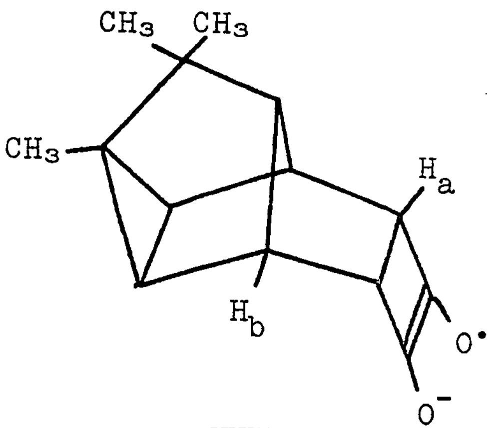
a^H=1.29 (2H) H_b
0.46 (2H) H_c
0.09 (≥3H) CH_3's

Chart VI



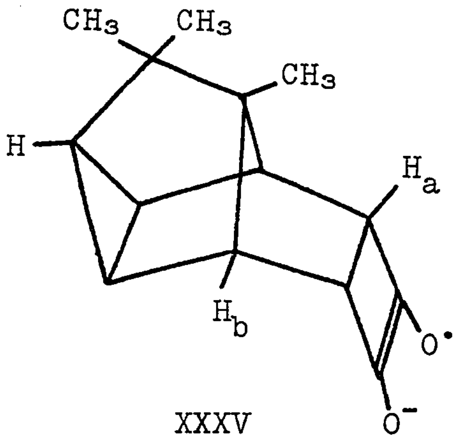
XXXIV

a^H=10.8 (2H) H_a
0.39 (2H) H_b
0.16 (2H) H_c



XXXVI

a^H=10.7 (2H) H_a
0.37 (2H) H_b



XXXV

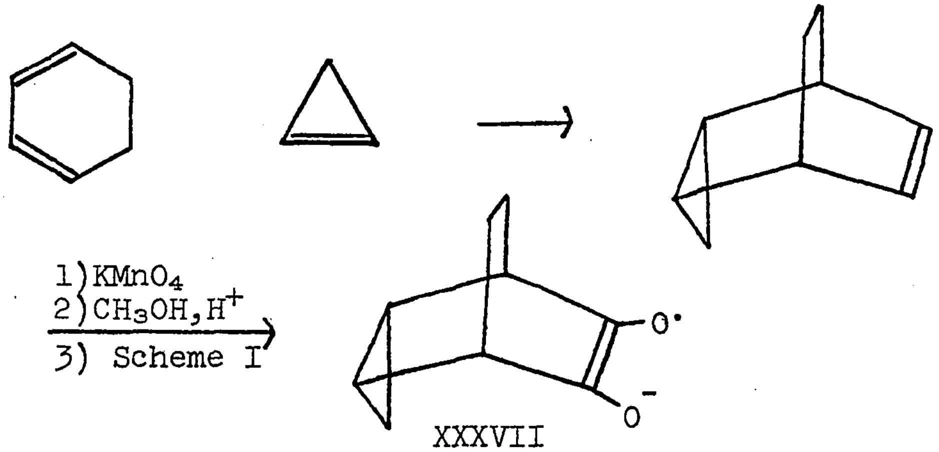
a^H=10.9 (2H) H_a
0.40 (2H) H_b

methyl derivative. The other isomer obtained from the mixture showed two protons about 1.38 ppm and another proton at 2.18 ppm. The two higher field protons are the cyclopropyl protons and the other is the C_4 proton which has been shifted 0.4 ppm upfield (compared to the unsubstituted system) by shielding due to the 7,7-dimethyls. This isomer must then be the 1,7,7-trimethyl derivative. With this assignment being definite, the assignment of structure to all the other previous isomers in the synthetic route is now complete.

The spectra of XXX, XXXI, XXXII, and XXXIII allow the complete assignment of all hfsc in this system. The large triplet splitting, 0.98 G in XXX and 1.20-1.33 G in XXXI through XXXIII, is assigned to the α-protons. The 0.40-0.50 triplet splittings in these four semidiones is assigned to the _endo_ cyclopropyl protons, H_c. The additional triplet splitting (0.20 G) in XXXI is due to the H_e protons. Both the splitting and these protons are absent in XXXII and XXXIII.

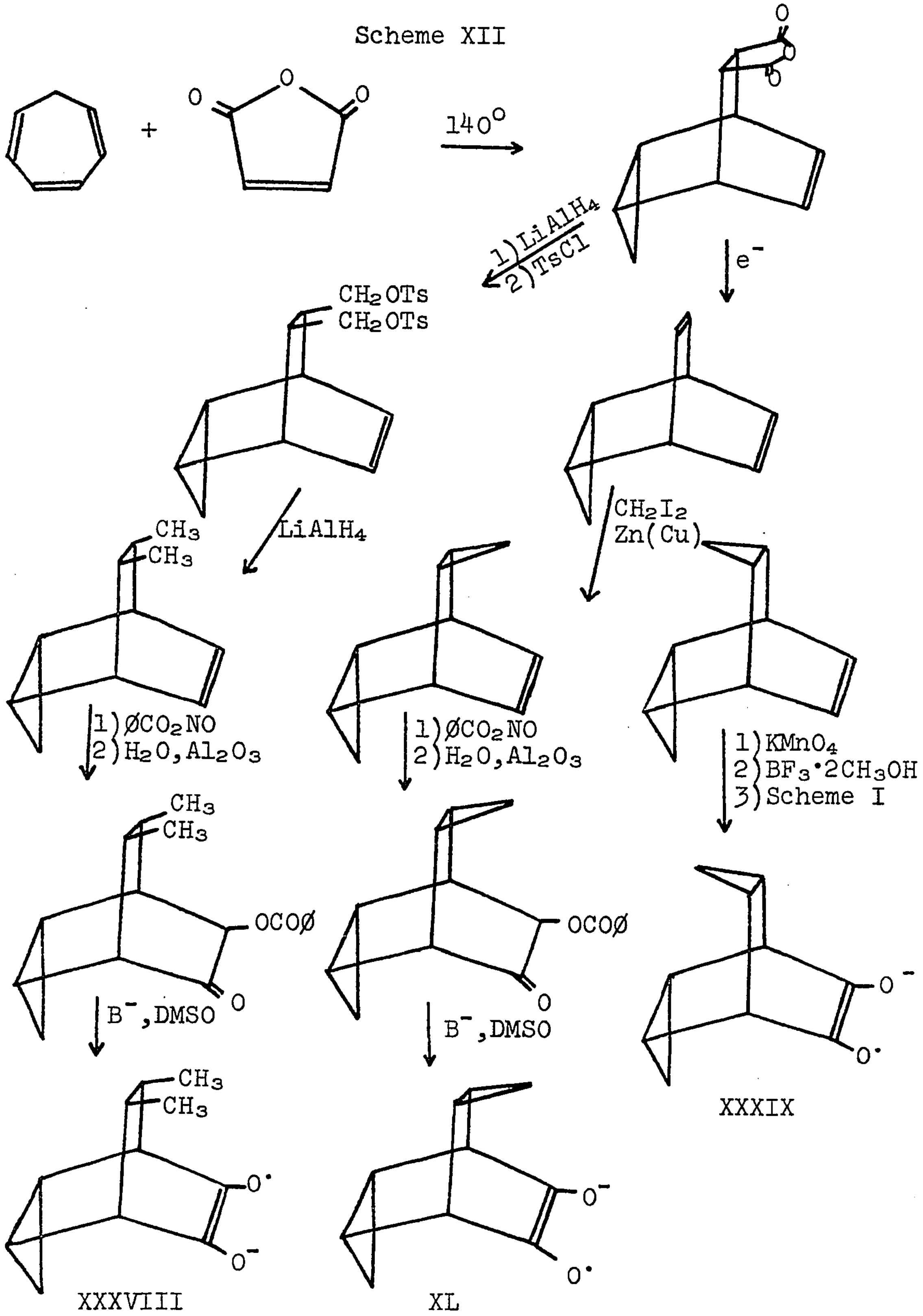
Semidione XXXIV was originally prepared by Whittle (14). Figure 31 shows that the fine structure, originally interpreted as a doublet of triplets, is a triplet of triplets. The absence of the smaller triplet in the spectra of XXXV and XXXVI assigns this splitting to protons H_c in XXXIV. The 0.4 G triplet is presumably due to protons H_b and the large triplet must be due to the α-protons H_a. In these three semidiones, the absence of any doublet splitting confirms the assignment of the doublet splitting in the chair form of the seven-membered ring to the γ-equatorial protons.

We next turned our attention toward the cyclopropyl derivatives of the bicyclo[2.2.2]octane-2,3-semidione system. As demonstrated in the bicyclo[2.2.1]heptane system by semidiones XXIX and XXX, the effect of an exo cyclopropyl group on the bridgehead proton is quite large, whereas the endo group had little effect. The preparation of semidiones XXXVII (as shown below) XXXVIII, XXXIX and XL (as shown in Scheme XII) would allow the examination of this effect on a bridgehead proton, which in the parent system is in the nodal plane of the π-system. The spectra are shown in Figures 34 through 39 and the analyses are shown in Chart VII. Semidione XXXVII showed splitting from eight of its ten hydrogens. The large triplet is assigned to protons H_a by analogy to the parent bicyclo[2.2.2]octane-2,3-semidione. The two doublets must be due to protons H_d and H_e. The two small triplets are assigned to protons H_c and H_s. This was confirmed by substitution of deuterium into the bridgehead position by exchanging



XXXVII

Scheme XII



+
140°
1) LiAlH4
2) TsCl
e⁻
CH2OTs
CH2OTs
LiAlH4
CH2I2
Zn(Cu)
CH3
CH3
1) ØCO2NO
2) H2O, Al2O3
1) ØCO2NO
2) H2O, Al2O3
1) KMnO4
2) BF3·2CH3OH
3) Scheme I
OCOØ
O
OCOØ
O
B⁻, DMSO
B⁻, DMSO
O⁻
O·
O·
O⁻
O⁻
O·
XXXVIII
XL
XXXIX

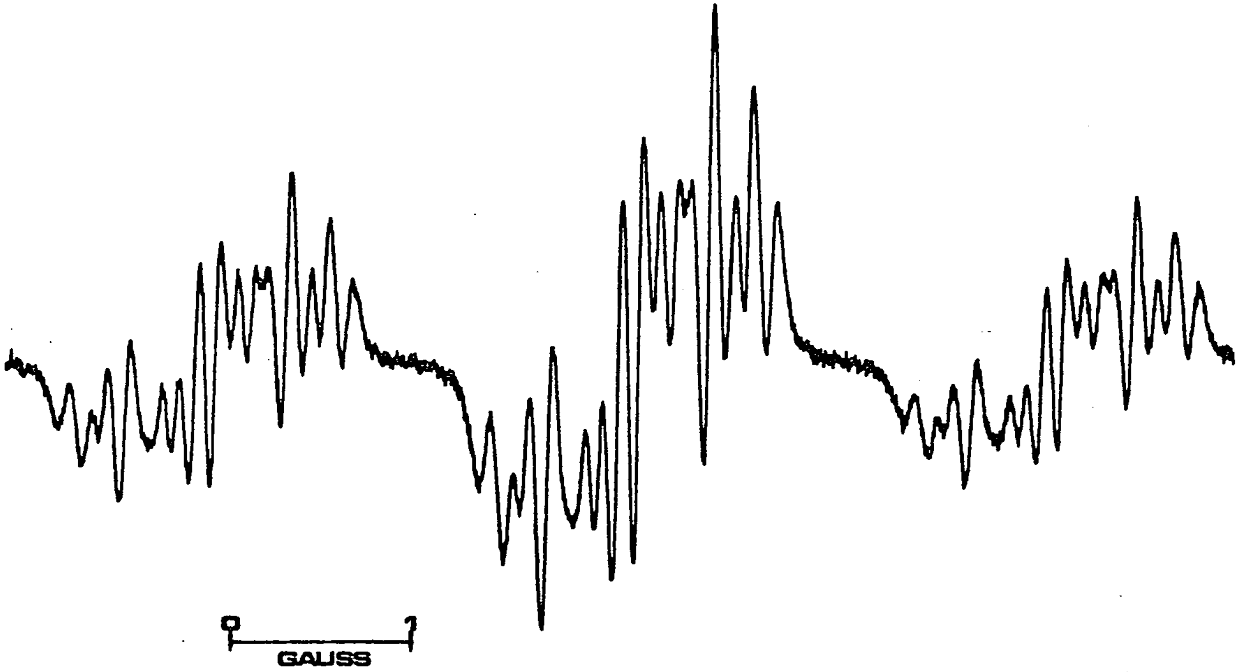


Figure 34. The first derivative esr spectrum of *endo*-tricyclo[3.2.2.$0^{2,4}$]-nonane-6,7-semidione (XXXVII) in DMSO.

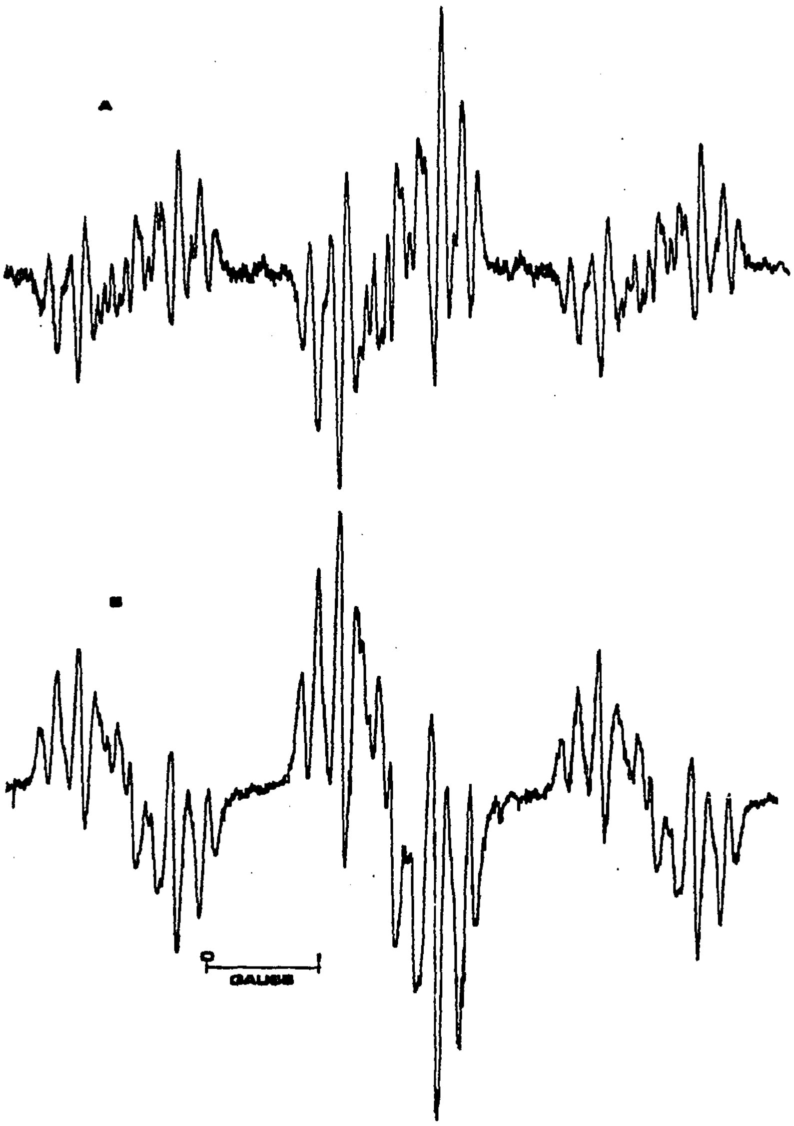


Figure 35. The first derivative esr spectra of endo-tricyclo[3.2.2.0^{2,4}]nonane-6,7-semidione (XXXVII) in DMSO; A) the diesters were equilibrated in basic methanol, B) the diesters were equilibrated and the α-protons exchanged in methanol-d.

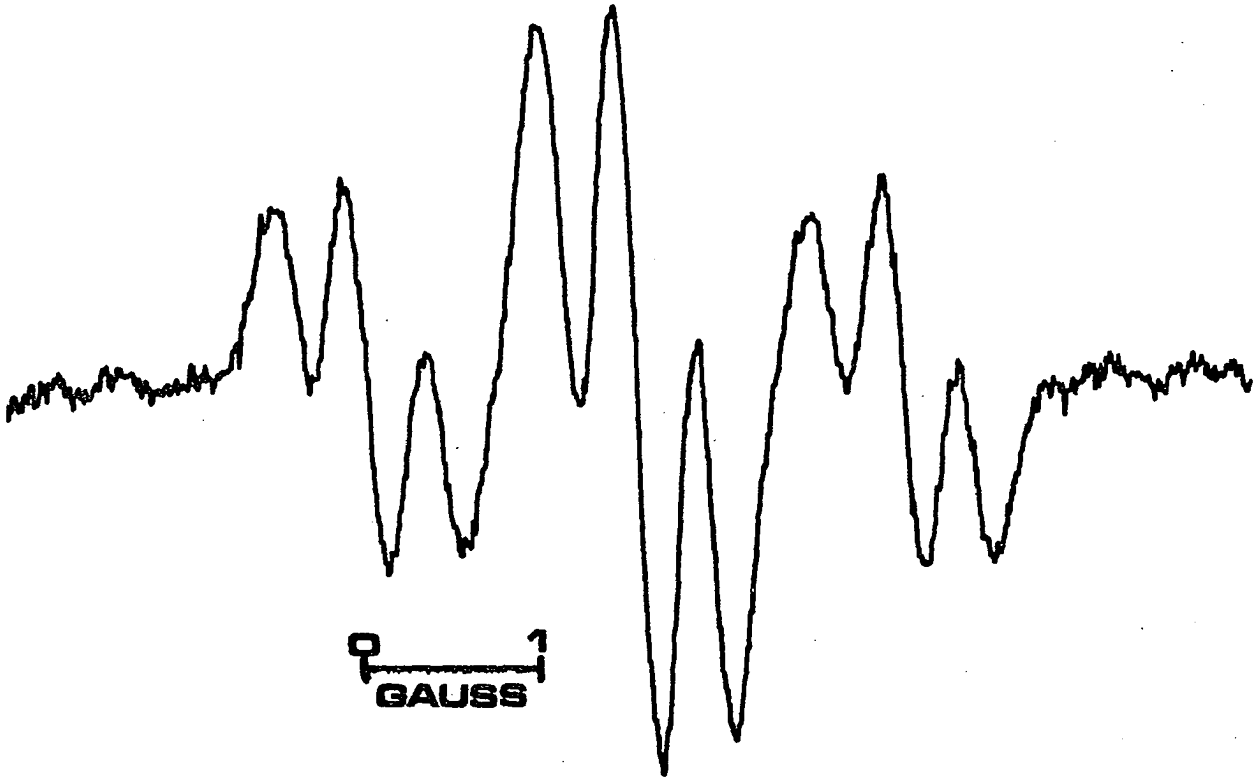


Figure 36. The first derivative esr spectrum of *endo*,*endo*-8,9-dimethyl-*endo*-tricyclo[3.2.2.$0^{2,4}$]nonane-6,7-*semidione* (XXXVIII) in DMSO.

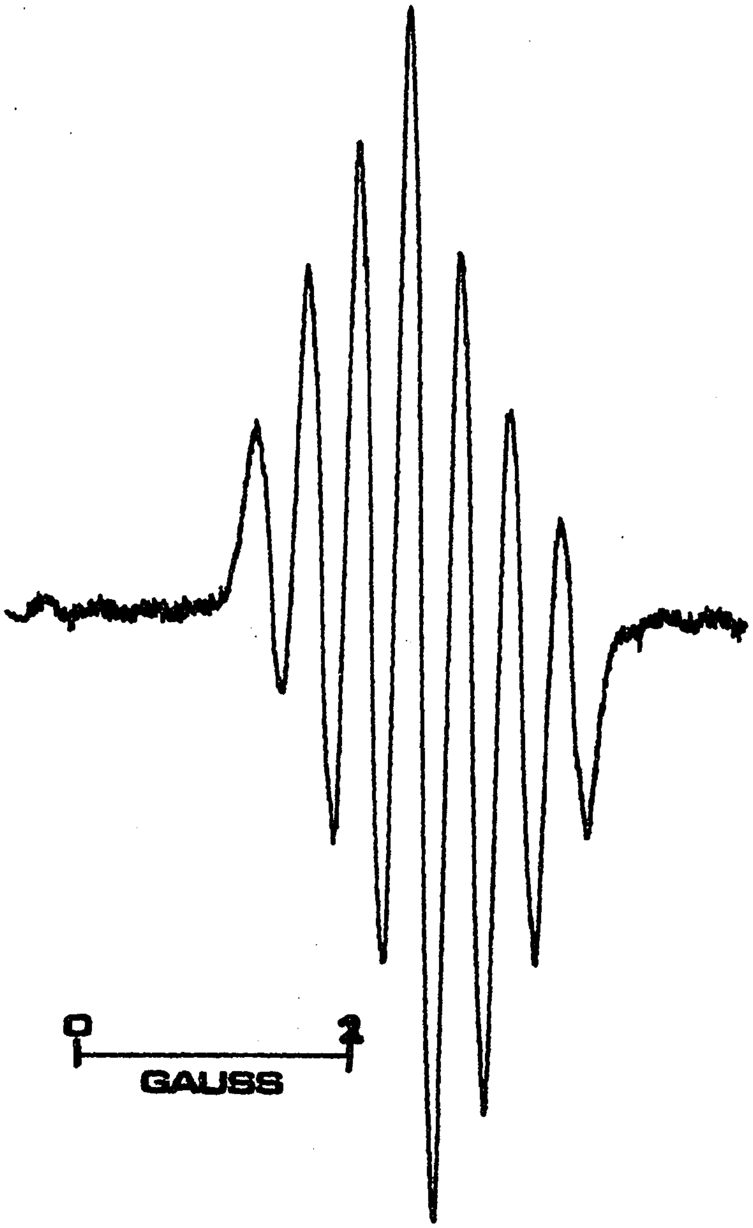


Figure 37. The first derivative esr spectrum of endo,endo-tetracyclo[3.2.2.$0^{2,4}$.$0^{6,8}$]decane-9,10-semidione (XL) in DMSO.

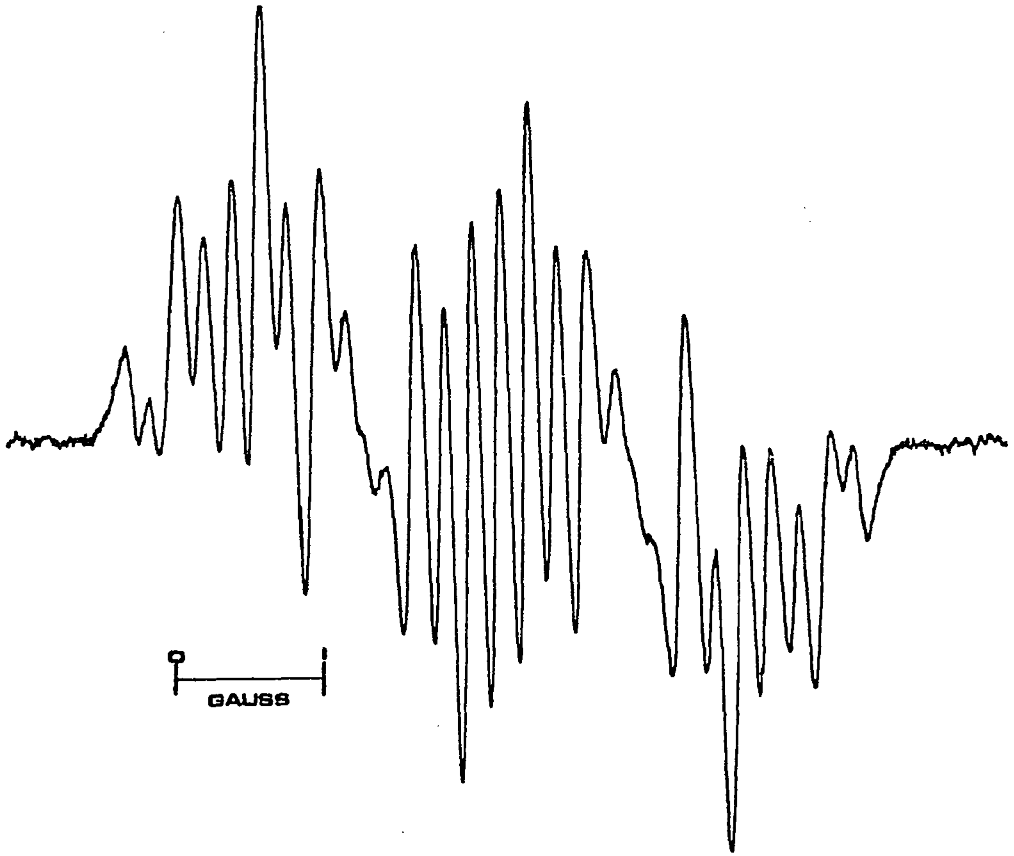


Figure 38. The first derivative esr spectrum of exo,endo-tetracyclo-$[3.2.2.0^{2,4}.0^{6,8}]$decane-9,10-semidione (XXXIX) in DMSO.

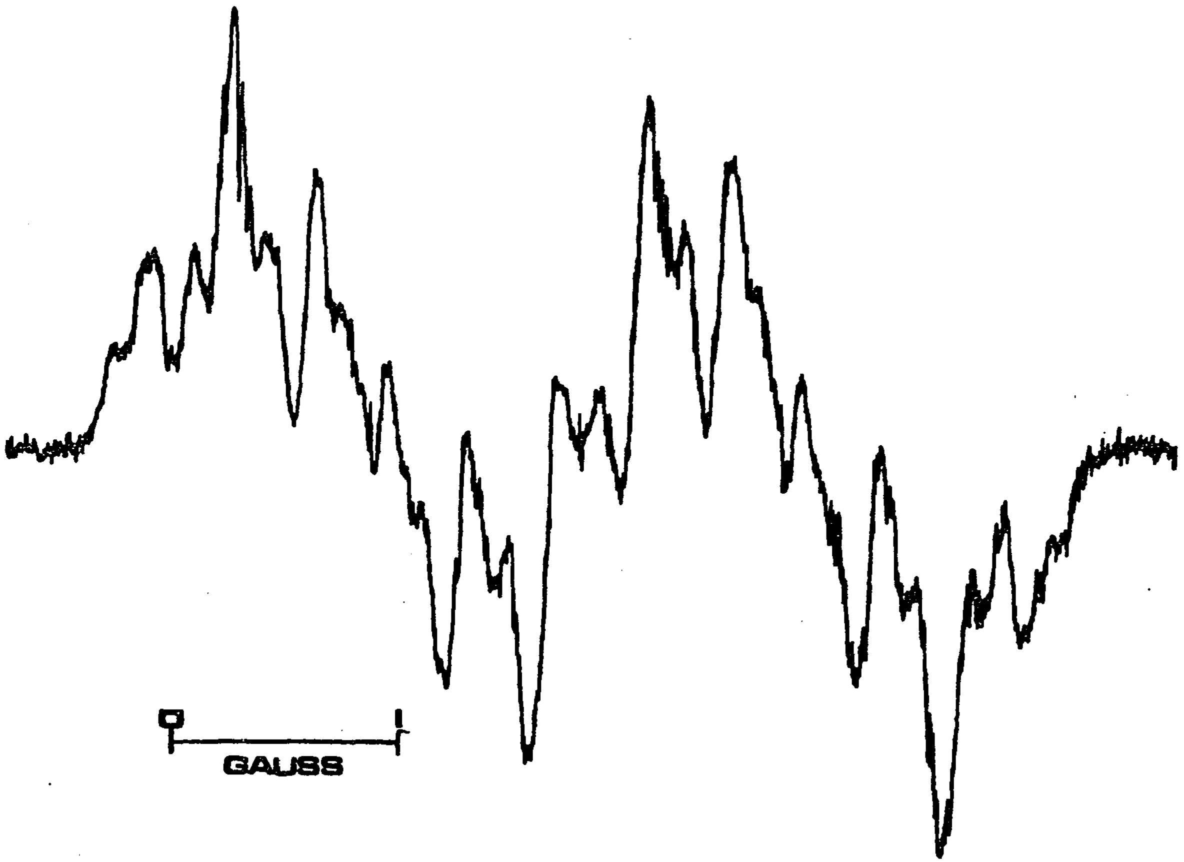
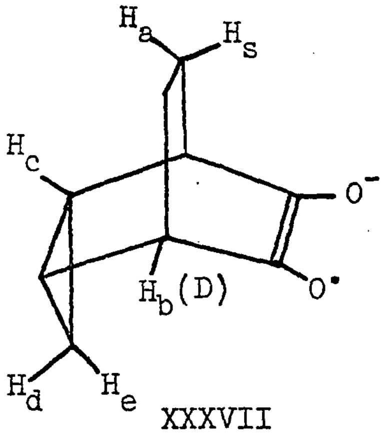
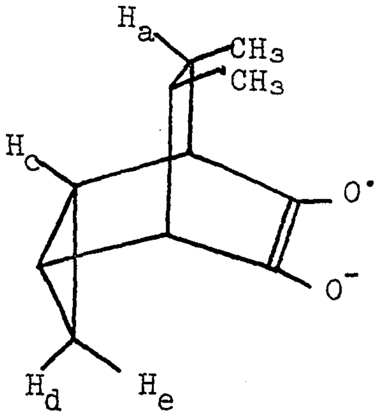


Figure 39. The first derivative esr spectrum of XXXIX in DMSO after the α-protons had been replaced with deuteriums.

Chart VII



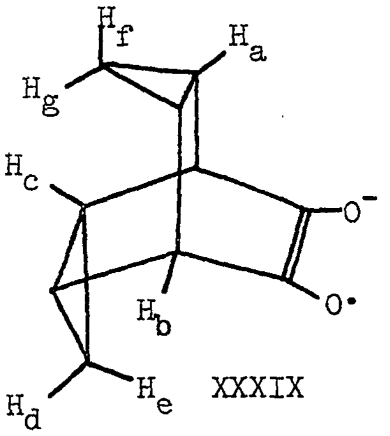
XXXVII



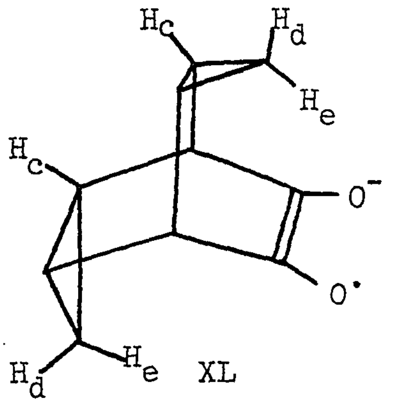
XXXVIII

a^H=2.32 (2H) H_a
0.21 (2H) H_s or H_c
0.13 (2H) H_c or H_s
0.51 (1H) H_d or H_e
0.39 (1H) H_e or H_d

a^H=1.52 (2H) H_a
0.44 (2H) H_d, H_e



XXXIX



XL

a^H=0.57 (2H) H_b
0.37 (2H) H_c or H_a
1.78 (1H) H_f
0.66 (1H) H_d or H_e
0.39 (1H) H_e or H_d
0.15 (1H) H_g

a^H=0.76 (2H) H_d or H_e
0.38 (2H) H_e or H_d
0.06 (4H) H_c

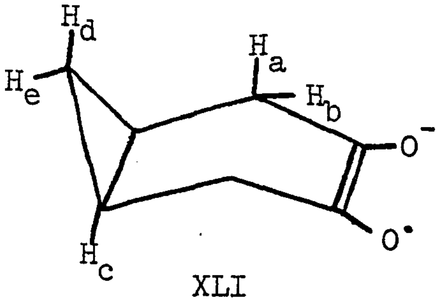
the α-hydrogens of the diester precursor. Although the spectrum of the deuterated material (Figure 35 B) appears to be greatly different from that of the undeuterated material (Figure 34) the analyses of the spectra give splitting constants within 0.02 G. Furthermore, when the diester was equilibrated in methanol, rather than methanol-d, the crude product gave Figure 35 A, essentially identical to 35 B. The change in the appearance of the spectra is attributed to the presence of impurities, mainly the trans diester, in the equilibrated material.

The corresponding olefins of XXXVIII and XL are both extremely resistant to oxidation. Neither are affected by potassium permanganate in refluxing acetone or water. Consequently another method of generation of the semidiones was sought. Benzoyl nitrite added readily to the hindered double bond, even at room temperature, and the adduct could be hydrolyzed by wet alumina to the benzoic acid esters of the α-hydroxy ketones. In situ hydrolysis of the esters with potassium t-butoxide in DMSO, generated the corresponding semidiones. Semidione XXXVIII had been generated previously by Holland (15) from the ketone, and thus the method is established as working. Although they are not resolved, fine splittings in the spectrum of XXXVIII are present as indicated by the broadness of the lines in the spectrum (Figure 36). Assignment of the large splittings was made by comparison to semidione XXXVII.

Semidione XL gave the spectrum shown in Figure 37. Two triplets of 0.76 and 0.38 G are present and these must be assigned to protons H_d and H_e. A smaller quintet splitting of 0.06 G is barely discernable and must be assigned to the 2V zig-zag protons H_c. This dramatic decrease in the hfsc of 2V protons, when they become cyclopropyl methine protons, had been previously noted in semidione XXIX, in the bicyclo-[2.2.1]heptane system.

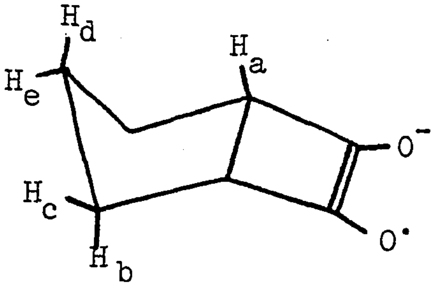
Semidione XXXIX was prepared to determine the effect of the cyclopropyl ring, which faces away from the π-system, on the bridgehead protons. The spectrum is shown in Figure 38. In Figure 39, the spectrum of XXXIX, after the bridgehead protons had been replaced with deuterium, is shown. As was the case with semidione XXX, the cyclopropane ring has had a large effect on the splittings of the bridgehead protons. In fact, the largest triplet splitting, 0.57 G, must be assigned to the bridgehead protons, as evidenced by the lack of this splitting in the deuterated molecule. As with XXX, this change is partly attributed to an effect on the molecular orbitals of the system rather than to a geometrical change. That such an effect, by a remote group in the molecule, on the hfsc of protons nearer to the π-system, does occur is indeed surprising. It is thus very gratifying that, to a certain extent, this effect is predicted by Extended Huckel calculations (see next section).

A few more semidiones remain which are pertinent to the discussion of these systems. The parent seven-membered ring systems, to which these polycyclic semidiones compare, are XLI (for XXIX to XXXIII, and XXXVII to XL), and XLII (for XXXIV to XXXVI). The syntheses of XLI and XLII are shown in Schemes XIII and XIV respectively, and their spectra in Figures 40 and 41 respectively. Although they both have been drawn in the chair conformation, the boat conformation is possible for XLI, and the probable conformation XLII is one which is intermediate between the chair and boat, namely one with the five-membered ring nearly planar.



XLI

a^H=13.3 (2H) H_a
6.00 (2H) H_b
0.22 (2H) H_c
0.50 (1H) H_d or H_e
0.09 (1H) H_e or H_d

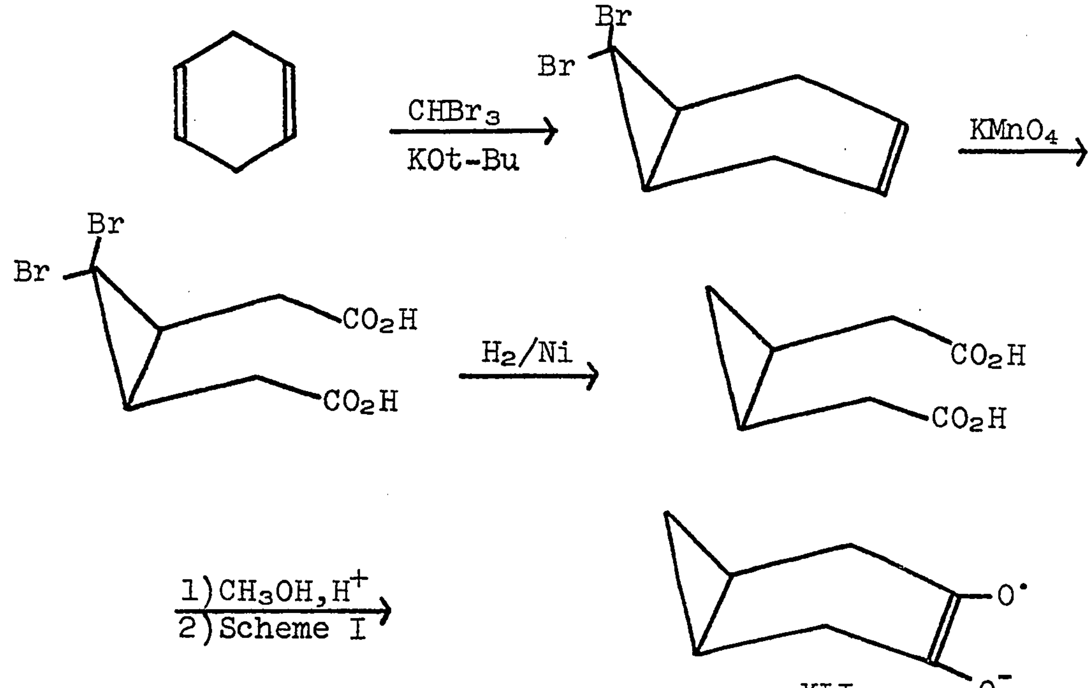


XLII

a^H=12.8 (2H) H_a
0.62 (2H) H_c, H_d or H_e
0.30 (1H) H_e or H_d
0.06 (2H) H_c

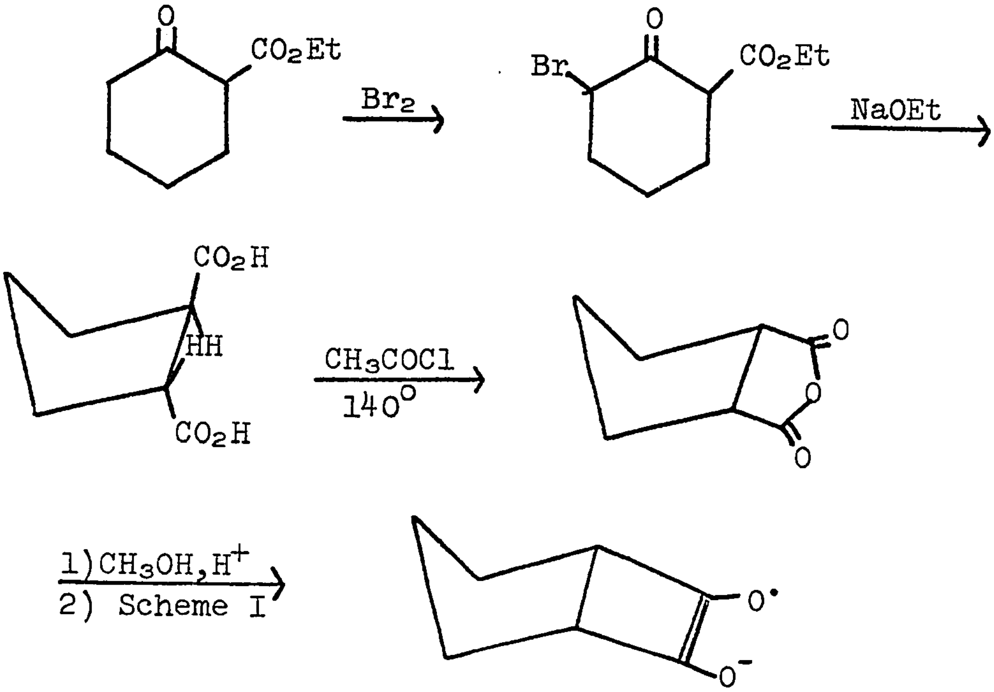
Semidione XLI displays two large triplets which are assigned to the α-hydrogens. The small triplet must then be due to the cyclopropyl methine hydrogens. The doublet hfsc of 0.50 G is unique in that it is too small, when compared to predicted values, for the chair conformation. Basing the prediction on cycloheptanesemidione, an increase by the factor

Scheme XIII



XLI

Scheme XIV



XLII

Figure 40. The first derivative esr spectrum of bicyclo[4.1.0]heptane-3,4-semidione (XLI) in DMSO.

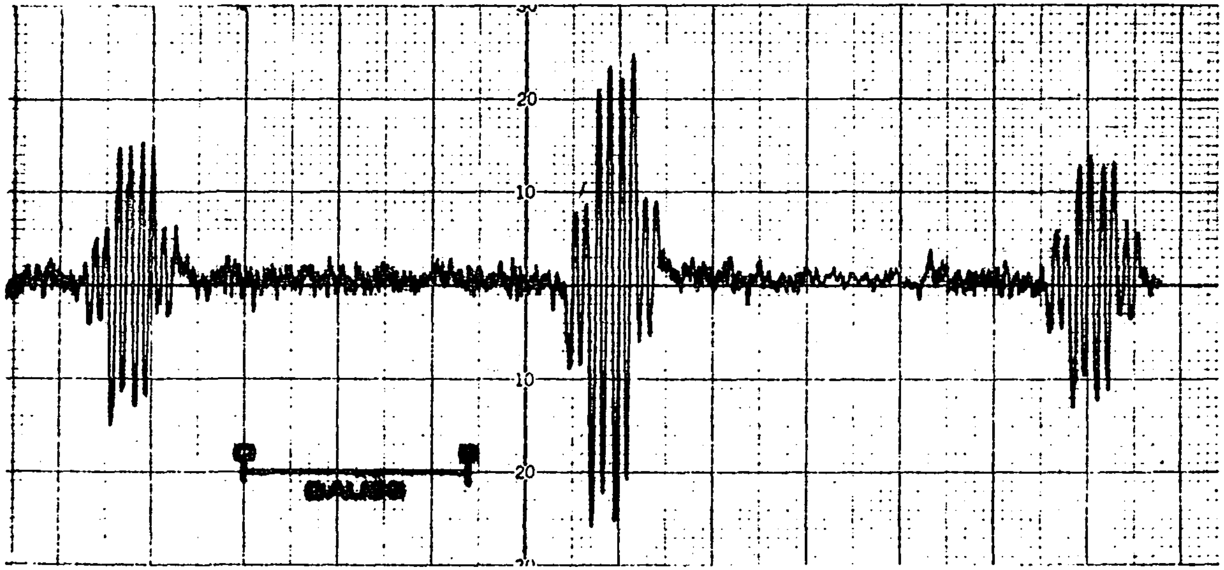
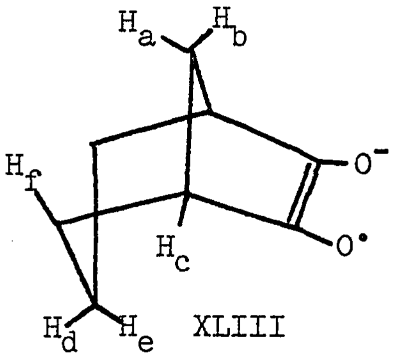


Figure 41. The first derivative esr spectrum of bicyclo[3.2.0]heptane-6,7-semidione (XLII) in DMSO.

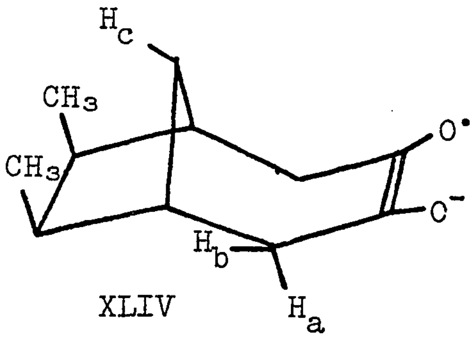
of ~1.7 would be expected, yielding a hfsc of ~0.92 G. If the prediction was instead based on going from XXVI to XLI, a decrease by a factor of 2.08 (compare XX to I), would give a predicted value of 0.95 G, agreeing well with the other predicted hfsc. In each case, the actual value of the hfsc is too small by a factor of almost 2. However, the hfsc of the γ-hydrogen is in the range of hfsc for boat conformations of the seven-membered ring.

The hfsc of γ-hydrogens for the boat form have been in the range of 0.45-0.76 G, for the semidiones already discussed. Two more semidiones were prepared in which the boat conformation of the seven-membered ring is the most likely one. These semidiones are XLIII and XLIV. XLIII had been



XLIII

a^H=5.58 (2H) H_c
4.00 (1H) H_a
1.09 (1H) H_b
0.51 (3H) H_f, H_d
0.20 (1H) H_e



XLIV

a^H=9.85 (2H) H_a
2.50 (2H) H_b
0.55 (1H) H_c

previously prepared by Chang (12) and the spectrum is shown in Figure 42. However, better resolution was obtained in this case, and a new analysis of the spectrum was necessary. The most likely conformation of XLIII is as shown with the seven-membered ring being in the boat conformation. The assignment of conformation is based on two points. First, the characteristic 2 G hfsc from the β-position of a chair is not present, and second, a doublet hfsc of the correct magnitude for the chair form, is not present. The γ-hfsc for a chair would be 1.9-2.0 G based on going from XX to XLIII or from XXX to XLIII. Semidione XLIV, whose spectrum is in Figure 43, is simply the dimethyl derivative of IX. An impurity in the spectrum adds additional lines to the center of the large triplet. The 0.55 G γ-hfsc again agrees with the structure of the seven-membered ring being a boat rather than a chair (see IX).

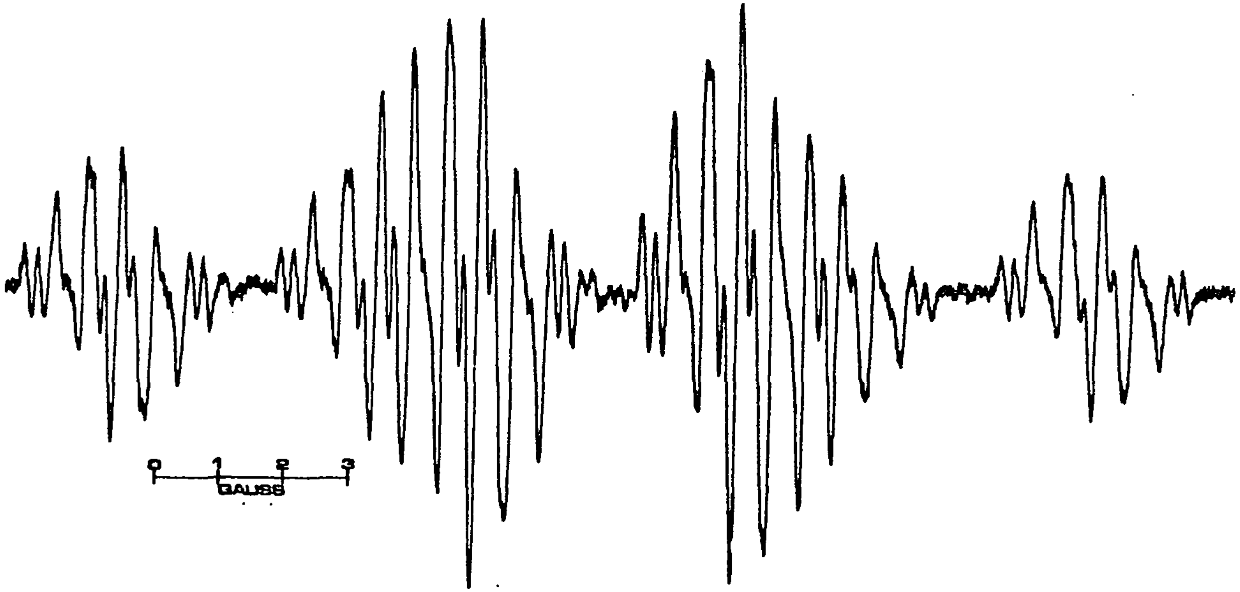


Figure 42. The first derivative esr spectrum of bicyclo[3.2.1]octane-6,7-semidione (XLIII) in DMSO.

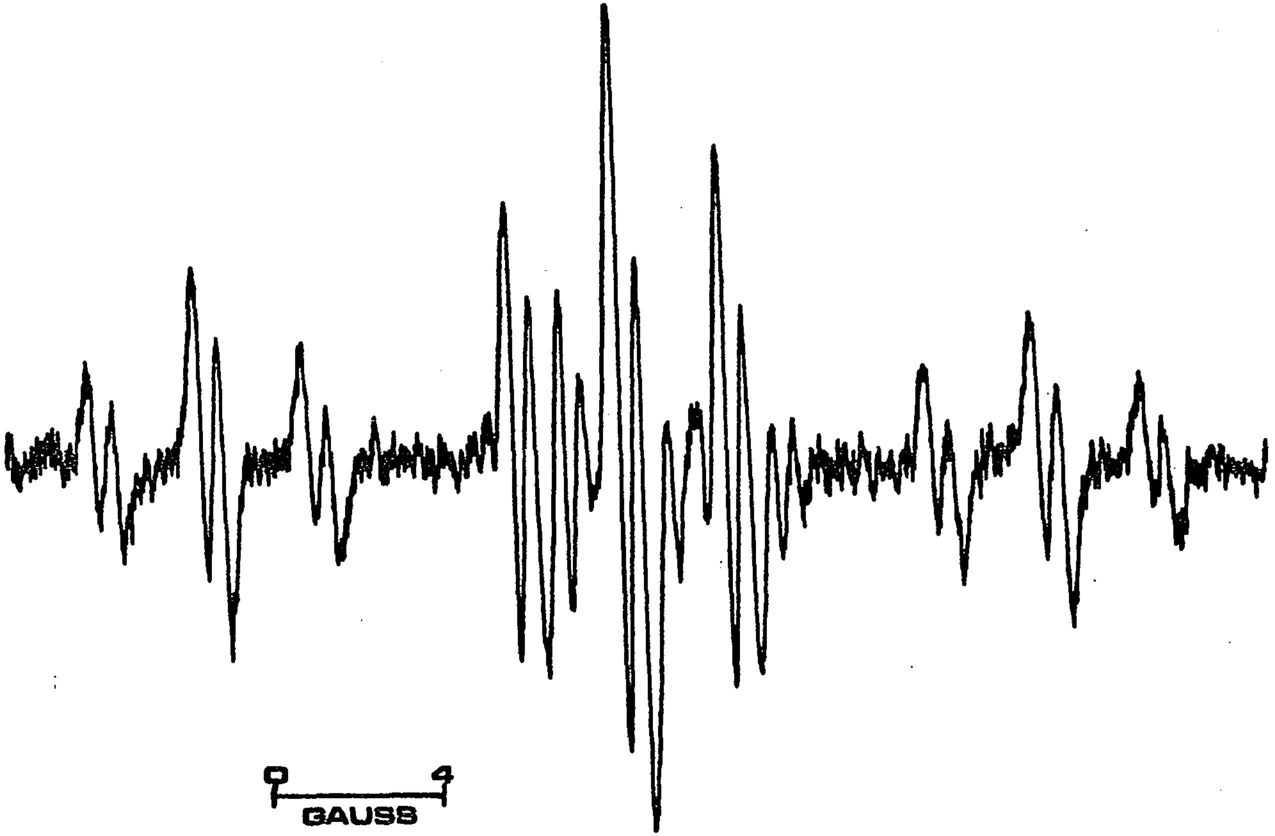


Figure 43. The first derivative esr spectrum of exo,exo-7,8-dimethylbicyclo[4.2.1]nonane-3,4-semidione (XLIV) in DMSO.

EXTENDED HUCKEL CALCULATIONS

Theory

The molecular orbitals, ψ_u, of the system are formed as linear combinations of the atomic orbitals, φ_{ui}, which are nor-

$$\psi_u = \sum_i c_{ui}\varphi_{ui} \qquad (1)$$

malized (50) according to equation 2, and are orthogonal to

$$\sum_i c_{ui}^2 + \sum_{i \neq j} c_{ui}c_{uj}S_{ij} = 1 \qquad (2)$$

the other orbitals on the same atom. The group overlap integrals are represented by S_{ij}. The overlap matrix is calculated by the method of Hoffmann and Lipscomb (51) using a basis set of Slater type orbitals (equation 3), where N is the normali-

$$(n,l,m,z) = Nr^{n-1}\exp(-zr)Y_l^m(\theta,\epsilon) \qquad (3)$$

zation factor, n, l, and m are quantum numbers, z is the orbital exponent, Y_l the spherical harmonic, and r, θ, and ϵ the respective polar coordinates. The orbital exponents used for the calculations were essentially those obtained by Cusachs (52) using the relation in equation 4, where values of $\langle r \rangle$ have

$$z = \frac{n + \frac{1}{2}}{\langle r \rangle} \qquad (4)$$

been calculated from the many-term SCF functions (53-56). While it is impossible to adequately reproduce all the properties of a SCF function with a Slater type orbital, it is still possible to represent one property accurately using a single Slater type orbital. In the case of overlap, Cusachs finds that the calculated orbital exponents using ⟨r⟩ do closely reproduce the overlap optimized values. These orbital exponents were not corrected for charge since when charge transfer does occur, the charged neighbor atoms exert an electrostatic potential which tend to cancel the charge transfer effects (52).

The diagonal elements of the Hamiltonian matrix, H_{ii}, or coulomb integrals, were calculated using equation 5, according

$$H_{ii} = H_{ii}^{\circ} - AQ_i - BQ_b^{*} \tag{5}$$

to the method of Cusachs (57), where H_{ii}° is the valence state ionization potential (VSIP), AQ_i is the charge transfer correction term, and BQ_b^{*} is the neighbor atom potential correction term. A and B are constants, different for different elements, Q_i is the net charge on atom i, and Q_b^{*} is the neighbor atom "effective charge" term. The calculations were permitted to run to charge self-consistency, usually to within 0.02 units.

To obtain convergence of the charges in the least number of iterations, a damping factor D had to be included. All changes in the net charges of the atoms and the neighbor atom "effective charge" term were damped using equations 6 and 7,

$$Q_i(\mathrm{I}) = \frac{DQ_i(\mathrm{I}) + Q_i(\mathrm{II})}{1 + D} \tag{6}$$

$$Q_b^*(I) = \frac{(D - 0.5)Q_b^*(I) + Q_b^*(II)}{0.5 + D} \qquad (7)$$

where I corresponds to the input and II refers to the output of the calculations. The new Q_i and Q_b^* were then used for the next iteration. The values of D were generally in the range of 2.5 to 3.0, and six to eight iterations were generally required for convergence.

The off diagonal elements, H_{ij}, were obtained from the overlap matrix by a modification of Cusachs formula (58) and is shown in equation 8, where S_{ij} are the group overlap inte-

$$H_{ij} = S_{ij}(2 - |S_{ij}|)(H_{ii}H_{jj})^{\frac{1}{2}} \qquad (8)$$

grals and $|S_{ij}|$ are the atomic overlap integrals. The calculation of the $S_{ij}(2 - |S_{ij}|)$ terms is done in the local coordinate system prior to rotation to the molecular coordinate system. The use of the geometric mean of H_{ii} and H_{jj} is the modification that Ballhausen and Gray (59) applied to the Wolfsberg-Helmholz formula (60).

Since the terms chosen in this program were designed to closely match the overlap integrals, without regard for predicting other properties, such as those depending on the shape of the orbital near the nucleus, it was felt that the proton hyperfine splitting constants could best be predicted using the coefficients of the hydrogen 1s atomic orbitals in the molecular orbital containing the unpaired electron. When considering just the first order Fermi contact term, the hyperfine splitting constants are given by equation 9. Evaluation

$$a^H = -\frac{16}{3}\pi g_H \beta_H c_u{}^2 \varphi^2(H_{1s}) \qquad (9)$$

of this expression gives $a^H = 878\ c_u{}^2$ G. The scaling factor used in this work was $a^H = 790\ c_u{}^2$ G, where the major difference is due to the normalization factor chosen. In most cases, $\Sigma c_{ui}{}^2$ was approximately equal to 1.11, and hence a reduction of 10% in the scaling factor was used. While approximating the normalization of $\Sigma c_{ui}{}^2 = 1$, this factor kept the relative differences in normalization between molecules caused by inclusion of the overlap term. In Table 2 are listed the various input parameters used in the calculations.

Table 2. Input parameters used in the Extended Huckel Calculations.

Orbital	VSIP	A	B	z	n
C_{2s}	-19.5	11.9	14.7	1.57	2
C_{2p}	-11.2	11.9	14.7	1.46	2
O_{2s}	-33.2	15.2	18.8	2.19,	2
O_{2p}	-16.1	15.2	18.8	2.03	2
K_{4s}	- 4.3	4.0	2.1	0.67	3
K_{4p}	- 2.7	4.0	2.1	0.44	3
H_{1s}	-13.6	0.0	0.0	1.20	1

Geometrical Considerations

Although a number of precise structural studies have been made on several bicyclic systems (61-67), there is little or no data available for semidiones or even the structurally close diketone systems. The importance of the calculations depends on the ability to predict hyperfine splitting constants with reasonable accuracy, and without the necessity of an exact structural study.

In general, the structures were constructed using the following rules: saturated C-C bond lengths are 1.54Å, the OC-CO bond lengths are 1.40Å (the calculated bond order for this bond is 0.40, and a decrease in the diketone bond by 0.07Å was made using the published bond-order bond-length relationship (68) of Streitwieser), C=O bond lengths are 1.22Å, C-H bond lengths are 1.09Å, for methine hydrogens all H-C-C bond angles are equal, for methylene hydrogens all H-C-C bond angles are equal and the H-C-H bond angles are 111°, for methyl groups all H-C-C bond angles are equal and all H-C-H bond angles are 109.5°, when a hydrogen was replaced by a methyl group all angles remain unchanged, the angle between the two carbonyl bonds was 70° (variation of this angle had little effect on the calculations), and the internal angles for the ring systems were chosen to try to minimize distortion. Where structural analogies were available in the literature, such as for the bicyclo[2.2.1]heptane system, the necessary modifications were made to convert the structure to one containing the semidione functional group.

The geometries were then varied to observe how the predicted hyperfine splitting constants changed.

Results

Butane-2,3-semidione

This seemingly simple system was used to test the applicability of our method of calculating proton hyperfine splitting constants (hfsc). This system also offers complexity because of rotational conformers of the methyl groups, *cis* and *trans* isomerization, and distortion due to twisting of the central carbon-carbon bond. In the past, it has been difficult to obtain reasonable agreement between the experimental and calculated results for this system (10). The geometries used in the calculations are shown in Figure 44, and the results are given in Table 3. When structure A was used, the calculated hfsc for the *cis* isomer was 5.75 G, and the hfsc for the *trans* isomer was 6.17 G. Varying bond angles, changing the rotational conformation of the methyl group, or using a structure with a slight twist about the C_2-C_3 bond had little effect on the calculated values. In all these cases, for simiilar structures, the *trans* hfsc was predicted to be larger than that of the *cis*, whereas the reverse is true experimentally.

Previous experimental work suggested the possibility of the potassium ion being chelated with the bidentate *cis*-semidione group. When the potassium was included in the calculations for the *cis* isomer, a large increase resulted in the pre-

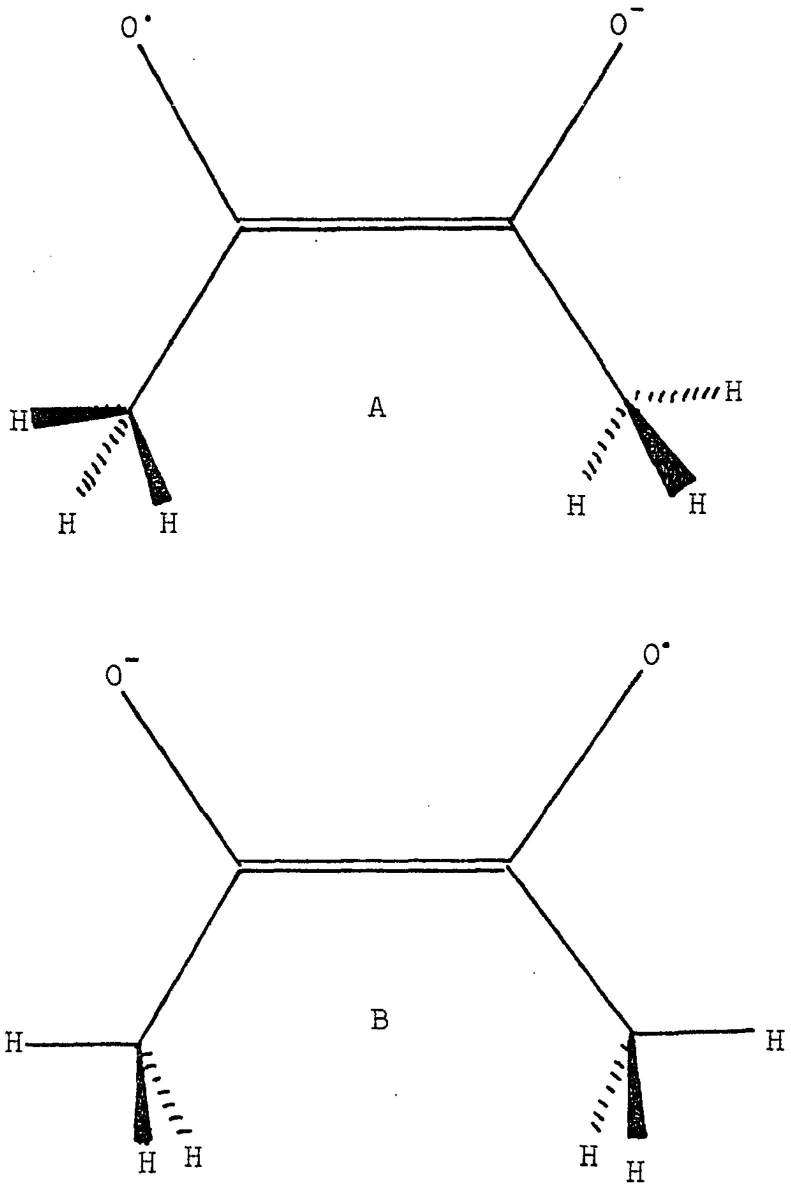


Figure 44. Two of the structures used in the calculations for the *cis*-isomer of butane-2,3-semidione. For the *trans*-isomer, a 180° rotation about the carbon-carbon double bond was executed.

Table 3. Observed and calculated splitting constants for butane-2,3-semidione.

Structure	cis	trans
Obsd.[a]	7.0[b]	5.6[b]
No K		
Calcd. A	5.75	6.17
Calcd. B		5.78
With K s and p		
Calcd. A 1.8Å	9.50	
Calcd. A 2.2Å	8.80	
Calcd. A 2.4Å	8.42	
With K s		
Calcd. A 2.4Å	8.34	
Calcd. B 2.4Å	8.04	
With Na s		
Calcd. A 2.15Å	8.75	
With K s		
Calcd. A[c] 3.0Å		7.59

[a] In DMSO.

[b] Potassium as the gegenion.

[c] Distance from one oxygen in a line parallel to the C_2-C_3 bond.

dicted hfsc. Including the p-orbitals of the potassium ion had little effect on this value, which was now greater than the predicted hfsc for the trans isomer. Another interesting experimental fact has been observed. In weakly ionizing solvents such as dimethoxyethane, the splitting constants are larger than those observed when solvents with a greater ionizing ability, such as dimethylsulfoxide, are used (69). In a solvent such as DME, the potassium-oxygen bond distance would be expected to be shorter than the bond length in DMSO. When the potassium-oxygen bond length was varied in the calculations, the predicted hfsc was greater for the structure with the shorter bond distance. This trend is in excellent agreement with the experimental facts.

Another experimental fact which has been noted, is that the hfsc increases when the gegenion is changed from potassium to sodium to lithium. Using sodium as the gegenion in the calculations also predicts a slight increase in the hfsc.

Bicyclo[3.1.0]hexane-2,3-semidione

The geometry and numbering for this system is shown in Figure 45. The five-membered ring was assumed to be planar, with the two oxygens in the plane of the ring. The internal angles of the ring are as shown, and two angles, 105° and 108°, between the planes of the three- and five-membered rings were used for the calculations. In the methyl substituted compounds it was assumed that the carbon of the methyl group makes the same bond angles as the hydrogen which it has replaced.

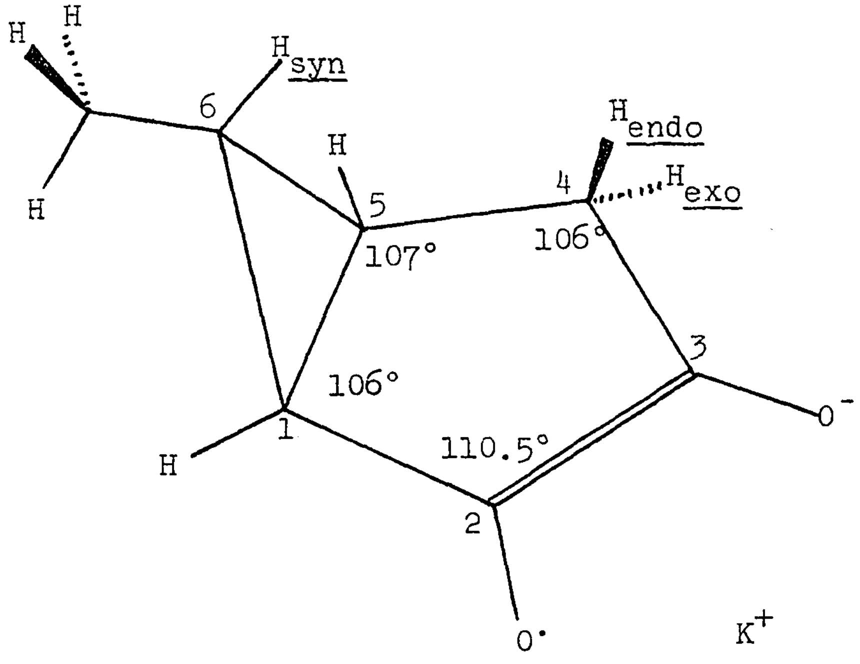


Figure 45. The geometry and numbering for anti-6-methylbicyclo[3.1.0]hexane-2,3-semidione. Structure A has an angle of 108° between the planes of the three- and five-membered rings, and Structure B has an angle of 105°. The rotational conformer of the methyl group is as shown.

In most cases only one rotational conformer of the methyl group was considered. However, in the cases where more than one rotamer was considered, the predicted hfsc underwent little change.

In the unsubstituted case, good agreement with the experimental values was obtained for each case, and possibly better agreement would have resulted for a model whose structure was between the two considered. The fact that the ratio of $a^{H}_{\underline{exo}}$ to $a^{H}_{\underline{endo}}$ is not closer to the experimentally observed value is presumably due to the assumption of planarity for the five-membered ring. However it is still interesting to note that the assumption of planarity does lead to the prediction of a marked difference between the exo- and endo-hydrogens in the correct direction, even though in our model the dihedral angles of these hydrogens with respect to the p-orbital of the adjacent π-system carbon are equal. This demonstrates that the application of the Heller-McConnell equation (70) to calculate dihedral angles in unsymmetrical molecules may be invalid.

The observed (13) and calculated values for this system are shown in Table 4. In all cases good agreement with the experimental values was obtained. The predicted hfsc are in the correct order, but their absolute values are too large. Two possible sources of error are present in the calculations of the methyl substituted compounds. The assumption that the methyl group makes the same bond angles as the hydrogen it re-

Table 4. Observed and calculated splitting constants for bicyclo[3.1.0]hexane-2,3-semidiones.

Hydrogen	1	4-*exo*	4-*endo*	5	6-*anti*	6-*syn*
Unsubstituted						
Obsd.	4.0	14.9	7.86	0.8	4.0	0.8
Calcd. A	4.27	13.91	9.79	0.67	3.54	0.49
Calcd. B	3.41	13.64	9.91	0.71	4.30	0.89
anti-6-methyl						
Obsd.	4.3	14.3	7.6	0.9	0.4[a]	0.9
Calcd. A	3.78	14.25	10.30	0.77	0.99[b]	0.59
Calcd. C[c]	3.51	13.97	10.09	0.66	1.09[b]	0.56
syn-6-methyl						
Obsd.	4.6	14.3	7.4	1.1	1.5	<0.1[a]
Calcd. A	4.87	12.72	9.28	0.58	0.40	0.24[b]
6,6-dimethyl						
Obsd.	5.1	14.6	7.6	0.9	0.45[a]	0.0[a]
Calcd. A	4.38	12.98	9.61	0.64	1.16[b]	0.23[b]

[a] $a^{H}_{CH_3}$, three equivalent hydrogens observed.

[b] Average value for one rotamer only.

[c] Structure C is the same as structure A with the exception that the methyl group has been rotated 60°.

places is probably the largest source. Secondly, the possibility of distortion introduced into the rest of the molecule was not included in calculation of structures.

Bicyclo[2.2.1]heptane-2,3-semidione

The experimental (15) and calculated results for this system are shown in Table 5. Two geometries were used for the calculation and these are given in Figure 46. Fairly good agreement between experimental and calculated values was obtained. As can be seen, a large variation in the predicted hfsc occurs when the geometry is changed. In fact, the calculations for this system were more sensitive to geometrical changes than any other system that we used. The largest difference between the predicted and observed splittings were for the α-hydrogens. All the other differences could have been corrected by a change in geometry, but the hfsc of the α-hydrogens remained fairly constant.

Two facts stemming from the calculations are interesting to note. First of all, in the *syn*-7-methyl compound, a large decrease in the splitting of the *anti*-7-hydrogen is predicted. Qualitatively this agrees with the experimental facts, although quantitatively the prediction is too large. This parallels the case of the *anti*-6-hydrogen in *syn*-6-methylbicyclo[3.1.0]hexane-2,3-semidione. As in previous calculations, only one structure was used for the calculation on the methyl substituted compounds, and the possible sources of error remain the same. A second interesting point is that the *anti*-7-methyl splitting

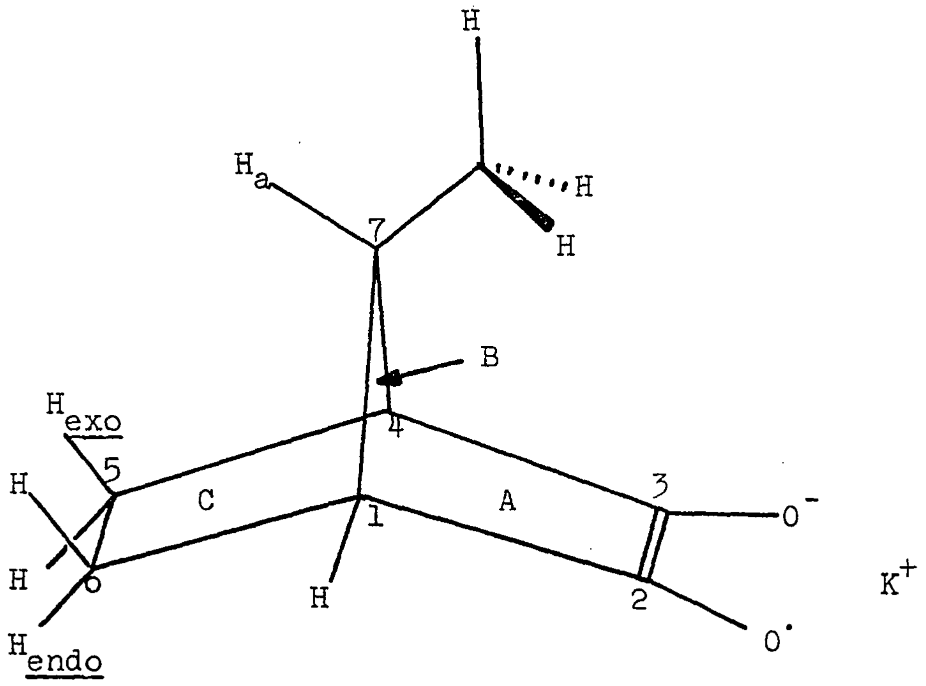


Figure 46. The geometry and numbering for *syn*-7-methylbicyclo[2.2.1]heptane-2,3-semidione. The distance from C_1 to C_4 is 2.25Å. Structure A had $\angle_{AC}$=110° and $\angle_{AB}$=125°. Structure B has $\angle_{AC}$=114° and $\angle_{AB}$=123°.

Table 5. Observed and calculated splitting constants for bicyclo[2.2.1]heptane-2,3-semidione.

Position	1(4)	5,6-*exo*	5,6-*endo*	7-*anti*	7-*syn*
Unsubstituted					
Obsd.	2.49	2.49	0.0	6.47	0.41
Calcd. A	1.41	2.67	0.60	5.28	0.22
Calcd. B	1.71	1.65	0.22	7.30	0.59
anti-7-methyl					
Obsd.	2.37	2.37	0.09	0.19[a]	0.49
Calcd. B	1.94	1.67	0.24	0.05[b]	0.66
syn-7-methyl					
Obsd.	2.52	2.52	0.0	3.11	0.18[a]
Calcd. B	1.39	1.62	0.30	1.66	0.44[b]

[a] $a^{H}_{CH_3}$, three equivalent hydrogens observed.

[b] Average value for one conformation only.

is calculated to be less than the *syn*-7-methyl splitting. This is in agreement with experiment, and it is especially noteworthy when one also considers that in the bicyclo[3.1.0]hexane-2,3-semidione system, just the opposite is true, namely the experimental and calculated values for the *anti*-6-methyl are larger than the values for the *syn*-6-methyl. Just why this is so, is still somewhat vague, but since the Extended Huckel method takes into account through space (and through bond) overlaps

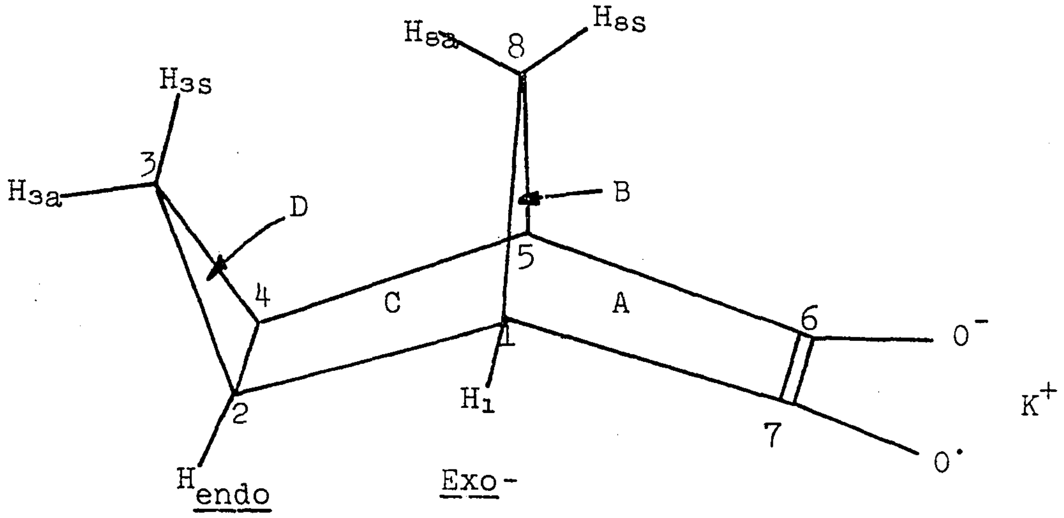
Table 6. Observed and calculated splitting constants for tricyclo[3.2.1.0^{2,4}]octane-6,7-semidione.

Position	1(5)	8a	8s	3a	3s	2,4-*exo*	2,4-*endo*
Exo-							
Obsd.	0.98	7.61	1.05	3.45	0.20	----	0.40
Calcd. A	0.62	5.18	0.33	3.09	0.15	----	0.01
Calcd. B	1.04	7.54	0.85	2.97	0.35	----	0.03
Endo-							
Obsd.	2.88	7.78	1.37	0.47 or	0.15	0.34	----
Calcd. A	2.16	6.08	0.73	1.55	1.24	0.66	----
Calcd. B	2.25	8.06	1.06	0.74	0.56	0.48	----

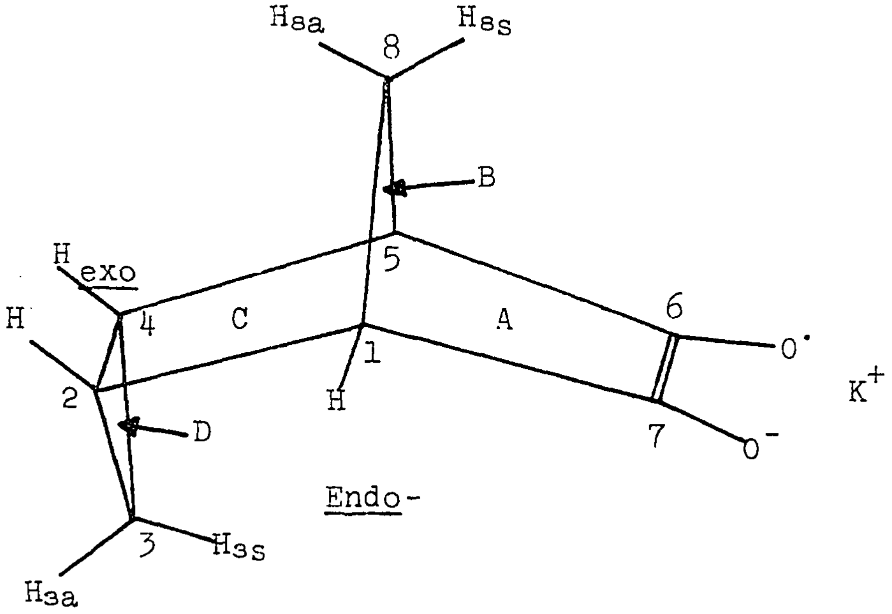
rather than spin polarization type coupling mechanisms, the solution would then seem to lie in that direction.

Exo- and endo-tricyclo[3.2.1.0^{2,4}]octane-6,7-semidione

The geometry and numbering for these compounds is shown in Figure 47. The structure of bicyclo[2.2.1]heptane-2,3-semidione was used to form the basic geometry with the addition of a cyclopropyl ring. The angle between plane D of the cyclopropyl ring and plane C in the molecule was taken to be 117° (62). The results of the calculations are shown in Table 6. In each case, structure B gave excellent results. Some very interesting qualitative results can also be noted. When comparing the bicyclooctane system to the bicycloheptane system, the positions of the hydrogens α to the semidione group has



Exo-



Endo-

Figure 47. The geometry and numbering for exo- and endo-tricyclo[3.2.1.$0^{2,4}$]octane-6,7-semidione. The dis- from C_1 to C_5 is 2.25Å. Structure A has $\angle_{AC}$=110° and $\angle_{AB}$=125°. Structure B has $\angle_{AC}$=114° and $\angle_{AB}$= 123°. $\angle_{CD}$=117°.

not changed, and yet a large change in the hfsc is predicted in each case. For the exo-compound a large decrease in the hfsc of the α-hydrogens is predicted and in the endo-compound a large increase is predicted. Both of these trends are in excellent agreement with the experimental results. In addition, a large decrease in the hfsc of the 2,4-exo hydrogens of the endo-compound is also predicted and this too agrees with the experimental results.

One other fact is also interesting to note. In the exo-compound, the calculated splittings of the cyclopropyl methylene hydrogens is relatively insensitive to the structural change from A to B. However, for the endo-compound, the reverse is true. This is explained by the fact that in the endo-compound, this group is quite close to the π-system in which the unpaired electron mainly resides. A small change in geometry would therefore cause a large change in the atomic orbital overlap between these two parts, and would therefore cause a large change in the predicted splittings. Because of this, it is gratifying to note that the predicted splitting constants for the 3-syn- and the 3-anti-hydrogens in this case, did come as close as they did to the experimental values.

Cycloheptanesemidione

The geometries of the chair and boat conformations of this system are given in Figure 48 and the results of the calculations are given in Table 7. The dihedral angles of the α-hydrogens, used in forming structrues B and C were those

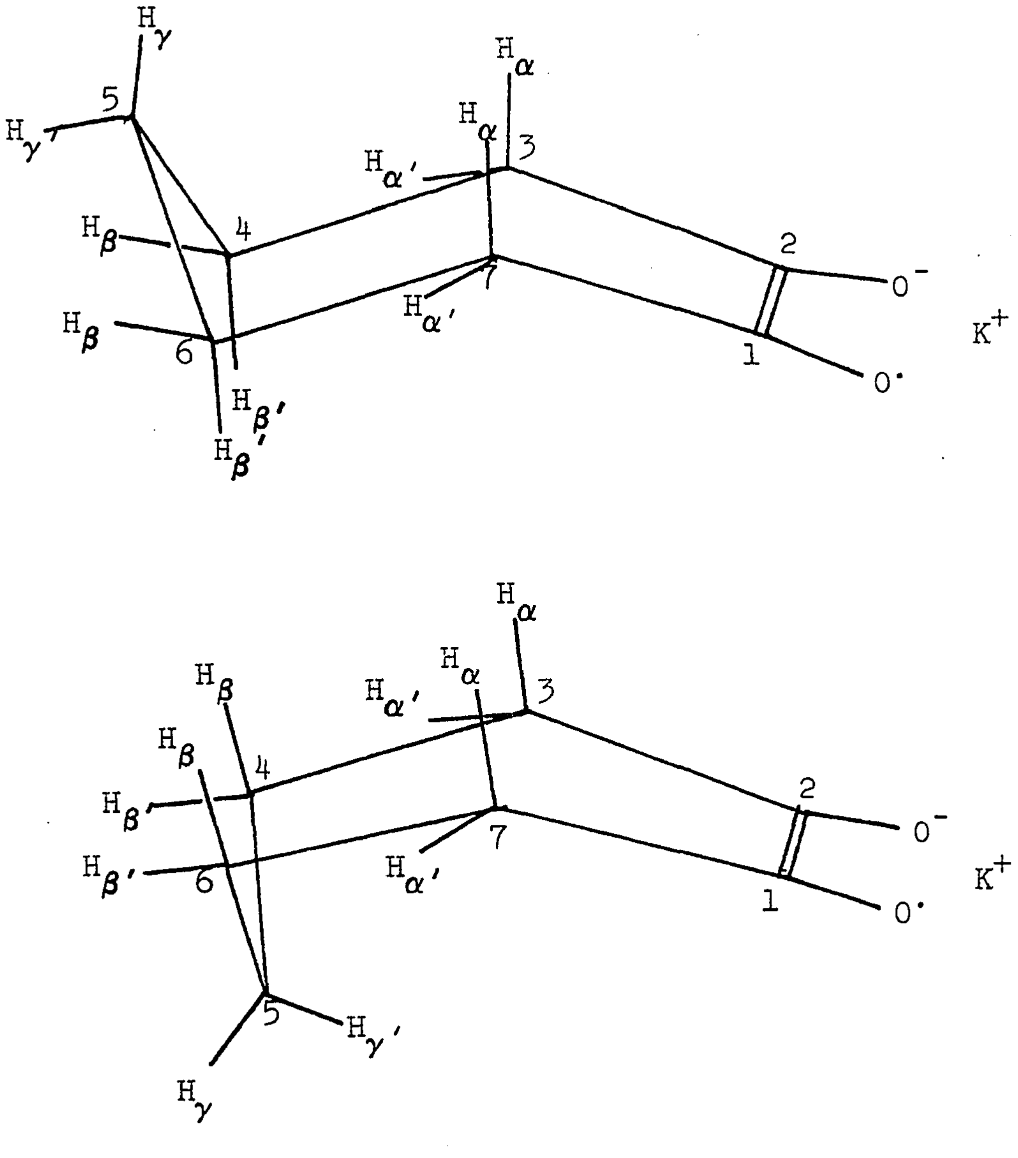


Figure 48. The geometry of the chair and boat conformations of cycloheptanesemidione. Three structures were used.

	$\angle_{234}$	$\angle_{345}$	$\angle_{456}$	dihedral ∠ of α H
Structure A	109°	109°	109°	71° and 11°
Structure B	111°	111°	107°	79° and 19°
Structure C	111°	111°	110°	89° and 39° .

Table 7. Observed and calculated splitting constants for cycloheptanesemidione.

Hydrogen	H_α	$H_{\alpha'}$	H_β	$H_{\beta'}$	H_γ	$H_{\gamma'}$
Obsd.	6.60	0.28	2.05	0.28	0.0	0.56
Calcd. A_1[a]	7.26	0.93	2.15	0.24	0.29	1.37
Calcd. A_2	7.33	2.09	1.97	0.01	5.07	4.20
Calcd. B_1	8.21	0.43	1.90	0.27	0.12	1.26
Calcd. B_2	9.56	1.10	1.24	0.17	2.47	2.21
Calcd. C_1	6.15	0.60	2.60	0.83	0.00	1.90
Calcd. C_2	9.18	0.25	0.22	0.09	0.92	1.51

[a] Different letters refer to calculations using different angles and the subscripts 1 and 2 refer to the chair and boat conformations respectively.

obtained by solution of the Heller-McConnell equation. In addition, the dihedral angles of B are those obtained for cycloheptene using nmr spectroscopy (31). After choosing the dihedral angles of these hydrogens, the overall structure was then formed by choosing internal bond angles which were distorted only slightly from the usual values.

In each case, the splitting constants calculated for the chair conformation were in better agreement with the experimental results. The main difference between the experimental and calculated values occurs in the γ-position, and the probable cause of this is due to the inadequacies of calculating the true geometry of this system. However, one of the main advantages of our calculations has been the ability to predict hyperfine splitting constants in reasonable agreement with the experimental facts, even though an exact geometry for the system was not available.

Bicyclo[2.1.1]hexane-2,3-semidione

The geometry and numbering of this compound is shown in Figure 49. Wilcox (71) calculated the geometry for the bicyclo[2.1.1]hexene system using two different methods. In one case an angle L was calculated to be 139° on the basis of angle strain, and in the other case it was calculated to be 137° on the basis of nonbonded repulsions. In our calculations we used angles of 136° and 140°, while making the necessary modifications to convert the geometry of the alkene to that of the semidione. The results of the calculation are shown in Table 8.

The system was an interesting one to use for the calculation in that it has the largest 2V splitting constant yet observed (14). The results of the calculation agree well with the experimental values, and possibly better agreement could have been obtained using a value of L of about 134°. The predicted hyperfine splitting constant for $H_{5(6)_a}$ was the largest predicted 2V splitting constant in all of our calculations. For $H_{1(4)}$ the predicted hfsc was 0.00 in the structures tried. These two hydrogens lie in the nodal plane of the π-system, and since the molecule is symmetrical about this plane, the predicted value of all cases would be zero.

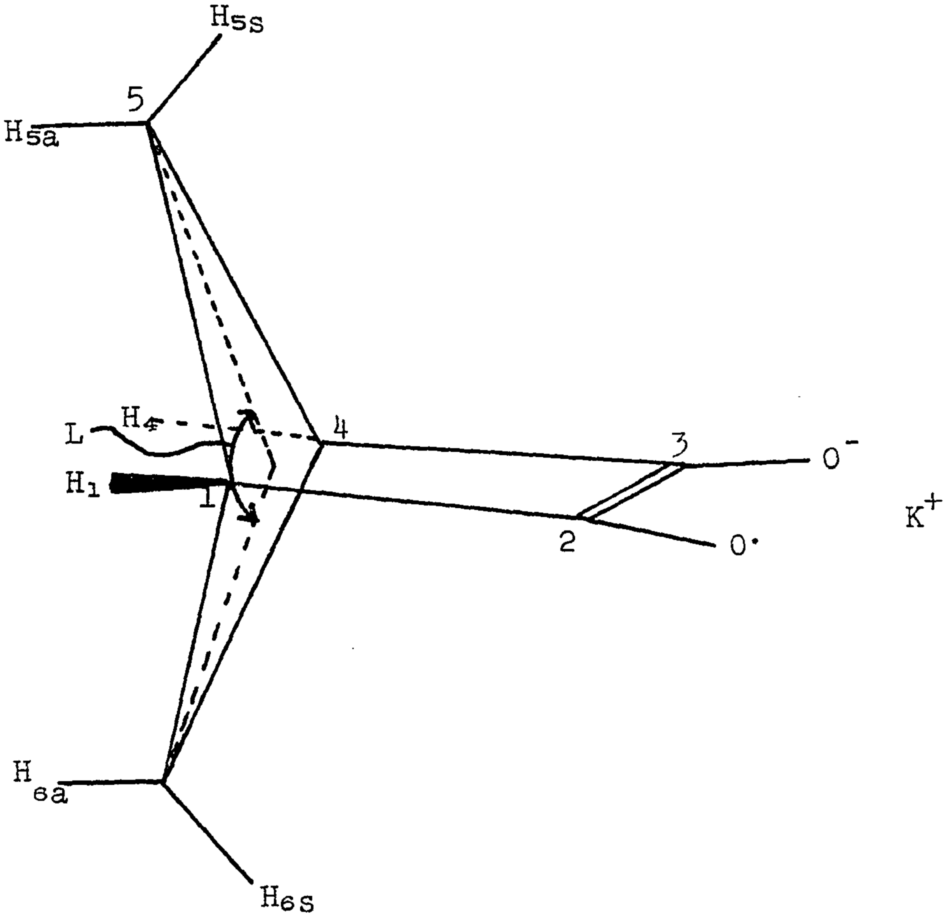


Figure 49. The geometry and numbering for bicyclo[2.1.1]hexane-2,3-semidione. Two structures were used: Structure A had ∠L=140° and Structure B had ∠L=136°: distance C_1-C_4 = 2.07Å.

Table 8. Observed and calculated splitting constants for bicyclo[2.1.1]hexane-2,3-semidione.

Hydrogen	1(4)	5(6)a	5(6)s
Obsd.	0.20	10.10	0.40
Calcd. A	0.0	12.70	1.54
Calcd. B	0.0	10.89	0.79

The probable coupling mechanism of these protons is spin polarization, and Extended Huckel Calculations do not include this.

Cyclobutanesemidiones

Calculations were run on the parent system and three bicyclic systems. These three systems were: bicyclo[2.1.0]-pentane-2,3-semidione, bicyclo[2.2.0]hexane-2,3-semidione, and bicyclo[3.2.0]heptane-6,7-semidione. The first two bicyclic systems have thus far resisted synthesis. The geometries for these three bicyclic systems are shown in Figures 50 and 51 and the results of the calculations are given in Tables 9 through 12.

For the parent system, the geometry follows directly from our chosen set of rules. Good agreement between the observed (14) and calculated values resulted with the difference being only 10%. For the unknown bicyclo[2.1.0]pentane-2,3-semidione and bicyclo[2.2.0]hexane-2,3-semidione, the calculated values for the α-hydrogens are surprisingly small. The synthesis

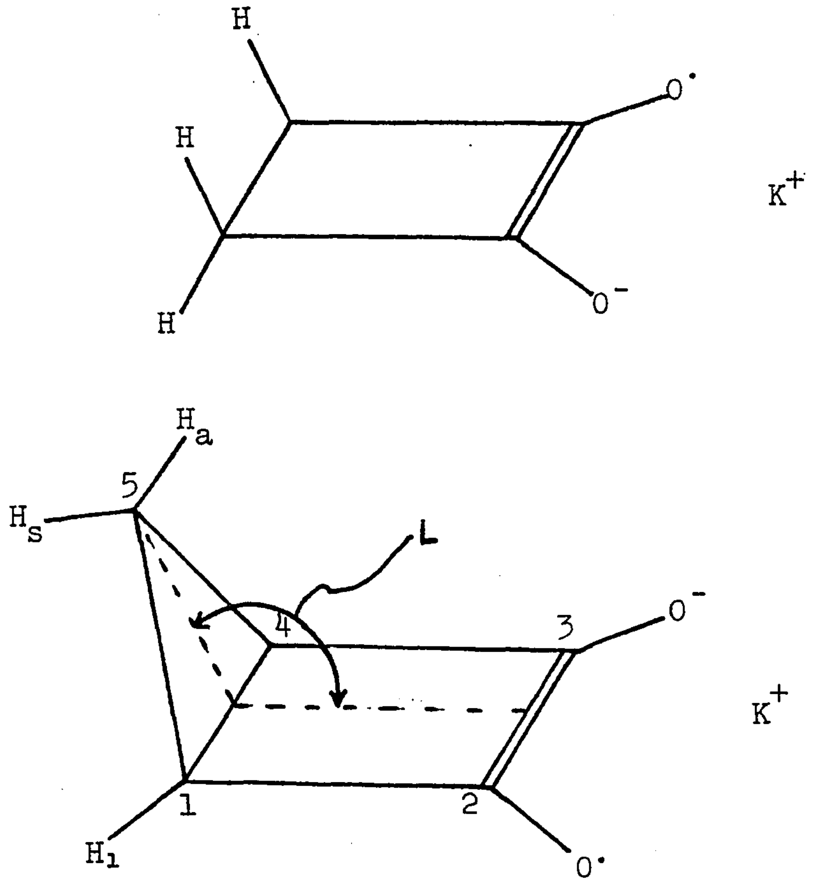


Figure 50. The geometry and numbering for cyclobutanesemidione and bicyclo[2.1.0]pentane-2,3-semidione. For the bicyclic system two structures were used. Structure A had ∠L=115° and Structure B had ∠L=120°.

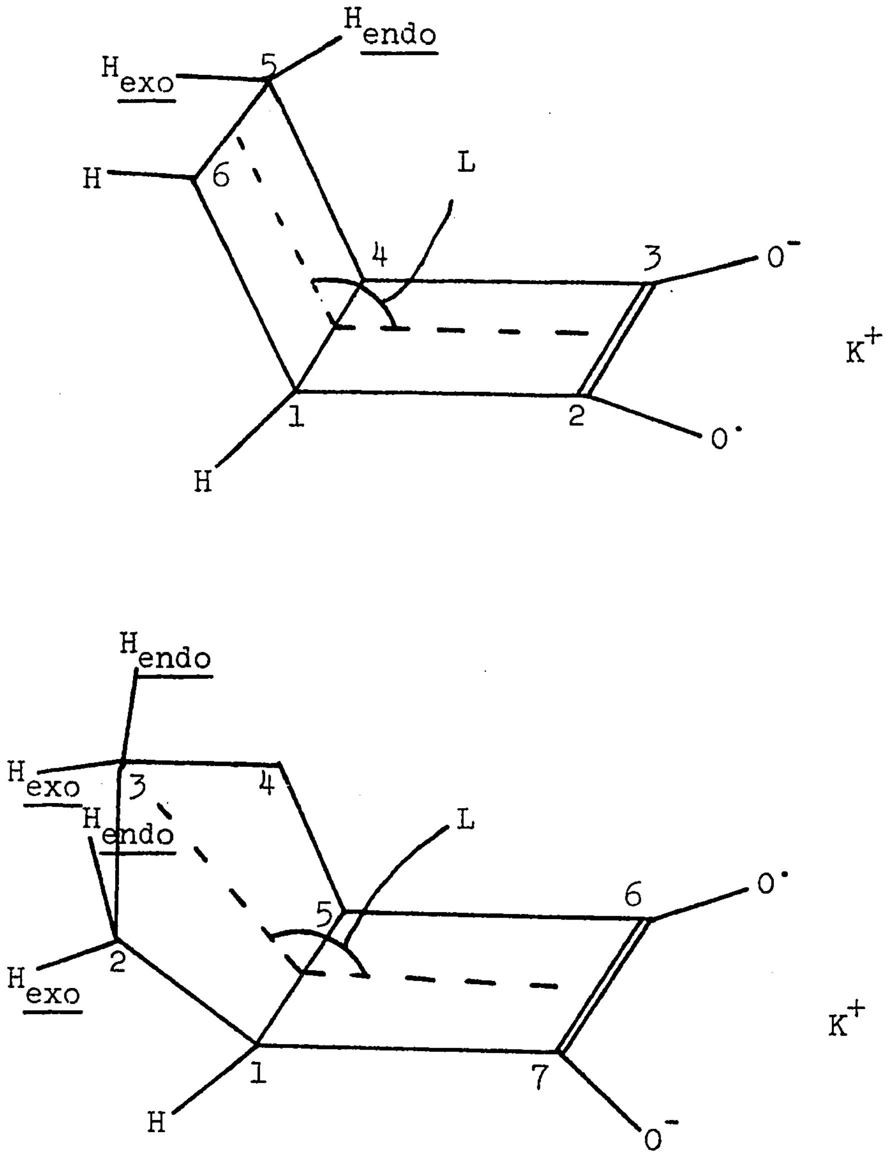


Figure 51. The geometry and numbering for bicyclo[2.2.0]hexane-2,3-semidione and bicyclo[3.2.0]heptane-6,7-semidione. Structure A had ∠L=115° and Structure B had angle L=120°.

Table 9. Observed and calculated splitting constants for cyclobutanesemidione.

Obsd.	13.9
Calcd.	15.4

Table 10. Calculated splitting constants for bicyclo[2.1.0]-pentane-2,3-semidione.

Position	1(4)	5-a	5-s
Calcd. A	2.11	0.13	8.53
Calcd. B	3.02	0.06	5.95

Table 11. Calculated splitting constants for bicyclo[2.2.0]-hexane-2,3-semidione.

Position	1(4)	5(6)-*exo*	5(6)-*endo*
Calcd. A	5.30	2.03	0.50
Calcd. B	7.08	1.26	0.16

Table 12. Observed and calculated splitting constants for bicyclo[3.2.0]heptane-6,7-semidione.

Position	1(5)	2(4)-*exo*	2(4)-*endo*	3-*exo*	3-*endo*
Obsd.	12.8	0.62	0.06	0.62 or	0.30
Calcd. B	14.85	0.93	0.59	0.91	0.44
Calcd. A	11.78	2.10	1.44	1.02	0.27

Table 13. Observed and calculated splitting constants for bicyclo[2.2.2]octane-2,3-semidione.

Position	1(4)	exo	endo
Obsd.	0.0	2.09	0.0
Calcd. A	0.0	1.72	0.32
Calcd. B	0.0	3.22	0.19

of either of these systems is eagerly awaited to see just how well the observed values will agree with the calculated ones.

Bicyclo[3.2.0]heptane-6,7-semidione is known and the calculated values, with the exception of the 2(4)-endo-position, for Structure A agree quite well with the observed hfsc. Perhaps better agreement could have been obtained if the five-membered ring was assumed to be nonplanar or if the angle between the rings was chosen to be slightly greater than 120°.

Bicyclo[2.2.2]octane-2,3-semidione

The observed and calculated values are given in Table 13 and the geometries used in the calculations are shown in Figure 52. Structure B is the same structure that Underwood and Givens (32) used in their calculations. This structure has tetrahedral carbon bond angles of ~120° and ~100°. Structure B with angles approximately 110° was felt to be much more reasonable. Agreement between calculated and observed (12) values using Structure A is fairly good, except that the endo-protons are not observed experimentally whereas the program

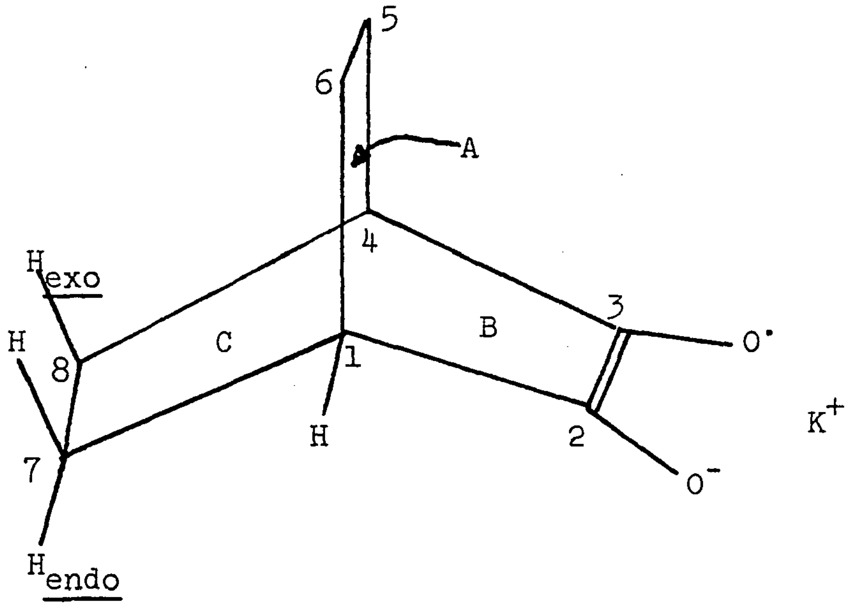


Figure 52. The geometry and numbering for bicyclo[2.2.2]octane-2,3-semidione. The angles between planes A, B and C were 120°, and the C_1-C_4 distance was 2.65Å for Structure A and 3.00Å for Structure B.

Table 14. Observed and calculated splittings for *exo*- and *endo*-tricyclo[3.2.2.$0^{2,4}$]nonane-6,7-semidione.

Position	1(5)	2(4)n	3a	3s	8(9)x	8(9)n	2(4)x
Exo-							
Obsd.[a]	0.65	0.32	1.98	0.20	2.21	0.00	----
Calcd. A	0.13	0.00	2.06	0.10	1.60	0.47	----
Endo-							
Obsd.	0.00	----	0.51 or	0.39	2.32	0.21 or	0.13
Calcd. A	0.03	----	1.26	0.86	2.00	0.50	0.34

[a] Assignment based on comparison to semidiones XXXVII to XL.

does predict an observable hfsc. This is the same as what happened in the case of bicyclo[2.2.1]heptane-2,3-semidione.

Exo- and Endo-tricyclo[3.2.2.0]nonane-6,7-semidione

The results of the calculations are given in Table 14 and the geometries used for the calculations are shown in Figure 53. The calculations on these two systems were preformed to see if an observable hfsc would be predicted for the bridgehead protons. Experimentally, bridgehead splittings are observed for the *exo*-isomer whereas they are not observed for the *endo*-isomer. The results of the calculations predict an observable hfsc only for the exo-isomer, although qualitatively the predicted hfsc is too small. That an observable hfsc would be predicted is surprising in that the structures used had the bridgehead protons in the nodal plane of the

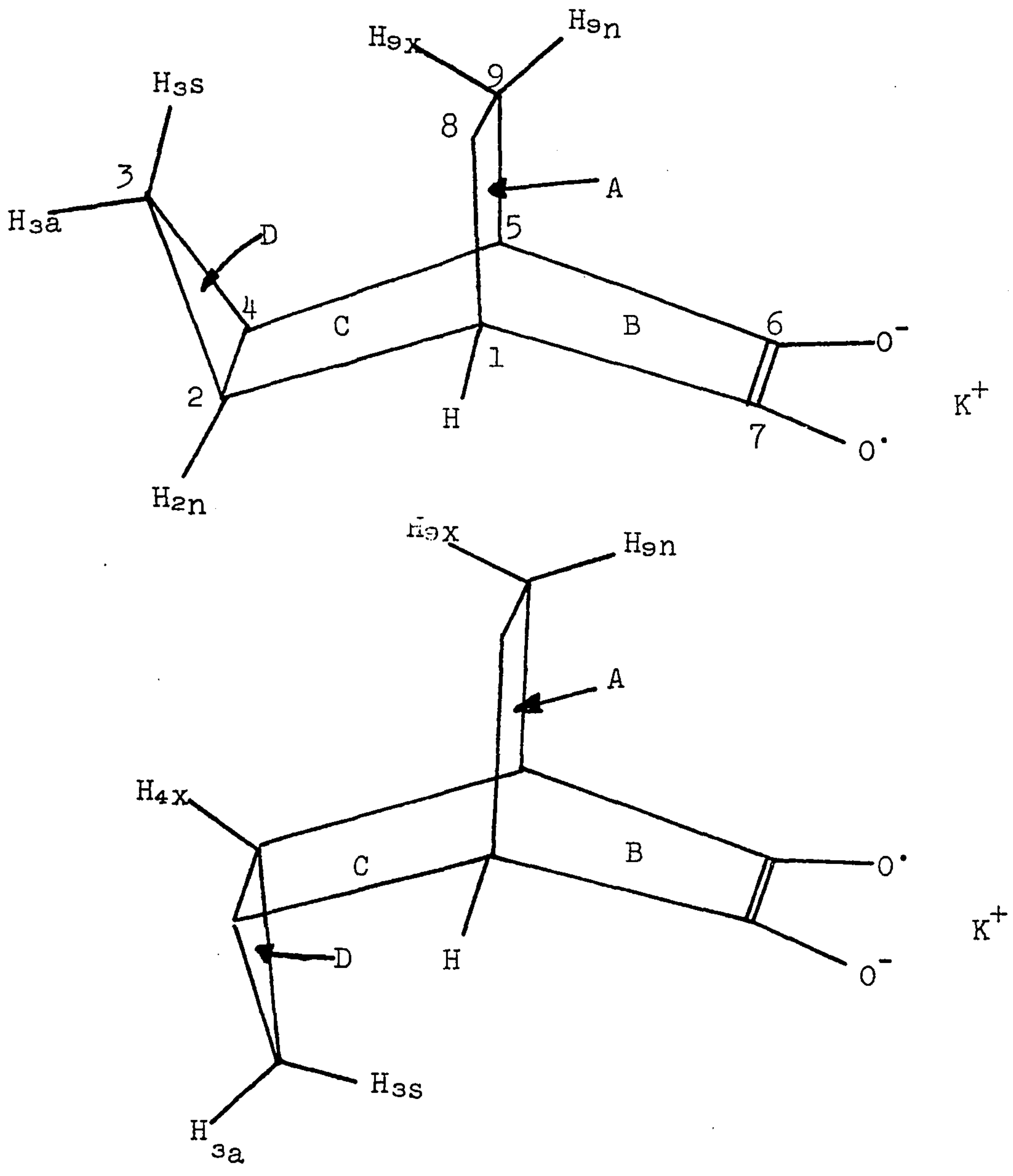


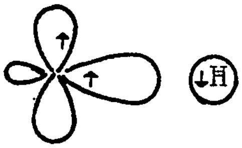
Figure 53. The geometry and numbering for exo- and endo-tricyclo[$3.2.2.0^{2,4}$]nonane-6,7-semidione. The angles between planes A, B, and C were 120° and the angle between planes C and D was 115°. The C_1-C_5 distance was 2.65Å.

π-system. The results then suggest that the observable hfsc of the bridgehead protons in the *exo*-isomer is a result of two effects. First, a slight structural change in the molecule and second, that the cyclopropyl ring has an effect on the molecular orbitals of the system, giving rise to a slight spin density around the bridgehead protons. No attempt was made to improve the results of the calculations by changing the input geometries.

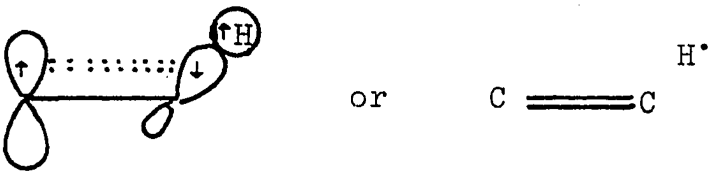
THE EFFECT OF A CYCLOPROPYL RING ON LONG RANGE HYPERFINE SPLITTING CONSTANTS

A number of mechanisms have been proposed whereby the unpaired electron spin density can be delocalized into the 1s atomic orbital of hydrogen, thus enabling coupling between the nucleus of the atom and the unpaired electron. Most of these mechanisms have one thing in common. Only localized orbitals bonding one atom to the next are given consideration. Hoffman and Lipscomb (51), with their Extended Huckel Theory, broke free of this confinement and gave consideration to molecular orbitals extending over the whole molecule. In these orbitals, even remote groups could have an appreciable effect on the bonding patterns of atoms closer to the orbitals in which the unpaired electron mainly resides. In any case, whatever the mechanism by which the electron spin density "enters" into the 1s orbital of the hydrogen, the electron will have a finite probability of being at the nucleus, and the nuclear spin will then couple with the electron spin as described by the Fermi contact mechanism (72).

One of the delocalization mechanisms is the spin polarization mechanism. For example, a hydrogen bonded directly to a carbon atom, which is part of the π-system in which this unpaired electron resides, feels the unpaired spin density via the σ-bonding electrons of the carbon hydrogen bond. A valence bond picture of this mechanism is shown below for XLV.



A second proposed method of spin transfer is via hyperconjugation, where the orbial containing the unpaired electron overlaps with the carbon hydrogen bonding orbital (XLVI) in the cases where the hydrogen is an addition bond further removed. This type of overlap would naturally be dependent on

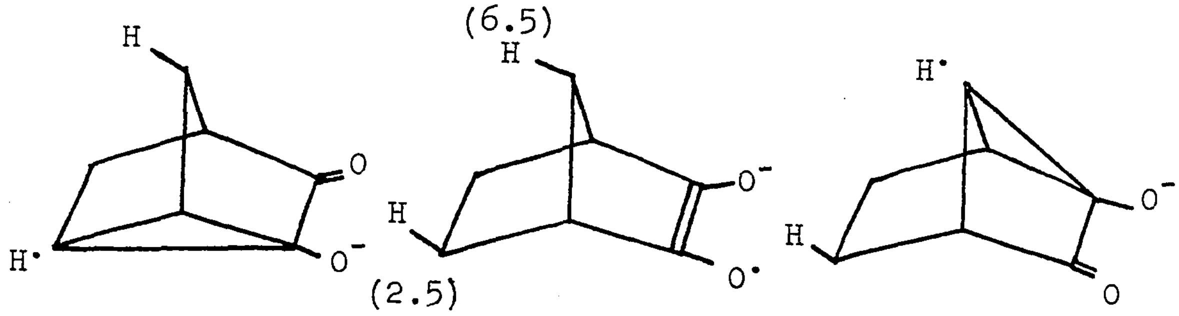


the dihedral angle made by the axis of these two orbitals. The magnitude of the hyperfine interactions could then be given by the Heller-McConnell (70) equation where the ρ is

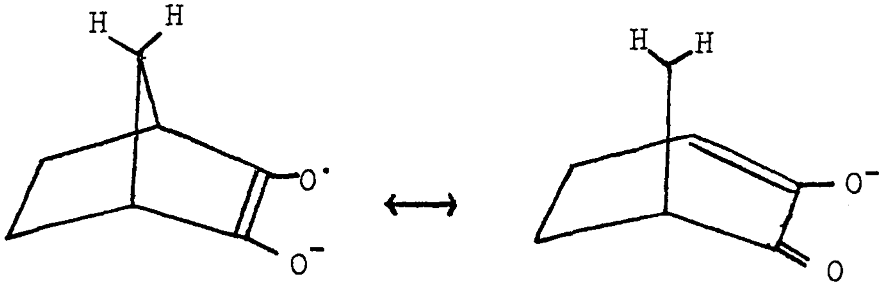
$$a^H = \rho_C(B_o + B\cos^2\theta)$$

the spin density on the adjacent carbon of the π-system, B_o the spin polarization term, and $B\cos^2\theta$ the hyperconjugation term.

For interactions with protons one more bond removed from the π-system, mechanisms similar to the previous two have been applied. Homohyperconjugation is then the obvious extension of hyperconjugation, and nicely explains the sterospecific nature of the 2V hyperfine interactions. An example of this is the case of bicyclo[2.2.1]heptane-2,3-semidione where large hfsc are observed for <u>anti</u>-7- and <u>exo</u>-5,6-protons but only small interactions occur for the corresponding <u>syn</u>- and <u>endo</u>-protons. Carbon-carbon hyperconjugation can be used to

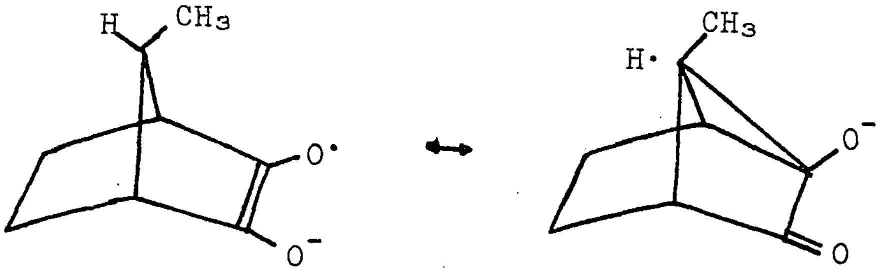


account for the small splitting of the <u>syn</u>-proton, and also for small changes in the magnitude of these splittings.

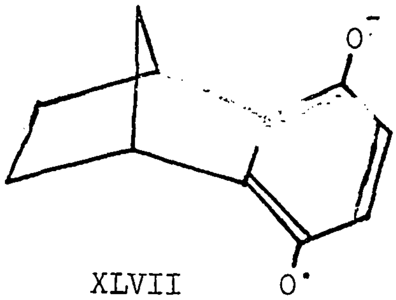


Homohyperconjugation also nicely accounts for the decrease in 2V splittings upon alkyl substitution into the <u>syn</u> or <u>endo</u> positions. The substituent is thought to introduce a steric hindrance of the "bond formation".

In systems where the symmetry of the π-orbital forbids homohyperconjugation, e.g., in XLVII, Kosman and Stock (73)

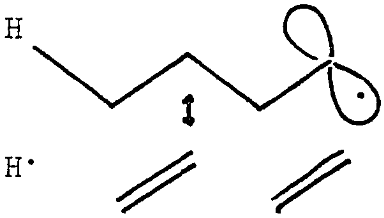


have concluded that the small splittings are due to a spin polarization type of mechanism.

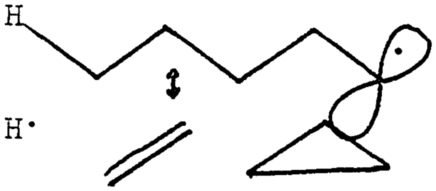


XLVII

The extension of these mechanisms for the 2½V and 3V interactions are shown as XLVIII and IL. As evidenced by



XLVIII

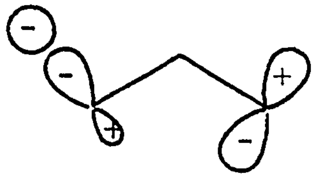


IL

the preceding work, the 2½V interactions are as highly stereospecific as the 1½V and 2V interactions, and they also show a direct dependence on bond angles (as hyperconjugation) and on the trans-coplanarity of the bonds (as does homohyperconjugation). It would seem rather unreasonable to require a fundamentally different mechanism to explain hyperfine interactions for hydrogens which differ in distance from the π-system by an additional σ-bond (as in going from the 2V to the $2\frac{1}{2}$V).

The Hoffman-Lipscomb Extended Huckel Theory forms orbitals which extend over the whole molecule. These orbitals are then qualitatively ordered with respect to energy, and the valence electrons of the molecule are added in pairs to the molecular orbitals in the order of increasing energy. After all the pairs of electrons have been added, one final electron remains (in the case of radicals) and this is added to the next orbital. The results of the calculations indicate that this orbital mainly consists of the π-system, but added to this are contributions from other orbitals in the molecule. This orbital then allows the electron to be in other parts of the molecule, and hence able to couple with certain atoms, depending on their contributions to the formation of this orbital.

The two main differences between this and the previous theories is that first, the unpaired electron spin needs no direct bond between the π-system and the part of the molecule which has hyperfine interactions: namely, an anti-bonding orbital in a certain section would suffice for the spin delocalization, as in L. Secondly, direct overlap between the π-system and the other part of the molecule is no longer required, as evidenced by predictions of large hfsc for $2\frac{1}{2}$V



L

protons.

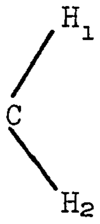
One main success of the Extended Huckel Theory is that electron delocalization is optimized when the atoms are arranged in a <u>trans</u>-coplanar manner. Just why this is so, is still uncertain, but the fact remains that it totally agrees with the experimental facts.

The introduction of a cyclopropyl ring into a molecule causes great changes in the predicted hfsc of the calculations. The cyclopropane ring itself contains a great mass of interacting orbitals confined into a small spacial volume, and it is thus quite reasonable to expect large changes in overlap in the rest of the molecule when this moiety is introduced.

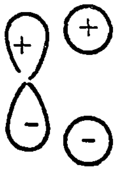
For example, consider the bicyclo[3.1.0]hexane-2,3-semidione system. The five-membered ring must have a structure quite similar to cyclopentadiene since the double bond of the π-system and the cyclopropane ring each require eclipsed bonds extending from them. This would require the methylene carbon to be in the same plane as the other carbons of the ring. With this requirement also, follows the requirement that the hydrogens of this methylene carbon must make the same dihedral angle with the axis of the p_z π-system orbital of the adjacent carbon.

Experimentally these two hydrogens have hfsc of 14.9 and 7.86 G. Hyperconjugation predicts that two hydrogens on the same carbon, which both make the same dihedral angle with respect to the adjacent p_z orbital of the π-system must also have the same hfsc, and that hydrogens with different dihedral angles would have different hfsc. Consequently, solution of the Heller-McConnell equation (70) gives dihedral angles for these hydrogens of ~45° and ~15°. Dihedral angles such as these would require an extremely distorted geometry for the five-membered ring. Using an undistorted five-membered ring geometry in the Extended Huckel calculations predicts hfsc for these hydrogens, which have the same dihedral angles, of ~9 G and ~14 G. These values are quite close to the experimental values and are in direct contradiction to the Heller-McConnell equation. Now the question arises as to how hydrogens which have the same dihedral angles can have different hfsc.

The answer to this question lies in the unsymmetrical substituent on the ring. The cyclopropane ring, with its great number of orbitals in a small volume, is probably one of the best ways to remove the symmetry of the molecular orbital about the ring (the symmetry that is being discussed is the plane of symmetry containing the five carbon atoms of the ring). Consider the three atoms of LIa. LIb shows the orbitals of these atoms which contribute to the particular molecular orbital containing the unpaired electron, when the system has a symmetrical ring. Since there is equal overlap in this case the hydrogens would be predicted to have equal hfsc.

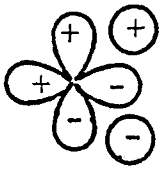


LIa

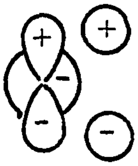


LIb

Introduction of the close unsymmetrical moiety into the ring causes additional orbitals of this carbon to be used in the formation of an unsymmetrical molecular orbital. In LIc and LId, a p orbital and an s orbital have now been introduced into the system. In each case, by virtue of the signs we have chosen for these orbitals, the amount of overlap with H_1 has decreased, and the amount of overlap with H_2 has increased.



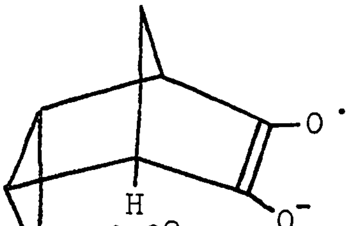
LIc



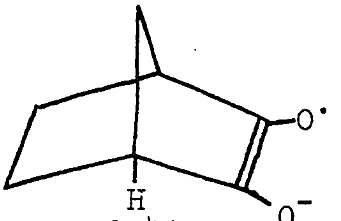
LId

Since the extent of electron delocalization onto the hydrogens, and hence the size of the hfsc, depends directly on the amount of overlap, H_1 would now have a smaller hfsc than H_2. The more that these additional orbitals participate in the formation of the molecular orbital of the molecule, the greater will be the difference between the hfsc of H_1 and H_2. This is exactly what happens in the case of bicyclo[3.1.0]-hexane-2,3-semidione. Introduction of the cyclopropl orbitals causes these additional orbitals to be used, and the predicted hfsc for $H_{\underline{exo}}$ and $H_{\underline{endo}}$ are quite different.

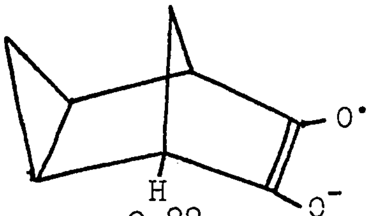
A second example of the effect of the cyclopropyl ring is given in the series of XXX, VII, and XXIX. Qualitatively



0.98
(1.04)
XXIX



2.49
(1.71)
VII



2.88
(2.25)
XXX

the same effect occurs on the α-hydrogens of bicyclo[2.2.1]-heptane-2,3-semidione (VII). Introduction of the <u>exo</u> or <u>endo</u>-cyclopropyl rings in XXX and XXIX causes a drastic change in the observed values of the hfsc of the bridgehead protons. The calculated values (in parentheses) follow this same trend, although the dihedral angle of this hydrogen has not been changed. Although this change in hfsc is not inconsistent with the Heller-McConnell equation, since it could be accounted for by a drastic change in the B_o term, the validity of using an equation which must have "correction factors" which change for similar molecules is somewhat dubious.

The change in the hfsc of the bridgehead proton of VII is totally consistent with the difference between the 4-exo- and 4-endo-protons of bicyclo[3.1.0]hexane-2,3-semidione. The bridgehead proton is on the same side of plane C (Figure 47) as the exo-cyclopropyl ring. The 4-endo-proton of the bicyclohexane system is also on the same side of the five-membered ring plane as the cyclopropane ring. Both these protons have hfsc which are reduced in magnitude. Conversely, the 4-exo-proton of the bicyclohexane system, and the bridgehead proton of XXIX are on opposite sides of the ring, and both these protons show an increase in their hfsc.

As evidenced by the results concerning these cyclopropane compounds, and the calculations on the other molecules in the "Extended Huckel Calculations" chapter, the molecular orbital method of quantitative prediction of hfsc can be quite successful. It would therefore appear that the main way in which proton hfsc occur in rigid semidiones, is via electron delocalization in the molecular orbitals of these systems. But that is not to say that this is the only cause of proton hfsc. Effects of electron polarization are probably present to some extent. In fact, in numerous cases, such as XLVII, certain proton hfsc are predicted to be zero by the molecular orbital method of calculation. These protons nevertheless have observable hfsc, and an electron polarization mechanism would be required to explain their splittings.

Various theoretical methods of long-range quantitative prediction of hfsc via spin polarization have been developed (74-76). As with the molecular orbital theory, these methods can be quite successful in some cases, but are incorrect in other instances. Thus, although there are many theories which can account for many experimental facts, no unique explanation exists for the mechanism of long-range hyperfine interactions.

EXPERIMENTAL

Reagents

Common solvents and chemicals were obtained from commercial sources and used without further purification. Sodium-potassium alloy was prepared by mixing the desired amounts of each metal in refluxing dimethoxyethane (DME) under nitrogen. The liquid alloy could be pipetted out and stored for appreciable lengths of time under dimethoxyethane.

Preparation of Semidiones

The semidiones were prepared as solutions in the standard apparatus (15). Four precursors to the radicals were used: diesters, ketones, bis(trimethylsiloxy)alkenes, and benzoyl esters of α-hydroxy ketones. The solvents used were DME when diesters were the precursors and usually DMSO for the other precursors. The methods of generation have been described elsewhere (12-15) except for the benzoyl esters, and these could be handled in the same manner as the bis(trimethylsiloxy)alkenes.

Recording of Spectra

The esr spectra were obtained from either a Varian E-3 spectrometer using a 4 inch magnet and 100 KHz field modulation or a Varian V-4500 spectrometer with a 9 inch magnet and 100 KHz field modulation. Nmr spectra were recorded on a Varian A-60 spectrometer. Infrared spectra were recorded on a Perkin-Elmer Model 21 Double Beam Spectrometer. Mass spectra were obtained with an Atlas CH4 spectrometer.

Preparation of Compounds

Bis(trimethylsiloxy)alkenes

If possible, the bis(trimethylsiloxy)alkenes were prepared from the pure diesters. A 10-50 mg sample of the diester was mixed with 1-2 ml of chlorotrimethylsilane in 20 ml of ethyl ether or dimethoxyethane. The solution was degassed with N_2 for 5 min and 0.1-0.25 ml of sodium-potassium alloy (1:3-1:4 by weight) was added. The mixture was vigorously stirred under N_2 for 1-4 hr and then filtered. The solid material filtered off must be disposed of with care, usually covering it with xylene and slowly adding methanol is satisfactory. The clear solution is condensed under vacuum to remove all volatile substances. The crude bis(trimethylsiloxy)alkene remains as either an oil or a solid and may be used for generation of the semidione without further purification.

Dimethyl 4-methylpimelate (IIp)

This diester was prepared from the corresponding glutaric acid via the Arendt-Eisnert reaction (77). The procedure given here is general and was used for all the reactions of this type. 3-Methylglutaric acid (3.8 g) was added to 40 ml benzene with 10 ml of thionyl chloride and a few drops of pyridine. The mixture was stirred for 4 hr at room temperature and for 1 hr at 45°. The solvent and excess thionyl chloride were removed under reduced pressure and an additional 40 ml of benzene was added and removed under reduced pressure to remove the final traces of thionyl chloride. The diacid chloride was dissolved in 100 ml of ether and filtered through glass wool. The ether solution was then added to an etheral solution of diazomethane (excess), prepared from 33 g of Diazald (78) at 0°. When the addition was complete, the solution was allowed to slowly warm to room temperature overnight. The ether was removed under reduced pressure to give the crude bis(diazo)ketone (caution is advised as this type of compound is unstable and can decompose with explosive force). The bis(diazo)ketone was dissolved in 50 ml of methanol. A mixture of 0.5 g silver acetate in 5 ml of triethylamine was added in portions to this stirred solution. After the addition and nitrogen evolution was complete, the solution was heated to reflux, decolorized with charcoal, filtered, and cooled. The solvent was removed under reduced pressure and the residue taken up in 100 ml of ether. The ether solution was washed with 2 N hydrochloric acid and 10% sodium bicarbonate and then dried over magnesium sulfate. Filtering and removal of the ether under reduced pressure gave 2.1 g of the crude diester. Final purification was accomplished by vpc through a 5′ by ¼" column (10% QF-1, 15% FFAP, 15% Carbowax 20 M, and 20% DEGS gave the best separation for all the diesters) at 160-200° depending on the helium flow: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.45-2.1 (t,4,J=7 Hz), 2.1-1.0 (m,5), 1.0-0.85 (m,3); mass spectrum (70 eV) m/e (rel intensity) M^+=202 (0), 171 (21), 143

(3).

Dimethyl 4,4-dimethylpimelate (IIIp)

Using the procedure for IIp, from 0.5 g of 3,3-dimethylglutaric acid was obtained 200 mg of the diester: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.4-1.95 (m,4), 1.75-1.3 (m,4,), 0.88 (s,6); mass spectrum (70 eV) m/e (rel intensity) M^+=216 (0), 185 (15), 157 (7).

Dimethyl 3-methylpimelate (IVp)

Using the procedure for IIp, from 3.7 g of 2-methylglutaric acid was obtained 3.4 g of the diester: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.5-2.0 (m,4), 1.9-1.05 (m,3); mass spectrum (70 eV) m/e (rel intensity) M^+=202 (0), 171 (25), 143 (4).

Dimethyl meso-3,5-dimethylpimelate (Vp) and Dimethyl d,l-3,5-dimethylpimelate (VIp)

Using the procedure for IIp, from 3.6 g of the meso- and d,l-2,4-dimethylglutaric acids was obtained 2.4 g of the mixed diesters. The mixed diesters (1.5 g) and 4.0 g of potassium hydroxide in 50 ml of ethanol were refluxed for 10 hr. The solvent was removed under reduced pressure and 8 ml of water was added. After acidifying with 50% sulfuric acid, the mixture was extracted three times with ethyl acetate. After drying, the solvent was removed to give the mixture of diacids. To the mixture in a centrifuge tube was added 3 ml of benzene. This was then heated to reflux, cooled, and centrifuged. Decanting off the benzene, which contained the meso-diacid, left the crude d,l-diacid. Recrystallization from 50/50 benzene-acetone gave 220 mg of the d,l-diacid mp 136-138° [lit (79) 139-140°]. The decanted benzene solution was heated to remove most of the benzene, and 1 ml of ethyl acetate was added. The mixture was heated to reflux and then cooled to -20° for 10 hr. Decantation of the solvent left a mixture of the diacids, but removal of the ethyl acetate from the decanted portion left an oil which solidified on standing. Recrystallization from 50/50 benzene-hexane gave relatively pure meso-diacid (the impurity was a small amount of the d,l form) mp 75-82° [lit (79) 95-96°], 75 mg. Both isomers were esterfied with boron trifluoride methanol complex (80): d,l-isomer: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 1.65-2.3 (m,6), 1.3-1.05 (m,2), 1.05-0.85 (d,6,J=6.5 Hz); mass spectrum (70 eV) m/e (rel intensity) M^+=216 (0), 185 (25), 157 (3): meso-isomer: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.4-1.7 (m,2), 1.05-0.85 (d,6,J=6.5 Hz); mass spectrum (70 eV) m/e (rel intensity) M^+=210 (0), 185 (15), 157 (3). The fine structure of the ir and pmr spectra of the two isomeric diesters were distinctly different.

Cis-1,3-cyclopentanedicarboxylic acid

Norbornylene was oxidized according to the method of Birch *et al.* (81). In 100 ml of octane was dissolved 50 g of norbornylene and this solution was added to 1.5 l. of water in a 5 l. round bottom flask equipped with a high speed stirrer, thermometer, and carbon dioxide inlet tube. A steady stream of carbon dioxide was passed into it while a saturated solution of 270 g of potassium permanganate in water was added with vigorous stirring and at a rate such that the temperature did not go above 50°. After the addition was complete and the color of permanganate had disappeared, sulphur dioxide (from hydrochloric acid and sodium bisulphite) was passed into the solution until the brown color of manganese dioxide had been removed. The solution was concentrated to 1 l., acidified with a solution of 250 g of sulfuric acid in 350 g of water, and extracted with three 250 ml portions of ether. Removal of the ether followed by drying with a Dean-Stark apparatus using benzene, and recrystallization from benzene, yielded 21 g of crystals, mp 117.5-119° [lit (81) 119.9-120.6°].

Dimethyl cis-1,3-cyclopentanediacetate (IXp)

Using the procedure for IIp, 8.3 g of cis-1,3-cyclopentanedicarboxylic acid was chain extended to give 7.0 g (62%) of the desired diester, bp 107-112° at 0.5 mm: ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.50-0.60 (m,12); mass spectrum (70 eV) m/e (rel intensity) M^+=214 (0). 183 (20), 165 (6). See lit (82,83).

Exo-2-syn-7-dibromobicyclo[2.2.1]heptane

The procedure of Kwart and Kaplan (84) was used to brominate 60 g of norbornene. To the norbornene in 300 ml of CCl_4 with 51 g of dry pyridine, was added 102 g of bromine dropwise, while the flask was cooled in a salt-ice bath.

After the addition, the solution was filtered, washed with 6 N hydrochloric acid, and dried with magnesium sulfate. Removal of solvent, followed by fractional distillation afforded 46.4 g of the dibromide, bp 80-90° at 0.2 mm [lit (15) 103-107° at 4 mm].

Syn-7-bromobicyclo[2.2.1]heptene

Potassium (7.4 g) was dissolved in 165 ml of hot t-butyl alcohol, and to this solution was added 46.4 g of exo-2-syn-7-dibromobicyclo[2.2.1]heptene. After refluxing 12 hr the volume of the solution was doubled by the addition of water, and 50 ml of ether was then added. The layers were separated and the aqueous layer extracted three times with 100 ml of ether. The organics were combined, dried with magnesium sulphate, and distilled to give 17.0 g of product bp 55-60° at 7mm, [lit (84) 68-70° at 13 mm]: pmr neat δ 6.05-5.85 (m,2), 3.90-3.75 (m,1), 3.05-2.80 (m,2), 1.95-0.85 (m,4).

Anti-(85%) and syn-(15%)-7-deuterobicyclo[2.2.1]heptene

This was prepared and analyzed by G. Holland (15) from syn-7-bromobicyclo[2.2.1]heptene.

Trans-(85%) and cis-(15%)-2-deutero-cis-1,3-cyclopentanedicarboxylic acid

The deuterated norbornylene was oxidized in the same manner as the undeuterated material: the presence of one deuterium was confirmed by the pmr and the mass spectra.

Dimethyl trans-(85%) and cis-(15%)-2-deutero-cis-1,3-cyclopentanediacetate (IX-d_1p)

This material was prepared from the deuterated cyclopentanedicarboxylic acid using the procedure which had been used for the preparation of the undeuterated IXp. The pmr spectrum and mass spectrum agreed with the incorporation of one deuterium into the molecule.

Dimethyl trans-(50%) and cis-(50%)-2-deutero-cis-1,3-cyclopentanedicarboxylic acid

Dimethyl *trans*-(85%) and *cis*-(15%)-2-deutero-*cis*-1,3-cyclopentanedicarboxylate was prepared according to the procedure described by Holland (15) from the corresponding diacid. The diester 0.5 g in 50 ml of methanol to which 0.3 g of sodium had been added, was refluxed for 24 hr. Water (5 ml) was added and the solution refluxed for another three hr. Removal of solvent, addition of 10 ml of water, acidification with 50% sulfuric acid, extraction with three 50 ml portions of ether, drying with magnesium sulfate, and removal of solvent, left the crude product which was used without further purification.

Dimethyl trans-(50%) and cis-(50%)-2-deutero-cis-1,3-cyclopentanediacetate (IX-d_1p)

The product was prepared from the corresponding cyclopentane dicarboxylic acid using the procedure described for the 85:15% material. The presence of one deuterium was confirmed by pmr and mass spectrum.

Potassium azodicarboxylate

Potassium azodicarboxylate was prepared from azodicarbonamide using the procedure of Thiele (85).

Cis-4,5-dideuterocyclohexene

Preparation using deuterodiimide 1,4-cyclohexadiene, (17 g) in 20 ml of benzene was mixed with a solution of 24 g of potassium azodicarboxylate in 100 ml of methanol-d (86). Acetic acid-d, prepared by mixing and warming equimolar quantities of acetic anhydride and deuterium oxide (28 g) was added over a period of 1 hr. The mixture was stirred for 3 hr and 250 ml of ether was added. The etheral solution was washed with 50 ml of water, 50 ml of aqueous sodium bicarbonate, and 50 ml of water. After drying with magnesium sulfate, careful distillation gave a fraction consisting of benzene, 1,4-cyclohexadiene, and cis-4,5-dideuterocyclohexene; the latter two in a ratio of 6:1. This mixture was then oxidized without further separation.

Preparation with deuterodiborane A composite of the methods of Brown and Murray, (87) and Sondheimer and Wolfe (88) was used for this reaction. To a mixture of 16 g of 1,4-cyclohexadiene, 50 ml of diglyme, and 2 g of lithium aluminum deuteride under nitrogen, was added 75 mmoles of boron trifluoride-etherate over a period of 1 hr. The solution was stirred an additional 30 min and 20 g of acetic acid-d was added. The mixture was heated to reflux for 2 hr and the product slowly distilled. Redistillation gave 3.5 g of a

1:1 mixture of starting material and deuterated product, which was oxidized without further purification.

Dimethyl meso-3,4-dideuteroadipate

The crude mixture from the deuterodiimide reaction was oxidized with 180 g of potassium permanganate in 1.5 l. of acetone using the procedure for oxidizing endo-tricyclo-[3.2.1.$0^{2,4}$]oct-6-ene to dimethyl bicyclo[3.1.0]hexane-endo, endo-2,4-dicarboxylate (XXIXp). The mixture of crude diacids was refluxed with 100 ml of methanol containing a trace of acid for 4 hr. Removal of solvent, addition of 150 ml of ether, extraction with 20 ml of aqueous sodium bicarbonate, drying, and removal of solvent, gave a mixture of diesters. The crude mixture was purified by vpc with a 5' by ¼", 15% Carbowax column at 150° to give 0.6 g of the pure product: pmr (CCl_4) δ 3.60 (s,6), 2.45-2.15 (m,4), 1.75-1.45 (m,2+). Repeated integration gave the result that the product from the deuterodiimide reaction had at least 80% of the desired deuterium incorporated and from the deuterodiborane, at least 90% deuterium incorporation.

Dimethyl erythro-3,4-dideuteropimelate (XIIp)

The deuterated dimethyl adipate (0.5 g) was refluxed in 50 ml of methanol containing an equimolar amount of sodium hydroxide for 4 hr. Removal of solvent, acidification with 2 M sulfuric acid, and extraction with ether, gave a solution of the three possible products. Drying with magnesium sulfate and removal of solvent gave the crude acid-ester which was chain extended using the Arendt-Eisnert procedure for IIp. The crude dimethylpimelate was purified by vpc using a 5′ by ¼" Carbowax 20 M column at 160° to give 0.2 g of the pure product: pmr (CCl_4) δ 3.60 (s,6), 2.45-2.10 (m,4), 1.90-1.25 (m,4+). The retention time on this particular column was identical to an undeuterated sample of this diester.

2-Carbethoxycyclohexanone

This ester was prepared from 196 g of cyclohexanone and 292 g of diethyl oxylate according to the method of Snyder et al. (89). The yield was 164.8 g of product, bp 120-130° (37 mm) [lit (89) 125-140° (40 mm)]: pmr (CCl_4) δ 4.40-3.95 (q,2,J=7 Hz), 2.40-1.50 (m,8), 1.45-1.15 (t,3,J=7 Hz).

β-(1-Carbethoxy-2-ketocyclohexyl)-propionaldehyde

The condensation of 25 g of 2-carbethoxycyclohexanone with 10 g of acrolein in ethanol was done using the procedure of Cope and Synerholm (90). The product, 18.2 g, had a bp 109-112° (0.2 mm) [lit (90) 140-143° (1.5 mm)]: pmr (CCl_4) δ 9.65-9.55 (t,1,J=1.2 Hz), 4.40-3.95 (q,2,J=7 Hz), 2.65-1.45 (m,12), 1.45-1.15 (t,3,J=7 Hz).

1-Carbethoxybicyclo[3.3.1]non-3-en-9-one

β-(1-Carbethoxy-2-ketocyclohexyl)-propionaldehyde (18 g) was added to 36 ml of concentrated sulfuric acid according to the procedure of Cope and Synerholm (90). The workup and distillation gave 8.0 g of product which solidified on standing: mp 45.5-46.5° [lit (90) 48.5-49.5°]; pmr (CCl_4) δ 6.15-5.80 (m,1), 5.75-5.35 (m,1), 4.40-3.95 (q,2,J=7 Hz), 3.65-1.50

(m,9), 1.45-1.15 (t,3,J=7 Hz).

Diethyl 1,5-cyclooctenedicarboxylate

The diester was prepared from 1-carbethoxybicyclo-[3.3.1]non-3-ene-9-one using the method of Cope *et al*. (91): pmr (CCl_4) δ 7.10-6.70 (t,1,J=8 Hz), 4.40-3.80 (m,4), 2.70-1.45 (m,11), 1.45-1.05 (m,6).

Dimethyl 1,5-cyclooctanedicarboxylate (XVIIIp)

Potassium hydroxide (2.0 g) and 2.0 g of diethyl 1,5-cyclooctenedicarboxylate was refluxed overnight in 100 ml of ethanol. The solvent was removed under reduced pressure and 10 ml of water were added to the residue. After acidifying it with concentrated hydrochloric acid, the mixture was extracted three times with 75 ml of ether. Drying and removal of the ether left 1.9 g of crude diacid mp 175-200°, which gave 0.85 g of material mp 208-214° after one recrystallization from ethyl acetate [lit (91) 217.5-219.5°]. Half of this material was hydrogenated in 20 ml of acetic acid at 30 psi using 10% Pd/C as a catalyst. Filtering and removal of the solvent left the crude diacid. Acetic anhydride (10 ml) was added to the crude product and the mixture refluxed for 4 hr, in order to convert the *cis* and *trans* mixture into the *cis*-anhydride. The acetic anhydride was removed under reduced pressure, and 15 ml of methanol with a trace of acid, was added to the residue. Refluxing for 4 hr, removal of solvent, addition of 100 ml ether, washing with dilute sodium bicarbonate, drying, and removal of solvent, gave 290 mg of the desired product. An analytical sample was purified by glpc at 190° through a 10% QF-1 column (5′ by ¼″) to give a product which solidified on standing mp 39-46°; pmr (CCl_4) δ 3.58 (s,6), 2.65-2.15 (m,2), 2.15-1.35 (m,12); ir neat 5.74μ; mass spectrum (70 eV) m/e (rel intensity), M^+=228 (1), 197 (12), 169 (37).

1-Bromo-2-cycloheptene

From 100 g of cycloheptene, 184.5 g N-bromosuccinimide, and 1.3 g benzoyl peroxide in 700 ml of carbon tetrachloride, was obtained 76 g (42%) of product according to the method of Cope *et al*. (92), bp 57-60° at 3 mm.

1,3-cycloheptadiene

Quinoline (112 g) was added to the bromocycloheptene in the manner described by Cope *et al*. (92). The workup gave 32.4 g of product bp 118-120° (79%); pmr neat δ 5.70 (s,4), 2.50-2.10 (m,4), 2.05-1.50 (m,2).

Bicyclo[3.2.2]non-6-ene-endo, cis-8,9-dicarboxylic anhydride

Cycloheptadiene (70 g) and 74 g of maleic anhydride were heated to reflux in 150 ml of xylene for two hours. The solvent was removed under reduced pressure to give a residue which was recrystallized from ethyl acetate-hexane yielding 39.7 g of crystalline product mp 102-104° [lit (93) 110-111°]; pmr ($CDCl_3$) δ 6.30-6.10 (m,2), 3.40-3.50 (m,2), 3.15-2.85 (m,2), 1.80-1.60 (m,6).

Bicyclo[3.2.2]nonane-endo,cis-6,7-dicarboxylic anhydride

Bicyclo[3.2.2]non-6-ene-endo,cis-8,9-dicarboxylic anhydride (48 g) was hydrogenated in 150 ml ethyl acetate using 1 g of 10% Pd/C as a catalyst to give an 85% yield of product mp 152-155° [lit (93) 156-157°]: pmr (CH_2Cl_2) δ 3.25-3.15 (m,2), 2.50-2.30 (m,2), 1.90-1.50 (m,10).

Bicyclo[3.2.2]non-6-ene

Bicyclo[3.2.2]nonane-endo,cis-6,7-dicarboxylic anhydride was refluxed with 400 ml of methanol containing a trace of acid for 10 hr. To the mixture was added two equivalents of sodium methoxide and the mixture refluxed an additional 10 hr. The resulting solution was added to 500 ml of 1 N sodium hydroxide and the methanol distilled off. The mixture was refluxed 4 hr, cooled, acidified with 50% sulfuric acid, and extracted four times with 250 ml of ether. The ether was dried and removed under reduced pressure to presumably give the trans diacid. The crude diacid was then added to 80 g of lead tetraacetate (94) in 500 ml of pyridine in a 1 l. round bottom flask equipped with a reflux condenser, and heated to 75° for 30 min. The remaining solution was mixed with enough dilute nitric acid to make it acidic to Congo Red. This mixture was then extracted with three, 250 ml portions of ether, and the combined ether extracts were dried and the solvent distilled off to give 6.6 g of the crude olefin which was greater than 90% pure by glpc. An analytical sample prepared by glpc had mp 107-108°: pmr (CCl_4) δ 6.15-

5.95 (m,2), 2.60-2.20 (m,2), 1.85-1.30 (m,10).

Dimethyl cis-1,4-cycloheptanedicarboxylate (XXp$_1$)

Bicyclo[3.2.2]non-6-ene (5 g), 2.7 g of ammonium sulfate, 12 g of potassium permanganate, and 215 ml of water, were stirred for 20 hr. The resulting solution was filtered and the volume reduced to 50 ml by removal of the solvent under reduced pressure. This solution was then acidified with 50% sulfuric acid and extracted three times with 100 ml of ether. To this etheral solution was added an etheral diazomethane solution (78) until the characteristic color of diazomethane persisted. Removal of solvent gave a mixture of products from which the semidione was generated without further purification. The α,α'-dideuterodiester was obtained by exchanging the α-hydrogens in methanol-d containing a small amount of sodium methoxide. Removal of the solvent, dissolving the residue in ether, washing with water, and removal of the solvent left the crude deuterated mixture. Both the deuterated and undeuterated esters were used for generation of the semidione without further purification.

2-Chloro-1-cyanoethyl acetate

Oxalic acid dihydrate (330 g) and 400 g of chloroacetaldehyde diethyl acetal were placed in a 1 l. round bottom flask and heated to boiling. A distillate was collected into a receiver containing 100 g of water. The distillate (275 g, bp 85-90°) and water were diluted with an additional 100 ml of water and added rapidly to a solution of 130 g of sodium cyanide in 400 ml of water cooled in a salt-ice bath. After stirring 10 min, the mixture was extracted four times with 200 ml of ether. The extracts were dried, solvent stripped off, and distilled to give 106.5 g of crude product (55%) bp 60-70° at 10 mm: pmr same as published (95).

α-Acetoxyacrylonitrile

2-Chloro-1-cyanoethyl acetate (106.5 g) was diluted with 1 l. of ether. Over a period of 15 min, 110 ml of triethyl amine in 100 ml of ether was added to this solution. The mixture was stirred for 7 hr and the solution and solid were washed five times with 60 ml of 10% hydrochloric acid and once with 50 ml of water. After drying, a pinch of catchecol was added and the ether stripped off. Distillation gave 54.5 g of product (68%) bp 69° at 11 mm: pmr was the same as published (95).

Bicyclo[3.2.2]non-6-en-8-one

1,3-Cycloheptadiene (8.5 g) and 10 g of α-acetoxy-acrylonitrile were heated in a sealed tube at 140° for 5 days. The liquid, which had darkened, was added to warm sodium methoxide in methanol, prepared from 2 g of sodium in 100 ml of methanol. After standing an hour, 500 ml of water was added and the solution extracted three times with 100 ml portions of methylene chloride. The combined extracts were dried over magnesium sulfate and the solvent was distilled off. To the remaining oil, 50 ml of carbon tetrachloride was added. Filtering and the removal of the solvent gave 0.6 g of crude product. Purification by glpc gave 250 mg of pure ketone identical to a sample prepared using the route described by Freeman *et al.* for similar ketones (96): pmr (CCl_4) δ 6.45-5.85 (m,2), 2.95-2.50 (m,2), 2.40-2.20 (m,2), 2.00-1.40 (m,6).

Bicyclo[3.2.2]nonan-6-one (XXp_2)

Hydrogenation of bicyclo[3.2.2]non-6-en-8-one in methanol gave the product in quantitative yield when 10% Pd/C was used as a catalyst: mp 167-169° (sealed tube) [lit (97) mp 170° (sealed tube)]. Generation of the semidione, using base and O_2 in DMSO, gave a signal identical to that from XXp_1.

Bicyclo[3.2.2]non-6-ene-endo,cis-8,9-dimethanol

Bicyclo[3.2.2]non-6-ene-*endo*,*cis*-8,9-dicarboxylic anhydride in 250 ml of ether was slowly added to a mixture of 21 g of lithium aluminum hydride in 500 ml of ether. The mixture was refluxed 3 hr after the addition was complete. Water (60 g) was slowly added to the mixture to decompose any remaining $LiAlH_4$. An additional 1 l. of ether was added, the whole mixture filtered, and the ether removed under reduced pressure, to give the crude product which solidified on standing. Recrystallization from methanol gave 13.2 g of product mp 65.5-67.5°: pmr ($CDCl_3$) δ 6.10-5.85 (m,2), 3.75-3.40 (m,6), 2.55-2.15 (m,4), 1.65-1.40 (m,6).

Bicyclo[3.2.2]non-6-ene-endo,cis-8,9-dimethanol ditosylate

In 125 ml of pyridine, 13.2 g of bicyclo[3.2.2]non-6-ene-*endo*,*cis*-8,9-dimethanol and 38 g of p-toluenesulfonylchloride was dissolved and stirred for 24 hr. The mixture was poured into 400 ml of ice cold 6 N hydrochloric acid and the mixture was extracted three times with 300 ml of ethyl acetate. The combined extracts were washed with 100 ml of 6 N hydrochloric acid and 75 ml of saturated sodium bicarbonate. Removal of solvent after drying with magnesium sulfate gave 31 g of an oil. Recrystallization from methanol gave 20.6 g of crystals, mp 90-91°: pmr ($CDCl_3$) δ 7.90-7.65 (d,4,J=8.4 Hz), 7.45-7.20 (d,4,J=8.4 Hz), 5.95-5.75 (m,2), 4.00-3.70 (m,4), 2.55-2.20 (m,10), 1.65-1.20 (m,6).

Endo,cis-8,9-dimethylbicyclo[3.2.2]non-6-ene

Into a refluxing mixture of 6 g of lithium aluminum hydride in 600 ml of ether was added 20 g of bicyclo[3.2.2]-non-6-ene-*endo*,*cis*-8,9-dimethanol ditosylate via a soxlet extractor. The mixture was refluxed for three days and then 50 ml of saturated ammonium chloride solution was slowly added. After filtering and drying, the ether was distilled off to leave 5.8 g of crude olefin, greater than 95% pure by pmr and glpc: pmr neat δ 6.15-5.90 (m,2), 2.30-1.90 (m,4), 1.65-1.35 (m,6), 1.00-0.80 (m,6).

Dimethyl cis,cis-2,3-dimethylcycloheptane-cis-1,4-dicarboxylate (XXIp)

Endo,*cis*-8,9-dimethylbicyclo[3.2.2]non-6-ene (5.8 g) was added to a mixture of 22 g of potassium permanganate and 1.6 g of sodium bicarbonate in 500 ml of acetone and the mixture was then stirred for 20 hr at room temperature. The mixture was filtered and the filtercake was washed with acetone, and then added to 200 ml of water. Sulphur dioxide was bubbled through the mixture until the color of the manganese dioxide had vanished. The solution was acidified with 50% sulfuric acid and the resulting solution extracted with three 200 ml portions of ether. After drying the combined ether extracts, the ether was removed and the crude mixture esterfied with boron trifluoride methanol complex (80). The resulting product was a mixture of compounds, as had been the case with the parent compound. Generation of semidione gave a spectrum consistant with the desired radical.

Dimethyl cis-1,3-cyclobutane-1-acetate-3-carboxylate (XXIIIp)

Treatment of 6.4 g of cis-cyclobutane-1,3-dicarboxylic anhydride (98) with 1.2 equivalent of methanol at reflux for 1 hr gave the monoester; pmr (CH_2Cl_2) δ 2.15-2.65 (m,4), 2.70-3.25 (m,2), 3.61 (s,3), 7.60 (s,1). The monoester was treated in the same manner as described for chain extension 3-methylglutaric acid in the preparation of IIp, yielding 5.9 g (58%) of the crude diester ~90% pure by glpc; ir neat 5.78μ; pmr (CCl_4) δ 1.55-3.15 (m,6), 3.61 (s,6); mass spectrum (70 eV) m/e (rel intensity) M^+=186 (1), 155 (36), 127 (14).

Dimethyl cis-1,3-cyclobutanediacetate (XXIIp)

A mixture of 3.2 g of cis-1,3-cyclobutanedicarboxylic anhydride and 3.2 g of 6 N hydrochloric acid was refluxed for 10 min. The mixture was extracted twice with 50 ml of ether and the extracts were then dried ($MgSO_4$). Removal of ether under vacuum left the solid diacid which was chain extended (see IIp) to give 3.1 g (61%) of product. The crude diester was purified by glpc on a 5′ by ¼″, 10% QF-1 column at 160°; ir neat 5.78μ; pmr (CCl_4) δ 1.1-1.7 (m,2), 2.10-2.60 (m,8), 3.60 (s,6); mass spectrum (70 eV) m/e (rel intensity) M^+= 200 (0), 169 (12), 141 (5).

Diethyl 2,2-dimethyl-cis-cyclobutane-1-acetate-3-carboxylate (XXVp)

This compound was prepared according to the method of Wielicki et al. (99); pmr ($CHCl_3$) δ 4.20-3.70 (q,4,J=7 Hz), 2.75-1.60 (m,6), 1.25-0.95 (t,6,J=7 Hz), 1.07 (s,3), 0.77 (s,3).

Diethyl 2,2-dimethylcyclobutane-cis-1,3-diacetate (XXIVp)

This compound was prepared according to the method of Wielicki et al. (99) but rather than being all cis, was a 2:1 mixture of cis:trans, as determined by pmr. The cis isomer showed two methyl peaks while the trans had only one.

Endo-tricyclo[$3.2.1.0^{2,4}$]oct-6-ene (XXIXb)

This olefin was prepared using the method of Closs and Krantz (49); pmr 5.75-5.55 (t,2,J=1.9 Hz), 2.9-2.6 (m,2), 1.9-1.6 (m,2), 1.45-1.15 (m,2), 0.75-0.20 (m,2).

Dimethyl bicyclo[3.1.0]hexane-endo,cis-2,4-dicarboxylate (XXIXp)

A solution of 4.9 g of endo-tricyclo[$3.2.1.0^{2,4}$]oct-6-ene in 300 ml of acetone was stirred and cooled (ice-bath) while

18.3 g of potassium permanganate was added in portions over a 6 hr period. The solution was allowed to warm slowly to room temperature, stirred for an additional 10 hr, and filtered. The filtercake, manganese dioxide, and the potassium salt of the desired diacid, was added to 250 ml of water, and sulfur dioxide was then bubbled through the stirred suspension until no manganese dioxide remained. The solution was acidified to Congo Red with 50% sulfuric acid and extracted with three 100 ml portions of ether. The combined ether extracts were reduced to a 50 ml volume and extracted with three 20 ml portions of 10% aqueous sodium bicarbonate. The extracts were combined, acidified to Congo Red with 50% sulfuric acid, and extracted with three 100 ml portions of ethyl acetate. The combined extracts were dried with magnesium sulfate, filtered, and the ethyl acetate removed under reduced pressure. The crude diacid was dissolved in 25 ml of methanol, and an etheral solution of diazomethane (78) was added until the characteristic color persisted. Removal of the solvent under reduced pressure gave 2.3 g (25%) of the diester. The sample was purified on a 15% Carbowax 20 M column, 5′ by $\frac{1}{4}$", at 190°: ir neat 5.78μ; pmr (CCl_4) δ 3.65 (s,6), 3.25-2.75 (m,2), 2.05-1.40 (m,4), 0.90-0.20 (m,2); mass spectrum (70 eV) m/e (rel intensity) M^+=198 (20), 167 (18), 139 (100).

<u>Exo-tricyclo[3.2.1.0^{2,4}]oct-6-ene (XXXb)</u>

To a hot solution of cupric acetate monohydrate (0.5 g) in 50 ml of glacial acetic acid was added 35 g of zinc, 30 mesh. The mixture was shaken for 3 min while being kept hot. The liquid was decanted off, and the residue washed with 50 ml of acetic acid and three times with 50 ml of ether. Ether (100 ml) and a few ml of methylene iodide were added to the couple. The mixture was gently warmed to reflux and 24.0 g of bicyclo[2.2.1]heptadiene with the remaining methylene iodide (83.0 g in all) was added dropwise for 1½ hr. The mixture was refluxed 20 hr and then cooled. The liquid was decanted into a separatory funnel containing ice and 1 N hydrochloric acid. The layers were shaken and separated and the ether layer washed with another 40 ml of acid. After washing with bicarbonate, the ether was dried and the mixture distilled to give 16.4 g (59%) of product, which was a 3:1 mixture of isomers (exo:endo) as analyzed by pmr in comparison to the pure endo product; exo isomer pmr (CCl_4) δ 6.40-6.25 (t,2,J=1.9 Hz), 2.80-2.60 (m,2), 1.50-1.15 (m,2), 1.10-0.60 (m,4).

Dimethyl bicyclo[3.1.0]hexane-exo,cis-2,4-dicarboxylate

A 13.4 g sample of the above mixture of olefins was oxidized with 65 g of potassium permanganate using the procedure for the preparation of XXIXp. A 6.2 g (24%) mixture of the diesters was obtained, which could be separated on a 5' by ¼" Carbowax 20 M column at 170°. The compound present in smaller quantity and having the shorter retention time, proved to be the endo-isomer upon comparison of its pmr with the previously prepared sample. The exo-isomer had spectral properties in agreement with its structure; ir neat 5.78μ; pmr (CCl_4) δ 3.60 (s,6), 2.83-2.60 (d,2,J=8 Hz), 2.55-2.25 (d,1,J=14.5 Hz), 1.85-1.25 (m,3), 0.80-0.00 (m,2); mass spectrum (70 eV) m/e (rel intensity) M^+=198 (30), 167 (33), 139 (100).

Dimethyl tetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]nonane-*endo*,*cis*-8,9-dicarboxylate

A sample of the dicarboxylic acid was esterfied with boron trifluoride methanol complex (80) to give the diester mp 64-66° [lit (100) 61-62°]; pmr (CCl_4) δ 3.60 (s,6), 3.25-3.10 (t,2,J=2.0 Hz), 2.32-2.15 (m,2), 1.90-1.70 (m,1), 1.55-1.45 (m,2), 1.27-1.15 (m,3); ir (CCl_4) 5.72μ; mass spectrum (70 eV) m/e (rel intensity) M^+=236 (40), 205 (25), 177 (15).

Tetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]non-8-ene (XXXIb)

Lead tetraacetate (94) (73 g) and 17.5 g of tetracyclo-[4.3.0.$0^{2,4}$.$0^{3,7}$]nonane-*endo*,*cis*-8,9-dicarboxylic acid were mixed with 250 ml of pyridine and the mixture degassed for 10 min with oxygen. The mixture was heated in an oil bath at 76° and after a few min the reaction began and quickly subsided. After standing an additional 5 min the mixture was cooled and poured into a cool solution of 250 ml of nitric acid in 1250 ml of water. The resulting mixture was extracted three times with 600 ml of ether, and the ether was washed twice with 150 ml of saturated sodium bicarbonate. After drying, the ether was distilled off and the product purified by bulb-to-bulb distillation under vacuum to give 1.55 g of the pure olefin; pmr (CCl_4) δ 6.02-5.92 (t,2,J=1.9 Hz), 2.64-2.47 (m,2), 2.00-1.80 (m,1), 1.80-1.60 (m,1), 1.60-1.47 (t,2,J=1.9 Hz), 1.28-1.03 (d,2,J=5 Hz).

Dimethyl tricyclo[2.2.1.$0^{2,6}$]heptane-endo,endo-3,5-dicarboxylate (XXXIp)

Oxidation of 1.4 g of the above olefin with 6.2 g of potassium permanganate (see XXXIX) gave 0.95 g of the solid diester on workup. Purification by glpc on a 5′ by ¼" 10% QF-1 column at 170° gave the analytical sample mp 80.5-81.5°; ir (CCl_4) 5.78μ; pmr (CCl_4) δ 3.54 (s,6), 2.67-2.50 (m,1), 2.45-2.33 (m,2), 1.60-1.15 (m,5); mass spectrum (70 eV) m/e (rel intensity) M^+=210 (4), 179 (25), 151 (24).

Endo,endo-2,6-dichloro-1,7,7-trimethylbicyclo[2.2.1]heptane

This compound was prepared according to the procedure of Kwart and Null (101), mp 170-173° [lit (101) 173°]; pmr (CCl_4) 4.45-4.10 (d,d,2,J=5.0 Hz, J=10.2 Hz), 2.90-2.20 (m,2), 1.90-1.65 (t,2,J=5.0 Hz), 1.65-1.40 (d,1,J=5.0 Hz), 1.05 (s,3), 0.96 (s,6).

1,7,7-Trimethylbicyclo[2.2.1]heptadiene

Using a modification of the method of Hanack *et al.*, (102) 6.5 g of sodium were dissolved in 100 g of 1-nonanol. To this solution heated with an oil bath to 245°, 25 g of *endo*,*endo*-2,6-dichloro-1,7,7-trimethylbicyclo[2.2.1]heptane was quickly added and the diolefin collected. Redistillation gave the product slightly contaminated with 1-nonanol. Glpc gave a sample mp 101-102° [lit (102)103-103.5°]; pmr δ 5.65-

6.45 (d,d,2,J=3.3 Hz, J=5.4 Hz), 6.35-6.20 (d,d,2,J=1.3 Hz, J=5.4 Hz, 3.1-2.90 (m,1), 1.20 (s,3), 1.01 (s,6).

Dimethyl 4,5,5-trimethyltetracyclo[$4.3.0.0^{2,4}.0^{3,7}$]nonane-endo,cis-8,9-dicarboxylate (XXXVIp) and Dimethyl 5,5,6-trimethyltetracyclo[$4.3.0.0^{2,4}.0^{3,7}$]nonane-endo,cis-8,9-dicarboxylate (XXXVp)

1,7,7-Trimethylbicyclo[2.2.1]heptadiene (22.9 g) and 18 g of maleic anhydride were added to 7 ml of xylene and the mixture was heated in an oil bath at 185-190° for 16 hr. Removal of solvent and recrystallization of the residue from 40 ml of ethyl acetate gave 4.5 g of a pure isomer mp 159-161°; pmr ($CDCl_3$) δ 3.52-3.38 (d,d,2,J=1.9 Hz, J=3.2 Hz), 2.48-2.33 (m,2), 1.30-1.20 (m,3), 0.86 (s,6), 0.84 (s,3). This isomer was the 5,5,6-trimethyl anhydride. Esterfication with boron trifluoride methanol complex (80) gave the pure dimethyl ester; pmr (CCl_4) δ 3.59 (s,6), 3.10-2.95 (m,2), 2.15-2.00 (m,2), 1.45-1.25 (d,2,J=5.0 Hz), 1.15-0.90 (t,1, J=5.0 Hz), 0.80 (s,6), 0.78 (s,3); ir (CCl_4) 5.73μ; mass spectrum (70 eV) m/e (rel intensity) M^+=278 (100), 247 (33), 219 (15). The mother liquor left from the recrystallizations was combined and condensed to leave a semi-solid residue. The residue was passed through a silica gel column (50/50 benzene/pentane) to give 17.3 g of a mixture of isomers by pmr. Esterfication (80) gave a mixture of diesters which were separated into 4 peaks by glpc through a 5′ by $\frac{1}{4}$" 15% FFAP column at 210°. The first and fourth peaks were unidentified, the third peak had a retention time and pmr identical to that of the 5,5,6-trimethyl diester. The second, and largest peak, was collected and identified as the 4,5,5-trimethyl diester mp 45-52°; pmr (CCl_4) δ 3.57 (s,6), 3.05-2.95 (t,2,J=2.0 Hz), 2.55-2.40 (m,2), 1.50-1.35 (m,1), 1.21-1.11 (m,2), 1.01 (s,3), 0.85 (s,6); ir (CCl_4) 5.73μ; mass spectrum (70 eV) m/e (rel intensity) M^+=278 (20), 247 (12), 219 (6). The mixture of anhydrides (4:1) was used in subsequent reactions without further purification.

5,5,6-Trimethyltetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]non-8-ene (XXXIIb)

5,5,6-Trimethyltetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]nonane-*endo*, *cis*-8,9-dicarboxylic anhydride (4.1 g) and 6 g of sodium carbonate were heated to 50° overnight in 100 ml of water. Following neutralization with hydrochloric acid, the diacid was filtered off, washed with water and dried to give 4.3 g of solid. Bisdecarboxylation with lead tetraacetate (14 g) in pyridine under the usual conditions (see XXXIb) gave 540 mg of product; pmr δ 6.03-5.92 (t,2,J=2.0 Hz), 2.45-2.30 (m,2), 1.70-1.50 (t,1,J=4.8 Hz), 1.33-1.16 (d,2,J=4.8 Hz), 0.80 (s,6), 0.60 (s,3).

4,5,5-Trimethyltetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$]non-8-ene (XXXIIIb)

Treatment of the 4:1 mixture (see XXXIIb) in the manner described above gave 0.9 g of a 1:1 mixture of two olefins, the 5,5,6-trimethyl olefin and the 4,5,5-trimethyl olefin. The former had an identical pmr to the sample described above, while the latter showed pmr δ 6.00-5.88 (t,2,J=2.0 Hz), 2.85-

2.65 (m,2), 1.50-0.90 (m,3), 1.04 (s,3), 0.83 (s,6). This mixture was difficult to separate in quantity and hence was used in the oxidation step without further separation.

Dimethyl 4,7,7-trimethyltricyclo[2.2.1.$0^{2,6}$]heptane-endo,endo-3,5-dicarboxylate (XXXIIp)

Oxidation of 0.5 g of 5,5,6-trimethyltetracyclo[4.3.0.-$0^{2,4}$.$0^{3,7}$]non-8-ene with potassium permanganate in acetone (see XXIXp) gave 350 mg of solid diacid which was esterfied (80) and purified by glpc 10% QF-1 column (5′ by ¼") at 175° to give 80 mg of pure diester mp 70-73°; pmr (CCl_4) δ 3.59 (s,6), 2.53 (s,2), 1.67-1.50 (d,2,J=5.3 Hz), 1.25 (s,3), 1.23-0.98 (m,1), 0.90 (s,6); ir (CCl_4) 5.78μ; mass spectrum (70 eV) m/e (rel intensity) M^+=252 (1), 221 (33), 193 (16).

Dimethyl 1,7,7-trimethyltricyclo[2.2.1.$0^{2,6}$]heptane-endo, endo-3,5-dicarboxylate (XXXIIIp)

Oxidation of the corresponding mixture of olefins (see XXXIIIb) (850 mg) with potassium permanganate (see XXIX), and esterfication (80) gave 240 mg of a 2:1 mixture, the minor product being the 4,7,7-trimethyl isomer. Separation was accomplished by a 10% QF-1 column (5′ by ¼") at 170°. The desired diester gave the following analysis; mp 65.5-68.5°; pmr (CCl_4) δ 3.50 (s,6), 2.85-2.75 (m,2), 2.25-2.10 (m,1), 1.43-1.33 (m,2), 1.05 (s,3), 0.95 (s,6); ir (CCl_4) 5.78μ; mass spectrum (70 eV) m/e (rel intensity) M^+=252 (10), 221 (40), 193 (30).

Endo-tricyclo$[3.2.2.0^{2,4}]$non-6-ene-endo,cis-8,9-dicarboxylic anhydride

The Diels-Alder adduct of maleic anhydride and cycloheptatriene was prepared according to the method of Alder and Jacobs (103) mp 101-101.5° [lit (103) 101°]; pmr ($CDCl_3$) δ 6.00-5.76 (m,2), 3.62-3.33 (m,2), 3.33-3.17 (m,2), 1.30-0.97 (m,2), 0.58-0.18 (m,2).

Tricyclo$[3.2.2.0^{2,4}]$octa-6,8-diene

The anodic oxidation of *endo*-tricyclo[3.2.2]non-6-ene-*endo*,*cis*-8,9-dicarboxylic anhydride according to the procedure of Radlick *et al*. (104) gave the desired olefin in 29% yield; pmr (CCl_4) δ 6.65-6.35 (m,2), 6.05-5.75 (m,2), 3.75-3.43 (m,2), 1.30-0.95 (m,2), 0.78-0.20 (m,2).

Endo,endo- and exo,endo-tetracyclo$[3.3.2.0^{2,4}.0^{6,8}]$dec-9-ene

Using the procedure described for the preparation of *exo*-tricyclo$[3.2.1.0^{2,4}]$oct-6-ene (XXXb), 2.7 g of tricyclo-$[3.2.2.0^{2,4}]$octa-6,8-diene reacted with 9 g of methylene iodide and 3.6 g of the zinc-copper couple at reflux for 3 hr to give 2.2 g bp 95-100° (15 mm) of a 2:1 mixture of olefins *endo*,*endo*:*exo*,*endo*. The ratio was determined by pmr which showed two types of olefinic protons. This mixture was then oxidized with permanganate without separation, yielding a single diacid and the unreacted *endo*,*endo*-isomer; pmr of *endo*,*endo* olefin in (CCl_4) δ 5.40-5.10 (m,2), 3.10-2.70 (m,2), 1.20-0.85 (m,4), 0.30-0.00 (m,4); pmr of the mixture showed the olefinic protons of the *exo*,*endo*-isomer at δ 6.10-5.85.

Dimethyl trans-tricyclo[5.1.0.0^{3,5}]octane-cis-2,6-dicarboxylate (XXXIXp)

The above mixture of olefins (2.2 g) was oxidized with 8.6 g of potassium permanganate in 150 ml of acetone buffered with 0.5 g of sodium bicarbonate using the procedure for XXIXp. Esterfication with boron trifluoride methanol complex, followed by purification on a 10% QF-1 glpc column gave 240 mg of the pure diester, mp 63.5-66°. Distillation of the recovered acetone gave 1.2 g of the endo,endo-olefin which had been unaffected by the permanganate. The diester had a pmr (CCl_4) δ 3.60 (s,6), 2.40-2.20 (m,2), 1.60 to -0.35 (m,8); ir (CCl_4) 5.75μ; mass spectrum (70 eV) m/e (rel intensity) M^+=224 (10), 193 (5), 165 (60).

Endo,endo-8,9-dimethyl-endo-tricyclo[3.2.2.0^{2,4}]non-6-ene (XXXVIIIp)

This olefin was prepared using the procedure of Holland (15), the same as was used for the preparation of endo,endo-8,9-dimethylbicyclo[3.2.2]non-6-ene. The spectral properties were the same as reported (15); pmr δ 5.85-5.60 (m,2), 2.70-2.35 (m,2), 2.20-1.75 (m,2), 1.10-0.70 (m,8), 0.15 to -0.10 (m,2).

Benzoyl nitrite method of preparation of semidiones from olefins

The following procedure can be considered general for stable semidiones. Endo,endo-tetracyclo[3.3.2.0^{2,4}.0^{6,8}]-dec-9-ene (130 mg) was mixed with 1 ml of methylene chloride and 300 mg of benzoyl nitrite in an nmr tube. After standing 10 hr the olefinic absorption had disappeared and the mixture was added to 10 ml of methylene chloride and washed twice with 10% sodium bicarbonate. After removing the solvent under reduced pressure, 25 ml of 3:1 hexane/benzene was added along with 3 g of grade III alumina. After refluxing for 4 hr, the mixture was dried and filtered, and the solvent removed to give the benzoic acid ester of the α-ketone. This could be used to generate the semidione in degassed DMSO containing potassium t-butoxide without further purification.

Endo-tricyclo[3.2.2.$0^{2,4}$]non-6-ene

A stirred suspension of 30 g of sodium amide in 50 ml of mineral oil was heated to 90° in a 250 ml three necked flask. A slow stream of nitrogen was passed through the flask while a solution of 50 ml of allyl chloride in 30 ml of mineral oil was added dropwise to the stirred suspension over a period of 8 hr. The generated cyclopropene was passed through a short condenser and bubbled into a solution of 5 g of 1,3-cyclohexadiene in 45 ml of pentane. To keep the cyclopropene from escaping, a dry ice acetone condenser was used as the passage for the escaping nitrogen. After the addition was complete, the pentane solution was stirred an additional 2 hr. Removal of the pentane followed by bulb-to bulb distillation under vacuum (0.5 mm) gave a fraction (1.3 g) which was 80% product and 20% cyclohexadiene. An analytical sample was obtained by glpc on a 5′ by ¼" 15% Carbowax 20 M column at 120°; mp 59-

60.5°; pmr (CCl_4) δ 5.90-5.57 (m,2), 2.83-2.50 (m,2), 1.73-0.96 (m,4), 0.96-0.60 (m,2), 0.08 to -0.27 (m,2).

Dimethyl bicyclo[4.1.0]heptane-endo,endo-2,5-dicarboxylate (XXXVIIp)

Oxidation of the above olefin (1.8 g) with potassium permanganate (7.0 g) in acetone (see XXIX) gave 1.57 g of the crude diacid. Esterfication with boron trifluoride methanol complex (80) gave 1.4 g of the diester. Purification by glpc at 190° on a 5′ by ¼" Carbowax 20 M column gave the analytical sample; ir neat 5.79μ; pmr (CCl_4) δ 3.60 (s,6), 3.0-2.6 (m,2), 1.9-1.1 (m,6), 0.75-0.25 (m,2); mass spectrum (70 eV) m/e (rel intensity) M^+=212 (6), 181 (2), 153 (87).

Cis-1,2-cyclopropanediacetic acid

This diacid was prepared according to the method of Hofmann, et al., (105) mp 128-130° [lit (105) 131-133°]; pmr (CH_3OH) δ 2.6-2.25 (m,4), 1.55-0.70 (m,3), 0.3 to -0.05 (m,1).

Dimethyl cyclopropane-cis-1,2-diacetate

A 1 g sample of the corresponding diacid was dissolved in 25 ml of methanol, and a solution of diazomethane in ether (78) was slowly added until the color of the diazomethane persisted. Half of the ether was then distilled into dilute acetic acid and the remaining solvent then removed under reduced pressure. The crude product was distilled under vacuum to give 0.8 g (68%) of product bp 93-95° (0.5 mm); pmr (CCl_4) δ 3.56 (s,6), 2.45-1.95 (m,4), 1.7-0.5 (m,3), 0.10 to -0.25 (m,1); mass spectrum (70 eV) m/e (rel intensity) M^+=186 (1), 155 (14), 127 (40).

Cis-1,2-cyclopentanedicarboxylic anhydride

This anhydride was prepared according to the method of Brenner (106): mp 69-70° [lit (106) mp 70-72°].

Dimethyl cis-1,2-cyclopentanedicarboxylate (XLIp)

The diester was prepared by refluxing 0.6 g of the corresponding anhydride with 10 ml of methanol to which 2 drops of concentrated sulfuric acid had been added, over a period of 1 hr. The mixture was diluted with 250 ml of ether and successively extracted three times with 25 ml of 10% sodium bicarbonate and two times with 25 ml of water. The ether solution was dried with magnesium sulfate and the solvent removed under reduced pressure. The product was purified by glpc on a 5′ by $\frac{1}{4}$" 20% DEGS column at 150° to give a 65% yield of product; pmr (CCl_4) δ 3.60 (s,6), 3.25-2.90 (m,2), 2.20-1.60 (m,6); mass spectrum (70 eV) m/e (rel intensity) M^+=186 (1), 155 (100), 127 (20).

Dimethyl trans,trans-2,3-dimethylcyclopentane-cis-1,4-diacetate (XLIVp)

This diester was prepared from *exo*,*exo*-5,6-dimethylbicyclo[2.2.1]hept-2-ene using the same sequence of reactions as was used in the preparation of the unmethylated material (IXp) from norbornene. Pure material was obtained by glpc on a 10% QF-1 column at 180°; pmr (CCl_4) δ 3.60 (s,6), 2.40-2.10 (m,4), 2.10-1.40 (m,5), 1.10-0.75 (m,7); ir neat 5.78μ; mass spectrum (70 eV) m/e (rel intensity) M^+=242 (0), 211 (8), 183 (1).

Sources of Chemicals

Chemical	
Substituted glutaric acids	Aldrich
Tetracyclo[4.3.0.$0^{2,4}$.$0^{3,7}$] nonane-*endo*,*cis*-8,9-dicarboxylic acid	Dr. G. W. Holland, Jr.
Exo,*exo*-5,6-dimethylbicyclo[2.2.1]-hept-2-ene	Dr. G. W. Holland, Jr.

BIBLIOGRAPHY

1. L. Michaelis, Chem. Revs., 16, 243 (1935).
2. L. Michaelis and E. S. Fetcher, Jr., J. Am. Chem. Soc., 59, 1246 (1937).
3. M. Adams, M. S. Blois, Jr., and R. H. Sands, J. Chem. Phys., 28, 774 (1958).
4. D. H. Geske and A. L. Balch, J. Phys. Chem., 68, 3423 (1964).
5. G. A. Russell, E. T. Strom, E. R. Talaty, K. -Y. Chang, R. D. Stevens, and M. C. Young, Rec. Chem. Prog., 27, 3 (1966).
6. L. H. Piette, M. Okamura, G. P. Rabold, R. T. Ogata, R. E. Moore, and P. J. Scheuer, J. Phys. Chem., 71, 29 (1967).
7. R. Dehl and G. K. Fraenkel, J. Chem. Phys., 39, 1793 (1963).
8. G. A. Russell and E. T. Strom, J. Am. Chem. Soc., 86, 744 (1964).
9. G. A. Russell and P. R. Whittle, J. Am. Chem. Soc., 89, 6781 (1967).
10. G. A. Russell and K. -Y. Chang, J. Am. Chem. Soc., 87, 4381 (1965).
11. G. A. Russell, K. -Y. Chang, and C. W. Jefford, J. Am. Chem. Soc., 87, 4383 (1965).
12. Kuo-Yuan Chang, Ph.D. thesis, Iowa State University of Science and Technology, Ames, Iowa, 1965.
13. J. J. McDonnell, Ph.D. thesis, Iowa State University of Science and Technology, Ames, Iowa, 1968.
14. P. R. Whittle, Ph.D. thesis, Iowa State University of Science and Technology, Ames, Iowa, 1969.
15. G. W. Holland, Ph.D. thesis, Iowa State University of Science and Technology, Ames, Iowa (1969).
16. G. A. Russell, G. W. Holland, and K. -Y. Chang, J. Am. Chem. Soc., 89, 6629 (1967).

17. G. A. Russell and E. R. Talaty, J. Am. Chem. Soc., 86, 5345 (1964).

18. E. R. Talaty and G. A. Russell, J. Am. Chem. Soc., 87, 4867 (1965).

19. E. R. Talaty and G. A. Russell, J. Org. Chem., 31, 3455 (1966).

20. G. A. Russell, E. R. Talaty, and R. H. Horrocks, J. Org. Chem., 32, 353 (1967).

21. G. A. Russell, G. R. Underwood, and D. C. Lini, J. Am. Chem. Soc., 89, 6636 (1967).

22. G. A. Russell, Science, 161, 423 (1968).

23. G. A. Russell in "Radical Ions", E. T. Kaiser and L. Kevan, ed., John Wiley and Sons, Inc., New York, N.Y., 1968, Chapter 3.

24. N. L. Allinger and W. Szkrybalo, J. Org. Chem., 27, 722 (1962).

25. N. L. Allinger, J. A. Hirsch, M. A. Miller, and I. J. Tyminski, J. Am. Chem. Soc., 90, 5773 (1968).

26. S. Kabuss, H. Friebolin, and H. Schmid, Tetrahedron Letters, 469 (1965).

27. R. Knorr, C. Ganter, and J. D. Roberts, Angew. Chem. Internat. Edit., 6, 556 (1967).

28. S. Kabuss, A. Luttrunghaus, H. Friebolin, H. G. Schmid, And R. Mecke, Tetrahedron Letters, 719 (1966).

29. H. Hart and J. L. Corbin, J. Am. Chem. Soc., 87, 3135 (1965).

30. E. Grunwald and E. Price, J. Am. Chem. Soc., 87, 3139 (1965).

31. G. V. Smith and H. Kriloff, J. Am. Chem. Soc., 85, 2016 (1963).

32. G. R. Underwood and R. S. Givens, J. Am. Chem. Soc., 90, 3713 (1968).

33. G. A. Russell, P. R. Whittle, and J. J. McDonnell, J. Am. Chem. Soc., 89, 5515 (1967).

34. G. A. Russell and J. J. McDonnell, Tetrahedron Letters, 4213 (1968).

35. J. Warkentin and E. Sanford, J. Am. Chem. Soc., 90, 1667 (1968).

36. S. J. Cristol and A. L. Noreen, J. Am. Chem. Soc., 91, 3969 (1969).

37. E. E. van Tamelen, R. S. Dewey, and R. J. Timmons, J. Am. Chem. Soc., 83, 3725 (1961).

38. H. C. Brown, "Hydroboration", W. A. Benjamin, Inc., New York, N.Y., 1962, p. 130.

39. W. A. C. Brown, G. Eglinton, J. Martin, W. Parker, and G. A. Sim, Proc. Chem. Soc., 57 (1964).

40. W. A. C. Brown, J. Martin, and G. A. Sim, J. Chem. Soc., 1844 (1965).

41. M. Dobler and J. D. Dunitz, Helv. Chim. Acta., 47, 695 (1964).

42. I. Laszlo, Rec. Trav. Chim., 84, 251 (1965).

43. N. C. Webb and M. R. Becker, J. Chem. Soc. (B), 1317 (1967).

44. E. N. Marvel and R. S. Knutson, J. Org. Chem., 35, 388 (1970).

45. M. P. Doyle and W. Parker, J. Chem. Soc. (D), 319 (1969).

46. A. J. Baker, A. M. Chalmers, W. W. Flood, D. D. MacNicol, A. B. Penrose, and R. A. Raphael, J. Chem. Soc. (D), 166 (1970).

47. J. Dale, I. Laszlo, and W. Ruland, Proc. Chem. Soc., 190 (1964).

48. H. E. Simmons and R. D. Smith, J. Am. Chem. Soc., 81, 4256 (1959).

49. G. L. Closs and K. D. Krantz, J. Org. Chem., 31, 638 (1966).

50. R. S. Drago and H. Petersen, Jr., J. Am. Chem. Soc., 89, 3978 (1967).

51. R. Hoffman and W. N. Lipscomb, J. Chem. Phys., 36, 2179 (1962).

52. L. C. Cusachs and J. H. Corrington, "Yale Symposium in Sigma Molecular Orbital Theory," O. Sinanoglu and K. Wilberg, Editors, Yale University Press.

53. E. Clementi, J. Chem. Phys., 38, 996, 1001 (1963).

54. E. Clementi, J. Chem. Phys., 41, 295, 303 (1964).

55. E. Clementi, IBM J. Res. Devel., 9, 2 (1965) and supplement.

56. C. Froese, J. Chem. Phys., 45, 1417 (1966).

57. J. H. Corrington and L. C. Cusachs, J. Chem. Phys., to be published.

58. L. C. Cusachs, Sanibel Symposium, 1964; p. 36 of Report No. 50 of the Quantum Theory Project, U. of Florida, Gainesville, Fla.

59. C. J. Ballhausen and H. B. Gray, Inorg. Chem., 1, 111 (1962).

60. M. Wolfsberg and L. Helmholz, J. Chem. Phys., 20, 837 (1952).

61. A. C. McDonald and J. Trotter, Acta. Crystallogr., 18, 243 (1965).

62. A. C. McDonald and J. Trotter, Acta. Crystallogr., 19, 456 (1965).

63. N. C. Baenziger, J. R. Doyle, and C. Carpenter, Acta. Crystallogr., 14, 303 (1961).

64. H. G. Norment, Acta. Crystallogr., 18, 627 (1965).

65. F. R. Ahmed and E. J. Gabe, Acta. Crystallogr., 17, 603 (1964).

66. W. H. Grant and J. C. Speakman, Acta. Crystallogr., 15, 292 (1962).

67. T. N. Margulis, L. Schiff, and M. Rosenblum, J. Am. Chem. Soc., 87, 3269 (1965).

68. A. Streitwieser, "Molecular Orbital Theory for Organic Chemists", John Wiley and Sons, Inc., New York, N.Y., 1961, p. 165.

69. G. A. Russell, D. F. Lawson, D. C. Lini, R. D. Stephens, H. L. Malkus, and G. R. Underwood, J. Am. Chem. Soc., to be published.

70. H. C. Heller and H. M. McConnell, J. Chem. Phys., 32, 1535 (1960).

71. C. F. Wilcox, J. Am. Chem. Soc., 82, 414 (1960).

72. E. Fermi, Z. Physik, 60, 320 (1930).

73. D. Kosman and L. M. Stock, J. Am. Chem. Soc., 91, 2011 (1969).

74. J. P. M. Bailey, and R. M. Golding, Mol. Phys., 12, 49 (1967).

75. Z. Luz, J. Chem. Phys., 48, 4186 (1968).

76. M. Barfield, J. Phys. Chem., 74, 621 (1970).

77. A. I. Vogel, "A Testbook of Practical Organic Chemistry", 3rd ed., John Wiley and Sons, Inc., New York, N.Y. 1966, p. 902.

78. A. I. Vogel, "A Textbook of Practical Organic Chemistry", 3rd ed., John Wiley and Sons, Inc., New York, N.Y. 1966, p. 971.

79. N. L. Allinger, J. Am. Chem. Soc., 81, 232 (1959).

80. L. D. Metcalfe and A. A. Schmitz, Anal. Chem., 33, 363 (1961).

81. S. F. Birch, W. J. Oldham, and E. A. Johnson, J. Chem. Soc. 818 (1947).

82. T. L. Westman, R. Paredes and W. S. Brey, Jr., J. Org. Chem. 29, 2448 (1964).

83. T. L. Westman, R. Paredes and W. S. Brey, Jr., J. Org. Chem. 28, 3512 (1963).

84. H. Kwart and L. Kaplan, J. Am. Chem. Soc., 76, 4072 (1954).

85. J. Thiele, Ann. 271, 127 (1892).

86. A. Streitwieser, Jr., L. Verbit, and P. Stang, J. Org. Chem., 3706 (1964).

87. H. C. Brown and K. Murray, J. Am. Chem. Soc., 81, 4108 (1959).

88. F. Sondheimer and S. Wolfe, Can. J. Chem. 37, 1870 (1959).

89. H. R. Snyder, L. A. Brooks, and S. H. Shapiro, "Organic Synthesis Collective Volume II", p. 531.

90. A. C. Cope and M. E. Synerholm, J. Am. Chem. Soc., 72, 5228 (1950).

91. A. C. Cope, E. S. Graham, and D. J. Marshall, J. Am. Chem. Soc., 76, 6159 (1954).

92. A. C. Cope, T. A. Liss, and G. W. Wood, J. Am. Chem. Soc., 79, 6289 (1957).

93. E. P. Hohler, M. Tishler, H. Potter, and H. T. Thompson, J. Am. Chem. Soc., 61, 1057 (1939).

94. A. I. Vogel, "A Textbook of Practical Organic Chemistry", 3rd ed., John Wiley and Sons, Inc., New York, N.Y. 1966, p. 199.

95. R. M. Novak, J. Org. Chem., 28, 1182 (1963).

96. P. K. Freeman, D. M. Balls, and D. J. Brown, J. Org. Chem., 33, 2211 (1968).

97. K. Alder, S. Hartung, and G. Hausmann, Ber., 89, 1972 (1956).

98. N. L. Allinger and L. A. Tushaus, J. Org. Chem., 30, 1945 (1965).

99. E. A. Wielicki, C. J. Boone, R. D. Evans, M. R. Lytton, H. B. Summers, Jr., and G. W. Hedrich, J. Polymer Sci., 38, 307 (1959).

100. G. N. Schrauzer and P. Glockner, Ber., 97, 2451 (1964).

101. H. Kwart and G. Null, J. Am. Chem. Soc., 78, 5943 (1956).

102. M. Hanack, H. Eggensperger, and R. Hahnle, Ann., 652, 96 (1962).

103. K. Alder and G. Jacobs, Ber., 86, 1528 (1953).

104. P. Radlick, R. Klem, and S. Spurlock, Tetrahedron Letters, 5117 (1968).

105. K. Hofmann, S. Orochena, S. Sox, and G. Jeffrey, J. Am. Chem. Soc., 81, 995 (1959).

106. J. E. Brenner, J. Org. Chem., 26, 22 (1961).

ACKNOWLEDGEMENTS

I would like to express my gratitude to Professor Glen A. Russell for his conception of the problem, his helpful suggestions, his patience, and especially for the opportunity to work for him during these three years at Iowa State. His efforts toward the continuance of my National Science Foundation graduate fellowship and securing a suitable industrial position are greatly appreciated.

Special thanks go to Professor Joseph B. Lambert (Northwestern University) who introduced me to chemical research and helped secure the first two years of my NSF fellowship. Thanks also belong to Professors Kinstle, Trahanovsky, Angelici, and Metzler who served as members of my committee, and to the members of the Russell group and Chemistry department for hours of helpful discussion.

Appreciation is extended to my parents, who encouraged me, in both good and bad times, throughout many years of education. Thanks also to my wife's parents, who have been more than gracious in the time I have known them.

My wife, Linda, deserves special appreciation. In addition to being a loving wife, teaching first grade for a year to help support us, and presenting me with a fine son, William, her help, by proofreading, correcting grammar and spelling, and by typing the final draft of this thesis, was invaluable.

I also wish to thank the National Science Foundation for three years of fellowship, and the Department of Chemistry for a quarter time teaching assistantship, both of which provided financial support during the course of this work.