

STABILIZATION OF CARBONIUM IONS
IN THE VICINITY OF METALLOCENE NUCLEI

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ABSTRACT

A remarkable stabilization imparted to a carbonium ion by an adjacent metallocene nucleus has been demonstrated by a solvolytic study of substituted metallocenylcarbinyl acetates. The solvolysis mechanism has been shown to be an uncatalyzed alkyl-oxygen fission of the neutral ester by a study of the hydrolysis under a variety of conditions and by determination of the products from the ethanolyses. Participation of the metal in the solvolyses by direct bonding between the metal and the incipient carbonium ion center is indicated by the effects of simple substituents, by the effect of joining the rings by a three-carbon bridge, by the solvolysis of the acetate vinylogous to methylferrocenylcarbinyl acetate and by the stereochemistry of the solvolyses of derivatives with substitution in the 2-position of the ferrocene nucleus. A plausible molecular orbital model for such participation has been suggested in qualitative terms.

Spectra of the ferrocene derivatives prepared in this study are correlated and discussed. Evidence is presented which demonstrates intramolecular hydrogen bonding to the metal atom in substituted metallocenylcarbinols, and which indicates that the rings of 1,1'-trimethyleneferrocene are tilted.

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CHAPTER I

INTRODUCTION

The great reactivity of ferrocene toward electrophilic substitution reagents has classified this substance as a highly electron-rich aromatic system. Therefore, a carbonium ion conjugated with one of the rings should be highly stabilized. Also, in addition to this classical conjugative stabilization, metallocene systems possess the further possibility of direct electron release by the metal to an electron deficient center such as a carbonium ion. The object of this research is to study the stability of such carbonium ions and the manner in which metallocenes may release electrons by measuring the solvolysis rates of metallocenylcarbinyl acetates. In Part A of this introduction, evidence for the ready electron-release by metallocene systems is examined in some detail. Part B provides a background of information on ester solvolysis by alkyl-oxygen fission which is necessary to determine that the solvolyses studied actually proceed by a carbonium ion mechanism.

A. Evidence for Electron Release by Metallocene Systems.

Ferrocene exhibits remarkable reactivity in many of its electrophilic substitution reactions. Of these substitutions, Friedel-Crafts acylation has been studied in the greatest detail. Broadhead, Osgerby and Pauson (3) competitively acetylated ferrocene and anisole with aluminum chloride-acetyl chloride complex. Despite a ten-fold

excess of anisole over ferrocene, acetylferrocene was the only ketonic product isolated. In a similar experiment with equimolar quantities of ferrocene and phenol, acetylferrocene was again the only ketone produced. While these experiments fail to give any really quantitative measure of the reactivity of ferrocene, this compound may be estimated to be at least of the same order of reactivity as phenol, and greater than 10^3 times as reactive as anisole toward acetylation. Unfortunately, there has been no other quantitative comparison between the reactivity of ferrocene and that of other aromatic systems. For this reason, one can estimate the ability of ferrocene to release electrons in electrophilic substitutions only by comparing the conditions required to bring about the same reaction with different substrates. Such comparisons always suffer from uncertainty as to whether the conditions used are comparable and are the least vigorous required to produce complete reaction, and as to the meanings of yield data.

Ferrocene is acetylated under qualitatively mild reaction conditions. A good yield of acetylferrocene is produced by saturating a solution of acetic anhydride and ferrocene in methylene chloride with boron trifluoride at 0° , and allowing this mixture to warm to room temperature over four hours (3,4). Resorcinol is similarly acetylated without solvent in 96 hours at 0° (5). Thiophene and furan have been acetylated by adding boron trifluoride etherate to a mixture of the heterocycle and acetic anhydride. In both cases, the highest temperature during the reaction was 110° , and with the latter, the temperature rose this high spontaneously (6).

Ferrocene is acetylated by heating on a steam bath for 10 min.

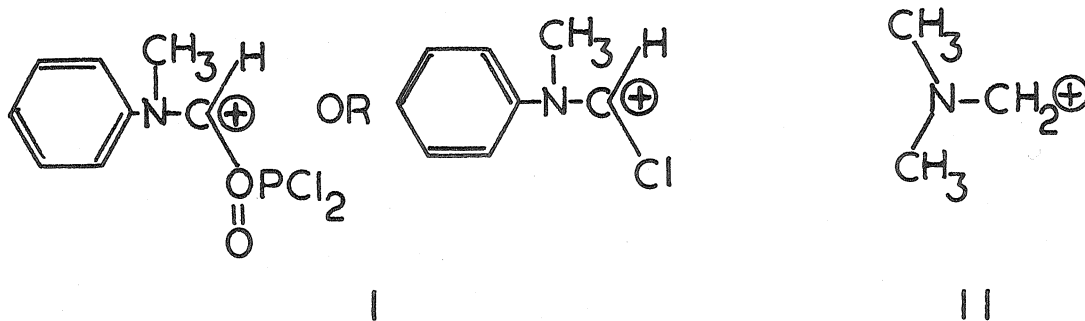
with acetic anhydride and 85% phosphoric acid (7). A procedure used for furan and several substituted thiophenes involves heating for 2 hrs. at 100-110°. Thiophene (8) and ferrocene (9) have both been acetylated in anhydrous hydrofluoric acid. With thiophene, the reaction was run with acetic acid for 1 hr. at 20°; with ferrocene, acetic anhydride was used, and the mixture was heated to 40-45° for 12 hrs. Another indication of high reactivity toward acetylation is the reaction of ferrocene with silicon tetraacetate and stannic chloride, a procedure also applied to thiophenes and furans (10).

From these acetylation results, it appears quite likely that ferrocene is of about the same order of reactivity as thiophene, furan and resorcinol toward acetylation.

The situation is much less clear with respect to Friedel-Crafts alkylation. In anhydrous hydrofluoric acid, ferrocene is not alkylated by propylene or diisobutylene at temperatures up to 30°, and decomposes above this temperature (9). This may be contrasted to the ready alkylation of benzene by a variety of olefins at 0° (11). Alkylation of ferrocene with alkyl halides was reported not to occur by Riemschneider and Helm (12), while Vogel, Rausch and Rosenberg report that alkylation yields inseparable mixtures of products (13). Russian workers prepared a number of mono- and poly-alkylated ferrocenes by a variety of alkylation procedures (14-17). As an example, ferrocene was alkylated with excess ethyl bromide and aluminum chloride in petroleum ether solution. The mixture was maintained at 50-60° for 5-6 hrs., and over half of the ferrocene was recovered unchanged (15). This may be compared with the ethylation of benzene, where reaction

without solvent produced a 90% yield of triethylbenzene after 24 hrs. at 0-25° (18). These results suggest that ferrocene perhaps does not exhibit its unusual reactivity in alkylation reactions. Possible explanations for this are the preferential removal of ferrocene from the reaction mixture by protonation or other complexation (19), or alternatively, failure of ferrocene to react readily with trigonal attacking species (see discussion, also reference 20).

While ferrocene may not show extremely high reactivity in ordinary alkylation reactions, it is substituted in two reactions quite similar to alkylation. Formylation (21,22) (with N-methylformanilide and phosphorous oxychloride) and aminomethylation (23) (with formaldehyde and dimethylamine) probably proceed through attack by the trigonal carbonium ions I and II.



In both cases, the carbonium ions are highly stabilized, and so substitute only very reactive aromatic compounds. One set of reaction conditions reported for the formylation of ferrocene specifies addition of the formanilide at 50° over a period of 1.25 hrs., followed by cooling to room temperature and stirring for 3 hrs. (7; see also 3,48). Formylation of 2-ethoxynaphthalene requires heating on a steam bath for 6 hrs. (24); thiophene reacts slowly at room temperature, and the reaction

is completed at steam bath temperature (25). Aminomethylation of ferrocene requires 5 hours' reflux in acetic acid solution (26), or 7 hours' heating on a steam bath in acetic acid with phosphoric acid added as catalyst (27). Aminomethylations of thiophenes (28) and furans (29) have been carried out primarily in aqueous solution. A comparison of aminomethylation reactions of styrenes in the two media leads to the conclusion that the conditions for ferrocene may be somewhat more vigorous (30).

Mercuration of ferrocene with mercuric acetate occurs very rapidly in ether-alcohol or benzene-alcohol mixtures at room temperature (10,31). Furan likewise reacts almost instantaneously with mercuric acetate (32). Benzene, by comparison, must be heated in acetic acid for 5 hrs. at 100° (33).

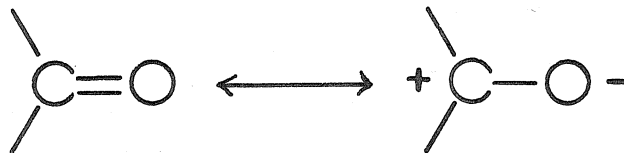
Sulfonation of ferrocene in aqueous sulfuric acid solutions apparently is excluded because of the oxidizing power of this reagent. However, such reagents as sulfuric acid (9) or chlorosulfonic acid (34) in acetic anhydride produce sulfonation at low temperatures. A useful comparison may be found in the sulfonation with sulfur trioxide-pyridine complex. At 100° in methylene chloride, ferrocene reacted in 4 hrs. (35); furan, in 8-10 hrs.; thiophene and anisole, in 10 hrs.; and benzene failed to react after 20 hrs. at 140° (36).

Ferrocene cannot be directly nitrated (37) or halogenated (38), but this is due to the sensitivity of the system to oxidation, rather than to a lack of reactivity.

From the above qualitative comparisons, it is evident that ferrocene is in the same class as thiophene and furan in its reactivity

toward electrophilic substitution reagents. This high reactivity strongly suggests that ferrocene can also release electrons readily to stabilize a carbonium ion. Osmocene and ruthenocene appear qualitatively to be less reactive than ferrocene (39,40), and competitive acetylation shows that ruthenocene reacts more slowly than ferrocene by a factor of at least five (20). On this basis, osmocene and ruthenocene might be expected to be less effective in stabilizing a carbonium ion.

The infrared carbonyl stretching frequency of acetylferrocene provides another suggestion that metallocenes should be very effective at electron release. It has been shown for a series of substituted acetophenones that a plot of the carbonyl frequency against Hammett's sigma is linear. This indicates that changes in the carbonyl frequency parallel the ability of the substituted phenyl moiety to release electrons (41,42). Also, a correlation has been made between the carbonyl frequency and the bond order calculated by an independent method (42). Since either inductive or conjugative electron release by the aryl residue would tend to stabilize a dipolar resonance structure for the carbonyl group, greater electron release should result in a bond with less double bond character and a lower stretching frequency (42,43).



The carbonyl stretching frequencies of acetyl ferrocenes are quite low, indicating a large degree of electron release to the carbonyl group (44,45). Quantitative comparisons with values available in the

literature are somewhat difficult, since medium effects are quite great, and the Hammett correlation has been shown to apply only in dilute solutions. Some values observed in carbon tetrachloride are listed in Table I.

Table I

Infrared Carbonyl Stretching Frequencies of Aryl Ketones in Dilute Carbon Tetrachloride Solution

<u>Ketone</u>	<u>(cm⁻¹)</u>	<u>Reference</u>
acetophenone	1692	(43)
<u>p</u> -methoxyacetophenone	1684	(43)
<u>p</u> -aminoacetophenone	1677	(43)
5-chloro-2-acetylthiophene	1669	(47)
acetylferrocene	1676	(46)

Some values observed in pure liquids are listed in Table II.

Table II

Infrared Carbonyl Stretching Frequencies of Aryl Ketones (Neat)

<u>Ketone</u>	<u>(cm⁻¹)</u>	<u>Reference</u>
acetophenone	1683	(44)
1,1'-dimethyl-3-acetylferrocene	1666	(44)
2-acetylthiophene	1667	(47)
3,5-dimethyl-2-acetylthiophene	1653	(47)

A similar comparison of aldehydes in chloroform yields values of 1681 cm^{-1} for ferrocenecarboxaldehyde (48) and 1687 cm^{-1} for thiophene-2-aldehyde (49). Acetylruthenocene and acetylosmocene are reported to absorb at 1658 cm^{-1} and 1670 cm^{-1} under conditions where acetylferrocene absorbs at 1658 cm^{-1} . (Probably these values are in nujol mulls, in which case the numbers are not a valid comparison (40.)) In carbon tetrachloride, acetylruthenocene and acetylosmocene both absorb at 1682 cm^{-1} (46).

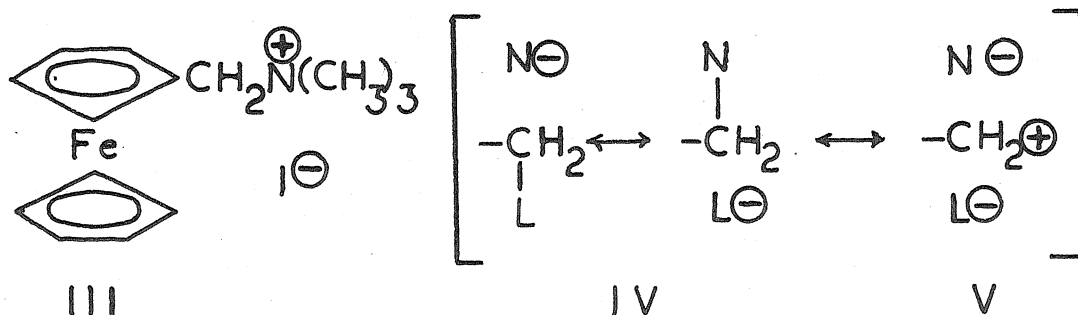
The basicities of ferrocene carbonyl compounds provide further indication of strong conjugative electron release. The aldehyde is precipitated as a solid hydrochloride from ether solution with anhydrous hydrogen chloride (50), and the Russian workers have used extraction into concentrated hydrochloric acid solution as a means of purifying some alkylacetylferrocenes (51). Also, it has been reported that the aldehyde is not extracted from ether solution with saturated aqueous sodium bisulfite (2). Such a lack of reactivity indicates a large amount of resonance energy due to conjugation of the carbonyl group with the ring.

α -Ferrocenylcarbinols have been found to yield ethers on several occasions under unexpectedly mild conditions. A reduction of ferrocenecarboxaldehyde over Raney nickel catalyst led, not to the expected ferrocenylcarbinol, but instead to bis-ferrocenylcarbinyl ether (7). The same ether was isolated from attempts to prepare ferrocenylcarbinyl chloride or bromide (52). Phenylferrocenylcarbinol forms its methyl ether on refluxing in methanol, while its isopropyl ether was isolated from a Meerwein-Ponndorff reduction of benzoylferrocene.

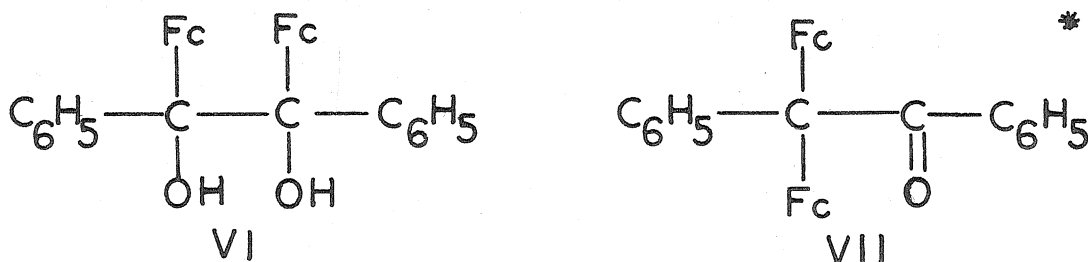
The symmetrical ether of this carbinol resulted from attempts to prepare the bromide with phosphorous tribromide, or from treatment with *p*-toluenesulfonyl chloride (53). These reactions are all indications of high carbonium ion reactivity of substituents on the carbon atom adjacent to the ferrocene nucleus.

The failure to isolate any ferrocenylcarbinyl halides or tosylates (52,53) is probably quite indicative of their great reactivity in S_N1 reactions. Ferrocenylcarbinyl chloride has probably been prepared in solution, and has participated quite readily in alkylations (52). Another indication of high carbonium ion reactivity adjacent to a ferrocene ring may be noted in the very ready acid hydrolysis of the ethylene glycol acetal of ferrocenecarboxaldehyde, which precludes its use as a protective group.

The quaternary ammonium salt (ferrocenylmethyl)trimethylammonium iodide III undergoes displacements with a wide variety of nucleophilic reagents to yield ferrocenylcarbinyl derivatives (26,27, 54,55). No mechanistic work has been done on these reactions, but it seems possible that some of them may proceed by a carbonium ion mechanism. At least, there is probably a large contribution to the transition state of resonance forms, such as V, in which a positive charge is placed on the carbinyl carbon.



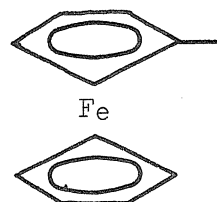
Weliky and Gould prepared the pinacol VI by reduction of



benzoylferrocene with methylmagnesium bromide and cobalt(II) chloride. When dry hydrogen chloride was passed over a benzene solution of this compound, it rearranged with ferrocenyl migration to the corresponding pinacolone VII. Migration of the ferrocenyl group cannot be given much significance, since the stereostructure of the pinacol is not known. However, the great ease of the rearrangement signifies that a ferrocene nucleus is very important in stabilizing the intermediate carbonium ion.

Lou and Hart measured the solvolysis rate of ferrocenoyl chloride in 95% acetone-5% water. They found that at 25°, its rate is 1.63 times that of benzoyl chloride (56). Unfortunately, this experiment fails to indicate anything concerning the ability of a ferrocenyl group to stabilize a carbonium ion. Brown and Hudson (57,58) have studied the hydrolysis of a number of substituted benzoyl chlorides in solvents of various composition. They found that in 95% acetone, the reactions proceed almost exclusively by a bimolecular mechanism in

* The symbol Fc refers to a ferrocenyl grouping:



which electron-withdrawing substituents stabilize the transition state. Thus, the relative rates of p-nitro, unsubstituted, and p-methoxybenzoyl chlorides are 35:1.0:0.6. As the water content of the solvent is increased, those benzoyl chlorides with electron-releasing substituents begin to react more rapidly by an S_N1 mechanism, so that the relative rates of the same compounds in 50-50 aqueous acetone become 11.5:1.0:30. Mesitoyl chloride shows an even more marked tendency to shift to S_N1 in mechanism. If the experiment of Lou and Hart had been performed in a more highly ionizing solvent, it might have provided a valid test of the ability of ferrocene to release electrons.

The ionization constants of ferrocenecarboxylic acids provide another quantitative comparison between the metallocenes and other aromatic compounds. Some pK_a values for a selected set of carboxylic acids are given in Table III.

Table III

pK_a Values in Water at 25° C.

<u>Acid</u>	<u>pK_a</u>	<u>Reference</u>
Ferrocenecarboxylic acid	4.4	(59)
Thiophene-2-carboxylic acid	4.49	(60)
Thiophene-3-carboxylic acid	4.11	(60)
<u>p</u> -Nitrobenzoic acid	3.44	(61)
Benzoic acid	4.20	(61)
<u>p</u> -Methoxybenzoic acid	4.47	(61)

It may be seen that the thiophene- and ferrocenecarboxylic acids are not greatly different from benzoic acid, despite the greatly enhanced reactivities of thiophene and ferrocene to electrophilic substitution. Solvolysis rates of substituted benzyl tosylates have been correlated in a limited fashion by the Hammett equation. This is really a linear relation between the logarithm of the solvolysis rate and the pK_a of the corresponding substituted benzoic acid. However, the point for p-methyl was slightly off the line, and p-methoxy deviated very greatly. This may be seen by comparing the above pK_a values with the corresponding relative logarithmic rates for p-nitro-, unsubstituted and p-methoxybenzyl tosylates: -1.7, 0.0 and +4.4 (62). When there is a substituent which can conjugate directly with the carbonium ion center, the stabilization is far greater than would have been predicted from the simple Hammett correlation. From other information available about the electron-releasing ability of ferrocene, the correlation between acid pK_a 's and carbonium ion stabilities might be expected to break down here, also.

In addition to chemical evidence, molecular orbital calculations based on a simple model for a metallocene ring predict a large delocalization energy for an α -metallocenyl carbonium ion, and show that the charge of the carbonium ion should be well distributed over the ring (see p. 69).

From the various comparisons which have been made between metallocene and other aromatic systems, it appears quite likely that the metallocene nucleus should be highly effective in releasing electrons to stabilize a carbonium ion. This prediction was verified by

the observation that methylferrocenylcarbonyl acetate solvolyzes at a rate somewhat greater than that of triphenylmethyl acetate*. Further research was carried out to clarify the mechanism of this stabilization, to observe the ability of other metallocenes to stabilize such carbonium ions, and to study electronic and steric interactions within various ferrocene derivatives. These results are discussed in Part II. In the course of this work, various spectral correlations were used in assigning structures and in learning of interactions which affect the solvolyses. A discussion of these comprises Part III.

* Hereafter to be referred to as trityl acetate.

B. Ester Hydrolysis by Alkyl-Oxygen Fission.

Day and Ingold (63) have made a comprehensive survey of the possible mechanisms for ester hydrolysis. They classify these mechanisms on the basis of three criteria:

- (a.) Either the ester or its conjugate acid is the reacting species (indicated by B or A).
- (b.) Either the acyl-oxygen or the alkyl-oxygen bond in the ester linkage is cleaved in the reaction (indicated by AC or AL).
- (c.) Either the reacting ester species decomposes unimolecularly, or it is attacked bimolecularly in the rate-determining step (indicated by 1 or 2).

In this research, the solvolysis of metallocenylcarbonyl acetates is studied. In order to establish the relevance of the results obtained to the stability of metallocenylcarbonium ions, the mechanism of the solvolysis reaction must be determined as a unimolecular alkyl-oxygen hydrolysis of the neutral ester (or a $B_{AL}1$ hydrolysis). If the acetates react by acyl-oxygen fission, the stability of the carbonium ion is not indicated by the rate of the reaction. If alkyl-oxygen fission occurs, but the reaction is bimolecular, then S_N2 reactivity of metallocenyl-carbonyl derivatives is being measured, rather than S_N1 reactivity. Finally, if the conjugate acid rather than the free ester is reacting, the rate is a composite of the basicity of the ester and the solvolysis rate of its conjugate acid. Again, no true indication of carbonium ion stability is obtained. Since many excellent

reviews of ester hydrolysis (64-68), and alkyl-oxygen heterolysis in particular (69), are available, there will be no attempt to be at all comprehensive here. Rather, the types of alkyl-oxygen fission reactions that have been observed will be surveyed along with the experiments which have led to the assignments of mechanisms, and the situations in which these mechanisms are likely to occur.

Bimolecular hydrolysis of the neutral ester is the least frequently observed alkyl-oxygen fission. According to Ingold (64), it is quite likely that this is a fairly reasonable reaction path for the hydrolysis of any ester not highly hindered in the alcohol portion. However, the reactivity of nucleophiles toward the unsaturated carbon of the carbonyl group is considerably greater than toward the carbinyl carbon, so that alkyl-oxygen fission is observed only in special cases.

β -Lactones are an example. While acidic and basic hydrolyses of β -lactones proceed with acyl-oxygen fission, hydrolysis by attack of water in a pH range from 2 to 8 occurs by alkyl-oxygen fission (70). This is facilitated by a considerable release in bond-angle strain with opening of the four-membered ring, combined with the fact that water is relatively less reactive toward carbonyl carbon than toward tetrahedral carbon*. Over this pH range, the hydrolysis rate of β -butyrolactone is independent of the acidity, and the product is produced with

* According to Swain and Scott (71), hydroxide ion is 10^3 times more reactive than water towards ethyl tosylate, 10^4 times more reactive towards methyl bromide, and 10^{10} times more reactive towards ethyl acetate.

inversion of configuration at the carbinol carbon.

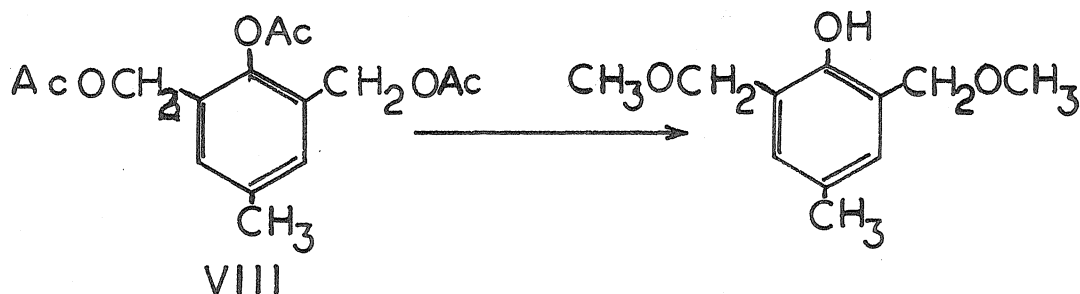
Another technique for observing bimolecular base-catalyzed alkyl-oxygen fission is elimination of concurrent acyl-oxygen fission. Treatment of a methyl ester with methoxide ion can regenerate only starting material by acyl-oxygen ester interchange. But alkyl-oxygen fission results in the formation of dimethyl ether and carboxylate ion. This experiment has been performed on methyl benzoate, methyl mesitoate, and methyl 2, 4, 6-tribromobenzoate with the expected results (72). A very approximate calculation based on the data of this paper yields a rate constant of $8 \times 10^{-6} \text{ l.mole}^{-1} \text{ sec}^{-1}$ at 100° for S_N2 attack on the methyl group of methyl benzoate. This may be compared with an extrapolated rate constant of $2.16 \times 10^{-1} \text{ l.mole}^{-1} \text{ sec}^{-1}$ for the acyl-oxygen hydrolysis of methyl benzoate in 80% methanol-20% water*. These numbers are not completely comparable due to a difference in the nucleophile and the solvent, but they do at least indicate an order of magnitude for the preference of acyl-oxygen over alkyl-oxygen fission.

In the hydrolysis of esters of 2,6-dimethylbenzoic acids, acyl-attack might be expected to be sufficiently hindered that alkyl-oxygen fission would be observed. However, a predominance of acyl-oxygen fission has been demonstrated (by hydrolysis of methyl mesitoate in H_2O^{18} enriched water), despite a rate decrease of about 10^3 relative

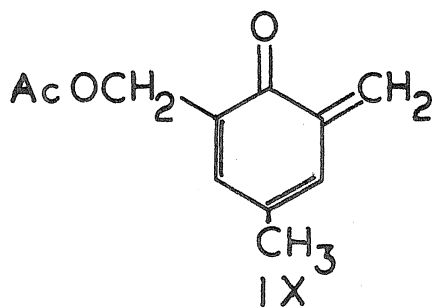
* This value is estimated from the rate constant at 25° and the activation energy given in reference (73).

to ethyl benzoate * (74). Since a series of methyl 4-substituted-2,6-dimethylbenzoates is fitted well to a Hammett plot, the same mechanism is indicated for all such esters.

Another reported case of a methanolysis involves treatment of the triacetate VIII with methanolic potassium hydroxide (77):



Since no kinetic or mechanistic data is given, it is quite possible that the first step is saponification of the phenyl acetate linkage. This may be followed by solvolysis of the other two acetate groups by way of intermediates such as IX.



It thus appears that bimolecular alkyl-oxygen fission is an insignificant reaction except in cases where the acyl-oxygen reaction is somehow eliminated. In addition, it should be easily recognizable kinetically by the effect of added nucleophiles or bases.

* This approximate value is obtained by extrapolation of a value in a slightly different solvent at 40° to 125° (75), and comparing this with the value reported in reference (76).

Hydrolysis by ionization of the alkyl-oxygen bond may be expected to occur whenever the carbonyl portion provides a carbonium ion sufficiently stable to compensate for the ineffectiveness of the carboxylate ion as a leaving group. As with any S_N1 reaction of a neutral substrate, such ionization will be favored by polar solvents. The hydrolysis will be greatly assisted by protonation of the ester, since the neutral carboxylic acid is a much better leaving group. However, the carbonium ion formed must still be a stable one, since ionization must compete with nucleophilic attack on the protonated carboxyl group.

The mechanism of unimolecular alkyl-oxygen fission may be established by observation of several distinguishing features. The most clear-cut criterion is the disposition of the ether oxygen of the ester, which may be determined by hydrolysis of esters with an excess of O^{18} in this position. Alternatively, an isotopically normal ester may be hydrolyzed in solvent enriched with H_2O^{18} . Alcoholysis of the neutral ester is an equivalent method. In this case, alkyl-oxygen fission will produce an ether and the carboxylic acid, rather than the usual transesterification products. Several other observations pertinent to the carbonium ion may be made in certain cases. Thus, if the alcohol has optical activity due to asymmetry at the carbonyl carbon, the usual S_N1 results of racemization with partial inversion will be expected. If ionization produces an allylic cation, rearrangement to a mixture of allylic isomers may be expected. Similarly, Wagner-Meerwein rearrangement will occur if the carbonium ion rearranges in other solvolyses, or olefin may arise if the carbonium ion loses a

proton. These observations, in addition to the usual kinetic criteria, can serve to establish the mechanism of unimolecular alkyl-oxygen fission.

Such alkyl-oxygen fission has been well verified for esters of tertiary alcohols. The relative acid hydrolysis rates of some alkyl acetates are listed in table IV.

Table IV

Relative Hydrolysis Rates of Alkyl Acetates in Water at 25° C. (64)

<u>Alcohol</u>	<u>k (Rel.)</u>
Methyl	1
Ethyl	0.97
<u>i</u> -Propyl	0.53
<u>t</u> -Butyl	1.15

The rate decreases from methyl to i-propyl, probably due to increasing steric hindrance. The rate increase with t-butyl results from the incursion of alkyl-oxygen fission. Such an increase in rate is often diagnostic of a change in mechanism. Another criterion is the effect of substituents in the acid portion of the ester. An electron-withdrawing substituent will make the carboxylate ion or carboxylic acid a better leaving group, and thus increase the rate of alkyl-oxygen fission. In concentrated sulfuric acid, p-nitro substitution decreases the hydrolysis rate of ethyl benzoate by a factor of 70, but increases that of i-propyl benzoate 200-fold. Further, rates of the unsubstituted

benzoates follow the sequence: methyl > ethyl < i-propyl < t-butyl. These results indicate a change in mechanism to alkyl-oxygen heterolysis with the i-propyl ester (79).

Cohen and Schneider (80) studied the uncatalyzed methanolyses of t-butyl benzoate and t-butyl mesitoate. In both cases, t-butyl methyl ether was formed, and control experiments showed that it could not have arisen from t-butanol formed by a normal acyl-oxygen ester interchange. Both reactions were strongly acid catalyzed. In sodium methoxide solution, normal ester interchange took place with the benzoate, but no reaction of either sort occurred with the mesitoate. This result was interpreted to mean that in the alkyl-oxygen fission reaction, a small amount of solvolysis of the neutral ester occurred, and that the benzoic or mesitoic acid thus formed catalyzed the major portion of the reaction. Studies of the acid-catalyzed hydrolysis of t-butyl acetate with isotopic oxygen have shown that the reaction in aqueous dioxan occurs predominantly by acyl-oxygen fission. However, when the solvent is changed to pure water, a large rate increase is accompanied by a shift of mechanism to alkyl-oxygen fission (81). It has also been shown that an optically active tertiary acetate is hydrolyzed in acid with racemization and partial inversion (82); an active tertiary acid phthalate solvolyzes with predominant inversion (83).

Stimson and co-workers (84) have studied the kinetics of acid catalyzed solvolysis of several t-butyl and benzhydryl esters in aqueous alcohol and acetone. t-Butyl mesitoate, which should react almost entirely by alkyl-oxygen fission, was found to have an Arrhenius energy of activation of about 30 kcal. and an entropy of activation

positive by about 10 e.u. in a variety of solvent compositions (84a,b). The same general kinetic behavior was exhibited by t-butyl benzoate (84c), benzhydryl mesitoate and benzhydryl benzoate (84e), and so these esters were considered to react also by alkyl-oxygen fission. In contrast, the formates of benzhydrol and t-butanol had Arrhenius energies of about 17 kcal., and entropies of activation negative by about 16 e.u. (84d,e). These values are quite similar to the activation parameters observed for acyl-oxygen fission, and so it is likely that there has been a change in mechanism. Benzhydryl acetate was found to exhibit intermediate behavior. In 80% acetone, the activation parameters are quite similar to those of the mesitoate, but in more aqueous solvents the activation energy decreased and varied with temperature, suggesting the simultaneous operation of two mechanisms.

In the acid-catalyzed hydrolysis of t-butyl benzoate and some other tertiary esters, olefin was shown to be formed in a first order reaction. The fraction of olefin formed in the reaction was independent of the acidity of the medium, and nearly identical with that formed in solvolysis of the corresponding halides. This provides quite clear-cut evidence for the intermediacy of a carbonium ion in these reactions (84f).

Kenyon and co-workers have reported a large body of information concerning alkyl-oxygen fission of acid phthalates and some other esters (69). Alkyl-oxygen fission has been demonstrated in weakly basic or neutral solution by partial racemization or allylic rearrangement of the alcohols formed. In strongly basic solution, the hydrolysis was found to occur in most instances with acyl-oxygen fission, and

an estimate could be made of the aptitude of the ester toward alkyl-oxygen fission by observing the basicity which was required to produce optically pure product.

When the hydrogen phthalate of 1-phenylethanol was hydrolyzed in aqueous sodium carbonate, about 20% racemization occurred. Several esters of this alcohol were found to solvolyze with racemization in formic acid; solvolysis in acetic acid did not occur at 100°, but was successful when some water was added; solvolysis in aqueous alcohols did not occur (85). 1-Tetra-*l*-hydrogen phthalate appears to be somewhat more reactive, as it solvolyzes readily in formic and acetic acids, and yields largely racemized alcohol (with some retention) on hydrolysis with aqueous sodium carbonate at 100° (86). Replacement of phenyl by more electron-rich aromatic residues, and use of benzhydrol derivatives, produces a greater shift toward alkyl-oxygen fission. Thus, while benzyl hydrogen phthalate appears to show little or no tendency toward alkyl-oxygen fission, *p*-methoxybenzyl hydrogen phthalate undergoes some carbonium ion reactions. Replacement of phenyl by furyl (87a) or thienyl (87b) residues similarly increases the tendency toward alkyl-oxygen fission. At the most reactive end of the scale, hydrolysis of the acid phthalate of 4-methoxybenzhydrol, even with 10 *N* aqueous alkali, produced largely racemic alcohol (88). Unfortunately, no kinetic data are available in any of these instances. The use of acid phthalates for many of the experiments also leads to some mechanistic uncertainty due to possible effects of the other carboxyl group in its ionized or unionized forms (68).

The solvolysis of trityl esters has been studied quite carefully.

Hammond and Rudesill solvolyzed trityl benzoate in methyl ethyl ketone-ethanol (89). They found the reaction to be cleanly first order, strongly acid-catalyzed, and accelerated by added methoxide ion to a lesser extent than by added sodium perchlorate. The isolation of trityl ethyl ether establishes the occurrence of alkyl-oxygen fission.

A more complete study of the solvolysis of trityl acetate was carried out by Bunton and Konasiewicz (90). An isotopic oxygen study of the hydrolysis in aqueous dioxan proved that the reaction proceeds by alkyl-oxygen fission, although with added base some acyl-oxygen fission begins to intervene. With the exception of salt effects, the reaction rate is nearly independent of added acetic acid, tetraethylammonium hydroxide, triethylamine, pyridine and lithium hydroxide. Lithium acetate produces a common ion rate repression, and sulfuric acid catalyzes the reaction very strongly. The reaction rate is highly dependent upon the solvent composition.

The methanolysis is likewise a cleanly first-order reaction. It shows typical common-ion rate-repression, positive salt effect by lithium chloride, and no catalysis by added sodium methoxide. The product is trityl methyl ether. At higher concentrations of sodium methoxide, the rate increased, and some methyl benzoate was isolated, indicating some reaction by acyl-oxygen fission.

Unimolecular alkyl-oxygen fission is, therefore, found to be a quite common reaction. This mechanism may be recognized by a study of the reaction products, by the rapidity of the reaction under conditions where acyl-oxygen fission is slow, and by a kinetic behavior typical of S_N1 reactions.

CHAPTER II

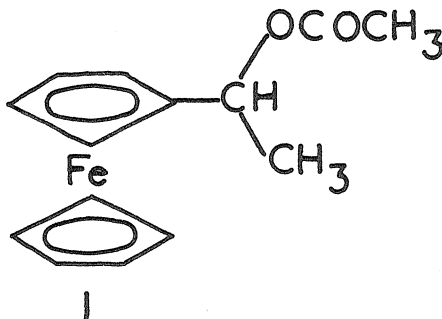
RESULTS AND DISCUSSION

A. Stabilization of Carbonium Ions by Metallocene Nuclei

1. Solvolysis of Methylferrocenylcarbonyl Acetate - Hydrolysis

Mechanism and Carbonium Ion Stability

An early trial kinetic run in 60% acetone established that methylferrocenylcarbonyl acetate (I) solvolyzes considerably more



rapidly than trityl acetate. The products of the ethanolysis of the ferrocene derivative were studied to determine the position of cleavage, and a number of solvolyses were performed in 80% acetone to elucidate more clearly the mechanism of the hydrolysis reaction.

Products of ethanolysis. - Ethanolysis of methylferrocenylcarbonyl acetate produces the ethyl ether of the carbinol, which is identical with ether prepared independently. However, in a control experiment, ether was also isolated when the carbinol was refluxed with one half equivalent of acetic acid in ethanol. It is thus possible that the solvolysis proceeds mostly by acyl-oxygen fission, and that acetic acid, formed in hydrolysis by a trace of moisture, catalyzes reaction of the carbinol with ethanol. Such a reaction

would provide strong evidence for the stability of the carbonium ion, but its presence interferes with a rigorous proof that the ester solvolyzes by alkyl-oxygen fission.

To remove this ambiguity as to the meaning of ether isolation, the other ethanolysis product was investigated. Whereas acyl-oxygen fission should produce ethyl acetate, alkyl-oxygen fission results in acetic acid. After a suitable reflux period, the ethanolysis solution was titrated and found to contain the amount of acetic acid predicted on the basis of exclusive alkyl-oxygen fission. A control experiment showed that no unexpected reaction to produce acetic acid from ethyl acetate occurs in the presence of methylferrocenylcarbinol. Therefore, the ethanolysis must proceed almost exclusively by alkyl-oxygen fission, and, by analogy, the hydrolysis should do so also.

Variation of hydrolysis conditions. - Solvolysis results for methylferrocenylcarbinyl acetate in aqueous acetone are summarized in Table I.

The magnitude of the neutral hydrolysis rate is a very good indication that the reaction follows a $B_{AL}1$ mechanism. The comparable rate for trityl acetate at 30° is $2.58 \times 10^{-5} \text{sec}^{-1}$, so methylferrocenylcarbinyl acetate solvolyzes at a rate greater than that of trityl acetate by a factor of 6.53. Since trityl acetate has been shown to solvolyze by a $B_{AL}1$ mechanism under conditions where no acyl-oxygen fission occurs (90), it is reasonable to conclude that the same mechanism prevails with methylferrocenylcarbinyl acetate.

The activation parameters for methylferrocenylcarbinyl acetate and trityl acetate are 19.0 and 22.1 kcal., and -13.2 and -6.7 e.u.

respectively. Values for other α -metallocenylcarbonyl acetates fall in this general range. The similarity of these parameters is additional evidence for the identity of the two mechanisms.

Table I

Solvolysis of Methylferrocenylcarbonyl Acetate

<u>T °C.</u>	<u>Solvent, "% Acetone"</u> ^a	<u>Added Solute</u>	<u>k x 10⁵ sec⁻¹</u>	<u>Number of runs</u>
30	80	-----	17.02	5
30	80	.00724 <u>M</u> NaClO ₄	16.67	2
30	80	.00716 <u>M</u> NaOAc	3.63	2
30	80	.00718 <u>M</u> NaOH	20 ^b	2
30	82	-----	11.59	2
0	80	-----	.49	4
0	80	.00160 <u>M</u> HCl	1.45	1
0	60	-----	8.41	1

^aThe solvent "80%" acetone is 80.7% acetone by volume. "82%" acetone is probably about 82.7% by volume. The 60% acetone was made up by volume.

^bEstimated maximum initial rate.

The solvolysis rate of methylferrocenylcarbonyl acetate is strongly dependent upon the composition of the solvent. Such a dependence is characteristic of an S_N1 reaction (91). Two notable attempts have been made to correlate solvolysis rates with solvent composition. The two-parameter mY equation of Winstein and co-workers (92):

$$\log (k/k_0) = mY$$

expresses the relative solvolysis rate at 25° as a function of the solvent "ionizing power", Y, and the sensitivity of the substrate, m.

Further work has shown the substrate parameter, m , is also dependent on the solvent pair chosen (93). As an example, the solvolysis of benzhydryl chloride is correlated poorly by a single m value of 0.927. But if separate m values such as 0.740 for ethanol-water, 1.106 for acetone-water, and 1.049 for dioxan-water are used, the correlation is excellent.* Such a dispersion of lines is to be expected in a two-parameter correlation, since the ionizing power should be a composite property, depending on such factors as the dielectric constant and the electrophilic and nucleophilic nature of the solvent. Particularly great deviations from a single mY line are to be expected when the leaving group is susceptible to acid-catalysis (e.g., fluoride or acetate), or where the carbonium ion has a particularly diffuse charge distribution (e.g., benzhydryl or trityl vs. t-butyl).

Correlations for trityl acetate based on available solvolysis data from the literature are summarized in Table II. An attempt to fit the data to a single m value results in very wide scatter.

A rough estimate of m may be made for methylferrocenylcarbonyl acetate from the data in Table I at various solvent compositions. Such a treatment yields m values of 0.82 at 0°, and 0.78 at 30°, which are quite similar to that for trityl acetate in acetone-water. Similar values of about 0.88 for methylruthenocenylcarbonyl acetate at 0° and 0.66 for α -acetoxy-1,1'-trimethyleneferrocene at 45° are obtained.

*The correlation coefficient r is used to estimate the degree of correlation of two variables with random errors. A unit value of r indicates no correlation, while $r = 0$ indicates a perfect linear relationship. With a single m , r is 0.408, while the average r for various solvent pairs is 0.02.

Table II

mY Correlation of Trityl Acetate Solvolysis Rates
in Partially Aqueous Solvents

<u>Slow Solvent</u>	<u>Range - % Slow Solvent</u>	<u>T °C.^a</u>	<u>Points, number</u>	<u>m</u>	<u>Reference</u>
Methanol	69.5-100	25	3	0.51	(90, 94)
Ethanol	60-80	25	2	0.50	(94)
Acetone	50-80	25	2	0.83	(94)
Dioxan	80-85	65	4	1.48 ^b	(90)
Acetone	60-80.7	0	2	0.91 ^b	present work

^aValues of m are expected to have some temperature dependence, but this is predicted not to be very great (92a).

^bWhen necessary, Y values were obtained by interpolating graphically from the data of reference 92b.

A second correlation of solvolysis rates has been proposed by Swain and co-workers (94). Their four-parameter equation:

$$\log (k/k_0) = c_1 d_1 + c_2 d_2$$

takes into account both the nucleophilic and electrophilic nature of the reaction. Trityl acetate is correlated fairly well by this equation, but insufficient data for methylferrocenylcarbonyl acetate are available to evaluate the three unknown parameters (c_1 , c_2 and $\log k_0$).

Several solvolysis runs with added solutes are reported in Table I. Since sodium perchlorate has a negligible influence on the rate, it may be assumed that simple salt effects of the other added solutes are small, and that any rate changes are ascribable entirely to specific effects.

Added acetate ion has a strong common ion rate repression on

the solvolysis of methylferrocenylcarbinyl acetate. Swain, Scott and Lohman (95) have determined the selectivities of several carbonium ions by measuring their relative rates of reaction with various nucleophiles. Some of these results are presented in Table III.

Table III

Relative Rates of Nucleophiles toward Carbonium Ions (95)

<u>Nucleophilic Reagent</u>	<u>Cation</u>		
	Triphenylmethyl	Benzhydryl	<u>t</u> -Butyl
H ₂ O	1	1	1
CH ₃ COO ⁻	1100	-	-
Cl ⁻	3100	120	180
N ₃ ⁻	280,000	170	3.9

The trityl cation shows the greatest selectivity between various nucleophiles, presumably because its stability allows it to survive sufficient collisions with solvent that it may react selectively with the strongest nucleophile present. These competition results were shown to be fairly independent of the solvent mixture employed in the competition of azide ion for the trityl cation, but this was not demonstrated for acetate. A similar calculation based on the trityl acetate solvolyses of Bunton and Konasiewicz (90) in 80% dioxan shows that acetate competes more effectively than water by a factor of only 90. In absolute methanol, the competition factor between acetate and methanol is 76. These figures are smaller than that of Swain by at least a factor of 10. Swain's results were obtained by solvolysis of trityl chloride in a solvent which contained only 6% water, and $2.5-7.5 \times 10^{-3}$ moles of sodium acetate per liter.

In a solvent such as this, most of the water may be tied up in solvation, so the numbers calculated from Bunton's work may be more nearly comparable with the present results. From the data in Table I, acetate is calculated to compete more effectively than water for the methylferrocenylcarbonium ion by a factor of 5500. Such a large competition factor suggests that the methylferrocenylcarbonium ion is quite stable by comparison with the trityl cation. This rate-repression is difficult to explain by any mechanism not involving a carbonium ion intermediate.

The runs with added sodium hydroxide exhibited a fall-off in rate during the course of the reaction. This is most likely because acetate ion rather than acetic acid is then a solvolysis product, and this acetate ion can cause a common ion rate repression. The results were also complicated by increased absorption of carbon dioxide from the air. The maximum initial rate showed a possible increase of about 20% over the uncatalyzed rate. Two explanations for such an increase are suggested. If a small portion of the neutral reaction proceeds by nucleophilic attack of water upon the carbonyl carbon of the undissociated ester, then an increase in rate might be expected on addition of the more nucleophilic hydroxide ion. The concentrations of hydroxide ion and water in the solution are 7.2×10^{-3} and 11.1 M respectively, and a lower limit of 10^3 may be accepted for their relative reactivities toward aliphatic carbon (71). This concentration of hydroxide ion should then increase the reaction rate by at least 60% of the rate of nucleophilic displacement by water. Therefore, this mechanism for the increase in rate cannot be excluded, even though most of the neutral hydroly-

sis proceeds via a carbonium ion.

A more reasonable explanation for the rate increase is the incursion of B_{AC}^2 hydrolysis by hydroxide ion. This was found to be the case with trityl acetate by Bunton and Konasiewicz (90). In 80% dioxan, the addition of 0.015 M sodium hydroxide resulted in 22% of acyl-oxygen fission. A crude estimate of this saponification rate may be made for the present case. Benzyl acetate is saponified with a second order rate constant of 1.0×10^{-1} l. mole⁻¹ sec⁻¹ at 30° in 60% acetone (96). If only a minor solvent effect is assumed, and a ten-fold rate decrease due to the additional methyl group is allowed (this is the factor observed between allyl and α -methylallyl acetates in water (97)), an approximate rate constant of 1.0×10^{-2} l. mole⁻¹ sec⁻¹ might be estimated. If 20% of the solvolysis rate of methylferrocenylcarbonyl acetate in base is assumed due to a saponification reaction, then the second order rate constant for such a reaction would be 0.5×10^{-2} l. mole⁻¹ sec⁻¹, which is close to the value predicted for α -phenylethyl acetate. Thus, a rate increase of this magnitude due to normal saponification is expected.

The solvolysis of methylferrocenylcarbonyl acetate is strongly acid-catalyzed. If the rate of the uncatalyzed reaction is subtracted from that in the presence of acid, a second order rate constant of 6.0×10^{-3} l. mole⁻¹ sec⁻¹ at 0° is calculated for the acid hydrolysis. A similar rate constant for trityl acetate (calculated from the data of Bunton and Konasiewicz (90) in 80% dioxan at 25°) is 2.1×10^{-2} l. mole⁻¹ sec⁻¹. Since the solvent and temperature both differ, it is impossible to make a very valid comparison. If the results obtained by Stimson and co-workers (84c, e) for benzhydryl

acetate and t-butyl benzoate at 85° are extrapolated to 0°, rate constants of 1.5×10^{-7} and 1.9×10^{-7} are obtained. It is thus seen that the acid-catalyzed hydrolysis of methylferrocenylcarbonyl acetate has a rate greater than the alkyl-oxygen fission rates for those two compounds by a factor of 10^4 .

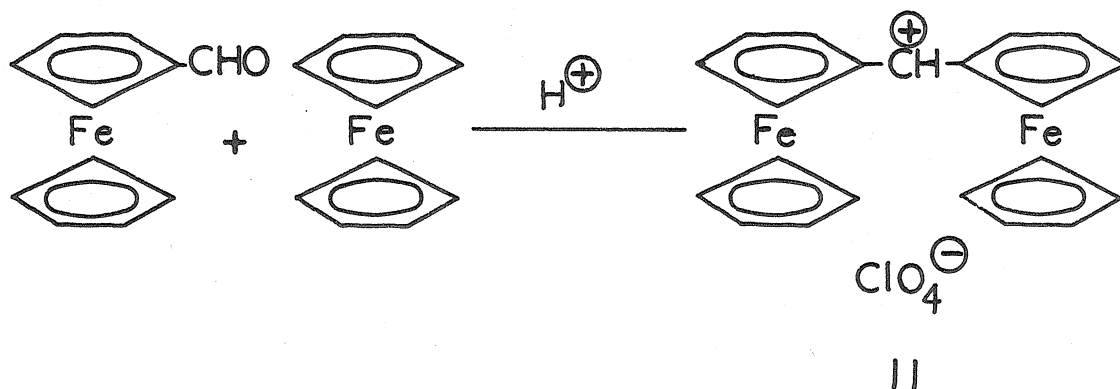
Despite the rate of the acid-catalyzed hydrolysis, none of the rate curves for the metallocenylcarbonyl acetates studied exhibit any autocatalysis. A very rough estimate may be made of the magnitude of the hydronium ion-catalyzed reaction to be expected in the neutral hydrolysis. Although no data are readily available for ionization constants in 80% acetone-water, the ionization constant of acetic acid in this medium might be expected to fall between those in 80% methanol-water and 80% dioxan-water. These values are 4.0×10^{-7} and about 3.6×10^{-11} respectively (98). Toward the end of a solvolysis run, the acetic acid concentration reaches a maximum value of about 3×10^{-3} M. If a maximum ionization constant of 10^{-7} is assumed, the hydronium ion concentration would be 1.7×10^{-5} , and the pseudo first order rate constant at 0° would be 1×10^{-7} . This is about 2% of the uncatalyzed rate, and probably beyond the limits of observability. Since the acid-catalyzed reaction undoubtedly has a lower enthalpy of activation than the solvolysis, its rate would become more negligible at higher temperatures. General acid catalysis by the acetic acid, which might also be anticipated, is likewise lacking under these solvolysis conditions.

Recent evidence for α -metallocenylcarbonium ion stability. -

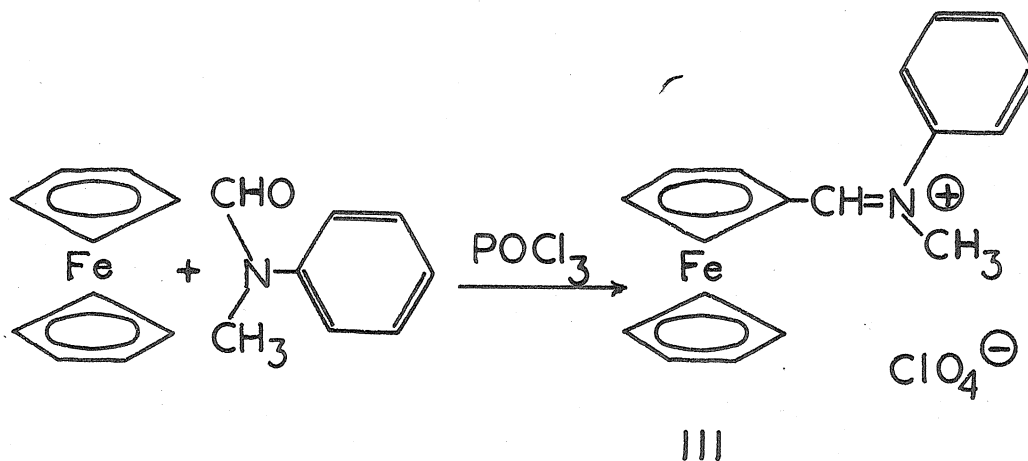
Since the preliminary communication of the results of this research (99), other experimental findings have been published which confirm

the conclusions made here as to the stability of α -metallocenyl carbonium ions.

The diferrocenylcarbonium ion (II) was isolated as its perchlorate salt from the acid-catalyzed reaction of ferrocenecarboxaldehyde with ferrocene (100). This salt is reported to react slowly

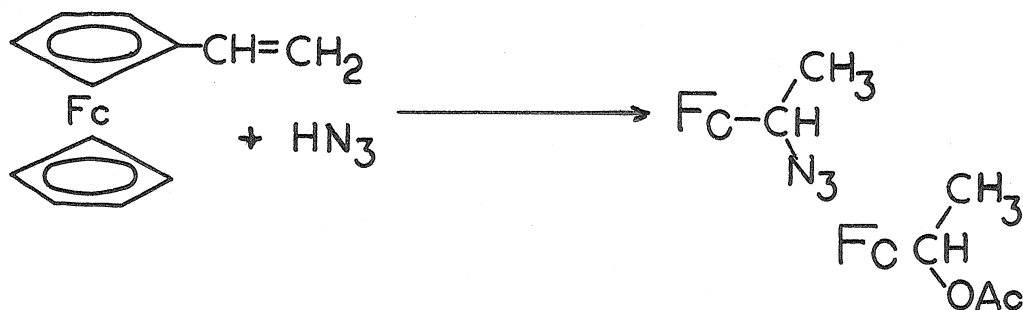


with weakly basic aqueous solution to form diferrocenylcarbinol. The primary complex from the formylation of ferrocene with N-methylformanilide (III) has also been isolated as the perchlorate salt (100), which hydrolyzes in water to ferrocenecarboxaldehyde. Since such salts as these are isolated only for carbonium ions of high



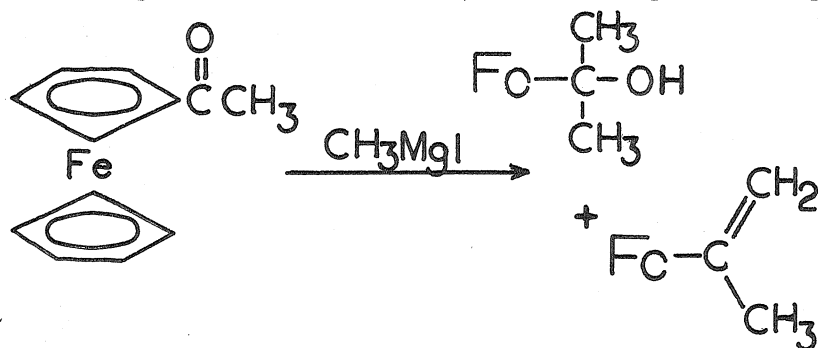
stability, they provide strong evidence for the ability of a ferrocene nucleus to stabilize the carbonium ion.

Vinylferrocene is extraordinarily reactive toward addition of weak acids such as acetic and hydrazoic acids (101). Such electrophilic additions are generally considered to proceed through an intermediate carbonium ion (or other similarly stabilized species with protonated double bond), so the facility of this reaction suggests the intermediacy of a very stable carbonium ion. The azide



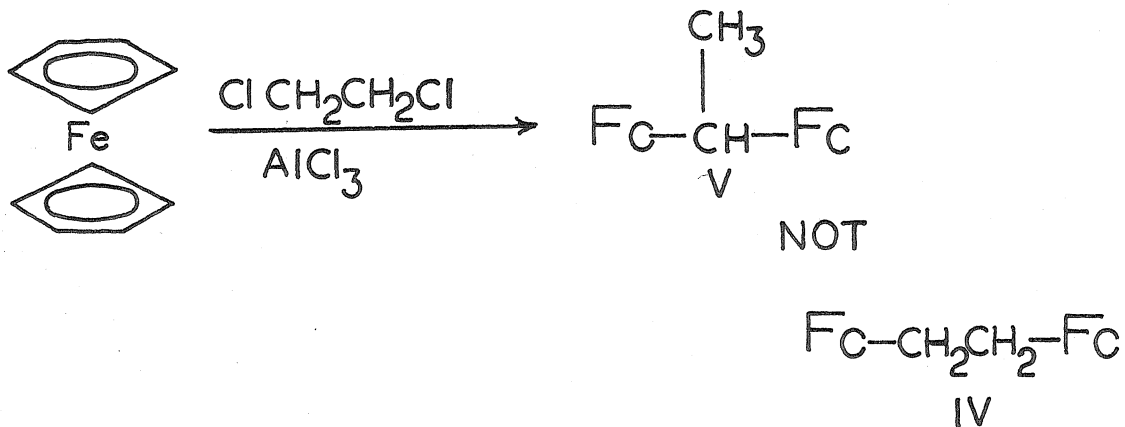
was also formed by similar treatment of the corresponding carbinol with hydrazoic acid in benzene-acetic acid solution.

The product of addition of methylmagnesium iodide to acetylferrocene contained a large proportion of the alkene in addition to the expected carbinol (102). An attempt in the present work to



prepare the somewhat hindered tertiary acetate by addition of acetic acid to the alkene resulted in quantitative conversion to non-sublimable polymer through the carbonium ion.

Treatment of ferrocene with 1,2-dichloroethane under Friedel-Crafts conditions yields a product originally assigned (14) the structure of 1,2-diferrocenylethane (IV). However, more recent work



(103) has shown its structure to be 1,1-diferrocenylethane (V).

The intermediate primary carbonium ion (or partially free carbonium ion) must rearrange to the vastly more stable methylferrocenylcarbonium ion before reacting with a second molecule of ferrocene.

The rearrangement occurs in this instance, although similar alkylation of benzene proceeds smoothly to bibenzyl.

Ferrocenylcarbinol has been studied by Levenberg (104) in strongly acidic media. This carbinol has an ρ value of 3.9 in sulfuric acid, which indicates ionization to a carbonium ion, rather than the simple protonation found with most alcohols. The nuclear magnetic resonance (NMR) spectrum of this carbonium ion shows that the positive charge is delocalized through the entire molecule. These results will be discussed further in connection with substituent effects on the carbonium ion stability.

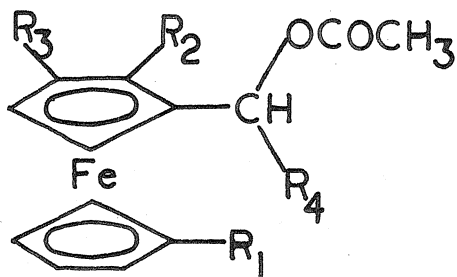
While undoubtedly classical resonance stabilization is a major factor in determining the stability of metallocenylcarbonium ions,

the metal must also have a significant role. First of all, polarization of the ring-metal bonds would tend to stabilize the positive charge by distributing it throughout the molecule. Beyond this, there is the possibility of some direct interaction of the metal orbitals with the carbonium ion center. This possibility must be kept in mind during the discussion to follow, and will be considered in detail in a later section (see p. 108)

Summary. - Methylferrocenylcarbinyl acetate has been shown to solvolyze by uncatalyzed alkyl-oxygen fission. This mechanism is demonstrated by the isolation of acetic acid in the ethanolysis, the magnitudes of the uncatalyzed and acid-catalyzed hydrolysis rates, the activation parameters for the solvolysis, common ion rate repression by acetate ion, the solvent effect, and lack of catalysis by acetic acid formed in the reaction. The large common ion rate-repression provides evidence that the carbonium ion is highly stabilized, and able to react selectively with the strongest nucleophile present. Finally, the stability of this α -metallocenylcarbonium ion helps to explain the occurrence of some other unusual reactions in the ferrocene series.

2. Effects of Heteroannular Substitution

A primary area of interest in physical organic chemistry is the correlation of variations in structure with their effects on reactivity. Studies of this sort can provide insight into the electronic and steric interactions present within molecules, as well as into the more intimate details of the mechanisms of reactions. The solvolysis of substituted ferrocenylcarbinyl acetates (VI) is a convenient reaction in which to study these effects in an attempt to learn



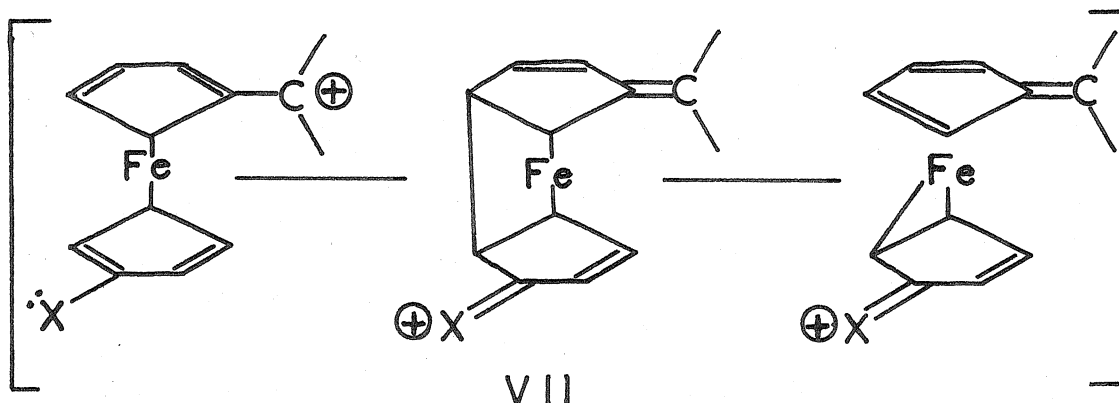
VI

more about metallocene systems, and their ability to stabilize an electron-deficient center.

In the metallocenes, a substituent on one ring can exert an influence upon reactions occurring on the other ring or on the metal itself. Qualitatively, it was realized early that an acetyl group in one ring deactivates the second ring to further acetylation (4, 105). Unfortunately, there is very little competitive rate data for substituted ferrocene derivatives, so quantitative comparisons for electrophilic substitutions are not possible.

Changes in the electron density on one ring, brought about either by inductive or conjugative interaction of the ring with its substituents, could be relayed through the ring-metal bonds to a re-

action center on the other ring. In this sense, a 1'-substituent might be likened to a meta-substituent on a phenyl derivative (106a). Such an inductive transmission of effects would depend upon the nature and polarizability of the ring-metal bonds. While the classical type of direct conjugative interaction between heteroannular substituents is not possible, valence bond structures such as VII might make important contributions to the resonance hybrid in reactions calling for strong electron release or withdrawal. If the metal atom participates directly in the reaction, electronic effects may be transmitted both to the metal and through it to the conjugated system of the other ring.



The field effect of a heteroannular substituent should vary with the relative orientation of the two rings, since the direction and distance of the dipole are changed (106b). Field interactions could be strong enough to interfere with the rotation of the rings, and could merge into the situation where covalent bonding occurs between the substituent and the reaction center. These possibilities are more analogous to aliphatic and ortho-substituted derivatives than to meta and para substitution in benzene derivatives.

Substituent effects in other ferrocene reactions. - Substituent

effects have previously been studied for two reactions of ferrocene derivatives. Benkeser and Hall (107) report that the ionization constants of 1'-substituted ferrocenecarboxylic acids (in 66% ethanol) are correlated poorly by σ_m (108), fairly well by σ_p (108) and quite well by σ^* (109). They interpret this to mean that inductive effects predominate, and that interannular resonance effects are negligible. Since direct resonance between the substituent and the reaction center in carboxylic acid ionizations is generally considered slight (110), it is quite reasonable that the resonance contribution should be still smaller in this case than with meta- and para-substituted benzoic acids. From the plots given by Benkeser and Hall, ρ values of 1.4 for the σ_m correlation and 0.94 for the σ_p correlation may be estimated. Comparison of these with a ρ value of 1.52 (108b) or 1.46 (111) for benzoic acids in 50% ethanol suggests that electronic effects are transmitted quite readily between the ferrocene rings.

An uncertainty arises in this correlation, however. Since no σ^* values were available for carboxy or carboethoxy, these points were not plotted. But if the reasonable assumption is made that these substituent constants should be nearly identical with that for carbomethoxy (as they are with σ_m and σ_p (108b)), then these points fall quite far from the line, and the fit is probably worse than for σ_p . Another complication which was not considered is the possibility of intramolecular hydrogen bonding, such as that observed for methyl-(1'-carbomethoxyferrocenyl)carbinol (see p. 134). This type of interaction could serve to decrease the acid strengths of the compounds with polar substituents, and might well alter the conclusion as to

which substituent constant best fits the data. Results reported by Nesmeyanov et al. (112) show similar scatter when plotted against the various substituent constants. With the many complications which may arise in these substituent effects, it is obvious that a more extensive series of compounds must be investigated before any conclusions can be drawn about the transmission of electronic effects between the rings.

The chronopotentiometric oxidation of several ferrocene derivatives has been studied by Bublitz, Hoh and Kuwana (113). They find that the oxidation is made easier by electron-releasing substituents, and more difficult by ones which withdraw electrons. A plot of $E_{\frac{1}{4}}$ values (equal to the polarographic $E_{\frac{1}{2}}$ for reversible electrode reactions against σ^* gives a straight line if the points for acetyl- and diacetylferrocene are not included. The effect of the acetyl groups is additive, and they appear to exert a considerably greater effect than one would expect from their σ^* values. This deviation suggests an appreciable resonance effect, and indeed the data may be correlated reasonably well using either σ_p or σ_m .

1'-Substituent effects on ferrocenylcarbonyl acetate solvolyses. -

In this research, a limited attempt was made to study the effects of heteroannular substitution. Compounds were prepared bearing methyl and carbomethoxy groups in the far ring, as well as compounds with methyl groups in both rings. Pertinent relative rate constants and activation parameters are summarized in Table IV.

While no serious conclusion can be drawn from a Hammett plot of only three points, such plots of the present data may still be instructive. Use of σ_p gives poor correlation, while either σ' or

TABLE IV

Solvolysis Rates of 1'-Substituted Methylferrocenylcarbinyl Acetates^a

1'-Substituent	Rel. k, 30°C.	Rel. k, 0°C.	$\Delta\Delta H^\ddagger$ (kcal.)	$\Delta\Delta S^\ddagger$ (e.u.)
A. No homoannular substituent				
CH ₃ ^b	1.97	2.11	-0.42 ± 0.38	0.0
H	1.00	(1.00)	(0.00 ± 0.57)	(0.0)
-COOCH ₃ ^b	0.0140		+2.33 ± 1.13	+1.5
B. Homoannular 3-methyl substituent				
CH ₃ ^b	1.81	1.81	-0.01 ± 0.65	-0.3
H ^b	(1.00)	(1.00)	(0.00 ± 0.35)	(0.00)
C. Homoannular 2-methyl substituent, fast isomer				
CH ₃ ^b	1.77	2.10	-0.92 ± 0.60	-1.9
H	(1.00)	(1.00)	(0.00 ± 0.27)	(0.00)
D. Homoannular 2-methyl substituent, slow isomer				
CH ₃ ^b	1.89	2.15	-0.69 ± 0.45	+3.7
H	(1.00)	(1.00)	(0.00 ± 0.54)	(0.00)

^aFor complete data see Table IV, p. 203, Chapter III of this thesis.^bExtrapolated from other temperatures.

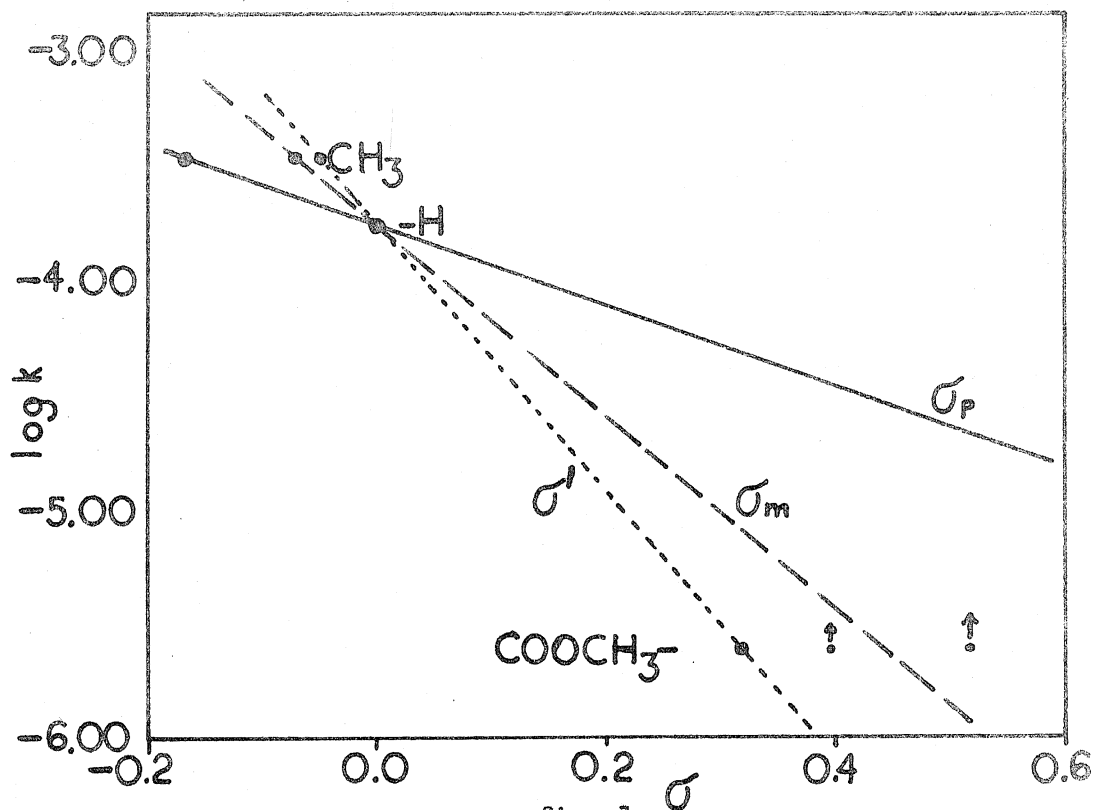


fig. 1a
Plot of log k for heteroannular substituents
vs. σ_p , σ_m and σ'

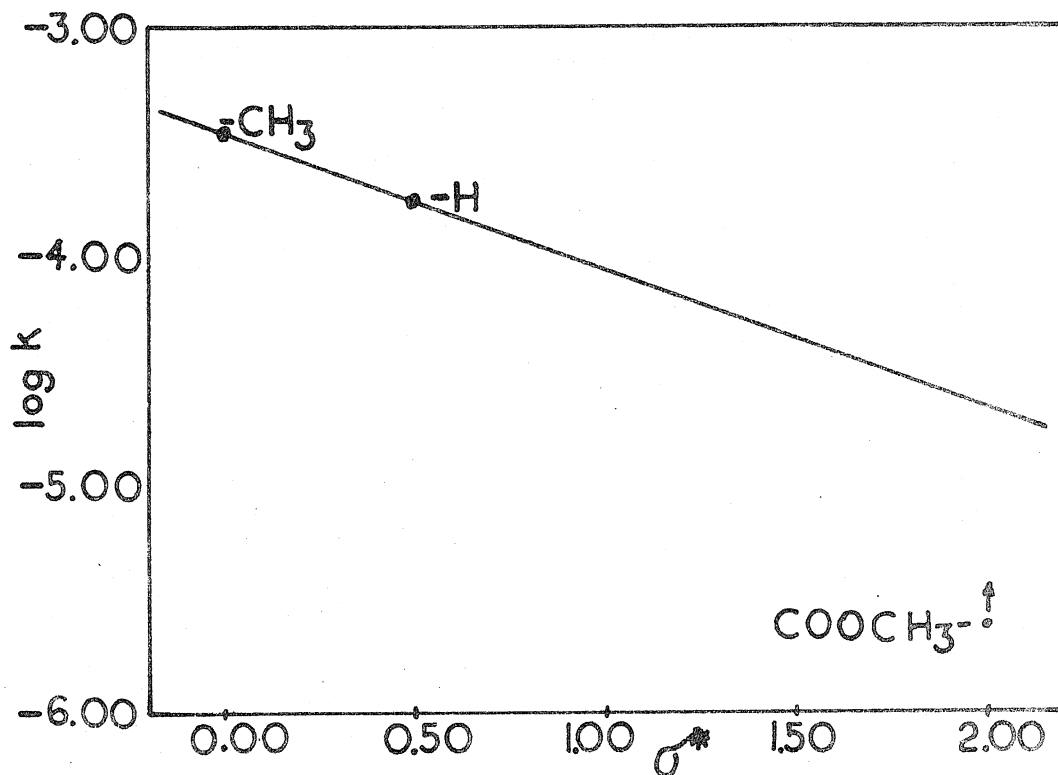


fig. 1b
Plot of log k for heteroannular substituents vs. σ^*

σ_m give reasonably linear plots (fig. 1a, p. 42). Correlation with σ^* is not very good (fig. 1b, p. 42). Approximate values for the reaction constant, ρ , are -5.9 for the σ' correlation and -4.6 for σ_m . Other substituents which would be particularly valuable in extending such correlations, and which might be accessible in the ferrocene series, are iodo, phenyl, cyano, acetyl and trimethylsilyl.

Since the present data are correlated by σ' or by σ_m , but not by σ_p , direct conjugative electron release to the carbonium ion by the methyl group is probably very slight, and field effects or inductive transmission through the metal most likely predominate.* Electronic influences of substituents might reasonably be transmitted similarly in this reaction and in the oxidation, as both reactions must develop a partial positive charge in the transition state. Since the resonance contribution to the oxidation reaction is evident only with the acetyl substituents and not with the carboxy group, solvolysis of the 1'-acetyl derivative must be performed before a valid comparison of the two reactions may be drawn.

The average effect of a 1'-methyl substituent in these solvolyses is about a factor of 1.9 in the rate. From consideration of the possible modes of electron release, and from the fair correlation of these solvolysis rates with σ_m , a comparison of the effect in this series with that of a meta-methyl substituent on solvolyses and ionizations in the benzene series seems in order. Some pertinent data are summarized in Table V. The effect of a 1'-methyl group

It is not immediately obvious whether σ' or σ^ is the inductive substituent constant which should be applicable in this system. The significance of the fit of the data to σ' rather than to σ^* is thus uncertain.

TABLE V

Effect of meta-Methyl Substitution on Solvolyses and Ionizations

Reaction	$\frac{k_{m-CH_3}}{k_H}$	$\frac{K_{m-CH_3}}{K_H}$	Ref.
X-C ₆ H ₄ (CH ₃) ₂ CCL, 90% Acetone, 25° C.	2.0		(114)
X-C ₆ H ₄ CH ₂ -OSO ₂ C ₆ H ₄ CH ₃ , 76.6 mole % H ₂ O in acetone, 25° C.	1.8		(115)
X-C ₆ H ₄ (C ₆ H ₅)CHCl, 90% ethanol, 0° C.	2.3		(116)
X-C ₆ H ₄ (C ₆ H ₅)CHCl, 80% acetone, 0° C.	1.75		(116)
X-C ₆ H ₄ (C ₆ H ₅)CCL, SO ₂ , 0° C.		2.3	(117)
(X-C ₆ H ₄) ₃ CCL, H ₂ SO ₄ , 25° C.		1.90	(118)

on the ferrocenylcarbinyl acetate solvolyses is seen to be of the same order of magnitude as those tabulated.* The ρ value (about -5) observed in this research for 1'-substitution in the ferrocenylcarbinyl system is quite similar to a value for ρ of -4.62 for the σ^+ correlation of solvolyses of phenyldimethylcarbinyl chlorides (114b).

*When two or three aryl groups are attached to the carbinyl carbon, the question arises whether the effect of only one substituent, or of one in each ring, should be considered. With only methyl substitution, the effect of the substituent is small relative to the effect of an additional phenyl on the carbinyl carbon, so that the unsubstituted rings will probably continue to bear nearly their share of the charge. This is supported by evidence that effects of subsequent substitution are approximately additive (117, 118b). The ρ values for symmetrical substitution are nearly equal for di- and tri-arylmethanol ionizations (118c). This value is twice that for monosubstitution in the di-arylmethanols, and about 2.7 times that for monosubstitution in the tri-arylmethyl chlorides (118c). Even with this uncertainty, the effect of a 1'-methyl group in the methylferrocenylcarbinyl acetate solvolysis is quite comparable in magnitude with that of the meta-methyl group.

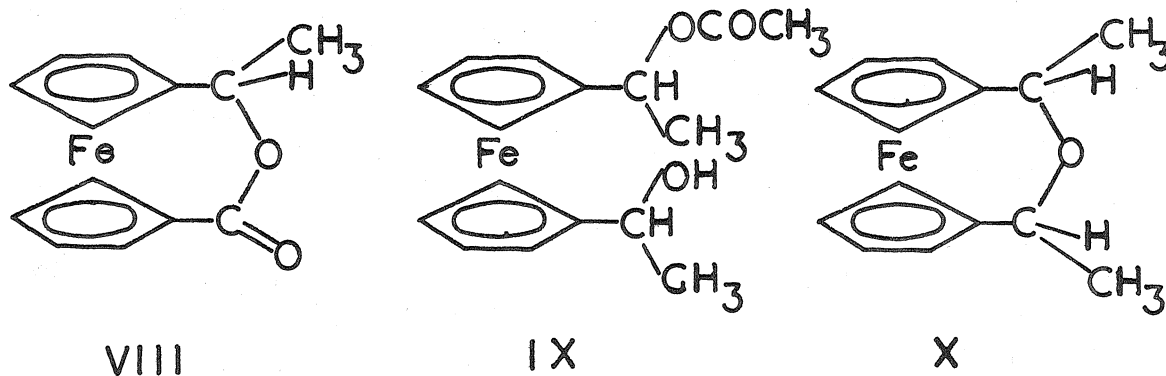
This confirms comparison between the 1'-position in a substituted ferrocene and the meta position in a substituted benzene.

Garwood (20) has shown that an ethyl group on a ferrocene nucleus has a very small effect (about 2.5) on the partial rate factor for acetylation in the 1'-position. This is considerably smaller than the partial rate factor of 10.4 (relative to a position in benzene) for acetylation in the meta position of ethylbenzene (119). This contrast between the acetylations and the solvolyses may reflect a difference in the way the ferrocene nucleus can respond to the electron demands in these two reactions. This will be discussed in more detail later (see p. 96).

One of the original reasons for selecting the carbomethoxy substituent for these solvolyses was to investigate the possibility of participation by the oxygen atoms of this group. Such participation should be accompanied by a rate enhancement, a lowering of the enthalpy of activation, and possibly a more negative entropy of activation, due to the loss of nearly free rotation of the rings.* Since solvent participation at the rear is probably negligible in these solvolyses (see p. 56), participation by the carbomethoxy would not be expected to make the entropy of activation less negative (120). Although there are relatively large errors in the activation parameters, it is apparent that the entropy of activation is not appre-

*The entropy due to free rotation in ferrocene has been calculated to be 5.38 e.u. (121), which corresponds to 1610 cal. in free energy at 300° K. This value would be increased in a substituted ferrocene. Of course, it is possible that rotation in the ferrocenylcarbonium ion is hindered even without interaction with the substituent, due either to changes in the ring-metal bonding or to solvent orientation around the cationic center.

ciably more negative than in the unsubstituted compound. Since there is no model compound available for comparison, it is impossible to tell for certain whether or not the rate is enhanced. However, some information may be derived from the Hammett plots. The best correlation is obtained for σ' , which also predicts the lowest rate for the acetate with 1'-carbomethoxy substitution. Therefore, if there were any rate enhancement due to participation, the normal rate in the absence of participation would be much too small for correlation by any of the substituent constants. It may then be concluded that there is no participation by the carbomethoxy group. This line of reasoning would, of course, be reinforced by rate data for more compounds. The cyano derivative would be particularly useful in this connection, since it has a strong electron-withdrawing effect, but could not participate due to its linear shape. The lactone VIII which might have resulted from this solvolysis was not isolated from



the reaction. Another compound of interest in this connection would be an acetate (e.g. IX) of the reduction product from diacetylferrocene, in which participation could produce the cyclic ether X as the solvolysis product.

From parts B-D of Table IV, it may be seen that the effect of

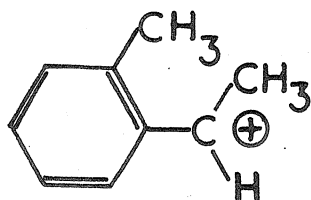
the heteroannular methyl group changes very little with homoannular methyl substitution. However, it does appear that the compounds with 3-methyl substitution deviate slightly from the pattern. Such an irregularity could result from repulsions between groups on the two rings. A methyl group in the 3-position does not permit the heteroannular substituent to rotate as freely into a position in which it can avoid the carbonyl group, and might therefore alter its field and steric effects. This hypothesis could readily be tested by the synthesis of derivatives with bulkier groups.

Much more could be learned about transmission of electronic effects between the two rings of the metallocenes by solvolyses of other 1'-substituted acetates. This study could well be extended to derivatives of ruthenocene and osmocene. It would also be valuable to study the effects of the same 1'-substituents on the ionization constants of the carboxylic acids and on the partial rate factors for acetylation in the 1'-position, since this would allow a comparison of the substituent effects in three reaction series.

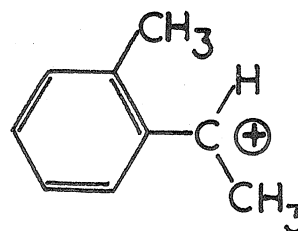
3. Effects of 2-Alkyl Substitution - Stereochemistry of the Solvolysis

Isomerism of 2-substituted derivatives. - By analogy with benzene derivatives, when a substituent is located in the 2-position relative to the carbonyl grouping, steric effects may be expected to manifest themselves. Thus, if we consider the solvolysis of a 2-substituted α -phenylethyl derivative, two carbonium ion intermediates are possible, XI and XII. Steric interaction with the adjacent methyl group is minimized in XII, so the solvolysis should proceed almost

entirely through this carbonium ion. Since the carbonium ion has a plane of symmetry, optically isomeric derivatives differing only in the configuration about the carbinyl carbon will show identical behavior on solvolysis. However, in a metallocene derivative, there is an additional element of asymmetry due to the metal atom and the second ring, so that any derivative substituted with two unlike groups on the same ring will have the possibility of optical isomerism (122).



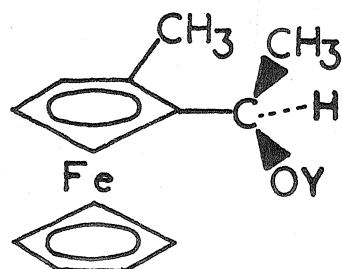
XI



XII

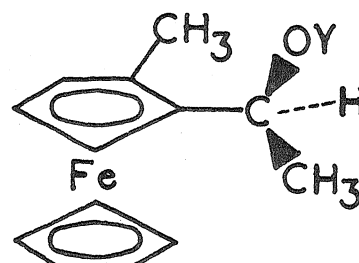
Therefore, the regions on the two sides of the ring plane will differ greatly. For simplicity, in all drawings the carbinyl substituent will be placed on the upper ring, as with XIII-XVI, and the two regions may then be referred to as "above" and "below" the plane of the ring. Due to this additional asymmetry, two pairs of enantiomers will exist when the carbinyl carbon is an asymmetric center. This situation is illustrated for one enantiomer of each pair for the isomers of methyl(2-methylferrocenyl)carbinyl derivatives (XIII and XIV) and the α -substituted 1,2-tetramethyleneferrocenes (XV and XVI). Similar isomers must also exist with 1,3-substitution. However, the second asymmetry in the molecule is far enough removed from the carbinyl carbon that its effect upon the chemical behavior is not noticeable.

Reduction of α -keto-1,1'-tetramethyleneferrocene with lithium aluminum hydride led to the expected two isomeric alcohols. The



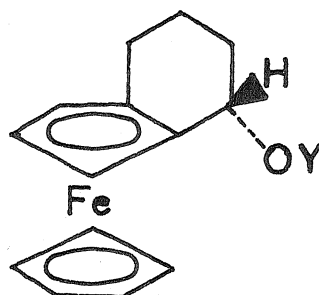
XIII

a. Y=H
b. Y=COCH₃



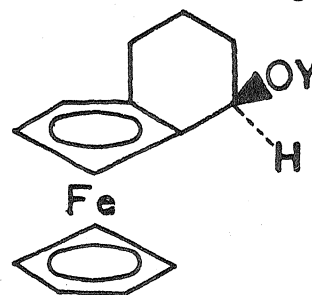
XIV

a. Y=H
b. Y=COCH₃



XV

a. Y=H
b. Y=COCH₃



XVI

a. Y=H
b. Y=COCH₃

isomer which passed through the chromatographic column more rapidly and showed hydrogen bonding to the metal was assigned the endo structure XVa; the isomer which chromatographed more slowly and showed only free (or ring-bonded) hydroxyl in the infrared was assigned the exo structure XVIa (see p. 131; also ref. 123). The two isomers were produced in a ratio of exo : endo = 9.5 : 90.5.* Thus, the presumably less stable endo isomer was formed by preferential hydride transfer from the less hindered "upper" side of the ring.

*The same reduction reported by Trifan and Bacskai (123) led to an isomer ratio of 11 : 89.

Similar reduction of 2-acetylmethylferrocene, 2-acetyl-1,1'-dimethylferrocene and 2-acetyl-1,1'-trimethyleneferrocene led to isomeric carbinol pairs which showed the same relationship between infrared spectra and chromatographic behavior as the α -hydroxy-1,2-tetramethyleneferrocenes. For this reason, they were assigned the pseudo-endo and pseudo-exo structures corresponding to those shown in XIIIa and XIVa (see p. 132). In these isomers, the predominant conformations are probably those shown, due to minimization of the interaction with the adjacent ring substituent. The relative proportions of pseudo-endo to pseudo-exo alcohols were 49 : 51 for 2-acetylmethylferrocene and 43 : 57 for 2-acetyl-1,1'-dimethylferrocene. For 2-acetyl-1,1'-trimethyleneferrocene, the pseudo-endo isomer was isolated in 63% yield, and the pseudo-exo isomer in 16% yield. This ratio of 80 : 20 must be considered a maximum, since an undetermined quantity of ether was also formed, which probably contained a preponderance of the more reactive pseudo-exo isomer. Since the acetyl group may exist in either of two conformations, rationalization of these isomer ratios is somewhat complicated. NMR spectra at room temperature failed to show two slowly interconverting forms of the acetyl compounds, so either one conformation predominates strongly, or equilibration is rapid. The difference observed with trimethylene bridging may result either from greater steric bulk of the bridge in the region between the rings or from the proximity of the other ring due to ring tilting (see pp. 75, 147).

Acetates were prepared from the alcohols by treatment with acetic anhydride in pyridine. Since the C-O bond is not broken in this reaction, the configurations about the carbonyl carbon are not altered.

From the relative chemical shifts of various protons in the NMR spectra of the acetate isomers, it is likely that minimization of the interaction with the ring substituent determines the predominant conformation here as in the alcohols (see p. 146). Thus, conformations of the type of XIIIb and XIVb are probably close to those existing in the acetates.

A limited attempt to equilibrate the methyl(2-methylferrocenyl)-carbonyl acetates by allowing them to stand overnight with acetic acid resulted in some isomerization of the pseudo-endo acetate, and very slight isomerization of the pseudo-exo isomer. On a considerably longer period of isomerization, only non-distillable polymer was formed. These results suggest but do not demonstrate that the pseudo-exo isomer may be the more stable.

Stereochemistry of the solvolyses. - In Table VI, pertinent data for solvolyses of the derivatives with 2-substitution are summarized. With a trimethylene bridge in the 2-position, results are qualitatively similar. However, due to certain other features of those compounds, their solvolysis rates will be considered in a subsequent section (see p. 75).

The solvolyses of the α -acetoxy-1,2-tetramethyleneferrocenes will be considered first. The rate constant observed for the faster exo isomer is very close to that for the 3-methyl isomer (see Table VII, p. 62) and to that for the faster of the 2-methyl isomers. The rate increase over that of the unsubstituted derivative is thus of the magnitude expected from electron release by the alkyl group. The endo compound, however, is slower than its diastereomer by a factor of about 2500. Essentially all of this rate decrease arises

from the increased enthalpy of activation.* Obviously, then, it is much more favorable for the acetate to depart "upward" away from the rest of the molecule than it is for ionization to occur "downward" toward the iron.

The most likely, and certainly the most attractive, explanation for this large rate difference is that solvolyses of metallocenyl-carbonyl acetates are assisted by direct nucleophilic participation from the rear by a filled orbital of the metal. Such participation would be impossible in the endo isomer, and so it should solvolyze at a greatly decreased rate. From the enthalpies of activation, one might estimate that this participation is equal to the difference in activation energies, or 4.5 kcal. This conclusion has been reached by Trifan and Bacskai (123), who solvolyzed the same pair of isomers.

While metal participation may be the most reasonable explanation for much of this large rate difference, there are other factors which should contribute substantially. First of all, if the acetate departs "downward", it will be repelled by the hydrogen atoms on the second ring. A very simple model of this is shown in XVII, where distances used are accepted values for bond lengths and angles (124, 125), and the ferrocene rings are assumed to be eclipsed. Geometrical calculation shows that the ether oxygen can approach a hydrogen on the far ring as closely as 2.18 Å in the ester molecule. Of course, this distance could be made slightly greater by staggering of the rings, but nevertheless, this is somewhat closer than the sum of the van der Waals radii of hydrogen and oxygen, 2.6 Å (126). In

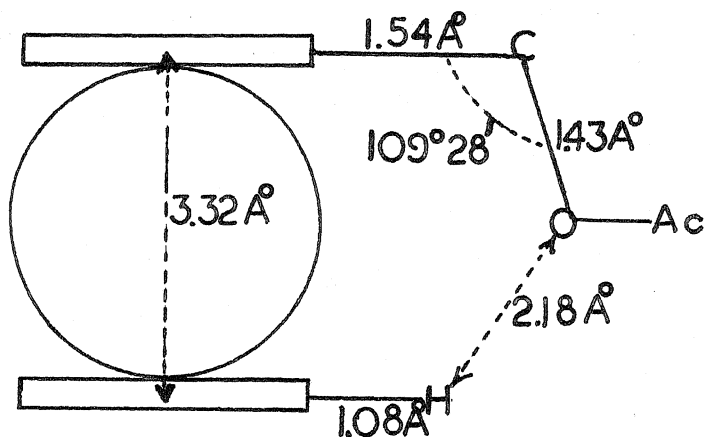
*Similar results have been obtained by Trifan and Bacskai (123).

TABLE VI

Solvolysees of 2-Substituted Ferrocenylcarbonyl Acetates^a

Compound	Rel. k_{100}	$\Delta\Delta H^\ddagger$ (kcal.)	$\Delta\Delta S^\ddagger$ (e.u.)
A. No Heteroannular Substitution			
Methylferrocenylcarbinol	1.000	0.0 ± 0.6	0.0
α -Acetoxy-1,2-tetramethyleneferrocene, endo isomer	0.00165 ^b	$+4.5 \pm 1.3$	$+2.2$
α -Acetoxy-1,2-tetramethyleneferrocene, exo isomer	4.24	-0.5 ± 0.4	$+1.2$
Methyl(2-methylferrocenyl)carbinyl acetate, Ψ -endo isomer	0.376	$+0.2 \pm 0.5$	-1.6
Methyl(2-methylferrocenyl)carbinyl acetate, Ψ -exo isomer	4.28	$+0.1 \pm 0.3$	$+4.3$
B. Heteroannular Methyl Substitution			
Methyl(1'-methylferrocenyl)carbinyl acetate	1.00 ^b	0.0 ± 0.4	0.0
Methyl-2-(1,1'-dimethylferrocenyl)carbinyl acetate, Ψ -endo isomer	0.222	0.0 ± 0.4	-2.5
Methyl-2-(1,1'-dimethylferrocenyl)carbinyl acetate, Ψ -exo isomer	3.82 ^b	0.0 ± 0.6	$+2.4$

^aFor complete kinetic data see Table IV, p. 203 in Chapter III.^bExtrapolated from other temperatures.



XVII

the transition state for solvolysis, the C-O bond would be lengthened, and would become more nearly perpendicular to the ring planes. These changes would considerably increase the repulsion. The magnitude of an effect such as this would be somewhat difficult to calculate, since relief of strain could occur by bending a number of bonds with small force constants. However, it might easily account for 1 kcal. or more of the difference in activation energies. In addition, the leaving acetate group might experience repulsion from the filled iron orbitals. It is possible also that the acetate would be less favorably solvated, or that its rotations would become more restricted in this transition state. Any of these effects would decrease the solvolysis rate of the endo isomer. Since the charge distribution is not known certainly for ferrocene, it may be that the iron bears a slight negative charge. (Pauling reaches this conclusion on the basis of a resonating-bond treatment of ferrocene (127).) Then, such a charge might oppose the charge separation on ionization, and slow the solvolysis of the endo isomer.

In addition to solvolyses of the α -acetoxy-1,2-tetramethyleneferrocenes, Trifan and Bacskai (123) report that α -tetralyl acetate, the benzene analog, solvolyzes more slowly than the endo isomer by a factor of 600, which is due entirely to a less favorable entropy of activation. They conclude from this that no "residual driving force is still present in the endo isomer compared to its phenyl analog".

If repulsion by the second ring and the other effects mentioned above contribute appreciably to the high enthalpy of activation for the endo isomer, then the result for α -tetralyl acetate is quite readily rationalized. These compounds are secondary arylmethyl acetates, and their solvolysis need not be completely limiting (128). In α -tetralyl acetate, then, nucleophilic solvent participation may make an important contribution with an attendant decrease in entropy (120). With endo- α -acetoxy-1,2-tetramethyleneferrocene, delocalization of the positive charge into the ring by resonance may be more effective than in the benzene derivative, necessitating less solvation. However, the other factors increase the enthalpy of activation, and slow the reaction.

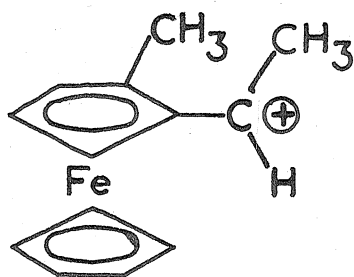
Solvolysis of either isomer of α -acetoxy-1,2-tetramethyleneferrocene yields only the exo alcohol as the reaction product. In this research, the reaction was at least 99% stereospecific, while Trifan and Bacskai report better than 99.5% (123). The endo alcohol isomerizes only slightly under the most vigorous solvolysis conditions. If there were no direct bonding between the iron and the carbonyl carbon in the ferrocenylcarbonium ion, solvent collapse to products might be expected to be controlled primarily by steric fac-

tors. In the absence of a good estimate of the magnitude of these steric factors, it is impossible to predict the product ratio in the absence of metal participation.* However, the high stereospecificity observed may probably be taken as evidence for bonding between the iron and the carbonyl carbon in the metallocenylcarbonium ion. This stereospecificity would arise from bonding to the "inner" side of the carbonium ion by the metal, which permits collapse of solvent only from the "upper" side. Presumably this bonding would begin after departure of the acetate in solvolysis of the endo isomer.

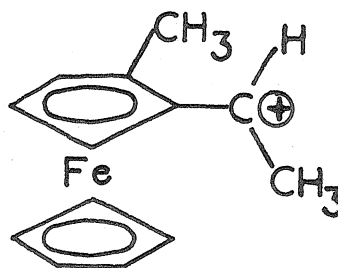
These results hold further implications for the solvolyses of other metallocenylcarbonyl acetates. First of all, since the back side of the forming carbonium ion is bonding to the iron, or is at least very severely hindered to solvent approach, these solvolyses must be quite limiting in nature. Second, these results predict that solvolyses of ferrocenylcarbonyl acetates should proceed with retention of configuration. No solvolyses of optically active ferrocenylcarbonyl derivatives have been reported, but the results to follow provide an equivalent of this demonstration.

Solvolyses of the ferrocenylcarbonyl acetates with 2-methyl substitution can lead to isomeric carbonium ions of the type XVIII and XIX. It may easily be seen that if departure of the acetate

*Trifan and Bacskai (123) suggest that the isomer ratio of about 9 : 1 observed in the reduction of the ketone with lithium aluminum hydride is a reasonable estimate of the ratio of exo to endo solvent collapse in the absence of iron participation. This is, however, an unrealistic approach. Reductions of ketones with lithium aluminum hydride frequently show "product development control", in which the more stable isomer is produced (129). Despite that tendency, the less stable isomer is produced in this reduction, so that such an estimate of the steric effect in solvent attack is probably low.



XVIII



XIX

is limited to the "upward" direction, then XVIII would arise from the pseudo-endo isomer (XIIIb) and XIX would arise from the pseudo-exo isomer (XIVb). It is shown in Table VI that the pseudo-exo isomers solvolyze faster by a factor of about 11.5 than their corresponding pseudo-endo isomers in both cases.

Since the pseudo-exo isomer appears also to be the more stable, it may be calculated that the transition state leading to the less hindered carbonium ion has a lower free energy by at least 640 cal. The difference in rate is in each case due to the difference in the entropy of activation alone. While the differences are only about twice the combined experimental errors of the two compounds, duplication of this result for two sets of compounds makes the conclusion more dependable. This result is a composite of the energy and entropy differences of the starting acetates and the transition states, including the effects of solvation and hindered rotations. It should not be interpreted as evidence that the carbonium ions differ in their entropies, but not in their enthalpies. In fact, this result shows that it is impossible to estimate the difference in repulsion energies between the two carbonium ions by this method without also evaluating the temperature dependence of the equilibrium between the

acetates.

The products from the solvolyses of all four of the acetates with 2-substitution were formed with complete retention of configuration within the limits of error of the measurements ($\sim 1\%$). Since the carbonyl carbon is not constrained into a ring, as in the derivatives of 1,2-tetramethyleneferrocene, it is conceivable that rotation about the bond to the ring could occur. In this way, a mixture of the isomers might result. Retention of configuration then provides concrete evidence that rotation about the bond to the ring does not occur with appreciable frequency in the carbonium ion, and that the ionization and recombination steps are stereospecific in the open chain case as well as in the cyclic system. The difficulty encountered in attempting to isomerize the acetates is also consistent with retention of configuration. This lack of rotation follows from the hypothesis of bonding between the carbonyl carbon and the metal. However, the result does not provide additional compelling evidence for that proposal, since strong conjugation with the ring should also present a very considerable barrier to rotation. Indeed, it has been demonstrated that such rotation does not occur in the allylic butenyl cation under solvolytic conditions (130).

The important results concerning the stereochemistry of this reaction may be summarized as follows. Solvolysis of ferrocenylcarbonyl acetates and subsequent recombination of the carbonium ion with solvent occur almost exclusively on the side of the ring plane away from the center of the molecule. The most probable explanation for this result is nucleophilic participation by the metal from the rear, but other factors, such as steric hindrance from the far ring, may make

important contributions. This result indicates that these solvolyses are quite limiting in nature. Retention of configuration in the open-chain derivatives shows that rotation about the bond between the ring and the carbonyl carbon does not occur in the carbonium ion.

Steric effects of 2-alkyl substitution. - Considerable evidence is available to support the fact that steric effects between adjacent substituents are much smaller with ferrocene derivatives than with their benzene analogs (44). This is presumably due to the wider angular spread of the exocyclic bonds in ferrocene (72° vs. 60°). Acetylation of 1,1'-dimethylferrocene with acetyl chloride - aluminum chloride led to a ratio of 3-acetyl : 2-acetyl product of 2.3 : 1 (44). With ethyl or *i*-propyl substitution, this ratio is increased to 3.0 : 1 (45b) and 4.3 : 1 (44) respectively. These ratios may be compared fairly realistically with para : ortho ratios from acetylation of substituted benzenes. The ratios for toluene and ethylbenzene are 83 : 1 and 320 : 1, while no o-acetyl product was isolated from acetylation of *i*-propylbenzene (119). This indicates a markedly smaller steric effect in the ferrocene substitutions.

Of the three toluic acids, the meta and para isomers are weaker than benzoic acid by about 0.1 pK unit, while o-toluic acid is stronger by 0.3 pK units. This difference for the ortho isomer has been attributed to steric hindrance to conjugation with the ring (131). Similar data for the dimethylferrocenecarboxylic acids in water (44) are listed on the following page. Since the 2-substituted acid is weaker than the 3-isomer rather than stronger, it is concluded that such a steric effect has less importance in the ferrocene series.

Ferrocenecarboxylic acid	4.4
1,1'-dimethyl-2-ferrocenecarboxylic acid	5.4
1,1'-dimethyl-3-ferrocenecarboxylic acid	4.7

Similarly, ultraviolet spectra of 2-acylalkylferrocenes show a lack of steric effect. Braude and Sondheimer (132) find that an ortho-methyl substituent decreases the intensity of the K band of acetophenone by a factor of 0.6, which they ascribe to steric hindrance to coplanarity. However, in 1-indanone or α -tetralone, where such hindrance is reduced by ring formation, this effect is much smaller. In the case of ferrocene derivatives (see p. 136) the extinction coefficient is unchanged or even slightly increased (44), and essentially no change is produced by ring-formation.

Solvolyses of the faster isomers of the ferrocenylcarbonyl acetates with 2-methyl substitution are slightly faster than the 3-methyl isomers. The effect of joining the side chain to the 2-substituent in α -acetoxy-1,2-tetramethyleneferrocene produces a negligible effect. These results may be contrasted with analogous ones in the benzene series (133). In the solvolysis of α -phenylethyl chloride in 80% ethanol at 25°, an o-methyl substituent produces a rate increase of 22-fold (p-methyl substitution has been estimated to produce an effect of 35-fold in 80% acetone (134a)). However, if the ortho substituent and the side chain are joined in a five-membered ring, the rate is now faster by a factor of 870. Enlarging the ring brings puckering and loss of coplanarity, with a subsequent decrease in the relative rate to 240 and 9 with 6- and 7-membered rings. In the case of ferrocene, the increase in the angles between exocyclic bonds probably reduces the effect of puckering. Therefore,

the absence of a significant change on ring-formation should suggest that steric hindrance between the carbonium ion center and the 2-substituent is very small. This estimate must be considered approximate to the extent that steric compression in the ground state may differ between the two compounds.

4. Rate Effects of Homoannular and Carbinyl Substitution

In contrast with 1'-substitution, groups introduced either on the carbinyl carbon (the α -position) or on the ring bearing it can interact with the carbonium ion center directly or through the conjugated system of the ring. For this reason, it should be possible to compare effects of 2-, 3- and α -substitution on the solvolysis rates of ferrocenylcarbinyl acetates with those of ortho, para and α -substitution on solvolyses of suitable compounds of the benzylic type. In this research, the effect of methyl substitution on the ring, and methyl or phenyl substitution on the carbinyl carbon was studied. Pertinent results are summarized in Table VII. Only the faster of each pair of 2-substituted isomers is included, since the faster isomers appear to reflect less of the steric effect possible in that position. These steric effects have been discussed at some length in the previous section. Discussion of compounds with trimethylene bridging will be deferred until the next section (see p. 75), since bridging introduces additional effects.

Comparisons with substituted benzyl systems. - In relating substituent effects to those in the benzene series, several difficulties are encountered. It was shown in the previous section (see p. 56)

TABLE VII

Solvolysis Rates of Ferrocenylcarbinyl Acetates
with Homoannular and α -Substituents^a

Compound	Rel. k_{300}	$\Delta\Delta H^\ddagger$ (kcal.)	$\Delta\Delta S^\ddagger$ (e.u.)
A. Effect of α -Substitution			
Ferrocenylcarbinyl Acetate	(1.00)	(0.0 \pm 0.6)	(0.0)
Methylferrocenylcarbinyl Acetate	10.5	-1.4 \pm 0.6	0.0
Phenylferrocenylcarbinyl Acetate	106 ^b	-3.1 \pm 0.5	-0.9
B. Effect of Homoannular Substitution - No Heteroannular Substituent			
Methylferrocenylcarbinyl Acetate	(1.00)	(0.0 \pm 0.6)	(0.0)
Methyl(3-methylferrocenyl)carbinyl Acetate	3.51 ^b	-1.2 \pm 0.3	-1.5
Methyl(2-methylferrocenyl)carbinyl Acetate, Ψ -exo isomer	4.28	+0.4 \pm 0.3	+4.3
α -Acetoxy-1,2-tetramethyleneferrocene	4.24	-0.5 \pm 0.4	+1.2
C. Effect of Homoannular Substitution - Heteroannular Methyl Substituent			
Methyl(1'-methylferrocenyl)carbinyl Acetate	(1.00) ^b	(0.0 \pm 0.4)	(0.0)
Methyl-3-(1,1'-dimethylferrocenyl)carbinyl Acetate	3.22 ^b	-0.8 \pm 0.6	-0.3
Methyl-2-(1,1'-dimethylferrocenyl)carbinyl Acetate, Ψ -exo isomer	3.83 ^b	-0.1 \pm 0.6	+2.4

^aFor complete kinetics results, see Table IV, p. 203 in Chapter III.
^bExtrapolated from other temperatures.

that the solvolyses of ferrocenylcarbinyl acetates are probably limiting - i.e., they should be quite independent of the nucleophilicity of the solvent (128). To be valid, comparisons must then be made with other solvolyses which are also limiting. Another complication, whose contribution may be difficult to assess, is the importance of ion pair return. The ionization rate of benzhydryl chloride in acetic acid has been estimated to be at least 10 times the solvolysis rate as determined titrimetrically (193). The solvent in which the comparison is made can also be very important. Thus, for example, benzhydryl chloride solvolyzes 1000 times more rapidly than t-butyl chloride in methanol, but only 25 times more rapidly in 70% acetone (92b, 93).

Possibly a more serious problem arises from the fact that the great majority of the solvolysis results recorded in the chemical literature involve neither a carbonium ion as stable as the ferrocenylcarbonium ion nor a leaving group as poor as a carboxylate ion. In order to quantitatively compare substituent effects on ferrocenylcarbinyl acetate solvolyses with those on other solvolyses, we should be able to evaluate the effect of simultaneous large changes of both the leaving group and the carbonium ion upon the substituent effect. This is only partly feasible. The change to a much poorer leaving group might be expected to increase demands for electron release on the carbonium ion, and thus increase the sensitivity of the solvolysis rate to variations in structure. In 80% acetone at 30°, the rate ratio of trityl acetate to α -tetralyl acetate is 5×10^4 (123, and results presented in Table IV, p.203 in Chapter III of this thesis). The similar ratio for the chlorides in 85% acetone at 25° is 2 x

10^6 .* Since solvolyses of fluorides and acetates should both be somewhat susceptible to catalysis by hydrogen bonding (138), and since trityl fluoride and trityl acetate solvolyze at comparable rates (94), data for fluorides may provide a reasonable substitute for more data on acetates. The rate ratio of trityl fluoride to benzhydryl fluoride in 80% ethanol at 25° is 10^3 (94), while in 85% acetone, the ratio for the corresponding chloride is 10^5 .** These results indicate that the poorer leaving group may not increase the sensitivity of the solvolysis rate to structural variations in the carbonium ion. The prediction might also be made that when the carbonium ion is very highly stabilized to begin with, additional changes in structure should not be as important in determining the solvolysis rate. However, this prediction does not receive much confirmation from the substituent effects summarized in Tables VIII and IX. The comparisons in these tables will be discussed in more detail below. From the considerations mentioned here, it appears that, within very rough limits, large differences in substituent effects between benzylic systems and the ferrocenylcarbonyl acetates should not be due merely to the changes in carbonium ion stability and in the effective-

*The rate constant for trityl chloride was extrapolated by Swain (136) from lower temperatures. That for α -tetralyl chloride was estimated from the rate in 80% ethanol (133) using the average m value for α -phenylethyl chloride (137) and an interpolated Y value for 85% acetone (92b). The ratio reported above is undoubtedly quite crude.

**The rate for benzhydryl chloride was interpolated by the mY relationship from data in other acetone - water mixtures (93). The value for trityl chloride was extrapolated by Swain from data of lower temperatures (136). Since the two fluorides are reported to have similar solvent dependence in their rates (94), the ratio obtained for the fluorides should be directly comparable with that given for the chlorides.

ness of the leaving group.

Replacement of an α -hydrogen of ferrocenylcarbinyll acetate by a methyl group produces a rate increase of about 10, while a phenyl group enhances the rate 100-fold. It is likely, then, that a phenyl group has about the effect of two methyl groups, a rough generalization which has been frequently made (139).*

Some rate comparisons for α -substitution in the benzene series are summarized in Table VIII. While rate ratios vary greatly with the nature of the solvent employed, and comparisons are not always possible in the best solvents, it is readily obvious that the effects are considerably greater than they are with the ferrocenylcarbinyll acetates. The effect of a methyl group ranges from 10^3 to 10^5 or more for a limiting solvolysis. (Solvolysis of benzyl chloride in ethanol or 80% ethanol is quite sensitive to solvent nucleophilicity.) In less-ionizing solvents, a phenyl substituent produces a rate increase of 3×10^3 to 10^5 , but results are not available in the faster, more ionizing solvents. It is significant to note that the effect does not decrease greatly between benzhydryl and trityl, and that the effect here is greater than in the ferrocenylcarbinyll acetate series by 10^2 to 10^3 . Unfortunately, there are no comparisons available for further α -substitution on a carbonium ion of stability comparable with that of the trityl cation or the ferrocenylcarbonium ion.

The 3-position of a ferrocenylcarbonium ion is quite analogous to the p-position of the benzyl cation; a substituent can interact

*A limited attempt to prepare the acetate of dimethylferrocenylcarbinol failed because of the slowness of the reaction, but the preparation would probably succeed with a longer reaction time.

with the cationic center by resonance, but its steric effect should be negligible. In the solvolyses of ferrocenylcarbiny acetates, a rate increase of about 3.5 is produced by a 3-methyl substituent. Some comparisons of p-methyl substituted phenyl derivatives are listed in Table IX. The effect of the methyl group increases as the solvolysis becomes more limiting, as shown by the benzyl bromide and α -phenylethyl chloride ratios. As mentioned previously (see footnote, p. 44), there is some ambiguity about the figures which should properly be used for benzhydryl and trityl. For symmetrical p-methyl substitution, the ratios for benzhydryl and trityl would be greater by factors of 83 and 20 respectively than that for methylferrocenylcarbiny acetate (provided the effects of successive methyl groups are equal for the trityl solvolysis). On the other hand, if the effect of one p-methyl group is the significant value, then the solvolyses in this research are quite comparable with either trityl or benzhydryl. At any rate, 3-methyl and p-methyl substitution are probably more nearly equivalent in effect than α -substitution in these two types of systems. The much larger substituent effect on ionization equilibria indicates that charge separation in the solvolysis transition state is not very complete for trityl and benzhydryl derivatives. This comparison suggests that determination of ionization constants of ferrocenylcarbinols in sulfuric acid, if experimentally feasible, might provide more insight into the effects of substitution on the carbonium ion stability.

The effect of substitution in the 2-position has previously been discussed (see p. 59). It appears that steric effects are small for the faster exo or pseudo-exo isomers, and that the electronic effect

TABLE VIII

Rate Differences in Halide Solvolyses due to α -Substitution

Reaction	R	R'	$k_{R'}/k_R$	Ref.
$(CH_3)_2C(R)Br$, HCOOH, 100° C.	H	CH ₃	4×10^6	(140)
$C_6H_5CH(R)Cl$, HCOOH, 25° C.	H	CH ₃	1.3×10^5	(137, 141)
" , CH_3COOH , 50° C.	H	CH ₃	370	(142)
" , ethanol, 50° C.	H	CH ₃	15	(128a, 137)
" , 50% ethanol, 50° C.	H	CH ₃	400	(128a, 137)
$(C_6H_5)CH_2RCOCl$, 90% acetone, 70° C.	H	CH ₃	910	a
$(C_6H_5)HRCOCl$, ethanol, 50° C.	H	C ₆ H ₅	2.9×10^3	(93, 128a)
" , 80% ethanol, 50° C.	H	C ₆ H ₅	1.1×10^5	(b, 128a)
" , acetic acid, 50° C.	H	C ₆ H ₅	1.5×10^4	(142)
$(C_6H_5)_2RCOCl$, 60% ether - 40% ethanol, 25° C.	H	C ₆ H ₅	1.6×10^4	(144)
" , 85% acetone, 25° C.	H	C ₆ H ₅	1.2×10^5	(c, 136)
$(C_6H_5)HRCOCl$, ethanol, 25° C.	CH ₃	C ₆ H ₅	270	(93, 137)
" , 80% ethanol, 25° C.	CH ₃	C ₆ H ₅	1350	(93, 137)
" , acetic acid, 25° C.	CH ₃	C ₆ H ₅	49	(93, 137)

^aThe rate for phenyldimethylcarbonyl chloride was extrapolated from data at lower temperatures in reference 114. The rate for α -phenylethyl chloride was extrapolated by the mY relationship (92) from data in 60 and 80% acetone (134b).

^bThe rate for benzhydriyl was extrapolated by Streitwieser (128b) from data in ref. 143.

^cThe rate for benzhydriyl chloride was interpolated by the mY relationship (92) from data in other acetone - water mixtures (93).

TABLE IX

Effects of p-Methyl Substitution
on Solvolyses and Ionizations

<u>Reaction</u>	$\frac{k_{p-CH_3}}{k_H}$ or $\frac{K_{p-CH_3}}{K_H}$	<u>Ref.</u>
X-C ₆ H ₄ -CH ₂ Br, 90% ethanol, 30° C.	4.3	(1145)
X-C ₆ H ₄ CH ₂ Br, 90% ethanol, AgNO ₃ , 0° C.	65	(1145)
X-C ₆ H ₄ CH ₂ Br, HCOOH, 25° C.	58	(1146)
X-C ₆ H ₄ (CH ₃)CHCl, 80% acetone, 70° C.	37	(1134)
X-C ₆ H ₄ (CH ₃) ₂ CCl, 90% acetone, 25° C.	26.0	(1114)
X-C ₆ H ₄ (C ₆ H ₅)CHCl, 80% acetone, 0° C.	33 (30)	(117,137)
(X-C ₆ H ₄) ₂ CHCl, 80% acetone, 0° C.	296	(1147)
X-C ₆ H ₄ (C ₆ H ₅) ₂ CCl, 60% ether - 40% ethanol, 25° C.	4.1	(1144)
X-C ₆ H ₄ (C ₆ H ₅)CHOH, H ₂ SO ₄ , 25° C.	84	(118b)
(X-C ₆ H ₄) ₂ CHOH, H ₂ SO ₄ , 25° C.	950	(118a)
X-C ₆ H ₄ (C ₆ H ₅) ₂ CCl, SO ₂ , 0° C.	18	(117)
X-C ₆ H ₄ (C ₆ H ₅) ₂ COH, H ₂ SO ₄ , 25° C.	25	(118b)
(X-C ₆ H ₄) ₃ COH, H ₂ SO ₄ , 25° C.	1180	(118a)

of the alkyl group is nearly equivalent to that observed in the 3-position.

The solvolysis rate effects of alkyl substitution in the various positions of the ferrocenylcarbonyl acetate molecule may now be summarized. In the 1'-position, the effect is roughly equal to that of a meta-substituent. In homoannular ring positions, the effect is smaller than that of p-methyl substituents by factors of 1.5 to 100, depending on the particular system used for comparison, and on whether substituents on one or all rings of poly-aryl carbonyl chlorides are considered. In the α -position, an alkyl substituent is less effective than an α -substituent in benzyl derivatives by factors of 10^2 to 10^4 .

Interpretation of substituent effects. - The ring of the ferrocenylcarbonium ion bearing the formal cationic center is the six-atom conjugated system of fulvene. To the extent that a metallocene may be treated as a compound formed from the metal and two cyclopentadienyl radicals (148), the carbonium ion may be considered as a compound formed by replacement of one cyclopentadienyl radical by a radical cation. Using this simple model of a fulvene radical cation, effects of substituents on this carbon skeleton may be estimated from LCAO molecular orbital calculations (149).* Equilibrium constants for ionization of tri-arylmethyl chlorides in sulfur dioxide (150) and the solvolysis rates of some arylmethyl chlorides (151) have been correlated on the basis of molecular orbital treatments.

Two notable differences are evident when such a treatment is

*All calculations are made with neglect of resonance integrals between non-adjacent atoms and of non-orthogonality of atomic orbitals on different nuclei.

applied to the ferrocenylcarbonium ion. First, the fulvene skeleton is a "non-alternant" hydrocarbon system, since it contains an odd-membered ring (152). The molecular orbitals obtained for such a system will not generally be self-consistent, and will lead to charge distribution in the neutral species (153). Less confidence may be placed in results obtained from such systems. The second difference is that perturbation of the simple LCAO orbitals by the iron will certainly be significant. Indeed, the major ring-metal bonding in ferrocene is represented in molecular orbital terms as a two-electron bond between an iron orbital and a molecular orbital of the ring (148c). Thus, in addition to uncertainty as to the perturbations produced by the iron, at least one of the ring orbitals must be used for bonding to the iron. All of this serves to place less confidence in the fulvene orbitals as being a proper representation of those of the carbonium ion.

The inductive effect of an alkyl group will slightly increase the electron density on the carbon to which it is attached. This will make that carbon atom more electropositive, and thus stabilize a positive charge in that position. The stabilizing effect of a methyl group should then be related to the positive charge on the carbon atom to which it is attached. Longuet-Higgins has treated the effects of aza or methyl substituents on aromatic substitution by a perturbation method of this sort (154). In the benzyl cation, rate enhancements by methyl groups in the para- and α -positions may be estimated as 20 and 10^5 respectively. These correspond to decreases in the free energy of activation of 1.8 and 6.9 kcal., which are nearly proportional to the charge distribution of $1/7$ in each ortho or para

position and 4/7 in the α -position (155) predicted from simple molecular orbital calculations. While this procedure is very qualitative, the results are of the proper order of magnitude.

Electron distributions and energies for the four lower orbitals of the fulvene system are tabulated in Table X. Of the five electrons in this six-carbon system, two will be placed in ϕ_1 . Either ϕ_2 or ϕ_3 will be used for bonding to the iron (see p. 91) and will thus contain one of the electrons, while the remaining two are placed in the other orbital. From this model, a free radical or a carbanion adjacent to the ring is predicted to be less favorable than a carbonium ion, since electrons must be placed in anti-bonding ϕ_4 . In Table XI, the electron distributions are tabulated which are predicted in the carbonium ion on the basis of four assumptions. For A and B, orbitals ϕ_2 and ϕ_3 respectively are used for the ring-metal bond (see p. 91) and accordingly, one electron is placed in that orbital. C and D use the same two orbitals for bonding, but 50% ionic character is attributed to the bond to help distribute the charge to the metal and the second ring. These distributions may be compared with the observed changes in the free energy of activation produced by methyl substitution in the α -, 2- or 3-position which are tabulated in the last column of Table XI. None of these electron distributions give very acceptable agreement with the observed substituent effects.*

If the methyl group is treated as a carbanion center (156),

*In the case of the ferrocenylcarbonium ion, the result is every bit as good if one considers the effect of electron release by the methyl group only on the lowest unfilled orbital, the "frontier orbital" (156). In the case of the benzyl cation, the two methods must produce equivalent results (145).

TABLE X

Energies and Orbital Densities of Fulvene Orbitals

<u>Position</u>	Orbital			
	<u>ϕ_1</u>	<u>ϕ_2</u>	<u>ϕ_3</u>	<u>ϕ_4</u>
	0.062	0.250	0.000	0.561
2	0.185	0.00	0.362	0.123
3	0.148	0.250	0.138	0.078
1	0.273	0.250	0.000	0.036
α	2.115	1.000	0.618	-0.254

TABLE XI

Charge Distributions in "Fulvene" System
of Ferrocenylcarbonium Ions and Increments in ΔF^{\ddagger}
for Solvolyses Due to Methyl Substitution

<u>Position</u>	A ϕ_2 used for bonding	B ϕ_3 used for bonding	C ϕ_2 used for polarized bond	D ϕ_3 used for polarized bond	<u>$\Delta \Delta F^{\ddagger}$</u>
α	0.627	0.377	0.502	0.377	1.41
2	-0.094	0.268	-0.094	0.087	0.87
3	0.178	0.066	0.053	-0.003	0.75

the π -electron energies of the ground state and the carbonium ion may be calculated. This type of calculation of course involves an extreme overestimation of the hyperconjugation of the methyl group, and a more rigorous calculation would include a suitable alteration of resonance and coulomb integrals. For this type of treatment, the question again arises as to which orbital should be used for bonding to the metal. In a rough calculation of this sort, if ϕ_2 is consistently used for the ring-metal bond (i.e., if the unpaired electron is placed in ϕ_2), the carbonium ion is stabilized by 0.84β , 0.42β and 1.07β respectively by substitution of the carbanion in the 2-, 3- and α -positions. The comparatively small influence of α -substitution results from the destabilizing influence of a carbanion adjacent to the ring. Use of the next higher orbital for the ring-metal bond produces corresponding figures of 0.08β , 0.20β and 1.33β . Thus, the relative effect predicted for a substituent is altered by the choice of the orbital used for bonding to the metal, regardless of the type of treatment used. Both treatments probably involve such great approximations that their significance is very questionable.

Two general rationalizations of the observed substituent effects may be made. First, it may be suggested that the charge is more evenly distributed to the ring positions than in the benzyl cation. Then, the relatively small substituent effects on the fulvene system, and fairly large heteroannular effects could be attributed to inductive electron release by the iron and the other ring. However, with this explanation, it is still difficult to quantitatively explain the differences. The ρ -value for heteroannular substituents quite

closely approximates that for meta-substituents on carboxylic acid ionizations. Similarly, in the solvolyses, a crude σ value for the effect of heteroannular substituents is about -5, which compares fairly well with a value of -4.6 (114b) for phenyldimethylcarbinyl chloride solvolyses, or -3.7 (118c) for monosubstituted benzhydryl chloride solvolyses. Thus, even wide variation of the reaction type leaves the 1'-position nearly equivalent in its electronic effect to a meta position. A primarily inductive or field mechanism is indicated for transmission of the effect. If the heteroannular effect were transmitted to the carbonium ion principally through the π -electron system of the ring, it would seem that homoannular substituents, which are directly attached to this conjugated system, should be more effective than they are in stabilizing the positive charge.

The second rationalization involves direct participation by the metal. In this case, since there is considerable covalent bonding of the iron to the carbinyl carbon, only a portion of the incipient positive charge can be delocalized through the "fulvene" system of the ring. The remainder is passed directly to the iron and is distributed to the second ring, accounting for the large effect there. Perhaps even a portion of the homoannular substituent effect might be transmitted through the ring-metal and metal-carbonium ion bonds.

5. Effect of Trimethylene Bridging

A three-carbon bridge joining the two rings of ferrocene should strongly affect the geometry of the molecule. If the bridge were in a plane perpendicular to that of the two rings, normal tetrahedral bond angles of carbon would require that the two rings slope toward each other at the edge opposite the bridge at an angle of $31^{\circ}36'$ (fig. 2a, p.76). Geometrical calculations using accepted bond lengths (124) show that the ring carbon atoms to which the bridge is attached would be 1.68 \AA apart, and the ones at the far edges of the rings would be separated by only 0.51 \AA . Since the normal distance between the ferrocene rings is 3.32 \AA (125a), considerable distortions are required to reduce strain. If the bridge is twisted from the perpendicular plane, a configuration can be reached where the rings are parallel, (fig. 2B). However, with this twisting, the interannular distance would remain close to 1.68 \AA . With continued twisting of the bridge, tilting in the other sense will occur, with the far edges of the rings farther apart. Additional relief of strain may come from an increase in bond angles on the bridge, and the final configuration will be that which minimizes the total strain energy. Since the edges of the rings to which the bridge is attached will probably remain closer together than the normal ring distances, it is logical to suppose that part of the strain will be taken up in a non-linear ring-metal-ring bond, as in fig. 2c. Furthermore, additional strain might be relieved if the metal is moved slightly to a position even further from the bridge, as in fig. 2d. Elsewhere

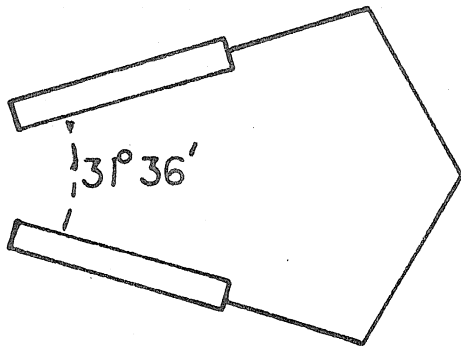


fig. 2a

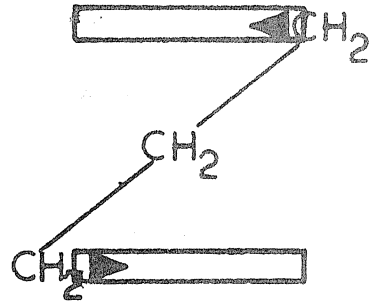


fig. 2b

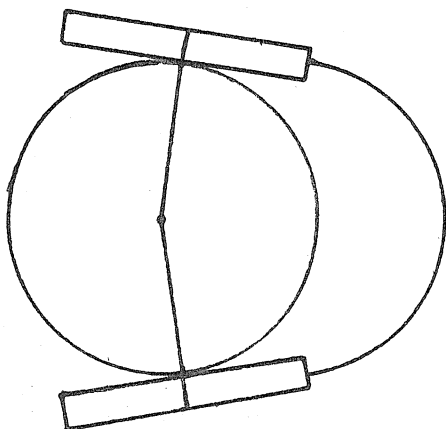


fig. 2c

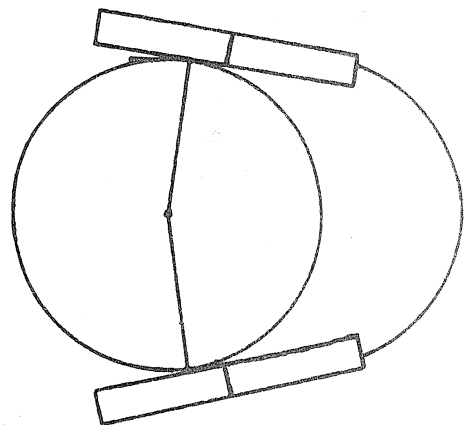


fig. 2d

in this thesis, evidence from infrared (see p. 130) and NMR (see p. 147) spectra is presented which favors such structures as these latter two.

Such molecular distortions may be expected to have quite noticeable effects upon the solvolysis rates of ferrocenylcarbinyl acetates substituted with a trimethylene bridge. Pertinent results for these compounds, as well as for α -acetoxy-1,1'-trimethyleneferrocene, are reported in Table XII.

With substitution by a trimethylene bridge in the 3-position, a rate increase of 24.5-fold is observed, along with a possible slight decrease in the activation energy. In the absence of special effects, this compound should show a reactivity very similar to that of methyl 3-(1,1'-dimethylferrocenyl)carbinyl acetate, in which the two methyl groups produce a rate enhancement of only 6.36. Thus there is an extra 3.9-fold rate increase due to bridging. When the trimethylene bridge is in the 2-position, the usual two separable isomers result. Both of the acetates solvolyze at rates slower than their methyl analogs. The pseudo-exo isomer is slower by a factor of 2.75, while the rate decrease for the slower pseudo-endo isomer is 36.5, and is accompanied by an increase in activation energy.

TABLE XII

Solvolyses of Bridged Ferrocenylcarbinyl Acetates.^a

Compound	Rel. k_{300}	$\Delta\Delta H^\ddagger$ (kcal.)	$\Delta\Delta S^\ddagger$ (e.u.)
Methylferrocenylcarbinyl acetate	1.00	(0.0 \pm 0.6)	(0.0)
Methyl-3-(1,1'-trimethyl-eneferrocenyl)carbinyl acetate	24.5 ^b	-1.0 \pm 1.4	+2.4
Methyl-2-(1,1'-trimethyl-eneferrocenyl)carbinyl acetate, Ψ -endo isomer	0.0174	+2.2 \pm 0.8	+2.6
Methyl-2-(1,1'-trimethyl-eneferrocenyl)carbinyl acetate, Ψ -exo isomer	2.74	-0.8 \pm 0.4	-0.6
α -Acetoxy-1,1'-trimethyleneferrocene	0.0133 ^b	+3.5 \pm 1.7	+3.5

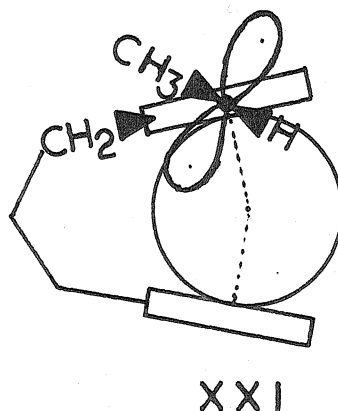
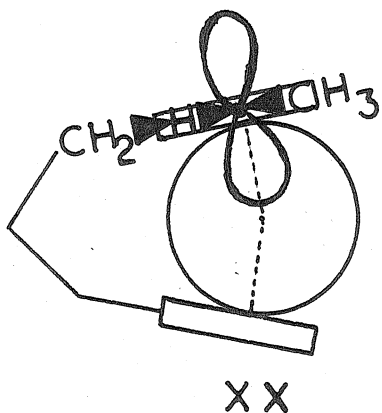
^aSee Table IV, p. 203 in Chapter III for complete kinetic results.

^bExtrapolated from other temperatures.

These effects are quite readily rationalized as resulting from metal participation in the solvolyses. If a ferrocenyl carbonium ion has the same geometry as the unionized ester, the distance between the metal and the carbinyl carbon will be about 3.19 Å. This bond length corresponds to less than 1/100 of a single bond (157) if the single bond radii of Pauling (158) are used. It is thus reasonable to suppose that if the metal exerts a driving force on the reaction by direct participation, it will shift to a position where it can bond more favorably to the carbinyl carbon (this will be discussed in molecular orbital terms

on p. 82). In the acetate with a trimethylene bridge in the 3-position, the metal may already be shifted into such a position, or, if not, such a shift on formation of the carbonium ion will relieve steric strain. This solvolysis should then be accelerated.

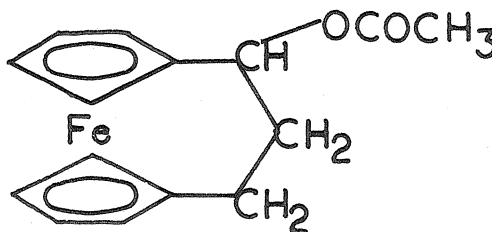
With trimethylene substitution in the 2-position, exactly the inverse line of reasoning would hold, and the solvolysis should be retarded. However, the slowing effect is not equal for both 2-bridged isomers. This could be due to a steric acceleration of the pseudo-exo isomer by ground state repulsions from the other ring. A more attractive explanation fits well with the idea of metal participation. The carbonium ion XX from the pseudo-exo isomer is probably fairly free of steric repulsion between the bridge and the carbonyl grouping. However, the carbonium ion from a pseudo-endo isomer will be quite cramped. Slight rotation from coplanarity with the ring may help relieve this repulsion. Since the trimethylene bridge will have much of its bulk between the rings, such twisting in this carbonium ion may be limited to the direction which is shown in XXI. But this inclines the vacant carbonium ion p-orbital



away from the metal, decreases overlap, and destabilizes the carbonium ion (see p. 82).

It is thus seen that the effects of trimethylene bridging are quite consistent with metal participation. The general rate increase in the 3-position and decrease in the 2-position could also be ascribed to alterations in inductive and field interactions due to bridging. However, this explanation fails to give a very good account for the large difference in effect with the two 2-substituted isomers.

α -Acetoxy-1,1'-trimethyleneferrocene XXII has a solvolysis rate which is decreased by a factor of 149 below that of a reasonable model compound, methyl(1'-methylferrocenyl)carbonyl acetate. This large rate decrease probably arises from two factors. First,



XXII

the iron is "squeezed" away from the carbonyl carbon by the bridging. This effect should be more serious than with the pseudo-exo isomer of methyl-2-(1,1'-trimethyleneferrocenyl)carbonyl acetate.

This second contributing effect is that the carbonium ion center is probably not coplanar with the ring, and so loses some of its resonance stabilization. Due to the ring tilting present in the unionized ester, this may not be as serious an effect as it might

appear to be at first glance. An effect probably due to this same loss of coplanarity is observed in the ultra-violet and visible spectra of the parent ketone, α -keto-1,1'-trimethyleneferrocene (see p. 136). The positions of the maxima are shifted only slightly (7 μ in the visible is the maximum), but the extinction coefficients are reduced to about 60% of those observed for 1'-acetylmethylferrocene. This is the effect generally found when steric hindrance forces the carbonyl function out of coplanarity with an aromatic ring (132). Such steric hindrance reduces the extinction coefficients of the K-bands (240-260 μ) of 2-methylacetophenone and 2,4,6-trimethylacetophenone to about 60% and 20% respectively of the expected values. In t-butyl phenyl ketone, the reduction is to about 70% of that in acetophenone. An extreme case of such hindrance to coplanarity is found in the ketone derivatives of (2.2)paracyclophane, in which the carbonyl group must be very nearly perpendicular to the ring plane (159). In this case, there appears to be no K-band present. It thus appears that the loss of coplanarity in α -keto-1,1'-trimethyleneferrocene approximates that produced by one ortho-methyl group or three α -methyl groups in acetophenone. X-ray crystal studies of 1,1'-trimethyleneferrocene and α -keto-1,1'-trimethyleneferrocene would certainly add much to our understanding of the effect of structure on the reactivities of these compounds.

6. Molecular Orbital Description of Metal Participation

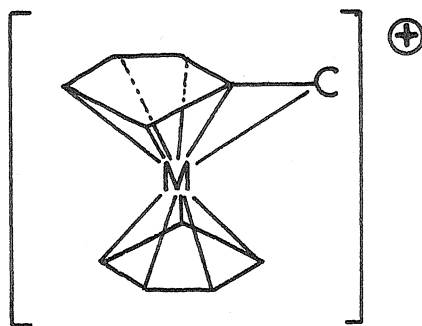
Participation by the metal atom has been cited several times in this thesis as a reasonable explanation for some of the phenomena observed in solvolyses of substituted ferrocenylcarbinyl acetates. Before proceeding to a discussion of the effect of changing the central metal atom, it will be helpful to consider the electronic structure of the metallocenylcarbonium ion to see whether a reasonable model for such participation can be given. Nucleophilic metal participation from the rear in the solvolysis implies that there is direct bonding in the carbonium ion between the carbinyl carbon and the metal. Therefore, rotation about the bond joining the carbinyl carbon to the ring should be prevented, and solvent collapse should occur exclusively from the "upper" side. Furthermore, a considerable portion of this bonding should be present in the transition state, which would favor departure of the leaving group in the "upward" direction.

The first question to be answered is whether overlap is appreciable between the metal orbitals and the p-orbital on the carbinyl carbon. A rough calculation was made using the same assumption as that of Dunitz and Orgel (148d) concerning the radical component of the wave function for the 3d orbitals.* The overlap integral of the $3d_{\underline{t_1}}$ iron orbital** (see fig. 3b, p. 84)

*Calculations were performed in a manner similar to that of Dunitz and Orgel (148d), using overlap integrals from standard tables (160).

**In this discussion, the d and p orbitals of the metal will be identified by their angular momentum about the five-fold symmetry axis of the cyclopentadienyl ring. This is equal to the number of nodal planes which fall along the axis, and thus determines the symmetry of the part of the orbital with which the orbitals of the ring may overlap. Thus, d_{z^2} will be referred to as d_0 , d_{xz} and d_{yz} will be referred to as $d_{\underline{t_1}}$, and d_{xy} and $d_{x^2-y^2}$ will be referred to as $d_{\underline{t_2}}$ (1486).

with a ring carbon was found to be 0.192, while that with the carbonyl carbon was 0.020, provided the carbonium ion has the same geometry as the unionized ester. The most likely geometry for the carbonium ion would be that in which the strongest possible bonds to both rings are formed. Therefore, the "upper" ring might be shifted relative to the remainder of the molecule to a position such as in XXIV, in which overlap of metal orbitals with p-orbitals on all six carbon atoms is maximized. If the shift is



XXIV

0.2 Å in the direction which shortens the distance between the metal and the carbonyl carbon, the overlap integral is then 0.175 with the furthest ring carbons, 0.201 with the ring carbon bearing the carbonyl substituent, and 0.032 with the carbonyl carbon.

Similar overlaps with the metal $3d_{+2}$ orbital will be slightly smaller. Therefore, the concept of bonding between the metal and the carbonyl carbon is quite reasonable, although this bond should undoubtedly be weaker than those to the ring carbons.

A simple molecular orbital treatment (148b,c) will be most

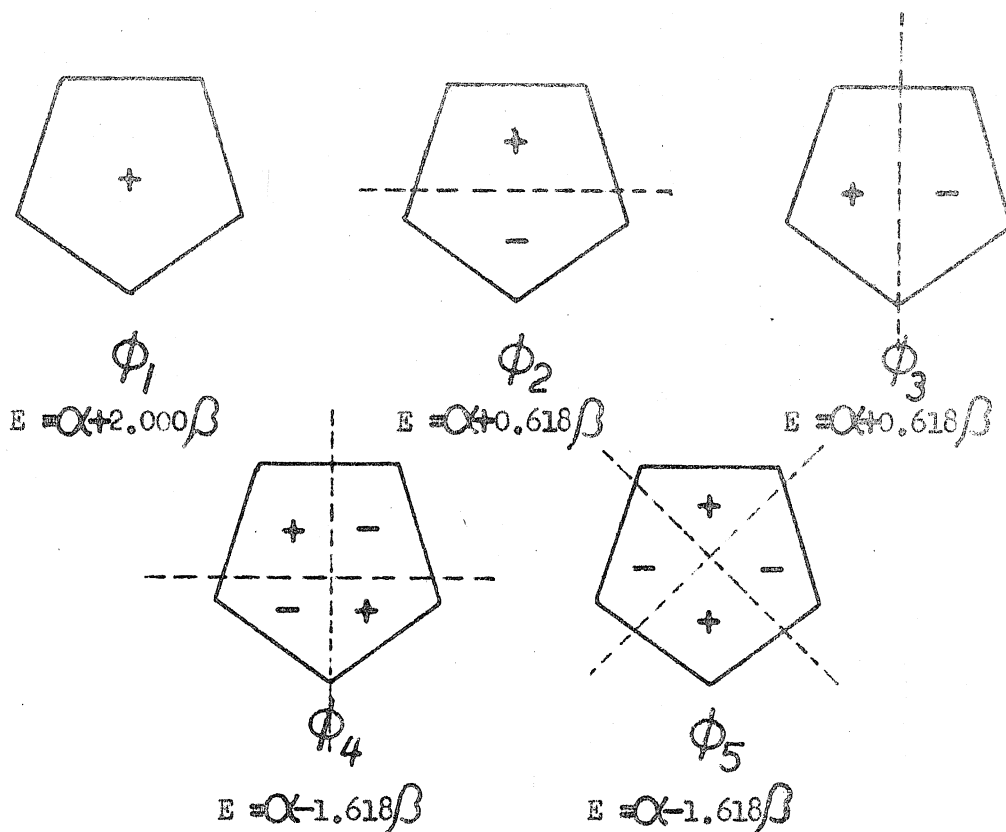


fig. 3a

LCAO molecular orbitals for cyclopentadienyl

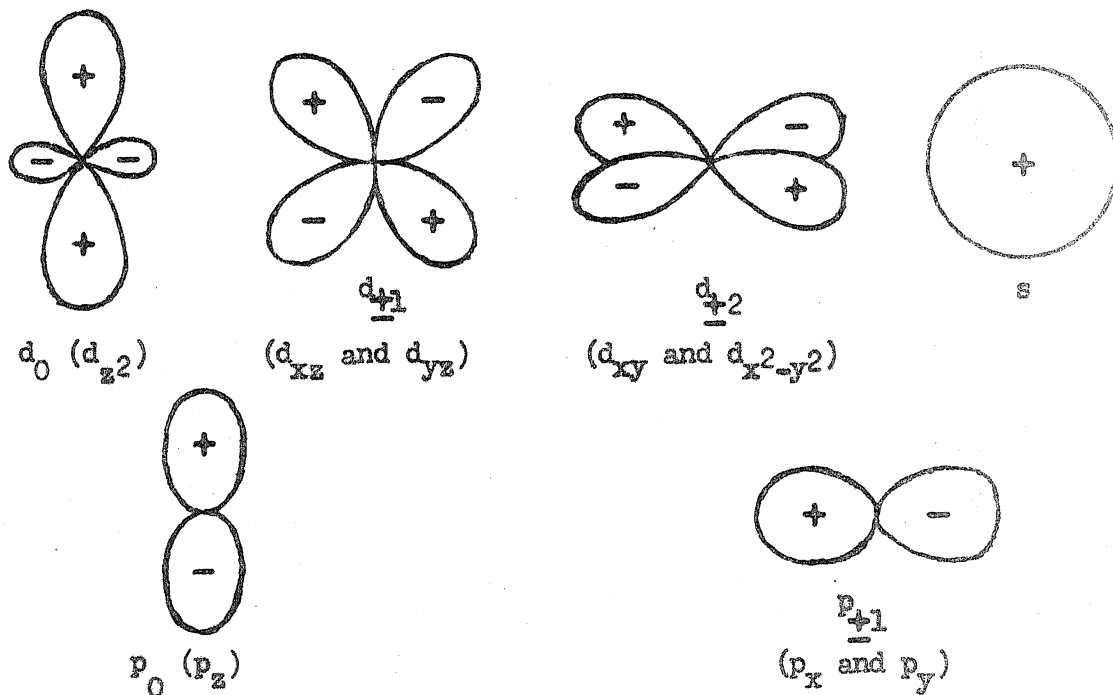
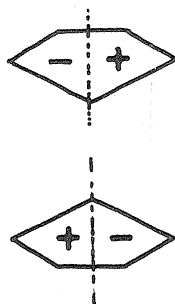


fig. 3b

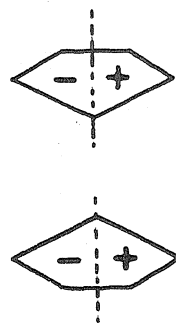
Metal orbitals for metallocene bonding

useful for discussion of the electronic structure of the ferrocenyl-carbonium ion. In such treatments of bonding in metallocenes (148), a molecular orbital for the metallocene molecule is formed by combining an LCAO orbital of the π -electron systems of the rings (fig. 3a, p. 84) with a metal orbital (fig. 3b, p. 84) of the proper symmetry. When such a pair of orbitals are of approximately the same energy, and when there is a sizeable overlap integral between them, they will interact to produce a bonding orbital and a higher energy antibonding orbital. If the energy and overlap requirements are only poorly satisfied, this interaction will be small, and the orbitals will closely resemble the original iron and ring orbitals.

The primary differences between several such molecular orbital treatments arise from deciding to what extent the orbitals can interact to produce bonding. Moffitt (148c) has calculated that the ring orbitals ϕ_2 or ϕ_3 (see fig. 3a) are of very nearly the same energy as the metal $3d_{\pm 1}$ orbitals, and that these orbitals therefore account for the major share of the ring-metal bonding. The process of combining orbitals will be illustrated for this portion of the bonding. If the ϕ_2 orbitals on each ring (which are assumed to interact negligibly with each other) are combined, two nearly degenerate molecular orbitals for the entire carbon skeleton of the metallocene result. One of these, XXV, has the same symmetry properties as one of the metal $3d_{\pm 1}$ orbitals; the other, XXVI, is of symmetry similar to that of one of the $p_{\pm 1}$ orbitals of the metal.



XXV



XXVI

Now, if orbital XXV and a d_{xz} orbital are combined, two molecular orbitals result. One will be strongly bonding, and will be concentrated in the regions between the metal and the two rings. The second will be antibonding and of high energy. If two electrons are placed in the bonding orbital, then there is a covalent bond joining both rings to the metal. A second such bond may be formed utilizing the ring ϕ_3 orbitals and the other metal $3d_{xz}$ orbital. We are left now with the two ring-system orbitals, XXVI, which have the same symmetry as the metal $4p_{xz}$ orbitals. The general consensus seems to be that overlap between $4p_{xz}$ and XXVI is not exceedingly great, and that the $4p_{xz}$ orbitals are of somewhat higher energy (however, see ref. 148f). Therefore, interaction will be small, and we will be left with orbitals which are quite similar to the starting metal $4p_{xz}$ and ring XXVI orbitals. Electrons placed in these ring orbitals will then contribute to the bonding within the rings, but will supply little ring-metal bonding energy.

A treatment similar to that given above would be followed for all other sets of orbitals with the proper symmetry. Dunitz and

Orgel (148d) have calculated that the bonding orbitals formed using $3d_{\underline{+1}}$ metal orbitals will have an energy lowered by 2 e.v. per electron, or a total of 8 e.v. for the two electron-pair bonds. They estimate that the bonding energy resulting from use of the ring ϕ_1 orbitals and metal $4s$ orbitals is 2.8 e.v., and an additional bonding energy of 1.6 e.v. arises from overlap of the ring orbitals ϕ_4 and ϕ_5 with metal $3d_{\underline{+2}}$ orbitals.

While a treatment of this sort is most useful for any type of quantitative work, orbitals are combined and recombined so many times that it may be difficult to visualize the bonds which result.

This will be particularly true when the high symmetry of the ferrocene system is lost, as in the ferrocenylcarbonium ion. Therefore, a less rigorous description, similar to that originally presented by Craig, Maccoll, Nyholm, Orgel and Sutton (148b) will be used. Ring orbital ϕ_2 of one ring (let us call this ring A) is of proper symmetry to overlap with one half of a metal $3d_{\underline{+1}}$ orbital. Similarly, ϕ_3 of ring B can overlap with half of the other $3d_{\underline{+1}}$ orbital. This corresponds to a two-electron ring-metal bond for each ring. However, instead, we could use ϕ_3 of ring A and ϕ_2 of ring B for the bonds, so we must consider resonance between these two equivalent descriptions. (This combination of orbitals also produces two antibonding orbitals, which need not concern us because of their high energy.) There remains on each ring an orbital which is a hybrid of ϕ_2 and ϕ_3 ; these provide bonding within the ring.

Neglecting for the moment smaller contributions to the bonding from other orbitals, we may proceed to place electrons into the

available orbitals. In metallocenes of the iron family, there will be five valence electrons from each cyclopentadienyl radical and eight from the metal.* Eight electrons may be immediately placed into strongly bonding orbitals: a ϕ_1 orbital and a ring-metal bonding orbital for each ring. Four more electrons will go into the ring ϕ_2 and ϕ_3 orbitals which were not used for the ring-metal bond, while anti-bonding ring orbitals ϕ_4 and ϕ_5 will remain empty. Six electrons must then be placed into the remaining iron orbitals. Moffitt (148c) has added the refinement that the metal $3d_0$ and $4s$ orbitals are combined in the field of the ring electrons to produce two hybrid orbitals: one is of higher energy and is directed toward the rings, while the other is of lower energy and forms an equatorial belt around the metal. With the addition of this splitting, the magnetic properties of ferrocene are explained if the remaining electrons are placed in the "equatorial" hybrid orbital and the d_{+2} orbitals.

We may now consider the other possibilities for ring-metal bonding as perturbations of this system. Bonding utilizing the ring ϕ_1 orbitals and any of the iron orbitals of suitable symmetry ($3d_0$, $4s$, $4p$, or various hybrids) will correspond to a dative bond from the ring to the metal. Conversely, bonding utilizing the ring ϕ_4 and ϕ_5 orbitals and metal $3d_{+2}$ orbitals will be a dative bond from the metal to the ring. Due to the relatively low energy ring ϕ_1 orbitals,

*In molecular orbital terms this is identical with two cyclopentadienyl anions and a ferrous ion.

and the relatively high energy of the ϕ_4 and ϕ_5 orbitals, these contributions will be of diminished importance. Also, since the two dative bonds would be formed in opposite directions, their polarities will cancel, leaving little or no net charge separation.

The metallocenylcarbonium ion is formally derived from the parent metallocene by replacing one of the cyclopentadienyl radicals by the fulvene skeleton containing only five electrons. The orbitals of the fulvene system are shown in fig. 4.* If the ring bearing the carbinyl carbon is considered as an isolated system with five π -electrons, it is possible to calculate the increase in the delocalization energy which results on ionization to the carbonium ion. This treatment is somewhat complicated by the fact that ϕ_2 and ϕ_3 , the two orbitals of the proper symmetry type for bonding with the metal $3d_{z^2}$ orbitals, are of different energy. A single electron must be placed into one of them to represent the ring-metal bond. If the odd electron is placed in ϕ_3 , the increase in delocalization energy on ionization to the carbonium ion is 0.994β . If the unpaired electron is in ϕ_2 , the corresponding value is 0.612β . This is a rude estimate of the energy due solely to delocalization of the charge into the ring. These values may be compared with gains in delocalization energy of 0.72β (161) and 1.800β (150) on ionization to the benzyl and trityl cations respectively.

*All calculations were made neglecting resonance integrals between non-adjacent atoms and non-orthogonality of orbitals on different atoms.

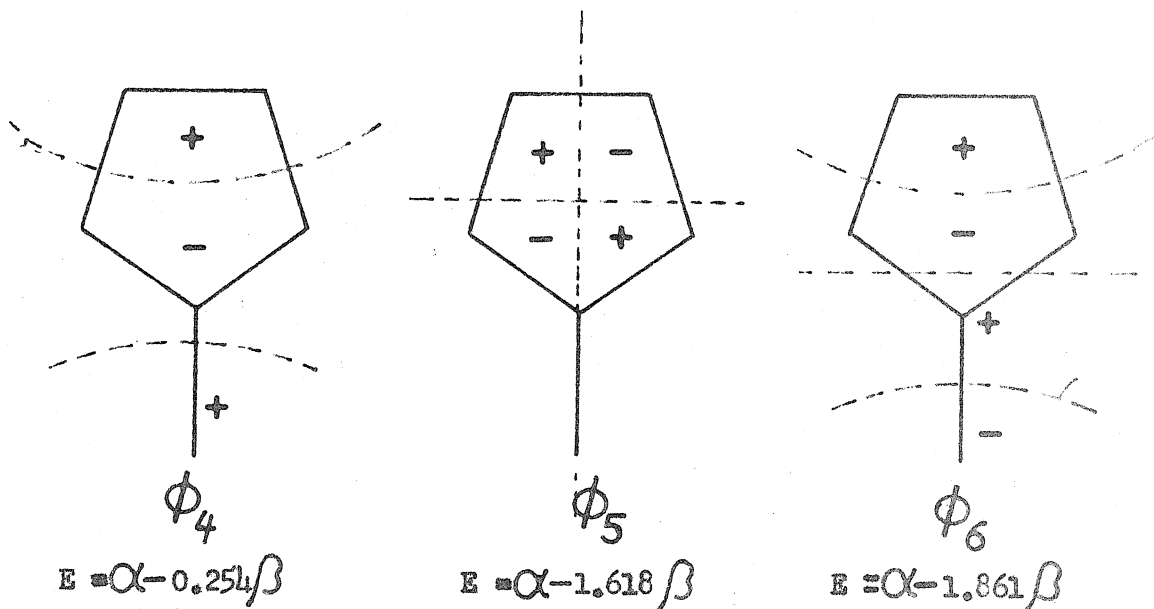
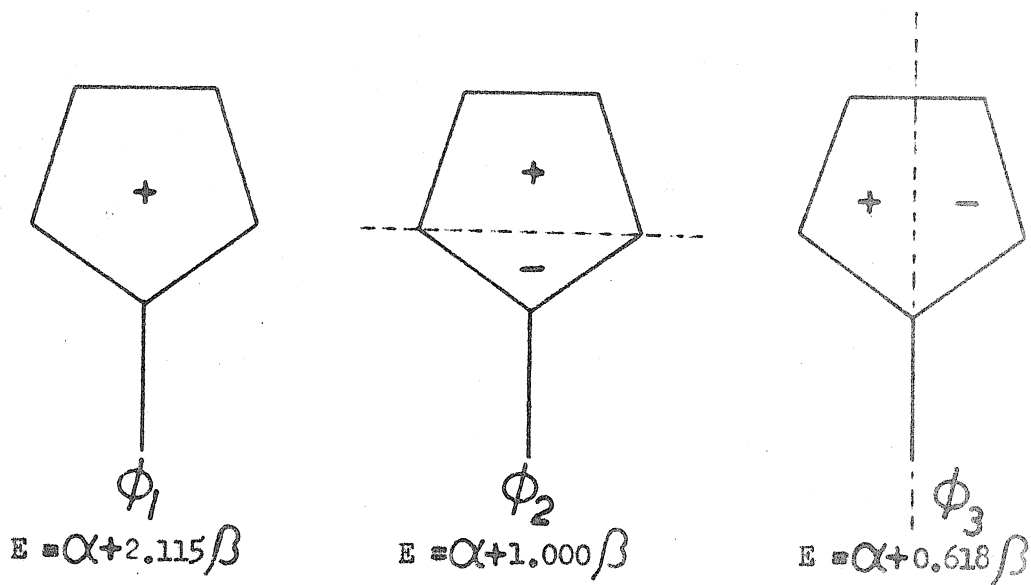


fig. 4

LCAO molecular orbitals for fulvene system

Now we may consider the bonding of the fulvene system to the metal. Two electrons may surely be placed in orbital ϕ_1 , since it is very strongly bonding within the carbon framework. As in the parent metallocene, we must consider two resonance structures for the bonding with metal $3d_{+1}$ orbitals. In one of these, ϕ_2 participates in ring-metal bonding, while in the other, ϕ_3 is used; in either case, the other orbital contains an electron pair which contributes primarily to bonding within the carbon framework. In the carbonium ion, however, there are two important differences from the metallocene molecule. First, the two structures probably differ somewhat in energy, and will thus not make equal contributions to the resonance hybrid. In the limit, one of the two canonical forms might be much more stable, and so only one of the two ring orbitals would effectively contribute to the bond. The second difference is that orbital ϕ_2 has considerable density on the carbonyl carbon. It is reasonable to suppose that overlap of ϕ_2 with a metal $3d_{+1}$ orbital will include a contribution from that part of ϕ_2 in the vicinity of the carbonyl carbon (see p. 82). This is the equivalent of a partial bond between the metal and the carbonyl carbon, and should lead to the observed stereochemical consequences of such bonding. The importance of this bonding will depend upon the magnitude of the overlap of the $3d_{+1}$ orbital with a p-orbital on the carbonyl carbon, and upon the contribution to the resonance hybrid of the structure utilizing ϕ_2 for bonding to the metal. Due to the very qualitative nature of this treatment, and to its inherent weaknesses (see p. 69), no prediction will be made as to

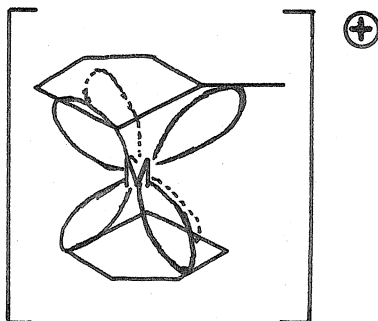
which resonance structure should in fact be the more important one.

A simple picture such as this would account for the stereochemical results presented in this thesis. Due to bonding to the rear side of the carbonyl carbon, rotation about the bond to the ring would be prevented, and solvent collapse should occur from the "upper" side. Departure of the acetate in the "downward" direction would be unfavorable, since overlap of the $3d_{z^2}$ orbital with the incipient p-orbital on the carbonyl carbon would be prevented in the transition state. However, "metal participation" is a questionable term to apply to this description. Interaction of the metal with the orbitals of the rings is very significant in both the unionized acetate and in the carbonium ion, and there is no radical change in the existing bonding on ionization aside from addition of the p-orbital on the carbonyl carbon to the conjugated system of the ring. Thus, it would be very difficult to apportion part of the carbonium ion stability to delocalization of the charge into the C_6 system, and part to participation by the metal.

A further change in bonding in the carbonium ion might more aptly be described as metal participation. Whereas a dative bond from the metal $3d_{z^2}$ orbitals to orbitals ϕ_4 and ϕ_5 of the cyclopentadienyl rings makes a relatively small contribution to bonding in the parent metallocene (148d), the situation might be considerably different in the carbonium ion. The ϕ_4 orbital of the fulvene system (fig. 4) is only slightly antibonding. While its symmetry is not precisely that of the $3d_{z^2}$ orbital, overlap should still be quite appreciable. Besides, perturbation by the field of

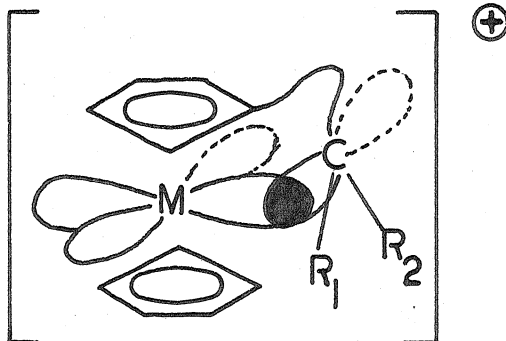
the metal may well bring about mixing of the simple one-electron LCAO orbitals to produce an orbital of more favorable symmetry. Therefore, the dative bond in the carbonium ion may be much stronger, and thus provide a driving force for the solvolysis. If overlap with that part of the ϕ_{11} orbital in the vicinity of the carbonyl carbon is appreciable, the usual stereochemical consequences of participation should be observed.

Linnett (148e) has shown that the metallocene molecular orbitals may be rehybridized to yield a picture which is possibly more readily visualized. In this description, three equivalent bonds are formed by the metal with each cyclopentadienyl ring. These would all be quite strongly polarized toward the rings, so that there would be no charge separation. The remaining six electrons are placed in three orbitals concentrated primarily in an equatorial belt about the metal. This description, derived from the earlier molecular orbital picture, is quite similar to that proposed by Fischer and co-workers (162). In this description, the carbonium ion might have a similar structure represented by XXVII. The picture of this sort for the metallocenes themselves is mathematically equivalent to the molecular orbital description given earlier in this section. Therefore, such a description of the carbonium ion might likewise be equivalent to the molecular orbital description presented above.



XXVII

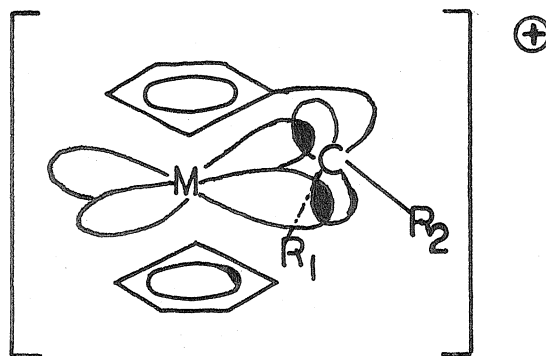
Additional models for metal participation may be envisioned which do not require that the carbonium ion be conjugated with the ring. In the simplest form, a σ bond might be formed utilizing one lobe of a d_{+2} orbital and one lobe of the carbonium ion p-orbital as in XXVIII. If the carbonium ion is adjacent to the ring, this type of participation will be only a partial picture of the dative bond described previously, since the p-orbital should surely be involved in resonance with the ring. The usual



XXVIII

stereochemical implications of participation should apply.

Another possibility would be a π -bond to an isolated carbonium ion center, as in XXIX. A particularly favorable case would be a derivative of the bridged alcohol, β -hydroxy-1,1'-trimethyleneferrocene. Since bonding of this sort in the transition state would amount to front side participation, such stabilization of the carbonium ion might be possible only after departure of the leaving group. An ion stabilized in this fashion should then fail to exhibit retention of configuration, despite possible rate enhancement through initial σ -participation.



XXIX

7. Effect of Varying the Metal Atom

The relative solvolysis rates of the methylmetallocenylcarbonyl acetates, where the metal is iron, ruthenium and osmium, are 1.00 : 1.36 : 5.36. Pertinent data are summarized in Table XII.

TABLE XII

Effect of Varying the Metal^a

<u>Compound</u>	<u>Rel. k_{300}</u>	<u>ΔH (kcal.)</u>	<u>ΔS (e.u.)</u>
Methylferrocenylcarbonyl acetate	1.00	18.9 \pm 0.6	-13.2
Methylruthenocenylcarbonyl acetate	1.36	19.3 \pm 0.3	-11.4
Methylosmocenylcarbonyl acetate	5.36	18.5 \pm 0.7	-11.2

^aSee Table IV, p.203 in Chapter III for complete kinetics results.

The above reactivity sequence may be contrasted with that for electrophilic aromatic substitution. Competitive acetylation of ferrocene and ruthenocene with acetic anhydride - boron trifluoride indicates that ferrocene is more reactive by a factor of at least five (20), and results of Rausch, Fischer and Grubert (40) clearly show that more vigorous conditions are required for acetylation of osmocene than for the other two metallocenes. Since both the solvolysis and the acetylation require a strong release of electrons by the metallocene nucleus, the difference in reactivity sequences should indicate that the mode of electron release differs between the two reactions. Thus, for instance, in at least one of these two reactions, simple inductive electron release by polarization of the ring-metal bonds may be complicated by a second mechanism, such as direct electron release by the metal.

Hydrogen bonding behavior in the metallocene series exhibits a similar divergence of trends. Intermolecular hydrogen bonds to the aromatic π -electron system of ferrocene are stronger than those to ruthenocene (163), following the order of reactivity

toward acetylation. However, intramolecular hydrogen bonds of the methylmetallocenylcarbinols follow the same sequence of strengths as the solvolysis rates (see p.127, also ref. 163). These intramolecular bonds are most likely formed to the central metal atom. Thus, the suggestion might be made that electron release through the rings is favored in ferrocene, but that direct release by the metal is more favorable in ruthenocene and osmocene.* However, geometrical factors may be of considerable importance in determining hydrogen bond strengths (see p.128). Furthermore, the energies and electron demands involved in hydrogen bonding are so much smaller than in the solvolysis and acetylation, that such extrapolation is quite risky. Thus, more electronegative atoms are generally considered to be better electron donors in hydrogen bond formation (164, but see also 165), despite their decreased ability to release electrons inductively through bonds. Protonation of the metallocenes is also reported to occur on the metal (166). In contrast with hydrogen bonding to the metal, and in agreement with electrophilic substitution, the order of basicities is: ferrocene > ruthenocene > osmocene.

*Trifan (163) proposes that the relative solvolysis rates of the carbonyl acetates with ferrocenyl- and ruthenocenyl-substitution may not truly reflect the magnitude of the difference in participation energy between the two metals. He suggests that the relative enthalpies of activation might provide a better comparison. However, Table XII shows that changes in both the enthalpy and entropy of activation are constant within the experimental error throughout the series, and no significant trend is obvious.

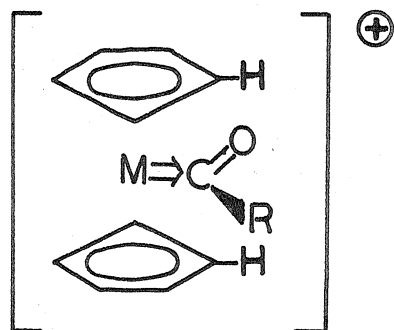
Unfortunately, several plausible explanations for the divergent reactivity sequences in solvolysis and acetylation may be advanced. Therefore, the results obtained cannot provide convincing proof for the operation of any single effect. This is all the more so, since the differences in solvolysis rates are really quite small compared to the effects frequently observed in such reactions. Also, no really quantitative measure of the differences in reactivity toward acetylation is available. A portion of the difference which might be quite difficult to evaluate realistically could arise merely from slightly different spacings of the electronic levels of the central metal atom. If the energy levels of the metal are shifted slightly relative to the ring energy levels, then changes in bonding which occur in the transition states for the two reactions will also differ between the metals. Since the total energy of the ring-metal bonding in ferrocene is estimated in the vicinity of 160 kcal. per ring (148d), relatively small differences in bonding energy would be reflected as large changes in reaction rates.

A marked difference between the two reactions under consideration lies in the changes which occur in the conjugated system of the ring in the transition state. In the solvolysis reaction, the conjugated system is being extended to an exocyclic carbon atom. It was shown in the previous section (see p. 82) that, in the ferrocenylcarbonium ion, overlap of the metal 3d orbitals with the p-orbital on the carbonyl carbon is not great. In ruthenium or osmium, the 4d and 5d orbitals are more extended, and so overlap

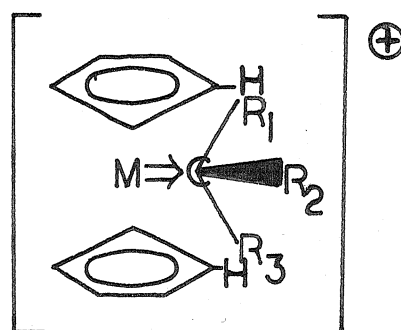
with the entire fulvene skeleton of the carbonium ion should be improved relative to overlap with only the cyclopentadienyl ring. Thus, bonding in the ruthenocenyl- or osmocenylcarbonium ions might be stronger, and "metal participation" would be greater. In electrophilic substitution, a pair of electrons is being localized on one carbon atom, and the conjugated system is decreased in extent. Therefore, the more extended ruthenium or osmium orbitals may offer no advantage, while the more concentrated orbitals of iron may overlap more favorably with the smaller π -electron system. In addition, bonding between the metal and the ring may very well be weakened in the transition state for electrophilic substitution. Since the ring-metal bonding is probably slightly stronger in ruthenocene than in ferrocene (121), a greater loss in energy might result in ruthenocene from this bond weakening. Therefore, electrophilic substitution of ruthenocene would be retarded. Furthermore, ruthenium and osmium are more electronegative than iron, and so should release electrons less readily through covalent bonds to the rings. Combination of the size factor with either of these latter two effects could explain the reactivity sequence observed.

Another explanation would entail some special effects in the acetylation reaction. Ferrocene, ruthenocene and osmocene are protonated to give species in which the added proton is magnetically equivalent with respect to all ten of the ring protons (166). This result has been interpreted as direct protonation of the metal. Similarly, the attacking species may bond directly to the metal in the intermediate or transition state for electrophilic substitution

(166). Such bonding would be consistent with the apparent reactivity of ferrocene toward reagents of differing steric requirements. Thus, ferrocene is extremely reactive toward acylation (see p. 1). In the acylium ion, only two groups are fastened to the attacking carbon atom. If this carbon atom bonds first to the metal, the two groups can occupy positions in a plane parallel with those of the rings as in XXXa in which steric repulsions with the rings will be minimized. However, a trigonal attacking reagent, such as a carbonium ion in an alkylation reaction, will experience greater steric repulsions as in XXXb,



XXXa



XXXb

and the reaction may be hindered. This appears to be the case for simple alkylations (see p. 3). In the aminomethylation reaction, the attacking species is highly stabilized, but small carbonium ion, and the reaction conditions used are reasonably comparable with those used for the very reactive aromatics such as thiophene (see p.4).

The tendency of the metal to participate in additional bonding to an attacking electrophile need not parallel its ability to release electrons to the rings, since different orbitals are used and the spacing of the orbital levels may differ between metals. In particular, the hybrid "equatorial" orbital has been suggested for use in protonation (166). The relative contributions of $3d_0$ and $4s$ to this hybrid orbital will depend upon the metal involved and on the distance between the metal and the rings. This change in hybridization would affect the energy and geometry of the orbital, and thus the strength of the bond. Another contributing factor in both substitution and protonation may be bonding of the attacking reagent to both rings as well as to (or instead of to) the metal. The interannular distance in ferrocene is 3.32 \AA (125a), so quite substantial partial bonds could be formed to both rings if the reagent were to approach closely enough to bond to the iron. In ruthenocene or osmocene, where the rings are farther apart (125b,c), these bonds would be longer and weaker. It is reasonable that bonding both to the rings and to the metal would exist if the electrophile were to approach closely enough for either to occur. Thus, these two effects may be complementary and not readily separable.*

*This suggestion of bonding to both rings in the acetylation reaction has interesting implications for the acetylation of 1,1'-trimethyleneferrocene. Since the trimethylene bridge has greater bulk in the region between the rings than a pair of methyl groups, substitution in the 2-position should be particularly

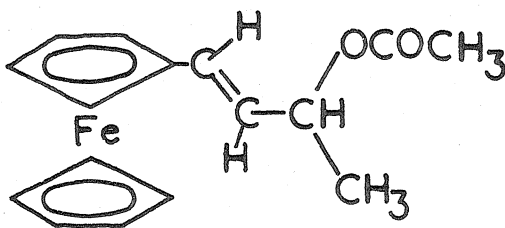
Thus, since more than one explanation is available for the two reactivity series, the results of this section do not constitute definite proof of metal participation in either reaction. Nevertheless, the results are quite compatible with the presence of either or both types of direct interaction with the metal, and indeed such participation does provide the most attractive explanation.

8. Solvolysis of Methyl(2-ferrocenylvinyl)carbinyl Acetate.

In the trans isomer of methyl(2-ferrocenylvinyl)carbinyl acetate XXXI, the ferrocene nucleus is geometrically removed from the carbinyl carbon, but the positive charge can still be delocalized into the ferrocene nucleus by resonance. The infrared spectra of the acetate and the corresponding alcohol and ketone

strongly retarded sterically. However, the two carbon atoms in the 3-position of each ring are pushed farther than the normal distance apart due to ring tilting, so bonding to both rings during substitution should be hindered there also. Thus this compound should show a decreased reactivity relative to ferrocene, as it has indeed been reported to do (167). Also, from the results of this research, retarding effects in both positions must be very nearly equal, since the ratio of 2- to 3-substitution of about 1 : 3 closely approximates that reported for ethylferrocene (45).

The importance of bonding to the two rings is also compatible with the protonation results (166). If the proton forms a bridge bond between carbon atoms of the two rings, the hydrogens on these two carbon atoms should be magnetically different from the others. However, if rearrangement of the proton from carbon to carbon were very rapid, all of the ring hydrogens would become equivalent. Such rearrangement would be favored by the weak C-H bonds, and by the entropy (5.38 e.u., corresponding to 1610 cal. in free energy at 300°K) which would be lost if free rotation of the rings were stopped (121). If splitting of the ring hydrogens by the proton is transmitted through these weak C-H bonds, then perhaps the lack of splitting in protonated ruthenocene and osmocene may be due to longer and weaker proton-ring bonds, rather than to rapid exchange catalyzed by unprotonated metallocene.



XXXI

from which it was prepared all exhibit infrared absorption at about 960 cm^{-1} , in the region generally assigned to the out-of-plane deformation of the hydrogens on a trans disubstituted olefin (168). In only the alcohol was there a very weak absorption about 690 cm^{-1} which might be assigned to a cis olefin. The alcohol showed no hydrogen-bonded hydroxyl absorption, as might be expected if it had the cis configuration about the double bond (see p. 133). Furthermore, the nuclear magnetic spectra of the vinyl hydrogens of all three compounds showed a splitting of about 15-16 c.p.s., which is in the range customarily reported for trans olefins (169). Therefore, on the basis of the spectral evidence, the compounds were all assigned the trans structure in which the carbinyl grouping is geometrically isolated from the ferrocene nucleus.

Methyl(2-ferrocenylvinyl)carbinyl acetate solvolyzes more slowly than methylferrocenylcarbinyl acetate by a factor of 0.63. In solvolyses of allylic chlorides, methyl substitution produces comparable effects in either the 1- or 3-position (170). A phenyl

group in the 3-position is intermediate between one and two methyl groups in its effect. A general rule is that in solvolyses allyl chloride corresponds roughly to benzyl or i-propyl, and that substitution on either terminal carbon produces about the same effect that the sum of such substitution would produce on benzyl or i-propyl chlorides. Thus, the vinyl group produces its own sizeable carbonium ion stabilization, and also transmits effects from the 3-position with but little diminution. For example, crotyl chloride solvolyzes about 10^4 times as fast as benzyl chloride in formic acid or 50% ethanol (141, 170). On this basis, we might expect methyl(2-ferrocenylvinyl)carbonyl acetate to solvolyze more rapidly than methylferrocenylcarbonyl acetate by a factor of nearly 100, since this is the rate enhancement produced by a phenyl group in the ferrocenylcarbonyl acetate series. This is about 160 times greater than the observed rate, and this difference could be ascribed to the loss of participation by the metal at the rear of the carbonyl carbon.

Two considerations add some uncertainty as to the magnitude of this rate enhancement due to metal participation. First, it is possible that the vinyl group might not be quite so effective at transmitting the effect of a substituent which releases electrons as strongly as the ferrocenyl group. Perhaps, also, in such circumstances as these, electron release by the vinyl group itself would be somewhat curtailed. These effects would suggest that the loss in rate calculated above is the maximum due to participation.

Despite the impossibility of overlap of metal orbitals with the

p-orbital on the carbonyl carbon, the positive charge might yet receive some stabilization by participation at the γ -carbon of the allylic system. Anchimeric assistance at the γ -carbon of an allylic system has apparently not been investigated. In molecular orbital terms, this would amount to bonding between an iron orbital and only a portion of one of the molecular orbitals of the conjugated system. The overlap would, of course, be decreased, but perhaps an orbital of the ring system would be of favorable energy for formation of a dative bond from the metal. This would tend to minimize the effect of removing the reacting center from the proximity of the metal.

The solvolysis of methyl(2-ferrocenylvinyl)carbonyl acetate proceeds with no measurable allylic rearrangement (171). This result is to be expected, since it preserves the conjugation of the double bond with the ring, and possibly also any direct interaction which might conceivably occur between the metal orbitals and the vinyl group.

The result presented in this section provides good evidence for the importance of rate enhancement in solvolyses of substituted ferrocenylcarbonyl acetates due to direct participation by the metal orbitals. Since it is probably unlikely that the large electron release by the ferrocene nucleus could completely cancel the stabilizing effect of the vinyl group on the carbonium ion, at least part of the difference between the expected and observed rates must be significant. Other similar experiments which might shed further light on this area would be solvolyses of ruthenocene

and osmocene analogs of methyl(2-ferrocenylvinyl)carbonyl acetate (in which a different balance between participation and conjugative stabilization would be expected), and a study of the effect of ring substitution. Until the two possible conflicting sources of uncertainty referred to above can be evaluated, the rough estimate of a factor of 150 due to metal participation might be accepted tentatively.

9. β -Ferrocenylcarbonium Ions

Trifan (123) has reported that the tosylate of β -ferrocenylethanol solvolyses in 80% acetone at a rate exceeding that of β -phenylethyl tosylate by a factor of 537. This rate increase might result from participation either by a filled iron orbital or by the π -electrons of the ring. A third possibility is that the solvolysis is anchimerically assisted by hydride migration. The large degree of stabilization by resonance or metal participation in the α -position could provide the driving force. This possibility was made particularly plausible by the demonstration (103) that such a rearrangement occurs on alkylation of ferrocene with 1,2-dichloroethane. Therefore, a sample of β -ferrocenylethyl tosylate was solvolysed in refluxing 80% acetone, and the product was isolated. Within the limits of detection ($\sim 2\%$), the sole reaction product was the starting alcohol, β -ferrocenylethanol. Therefore, the driving force for the reaction is not rearrangement to the α -ferrocenylcarbonium ion. The actual magnitude of the driving force in this reaction due to participation by the metallo-

cene nucleus cannot be accurately evaluated, since the inductive effect of a ferrocenyl grouping is unknown. Generally a rate decrease by a factor of 10 is attributed to the inductive effect of a β -phenyl group (172).

A derivative of the alcohol β -hydroxy-1,1'-trimethyleneferrocene should provide a favorable geometrical arrangement for participation by metal orbitals, but prohibitive strain should prevent participation by the π -electrons of the rings. The acetate of this alcohol was solvolyzed in 60% acetone at 45°. After three days, no noticeable reaction had occurred. α -Acetoxy-1,1'-trimethyleneferrocene has a half-life of 75 minutes under these conditions.

A sample of the tosylate of β -hydroxy-1,1'-trimethyleneferrocene was prepared which, because of the small sample size and poor crystallizing characteristics, was quite impure. An exploratory solvolysis of one portion of the product at 10° in 80% acetone showed the presence of two components. The rate of the faster of these exceeded a crudely extrapolated rate for cyclopentyl tosylate (173) by a factor of about 75. This rate was also faster than that of tosyl chloride under these conditions by a factor of 20. The sole product recovered from the solvolysis was unrearranged alcohol. This tentative result suggests that further work should be done on both the rate and stereochemistry of solvolysis of this and similar compounds.

10. Summary of Evidence for Nucleophilic Metal Participation in Metallocenylcarbinyl Acetate Solvolyses.

Earlier in this thesis, two plausible models for metal participation in α -metallocenylcarbonium ions have been proposed (see p. 89). These models were presented on a strictly qualitative basis which suggests quite strongly that the most stable electronic configuration of an α -metallocenylcarbonium ion should include appreciable bonding between the carbinyl carbon and the metal. In addition, overlap of filled metal orbitals with positive centers not in conjugation with the ring is also reasonable. Since the presentation was entirely qualitative, no estimate was made of the magnitude of the stabilization to be gained from such participation. During the discussion of the results of this research, several pieces of experimental data have been considered which are most easily explained with reference to the concept of metal participation. These will now be summarized, and their contributions in support of this concept will be examined.

The best starting point for such a discussion is the stereochemistry of the solvolysis reaction as illustrated by the solvolyses of 2-alkyl derivatives. The large difference in solvolysis rates between the exo and endo isomers of α -acetoxy-1,2-tetramethyleneferrocene (see p. 51) provides the least ambiguous evidence for direct contribution of electrons to the reaction center by some other part of the system "below" the plane of the ring. The distance between the rings, and the correlation of substituent effects on the far ring by primarily inductive substituent constants

(see p. 40) decreases the likelihood that the participation is by electrons on the second ring. It is then probable that the direct electron release is from the metal. While steric factors may contribute appreciably to the energy difference between the two transition states, such a great energy difference is difficult to account for without considering the availability of the metal orbital for back side participation. The different solvolysis rates within the pairs of open-chain 2-alkyl derivatives (see p. 56) supports the specificity of the reaction for departure of the leaving group away from the metal. This difference is in the direction to be expected on the basis of the relative stabilities of the two carbonium ions formed.

Solvolysis products from all of the 2-substituted acetates are formed completely by solvent collapse from the side of the carbonium ion away from the metal. Such a result is quite consistent with bonding by the metal to the back side of the carbonium ion. However, it is not unreasonable that purely steric factors could account for much of the stereospecificity of product formation (see p. 56). Similarly, lack of rotation in the carbonium ion about the bond between the carbonyl carbon and the ring is expected from metal participation, but should also result merely from strong conjugation with the ring.

The relative solvolysis rates of the three acetates substituted with a trimethylene bridge provide good supporting evidence for metal participation (see p. 75). In particular, the large difference between the two isomers substituted in the

2-position is difficult to rationalize on any other basis. The solvolysis rate of α -acetoxy-1,1'-trimethyleneferrocene was originally proposed as evidence for metal participation (99). It was felt that, due to loss of coplanarity with the rings, the rate should be much smaller than observed. However from the spectrum of the corresponding ketone, and from the most reasonable geometrical model for these compounds, it now appears that the loss of coplanarity had been overestimated. The rate decrease probably is due to an appreciable contribution from the effect of "squeezing" the metal away from the bridge, as well as from the loss of coplanarity.

The effects of methyl substitution in various positions on the ferrocenylcarbonyl acetate skeleton are consistent with direct participation by the metal (see p. 69). The relatively small effect of α -substitution and the large effect of 1'-substitution suggest that a large portion of the charge is distributed to the second ring by a process which does not require transmission of the effect through the conjugated fulvene system. Such a process could be nucleophilic metal participation. Other explanations for the observed substituent effect may be advanced, but they are probably less satisfactory.

The effect of changing the central metal atom of the metallocene is still quite ambiguous (see p. 95). The opposition of trends in acetylation and in the solvolyses is quite consistent with metal participation in one or both of these two reactions, but the number of reasonable explanations is too great to allow

any firm conclusions to be drawn.

The solvolysis of methyl(2-ferrocenylvinyl)carbonyl acetate yields an estimate of a factor of 150 in the rate for metal participation (see p.102). This number is uncertain to the extent that the vinyl group may fail to transmit a portion of the conjugative electron release by the ferrocene nucleus, and to the extent that the metal may participate at the γ -carbon of the allylic system. The estimated factor is considerably smaller than that of about 2500 derived from the solvolyses of the two isomeric α -acetoxy-1,2-tetramethyleneferrocenes. However, as noted previously (see p. 52), the factor of 2500 is probably a maximum for metal participation, since other effects may be expected to contribute substantially.

β -Ferrocenylcarbonium ions appear to receive some degree of assistance from the metal atom or from the π -electrons of the ring, judging from the results of Trifan (123) and from the rough solvolysis rate obtained in this research (see p. 107) for the tosylate of β -hydroxy-1,1'-trimethyleneferrocene. Additional research, particularly in determining the effects of structure and the stereochemistry on the solvolysis, will be necessary to obtain a clearer picture of this participation. Carbonium ions separated by a longer carbon chain from the metallocene nucleus appear to receive less assistance (20).

Other evidence for nucleophilic participation of the iron comes from protonation (163) and hydrogen bonding (166). Direct protonation of the metal, and intramolecular hydrogen bonding to the metal are reasonably well established, but the opposition in trends

with changes in the metal has not been satisfactorily explained.

In summary, it may be stated that very good indicative evidence for participation by the metal in solvolyses of α -metallocenylcarbonyl derivatives has been obtained. While much of the data reported in this thesis may be adequately explained without reference to participation by the metal, such participation is strongly supported by some of the evidence, and indeed provides the most satisfying rationalization for all of the available facts. Determination of the direct influence of the metal on reactions of the metallocenes thus remains an area with much promise for further research.

B. Spectra of Ferrocene Derivatives

1. Correlation of Structures of Isomeric Ring-substituted Ferrocene Derivatives with Infrared Spectra

Several correlations have been made between the structures of isomeric substituted ferrocenes and their infrared spectra. A generalization implicit in most such discussions is that the spectrum resulting from one ring and its substituents will be essentially independent of that from the other ring, except in so far as interannular electronic effects may produce minor frequency shifts. Such a generalization is quite reasonable on the basis of the spectral assignments of Lippincott and Nelson (174) for ferrocene. According to their assignments, the symmetrical and antisymmetrical ring-metal stretching frequencies appear at 303 and 478 cm^{-1} , the corresponding ring-tilting modes are at 388 and 492 cm^{-1} , and the ring-metal bending mode is at about 170 cm^{-1} . Since these absorptions are out of the range of measurements generally made for qualitative infrared structural studies, their contribution to the spectra of ferrocene derivatives may generally be neglected. This rule of the independence of the rings may be expected to fail in a few instances, as for weak bands due to combination frequencies (782 cm^{-1} for ferrocene) or to a breakdown of selection rules (1051 and 1088 cm^{-1} for ferrocene). Other cases may arise where there is interaction between substituents on two different rings, such as the double carbonyl stretching frequency due to hydrogen bonding in methyl-(1'-carbomethoxyferrocenyl)carbinol (see p.134).

The most clearly applicable generalizations have been made for alkyl-acetylferrocenes (44,45,175). However, these generalizations are not as useful as they might be, since different authors have cited separate spectral regions as the ones useful for correlations, and spectra have been reported in different media. Thus, Rinehart reports his spectra as liquid smears or nujol mulls, which should lead to the most marked sort of medium dependence. Rosenblum's spectra of acetylethylferrocenes are reported for carbon tetrachloride solutions, while those of acetylphenylferrocenes are in chloroform solution. In the present work, trimethyleneferrocene, methylferrocene and dimethylferrocene were acetylated and it was necessary to securely assign structures to the acetyl derivatives of the first two compounds. Spectra were taken with some variation in media, and the results obtained are compared here with previous correlations. The attempt has been made to consider all spectral regions which may be of use for structural determinations. Additional confirmation for some correlations is obtained by considering the spectra of other intermediates prepared in this research.

When a substituent is introduced into one of the rings, changes of two types will occur in the spectrum. First, the substituent itself will exhibit its characteristic absorption bands. Of these, probably the only one of importance for present purposes is the aromatic ketone band in the vicinity of 1280 cm^{-1} cited by Rinehart (44). All available results for this region are summarized in Table XIII. Rinehart's generalization that the 3-substituted derivative absorbs at a higher frequency than the 2-substituted isomer extends to all compounds studied in this research.

TABLE XIII

Aromatic Ketone Absorption of Acylferrocenes

Compound	(cm ⁻¹)					Refs.
	Nujol (N) or Smear (S)	CS ₂	CCL ₄	CHCl ₃		
Acetylferrocene	1280 (N) 1285 (N)	1272	1275	1275	a, (44,45)	
1'-Methylacetylferrocene	1280 (N)	1275	1280		a	
2-Methylacetylferrocene	1271 (N)	1272			a	
3-Methylacetylferrocene	1299 (N)	1292			a	
2-Acetyl-1,1'-dimethylferrocene	1274 (S)	1273			a, (44)	
3-Acetyl-1,1'-dimethylferrocene	1299 (N)	1295			a, (44)	
2-Acetyl-1,1,1'-diisopropylferrocene	1269 (S)				(44)	
3-Acetyl-1,1,1'-diisopropylferrocene	1285, 1280 (S)				(44)	
2-Acetyl-1,1,1'-trimethyleneferrocene	1280 (N)	1278	1282		a	
3-Acetyl-1,1,1'-trimethyleneferrocene	1290 (N)	1285	1293		a	
α-Keto-1,2-tetramethyleneferrocene	1281 (N) ^b	1278			a, (181)	
α-Keto-1,1-trimethyleneferrocene	1266 (N) ^b	1265			a, (181)	

^aSpectra determined in present work.

^bPresumed to be in nujol mull by analogy with other data of these authors.

However, the actual positions of the peaks are dependent upon the medium and the substituent. Rosenblum does not report this absorption, so confirmation for ethyl and phenyl substitution is impossible.

The second type of change involves vibrational modes of the ring. Several features in the spectra of benzene derivatives are quite characteristic of the degree and orientation of substitution, but independent to some degree of the particular substituents (176). These frequencies correspond to: C-H out-of-plane bending modes, C-H inplane bending modes, C-C stretching modes, and combination absorptions of the C-H out-of-plane bending modes. Due to strong coupling of vibrations, the number of adjacent hydrogen-bearing carbonatoms appears to be important, and so the orientation of substituents is of major importance in determining the number and position of peaks in these regions. However, shifts of varying magnitude are observed, depending on the ability of the substituents to withdraw or release electrons, while conjugated substituents are frequently responsible for a large enhancement in intensity. Similar features should be expected in the spectra of substituted ferrocenes.

In ferrocene itself, strong absorptions associated with ring-breathing and C-H in-plane bending modes of an unsubstituted ring appear at about 1105 and 1000 cm^{-1} (9 and 10 μ). These are quite independent of the medium, and the presence of both peaks is generally diagnostic of an unsubstituted ring (177).

A weak to medium peak near 1228 cm^{-1} in compounds containing a ring with only a methyl group (1218-1234 cm^{-1} in substituted trimethyleneferrocenes) may be fairly general for a ring bearing

just an alkyl substituent. A fairly strong peak at 1110-1115 cm^{-1} is characteristic of a ring containing only an acetyl group. There may be some room for confusion with the 1105 cm^{-1} peak for an unsubstituted ring, but despite changes in medium, the two ranges remain distinct. Another peak at about 1110 cm^{-1} , which appears in all of the ring-substituted trimethyleneferrocenes, may be characteristic of the unsubstituted bridge. When an acetyl and an alkyl group are in the same ring, weak absorption appears near 1173 cm^{-1} for 1,2-orientation, and medium to strong absorption is observed near 1185 cm^{-1} for 1,3-orientation. These latter two sometimes appear as doublets.

Between 1050 and 1000 cm^{-1} there is absorption for all of the compounds studied, but there appears nothing which is very characteristic of the substitution. However, with an alkyl and an acetyl substituent on the same ring, there is additional absorption at about 1072 cm^{-1} .

Rosenblum has proposed a correlation for the region between 880 and 930 cm^{-1} based on his study of acetylations of ethyl- and phenylferrocenes. From the data published by Rinehart for the acetylation products of dimethyl- and diisopropylferrocenes, similar generalizations may be made. These are summarized in Table XIV, parts A and B. There is a considerable discrepancy between these two reports for the 3-alkylacetylferrocenes. The results obtained in the present work for a somewhat more extended region of the spectrum are presented in Table XV. They are briefly summarized in Table XIV-C.

These results agree quite well with those of Rinehart. Since

TABLE XIV

Spectral Correlations in Region 1000-860 cm^{-1}

A. Correlations by Rosenblum (45,175)

only acetyl	892
only phenyl	899
1,2-acetylethyl	921
1,2-acetylphenyl	913
1,3-acetylethyl	905, 921
1,3-acetylphenyl	897, 905

B. Correlations from data of Rinehart (44)

only alkyl	925
only acetyl	896, 965
1,2-alkylacetyl	930
1,3-alkylacetyl	903, 938, 968

C. Correlations based on present research.

only methyl	922(m)
only trimethylene	954(w) ^a , 910(m), 865(w)
only acetyl	958(m) ^a , 891(m-s)
2-acetylmethyl	972(w), 930(m), (880?)
2-acetyltrimethylene	998(w), 924(m) ^a , 883(m)
3-acetylmethyl	(983?), 965(m) ^a , 938(m) 905(m), 898(w) ^a
3-acetyltrimethylene	(967(m-s), 923(w-m), 905(m) ^a 899(m), 881(w) ^a

^a. Considerable solvent dependence.

TABLE XV

Infrared Absorption of Acetylalkylferrocenes in Region 1000-850 cm^{-1}

<u>Compound</u>	<u>Medium</u>	<u>Absorption (ν cm^{-1})</u>	
1,1'-Dimethyl-ferrocene	CS ₂	922	
	Nujol	922	
Acetylferrocene	CS ₂	954	890
	Nujol	961	892
	CCl ₄	956	891
	CHCl ₃	960 (920)	892
1'-Acetylmethyl-ferrocene	CS ₂	955	891
	Nujol	965	898
	CCl ₄	960	890 895
2-Acetylmethyl-ferrocene	CS ₂	972 (952)	880
	Nujol	973	(913) (895)
2-Acetyl-1,1'-dimethyl-ferrocene	CS ₂	970	880
	Smear	972	(890)
3-Acetylmethyl-ferrocene	CS ₂	981	938
	Nujol	970	937 (922) 903 898 (875)
3-Acetyl-1,1'-dimethyl-ferrocene	CS ₂	983	940
	CS ₂	965	905 900

TABLE XV (cont.)

<u>Compound</u>	<u>Medium</u>	<u>Absorption (ν cm⁻¹)</u>
1,1'-trimethylene-ferrocene	CS ₂	910
	Nujol	909
	CCl ₄	910
2-Acetyl-1,1'-trimethylene-ferrocene	CS ₂	948
	Nujol	921 909
	CCl ₄	928 912 922 912
3-Acetyl-1,1'-trimethylene-ferrocene	CS ₂	965 (950)
	Nujol	920 909 902 897
	CCl ₄	923 912 907 899 925 912 905 901
		860 868 860
		880 863 885 864 885 868
		881 865 883 869 860

the acetylated trimethyleneferrocenes studied both have a ring without an acetyl substituent, it is not possible to decide on this basis whether the three bands cited arise from the bridge or from the ring. However, only the one about 910 cm^{-1} is consistently present in the trimethyleneferrocenes with substitution on the bridge. It may be noted that CH_2 rocking frequencies appear at 910 cm^{-1} for cyclobutane and at 977, 930 and 890 cm^{-1} for cyclopentanes (178). Absence of the 930 cm^{-1} band in α -keto-1,2'-tetramethyleneferrocene (although it is a 2-alkylacylferrocene) provides an indication of the limitations of these correlations. Such a correlation must be applied with a great deal of caution to any compound other than simple acetylated alkylferrocenes.

In addition to correlations of acetylalkylferrocenes, Rinehart (44) cites several bands which correspond to a ring substituted with an ethyl and a methyl group in a 1,2- or 1,3-orientation. A comparison of these numbers with the spectra of some carbinols and acetates prepared in this study which have similarly oriented saturated substituents gave no correlation. Therefore, these bands must vary somewhat with the substituent. Unfortunately, the spectra of these compounds were too complex to allow satisfactory correlation.

2. Infrared Carbonyl Stretching Frequency.

The carbonyl stretching frequencies of acetylferrocene, acetyl-ruthenocene and acetylosmocene were determined (calibration against atmospheric carbon dioxide) in an attempt to find a correlation with the solvolysis rates of the corresponding carbonyl acetates.

The frequencies found in carbon tetrachloride are as follows:

acetylferrocene	1676 cm^{-1}
acetyl-ruthenocene	1682 cm^{-1}
acetylosmocene	1682 cm^{-1}

The shift observed is slight, and is not in the direction expected from the relative solvolysis rates.

In the alkylacetylferrocenes, the spectra in carbon disulfide show a shift of about 7 cm^{-1} to lower frequencies (from 1778 to 1771 cm^{-1}) with homoannular alkyl substitution. Spectra in a nujol mull or liquid smear are less consistent due to medium effects.

3. Infrared Hydroxyl Stretching Frequencies

Nature of the hydrogen-bonded species. - The role of the ferrocene nucleus as a hydrogen bond acceptor has been studied by Trifan and co-workers. In the initial communication of that work (179), methylferrocenylcarbinol was reported to exhibit two concentration-independent hydroxyl stretching bands at 3617 and 3574 cm^{-1} in carbon tetrachloride. The former was assigned as a free hydroxyl stretching frequency, and the latter as a hydroxyl group hydrogen-bonded to the ring. Later communications (123,163)

interpret this compound as being in equilibrium between bonding to the ring and to the metal, with the bond to the metal being the stronger of the two.

In the present work, spectra were taken in carbon disulfide, since this solvent appeared to be most advantageous for other regions of the spectra. Positions of the bands observed are summarized in Table XVI. Two peaks were generally present, a sharp one at about 3600-3610 cm^{-1} and a broader one at about 3575 cm^{-1} . A spectrum of methylferrocenylcarbinol in carbon tetrachloride had peaks at 3618 and 3578 cm^{-1} . No further resolution of the 3618 cm^{-1} band was obtained in either solvent. Since the peak at higher frequency is assigned by Trifan to hydrogen-bonding to the ring, the separation between the peaks may not be taken as an exact measure of the strength of the hydrogen bond to the metal. This is particularly true in the spectra in carbon disulfide, since the higher frequency band is lowered somewhat relative to the spectrum in carbon tetrachloride. However, large changes in the separation of the two peaks, or in the position of the lower frequency peak, should be significant.

While Trifan's interpretation readily fits the data, he presents no arguments to show that the two hydrogen-bonded peaks are not due to bonding to the two rings. Certainly the hydroxyl group would be located in a reasonably good position to bond to the "inside" of the second ring, since this might formally be considered a six-membered ring (including the hydrogen).

TABLE XVI

Infrared Hydroxyl Stretching Frequencies of Mettalocene-substituted

Alcohols in Carbon Disulfide

<u>Alcohol</u>	<u>ν (cm⁻¹)^d</u>
Ferrocenylcarbinol	3610 3578
Methylferrocenylcarbinol	3605 <u>3581</u>
Dimethylferrocenylcarbinol	3600 <u>3574</u>
Phenylferrocenylcarbinol	3596 <u>3572</u>
β -Ferrocenylethanol	<u>3622</u> 3595 3537
δ -Ferrocenylbutanol	<u>3626</u> (3504)
Methylruthenocenylcarbinol	3608 <u>3526</u>
Methylosmocenylcarbinol	3609 <u>3506</u>
Methyl(1'-carbomethoxyferrocenyl)carbinol	3605 3552 <u>3508</u>
<u>exo-α</u> -Hydroxy-1,2-tetramethyleneferrocene	3610 ^b
<u>endo-α</u> -Hydroxy-1,2-tetramethyleneferrocene	(3608) <u>3561^a</u>
Methyl(2-methylferrocenyl)carbinol, Ψ - <u>exo</u> isomer	<u>3604</u> 3580
Methyl(2-methylferrocenyl)carbinol, Ψ - <u>endo</u> isomer	^e
Methyl-2-(1,1'-dimethylferrocenyl)carbinol, Ψ - <u>exo</u> isomer	<u>3604</u> 3581

TABLE XVI, (cont.)

Alcohol	ν (cm ⁻¹) ^d
Methyl-2-(1,1'-dimethylferrocenyl)carbinol, Ψ - <u>endo</u> isomer	(3605) <u>3578</u>
Methyl-2-(1,1'-trimethyleneferrocenyl)carbinol, Ψ - <u>exo</u> isomer	3602
Methyl-2-(1,1'-trimethyleneferrocenyl)carbinol, Ψ - <u>endo</u> isomer	(3609) <u>3575</u>
Methyl-3-(1,1'-trimethyleneferrocenyl)carbinol	3608 <u>3550</u>
α -Hydroxy-1,1'-trimethyleneferrocene	3609
β -Hydroxy-1,1'-trimethyleneferrocene	3612
Methyl(2-ferrocenylvinyl)carbinol	3608

^aPeak skewed toward lower frequency

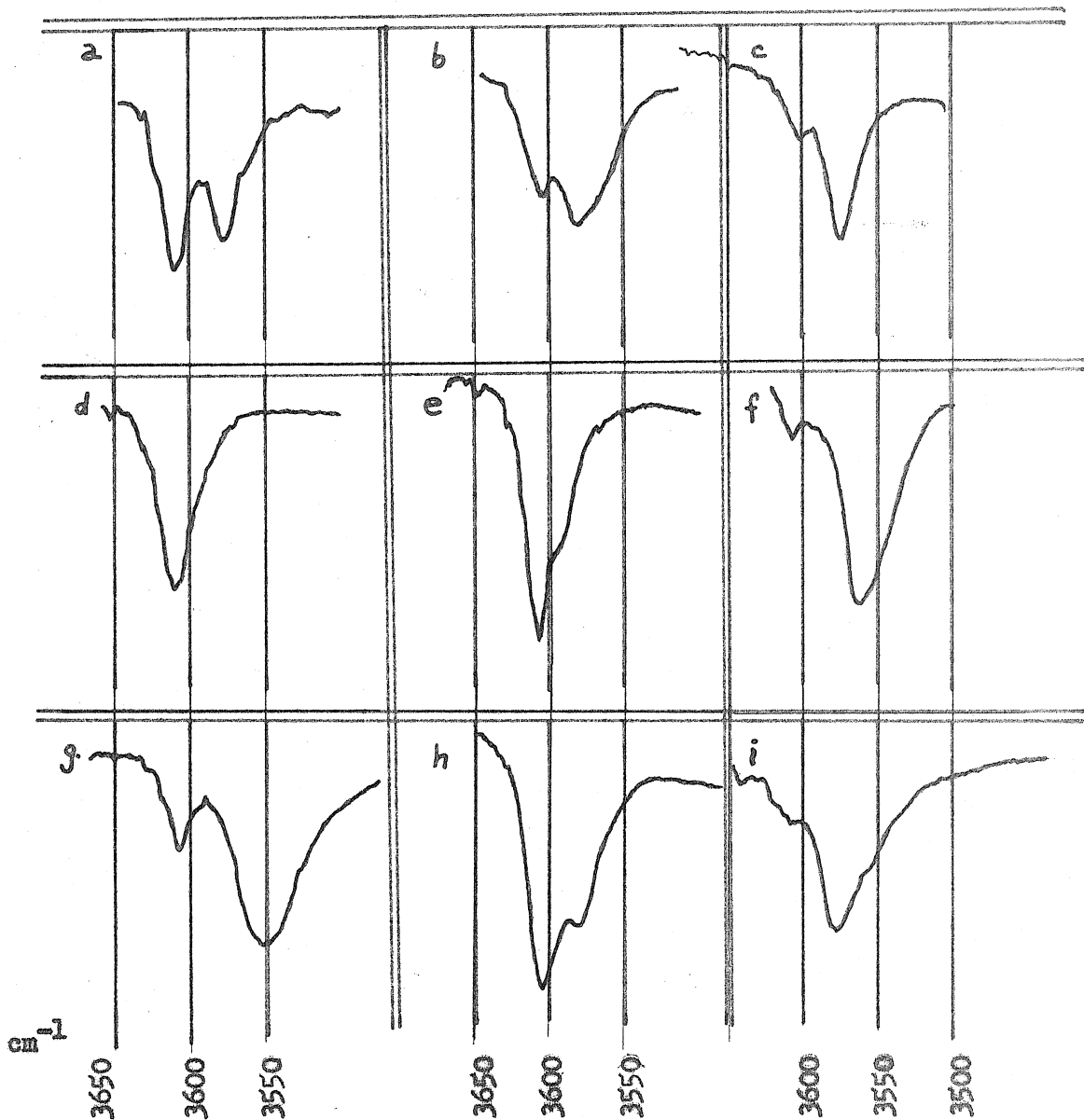
^bShoulder to lower frequency

^cShoulder to higher frequency

^dStronger peak is underlined.

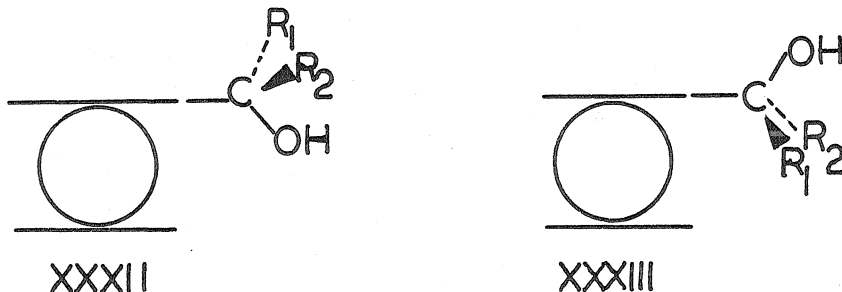
fig. 5

Infrared hydroxyl stretching spectra of substituted ferrocenylcarbinols



- | | |
|--|--------------------------------------|
| a. Ferrocenylcarbinol | b. Methylferrocenylcarbinol |
| c. Dimethylferrocenylcarbinol | d. Methyl(2-ferrocenylvinyl)carbinol |
| e. <u>exo</u> - α -Hydroxy-1,2-tetramethyleneferrocene | |
| f. <u>endo</u> - α -Hydroxy-1,2-tetramethyleneferrocene | |
| g. Methyl-3-(1,1'-trimethyleneferrocenyl)carbinol | |
| h. Methyl-2-(1,1'-dimethylferrocenyl)carbinol, Ψ - <u>exo</u> isomer | |
| i. Methyl-2-(1,1'-dimethylferrocenyl)carbinol, Ψ - <u>endo</u> isomer | |

The results in Table XVI show quite conclusively that the low frequency band is due to hydrogen bonding to the metal. In the series ferrocenylcarbinol, methylferrocenylcarbinol, dimethylferrocenylcarbinol, the low frequency band increases in relative magnitude. (See fig. 5, p.126.) Since steric congestion should



be greater in the region between the rings, a conformation similar to XXXII will become more heavily populated as R₁ and R₂ are changed from hydrogen to methyl. Since such substitution increases the magnitude of the 3575-3580 band, the hydrogen bond must be to a portion of the molecule between the rings. Trifan (163) reports on the spectra of these same compounds, but makes no mention of the change in intensities. He does note that the $\Delta\nu$ values decrease in this sequence, as expected from the normal hydrogen bond acidity sequence: primary > secondary > tertiary. Therefore, the shift in the equilibrium must be due not to the acidity of the proton, but to the steric factor cited above. The relative magnitudes of the two peaks in phenylferrocenylcarbinol quite closely approximate those of methylferrocenylcarbinol.

In the series of compounds methylferrocenylcarbinol, methylruthenocenylcarbinol, methyl-osmocenylcarbinol, the position of the low frequency band shifts strongly toward lower frequencies. Values

of $\Delta\nu$ for this series are 24, 82 and 103 cm^{-1} . Trifan reports values of 48 and 102 for the first two compounds. Let us consider the two possibilities that this band is due to hydrogen bonding to the metal or to the second ring. The interannular distances in ferrocene and ruthenocene are 3.32 and 3.68 A° respectively (115a,b). Osmocene is reported to be almost identical with ruthenocene (125c). Calculations of some distances may be made on the simple model of fig. 6a, p.129, in which the requisite bond lengths and angles were obtained from Pauling, "The Nature of the Chemical Bond"(124). The hydrogen of the hydroxyl group is found to be in the position shown in fig. 6b. No allowances are made for changes in bond angles and bond lengths which might result from formation of the hydrogen bond.

The contribution from a resonance form in which the hydrogen is bonded covalently to the hydrogen bond acceptor may be calculated from the distance between the hydrogen and the acceptor (157). For bonding to the second ring, contributions of 1.7 and 0.5% are calculated for the ferrocene and ruthenocene cases. Osmocene should be the same as ruthenocene (150c). If the skew conformation of the rings is considered, the respective contributions are 0.9% and 0.3%. These would be very weak hydrogen bonds, and the order of their strengths does not correspond to that found experimentally, even if it is granted that the ferrocene assumes predominately a staggered conformation and the ruthenocene an eclipsed conformation, as the respective metallocenes do in the crystal (150).

For calculations of the bonds to the metal, covalent single-bond radii given by Pauling (158) are used. These are 1.165, 1.246 and 1.260 A° for iron, ruthenium and osmium respectively. Using

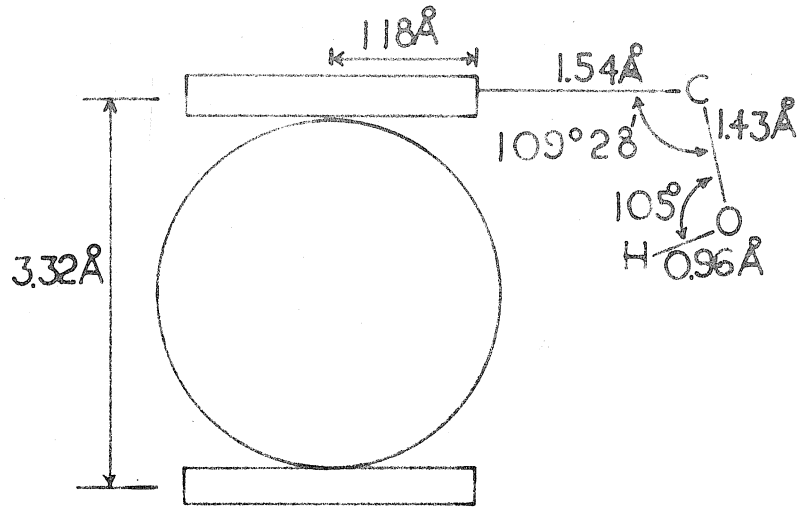


fig.6a

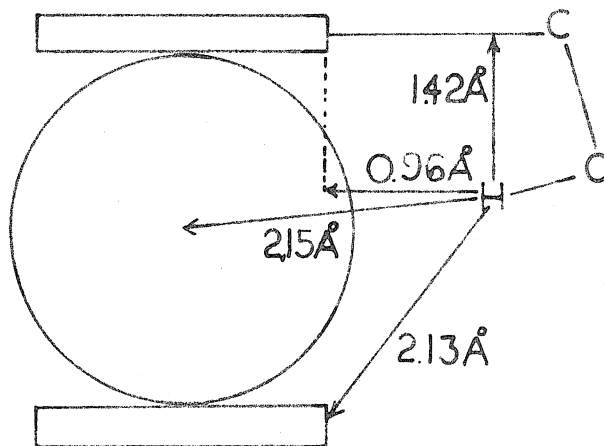


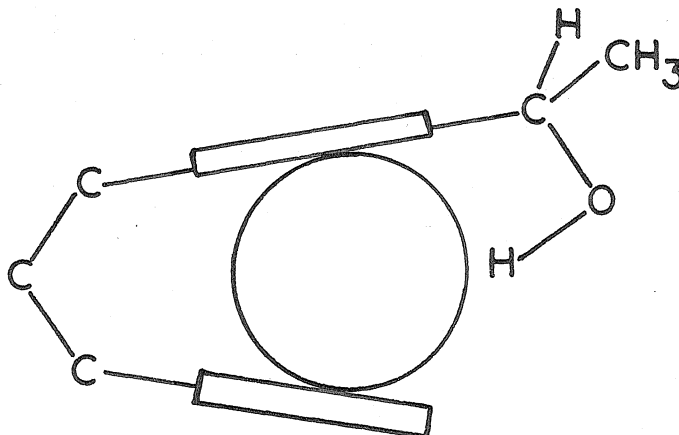
fig.6b

these values, covalent contributions to a hydrogen bond of 7.2, 8.8 and 9.5% may be calculated. Slightly different values obtained using octahedral radii (158) likewise indicate a weaker bond for iron. Since the exact hybridizations and strengths of such bonds are not known, rigorous predictions cannot be made. However, it is important to note that the results expected merely on the basis of the size of the metal atom agree with the experiment, while the opposite result is predicted for bonding to the far ring. The order of hydrogen bond strengths for these compounds thus presents a good argument that the lower frequency band is due to hydrogen bonding to the metal.

Trifan (163), working with ferrocene and ruthenocene derivatives, reports $\Delta\nu$ values of 48 and 102 cm^{-1} respectively for the methylmetallocenylcarbinols, while for β -metallocenylethanol, similar values are 99 and 171 cm^{-1} . Geometrical calculations show that the hydrogen can approach as close as 1.55 A° to the center of the molecule in the β -metallocenylethanol, so the optimum hydrogen bond should be possible in both cases. Thus, aside from the steric factor, the heavier metals are probably capable of forming a stronger hydrogen bond. This is probably to be expected from the greater electronegativity of ruthenium and osmium, 2.2 as opposed to 1.8 for iron (180, but see also 165). Trifan states that, in contrast, bonding to the ring is weaker in ruthenocene. The relationship of these results to other metallocene reactions is discussed on pp. 95 to 102 of this thesis.

The spectra of the (trimethylenoferrocenyl)carbinols are also best interpreted if the lower frequency band results from hydrogen-bonding to the metal. When the bridge is in the 3-position relative

to the carbinol substituent, the low frequency band is shifted to 3550 cm^{-1} . This is about $20\text{-}30 \text{ cm}^{-1}$ to lower frequency than the other substituted ferrocenylcarbinols. If the rings are tilted in these bridged compounds, and the iron atom is "squeezed" away from the bridge as illustrated in exaggerated fashion in XXXIV, then

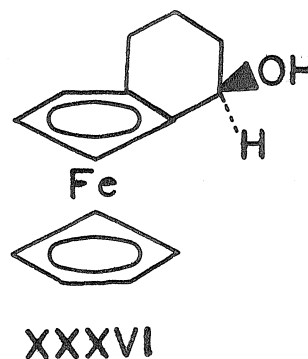
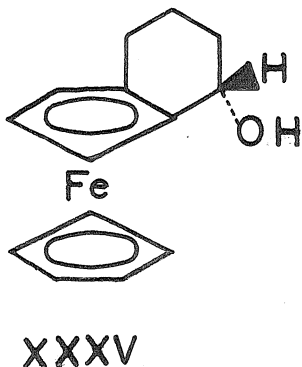


XXXIV

the hydrogen atom should approach the iron more closely, and a stronger bond should be possible. However, bonding to the other ring should become more difficult. Evidence from NMR spectra (see p. 147) also indicates a tilting of the rings. When the bridge is in the 2-position, the spectrum is quite similar to those of compounds with 2-methyl substitution. If the hydrogen bond were formed to the second ring, it should be made stronger by this tilting. Rotations about several of the bonds should be able to minimize weakening of the hydrogen bond due to displacement of the metal. Thus, results for these bridged compounds are consistent with hydrogen bonding to the metal.

Structures of isomeric 2-substituted carbinols. - Establishment of the steric requirements for formation of the hydrogen bond absorbing at $3575\text{-}3580 \text{ cm}^{-1}$ permits use of this portion of the spectrum to assign

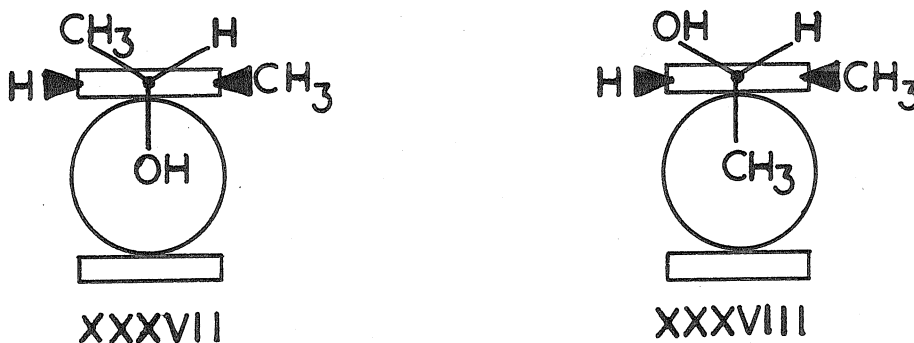
structures to the 2-substituted carbinol isomers. Such assignments are valid whether the hydrogen-bond acceptor is the metal or the π -electrons of the second ring. Of the two isomeric α -hydroxy-1,2-tetramethyleneferrocenes, one absorbs at 3561 cm^{-1} , and passes through the chromatographic column rapidly. This should be the endo-isomer, XXXV, which is well suited for the intramolecular hydrogen bonding,



and in which the hydroxyl group is more hindered from bonding to the alumina. (The especially low frequency of this band compared with the substituted methylferrocenylcarbinols may result from removal of interaction between the methyl group and the adjacent ring hydrogen. Such interaction could force the hydroxyl slightly away from the optimum position for bonding.) The second isomer, assigned the exo-structure XXXVI, passes through the chromatographic column more slowly, and exhibits absorption only at 3610 cm^{-1} . There is some evidence in this case for partial resolution into a free and a ring-bonded hydroxyl (see fig. 5, p.126).

The carbinols with methyl or trimethylene substitution in the 2-position are also separable into two isomers; one moves rapidly through the column and exhibits mainly metal-bonded hydroxyl, and the other is retained more strongly by the column, and absorbs at about

3605 cm^{-1} . These properties are quite analogous to those for the exo and endo isomers of α -hydroxy-1,2-tetramethylenferrocene. Conformations similar to those illustrated for XXXVII and XXXVIII probably prevail for the two isomers, because they minimize steric



repulsions by placing the smallest substituent, hydrogen, closest to the ring methyl. They may therefore be expected to behave as pseudo-endo and exo isomers in their chromatographic and hydrogen bonding behavior. These structures are assigned to the isomers on this basis.

Other Information from Hydroxyl Stretching Frequencies. - The trimethylenferrocenes substituted with a hydroxyl group on the bridge either in the α - or β -position exhibit only free hydroxyl absorption. This is to be expected, since the hydroxyl group is oriented away from the remainder of the molecule, even though it is constrained to a position between the rings.

Methyl(2-ferrocenylvinyl)carbinol exhibits absorption only at 3608 cm^{-1} . From NMR evidence (see p.180) and infrared bands in the region for double bonds (see p. 103), this compound has been fairly securely assigned as the trans isomer. The lack of metal-bonded hydroxyl is negative evidence supporting this assignment. Trifan (163)

reports that the saturated analog of this alcohol, γ -ferrocenylpropanol, is not in equilibrium with a metal-bonded hydroxyl form, due to the large loss in entropy that would result. However, with a double bond in the chain, the loss of entropy would be reduced.

The spectrum of methyl(1'-carbomethoxyferrocenyl)carbinol has a double carbonyl spectrum at 1724 and 1705 cm^{-1} . The peak at 1705 cm^{-1} disappears when the hydroxyl function is blocked by formation of the methyl ether or acetate. The rather complex hydroxyl absorption (see Table XVI) confirms that hydrogen-bonding is responsible for this anomaly. It is suggested that the 3552 cm^{-1} maximum results from hydrogen bonding to the ether oxygen of the carbomethoxy group, while the 3508 cm^{-1} band is due to bonding to the carbonyl oxygen.

4. Infrared Spectra of Diastereomeric Carbinols

The infrared spectra of the pairs of 2-substituted carbinols prepared in this research show slight differences in regions other than the hydroxyl stretching frequency. The important differences are summarized in Table XVII.

TABLE XVII

Spectral Differences Between Isomeric 2-Substituted Carbinols

<u>Compound</u>	<u>ν (cm⁻¹)</u>					
Methyl(2-methyl-ferrocenyl)carbinol Ψ - <u>exo</u> isomer	1275	1255			958	880
	1280	1246		1130	900	
Methyl-2-(1,1'-dimethyl-ferrocenyl)carbinol Ψ - <u>exo</u> isomer	1275	1255	1226		958	880
	1280	1250	1220	1135	900	
Methyl-2-(1,1'-tri-methyleneferrocenyl)-carbinol, Ψ - <u>exo</u> isomer	1275	1255			985	932
	1275	1257	1242	1135		883
α -Hydroxy-1,2-tetramethyleneferrocenyl)carbinol <u>exo-isomer</u>		1250		1124	980	907
		1242		1135	990	880

In addition, in the region 1100-1050 cm⁻¹ there are general qualitative similarities among the fast and slow isomers.

The differences in the mono- and dimethyl cases are of particular interest. If the spectra of the rings are completely additive, then the two pairs should exhibit exactly the same differences. However, if there is some interaction between substituents on the two rings of the dimethyl compounds, this might show up in the spectra. Such an interaction might lead to a difference in the ground state energies in the solvolyses of the corresponding acetates. A hint of such an interaction appears in the region around 1226 cm⁻¹ (a band probably due to a ring bearing only an alkyl substituent).

The differences observed between the isomers of the methyl carbinols are considerably greater than those between the isomeric α -hydroxy-1,2-tetramethyleneferrocenes. This may be due to the

removal of steric interaction with the adjacent alkyl group in the cyclic compounds. Unfortunately, there is no consistent difference extending through all of these pairs which would serve to characterize the endo or exo conformation of the hydroxyl group.

5. Ultraviolet Spectra of Metallocene Derivatives

Rinehart (44) has correlated the positions and intensities of the ultraviolet maxima of alkylacetylferrocenes in the 225-30 and 270 μ regions with their structures. The results in Table XVIII confirm and somewhat extend these correlations. Rinehart found that substitution by methyl or isopropyl in the 3-position of acetylferrocene brings about a slight bathochromic shift and little change in the extinction coefficient. Substitution in the 2-position leaves the maxima little changed, but increases the intensity of absorption. The present results show nearly the same pattern. Substitution in the 2-position gives a bathochromic shift of about 1-2 μ in both regions, while 1'- and 3-substitution give shifts of 2-3 and 4 μ respectively. These shifts are approximately additive. The spectrum of α -keto-1,2-tetramethyleneferrocene is almost identical with that of 2-methylacetylferrocene, indicating that steric factors play little part in the 2-substituted compounds. The third absorption maximum, at about 320-342 μ , shows a strong bathochromic shift of about 15 μ in alcohol solvents relative to cyclohexane. This maximum also appears at slightly longer wave-length for the 1'- and 3-isomers than for the 2-isomers. The same is true of the

TABLE XVIII

Ultraviolet Absorption of Alkylacylferrocenes^a

Substituents	Solvents	I		II		III ^c		IV		Ref. ^b
		λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	
Acetyl	Cyclohexane	221	22,000	267	5380	320	1070	447	300	(45) (44) (20)
	Ethanol	225	14,500	268	5370	335	1120	455	425	
	Ethanol	226	16,500	269	6500					
	Methanol	225	17,900	269	6160			458		
1'-methylacetyl	Cyclohexane	224	20,900	269	5200	324	1120	448	340	
	Cyclohexane	222.5	22,400	267	5600	320	1000	448	275	
	Cyclohexane	225.5	19,500	271	5375	321	1060	449	325	
1'-Ethylacetyl	Ethanol	228	15,200	270	5760	340	1290	460	540	(45) (45) (45)
	Ethanol	225	18,600	268	7100	335	1120	460	430	
	Ethanol	230	15,200	272	6460	340	1120	460	490	
2-acetyl-1,1'-dimethyl	Cyclohexane	224.5	22,600	270	5700	324	1050	452	300	(44)
	Ethanol	227	18,000	271	6800					
	Cyclohexane	228.5	18,400	272.5	4800	325	1000	449	330	
3-acetyl-1,1'-dimethyl	Ethanol	323	15,800	274	6600					(44)
	Methanol	232.5		274		342				
2-acetyl-1,1'-diethyl	Methanol	226		270						(20) (20)
	Methanol	231		274						
2-acetyl-1,1'-diisopropyl	Ethanol	226	18,200	271	6700					(44) (44)
	Ethanol	231	15,600	273	6700					
2-acetyl-1,1'-trimethylene	Cyclohexane	223	21,000	261	5150	317	900	435	400	
	Methanol	224	16,400	265	6830	337	1220	444	590	
	Cyclohexane	225	21,000	263	6000	321	1620	447	550	
	Methanol	229	14,900	266.5	8200	338	1880	456	920	

TABLE XVIII, (cont.)

Substituents	Solvents	I		II		III ^c		IV		Ref. ^b
		λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	
α -keto-1,1'-trimethylene	Cyclohexane	225	14,300	267	3550	319	830	441	210	
α -keto-1,1'-trimethylene	Methanol	shoulder	225	269		336				
α -keto-1,2-tetramethylene	Cyclohexane	223	22,800	269	5500	318.5	900	453	250	
α -keto-1,2-tetramethylene	Ethanol	226	17,600	270	7500					(44)

^aDetermined on a Cary recording ultraviolet spectrophotometer.

^bWhere reference is not given, results are from present work.

^cA definite shoulder appears invariably about 360 m μ .

maximum at 450 m μ .

The acetyl 1,1'-trimethyleneferrocenes are somewhat anomalous. Although the generalization still holds that 3-substitution produces a larger bathochromic than 2-substitution, these shifts are generally smaller, except for the maximum at about 450 m μ . In the 2-isomer, this maximum is shifted about 10-12 m μ to shorter wave length, while it is unchanged from acetylferrocene in the 3-isomer. There is a definite enhancement in the intensity. These anomalies may probably be ascribed to effects of ring-tilting on the chromophores. The greatly enhanced intensity for the 3-isomer in methanol may possibly indicate some direct interaction of the iron with the carbonyl grouping.

The spectrum of α -keto-1,1'-trimethyleneferrocene generally resembles those of the other acylalkylferrocenes, except for the reduced intensity of all of its maxima. In particular, the absorption at 225 m μ is reduced sufficiently in methanol that it appears only as a shoulder (see also ref. 181). This is the result to be expected when the carbonyl group is twisted out of the plane of the ring (132).

Ultraviolet spectra were taken of a number of compounds with substitution on a trimethylene bridge between the rings. With a hydroxyl group* or no substitution on the bridge, the spectra were very similar to that of dimethylferrocene. They exhibit maxima at about 440 and 320 m μ , and strong end absorption with shoulders. The 440 m μ band was stronger by a factor of 2-3. When the substituent was unsaturated (β -keto-1,1'-trimethyleneferrocene, 1,1'-(α -carbethoxy-

*These compounds were kindly supplied by W. Mock.

β -ketotrimethylene)ferrocene and their enol acetates)*, the relative intensities of the two peaks were reversed. While insufficient data are available to draw any very useful conclusions, it appears quite possible that there is interaction between the metal and the unsaturated grouping.

An attempt was made to determine the keto-enol equilibrium constant of 1,1'-(α -carbomethoxy- β -ketotrimethylene)ferrocene by comparison of its spectrum with that of its enol acetate. However, any specific enol acetate absorption was sufficiently masked by the ferrocene end absorption that no conclusion could be drawn.

Ultraviolet spectra of three carbomethoxyferrocenes are summarized in Table XIX. The reduced intensity of the 215 μ band of the hydroxy ester may be due to partial loss of coplanarity of the ester function with the ring due to hydrogen bonding.

Table XIX

Ultraviolet Spectra of Carbomethoxyferrocenes										
Compound	λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ	λ_{\max}	ϵ
Carbomethoxy-ferrocene	213	34,000	264	4500	304	960	^b (335 290)	453	196	
Methyl(1'-carbomethoxy-ferrocenyl)-carbinol	215	28,000	264.5	4600	307	1040	^b (337 345)	444	220	
same, acetate	214	34,000	^b (260 5000)		302	900	^b (334 275)	442	202	

^aSpectra determined on a Cary recording ultraviolet spectrophotometer in carbon disulfide.

^bShoulder

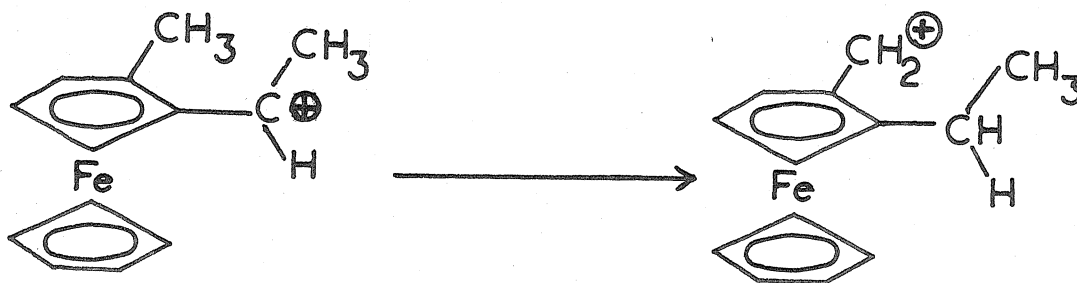
*This compound was kindly supplied by W. Mock.

6. Nuclear Magnetic Resonance Spectra

Substituted ferrocenylcarbinyl acetates. - Reduction of a 2-acylalkylferrocene leads to a pair of isomeric alcohols, which in this work were converted to the corresponding acetates. Two explanations appear reasonable for this isomerism. The more likely possibility is that the isomers are diastereomers. Any ferrocene derivative in which one ring is substituted with two unlike substituents will have optical activity. (Indeed, α -keto-1,2-tetramethylenferrocene has been resolved (122a), and the diacetylation product from 1,1'-dimethylferrocene has been separated into "meso" and "dl" forms (122b).) In addition to this asymmetric ring substitution, the carbinyl carbon is an asymmetric center, so two chemically different isomers should exist, each of which consists of a pair of enantiomers. Such isomers exist whether the substituents are situated in the 1,2- or the 1,3-position relative to each other. However, when the alkyl substituent is in the 3-position, it is sufficiently far removed from the carbinyl carbon that the isomers should differ negligibly in their chemical behavior. In the 2-position, though, an "ortho" effect should give rise to observable differences. The infrared spectra and chromatographic behavior of the alcohol pairs have already been discussed on the basis of this isomeric relationship (see p. 131), and preferred conformations for the isomeric carbinols have been suggested (XXXVII and XXXVIII).

An alternative possibility that the second isomer is formed by abstraction of a hydride from the adjacent alkyl group has not yet been excluded. This could occur through a carbonium ion intermediate

inadvertently formed during preparation of the carbinol:



In this case, there would appear to be only two isomers, provided the diastereomeric secondary alcohols and acetates showed no differences in behavior. Such a situation would agree with the chromatographic and solvolytic behavior observed, although the infrared differences might be somewhat difficult to explain.

The NMR spectra of the isomeric methyl(2-methylferrocenyl)-carbinyl acetates (fig. 8, p. 150) clearly demonstrate that the first explanation is the correct one. Both isomers show the same resonance peaks, consistent only with the unrearranged structure, although the positions differ slightly between isomers. Similar spectra were obtained for the other pairs of 2-substituted acetates.

In Table XX are listed the important peaks for a number of these acetates, along with their most reasonable assignments. The hydrogen and methyl groups attached to the carbinyl carbon of the methylcarbinyl acetates are readily recognized by their splitting into a quartet and doublet respectively. The splittings for these methyl doublets of the methyl(2-methylferrocenyl)carbinyl acetate isomers were found to be 6.1 c.p.s. by rapid substitution of a tube of ethanol, and calibration against the ethanol quartet.

TABLE XX

Nuclear Magnetic Resonance Spectra of
Substituted Ferrocenylcarbiny Acetates^a

Compound	Carbiny Hydrogen	Ring ^c Hydrogens	Ring Methyl (Homocannular)	Ring Methyl (Heterocannular)	Acetate Methyl	Trimethylene Bridge	Carbiny Methyl	Calibration ^b method
Methyl(1'-methylferro- cenyl)carbiny acetate	71	188		308	315		331	C
Methyl(2-methylferro- cenyl)carbiny acetate, slow isomer	68.3	190	320		324		351.5	B ^d
Methyl(2-methylferro- cenyl)carbiny acetate, fast isomer	62	200	316		330		338	A ^d
Methyl-3(1,1'-dimeth- ylferrocenyl)car- biny acetate	76.3	203	324	321	327		344	B
Methyl-2-(1,1'-dimeth- ylferrocenyl)car- biny acetate slow isomer	67	195	320	320	324		347	A ^d
fast isomer	c	e	316	320 or 324	327		334	C ^d
Methyl-3-(1,1'-trimeth- yleneferrocenyl)- carbiny acetate	75,77				330	330	341,344	B
Methyl-2-(1,1'-trimeth- yleneferrocenyl)- carbiny acetate slow isomer	70				321		353	A
fast isomer	65				328		339	A
α -Acetoxy-1,2-tetra- methyleneferrocene endo (slow) isomer	98.6	189			320			B
exo (fast) isomer	58	197			328			A

TABLE XX, (cont.)

^aSpectra were taken by Dr. P. R. Shafer and Mr. D. Davis using a Varian Associates nuclear magnetic resonance spectrophotometer with a super-stabilizer. All spectra were taken at 60 mc. in benzene solvent (this solvent permitted resolution of peaks which fell at the same place in carbon tetrachloride).

^bResonance positions are reported in cycles per second upfield from the solvent benzene. Three methods of calibration were used: A. Calibration against side-bands at 125, 260, and 380 c.p.s. from benzene. The maximum variation observed within a spectrum was about 1%. B. Calibration against the separation between benzene solvent and added tetramethylsilane. The maximum deviation found from the average separation was 4%. C. Calibration relative to benzene assuming the average scale found in B. Probable errors for the three methods are as follows: A, 1 c.p.s.; B, 2%; C, 4%. While actual resonance positions found by B and C may be considerably in error, differences between fairly closely-spaced peaks should be as good as those found by A.

^cPosition reported for strong sharp resonance probably corresponding to ring not bearing carbinyl substituent.

^dRelative positions of methyl hydrogens determined in a mixture with isomer, so comparison between the two isomers is accurate to about 1 c.p.s.

^eNot determined, since spectrum was run on mixture.

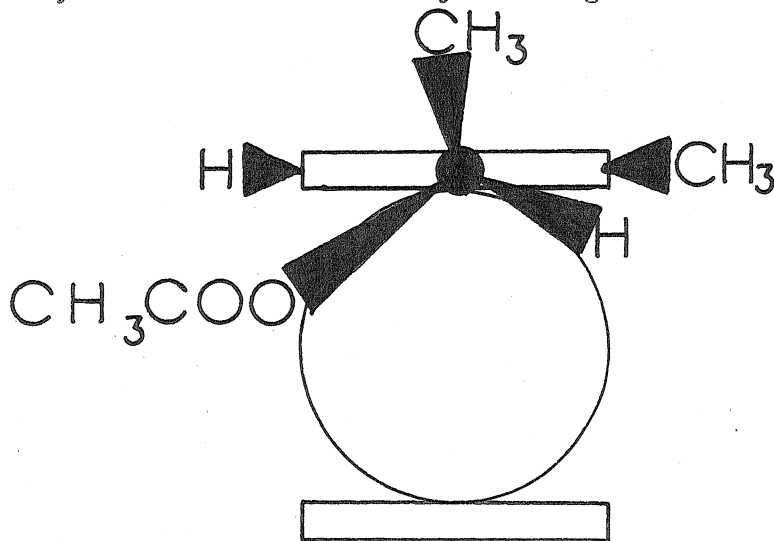
The splitting was the same within the limit of measurement (~ 0.5 c.p.s.) for all of the other methylcarbonyl acetates. Good spectra of the quartets were somewhat more difficult to obtain, since they frequently fell close to the ^{13}C satellite of the solvent benzene, and since many of the spectra were taken with fairly dilute solutions. However, in all cases, this splitting was of the same magnitude. In the spectra of the α -acetoxy-1,2-tetramethyleneferrocenes, the expected triplet had a splitting of about 5 c.p.s. Other hydrogens on the saturated ring were sufficiently split that no further deductions could be made about them.

The acetate and ring methyl groups are somewhat more difficult to assign. The peak to higher field is tentatively assigned to the acetate methyl because the acetate absorptions for the isomers of α -acetoxy-1,2-tetramethyleneferrocene and methyl-2-(1,1'-trimethyleneferrocenyl)carbonyl acetate appear at the same place and respond similarly to changes in the configuration about the carbonyl carbon. Assignment of the ring methyls as homoannular or heteroannular in the three compounds with both types of methyl groups was made primarily by analogy with the relative methyl group positions of the other compounds. A trimethylene bridge gives rise to a fairly complex spectrum when there is a substituent adjacent to it, but otherwise it appears as a sharp singlet.

Very little was done to interpret the splitting and position of the ring protons. Generally, the ring bearing the carbonyl carbon exhibited considerable splitting, while an unsubstituted ring or a ring with only methyl substitution appeared as a sharp singlet. In

such cases, the absorption due to that ring is recorded in the table.

Despite the rather questionable assignments for the methyl hydrogens, some further points of interest may be noted. In the two isomers of α -acetoxy-1,2-tetramethyleneferrocene, the endo compound has its acetate methyl resonance at lower field and its carbinyll hydrogen resonance at higher field than the exo isomer. These shifts are probably the resultant of the ring current fields of the two rings, along with effects due to different proximity to the iron and to the second ring. The effect upon the acetate resonance is smaller, since its methyl group will be quite far from the metallocene nucleus most of the time. These same shifts carry over to the open-chain compounds, and, in addition, a consistent shift appears for the carbinyll methyl group resonance. It is therefore likely that the acetate is in a predominantly endo conformation in all of the slow isomers, and is predominantly exo in the fast isomers. Examples of possible conformations are illustrated in XIII to XVI (see p. 49), and in a similar illustration below. Of course, other conformations may make significant contributions,



but placement of the acetate and methyl groups on the side away from the ring substituent probably determines the average conformation of the molecule.

From a picture such as this, shifts of the carbonyl hydrogens are predicted to be smaller in the open-chain compounds, since their average positions are closer to the plane of the ring. The hydrogens on the far ring and the homoannular methyl groups also exhibit shifts between isomers, which are probably due to proximity of the carbonyl substituents to the other ring.

Ring tilting in 1,1'-trimethyleneferrocenes. - Rinehart and co-workers (167) have reported evidence from NMR spectra which indicates tilting of the rings in a ferrocene derivative in which the rings are spanned by a two-carbon bridge. While the ring protons of a simple alkyl-substituted ring appear as a single sharp peak, in this derivative they appear as two triplets. This difference is considered due to the fact that with tilting, the hydrogens in the 2-position relative to the bridge are closer to the iron, and appear at higher field. It is also reported that the ring protons of 1,1'-trimethyleneferrocene are not split, but appear as a single peak. In this research, however, the spectrum of 1,1'-trimethyleneferrocene in benzene showed that the ring protons were split into a pair of unsymmetrical triplets separated by about 10 c.p.s., and with splittings of about 2 c.p.s. within the triplets. This spectrum is very similar to that of the protons on the substituted ring of acetylferrocene, in which the triplets are separated by about 31 c.p.s. In all spectra of other substituted trimethyleneferrocenes, the ring protons show considerable splitting.

The interpretation given by Rinehart for such a shift of the ring protons can be amplified to include the effect of the ring-current field (182). In ferrocene itself, all ring protons are in equivalent positions in the field of the other ring. However, as may be seen from fig. 7a, p. 149, tilting removes that equivalence, and thus subjects protons in the 2- and 3-positions to different resultant fields. This effect will be quite important also for substituents attached to the 2- and 3-positions of the bridged ferrocene.

A spectrum which provides further support for this ring tilting is that of methyl-3-(1,1'-trimethyleneferrocenyl)carbonyl acetate (fig. 8e, p. 151). The hydrogen attached to the carbonyl carbon is not simply a quartet. Instead, there are two quartets, shifted from each other by about 3 c.p.s. The methyl doublet shows similar doubling with a shift of about 2 c.p.s.

This spectrum is explicable on the basis of ring tilting. A substituent in the 3-position is generally far enough removed that its effect upon the properties of the diastereomeric alcohols or acetates is negligible. This is because the immediate environment of the carbonyl carbon has essentially a plane of symmetry. However, when the rings are tilted, a slight element of asymmetry is introduced in the vicinity of the carbonyl carbon. To one side, the rings are further apart, and very possibly the iron has shifted slightly to one side. Probably more important for the NMR spectrum, the field due to the π -electron system of the other ring no longer possesses symmetry in this region. A hydrogen of each isomer will see a certain field averaged over all of its conformations. If there

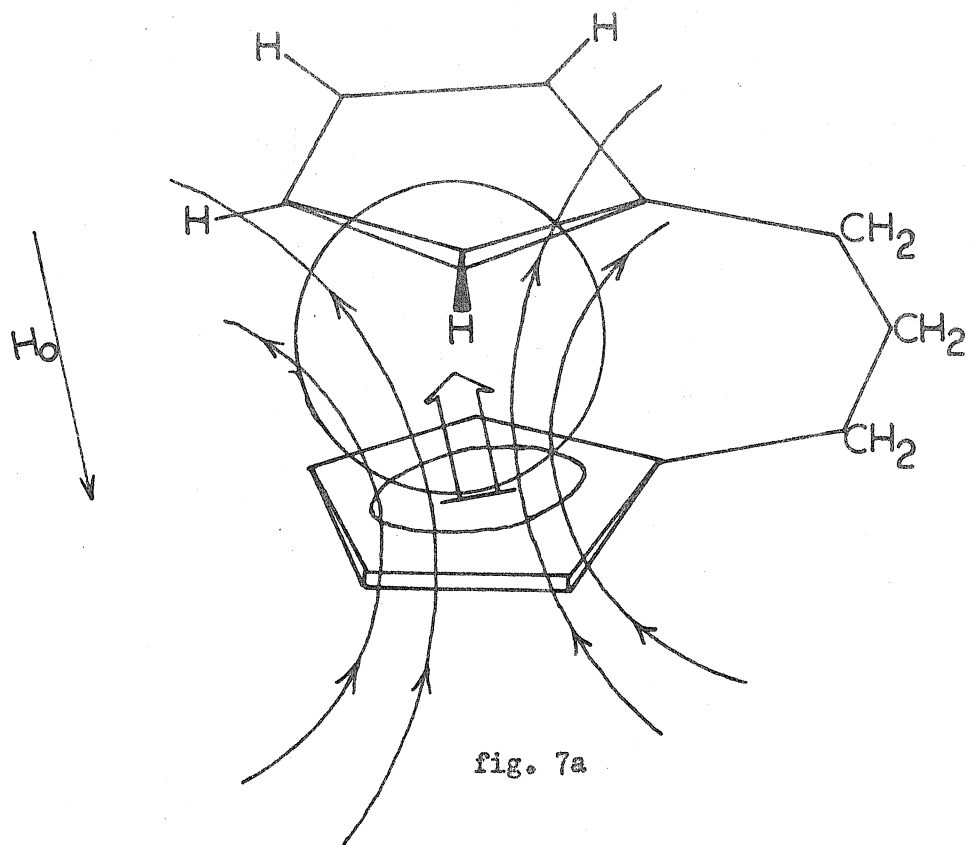


fig. 7a

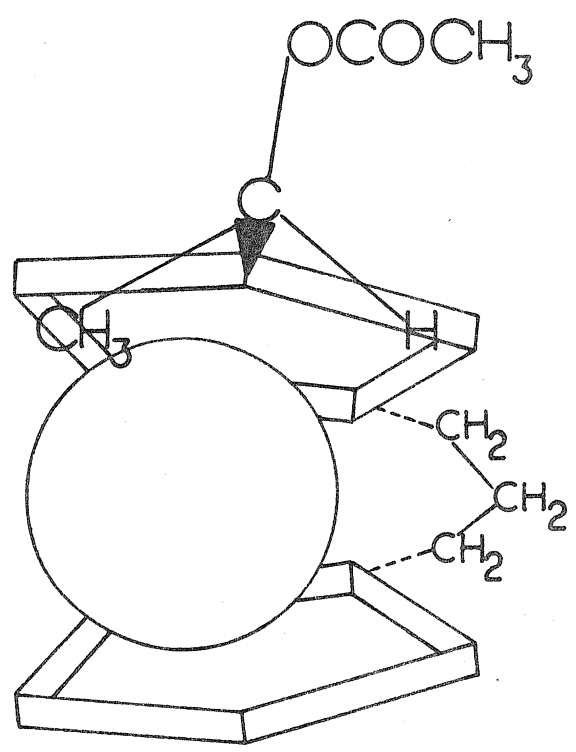
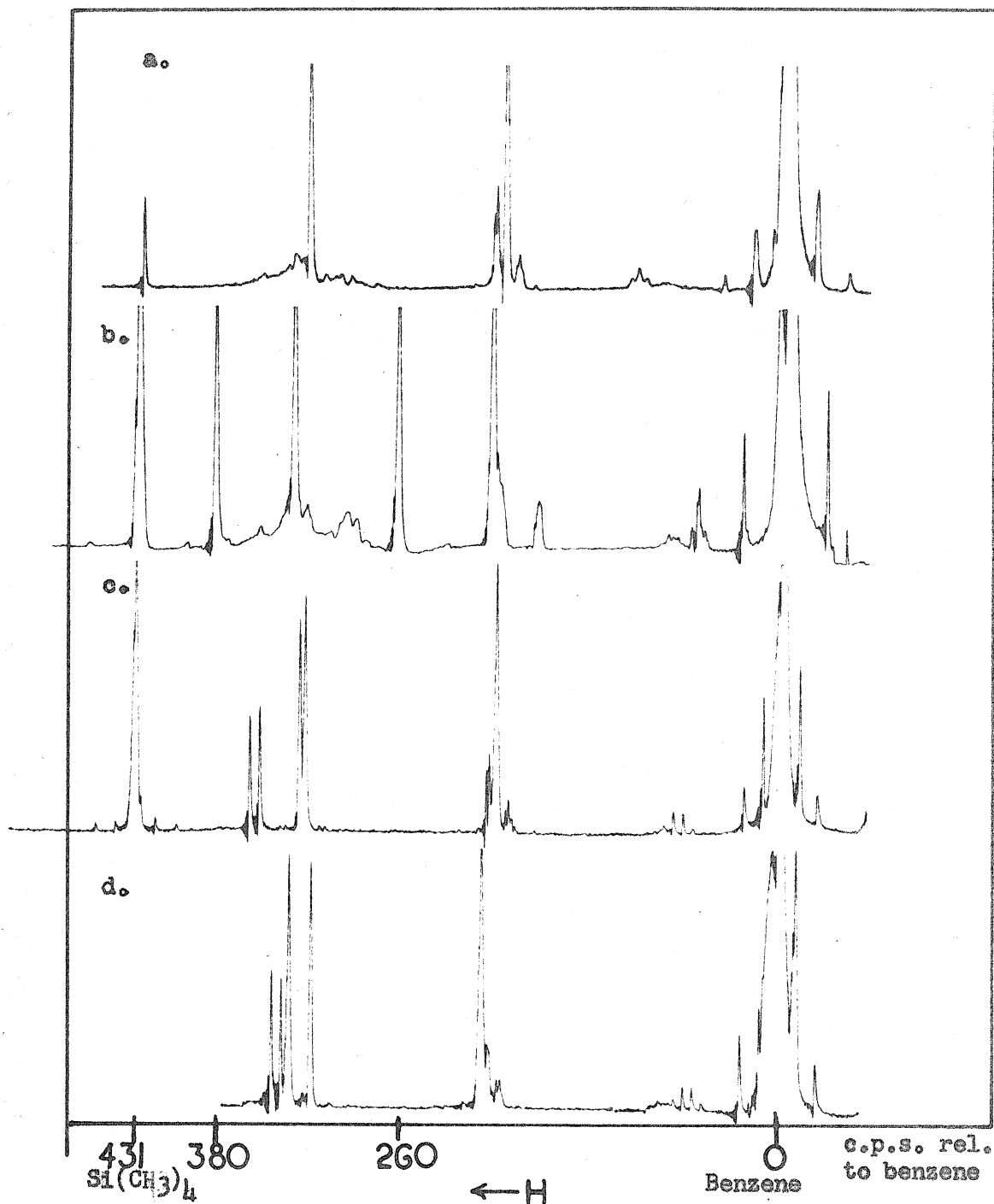


fig. 7b

fig. 8

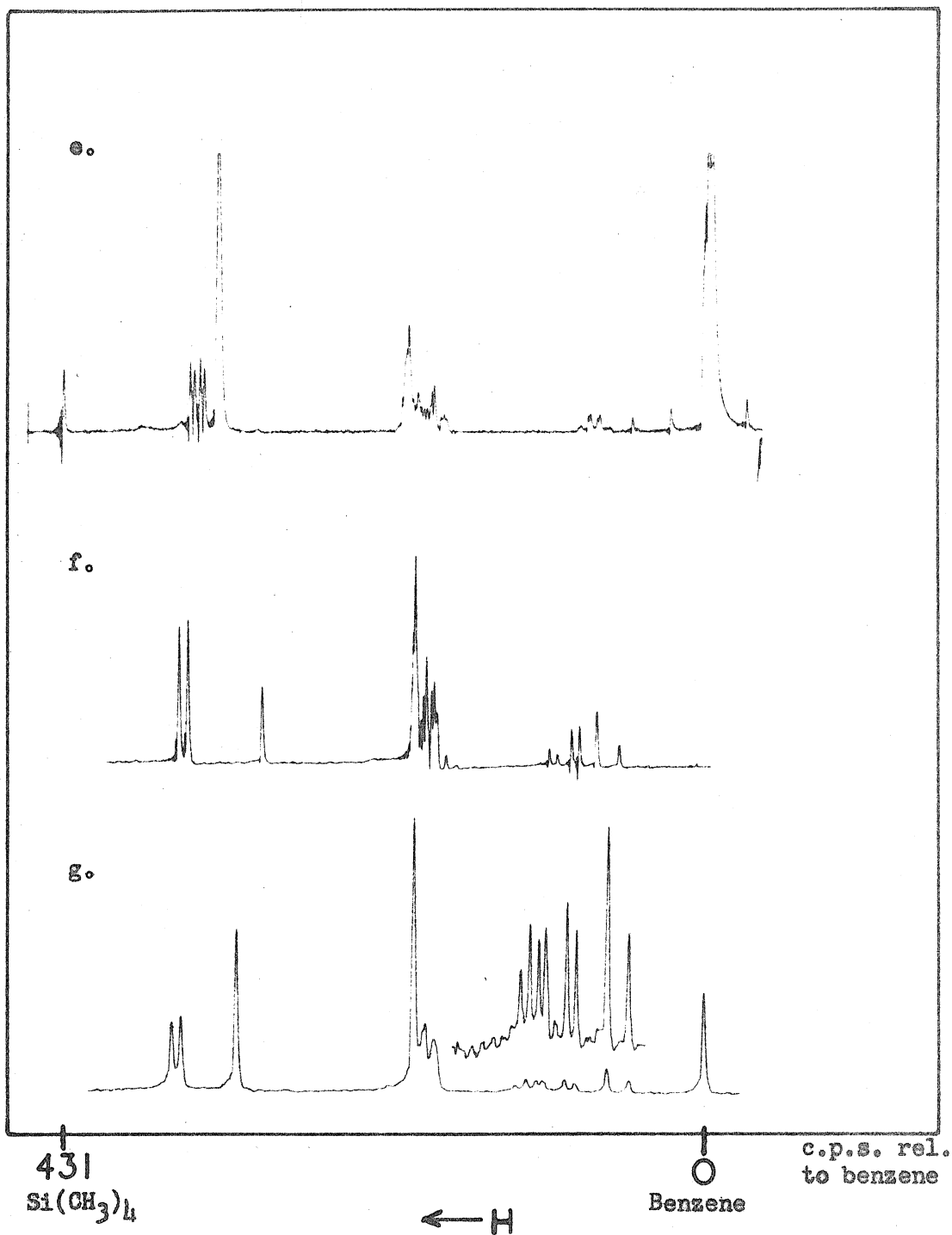
Nuclear magnetic resonance spectra



- a. endo- α -acetoxy-1,2-tetramethyleneferrocene in benzene
- b. exo- α -acetoxy-1,2-tetramethyleneferrocene in benzene
- c. methyl(2-methylferrocenyl)carbonyl acetate, slow isomer, in benzene
- d. methyl(2-methylferrocenyl)carbonyl acetate, fast isomer, in benzene

fig. 8, cont.

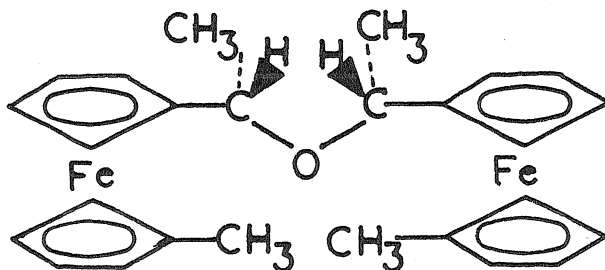
Nuclear magnetic resonance spectra



- e. Methyl-3-(1,1'-trimethyleneferrocenyl)carbinyl acetate in benzene
- f. Methyl(2-ferrocenylvinyl)carbinol in CS_2
- g. Methyl(2-ferrocenylvinyl)carbinyl acetate in CS_2 (trace of benzene)

were completely free rotation about the bond to the ring, or if all conformations had equal weight, then the average fields seen by hydrogens of the two isomers would be equal. However, if all conformations are not of equal weight, then different average fields will be seen by the hydrogens of the two isomers, and a spectrum such as that observed would be expected. This argument does not require that the conformational equilibrium differ between the isomers. The small splitting observed indicates that the effect is quite small. The lack of splitting of the acetate methyl is probably due to its greater distance from the nucleus.

Other NMR spectra. - The spectrum of the ether of methyl(1'-methylferrocenyl)carbinol presents another demonstration of asymmetry at the carbinyl carbon. Since there are two asymmetric carbon atoms, there will be isomers which may be called "meso" and



XXXIX

"dl", one of which is illustrated (XXXIX). In the spectrum of this compound, the carbinyl hydrogen appears to be a simple quartet. However, the doublet due to the carbinyl methyl and the singlet due to the ring methyl both appear double due to absorption by two isomers,

with separations of 4 and 2.2 cycles respectively. The surprisingly large effect on the heteroannular methyl group may be due to the ring current field from the other ferrocene nucleus.

Rotation about the bond between the cationic center and the ferrocene nucleus in an α -ferrocenylcarbonium ion is very highly hindered (see p. 58). This is probably a consequence of conjugation with the ring and bonding of the iron. Since acetylferrocene also contains a somewhat electron-deficient center adjacent to the ring, it is conceivable that the same forces which prevent rotation in the carbonium ion might hinder rotation here also. However, a spectrum of 2-acetylmethylferrocene showed only single sharp peaks for the acetyl and ring methyls. Similarly, 2-acetyl-1,1'-trimethyleneferrocene shows only a single peak for the acetyl methyl. Either rotation around the acetyl-ring bond is quite facile, or else rotation is hindered, but only one conformation exists in appreciable concentration in the equilibrium.

CHAPTER III

EXPERIMENTAL

All melting points are uncorrected. Analyses were performed by A. Elek, Los Angeles, Calif. (E), and by Schwartzkopf Micro-analytical Laboratories, Woodside, N. Y. (S).

A general consideration of the spectra of ferrocene derivatives is included in Part B of the Discussion. Therefore, spectral evidence will be mentioned only in connection with compounds whose structure is not quite satisfactorily determined by the method of preparation, and other spectra should be assumed consistent with the assigned structures.

Ferrocene was in part donated by the E. I. DuPont de Nemours Company, in part prepared by the procedure of Wilkinson (183), and in part obtained commercially.

Acetylferrocene was prepared by acetylation of ferrocene with acetic anhydride and boron trifluoride according to the procedure of Hauser and Lindsay (4). In contrast to the original report, however, considerable diacetylation occurred when a molar excess of acetic anhydride was used. When an equimolar quantity of this reagent was employed, acetylferrocene was obtained in yields of about 85% in a number of runs (m.p. and lit. m.p. 85-86°).

Ferrocenecarboxaldehyde was prepared by formylation of ferrocene with N-methylformanilide, catalyzed by phosphorous oxychloride. The variations reported by Graham and co-workers (7) and by Pauson and co-workers (3) were both utilized. In all cases, there was some difficulty in extricating the product by the methods reported, but satis-

factory results were obtained by purification through the bisulfite addition compound (7) as indicated by Rosenblum (48), m.p. 121-122° (lit. m.p. 119-20°, 121°, 124.5° (3,7,48)).

Ferrocenecarboxylic acid was prepared by oxidation of acetylferrocene with iodine in pyridine according to the procedure of Weinmayr (184). Yields in two runs were 50 and 52% of crude product, or on the basis of unrecovered starting material, 59%.

Carbomethoxyferrocene. - Crude ferrocenecarboxylic acid was esterified by refluxing with methanol and sulfuric acid (185). (Repeated filtration to remove tarry solid material greatly facilitated the separation of emulsions during extractions and washings.) Recrystallization of the product from hexane yielded about 85% of orange crystalline product, m.p. 70.5-71° (lit. m.p. 70-71° (185)).

Methylferrocene. - Nesmeyanov and co-workers (186) report the preparation of methylferrocene by reduction of ferrocenecarboxaldehyde, or reduction of ferrocenecarboxylic acid or its methyl ester with an excess of lithium aluminum hydride. However, when this was attempted, only ferrocenylcarbinol and bis-ferrocenylcarbinyl ether were isolated. Reference to the translation of the original article confirmed the suspicion that the lithium aluminum hydride had been prepared in situ from lithium hydride and aluminum bromide.

Carbomethoxyferrocene was treated by the mildest of the three procedures developed by Nystrom and Berger (187) for reduction with a mixture of lithium aluminum hydride and aluminum chloride. This produced methylferrocene in 28% yield, along with some apparently polymeric by-product. A small-scale reduction by the second procedure of Nystrom and Berger provided methylferrocene in 87% yield, and so

was repeated on a larger scale.

Lithium aluminum hydride (4.45 g., 117 mmole.) in anhydrous ether (300 ml.) was placed in a two-liter flask equipped with a Hershberg stirrer, a reflux condenser, and an additional funnel, and provided with a nitrogen atmosphere. Aluminum chloride (14.95 g., 112 mmole.) in 300 ml. of ether was added with stirring over a period of two minutes. After 5 min., carbomethoxyferrocene (18.0 g., 73.8 mmole.) in 300 ml. of ether was added at such a rate as to maintain gentle reflux (ca. 15 min.). When the addition was completed, the mixture was refluxed for 90 min. Ethyl acetate (20 ml.) followed by water (40 ml.) was added dropwise to decompose the excess hydride, the solution was filtered through celite, and the residue was washed with ether. The ether solution was washed twice with water and once with a solution of ascorbic acid in water, and the solvent was distilled, yielding a red-orange oil. This was chromatographed on 500 g. of neutral alumina with hexane-benzene (10 to 25% benzene). Removal of the solvent produced a red-orange oil which crystallized on cooling to -5° . The product consisted of 14.03 g. (95%) of soft orange crystals, m.p. $37.5-38.5^{\circ}$.

Methylacetylferrocenes. - Methylferrocene (13.0 g., 65 mmole.) and acetic anhydride (6.62 g., 64.8 mmole.) were dissolved in methylene chloride (150 ml.) in a 200 ml. flask equipped with a stirrer and a gas bubbling tube. The reaction mixture was cooled to 0° and saturated with boron trifluoride. Stirring was continued for 1.25 hrs. at 0° , and the mixture was then allowed to warm to room temperature over a period of 2.75 hrs. The reaction mixture was poured into an excess of aqueous sodium acetate, sufficient ascorbic acid was

added to reduce the ferricinium ion, and the aqueous phase was extracted several times with methylene chloride. The organic layer was washed twice with saturated aqueous sodium bicarbonate and dried over magnesium sulfate. Removal of the solvent yielded a red-brown oil which was dissolved in benzene-hexane and chromatographed on 1220 g. of acid-washed alumina (52 x 5.5 cm. column). A yellow band containing the starting material (0.80 g., 6.1%, m.p. 36-37.5°) was eluted in fraction 1 with about 1.1 l. of benzene-hexane. Development and elution of the monoacetylated products were carried out with benzene-ether mixtures. A faster-moving band of light orange partially separated from the major orange band, but no visible resolution of the larger band appeared to occur. The product was collected in 25 fractions as indicated in Table I.

The solid fractions and their neighboring semisolid fractions were worked up by a number of crystallizations to yield pure products. In this work-up, the products from a small-scale trial run were also included. Thus, for example, cuts 2 and 3 were recrystallized from hexane to yield 1.013 g., m.p. 62.2-63.2°. Cut 4, along with a fraction of similar purity from the trial run, was recrystallized from liquors from the previous crystallization to yield 0.515 g., m.p. 59.5-61.5°. In a similar fashion, those fractions rich in the second and third acetylated components were treated to produce as much pure product as possible.

Several further chromatograms were performed on portions of the liquors and liquid fractions which were expected to be particularly rich in one or two of the isomers. The chromatographic procedure was varied by using neutral alumina, and by trying as eluent mixtures

TABLE I

Chromatography of Methylacetylferrocenes

<u>Fraction</u>	<u>^bVolume</u>	<u>% Ether in solvent</u>	<u>bwt. of product</u>	<u>Physical state or melting point</u>
1	1000 ml.	a	0.800	methylferrocene, 36-37.5°
2	2000	0.2	0.830	58.5-61.5°
3	1000	0.2	0.521	59-61°
4	900	0.2	0.454	gummy solid
5	900	0.2	0.410	semisolid
6	900	0.2	0.452	semisolid
7	1700	0.4	0.898	liquid at -5°
8	900	0.4-0.6	0.473	semisolid, m.p. 35°
9	1400	0.8-1.0	0.795	semisolid, m.p. 35°
10	1600	1.0-1.2	0.757	36-42°
11	900	1.2-1.4	0.678	39.5-41°
12	900	1.4-1.6	0.594	39.5-40.5°
13	1000	1.6	0.618	semisolid
14	900	1.6	0.484	semisolid
15	1000	1.6	0.473	liquid at -5°
16	1700	1.6	0.738	semisolid at -5°
17	900	1.8	0.364	semisolid at -5°
18	900	2.0	0.337	semisolid at -5°
19	1500	2.2-2.8	0.552	semisolid
20	900	3.5-5.5	0.314	semisolid
21	1700	6.5-10.0	0.711	semisolid
22	1600	15	0.729	49-58°
23	1500	15-20	0.797	57-61.5°
24	500	20	0.262	54-62°
25		a	-----	tar

Total ketone, 13.34 g. (90.5% based on unrecovered starting material)

^aFraction 1 was eluted with hexane-benzene mixture; fraction 25 was a methanol extract of the lower portion of the column.

^bSince the eluent composition was varied irregularly, analysis of the chromatogram by determining the weight of material per unit volume of solvent is not valid.

TABLE II

Acetylmethylferrocenes

Product	Position on Column	M.p., °C.	Wt., g.	Analysis. Calc'd for			
				C	H	Fe	
2-Acetylmethylferrocene	1	62.2-63.2	1.593	C ₁₃ H ₁₄ OFe: C, 64.55; H, 5.83; Fe, 23.04.			
				Found:	64.66	5.72	23.34
		59.5-61.5	0.659 2.252 g.				
1'-Acetylmethylferrocene	2	42.7-43.2	2.068	64.70	5.84	23.20	
				42.2-43.0	2.279 4.347 g.		
3-Acetylmethylferrocene	3	57.5-61.5°	1.085	64.61	5.92	23.22	
				56-60°	0.840		
				53-59°	0.292 2.217 g.		

benzene-chloroform, hexane-ether, hexane-chloroform, and hexane-benzene-chloroform. There may have been some improvement in the separation due to these variations, but it was not so significant as to have been readily obvious.

The structures of the isomers were assigned on the basis of spectral evidence discussed elsewhere and the relative positions of the isomers on the chromatographic column. These assignments are listed in Table II, along with the yields, melting points, and analytical data for each isomer. The 1,2 - and 1,1' - isomers crystallized well as dense prisms and needles respectively with sharp melting points. However, the smallest melting range that could be obtained for the 1,3 - isomer was 57.5-61.5° after sublimation and several recrystallizations from hexane.

The combined yield of purified monoacetylated material from both runs is 8.816 g. (52.4%; or on the basis of unrecovered methylferrocene, 55.8%).

A mixture of ferrocene-1,1'-dicarboxylic acid and 1'-acetylferrocenecarboxylic acid was prepared by the procedure of Rosenblum (45) in 77% yield of crude mixed acids. The mixture was esterified with methanol and sulfuric acid and separated chromatographically to yield 1,1'-dicarbomethoxyferrocene (59% overall; m.p. 113.7-114.5°, lit. m.p. 114-115° (37a)) and 1'-carbomethoxyacetylferrocene (6.5% overall, m.p. 100-101°, lit. m.p. 102-103° (45)).

1,1'-Dimethylferrocene. - Aluminum chloride (8.50 g., 64 mmole.) in ether (150 ml.) was added under nitrogen over a period of 3 min. to a stirred suspension of lithium aluminum hydride (2.50 g., 66 mmole.) in ether (250 ml.) in a 1 l. flask equipped in the customary

manner. After 5 min. stirring, dicarbomethoxyferrocene (6.38 g., 21.1 mmole.) was added. The diester proved insufficiently soluble in ether to add in a convenient volume, so part was added as a solid. The mixture was refluxed for 40 min. in addition to the 30 min. required to add the ester. Ethyl acetate (20 ml.) and water (20 ml.) were added over a period of 30 min., the reaction mixture was filtered through celite, and the ether was distilled to yield an orange oil. This was chromatographed on 250 g. of alumina with a 50-50 mixture of hexane and benzene. The major product band was rapidly eluted, and the solvent was removed to yield 3.13 g. (69%) of orange solid, m.p. 39-40.5° (lit. m.p. 32.5-33° (186b)).

A large number of other bands appeared in the chromatogram indicating several side products. None of these bands was isolated except for 0.2 g. of starting material, m.p. 110°.

Acetyldimethylferrocenes. - A solution of dimethylferrocene (3.11 g., 14.6 mmole.) and acetic anhydride (1.50 g., .0147 mole) in methylene chloride (90 ml.) was saturated with boron trifluoride at 0°. The mixture warmed to room temperature during a 3.5 hr. period of stirring. The reaction mixture was decomposed and a non-crystalline red-orange oil was isolated by the usual extraction procedure (see procedure for acetylation of methylferrocene).

The product mixture was chromatographed on neutral alumina with benzene. A fast-moving yellow band of starting material separated readily, and two orange bands of mono-acetylated material were partly resolved. After part of the first product had been eluted, the column was cut into sections, and the alumina was extracted with methanol.

Fraction	Band	Solvent	Wt., g.	Physical State
1	I	benzene	.490	partly crystalline
2	II	benzene	.474	partly crystalline at 0°
3	II	benzene	.370	liquid
4	II	methanol	.211	liquid
5	II, III	methanol	----	liquid
6	III	methanol	1.469	m.p. 50.7-52°

Fraction I was crystallized from methanol to yield .304 g. (9.8%) of dimethylferrocene, m.p. 38.7-40.5°. Fractions 2-4 yielded three crops of material on crystallization from pentane which totaled 0.77 g. (20.6%). All melted over 1 to 1.5° ranges in the vicinity of 25-26°. Fraction 6 was crystallized from hexane to yield 1.26 g. (33.8%), m.p. 51.7-53°. Liquors from the crystallizations were combined with fraction 5 and chromatographed to obtain additional quantities of the products. Acid-washed alumina produced complete separation when graded benzene-ether mixtures were used as eluents. The same products have been prepared from acetylation with acetyl chloride and aluminum chloride by Rinehart, Motz and Moon (44), who have assigned the structures 2-acetyl-1,1'-dimethylferrocene and 3-acetyl-1,1'-dimethylferrocene respectively (lit. m.p.'s 15-16° and 48.6° (44)).

Ferrocenylmethyltrimethylammonium iodide was prepared by aminomethylation of ferrocene followed by direct quaternization with methyl iodide as described by Osgerby and Pauson (27). Two runs provided yields of 58 and 72%.

β-Ferrocenylpropionic acid was prepared by two procedures.

A. The reaction of ferrocenylmethyltrimethylammonium iodide with

the sodium enolate of malonic ester produced the corresponding substituted malonic ester. This was directly hydrolyzed and decarboxylated to ferrocenylpropionic acid (as described by Osgerby and Pauson (27)) in an overall yield of about 30%, m.p. 116-118° (lit. m.p. 115° (27)).

Neut. equiv. Calcd. for $C_{13}H_{14}O_2Fe$: 259. Found: 262, 264.

B. In the second route, carbethoxylation of acetylferrocene catalyzed by sodium or potassium amides (4,188) yielded ethyl ferrocenylacetate. The crude keto ester was hydrogenated in acetic acid over Adams catalyst and hydrolyzed with sodium hydroxide (188) to produce the desired acid in about 38% overall yield from acetylferrocene, m.p. 118-119°.

α -Keto-1,1'-trimethyleneferrocene. - Trifluoroacetic anhydride (73 g., 350 mmole.) was added to 250 ml. of carbon tetrachloride (previously bubbled out with nitrogen for about 10 min.) in a 500 ml. round-bottomed flask wrapped in foil. β -Ferrocenylpropionic acid (7.38 g., 28.6 mmole.) was introduced under a stream of nitrogen, and the reaction mixture was allowed to stand at room temperature (30-35°) with occasional swirling for four hours. The contents of the flask were poured into a suspension of 70 g. (0.83 mole) of sodium bicarbonate in 150 ml. of water, and the aqueous layer was extracted with portions of methylene chloride until the extracts were nearly colorless. After the organic phase had been washed with saturated sodium bicarbonate solution and water and dried over magnesium sulfate, the solvent was evaporated to yield a dirty red-orange solid. This was chromatographed on 400 g. of alumina with ether-benzene mixtures (1 to 5% ether). After sufficient separation had occurred,

the column was extruded. The product band was separated and extracted with acetone, and the solvent was removed at reduced pressure to yield a solid, m.p. 143-144°. Crystallization from heptane produced 4.72 g. of orange rods, m.p. 144.5-145.5 (lit. m.p. 144-144.5° (181)).

Acidification of the aqueous phase with concentrated hydrochloric acid precipitated 1.10 g. (15%) of starting material, m.p. 117-118.5°. The yield of bridged ketone was 69%, or 81% on the basis of unrecovered starting material.

An earlier run with no solvent produced a 66% yield from 3.0 g. of β -ferrocenylpropionic acid and 100 g. of trifluoroacetic anhydride (181). Only starting material was recovered when the reaction was attempted in ether. Later runs showed that the temperature and reaction time used are the minimum for good conversion to ketone.

1,1'-Trimethyleneferrocene. - α -Keto-1,1'-trimethyleneferrocene (5.23 g., 21.9 mmole.) was hydrogenated over platinum oxide catalyst at 2-2.5 atm. in 150 ml. of glacial acetic acid. A total of 1.13 g. of catalyst in two portions was required to bring about consumption of the theoretical quantity of hydrogen in a period of 22.5 hrs. The catalyst was removed by filtration, and some of the solvent was distilled until a yellow solid had begun to precipitate. The mixture was added to an excess of sodium bicarbonate solution, and the product was extracted with petroleum ether. This extract was dried and chromatographed on 215 g. of neutral alumina. Elution of the major yellow product band with benzene-hexane (20-80) and removal of the solvent yielded 4.45 g. (90.5%) of yellow plates, m.p. 106-107°. Successive recrystallizations from hexane and methanol raised the melting point to 106.7-107.2° (lit. m.p. 106-107° (189), 105-106° (190)).

Anal. Calcd. for $C_{13}H_{14}Fe$: C, 69.06; H, 6.24; Fe, 24.70. Found (S): C, 68.90; H, 6.39; Fe, 24.71.

Mol. wt. Calcd: 226. Found (S): 676 (Rast, in camphor), 237 (isothermal distillation).

Acetyl-1,1'-trimethyleneferrocenes. - Several small-scale acetylations were first performed to determine the procedure which produces the best yield.

Acetylation with acetic anhydride-phosphoric acid (7) resulted in considerable tar-formation. Chromatography produced crude fractions melting at 70-75° and 91-99°. These were worked up further with products from the large-scale preparative run.

Silicon tetraacetate - stannic chloride (10) also resulted in some tar-formation, along with considerable diacetylation. The following materials were isolated by chromatography of the product from 1.0 g. of trimethyleneferrocene on 100 g. of acid-washed alumina with ether-benzene mixtures:

Band	Fraction	Elution Solvent (% Ether)	Wt., g.	%	Melting point
I	1	0	.098	9.8	99-104°
II	2	1.5	.14	11.8	69-76°
III	3	8	.14	11.8	81-91°
	4		.36	30.4	99.5-101°
IV	5	20	.12	9.9	viscous oil
V	6	25	.03	2.2	viscous oil
VI	7	35-40	.07	5.1	viscous oil

Band I consisted of starting material. Fractions 2 and 3 were purified further by rechromatography and crystallization from hexane

to yield .080 g., m.p. 76.7-78.5° and .081 g., m.p. 98.5-100.5° respectively. The total yields of fairly pure material from bands II and III were .08 g. (6.8%) and .44 g. (37.4%). Bands IV, V, and VI were probably diacetylated isomers. They could not be crystallized, and were not further characterized.

Acetic anhydride - boron trifluoride produced the best results on a small scale. After chromatography on neutral alumina and sublimation, the following products were obtained from 1.0 g. trimethyleneferrocene:

Band	Fraction	Before sublimation		After sublimation ^b		
		Wt., g.	M.p., °C.	Wt., g.	%	M.p., °C.
I	1	.032	102-106			
I	2 ^a	.072	104-106			
II	3	.191	74.7-77	.118	10	76-77.7
II	4 ^c			.084	7.1	68-74
III	5 ^c		99-100.5	.557	47.1	98.7-100.5
				.035	3.0	86-94
III	6 ^c	.084	88-95	.068	5.7	95-99

^aRecovered by reduction of ferricinium ion with ascorbic acid.

^bSublimation of the crude fractions was complicated by the simultaneous molecular distillation of an oil.

^cWashed from segments of extruded column with acetone.

The fractions were purified further with the products from the large-scale run. The yields here are 17.1% of band II and 55.8% of band III. When recovered starting material is taken into account, the total yield is 81% of mono-acetylated product.

1,1'-trimethyleneferrocene was acetylated on a 5.65 g. (25 mmole.) scale by the usual procedure with acetic anhydride - boron

trifluoride (4). Chromatography on neutral alumina (600 g.) produced the following products:

Band	Fraction	Wt., g.	Melting point
I	1	0.6	103.5-106°
II	2	0.311	70.5-75°
II	3	0.870	75-77.5°
II	4	0.348	74-76.5°
II	5 ^a	0.208	partly crystalline oil
III	6 ^a	3.693	100-100.7°
III	7 ^a	0.420	98.7-100°

^aWashed from portions of extruded column with methanol and chloroform.

The starting material (band I) was sublimed to yield 0.62 g. (11%), m.p. 104.5-106°. The materials in bands II and III were worked up further in conjunction with materials from the previous three runs which appeared to be of about the same purity. Recrystallizations, sublimations, and rechromatograms of liquors were employed. On the basis of spectral evidence and the relative position of the isomers in chromatography, the structures 2-acetyl- and 3-acetyl-1,1'-trimethyleneferrocene are assigned to the products of bands II and III. The total product from all four runs is tabulated in Table III along with the appropriate melting points of fractions and analyses.

1-Acetyl-1'-carbomethoxyferrocene. - Nesmeyanov and Reutov (112) report the acetylation of carbomethoxyferrocene in 58% yield. An attempt to follow their procedure led to a 30% yield of the desired product, along with recovery of 62% of the starting material. Since the conditions specified appeared to be rather mild, the reaction was repeated under more vigorous conditions.

TABLE III

Acetyl-1,1,1'-trimethyleneferrocenes

Product	M.P., °C.	Wt., g.	%	Analysis. Calc'd for $C_{15}H_{16}OFe$: C, 67.19; H, 6.02;		
				Fe, 20.83 Found:	C	H
2-Acetyl-1,1,1'-trimethyleneferrocene	77.5-78.5	1.603		67.48	6.27	
	74-76	<u>.041</u>				
		1.644 g.	16.1			
3-Acetyl-1,1,1'-trimethyleneferrocene	100-101	4.906		67.09	6.08	20.65
	98-100	<u>0.110</u>				
		5.016 g.	49.0			

^aPercent yield is based on an initial quantity of 8.647 g. of trimethyleneferrocene. Total yield was 65.1% of purified products.

Acetyl chloride (3.67 g., 47 mmole.) was added to a stirred suspension of powdered aluminum chloride (11.5 g., 86 mmole.) in methylene chloride (70 ml.) under nitrogen. Over a period of 10 min., carbomethoxyferrocene (8.0 g., 32.8 mmole.) in methylene chloride (80 ml.) was added. The solution warmed slightly. The reaction was stirred at room temperature for 3.25 hrs. and poured over ice. Sufficient acid was added to allow separation of the layers, and the product was extracted into methylene chloride. The combined organic phase was washed three times with sodium bicarbonate solution and once with water. After drying over magnesium sulfate, the solvent was removed to yield a dark red solid, m.p. 99-100.5°. One recrystallization from heptane produced 8.59 g. (91.5%), m.p. 101-101.7° (lit. m.p. 102-103° (45a), 92.5-94.5° (112)).

An additional small quantity of identical material was obtained as a by-product from the hypochlorite oxidation of diacetylferrocene.

Ethyl γ -ferrocenylbutyrate was prepared according to the procedure of Thompson (191) by Clemmensen reduction of crude β -ferrocenylpropionic acid (supplied by D. Garwood). γ -Ferrocenylbutyric acid was obtained by saponification of this ester.

α -Keto-1,2-tetramethyleneferrocene was prepared by cyclization of γ -ferrocenylbutyric acid with trifluoroacetic anhydride. The procedure used was identical with that described earlier for α -keto-1,1'-trimethyleneferrocene, except that the reaction time was reduced to 2.25 hrs. In a large-scale run, most of the product decomposed quite vigorously when a solution of the crude material was distilled to an oil under vacuum on a steam bath. A smaller run performed on acid (1.01 g., 3.7 mmole.) recovered unchanged from the large run produced

a yield of 0.643 g. (68%) of red solid, m.p. 83-84° (lit. m.p. 85.4-85.7° (181), 84° (192)). Recrystallization of the product from hexane raised the melting point to 85-85.5°.

Methyl (2-ferrocenylvinyl) ketone. - Ferrocenecarboxaldehyde (9.07 g., 42.3 mmole.) and acetone (25 ml., 31.6 g., 544 mmole.) were dissolved in a mixture of ethanol (40 ml.) and water (20 ml.). Sodium hydroxide solution (2.0 g., or 50 mmole. in 10 ml. water) was added, and the reaction mixture was allowed to stand for 4 hrs. at room temperature. Water was added until precipitation occurred (ca. 30 ml.), and the product was separated by filtration. A deep red crystalline product, m.p. 77.5-83°, was obtained, which weighed 9.7 g. after drying. From the liquors, an additional small amount of low-melting product was obtained. One portion of the product was recrystallized once from ethanol - water and twice from hexane to yield about 1.8 g. melting at 86-87°. One recrystallization from ethanol - water and sublimation at 65° C. and 1-2 u yielded 0.86 g. more product melting at 87.2-88°. Other portions of the product were chromatographed on neutral alumina, and eluted with 3-4% ether in benzene. Several fractions melting between 75 and 85° were collected, and were further purified by sublimation. After the product had been almost entirely eluted from the column, the alumina retained a dark brown or purple color.

Anal. Calcd. for $C_{14}H_{14}OFe$: C, 66.17; H, 5.55; Fe, 21.98. Found (S): C, 66.44; H, 5.68; Fe, 21.91.

The infrared spectrum of the product exhibits absorption at 1692, 1669 and 1630 cm^{-1} in carbon disulfide. The second and third of these may be assigned to the carbonyl and double bond stretching

modes, while the first, which is much weaker than the 1669 peak, might be due to a carbonyl group which is conjugated with the double bond, but out of conjugation with the ring due to rotation or to a cis-disposition about the double bond. The aliphatic CH stretch region showed only very weak absorption which might be attributed to the methyl group, but an inspection of spectra of several substituted acetylferrocenes showed that such absorption was often lacking there also. Absorption at 964 or 976 cm^{-1} might be attributed to the CH out-of-plane deformation on a trans-disubstituted double bond, while absorption is lacking in the 690 cm^{-1} region, which is generally assigned to the similar vibration of cis-disubstituted double bonds (168).

In the ultraviolet and visible regions, the product has λ_{max} 255 $\text{m}\mu$ (ϵ 12,300), λ_{max} 298 $\text{m}\mu$ (ϵ 16,000), λ_{max} 365 $\text{m}\mu$ (ϵ 2140), λ_{max} 467 $\text{m}\mu$ (ϵ 1200) and end absorption with an extinction coefficient of 25,000 at 210 $\text{m}\mu$ in cyclohexane solution.

The nuclear magnetic resonance (NMR) spectrum of the ketone is shown on p. 157. In addition to aromatic hydrogens, the spectrum clearly shows the methyl singlet and a quartet due to the vinyl hydrogens. The coupling constant between the vinyl hydrogens is found by calibration with sidebands to be 16 c.p.s., which is in the range to be expected for splittings by protons located trans-across a double bond (169).

On the basis of the infrared and NMR spectra, the product obtained from this reaction is assigned the structure methyl trans-2-ferrocenylvinyl ketone.

In the purification of this ketone by sublimation, a deep red-

violet solid remained behind in the bottom of the tube, m.p. 130°. In the ultraviolet and visible regions, it exhibits strong end absorption at 210 m μ , a complex peak with maxima at 249, 254 and 261 m μ , and peaks at 299 and 480 m μ . If molar extinction coefficients are calculated on the basis of the molecular weight of the major product, the extinction coefficient at 210 m μ is 40,000, and values of 8000, 9200 and 1800 respectively are obtained for the peaks. While this compound was not investigated further, it appears quite likely that it should be the product of condensation of two molecules of ferrocenecarboxaldehyde with one molecule of acetone.

Vinylferrocene was prepared by pyrolysis of methylferrocenyl-carbinyl acetate as described by Arimoto and Haven (193), and purified by sublimation and chromatography, m.p. 54 - 55° (lit. m.p. 48-49° (193)). The ultraviolet and visible spectra had λ_{\max} 446 m μ (ϵ 256), λ_{\max} 274.5 m μ (ϵ 7860), λ_{\max} 225 m μ (ϵ 23,300) and λ_{\max} 212 m μ (ϵ 24,700) in cyclohexane. (Reported spectrum: λ_{\max} 442 m μ (ϵ 1130) and λ_{\max} 273 m μ (ϵ 7640) in methanol (193)).

Osmocene. - Osmium tetrachloride was prepared in a number of small batches by passing chlorine gas over finely powdered osmium metal in a quartz tube heated to 700-750° (194). The crude, somewhat moist product which condensed beyond the heated portion of the tube was used for the reaction without further purification.

Sodium sand (3.8 g., 165 mmole.) was stirred in 75 ml. of tetrahydrofuran (purified by refluxing the commercial solvent over potassium hydroxide and distilling from lithium aluminum hydride) in a 500 ml. three-necked flask provided with a condenser, a Hershberg stirrer, a dropping funnel, and a nitrogen atmosphere. Freshly

cracked cyclopentadiene (16.1 ml., 12.8 g., 194 mmole.) was added dropwise over 15 min., and the mixture was stirred until the sodium had completely reacted (4.5 hrs.). Osmium tetrachloride (12.7 g., 0.038 mole) was added as a solid, and the reaction mixture was stirred for 5 days at room temperature. The solvent was removed under reduced pressure, and the flask was swept with nitrogen for 8 hrs. A cold-finger condenser was inserted in the flask, and the product was sublimed at 95-105° and about 1 mm. pressure. In this manner, 1.25 g. (10.4%) of pale yellow crystalline product was obtained, m.p. 227-229° (lit. m.p. 229-230° (40)). In other runs, most of which led to a lower yield, the osmocene was isolated by continuous extraction with petroleum ether of the solid residue remaining after removal of the tetrahydrofuran, followed by chromatography of the extract. (see ref. 125c).

Acetylosmocene. - Favorable experimental conditions for the acetylation of osmocene with acetic anhydride and 85% phosphoric acid were determined in several 50 mg. runs, and the major portion was acetylated by this procedure. Osmocene (0.41 g., 1.28 mmole.), acetic anhydride (40 ml.) and 85% phosphoric acid (5 ml.) were mixed in a flask under a nitrogen atmosphere. Nitrogen had previously been bubbled through the acetic anhydride and phosphoric acid for at least 20 min. The osmocene dissolved with some evolution of heat, and the flask was then heated to 80°. The mixture soon separated into two phases, and so it was swirled occasionally during the course of the heating. After 4 hrs., the flask was cooled to room temperature, and the contents were poured into aqueous sodium carbonate solution and allowed to stand for 1.5 hr. to decompose the acetic

anhydride. The product was extracted into methylene chloride, the solution was dried over magnesium sulfate, and the solvent was distilled to yield a yellow solid. The product was chromatographed on alumina with benzene. Elution of the major yellow band and removal of the solvent yielded 0.385 g. (85%) of yellow crystals, m.p. 129-129.5°. Sublimation at 70-80° followed by two recrystallizations from *n*-heptane raised the melting point to 129.5-130° (lit. m.p. 126° (40)). A faint, slower-moving yellow band possibly indicating a trace of diacetylation was not isolated.

Ruthenocene was prepared from ruthenium acetylacetonate and cyclopentadienyl magnesium bromide according to the procedure of Wilkinson (195). The product was separated from polymeric side-products by steam distillation, chromatography, and crystallization from hexane, m.p. 198.5-200° (lit. m.p. 195.5° (195), 199-200° (40)).

Acetyl ruthenocene. - Ruthenocene (2.5 g., 10.8 mmole), acetic anhydride (15 ml.) and 85% phosphoric acid (1.5 ml.) were heated on a steam bath for 10 min. with occasional shaking. The mixture was cooled to room temperature, poured into sodium bicarbonate solution and allowed to stand for three hours to decompose the acetic anhydride. The product was extracted into methylene chloride, and the organic phase was washed with water twice, dried over magnesium sulfate, and evaporated to dryness. The product was purified by chromatography on 80 g. of alumina with benzene - ether mixtures (1 to 5% ether). The column was extruded, and the major yellow band was washed from the alumina with methylene chloride and acetone. Removal of the solvent yielded 2.55 g. (85%) of a light-yellow product, m.p. 112.5-113°. Sublimation (60-70°) and two recrystallizations (hexane)

raised the melting point to 113.5-114° (lit. m.p. 111-112° (40)).

Triphenylmethyl chloride (trityl chloride) was prepared by the method of Bachmann (196), m.p. 111.5-113° (lit. m.p. 111-112° (196)).

Triphenylmethyl acetate (trityl acetate) was prepared by the method of Gomberg and Davies (90, 197) from trityl chloride and silver acetate. Recrystallization from petroleum ether and i-propyl ether gave a product melting at 84-84.5° (lit. m.p. 83° (90)). This product was found to decompose over a period of time even when stored in a vacuum desiccator, and so was prepared freshly for each series of kinetics runs.

Preparations of metallocenylcarbinols by lithium aluminum hydride reductions. - The majority of the carbinols studied in this research were prepared by reducing the corresponding ketones (or aldehyde) with lithium aluminum hydride. Since all of these reductions followed a fairly standard procedure, a general method will be outlined. Following this, any minor variations or specific points will be discussed briefly for each compound.

In the general procedure, the ketone, dissolved in a minimum volume of anhydrous ether, was added with stirring to an excess of lithium aluminum hydride suspended in a small quantity of ether. A considerably larger excess of hydride was used in the smaller runs to ensure that reaction with traces of moisture would not consume all of the reagent. This addition was carried out quite rapidly, the only limitation to this being the vigor of evolution of hydrogen due to traces of moisture in the ether. After the reaction mixture had been stirred for the desired period of time, it was decomposed with a small amount of water added slowly from a dropper, and the ether

solution of the carbinol was decanted from the residue and washed with water. In the early runs, the reaction was allowed to proceed for an hour or more under reflux, and the ether solution was dried over magnesium sulfate and evaporated at reduced pressure on a steam bath. However, it was found later that this procedure often led to the formation of ethers from the more reactive carbinols, and specifically, the drying over magnesium sulfate was definitely found to be responsible for ether formation. Therefore, the entire procedure was made somewhat less vigorous. The reduction was found to be complete after about 3 min. stirring, and instead of drying the solution, it was diluted with benzene and directly evaporated at temperatures not exceeding 50° on a rotary evaporator. If any droplets of water were present, benzene was added, the solution was decanted to another flask, and the evaporation was repeated.

While chromatography of the alcohols on acid-washed alumina produced considerable ether-formation, neutral alumina catalyzed no such reaction. If the alumina was deactivated by allowing a dish of it to stand in the air for a period of time up to five hours, development occurred at a convenient rate with mixtures of benzene and ether containing between 30 and 70% ether, and addition of about 1% of methanol to such a solvent brought about rapid elution. Such a chromatographic procedure produced clean separation of mixtures of two isomeric carbinols which result from 2-substituted acetylferrocenes.

Analyses of the liquid carbinols were generally not satisfactory, either before or after chromatography. Some of the difficulty may be attributed to a small amount of spontaneous ether formation

or to undefined forms of decomposition which frequently occur with liquid ferrocene compounds. An attempt at molecular distillation of one of the alcohols resulted only in ether - formation, and so this was not used as a means of purification. However, the acetates from these alcohols gave quite satisfactory analyses after molecular distillation, and such analyses of derivatives of the alcohols were accepted as proof that no unexpected change in molecular composition had occurred.

Preparations of metallocenylcarbinyl acetates. - A standard procedure was used for the preparation of all of the acetates in this study. The general procedure is a slight modification of that used by Arimoto and Haven for methylferrocenylcarbinyl acetate (193). About 1 g. of the alcohol (4.6 mmole. or less) was placed in a large side-arm test tube or in a small molecular still, depending upon whether the acetate was expected to be solid or liquid. Pyridine (5 ml.) and acetic anhydride (2 ml., 21 mmole.) were added and the reaction vessel was closed to the atmosphere and allowed to stand overnight at room temperature. The pyridine, acetic anhydride and acetic acid were evaporated at room temperature and about 1 mm. pressure, and the acetate was then either sublimed onto a cold finger condenser or molecularly distilled, usually at about 45-55° and 1-2 μ . Under these conditions, analytically pure acetate was usually obtained, and quite clean separation from bis-ether or unchanged alcohol usually occurred. (An exception to this latter generalization was in cases such as dimethylferrocenylcarbinol or endo- α -hydroxy-1,2-tetramethyleneferrocene, where the alcohol also sublimed. In these cases, the hydroxyl group is sufficiently hindered that molecular

association is limited.)

In cases where a large proportion of bis-ether was present after distillation of the acetate, more acetate could be formed by dissolving the molecular still residue in acetic acid with a small amount of acetic anhydride added, and allowing this mixture to stand at room temperature for several hours. Removal of the acetic acid followed by molecular distillation usually produced acetate of satisfactory purity, except that partial isomerization sometimes occurred with acetates bearing a 2-substituent on the ferrocene ring.

Solid acetates were stored over sodium hydroxide pellets and paraffin shavings until used. Portions of the liquid acetates of suitable size for kinetics were sealed into 1-ml. ampules under nitrogen until they were used. Liquid acetate remaining on the condenser or in the dropper was generally used immediately for a kinetic run, or for spectra.

Ferrocenylcarbinol was prepared by reduction of ferrocenecarboxaldehyde with lithium aluminum hydride as described by Graham and co-workers (7). Material melting at $79.5-80^{\circ}$ was obtained by recrystallization from hexane (lit. m.p. $74-76^{\circ}$ (7), $80-81^{\circ}$ (55)). A small additional quantity of this carbinol was prepared by the method of Lindsay and Hauser (55). This would probably be the preferred method for further preparations.

The acetate prepared in pyridine melted at $77.2-78^{\circ}$ after sublimation and recrystallization from i-propyl ether.

Anal. Calcd. for $C_{13}H_{14}O_2Fe$: C, 60.49; H, 5.47. Found (E):
C, 60.17; H, 5.44.

Methylferrocenylcarbinol prepared by reduction of acetylferro-

cene with lithium aluminum hydride melted at 78.2-78.7° after recrystallization from hexane (lit. m.p. 73-75° (193)).

The acetate melted at 70.2-71° after sublimation and recrystallization from i-propyl ether (lit. m.p. 67-68° (193)).

Dimethylferrocenylcarbinol was prepared by G. Ihler from acetylferrocene and methylmagnesium bromide, m.p. 64.5-65°.

Anal. Calcd. for C₁₃H₁₆OFe: C, 63.96; H, 6.61; Fe, 22.88. Found (S): C, 64.01; H, 6.69; Fe, 23.39.

A by-product from this reaction, m.p. 64-66°, was assigned the structure 1-methyl-1-ferrocenylethylene.

Anal. Calcd. for C₁₃H₁₅Fe: C, 69.05; H, 6.24; Fe, 24.70. Found (S): C, 69.30; H, 6.14; Fe, 24.53.

An attempt to prepare dimethylferrocenylcarbonyl acetate by the pyridine procedure resulted only in sublimation of the starting alcohol. The alkene was treated for two hours with acetic acid in a molecular still, but no product distilled to the condenser over a period of 8 hrs. at 75° and 1-2 μ .

Phenylferrocenylcarbinol was prepared by reduction of benzoylferrocene by V. Engleman, m.p. 80.5-81.2° (lit. m.p. 81-82° (53), 80.3-80.5° (198)).

The acetate was prepared in pyridine and sublimed slowly at 65° to yield a yellow crystalline product, m.p. 103-103.7°. Recrystallization of unsublimed residue from i-propyl ether produced additional material of the same purity.

Anal. Calcd. for C₁₉H₁₈O₂Fe: C, 68.28; H, 5.43; Fe, 16.71. Found (S): C, 68.30; H, 5.66; Fe, 16.63.

Methyl(trans-2-ferrocenylvinyl)carbinol was prepared by reduction

(3 min. stirring) of methyl trans-2-ferrocenylvinyl ketone (1.43 g., 5.5 mmole.) with lithium aluminum hydride (0.60 g., 16 mmole.). The orange solid obtained, m.p. 90.2-92°, was chromatographed in the customary fashion. A fast-moving fore-run (possibly an ether) rapidly separated, but a faint red band (possibly starting material) failed to separate completely from the major yellow-orange product band. Therefore, the column was extruded, and the center portion of the product band was washed from the alumina with methanol-benzene. Removal of the solvent yielded a product melting at 91-92°.

Anal. Calcd. for $C_{14}H_{16}Fe$: C, 65.65; H, 6.30; Fe, 21.81. Found (S): C, 65.55; H, 6.11; Fe, 21.61.

The ultraviolet spectrum had λ_{max} 448 m μ (ϵ 293), λ_{max} 278 m μ (ϵ 9100) and λ_{max} 228 m μ (ϵ 22,600), which is quite similar to vinylferrocene. In the NMR spectrum, the vinyl hydrogens split each other by about 15 c.p.s., indicating a trans-disubstituted double bond (169). The infrared absorption had only one hydroxyl stretching frequency at 3609 cm^{-1} . In the fingerprint region, strong absorption at 961 cm^{-1} weak absorption at 680 cm^{-1} might correspond to hydrogen deformations on trans- and cis-double bonds respectively.

The acetate was prepared in the customary manner from 0.50 g. of the carbinol, and was molecularly distilled at 55-60°. The product crystallized during transfer to ampules, m.p. 69-70°. The ultraviolet and visible spectrum had λ_{max} 447 m μ (ϵ 316), λ_{max} 278 m μ (ϵ 9500) and λ_{max} 229 m μ (ϵ 22,900). In the NMR spectrum, the vinyl hydrogens split each other by about 15 c.p.s., indicating a trans-disubstituted double bond. In the infrared, there was a strong peak at 960 cm^{-1} , and no absorption in the 690 cm^{-1} region. (168).

Anal. Calcd. for $C_{16}H_{18}O_2Fe$: C, 64.45; H, 6.08; Fe, 18.73.

Found (S): C, 64.77; H, 6.08; Fe, 20.74.

Methyl(1'-methylferrocenyl)carbinol from reduction of 1'-acetylmethylferrocene was a cloudy orange oil. Molecular distillation was attempted, but no distillate appeared until a pot temperature of 150-160° was reached. The distillate was a clear red-orange oil which lacked infrared absorption in the vicinity of 3600 cm^{-1} . The ultra-violet and visible spectrum was that of an alkyl-substituted ferrocene (λ_{max} at 440 and 322 m μ , with extinction coefficients of about 124 and 112 calculated for a single ferrocene residue). The analysis was consistent with the structure bis-methyl(1'-methylferrocenyl)carbinyl ether.

Anal. Calcd. for $C_{26}H_{30}OFe_2$: C, 66.41; H, 6.43. Found (E): C, 66.24; H, 6.45.

A portion of this substance was hydrolyzed in acetone-water solution with added acetic acid to a product mixture which was shown on chromatography to contain some alcohol.

The acetate was prepared in pyridine, using carbinol from reduction (15 min. reflux) of 1'-acetylmethylferrocene (1.00 g., 4.14 mmole.) with lithium aluminum hydride (0.20 g., 5.3 mmole.). It is a clear, red-orange oil.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34; Fe, 19.52.
Found (S): C, 63.17; H, 6.51; Fe, 19.78.

Additional acetate was obtained by treating the still pot residue with acetic acid for 6 hrs.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34; Fe, 19.52.
Found (S): C, 63.19; H, 6.49; Fe, 19.75.

Methyl(3-methylferrocenyl)carbinol was prepared by reduction (45 min. reflux) of 3-acetylmethylferrocene (1.085 g., 4.49 mmole.) with lithium aluminum hydride (0.10 g., 2.7 mmole.). The acetate was prepared directly from the crude alcohol in pyridine, and additional acetate was obtained by treating the still pot residue with acetic acid.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34; Fe, 19.52.
Found (S): C, 62.98; H, 6.43; Fe, 19.51.

A mixture of the two isomeric methyl(2-methylferrocenyl)carbinols resulted from reduction (1 hr. reflux) of 2-acetylmethylferrocene (1.00 g., 4.14 mmole.) with lithium aluminum hydride (0.19 g., 5 mmole.). An acetate mixture was prepared from the crude alcohol in pyridine.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34; Fe, 19.52.
Found (S): C, 63.13; H, 6.37; Fe, 19.38.

Treatment of the still pot residue with acetic acid for 8 hrs. produced additional acetate mixture.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34; Fe, 19.52.
Found (S): C, 63.24; H, 6.43; Fe, 19.22.

In a subsequent preparation (from 0.56 g. ketone, 5 min. reflux), acetate from the treatment in pyridine was found by NMR to be a mixture of two isomeric acetates in the ratio 4:1. Solvolysis of this sample showed the slower of the two isomers to predominate by a ratio of 3.38:1. Acetate from acetic acid treatment of the residue partly crystallized, and a small sample of solid isomer purified by recrystallization melted at 55° . The NMR spectrum of the isomer mixture showed that the relative proportions of the isomers had been reversed,

and that the other isomer predominated by a ratio of about 0.8:1. Solvolysis results indicated also a slight predominance of the faster isomer.

The product of a third reduction of 0.61 g. (2.5 mmole.) of ketone with 0.20 g. (5.3 mmole.) of lithium aluminum hydride (3 min. stirring at room temperature) was chromatographically separated into the two isomeric methyl(2-methylferrocenyl)carbinols. The first band on the chromatogram yielded 0.289 g. (47%) of an alcohol which crystallized, m.p. 55-56°. An unrecrystallized sample analyzed slightly high for carbon and hydrogen. The acetate was a liquid, and was the slower of the two isomers in solvolysis.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34. Found (S): C, 63.19; H, 6.54.

The second band on the chromatogram yielded 0.300 g. (49%) of a liquid alcohol, which was converted to a solid acetate, m.p. 54-55.2° after recrystallization from hexane. This product was identical with the solid acetate isolated on the previous run, and was the faster of the two isomers in solvolysis.

Anal. Calcd. for $C_{15}H_{18}O_2Fe$: C, 62.96; H, 6.34. Found (S): C, 63.28; H, 6.46.

A mixture of α -hydroxy-1,2-tetramethyleneferrocenes was obtained by reduction (7 min. stirring) of α -keto-1,2-tetramethyleneferrocene (0.50 g., 1.8 mmole.) with lithium aluminum hydride (0.17 g., 4.5 mmole.).

A small-scale trial chromatogram indicated a predominance of an isomer which passed through the column quite rapidly. The infrared spectrum had a strong peak at 3562 cm^{-1} and weak absorption at

about 3610 cm^{-1} .

A mixture of acetates was prepared by the pyridine method. Kinetics run on this mixture indicated about 7% of an isomer which reacted rapidly and 93% of a slower isomer.

Anal. Calcd. for $\text{C}_{16}\text{H}_{18}\text{O}_2\text{Fe}$: C, 64.45; H, 6.08; Fe, 18.73.

Found (S): C, 64.43; H, 6.29; Fe, 18.95.

The alcohol preparation was repeated (0.3 g. of ketone and 0.13 g. of lithium aluminum hydride, with 3 min. stirring), and the alcohol was treated with acetic acid for 15 hrs. Part of the product was molecularly distilled. The residue and distillate had nearly identical infrared spectra, with absorption at both 1735 and 3565 cm^{-1} , which indicates the presence of both acetate and alcohol. Solvolysis of this mixture indicated that only about 25% of the product was acetate, and that most of this was the faster isomer.

A third batch of mixed alcohols was prepared (0.48 g. of ketone and 0.18 g. of lithium aluminum hydride, 3 min. stirring), and separated chromatographically into two isomers. The first band eluted from the column yielded 0.435 g. (87%) of a liquid alcohol which had infrared absorption at 3562 cm^{-1} .

Anal. Calcd. for $\text{C}_{14}\text{H}_{16}\text{OFe}$: C, 65.65; H, 6.30; Fe, 21.81.

Found (S): C, 65.44; H, 6.47; Fe, 21.61.

Solvolysis of acetate prepared by the pyridine method from this alcohol showed the presence of only the slower isomer.

The second alcohol was eluted from the column by adding a trace of methanol to the solvent. This fraction weighed 0.046 g. (9.2%), and crystallized as a yellow solid, m.p. $70.5-72^\circ$ (lit. m.p. $71.5-72.5^\circ$ (123)). Additional alcohol obtained by recovery of products

from solvolyses was combined with this alcohol to prepare acetate. Both pyridine and acetic acid preparations were found necessary. Recovered alcohol from solvolyses of these acetate preparations provided further material for another acetate sample. This last time, the acetate crystallized, m.p. 68.5-69.5° (lit. m.p. 64-65° (123)).

Methyl-3-(1,1'-dimethylferrocenyl)carbinol was prepared by reduction (3 min. stirring) of 3-acetyl-1,1'-dimethylferrocene (0.75 g., 2.9 mmole.) with lithium aluminum hydride (0.15 g., 4.0 mmole.).

The acetate was prepared directly in pyridine in 84% overall yield from the ketone.

Anal. Calcd. for $C_{16}H_{20}O_2Fe$: C, 64.02; H, 6.72; Fe, 18.61.
Found (S): C, 64.25; H, 6.83; Fe, 18.60.

Methyl-3-(1,1'-trimethylenferrocenyl)carbinol was prepared by reduction (3 min. stirring) of 3-acetyl-1,1'-trimethylenferrocene (0.60 g., 2.2 mmole.) with lithium aluminum hydride (0.10 g., 2.7 mmole.).

The acetate was prepared in pyridine from the crude alcohol, and was molecularly distilled at 75° to yield a clear orange oil.

Anal. Calcd. for $C_{17}H_{20}O_2Fe$: C, 65.40; H, 6.46; Fe, 17.89.
Found (S): C, 65.50; H, 6.68; Fe, 18.04.

In an earlier preparation of the alcohol, in which less care was taken to prevent ether-formation, the ether was almost the sole product. Some acetate was prepared by treatment with acetic acid and molecular distillation at 70°, but the product gave a poor analysis, and solvolyses of the product from this acid-catalyzed acetate-formation gave inconsistent results. A large portion of the material

failed to distill, and was found to be a hard brown resin.

A mixture of two isomeric methyl-2-(1,1'-dimethylferrocenyl)-carbinols was prepared by reduction (3 min. stirring) of 2-acetyl-1,1'-dimethylferrocene (0.71 g., 2.6 mmole.) with lithium aluminum hydride (0.17 g., 4.5 mmole.). Chromatography yielded two alcohol bands.

The first isomeric alcohol eluted from the column was 0.271 g. (38%) of a cloudy orange oil, which exhibited hydroxyl absorption in the infrared at 3578 cm^{-1} , and a possible weak peak at 3607.5 cm^{-1} .

The acetate was prepared directly from the crude alcohol in pyridine. However, only a small amount of acetate distilled, so the remainder in the still pot was treated with acetic acid to produce additional acetate. The acetate from the acid-catalyzed preparation was found by NMR to consist of a mixture of isomers. The more abundant acetate isomer corresponded to the alcohol from which it was prepared. A poor analysis was obtained for this acetate. Alcohol recovered from solvolyses had a reasonably satisfactory analysis.

Anal. Calcd. for $\text{C}_{14}\text{H}_{18}\text{OFe}$: C, 65.14; H, 7.03; Fe, 21.64.

Found (S): C, 65.24; H, 6.94; Fe, 22.06.

Additional acetate was prepared from this recovered alcohol.

The second alcohol eluted from the column was a cloudy oil weighing 0.366 g. (51%). The infrared spectrum had a peak at 3604.5 cm^{-1} with a weaker peak at 3582 cm^{-1} .

The acetate was prepared in the usual manner in pyridine.

Anal. Calcd. for $\text{C}_{16}\text{H}_{20}\text{O}_2\text{Fe}$: C, 64.02; H, 6.72; Fe, 18.61.

Found (S): C, 63.96; H, 6.62; Fe, 18.91.

A mixture of the two isomeric methyl-2-(1,1'-trimethyleneferro-

cenyl)carbinols was prepared by reduction (3 min. stirring) of 2-acetyl-1,1'-trimethyleneferrocene (1.11 g., 4.0 mmole.) with lithium aluminum hydride (0.21 g., 5.5 mmole.). Chromatography produced separation into a fore-run of ether and two alcohol bands.

The first alcohol to be eluted (0.70 g., 63%) crystallized to a yellow solid, m.p. 80-81°, which had a strong hydroxyl absorption in the infrared at 3575 cm⁻¹ and a very weak peak at 3608.5 cm⁻¹.

Anal. Calcd. for C₁₅H₁₈OFe: C, 66.69; H, 6.71; Fe, 20.67.

Found (S): C, 66.95; H, 6.50; Fe, 20.65.

The acetate was prepared from 520 mg. of the alcohol in pyridine. One sample crystallized to a solid, m.p. 60-61°.

Anal. Calcd. for C₁₇H₂₀O₂Fe: C, 65.40; H, 6.46; Fe, 17.89.

Found (S): C, 65.14; H, 6.41; Fe, 18.31.

The second alcohol weighed 0.18 g. and melted at 160-161.5°. However, alcohol recovered from solvolyses melted first at 90-91° and resolidified, melting finally at 160°. A sample of this recovered alcohol recrystallized from hexane as yellow needles melting at 161-162°.

Anal. Calcd. for C₁₅H₁₈OFe: C, 66.69; H, 6.71; Fe, 20.67.

Found (S): C, 66.55; H, 6.55; Fe, 20.68.

Both alcohol samples had infrared hydroxyl absorptions at 3603 cm⁻¹, and only minor intensity differences were noted in a few weak peaks in the fingerprint region. Acetate prepared from a small sample of recovered alcohol solvolyzed at a rate about 15% lower than that observed for the original acetate (run 138), but for such a small sample, this is within the limit of the expected error. The double melting point may be due to the existence of two crystalline

forms, or to loss of water to form the ether on heating (although no condensed moisture was noted near the top of the melting point capillary).

Preparation of the acetate was attempted in the customary fashion in pyridine, but the alcohol appeared to be only slightly soluble in the reaction mixture, and failed to dissolve after standing for about 20 hrs. Only 0.045 g. of orange oil distilled. This product had strong carbonyl absorption and very weak hydroxyl absorption in the infrared, while the solid residue remaining in the pot had neither. The residue in the still pot dissolved in acetic acid, and the acetate product obtained in this manner crystallized to a yellow-orange solid, m.p. 74.7-75.7°.

Anal. Calcd. for $C_{17}H_{20}O_2Fe$: C, 65.40; H, 6.46; Fe, 17.89.
Found (S): C, 65.19; H, 6.39; Fe, 18.12.

Methylruthenocencylcarbinol was prepared by reduction (2 hrs. reflux) of acetyl-ruthenocene (2.21 g., 8.02 mmole.) with lithium aluminum hydride (0.30 g., 7.9 mmole.). The crude product, m.p. 60-63°, was recrystallized from heptane to produce two crops: 0.96 g. (43%), m.p. 64-64.2° and 0.61 g. (27%), m.p. 63-63.5°.

Anal. Calcd. for $C_{12}H_{14}ORu$: C, 52.23; H, 5.11. Found (E): C, 52.16; H, 5.16.

The acetate was prepared in pyridine and sublimed at 50° to yield a solid product which melted at 64-64.5° after recrystallization from i-propyl ether or hexane.

Anal. Calcd. for $C_{14}H_{16}O_2Ru$: C, 52.88; H, 5.07. Found (E): C, 53.01; H, 5.03.

Methylosmocencylcarbinol was prepared by reduction (45 min.

stirring) of acetylosmocene (0.548 g., 1.51 mmole.) with lithium aluminum hydride (0.10 g., 2.6 mmole.). The crude product melted at 72.5-74°, and after two recrystallizations from heptane melted at 74-74.5°. The analysis was unsatisfactory.

The acetate prepared in pyridine and sublimed at 50° melted at 64-66.5°. Two crops from recrystallization from i-propyl ether - heptane had m.p. 67.2-67.7°.

Anal. Calcd. for C₁₄H₁₆O₂Os: C, 41.37; H, 3.97; Os, 46.79.
Found (S): C, 41.22; H, 4.17; Os, 47.16, 46.38.

Methyl(1'-carbomethoxyferrocenyl)carbinol. - A solution of 1'-carbomethoxyacetylferrocene (1.15 g., 4.0 mmole.) in methanol (75 ml.) was stirred in a beaker. To this was added solid sodium borohydride (1.0 g., 26.5 mmole.) over a period of about 30 sec. The mixture was stirred for 3 min., and 7 ml. of acetone was added. The solution was poured into water, and ammonium chloride was added until the mixture was only slightly basic. The product was extracted from the aqueous methanol phase with several portions of methylene chloride. The organic solution was washed a number of times with water, and once with sodium bicarbonate solution. After the solution had been dried over magnesium sulfate, the solvent was removed to yield an orange oil. This oil was chromatographed on 30 g. of neutral alumina with benzene - ether mixture as development solvent (1 to 12% ether). The major band was isolated by extruding the column and washing with acetone. Some of the product was too strongly adsorbed to be removed in this fashion. The acetone was distilled to yield an oil which slowly crystallized to an orange solid, m.p. 55-58°. This was crystallized from hexane to yield two crops of

crystals: 0.65 g. (56%), m.p. 57.5-58.7° and 0.20 g. (17%), m.p. 56.5-58.2°.

Anal. Calcd. for $C_{14}H_{16}O_3Fe$: C, 58.45; H, 5.60; Fe, 19.37.

Found (S): C, 58.37; H, 5.64; Fe, 19.59.

The infrared spectrum exhibited two bands in the carbonyl region at 1724 and 1705 cm^{-1} which did not change in relative intensity on recrystallization or dilution.

The methyl ether was prepared for the purpose of spectral comparison by refluxing the alcohol (0.1 g., 0.35 mmole.) with 25 ml. of methanol and one drop of glacial acetic acid overnight. It was isolated as an orange oil by extraction and chromatography on alumina. The infrared spectrum exhibited carbonyl absorption only at 1722 cm^{-1} .

A small sample of the hydroxyester was saponified to a poorly characterized acid, and lactone-formation was attempted unsuccessfully with toluenesulfonic acid in benzene.

In a larger scale preparative run, the excess hydride was decomposed by addition of glacial acetic acid. This probably catalyzed ether-formation, which greatly hindered the product isolation. A sufficient quantity of material for further work was obtained by a combination of recrystallization, sublimation, chromatography and hydrolysis of the ether in aqueous acetone, catalyzed by acetic acid.

The acetate was prepared from 3 g. of the alcohol by the pyridine procedure and distilled in a larger molecular still (ca. 10 cm. in diameter and 7 cm. path length) at 110°. The product was an oil, n_D^{25} 1.5721. The infrared spectrum exhibited carbonyl absorption at 1720 cm^{-1} with a shoulder at about 1725 cm^{-1} .

Anal. Calcd. for $C_{16}H_{18}O_4Fe$: C, 58.20; H, 5.49. Found (E): C,

58.13; H, 5.64.

α -Hydroxy-1,1'-trimethyleneferrocene. - A suspension of α -keto-1,1'-trimethyleneferrocene (1.32 g., 5.45 mmole.) in 250 ml. methanol was stirred while sodium borohydride (3 g., 79 mmole.) in methanol (50 ml.) was added quite rapidly. The color of the solution immediately lightened, and the suspended ketone dissolved. After a total of 10 minutes' stirring the solution was cooled to 0°, and acetone (10 ml.) was added to destroy the excess hydride. Water (500 ml.) was added, and the product was extracted from the aqueous methanol phase with methylene chloride. The organic solution was washed with water three times, dried over magnesium sulfate, and evaporated to a yellow-orange solid, m.p. 153-155.5°. The product was chromatographed on 90 g. of alumina with benzene followed by 5% ether in benzene as development solvent. A small quantity of material rapidly passed through the column. The column was extruded, and the main product was washed from the alumina with methylene chloride and acetone. Removal of the solvent yielded a yellow solid, m.p. 156.5-157.5°. Analysis of this alcohol was unsatisfactory, but the acetate gave an acceptable analysis.

The acetate was prepared in pyridine, and sublimed at 50-100°. Two crops of product which melted at 135-136.2° were collected.

Anal. Calcd. for $C_{15}H_{16}O_2Fe$: C, 63.41; H, 5.68. Found (E): C, 63.50; H, 5.65.

β -Hydroxy-1,1'-trimethyleneferrocene, m.p. 148.5-149°, was prepared by W. Mock. The acetate was prepared in pyridine, and two crops of product were obtained by sublimation at 45-80°, m.p. 124-125° and 125-125.5°.

Anal. Calcd. for $C_{15}H_{16}O_2Fe$: C, 63.41; H, 5.68. Found (E): C, 63.35; H, 5.74.

The tosylate was prepared in γ -collidine. β -Hydroxy-1,1'-trimethyleneferrocene (0.260 g., 1.06 mmole.) was dissolved in 2 ml. of γ -collidine (distilled and dried over barium oxide) in a 5-ml. volumetric flask, and p-toluenesulfonyl chloride (0.204 g., 1.06 mmole., m.p. 68-69°) was added. The flask was stoppered and wrapped in aluminum foil. After 7 hrs. at room temperature, a large quantity of salt had precipitated. After a total reaction time of 26 hrs., the mixture was poured into an excess of dilute sulfuric acid, and the product was extracted into methylene chloride. The organic phase was washed with dilute sulfuric acid, with water, and twice with saturated sodium chloride, and the solvent was evaporated to yield a gummy orange solid. The crude product had infrared absorption at 1180 and 1192 cm^{-1} (also observed in p-toluenesulfonyl chloride and cyclohexyl tosylate) and weak hydroxyl absorption at 3610 cm^{-1} . With the exception of a peak appearing at 1100 cm^{-1} in the product and about 1084 cm^{-1} in tosyl chloride, the spectrum could be represented to a good approximation by a superposition of the spectra of the two starting materials. However, several peaks present in α -hydroxy-1,1'-trimethyleneferrocene were absent.

The crude product was dissolved in ether, and pentane was added until the solution began to turn cloudy. A precipitate formed when the solution was cooled to -70° and did not dissolve when warmed to 0°. A yellow product weighing 0.056 g. was collected by filtration and dried over sodium hydroxide pellets and paraffin shavings. It darkened at about 110°, and partially melted over the range 115-120°.

This recrystallized product and the material remaining in the liquors had essentially identical infrared spectra. The liquors were concentrated and an additional crop of product weighing 0.073 g. was collected, which darkened slowly on heating, but had not melted at 160°. A portion of this second crop was analyzed.

Anal. Calcd. for $C_{20}H_{20}O_3FeS$: C, 60.61; H, 5.09; Fe, 14.09; S, 8.09. Found (S): C, 62.17; H, 5.10; Fe, 22.61; S, 7.08. No Cl was found.

There is probably some error in this analysis, since only 3% is left for oxygen.

An attempt to purify a small portion of the tosylate by chromatography on neutral deactivated alumina produced a trace of partially solid yellow product whose infrared spectrum had a number of strong bands (including strong absorption between 1700 and 1800 cm^{-1}) not present in any of the other materials of this series. This material was not identified.

Kinetic procedure. - Most of the solvolyses were performed in an "80%" acetone mixture. This solvent was prepared by diluting 200 ml. of boiled distilled water (measured at 25°) to 990 ml. with purified acetone (at 25°) and equilibrating a 99-ml. aliquot (measured at room temperature) of this stock solvent to the reaction temperature in a 100 ml. volumetric flask. A small tube which contained a weighed sample of substrate dissolved in 1 ml. of acetone was added to start the reaction. Acetone used was reagent grade solvent further purified by the procedure of Kochi and Hammond (199). After a number of runs had been completed, this procedure was altered to further standardize the solvent composition by measuring the 99

ml. aliquots at a constant temperature. The temperature chosen was 30° to most nearly duplicate the composition used for the earlier runs. The "82%" acetone solution was similarly prepared by dilution of 18 ml. of water for each run, while early runs were performed in a solvent containing 60 ml. of acetone and 40 ml. of water.

The density of a typical "80%" acetone preparation was determined at 25° in order to define its composition more exactly. Calculation based either on the volume of solution per volume of water or on the equation relating density to composition (200) indicates that the solvent is 76.65% acetone by weight, or that it has the composition of a mixture made up of 80.7 ml. of acetone and 19.3 ml. of water.

At suitable intervals after the reaction had been started, a 5 ml. aliquot was removed and titrated with standard sodium hydroxide (standardized against potassium acid phthalate and constant-boiling hydrochloric acid). The titrations were carried out in the following manner. Approximately 10 ml. of a quenching solution (85% reagent acetone - 15% boiled distilled water) was run into a test tube equipped with a two-hole rubber stopper and containing a Teflon-covered magnetic stirring bar. This was cooled on an ice bath or ice-salt bath while nitrogen was bubbled through it. After at least five minutes (the minimum time necessary for sharp reproducible end points), an aliquot of the reaction solution was added while the gas-bubbling tube was raised to a position slightly above the surface of the solution. The time when the pipette was half empty was recorded as the time for the point. This was read from a clock or stopwatch, depending on the rate of the reaction. After addition of the sample, the

burette was lowered through a hole in the stopper, and its capillary tip was allowed to extend just below the surface of the solution for the titration. In this manner, duplicate titrations (as, for instance, infinity titers) could customarily be reproduced within .003 ml. or better out of a total volume of 0.700 ml.

For runs at temperatures higher than 45° , a sealed ampule technique was used. The solution was made up in the customary fashion in a 100 ml. volumetric flask, and samples of approximately 6 ml. were transferred to constricted 10 ml. pyrex culture tubes which had been carefully washed and dried. These tubes were then sealed and equilibrated in the constant temperature bath at the desired temperature. Ampules were removed from the bath at suitable time intervals, quenched by immersion in ice water, and opened after being wiped free of oil and brought to a constant temperature. A 5-ml. sample was pipetted out of the ampule and titrated in the usual manner. Generally, the results from the sealed ampule runs were considerably poorer than the other results. A fair amount of this difficulty resulted from a decrease in the sharpness of end points.

The kinetics runs were performed in constant temperature baths which maintained the temperature to within about 0.03° of the stated temperature. The thermometers used were checked against an NBS calibrated thermometer, and temperatures were corrected wherever necessary.

Depending upon the reaction rates, various runs were followed less than 50% or greater than 90% to completion. Generally, in at least one run with any particular compound, the reaction was followed through at least two to three half-lives to be certain that no sig-

nificant deviation from first-order kinetics was suggested. After a time estimated as equal to or greater than ten half-lives, duplicate infinity titers were taken.

Calculation of rate constants. - The reaction rate constant was calculated using the standard integrated first-order rate equation (201):

$$\log(a-x) = \frac{kt}{2.303} + \log a$$

where a is the infinity titer, x is the titer at time t, and k is the first-order constant. Rough values of the rate constant were determined by plotting (a-x) vs. t on semi-logarithmic graph paper and drawing what appeared to be the best straight line. The half-life was estimated from this line, and the rate constant was calculated from the equation (202):

$$k = \frac{\ln 2}{t_{\frac{1}{2}}} = \frac{0.693}{t_{\frac{1}{2}}} .$$

Final values of the rate constants were calculated on a Burroughs 220 computer by a weighted least squares technique similar to that proposed by Roseveare (203). These generally agreed with rate constants estimated from the slope within 2%. The program was set up by N. Jones of California Institute of Technology. In one case, incorrect data were punched on the data tape. Rather than repeating the computer work, the rate constant estimated from the slope was used.

According to statistical theory, a weighting factor should be chosen which is inversely proportional to the variance (square of the standard deviation) for the points (204). If the standard deviation is constant for all points, then the weighting factor will

likewise be constant, and an unweighted least squares treatment is called for. In the present case, this would correspond to a constant deviation in $\log(a-x)$ for any point, or a constant fractional error in $(a-x)$. Also, as pointed out by Roseveare, this type of treatment can be used for small errors in the time, since during any small increment of time the reaction which occurs is proportional to the amount of material which has not yet reacted, or to $(a-x)$. In all kinetic runs performed in this study, the error in measurement of time was probably never more than 1% of one half-life, and was generally far less than this. It can be calculated from the equations given above that this corresponds to less than 0.7% of the total titer at any given time, and is thus probably less than the error in the measurement of volumes for most cases. There is, however, a source of error which falls into this category, and would therefore have this type of a weighting factor. In reactions run at temperatures removed from that of the room, the sample is removed with a pipette at a temperature different from that of the solution, and so the solution temperature is slightly changed for a short period of time during transfer of the sample. Then the titer will include a small error due to the change in reaction rate which occurs during this time. The error should be proportional to the amount of material which has not yet reacted, and should vary in a random manner with the time which is taken to transfer the sample. Such an error should be particularly noticeable for a fast reaction run at a low temperature and high concentration. A similar type of error would occur if the delivery volumes for the pipettes used vary by a percent or so.

The most obvious type of error present is an error in measuring the amount of standard sodium hydroxide used to titrate the aliquot. In this case, the error is not proportional to $(a-x)$, but is a constant increment in $(a-x)$. Since the error becomes a larger fraction of the quantity $(a-x)$ for points toward the end of the reaction, a weighting function should be used which gives less weight to deviations of these points in determination of the least squares line. Such a function may be derived in the following manner. If $d(a-x)$ is the error in $(a-x)$, and if

$$y = \ln(a-x),$$

then in the limit,

$$dy = d(\ln(a-x)) = \frac{d(a-x)}{a-x} .$$

For small errors, the standard deviation of $\log(a-x)$ should then be proportional to the standard deviation of $(a-x)$ divided by $(a-x)$. If this standard deviation is a constant, the weighting factor will then be inversely proportional to $(a-x)^2$. If the standard deviations due to the two types of errors are combined, one obtains the weighting function:

$$w = \frac{1}{m^2 + p^2/(a-x)^2}$$

where m is the constant error in $\log(a-x)$ and p is the titration error. An inspection of the plots for a number of runs suggested that both types of errors were significant, but in different proportions for different runs. Rather than attempt to balance these two factors differently for every run, a compromise was adopted whereby the contributions from the two types of error became equal at one half-life. If the titration error is estimated as 0.002 ml., and the substitution $z = a-x$ is made, one can arrive at such an equation:

$$w = \frac{1}{\frac{.004^2}{z_1} + \frac{.002^2}{z}}$$

where z_1 is the value of $(a-x)$ for the first point. Such a weighting function as this cannot be expected to give the best estimate of the proper weights for every run, but it is more justifiable than an unweighted least square treatment or one in which only titration errors are considered. At the worst, in the absence of systematic error affecting principally the initial points, it can only increase the standard deviation calculated for the slope, and place unwarranted weight upon some points in determination of the rate constant.

Two systematic errors which might serve to produce deviations between duplicate runs are immediately apparent. The strong dependence of the rate upon the solvent composition leads to a strong possibility of error due to variations in the solvent preparation. A variation of only 0.1% in the composition of the solvent might well result in an error of 2% in the rate. Therefore, this type of error may account for much of the deviation observed between runs.

An error in the infinity titer will produce a percentage error in the rate constant at least as great as that in the titer. Results were calculated for run 40 by unweighted least squares using the observed infinity titer, and also with infinity values high and low by 2%. These artificially introduced errors resulted in a slight noticeable curvature in the graph for the reaction, and errors of about 4% in the calculated rate constants. With the weighted least squares, errors of this sort may be minimized, but they must remain greater than that in the infinity titer. Because of the relative sensitivity of the rate constant to such errors, the observed infin-

ity values were discarded in several cases, and the values based on the weight of the acetate solvolyzed were used. Such an alteration of the data was never made unless most of the following conditions were met: (1.) The observed value was too high, as would be expected if evaporation of solvent or absorption of carbon dioxide from the air had occurred. (2.) Rate constants for duplicate runs differed by more than the expected error. (3.) End points for the infinity titer were not sharp. (4.) The corrected point for the temperature in question would fall closer to the activation energy plot defined by runs at other temperatures. (5.) Other solvolyses of the same batch of acetate had infinity titers close to the predicted values. (6.) There was reason to believe that the sample had been contaminated during the run. Such cases as these will be specifically noted in discussions of the kinetics for individual compounds.

Errors in the rate constants due to variations in temperature are probably negligible. For a reaction with a 20 kcal. energy of activation, an error in the temperature of 0.1° corresponds to an error in the rate constant of only about 1% at the temperatures used for these solvolyses. This approximates the magnitude of errors to be expected from other sources.

The equations used for calculation slope, rate constant and their standard deviations are (205):

$$b = + \frac{\sum w_i \sum w_i t_i y_i - \sum w_i t_i \sum w_i y_i}{\sum w_i \sum w_i t_i^2 - (\sum w_i t_i)^2}$$
$$k = - \frac{2.303}{60} b \text{ (sec}^{-1}\text{)}$$

$$\sigma_b = \sqrt{\frac{\sum w_i [\sum w_i y_i^2 - a \sum w_i y_i - b \sum w_i t_i y_i]}{(n-2) [\sum w_i \sum w_i t_i^2 - (\sum w_i t_i)^2]}}; \sigma_k = \frac{2.303}{60} \sigma_b$$

$$a = \frac{\sum w_i y_i}{\sum w_i} - b \frac{\sum w_i t_i}{\sum w_i}$$

where y_i is the $\log(a-x)$ value for the i^{th} point, t_i is the time for that point, n is the number of points, and summations are all taken over the n points.

Rate constants for all runs performed are tabulated in Table IV, along with other information pertaining to the run. In the last column, the averages of duplicate rate constants are listed. The standard deviations are obtained by adding the average variance within the runs to the variance from the mean value of k . While the standard deviation within a run provides a good estimate of the error expected from scatter, the deviations from the mean value of k are a poor estimate of the systematic errors between runs, due to the small number of duplicate runs performed. Therefore, the listed standard deviations are not to be taken too seriously. When only one run was performed at a certain temperature, no standard deviation is listed in the last column. Rate constants indicated in parentheses were not used for further calculations.

Activation parameters were calculated from the usual equation (206):

$$\log(k/T) = \log\left(k \frac{h}{h}\right) + \frac{\Delta S^\ddagger}{2.303R} - \frac{\Delta H^\ddagger}{2.303RT}$$

When the kinetics were observed at two or three temperatures, ΔH^\ddagger was calculated between the extreme temperatures by the modified

equation:

$$\Delta H^\ddagger = \frac{2.303 RT_1 T_2}{T_1 - T_2} \left[\log(k_1/T_1) - \log(k_2/T_2) \right]$$

In such a calculation, ΔH^\ddagger may be considered a function of the rate constants at the two temperatures, and so the variance of this estimate of ΔH^\ddagger is the same function of the variances of k_1 and k_2

(207). In the approximation of small error, this reduces to:

$$\sigma_{\Delta H^\ddagger} = \frac{2.303 RT_1 T_2}{T_1 - T_2} \sqrt{\left(\frac{\sigma_{k_1}}{k_1}\right)^2 + \left(\frac{\sigma_{k_2}}{k_2}\right)^2}$$

When duplicate determinations of k_1 and k_2 were not available, the standard deviations were generally assumed for this calculation to be twice those calculated from scatter within the run, so as to allow for systematic errors. If the kinetics were observed at three temperatures, the rate constant for the middle temperature was calculated from the activation parameters. If this calculated value agreed within about one standard deviation with the experimentally observed value, agreement was considered satisfactory. In one case this was verified by a least squares calculation of the standard deviation in ΔH^\ddagger . The deviation obtained in this manner was small with respect to that due to inaccuracies in the rate constants at the extreme temperatures. When the rate constant at the middle temperature did not fall close to the line, a least squares calculation (weighted or unweighted) was performed to obtain an estimate of the variance due to this error, and the total variance used was the sum of those from the two sources.

When the kinetics were observed at four temperatures, ΔH^\ddagger was calculated from the least squares slope, weighted or unweighted

TABLE IV

Rate Constants for Solvolyses^a

Compound	T°C	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k _{av} ^c
Ferrocenylcarbonyl Acetate	15.00	43	5.59	35	0.2526 ± 0.0017	0.2523 ± 0.0022
		44	4.98	35	0.2534 ± 0.0017	
		45	3.98	35	0.2509 ± 0.0024	
	30.00	20	2.81	84	1.605 ± 0.013	1.624 ± 0.021
		21	3.06	77	1.631 ± 0.013	
22		3.99	84	1.636 ± 0.008		
35.00	10	2.94	65	2.903 ± 0.017	2.895 ± 0.028	
	11	3.41	65	2.909 ± 0.025		
	12	4.39	57	2.873 ± 0.017		
(60% Acetone)	0.00	28	3.84	92	7.789 ± 0.090	7.844 ± 0.119
		29	4.91	91.5	7.897 ± 0.080	
		30	5.85	92.5	7.947 ± 0.059	
		66	5.50	73	7.744 ± 0.060	
		3a	1.8	15	0.8	
Methylferrocenylcarbonyl Acetate	0.00	13	3.98	61	0.4870 ± 0.0032	0.4898 ± 0.0056
		14	2.83	73	0.4943 ± 0.0024	
		15	3.41	73	0.4838 ± 0.0037	
		16	3.16	59	0.4940 ± 0.0015	
		69	4.71	46	(0.4699 ± 0.0053)	
		34	3.65	94	3.07 ± 0.020	
35	4.60	71	2.965 ± 0.018			
36	6.10	92	3.007 ± 0.020			

TABLE IV (Cont.)

Compound	TOC	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k ^c eV
Methylferrocenyl Carbinyl Acetate (cont.)	30.00	17	2.84	91	17.03 ± 0.11	
		18	3.26	75	17.10 ± 0.11	
		19	4.36	95.5	17.10 ± 0.08	
		57	5.65	84	(16.20 ± 0.10)	17.02 ± 0.15
		58	4.30	86	16.85 ± 0.08	
		7	4.05	94	28.17 ± 0.26	
with 0.0072M sodium perchlorate	35.00	8	4.90	96.5	30.18 ± 0.21	
		9	2.49	92	31.01 ± 0.40	29.79 ± 1.49
	30.00	61	5.36	79	16.80 ± 0.04	16.67 ± 0.31
with 0.007M sodium acetate		62	3.53	73	16.53 ± 0.34	
	30.00	59	5.03	54	3.640 ± 0.021	3.627 ± 0.028
with 0.00718M sodium hydroxide		60	3.61	54	3.614 ± 0.022	
	30.00	62a	3.60	-d	21.2d	20.0 ± 1.3
with 0.00160M hydrochloric acid (82% acetone)		62b	5.19	-d	19.1d	
	0.00	63	4.09	44	1.455 ± 0.019	1.455
(60% acetone)	30.00	55	4.12	80	11.55 ± 0.035	11.59 ± 0.07
		56	4.71	81	11.64 ± 0.046	
	0.00	1	2.08	76	8.41 ± 0.12	8.41

TABLE IV (Cont.)

Compound	TOC	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k _{av} ^c
Phenylferrocenylcarbonyl Acetate	0.00	103	2.40	86	6.659 ± 0.043	6.623 ± 0.068
		104	3.29	78	6.587 ± 0.046	
	10.00	101	2.99	88	21.02 ± 0.05	21.16 ± 0.22
		102	4.73	84	21.31 ± 0.11	
Methyl(2-ferrocenylvinyl)- carbonyl acetate	10.00	145	2.78	82	1.106 ± 0.008	1.093 ± 0.020
		146	3.18	79	1.079 ± 0.006	
	30.00	141	(3.4)	89	10.45 ± 0.057	10.67 ± 0.33
		142	2.56	83	10.90 ± 0.10d	
	42.50	144	2.53	88	37.01 ± 0.25	37.01
Methyl(3-methylferrocenyl)- carbonyl acetate	0.00	81	2.92	64	2.108 ± 0.027	2.114 ± 0.021
		82	3.99	64	2.120 ± 0.018	
	10.00	79	(5.2)	75	6.679 ± 0.035	6.795 ± 0.186
		80	3.18	71	6.910 ± 0.120	
	20.00	77	(3.5)	88	21.30 ± 0.09	21.08 ± 0.34
		83	4.13	86	20.86 ± 0.17	
Methyl(1'-methylferrocenyl)- carbonyl acetate	0.00	73	3.85	83	1.046 ± 0.005	1.032 ± 0.021
		74	4.23	81	1.018 ± 0.005	
	10.00	75	3.74	81	3.540 ± 0.017	3.536 ± 0.018
		76	4.20	82	3.53 ± 0.013	
	20.00	78	5.21	79	11.35 ± 0.07	11.35

TABLE IV (Cont.)

<u>Compound</u>	<u>TOC</u>	<u>Run</u>	<u>Conc.^b 10³m/l</u>	<u>% Followed</u>	<u>10⁵k</u>	<u>10⁵k_{av}^c</u>
Methyl(2-methylferrocenyl)- carbonyl acetate, slow isomer	10.00	117	3.88	47	0.5033 ± 0.0086	0.4952 ± 0.0134
		118	3.46	48	0.4871 ± 0.0049	
	30.00	87a	d	70	5.62	5.73 ± 0.16
		87b	d	78	5.85	
	40.00	119	(1.7)	74	14.44 ± 0.26	14.44
	45.00	137	(2.8)	80	23.77 ± 0.11	23.77
Methyl(2-methylferrocenyl)- carbonyl acetate, fast isomer	0.00	114	2.55	89	1.926 ± 0.017	1.907 ± 0.034
		115	2.97	91	1.888 ± 0.024	
	10.00	116	2.55	92.5	6.902 ± 0.097	6.902
	30.00	87a	d	95	73.4	72.8 ± 0.8
		87b	d	95	72.2	
<u>α</u> -Acetoxy-1,2-tetra- methyleneferrocene, <u>endo isomer (slow)</u>	45.00	105	d	42	(0.157 ± 0.002) ^d	0.187
		109	(3.4)	d	0.187 ± 0.004	
	63.50	110	3.36	90	1.623 ± 0.034	1.574 ± 0.079
		111	2.76	90	1.524 ± 0.041	
	80.00	107	(2.0)	66	8.14 ± 0.22	8.24 ± 0.26
		108	2.76	92.5	8.34 ± 0.20	

TABLE IV (Cont.)

Compound	TOC	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k ^c av	10 ⁵ k ^c av
α-Acetoxy-1,2-tetra- methyleneferrocene, <u>exo isomer (fast)</u>	0.00	139	(2.3)	64	2.189 ± 0.047	2.189
	10.00	106	^d	92	7.64 ± 0.11	7.64
	25.00	140	(4.0)	93.5	40.36 ± 0.27	40.36
α-Acetoxy-1,1'-trimethylene- ferrocene	30.00	143	2.52	94	72.09 ± 0.46	72.09
	15.00	45a	2.03	84 ^d	0.0035	0.0035
	30.00	53 54	1.65 1.82	37 37	0.225 ± 0.004 0.227 ± 0.008	0.226 ± 0.007
(60% acetone)	45.00	46 47	1.74 (1.1)	24 ^d 79 ^d	1.34 ± 0.014 ^e 1.44 ± 0.018 ^e	1.39 ± 0.07
	45.00	68	1.86	88	15.42 ± 0.115	15.42
	0.00	96 100	3.37 6.01	60 81	3.888 ± 0.026 3.765 ± 0.013	3.826 ± 0.089
Methyl-3-(1,1'-dimethyl- ferrocenyl)- carbonyl acetate	10.00	95 99	3.66 5.62	80 82	12.85 ± 0.05 12.43 ± 0.07	12.64 ± 0.30
	24.30	97	5.17	95	60.44 ± 0.85	60.44

TABLE IV (Cont.)

Compound	TOC	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k _{av} ^c
Methyl-3-(1,1,1'-trimethylene-ferrocenyl)-carbinyll acetate	0.00	88	(1.8)	91.5	(13.60 ± 0.09) ^d	14.15 ± 0.37
		89	(4.6)	81	(12.23 ± 0.13) ^d	
		92	3.61	93.5	14.52 ± 0.14	
		98	4.49	87	13.77 ± 0.10	
Methyl-2-(1,1,1'-dimethyl-ferrocenyl)carbinyll acetate, slow isomer	10.00	90	2.97	94.5	(43.00 ± 0.67) ^d	47.27 ± 1.31
		91	1.07	93.5	(43.93 ± 0.54) ^d	
		93	3.45	97	46.38 ± 0.45	
		94	3.40	96.5	48.16 ± 0.23	
Methyl-2-(1,1,1'-dimethyl-ferrocenyl)carbinyll acetate, slow isomer	0.00	124	0.98	46	0.3348 ^d	0.3348
	10.00	131	(2.3)	66	1.066 ± 0.022	
	30.00	122	2.93	90	10.92 ± 0.26	
		123	(1.7)	82	10.02 ± 0.20	
Methyl-2-(1,1,1'-dimethyl-ferrocenyl)carbinyll acetate, fast isomer	0.00	134	2.88	82	3.980 ± 0.041	3.994 ± 0.036
		135	3.33	82	4.007 ± 0.013	
	10.00	132	2.84	81	13.89 ± 0.08	
		133	(2.8)	81	13.68 ± 0.17	
Methyl-2-(1,1,1'-trimethylene-ferrocenyl)carbinyll acetate, slow isomer	30.00	120	(3.4)	67	0.300 ± 0.005	0.297 ± 0.006
		121	3.02	74	0.295 ± 0.003	
	45.00	128	2.75	76	1.713 ± 0.024	
		129	3.15	75	1.696 ± 0.009	
	70.32	130	3.86	79	25.59 ± 1.49	25.59

TABLE IV (Cont.)

Compound	T°C	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k _{av} ^c
Methyl-2-(1,1'-trimethylene-ferrocenyl)-carbonyl acetate, fast isomer	0.00	127	2.23	77	1.528 ± 0.024	1.528
	10.00	136	(1.7)	86	5.071 ± 0.080	5.071
	30.00	125 138	1.48 ^d	97.5 90.5	46.71 ± 0.87 (39.9)	46.71
Methyl(1'-carbomethoxy-ferrocenyl) carbonyl acetate	35.00	84 85	6.15 5.74	61 60	0.428 ± 0.0186 0.4472 ± 0.0024	0.4379 ± 0.0187
	45.00	70 86 87	3.47 3.05 4.76	76 85 83	1.387 ± 0.022 1.386 ± 0.012 (1.447 ± 0.020)	1.394 ± 0.023
	63.50	112 113	2.92 3.20	80 82	10.33 ± 0.40 9.73 ± 0.22	10.03 ± 0.53
Methylruthenocencylcarbonyl acetate	0.00	50 51	3.00 3.62	53 52	0.6224 ± 0.0035 0.6116 ± 0.0044	0.6170 ± 0.0087
	15.00	40 41	2.74 3.86	67 68	4.130 ± 0.019 4.155 ± 0.029	4.142 ± 0.030
	21.30	64 65	2.77 3.31	76 76	8.682 ± 0.050 8.728 ± 0.049	8.705 ± 0.059
(60% Acetone)	30.00	23 24	2.28 2.56	83 83	23.99 ± 0.18 22.45 ± 0.20	23.22 ± 1.105
	0.00	3	2.96	46	13.27 ± 0.38	13.27

TABLE IV (Cont.)

Compound	T ^o C	Run	Conc. ^b 10 ³ m/l	% Followed	10 ⁵ k	10 ⁵ k ^c av
Methylsomoocetylcarbonyl acetate	0.00	49	2.54	91.5	2.910 ± 0.024	2.910
	15.00	42	2.30	73	18.56 ± 0.14	18.56
	30.00	52	1.42	94	91.45 ± 1.57	91.45
Trityl acetate	15.00	37	3.56	61	0.3447 ± 0.0019	0.3420 ± 0.0030
		38	4.55	61	0.3408 ± 0.0020	
		39	5.89	60	0.3405 ± 0.0016	
	30.00	25	4.32	93	2.555 ± 0.032	2.582 ± 0.033
		26	2.96	91.5	2.588 ± 0.014	
		27	5.39	92	2.605 ± 0.011	
	35.00	4	7.29	78	(3.777 ± 0.109)	4.324 ± 0.122
		5	6.92	78	4.397 ± 0.069	
		6	7.42	97	4.251 ± 0.061	
	45.00	31	6.19	95	15.11 ± 0.09	14.90 ± 0.26
		32	5.00	95	14.95 ± 0.10	
		33	3.98	94.5	14.64 ± 0.12	
(60% Acetone)	0.00	2	2.89	81	0.967 ± 0.006	0.967

Notes to TABLE IV.

^aResults in "80%" Acetone unless otherwise noted.

^bInitial concentration of substrate if weighed quantity was used. Figures in parentheses estimated from infinity titers.

^cAverage of runs under identical conditions.

^dSee body of experimental section for discussion of this value.

^eRun consecutively on same sample; see body of experimental section.

TABLE V

Activation Parameters and Relative Rates of Solvolyses

Compound	$k_{300} \times 10^5$	Rel. k_{300}	ΔH	ΔS
Ferrocenylcarbonyl Acetate	1.624	0.0954	20.40 \pm 0.58	-13.2
Methylferrocenylcarbonyl acetate	17.02	1.000	18.97 \pm 0.57	-13.2
Phenylferrocenylcarbonyl acetate	172.38 ^a	10.12	17.29 \pm 0.52	-14.1
Methyl(2-ferrocenylvinyl)carbonyl acetate	10.67	0.626	18.65 \pm 0.34	-15.2
Methyl(3-methylferrocenyl)carbonyl acetate	59.68 ^a	3.51	17.77 \pm 0.35	-14.7
Methyl(1'-methylferrocenyl)carbonyl acetate	33.6 ^a	1.973	18.55 \pm 0.38	-13.2
Methyl(2-methylferrocenyl)carbonyl acetate, slow isomer	5.73	0.376	19.19 \pm 0.54	-14.9
Methyl(2-methylferrocenyl)carbonyl acetate, fast isomer	72.8	4.28	19.40 \pm 0.27	-8.9
α -Acetoxy-1,2-tetramethyleneferrocene, slow isomer (<u>endo</u> -)	0.0282 ^a	0.00165	23.50 \pm 1.3	-11.0
α -Acetoxy-1,2-tetramethyleneferrocene, fast isomer (<u>exo</u> -)	72.1	4.24	18.49 \pm 0.40	-12.0
α -Acetoxy-1,1'-trimethyleneferrocene	0.226	0.0133	22.5 \pm 1.7	-9.7
Methyl-3-(1,1'-dimethylferrocenyl)- carbonyl acetate	108.18 ^a	6.36	17.76 \pm 0.65	-13.5

TABLE V (Cont.)

Compound	$k_{300} \times 10^5$	Rel. k_{300}	ΔH	ΔS
Methyl-3-(1,1'-trimethyleneferrocenyl)-carbinyll acetate	416.5 ^a	24.5	17.98 ± 1.36	-10.1
Methyl-2-(1,1'-dimethylferrocenyl)-carbinyll acetate, slow isomer	10.85	0.636	18.50 ± 0.45	-15.7
Methyl-2-(1,1'-dimethylferrocenyl)-carbinyll acetate, fast isomer	128.8 ^a	7.55	18.48 ± 0.60	-10.8
Methyl-2-(1,1'-trimethyleneferrocenyl)-carbinyll acetate, slow isomer	0.297	0.0174	22.21 ± 0.80	-10.6
Methyl-2-(1,1'-trimethyleneferrocenyl)-carbinyll acetate, fast isomer	46.71	2.74	18.18 ± 0.44	-13.8
Methyl(1'-carbomethoxyferrocenyl)-carbinyll acetate	0.238 ^a	0.0140	21.30 ± 1.13	-11.7
Methylruthenocenylcarbinyll acetate	23.22	1.362	19.34 ± 0.27	-11.4
Methylosmocenylcarbinyll acetate	91.45	5.36	18.54 ± 0.67	-11.2
Trityll acetate	2.58	0.151	22.13 ± 0.70	-6.7

^aExtrapolated from other temperatures.

depending on the relative accuracy of the rate constants. The variance obtained in this manner was generally combined with that calculated between the extreme points, or the two which received the largest weight in the least squares calculation.

In all cases, ΔS^\ddagger was determined for each temperature as an internal check for errors. The average value is recorded in the table.

It is realized that the confidence limits obtained in this manner are extremely crude, and their validity probably varies quite widely between compounds. Nevertheless, they do provide as impartial an estimate of the reliability of the activation parameters as may be obtained simply, and so they may be at least partially justified on this basis.

Activation parameters, rate constants at 30° and relative rate constants at 30° are tabulated in Table V. Following this, any irregularities or points of note in the kinetics are discussed, and the method used for the activation parameter calculation is mentioned for each compound.

Typical kinetic data from three runs are given in Tables VI-VIII.

Ferrocenylcarbonyl acetate. - Activation parameters were calculated by unweighted least squares. The standard deviation in ΔH^\ddagger was obtained by combining that from the least squares treatment (0.52 kcal.) with that calculated from the deviations of the rate constants at 15 and 45° (0.25 kcal.).

Methylferrocenylcarbonyl acetate. - One run each at 0 and 30° were discarded due to large deviations within the runs and from the

mean. The activation energy was determined by the weighted least squares treatment, primarily because of the large deviation (5%) in the rate constant at 35°. The standard deviation was estimated by combining that from the least squares calculation (0.54 kcal.) with that calculated between the rate constants at 0 and 30° (0.18 kcal.).

Solvolyses in "82%" acetone with added sodium acetate or sodium perchlorate showed good kinetic behavior and reproducibility. However, the runs with added sodium hydroxide curved strongly upward, and the infinity titers were larger than the expected values by about 20%. The initial slopes led to rate constants of 12.8 and 15.4 $\times 10^{-5} \text{sec}^{-1}$. Rate constants after completion of half of the reaction were 6.6 and 7.2 $\times 10^{-5} \text{sec}^{-1}$ respectively. The upward curvature and high infinity values were partly due to uptake of atmospheric carbon dioxide by the alkaline solvolysis solution, and so the data were plotted again using theoretical infinity values. This time, rate constants of 21.2 and 19.1 $\times 10^{-5} \text{sec}^{-1}$ were obtained for the first few points, and the plots showed a less pronounced upward curvature. Since these rate constants would include also the rate of uptake of carbon dioxide by the solution, they must be considered maximum values for the initial rate.

Phenylferrocenylcarbonyl acetate gave good straight line plots which agreed well between duplicate runs.

Methyl(2-ferrocenylvinyl)carbonyl acetate. - For run 142 at 30°, a mistake was made on the computer data tape, and so the rate constant determined graphically from the half life was used. No large error is anticipated from this, since a similar rate constant

for the duplicate run agreed with the least squares value within about 1%. The activation energy was calculated between 10 and 42.5°, with a standard deviation of 1.5% assumed for run 144 at 42.5°. The rate constant of $10.44 \times 10^{-5} \text{sec}^{-1}$ at 30° calculated from the activation parameters agreed exactly with run 141, and was 2.2% (0.7 standard deviation) from the average observed value.

Methyl(3-methylferrocenyl)carbonyl acetate. - Infinity titers for runs with material prepared in pyridine (run 81 at 0°, run 80 at 10° and run 77 at 20°) were low by at least 15%. Infinity titers were slightly low also for material prepared with acetic acid, on which a satisfactory analysis was obtained. However, since these two batches of acetate solvolyzed with essentially identical rates, it may be assumed that the primary impurity present was the alcohol or the ether, neither of which should affect the kinetics. The rate constant at 10° calculated from the activation parameters is $6.93 \times 10^{-5} \text{sec}^{-1}$, which agrees within 2% (0.74 standard deviation) with the experimental value.

Methyl(1'-methylferrocenyl)carbonyl acetate. - Activation parameters were calculated from runs at 0 and 20° (assuming a deviation of 1% for run 78 at 20°). The calculated rate constant of $3.560 \times 10^{-5} \text{sec}^{-1}$ at 10° agreed with the experimental value within 0.7%.

Methyl(2-methylferrocenyl)carbonyl acetate. - Mixtures of the two stereoisomeric acetates were first solvolyzed at 30° in runs 87a and b. The rates of the two compounds were readily resolved by extrapolation of the later points to the log(a-x) axis (208). The titers for the faster isomer were determined by the difference

between observed titers and those indicated by the line. The line for the slow isomer was adjusted so as to minimize deviations from both lines. The intercepts with the $\log(a-x)$ axis showed that the slow isomer accounted for 77.1 and 48.9% respectively of the two samples. Since all rate constants were evaluated graphically, no standard deviations were obtained. However, the rate constants for the faster isomer were much more sensitive to variations in the extrapolated line. Since this constant fell very close to the line for $\log k/T$ vs. $1/T$, both constants are probably reasonably accurate.

Separated isomers were used for the remainder of the runs. The activation parameters for the slower isomer were calculated by the unweighted least squares procedure. Standard deviations ΔH^\ddagger of about 0.40 kcal. obtained both from the least squares and from the standard deviations of the 10 and 45° constants were combined to obtain the tabulated standard deviation.

Runs for the fast isomer showed slightly more than the usual amount of scatter, and two points in run 115 at 0° were discarded. Activation parameters obtained from rate constants at 0 and 30° were used to calculate a value of $6.97 \times 10^{-5} \text{sec}^{-1}$ for 10°, which agrees within 1% of the experimental value of $6.90 \times 10^{-5} \text{sec}^{-1}$.

endo- α -Acetoxy-1,2-tetramethyleneferrocene. - All runs except #105 at 45° were performed in sealed ampules. This run was discarded because of inconsistency with the rest of the data and since a large amount of solvent evaporation should be expected. During run #109, some difficulty was experienced with the constant temperature bath. As a result, the reaction was followed for three periods of time, and values of $\log\left(\frac{a-x}{a}\right)$ for all periods were plotted against t . In

this way, the reaction was followed 70% to completion. Run 107 at 80° was performed on a mixture of the two acetates, and was followed after the exo isomer had completely reacted. The infinity titers for this run were not reproducible, and were somewhat higher than expected, so the theoretical infinity value was used. Activation parameters were calculated by the weighted least squares procedure.

exo- α -Acetoxy-1,2-tetramethyleneferrocene. - Run 106 was performed on a mixture of the two diastereomeric acetates prepared in acetic acid. Due to the difference in rates, the solvolysis of the exo isomer proceeded to completion in a period of time in which no reaction of the slower endo isomer could be detected. The other runs were performed on pure exo acetate. Acetate for run 143 was prepared from alcohol recovered from runs 139 and 140. The activation parameters calculated by least squares reproduce the rate constants with an average deviation of 1.5%, and a maximum deviation for run 140 at 25° of 3.5%, indicating a fairly high degree of accuracy.

α -Acetoxy-1,1'-trimethyleneferrocene. - Run 45a at 15° can provide only a very crude estimate of the reaction rate at that temperature, since the reaction was followed to such a low degree of conversion. Run 46 was interrupted after about 25% reaction and then continued the following day as run 47. Since the observed infinity titers agreed well with the predicted values for these two runs, the theoretical infinity titers were used for runs 53 and 54. Only the points for 30 and 45° were used for calculation of the activation parameters.

Methyl-3-(1,1'-dimethylferrocenyl)carbonyl acetate gave good

straight line plots, but differences between duplicate runs were about 3%. Activation parameters calculated from the points at 0 and 24.3° yield a value for the rate constant at 10° of $12.57 \times 10^{-5} \text{sec}^{-1}$, which agrees within 0.6% with the observed value of $12.64 \times 10^{-5} \text{sec}^{-1}$. A deviation of 3% was assumed for run 97 in estimating the error limits of ΔH^\ddagger .

Methyl-3-(1,1'-trimethyleneferrocenyl)carbinyl acetate. - Of three runs (88-90) performed on acetate prepared in acetic acid, two showed a strong drift late in the reaction, and all three failed to give good agreement with runs performed on material prepared in pyridine. For these reasons, and because a large amount of resin was formed in the preparation in acetic acid, these runs were not included in further calculations. Also run 91 at 10°, which was performed on too small a scale to allow accuracy, was disregarded. Even when these runs were discarded, agreement between duplicate runs was good only to about 3%, probably due to the rapidity of the reaction. For these reasons, the values of ΔH^\ddagger and ΔS^\ddagger which were obtained must be considered with reservation.

Methyl-2-(1,1'-dimethylferrocenyl)carbinyl acetate. - In run 124 at 0°, the first point was discarded due to a large deviation from the line. There appeared to be a possible slight upward curvature in the plot. The activation parameters were calculated by the unweighted least squares procedure, and the standard deviation in ΔH^\ddagger was estimated by combining equal values of 0.48 from the least squares and from the standard deviations of the rate constants.

Methyl-2-(1,1'-dimethylferrocenyl)carbinyl acetate, fast isomer. - Good kinetic plots were observed for this compound in all runs

at both 0 and 10°.

Methyl-2-(1,1'-trimethyleneferrocenyl)carbiny l acetate, slow isomer. - Good kinetic plots were obtained for the runs at 30°, but a slight upward curvature raises some doubt about the values observed at 45°. The run at 70.32° (#130) was performed in sealed ampules, and showed quite large scatter. Activation parameters were calculated by the weighted least squares procedure, and the standard deviation obtained in this manner (0.44 kcal.) was combined with that calculated between 30 and 45° (0.68 kcal.) to obtain the tabulated value.

Methyl-2-(1,1'-trimethyleneferrocenyl)carbiny l acetate, fast isomer. - Run 138 at 30°, which was performed roughly on a small sample to check the identity of a recovered alcohol, was not included in further calculations. Activation parameters calculated between 0 and 30° (with assumed 2.5% standard deviation for the rate constants) yielded a value of $5.158 \times 10^{-5} \text{ sec}^{-1}$ for the rate constant at 10°. This agrees with the observed constant within 1.5%.

Methyl(1'-carbomethoxyferrocenyl)carbiny l acetate. - Results for this compound showed somewhat greater scatter and deviations between runs than most of the compounds, probably due to the slowness of the solvolyses. The runs at 63.5° were performed in sealed ampules, while all other runs were done by the usual aliquot technique. Due to evaporation of solvent, the theoretical infinity values were used for runs at 45°. A point included in calculations for run 87 led to an excessively large deviation within the run, so the rate constant estimated from the half-life was substituted. A fourth run at 45° was discarded entirely due to its scatter. Activation parameters calculated from the rate constants at 35 and 63.5° reproduced a value

of $1.399 \times 10^{-5} \text{sec}^{-1}$ for 45° , which agrees within 0.4% (about 0.2 standard deviations) with the experimental constant. An attempt to follow the reaction in 60% acetone failed due to decomposition or precipitation during the run.

Methylruthenocenylcarbinyl acetate gave good straight line plots for all runs. Points for all temperatures fall on the least squares line with a maximum deviation of less than 1%.

Methylosmocenylcarbinyl acetate gave straight line plots in all three runs, but considerably greater scatter was observed for the 30° run, due to the rapidity of the reaction. In a plot of $\log(k/T)$ vs. $1/T$, the 15° point fell off the line determined by the other two temperatures by about 4%. Therefore, the weighted least squares treatment was used to obtain activation parameters. To estimate the standard deviation in ΔH^{\ddagger} , the value from the least squares treatment (0.36 kcal.) was combined with that estimated using twice the deviations observed within the kinetic runs at 0 and 30° (0.57 kcal.).

Trityl acetate. - The activation parameters were determined by the unweighted least squares procedure.

Product recovery from hydrolyses. - Products were isolated from the solvolyses of several of the carbinols by a standard procedure. The portions of solvolysis solutions used for the titrations and the portions remaining in the volumetric flask were diluted with several hundred milliliters of water, and the product was extracted from the aqueous phase with methylene chloride. The organic solution was washed with water three to five times, and where quantities of carbinol were small, the aqueous washes were again extracted with methylene chloride. The methylene chloride was evaporated at reduced

TABLE VI

Run 51. Solvolysis of Methylruthenocenylcarbinyl Acetate,

"80%" Acetone, 0° C.

Sample: 0.1122 g.

Initial concentration: 0.00362 m/l.

<u>Titration</u>	<u>Titer, (x ml. 0.0359 N NaOH)</u>	<u>Titer of unchanged acetate</u>	<u>t (min.)</u>
1	0.018	0.497	16
2	0.022	0.493	38
3	0.042	0.473	169
4	0.052	0.463	227
5	0.076	0.439	342
6	0.136	0.379	750
7	0.218	0.297	1443
8	0.238	0.277	1616
9	0.267	0.248	1902

Infinity titers: 0.515, 0.516 ml.

Theoretical infinity titer: 0.519 ml.

% Followed to completion: 52

Rate constant:

$6.24 \times 10^{-6} \text{ sec}^{-1}$ (unweighted least squares)

$(6.116 \pm 0.044) \times 10^{-6} \text{ sec}^{-1}$ (weighted least squares)

TABLE VII

Run 95. Solvolysis of Methyl-3-(1,1'-dimethylferrocenyl)carbonyl

Acetate, "80%" Acetone, 10° C.

Sample: 0.109 g.

Initial concentration: 0.00366 m/l.

<u>Titration</u>	<u>Titer, (x ml. 0.0368 N NaOH)</u>	<u>Titer of unchanged acetate</u>	<u>t (min.)</u>
1	0.013	0.494	3.5
2	0.068	0.439	18.5
3	0.111	0.396	32.0
4	0.152	0.355	46.0
5	0.195	0.312	63.0
6	0.260	0.247	92.0
7	0.301	0.206	116.0
8	0.320	0.187	130.0
9	0.349	0.158	151.0
10	0.376	0.131	177.0
11	0.405	0.102	207.0

Infinity titers: 0.506, 0.510, 0.506 ml.

Theoretical infinity titer: 0.509 ml.

% Followed to completion: 80

Rate constant:

$1.28 \times 10^{-4} \text{sec}^{-1}$ (est. from plot)

$(1.243 \pm 0.007) \times 10^{-4} \text{sec}^{-1}$ (weighted least squares)

TABLE VIII

Run 102. Solvolysis of Phenylferrocenylcarbinyl Acetate,

"80%" Acetone, 10° C.

Sample: 0.158 g.

Initial concentration: 0.00473 m/l.

<u>Titration</u>	<u>Titer, (x ml. 0.0368 N NaOH)</u>	<u>Titer of unchanged acetate</u>	<u>t (min.)</u>
1	0.054	0.597	1.4
2	0.127	0.524	11.5
3	0.201	0.450	23.5
4	0.262	0.389	34.3
5	0.319	0.332	46.9
6	0.373	0.278	60.9
7	0.424	0.227	75.5
8	0.455	0.196	87.9
9	0.486	0.165	101.7
10	0.515	0.136	118.5
11	0.547	0.104	139.2

Infinity titers: 0.651, 0.652 ml.

Theoretical infinity titer: 0.664 ml.

% Followed to completion: 84

Rate constant:

$2.11 \times 10^{-4} \text{sec}^{-1}$ (est. from plot)

$(2.13 \pm 0.014) \times 10^{-4} \text{sec}^{-1}$ (weighted least squares)

pressure on a water bath which did not exceed a temperature of 50°. Benzene was added, and the evaporation was repeated to yield an oil or a solid. This residue was then frequently chromatographed as described previously for the preparations of the carbinols (see p. 176). It was observed that about 1 mg. of a carbinol could be detected quite readily as a band in the chromatogram. Product recoveries from solvolyses of the various carbinols are briefly discussed below.

Methylferrocenylcarbinyl acetate. - A sample of 0.153 g. (0.56 mmole.) of the acetate was solvolysed in "80%" acetone at 40-45°. The crude product without chromatography weighed 0.096 g. (75%) and melted at 75-77.5° (m.p. pure, 79.5-80°). Recrystallization from hexane raised the melting point to 77.5-78.5°, with a recovery of 52% of the total theoretical yield. None of the ether was noted on chromatography of a portion of the crude product. On another occasion, the visible spectrum of a solvolysis solution was observed. The spectrum was identical with that of the carbinol or the acetate (λ_{\max} 440 m μ , ϵ 100) and did not show any shift to longer wave length or enhancement in intensity such as might be expected for vinylferrocene (in this solvent, λ_{\max} 448 m μ , ϵ 246). No attempt was made to ascertain whether vinylferrocene is hydrated under these conditions.

Phenylferrocenylcarbinyl acetate. - About 65% of crude alcohol was recovered from the remnants of the hydrolyses. This alcohol had m.p. 75-79° (m.p. pure, 80.5-81.2°). A portion chromatographed as usual showed only one band.

Methyl(2-ferrocenylvinyl)carbinyl acetate. - The solvolysis product melted at 86-89° before chromatography (previous melting

point, 91-92°; mixed m.p. 89-91°). On chromatography, a faint band which was not visible on the column passed through rapidly. A weak red-orange band preceding the main band contained no hydroxyl absorption in the infrared. The major orange product band was collected in three fractions. All had infrared spectra identical with the original alcohol.

Methyl(2-methylferrocenyl)carbiny acetate. - Solvolysis solutions for the fast isomer were worked up in the usual manner. Only one band appeared in the chromatogram; infrared spectra of the first and last portions of this band were identical and the same as that of the corresponding alcohol.

Solvolysis solutions for the slow isomer were similarly treated. Since the alcohol corresponding to this acetate is the faster-moving one on chromatography, only the last traces of product leaving the column were investigated by infrared spectroscopy. This spectrum was identical with that of the alcohol corresponding to the acetate.

α-Acetoxy-1,2-tetramethyleneferrocene. - Solvolysis solutions from pure endo (slow) acetate were treated in the customary fashion. The material recovered contained some acetate and ether, which passed rapidly through the column. There was only one alcohol present, and this was shown to be the exo alcohol on the basis of infrared spectrum and solvolysis of acetate prepared from it. On the basis of the quantity of recovered alcohol and the limits of detection in chromatography, the alcohol product was at least 99% exo. In a control run, 0.068 g. of the endo alcohol was heated for 24 hrs. at 80° in "80%" acetone with an equimolar amount of acetic acid. Of this, 0.050 g. was recovered after chromatography. The last fraction of about

0.004 g. was shown by its infrared spectrum to consist partly of exo alcohol. The remainder was pure endo alcohol. On this basis it may be estimated that about 6% of the starting alcohol isomerized under these vigorous conditions.

A product study of the exo acetate solvolysis showed the presence of only exo alcohol.

Methyl-2-(1,1'-dimethylferrocenyl)carbiny l acetate. - Solvolysis of each acetate resulted only in the corresponding carbinol, as shown by infrared spectra of the product from chromatography.

Methyl-2-(1,1'-trimethyleneferrocenyl)carbiny l acetate. - The solvolysis solution from the slow acetate yielded on chromatography a small amount of ether or acetate, and only one alcohol, m.p. 78-79.5°. The corresponding alcohol melted previously at 80-81°.

The solvolysis product from the fast acetate yielded no ether, and only a single alcohol, m.p. 90-91°. The infrared spectrum was identical with that of the alcohol corresponding to this acetate, but that alcohol melted at 160-161.5°. It was later shown that the alcohol melts or undergoes a transition at about 90°, and melts finally at about 160°.

Methyl(1'-carbomethoxyferrocenyl)carbiny l acetate. - The solvolysis product was isolated before chromatography as an orange oil which slowly crystallized under a small amount of pentane. The yield of recovered product is estimated as 75% of theoretical, m.p. 57.2-58.7° (previous m.p. and mixed m.p. 57.5-58.7°). No indication of lactone-formation was noted.

Methylsmocenylcarbiny l acetate. - Solvolysis solutions were worked up after several weeks' standing at room temperature. Ace-

tate was prepared from the crude alcohol in the usual manner in pyridine and acetic anhydride. The product melted at 63.5-65.5° (previous m.p. 67.2-67.7°), and had an infrared spectrum identical with previously prepared material. After one recrystallization from *i*-propyl ether, the product analyzed properly for carbon, hydrogen and osmium (see p. 189).

Alcoholysis of methylferrocenylcarbinyl acetate. - In a preliminary trial, 0.145 g. (0.63 mmole.) of acetate was refluxed in methanol (25 ml.) for 3 hrs. The solvent was removed under vacuum, 50 ml. of benzene was added, and the solvent was again removed to yield an orange oil. The infrared spectrum of this substance exhibited no stretching frequencies in the regions expected for hydroxyl or carbonyl. In a control run, some of the carbinol was treated similarly. The infrared spectrum of the material recovered was similar to that of the starting carbinol.

A more complete study was made of the ethanolysis products. Methylferrocenylcarbinyl acetate was found to hydrolyze at least partially on an alumina column, regardless of the grade of alumina used. Milder adsorbents (magnesium sillicate, calcium carbonate and magnesium oxide) were unsatisfactory due to insufficient retention. The carbinol underwent some ether formation on acid-washed alumina, but on Merck chromatographic alumina which was not designated as acid-washed, the carbinol and its ethyl ether were cleanly separated by elution with a 50-50 mixture of benzene and ether. This procedure was used subsequently to isolate the ether.

A sample of the ethyl ether of methylferrocenylcarbinol was prepared by passing hydrogen chloride gas slowly for about 20 sec.

into a solution of methylferrocenylcarbinol (1.65 g., 7.2 mmole.) in absolute ethanol (100 ml.). The mixture was allowed to stand for 1 hr. in a stoppered flask at room temperature, and then poured into an excess of dilute aqueous sodium acetate. The product was extracted into methylene chloride, the organic phase was washed several times with water, and the solvent was removed at reduced pressure, leaving an orange oil. The oil was chromatographed as described above on 30 g. of alumina, and the product in the major yellow band was transferred to a Hickman-type molecular still. After distillation at 50° and about 5-10 μ , the product had n_D^{25} 1.5743. The infrared spectrum was quite consistent with the structure of the ether, and showed no hydroxyl stretching band.

Anal. Calcd. for $C_{14}H_{18}OFe$: C, 65.14; H, 6.98. Found (E): C, 65.12; H, 7.06.

Methylferrocenylcarbinyl acetate (1.5 g., 5.5 mmole.) was solvolyzed in 300 ml. of refluxing absolute ethanol for 3 hrs. The ethanol was distilled to a small volume, 200 ml. of benzene was added, and again the volume was reduced. The mixture was chromatographed directly as above. Most of the product passed swiftly through the column, leaving behind a small band of the alcohol. After distillation in a Hickman molecular still, the product had n_D^{25} 1.5741, and an infrared spectrum identical with that of the authentic ethyl ether.

In a control run, a sample of methylferrocenylcarbinol (0.5 g., 2.2 mmole.) was treated for an equal period of time in an ethanol solution containing 0.062 ml. (1 mmole.) of acetic acid. Work-up as before by chromatography yielded predominantly the ethyl ether.

A sample of methylferrocenylcarbinyl acetate (0.10 g., 0.37 mmole.)

was refluxed in absolute ethanol (50 ml.). After 1.5 and 6 hrs., 10 ml. aliquots were removed, poured into water, and titrated with 0.0376 N sodium hydroxide. Both titrations required an amount of base 5% in excess of the expected amount (2.00 ml.). In a control run, methylferrocenylcarbinol (0.1 g., 0.43 mmole.) was similarly refluxed with methanol (50 ml.) and ethyl acetate (0.03 g., .35 mmole.). After 6 hrs., titration of a 10 ml. aliquot required 0.07 ml. of base, as compared with the indicator blank of 0.05 ml.

Ethanolysis of α -acetoxy-1,1'-trimethyleneferrocene. - A sample of α -acetoxy-1,1'-trimethyleneferrocene (0.035 g., 0.12 mmole.) was heated at reflux in 50 ml. of absolute ethanol for 2 weeks. Titration of a 10 ml. aliquot required 0.018 mmole. of base, 75% of the theoretical quantity. The end point was quite sharp, and changing from cresol red (pH 7.2-8.8) to thymol blue (pH 8.2-9.6) gave a negligible change in the titer, so it may be safely assumed that the titer was not due to absorbed carbon dioxide.

The remainder of the solution was concentrated to dryness at reduced pressure, and the residue was chromatographed on alumina with 50-50 benzene - ether. Only a fast-moving band of ether was present, and no alcohol was detected.

Solvolysis of tosylate of β -hydroxy-1,1'-trimethyleneferrocene. - Solvolyses were performed on two crops of tosylate (see p. 192). The first of these (first crop from recrystallization, decomposed to tar at 115-120°, not analyzed) was solvolyzed in "80%" acetone at 10° by the usual kinetic procedure. The kinetic plot was consistent with solvolysis of a slow component ($k = 1.20 \times 10^{-5} \text{sec}^{-1}$) and a faster component ($k = 7.1 \times 10^{-5} \text{sec}^{-1}$), although the precision of

the data was insufficient to test this very critically. The rate constant for the slower component is particularly crude. The total acid formed was 65% greater than the amount predicted on the basis of pure tosylate.

The second solvolysis (second crop from recrystallization, darkened with no melting to 160°, analyzed poorly for the tosylate, but showed no chlorine) was performed in "70%" acetone at 10°. The infinity titer was about 70% of that expected, but the kinetic plot gave a fairly straight line ($k = 12 \times 10^{-5} \text{sec}^{-1}$).

For comparison with the solvolysis rates of the two tosylate crops, p-toluenesulfonyl chloride was solvolyzed in "80%" acetone at 10°. (Tosyl chloride solvolyzed was commercial material, purified by washing a benzene solution with aqueous sodium hydroxide, followed by drying the solution over potassium carbonate, concentrating to a small volume and allowing the product to crystallize, m.p. 68-69°). Since the reaction was quite slow, it was followed less than one half life, and the final titer was estimated from the weight of compound solvolyzed. The rate constant estimated from the slope was $0.34 \times 10^{-5} \text{sec}^{-1}$.

The product from the two tosylate solvolyses was isolated by extraction in the customary manner. A solid product was obtained, m.p. 135.5-138.5°. Chromatography revealed only one yellow band of alcohol, m.p. 145-147° (m.p. of β -hydroxy-1,1'-trimethyleneferrocene, 149-150°; mixed m.p. 147.5-149°). The infrared spectrum was identical with that of β -hydroxy-1,1'-trimethyleneferrocene, and differed markedly from that of α -hydroxy-1,1'-trimethyleneferrocene.

Preparation and solvolysis of tosylate of β -ferrocenylethanol. -

A mixture of β -ferrocenylethanol* (0.22 g., 0.96 mmole.), *p*-toluenesulfonyl chloride (0.18 g., 0.95 mmole.) and pyridine (3 ml.) was allowed to react for 24 hrs. at 0°. The solution was poured into excess 2 N sulfuric acid, and the product was extracted into methylene chloride. The organic solution was washed with dilute sulfuric acid, water, and saturated aqueous sodium chloride. The solvent was removed to yield an oil which crystallized. Recrystallization from ethyl acetate - hexane produced 0.147 g. (40%) of orange crystals, m.p. 76-77°. The infrared spectrum lacked hydroxyl adsorption, but possessed bands consistent with a tosylate.

Anal. Calcd. for $C_{19}H_{20}O_3FeS$: C, 59.39; H, 5.25; Fe, 14.54.

Found (S): C, 59.99; H, 5.32; Fe, 14.50.

The tosylate was solvolyzed in two portions. In the first, 0.105 g. of the tosylate was heated at 50° in 80 ml. of 50-50 acetone - water for 12 hrs. In the second, 0.020 g. of the tosylate was heated for a similar time in 8 ml. of the same solvent, with 0.030 g. of solid barium carbonate added. In both cases, the only product isolated was β -ferrocenylethanol. In the former case, this was shown by the identity of the infrared spectra of the first and last traces of material in the single band of the chromatogram.

*Kindly furnished by D. Garwood.

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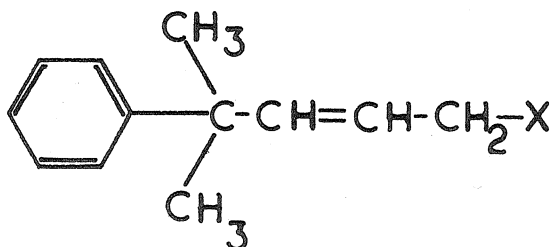
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PROPOSITIONS

1. A study is proposed to investigate possibilities for anchimeric assistance at the γ -position in solvolyses of allylic derivatives. This case is vinylogous to the carefully studied neighboring group participation observed for β -alkyl or β -aryl groups in saturated systems (1). Solvolyses of such compounds as I would be involved in such a study. In particularly favorable cases, rearrangement to the homoallylic isomer might be anticipated.



2. A study comparing the effects of substituents on solvolyses and electrophilic substitution reactions is proposed in a series of derivatives of an electron-rich aromatic system such as thiophene. This study could produce useful results in several areas. First, the solvolyses should proceed through carbonium ions of stability comparable to the trityl cation, but with less bulky substitution about the seat of the reaction. Second, in an aromatic system which is so effective by itself in supplying electrons to a deficient center, the quantitative effects of substituents might well be altered markedly. Little comparative data has been obtained which

permits a satisfactory evaluation of substituent effects. Third, a sufficient measure of success has been observed in correlation of electrophilic reactions in benzene derivatives (2) that it would be of interest to determine the applicability to another system. The study proposed would provide a severe test for such a correlation.

3. Studies of solvolyses of o-biphenylcarbinyl derivatives are proposed. Several results might be anticipated. First, nucleophilic participation by the o-phenyl group might be observed, with the production of fluorenes. Perhaps a carbonium ion so favorably situated sterically might succeed in displacing 2'-substituents such as bromine or carboxy. With 2,6-dimethyl substitution on the second ring, intramolecular hydride abstraction would be sterically favored. Steric and electronic effects on such a rearrangement could be investigated by introduction of suitable substituents.

4. An o-substituted acetophenone or benzaldehyde may exist in either of two coplanar conformations. Interconversion between these two forms will be hindered by conjugation of the carbonyl function with the ring, which introduces a degree of double bond character to the bond joining the carbonyl group to the ring. The position of equilibrium will depend upon the bulk and polar nature of the substituents, both in the o-position and on the acetyl methyl group. The rate of interconversion will depend also upon the conjugative and inductive effects of substituents on the ring. An NMR study of such ketones or aldehydes at reduced temperatures could determine the position and rate of the equilibration (3). The barrier thus

observed to rotation would be a direct measure of the conjugation between the ring and the carbonyl group, and substituent effects might cast light on the magnitude of direct conjugation between the substituent and the carbonyl group through the ring.

5. Several experiments concerning acid-catalyzed decompositions of diazo-compounds are proposed.

A rate-determining proton transfer has been established for the reaction of diphenyldiazomethane in ethanol with strong acids, and for at least a portion of the same reaction with weak acids by determination of the isotope effect in partially deuterated ethanol. (1a, b). The diazonium ion thus formed subsequently loses nitrogen to produce a carbonium ion. The remainder of the reaction with weak acids may proceed through an ion pair or through simultaneous reaction of both the oxygen and hydrogen of the acid with the diazo-compound. Since different isotope effects would be expected for these latter two mechanisms, determination of the isotope effect for both reaction paths with weak acids in deuterated ethanol would be instructive. Identity of the isotope effect for the two reaction paths would support the ion-pair mechanism. Rearrangement of the carbon skeleton during decomposition of a diazo compound can provide evidence for a carbonium ion intermediate (1c). Comparison of the isotope effects in reactions proceeding with rearrangement with those of similarly constituted diazo-compounds which do not rearrange may allow assignment of a carbonium ion mechanism to other decompositions. Finally, the variation of the isotope effect with changes in the diazo compound, with changes in the nature of the proton-donating acid or with changes

in the medium may provide an indication of the nature of the transition state in the proton-transfer process.

Although decomposition of diphenyldiazomethane probably occurs by a rate-determining proton transfer, decomposition of diazoacetic ester proceeds through reversible protonation followed by rate-determining loss of nitrogen (5). The difference in mechanism may probably be ascribed to destabilization of a carbonium ion by the carboxy group. While diphenyldiazomethane is decomposed more rapidly by acid than phenyldiazomethane, a phenyl group increases the decomposition rate of diazoacetophenone (6). Therefore, this compound may be intermediate between the two extremes in reaction mechanism. By varying substituents on the two phenyl groups of this or similar compounds, it may be possible to change the rate determining step of the reaction. Then by extrapolation of the substituent effects into the region where neither step is rate-determining, a rough separation of the rate constants for both steps might be obtained, along with an estimate of the driving force which carbonium ion stability gives to the step in which nitrogen is lost.

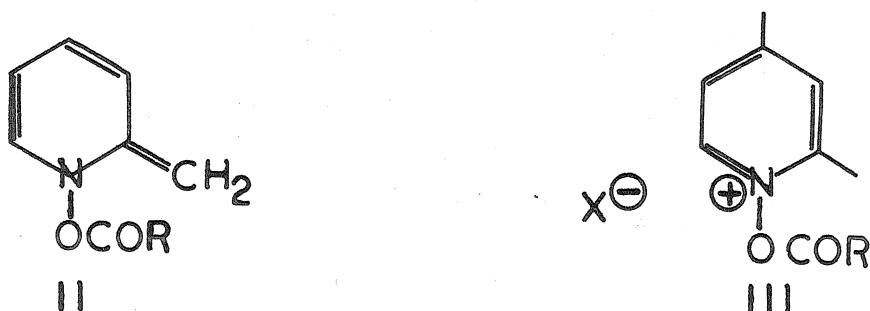
6. The question as to whether electron release by an alkyl group has a favorable or unfavorable influence on an S_N2 reaction has not been properly resolved. The accelerating effect of γ -substituents on reactions of allylic systems (7) or of p -alkyl substituents on reactions of benzylic systems (8) has been cited as evidence that electron release may stabilize the S_N2 transition state (9). However, the suggestion has also been made that the rate enhancement in these systems is due to a large degree of " S_N1 -like" character in the S_N2

transition state (10). An electron-withdrawing substituent such as benzoyl or carbomethoxy in the α -position of such systems should greatly decrease the tendency toward reaction through a carbonium ion, and thus reduce the " S_N1 -like" character of the transition state. The effect observed for γ - or p -alkyl substituents should then be a measure of the effect of electron release or withdrawal upon a reaction of more exclusively " S_N2 character", in which bond-making supplies the predominant driving force.

7. The S_N1 mechanism has never been clearly demonstrated for the hydrolysis of quaternary ammonium salts. A kinetic study of the hydrolyses of such reactive salts as grammine methiodide (11), ferrocenylmethyltrimethylammonium iodide or thienylmethyltrimethylammonium iodide is proposed to determine whether such a mechanism exists.

8. Treatment of a pyridine-1-oxide with a carboxylic acid anhydride results in rearrangement to the corresponding 2-pyridone (12). If an alkyl group is in either the 2- or 4-position, the product is instead the acetate of the corresponding 2- or 4-pyridylcarbinol (13). In the rearrangement of 4-methylpyridine-1-oxide, some 3-hydroxy-4-methylpyridine was isolated (14). The mechanism of the rearrangement of 2-methylpyridine-1-oxide has received some attention. It has been found (15) that free radicals are present in the reaction mixture, but that trapping the free radicals does not decrease the yield of the reaction. Also, an added carboxylate ion does not enter the product. These results have suggested that rearrangement of the anhydro base II occurs either intramolecularly or via an ion or radi-

cal pair mechanism.



The rearrangement to the 2-pyridone might be investigated for free radical intermediates and for intermolecularity by the same general techniques as those used for the rearrangement to the 2-pyridylcarbinols. The course of the reaction when the 2- and 6-positions are both blocked (possibly by halides) might also be investigated.

Rearrangement to the pyridyl carbinols could be looked into further. Competition between 2- and 4-methyl groups would be of interest. Also, the question as to whether proton-removal to form the anhydro base is rate-determining could be investigated by labeling the methyl group with deuterium and performing the reaction in the presence of a proton source. The intramolecularity of the rearrangement to the 4-pyridylcarbinol should also be investigated.

In both rearrangements, a probable intermediate is the salt III. Subsequent rearrangement in either instance may proceed by a cyclic mechanism or by caged ions or radicals. Determination of the disposition of the two oxygen atoms of the cation of the salt by labeling with ^{18}O is proposed. If the two oxygen atoms are equilibrated in the final product, the cyclic mechanism must then be eliminated. If they are not equilibrated, then either a cyclic mechanism or a tightly

oriented ion or radical pair is indicated. This experiment would be of particular interest in the rearrangement of 4-methylpyridine-1-oxide.

9. An activated cyclopropane molecule, formed either by collisional activation or by reaction of a carbene (methylene) with an olefin, can decompose by cleavage of a C-C ring bond and shift of a hydrogen to form an olefin (16,17). Although this reaction has been studied quite extensively, its mechanism is still not securely determined. The near identity of the reaction products from methylcyclopropane from several sources suggests that the excess energy of the activated molecule is transferred between the normal vibrational modes. In this connection, the reaction of vinylcyclopropane with CD_2 from deuterated diazomethane would be of interest. Since the two rings of the activated bicyclopropyl molecule would be distinguishable, it should be possible to estimate the extent to which energy is transferred between the rings by the fraction of the deuterium remaining in the cyclopropane ring of the products (after subtraction of the insertion products). Also of interest might be the kinetics of the thermal decomposition of bicyclopropyl. If the kinetics could be followed at a sufficiently low pressure to observe the change from first- to second-order kinetics, further information could be obtained about the transfer of energy between normal modes (16). (The infrared and Raman spectra should be examined to determine the extent of coupling of vibrations between the two rings.) Activation energies for the decomposition of bicyclopropyl and of vinylcyclopropane, along with the product distributions from these pyrolyses, could be determined.

These results might provide information as to the driving force supplied by the second cyclopropane ring or by vinyl conjugation with a forming free radical.

10. A study of the electron exchange between ferrocene and ferricinium ion, or between this system and other redox couples is proposed. This reaction might be followed by the magnetic resonances of the ring protons, or by the hyperfine EPR splitting of the odd electron of the ferricinium ion. The dependence of this rate upon the bulk of alkyl substituents or upon bridging might provide insight into the manner in which the electron is transferred.

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