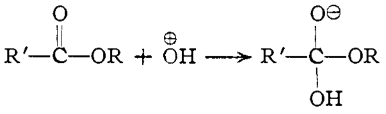
tions allow secondary hydrogen isotope effects to be used as criteria for elucidation of mechanisms of organic reactions. Halevi[10a] has shown that the acid-dissociation constant of phenylacetic acid is greater than that of phenylacetic-α,α-d_2 acid; this difference is due to more effective electron release from the C–D bond than from the C–H bond. This difference in acid-dissociation constants must arise from a difference in the ground states of the two molecules. On the other hand, some experiments[3] show that the heavier hydrogen isotope has a smaller electron release through conjugative mechanisms.

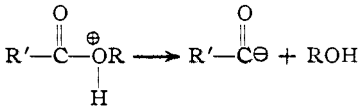
The rate-determining step in the basic hydrolysis of most esters generally is thought to be an attack of a hydroxyl ion on the carboxylate carbon[11]



$$R'-\overset{\overset{O}{\|}}{C}-OR + \overset{\oplus}{OH} \longrightarrow R'-\underset{\underset{OH}{|}}{\overset{\overset{O\ominus}{|}}{C}}-OR$$

Electron-releasing groups attached to the benzene ring of benzoates cause a reduction in the rate of hydrolysis. In this case, the tritium atom in the p-methyl group slows the reaction by its greater ability to release electrons by the inductive process. Since the release of electrons is not demanded by the attacking reagent, the electromeric mechanism is not called into play.

The rate-determining step in the hydrolysis of esters in 99–100% sulfuric acid is thought to be the production of an acylium ion[12]



$$R'-\overset{\overset{O}{\|}}{C}-\underset{\underset{H}{|}}{\overset{\oplus}{O}}R \longrightarrow R'-\overset{\overset{O}{\|}}{C}\ominus + ROH$$

Esters of p-toluic acid react approximately four times as rapidly as corresponding benzoate esters.[13] In this case the electromeric effect probably operates since electron release from the p-methyl group speeds the reaction. If the tritium atom releases electrons less readily than the protium atom, the reaction rate for the labeled molecule would be less than for the ordinary molecule. On the other hand, the greater release of electrons by inductive effect of tritium would cause the reaction to be faster for the tritium-labeled compound. These effects oppose one another, and in this particular case they cancel one another within experimental error. The labeled molecule reacts at the same rate as the ordinary molecule.

Acknowledgment.—The authors are grateful to Professor E. A. Halevi for his interest in this work and for copies of manuscripts of his papers.

[11] C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p. 754.

[12] *Ibid.*, p. 769.

[13] E. D. Hughes and J. Graham, private communication.

STILLWATER, OKLA.

[CONTRIBUTION FROM THE DEPARTMENTS OF CHEMISTRY OF THE ILLINOIS INSTITUTE OF TECHNOLOGY AND BRANDEIS UNIVERSITY]

The Structure and Chemistry of Ferrocene. IV. Intraannular Resonance Effects[1]

BY MYRON ROSENBLUM[2]

RECEIVED FEBRUARY 10, 1959

Both phenylferrocene and 1,1′-diphenylferrocene have been subjected to Friedel–Crafts acetylation, and the structures of the resulting isomeric acetylphenylferrocenes and acetyl-1,1′-diphenylferrocenes have been established. The structures of all the isomers also have been correlated with their infrared and ultravolet absorption spectra. Relative site reactivities for non-equivalent ring positions in phenyl- and in 1,1′-diphenylferrocene have been determined from the proportions in which the various isomers are formed. For phenylferrocene these are 1′:2:3 = 1.1:1.0:1.0, while for 1,1′-diphenylferrocene they are 2:3 = 1.0:1.0. It is suggested that a phenyl substituent inductively deactivates the substituted ferrocene ring toward acylation, but that superimposed resonance effects render positions adjacent to the phenyl substituent relatively more accessible to electrophilic attack than the more remote ring sites.

In a previous communication[3] evidence pertaining to the ring rotational barrier in ferrocene was presented, and it was demonstrated that rotation of the rings with respect to one another was essentially unhindered at normal temperatures in all but the solid state.[4]

In the present paper we consider the general problem of electronic interactions in ferrocene derivatives, and in particular the effect of such interactions in determining the ease and position of entry of an acetyl group into the substituted ferrocene ring during the course of electrophilic substitution.

The acetylation of ethylferrocene (Ia) has been shown to lead to the formation of three isomeric acetyl-ethylferrocenes (IIa, IIIa, IVa).[3] From the proportion in which these isomers are formed, the relative reactivities of each of the non-equivalent ring cites in ethylferrocene were estimated to be 1′:2:3 = 1:1.4:4.2.

The somewhat greater reactivity of both positions within the alkylated ring compared with sites in the unsubstituted ring is most readily understandable in terms of a more effective inductive or hyperconjugative activation of the substituted ring by the alkyl group. Such activation bears a close qualitative analogy with the effect of alkyl substitution on the reactivity of

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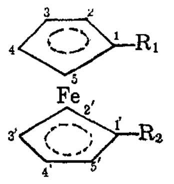
[1] Presented in part at the 133rd Meeting of the American Chemical Society, San Francisco, Calif., April, 1958.

[2] Department of Chemistry, Brandeis University, Waltham 54, Mass.

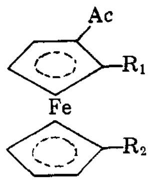
[3] M. Rosenblum and R. B. Woodward, THIS JOURNAL, **80**, 5443 (1958).

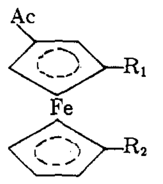
[4] Yu. T. Struchkov, *Zhur. Obshch. Khim.*, **27**, 2039 (1957), has estimated that the potential barrier to rotation of the rings in ferrocene is appreciably higher than in ethane, but somewhat lower than in biphenyl.



Ia, R_1 = Et, R_2 = H
b, R_1 = C_6H_5, R_2 = H
c, R_1 = R_2 = C_6H_5
d, R_1 = R_2 = Me
e, R_1 = R_2 = *i*-Pr

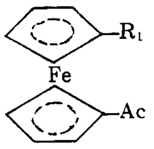
AcCl $\downarrow$ $AlCl_3$

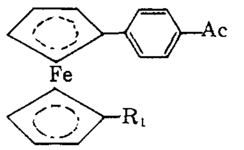




IIa, R_1 = Et, R_2 = H
b, R_1 = C_6H_5, R_2 = H
c, R_1 = R_2 = C_6H_5

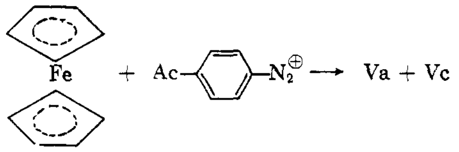
IIIa, R_1 = Et, R_2 = H
b, R_1 = C_6H_5, R_2 = H
c, R_1 = R_2 = C_6H_5





IVa, R_1 = Et
b, R_1 = C_6H_5

Va, R_1 = H
b, R_1 = C_6H_5
c, R_1 = *p*-Ac-C_6H_5



benzenoid aromatics in electrophilic substitution processes.

While the greater reactivity of sites within the alkylated ring is best attributed to unequal electronic activation by the ethyl substituent of each of the aromatic rings, steric factors may be expected to play a more important, if not predominant, role in determining the course of homoannular acetylation. The importance of such factors is perhaps best illustrated in the decreasing ratio of 1,2- to 1,3-acetyl-alkylferrocenes formed in these reactions as the steric requirement of the alkyl group is increased. Thus, the ratios of 1,2- to 1,3-acetyl-alkylferrocenes formed in the acetylation of 1,1′-dimethylferrocene (Id) and 1,1′-diisopropylferrocene (Ie) have been reported by Rinehart, Motz and Moon to be 1 : 2.3 and 1 : 4.3, respectively.[5]

With these considerations in mind, we sought to define the electronic effects of a substituent upon the reactivity of sites within a substituted ferrocene ring, through acylation of *p*-substituted phenylferrocenes. In such derivatives resonance effects may be expected to be appreciably greater than in the alkylferrocenes. Moreover, the magnitude as well as the sense of these interactions might be altered independently without substantially changing the steric demands of the substituent. In the present report the results obtained in a study of the acetylation of both phenylferrocene and 1,1′-diphenylferrocene are set forth.

Acetylation of phenylferrocene (Ib) in the presence of acetyl chloride and aluminum chloride, yielded three acetyl-phenylferrocene isomers (m.p.'s 73°, 93° and 114°) which must possess structures IIb, IIIb and IVb. In addition to these substances, a very small amount (approximately 1% of the product weight) of a fourth substance, m.p. 176°, isomeric with the above disubstituted ferrocene derivatives, was isolated by careful chromatographic purification of the reaction mixture. Its carbonyl absorption peak lay at distinctly shorter wave length (5.98 μ) than those of the remaining isomers (6.03 μ). Furthermore, the presence of very intense absorption at 6.24 μ in the spectrum of this isomer, characteristic of a C_6H_5CO grouping, contrasted with the very moderate phenyl absorption at this wave length in the spectra of the other isomers. These observations suggested its structure to be that of an acetylphenyl substituted ferrocene. The identity of this substance with *p*-acetylphenylferrocene (Va) was established by comparison with a sample of Va prepared from ferrocene and diazotized *p*-aminoacetophenone according to the general procedure of Broadhead and Pauson.[6]

It may be noted that the formation of this substance in substantially lower yield than that of the remaining acetyl-phenylferrocene isomers is indicative of the considerably greater reactivity of the ferrocene nucleus compared with benzene in electrophilic substitution processes.[7]

The structural identity of each of the acetyl-phenylferrocene isomers was established in the following manner. Of the three substances, only that melting at 92–93° failed to exhibit absorption in the infrared near 9 and 10 μ, characteristic of an unsubstituted ferrocene ring.[8] It must therefore possess structure IVb (1-acetyl-1′-phenylferrocene).

Before taking up the question of structural assignments for the remaining homoannularly disubstituted isomers IIb and IIIb, it is necessary to consider briefly the results obtained in a study of the acetylation of 1,1′-diphenylferrocene (Ic). Treatment of this substance with acetyl chloride and aluminum chloride led, as anticipated, to three isomeric acetyl-diphenylferrocenes. One of these, m.p. 151–152°, is formed in very low yield and may be assigned the structure of 1-*p*-acetylphenyl-1′-phenylferrocene (Vb) on the basis of its infrared spectrum. In particular, the spectrum of this substance is a composite of the spectrum of *p*-acetylphenylferrocene (Va) and of phenylferrocene (Ib), and lacks only the two bands near 9 and 10 μ present in the spectra of the latter substances.

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[5] K. L. Rinehart, K. L. Motz and S. Moon, THIS JOURNAL, **79**, 2749 (1957).

[6] G. D. Broadhead and P. L. Pauson, *J. Chem. Soc.*, 367 (1955).

[7] For other qualitative evidence bearing on this point, *cf.* M. Rosenblum, *Chemistry & Industry*, 72 (1957); P. L. Pauson, *Quart. Revs.*, **9**, 351 (1955), and ref. 5.

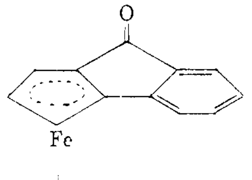
[8] M. Rosenblum, Ph.D. thesis, Harvard University, August, 1953. For subsequent references to and examples of this generalization *cf.* P. L. Pauson, THIS JOURNAL, **76**, 2187 (1954); K. L. Rinehart, K. L. Motz and S. Moon, *ibid.*, **79**, 3420 (1957); A. N. Nesmeyanov, L. A. Kazitsina, B. V. Lokshin and I. I. Kritskaya, *Doklady Akad. Nauk, S.S.S.R.*, **117**, 433 (1957); M. Rosenblum and R. B. Woodward, ref. 3.

We have discussed previously the additive nature of the spectra of ferrocene derivatives and the application of this principle in the elucidation of the structures of various ferrocene derivatives.[9]

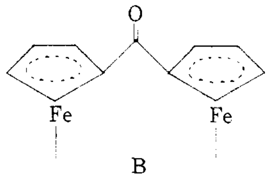
The comparative ease with which the isomeric acetyl-diphenylferrocenes (IIc and IIIc) could be separated chromatographically, contrasting with the experimental difficulties attending the separation of the acetyl-phenylferrocene isomers (IIb, IIIb, IVb and Va), recommended the structural elucidation of these substances in preference to the latter ferrocene derivatives. Thus, although *p*-acetylphenylferrocene (Va) and 1-acetyl-2-phenylferrocene (IIb) were separated readily from one another and from the remaining isomers, these latter substances (IIIb and IVb) were only partially resolved by the alumina column when 2.20 g. of the reaction mixture was placed on 3.0 kg. of alumina and eluted continuously with Skellysolve B for a period of approximately four months.[10]

The elucidation of the structures of each of the acetyl-diphenylferrocenes (IIc and IIIc) was effected by taking advantage of the presence of the phenyl group in these derivatives and of its proximity to the acetyl function in isomer IIc alone. That isomer (an oil), believed to possess structure IIc on the basis of its infrared spectrum (*vide infra*), was converted by treatment with hypochlorite to the corresponding diphenylferrocenecarboxylic acid (VI). This substance was converted, without purification, to the acid chloride VII. Treatment of the acid chloride with aluminum chloride yielded a neutral ketonic substance (VIII), m.p. 123–126°, which exhibited infrared absorption in the carbonyl region at 5.90 μ.

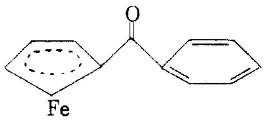
Of the three carbonyl chromophores capable of formation (A, B or C) the spectral evidence is consistent with A alone.



A



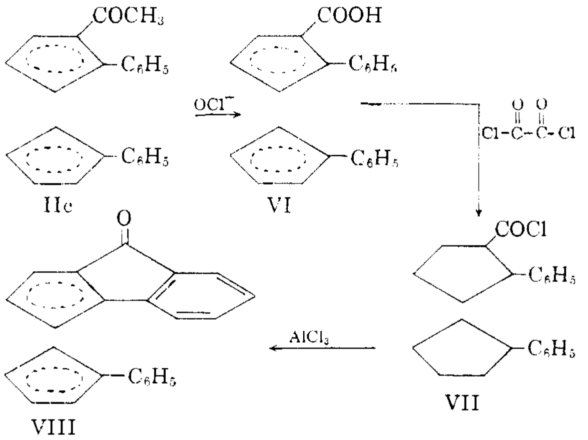
B



C

Diferrocenyl ketone, possessing chromophore B, exhibits carbonyl absorption at 6.20 μ,[11] while benzoylferrocene, exemplified by carbonyl chromophore C, exhibits absorption at 6.09 μ. We may anticipate that the inclusion of this latter chromophore within a strained five-membered ring as in A would lead to an appreciable decrease in the wave length of carbonyl absorption. Benzophenone exhibits carbonyl absorption at 6.02 μ[12] while the carbonyl peak of fluorenone is at 5.82 μ.[13] The decrease in wave length of carbonyl absorption observed in constraining a benzoylferrocene carbonyl chromophore within a five-membered ring is thus closely parallel to that observed in the relevant benzenoid analogs.

The degradative evidence permits the assignment of structure IIc to the non-crystalline acetyl-diphenylferrocene isomer. The second isomer, m.p. 113°, must then possess structure IIIc. Furthermore, these assignments allow the structural identification of the two remaining acetyl-phenylferrocene isomers. On the basis of their infrared spectra, the isomer melting at 73° may be assigned structure IIb, while that melting at 114° must possess structure IIIb.



Site Reactiviites.—The relative reactivities of each of the non-equivalent ring sites in phenylferrocene and in 1,1′-diphenylferrocene were determined both by chromatographic and by ultraviolet absorption analysis of the reaction mixtures. Relative site reactivities for phenylferrocene could not be determined directly by chromatographic analysis owing to the difficulties encountered in attempts to separate isomers IIIb and IVb. These reactivities were instead calculated from the combined yield of IIIb and IVb, the yield of isomer IIb and the relative yields of isomers IIc and IIIc. These latter two substances were separated readily from one another on alumina, employing one kilogram of adsorbent per gram of mixture. The agreement between the values of site reactivities determined by chromatographic analysis and those determined subsequently by spectroscopic analysis is in all cases good. These figures are recorded in Table I.

The data of Table I present a significant contrast with those obtained from the acetylation of ethylferrocene. Firstly, whereas an ethyl substituent was observed to facilitate acetylation within the substituted ring, the effect of a phenyl substituent is to retard such a process, although very slightly. Steric interactions alone clearly can not account for such an effect, since the relatively unhindered 3-position as well as those sites adjacent to the phenyl group are each less reactive than

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(9) M. Rosenblum (ref. 8, p. 64), and *Chemistry & Industry*, 953 (1958).

(10) We are deeply indebted to Mr. Vincent Story for his assistance in maintaining continuous operation of the chromatographic column during this period.

(11) E. Cendes, private communication.

(12) H. W. Thompson and P. Torkington, *J. Chem. Soc.*, 640 (1945).

(13) M. L. Josien and N. Fuson, *Bull. soc. chim. France*, 389 (1952).

TABLE I

RELATIVE SITE REACTIVITIES FOR THE ACETYLATION OF PHENYLFERROCENE AND 1,1'-DIPHENYLFERROCENE

Ring positions in 1,1'-diphenylferrocene	Relative site reactivities A^a	B^b
2	1.1	1.0
3	1.0	1.0
para	0.01	..[d]
Ring positions in phenylferrocene		
1'	1.1[c]	1.2
2	1.0	1.0
3	1.0	1.0
para	*ca.* 0.008	..[d]

[a] Relative site reactivities determined by chromatographic analysis. [b] Relative site reactivities determined by spectroscopic analysis. [c] Determined on the basis of the assumption that isomers IIb and IIIb are formed in a ratio identical with that of IIc to IIIc. [d] The amount of *p*-acetylphenyl substituted ferrocenes present in the reaction mixture was neglected in the spectroscopic analysis.

positions within the unsubstituted ring. Instead the observations suggest inductive deactivation of the phenylated ferrocene ring by the substituent, an effect similar to that encountered in halogenated benzenoid systems. Such an interpretation is, moreover, consistent with the observed electron-withdrawing character of the phenyl substituent in biphenyls.[14] For the phenylated ferrocenes, the existence of a dipole associated with the bond joining the two aromatic rings is further supported by the observation that the dipole moment of *p*-chlorophenylferrocene is 2.09 D.,[15] while those of chlorobenzene and of *p*-chlorobiphenyl are 1.58[16] and 1.66 D.,[16] respectively.

Of particular interest with regard to the question of intraannular resonance effects in ferrocene derivatives is the alteration in the relative reactivities of the 2- and 3-positions within the substituted ring when an alkyl group is replaced by a phenyl substituent. For the alkylated ferrocenes the reactivity of the 2-position approaches that of the 3-position as the steric requirement of the alkyl group is diminished. However, even for 1,1'-dimethylferrocene, wherein steric hindrance at positions adjacent to the alkyl group is reduced to a minimum, the reactivity of these sites remains significantly less than that of the 3-positions.[5] It would appear highly unlikely that the equivalence of these site reactivities in the phenyl substituted ferrocenes can be attributed to lower steric requirements of a phenyl group compared with those of a methyl substituent.[17] Furthermore, the difference in electronegativities of a methyl and a phenyl substituent is such that inductive deactivation rather than activation of the ring positions more proximate to the phenyl group would be anticipated.[18] Instead, the results strongly suggest that electrophilic substitution at ring sites adjacent to the phenyl substituent involves a transition state more highly stabilized by resonance interactions with the substituent than does the alternate process which results in the introduction of an acetyl function at the 3-positions of the substituted ring.

Infrared Spectra.—The infrared spectra of ferrocene derivatives constitute an important source of information regarding not only the character of substituent groups in polysubstituted ferrocenes, but their relative disposition as well. Earlier we drew attention to the fact that ferrocene derivatives possessing an unsubstituted ring could in general be differentiated from those in which both rings were at least monosubstituted by the appearance of moderately intense absorption peaks near 9 and 10 μ in the spectra of the first class of derivatives, and the absence of one or both of these peaks in the latter class of derivatives.[3,8] More recently, it was suggested that the isomeric 1,2- and 1,3-homoannularly disubstituted acetylalkylferrocenes also could be identified on the basis of their infrared spectra.[5,9] Those isomers possessing a 1,2-orientation of such groups within a ferrocene ring were shown to exhibit moderate absorption at 10.85 μ, while derivatives in which the substituents were 1,3 disposed possessed a doublet absorption near 10.85 and 11.05 μ. Subsequently, the preparation and structural elucidation of the ferrocene derivatives reported herein made it possible to extend these correlations to encompass these substances as well.[9] Data relevant to these observations are summarized in Table II.

For the acetyl-phenylferrocenes, the absorption band which characterizes the 1,2-isomers is displaced to 10.96 μ, while the doublet associated with a 1,3-disposition of the substituents is shifted to 11.05 and 11.15 μ. In addition to these bands, those phenylated ferrocenes in which a ferrocene ring is singly substituted by a phenyl substituent exhibit further absorption near 11.27 μ. While the present data do not allow a certain assignment for these bands, it is of interest to note that the symmetric C–H out-of-plane bending mode in benzenoid aromatics gives rise to absorption peaks in the region of 12–15 μ, the positions of which have

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(14) *Cf.* for example P. B. D. de la Mare and M. Hassan, *J. Chem. Soc.*, 3004 (1957); and H. C. Brown, Y. Okamoto and T. Inukai, THIS JOURNAL, **80**, 4964 (1958).

(15) We are greatly indebted to Professor M. T. Rogers of Michigan State University for the determination of the dipole moment of *p*-chlorophenylferrocene.

(16) J. W. Smith, "Electric Dipole Moments," Butterworths Scientific Publications, London, 1955, p. 221.

(17) The comparative effectiveness of a phenyl and of a methyl substituent in retarding *ortho* acylation in benzenoid systems is difficult to assess, since these reactions appear to be characterized by a relatively high steric sensitivity, and consequently the yields of such products, if any, have not generally been reported; *cf.* for example R. Adams and C. R. Noller in "Organic Syntheses," Coll. Vol. I, John Wiley and Sons, Inc., New York, N. Y., p. 111, and L. M. Long and H. R. Henze, THIS JOURNAL, **63**, 1939 (1941). For electrophilic substitution reactions such as chlorination, nitration and bromination, which exhibit a lower steric sensitivity, the ratio of *ortho* to *para* substitution product is always greater for toluene than for biphenyl. For non-catalyzed chlorination reactions, *cf.* H. C. Brown and L. M. Stock, *ibid.*, **79**, 5175 (1957), and C. M. Segura Savoy and J. L. Abernethy, *ibid.*, **64**, 2219 (1942). For nitration reactions, *cf.* W. W. Jones and M. Russell, *J. Chem. Soc.*, 921 (1947); P. P. Sherygin, A. V. Topchieu and V. A. Anan'ina, *J. Gen. Chem. U.S.S.R.*, **8**, 981 (1938); G. Schultz, H. Schmidt and H. Strafser, *Ann.*, **207**, 352 (1881), and F. Bell, J. Kenyon and P. H. Robinson, *J. Chem. Soc.*, 1242 (1926). For bromination reactions, *cf.* H. C. Brown and L. M. Stock, THIS JOURNAL, **79**, 1421 (1957), and R. E. Buckles, E. A. Hausman and N. G. Wheeler, *ibid.*, **72**, 2494 (1950).

(18) J. D. Roberts, R. A. Clement and J. J. Drysdale, *ibid.*, **73**, 2181 (1951).

TABLE II

Ferrocene derivative	Characteristic absorption peaks, μ[a]						
Phenylferrocene	11.27	. . .	. . .	. . .	10.00	9.07	. .
1-Acetyl-1′-phenyl-	11.27	11.19	. . .	. . .	. . .	. .	8.98
1-Acetyl-2-phenyl-	. . .	. . .	. . .	10.96	9.99	9.05	. .
1,1′-Diphenyl-2-acetyl-	11.28	. . .	. . .	10.97	. . .	. .	. .
1-Acetyl-3-phenyl-	. . .	11.17	11.05	. . .	10.00	9.06	. .
1,1′-Diphenyl-3-acetyl-	11.30	11.15	11.05	. . .	. . .	. .	. .

[a] Spectra were determined in chloroform solution.

been shown to be characteristic of the disposition of substituents on the aromatic ring.[19]

The spectra of acetyl- and 1,1′-diacetylferrocene, and in general all those ferrocene derivatives in which the acetylated ring is unencumbered by further substitution, exhibit two medium intensity bands near 8.97 and 11.17 μ, in addition to a strong absorption peak near 6.9 μ. The former two bands are not present in the spectra of derivatives in which an alkyl substituent occupies a position within the acetylated ring.[9] These peaks are shifted only slightly to 8.93 and 11.35 μ in the spectrum of trideuterioacetylferrocene[20] and occur at 9.12 and 11.35 μ in the spectrum of 1,1′-dipropionylferrocene. As for the homoannularly disubstituted acetyl-phenylferrocenes, both 1-acetyl-2-phenyl- and 1,1′-diphenyl-2-acetylferrocene fail to exhibit either of these peaks characteristic of an acetylated ferrocene ring. The spectra of the 1,3-isomers similarly lack absorption at 8.93 μ, but do exhibit a peak near 11.17 μ, which has been associated with the doublet characteristic of the 1,3-grouping of the substituents.

The relatively intense absorption peak near 6.9 μ, characteristic of a ferrocene ring bearing an acetyl substituent alone, remains invariant in both position and intensity in trideuterioacetylferrocene, and hence cannot be attributed to a C–H deformation mode of the acetyl function. Further evidence in support of this view is seen in the fact that formylferrocene,[21] ferrocenecarboxylic acid,[22] 1,1′-dicarbazidoferrocene[21] and chlorocarbonylferrocene[21] possess moderate to strong absorption at this wave length. The 6.9 μ band shifts to somewhat longer wave length (0.1–0.2 μ) in the spectra of homoannularly disubstituted acetylethylferrocenes and acetylphenylferrocenes, the displacement being greatest for the latter substances and for the 1,2-isomers within each of these groups of derivatives.

Ultraviolet Spectra.—Absorption maxima in the region of 200–300 mμ, which characterize the isomeric acetyl-phenyl- and acetyl-1,1′-diphenylferrocenes are recorded in Table III.

TABLE III

Ferrocene derivative	λ_{max}, mμ[a]	E_{max}	λ_{max}, mμ	E_{max}
Phenylferrocene	238	17,600(16,100)[d]	278	10,600(9,900)
1,1′-Diphenylferrocene	239	24,700(18,700)[d]	281	16,500(14,400)
1-Acetyl-2-phenyl-	227	17,400	265	11,500
1-Acetyl-1′-phenyl-	236	16,500	267	10,500
1-Acetyl-3-phenyl-	245	23,600	270[b]	11,300
1,1′-Diphenyl-2-acetyl-	235	26,200	265	19,200
1,1′-Diphenyl-3-acetyl-	237	24,900	270[b]	19,400
	253	25,400		
p-Acetylphenyl-	266	11,500	304	18,500
1-Acetyl-2-ethyl-	225	18,600	268	7,100
1-Acetyl-1′-ethyl-	228	15,100	270	5,800
1-Acetyl-3-ethyl-	230	15,100	272	6,500
Acetylferrocene	225	14,600(16,500)[c]	268	5,400(6,500)[c]

[a] All spectra were determined in 95% ethanol solution. [b] This peak is not resolved, but occurs as a shoulder on the lower wave length peak. The point of inflection in the curve has been taken as λ_{max} [c] Ref. 5. [d] V. Weinmayr, THIS JOURNAL, **77**, 3012 (1955).

The values of λ_{max} for the isomeric acetyl-phenyl- and acetyl-diphenylferrocenes reveal a rather interesting correspondence with those of the acetyl-ethylferrocene isomers. For the acetyl-phenylferrocenes, the low wave length absorption peak near 230 mμ is shifted progressively to longer wave length as the disposition of chromophoric groups on the rings is changed from 1,2 to 1,1′ to 1,3. This is the same order observed for the acetyl-ethylferrocenes, although the difference in λ_{max} between successive members of the acetyl-phenylferrocene series is somewhat greater (9 mμ) than it is for the acetyl-ethylferrocene isomers (2 mμ). Furthermore, the difference of 18 mμ in the short wave length maxima of the 1,2- and 1,3-acetyldiphenylferrocenes corresponds very closely to the separation of these maxima in the related 1,2- and 1,3-acetyl-phenylferrocene isomers. A very similar regularity may be observed for these isomers at the higher wave length maxima in the region of 270 mμ, although here the shift in maxima is not as great in magnitude as for the lower wave length peaks.

We have previously drawn attention to the correspondence between the structures of isomeric acetyl-ethylferrocenes and their relative absorbabilities on alumina.[3] The order of increasing adsorbability was found to be: 1-acetyl-2-ethylferrocene, 1-acetyl-1′-ethylferrocene, 1-acetyl-3-ethylferrocene. Moreover, the difference in adsorbability between the first two of these substances was considerably greater than that between the latter two isomers. The qualitative differences in the adsorption properties of these isomers was observed to be maintained for the isomeric ethyl-

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(19) H. L. McMurry and V. Thornton, *Anal. Chem.*, **24**, 318 (1952); C. G. Cannon and G. B. B. M. Sutherland, *Spectrochim. Acta*, **4**, 373 (1951). *Cf.* also E. R. Lippincott and R. D. Nelson, *ibid.*, **10**, 307 (1958), for a comparison of the force constants for the C–H out-of-plane bending mode in ferrocene and in benzene.

(20) This substance was prepared by base-catalyzed exchange with D_2O. Although the vibrational modes responsible for the absorption peaks at 8.97 and 11.17 μ are *not* identifiable, they clearly can not be C–H modes associated with the acetyl group.

(21) M. Rosenblum (ref. 7); P. J. Graham, R. V. Lindsey, G. E. Parshal, M. L. Peterson and G. M. Whitman, THIS JOURNAL, **79**, 3416 (1957); J. K. Lindsay and C. R. Hauser, *J. Org. Chem.*, **22**, 355 (1957); F. D. Broadhead, J. M. Osgerby and P. L. Pauson, *Chem. and Ind.*, 209 (1957).

(22) M. Rosenblum (ref. 9); R. A. Benkeser, D. Goggin and C. Schroll, THIS JOURNAL, **76**, 4025 (1954); A. N. Nesmeyanov, F. G. Perevalova and Z. A. Beinoravichute, *Doklady Akad. Nauk, S.S.S.R.*, **112**, 439 (1957).

1,1′-diacetylferrocenes as well as for the acetyl-1,1′-dimethyl- and acetyl-1,1′-diisopropylferrocenes reported by Rinehart.[5] These same regularities persist for the acetyl-phenyl- and acetyl-1,1′-diphenylferrocene isomers reported herein. Thus, 1-acetyl-2-phenylferrocene precedes and is relatively easily separated from 1-acetyl-1′-phenylferrocene and from 1-acetyl-3-phenylferrocene, which follow in that order, when mixtures of these substances are subjected to chromatographic purification. Similarly, when mixtures of 1,1′-diphenyl-2-acetyl- and 1,1′-diphenyl-3-acetylferrocene were chromatographed, the 1,2-isomer separated readily from the 1,3-isomer and was eluted first from the column.

While these qualitative observations clearly can not be adduced as structural evidence, they nevertheless appear to constitute a useful guide in the elucidation of structures for closely related ferrocene derivatives.

In this connection, it is of interest to note that 1,2-diacetylferrocene,[3,23] formed in low yield in the acetylation of ferrocene, is eluted before 1,1′-diacetylferrocene, the major product of the reaction.

Acknowledgment.—This investigation was supported by a research grant (RG-4772) from the National Institutes of Health, Public Health Service.

Experimental[24]

Phenylferrocene (Ib) and 1,1′-Diphenylferrocene (Ic).—The general procedure described by Broadhead and Pauson[6] was employed for the preparation of these substances. A solution of diazotized aniline prepared from 7.5 g. of aniline (0.08 mole), 5.8 g. of sodium nitrite (0.09 mole), 5 cc. of concentrated sulfuric acid and a minimum amount of water, was added rapidly to a stirred solution of 10 g. of ferrocene (0.054 mole) in 400 cc. of acetic acid. After allowing the reaction to proceed overnight at room temperature, the resulting dark brown solution was poured into approximately one liter of water and then was treated with bisulfite to reduce ferricinium and phenyl ferricinium salts. The aqueous solution was extracted several times with ether and the combined ether extracts were washed several times with water, carbonate solution and finally again with water. Solvent was removed, leaving 13 g. of dark brown, partly crystalline oil. Steam distillation of the crude product gave 1.4 g. of unreacted ferrocene. The residue was taken up in ether, and the solution was dried over magnesium sulfate. After removal of solvent, the crude mixture was taken up in Skellysolve B and chromatographed on 600 g. of Merck alumina. Elution was carried out with Skellysolve B. In this manner 5.35 g. of phenylferrocene, m.p. 90–100°, and 0.80 g. of 1,1′-diphenylferrocene, m.p. 156–157°, was obtained (lit.[25] m.p. 154°). Recrystallization of the crude phenylferrocene from ether–Skellysolve B solution gave 5.0 g. of this substance, m.p. 114–115° (lit.[25] m.p. 109–110°).

The disubstituted substance can be made the major product of the reaction, by employing a twofold excess of the diazonium salt and by carrying out the reaction at 0°.

***p*-Acetylphenylferrocene (Va) and 1,1′-Bis-*p*-acetylphenylferrocene (Vc).**—A solution of diazotized *p*-aminoacetophenone was prepared from 34 g. of *p*-aminoacetophenone (0.25 mole), 20 g. of sodium nitrite (0.30 mole) and 8.3 cc. of concentrated sulfuric acid, in 150 cc. of water. This was added rapidly to a solution of 10 g. of ferrocene (0.054 mole) in 350 cc. of acetic acid. The dark brown solution was allowed to stir overnight at room temperature, and then was poured into approximately one liter of water. The aqueous solution was treated with bisulfite, and then extracted several times with a mixture of ether and chloroform. Purification of the crude reaction product and separation of the components was effected by chromatography on 300 g. of neutral, grade two, Woelm alumina, with isolation of these various compounds: ferrocene, 0.7 g.; acetophenone,[26] identified as its dinitrophenylhydrazone, 1 g.; *p*-acetylphenylferrocene (Va), m.p. 176–178°, 0.075 g.; and 1,1′-bis-*p*-acetylphenylferrocene (Vc), m.p. 243–245° dec., 0.90 g.

Anal. Calcd. for $C_{18}H_{16}OFe$: C, 71.07; H, 5.30; Fe, 18.36. Found: C, 71.07; H, 5.22; Fe, 18.17. Calcd. for $C_{26}H_{22}O_2Fe$: C, 73.95; H, 5.25; Fe, 13.23. Found: C, 74.25; H, 5.38; Fe, 13.51.

Acetylation of Phenylferrocene (Ib). Formation of Isomeric Acetylphenylferrocenes IIb, IIIb, IVb and Va.—Phenylferrocene (2.0 g., 7.65 mmoles) was dissolved in approximately 75 cc. of dry methylene chloride. To this solution was added 1.02 g. (7.6 mmoles) of sublimed aluminum chloride. The mixture was cooled in an ice-bath and kept under an atmosphere of dry nitrogen. Freshly distilled acetyl chloride (0.79 g.) in approximately 25 cc. of dry methylene chloride was added to the reaction mixture over a period of 30 minutes. The reaction was allowed to proceed at 0° for a period of three hours and then at room temperature for an additional hour. The dark purple solution then was cooled in an ice-bath and poured into water. The organic phase was withdrawn and the aqueous phase then was treated with bisulfite and extracted several times with ether. The organic solutions were combined, washed with water to neutrality and dried over magnesium sulfate. Removal of solvent left 2.29 g. of partially crystalline, dark red oil. This product was taken up in 500 cc. of Skellysolve B and placed on a chromatograph column prepared from 3.0 kg. of neutral, grade 2 Woelm alumina. Elution was carried out with Skellysolve B.

After one week of continuous elution, the first band consisting of recovered phenylferrocene had been collected. The crude product weighed 221 mg. and after recrystallization from Skellysolve B gave a total of 95 mg. of product, m.p. 113–114°, identical by mixed m.p. determination with phenylferrocene.

A second colored band followed the above fraction, but due to the high dilution on the column it was barely visible. This fraction was collected after approximately 3 weeks of elution. It was rechromatographed on 250 g. of alumina, using ether as eluent, in order to separate it from a high boiling oil which accompanied this and other fractions and which appears to be present in small concentrations in the solvent. In this manner 15.6 mg. of product was isolated, which after one recrystallization from ether–Skellysolve B solution gave 8.5 mg. of substance, m.p. 86–87°, identical by mixed m.p. determination with acetylferrocene.

p-Acetylphenylferrocene (Va) was not isolated in this experiment, but in a previous run chromatographic purification of 1.02 g. of crude acetylation product gave, after one recrystallization from ether–petroleum ether solution, 4 mg. of a substance, m.p. 174–176°, which proved by mixed m.p. determination to be identical with *p*-acetylphenylferrocene prepared from ferrocene and diazotized *p*-aminoacetophenone.

The third band began to come through the column after approximately eight weeks of elution and was collected over a period of two weeks. A total of four fractions were cut (approximately 80 liters each). These were combined and rechromatographed twice more, once on 300 g. of alumina, using petroleum ether–benzene (4:1) as eluent, and again on 100 g. of alumina employing ether as eluent. Removal of solvent left 169 mg. of red oil, which on standing for several days began to crystallize. The product was triturated with ether and in this manner 152 mg. of amber colored octahedral crystals was obtained, m.p. 70.5–72.5°. An additional re-

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(23) J. H. Richards and T. J. Curphy, *Chemistry & Industry*, 1456 (1956).

(24) All melting points were determined using a Fisher–Johns melting point apparatus, and are uncorrected. Infrared spectra were taken with a Perkin–Elmer double beam recording spectrophotometer, model 21. Ultraviolet absorption spectra were determined with the aid of a Cary recording spectrophotometer, model 14, and were taken in 95% ethanol solution. Analyses were performed at Micro-Tech Labs, Skokie, Ill.

(25) P. L. Pauson, THIS JOURNAL, **76**, 2187 (1954).

(26) Although the detailed course of these arylation reactions has not been defined, a plausible path would involve the aryl radicals as intermediates. Such radicals might be generated through initial reduction of the diazonium salts by ferrocene and then loss of nitrogen from the resulting diazoaryl radicals. The formation of acetophenone in the above experiment is then explicable in terms of aryl radical attack of the solvent. *Cf.* P. L. Pauson, *Quart. Revs.*, **9**, 391 (1955).

crystallization from low boiling petroleum ether gave 122 mg. of 1-acetyl-2-phenylferrocene (IIb), m.p. 72.5–74.0°.

Anal. Calcd. for $C_{18}H_{16}OFe$: C, 71.07; H, 5.30; Fe, 18.36. Found: C, 70.83; H, 5.17; Fe, 18.01.

The main orange band which followed the above fraction began to emerge from the column after approximately nine weeks. No separation of this band into components was evidenced throughout the following seven weeks during which time this latter band was eluted. A total of eleven fractions were cut. These were separately rechromatographed on 100 g. of alumina using ether as eluent. The total amount of crystalline product from these fractions weighed 570 mg. Fractions 4A through 4G consisted predominantly of 1-acetyl-1′-phenylferrocene, while the latter fractions contained larger amounts of the third isomer, 1-acetyl-3-phenylferrocene. Fractions 4A through 4E were combined and recrystallized from ether–petroleum ether solution to give 130 mg. of IVb, m.p. 89–92°, as orange rods. One additional recrystallization raised the melting point to 92.5–93.5°.

Anal. Calcd. for $C_{18}H_{16}OFe$: C, 71.07; H, 5.30; Fe, 18.36. Found: C, 70.35, 71.18; H, 5.01, 5.21; Fe, 18.06.

On recrystallization, fraction 4H through 4K, yielded 75 mg. of IIIb as orange rods, m.p. 112–114°. This was recrystallized for analysis from ether–petroleum ether solution (m.p. 113–114°).

Anal. Calcd. for $C_{18}H_{16}OFe$: C, 71.07; H, 5.30; Fe, 18.36. Found: C, 70.83; H, 5.58; Fe, 18.18.

Acetylation of 1,1′-Diphenylferrocene (Ic). Formation of Isomeric Acetyl-1,1′-diphenylferrocenes IIc, IIIc and Vb.—Diphenylferrocene (0.500 g., 1.5 mmoles) was taken up in approximately 75 cc. of dry methylene chloride. The solution was cooled in an ice-bath and kept under an atmosphere of nitrogen. Aluminum chloride (0.200 g., 1.5 mmoles) was added. A solution of 0.150 g. (2.0 mmoles) of freshly distilled acetyl chloride in approximately 25 cc. of dry methylene chloride then was added to the stirred reaction mixture over a period of 30 minutes. The reaction was allowed to continue at 0° for 4.5 hours, and then at room temperature for an additional 1.5 hours. The dark purple solution next was cooled and decomposed with ice and water. The organic phase was withdrawn, and the aqueous phase was extracted several times with ether. The combined organic extracts were washed with sodium carbonate solution, then with water to neutrality, and finally were dried over magnesium sulfate. Removal of solvent left 553 mg. of a partly crystalline red oil, which was taken up in a small volume of benzene–Skellysolve B mixture (1:1) and placed on a column of 550 g. of neutral, grade 2 alumina. Elution was carried out using the same solvent mixture. Unreacted diphenylferrocene, 130 mg., m.p. 105–130°, was recovered in the first fraction. This band separated clearly from the band containing acetylated material. Successive recrystallizations of this product from ether–Skellysolve B gave 85 mg. of pure 1,1′-diphenylferrocene, m.p. 154–156°. On continued elution, the major band separated into three distinct bands. The first of these gave 12 mg. of 1-*p*-acetylphenyl-1′-phenylferrocene (Vb), m.p. 151–152°, as orange crystals, after recrystallization of the crude product from ether–Skellysolve B mixtures. This substance was not analyzed, but its spectrum is equivalent to a composite of a spectrum of bis-*p*-acetylphenylferrocene and of 1,1′-diphenylferrocene.

The second band yielded 220 mg. of orange oil. This was rechromatographed twice on 40 g. of neutral alumina to give 140 mg. of orange gum (IIc) which resisted attempts to crystallize it. Treatment with 2,4-dinitrophenylhydrazine gave the derivative as black needles, m.p. 131–133°.

Anal. Calcd. for $C_{30}H_{24}O_4N_4Fe$: C, 64.30; H, 4.32; N, 10.00; Fe, 9.97. Found: C, 64.74; H, 4.60; N, 10.11; Fe, 10.31.

The final band yielded 157 mg. of orange crystalline material. After one recrystallization from ether–Skellysolve B solvent, 110 mg. of 1,1′-diphenyl-3-acetylferrocene (IIIc) was obtained as orange needles, m.p. 113–114°.

Anal. Calcd. for $C_{24}H_{20}OFe$: C, 75.80; H, 5.30; Fe, 14.69. Found: C, 75.78; H, 5.28; Fe, 15.01.

A dinitrophenylhydrazone of this product was obtained as black needles, m.p. 224–226°.

Anal. Calcd. of $C_{30}H_{24}O_4N_4Fe$: C, 64.30; H, 4.32; N, 10.00; Fe, 9.97. Found: C, 64.05; H, 4.55; N, 9.76; Fe, 10.57.

In a second run, acetylation of 500 mg. of diphenylferrocene gave 83 mg. of both the 1,2- and 1,3-isomers above.

Degradation of 1,1′-Diphenyl-2-acetylferrocene (IIc).—1,1′-Diphenyl-2-acetylferrocene (0.30 g., 0.78 mmole) was taken up in 20 cc. of methanol, and 5 cc. of 1 *N* sodium hydroxide solution was added to this. The solution was stirred in an atmosphere of nitrogen and protected from the light. A solution, 0.71 molar in hypochlorite (3.5 cc., 2.50 mmoles), was added over a period of 5 minutes. After allowing the reaction to proceed for three hours at room temperature, an additional 0.5 cc. of hypochlorite solution and 5 cc. of 1 *N* sodium hydroxide solution were added. Reaction was continued for a total of 7 hours at room temperature. The solution then was heated overnight after the addition of 3 cc. of 1 *N* sodium hydroxide. The reaction mixture was then cooled, poured into 100 cc. of water, and extracted several times with ether. The combined ether extracts were washed once with sodium hydroxide solution. The basic aqueous solutions were combined and acidified with concentrated hydrochloric acid. The acid, which crystallized from solution, was collected and dried. It weighed 133 mg. and melted with decomposition at 190–193°.

This product was taken up in 10 cc. of dry methylene chloride, and 10 drops of oxalyl chloride were added. The solution was allowed to stand overnight in the dark. Solvent now was removed *in vacuo*, and the residue was pumped down for 3 hours to remove residual oxalyl chloride. The product was taken up in 10 cc. of dry methylene chloride and a small amount of sublimed aluminum chloride was added to the solution. Reaction was allowed to proceed for a period of 2 hours at room temperature. Water then was added and the reaction was worked up in the usual manner. The product was chromatographed twice on 30 g. of alumina employing ether as eluent. The crystalline product, weighing 11 mg., had a m.p. of 105–110°. It was recrystallized twice from ether–petroleum ether solutions to give 7 mg. of dark red blocks, m.p. 123–126° (VIII).

Anal. Calcd. for $C_{23}H_{16}OFe$: C, 75.85; H, 4.43. Found: C, 75.89; H, 4.83.

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