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Reactions of Ferrocene and Acetylferrocene with Carbon-Centered Free Radicals

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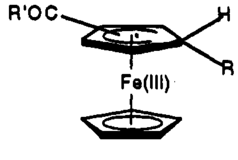
Homolytic substitutions of ferrocene with a variety of carbon-centered radicals have been investigated. Reactions with synthetic utility have only been obtained in the cases of ambiphilic radicals (cyanomethyl and alkoxycarbonylmethyl), whereas nucleophilic radicals ($R^\bullet$ and $RCO^\bullet$) give relatively low yields, and no reaction at all is observed with electrophilic radicals (malonyl, methylmalonyl). The reaction of acetylferrocene with cyanomethyl and ethoxycarbonylmethyl radicals leads to the formation of homo- and heteroannular disubstituted products. The mechanistic implications of these results are discussed.

Ferrocenes are interesting substrates with important applications in chemistry and biology, whose reactions have raised considerable interest.[1] However, very little attention has thus far been given to the synthetic and mechanistic aspects of the reactions of ferrocenes with carbon-centered radicals, in spite of the fact that, in the last decade, the synthetic potential of homolytic aromatic substitutions has become well established.[2]

Previous studies by Beckwith and Leydon suggested that ferrocene itself is not in fact reactive toward free radicals (aryl, cyanodimethyl, or chloromethyl radicals), but that oxidation to the ferricenium ion is first required.[3] This oxidation is relatively easy, since the oxidation potential of ferrocene can be as low as 0.72 V vs SHE in MeCN.[4] Moreover, it has also been suggested that the free radical $R^\bullet$ first attacks the iron atom of the ferricenium ion, giving a species which then rearranges to a positively charged σ complex, such as those proposed for the electrophilic aromatic substitutions. Subsequent proton loss then leads to the substituted ferrocene. Evidence in support of this hypothesis has recently been obtained in the homolytic acylation of ferrocene.[5] It has been observed that, when disubstitution occurs, the second acyl group attacks the unsubstituted cyclopentadienyl ring exclusively, as predicted by the mechanism involving a preliminary attack of the free radical on the iron atom (Scheme I, R′ = R = Ar). Accordingly, due to the electron-withdrawing effect of the acyl group, the intermediate 1 will almost exclusively rearrange to the positively charged σ-complex 2 (leading to the heteroannular disubstituted ferrocene), much more stable than the isomeric σ-complex 3, from which the homoannular (1,2 and 1,3)-disubstituted ferrocene can be formed.

In contrast, a direct attack of the acyl radical on the cyclopentadiene rings would not be expected to discriminate much between the two rings. In fact, some preference for the homoannular substitution would be expected, because the acyl radical is nucleophilic and, furthermore, the more stable σ radical intermediate would now be the one (4, R = R′ = Ar) in which the unpaired electron is stabilized by the acyl group.



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In view of the mechanistic complexity, and also in order to investigate possible synthetic applications of this process, we undertook to study the reactions of ferrocene with a series of carbon-centered radicals (acetyl, ethyl, methyl, methoxycarbonylmethyl, ethoxycarbonylmethyl, cyanomethyl, and malonyl) with properties ranging from strongly nucleophilic (acetyl) to strongly electrophilic (malonyl). The results of this study, which also includes some reactions of acetylferrocene, are reported herein.

Results and Discussion

The alkyl radicals were generated from the reactions of the corresponding alkyl iodides with methyl radicals

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(1) See, for example: Scutaru, D.; Mazilu, I.; Tataru, L.; Vata, M.; Lixandru, T. *J. Organometal. Chem.* **1991**, *406*, 183. Scutaru, D.; Tataru, L.; Mazilu, I.; Diaconu, E.; Lixandru, T.; Simionescu, C. *J. Organometal. Chem.* **1991**, *401*, 81. Hayashi, T.; Matsumoto, Y.; Morikawa, I.; Ito, Y. *Tetrahedron: Asymmetry* **1990**, *1*, 151. Vessieres, A.; Vaillant, C.; Gruselle, M.; Vichard, D.; Jaouen, G. *J. Chem. Soc., Chem. Commun.* **1990**, 837. Hayashi, T.; Hayashikari, K.; Kikoi, T.; Ito, Y. *J. Am. Chem. Soc.* **1988**, *110*, 8153. Hayashi, T.; Kanehira, K., Kumuda, M. *J. Org. Chem.* **1988**, *53*, 113. Bard, A. J.; Gan, F. F.; Kwak, J.; Lev, O. *Anal. Chem.* **1989**, *61*, 132. Bard, A. J.; Kwak, J. *Anal. Chem.* **1989**, *61*, 1221, 1794. Hayashi, T.; Mise, T.; Fukushima, M.; Kagotani, M.; Nagashima, N.; Hamada, Y.; Matsumoto, A.; Kawakami, S.; Konishi, M.; Yamamoto, K.; Kumada, M. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1138. Motonashi, N.; Meyer, R.; Gollapudi, S. R.; Bhattiprolu, K. R. *J. Organometal. Chem.* **1980**, *398*, 205.

(2) For reactions promoted by nucleophilic radicals see: Minisci, F.; Vismara, E.; Fontana, F. *Heterocycles* **1989**, *28*, 489. Minisci, F. *Top. Curr. Chem.* **1976**, *62*, 3. For reactions promoted by electrophilic radicals, see: Baciocchi, E.; Dell'Aira, D.; Ruzziconi, R. *Tetrahedron Lett.* **1986**, 2763. Santi, R.; Fiorani, T.; Strologo, S. *J. Org. Chem.* **1989**, *54*, 2703.

(3) Beckwith, A. L. J.; Leydon, R. J. *Tetrahedron Lett.* **1963**, 365. Little, W. F.; Lynn, K. N.; Williams, R. *J. Am. Chem. Soc.* **1963**, *85*, 3055. Bin Din, L.; Meth-Cohn, O.; Walshe, N. D. A. *Tetrahedron Lett.* **1979**, 4783.

(4) Bordwell, F. G.; Harrelson, J. A.; Satish, A. V. *J. Am. Chem. Soc.* **1989**, *54*, 3101.

(5) Lampard, C.; Murphy, J. A. *Tetrahedron Lett.* **1991**, *32*, 4993.

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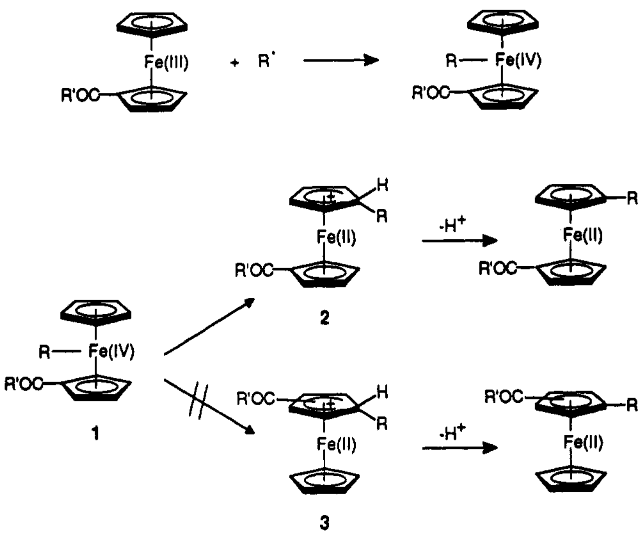
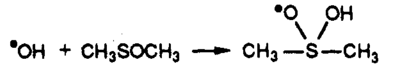
Scheme I

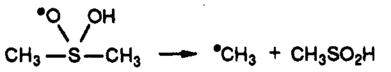


produced by the reaction of Fe^{+2} with H_2O_2 in DMSO (eqs 1–4).[6] Of course, no alkyl iodide was added when the reaction of the methyl radical was studied.

$$H_2O_2 + Fe(II) \longrightarrow {}^{\bullet}OH + {}^{-}OH + Fe(III) \qquad (1)$$



$$^{\bullet}OH + CH_3SOCH_3 \longrightarrow CH_3{-}\overset{\bullet O\ \ OH}{\underset{}{S}}{-}CH_3 \qquad (2)$$



$$CH_3{-}\overset{\bullet O\ \ OH}{S}{-}CH_3 \longrightarrow {}^{\bullet}CH_3 + CH_3SO_2H \qquad (3)$$

$$^{\bullet}CH_3 + RI \longrightarrow CH_3I + R^{\bullet} \qquad (4)$$

In some cases, however, the addition of $FeSO_4$ was omitted or ferrocene was replaced by a ferricenium cation. In order to form the acetyl radical, t-BuO_2H and acetaldehyde (eqs 5,6) replaced H_2O_2 and the alkyl iodide,

$$t\text{-}BuO_2H + Fe(II) \rightarrow t\text{-}BuO^{\bullet} + {}^{-}OH + Fe(III) \qquad (5)$$

$$t\text{-}BuO^{\bullet} + CH_3CHO \rightarrow CH_3CO^{\bullet} + t\text{-}BuOH \qquad (6)$$

respectively, and acetic acid was used as the solvent.[7] The yields of the products (identified by GC-MS and GC comparison with authentic specimens) and of the unreacted substrate for the various reactions are reported in Table I.

The efficiency of the substitution process is relatively low with nucleophilic radicals (acetyl and alkyl radicals, entries 1–3 in Table I), but it becomes fair to good with ambiphilic radicals[8] (cyanomethyl, methoxycarbonylmethyl, and ethoxycarbonylmethyl radicals, entries 4,5,7 in Table I) acquiring synthetic significance. Surprisingly, the electrophilic malonyl radical (entry 8 in Table I) does not exhibit any reactivity. Yields do not significantly change when ferricenium trichloroacetate is used as the starting substrate in place of ferrocene (entries 9 and 10 in Table I) or when the reaction of ferrocene is carried out in the absence of $FeSO_4$ (entry 6 in Table I).

These results are consistent with the hypothesis that free radical reactions of ferrocene occur following oxidation to ferricenium ion. Under our conditions, oxidation of ferrocene by H_2O_2 is certainly feasible and indeed we have found that substitution reactions can also take place in the absence of $FeSO_4$. Clearly, the ferrocene itself provides the iron(II) species which generates $OH^{\bullet}$ (eq 1) and is thus converted into the ferricenium cation. Moreover, we find similar yields starting from either ferrocene or ferricenium trichloroacetate.

Table I. Reactions of Ferrocene (FcH) and Ferricenium Trichloroacetate (FcH^+) with Carbon-Centered Radicals in DMSO

entry	radical, $R^{\bullet a}$	product; yield, %[b]	recovered FcH, %[b]
		FcH	
1	$^{\bullet}COCH_3$[c]	$FcCOCH_3$; 22	3
2	$^{\bullet}CH_3$	$FcCH_3$; 16[d,e]	60[d]
3	$^{\bullet}C_2H_5$	FcC_2H_5; 15[d,e]	62[d]
4	$^{\bullet}CH_2CO_2Et$	$FcCH_2CO_2Et$; 47	31
5	$^{\bullet}CH_2CO_2Me$	$FcCH_2CO_2Me$; 43 (45)[d]	41 (40)[d]
6		32[d,f]	26
7	$^{\bullet}CH_2CN$	$FcCH_2CN$; 70	12
8	$^{\bullet}CH(CO_2Et)_2$	*g*	40
		FcH^+	
9	$^{\bullet}CH_2CO_2Me$	$FcCH_2CO_2Me$, 40	13
10	$^{\bullet}CH_2CN$	$FcCH_2CN$; 72	10

[a] Generated by the corresponding alkyl iodide (see text). [b] Yield of isolated product (see text). [c] Generated by CH_3CHO and t-BuO_2H in AcOH (see text). [d] Determined by GC, with respect to the starting ferrocene. [e] Accompanied by small amounts of disubstituted ferrocene. [f] Reaction carried out in the absence of $FeSO_4$. [g] No formation of malonylferrocene was detected. The diethyl iodomalonate is almost completely reduced to the corresponding malonate.

The more efficient process observed with ambiphilic radicals, like $^{\bullet}CH_2CN$ and $^{\bullet}CH_2CO_2Et$, compared with that for nucleophilic and electrophilic radicals, is difficult to rationalize. Certainly, the sensitivity of the reaction to polar effects is quite low (acetyl and alkyl radicals behave similarly), and presumably this might favor those radicals which are less influenced by the electron density in the substrate.

The "nonreactivity" of malonyl radicals is also surprising. A possible explanation is that malonyl radical ($E° = 0.73$ V vs SHE in DMSO)[4] is reduced by $FeSO_4$ at a rate higher than that of attack on the substrate.[9a] Indeed, formation of substantial amounts of diethyl malonate was observed in the malonylation experiment (Table I, entry 8) as well as when the reaction was carried out in the absence of ferrocene.

To gain further information, the reactions of acetylferrocene (with a redox potential 0.24 V more positive than ferrocene[11]) with both $^{\bullet}CH_2CN$ and $^{\bullet}CH_2CO_2Et$ were also investigated, and the results are displayed in Table II. The yields of products were lower than those obtained with ferrocene, and, moreover, it was observed that only ferrocene undergoes cyanomethylation when a mixture of ferrocene and acetylferrocene is allowed to react with $^{\bullet}CH_2CN$. A very interesting finding is that with both radicals, homo- and heteroannular substitution occur. In the reaction with $^{\bullet}CH_2CO_2Et$, the major product is the homoannular 1,2-disubstituted ferrocene, accompanied by

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(6) Minisci, F.; Vismara, E.; Fontana, F. *J. Org. Chem.* **1989**, *54*, 5224.

(7) Caronna, T.; Gardini, G. P.; Minisci, F. *Chem. Commun.* **1969**, 201.

(8) Beranek, I.; Fischer, H. In *Free Radicals in Synthesis and Biology*; Minisci, F., Ed.; Nato, ASI Series; Kluwer Academic Publishers: Dordrecht, 1989; pp 303–316.

(9) (a) This situation does not hold for addition reactions to the double bond[10] and, moreover, pyrrole has been found to give high yields of malonylation products under the conditions used for ferrocene.[9b] However it is possible that alkenes and pyrrole are much more reactive than ferrocene with the strongly electrophilic malonyl radicals. (b) Baciocchi, E.; Muraglia, E.; Sleiter, G. *J. Org. Chem.* **1992**, *57*, 6817.

(10) Citterio, A.; Minisci, F. *J. Org. Chem.* **1982**, *47*, 1759.

(11) Tagaya, H.; Hashimoto, T.; Karasu, M.; Izumi, T.; Chiba, K. *Chem. Lett.* **1991**, *12*, 2113.

Table II. Reactions of Acetylferrocene with $\cdot CH_2CN$ and $\cdot CH_2CO_2Et$ in DMSO

radical, R•[a]	Products (yield, %)[b]	recovered AcFc (%)[b]
$\cdot CH_2CN$	2-(cyanomethyl)-1-acetylferrocene; 8 (12)[c] 1'-(cyanomethyl)-1-acetylferrocene; 8 (10)[c]	48
$\cdot CH_2CO_2Et$	ethyl 2-acetyl-1-ferrocenylacetate; 4 (7)[c] ethyl 1'-acetyl-1-ferrocenylacetate and ethyl 3-acetyl-1-ferrocenylacetate[d]	52

[a] Generated by the corresponding alkyl iodide (see text). [b] Yield of isolated product (see text). [c] Determined by GC, with respect to the starting acetylferrocene. [d] As an inseparable mixture (see text). The overall yield is around 3%. 1,1':1,3 molar ratio is 3.6:1 (determined by NMR).

the 1,3- and 1,1'-disubstituted isomers. In the case of $\cdot CH_2CN$, 1,2- and 1,1'-disubstituted ferrocene were obtained (see Experimental Section for details).

A further important observation is that acetylferrocene does not react in the absence of $FeSO_4$, suggesting that this substrate cannot reduce H_2O_2 to a significant extent and thus cannot produce the $\cdot OH$ needed for the generation of the alkyl radicals. It may be, therefore, that in contrast with ferrocene itself, acetylferrocene reacts as such with carbon-centered free radicals, when the latter are formed by $FeSO_4/H_2O_2$ (eqs 1–4). However, it cannot be excluded that the reaction proceeds through the acetylferricenium cation, albeit formed in extremely small amounts, since the reactivity towards free radicals of this species, which has an unpaired electron, would be much larger than that of acetylferrocene.[12] At present, a clear distinction between the two pathways is not possible.

In any case, on the basis of the arguments previously presented, the observation that acetylferrocene gives homo- and heteroannular substitution with both $\cdot CH_2CN$ and $\cdot CH_2CO_2Et$ allows us to dismiss the mechanism described in the Scheme I ($R' = CH_3$, $R = CH_2CN$, CH_2CO_2Et), whereas it clearly supports a direct homolytic attack on the carbocyclic ring.

As $\cdot CH_2CN$ and $\cdot CH_2CO_2Et$ both lie on the borderline between nucleophilic and electrophilic character, no significant difference in reactivity would be expected, on this basis, for the acetyl-substituted and the unsubstituted cyclopentadienyl rings. In this case it is most likely the stability of the intermediate σ radical that is the most important factor and we would expect more substitution at the ring bearing the acetyl group, especially at the 2-position. Indeed, this is what was in fact observed, although the preference for homoannular substitution appears to be very small. In this respect, it is of interest to note that both homo- and heteroannular substitution have also been observed in the *p*-nitrophenylation of acetylferrocene with (*p*-nitrophenyl)diazonium cation, a reaction presumably involving the *p*-nitrophenyl radical.[13] This radical should exhibit polar effects not very different from those of the radicals studied in the present work.[14]

Finally, the question remains as to why nucleophilic acyl radicals apparently follow a mechanistic pathway different from that of $\cdot CH_2CN$ and $\cdot CH_2CO_2Et$ in the reaction with acetylferrocene, leading exclusively to heteroannular substitution. One possible suggestion is that, in the case of acylation, oxidation of acyl radicals by ferricenium cation may occur.[16] An acyl cation and acetylferrocene are formed and an electrophilic aromatic substitution ensues, which, of course, is expected to lead to the 1,1'-disubstituted derivative, almost exclusively.[5] This pathway would certainly be excluded for $\cdot CH_2CN$ and $\cdot CH_2CO_2Et$, since the oxidation of these species is much more difficult than that of an acyl radical.[17]

Experimental Section

Proton nuclear magnetic resonance (^1H NMR) spectra were recorded at 80 MHz on a Bruker instrument in $CDCl_3$ solution. Melting points are uncorrected. Mass spectra were obtained on a Hewlett-Packard 5970 mass-selective detector, operating at 70 eV, coupled with a 5890 GC. GC analyses were performed on a Hewlett-Packard 5859 instrument. Diethyl iodomalonate was prepared according to the literature.[19]

Alkylation Reactions of Ferrocene and Ferricenium Trichloroacetate (general procedure). H_2O_2 40% (2.0 mmol) was added dropwise to a stirred mixture of the substrate (1.0 mmol), alkyl iodide (2.0 mmol), and $FeSO_4{\cdot}7H_2O$ (0.056 g, 0.2 mmol) in 7.0 mL of DMSO, maintained at room temperature with a water bath. After 15 min, the mixture was diluted with brine, followed by addition of ascorbic acid and extraction with diethyl ether. The organic layer was washed with brine and dried over anhydrous Na_2SO_4, and the solvent was removed by evaporation under reduced pressure. The yields of products and their characterization are as follows:

Methylferrocene: comparison with authentic sample, prepared from ferrocenecarboxaldehyde by modified Clemmensen reduction;[20] yield 16% (determined by GC using acetylferrocene as internal standard).

Ethylferrocene: comparison with authentic sample, prepared from acetylferrocene by modified Clemmensen reduction;[20] yield 15% (determined by GC using acetylferrocene as internal standard).

Methyl ferrocenylacetate: the product was isolated by column chromatography on silica gel eluting first with petroleum ether (bp 40–70 °C) to recover the unreacted ferrocene and then with diethyl ether–petroleum ether (bp 40–70 °C), 1:1, to obtain the product (comparison with authentic sample),[21] yield 42%.

Ethyl ferrocenylacetate: the product (comparison with authentic sample)[21] was isolated in 45% yield after sublimation of the unreacted ferrocene and distillation of the unreacted alkyl iodide.

Ferrocenylacetonitrile: the product was isolated by column chromatography on silica gel eluting first with petroleum ether (bp 40–70 °C) to recover the unreacted ferrocene, then with diethyl ether–petroleum ether (bp 40–70 °C), 1:2, to obtain the product (comparison with a commercial sample, Aldrich), yield 70%.

Acetylation of ferrocene: *tert*-butyl hydroperoxide (3.0 mmol) and an aqueous saturated solution of $FeSO_4{\cdot}7H_2O$ (3.0 mmol) were simultaneously added dropwise to a stirred solution of ferrocene (1.0 mmol) and acetaldehyde in 5.0 mL of acetic acid, maintained at room temperature with a water bath.

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[12] The reactivity of acetylferricenium cation could not be tested since as far as we know no synthesis of this compound is reported in the literature. Attempts in our laboratories to obtain this compound have thus far failed (B. Floris, unpublished observations).

(13) Perevalova, E. G.; Simukova, N. A.; Nikitina, T. V.; Reshetov, P. D.; Nesmeyanov, A. N. *Akad. Nauk. SSSR, Otd. Khim. Nauk.* 1961, 77. We are grateful to a referee for having drawn our attention to this paper.

(14) The phenyl radical exhibits a slight nucleophilic character toward protonated pyridines.[15] Thus the *p*-nitrophenyl radical should be ambiphilic or slightly electrophilic.

(15) Minisci, F. *Top. Curr. Chem.* 1976, *62*, 1.

(16) Kochi, J. K. In *Free Radicals*; Kochi, J. K., Ed.; John-Wiley & Sons: New York, 1973; pp 629–630.

(17) The ionization potential of $CH_3CO\cdot$ is 7 eV,[18] much lower than those of $\cdot CH_2CN$ (10.87 eV)[8] and $\cdot CH_2CO_2Et$ (ca. 10.5 eV)[8]. The same conclusion holds for the *p*-nitrophenyl radical, whose ionization potential is 9.1 eV.[18]

(18) Lias, S. G.; Bartmess, G. E.; Liebman, J. F.; Holmes, J. L.; Levin, R. D.; Mallard, W. G. *J. Phys. Chem. Ref. Data* 1988, *17* (Suppl. 1).

(19) Curran, D. P.; Meng-Msin, C.; Spletzer, E.; Seong, C. M.; Chang, C.-T. *J. Am. Chem. Soc.* 1989, *111*, 8872.

(20) Di Vona, M. L.; Floris, B.; Luchetti, L.; Rosnati, V. *Tetrahedron Lett.* 1990, *42*, 6081.

(21) Roberts, D. T.; Little, W. F.; Bursey, M. M. *J. Am. Chem. Soc.* 1967, *89*, 6156.

After 60 min, the mixture was worked up as described in the alkylation reactions procedure. The residue was subjected to column chromatography on silica gel eluting first with petroleum ether (bp 40–70 °C) to recover the unreacted ferrocene and then with diethyl ether. The yield of acetylferrocene (comparison with a commercial sample) was 22%.

Alkylation Reactions of Acetylferrocene. The 1,2-disubstituted products were identified on the basis of the ^1H NMR spectra which showed the pattern expected for 1,2-disubstituted-ferrocenes:[22] a singlet due to the five protons of the unsubstituted aromatic ring, three triplets due to the three protons of the disubstituted aromatic ring, whereas the methylene protons of the CH_2CN or CH_2CO_2Et group gave rise to an AB pattern presumably due to restricted rotation or a substantial disparity in the population of the various side-chain conformations. Moreover, the infrared spectra of the two compounds exhibited bands at 9 and 10 μm, typical of homoannular disubstituted ferrocenes.[23]

General Procedure. H_2O_2 40% (2.0 mmol) was added dropwise to a stirred mixture of acetylferrocene (0.228 g, 1.0 mmol), alkyl iodide (2.0 mmol), and $FeSO_4 \cdot 7H_2O$ (0.056 g, 0.2 mmol) in 7.0 mL of DMSO and kept at room temperature with a water bath. After 15 min, the mixture was diluted with brine and extracted with diethyl ether. The organic layer was washed with brine and dried over anhydrous Na_2SO_4, and the solvent was removed by evaporation under reduced pressure. The residue was treated as follows:

(a) Reaction with ${}^{\bullet}CH_2CN$. The reaction products were isolated by column chromatography on neutral alumina (IV Brockmann grade) eluting with petroleum ether (bp 40–70 °C)–ethyl acetate, 5:1. After the unreacted acetylferrocene eluted first, two different fractions were collected: the first, a bright orange solid which was recrystallized from hexane, mp 85.5–86.0 °C, was identified as **2-(cyanomethyl)-1-acetylferrocene**, yield 8% (12%, determined by GC-MS using *p*-nitrotoluene as internal standard) on the basis of the following analytical data: mass spectrum, m/z (rel inten) 267 (M^+, 100), 240 ($M^+ - HCN$, 33), 225 (33), 224 ($M^+ - COCH_3$, 44), 121 ($CpFe^+$, 25), 56 (Fe^+, 54); ^1H NMR δ (ppm) 2.38 (s, 3 H, $COCH_3$), 3.46–4.30 (AB system, δ_1 = 3.62, δ_2 = 4.17, J = 18.9 Hz, 2 H, CH_2CN), 4.25 (s, 5 H, unsubstituted Cp protons), 4.44 (t, J = 2.8 Hz, 1 H, disubstituted Cp proton), 4.62–4.73 (m, 2 H, disubstituted Cp protons); IR, absorption maxima (cm^{-1}) 2254 (CN), 1664 (CO), 1108, 1003. Anal. Found for $C_{14}H_{13}FeNO$ (calcd): C, 63.17 (62.95); H, 5.06 (4.91); N, 5.26 (5.24).

The second, a bright orange solid which was recrystallized from cyclohexane, mp 83.5–84.5 °C, was identified as **1′-(cyanomethyl)-1-acetylferrocene**, yield 8% (12%, determined by GC–MS using *p*-nitrotoluene as internal standard) on the basis of the following analytical data: mass spectrum, m/z (rel inten) 267 (M^+, 100), 225 (24), 224 ($M^+ - COCH_3$, 82), 163 ($M^+ - CpCH_2CN$, 11), 134 (28), 121 ($CpFe^+$, 19), 56 (Fe^+, 53); ^1H NMR δ (ppm) 2.38 (s, 3 H, $COCH_3$), 3.34 (s, 2 H, CH_2CN), 4.19–4.25 (m, 4 H, CH_2CN-substituted Cp protons), 4.55 (t, J = 1.9 Hz, 2 H, 3-*H* and 4-*H* CH_3CO-substituted Cp protons), 4.79 (t, J = 1.9 Hz, 2 H, 2-*H* and 5-*H* CH_3CO-substituted Cp protons); IR, absorption maxima (cm^{-1}) 2256 (CN), 1667 (CO), 1116. Anal. Found for $C_{14}H_{13}FeNO$ (calcd): C, 62.53 (62.95); H, 4.79 (4.91); N, 5.29 (5.24).

(b) Reaction with ${}^{\bullet}CH_2CO_2Et$. The reaction products were isolated by column chromatography on neutral alumina (IV Brockmann grade) eluting with petroleum ether (bp 40–70 °C)–ethyl acetate, 8:1. After the unreacted acetylferrocene eluted first, two different fractions were collected: the first, a bright orange solid which was recrystallized from petroleum ether (bp 40–70 °C), mp 77.5–78.0 °C, was identified as **ethyl 2-ethyl-1-ferrocenylacetate**, yield 4% (7%, determined by GC-MS using *p*-nitrotoluene as internal standard) on the basis of the following analytical data: mass spectrum, m/z (rel inten) 314 (M^+, 100), 241 ($M^+ - CO_2Et$, 28), 240 (62), 175 (22), 121 ($CpFe^+$, 17), 56 (Fe^+, 10); ^1H NMR δ (ppm) 1.24 (t, J = 7.1 Hz, 3 H, $CO_2CH_2CH_3$), 2.37 (s, 3 H, $COCH_3$), 3.46–4.30 (AB system, δ_1 = 3.59, δ_2 = 3.99, J = 16.8 Hz, 2 H, CH_2CO_2Et); 4.13 (q, J = 7.1 Hz, 2 H, $CO_2CH_2CH_3$), 4.14 (s, 5 H, unsubstituted Cp protons), 4.37 (t, J = 2.7 Hz, 1 H, disubstituted Cp proton); 4.53–4.66 (m, 2 H, disubstituted Cp protons); IR, absorption maxima (cm^{-1}) 1729 (CO ester), 1664 (CO acetyl), 1108, 1002. Anal. Found for $C_{16}H_{18}FeO_3$ (calcd): C, 61.41 (61.17); H, 5.96 (5.78).

The second, ca. 9 mg of a red oil, showed a single peak at GC-MS and a mass spectrum, m/z (rel inten) 314 (M^+, 100), 268 ($M^+ - EtOH$, 82), 241 ($M^+ - CO_2Et$, 24), 240 (10), 207 ($M^+ - CpCOCH_3$, 11), 163 (20), 151 ($CpCH_2CO_2Et^+$, 9), 135 ($M^+ - (CpCH_2CO_2Et + CO)$,[21] 21), 121 ($CpFe^+$, 10), 56 ($Fe^+$, 25) in agreement with the structure of an acetylferrocene ethyl acetate. The ^1H NMR spectrum of this chromatographic fraction, however, indicated that both **ethyl 1′-acetyl-1-ferrocenylacetate** and **ethyl 3-acetyl-1-ferrocenylacetate** were present, showing the following signals: δ (ppm) 1.25 (t, J = 7.1 Hz, $CO_2CH_2CH_3$), 2.35 (s, $COCH_3$), 3.22 (s, CH_2CO_2Et 1,1′-isomer), 3.33 (s, CH_2CO_2Et 1,3-isomer), 3.99–4.26 (m, $CO_2CH_2CH_3$, CH_2CO_2Et-substituted Cp protons 1,1′-isomer and unsubstituted Cp protons 1,3-isomer), 4.42 (t, J = 2.1 Hz, 3-*H* and 4-*H* ring protons of $COCH_3$-substituted Cp in the 1,1′-isomer), 4.67 (t, J = 2.1 Hz, 2-*H* and 5-*H* ring protons of $COCH_3$-substituted Cp in the 1,1′-isomer). The protons of the substituted Cp in the 1,3-isomer appear between δ 4.3 and 4.7, and are partially overlapped with the δ 4.42 and 4.67 signals of the 1,1′-isomer, which is the predominant component of the mixture (3.6:1, by comparison of the CH_2CO_2Et singlets). The assignment of singlets at δ 3.22 and 3.33 to the 1,1′ and 1,3-isomer, respectively, was made on the basis of the argument that the methylene protons of CH_2CO_2Et group are more deshielded when this group is in the acetyl-substituted ring (1,3-isomer).[24]

Competitive Reaction of Ferrocene and Acetylferrocene. When an equimolar mixture of ferrocene and acetylferrocene was allowed to react with $ICH_2CN/H_2O_2/Fe^{+2}$ in DMSO, under the conditions described above, only ferroceneacetonitrile was formed (GC-MS analysis).

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Supplementary Material Available: ^1H NMR (80 MHz) in $CDCl_3$ of 2-(cyanomethyl)-1-acetylferrocene, 1′-(cyanomethyl)-1-acetylferrocene, and ethyl 2-acetyl-1-ferrocenylacetate (3 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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