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SOME ASPECTS OF THE MERCURIATION OF FERROCENE

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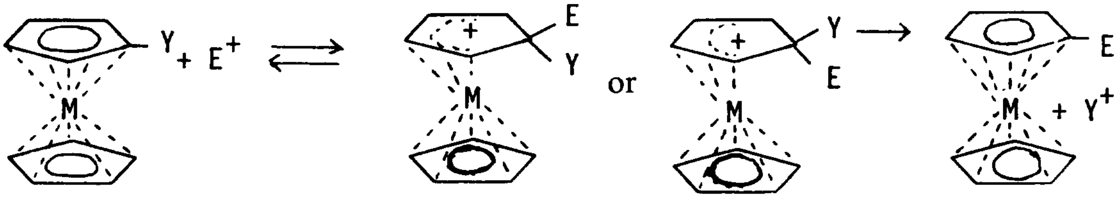
Abstract—The kinetics of mercuriation of ferrocene with $Hg(OAC)_2$ have been reinvestigated and the data interpreted in terms of rapid complex formation followed by rate determining conversion of the complex to products. The nature of analogous complexes with $HgCl_2$ was investigated by an NMR method which suggested the formation of a 1:1 iron-bound mercury species. Product analyses of the mercuriation reaction revealed evidence for homoannular disubstitution. The homoannular derivative is subsequently converted to the 1,1′-disubstituted product. Improved syntheses of the acetatomercuri ferrocenes is also reported.

Interest in ferrocene and its derivatives has continued to grow since its discovery in 1951.[1] More recently, attention has been turned to its reactivity particularly with respect to electrophilic substitution. However, due to oxidation to ferricinium salts, nitration and halogenation cannot be studied. Acylation[2] has been investigated in a semiquantitative manner and the kinetics and mechanism of several other electrophilic substitutions have been recently reported viz hydrogen isotopic exchange,[3] protodesilylation,[4,5] protodeboronation[4] and thalliation and mercuriation.[3,6,7] Kitching[8] has reviewed some of the earlier work on mercuriation. This paper deals with some aspects of the latter reaction.

RESULTS AND DISCUSSION

Two principal mechanisms have been advanced for electrophilic substitution in ferrocene and its analogues. The first is the now generally accepted scheme for substitution in aromatic systems with the extra stereochemical problem of the direction of attack by the incoming electrophile (M = Fe, Ru, Os; Y = H, HgCl, $SiMe_3$, etc)

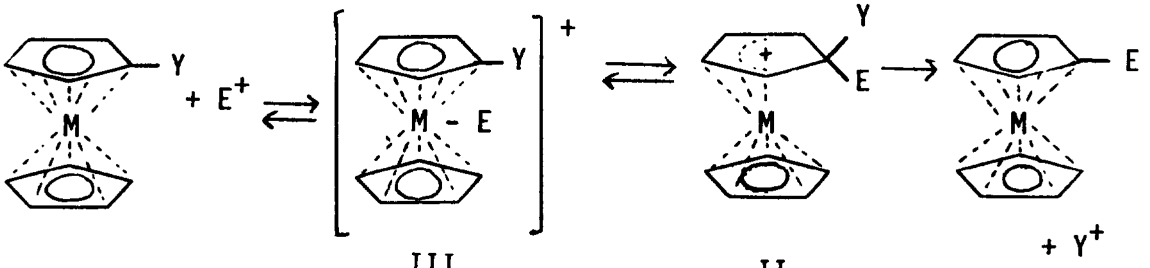


I (*exo*-E) II (*endo*-E) ..... (1)

In principle, either the formation of I/II or their decomposition can be rate determining. It is possible that with certain substituents either I or II will predominate depending on the importance of any direct interaction between Y (or E) and the metal atom.

The second proposed mechanism is a variant on (1) whereby a complex is first formed by direct attack on the central metal atom (III) with subsequent rearrangement to give specifically II.

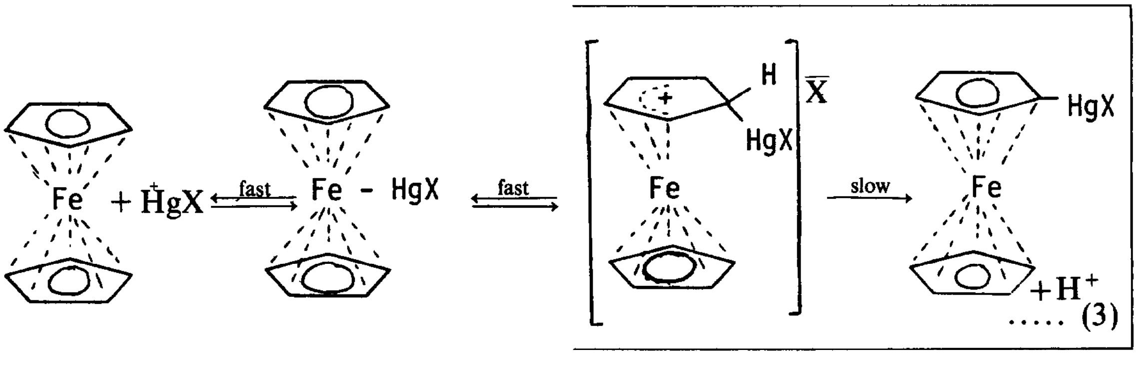
The propositions have been elegantly set out and criticised by Traylor.[3] Evidence for the existence of direct metal–electrophile interaction comes from NMR studies of ferrocene in strongly acidic media.[9,11] ($BF_3.H_2O$) where very highly shielded protons were observed similar to those found for other transition metals bounded to hydrogen.[12] Recently, we have found similar behaviour in trifluoromethanesulphonic acid.[13] The iron-bound proton appears at −2.25 ppm (line width 12 Hz) in the NMR spectrum of the solution and the iron oxidises only slowly in this medium. The linewidth of the cyclopentadienyl signal in freshly prepared solution (9 Hz) was much larger than that in



III II ..... (2)

CCl_4 (1 Hz), suggesting a dynamic process, and the ring protons were strongly deshielded (4.83 ppm). Compared with those in solvent acetic acid (4.27 ppm). Evidence for other metal electrophile interactions is extremely sparse. Interestingly, a Ru–Hg bond has been detected in complexes of ruthenocene and mercuric halides.[14] An important destabilising factor in structures such as III is the relative ease with which the metal atom in thesesystems loses electrons (viz. the facile formation of ferrocenium compounds in acidic media). Indeed the corresponding ferrocene–mercuric halide complex undergoes such oxidation in the solid state on standing.[14] Even if such complexes are formed it still remains to be shown unambiguously that they lie along the reaction coordinate for electrophilic substitution. The evidence overall suggests that they do not. In particular Rosenblum and Abbate[15] have shown from a detailed stereochemical study of intramolecular ring acylation using cyclisation of epimeric acids (*endo* and *exo*) that no particular advantage accrues for endocyclic ring substitution. Also protodesilylation of 1-trimethylsilylferrocene proceeds at fairly low acid concentrations where the concentration of species such as III (E = H) is extremely small (ca. 10^{-10} M) which would imply an extraordinary reactivity of such complexes if they are to participate meaningfully in the reaction. For mercuriation a kinetic isotope effect of 3.2 has been reported[3a] (though no experimental details as yet have appeared, also see Ref. 3b). From correlations with σ^+ ("outside" = *exo*) and σ^+ ("inside" = *endo*), the mercury apparently attacks using the "inside" electrons (see Ref. 3 for the definitions and evaluation of the above parameters). Attack therefore appears to be at the metal side of the cyclopentadienyl rings.

From this finding one cannot therefore rule out metal–metal interaction in the intermediate as shown below.



..... (3)

(a) *Kinetics of mercuriation of ferrocene.* Only limited study has been made of this synthetically important reaction. Floris and Illuminati[6] reported relative rate constants for attack by mercuric acetate in solvent acetic acid, though actual values were not listed. They found a ferrocene/benzene rate ratio of 10.[9] The reactions were followed spectrophotometrically at 302 nm under pseudo-first order conditions ($[Fe(cp)_2]:Hg(OAc)_2 \geq 15$) and apparently calculated the true second order rate constant from $k_2 = \dfrac{k_1}{[Fe(cp_2)]}$ as done for the corresponding thalliation reaction reported in the same paper. We have recently studied the mercuriation reaction of simple aromatic compounds[16] spectrophotometrically-using $Hg(OCOCF_3)_2$ in CF_3CO_2H and $[ArH] \gg$ [mercuric salt], and hence shown that the data is best interpreted in terms of a rapidly formed π complex followed by a slow conversion into products. No spectroscopic or kinetic evidence for σ intermediates was obtained. The overall scheme postulated was

$$ArH + HgX_2 \overset{\text{fast}}{\rightleftarrows} [\pi \text{ complex}] \xrightarrow{\substack{\text{slow}\\ k_2}} ArHgX + HX \qquad [X = CF_3CO_2]. \tag{4}$$

From this formulation, assuming that the π complex formed is always in a rapidly established equilibrium with reactants, the following equation was derived

$$\frac{1}{k_1\text{obs}} = \frac{1}{Kk_2}\cdot\frac{1}{ArH} + \frac{1}{k_2} \tag{5}$$

where k_1^{obs} is the observed pseudo-first order rate constant. Thus a plot of $(k_1^{obs})^{-1}$ against $[ArH]^{-1}$ yields values of both K and k_2. Accordingly, we used this approach in the mercuriation of ferrocene, using essentially the same conditions as Floris and Illuminati. Ferrocene (0.01 M) alone in acetic acid is stable over a period of ~10 hr at room temperature, thereafter progressive oxidation occurs to give a green-brown solution. Ferrocene in HOAc shows two principal UV maxima at 323 nm ($\varepsilon = 49$) and 435 nm (ε 105). On adding $Hg(OAc)_2$, a rapid increase in absorption occurs in the region 290–350 nm. The final spectrum shows a new maximum at 317 nm and corresponds almost exactly with the spectrum of acetato-mercuri-ferrocene in this region. From the absorption at 317 nm the reaction was 89 % complete at 25° ([ferrocene] = 0.01 M $[Hg(oAc)_2] = 5 \times 10^{-4}$ M, t = 5 min). In particular, no evidence of any ferrocenium ion ($\lambda_{max} = 620$) was observed during the reaction. First order rate constants were obtained at various concentrations of ferrocene and the values appear in Table 1. A plot of the data according to (5) yielded values of $K = 115 \pm 25 \text{ l mol}^{-1}$, and $k_2 = 0.11 \pm 0.01 \text{ s}^{-1}$ (correlation coefficient 0.987). Thus the data is reasonably consistent with the above

Table 1. Pseudo-first order rate constants, k_1^{obs} (s^{-1}) for the reaction of ferrocene with mercuric acetate (5×10^{-4} M) in acetic acid at 25°

[Ferrocene] 10^3 M	4.03	5.97	7.58	8.33	9.62	15.76
10^2 k_1^{obs}	3.45	4.12	4.91	5.45	5.80	6.52
	3.31	4.15	4.91	5.53	5.81	6.49

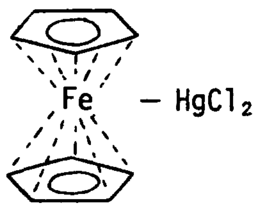
hypothesis. Additional evidence of intermediate formation is the appearance of a transient red colour when concentrated solutions of $Fe(cp)_2$ and $Hg(oAc)_2$ are mixed, however it is not clear whether this is due to π or iron-bound mercury species. The value of K is some two orders of magnitude greater than the corresponding complexes for simple aromatics with $Hg(OcOCF_3)_2$. However the latter is a much stronger electrophile than $Hg(oAc)_2$ so that a direct comparison is unfortunately not possible. Illuminati *et al.*[11] have identified π-H-bonded species of ferrocenes in various acidic media and found that the formation constants are between one and two orders of magnitude greater than that for benzene. The non-appearance of any highly shielded proton in the NMR spectra of these solutions (*cf* BF_3–H_2O) precluded any metal–H-bound species. It would therefore be interesting to ascertain if similar K(ferrocene)/K(benzene) ratios occur for mercuriation. Qualitatively, in view of the differences in electrophilicity (or Lewis acidity) between $Hg(OAc)_2$ and $Hg(OCOCF_3)_2$, the ratio is likely to be much lower than those found for the proton complexes. Moreover, since mercuric salts are generally considered to be weaker electrophiles than acid protons, their selectivity should be correspondingly larger and thus the above ratio should be even larger than those for protiation.

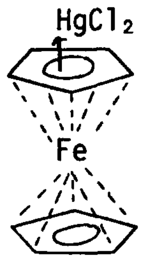
It was noted that values of k_2 obtained for thalliation[6] also tended to increase with decreasing ferrocene concentration. Accordingly we subjected the data to the above treatment and found that, although the linear dependence of the plots was less secure (correlation coefficient 0.912), a similar mechanism is probably operating. A K value of ~90 was found, i.e. very similar to that for mercuriation though the errors involved are large due to the scatter on the plot of eqn (5).

(b) *Ferrocene–mercuric halide complexes.* Since mercury–iron interaction could be important in mercuriation of ferrocene, an attempt was made to characterise complexes formed with very weakly electrophilic mercury derivatives—mercuric halides. Morrison and Hendrickson[14] have isolated a complex with stoichiometry $Fe(cp)_2.7HgCl_2$ when ferrocene is treated with a large excess of $HgCl_2$ in ether. The red complex precipitates out from most organic solvents using relatively concentrated solutions. The red compound gradually turned blue (oxidation) without a change in composition and a second complex $Fe(cp)_2.2HgCl_2$ was obtained by crystallisation from water. By analogy with the more stable ruthenocene complexes, a mercury–iron bond was postulated. The exact structure of the red complex is however at present unknown and the stoichiometry presents something of a problem. The authors have suggested that the complex has a ferrocene–mercury bonded structure with a large excess of "lattice" $HgCl_2$.

Evidence for a charge-transfer $(cp)_2Fe \rightarrow HgX_2$ at 360 nm has recently been put forward,[17] tending to confirm the Fe–Hg bond. Accordingly, we set out to obtain NMR evidence for the existence of these complexes in solution. The addition of mercuric chloride (0.1–0.6 M) solutions to ferrocene (0.01 M) in solvent acetone caused a small but reproducible downfield shift and broadening of the cyclopentadienyl singlet.

The concentrations employed were much lower than those used in the preparation of $Fe(cp)_2.7HgCl_2$. The colour of the solutions was pale yellow and no precipitation of the red complex was observed. The appearance of the cyclopentadienyl resonance as a singlet is more in keeping with an Fe-bound mercury (I) than π bonded mercury (II), since in the latter, the upper ring protons should be more deshielded than those in the lower ring, unless efficient transannular transmission of electronic effects occurs. The evidence on this point is conflicting.[10] Table 2 lists the observed chemical shifts and linewidths. The data fitted the NMR equivalent of the Benesi–Hildebrand equation for a 1:1 stoichiometry (correlation coefficient 0.967), though such plots do not always reveal the presence of higher order complexes.[18] A 1:7 stoichiometry would however produce marked curvature on these simple plots. The results suggest that in dilute solution the species present in solution is not $Fe(cp)_2.7HgCl_2$ but a complex of much lower order in $HgCl_2$. If a 1:1 stoichiometry is assumed, a value of the formation constant (K_c) of the complex of 1.1 ± 0.2 at 23° is found. From linewidth measurements, the rate constant for dissociation of the complex was calculated as 2.8 s^{-1}. The above evidence together with that of Fe–Hg charge-transfer[17] supports the formation of Fe–Hg bonds in the complex. Such bonds are by no means unknown.[19,20] Their mechanistic importance is still open to question though on balance it seems likely that they play a role in the mercuriation of ferrocene.





(c) *Reaction products.* One of the chief side reactions in mercuriation of ferrocene is oxidation to ferrocenium salts. Equimolar (0.1 M) mixtures of $Fe(cp)_2$ and $Hg(oAc)_2$ give about 20% oxidation after 1 min at 25°. However if a large excess of ferrocene is present little or no oxidation occurs. The reason for this behaviour is not clear.

Even using large excesses of ferrocene, dimercuriation occurs to a significant extent,[21,22] the rings being heteroannularly substituted. This is rather puzzling in view of the slightly activating effect of mercury substituents, particularly since some homoannular diacylation has been found[23] where the acyl substituent is deactivating.

Table 2. Chemical shifts (Δ, Hz) relative to ferrocene for various concentrations of $HgCl_2$ (M), together with the corresponding linewidths ($\nu_{1/2}$, Hz) in acetone at 23°. $[Fe(cp)_2] = 0.01$ M

$HgCl_2$	0	0.1	0.2	0.3	0.4	0.5	0.6
Δ	0	2.0	3.2	4.6	6.1	7.3	8.0
$\nu_{\frac{1}{2}}$	0.8	1.0	1.1	1.5	1.5	1.7	1.8

Reaction mixtures of $Fe(cp)_2$ and $Hg(oAc)_2$ (1:2) in HoAc were quenched in water/$CDCl_3$ mixtures and NMR spectra of the $CDCl_3$ layers were run. As well as the sharp singlets for unreacted ferrocene (4.27) and the mono-mercuriated derivative (4.33), an additional sharp singlet occurred at 4.41 ppm. This signal decreased when further $Hg(oAc)_2$ was added or on standing. The peak cannot be due to the 1,1′ dimercuriated species since this gives a complex multiplet in the cyclopentadienyl region. When the extracts were chromatographed and developed in iodine vapour, three spots were obtained containing mercury (a distinctive blue-grey coloration) with R_f values of 0.78, 0.22 and 0. The latter two were due to the mono and bis derivatives respectively. Ferrocenium salts had zero R_f values under the conditions used, as did the $Fe(cp)_2/HgCl_2$ complexes described earlier. The R_f value of the unknown is fairly close to that of ferrocene itself (0.86) which is characterised by its deep brown colour with I_2. The conclusion therefore is that some 1,2 dimercuriated ferrocene is formed initially with subsequent rearrangement to the more thermodynamically stable 1,1′ form. After 1 min at room temperature using $[Fe(cp)_2] = 0.05$ M, $Hg(oAc)_2 = 0.1$ M 45% of the ferrocene had reacted to give 19% mono, 16% 1,2 and 10% 1,1-substituted ferrocenes. The solution was refluxed for 5 min and analysed again. 59% of the ferrocene had reacted to give 17% mono, 3% 1,2 and 39% 1,1′ substituted ferrocenes.

It was also noted that chromatographs of commercial samples of mono and bis chloromercuri-ferrocenes showed the presence of some homo-bis derivative (R_f 0.78). The synthesis of 1 acetatomercuri and 1,1′ bis(acetatomercuri) ferrocenes is also reported (Experimental).

EXPERIMENTAL

Ferrocene (Aldrich Chemicals Ltd.) was purified by sublimation prior to use. 1-Chloromercuri- and 1,1′ bis(chloromercuri-)ferrocenes were purchased from Aldrich Chemicals Ltd. $HgCl_2$ was of Analar quality and $Hg(oAc)_2$ recrystallised from glacial AcOH. AcOH was purified by refluxing over P_2O_5 followed by fractional distillation. Acetone was of Analar quality.

NMR spectra were run on a Varian EM360 instrument housed in a constant temp room (18°) with a probe temperature of 23°. All chemical shifts are reported in ppm relative to TMS.

Commercially available precoated plates (Merck, silica gel 60F-254) were used in tlc experiments. The applied samples were eluted with $CHCl_3$, and after air drying were developed in iodine vapour.

Microanalyses were performed by Mr. M. Hart (University of Manchester).

Kinetic methods. Reactions of ferrocene with mercuric acetate were followed spectrophotometrically using a Unicam SP 1750 spectrophotometer equipped with a linear recorder and thermostatted cell block. Ferrocene was maintained in large excess throughout. The reaction was monitored by following absorption changes at 305 nm and pseudo-first order rate constants (k_1^{obs}) evaluated in the usual way. Duplicate runs were done for each ferrocene concentration used. The results were analysed using the relationship[16] (eqn 5) derived from the mechanistic scheme outlined previously (eqn 4).

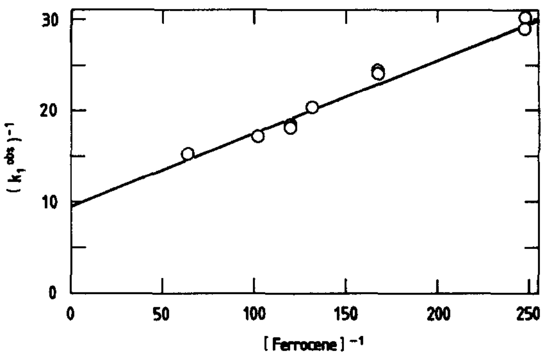


Fig. 1. Reciprocal plot of k_1^{obs} and [ferrocene] for reaction of ferrocene with mercuric acetate [5×10^{-4} M) in acetic acid at 25° (eqn 5)

The resulting plot appears in Fig. (1) using the data of Table 1, and values of K of 115 ± 25 l mol^{-1} and k_2 0.11 ± 0.01 s^{-1} are thus obtained. The correlation coefficient for 12 data points is 0.987. Plots of the corresponding data on thalliation (Ref. 6) showed a correlation coefficient of 0.912 and values of K and k_2 of 9 ± 5 l mol^{-1} and $8 \pm 3 \times 10^{-1}$ s^{-1}.

Complex formation. The NMR spectra of solutions of ferrocene (0.01 M) and $HgCl_2$ (0.1–0.6 M) in AR acetone were run immediately after mixing and the chemical shifts and linewidths measured relative to ferrocene itself (0.01 M). Table 2. The equilibrium constant K_c for the process

$$Fe(cp)_2 + HgCl_2 \overset{K_c}{\rightleftarrows} [\text{complex}] \quad (6)$$

was evaluated using (7) assuming a 1:1 stoichiometry.[18]

$$\frac{1}{[HgCl_2]} = K_c\Delta_0 \cdot \frac{1}{\Delta} - K_c \quad (7)$$

where $\Delta_0 = \delta(\text{ferrocene}) - \delta(\text{pure complex})$
$\Delta = \delta(\text{ferrocene}) - \delta(\text{solution})$.

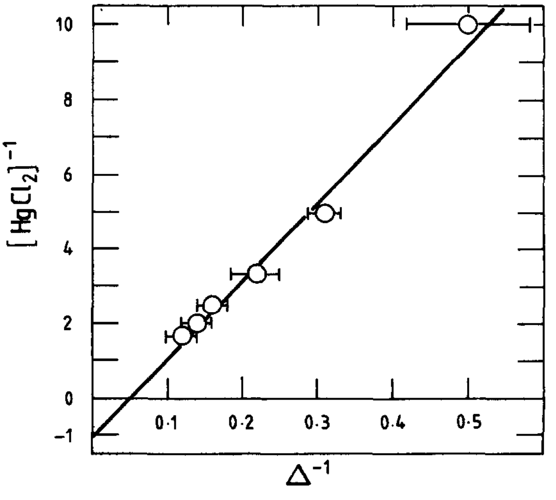


Fig. 2. Reciprocal plot of $[HgCl_2]$ and increment in chemical shift (Δ) for complex formation between ferrocene [0.01 M] and $HgCl_2$ in solvent acetone at 23° (eqn 7).

Figure 2 shows the relevant plot. Values of K_c and Δ_0 of 1.1 ± 0.2 l mol^{-1} and 20 Hz respectively were obtained.

Assuming the observed linewidths to be proportional to the molar concentration of the species present, then the linewidth of the pure complex ($\nu^c_{1/2}$) can be estimated from (8)

$$\Delta\nu_{1/2} = \nu_{1/2} - \nu^F_{1/2} = (\nu^c_{1/2} - \nu^F_{1/2})\cdot\frac{x}{a} \qquad (8)$$

where $\nu_{1/2}$ and $\nu^F_{1/2}$ are the linewidths observed for the $Fe(cp)_2/HgCl_2$ solutions and ferrocene (initial concentration a) respectively. x is the concentration of complex at equilibrium, calculated from K_c. A plot of $\Delta\nu_{1/2}$ vs x gave a straight line (correlation coefficient = 0.985, 7 data points) from which $(\nu^c_{1/2} - \nu^F_{1/2})n$ was calculated as 2.8 ± 0.2 Hz, which gives the rate constant for the dissociation of the complex.[24]

Preparation of 1-acetatomercuri ferrocene and 1,1′-bis(acetatomercuri)-ferrocene.[25] 1-chloromercuriferrocene (0.42 g 1.0 mmol) was dissolved in MeCN (40 ml) and treated portionwise with AgOAc (0.20 g 1.2 m mol). The mixture was refluxed for 0.5 h during which time the initial orange colour darkened considerably. The mixture was filtered and evaporated to give orange-brown crystals which were washed with a little cold methanol (0.40 g 89 % MP 122–3°). Found C 31.8, H 2.6. Calc. for $C_{12}H_{12}FeHgO_2$: C 32.4, H 2.7%. The NMR spectrum in $CDCl_3$ comprised two sharp singlets at 2.18 (CH_3) and 4.33 ppm (Cp, 5 H) and two triplets at 4.17 (2 H) and 4.53 ppm (2 H).

1,1′-bis(acetatomercuri)ferrocene was prepared in a similar manner from 1,1′-bis(chloromercuri)ferrocene in 50 % yield. The product was recrystallised from $CHCl_3$, m.p. 123–4°. The NMR spectrum in $CDCl_3$ comprised a sharp singlet (2.17 ppm, CH_3) and a complex multiplet (4.2–4.7 ppm 4 H).

This compound was also prepared in 46% yield by refluxing a soln of $Fe(cp)_2$ (1.86 g 0.01 mol) and $Hg(oAc)_2$ (3.18 g 0.01 mol) in MeCN (50 ml) for 10 min, filtering and allowing to crystallise at 0° to give yellow crystals, m.p. 125–6°.

REFERENCES

[1] T. J. Kealy and P. L. Pauson, *Nature* **168**, 1039 (1951).

[2] M. Rosenblum, *Chemistry of the Iron Group Metallocenes* Part 1, Wiley, New York (1965).

[3] [a] J. A. Mangravite and T. G. Traylor, *Tetrahedron Letters* 4457, 4461 (1967); [b] F. S. Yakusin, V. N. Setkina, E. A. Yakovleva, A. I. Shatenshtein and D. N. Kursanov, *Izv. Akad. Nauk. SSSR Ser. Khim.* **1**, 206 (1967).

[4] G. Cenchelli, B. Floris, G. Illuminati and G. Ortaggi, *J. Org. Chem.* **39**, 3948 (1974).

[5] G. Marr and D. E. Webster, *J. Chem. Soc.* 202 (1968).

[6] B. Floris and G. Illuminati. *Coord. Chem. Rev.* **16**, 107 (1975).

[7] B. Floris and G. Illuminati, *J. Organometal. Chem.* **168**, 203 (1979).

[8] W. Kitching, *Organometal. Chem. Rev.* **3**, 35 (1968).

[9] T. J. Curphey, J. O. Santer, M. Rosenblum and J. H. Richards, *J. Am. Chem. Soc.* **82**, 5249 (1960).

[10] M. Rosenblum, J. O. Santer and W. G. Howells, *Ibid.* **85**, 1450 (1963).

[11] G. Cenchelli, G. Illuminati, G. Ortaggi and A. M. Giuliani, *J. Organometal. Chem.* **127**, 357 (1977).

[12] M. L. H. Green, L. Pratt and G. Wilkinson, *J. Chem. Soc.* 3753 (1959).

[13] R. M. G. Roberts, unpublished observations.

[14] W. H. Morrison and D. H. Hendrickson, *Inorg. Chem.* **11**, 2912 (1972).

[15] M. Rosenblum and F. W. Abbate, *J. Am. Chem. Soc.* **88**, 4178 (1966).

[16] C. W. Fung, M. Khorramdel-Vehed, R. J. Ranson and R. M. G. Roberts, *J. Chem. Soc.* Perkin II, 267 (1980).

[17] O. Traverso, C. Chiorboli, V. Mazzi and G. L. Zenchrin, *Gazz. Chim. Ital.* **107**, 181 (1977).

[18] R. Foster, *Organic Charge-Transfer Complexes* Chap. 6. Academic Press, London (1969).

[19] M. J. Mays and J. D. Robb, *J. Chem. Soc.* A 329 (1968).

[20] R. M. G. Roberts, *J. Organometal. Chem.* **47**, 359 (1973).

[21] M. D. Rausch, *J. Org. Chem.* **28**, 3337 (1963).

[22] M. D. Rausch, L. P. Klemann, A. Siegel, R. F. Kovar and T. H. Gund, *Synth. in Inorg. and Metalorg. Chem.* **3**, 193 (1973).

[23] M. Rosenblum and R. B. Woodward, *J. Am. Chem. Soc.* **80**, 5443 (1958).

[24] J.-J. Delpuech, *Bull. Soc. Chim. Fr.* **10**, 2697 (1964).

[25] V. A. Nefedov and M. N. Nefedova, *Zh. Obsch. Khim.* **36**, 122 (1966).