

Spiroferrocenophanes

I *. 3-Spiro[5]ferrocenophane-1,5-diones from the direct condensation of diacetylferrocene with cycloalkanones

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Abstract

Condensation of diacetylferrocene with cyclohexanone, alkyl- or phenyl-cyclohexanones and cycloheptanone carried out in DMSO in the presence of KOH afforded 3-spiro[5]ferrocenophane-1,5-diones. Cyclopentanone and cyclooctanone failed to give the spiroferrocenophanediones. The mechanism of the reaction, its limitations and side products are discussed. Detailed analysis of the ^1H NMR and ^{13}C NMR spectra revealed an influence of the cyclohexane ring substituents on the flexibility of the spiroferrocenophanedione bridge. Fragmentation of the product molecules upon electron impact is also described.

Introduction

Ferrocenophanes are an interesting branch of ferrocene derivatives on which the attention of many researchers has been focused because of their geometry and stereochemistry [1]. Of these, [5]ferrocenophanes are the most popular for their availability [2–10] and the fact that the 5-membered bridge is the shortest one which is fully flexible and allows the ferrocene system to keep its usual geometry [11–14].

We have reported [15] that the use of DMSO as a solvent for the condensation of diacetylferrocene (DAF) with aldehydes leads to a considerable improvement in the yields of [5]ferrocenophane-1,5-dione. Some 3-alkyl derivatives of [5]ferro-

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cenophane-1,5-dione were obtained in yields 3–5 times higher than those obtained by the previous procedure [2].

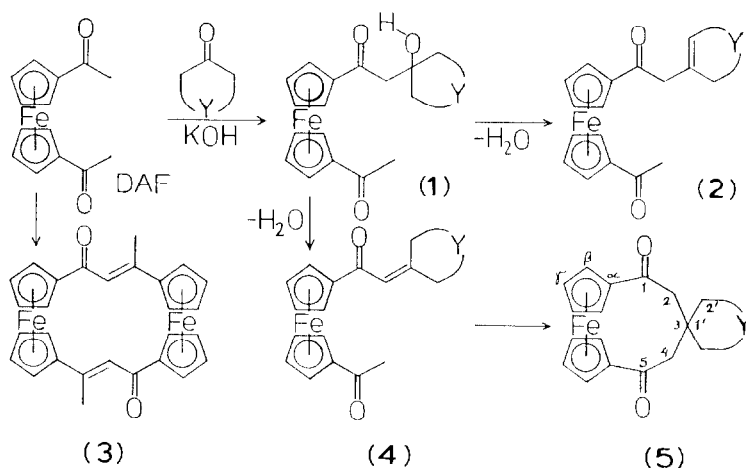
It was of great interest to find out if ketones, a less reactive group of carbonyl compounds, can also be used for the condensation with DAF under conditions similar to those applied for the reaction with aldehydes. We expected to obtain interesting 3,3-disubstituted [5]ferrocenophanes, a kind never reported before. In this paper, we discuss our efforts and describe a novel interesting group of [5]ferrocenophane derivatives.

Results and discussion

Attempts to extend the reaction of DAF on dialkyl and alkyl-aryl acyclic ketones were unsuccessful. After usual work-up of the reaction mixture, unchanged DAF was recovered and viscous polymeric substances derived from the ketone were obtained. Even more severe conditions did not help the reaction. Elevation of the temperature above 125 °C led to oxidation of DAF by DMSO [16–18] and only dark ferric oxides were separated.

The reaction was successful, however, when cyclic ketones were used. Heating of a DAF, cyclohexanone and KOH mixture dissolved in DMSO to 115–120 °C afforded the desired product, spiro[5]ferrocenophane-3,1'-cyclohexane-1,5-dione (**5a**) (Scheme 1). Use of the procedure applied in the case of aliphatic aldehydes [15], dropwise addition of cyclohexanone to the stirred DAF and KOH solution, did not produce an increase in the reaction yield. Potassium hydroxide solution appeared to form a separate phase, hence vigorous stirring of the reaction mixture had a strong influence on the product yield. The reaction was repeated several times under different conditions but the best yield of **5a**, in our hands, did not exceed 37%.

3- And 4-alkyl- or phenyl-cyclohexanones reacted similarly to unsubstituted cyclohexanone, giving the respective spiroferrocenophanediones (**5**) (Table 1). The comparatively lower yields of these products do not indicate that 3- and 4-substituted cyclohexanones are worse reagents because their reactions were not re-



Scheme 1

Table 1
Data on 3-spiro[5]ferrocenophane-1,5-diones **5**

	Y	Yield (%)	M.p. (°C)	Molecular formula	Analysis (found (calc) (%))		
					C	H	Fe
5a	CH ₂ CH ₂ CH ₂	37	256	C ₂₀ H ₂₂ FeO ₂	68.9 (68.6)	6.2 (6.3)	15.7 (16.0)
5b	CH ₂ CHMeCH ₂	16	227	C ₂₁ H ₂₄ FeO ₂	69.0 (69.2)	6.7 (6.6)	15.1 (15.3)
5c	CH ₂ CHEtCH ₂	18	236	C ₂₂ H ₂₆ FeO ₂	69.8 (69.9)	7.0 (6.9)	15.1 (14.8)
5d	CH ₂ CH(i-Pr)CH ₂	14	253	C ₂₃ H ₂₈ FeO ₂	70.5 (70.4)	7.5 (7.2)	14.4 (14.2)
5e	CH ₂ CH(t-Bu)CH ₂	25	277	C ₂₄ H ₃₀ FeO ₂	70.8 (70.9)	7.4 (7.4)	13.3 (13.7)
5f	CH ₂ CHPhCH ₂	18	255	C ₂₆ FeO ₂	73.4 (73.2)	6.5 (6.1)	13.5 (13.1)
5g	CH ₂ CMe ₂ CH ₂	10	275	C ₂₂ H ₂₆ FeO ₂	70.2 (69.9)	7.1 (6.9)	15.1 (14.8)
5h	CHMeCH ₂ CH ₂	21	261	C ₂₁ H ₂₄ FeO ₂	69.6 (69.2)	6.9 (6.6)	15.1 (15.3)
5i	CHPhCH ₂ CH ₂	12	252	C ₂₆ H ₂₆ FeO ₂	73.1 (73.2)	6.4 (6.1)	13.5 (13.1)
5j	CH ₂ CH(CH ₂) ₄ CH	10	257	C ₂₄ H ₂₈ FeO ₂	71.4 (71.3)	7.4 (7.0)	13.7 (13.8)
5k	CH ₂ CH ₂ CH ₂ CH ₂	1	235	C ₂₁ H ₂₄ FeO ₂	69.1 (69.2)	6.9 (6.6)	15.5 (15.3)

peated as in the case of cyclohexanone, and only the first entry data were taken. 2-Methylcyclohexanone failed to give a similar product, whereas 2-decalone reacted quite well (product **5j**), indicating that another saturated ring fused to that of cyclohexanone in the 3 and 4 positions does not disturb the reaction.

Cycloheptanone gave the corresponding spiroferrocenophanedione (**5k**), but in a very low yield. However, when cyclopentanone was used, only the initial DAF and a polymeric material derived from self-condensation of cyclopentanone were isolated. The reaction was repeated several times, changing the conditions, but the results were always very similar. Even traces of the desired spiro[5]ferrocenophane-3,1'-cyclopentane-1,5-dione were never detected.

Cyclooctanone did not give the corresponding spiro-ferrocenophanedione either, but careful separation of the reaction mixture afforded two new products, **21** (Y = (CH₂)₅) and **3** (Scheme 1). Re-examination of the reactions with cyclohexanones gave evidence that compounds **2** and **3** were always present in the reaction mixtures. Together with the products of self-condensation of cyclohexanones, they were separated as an oily fraction by column chromatography. Isolation of the individual compounds from this fraction was very difficult because chromatographic methods could not be used. The *R_f* values of these compounds appeared to be very similar, and they gave only one spot on the TLC plates. Fractional crystallization was satisfactorily used to separate the products derived from the reaction of DAF with cyclooctanone. However, only small fractions of the amount of **21** and **3** present in the oil could be isolated. Because such separation is a

time-consuming method, it was repeated only in the case of the mixture obtained from the reaction of DAF with cyclohexanone to give **2a** ($Y = (\text{CH}_2)_3$) and **3**.

Some comments must be made here about **3**, a product of the self-condensation of diacetylferrocene. To our knowledge, this ferrocenophane has never been reported in the literature, although a similar system obtained by condensation of DAF with diformylferrocene was described by Kasahara et al. [19,20]. A problem arises if the carbonyl groups in the product molecule are adjacent to the same ferrocene system, like in Karahara's ferrocenophane, or to two different ferrocene moieties, as given in Scheme 1. In other words, which acetyl group in the second condensation process acts as a nucleophile, after proton abstraction by the base? Comparison of the literature [19,20] and our NMR data reveals some essential differences between them. For example, Kasahara reported two groups of cyclopentadienyl proton signals, at δ 4.56 (bs, 8 H) and 4.83 (m, 8 H) ppm, whereas in our case (see the Experimental section), the pattern is quite different. This prompted us to assign the structure given in Scheme 1 to our product, although we are aware that additional investigations are required to provide full evidence for the structure. However, structural elucidation of **3** may be the subject of a separate report.

The data presented above indicate, therefore, that the cyclohexanone system is a very special one and that it is distinguished from all other ketones. What causes the favouritism of cyclohexanone? To answer this question, the reaction mechanism leading to the desired spiroferrocenophanediones must be considered. The comparatively low yields of the products, even in the case of cyclohexanones, should also be explained.

The reaction may be considered, in its first step (Scheme 1), as a crossed aldol condensation. The anion derived from DAF is formed with difficulty and only in a very low concentration because of the strong electron-donor properties of the ferrocene moiety [21–23]. Its attack on the ketone carbonyl group leads to hydroxyketone **1**. Two processes seem to be competing with this reaction. Nucleophilic attack of the anion derived from DAF may occur on the carbonyl group of another DAF molecule, giving in consequence, after several steps, a stable molecule of ferrocenophane **3**. The other process, even more important, is the self-condensation of cycloalkanones. Potassium hydroxide, under the severe conditions applied, can abstract protons not only from DAF but also from the cycloalkanone molecules. The cycloalkanone anion may act as a base on the DAF molecule but can also attack the carbonyl group of another cycloalkanone molecule. As a result, part of the cycloalkanone amount is lost to the reaction with DAF.

Hydroxyketone **1**, on the other hand, can eliminate a molecule of water in two different ways, giving unsaturated ketone **2** or **4**, with the carbon–carbon double bond isolated or conjugated to the carbonyl group, respectively. The ferrocene moiety, with its electron-releasing ability, seems to promote the first type of elimination. Such elimination—the formation of an isolated double bond—is a common process in the condensation of aliphatic ketones, e.g. 1-acetylcyclohexene [24] is formed in the reaction of cyclohexanone with acetone in the presence of sodium ethoxide. Although interconversion of unsaturated ketones **2** and **4** may be possible under the reaction conditions, ketone **2** usually dominates in the mixture, whereas only ketone **4** is the desired intermediate which can give, by internal Michael type addition, spirodione **5**.

Two factors which are responsible for the direction in which the reaction goes

must be taken into account. The first factor is the reactivity of the carbonyl group of the ketone used. The very low concentration of the anion derived from DAF requires high reactivity of the ketone. There are many reports in the literature on the reactivity of ketone carbonyl groups [25–34]. According to all these data, the most reactive are the carbonyl groups of cyclobutanone and cyclohexanone. All other cycloalkanones and all dialkyl ketones are less reactive towards nucleophiles.

The second factor which seems to play an important role in the reaction under discussion is the acidity of the ketone α -hydrogen atoms. More acidic ketones lose their α protons faster, and form anions which can compete with the anion derived from DAF in the nucleophilic attack on the carbonyl groups and are responsible for the reaction going in the wrong direction. Because we were unable to find literature data on direct acidity measurements of the ketones of interest, we decided to make a comparison of their enolization constants, assuming that, in the first approximation, there is a linear relationship between both constants, acidity and enolization. According to the literature [35], base-catalysed enolization of cycloalkanones with respect to the ring size of the ketone can be arranged in the order: 3 > 4 > 5 > 6.

Condensation of acetone with cyclic ketones in the presence of bases may also serve as a model for our reactions. Thus, when a mixture of cyclohexanone and acetone was treated with sodium alkoxide, the anion derived from acetone attacked the carbonyl group of cyclohexanone, giving 1-acetonylcyclohexene [24]. However, a mixture of cyclopentanone and acetone under similar conditions gave 2-isopropylidenecyclopentanone [36,37] as a product of nucleophilic attack of the anion derived from cyclopentanone on the acetone carbonyl group.

The above facts indicate why cyclopentanone did not give the spiroferrocenophanedione. The comparatively high reactivity of the cyclohexanone carbonyl group and its low tendency towards enolization give this ketone a special position among the aldol condensation reagents.

Spectral data and structural considerations

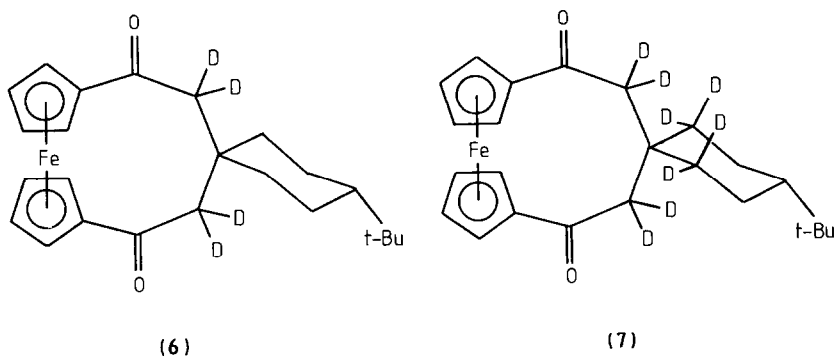
¹³C NMR spectra. The occurrence of more signals in the ¹³C NMR spectra of the spiroferrocenophanediones derived from 4-substituted cyclohexanones than we expected at the beginning stimulated their thorough analysis. 4'-t-Butylspiro[5]ferrocenophane-3,1'-cyclohexane-1,5-dione, **5e**, was chosen as a model compound because of the stability of the cyclohexane ring conformation with the equatorial t-butyl substituent. Off-resonance and selective decoupling techniques were used to identify the resonances resulting from the t-butyl group. The values of δ 27.41 (Me) and 32.31 ppm (quaternary carbon atom) obtained correspond well with the data for t-butylcyclohexane [38], δ 27.57 and 32.59 ppm, respectively. The second quaternary carbon signal at δ 46.01 ppm (C(3)), as well as the peak arising from the tertiary carbon (C(4')) at δ 47.81 ppm, was also easily recognized from the decoupling characteristics.

To distinguish the methylene group resonances, spectra of the selectively deuterated derivatives, **6** and **7**, were analysed. The disappearance of the peaks at δ 39.48 and 49.41 ppm in the spectrum of **6** indicated that these were the C(2) and C(4) resonances. The difference in the chemical shifts of these signals, 9.93 ppm, agrees well with that between the shifts of the equatorial and the axial methyl group resonances in 1,1-dimethylcyclohexane [39]. The upfield shift of the axial methyl groups on the cyclohexane ring due to the interaction of two axial hydrogens has

Table 2
Carbon-13 chemical shift data for the spiroferrocenophanediones (in ppm)

	C- α	C- β	C- γ	C(1) C(5)	C(2) C(4)	C(3)	C(2') ^a	C(3') ^b	C(4') ^c	Substituents
5a	80.57	74.07	71.01	203.67	44.57	46.36	38.44	22.01	26.04	
5b	80.42	74.07	71.01	203.14	39.94	45.99	38.07	30.60	32.17	22.23
	80.72			204.34	48.90					
5c	80.50	74.07	71.09	203.07	39.94	46.29	38.07	28.13	38.89	11.32
	80.72			204.34	48.97					
5d	80.50	74.07	71.08	203.07	39.71	46.21	38.37	25.22	43.67	19.76
	80.79			204.42	49.27					
5e	80.45	74.06	71.07	203.01	39.48	46.01	38.66	22.71	47.81	27.41
	80.78			204.45	49.41					
5f	80.42	74.15	70.93	202.54	39.11	46.95	38.52	32.84	39.86	125.76
	80.72			203.89	49.57					128.15
5g	80.65	74.07	71.01	203.74	44.34	46.14	34.11	34.93	29.48	28.73
5h	80.42	74.07	71.01	203.07	40.16	47.10	46.96	27.91	34.86	22.08
	80.79			204.40	49.65					
5i	80.42	74.15	70.93	202.54	39.94	46.29	47.03	32.91	39.19	125.84
	80.72			203.89	49.65	^d	38.22	22.23	^d	128.23
5j	80.34	74.00	70.86	202.62	^d	^d	^d	^d	^d	^d
	80.72			204.04						
5k	80.57	74.07	71.08	203.67	45.61	49.72	40.16	22.53	30.00	
6	80.42	74.15	71.08	203.22	^e	45.76	38.66	22.75	47.85	27.46
	80.71			204.64						
7	80.42	74.07	71.01	203.22	^e	45.54	^e	22.53	47.70	27.46
	80.72			204.65						32.32

^a Also C(6') in the case of cyclohexane derivatives or C(7') in the case of cycloheptane. ^b Also C(5') in the case of cyclohexane derivatives or C(6') in the case of cycloheptane. ^c Also C(5') in the case of cycloheptane derivatives. ^d The occurrence of many peaks having similar chemical shift values makes assignment difficult. ^e Multiplet of low intensity arising from coupling with the deuterium nuclei.



been a well-known phenomenon since the 1960s [40]. Quite surprising, however, is our observation that a substituent in the 4' position of the cyclohexane ring can differentiate not only the carbon atoms attached directly to the ring but also other atoms. The difference in the chemical shifts of the carbonyl groups of **5e** appeared to be 1.44 ppm and that of the α -cyclopentadienyl ring carbon atoms, 0.33 ppm.

Similarly as above, the C(2') and C(6') peak of **5e**, δ 38.66 ppm, could be unequivocally assigned based on the spectrum of its deuterated derivative **7**. The remaining methylene group signal, in the highest field, δ 22.71 ppm, was assigned to the C(3') and C(5') carbon atoms.

The considerable upfield shifts, observed in the spectra of **6** and **7** of the resonances arising from the sp^3 carbons neighbouring the CD₂ groups (0.25 and 0.47 ppm for the C(3) signal of **6** and **7**, respectively, and 0.18 ppm for the C(3') signal of **7**) are characteristic of deuterated hydrocarbons [41–43]. The smaller upfield shift (0.09 ppm) of the C(4') signal in the spectrum of **7**, γ deuterium effect, can also be similarly interpreted [43]. The downfield shift of the carbonyl carbon signals caused by the adjacent CD₂ groups, 0.19 ppm in the spectrum of **6**, is also a well-known phenomenon [44].

Assignment of the ferrocene carbon resonances was comparatively easy based on the data given by Nesmeyanov et al. for the parent system, [5]ferrocenophane-1,5-dione [45]. The differences in the chemical shifts of the cyclopentadienyl ring carbons of spiroferrocenophanedione **5e** in relation to Nesmeyanov's data do not exceed 1.1 ppm.

Assignment of the carbon resonances of the other spiroferrocenophanediones **5** was done on the basis of the parameters established for **5e**. By comparing the spectrum of **5b** with the literature data for methylcyclohexane [40], we were able to assign without doubt the signal at δ 22.23 ppm to the methyl carbon resonance. Comparison of the effects caused by the methyl group in methylcyclohexane with those caused by the t-butyl group led in a simple way to the assignment of the cyclohexane ring carbon resonances of **5b** (Table 2). Other spiroferrocenophanediones, **5a** and those bearing a substituent at C(4'), were treated similarly. 1,1,3-Tri-methylcyclohexane [40] was used as a model compound for assignments in the spectrum of the C(3') methyl substituted derivative **5h**.

¹H NMR spectra. The proton resonances of the spiroferrocenophanediones are given in Table 3. The observed chemical shift values of the cyclopentadienyl ring

Table 3

Proton NMR ^a and IR ^b spectral data for the spiroferrocenophanediones

	H- β	H- γ ^c	H(2,4)	Cyclohexane or cycloheptane ring	Substituent on the cyclohexane ring	$\nu(\text{C}=\text{O})$
5a	4.78m	4.51t	2.48s	1.51m (6H) 1.93m (4H)	–	1660
5b	4.78m	4.51t	2.40bs 2.54s	1.0–1.8m	0.93d (3.76, 3H)	1658
5c	4.77m	4.52t	2.45bs 2.53s	1.0–1.8m	0.89t (5.63, 3H) ^d	1657
5d	4.77m	4.50t	2.38bs 2.54s	1.0–1.8m	0.88d (6.10, 6H) ^d	1657
5e	4.78m	4.50t	2.42bs 2.53s	1.0–1.8m	0.86s (9H)	1662
5f	4.79m	4.50t	2.42bs 2.70s	1.1–2.2m (8H) 2.95m (1H)	7.22m (5H)	1662
5g	4.78m	4.51t	2.47s	1.37t (6.57, 4H) 1.94t (6.57, 4H)	0.93s (6H)	1654
5h	4.78m	4.51t	2.46m 2.57s	1.0–1.9m	0.93d (6.10, 3H)	1659
5i	4.80m	4.51t	2.42bs 2.71s	1.1–2.1m (8H) 2.85m (1H)	7.29m (5H)	1661
5j	4.77m	4.51t	2.39bs 2.58s	0.9–1.9m	^d	1660
5k	4.77m	4.50t	2.44s	1.57bs (8H) 2.05m (4H)	–	1658
6	4.78m	4.51t	–	1.0–1.8m	0.87s (9H)	1658
7	4.78m	4.51t	–	1.19m (3H) 1.67d (10.33, 2H)	0.87s (9H)	1660

^a Chemical shifts are given in ppm and coupling constants (in parentheses) in Hz. ^b Wavenumbers are given in cm^{-1} . ^c The coupling constants of the triplets are 1.88 Hz. ^d All or part of the signals overlap with those of the cyclohexane ring.

protons ($\delta\beta$ 4.77–4.80 and $\delta\gamma$ 4.50–4.51 ppm) correspond to the literature data on [5]ferrocenophane-1,5-dione [45] ($\delta\beta$ 4.82 ppm and $\delta\gamma$ 4.55 ppm) and diacetylferrocene [46] ($\delta\beta$ 4.75 ppm and $\delta\gamma$ 4.48 ppm). The characteristic splitting of the γ -proton signals into triplets, as special superpositions of the AA'BB'-type proton system resonances, is also consistent with the data on acetyl- and diacetyl-ferrocene [46].

The spectra of the spiroferrocenophanediones possessing symmetrical molecules, **5a**, **5g** and **5k**, revealed singlets (4H) at δ 2.44–2.48 ppm which were assigned to the C(2) and C(4) protons. The consistency of this value with the chemical shift of the methylene groups of [5]ferrocenophane-1,5-dione [45] (δ 2.50 ppm) indicates the same bridge conformation of both molecules. The sharp singlets of the C(2) and C(4) proton resonances, indicating magnetic equivalence of the methylene group protons, reflect conformational flexibility of the bridge [11,12]. The strain introduced into the bridge of such molecules by the spiro system must therefore be rather small.

Similar to the situation in ¹³C NMR, the bridge methylene group protons of the unsymmetrical molecules (a substituent at the C(3') or C(4') cyclohexane ring carbon) appeared as two independent signals: a sharp singlet (lower field) and a

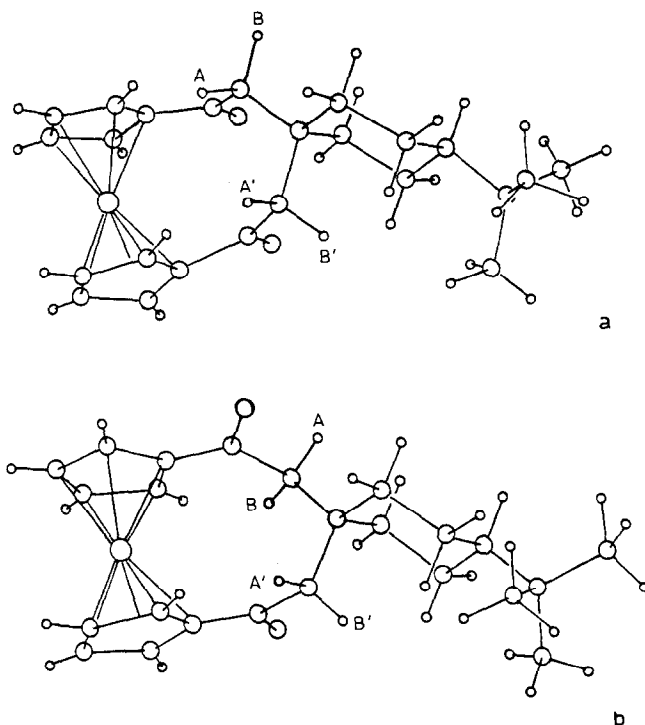


Fig. 1. Dreiding models of the two stable conformers of spiroferrocenophanedione **5e**.

broad singlet or multiplet (higher field). The downfield singlet can be attributed to the equatorial methylene group, and the upfield resonance to the axial one [40,47]. Interconversion of the cyclohexane ring between its two chair conformations favours the conformer with the substituents equatorial. As a result, in the case of 4'-substituted derivatives, the *trans*-bridge methylene group is preferentially equatorial and the *cis* group is axial (Fig. 1).

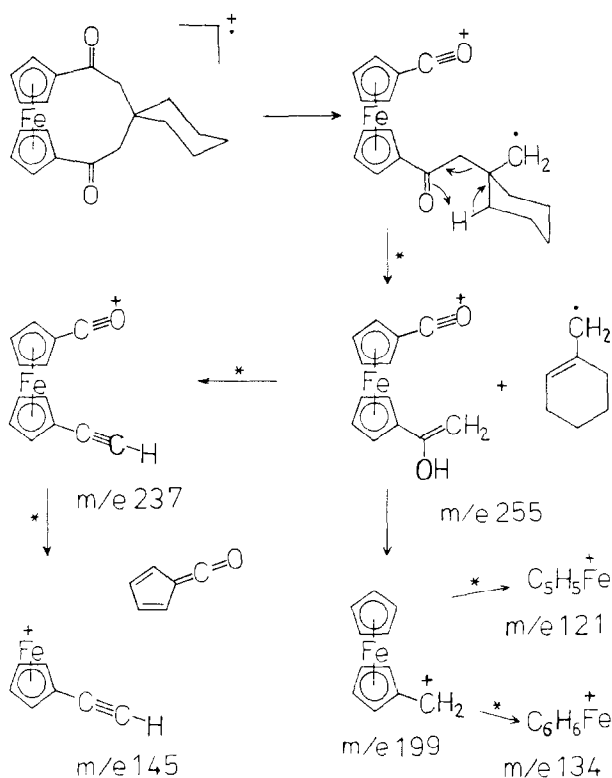
The spiroferrocenophanedione bridge can adopt two stable conformations: with eclipsed (a) or opposed (b) carbonyl groups [12,14,48] (Fig. 1). Rotation of the equatorial $\text{CH}_2\text{C}=\text{O}$ group in form a leads to form b. Protons A and B on the C(2) carbon atom interchange their space locations in relation to the ferrocene moiety during this process. Proton A moves from the deshielding zone of the ferrocene system to the shielded space [49], whereas proton B undergoes this transformation in the opposite direction. Fast interconversion of the bridge gives both protons the same average magnetic environment and results in a sharp singlet of their resonances. Broadening of the axial methylene signal arising from the incomplete magnetic equivalence of protons A' and B' indicates a barrier to rotation for this group.

The hydrocarbon ring proton parts of the spectra of the symmetrical spiroferrocenophanediones revealed two multiplets. The lower field multiplet (1.93–2.05 ppm) can be assigned to the methylene group protons adjacent to the spiro-carbon atom, as they are located in the deshielding zone of the ferrocene moiety [49]. A more complex picture is observed in the spectra of spiroferrocenophanediones

bearing a substituent on the cyclohexane ring where one conformational form is highly favoured. Under these conditions, the proton resonances broaden into bands as a result of the large amount of spin-spin splittings between non-equivalent protons. Deuterium labelling (7), however, enabled the regions of absorption arising from the C(3') and C(5') axial (δ 1.19 ppm) and equatorial (δ 1.67 ppm) protons to be distinguished.

IR spectra. The IR spectra of the spiroferrocenophanediones exhibited strong bands of the carbonyl stretching vibrations (Table 3). The wavenumber values of the bands, ν 1660 cm^{-1} , are consistent with data obtained previously for [5]ferrocenophane-1,5-diones [4,15], indicating flexibility of the spiroferrocenophanedione bridge and coplanarity of the carbonyl groups with the adjacent cyclopentadienyl rings similar to those described for the parent [5]ferrocenophane-1,5-dione system [12].

Mass spectra. An interesting phenomenon can be observed in the mass spectra of spiroferrocenophanediones 5. All the more intensive ion peaks, except those of the molecular ions and the ions closely related to them, are the same, regardless of the substituents present on the cyclohexane ring (Table 4). This fact indicates that the molecular ion loses the cyclohexane moiety as a neutral species or a radical in the first step. All the other intensive ions, with m/e 255 or below, are the same. A probable fragmentation pathway of the spiroferrocenophanedione 5 molecules leading to the most intensive ions is given in Scheme 2.



Scheme 2

Table 4

Principal ions in the mass spectra of spiroferrocenophanediones **5**

	Rel. intensities of m/e (%)										
	M^+	$M^+ - 2$	256	255	237	199	165	145	134	121	120
5a	100	7	12	54	21	15	6	8	7	15	12
5b	100	8	9	47	16	12	6	7	7	14	10
5c	100	9	6	42	13	10	5	6	5	8	8
5d	100	8	8	43	13	8	4	4	4	7	3
5e	100	8	10	51	16	14	7	7	6	15	5
5f	100	7	8	31	12	8	5	4	5	7	5
5g	100	8	9	47	17	15	8	9	9	15	10
5h	100	8	8	40	15	10	7	7	6	12	10
5i	100	8	8	29	13	10	5	6	7	11	6
5j	100	7	7	30	12	12	6	6	5	12	6
5k	100	8	12	68	21	11	5	5	7	11	7

Initial ionization of the ketone function followed by a six-centred McLafferty-type rearrangement of the α -hydrogen atom from the cyclohexane ring gives a stable ion of m/e 255 and a substituted allyl radical. The same cation (m/e 255) was reported in the mass spectrum of diacetylferrocene [50] and seems to be relatively stable because of the electron-donating abilities of the ferrocene moiety. This cation loses a molecule of water, producing an electron symmetrical ion of m/e 237. The last ion can be cleaved to the cyclopentadienyldiene ketene molecule and the ion of m/e 145.

Another pathway of the degradation of the ion at m/e 255 is extraction of two molecules of carbon monoxide to the ion at m/e 199, which is known to be very stable. Such transformation of the ion at m/e 255 was described previously in the case of diacetylferrocene [50]. The ion at m/e 199 was detected as a very strong peak in the mass spectra of several alkyl derivatives of ferrocene [51] and was also identified in the spectra of acylferrocenes [52]. Decomposition of this ion results in two possible fragments, giving peaks at m/e 121 and 134. The fragmentations given, except that involving the loss of two CO molecules and rearrangement ($255 \rightarrow 199$), are supported by the presence of suitable metastable ions.

Experimental

Melting points are uncorrected. ^1H NMR and ^{13}C NMR spectra were obtained on a 100-MHz Tesla BS 567A spectrometer using CDCl_3 as a solvent and tetramethylsilane as an internal reference. IR spectra were obtained on a Specord 75 IR (Carl Zeiss, Jena) spectrophotometer for samples taken as hexachlorobutadiene mulls. Mass spectra were taken on a LKB-9000S spectrometer.

To perform elemental analysis on iron, a 10 mg sample of the ferrocene derivative was dissolved in concentrated sulphuric acid (1 ml) at 60°C , and the solution was cooled to room temperature and mineralized by oxidation with 30% hydrogen peroxide (0.25 ml). The resulting solution was diluted with water, treated with 5-sulphosalicylic acid and neutralized with ammonia. The iron concentration was measured spectrophotometrically (UV/VIS VSU-2P, Carl Zeiss, Jena Spectrophotometer) following the procedure in ref. 53.

Diacetylferrocene was obtained by acetylation of ferrocene with acetyl chloride in the presence of aluminium chloride [54]. 4-Isopropylcyclohexanone was obtained from 4-isopropyl-2-cyclohexen-1-one [55] by catalytic (PtO_2) hydrogenation. A similar procedure was used to prepare 4-ethylcyclohexanone. 4-Isopropyl-2-cyclohexen-1-one and 4-ethyl-2-cyclohexen-1-one used for the hydrogenation were obtained from the reaction of isovaleraldehyde and butyraldehyde enamines, respectively, with methyl vinyl ketone [55].

Hydrogenation of 4,4-dimethyl-2-cyclohexen-1-one, obtained by condensation of isobutyraldehyde with methyl vinyl ketone [56], afforded 4,4-dimethylcyclohexanone. Reaction of 1-morfolino-1-cyclohexene with methyl vinyl ketone gave 3-keto- Δ^4 -octalin [57], which was then hydrogenated to 2-decalone. Reaction of β -dimethylaminopropiophenone with methyl acetoacetate afforded 3-phenyl-2-cyclohexen-1-one [58], which was hydrogenated to 3-phenylcyclohexanone. 4-Phenylcyclohexanone was obtained by reaction of 2-cyclohexen-1-one with benzene in the presence of aluminium chloride and dry hydrogen chloride [59]. All other cycloalkanones used for the reaction with DAF, i.e. cyclopentanone, cyclohexanone, 3- and 4-methylcyclohexanone, 4-*t*-butylcyclohexanone, cycloheptanone and cyclooctanone, were commercial products.

The cycloalkanones and DMSO used for the reaction with DAF were distilled under reduced pressure prior to use. The purity of the obtained cycloalkanones was checked by NMR spectroscopy.

Condensation of DAF with cycloalkanones. General procedure

A mixture of DAF (5.40 g, 20 mmol), cycloalkanone (40 mmol), 50% water solution of potassium hydroxide (4.48 g, 40 mmol) and DMSO (40 ml) kept under argon at 115–120 °C (the oil bath temperature) was stirred vigorously for 2 h. After cooling to ambient temperature, the mixture was poured into a 10% solution of sodium hydrosulphite (400 ml) and extracted with chloroform (400 ml). The chloroform solution was washed with water (3×200 ml), dried over anhydrous magnesium sulphate, and the solvent was evaporated under reduced pressure. The residue was chromatographed on basic aluminium oxide (200 g) using benzene/chloroform (1/1) for elution. The first band contained the spiroferrocenophane-dione. Further elution with the same solvent afforded an oily fraction which, according to the NMR spectra, was a complex mixture.

The crude product was recrystallized from toluene or cyclohexanone. Sometimes two recrystallizations were required to obtain an analytically pure sample and in such situations both solvents, one after the other, were applied.

Reaction of DAF with cyclooctanone. Separation of 2I ($Y = (\text{CH}_2)_5$) and ferrocenophane 3

The reaction was carried out following the general procedure given above. The first fraction from column chromatography on basic aluminium oxide was an oily mixture and the second fraction appeared to be the starting DAF. The oily fraction was subjected to further chromatography using a column packed with silica gel (100 g) and benzene/chloroform/ethyl acetate (6/3/1) as eluant. Six oily fractions having similar R_f values were obtained. Their NMR spectra revealed that all of them were mixtures of at least three components, although in different proportions.

Two middle fractions were collected and dissolved in ether (3 ml). The solution was diluted with petroleum ether (2 ml), filtered and stored in a freezer. After a few days, the precipitate was filtered off, washed with petroleum ether and dried in a vacuum oven. The precipitate appeared to consist of brown-red needles and small deep-red polyhedrons. The crystals were separated manually.

The needles, 13 mg, m.p. 84°C, appeared to be ketone **2l** ($Y = (CH_2)_5$). Anal. Found: C, 69.6; H, 7.1. $C_{22}H_{26}FeO_2$ calc.: C, 69.9; H, 6.9%. 1H NMR: δ (ppm) 1.48 (8 H, m), 2.19 (4 H, m), 2.37 (3 H, s), 3.35 (2 H, bs), 4.50 (4 H, t, J 1.88 Hz), 4.79 (4 H, m) 5.54 (1 H, t, J 7.98 Hz). IR (HCB mull): ν (cm^{-1}) 1661 (C=O).

The polyhedrons, 4 mg, appeared to be ferrocenophane **3**. The product did not melt but decomposed slowly upon heating above 200°C. Anal. Found: C, 74.7; H, 5.6. $C_{28}H_{24}FeO_2$ calc.: C, 75.0; H, 5.4%. 1H NMR: δ (ppm), 1.57 (6 H, s), 4.50 (8 H, m), 4.58 (4 H, m), 4.81 (4 H, t, J 1.88 Hz), 6.59 (2 H, bs). IR ($CHCl_3$ solution): ν (cm^{-1}), 1641 (C=O), 1584 (C=C).

Separation of ketone 2a ($Y = (CH_2)_3$) and ferrocenophane 3 from the reaction mixture

Column chromatography of the mixture obtained from the condensation of DAF with cyclohexanone gave two fractions. The first fraction was spiroferrocenophanedione **5a** (see general procedure). The second fraction was chromatographed again using silica gel (100 g) and benzene/chloroform/ethyl acetate (2/2/1) as an eluant, and 100 ml fractions were collected. The first three fractions contained spiroferrocenophanedione **5a** (140 mg of the product was obtained after recrystallization of the samples). The fifth fraction was the largest one. It was dissolved in isooctane/toluene (20 + 5 ml) and the solution was stored in a freezer. The precipitate was filtered off, washed with petroleum ether and dried in a vacuum oven. The sample weight was 2 mg. The product, characterized by its NMR spectrum, appeared to be ferrocenophane **3**.

The filtrate, after separation of **3**, was evaporated and the residue was crystallized from isooctane. The precipitate that separated in the freezer was filtered off but is soon turned into an oil. The oil, 8 mg, was dried in a vacuum oven and characterized as ketone **2a**. Anal. Found: C, 68.8; H, 6.5. $C_{20}H_{22}FeO_2$ calc.: C, 68.6; H, 6.3%. 1H NMR: δ (ppm) 1.61 (4 H, m), 2.03 (4 H, m), 2.36 (3 H, s), 3.29 (2 H, bs), 4.49 (4 H, m), 4.77 (4 H, t, J 1.88 Hz), 5.59 (1 H, m). IR (HCB mull): ν (cm^{-1}) 1659 (C=O).

Preparation of deuterium-labelled spiroferrocenophanedione 6

Liquid potassium-sodium alloy (0.5 ml, 13 mmol) was dissolved in a solution of deuterium oxide (1.8 ml, 100 mmol) and freshly distilled diglyme (50 ml). Spiroferrocenophanedione **5e** (300 mg, 0.79 mmol) was added, and the solution obtained was sealed in a glass tube and heated in an oil bath at 160°C for 7 h. After cooling, the tube was opened and its contents were poured into water. The mixture was acidified with 5% HCl and extracted with chloroform (50 ml). The chloroform solution was washed with water (2×150 ml), dried over anhydrous magnesium sulphate and the solvent was evaporated.

The oil obtained (solution of the product in the remaining diglyme) was diluted with petroleum ether (50 ml) and stored in a freezer. The precipitate was filtered off, washed with ether and dried in a vacuum oven. Pure spiroferrocenophanedione **6**, 150 mg, m.p. 278°C, was obtained. Its IR spectrum exhibited two weak bands at

2143 and 2212 cm^{-1} , characteristic of CD stretching vibrations. The ^1H NMR and ^{13}C NMR spectral data are given in Tables 2 and 3, respectively. The mass spectrum, m/e , 410 (100%, M^+), 409 (30%, $M^+ - 1$), revealed some contamination of the sample with the trideuterated species.

Preparation of deuterium-labelled spiroferrocenophanedione 7

The general procedure for synthesis of spiroferrocenophanediones **5** was applied with some modifications. The reaction was carried out on a smaller scale, starting from 10 mmol of DAF. Instead of ordinary DMSO, dimethyl sulphoxide- d_6 (20 ml) was used as the solvent and water was replaced by deuterium oxide (2 ml).

Work-up of the reaction mixture and separation of the product as described in the general procedure afforded octadeuteriospiroferrocenophanedione **7** (1.0 g). Apart from the NMR spectra (Tables 2 and 3), it was characterized by IR spectroscopy (bands at 2109, 2143 and 2208 cm^{-1}). The mass spectrum, m/e , 414 (100%, M^+), 413 (80%, $M^+ - 1$) indicated the presence of heptadeuterated species in the sample.

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