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Synthesis of Antiprismatic [5.5]Ferrocenophane ([5](1,1′)[5](3,4′)Ferrocenophane)

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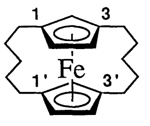
Synopsis. The title compound **2**, which is the first example of a C_2 symmetric dibridged ferrocenophane, has been synthesized via a base-catalyzed condensation of 3,4′-diacyl[5]ferrocenophane. The spectroscopic properties of **2** are briefly discussed by comparing them with the corresponding prismatic [5,5]ferrocenophane having C_{2v} symmetry.

In intramolecularly 1,3-dibridged ferrocenes with two polymethylene chains, there are, in principle, two geometric isomers bridged at the 1,1′- and 3,3′-positions and at the 1,1′- and 3,4′-positions of the cyclopentadienyl (Cp) rings, which are called "prismatic" and "antiprismatic" ferrocenophanes,[1)] respectively. Although a number of 1,3-dibridged ferrocenophanes have been prepared thus far,[1—7)] all of them are bridged in a prismatic form. There has been only one report on the preparation of [5](1,1′)[5](3,4′)ferrocenophane derivative (**3**) by Nesmeyanov,[8)] though its configuration has not be determined. The reason that no example exists of a structurally confirmed antiprismatic ferrocenophane may arise from the following problems: (i) Bridging of [n](1,1′)ferrocenophane-3-propanoic acids (n>2) by a heteroannularly cyclization reaction, which is usually employed for the preparation of dibridged ferrocenophanes, selectively gives 3′-bridged compounds, but no 4′-bridged compound. (ii) A spectroscopic distinction between prismatic and antiprismatic structures is not easy. This article describes the preparation of [5](1,1′)[5](3,4′)ferrocenophane (**2**) via a linking between the substituents of the two Cp rings, a determination of its antiprismatic configuration and a spectroscopic characterization of **2**, compared with the corresponding prismatic compound **1**.

An acylation of 3-acetyl[5]ferrocenophane (**4**)[4)] with 3-chloropropanoyl chloride and AlCl$_3$ gave three isomeric diacylferrocenophanes, **5a**—**5c**, which were easily convertible to enone **6a**—**6c** by elimination. The α'-substituted structures of **5a** and **5c** were ascertained by means of their ^{1}H NMR spectra, in which the 3′- and 4′-proton signals, respectively, appeared as triplets with ortho coupling constants (J=2.6 and 2.7 Hz). The desired β'-substituted compound **5b** was so unstable in solvents that it could not be characterized by ^{1}H NMR spectrometry. Compound **5b** was readily converted to stable enone **6b**, even by a treatment with neutral alumina in benzene. The ^{1}H NMR spectrum of **6b** showed a triplet signal with a meta coupling constant (J=1.4 Hz); its β'-substituted form was confirmed. At this stage it could not be determined whether **5b** and **6b** were 3,3′- or 3,4′-acylated phanes, although 3,4′-substituted structures were predictable due to a substitution disadvantage just below the position of the acyl group in ferrocenophanes.[9)] No other possible β'-acylated compound was isolated in the present reaction.

A second bridge formation was carried out according to a modified procedure in the preparation of [5](1,1′)ferrocenophane-1,5-dione reported by Barr and Watts.[10)] A crude mixture, obtained by acylation of **4**, without separating into each component, was treated by aq NaOH; dibridged diketone **7** was isolated (16% from **4**) from the many products by chromatography. An intramolecular Michael condensation of enone **6b** was also attempted, but the yield of **7** could not be improved (9%). The desired antiprismatically bridged structure of **7** was determined by ^{1}H NMR spectrometry in the



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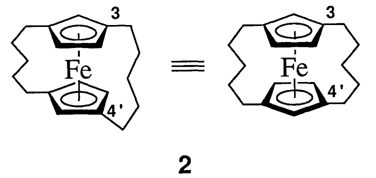

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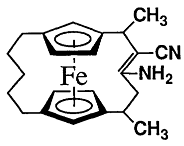

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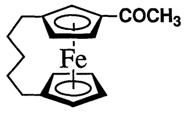

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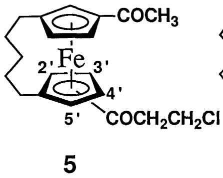

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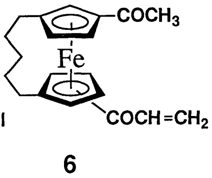

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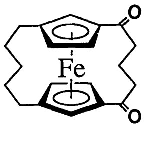

7

a: 2'-substituted
b: 4'-substituted
c: 5'-substituted

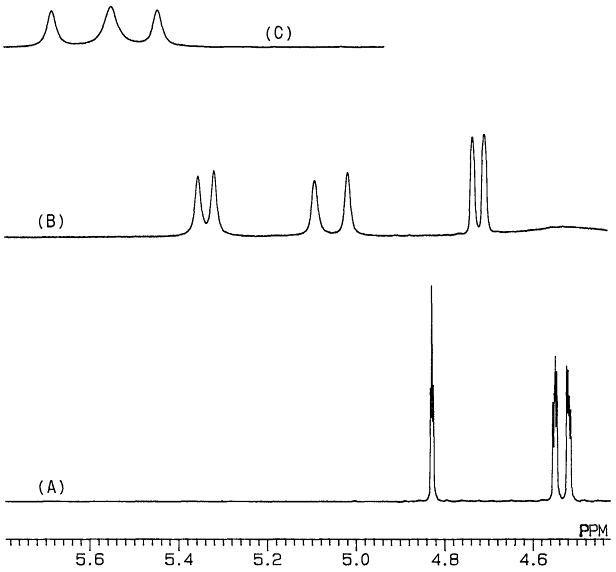

Fig. 1. Cp ring proton region in the ^{1}H NMR spectra of **7** in $CDCl_3$ without any additive (A), with tris[3-(trifluoromethylhydroxymethylene)-*d*-camphorato]europium(III) [Eu(tfmc)] (B), and with tris[(heptafluorobutanoyl)pivaloylmethanato]europium(III) [Eu(fod)] (C).

presence of a chiral shift reagent. [5](1,1′)[5](3,4′)Ferrocenophane-1,5-dione (**7**) is a racemic mixture of two chiral molecules, while the corresponding isomeric [5](1,1′)[5](3,3′)ferrocenophane-1,5-dione is a *meso* compound possessing two symmetric planes through the central iron atom. Accordingly, each proton signal of the former in the ^{1}H NMR spectrum should split into two signals due to diastereomeric interactions between a pair of enantiomers and a chiral shift reagent, but that of the latter prismatic diketone does not under the same conditions. The spectra of **7** in $CDCl_3$ without any additive, with chiral a shift reagent, [Eu(tfmc)], and with an achiral shift reagent, [Eu(fod)], are shown in Fig. 1. The desired bridging feature of **7** was proven in terms of the spectral behavior.

The reduction of the two carbonyl groups of **7** gave the antiprismatic [5.5]ferrocenophane **2**. The ^{1}H and ^{13}C NMR spectra of **2** are obviously distinguished from those of ferrocenophane **1**, of which the pprismatic structure was already confirmed.[7] It is interesting that the d–d* band of **2** in the electronic absorption spectrum in tetrahydrofuran (THF) shifted to a longer wavelength (456 nm) than that of **1** (444 nm; ferrocene, 440 nm in THF). The shift value of **2** resembles that of tetra-bridged [5_4](1,2,3,4)-ferrocenophane (460 nm).[11] A linear relationship between the hypsochromic shift of the d–d* band and a compression of the Cp–Fe–Cp distance has been found in multibridged ferrocenophanes.[12] An elongation of the Cp–Fe–Cp distance in [5_4]ferrocenophane (3.336 Å;[11] ferrocene, 3.32 Å[13]) was observed in an X-ray crystal analysis. It would therefore be suggested that the distance of the two Cp rings of **2** is a little longer than that of **1**, and that the two pentamethylene bridges in antiprismatic manner elongate the distance. A consideration using a Dreiding molecular model supports this assumption, that is, the molecule of **2** is somewhat strained by avoiding steric hindrance among the hydrogens of the polymethylene chains in a zigzag conformation, while that of **1** is in a relaxed conformation.

Experimental

Melting points were uncorrected. IR, mass and electronic spectra were obtained on the same instruments as those used in a previous report,[11] except for NMR spectra, which were measured on a JEOL JNM GSX500 spectrometer relative to tetramethylsilane as an internal standard.

Acylation of 3-Acetyl[5]ferrocenophane (4) with 3-Chloropropanoyl Chloride. A mixture of 3-chloropropanoyl chloride (2.52 g, 20.6 mmol) and $AlCl_3$ (3.10 g, 23.3 mmol) in dichloromethane (50 ml) was prepared under an Ar atmosphere and stirred at room temperature for 2 h. To the resulting suspension was added dropwise 3-acetyl[5]ferrocenophane (**4**)[4] (3.00 g, 10.1 mmol) in dichloromethane (30 ml). The reaction mixture was stirred at room temperature for 22 h, and then quenched with water. The hydrolysate was extracted with dichloromethane; and the extracts were washed with water, dried over $CaCl_2$, and evaporated. The crude was column-chromatographed over silica gel with benzene–ethyl acetate (10:1). The starting material **4** was recovered from first band. The second band yielded 3-acetyl-2′-(3-chloropropanoyl)[5](1,1′)ferrocenophane (**5a**) (0.11 g, 2.8%) as a red solid. IR (KBr) 1650 and 1670 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.64, 1.86, 2.24, 2.33, 2.53, and 3.05 (2H, 4H, 1H, 1H, 1H, and 1H, each m, $-CH_2-$ of bridge), 2.42 (3H, s, $-COCH_3$), 2.94 and 3.23 (each 2H, dt, *J*=6.2, 18.0 Hz, $-COCH_2-$), 3.90 (2H, t, *J*=6.2 Hz, $-CH_2Cl$), 4.28, 4.30, 4.57 and 4.67 (1H, 2H, 1H, and 1H, each m, Cp-H), 4.64 (1H, t, *J*=2.6 Hz, 4′-H of Cp); MS *m*/*z* (rel intensity) 386 (25, M$^+$), 350 (100, [M−Cl]$^+$).

The third band yielded 3-acetyl-5′-(3-chloropropanoyl)[5](1,1′)ferrocenophane (**5c**) (0.31 g, 7.9%) as a red solid. IR (KBr) 1640 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.67, 1.82, 1.90, 2.30, 2.45, and 2.99 (1H, 1H, 3H, 2H, 2H, and 1H, each m, $-CH_2-$ of bridge), 2.38 (3H, s, $-COCH_3$), 3.04 and 3.28 (each 1H, m, $-COCH_2-$), 3.80 and 4.00 (each 1H, m, $-CH_2Cl$), 4.20 (1H, t, *J*=2.7 Hz, 3′-H of Cp), 4.27, 4.59, 4.75 and 4.88 (each 1H, dd, *J*=1.3, 2.7 Hz, 4-, 5-, 2′-, and 4′-H of Cp), 4.54 (1H, t, *J*=1.3 Hz, 2-H of Cp).

These two compounds, **5a** and **5c**, could not be sufficiently purified due to the easy occurrence of elimination in solvents.

The fourth band yielded 3-acetyl-4′-(3-chloropropanoyl-[5](1,1′)ferrocenophane (**5b**) (1.16 g, 30%) as a red solid. The ^{1}H NMR spectrum of **5b** was contaminated with the many signals of enone **6b** generated by a rapid elimination in $CDCl_3$, and could not be sufficiently analyzed. The structure of **5b** was inferred from a structural determination of **6b** derived by the elimination of **5b**, as mentioned below.

3-Acetyl-4′-propenoyl[5](1,1′)ferrocenophane (6b). A crude mixture obtained by the acylation of **4** (1.00 g, 3.38 mmol) with 3-chloropropanoyl chloride (0.88 g, 7.21 mmol) and $AlCl_3$ (1.03 g, 7.77 mmol) according to the procedure described above was treated with alumina in benzene–ethyl acetate. The mixture was eluted and evaporated. The residue was column-chromatographed over alumina with benzene–ethyl acetate (10:1) to be separated into five bands. The third and fourth bands yielded 2′- and 5′-propenoyl-[5](1,1′)ferrocenophanes (**6a**, 0.06 g, 5% from **4**; **6c**, 0.14 g, 12%), respectively, as red oils.

The fifth band yielded 3-acetyl-4′-propenoyl[5](1,1′)ferrocenophane (**6b**) (0.63 g, 53%), which was recrystallized from hexane–ethyl acetate to give red prisms; mp 113—113.5 °C. IR (KBr) 1640 and 1660 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.84, 1.99

and 2.38 (4H, 2H and 4H, each m, $-CH_2-$ of bridge), 2.35 (3H, s, $-COCH_3$), 4.38, 4.70, 4.53 and 4.55 (each 1H, dd, J=1.4, 2.6 Hz, 4-, 5-, 2′-, and 3′-H of Cp), 4.59 and 4.61 (each 1H, t, J=1.4 Hz, 2- and 5′-H of Cp), 5.78 (1H, dd, J=1.8, 10.4 Hz, $=CH_2$ of propenoyl), 6.48 (1H, dd, J=1.8, 16.9 Hz, $=CH_2$ of propenoyl), 6.76 (1H, dd, J=10.4, 16.9 Hz, vinyl-H of propenoyl).

Found: C, 68.28; H, 6.27%. Calcd for $C_{20}H_{22}O_2Fe$: C, 68.59; H, 6.33%.

[5](1,1′)[5](3,4′)Ferrocenophane-1,5-dione (7). (1) The crude mixture obtained by acylation of **4** (3.00 g, 10.1 mmol) with 3-chloropropanoyl chloride (2.52 g, 20.6 mmol) and $AlCl_3$ (3.10 g, 23.3 mmol) was dissolved to ethanol (400 ml), and 10% aq NaOH (400 ml) was added. After the solution was stirred at room temperature for 12 h, a large excess of water was added. The mixture was extracted with dichloromethane, and the extracts was washed with saturated aq NaCl, dried over $CaCl_2$ and evaporated. The residue was column-chromatographed over silica gel to be separated into many bands. The seventh band eluted with benzene–ethyl acetate (20:1) yielded [5.5]ferrocenophane-1,5-dione (**7**) (0.43 g, 16% from **4**), which was recrystallized from hexane–ethyl acetate to give red needles; mp 246—246.5 °C. IR (KBr) 1670 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.66, 1.74, 1.94, 2.53 and 2.86 (each 2H, m, $-CH_2-$ of aliphatic bridge), 2.08, 2.11, 2.24, 2.28, 2.35 and 2.38 (each 1H, m, $-CH_2-$ of dioxo-bridge), 4.52 and 4.55 (each 2H, dd, J=1.5, 2.7 Hz, 4-, 5-, 2′-, and 3′-H of Cp), 4.83 (2H, t, J=1.5 Hz, 2- and 5′-H of Cp); ^{13}C NMR ($CDCl_3$) δ=23.83, 25.82, 26.00, 27.17, and 34.41 ($-CH_2-$), 68.67, 73.45 and 95.56 (Cp–C), 205.70 (C=O); MS m/z (rel intensity) 350 (100, M$^+$).

Found: C, 68.16; H, 6.25%. Calcd for $C_{20}H_{22}O_2Fe$: C, 68.59; H, 6.33%.

(2) To a solution of enone **6b** (80 mg, 0.23 mmol) in ether (5.0 ml) was added dropwise a solution of KOH (0.17 g) in ethanol (1.5 ml) at 0 °C. The mixture was stirred for 2 h, and then extracted with dichloromethane. The extracts were washed with saturated aq NaCl, dried over $CaCl_2$ and evaporated. Column chromatography on silica gel with benzene/ethyl acetate afforded two bands. The first band yielded diketone **7** (7 mg, 9%). The second band (24 mg) was an unknown red oil.

Both reactions of **6b** with aq KOH in ethanol (without ether) and with EtONa in ethanol gave no bridged diketone **7**.

[5](1,1′′)[5](3,4′)Ferrocenophane (2). Diketone **7** (200 mg, 0.57 mmol) in ether (50 ml) was added dropwise to a suspension of $LiAlH_4$ (60 mg, 1.6 mmol) and $AlCl_3$ (230 mg, 1.7 mmol) in ether (20 ml) at 20 °C. The mixture was decomposed with wet ether, and the hydrolysate was extracted with ether. The extracts were washed with saturated aq NaCl, dried over Na_2SO_4 and evaporated. Column chromatography on silica gel with benzene provided [5](1,1′)[5](3,4′)ferrocenophane (**2**) (0.171 mg, 93%) as the main band. An analytical sample was obtained by recrystallization from hexane–ethyl acetate as yellow needles; mp 122—123 °C. ^{1}H NMR ($CDCl_3$) δ=1.72, 1.99, 2.23, 2.34 and 2.37 (8H, 4H, 4H, 2H, and 2H, $-CH_2-$ of bridge), 3.75 (2H, t, J=1.5 Hz, 2- and 5′-H of Cp), 3.98 (4H, d, J=1.5 Hz, 4-, 5-, 2′-, and 3′-H of Cp); ^{13}C NMR ($CDCl_3$) δ=23.56, 26.25, and 26.53 ($-CH_2-$), 68.04, 68.71 and 87.92 (Cp–C); MS (m/z rel intensity) 322 (100, M$^+$; $\lambda_{\max}$ (THF) 456 nm (ε=119).

Found: C, 75.15; H, 8.16%; M$^+$, 322.1389. Calcd for $C_{20}H_{26}Fe$: C, 74.54, H, 8.13%; M, 322.1383. Calcd for $C_{20}H_{26}Fe\cdot 1/6\ (C_6H_{14})$: C, 74.89; H, 8.49%. (Hexane, C_6H_{14}, may originate in the solvent used in recrystallization.)

[5](1,1′)[5](3,3′)Ferrocenophane (1). The spectra of **1** previously reported (mp 86—87 °C[7]) were also measured on the same instruments in order to compare them with those of **2**. ^{1}H NMR ($CDCl_3$) δ=1.82, 2.00, 2.13, and 2.36 (8H, 2H, 2H and 8H, each m, $-CH_2-$ of bridge), 3.78 and 3.88 (2H and 4H, t and d, Cp-H); ^{13}C NMR ($CDCl_3$) δ=23.69, 24.60 and 25.94 ($-CH_2-$), 66.87, 68.74 and 87.01 (Cp–C); $\lambda_{\max}$ (THF) 444 nm (ε=124).

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