Preparation and Complexing Properties of Crown Ether Compounds Incorporating a Ferrocene Unit at 1,2- or 1,3-Positions

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(Received December 16, 1985)

Ten new crown ethers incorporating a ferrocene unit at 1,2- or 1,3-positions are reported. These crown ethers were synthesized by the reaction of 1,2- or 1,3-bis(hydroxymethyl)ferrocene with oligoethylene glycol ditosylate (n=1—5) with potassium t-butoxide by a high-dilution method. These new types of ferrocene crown ethers were examined for complexation behavior with alkali, alkaline earth, and transition-metal cations by solvent extraction. It was found to extract thallium ions most effectively.

Crown compounds with a ferrocene unit incorporated into a macrocyclic ring have recently received considerable attention. Polyoxaferrocenophanes,[1] polythiaferrocenophanes,[2] polyoxathiaferrocenophanes[3] and ferrocene cryptands[4] have been synthesized and their functions have been investigated. Before, we reported on the synthesis and the cation-complexing ability of ferrocene-containing oxo crown ethers.[5] Most of these ferrocenophanes and cryptands exhibit rather weak binding toward alkali metal cations, but better complexation toward silver and thallium ions. Furthermore, all of these ferrocenophanes and cryptands formed a macrocycle at the 1,1′-positions of a ferrocene ring. In this work we considered the effects of a ferrocene structure on the complexing ability of a macrocycle. We now report on the synthesis and give a survey of the complexing properties of new ferrocenophanes which contain crown-ether type units connected at the 1,2- or 1,3-positions of a ferrocene ring.

Results and Discussion

Synthesis. The following reactions were carried out in order to obtain 1,2-bis(hydroxymethyl)ferrocene (**1**) and 1,3-bis(hydroxymethyl)ferrocene (**2**) as starting materials. In connection with the synthesis of the ferrocenophanes (**4b—e**, **5a**, **6b—e**, and **7a**), it became desirable to synthesize 1,2- and 1,3-bis(hydroxymethyl)-ferrocenes (**1** and **2**) in quantity. 2-Lithio[(dimethylamino)methyl]ferrocene, which was prepared by the reaction of [(dimethylamino)methyl]ferrocene with t-buthyllithium, was condensed with paraformaldehyde to give 2-[(dimethylamino)methyl]ferrocenemethanol. The amino alcohol was quaternized by methyl iodide, this ammonium iodide was converted to ferrocene-1,2-dimethanol (**1**) by boiling with an aqueous alkali. A treatment of 1,3-diacetylferrocene with sodium hypobromite in dioxane–H_2O below 10°C led to the formation of 1,3-ferrocenedicarboxylic acid. Then, ferrocene-1,3-dimethanol (**2**) was synthesized by the usual $LiAlH_4$ reduction of the dimethyl ester, which was prepared by an acid-catalyzed esterification of 1,3-diacid. A new series of "crowned" ferrocenophanes were prepared by the synthetic sequence shown in Fig. 1.

We used a facile modification of the Williamson ether synthesis which was performed in aprotic solvents using tosylate as the leaving group, the potassium cation improved the yields by forming a template

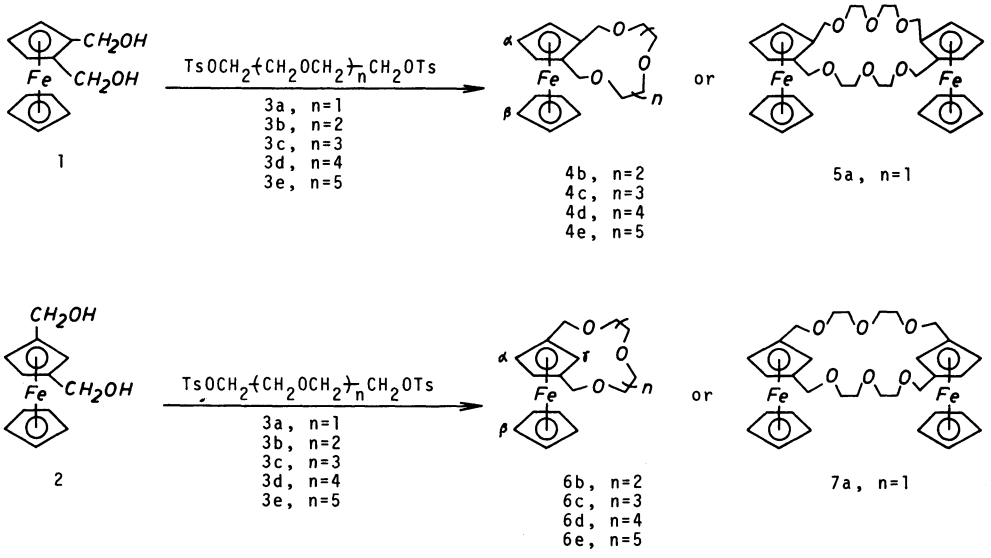

Fig. 1.

Table 1. Reaction of 1,2-Bis(hydroxymethyl)ferrocene and 1,3-Bis(hydroxymethyl)-ferrocene with Oligoethylene Glycole Ditosylates

Starting materials		Product	Yield/%	Mp θ_m/°C	Color
Ferrocene dialcohol	$TsOCH_2$-$(CH_2OCH_2)_n$-CH_2OTs				
1	n=1	**5a**	5.8	109—110	Yellow
1	n=2	**4b**	10.8	66—67	Yellow
1	n=3	**4c**	6.1	48—49	Yellow
1	n=4	**4d**	8.2	Oil	Orange
1	n=5	**4e**	7.6	Oil	Orange
2	n=1	**7a**	4.0	144—145	Yellow
2	n=2	**6b**	6.9	92—93	Yellow
2	n=3	**6c**	12.2	Oil	Orange
2	n=4	**6d**	17.3	Oil	Orange
2	n=5	**6e**	15.8	Oil	Orange

about which molecules could cyclize.[6] The reaction of diol (**1** or **2**) with the ditosylates of oligoethylene glycols (**3b—e**) in dry benzene in the presence of potassium *t*-butoxide gave crowned ferrocenophanes (**4b—e** and **6b—e**) in 5.8—10.8% yields for 1,2-ferrocenophanes or 4.0—17.3% yields for 1,3-ferrocenophanes, respectively, as yellow crystals or orange oils, along with unexpected polymeric materials (5—8 weight %). The starting materials (**1** and **2**) were recovered in every case in 40—60% yields. We tried to improve the product yields, but this could not be done by changing the reaction conditions (reaction time and solvent). Binuclear ferrocenophanes (**5a** and **7a**) were formed in the reaction of diethylene glycol ditosylate (**3a**) with **1** and **2**. This might indicate that the diethylene glycol chain (n=1) is too short to cyclize on the same cyclopentadienyl ring (1,2- or 1,3-positions). The results are summarized in Table 1. The structures of all ferrocenophanes, thus prepared, were determined on the bases of their IR, ^{1}H NMR, mass spectra and elemental analyses. The IR spectra of the ferrocenophanes showed bands caused by ether a linkage at 1090 or near 1127 cm^{-1}, by homoannular disubstituted ferrocene in 3105—3095, 1100, 1020—1000, and 820 cm^{-1} regions, and by methylene group in 2980—2920, 2880—2870, 1460—1420, and 1380—1360 cm^{-1} regions. In the ^{1}H NMR spectra, all the ferrocenophanes showed a similar pattern: methylene protons as a broad singlet at about 3.6 ppm, protons of methylene groups adjacent to the ferrocene ring at 4.26—4.39 ppm, unsubstituted cyclopentadienyl protons at 4.08—4.10 ppm as sharp singlets and substituted cyclopentadienyl protons as multiplets at 4.22—4.42 ppm. The mass spectra and the elemental analyses also confirmed the structures.

Extraction Ability. The complexing ability between synthesized polyoxaferrocenophanes (**4b—e**, **6b—e**, **5a**, and **7a**) and alkali, alkalin earths, and transition metal cations could be established by Pedersen's solvent extraction method.[7] The data are summarized in Table 2. These results indicate little or no extractability toward alkali metal cations (Li^+ and Na^+) for almost all of polyoxaferrocenophanes, except **4c** which exhibits selectivity toward the thallium cation.

Table 2. Extraction Data (Water-Dichloromethane)[a]

Compound	Extracted/%					
	Li^+	Na^+	K^+	Ba^{2+}	Tl^+	Ag^+
4b	0	2.9	0.7	5.3	14.9	Oxidation
4c	0.9	32.9	19.3	14.2	67.6	86.1
4d	4.3	4.3	13.4	19.2	66.4	Oxidation
4e	2.9	2.9	24.3	53.6	77.9	Oxidation
6b	0	0	0	10.0	4.4	Oxidation
6c	0	0	4.0	8.3	56.3	Oxidation
6d	0	0	11.4	0.7	66.3	25.7
6e	1.4	1.8	6.7	4.0	60.8	42.1
5a	0	1.8	9.0	6.4	56.2	Oxidation
7a	0	0	0	9.1	34.2	Oxidation

a) Equal volumes of water and dichloromethane, and picric acid at 7.0×10^{-5}M (1M=1 mol dm^{-3}). Concentration of ferrocenophane: 7.0×10^{-4}M. Concentration of metal nitrate: 0.1 M.

Furthermore, the extraction efficiency toward others cations (K^+, Ba^{2+}, and Tl^+) is dependent on the size of the crown ether ring in the polyoxaferrocenophanes, especially in the cases of **4b—e**. It is interesting that **4b—e** (1,2-ferrocenophanes) shows a high complexing ability compared with **6b—e** (1,3-ferrocenophanes), even though the latter has a large ring size, and even though these ferrocenophanes have similar structures. This can be explained by assuming that the proton at the 2-position of the substituted cyclopentadienyl ring of **6b—e** is more sterically hindered in the process of complexation. On the other hand, the attached position of ferrocene to the crown ether seems to influence the complexing ability. For example, 1,2-polyoxaferrocenophanes (**4b—e**) show a high complexing ability, except toward silver ions, compared with 1,1′-polyoxaferrocenophanes which were reported by Akabori et al.[1c] It should be emphasized that **4c** (n=3) has a high complexing ability toward sodium, thallium, and silver ions. It is also interesting that the extraction ability toward thallium ion shows a remarkable dependence on the cavity size in the macrocycle of **4b—e**. Binuclear polyoxaferrocenophanes (**5a** and **7a**) show a low extractability to-

ward metal cations (Li^+, Na^+, K^+, and Ba^{2+}), but show an appreciable selectivity toward thallium cations. A similar trend of affinity toward transition metal cations have been observed in hitherto reported "crowned" ferrocenophanes and these synthesized polyoxaferrocenophanes; this suggests that the iron atom of the ferrocene nucleus participates in the process of complexation. This means that the metal cation is drawn into the crown ether ring from the iron-atom side of ferrocene, even though the opposite side of the ring has less hindrance. In the case of a silver ion, the ferrocene nucleus changed to a ferricenium ion, which showed blue color in solution, upon oxidation with $AgNO_3$ (except **4c**, **6d**, and **6e**). This oxidation seems very sensitive to the crown-ring member since **4c** showed an 86.1% extractability and almost all cases showed oxidation reaction. These facts indicate that the distance between the iron atom of ferrocene and the incorporated silver cation influences the oxidation of ferrocene. A similar result was also observed in polyoxa-[1c] or polyoxathiaferrocenophanes.[3e,3f]

Experimental

Materials and Measurements. All melting points are uncorrected. Diethylene glycol, triethylene glycol and tetraethylene glycol were commercial products, pentaethylene glycol and hexaethylene glycol were prepared by reactions of tri- and diethylene glycol ditosylates with the sodium salt of ethylene glycol and diethylene glycol, respectively.[8] 1,2-Bis(hydroxymethyl)ferrocene[9] and 1,3-bis(hydroxymethyl)-ferrocene[10] were prepared as described in the literature. The other reagents employed were commercial materials or were prepared by the usual method. All inorganic compounds were reagents grade. The IR, ^1H NMR, mass, and electronic spectra were recorded on Hitachi 260-10, Hitachi R-22, Hitachi RMU-6M, and Hitachi 200-10 spectrometers, respectively.

General Procedure for Polyoxa[*n*](1,2)ferrocenophanes (5a and 4b—e) and polyoxa[*n*](1,3)ferrocenophanes (7a and 6b—e). A mixture of 1,2-bis(hydroxymethyl)ferrocene (**1**) (2.00 g, 0.0081 mol) or 1,3-bis(hydroxymethyl)ferrocene (**2**) (2.00 g, 0.0081 mol) and oligoethylene glycol ditosylate (n=1—5) (0.0081 mol) in 160 ml of dry benzene was added dropwise to a benzene solution (20 ml) of potassium *t*-butoxide (K: 0.8 g, 0.020 mol) over a period of 7 h at a refluxing temperature under nitrogen, and then further stirred for 20 h. After the solution has been cooled to room temperature, precipitated potassium tosylate was filtered off and washed with warm chloroform. Evaporation of the solvent left crude products as viscous oils; these were purified by silica-gel column chromatography. The first fraction eluted with benzene–ether (10:1) gave ferrocenophane (**5a**, **4b—e**, **7a**, and **6b—e**); the second fraction eluted with chloroform–methanol (5:1) recovered the starting dialcohol (**1** or **2**); and the last fraction eluted with chloroform–methanol (2:1) gave polymeric materials. The crude product was recrystallized from hexane. The results are summarized in Table 1.

2,5,8,22,25,28-Hexaoxa[9.9](1,2)ferrocenophane (5a). IR (KBr): 3080, 2950—2860, 1460, 1360, 1100, 1090, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.53 (br-s, 16H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.04 (s, 10H, Fc-H$\beta$), 4.26 (m, 6H, Fc-H$\alpha$), 4.36 (s, 8H, Fc-$C\underline{H_2}O-$) ppm. MS (70 eV) m/z 632 [M^+]. Found: C, 60.66; H, 6.30%. Calcd for $C_{32}H_{40}Fe_2O_6$: C, 60.78; H, 6.38%; M, 632.36.

2,5,8,11-Tetraoxa[12](1,2)ferrocenophane (4b). IR (KBr): 3080, 2920—2850, 1450, 1360, 1100, 1080, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.62 (br-s, 12H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.08 (s, 5H, Fc-H$\beta$), 4.28 (m, 3H, Fc-H$\alpha$), 4.36 (br-s, 4H, Fc-$C\underline{H_2}O-$) ppm. MS (70 eV) m/z 360 [M^+]. Found: C, 59.73; H, 6.66%. Calcd for $C_{18}H_{24}FeO_4$: C, 60.02; H, 6.72%; M, 360.23.

2,5,8,11,14-Pentaoxa[15](1,2)ferrocenophane (4c). IR (KBr): 3090, 2920—2850, 1460, 1355, 1100, 1085, 1020, 830 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.61 (s, 16H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.09 (s, 5H, Fc-H$\beta$), 4.28 (m, 3H, Fc-H$\alpha$), 4.34 (s, 4H, Fc-$C\underline{H_2}O-$) ppm. MS (70 eV) m/z 404 [M^+]. Found: C, 59.49; H, 6.89%. Calcd for $C_{20}H_{28}FeO_5$: C, 59.42; H, 6.98%; M, 404.29.

2,5,8,11,14,17-Hexaoxa[18](1,2)ferrocenophane (4d). IR (neat): 3090, 2950—2860, 1465, 1350, 1125, 1100, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.53 (s, 20H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.04 (s, 5H, Fc-H$\beta$), 4.26 (m, 3H, Fc-H$\alpha$), 4.36 (s, 4H, Fc-$C\underline{H_2}O-$) ppm. MS (70 eV) m/z 448 [M^+]. Found: C, 59.06; H, 7.23%. Calcd for $C_{22}H_{32}FeO_6$: C, 58.94; H, 7.19%; M, 448.34.

2,5,8,11,14,17,20-Heptaoxa[21](1,2)ferrocenophane (4e). IR (neat): 3100, 2950—2860, 1460, 1360, 1100, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.62 (s, 24H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.09 (s, 5H, Fc-H$\beta$), 4.28 (br-s, 3H, Fc-H$\alpha$), 4.39 (br-s, 4H, Fc-$C\underline{H_2}O-$) ppm. MS (70 eV) m/z 492 [M^+]. Found: C, 58.46; H, 7.40%. Calcd for $C_{24}H_{36}FeO_7$: C, 58.54; H, 7.37%; M, 492.39.

2,5,8,22,25,28-Hexaoxa[9.9](1,3)ferrocenophane (7a). IR (KBr): 3080, 2950—2850, 1460, 1350, 1100, 1090, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.52 (s, 16H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.08 (s, 10H, Fc-H$\beta$), 4.22 (s, 6H, Fc-H$\alpha$), 4.27 (s, 8H, Fc-$C\underline{H_2}O-$), 4.44 (s, 2H, Fc-H$\gamma$) ppm. MS (70 eV) m/z 632 [M^+]. Found: C, 60.52; H, 6.22%. Calcd for $C_{32}H_{40}Fe_2O_6$: C, 60.78; H, 6.38%; M, 632.36.

2,5,8,11-Tetraoxa[12](1,3)ferrocenophane (6b). IR (KBr): 3080, 2940—2850, 1450, 1350, 1100, 1090, 1010, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.43 (br-s, 12H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.10 (s, 5H, Fc-H$\beta$), 4.15 (s, 2H, Fc-H$\alpha$), 4.23 (br-s, 4H, Fc-$C\underline{H_2}O-$), 4.58 (s, 1H, Fc-H$\gamma$) ppm. MS (70 eV) m/z 360 [M^+]. Found: C, 60.13; H, 6.68%. Calcd for $C_{18}H_{24}FeO_4$: C, 60.02; H, 6.72%; M, 360.23.

2,5,8,11,14-Pentaoxa[15](1,3)ferrocenophane (6c). IR (neat): 3080, 2940—2850, 1450, 1350, 1120, 1100, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.51 (s, 16H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.12 (s, 5H, Fc-H$\beta$), 4.18 (m, 2H, Fc-H$\alpha$), 4.26 (s, 4H, Fc-$C\underline{H_2}O-$), 4.46 (s, 1H, Fc-H$\gamma$) ppm. MS (70 eV) m/z 404 [M^+]. Found: C, 59.33, H, 6.87%. Calcd for $C_{20}H_{28}FeO_5$; C, 59.42; H, 6.98%; M, 404.29.

2,5,8,11,14,17-Hexaoxa[18](1,3)ferrocenophane (6d). IR (neat): 3080, 2940—2850, 1460, 1360, 1125, 1100, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.56 (s, 20H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.08 (s, 5H, Fc-H$\beta$), 4.18 (m, 2H, Fc-H$\alpha$), 4.30 (s, 4H, Fc-$C\underline{H_2}O-$), 4.44 (s, 1H, Fc-H$\gamma$) ppm. MS (70 eV) m/z 448 [M^+]. Found: C, 58.90; H, 7.02%. Calcd for $C_{22}H_{32}FeO_6$: C, 58.94; H, 7.19%; M, 448.34.

2,5,8,11,14,17,20-Heptaoxa[21](1,3)ferrocenophane (6e). IR (neat): 3080, 2940—2850, 1460, 1360, 1125, 1100, 1000, 820 cm^{-1}. ^1H NMR ($CDCl_3$) δ=3.60 (s, 24H, $-OC\underline{H_2}C\underline{H_2}O-$), 4.10 (s, 5H, Fc-H$\beta$), 4.24 (m, 2H, Fc-H$\alpha$), 4.33 (s, 4H, Fc-$C\underline{H_2}O-$), 4.51 (s, 1H, Fc-H$\gamma$) ppm. MS (70 eV) m/z 492

[M^+]. Found: C, 58.46; H, 7.32%. Calcd for $C_{24}H_{36}FeO_7$: C, 58.54; H, 7.37%; M, 492.39.

Solvent Extraction Experiments of Metal Ions. The extraction ability of synthesized polyoxaferrocenophanes with metal picrates was examined by a method described in a previous paper.[5]

References

1) a) J. F. Biernat and T. Wilczewski, *Tetrahedron*, **36**, 2521 (1980); b) S. Akabori, H. Fukuda, Y. Habata, M. Sato, and S. Ebine, *Chem. Lett.*, **1982**, 1393; c) S. Akabori, Y. Habata, Y. Sakamoto, M. Sato, and S. Ebine, *Bull. Chem. Soc. Jpn.*, **56**, 537 (1983).

2) a) M. Sato, H. Watanabe, S. Ebine, and S. Akabori, *Chem. Lett.*, **1982**, 1753; b) M. Sato, S. Tanaka, S. Ebine, and S. Akabori, *Bull. Chem. Soc. Jpn.*, **57**, 1929 (1984).

3) a) G. Oepen and F. Vögtle, *Liebigs Ann. Chem.*, **1979**, 1094; b) B. Czech and A. Ratajczak, *Polish J. Chem.*, **54**, 767 (1980); c) B. Czech, A. Ratajczak, and K. Nagraba, *Monatsh. Chem.*, **113**, 965 (1982); d) M. Sato, M. Kubo, S. Ebine, and S. Akabori, *Tetrahedron Lett.*, **23**, 185 (1982); e) S. Akabori, Y. Habata, M. Sato, and S. Ebine, *Bull. Chem. Soc. Jpn.*, **56**, 1459 (1983); f) S. Akabori, S. Shibahara, Y. Habata, and M. Sato, *ibid.*, **57**, 63 (1984); g) M. Sato, M. Kubo, S. Ebine, and S. Akabori, *ibid.*, **57**, 421 (1984).

4) a) 3e), b); A. P. Bell and C. D. Hall, *J. Chem. Soc., Chem. Commun.*, **1980**, 163; c) P. J. Hammond, A. P. Bell, and C. D. Hall, *J. Chem. Soc., Perkin Trans. 1*, **1983**, 707.

5) T. Izumi, T. Tezuka, S. Yusa, and A. Kasahara, *Bull. Chem. Soc. Jpn.*, **57**, 2433 (1984).

6) J. Dale and P. Kristiansen, *Acta. Chem. Scand.*, **26**, 1471 (1972).

7) C. J. Pedersen, *Federation Proceeding*, **27**, 1305 (1968).

8) N. Newcomb, S. S. Moore, and D. J. Cram, *J. Am. Chem. Soc.*, **99**, 6405 (1977).

9) G. Marr, B. W. Rockett, and A. Rushworth, *J. Organometal. Chem.*, **16**, 141 (1969).

10) A. Kasahara, T. Izumi, Y. Yoshida, and I. Shimizu, *Bull. Chem. Soc. Jpn.*, **55**, 1901 (1982).