Facile synthesis of ferrocenyl silyl ethers and their utility as synthetic equivalents of hydroxyferrocenes

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The reactions of trialkylsilyltrifluoromethanesulfonic acid esters with four different cyclopent-2-en-1-ones afford the respective cyclopentadienyl silyl ethers, which can be transformed into the respective ferrocenyl silyl ethers in good yields; cleavage of the silyl ethers under basic conditions leads, *via* hydroxyferrocenes, to ferrocenyl–alkyl ethers.

Hydroxyferrocenes, in which an oxygen atom is bonded directly to the five-membered ring, are unstable compounds which are only available *via* tedious multi-step reactions, since oxygen-substituted cyclopentadienes are rare.[1] Consequently only a few hydroxyferrocenes and ferrocenyl alkyl ethers have been reported in the literature.[2]

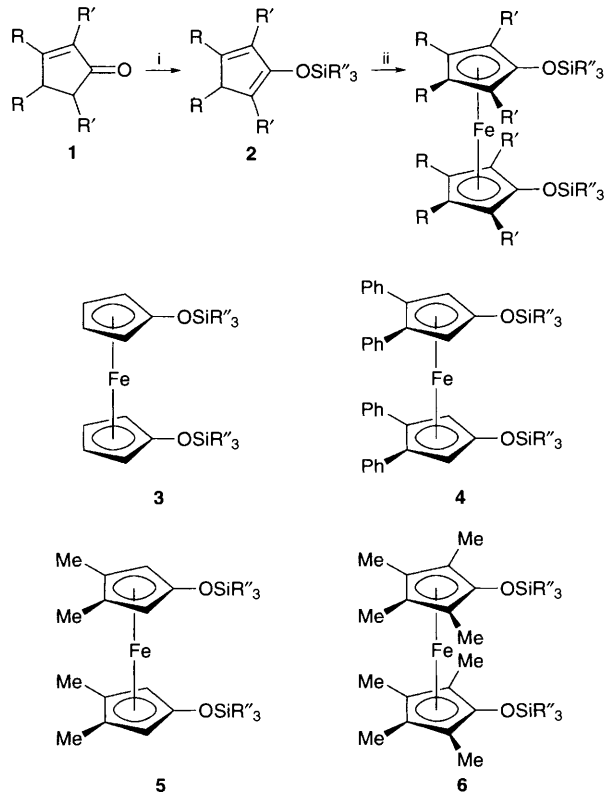
We have described recently a facile access to the related aminoferrocenes utilizing the enamine reaction of secondary amines with cyclopentenones.[3,4] In further investigations we have now found that the latter compounds are also ideal starting materials for the synthesis of hydroxyferrocenes as well as for the related ferrocenyl alkyl ethers.

The reaction of ketones with silylating reagents is known to lead to the corresponding silyl enol ethers.[5] Accordingly we have used the reaction of trialkylsilyltrifluoromethanesulfonic acid esters with four different cyclopentenones in light petroleum in the presence of triethylamine, to generate the corresponding cyclopentadienyl silyl ethers in almost quantitative yields (Scheme 1). In the course of our studies we have tested the reactions of the cyclopentenones cyclopent-2-en-1-one (R = R′ = H), 3,4-dimethylcyclopent-2-en-1-one (R = Me, R′ = H), 3,4-diphenylcyclopent-2-en-1-one (R = Ph, R′ = H) and 2,3,4,5-tetramethylcyclopent-2-en-1-one (R = R′ = Me) with three different esters of trifluoromethanesulfonic acid, *e.g.* the trimethylsilyl ester (R″ = Me), triethylsilyl ester (R″ = Et) and the triisopropylsilyl ester (R″ = Pr^i) (Scheme 1). In all cases the respective cyclopentadienyl silyl ethers are formed in yields > 90%. All cyclopentadienes, with the exception of the derivatives of the unsubstituted cyclopentenone (Diels–Alder dimerization), are stable compounds, whose characterization by NMR spectroscopy, however, is somewhat difficult, since different positions of the double bonds within the five-membered rings lead to a mixture of three different isomers. However, the 1,4-dienes are always the kinetically controlled products, which in the case of rapid work-up of the reaction mixture constitute the predominant isomer.

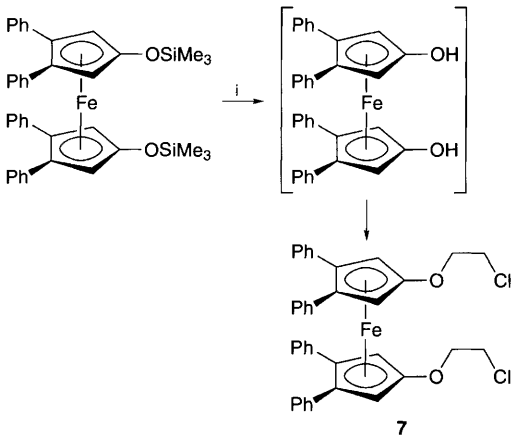
The synthesis of ferrocene silyl ethers *via* a standard reaction sequence (deprotonation of the cyclopentadiene in THF with Bu^{n}Li and reaction with $FeCl_2$)[4] was attempted with all cyclopentadienyl silyl ethers synthesized. Using $SiPr^i_3$ as the protecting group for the alcohol function, ferrocenes **3c**, **4c**, **5c** and **6c** were produced in yields of around 50%. With $SiMe_3$, however, only ferrocene **4a** could be synthesized, whereas with the other cyclopentadienyl trimethylsilyl ethers no metallocene could be isolated. Obviously the stability of the $SiMe_3$ protecting group is on the borderline to decomposition, since using very long reaction times or even refluxing the reaction mixture leads to drastic losses in the yield of **4a**. The $SiEt_3$ protecting group, on the other hand, is approximately 10–100 times more stable than $SiMe_3$ and under carefully controlled reaction conditions ferrocenes **4b** and **5b** can be isolated.[6]

The synthesis of ferrocenes **3–6** is even more simple, since it is not necessary to isolate the respective cyclopentadienyl silyl ether and it is more convenient to do a one-pot synthesis instead, which leads to the ferrocenes in yields of up to 40%.†,‡

The primary target of our investigation was to provide an easy access to substituted ferrocenyl alkyl ethers, therefore it is very important to understand which conditions are best suited to remove the silyl protecting group.[7] Ideally this should occur under basic conditions to generate *in situ* the highly sensitive ferrocenyl alcoholates, followed by ether formation. This requirement does not seem to be in accord with the basic conditions under which the ferrocenes are generated. Fortunately even the $SiMe_3$ groups survives the formation of the ferrocene **4a** and it seems that deprotonation of the cyclopentadiene is preferred *versus* cleavage of the silyl ether which normally should occur. In the case of **4a** we thus found it extremely easy to remove the $SiMe_3$ protecting group: simply stirring a DMF solution of **4a** at 80 °C with Na_2CO_3 leads to the formation of the respective dihydroxyferrocene (Scheme 2); addition of, for example, benzylbromide or 1-tosyl-2-chloroethane leads to the formation of the respective ferrocenyl alkyl



Scheme 1 Syntheses of the ferrocenyl silyl ethers. *Reagents*: i, $CF_3SO_3SiR''_3$ (R″ = Me, Et, Pr^i); ii, BuLi, $FeCl_2$; **3** (R = R′ = H), **4** [R = Ph, R′ = H), **5** (R = Me, R = H), **6** (R = R′ = Me).



Scheme 2 Synthesis of the ferrocenyl alkyl ether **7** *via* intermediate dihydroxyferrocene. *Reagents and conditions*: i, Na_2CO_3, DMF, 80 °C, + $ClC_2H_4(OSO_2C_6H_4Me)$.

ethers. In other cases the $SiEt_3$ protecting group is required which can also be removed easily using NaOH.

In conclusion, we have provided an extremely simple one-step synthesis of ferrocenyl silyl ethers, which can be converted easily into the corresponding ferrocenyl alkyl ethers. We are currently investigating the functionalization of the ferrocenes as well as the synthesis of other η^5-bonded cyclopentadienyl silyl ether complexes and their transformation into the respective alcohols and alkyl ethers.

Footnotes

† Synthesis of a cyclopentadiene (R = R′ = H; R″ = Pr^i) and the corresponding ferrocene (the yields given apply for the two-step reaction with isolation of the cyclopentadiene; in a one-pot synthesis the yield of the ferrocene is 40%): a stirred solution of cyclopentenone (10.5 mmol, 0.86 g) and triethylamine (12 mmol, 1.22 g) in pentane (25 ml) was treated with $CF_3SO_3SiPr^i_3$ (10 mmol, 3.06 g). After 15 min oily $[NHEt_3][CF_3SO_3]$ sitting on the bottom of the flask was removed with a syringe, and excess starting materials together with solvent were removed in vacuum at room temperature. The remaining oil was dried at 0.1 Torr for 15 min. The involatile triisopropylsiloxycyclopentadiene remained as a colourless oil in quantitative yield and was used directly for the synthesis of the ferrocenes. A solution of triisopropylsiloxycyclopentadiene (2.38 g, 10 mmol) in THF (50 ml) was cooled to −40 °C and treated with Bu^{n}Li (4 ml, 10 mmol). The reaction mixture was warmed to 0 °C over 15 min and $FeCl_2$ (5 mmol, 0.63 g) was added to the lithiated cyclopentadiene. Allowing the suspension to reach room temp. led to the formation of the ferrocene. After 2 h the volatiles were removed under reduced pressure and the residue was extracted with cyclohexane. The solution was filtered over a silica plug (5 cm) and the product eluted with cyclohexane. After evaporation of the solvent the pure product remained as an orange solid. Yield: 1.5 g (57%). ^{1}H NMR ($CDCl_3$): δ 1.13–1.27 (m, C_3H_7, 42 H), 4.24 (s, FcH, 4 H), 6.88–7.21 (m, ArH, 20 H). ^{13}C NMR ($CDCl_3$): δ 12.18, 17.92, 66.70, 81.56, 121.80, 125.47, 127.17, 130.05, 136.67.

Spectroscopic data for other compounds: **4a**, ^{1}H NMR ($CDCl_3$): δ 0.20 (s, 18 H, $SiMe_3$), 4.16 (s, 4 H, FcH), 6.95–7.22 (m, 20 H, ArH). ^{13}C NMR ($CDCl_3$): δ 0.02, 65.73, 81.15, 121.10, 125.53, 127.21, 129.98, 136.73. 1,1′-Bis(2-chloroethoxy)-3,3′,4,4′-tetraphenylferrocene **7**, ^{1}H NMR ($CDCl_3$): δ 3.52 (t, *J* 5.7 Hz, CH_2, 4 H), 3.82 (t, *J* 5.7 Hz, CH_2, 4 H), 4.38 (s, FcH, 4 H), 7.02–7.24 (m, ArH, 20 H). ^{13}C NMR ($CDCl_3$): δ 41.80, 60.95, 70.08, 81.20, 124.77, 126.16, 127.60, 129.74, 136.26.

‡ The following cyclopentadienes and ferrocenyl silyl ethers have been synthesized and characterized by NMR and elemental analysis (**a**, **b** and **c** denote $SiMe_3$, $SiEt_3$ and $SiPr^i_3$ protecting groups, respectively): **2a** (R = Me, R′ = H), **2a** (R = Ph, R′ = H); **2b** (R = Me, R′ = H), **2b** (R = Ph, R′ = H), **2b** R = R′ = Me); **2c** (R = R′ = H), **2c** (R = Me, R′ = H); **2c** (R = Ph, R′ = H), **2c** (R = R′ = Me); **3c**, **4a**, **4b**, **4c**, **5b**, **5c**, **6c**.

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