ORGANOMETALLICS

Large-Scale Preparation of 1,1'-Ferrocenedicarboxylic Acid, a Key Compound for the Synthesis of 1,1'-Disubstituted Ferrocene Derivatives

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Supporting Information

ABSTRACT: Efficient and simple methods for the large-scale preparation of 1,1'-ferrocenedicarboxylic acid, $fc(COOH)_2$, involving the sodium salts of cyclopentadienecarboxylic methyl and ethyl esters, $Na(C_5H_4COOR)$ (R = Me, Et), are presented. With $fc(COOH)_2$ at hand, the syntheses of various 1,1'-disubstituted compounds of the type fcX_2 (X = CH₂OH, COCl, CON₃, NCO, NHCOOMe, NHBoc, NH₂) were optimized and scaled up. The X-ray crystal structures of $fc(COOEt)_2$, $fc(NCO)_2 \cdot 1/_2 C_6 H_6$, and $fc-(NHCOOMe)_2$ ·MeOH are reported.

INTRODUCTION

Ever since the first synthesis of ferrocene¹ and the discovery of its sandwich² (or "Doppelkegel")³ structure and aromatic characteristics,⁴ the interest in this iconic molecule has never abated.⁵ Indeed, ferrocene and its derivatives are among the most important metallocenes, and the 1,1'-disubstituted derivatives especially have found numerous applications in asymmetric catalysis,⁶ biochemistry,^{7a} and material sciences^{7b} and as chelating ligand systems.^{7c} In particular, 1,1'-bis-(diphenylphosphino)ferrocene (dppf) and several related chiral and nonchiral 1,1'-diphosphinoferrocenes have attracted considerable attention because of their relevance for a number of metal-catalyzed reactions for the production of fine chemicals.^{7d,8,9}

Although ferrocene is nowadays commercially produced on the ton scale and is therefore a relatively cheap starting material, its 1,1'-disubstituted derivatives are still significantly more expensive.¹⁰ The most common methods for derivatization of ferrocene are Friedel–Crafts acylation,^{11,12} lithiation,^{8b,12} borylation,^{8b} and mercuration.^{8b,12} As a consequence, 1,1'disubstituted ferrocenes of the type fcY₂ with Y = C(O)Me, Li, BX₂, and HgX represent frequently used starting materials, and the following group of versatile derivatives can easily be prepared therefrom: Y = COOH,¹³ CHO,¹⁴ CH₂OH,¹⁵ B(OR)₂,^{8b,16} Br, I.¹⁷ For the latter species, a rather elaborate method for the efficient separation of mono- and dibromo/iodo-substituted ferrocenes, prepared from the lithiated species, by "oxidative purification" was reported recently.¹⁷

An alternative method toward 1,1'-disubstituted metallocenes is derivatization of the five-membered ring prior to construction of the metallocene core. This synthetic route is well established and routinely used for the synthesis of cyclopentadienyl transition metal complexes. For instance, the



sodium cyclopentadienides of the type Na⁺(C₃H₄Z)⁻ (Z = CHO, C(O)Me, COOEt/Me) were employed for the syntheses of nickelocenes and cobaltocenes,¹⁸ titanocene dichlorides,¹⁹ and several half-metallocene complexes²⁰ that are not available by electrophilic substitution of the corresponding metallocene. These reagents were also successfully employed for the syntheses of heterosubstituted ferrocenes of the type [(C₅H₄R)Fe(C₅H₄COOMe)] and [(Me₅C₅)Fe(C₅H₄COOMe)].²¹

Although the first preparation of cyclopentadienecarboxylic esters by Thiele dates back to 1900,²² the first report by Osgerby and Pauson on the use of Na(C₅H₄COOMe) (1^{Me}) for the synthesis of dimethyl 1,1'-ferrocenedicarboxylate (2^{Me}) did not appear until the early 1970s.²³ The reported low yield of only 28.5% might be ascribed to inefficient generation of 1^{Me} from sodium cyclopentadienide (NaCp) and methyl chloroformate. Curiously, even after the discovery of superior methods for the production of Na(C₅H₄Z), which were used for the synthesis of derivatized metallocenes (*vide supra*), no attempts were reported toward the syntheses of related, symmetrically substituted ferrocenes of the type fc(COOR)₂.

Initially, we were interested in obtaining significant amounts of 1,1'-disubstituted ferrocenes such as 1,1'-disocyanatoferrocene, $fc(NCO)_2$,²⁴ or 1,1'-diaminoferrocene, $fc(NH_2)_2$.²⁵ The former, $fc(NCO)_2$, can be conveniently produced from 1,1'-ferrocenedicarboxylic acid, $fc(COOH)_2$ (4), according to the four-step procedure optimized by van Leusen and Hessen²⁶ via Curtius rearrangement of 1,1'-bis(azidocarboxy)ferrocene, fc-

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 (CON_3) .²⁴ The classical preparative route toward 4 makes use of the haloform reaction starting from 1,1'-diacetylferrocene and NaOX solutions at temperatures below +5 °C (X = Br)^{13a} or at ca. 50 °C (X = Cl).^{13b} The main drawback of this method for larger scale preparations is clearly the production of large volumes of aqueous waste contaminated with significant amounts of halogenated organics (for example, up to 270 g of CHBr₃ for the production of 100 g of product), which is obviously not environmentally benign.

For $fc(NH_2)_2$ (10), an improved, large-scale synthesis was reported in 2000 by Arnold et al.²⁷ as an alternative to previous methods.²⁵ However, this route requires isolation of 1,1'dilithiated ferrocene [Li2fc·TMEDA], which is generally difficult to handle without a glovebox or Schlenk techniques because of its highly pyrophoric nature, and in addition, the copper-catalyzed coupling of $fc(Br)_2$ to $fc(N_3)_2$ was found to be difficult.²⁸ Moreover, precautions were recommended for handling the intermediate 1,1'-diazidoferrocene, $fc(N_3)_2$, because of its explosive nature (mp = 56 $^{\circ}$ C, dec). Finally, it should be noted that Kostyuk and Hierso et al. also found $fc(NHBoc)_2$ (9, Boc = *tert*-butoxycarbonyl) to be an excellent precursor for the synthesis of 10,²⁸ and a modified protocol for this reaction has been independently developed by us (see below). In addition, we wish to present herein a rapid and convenient, low-cost route for the preparation of 1,1'ferrocenedicarboxylic acid (4). Several reliable and scaled-up procedures toward valuable symmetrically substituted ferrocene derivatives, including $fc(CH_2OH)_2$ (3), $fc(NCO)_2$ (7), and $fc(NH_2)_2$ (10), are also described.

RESULTS AND DISCUSSION

Synthesis of 1,1'-Ferrocenedicarboxylic Acid (4). For the preparation of the key compound $fc(COOH)_2$ (4), we aimed at the preparation of the diesters $fc(COOR)_2$ (R = Me, 2^{Me} ; R = Et, 2^{Et}), which should be accessible by the reaction of FeCl₂ with the sodium salts Na(C₅H₄COOR) (R = Et, 1^{Et} ; R = Me, 1^{Me}). In previous protocols, the esters 1 were synthesized by reaction of NaCp with an excess of dimethyl or diethyl carbonate (DMC and DEC) in THF.^{18,20a} Similarly, our initial method (method 1) also started from NaCp, which was prepared in pure form from dicyclopentadiene according to the procedure established by Panda et al. (Scheme 1).²⁹ It was found that the following reaction can be carried out directly in concentrated DEC solution (~3 M), and quantitative formation of 1^{Et} was observed within 2 h.

At this stage, the slightly air-sensitive sodium salt 1^{Et} can be isolated as a crystalline material in 83% yield by recrystallization from hot acetonitrile after filtration. However, the crude reaction mixture obtained after evaporation of all volatiles (DEC and EtOH) could also be directly used without further purification for the subsequent reaction with ferrous chloride, which was preferably carried out in concentrated acetonitrile solution (~5 M) by stirring at 80 °C for 14–16 h.^{30,31} Thereby, the low-melting nature of the resulting diester 2^{Et} (mp = 41.5-42 $^{\circ}C)^{32}$ ensures that the reaction mixture remains homogeneous during this transmetalation step. After evaporation, hexane and a small amount of DMF for assisting the agglomeration of NaCl were added, and the mixture was filtered through Celite and concentrated under high vacuum to afford 2^{Et} as a dark orange, viscous oil in 84% overall yield. This procedure (method 1) allowed the production of a maximum of 70 g of 2^{Et} in a single run by use of a 0.5 L reaction flask. On





larger scales, handling the isolated NaCp becomes more and more difficult.

We regarded the encouraging results described above as a challenge to develop an even larger scale method (method 2). Since the only byproduct in the synthesis of 1^{Et} is ethanol and since NaCp can also be generated easily by deprotonation of cyclopentadiene (CpH) with alkali-metal alkoxides, we decided to generate NaCp from CpH by reaction with sodium ethoxide (NaOEt). Thus, careful addition of freshly cracked CpH to a cooled suspension of commercial NaOEt (96% purity) in DEC, followed by heating the reaction mixture to 95-97 °C, afforded 1^{Et} in spectroscopically pure form.³³ The concomitant formation of significant amounts of highly polar EtOH facilitates the processing of the following reaction with FeCl₂, which was added as several aliquots in solid form to the reaction mixture. Heating was continued for 4 h, and workup proceeded as described for method 1 (vide supra; for slight modifications, see Experimental Section). Method 2 finally afforded 2^{Et} in ca. 200 g quantity, corresponding to a ca. 60% yield in sufficient purity for further saponification to the diacid 4. Although this convenient one-pot method uses exceptionally cheap starting materials and avoids the time-consuming synthesis and isolation of large amounts of highly air-sensitive NaCp and 1^{Et}, it should be noted that the use of commercial grade NaOEt (96%) generally affords 2^{Et} in slightly lower purity compared to method 1. For higher demands, the diester can be further purified by distillation at 180 °C/0.015 mbar, which afforded 2^{Et} in only slightly lower yield (ca. 55%).

We also prepared dimethyl 1,1'-ferrocenedicarboxylate (2^{Me}) following method 1 by using dimethyl carbonate as solvent. Because of the lower solubility of Na(C₅H₄COOMe) (1^{Me}) in DMC and the higher melting point of the product 2^{Me} (mp = 113.5-114.5 °C),³⁴ both reaction steps were found to require significantly more solvent (~10 equiv) than was used for the synthesis of 2^{Et} . 2^{Me} was isolated as a yellow solid in 87% overall yield, albeit on a significantly smaller scale than 2^{Et} . The diesters themselves are valuable precursors in ferrocene chemistry; various amides,³⁵ monoesters of the type fc-(COOR)(COOH),^{32,36} and the diol 1,1'-bis(hydroxymethyl)ferrocene, fc(CH₂OH)₂ (3),¹⁵ can be prepared from them. The latter (3) had previously been synthesized by reduction of fc(COOH)₂,^{15b} fc(CHO)₂,^{15c} and, more conveniently, 2^{Me} , 1^{5c-f} with LiAlH₄ or NaBH₄. In our hands, the reduction of 2^{Et} was accomplished in 85% yield by using 1.75 equiv of

Organometallics

LiAlH₄, and 3 was isolated as a yellow microcrystalline powder on a 63 g scale (Scheme 2).

Scheme 2. Preparation of Dialcohol 3 and Diisocyanate 7



It should be noted that most previous protocols for the syntheses of the diesters 2^{Et} and 2^{Me} involved esterification of fc(COOH)₂ (4),^{13,32,37} while here the opposite approach was pursued, with the ester 2^{Et} serving as a precursor for the preparation of 4. Hence, saponification of the diester 2^{Et} on scales up to 150 g was performed at elevated temperature by addition of aqueous NaOH solution to an ethanol solution of 2^{Et} , producing the sodium salt fc(COONa)₂, which was isolated by filtration, dissolved in water, and protonated by addition of concentrated HCl. The precipitated diacid $fc(COOH)_2$ (4) was isolated by filtration and dried by heating at 60-70 °C in a large crystallizing dish overnight to afford 4 as an orange powder. Thereby, the yields varied depending on the starting material. When 2^{Et} , prepared by method 1, or distilled 2^{Et} , prepared by method 2, were employed, 4 was isolated in nearly quantitative yield. Saponification of the crude product obtained by method 2 gave lower yields of 69-77%, which corresponds to overall yields of 40-49% starting from cyclopentadiene. In most cases, however, 2^{Et} was not distilled and was used as received after workup according to method 2. By combination of this method with the subsequent saponification protocol, 90 g of 4 can routinely be prepared in a single run within 3 days, and we have reliably repeated this procedure at least 10 times in order to prepare and commercialize the compounds fc- $(COOEt)_2$ (2^{Et}), fc $(CH_2OH)_2$ (3), and fc $(NCO)_2$ (7) in amounts of 300 g (Figure 1).

Syntheses of 1,1'-Disubstituted Ferrocene Derivatives from 1,1'-Ferrocenedicarboxylic Acid (4). The transformation of 4 to 1,1'-diisocyanatoferrocene (7) was performed according to Petrovitch's method,²⁴ which had been further optimized by van Leusen and Hessen,²⁶ with small modifications shown in Scheme 2. In particular, for the



Article

Figure 1. Screw-cap bottles containing 200 g of 7, 300 g of 3, and 300 g of 2^{Et} (left to right). Higher quality images can be found in the Supporting Information.

synthesis of $fc(COCl)_2$ (5), the use of chloroform instead of dichloromethane not only shortened the reaction time considerably from over 14 h to only 2.5 h, but also allowed the amount of oxalyl chloride to be reduced from 4.8 to 3.1 equiv. Recrystallization of the crude red-brown product from hot *n*-heptane resulted in isolation of a bright red, crystalline material of analytical purity in 95% yield. Compound **5** appeared to be only slightly sensitive toward air and moisture and can be stored for months in tightly closed vessels.

1,1'-Bis(azidocarbonyl)ferrocene, $fc(CON_3)_2$ (6), was prepared according to the previous procedures by addition of an aqueous solution of sodium azide to an acetone solution of recrystallized 5. After extraction with dichloromethane, filtration through a silica pad, drying over Na2SO4, and evaporation, 6 was isolated in analytically pure form as a redorange powder. This method proved to be superior to the synthesis of 6 without isolation and purification of 5, since phase separation after addition of CH2Cl2 and therefore the complete removal of water proved difficult. It should be noted that the diazide 6 is susceptible to self-ignition upon contact with hot surfaces, and although 6 decomposes at considerably higher temperature (>100 °C) than $fc(N_3)_2$ (56 °C),²⁷ care should be taken upon handling the pure compound! The final Curtius rearrangement of 6 was performed on a 60 g scale by heating a 0.5 M toluene solution at 100 °C for 2 h, and the diisocyanate 7 was isolated as a yellow crystalline solid in 81% yield after filtration and crystallization from toluene solution.

To obtain the final target compound 1,1'-diaminoferrocene (10) from 7, the carbamate route was chosen. Two 1,1'-dicarbamates, fc(NHCOR)₂ with R = OMe (8)^{25b} and R = OtBu (9),³⁸ were simply prepared from 7 by treatment with the corresponding alcohols and were isolated in high yields as bright yellow, air-stable compounds (Scheme 3). Alternatively, 9 was also prepared directly from the diazide 6 in a similar fashion to that initially reported by Kraatz et al.³⁸ In our hands, addition of tBuOH to the toluene solution of fc(NCO)₂ (7) that was obtained after heating fc(CON₃)₂ (6) for 2 h at 110 °C in toluene afforded a solution of 9, which was isolated in 81–86% yield as an orange, microcrystalline solid after evaporation, dissolving in ethyl acetate/hexane, and filtration through silica.

The hydrolysis of methyl carbamate 8 under basic conditions (5% KOH in methanol/ H_2O , 1:1, reflux) was adopted from the procedure reported by Arimoto and Haven for *O*-benzylcarbamato-ferrocene, Fc-NHCOOBn.³⁹ In our case, prolonged

Scheme 3. Syntheses of Dicarbamates 8 and 9 (Boc = -COOtBu) and Their Hydrolysis to Diamine 10



reaction times up to 6 h were necessary to achieve high conversions. In contrast, the acidic hydrolysis of tertbutoxycarbonyl-protected (Boc) amines is known to proceed under milder conditions.⁴⁰ The method recently reported by Kostyuk and Hierso et al. utilized comparatively expensive trifluoroacetic acid, CF₃COOH, as an anhydrous acid source in excess of 10 equiv, albeit proceeding under very mild conditions $(CH_2Cl_2/-30 \ ^{\circ}C)$ and affording high yields.²⁸ However, we decided to use a solution of HCl in MeOH, produced in situ by reaction of acetyl chloride, CH₃COCl, with anhydrous MeOH, according to the original procedure developed by Nudelman et al.⁴¹ This method is clearly superior, since only a slight excess of acid and relatively cheap starting materials are required.⁴² Thus, treatment of dicarbamate 9 with HCl/MeOH (3 equiv, 75 min at 65 °C) resulted in a quick reaction with vigorous gas evolution,⁴³ and the diamine 10 was conveniently isolated in 84-93% yield after appropriate workup. Whereas aqueous workup proved to be convenient for small-scale preparation of 10^{28} we developed an alternative water-free procedure that involved addition of a methanolic KOH solution and removal of KCl by filtration through silica followed by extraction with CH₂Cl₂. Pure samples of yellowish-brown 10 were obtained by recrystallization from MeOH.

Crystal Structures. The ferrocene derivatives 2^{Et} , 7, and 8 were characterized by X-ray diffraction analysis. Single crystals of the composition 2^{Et} , $7 \cdot 1/_2 C_6 H_6$, and 8·MeOH were obtained by slow evaporation of their concentrated hexane, benzene, and MeOH solutions, respectively. Their molecular structures are presented in Figures 2 and 3, and selected crystallographic parameters are assembled in Table 1. In all three structures, the molecules adopt eclipsed, synperiplanar conformations with regard to the relative orientations of the Cp rings and of the substituents, as indicated by very small torsion angles $C1-Ct_1-Ct_2-C6$ (Ct = centroid of the Cp ring) of 0.1° (for 2^{Et} , ⁴⁴ 0.2° (for 7), and -1.2° (average value for two independent molecules of 8 in the asymmetric unit). Whereas the *anti*orientation of the functional groups in the structures of 2^{Et} and 8 renders the molecules almost C_2 -symmetric, the diisocyanate 7 exhibits an almost C_s -symmetric structure with a *syn*-conformation of the two aligned NCO moieties.

The ferrocene moieties do not feature any unusual structural features,⁴⁵ and the substituents show the expected bond



Figure 2. ORTEP diagram of 2^{Et} and $7 \cdot {}^{1}/_2 C_6 H_6$ shown with 50% thermal ellipsoids. Solvent molecules $C_6 H_6$ for 7 and hydrogen atoms have been omitted for clarity. Selected bond lengths (Å) and (torsion) angles (deg) for 2^{Et} : Fe–Ct₁ 1.653, Fe–Ct₂ 1.659, C1–C11 1.468(2), C6–C14 1.478(2), C11–O1 1.213(2), C14–O3 1.213(2), C11–O2 1.343(2), C14–O4 1.241(2); Ct₁–Fe–Ct₂ 178.7, C1–C11–O1 123.53(16), C6–C14–O3 124.55(16), O1–C11–O2 123.72(16), O3–C14–O4 124.38(16), C1–Ct₁–Ct₂–C6 0.1. Data for $7 \cdot {}^{1}/_2 C_6 H_6$: Fe–Ct₁ 1.651, Fe–Ct₂ 1.651, C1–N1 1.3880(19), C6–N2 1.3935(19), C11–N1 1.185(2), C12–N2 1.189(2), C11–O1 1.1751(18), C12–O2 1.1739(19); Ct₁–Fe–Ct₂ 178.52, C1–N1–C11 147.90(15), C6–N2–C12 142.54(15), N1–C11–O1 172.33(17), N2–C12–O2 172.82(18), C1–Ct₁–Ct₂–C6 0.2.



Figure 3. ORTEP diagram of 8·MeOH shown with 50% thermal ellipsoids. Only one of the two independent molecules is shown. Solvent molecules MeOH and hydrogen atoms, except those of the NH groups, have been omitted for clarity. Selected bond lengths (Å) and (torsion) angles (deg) for 8·MeOH: Fe–Ct₁ 1.661/1.656, Fe–Ct₂ 1.652/1.654, C1–N1 1.401(5)/1.397(6), C6–N2 1.410(5)/1.395(6), N1–C11 1.353(3)/1.350(5), N2–C13 1.349(5)/1.343(5), C11–O1 1.221(5)/1.221(5), C13–O3 1.213(5)/1.229(5), C13–O4 1.342(5); Ct₁–Fe–Ct₂ 178.5/178.13, C1–N1–C11 125.2(4)/124.8(4), C6–N2–C13 124.5(4)/126.1(4), N1–C11–O1 126.2(4)/125.9(4), N2–C13–O3 125.1(4)/126.4(4), N1–C11–O2 109.3(3)/109.4(4), N2–C13–O4 110.4(4)/109.3(3), C1–Ct₁–Ct₂–C6–0.7/–1.6.

lengths; for instance, the isocyanate groups in 7 are almost linear, as indicated by NCO angles of 172.33(17)° and 172.82(18)° with NC and CO distances of 1.185(2)/ 1.189(2) Å and 1.1751(18)/1.1739(19) Å, which resemble those in other structurally characterized isocyanates, cf. (p- $OCN-C_6H_4)_2CH_2$.⁴⁶ Analysis of the crystal packing reveals only weak intermolecular contacts in the case of 2^{Et} , with CH…O contacts ranging from 2.54 to 2.71 Å, which falls just slightly below the van der Waals cutoff criterion of 2.72 Å $(r_{vdW}(H) =$ 1.20 Å, $r_{vdW}(O) = 1.52$ Å).⁴⁷ Weak hydrogen bonding is also found in 7^{·1}/₂C₆H₆, with each molecule displaying two CH…O contacts of 2.38 and 2.53 Å with one of the neighboring molecules to afford chains of fc(NCO)₂ molecules parallel to the b axis, which are additionally linked by benzene molecules through weak CH…O contacts of 2.52 and 2.70 Å (Figure 4). The crystal structure of 8. MeOH features significantly stronger hydrogen bonds with two molecules forming a hydrogenbonded pair through two NH---O contacts of 2.08 Å; these pairs are linked by NH…O and OH…O contacts of 1.93/2.00 and 2.05/2.00 Å involving the methanol solvate molecules to form chains of alternating molecules of 8 and methanol parallel to [101], with ferrocene moieties oriented perpendicularly to the chain (see Figure 5).

Table 1. Selected Crystallographic Data for Compounds $fc(COOEt)_2$ (2^{Et}), $fc(NCO)_2$ (7·¹/₂C₆H₆), and $fc(NHCOOMe)_2$ (8·MeOH)

	2^{Et}	$7 \cdot \frac{1}{2} C_6 H_6$	8∙MeOH
empirical formula	$C_{16}H_{18}FeO_4$	$C_{15}H_{11}FeN_2O_2$	$C_{15}H_{20}FeN_2O_5$
fw	330.15	307.11	364.18
wavelength/Å	0.71073	1.54184	1.54184
cryst syst	monoclinic	triclinic	monoclinic
space group	$P2_1/c$	$P\overline{1}$	Pc
a/Å	13.7576(4)	7.8985(7)	11.2801(8)
b/Å	10.1798(2)	9.1385(8)	13.1742(8)
c/Å	10.6675(2)	10.3167(8)	12.0254(10)
lpha/deg	90	112.101(8)	90
β /deg	104.088(2)	91.731(7)	117.540(10)
γ/deg	90	112.435(8)	90
$V/Å^3$	1449.04(6)	624.46(9)	1584.6(2)
Ζ	4	2	4
$D_{\rm calc}/{ m g}~{ m cm}^{-3}$	1.513	1.633	1.527
μ/mm^{-1}	1.053	9.707	7.883
indep reflns	3305	2583	4826
R(int)	0.0457	0.0518	0.0637
R_1	0.0289	0.0249	0.0432
wR_2	0.0653	0.0667	0.1026
GOF	1.099	1.105	1.026



Figure 4. Packing diagram of $7 \cdot \frac{1}{2} C_6 H_6$ viewed perpendicular to the *bc* plane (slightly rotated for clarity). Hydrogen bonds C–H…O are indicated by dashed lines. Hydrogen bonds to the benzene molecules, which link the chains in the third dimension, are omitted for clarity.



Figure 5. Packing diagram of $8 \cdot \text{MeOH}$ showing chains of molecules parallel to [101]. Classical hydrogen bonds are indicated by dashed lines.

CONCLUSION

A convenient method for the preparation of diethyl ferrocenedicarboxylate, $fc(COOEt)_2$ (2^{Et}), on a very large scale (~200 g) from cheap, common starting materials (CpH, EtONa, DEC, and FeCl₂, no additional solvent) was presented, allowing the production of ~100 g of ferrocenedicarboxylic acid, $fc(COOH)_2$ (4), in a single run upon saponification. With large amounts of this material in hand, scaled-up procedures for the synthesis of the 1,1'-ferrocenediisocyanate $fc(NCO)_2$ (7)

were established, involving the preparation of the corresponding acid chloride and azide $fc(COCl)_2$ (5) and $fc(CON_3)_2$ (6). Furthermore, 1,1'-diaminoferrocene (10) can be made accessible in larger quantities from 6 or 7 via the carbamate $fc(NHBoc)_2$ (9). Although most of the reaction steps discussed herein have precedence in the literature, we feel that our protocols might be very useful for numerous other research groups interested in ferrocene chemistry and might therefore have a significant impact on further development of this research area, which is still unremittingly vivid more than 60 years after the discovery of ferrocene.

EXPERIMENTAL SECTION

General Remarks. Standard Schlenk-line techniques under inert gas atmosphere (N₂) were used for the syntheses of 1^{Et}, 2^{Et}, 2^{Me}, 3, 7, 8, 9, and 10. Solvents (toluene, *n*-heptane) and *tert*-butanol were dried over molecular sieves 3 Å; other common solvents were of solvent grade quality. Solvents for the synthesis of $fc(NH_2)_2$ were degassed prior to use. Reagent grade diethyl carbonate, dimethyl carbonate, EtONa (Acros, 96%), oxalyl chloride (Acros, 98%), and sodium azide were used without purification. FeCl₂⁴⁸ and Na(C₃H₃)²⁹ were prepared according to literature procedures. NMR spectra were recorded on Bruker DPX-200, AV II-300, and DRX-400. EI mass spectra were recorded on a Finnigan MAT 8400-MSS I or Finnigan MAT 4515. Melting points were determined with an MPM-HV2. Elemental analyses were performed at the Microanalytical Department of the Technical University of Braunschweig. Dimensions for diameter (Φ) and height (H) are given in millimeters.

X-ray Diffraction Studies. Data were recorded on various diffractometers from Oxford Diffraction, using monochromated Mo $K\alpha$ or mirror-focused Cu $K\alpha$ radiation. Absorption corrections were applied on the basis of multiscans. Structures were refined anisotropically on F^2 using the program SHELXL-97 (G. M. Sheldrick, University of Göttingen, Germany). Treatment of hydrogen atoms: NH and OH hydrogens were refined freely, methyls as idealized rigid groups allowed to rotate but not tip, other H using a riding model starting from calculated positions. Numerical details are summarized in Table 1. Complete data have been deposited at the Cambridge Crystallographic Data Centre under the numbers CCDC 942084 (2^{Et}), 942085 ($7 \cdot 1/_2 C_6 H_6$), and 942086 ($8 \cdot MeOH$). These data can be obtained free of charge from www.ccdc.cam.ac.uk/data request/cif.

Synthesis of Sodium (Ethoxycarbonyl)cyclopentadienide, $Na(C_5H_4COOEt)$ (1^{Et}). Diethyl carbonate (160 mL, 2.5 equiv) was added to solid Na(C₅H₅) (45.9 g, 0.52 mol) in a 0.5 L Schlenk flask, accompanied by mild warming (ca. 40 °C). The resulting thick suspension was placed in a preheated oil-bath (100-105 °C). The reaction mixture slowly liquefied, and a clear cherry-red solution formed. After stirring for 2.5 h, the volume of the reaction mixture was reduced in vacuo to two-thirds at 100 °C/3 mbar. Drying the syrup-like mass at 100 °C/<0.5 mbar for 30 min resulted in formation of a pale red semisolid residue (collected volume of condensate: 80-90 mL). This material was used without further purification to prepare 2^{Et} according to method 1. If desired, the compound could be isolated in analytically pure form by crystallization from hot filtered MeCN solution. An additional crop of the product was obtained by concentration of the mother liquor. Isolated yield: 83% (69.1 g). The compound is soluble in water, THF, acetone, and DMSO. ¹H NMR (DMSO- $d_{6'}$ 300.1 MHz, 300 K): δ 1.17 (t, ${}^{3}J_{\text{HH}} = 7.1$ Hz, 3H, CH₃), 3.96 (q, ${}^{3}J_{\text{HH}} = 7.1$ Hz, 2H, CH₂), 5.51 (m, HC^{3,4}), 6.10 (m, HC^{2,5}) ppm. ${}^{13}\text{C}\{{}^{1}\text{H}\}$ NMR (DMSO- $d_{6'}$ 75.5 MHz, 300 K): δ 13.3 (CH₃), 56.1 (CH₂), 108.4 (C¹), 108.9 (C^{3,4}), 111.2 (br s, C^{2,5}), 165.9 (C=O) ppm.

Method 1: Synthesis of Diethyl 1,1'-Ferrocenedicarboxylate, fc(COOEt)₂ (2^{Et}), Starting from 1^{Et} . To the semisolid, nonpurified material, obtained from the synthesis of Na(C₃H₄COOEt) (*vide supra*), solid FeCl₂ (36 g, 0.28 mol, theoretical amount of ca. 0.55 equiv) and MeCN (100 mL) were added successively with water-bath cooling. An exothermic reaction took place, with warming to ca. 50 °C and formation of a thin orange suspension. The slurry was heated to 80 °C with an overpressure-controller and stirred for 14-16 h. The volatiles were first evaporated in vacuo, and the solid was dried at 75-80 °C (0.5 mbar) and further at 100–110 °C (0.05 mbar) for 0.5 h. The isolation of the product was performed by addition of hexanes (150 mL), filtration of the resulting suspension through a short Celite pad (\oplus 150, H30), and rinsing the residue with hexanes until the filtrate was colorless. The filtration of the very fine suspension of NaCl was significantly accelerated by dropwise addition of DMF (7.0 mL) under vigorous stirring and further stirring for 30 min at 50 °C. If a low-quality batch of $Na(C_{s}H_{s})$ was used, an additional tarry, brown residue forms at this stage; an acidic aqueous workup, involving extraction with EtOAc, is recommended in this case. Volatiles from the collected filtrates were removed in vacuo (100 mbar) and further dried at 100 °C (0.5 \rightarrow 0.05 mbar) to yield a dark orange oil. Overall yield from $Na(C_5H_5)$: 84% (71.5 g) of a viscous, dark orange oil with sweet odor that solidifies on prolonged standing. An analytically pure sample was obtained by crystallization from hexane at 0 °C as a yellow, crystalline solid.

Method 2: Synthesis of Diethyl 1,1'-Ferrocenedicarboxylate, fc(COOEt)₂ (2^{Ef}) Starting from Cyclopentadiene. A 2 L threenecked flask, equipped with an effective mechanical stirrer and a reflux condenser with a bubbler, was charged with powdered EtONa (140 g, ca. 2.0 mol) and diethyl carbonate (700 mL, ca. 3 equiv). The suspension was cooled with an ice-bath and deaerated. Freshly prepared cyclopentadiene (130 g, ca. 160 mL, 2.0 mol) was added in two portions with an interval of 10 min, whereupon a thick, pale red to yellow suspension formed. The reaction mixture was vigorously stirred for 30 min without cooling. The flask was then immersed in a preheated oil-bath (110 °C). At an inner temperature of the reaction mixture of 40-50 °C, the reaction mixture liquefies; it was heated further for 4 h, maintaining the temperature at 95-97 °C with slight overpressure. The color of the reaction mixture fades from cherry-red or brown to pale yellow or light brown, depending on the purity of reagents used and efficacy of deaeration. The heating bath was removed, and solid FeCl₂ (130 g, 1.02 mol) was added at ca. 80 °C in five portions of 20 g at the beginning and in three smaller portions of 10 g at the end over 1 h. Each addition causes a short, but exothermic reaction (the use of low-purity FeCl₂ or too rapid addition of FeCl₂ without noticeable reaction-dissolution of added FeCl₂ and deepening of orange color-can result after an induction period in a vigorous reaction that can be controlled by the use of an effective reflux condenser). After addition of FeCl₂ the reaction mixture was stirred for 4 h at 95-97 °C. The further workup was performed similarly to that described in method 1. The volatiles (0.50 L) were first removed in vacuo, and the further workup should be performed in air. Hexane (0.60 L) and DMF (30 mL, dropwise) were added successively, and the brown reaction mixture was stirred at 50 °C for 30 min, whereupon a precipitate forms. The latter was conveniently filtered off using a Celite pad (D150, H30) and washed with hexane until the washings were almost colorless. The collected washings (1.4-1.6 L) were left for 1 h in a large beaker with air contact (some amount of black impurity precipitates). From the collected washings, a portion of 250 mL was diluted with hexane (250 mL), and the resulting suspension was stirred vigorously with 30 g of silica gel. The supernatant was collected by decantation, filtered using a folded filter paper, and evaporated on a rotary evaporator (650 mbar/70 °C). The collected volatiles (mainly hexane, ca. 300 mL) were used again for dilution of the next portion of 250 mL in the same flask, charged with used silica gel. The procedure was repeated, and concentrated product as a clear bright orange solution was collected. A small amount of solid impurity can form upon air contact. It was removed by filtration with the aid of a Celite pad (\oplus 50, H30), and the filtrate was concentrated on a rotary evaporator (600 \rightarrow 50 mbar/75 °C) and then *in vacuo* (5.0 $\rightarrow 0.05/100$ °C) using a short-path external trap cooled with liquid N_2 . Yield of the crude, dark orange, oily product: 58–63% (192–208 g). This material was used directly for further hydrolysis without purification. Higher purity product was obtained by air-cooled fractional short-path distillation (pot temperature for collecting forerun (ca. 20 g): 160 °C/0.060 mbar; for 2^{Et}: 160-180 °C/0.015

mbar; the orange, more viscous tails from distillation contain mainly a mixture of unidentified impurities). Yield: ca. 55% (ca. 180 g) of an orange oil that quickly solidifies upon standing. ¹H NMR (CDCl₃, 300.1 MHz, 300 K): δ 1.34 (t, ³J_{HH} = 7 Hz, 3H, CH₃), 4.27 (q, ³J_{HH} = 7 Hz, 2H, CH₂), 4.39 (m, 2H, HC^{2,5}), 4.82 (m, 2H, HC^{3,4}) ppm. ¹³C{¹H} NMR (CDCl₃, 75.5 MHz, 300 K): δ 14.5 (CH₃), 60.4 (OCH₂), 71.5 (C^{2,5}), 72.7 (C^{3,4}), 73.1 (C¹), 170.4 (C=O) ppm. Anal. Calcd for C₁₆H₁₈FeO₄ (330.16): C 58.21, H 5.50. Found: C 58.50, H 5.64.

Synthesis of Dimethyl 1,1'-Ferrocenedicarboxylate, fc-(COOMe)₂ (2^{Me}). The synthesis was performed as described for 2^{Et} (method 1) starting from NaCp (2.24 g, 25.7 mmol) and dimethyl carbonate (25 mL, 297 mmol, 12 equiv), to yield the crude Na(C₅H₄COOMe) (1^{Me}). Further treatment with FeCl₂ (1.80 g, 14.2 mmol, 0.55 equiv) in 20 mL of MeCN according to method 1 resulted in formation of the ferrocene 2^{Me}, which could be obtained in 87% overall yield after workup (3.38 g, 11.2 mmol). For 2^{Me}: ¹H NMR (CDCl₃, 300.1 MHz, 300 K): δ 3.77 (s, 3H, OMe), 4.35 (s, 2H, HC^{2,5}), 4.77 (s, 2H, HC^{3,4}) ppm. ¹³C{¹H} NMR (CDCl₃, 75.5 MHz, 300 K): δ 51.7 (OMe), 71.5 (C^{2,5}), 72.5 (C^{3,4}), 72.7 (C¹), 170.7 (COOMe) ppm. Anal. Calcd for C₁₄H₁₄FeO₄ (302.11): C 55.66, H 4.67. Found: C 55.51, H 4.83. For sodium salt 1^{Me}: ¹H NMR (DMSOd₆, 300.1 MHz, 300 K): δ 3.47 (OMe), 5.52 (C^{3,4}), 6.11 (C^{2,5}) ppm. ¹³C{¹H} NMR (DMSO-d₆, 75.5 MHz, 300 K): δ 48.7 (OMe), 108.0 (C¹), 109.2 (C^{3,4}), 111.2 (br s, C^{2,5}), 166.3 (C=O) ppm.

Synthesis of 1,1'-Bis(hydroxymethyl)ferrocene, fc(CH₂OH)₂ (3). A 1 L three-necked flask equipped with a reflux condenser, a 0.25 L dropping funnel, and magnetic stirring bar was charged with dry THF (250 mL). Powdered LiAlH₄ (20 g, 1.75 equiv) was added to the ice-cooled solvent under nitrogen atmosphere. A solution of distilled fc(COOEt)₂ (100 g, 0.303 mol) in THF (80 mL) was placed in a dropping funnel and was added to the stirred ice-cooled suspension of the reductant dropwise over 1 h. After the addition was completed, the reaction mixture was allowed to come to ambient temperature (0.5 h) and was heated with a water-bath to 45-50 °C for 1 h. The progress of the reaction can be monitored by TLC. After the reaction was complete, it was poured in small portions into ice-cooled EtOAc (250 mL) with vigorous stirring. After each addition, significant, but temporary, thickening of the mixture took place. To the thick, bright yellow suspension, water was carefully added (180-200 mL) in portions; the last 20-40 mL should be added in small portions and larger intervals, whereupon the inorganics separate as a compact creamy material. The brown organic phase was easily separated by decantation; the inorganics were thoroughly rinsed with EtOAc (5 \times 20 mL). The combined organic phases were dried with K_2CO_3 (3 × 25 g, pearls) with stirring. The brown organic phase was carefully concentrated in a rotary evaporator until the total volume was 200 mL. Crystallization was facilitated by scratching with a spatula and cooling with an ice-bath. The yellow powdery solid was filtered off, washed with toluene, and dried in vacuo (54 g). The volatiles from the mother liquor were completely removed, and the remaining solid was recrystallized from toluene (1 g/7 mL solvent), yielding an additional amount of product. The total amount of 63 g of product was obtained as a yellow solid (yield: 85%). ¹H NMR (CDCl₃, 300.1 MHz, 300 K): δ 3.67 (br s, $\nu_{1/2}$ = 5.5 Hz, 2H, OH), 4.17 (m, 4H, HC^{2,5}), 4.21 (m, 4H, $HC^{3,4}$), 4.40 (br s, $\nu_{1/2}$ = 3.3 Hz, 4H, CH_2O) ppm. ¹³C{¹H} NMR $(\text{CDCl}_3, 75.5 \text{ MHz}, 300 \text{ K}): \delta 60.3 (-CH_2O), 67.0 (C^{2,5}), 68.0 (C^{3,4}),$ 89.3 (C¹) ppm. Anal. Calcd for C₁₂H₂₄FeO₂ (246.09): C 58.57, H 5.73. Found: C 58.75, H 5.73.

Synthesis of 1,1'-Ferrocenedicarboxylic Acid, $fc(COOH)_2$ (4). To a solution of $fc(COOEt)_2$ (150 g, 0.454 mol), prepared by method 2, dissolved in hot EtOH (750 mL), was added a hot aqueous solution of NaOH (150 g, 8.2 equiv) in water (750 mL) in a 2 L round-bottom flask. (The entire amount of crude 2^{Et} obtained by method 2 can be used by changing to a larger flask.) The reaction mixture was placed in a preheated water-bath (70–75 °C) with an overpressure controller. Soon after, precipitation of an orange solid began, and the mixture was held at that temperature for 2 h without stirring. After cooling to 0 °C, the precipitated disodium salt was isolated by filtration and washed with ethanol to remove dark red-brown impurities. The bright orange salt was placed in a 2 L beaker and diluted with hot water to a total volume of 1.8 L with stirring. The dark brown solution was carefully acidified with concentrated HCl (0.20 L), whereupon the product precipitated as an orange solid. The ice-cooled slurry was filtered by means of a large Büchner funnel, washed thoroughly with water until the washings were almost colorless, dried at 60–70 °C on a large plate overnight, and ground to a powder. Yield: 69–77% (86–96 g) of a bright orange solid. The compound tends to electrostatic charging if powdered and is insoluble in all common solvents, except DMSO, DMF, MeOH/water mixtures, and aqueous alkalis. Solutions of 4 are slightly air-sensitive, turning darker. ¹H NMR (DMSO- d_{6t} 300.1 MHz, 300 K): δ 4.45 (m, 2H, HC^{2,5}), 4.69 (m, 2H, HC^{3,4}), 12.29 (br s, 1H, COOH) ppm. ¹³C{¹H} NMR (DMSO- d_{6t} 75.5 MHz, 300 K): δ 71.4 (br s, $C^{2,5}$), 72.6 ($C^{3,4}$), 73.4 (C^{1}), 171.3 (br s, C=O) ppm. Anal. Calcd for C₁₂H₁₀FeO₄ (274.05): C 52.59, H 4.08. Found: C 53.11, H 3.90.

Synthesis of 1,1'-Bis(chlorocarbonyl)ferrocene, fc(COCl)₂ (5). In a 1 L one-necked flask containing a suspension of finely powdered fc(COOH)₂ (90 g, 0.33 mol) in CHCl₃ (0.3 L) were added successively pyridine (1.2 mL, 5 mol %) and oxalyl chloride (90 mL, 3.2 equiv). The reaction mixture was heated at 60 °C with a reflux condenser until complete dissolution (ca. 2 h). The reaction was accompanied by vigorous gas evolution (neutralized by bubbling through a 10% solution of NaOH; fume hood!) and formation of a deep red solution. After the gas evolution ceased, it was stirred at that temperature for an additional 0.5 h to complete the reaction. All volatiles were removed under reduced pressure into a trap cooled with liquid nitrogen (this condensate containing oxalyl chloride can be continuously used for the next syntheses of 5).⁴⁹ The remaining dark red-brown solid can be used without purification for the synthesis of $fc(CON_3)_2$ according to the procedure b (vide infra). High-purity crystalline material was obtained as follows: the powdered crude material was dissolved in boiling *n*-heptane (300 mL for ca. 30 g; the mother liquor from the first crystallization was continuously reused for the residual part of the crude product), and the slightly cooled supernatant was decanted from a sticky black residue, followed by slow cooling to ambient temperature (with stirring) and after that on an icebath. The bright red microcrystalline solid was collected by quick filtration using a frit-filter, rinsed with small amounts of hexane, and dried in vacuo. Yield: 95% (97 g, 0.31 mol) of odorless, red, microcrystalline solid, which hydrolyzes only slowly in moist air. ¹H NMR (CDCl₃, 300.1 MHz, 300 K): δ 4.77 (s, 4H, HC^{2,5}), 5.05 (s, 4H, HC^{3,4}) ppm. ¹H NMR (C₆D₆, 300.1 MHz, 300 K): δ 3.92 (s, 4H, HC^{2,5}), 4.52 (s, 4H, HC^{3,4}) ppm. ¹³C{¹H} NMR (C₆D₆, 75.5 MHz, 300 K): δ 74.3 (C^{2,5}), 76.1 (C^{3,4}), 77.5 (C¹), 168.1 (C=O) ppm. Anal. Calcd for C₁₂H₈Cl₂FeO₂ (310.95): C 46.35, H 2.59. Found: C 46.50, H 2.51.

a. Synthesis of 1,1'-Bis(azidocarbonyl)ferrocene, fc(CON₃)₂ (6), Starting from 5. CAUTION! Avoid any contact with hot objects! In air and at temperatures over 100 °C intensive combustion might occur! Even small amounts (1-2 mg) of the compound decompose vigorously with self-ignition at temperatures close to the melting point $(mp = 112-115 \ ^{\circ}C)$.⁵⁰ In our case, we were unable to cause detonations by impacts with a hammer, nevertheless protective clothing should be worn! To a vigorously stirred solution of purified fc(COCl)₂ (63 g, 0.20 mol) in acetone (0.6 L) was added a solution of NaN_3 (29 g, 2.2 equiv) in 90 mL of water in four portions. After a mildly exothermic reaction (spontaneous precipitation of the product is possible), the reaction mixture was stirred at 45-50 °C for an additional 1 h. After that time, a concentrated solution of NaHCO₃ (50 mL) was added dropwise, resulting in the formation of a red thick suspension. Further slow addition of water (200 mL) was performed with manual swirling of the flask. The reaction mixture was further diluted with ice-cold water until the total volume was 2.0 L. The fine, deep red precipitate was filtered off using a large frit-filter and washed thoroughly with water. The sticky residue was taken up with 400 mL of CH₂Cl₂, the organic layer was separated, and the aqueous phase was extracted twice with CH₂Cl₂ (150 mL each). The combined organic layers were passed through a short plug of silica (H20, D40). The product was eluted with the same solvent $(R_f(CH_2Cl_2) = 0.36)$ and

dried over Na₂SO₄. The solvent was removed on the rotary evaporator. Trace amounts of moisture were removed by drying in oil-pump vacuum (0.03 mbar) at 50 °C. Yield: 92–97% (59.8–62.8 g) of a red-orange powder. The compound is slightly light-sensitive; therefore it should be stored in a dark, cool place in tightly closed flasks.

b. Synthesis of 1,1'-Bis(azidocarbonyl)ferrocene, fc(CON₃)₂ (6), Starting from 4. In a 1 L round-bottom flask fc(COOH)₂ (61 g, 0.22 mmol) was suspended in 225 mL of CHCl₃, followed by addition of pyridine (0.5 mL 3 mol %) and oxalyl chloride (60 mL, 3.2 equiv) (alternatively, 210 mL of a 1.1 M solution from previous synthesis, vide supra, and stoichiometric amount of oxalyl chloride (40 mL, 0.47 mmol) can be used). The mixture was heated to reflux and stirred at this temperature for 3 h. The major evolution of gas, including HCl, was observed in the first two hours of heating and was neutralized by a 10% NaOH solution. The solvent and excess oxalyl chloride were removed in vacuo to yield crude $fc(COCl)_2$ as a dark red solid. This residue was dissolved in 675 mL of acetone and stirred vigorously while adding NaN₃ (31.6 g, 2.2 equiv) dissolved in 90 mL of water. This solution was stirred for 1.5 h at 50 °C, whereupon NaCl forms, and after that treated with 100 mL of saturated NaHCO₂ and divided into two 2 L beakers, which were then each filled to 2 L with water. The mixtures were cooled with ice to ensure the complete precipitation of the product. The mixture was filtered through a large glass frit-filter and washed thoroughly with water (ca. 3-4 L). The red solid was dried first by sucking air through it and later in vacuo. At the end of the drying procedure the product was powdered and passed through a sieve. By this method 65.1 g (200 mmol, 91%) of $fc(CON_3)_2$ of a very fine reddish-brown powder was obtained. The product synthesized by method b is slightly more impure than that synthesized by method a, containing a brown impurity. Nevertheless, it can be used for further reaction to $fc(NCO)_2$ and $fc(NHBoc)_2.\ ^1H$ NMR (CDCl₃, 300.1 MHz, 300 K): δ 4.55 (HC^{2,5}), 4.89 (HC^{3,4}) ppm. ¹³C{¹H} NMR (CDCl₃, 75.5 MHz, 300 K): δ 72.1 (C^{2,5}), 74.1 (C^{3,4}), 74.3 (C1), 175.5 (C=O) ppm. Anal. Calcd for C12H8FeO2N6 (324.08): C 44.47, H 2.49, N 25.93. Found: C 44.37, H 2.72, N 25.57.

Synthesis of 1,1'-Diisocyanatoferrocene, fc(NCO)₂ (7). A 1 L round-bottom flask, equipped with a reflux condenser and a bubbler, was charged with dry $fc(CON_3)_2$ (64 g, 0.20 mol) in dry toluene (0.6 L), and the suspension was placed in a preheated oil-bath (110 °C). After the bath temperature rose to 95 $^{\circ}C$, vigorous N₂ evolution began (bath temp: 100 °C). Because of the exothermic nature of the decomposition, after a sluggish effervescence at the beginning, the progress of the reaction was controlled by the degree of immersion of the reaction flask into the oil-bath. After the gas evolution had completely ceased (ca. 2 h), the warm, deep yellow suspension was freed from a black precipitate by quick filtration in air through a short, dry Celite pad. Concentration of the filtrate in vacuo to ca. 75 mL and slow cooling to 0 °C led to crystallization of the product. This was isolated by filtration, rinsed with a toluene/hexane mixture (2:1), and dried in vacuo, leaving a yellow, crystalline solid. An additional crop of product was obtained from the concentrated mother liquor. The compound can be stored at 5 °C for months; nevertheless, slow decomposition with darkening can take place. It is therefore recommended to protect the product from moisture. Yield: 81% (43.4 g) of a yellow-brownish, microcrystalline solid. ¹H NMR (CDCl₃, 300 MHz, 300 K): δ 4.07 (m, 2H, HC^{3,4}), 4.34 (m, 2H, $HC^{2,5}$) ppm. ¹³C{¹H} NMR (CDCl₃, 75.5 MHz, 300 K): δ 65.9 ($C^{2,5}$), 66.7 (C^{3,4}), 90.7 (C¹), 123.5 (br s, NCO) ppm. Anal. Calcd for C12H8FeN2O2 (268.053): C 53.77, H 3.01, N 10.45. Found: C 53.62, H 3.21. N 10.33.

Synthesis of 1,1'-Bis[(methoxycarbonyl)amino]ferrocene, fc(NHCOOMe) (8). A suspension of $fc(NCO)_2$ (968 mg, 3.61 mmol) in 10 mL of dry methanol was heated to boiling and stirred while it cooled to room temperature. The yellow to orange precipitate was allowed to crystallize overnight. The supernatant was removed by decantation; the solid filtered and dried *in vacuo* to yield 93% (1.11 g, 3.35 mmol) of a yellow crystalline solid. ¹H NMR (Me₂CO-*d*₆, 300 MHz, 300 K), δ 3.65 (s, 3H, *Me*O), 3.92 (s, 2H, HC^{3,4}), 4.47 (br s, 2H, HC^{2,5}), 7.66 (br s, 1H, NH) ppm. ¹³C{¹H} NMR (Me₂CO-*d*₆, 75.5

Organometallics

MHz, 300 K): δ 52.1 (*MeO*), 62.2 (br s, $C^{2,5}$), 65.3 ($C^{3,4}$), 98.0 (C^{1}), 155.5 (C=O) ppm. Anal. Calcd for $C_{14}H_{16}FeN_2O_4$ (332.14): C 50.63, H 4.86, N 8.43. Found: C 50.90, H 4.95, N 8.31.

a. Synthesis of 1,1'-Bis[(tert-butoxycarbonyl)amino]ferrocene, fc(NHCOOtBu)₂ (9), Starting from 7. A stirred solution of fc(NCO)₂ (5.0 g, 19 mmol) in 20 mL of dry diethyl ether was treated with dry, molten tert-butanol (3.0 g, 2.2 equiv). This solution was stirred for 24 h at room temperature, at which time a yellow powder had precipitated. The powder was filtered off, washed with hexane, and dried in vacuo to yield a first fraction of 6.2 g of the product as a yellow powder. The filtrate was dried in vacuo, dissolved in 15 mL of hot ethyl acetate, and diluted with 45 mL of hexane. The solution was flushed through a short column with silica (H20, \oplus 40) and eluted with ca. 200 mL of a 1:3 mixture of ethyl acetate and hexane ($R_f = 0.31$). This solution was concentrated to a small volume of hot ethyl acetate, where the product crystallized. The supernatant was decanted, and the crystals were dried in vacuo to yield another 0.7 g of the product as orange crystals. Overall yield: 6.86 g (17 mmol, 89%).

b. Synthesis of 1,1'-Bis[(tert-butoxycarbonyl)amino]ferrocene, fc(NHCOOtBu)₂ (9), Starting from 6. In a 1 L Schlenk flask, finely powdered fc(CON₃)₂ (32.1 g, 0.10 mol) was suspended in 0.2 L of dry toluene. Because of the very vigorous gas evolution, we recommend using a flask with at least three times the volume of the solvent employed. This mixture was stirred at 110 °C for 2 h and then cooled to room temperature. The progress of the reaction can be monitored by TLC in toluene $(R_f[fc(CON_3)_2] = 0.26, R_f[fc(NCO)_2]$ = 0.82, $R_{\rm f}[\rm fc(NHBoc)_2] = 0.07$) since the intermediate product $fc(NCO)_2$ is moderately stable for a short period of time. Careful addition of dry, molten tert-butanol (35 mL, 3.0 equiv) to the cooled (0 °C) reaction mixture and heating to reflux for 5 min resulted in the formation of a brown solution. After removal of the volatiles, the residue was completely dissolved in 100 mL of warm ethyl acetate; 100 mL of hexane was added, and the mixture was passed through a short silica pad (H15, \bigcirc 100, $R_f = 0.85$ (EtOAc/n-C₆H₁₄, 1:1), >0.95 (EtOAc), 0.23 (CH₂Cl₂)), thus removing a black solid and a polar, dark brown impurity. Further elution with the same mixture of solvents (ca. 600 mL) and successive removal of the volatiles in vacuo resulted in isolation of an orange, microcrystalline solid. Yield: 81-83% (33.7–34.5g). Mp = 146–147 °C. ¹H NMR (200.1 MHz, CDCl₃, 300 K): δ 1.44 (s, 9H, C(CH₃)₃), 3.90 (m, 2H, HC^{3,4}), 4.28 (m, 2H, $HC^{2,5}$), 6.05 (br s, $\nu_{1/2}$ = 12 Hz, 1H, NH) ppm. ¹H NMR (300.1 MHz, MeCN- d_{3} , 300 K): δ 1.47 (s, 9H, $Me_{3}C$), 3.93 (m, 2H, $HC^{3,4}$), 4.32 (br s, 2H, HC^{2,5}), 6.80 (br s, 1H, NH) ppm. ¹³C{¹H} NMR (75.5 MHz, CDCl₃, 300 K): δ 28.4 (CMe₃), 62.9 (br s, $C^{2,5}$), 65.0 ($C^{3,4}$), 80.0 (CMe₃), 95.9 (C¹), 154.1 (C=O) ppm. Anal. Calcd for C₂₀H₂₈FeN₂O₄ (416.30): C 57.70, H 6.78, N 6.73. Found: C 57.65, H 6.87, N 6.85. MS (EI, 70 eV): m/z (%) = 416.2 (16) [M]⁺, 304.0 (100) [fc(NHCOOH)₂], 286.0 (41) [fc(NCO)₂], 268.0 (44) [fc(NCO)(NHCOOH)], 216.1 (36) $[fc(NH_2)_2]$, 180 (32) [Fe- $(C_5H_4-NHCOOH]$, 162.0 (36) $[Fe(C_5H_4-NCO)]$.

Synthesis of 1,1'-Diaminoferrocene, fc(NH₂)₂ (10). To an icebath-cooled fine suspension of fc(NHBoc)₂ (24.0 g, 57.8 mmol) in deaerated methanol (160 mL) was added acetyl chloride (12.9 g, 2.9 equiv) via a syringe, whereupon dissolution of the solid and darkening of the mixture sometimes took place. The reaction mixture was heated at 65 $^\circ\text{C}$ for 1.25 h, at which time the hydrochloride salt often precipitated as a yellow solid. The mixture was then cooled to room temperature, and a solution of KOH (9.7 g, 3.0 equiv) in 40 mL of deaerated methanol was added. During addition of the base, the solid dissolved to give a dark solution, and in the second half of the addition KCl precipitated. To this yellow suspension triethylamine (4 mL, 2 vol %) was added before it was filtered through a short plug of silica gel (H25, \oplus 40), which had been dampened with 15 mL of a methanol solution containing 2% triethylamine. The product was eluted with the mixture of methanol/triethylamine (2 vol %, ca. 5 \times 50 mL). All volatiles were evaporated in vacuo at 50 °C to result in an orange to brown solid. The crude product was extracted with CH₂Cl₂ (100 mL) and filtered through a short Celite pad (H20, \oplus 40) to remove a yellow solid and washed with CH_2Cl_2 (7 × 10 mL). After removal of the

solvent *in vacuo*, the product was obtained as a brown solid in yields of 84–93% (10.5–11.6 g). The use of a larger excess of KOH sometimes made it necessary to repeat the filtration steps. Analytically pure samples could be obtained by recrystallization from methanol. Mp = 180 °C. ¹H NMR (200.1 MHz, CDCl₃, 300 K): δ 2.56 (br s, $\nu_{1/2}$ = 17 Hz, 2 H, NH₂), 3.80 (m, 2 H, HC^{3,4}), 3.92 (br s, m, 2 H, HC^{2,5}) ppm. ¹³C{¹H} NMR (75.5 MHz, CDCl₃, 300 K): δ 60.5 ($C^{2,5}$), 64.5 ($C^{3,4}$), 103.7 (C^1), ppm. Anal. Calcd for C₁₀H₁₂FeN₂ (216.07): C 55.59, H 5.60, N 12.97. Found: C 55.01, H 5.66, N 12.45. MS (EI, 70 eV): m/z (%) = 216.0 (100) [M]⁺, 80.0 (30) [C₅H₄NH₂]⁺.

ASSOCIATED CONTENT

S Supporting Information

Crystallographic information files (cif) and additional pictures showing selected ferrocene derivatives. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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