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A Cyclic Fc–Histidine Conjugate: Synthesis and Properties – Interactions with Alkali Metal Ions

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The synthesis of the novel N,N^{π}-(ferrocenophane-1,1′-diyldicarbonyl)-bridged histidine methyl ester **1** and of the acyclic bis(histidine methyl ester) derivative **3** are reported. The structure of **1** was studied in the solid state and in solution. The single-crystal structure of **1** shows that both proximal ferrocenyl (Fc) carbonyl groups are *syn* with respect to each other, which is a new structural motif for Fc–amino acid conjugates. This new *syn* conformation allows effective binding to alkali metal cations. Binding is evaluated by cyclic voltammetry monitoring the halfwave potential of the Fc group. Cation binding causes a shift to lower potential ($Na^+ > Li^+ > K^+$, Cs^+). Upon binding, compound **1** shows selectivity towards Na^+ ions.

Introduction

With the increased interest in chemical sensor technology, redox-based sensing of molecular recognition events in host–guest systems has received considerable attention in recent years.[1] Binding of the guest to a host can affect the structure of the host and/or its electronic properties, which can be detected by a suitable redox-active probe, such as ferrocene (Fc). In this regard, specifically designed macrocycles have been studied to electrochemically recognize cationic or anionic species in polar solvents and in some cases neutral molecules.[2–4] Cyclic amides, a class of natural macrocycles are well known for their biological activities as antibiotics and ion-transport regulators in membranes.[5] These properties are attributed to their capability to capture and release metal ions.[6] However, it is recognized that to achieve good artificial cyclopeptide ionophores, a decrease of the conformational freedom is beneficial and can be achieved by introducing some constraints to the cyclic skeleton.[7] Recently, Cheng and co-workers used 1,*n*′-Fc-labelled cyclopeptides to recognize alkali ions,[8] in which the metal ions are thought to bind to the amide carbonyl groups. However, no structural details were provided, although it is proposed that the binding of the ions to the 1,*n*′-dicarbonyl groups proximal to the Fc unit are largely responsible for the changes in the half-wave potential upon metal ion binding. Various studies show that in acyclic[9–10] as well as in cyclic[11] 1,*n*′-dipeptide-substituted Fc conjugates both the carbonyl groups directly attached to the Fc unit adopt an *anti* conformation. Herein, we report the synthesis, characterization and electrochemical studies of a novel histidine-containing ferrocenophane, where both Fc-carbonyl groups adopt a *syn* conformation, which generates a recognition site for metal ions. As part of this study, we compare the binding properties of this new cyclic ferrocene conjugate with its acyclic 1,1′-bis(histidine methyl ester) derivative, which is prepared as part of this study.

Results and Discussions

The target ferrocenophane **1** was synthesized from 1,1′-ferrocenedicarboxylic acid and histidine methyl ester at very high dilutions in order to avoid oligomerization (Scheme 1). After purification by column chromatography, a reddish, crystalline solid was obtained in 38% yield.

The product was characterized by standard spectroscopic methods. The ^{1}H NMR spectrum shows the presence of an amide resonance at δ = 7.57 ppm, and seven resonances in a 1:1:1:1:1:1:2 intensity ratio in the region of δ = 4.86–4.36 ppm. The α-H is observed as a multiplet at δ = 4.88 ppm. The ^{13}C NMR spectrum reveals three signals at δ = 172.3, 172.2, and 169.5 ppm from carbonyl groups, the first of which is assigned to the ester C=O group, while the latter two are amide carbonyl groups. The IR spectrum shows the expected ester carbonyl band at 1731 cm^{-1} and a strong peak at 1652 cm^{-1} due to the amide group. Like most Fc–peptide derivatives, compound **1** exhibits a weak and broad absorbance in the visible region at λ_{max} = 449 nm. This band does not show a sizeable Cotton effect in the CD spectrum (Figure 4). Because the rotation about the Cp–Fe–Cp axis is restricted by the two substituents, the Fc unit

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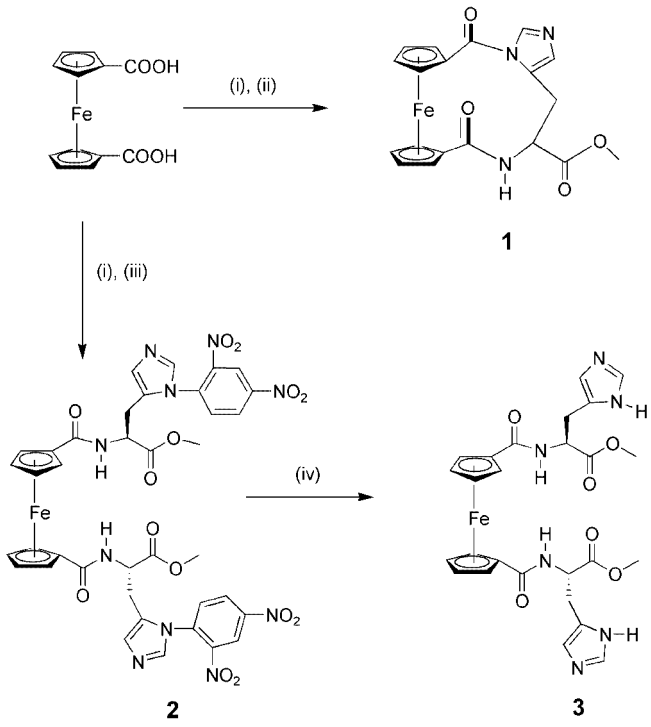

Scheme 1. Synthesis of of ferrocene–histidine conjugates **1** and **3**: (i) activation by EDC/HOBt, (ii) addition of a solution of histidine methyl ester and triethylamine at very high dilution at 0 °C after 30 min and stirring at room temperature for 12 h, (iii) addition of a solution of triethylamine and H-His(DNP)-OMe (cooling with ice bath), (iv) stirring with 10-fold molar excess of thiophenol in methanol at room temperature.

should show helical chirality.[9a,10a] As for other L-amino acids, we would have expected a strong positive band indicating a (*P*)-helical isomer. However, in the absence of a large database for CD spectra, two possibilities have to be considered: (a) compounds of this type display weak CD bands in the Fc region or (b) the absence of an intramolecular H-bond prevents the formation of a single conformation in solution and potentially both (*P*)- and (*M*)-helical isomers are formed in equimolar amounts. DFT calculations by Heinze have shown that (*P*)-helical conformations are energetically preferred for 1,1′-disubstituted Fc–L-amino acid conjugates.[12]

The acyclic compound **3** was prepared in order to compare its properties to those of the ferrocenophane **1**. Compound **3** was synthesized from ferrocenedicarboxylic acid by coupling with 2 equiv. of L-histidine(DNP) methyl ester in dichloromethane, followed by the deprotection of the imidazole group in methanol.[13] The desired compound **3** was obtained in 72% and was characterized spectroscopically. As shown in Figure 4, compound **3** displays a strong positive band in the CD spectrum in the Fc region indicating (*P*) helicity and a "Herrick-type" conformation of the system, as would be expected from an L-amino acid conjugate.[10a] This is in contrast to the very weak signal of the cyclic compound **1**.

Compound **1** was readily crystallized to yield rod-like red crystals by slow diffusion of hexanes into a dilute solution of compound **1** in chloroform. The structural presentation of compound **1** is given in Figure 1 and shows that one Fc unit is linked through the two carbonyl groups to the α-amino group as well as to the N^{π} atom of the imidazole group.

Figure 2 shows a packing diagram of compound **1** indicating the formation of a supramolecular helical structure in the absence of intermolecular H-bonding, reminiscent of Hirao's chirality assembly.[10a] The Fe–C(Cp) distances fall into the expected range of 2.033(3)–2.061(3) Å.

The two Cp rings are parallel [angle between the two Cp planes: 2.5(2)°]. The Cp–CO bond lengths are significantly different. The Cp ring attached to the α-N atom of His exhibits a Cp–CO distance of 1.485(4) Å, whereas the Cp–CO distance of the Cp ring connected to the N^{π} atom of the imidazole ring is shortened to 1.469(4) Å. This has also been observed in the structure of $Fc(CO–His–OMe)_2$.[14] The shortening of the Cp–CO distance is probably because of a greater electronic interaction of this Cp ring with the imidazole ring. As already observed in the structure of $Fc(CO–His–OMe)_2$ the Cp ring and the imidazole ring are not coplanar. However, the twist angle of 49.2(1)° is much larger than in $Fc(CO–His–OMe)_2$ (twist angle of 36.5°). The Cp–amide twist angle of 11.9(2)° is identical to the Cp–amide twist angle in $Fc(CO–His–OMe)_2$ (11.8°). The range of Cp–amide angles for Fc–amides and –peptides is between 5 and 20°.

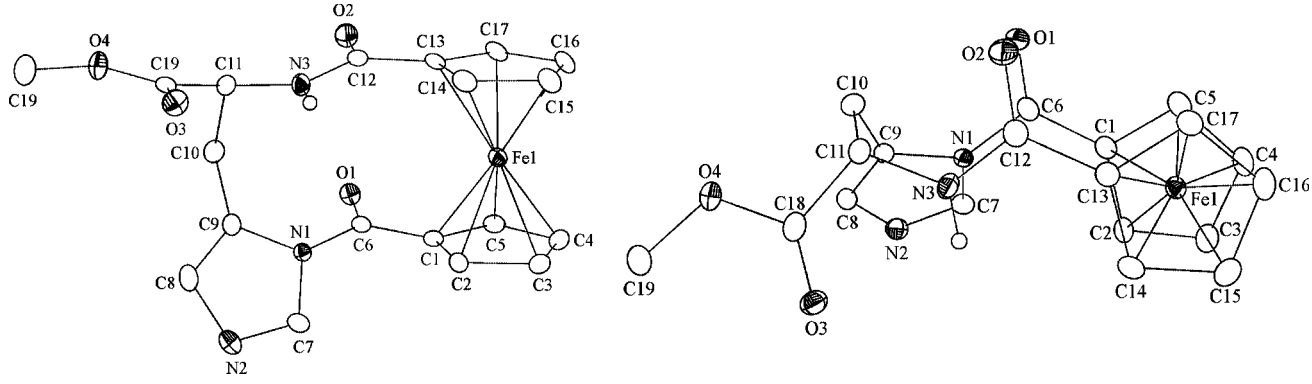

Figure 1. Two ORTEP diagrams of compound **1** showing all non-hydrogen atoms. Both C=O groups proximal to the Fc group are *syn* with respect to each other. All atoms are shown at the 30% probability level.

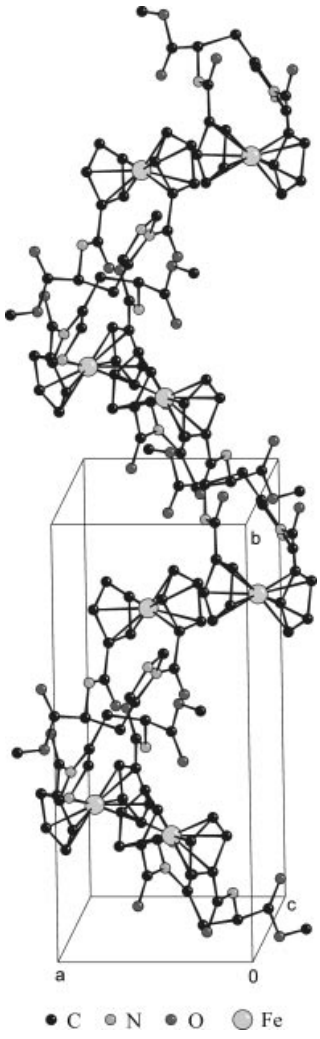

Figure 2. Helical intermolecular arrangement of compound **1**; view along the *c*-axis.

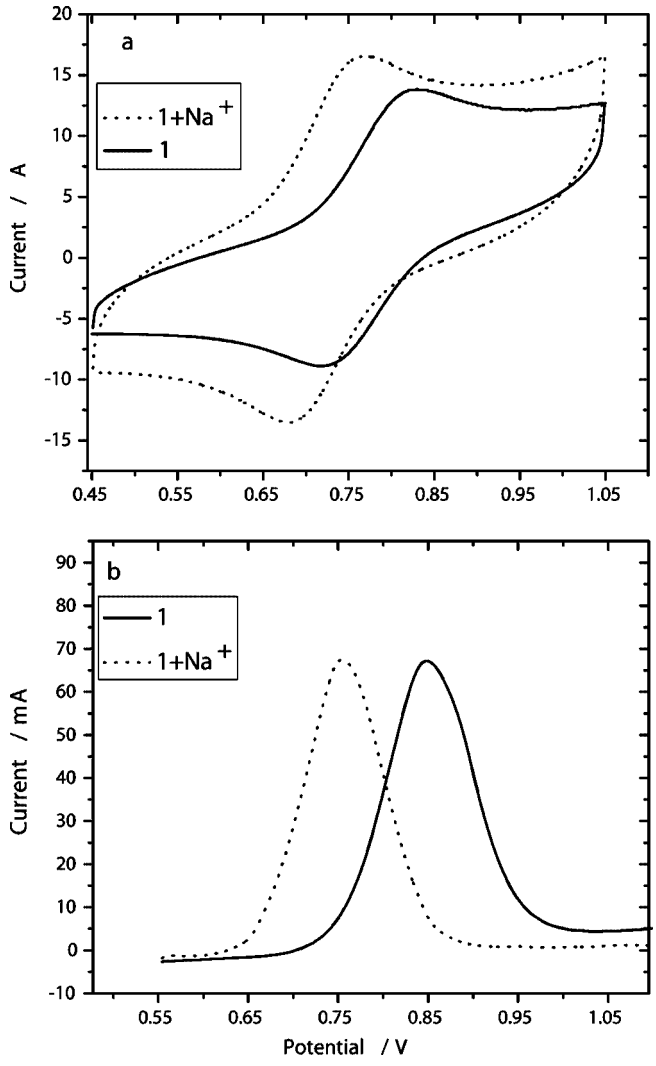

Figure 3. (a) Cyclic voltamogram at a scan rate of 0.1 V and (b) differential pulse voltamogram at a pulse width of 0.05 s of compound **1** before (——) and after (·····) the addition of $NaClO_4$ to the solution (1 mM solute in MeCN) using TBAP (0.1 M) as supporting electrolyte. Glassy carbon was used as working electrode, Ag/AgCl as reference and Pt as counter electrode.

Electrochemical studies [cyclic voltammetry (CV) and differential pulse voltammetry (DPC)] of compounds **1** and **3** were carried out in acetonitrile solutions with TBAP (0.1 M) as the supporting electrolyte. The CVs and DPVs for the compounds **1** and **3** are shown in Figure 3. Both compounds show quasi-reversible behavior (i_a/i_c = 1.1, and 1.09) with a halfwave potential 794 and 751 mV, for **1** and **3**, respectively.

In comparison, the monosubstituted compound Fc(CO–His–OMe) shows a reversible one-electron oxidation at 630 mV. $Fc(CO–His–OMe)_2$, having an addition Fc group linked to the N^{π} atom of the Im ring of His exhibits an additional wave at 762 mV.[14]

In the presence of alkali metal ions, some shifts in the $E_{1/2}$ value for compound **1** are noticeable. The halfwave potentials for the compounds **1** and **3** before and after addition of alkali metal ions are summarized in Table 1. Whereas the shift in the halfwave potential of **1** in the presence of Li^+ is shifted by 46 mV to lower potential, the presence of Na^+ causes a shift of 100 mV, making it significantly easier to oxidize the Fc group. The presence of other alkali metal ions does not cause any significant shifts in the halfwave potential.

We rationalize these potential shifts by the direct interaction of the metal ions with the two proximal *syn* carbonyl groups on the Fc unit. Association of ClO_4^- anions with the Fc unit will result in a lower redox potential as bound metal ions are very close to the Fc unit and surrounded by ClO_4^-. The larger metal ions K^+ and Cs^+ may not fit into the cavity provided by the two carbonyl groups and thus do not affect the electrochemical properties of the Fc group.

For compound **3** on the other hand, the addition of alkali ions causes no electrochemical change but only minor effects, as in the case of Cs^+. Here, the two proximal C=O groups are *anti*, and binding occurs through the ester carbonyl group and/or the imidazole nitrogen atom, which both are far away from the Fc moiety. Cation binding to

Table 1. Half-wave potentials [mV] (±5) of ferrocene conjugates **1** and **3** with or without alkali metal ions.[a]

Composition	**1**	**3**
Pure	794	751
Li	748	751
Na	695	748
K	772	754
Cs	772	773

[a] Measured by differential pulse voltammetry using glassy carbon as working vs. Ag/AgCl as reference, and Pt as counter electrode. Compounds **1** and **3** were at 1 mM concentration in CH_3CN containing 0.1 M TBAP. The $E_{1/2}$ value of the Fc/Fc^+ couple under the experimental conditions is 448(±5) mV (vs. Ag/AgCl). Halfwave potential recorded for pure compound and upon addition of 10 mol-equiv. of $MClO_4$ (M = Li, Na, K, Cs).

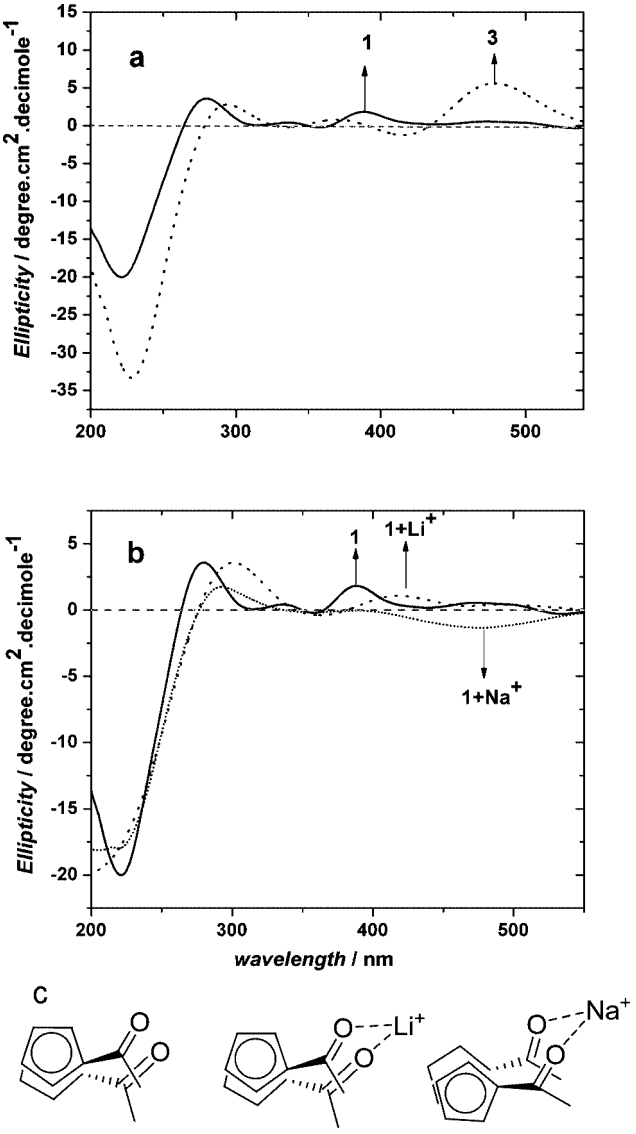

Figure 4. CD spectra in 1 mM solution in acetonitrile of (a) **1** and (b) **3** in the absence and presence of 10 equiv. of alkali metal (Li and Na) perchlorate salts and (c) schematic representation of change in conformation of the Fc entity of **1** with the addition of alkali metal salts.

the carbonyl groups causes the cathodic shift in the redox potential. Association of the ClO_4^- anion with the alkali cation does not appear to influence the redox potential of the Fc group.

We postulated that binding of the ions to the two proximal *syn* C=O group may in fact cause small structural changes in the Fc core. We decided to investigate compound **1** in the presence of alkali metal ions by CD spectroscopy, which allows us to evaluate if structural changes occur involving the helicity of the ferrocene. Figure 4 shows the CD spectra of compounds **1** and **3** and changes of conformation of Fc in **1** upon addition of alkali metal salts. In comparison to **3**, the Fc-based CD band of compound **1** around 400–450 nm is very weak, which indicates weak helical chirality.

However, in the presence of alkali metals, there are noticeable changes occurring in this region. Figure 4 shows the CD spectra of compound **1** in the presence of Li^+ and Na^+. Li^+ causes a bathochromic shift and the band broadens. The conformation of the Fc unit is not affected. The larger Na^+ ion, which in the electrochemistry studies shows the largest effect, causes an apparent change in the conformation of the Fc unit. The Fc band now has an apparent negative Cotton effect. Assuming coordination of the metal ion to the two proximal *syn* carbonyl groups, the smaller Li^+ will fit into the "binding site" established by compound **1** with only minor adjustment, whereas the larger Na^+ requires that the Cp rings slightly rotate towards (*M*) helicity (Figure 4). Interestingly, for compound **3**, only Cs^+ causes a sizeable effect in the halfwave potential. The CD spectrum of compound **3** in the presence of Cs^+ clearly shows that the intensity of the Fc band indicating (*P*) helicity decreases drastically, corroborating a structural argument for the influence of alkali metal binding on these Fc conjugates (Figure S1).

Conclusion

In conclusion, we provide details of the synthesis of a novel ferrocenophane, which displays an unusually *syn* conformation of the two proximal carbonyl groups, having the two Cp rings in an 1,1′-conformation. To the best of our knowledge this is the first example of an Fc–amino acid or –peptide conjugate that deviates from the classic Herrick conformation in such a drastic fashion. This conformation has consequences for the metal-recognition properties of this complex. The ferrocenophane **1** has the ability to recognize specific alkali elements, and displays the strongest change in the halfwave potential in the presence of Na^+ ions. The change in the halfwave potential is related to small structural changes that take place upon binding of the alkali metal ion to the proximal ferrocenyl C=O groups and small rotations of the two Cp rings of the metallocene.

Experimental Section

Synthesis and Characterization: All syntheses were carried out in air unless otherwise indicated. CH_2Cl_2 (BDH; ACS grade) used for

synthesis was dried with CaH_2 and distilled prior to use. $CDCl_3$ (Aldrich) was dried with CaH_2, and stored over molecular sieves (8–12 mesh; effective pore size 4 Å; Fisher) before use. EDC·HCl, HOBt (Quantum), BOP (Advanced Chemtech), $MgSO_4$, and $NaHCO_3$ (VWR) were used as received. For column chromatography, a column (i.d. 2.7 cm; length 45 cm) was packed 18–22 cm high with 230–400 mesh silica gel (VWR). For TLC, aluminum plates coated with silica gel 60 F_{254} (EM Science) were used. NMR spectra were recorded with a Bruker Avance 500 MHz spectrometer using a 5-mm broadband probe operating at 500.134 MHz (^{1}H) and 125.766 MHz (^{13}C{^{1}H}). Peak positions in both ^{1}H and ^{13}C NMR spectra are reported in ppm relative to TMS. The ^{1}H NMR spectra are referenced to the residual $CHCl_3$ signal at δ = 7.27 ppm. All ^{13}C{^{1}H} spectra are referenced to the $CDCl_3$ signal at δ = 77.23 ppm. Mass spectrometry was carried out with a VG Analytical 70/20 VSE instrument. Infrared spectra were obtained in KBr and recorded with a Perkin–Elmer model 1605 FT-IR (resolution: 4 cm^{-1}). 1,1′-Ferrocenedicarboxylic acid was synthesized from diacetylferrocene, which was synthesized from ferrocene by a known procedure.[15]

Synthesis of 1: 1,1′-Ferrocenedicarboxylic acid (0.0558 g, 0.2 mmol) was suspended in dichloromethane (100 mL). Diisopropylethylamine (DIPEA, 1 mL) was added to the solution at 0 °C. His-OMe·2HCl was added (0.048 g, 0.2 mmol) and stirring was continued. After 30 min, CH_2Cl_2 was added to the solution up to a total volume of 2 L. The reaction mixture was cooled to 0 °C (ice bath) for 15 min, followed by the addition of BOP (0.8 g, 2 mmol). After stirring at room temperature for 24 h, the volume of the solution was reduced to 400 mL by roto-evaporation. The organic solution was sequentially washed with saturated aqueous $NaHCO_3$, 10% aqueous citric acid, saturated $NaHCO_3$, and finally water. Traces of water were removed using anhydrous Na_2SO_4. After concentration, the crude product was purified by flash column chromatography using a chloroform/methanol solvent mixture (93:7, v/v; R_f = 0.35). The solvents were removed under reduced pressure. Compound **1** was obtained as a red crystalline solid in 32% yield (0.032 g). HRMS (ES): calcd. for $C_{19}H_{17}FeN_3O_4$ 407.1449; found 407.1410 [M]$^+$. FT-IR (KBr): $\tilde{\nu}$ = 3530 (br., s, N–H, w), 1731 (s, C=O, ester) 1652 (s, C=O, amide I), 1538 (s, amide II) cm^{-1}. UV/Vis (CH_3CN): λ (ε) = 449 (254 M^{-1} cm^{-1}) nm. ^{1}H NMR ($CDCl_3$): δ = 7.68 (s, 1 H, *o*-H of imidazole ring), 7.57 (br., s, 1 H, amide NH), 6.89 (s, 1 H, *m*-H of imidazole ring), 4.88 (m, 1 H, *α*-H of His), 4.86 (s, 1 H, *o*-H of Cp to Im ring), 4.80 (s, 1 H, *o*-H of Cp to Im ring), 4.77 (s, 1 H, *o*-H of Cp to CONH), 4.71 (s, 1 H, *o*-H of Cp to CONH), 4.48 (s, 1 H, *m*-H of Cp to Im ring), 4.46 (s, 1 H, *m*-H of Cp to Im ring), 4.36 (s, 2 H, *m*-H of other Cp attached to CONH), 3.82 (3 H, CH_3 of methyl ester), 3.24 (m, 2 H, β-H of His) ppm. ^{13}C{^{1}H}NMR ($CDCl_3$): δ = 172.3, 172.2, 169.5, 135.4, 135.0, 73.6, 73.5, 72.7, 72.5, 72.3, 72.0, 71.9, 70.5, 70.0, 53.0, 52.7, 29.3 ppm.

Synthesis of 2: To a solution of ferrocenedicarboxylic acid (0.274 g, 1 mmol), dissolved in dry CH_2Cl_2 (50 mL), was added HOBt (0.38 g, 2.5 mmol), and EDC·HCl (0.48 g, 2.5 mmol). The reaction mixture was stirred for 0.5 h and then cooled to 0 °C (ice bath). H–His(DNP)–OMe (0.67 g, 2 mmol) was dissolved in dichloromethane (40 mL) and Et_3N (0.5 mL, ca. 6 mmol) was added at 0 °C. The mixture was stirred at room temperature for 12 h. Workup was identical to that described for compound **1**. The crude product was purified by flash column chromatography using chloroform (R_f = 0.28) and afforded a reddish yellow solid of **2** (0.70 g, 77%). ^{1}H NMR ($CDCl_3$): δ = 8.84 (s, 1 H, 3-H of DNP), 8.04 (d, J_{HH} = 9 Hz, 1 H, 5-H of DNP), 7.86 (d, J_{HH} = 9 Hz, 1 H, 6-H of DNP), 7.85 (d, J = 9 Hz, 1 H, NH of amide), 7.60 (s, 1 H, *o*-H of imidazole), 6.91 (s, 1 H, *m*-H of imidazole), 4.89 (m, 1 H, α-H of His), 4.69 (s, 1 H, *o*-H of Fc), 4.66 (s, 1 H, *o*-H of Fc), 4.41 (s, 1 H, *m*-H of Fc), 4.36 (s, 1 H, *m*-H of Fc), 3.70 (3 H, CH_3 of methyl ester), 3.18 (m, 2 H, β-H of His) ppm.

Synthesis of 3: Compound **2** (0.45 g, 0.5 mmol) was dissolved in methanol (20 mL) and thiophenol (1.2 g, 10 mmol) was added. After stirring of the reaction mixture at room temperature for 7 h, methanol was removed and the product was purified by flash chromatography ($CHCl_3$/MeOH, 80:20; R_f = 0.27). The final product was obtained as an orange solid in 65% yield (0.19 g). HRMS (ES): calcd. for $C_{26}H_{28}FeN_6O_6$ 576.2214; found 576.2191 [M]$^+$. FT-IR (KBr): $\tilde{\nu}$ = 3540 (br., s, N–H), 1731 (s, C=O, ester), 1639 (s, C=O, amide I), 1533 (s, amide II) cm^{-1}. UV/Vis (CH_3CN): λ (ε) = 442 (240 M^{-1} cm^{-1}) nm. ^{1}H NMR $CDCl_3$): δ = 7.84 (d, J = 8 Hz, 1 H, NH of amide), 7.54 (s, 1 H, *o*-H of imidazole), 6.87 (s, 1 H, *m*-H of imidazole) 4.89 (m, 1 H, α-H of His), 4.69 (s, 1 H, *o*-H of Fc), 4.66 (s, 1 H, *o*-H of Fc), 4.41 (s, 1 H, *m*-H of Fc), 4.36 (s, 1 H, *m*-H of Fc), 3.70 (3 H, CH_3 of methyl ester), 3.18 (m, 2 H, β-CH_2 of His) ppm. ^{13}C{^{1}H}NMR ($CDCl_3$): δ = 173.3, 171.2, 135.5, 135.4, 131.4, 98.0, 72.2, 72.1, 71.3, 70.4, 53.4, 53.3, 28.8 ppm.

CD Measurements: CD spectra of CH_3CN solutions with a concentration of $1.0\cdot10^{-3}$ M were recorded under argon at 25 °C with a PiStar-180 spectropolarimeter (Applied Biophysics) using a quartz cell (path length 1 cm).

X-ray Crystallography: An orange plate-like crystal of compound **1** ($C_{19}H_{17}Fe_1N_3O_4$) (Table 2) with the approximate dimensions of 0.08 × 0.05 × 0.05 mm, coated with oil (Paratone 8277, Exxon), was mounted onto a nylon fiber of a CryoLoop™ device (diameter of the nylon fiber: 10 microns; loop diameter 0.1–0.2 mm; Hampton

Table 2. Crystallographic data for compound **1**.

Empirical formula	$C_{19}H_{17}Fe_1N_3O_4$
Formula mass	407.21
Crystal color, habit	orange, plate
Crystal dimensions [mm]	0.08× 0.05× 0.05
Crystal system	orthorhombic
Space group	$P2_12_12_1$
Unit cell parameters:	
a [Å]	7.2350(2)
b [Å]	16.5440(4)
c [Å]	14.0700(5)
V [Å^3]	1684.12(9)
Z	4
F(000)	840
$\rho_{calcd.}$ [Mg/m^3]	1.606
μ [mm]	0.928
Radiation	Mo-K_α (λ = 0.71073 Å)
Temperature [K]	173(2)
θ range for data collection [°]	1.90–26.37
Total reflections	6450
Independent reflections [$F_o^2 \geq 3\sigma(F_o^2)$]	3445 (R_{int} = 0.0426)
Observed reflection [$F_o^2 > 2\sigma(F_o^2)$]	2969
Index ranges	$-9 \leq h \leq 9, -19 \leq k \leq 20, -17 \leq l \leq 17$
Data/restraints/parameters	3445/0/245
Absolute structure parameter	–0.020(18) (1457 Friedel pairs)
S (Goodness-of-fit on F^2)	1.066
Final R indices:	
R_1[a] [$I_o > 2\sigma(I_o)$]	0.0401
wR_2[b] (all data)	0.0764
Max. shift/error in final cycle	0.001
Largest difference peak/hole [e$^-$ Å^3]	0.275/–0.318

[a] $R_1 = [\Sigma||F_o| - |F_c||]/[\Sigma|F_o|]$. [b] $wR_2 = \{[\Sigma w(F_o^2 - F_c^2)^2]/[\Sigma w(F_o^2)^2]\}^{1/2}$, where $w = [\sigma(F_o^2) + (0.0085\cdot P)^2 + (0.6243\cdot P)]^{-1}$ and $P = [\max(F_o^2,0) + 2F_c^2]/3$.

Research, USA) under a microscope. The crystal was then mounted onto the goniometer head, which was quickly transferred to the cold stream of the X-ray diffractometer. All measurements were made with a Nonius KappaCCD 4-Circle Kappa FR540C diffractometer using monochromated Mo-K_α radiation (λ = 0.71073 Å) at –100 °C. An initial orientation matrix and cell was determined from 10 frames using φ scans.[16] The X-ray data were measured using φ- and ω-scans.[16] Data reduction was performed with the HKL DENZO and SCALEPACK software,[17] which corrects for beam inhomogeneity, possible crystal decay, Lorentz and polarization effects. A multi-scan absorption correction was applied (SCALEPACK).[17] The structure was solved by direct methods (SHELXS-97)[18] and refined by full-matrix least-squares methods on F^2 with SHELXL97-2.[19] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included at geometrically idealized positions (C–H bond lengths 0.95/0.98/1.00 Å, N–H bond lengths 0.88 Å) and were not refined. The isotropic thermal parameters of the hydrogen atoms were fixed at 1.2 times that of the preceding carbon atom. CCDC-285760 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Electrochemical Measurements: The electrochemical experiments were carried out at room temperature with a CV-50W voltammetric analyzer. A gold electrode (diameter 50 μm) was used as the working electrode. 1 mM CH_3CN solutions of compounds **1** and **3** were prepared containing 0.1 M tetrabutylammonium perchlorate (TBAP). The measurements were carried out in a low scan rate of 100 and 10 mV/s for cyclic voltammetry (CV) and differential pulse voltammetry (DPV), respectively. A platinum wire (1 mm) was used as the counter electrode. The reference electrode was Ag/AgCl (BAS). The $E_{1/2}$ value of the Fc/Fc^+ couple under the experimental conditions was 448(± 5) mV (vs. Ag/AgCl).

Supporting Information (see footnote on the first page of this article): CD spectra and CVs of compound **3** with and without Cs^+.

Acknowledgments

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