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Synthesis and characterisation of water soluble ferrocenes: Molecular tuning of redox potentials

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Abstract

A range of novel water-soluble alkylated ferrocene sulfonate compounds are reported. Mono- and di-sulfonation on a series of alkyl ferrocenes produced 1,1′-dimethyl ferrocene sulfonate, 1,1′-dimethyl ferrocene disulfonate, 1,1′-diethyl ferrocene sulfonate, 1,1′-diethyl ferrocene disulfonate, *t*-butyl ferrocene sulfonate, *t*-butyl ferrocene disulfonate, ethyl ferrocene sulfonate, ethyl ferrocene disulfonate, *n*-butyl ferrocene sulfonate and *n*-butyl ferrocene disulfonate. All compounds were characterized by NMR spectroscopy, UV/Vis spectroscopy and electrochemical analysis. ^{1}H and ^{13}C NMR studies have revealed the formation of several isomers with sulfonation occurring on positions α and β to the alkyl substituent or on the unsubstituted cyclopentadienyl ring. Variation of the alkyl group allowed the isomeric pattern to be tuned such that the final products followed either electronic or steric control. Cyclic voltammetry of the resulting products showed that the redox potential of the iron centre can be easily manipulated by changing the substituents on the cyclopentadienyl rings. This result has significant implications in the future development of homogenous redox mediators for sensing applications.

Keywords: Alkylferrocene; Sulfonation; Mediator; Electrochemistry; NMR

1. Introduction

The development of robust electrochemical sensors often requires the use of mediators to reduce electrode fouling and improve selectivity and sensitivity. These mediators are typically split into two divisions: enzymatic and non-enzymatic catalysis [1–4]. Non-enzymatic electrocatalysts, while lacking much of the specificity inherent to biological systems, are often more robust and amenable to electrochemical manipulation. This is highlighted by the fact that commercial glucose sensors couple inorganic redox mediators (usually a ferrocene or hexacyanoferrate moiety) to the biological recognition element (glucose oxidase) in order to extract a viable analytical signal [5]. Electron transfer mediators are used predominately to enhance the sensitivity of the electrode response to analytes that tend to exhibit slow electrode kinetics at the bare, unmodified electrode substrate [6,7]. The ability to develop homogeneous mediators in which its redox potential can be manipulated to a specific set of analytes will aid in overcoming some of the selectivity issues inherent in these non-enzymatic systems.

Numerous groups have examined the properties of ferrocene and its derivatives due to its redox centre, the π-conjugated system and the resulting exclusive electron-transfer ability [8]. The iron centres redox potential can be manipulated *via* the introduction of either electron donating or withdrawing moieties onto the cyclopentadienyl rings. Substitution of these cyclopentadienyl rings can take place via variety of synthetic routes depending on which particular substituent is required [9–12]. Furthermore substitution of the ring with sulfonate groups allows the ferrocene to become water soluble [13–15]. Such derivatised ferrocenes

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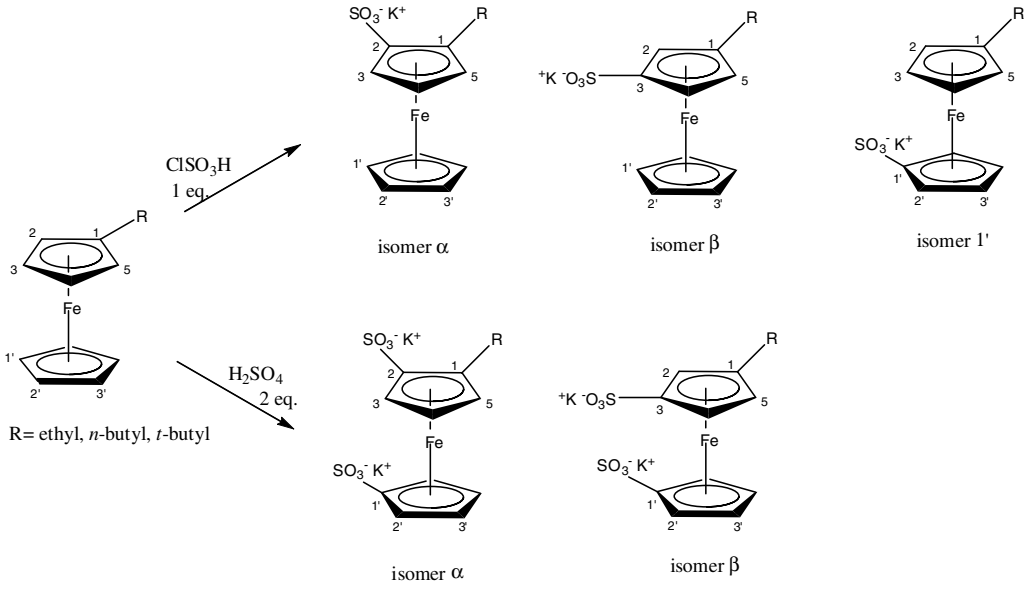


Scheme 1. Synthetic routes towards mono- and di-sulfonated mono-alkylated ferrocene and their isomers.

are prime candidates to be used either as homogeneous mediators in electrochemical sensors [16–18] or as anion dopants during the formation of cationic polymers [19–22].

Sulfonation of mono-alkylated 6-member aromatic rings is shown to favour substitution either *ortho* or *para* to the alkyl moiety with a range of isomers being produced depending on the nature of the alkyl moiety [23]. It could be envisaged that sulfonation of alkylated ferrocene will produce a host of isomers with substitution occurring either alpha or beta to the alkyl moiety or on the unsubstituted ring (Scheme 1). Herein, we report on the synthesis and characterization of a range of new water soluble aliphatic substituted ferrocene sulfonate compounds.

2. Results and discussion

2.1. Synthesis and characterization of mono and di-sulfonated mono-alkylated ferrocenes

Sulfonation of mono-alkylated ferrocenes led to mixtures of isomers being produced. Indeed, sulfonation can occur in positions α or β to the alkyl substituent or on the non-substituted ring (isomer 1′) (Scheme 1). It should be expected that the less hindered electron donating group would favour sulfonation on the α positions, while more bulky substituents would direct sulfonation on the β or 1′ positions. Mono-sulfonation of commercially available ethyl-, *n*-butyl- and *t*-butyl ferrocenes was first conducted using a stoichiometric amount of chlorosulfonic acid in acetic anhydride whilst di-sulfonation on the same alkyl ferrocenes was better achieved using 2 equiv. of sulfuric acid in acetic anhydride, both procedures were performed at room temperature. Lowering the temperature to −18 °C during addition of the acid did not result in changes in the final product. Due to the instability of the sulfonic acid groups, conversion to the corresponding potassium salt was then preferred and led to yields of 30–50% for the mono-sulfonated and 20–35% for the di-sulfonated mono-alkylated ferrocenes, after 24 h freeze drying. The products were then studied by ^{1}H and ^{13}C NMR in DMSO-d_6 in order to determine the ratio of the various isomers present. In addition, 2D NMR experiments (COSY, HMQC and HMBC) were carried out in order to assign chemical shifts for each of these isomers.

Table 1 details the ratio of isomers formed after mono-sulfonation of ethyl-, *n*-butyl- and *t*-butyl-ferrocenes. It can be seen that two or three isomers in each case are formed with sulfonation occurring preferentially on the unsubstituted cyclopentadienyl ring (Cp). This preference can be attributed to the fact that there are no steric constraints on this ring [12]. Furthermore, as the alkyl chain length is increased from ethyl to *n*-butyl the ratio of isomer α to β decreases significantly, and with the high steric bulk of the *t*-butyl group, sulfonation occurs only β to the alkyl group and on the unsubstituted Cp ring. These results suggest that sulfonation is stereo-controlled rather than electronically-controlled. NMR spectra of these mixtures showed that the chemical shift of the *ipso* carbon (C-1, Scheme 1) shifted downfield as follows: C-1 (isomer α) < C-1 (isomer β) C-1 (isomer 1′), in the case of ethylferrocene C-1, isomer α (88.1 ppm), isomer β (90.1 ppm) and isomer 1′ (91.4 ppm). A similar trend was observed for the

Table 1
The ratio of isomers for ethyl- *n*-butyl- and *t*-butyl mono sulfonated compounds

Alkyl ferrocene	Isomer α	Isomer β	Isomer 1′
Ethyl-	1	1.1	1.5
n-Butyl-	0.6	1	1.2
t-Butyl-	0	1	1.1

The ratio were measured from integration of ^{13}C and ^{1}H NMR spectra.

quaternary carbon bearing the sulfonate group (Scheme 1). In the case of ethyl ferrocene, C-2 was found at 94.4 ppm, C-3 at 95.7 ppm and C-1′ at 96.3 ppm. On the ^{1}H NMR spectra of ethyl and *n*-butyl ferrocenes, isomers α can be easily differentiated from isomers β and isomers 1′ by the non-equivalence of the CH_2 protons adjacent to the Cp ring. This non equivalence is clearly observed by the presence of doublets of quartets in the case of the ethyl and doublets of triplets in the case of the *n*-butyl group as opposed to a quartet found for the β or 1′ isomers. This behaviour is outlined in Fig. 1 which details the difference of chemical shift and multiplicity for the three isomers in the ^{1}H NMR spectrum of ethyl ferrocene mono-sulfonate. It can be further noticed that the chemical shifts of the CH_2 protons in the α isomer are shifted downfield (2.51 and 2.60 ppm) due to the spatial proximity of the electronegative sulfonate group as compared to isomers β and 1′ found at 2.25 and 2.33 ppm, respectively.

Di-sulfonation of the alkyl ferrocene compounds (Scheme 1) revealed the presence of equimolar amounts of isomers α and β in the case of *n*-butyl ferrocene, whereas the ethyl analogue formed a similar mixture but with a slight preference for the α isomer (1 (β):1.2 (α)), and *t*-butyl ferrocene formed exclusively isomer β. This is consistent with mono-sulfonation in which the ratio of α to β isomers decreased with increasing alkyl chain size and confirms that the regiochemistry of the sulfonation process is sterically controlled. ^{13}C NMR spectra of the ethyl- and *n*-butyl ferrocene disulfonate showed that the chemical shift of C-1′ shifted downfield from isomer α to isomer β (96.6–97.0 ppm for both compounds), therefore demonstrating that the chemical shift of C-1′ is influenced by the upper ring substituent and *vice versa*. Finally, it was noted that as in the case of unsubstituted ferrocene, di-sulfonation on the same cyclopentadiene ring was not observed for any of these compounds [13,14].

The UV/Vis spectra of both the mono- and di-sulfonated mono-alkylated ferrocenes in a pH 7, 0.1 M phosphate buffer solution, produced an absorbance maximum at 423 nm. These results showed that the spectra are independent of both the alkyl side chain length and the number of sulfonate groups attached to the Cp rings.

The voltammetric response of both the mono- and di-sulfonated mono-alkylated ferrocene sulfonate compounds were explored in a pH 7, 0.1 M phosphate buffer solution using a boron-doped diamond (BDD) electrode. Fig. 2 depicts the cyclic voltammetric response (scan rate = 100 mV s^{-1}) of solutions containing 1 mM of (a) *t*-butylferrocene mono-sulfonate and (b) *t*-butylferrocene di-sulfonate. These voltammograms reveal that both ferrocenes are electroactive in the potential range studied, with well defined oxidative peaks observed at +0.375 and +0.574 V and corresponding reduction peaks at +0.285 and +0.491 V for the mono- and di-sulfonated ferrocenes, respectively. These waves can be attributed to oxidation and reduction of the ferrocene complex to the ferricenium radical cation species. These results demonstrate that introduction of a second sulfonate moiety onto the

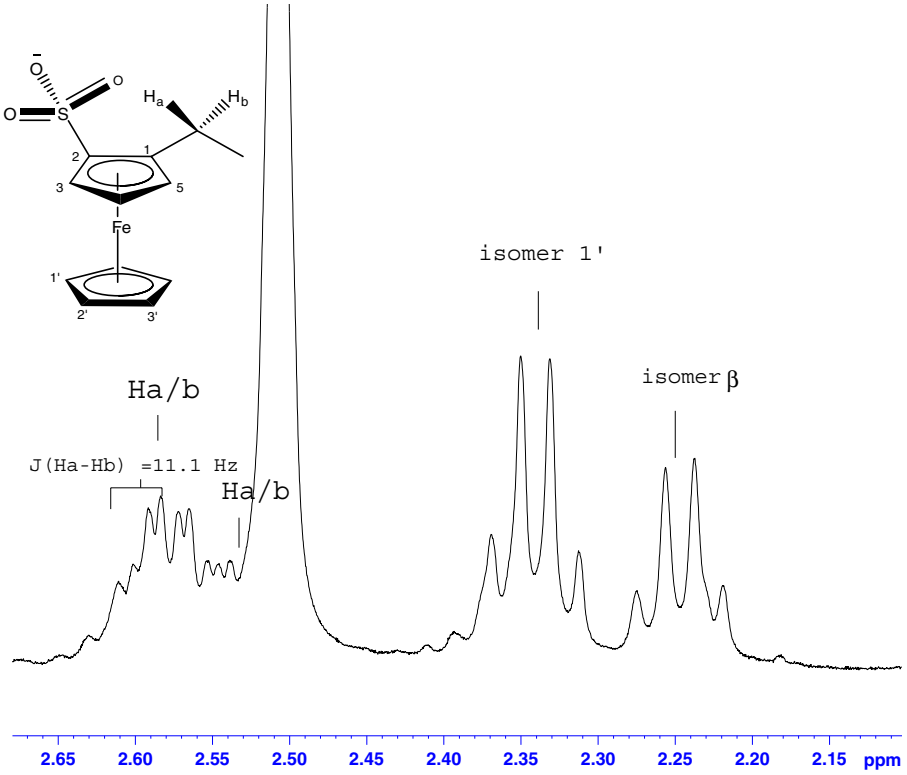


Fig. 1. ^{1}H NMR spectra of ethyl ferrocene mono-sulfonate highlighting the difference of chemical shift and multiplicity for the three isomers.

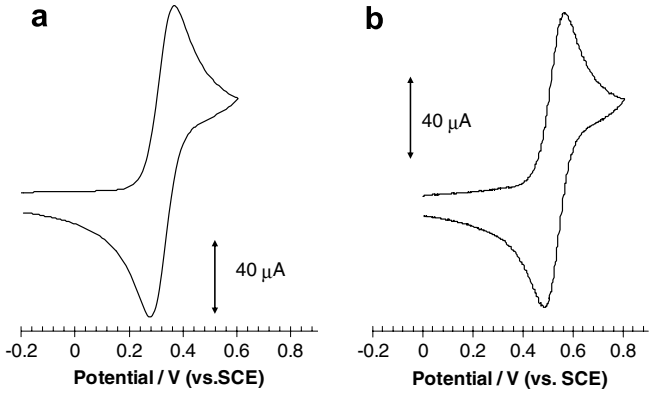


Fig. 2. Voltammetric response of solution containing 1 mM of: (a) *t*-butylferrocene mono-sulfonate, and (b) *t*-butylferrocene di-sulfonate recorded at a BDD electrode in pH 7, 0.1 M phosphate buffer. Scan rate: 100 mV s^{-1}.

cyclopentadienyl rings produces a ~200 mV shift towards more positive potentials. This trend can be rationalized by the electron-withdrawing effects of the sulfonate groups; the two sulfonate groups exercise a greater electron-withdrawing effect thus making the oxidation of Fe(II) to Fe(III) more difficult to accomplish.

A detailed analysis of the oxidative peak potentials obtained for all the sulfonated mono-alkylated species synthesized is detailed in Table 2. This indicates that varying the chain size of the substituent from ethyl to butyl has no significant effect on the oxidation potential of the ferrocene compound with the ethyl, *t*-butyl and *n*-butyl mono- and di-sulfonate derivatives producing similar oxidation potentials. The oxidation potentials of unsubstituted ferrocene mono-sulfonate and ferrocene di-sulfonate are also detailed in Table 2 for comparison [16]; as expected the corresponding alkylated ferrocene derivatives have a lower oxidation potential, due to the electron donating ability of the alkyl moiety. Adjusting the pH of the solution over the range 3–9 was found to have no effect of the voltammetric response of the ferrocene sulfonate species. However, lowering of the pH to pH 1, meant that the ferrocene sulfonates were no longer soluble as such their solution based voltammetry could not be measured.

Table 2
Oxidation peak potential, $E_{p,ox}$ and the peak-to-peak separation, ΔE_p measured for the ferrocene sulfonate compounds

Molecule	ΔE_p/V[a]	$E_{p,ox}$/V[a]
Ferrocene sulfonate	0.100	+0.430
n-Butyl ferrocene sulfonate	0.093	+0.366
t-Butyl ferrocene sulfonate	0.090	+0.375
Ethyl ferrocene sulfonate	0.106	+0.374
Ferrocene disulfonate	0.100	+0.650
n-Butyl ferrocene disulfonate	0.082	+0.573
t-Butyl ferrocene disulfonate	0.083	+0.574
Ethyl ferrocene disulfonate	0.081	+0.568
1,1′-Dimethyl ferrocene sulfonate	0.103	+0.304
1,1′-Diethyl ferrocene sulfonate	0.100	+0.320
1,1′-Dimethyl ferrocene disulfonate	0.089	+0.507
1,1′-Diethyl ferrocene disulfonate	0.102	+0.497

[a] vs. SCE.

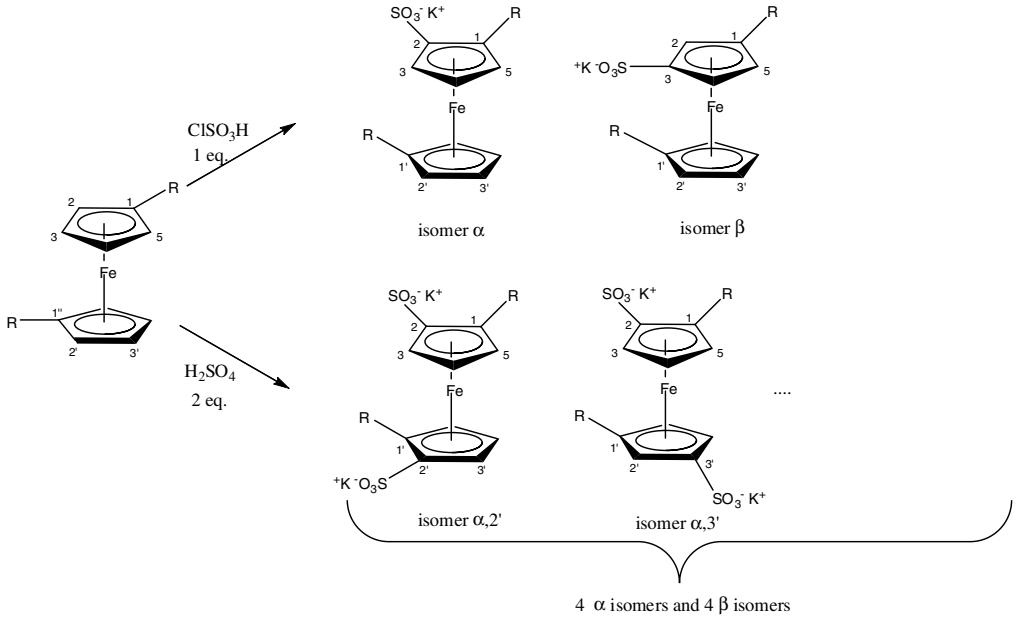
Finally, it should be noted that these experiments were conducted on the solutions prepared from the isomer mixtures. In each case only a single redox couple was observed suggesting that the redox potentials of each isomer are the same. Square wave voltammetry [24] was used to verify the above results. Again, in each case, only a single oxidation peak was obtained for each ferrocene under investigation.

2.2. Synthesis and characterization of mono- and di-sulfonated di-alkylated ferrocenes

Sulfonation of 1,1′-dimethyl ferrocene and 1,1′-diethyl ferrocene was also studied to evaluate the effect of introducing a second alkyl moiety on electrochemical responses of the sulfonated products formed. Mono-sulfonation on theses compounds followed a similar procedure as before, and conversion to the potassium salt led to isolation of deep orange materials in about 50–60% yields after 24 h freeze drying. As shown in Scheme 2, mono-sulfonation can generate only two isomers (α and β to the alkyl substituent) as both rings systems are identical. Based on ^{1}H and ^{13}C NMR, the ratio of isomers for 1,1′-dimethylferrocene sulfonate and 1,1′-diethylferrocene sulfonate was found to be 1:0.6 (α:β) and (1:1) (α:β), respectively. These results are in accordance with the fact that the methyl substituent is less bulky but more electrodonating than the ethyl group, therefore in the case of 1,1′-dimethylferrocene the sulfonation goes this time preferentially in α position and is electronically rather than sterically controlled. Isomers α and β can be identified using NMR experiments. Fig. 3 highlights the $^{2}J_{CH}$ and $^{3}J_{CH}$ correlations between methyl protons and quaternary carbons. In isomer α, the methyl protons of the substituted ring are shifted downfield to 2.04 ppm due to the proximity of the sulfonate group as opposed to 1.92 ppm for methyl protons in the unsubstituted ring, or 1.88 ppm when the sulfonate group is in β position.

Di-sulfonation on the two di-alkyl ferrocene materials was also investigated and following a similar procedure as that described earlier, the disulfonates salts were obtained in 35–45% yields as dark orange solids. The samples were studied by NMR with the ^{13}C spectra revealing 16 quaternary carbons (8C–SO_3^- and 8C-alkyl) belonging to 4 stereoisomers α and 4 steroisomers β as shown in Scheme 2. The regiochemistry of these isomers was indeterminable by NMR analysis.

The UV/Vis spectra of four solutions containing 1 mM of 1,1′-dimethylferrocene sulfonate, 1,1′-diethylferrocene sulfonate, 1,1′-dimethylferrocene di-sulfonate and 1,1′-diethylferrocene di-sulfonate respectively each dissolved in a pH 7, 0.1 M phosphate buffer solution, were next studied. Each spectrum revealed an absorbance maximum at ca. 423 nm, consistent with the sulfonated mono-alkylated ferrocene compounds and demonstrated that neither sulfonation nor alkylation had an effect on the UV/Vis results.



Scheme 2. Synthetic routes towards mono- and di-sulfonated di-alkylated ferrocene and their isomers.

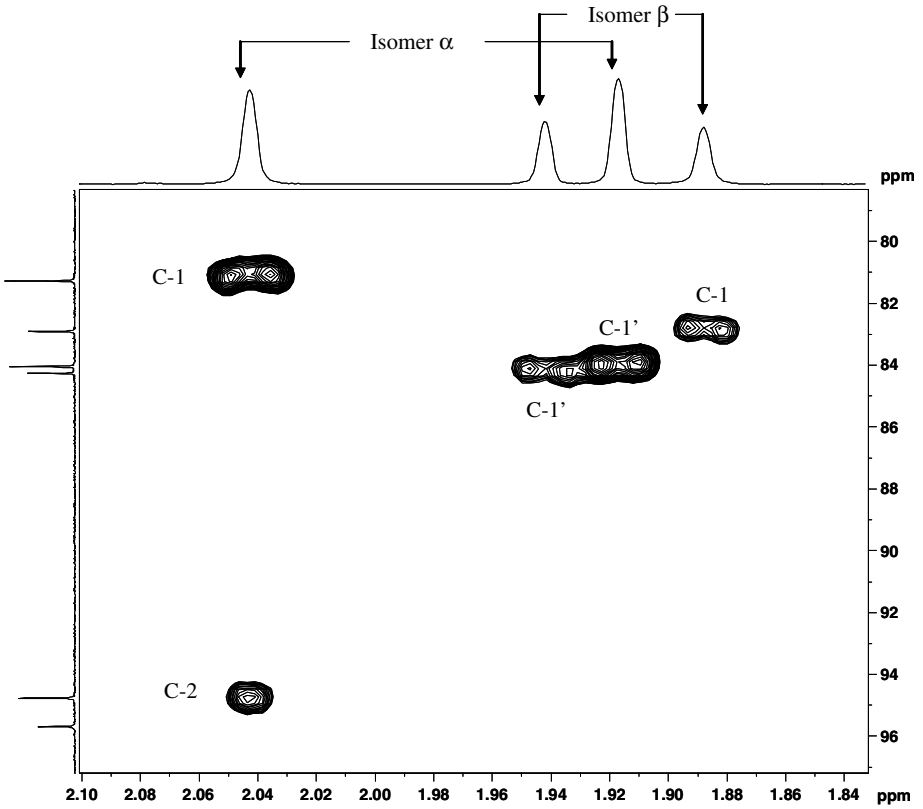


Fig. 3. A region of the ^{1}H ^{13}C HMBC spectrum of 1,1′-methylferrocene sulfonate showing $^{2}J_{CH}$ and $^{3}J_{CH}$ correlations between methyl protons and quaternary carbons.

The voltammetric responses of both the mono- and di-sulfonated di-alkylated ferrocene compounds were then studied. Fig. 4 depicts the voltammetric responses (scan rate = 100 mV s^{-1}) of 1 mM solution of (a) 1,1′-dimethylferrocene sulfonate and (b) 1,1′-dimethylferrocene di-sulfonate dissolved in a pH 7, 0.1 M phosphate buffer solution at a boron-doped diamond (BDD) electrode. As with the mono-alkylated ferrocenes, well defined oxidative and reductive peaks are observed for each species. The corresponding oxidation peak potentials for both the 1,

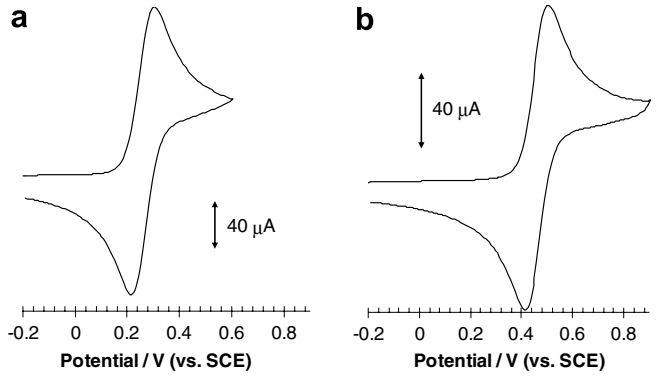


Fig. 4. Voltammetric response of solution containing 1 mM of: (a) 1,1′-dimethylferrocene mono-sulfonate, and (b) 1,1′-dimethylferrocene di-sulfonate recorded at a BDD electrode in pH 7, 0.1 M phosphate buffer. Scan rate: 100 mV s^{-1}.

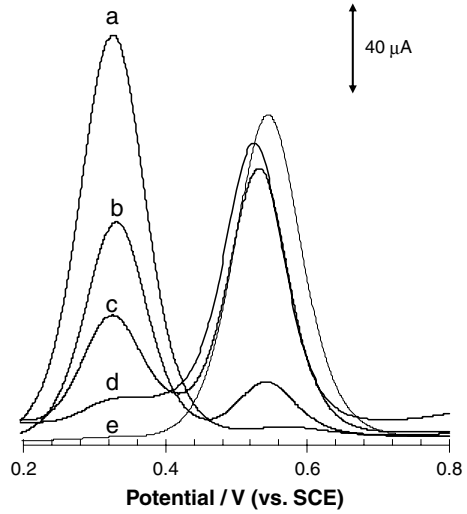


Fig. 5. Square wave voltammetric response of five samples (a–e) in with various equivalence ratios of chlorosulfonic acid to ethylferrocene, when dissolved in pH 7 phosphate buffer: (a) 0.9:1; (b) 1.1:1; (c) 1.6:1; (d) 2.1:1 and (e) is the ethylferrocene di-sulfonate.

1′-dimethyl and 1,1′-diethyl mono and di-sulfonated ferrocenes are given in Table 2. A comparison of all the data in Table 2 reveals that the introduction of a second sulfonate moiety into the cyclopentadienyl rings resulted in a ~200 mV shift towards more positive potentials, whilst the introduction of a second alkyl group lowered the oxidation potentials of the ferrocene compound. This can be attributed to the extra electron donating ability of the second alkyl moiety to the iron centre. The fact that the oxidation potential of the iron centre can be increased and decreased by varying the number of substituents on the cyclopentadienyl rings allows fine tuning of its redox chemistry, demonstrating their suitability as redox mediator for electrochemical sensors.

Finally, Table 2 details the peak-to-peak separations for all the ferrocene compounds studied, where in all cases the ferrocene sulfonates exhibit quasi-reversible heterogeneous electron transfer kinetics. Plots of oxidative peak current as a function of the square root of scan rate (not shown) were found to be linear confirming that the electrochemical responses, as shown in Fig. 1, are diffusion controlled. A plot of peak current as a function of concentration for each compound studied was found to be linear over the concentration range 0–1 mM with the peak potentials of the voltammetric response found to be independent of the pH of the solution. Therefore, one can safely assume that the origin of the voltammetric waves, as shown in Figs. 2 and 4, are due to the redox chemistry of the iron centre in the ferrocene moiety.

2.3. The effect of varying the equivalence ratio of chlorosulfonic acid to ferrocene

In order to probe further the sulfonation reaction, a short experiment was performed where the equivalence ratio of chlorosulfonic acid to ethylferrocene was varied from 0.9 to 2.1 and the resulting products analysed by electrochemical analysis.

Fig. 5 details the square wave voltammetric response of each of the products formed using the various equivalence ratios (a–d) along with the response of ethylferrocene di-sulfonate (e). At low equivalence ratios (response a) a single oxidative wave is observed at +0.330 V, consistent with the oxidation of ethylferrocene mono-sulfonate, however as the ratio is increased (b–d) the peak current at +0.330 V decays and a new wave emerges at +0.530 V. This is consistent with the subsequent generation of the disulfonated ethylferrocene in the reaction mixture. This is confirmed by the overlaid response of a 1 mM solution of pure ethylferrocene disulfonate which reveals a wave at ca. +0.540 V. This is entirely consistent with the NMR data detailed above and shows for the first time that chlorosulfonic acid can also be used to disulfonate alkylated ferrocenes.

3. Conclusion

The results outlined above highlight the synthesis, regiochemical and electrochemical characterization of a range of novel water soluble ferrocene compounds. Sulfonation of the various alkylated ferrocenes generates mixtures of isomers and the regiochemistry is controlled by the steric constraints imposed by the alkyl substituents. The bulky *t*-butyl group effectively blocks the α position on the substituted ring leading to sulfonation only in the β position whereas the less hindered alkyl substituents allows sulfonation to both α and β positions. The isomers resulting from the sulfonation of each compound were found to produce identical electrochemical behaviour. This implies that the position of the sulfonate group on the ferrocene has no significant effect on the electron density of the iron centre.

It was further shown that chemical manipulation of the number of substituents on the cyclopentadienyl rings allowed fine tuning of the ferrocene redox chemistry. This

offers the possibility of using such compounds as homogeneous mediators in electrochemical sensors.

4. Experimental

All chemicals were supplied by Aldrich Chemical Co. and used as received. The buffered solutions were prepared as follows: pH 4 potassium phthalate buffer (0.05 M) and pH 7 disodium hydrogen phosphate (0.025 M) and potassium dihydrogen phosphate (0.025 M).

^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker AV 400 MHz Ultrashield spectrometer and referred to DMSO-d_6 at 2.50 and 39.5 ppm respectively. Although the samples were soluble in D_2O, NMR experiments were performed in DMSO-d_6 for better resolution of the peaks. All chemical shifts are reported in ppm and coupling constants are reported in Hz.

Mass spectra were recorded under EI and ESI conditions at the EPSRC Mass Spectrometry Centre at Swansea University using either a Waters Micromass ZQ4000 or Micromass Quattro II mass spectrometers.

Melting points were obtained with a Stuart SMP10 melting point apparatus.

The UV/Vis spectra were collected over the wavelength range 200–800 nm using a Shimadzu 3010 UV/Vis/NIR spectrophotometer operating with a slit width of 0.1 nm and scanning at a rate of 20 nm/min. The spectra were collected using a quartz cuvette with an optical path length of 1 cm and calibrated against a reference of deionised water. Spectra were collected and analysed using HyperUV software (Lab Control, Cologne, Germany).

Electrochemical measurements were recorded using a PGSTAT30 potentiostat (Ecochemie, Netherlands) with a standard three-electrode configuration. A platinum wire (1 mm diameter, Goodfellow Metals, Cambridge, UK) provided the counter electrode and a saturated calomel electrode (SCE, Radiometer, Copenhagen) acted as the reference. The working electrode was composed of a boron-doped diamond (BDD, 3 mm diameter).

4.1. General procedure for the synthesis of ferrocene mono-sulfonate

To a solution of alkyl-ferrocene (4.1 mmol) in acetic anhydride (25 ml) stirred at room temperature was added drop wise chlorosulfonic acid (4.1 mmol). The resulting green solution was further stirred for 12 h at room temperature. The solution was then poured slowly into cold water (50 ml) and the resulting solution was further stirred for 1 h. Concentration of the solution under reduced pressure (50 °C, 50 mbar) gave a dark green slurry which was extracted with warm diethyl ether (4 × 25 ml) and the combined organic extracts were dried over sodium sulfate, filtered and concentrated under reduced pressure. The mono-sulfonic acids were more stable than the corresponding di-sulfonic acids but conversion to the corresponding potassium salt was the preferred option. It was found that the sulfonic acids derivatives tended to darken over time, as opposed to their corresponding potassium salts. The mono-sulfonic acids were dissolved in deionised water and neutralized to pH 3–4 with potassium hydroxide. The solution was then filtered and freeze dried for 24 h to give the salts as yellow crystalline solids. These could be further purified from recrystallisation from water:iso-propanol mixtures. NMR and melting point data are given below for the potassium salts alone.

4.2. General procedure for the synthesis of ferrocene di-sulfonate

To a slurry of alkyl-ferrocene (4.1 mmol) in acetic anhydride (25 ml) stirred at room temperature was added drop wise conc. sulfuric acid (4.1 mmol). The resulting green solution was further stirred for 12 h at room temperature. The solution was then poured slowly into cold water (50 ml) and the resulting solution was further stirred for 1 h. Concentration of the solution under reduced pressure (50 °C, 50 mbar) gave a dark green slurry which was extracted with warm diethyl ether (6 × 25 ml) and the combined organic extracts were dried over sodium sulfate, filtered and concentrated under reduced pressure.

The di-sulfonic acids were therefore dissolved in deionised water and neutralized to pH 3–4 with potassium hydroxide. The solution was then filtered and freeze dried for 24 h to give the salts as yellow crystalline solids. These could be further purified from re-crystallisation from water:iso-propanol mixtures. NMR and melting point data are given below for the potassium salts alone.

4.2.1. Ethylferrocene mono-sulfonate

Yield: 42%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α: δ 2.51 (1H, m, C*H*HCp), 2.60 (1H, dq, ^{gem}J 11.1 Hz, ^{3}J 7.7 Hz, CH*H*CH$_3$);
Isomer β: δ 2.25 (2H, q, J 7.7 Hz, CH$_2$Cp);
Isomer 1′: δ 2.33 (2H, q, J 7.4 Hz, CH$_2$Cp);
Isomer 1′ + isomer β + isomer α: δ 1.1 (3H + 3H + 3H, m, CH$_3$), 3.88–4.32 (8H + 8H + 8H, m, H–Cp);

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer α: δ 14.6 (CH$_3$), 21.1 (C*H*$_2$CH$_3$), 88.1 (C-1), 94.4 (C-2);
Isomer β: δ 14.6 (CH$_3$), 21.6 (C*H*$_2$CH$_3$), 90.1 (C-1), 95.7 (C-3);
Isomer 1′: δ 14.7 (CH$_3$), 21.3 (C*H*$_2$CH$_3$), 91.5 (C-1), 96.3 (C-1′);
Other signals: δ 64.2, 65.9, 66.4, 66.6, 67.3, 67.6, 67.7, 68.1, 68.7, 69.0, 69.8, 69.9;

M.p.: Did not melt up to 300 °C and showed no sign of decomposition
ESI-MS m/z: 293.1 $[M-H]^-$.

4.2.2. Ethyl ferrocene di-sulfonate

Yield: 20%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α: δ 1.06 (3H, dd, *J* 7.5 Hz, CH_3), 2.50 (2H, dq, ^{gem}J 11.7 Hz, ^3J 7.3 Hz, CH_2), 3.98 (1H, t, *J* 2.4 Hz, H-4), 4.34–4.02 (7H, m, H–Cp);
Isomer β: δ 1.08 (3H, t, *J* 7.2 Hz, CH_3), 2.36 (2H, q, *J* 7.2 Hz, CH_2), 4.34–4.02 (6H, m, H–Cp);

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer α: δ 14.9 (CH_3), 19.9 (CH_2), 67.2, 68.3, 68.7, 69.7, 70.2, 70.5, 71.1, 88.7 (C-1), 94.7 (C-2), 96.6 (C-1′);
Isomer β: δ 14.8 (CH_3), 21.0 (CH_2), 67.3, 67.6, 68.8, 69.2, 69.5, 69.8, 70.3, 91.3 (C-1), 95.9 (C-3), 97.3 (C-1′).

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 372 $[M-H]^{2-}$.

4.2.3. t-Butylferrocene mono-sulfonate

Yield: 45%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer β: δ 1.16 (9H, s, CCH_3), 3.96 (1H, dd,^3J 4.2 Hz, ^4J 2.0 Hz, H–Cp), 4.16 (5H, m, H–Cp′); 4.20 (1H, t, ^4J 1.9 Hz, H-2), 4.23 (1H, dd, ^3J 4.2 Hz, ^4J 2.0 Hz, H–Cp);
Isomer 1′: δ 1.16 (9H, s, CCH_3), 4.03 (2H, m, H–Cp′), 4.04 (2H, m, H–Cp), 4.14 (2H, m, H–Cp), 4.29 (2H, m, H–Cp′).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer β: δ 30.1 (CCH_3), 31.4 (CH_3), 64.1, 65.8 (C-4, C-5), 64.3 (C-2) 69.8 (C-1′), C-2′, C-3′, C-4′, C-5′), 95.3 (C-3), 100.8 (C-1);
Isomer 1′: δ 30.0 (CCH_3), 30.3 (CH_3), 66.15, 67.18 (C-2′, C-3′, C-4′, C-5′), 66.17, 69.4 (C-2, C-4, C-5), 96.4 (C-1′), 101.9 (C-1).

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 321.2 $[M-H]^-$.

4.2.4. t-Butyl ferrocene di-sulfonate

Yield: 63%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer β: δ 1.19 (9 H, s, CH_3), 4.04 (1H, dd, H-5), 4.13, 4.14 (2H, m, H-2′, H-5′), 4.17 (1H, dd, H-2), 4.45, 4.26 (2H, m, H-3′, H-4′), 4.40 (1H, dd, H-4).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer β: δ 30.1(CCH_3), 31.4 (CH_3), 64.4 (C-2), 67.3, (C-5), 68.5 (C-4), 69.9, 68.6 (C-2′, C-5′), 68.8, 70.4 (C-3′, C-4′), 95.7 (C-3), 97.0 (C-1′), 101.9 (C-1);
Isomer α: δ 31.4, 31.6, 66.8, 68.0, 69.4, 69.8, 70.5, 74.5, 94.9, 95.4, 96.2, 97.01.

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 400.3 $[M-H]^{2-}$.

4.2.5. n-Butyl ferrocene mono-sulfonate

Yield: 46%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α + isomerβ + isomer 1′: δ 0.86 (3H + 3H + 3H, m, CH_3), 1.28 (2H + 2H + 2H, m, C$H_2$$CH_3$), 1.29–1.39 (2H + 2H + 2H, m, C$H_2$$CH_2CH_3$), 4.04–4.17 (8H + 8H + 8H, m, H–Cp);
Isomer α: δ 2.45, 2.69 (1H + 1H, m,C*HH*Cp);
Isomer β: δ 2.25 (2H, m, CH_2Cp);
Isomer 1′: δ 2.33 (2H, m, CH_2Cp).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer 1′: δ 13.9 (CH_3), 22.1 (C$H_2$$CH_2$), 28.2 (Cp–$CH_2$), 32.9 (Cp$CH_2CH_2$), 89.7 (C-1), 96.8 (C-1′);
Isomer β: δ 13.9 (CH_3), 22.1 (C$H_2$$CH_3$), 28.5 (Cp–$CH_2$), 32.8 (Cp$CH_2$$CH_2$), 88.4 (C-1), 95.8 (C-3);
Isomer α: δ 14.0 (CH_3), 22.4 (C$H_2$$CH_3$), 27.0 (Cp–$CH_2$), 32.2 (Cp$CH_2CH_2$), 86.5 (C-1), 94.7 (C-2);
Other signals: δ 67.0, 67.6, 67.7, 68.7, 69.6, 69.9, 69.9.

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 321.0 $[M-H]^-$.

4.2.6. n-Butyl ferrocene di-sulfonate

Yield: 21%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α: δ 1.49 (1 H, m, CH_2C*H*HCH_2CH_3), 2.46 (1H, ddd, ^{gem}J 14.3 Hz, *J* 9.7 Hz, *J* 5.3 Hz, Cp–C*H*H), 2.71 (1H, ddd, ^{gem}J 14.3 Hz, *J* 9.7 Hz, *J* 5.3 Hz, Cp–C*H*H), 4.0 (1H, t, *J* 2.5 Hz, H-4), 4.06, 4.38 (2H, m, H-3, H-5);
Isomer β: δ 2.36 (2H, dt, *J* 7.5 Hz, Cp–C*H*H);
Isomer α + isomer β: δ 0.87 (3H + 3H, t, *J* 7.1Hz, CH_3), 1.28 (2H + 2H, m, C$H_2$$CH_3$), 1.39 (1H + 2H, m, C*H*HCH_2CH_3 + C$H_2$$CH_2CH_3$), 4.06–4.35, 4.40 (4H + 7H, m, H–Cp).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer α: δ 13.9 (*C*H_3), 22.0 (*C*$H_2$$CH_3$),26.7 (Cp-*C*$H_2$), 32.4 (Cp–$CH_2$*C*$H_2$), 67.3 (C-4), 70.4 (C-5), 87.3 (C-1), 94.8 (C-2), 96.6 (C-1′);

Isomer β: δ 14.1 (CH_3), 22.5 (CH_2CH_3), 27.9 (Cp-CH_2), 33.0 (Cp–CH_2CH_2), 89.7 (C-1), 96.1 (C-3), 97.3 (C-1′);
Isomer α + isomer β: δ 67.8, 68.1, 68.5, 68.8, 69.0, 69.3, 69.8, 69.9, 70.3, 70.7, 71.0, 71.3.

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*:400.3 $[M-H]^{2-}$.

4.2.7. 1,1′-Dimethylferrocene mono-sulfonate

Yield: 32%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α: δ 1.92 (3H, s, CH_3(1′)), 2.04 (3H, s, CH_3 (1)), 3.85, 3.88, 4.02, 4.17 (4H, m, H–Cp + H–Cp′);
Isomer β: δ 1.88 (3H, s, CH_3 (1)), 1.94 (3H, s, CH_3 (1′)), 3.90, 4.04, 4.11, 4.13 (4H, m, H–Cp + H–Cp′);
Isomer α + isomer β: δ 3.99, 3.95, 3.92 (6H, m, H–Cp′).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer α: δ 12.7 (CH_3 (1)), 13.7 (CH_3 (1′)), 65.05, 68.7, 69.3, 69.5, 70.3 (C–Cp′), 70.4 (C–Cp′), 71.5 (C–Cp′), 81.3 (C-1), 84.7 (C-1′), 94.75 (C-2);
Isomer β: δ 13.8 (CH_3 (1′)), 14.0 (CH_3 (1)), 66.8, 68.8, 68.9, 69.0, 71.2, 71.4, 82.9 (C-1), 84.3 (C-1′), 95.7 (C-3).

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 293.1 $[M-H]^-$.

4.2.8. 1,1′-Dimethylferrocene di-sulfonate

Yield: 24%.

^{1}H NMR (400 MHz, DMSO-d_6).
δ 1.78–1.99 (6H, m, CH_3), 3.67–4.24 (6H, m, H–Cp).

^{13}C NMR (100 MHz, DMSO-d_6).
11.9, 12.0, 12.3, 12.9, 13.3, 13.8, 13.9, 67.2, 67.6, 67.9, 68.2, 68.4, 68.7, 68.9, 69.3, 69.6, 69.9, 70.6, 70.9, 71.2, 71.5, 71.9, 72.1, 72.3, 72.7, 73.7, 81.5, 81.7, 81.8, 82.2, 83.9, 84.2, 84.3, 84.5, 94.8–96.9.

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 372 $[M-H]^{2-}$.

4.2.9. 1,1′-Diethylferrocene mono-sulfonate

Yield: 32%.

^{1}H NMR (400 MHz, DMSO-d_6).
Isomer α: δ 2.60, 2.48 (2H, m, CH_2CH_3–Cp), 3.85, 3.90, 4.17 (3H, m, H-3, H-4, H-5);
Isomer β: δ 2.24 (2H, m, CH_2CH_3–Cp), 4.12, 4.10, 3.91 (3H, m, H-2, H-3, H-5);
Isomer α + isomer β: δ 1.05–1.10 (12H, m, CH_3), 2.33 (4H, m,CH_2CH_3–Cp′), 3.96, 3.99, 4.01, 4.05, 4.08, 4.19, 4.27,4.32 (8H, m, H–Cp′).

^{13}C NMR (100 MHz, DMSO-d_6).
Isomer α: δ 19.9 (CH_2, Cp),67.9 (C-5), 87.8 (C-1), 94.5 (C-2);
Isomer β: δ 21.5 (CH_2, Cp), 89.9 (C-1), 95.8 (C-3).

M.p.: Did not melt up to 300 °C and showed no sign of decomposition.
ESI-MS *m*/*z*: 321.0 $[M-H]^-$.

4.2.10. 1,1′-Diethylferrocene di-sulfonate

Yield: 25%.

^{1}H NMR (400 MHz, DMSO-d_6).
δ 1.0–1.1 (48H, m, CH_3), 2.1–2.6 (32H, m, CH_2CH_3), 3.5–4.3 (48H, m, H–Cp).

^{13}C NMR (100 MHz, DMSO-d_6).
δ 14.9, 15.1, 15.14, 19.3, 19.5, 19.7, 19.9, 20.5, 20.7, 21.0, 21.05, 66.2–71.1, 88.1, 88.2, 88.3, 88.4, 90.7, 90.9, 91.0, 91.1, 94.4, 94.6, 94.75, 95.2, 95.7, 96.0, 96.3, 96.6;

ESI-MS *m*/*z*: 400.3 $[M-H]^{2-}$.
M.p.: Did not melt up to 300 °C and showed no sign of decomposition.

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