

# Synthesis and redox properties of novel ferrocenes with redox active 2,6-di-*tert*-butylphenol fragments: The first example of 2,6-di-*tert*-butylphenoxy radicals in ferrocene system

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## Abstract

Novel Schiff bases of ferrocenecarboxaldehyde bearing 2,6-di-*tert*-butylphenol fragments *N*-(3,5-di-*tert*-butyl-4-hydroxyphenyl)iminomethylferrocene (**1**) and *N*-(3,5-di-*tert*-butyl-4-hydroxybenzyl)iminomethylferrocene (**2**) have been synthesized and characterized. The oxidation of the compounds **1** and **2** by PbO<sub>2</sub> in solution leads to the formation of stable phenoxy radicals **1'** and **2'** studied by EPR spectroscopy. The redox properties of ferrocenes **1** and **2** were studied using cyclic voltammetry.

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**Keywords:** Ferrocene; Phenoxy radicals; Redox reactions; EPR; Cyclic voltammetry

## 1. Introduction

A family of ferrocene compounds are used as catalysts [1,2], sensors [3], luminescent systems, and molecular electronic devices [4] due to their well established redox properties. The application of ferrocene derivatives in biological areas and medicine is intensively investigated [5]. It is supposed that ferrocenes participate in biochemical redox processes, promoting formation of reactive oxygen species and other free radical metabolites [6].

Most of ferrocene derivatives undergo reversible one-electron oxidation forming ferrocenium cations (radical-cations) due to the redox activity of metal center. Construction of polytopic redox systems containing more than one redox center has attracted considerable interest, both from the fundamental and practical points of view [7]. The regulation of the electronic communication between two centers

can be achieved by using a redox active organic ligand [8].

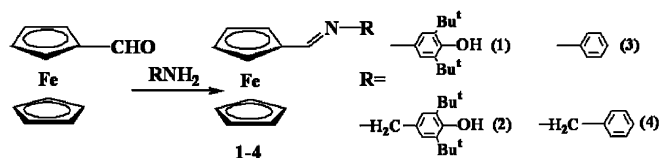
Previously, we have demonstrated that the introduction of 2,6-di-*tert*-butylphenol into transition metal complexes leads to the formation of stable polytopic redox systems which can be oxidized either on metal or ligand centers [9,10]. The involvement of the phenolic group or metal ion in oxidation of these complexes is manifested in the formation of polyfunctional catalytic systems which show positive and/or negative catalytic effects [11].

In this paper, we present the first example of Schiff bases of ferrocenecarboxaldehyde with conjugated **1** and non-conjugated **2** 2,6-di-*tert*-butylphenol groups.

## 2. Results and discussion

Schiff bases **1**, **2** were synthesized by the interaction of ferrocenecarboxaldehyde with the corresponding amines (Scheme 1). Phenyl and benzyl derivatives **3**, **4** were chosen as model compounds for the comparative electrochemical study, in order to establish the role of phenol pendants in

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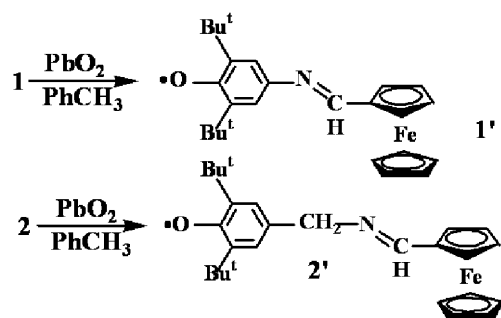
Scheme 1.

oxidation processes and they were prepared using the methods described earlier [12,13].

To prevent the oxidation of phenol containing amine, the synthesis of compound **1** was carried out in ethanol at room temperature using 4-amino-2,6-di-*tert*-butylphenol generated *in situ* from a more stable corresponding hydrochloride in the presence of  $\text{NEt}_3$ . The compounds **1–4** were isolated as orange solids, stable in the air and in solutions. They were characterized by elemental analysis, IR, UV–vis,  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopies. The IR spectra of complexes **1**, **2** exhibit absorption bands at 3639 and 3627  $\text{cm}^{-1}$  ( $\nu_{\text{O-H}}$ ), and at 1654 and 1643  $\text{cm}^{-1}$  ( $\nu_{\text{C=N}}$ ) correspondingly characteristic for non-associated sterically hindered phenols. Electronic absorption spectra show the intramolecular charge transfer bands in the ligand-metal system at  $\sim 450$  nm. As it follows from the spectral data, no oxidation of phenol substituents to the quinoid derivatives occurs in the synthesis of ferrocenes **1**, **2**.

The chemical oxidation of phenol derivatives **1**, **2** was carried out in toluene using lead dioxide yielding phenoxyl radicals **1'**, **2'** (Scheme 2).

The X-band EPR spectra measured at 293 K show the spin density distribution in the organic ligands. The experimental and simulated EPR spectra (Fig. 1) of radical **1'** exhibit 9 lines corresponding to the coupling of the unpaired electron with two equivalent *meta*-protons of the phenoxy ring ( $^1\text{H}$ ) and nitrogen atom of azomethine group ( $^{14}\text{N}$ ). The isotropic *g*-value for the radical **1'** is 2.0055 and hyperfine coupling constants ( $a_i$ ) are:  $a(2\text{H}) = 1.0$  G;  $a(^{14}\text{N}) = 5.9$  G. The radical **1'** is stable at room temperature in the absence of dioxygen for several days. The EPR spectrum of radical **2'** shows the multiple signal ( $g = 2.0030$ ) with hyperfine coupling constants:  $a(\text{H}) = 11.0$  G ( $-\text{CH}_2-$  group),  $a(2\text{H}) = 1.7$  G (*meta*-protons of the phenoxy ring),  $a(^{14}\text{N}) = 1.5$  G (Fig. 2).



Scheme 2.

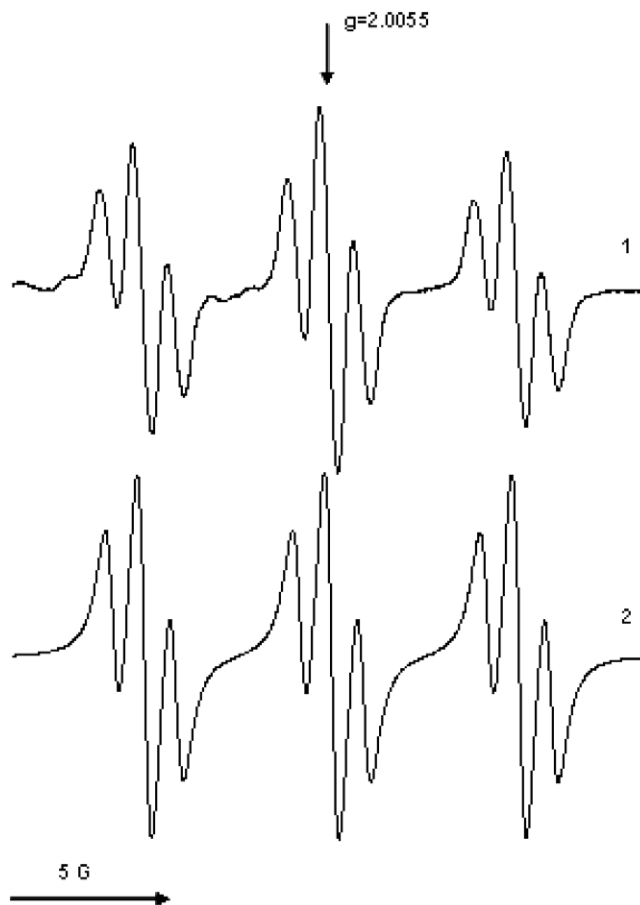


Fig. 1. Experimental **1** and simulated **2** EPR spectra of radical **1'** (toluene, 293 K).

Previously a number of analogues organic species – phenoxyl radicals generated in the oxidation of the corresponding Schiff bases of substituted benzaldehydes has been studied [14,15]. The stability and the values of hyperfine splitting constants of these radicals are influenced by the electron-withdrawing or electron-donating character of the *para*-substituent in the phenyl ring. For instance, the values of  $a(^{14}\text{N})$  are 4.8 and 3.4 G for *para*-methoxy- and *para*-nitrophenyl derivatives correspondingly. The ferrocene unit with Fe(II) center is electron-donating group [1] and increases the stability of radicals **1'** and **2'** as it has been shown by EPR. The analogues effect has been observed previously in P-centered radical-cations [16] and C-centered triphenylmethyl radicals [17] possessing ferrocenyl groups.

The high stability of species **1'** and **2'** is in agreement with a certain degree of electronic delocalization over the molecule.

The oxidation of ferrocene derivatives **1** and **2** by  $\text{AgSO}_2\text{CF}_3$  in chloroform gives purple solutions, and the deposition of Ag is observed. However, we failed to isolate the corresponding ferrocenium salts. This reaction was monitored by  $^1\text{H}$  NMR in  $\text{CDCl}_3$  at room temperature. The disappearance of the OH group's protons signals in

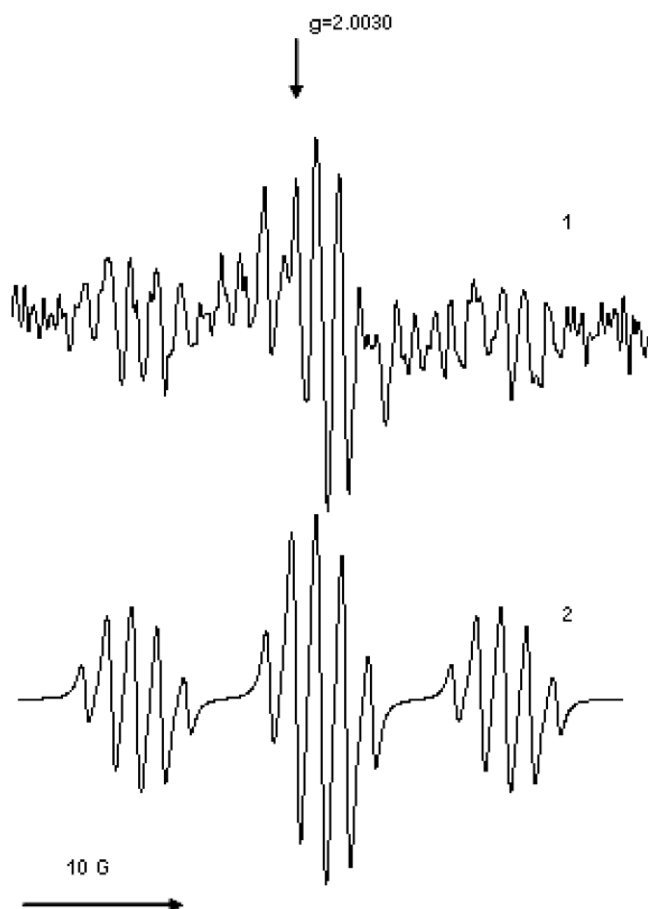


Fig. 2. Experimental **1** and simulated **2** EPR spectra of radical **2'** (toluene, 293 K).

NMR spectra confirms the assumption that the chemical oxidation is attributed to the phenol moiety that leads to the formation of quinoid derivatives as decomposition products.

As it was shown previously using cyclic voltammetry [18], the addition of antioxidants such as 2,6-di-*tert*-butyl-4-methylphenol or 3,5-di-*tert*-butyl-4-hydroxyanisole to ferrocene solutions saturated with O<sub>2</sub> in basic media prevents the complete decomposition of electrogenerated ferrocenium cation. It was proposed that the role of phenols is the reduction of initially formed ferrocenium cation.

Table 1  
Electrochemical data for compounds **1–4**<sup>a</sup>

Compound	$E_1$ · (V)	$E_2$ · (V)	$E_3$ · (V)
<b>1</b>	0.48 (irr.)	0.75/0.67	1.01/0.92
<b>2</b>	0.64 (irr.)	0.81/0.75	1.05/0.97
<b>3</b>	0.72/0.64	–	–
<b>4</b>	0.66/0.59	–	–

<sup>a</sup> Pt, CH<sub>3</sub>CN, concentration of compounds **1–4** are 0.7 mM, 50 mM Bu<sub>4</sub>NBF<sub>4</sub>, vs. Ag/AgCl/KCl, scan rate = 0.1 V s<sup>-1</sup>, 293 K.

Redox properties of the phenol derivatives **1**, **2** as well as of their phenyl analogues **3**, **4** were studied by cyclic voltammetry in CH<sub>3</sub>CN. The oxidation potentials are given in Table 1. The compounds **3**, **4** containing phenyl groups display typical for ferrocenes one-electron reversible oxidation at almost identical potential values which is attributed to Fe<sup>2+</sup>/Fe<sup>3+</sup> transformation (Fig. 3).

Ferrocenes **1** and **2** show more complex electrochemical behavior due to the presence of two redox active fragments – phenol and ferrocene moieties. In the case of **1** these fragments are conjugated and linked via –N=CH– bridge. In the case of **2** the linker also contains –CH<sub>2</sub>– fragment which may impede redistribution of electron and spin density between the two fragments. Compounds **1** and **2** show three oxidation peaks: one-step irreversible and two-steps reversible redox waves.

In the case of **1** the first irreversible one-electron step can be attributed to ferrocene-centered oxidation. The oxidation potential ( $E_1 = 0.48$  V) is comparable with that of unsubstituted ferrocene ( $E_{\text{Fc}/\text{Fc}^+}^+ = 0.51$  V, [18]).

As it has been shown previously for a series of *para*-substituted 2,6-di-*tert*-butylphenols, the first irreversible oxidation potentials are observed at much higher values [19]. For 2,6-di-*tert*-butyl-4-methylphenol and 2,6-di-*tert*-butyl-4-carboxyphenol, for instance, these values are 1.21 and 1.68 V, respectively, versus. SCE [18].

The absence of the corresponding reduction peak in the reverse scan means that primarily formed ferrocenium cation disappears due to some chemical transformations (Scheme 3). Since 2,6-di-*tert*-butylphenol is the electron-donating group, the most probable pathway is intramolecular reduction of iron(III) center. The electrochemically induced intramolecular electron transfer (IET) results in the formation of the radical-cation at the phenol group, followed by proton abstraction. The analogues IET process was observed previously for  $\pi$ -cyclopentadienyl iron complexes associated with the intramolecular rearrangement of the ligand to metal system [20]. The next reversible one-electron step corresponds to the oxidation of ferrocene moiety at higher potential ( $E_2 = 0.75$  V).

The third oxidation step is associated with a well-known reversible process of one-electron oxidation of phenoxyl radical [21,22] and is observed at  $\sim 1$  V due to the presence of electron-withdrawing ferrocenium substituent. Since X-band EPR spectra of ferrocenium species are observed at cryogenic temperature due to rapid relaxation [16,23] we failed to register the corresponding products formed by in situ EPR spectroscopy.

Redox behavior of compound **2** is analogues. Cyclic voltammogram of **2** (Fig. 3c) shows three redox processes at oxidation potentials slightly shifted ( $\Delta E_1 = 0.16$ ,  $\Delta E_2 = 0.06$ ,  $\Delta E_3 = 0.04$  V, respectively). Second and third reversible oxidation peaks are even more pronounced. Therefore, the presence of –CH<sub>2</sub>– linking group does not prevent the ability of 2,6-di-*tert*-butylphenol to act as an intramolecular electron donor. To confirm the assumption that phenol substituent plays a role of the intramolecular one-electron

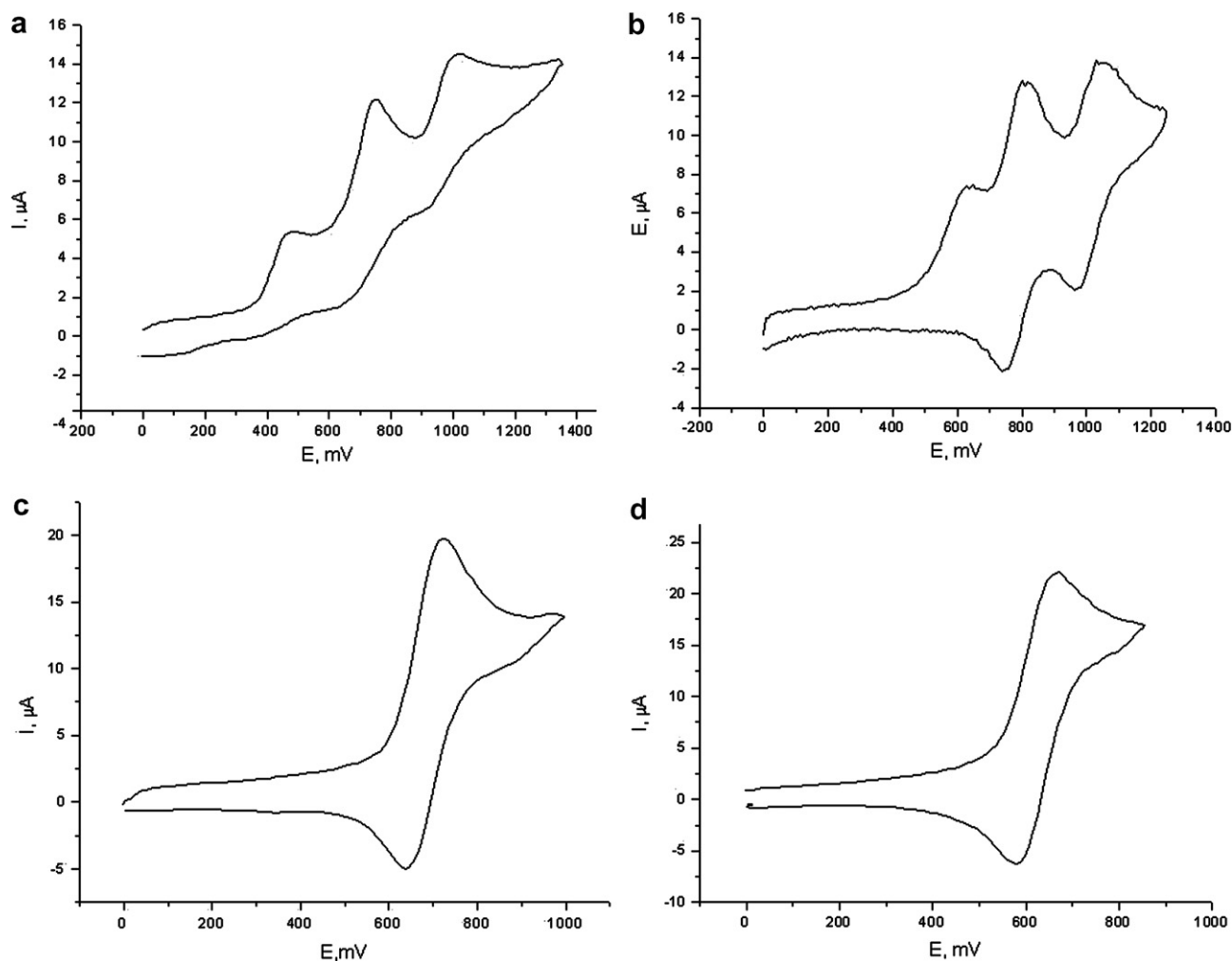
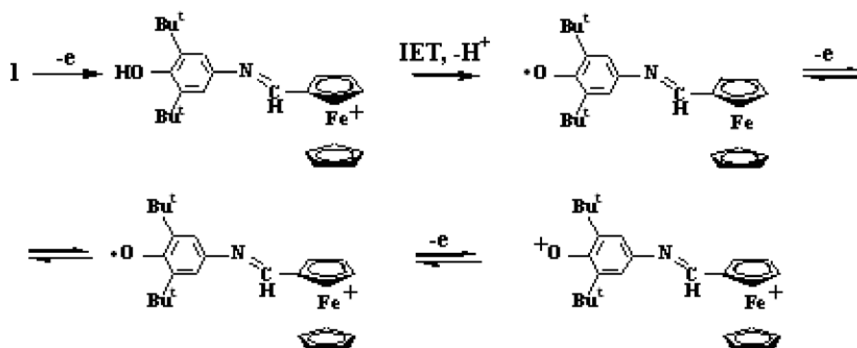


Fig. 3. Cyclic voltammograms of 0.7 mM of **1** (a), **2** (b), **3** (c), and **4** (d) at 293 K. Conditions: Pt, CH<sub>3</sub>CN, 50 mM Bu<sub>4</sub>NBF<sub>4</sub>, vs. Ag/AgCl/KCl, scan rate = 0.1 V s<sup>-1</sup>.



Scheme 3.

donor an additional experiment was carried out. 2,4,6-Tri-*tert*-butylphenol was added to the solution of **3** in CH<sub>3</sub>CN and cyclic voltammogram was recorded. However, no reduction of ferrocenium cation by phenol was observed. Thus, it can be proposed that the role of phenol group in ferrocene redox behavior is associated with the intramolecular effect of one-electron donor.

### 3. Conclusion

The novel ferrocene derivatives with 3,5-di-*tert*-butyl-4-hydroxyphenyl substituents exhibit the properties of multi-step redox systems and may serve as models for the study of intramolecular electron transfer between two redox active sites of the molecule (the phenol and ferrocene groups).

#### 4. Experimental

$\text{CDCl}_3$  (Merck) was used without further purification, other solvents were routinely distilled and dried prior to use. Aniline, benzylamine and ferrocenecarboxaldehyde were obtained commercially (Aldrich), 4-amino-2,6-di-*tert*-butylphenol hydrochloride was prepared according to the known procedure [24]. The  $^1\text{H}$  and  $^{13}\text{C}\{\text{H}\}$  NMR spectra were recorded with a Bruker Avance-400 FT-spectrometer.

IR spectra were recorded with a IR200 (Thermo Nicolet) spectrophotometer in KBr pellets. UV–vis spectra were obtained with a Cary 219 Varian spectrophotometer in  $\text{CHCl}_3$ . EPR spectra were recorded with a Bruker EMX, Bruker ELEXSYS E-500-10/12 spectrometers in the O-band range (9.8 GHz). The measurements were carried out after pre-evacuation of samples solutions (concentration 0.1 mM). The oxidant  $\text{PbO}_2$  (Aldrich) was taken in a tenfold excess. Cyclic voltammetry experiments were performed in  $\text{CH}_3\text{CN}$  solution with 0.05 M  $\text{Bu}_4\text{NBF}_4$  as supporting electrolyte using a model IPC-Win potentiostat. A platinum working electrode, platinum wire auxiliary electrode and aqueous silver/silver chloride reference electrode were used.

##### 4.1. *N*-(3,5-di-*tert*-butyl-4-hydroxyphenyl)-iminomethylferrocene (**1**)

Ferrocenecarboxaldehyde (0.43 g, 2.01 mmol) and 4-amino-2,6-di-*tert*-butylphenol hydrochloride (0.52 g, 2.02 mmol) were dissolved in ethanol (7 ml) and a few drops of  $\text{NEt}_3$  were added. The mixture was stirred for 15 min at room temperature, and then the orange precipitate was filtered off, washed with hexane, and dried in vacuo. Yield of **1** 0.56 g (66%), m.p.: 184–185 °C.

$^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  8.35 (s,  $\text{CH}=\text{N}$ , 1H); 7.05 (s, ArH, 2H); 5.13 (s, ArOH, 1H); 4.81 (s,  $\text{H}_{\text{fer}}$ , 2H); 4.47 (s,  $\text{H}_{\text{fer}}$ , 2H); 4.26 (s,  $\text{C}_5\text{H}_5$ , 5H); 1.50 (s,  $\text{C}(\text{CH}_3)_3$ , 18H).  $^{13}\text{C}$  NMR (101 MHz,  $\text{CDCl}_3$ ):  $\delta$  158.69 (s,  $\text{CH}=\text{N}$ ); 136.66 (s,  $\text{C}-\text{C}(\text{CH}_3)_3$ ); 117.39 (s,  $\text{C}_6\text{H}_2$ ); 70.94 (s,  $\text{C}_5\text{H}_4$ ); 69.64 (s,  $\text{C}_5\text{H}_4$ ); 69.17 (s,  $\text{C}_5\text{H}_5$ ); 68.81 (s,  $\text{C}_5\text{H}_4$ ); 34.47 (s,  $\text{C}(\text{CH}_3)_3$ ); 30.29 (s,  $\text{C}(\text{CH}_3)_3$ ).

Elemental analysis: Anal. Calc. for  $\text{C}_{25}\text{H}_{31}\text{FeNO}$ : C, 71.95; H, 7.49; N, 3.36; Fe 13.42. Found: 71.88; H, 7.49; N, 3.65; Fe 13.28%.

IR (KBr pellet,  $\text{cm}^{-1}$ ):  $\nu(\text{OH})$  3639,  $\nu(\text{CH})$  2870–2958;  $\nu(\text{C}=\text{N})$  1654.

UV–vis,  $\lambda_{\text{max}}$ , nm (ln  $\epsilon$ ): 457 (4.3); 330 (6.9).

##### 4.2. *N*-(3,5-di-*tert*-butyl-4-hydroxybenzyl)-iminomethylferrocene (**2**)

Ferrocenecarboxaldehyde (0.20 g, 0.93 mmol) and 3,5-di-*tert*-butyl-4-hydroxybenzylamine (0.22 g, 0.93 mmol) were dissolved in benzene (15 ml) and the reaction mixture was refluxed for 2 h with the azeotrope distillation of water. The mixture was rotary evaporated. The red-brown solid residue was washed with hexane and dried in vacuo to dryness. Yield of **2** 0.31 g (77%), m.p.: 125–126 °C.

$^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  8.26 (s,  $\text{CH}=\text{N}$ , 1H); 7.13 (s, ArH, 2H); 5.15 (s, ArOH, 1H); 4.70 (s,  $\text{H}_{\text{fer}}$ , 2H); 4.58 (s,  $\text{ArCH}_2$ , 2H); 4.38 (s,  $\text{H}_{\text{fer}}$ , 2H); 4.18 (s,  $\text{C}_5\text{H}_5$ , 5H); 1.47 (s,  $\text{C}(\text{CH}_3)_3$ , 18H).  $^{13}\text{C}$  NMR (101 MHz,  $\text{CDCl}_3$ ):  $\delta$  161.30 (s,  $\text{CH}=\text{N}$ ); 152.90 (s,  $\text{C}_{\text{ar}}-\text{OH}$ ); 135.95 (s,  $\text{C}-\text{C}(\text{CH}_3)_3$ ); 128.35 (s,  $\text{C}_{\text{ar}}-\text{CH}_2$ ); 124.88 (s,  $\text{C}_6\text{H}_2$ ); 73.19 (s,  $\text{C}_5\text{H}_4$ ); 70.38 (s,  $\text{CH}_2$ ); 69.97 (s,  $\text{C}_5\text{H}_4$ ); 69.06 (s,  $\text{C}_5\text{H}_5$ ); 68.61 (s,  $\text{C}_5\text{H}_4$ ); 34.38 (s,  $\text{C}(\text{CH}_3)_3$ ); 30.34 (s,  $\text{C}(\text{CH}_3)_3$ ).

Elemental analysis: Anal. Calc. for  $\text{C}_{26}\text{H}_{33}\text{FeNO}$ : C, 72.39; H, 7.71; N, 3.25; Fe, 12.94. Found: C, 71.56; H, 7.77; N, 3.19; Fe 12.83%.

IR (KBr pellet,  $\text{cm}^{-1}$ ):  $\nu(\text{OH})$  3627,  $\nu(\text{CH})$  2870–2998;  $\nu(\text{C}=\text{N})$  1643.

UV–vis,  $\lambda_{\text{max}}$ , nm (ln  $\epsilon$ ): 448 (6.3); 336 (7.3).

##### 4.3. *N*-phenyl-iminomethylferrocene (**3**)

Ferrocenecarboxaldehyde (0.28 g, 1.3 mmol) and aniline (0.30 g, 1.3 mmol) were dissolved in ethanol (3 ml) and the solution was left at 0 °C for 2 days. The precipitate formed was filtered off, washed with hexane and dried in vacuo to dryness. Yield of **3** 0.25 g (67%), m.p.: 76–77 °C. (m.p.: 77 °C [12]).

##### 4.4. *N*-benzyl-iminomethylferrocene (**4**)

Ferrocenecarboxaldehyde (0.22 g, 1.0 mmol) and benzylamine (0.21 g, 2.0 mmol) were dissolved in benzene (10 ml). The reaction mixture was refluxed for 2 h, and left at room temperature overnight. The reaction mixture was rotary evaporated to dryness. The solid residue was washed with hexane and dried in vacuo. Yield of **4** 0.24 g (77%), m.p.: 105–106 °C. (m.p.: 102 °C [13]).

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