A ferrocenyl–guanidine derivative as a highly selective electrochemical and colorimetric chemosensor molecule for acetate anions

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PAPER

A ferrocenyl-guanidine derivative as a highly selective electrochemical and colorimetric chemosensor molecule for acetate anions†

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A highly preorganized chemosensor molecule **1** based on a ferrocenyl-guanidine decorated with a chromogenic aryl azo moiety recognizes the acetate anion in acetonitrile solution. At first, receptor **1** underwent two-step oxidation events. Initially, oxidation of **1** occurs at the Fe(II) centre (E_p = 440 mV) to form a ferrocenium species, followed by fast electron transfer from the guanidine moiety of the receptor to the Fe(III) centre with concomitant generation of an Fe(II) species with a radical cation centred at the nitrogen atom. In the second step, the radical cation species formed should undergo electrochemical oxidation at higher potential (E_p = 830 mV). This assumption is supported by spectroelectrochemical studies. A remarkable cathodic shift (182 mV) of the ferrocene/ferrocenium oxidation peak (E_p = 440 mV) and a progressive red-shift ($\Delta\lambda$ = 30 nm) of the low energy band are observed in its absorption spectrum upon complexation of receptor **1** with the acetate anion. This change in the absorption spectrum is accompanied by a colour change from yellow to orange, which can be used for the "naked-eye" detection of this anion. Its monoprotonated form is able to selectively sense the less basic Cl^-, Br^-, NO_3^-, and HSO_4^- anions: the oxidation redox peak at E_p = 865 mV is cathodically shifted (107–182 mV).

Introduction

The development of neutral receptors capable of binding and sensing anionic species with biological and environmental interest has emerged recently as a key research theme within the general area of supramolecular chemistry and still constitutes a continuously growing area of research.[1] Among the anions, carboxylate anions are some of the most biochemically important anions because they are present in amino-acids, enzymes, antibodies and metabolic intermediates where they contribute to their biochemical characteristics.[2] Although carboxylates bind strongly to hydrogen-bond donors, their basicity can also lead to deprotonation and decomposition.[3] Within this field, acetate recognition is of particular importance because this anion is a critical component of numerous metabolic processes. Moreover, the rate of acetate production and oxidation has frequently been used as an indicator of organic decomposition in marine sediments.[4] Moreover, this anion is a possible tracer for malignancies and has been extensively investigated in prostate cancer and its metastases.[5] Therefore, recognition and sensing of this biologically functional Y-shaped acetate anion is a matter of increasing interest.[6] Unfortunately, these acetate chemosensors usually also display responses to other basic anions such as dihydrogen phosphate and fluoride, especially the latter.[7]

The design of selective receptors for anions requires that the geometry and basicity of the anion and the nature of the solvent medium be taken into account. Complementarity between the receptor and the anion is clearly crucial in determining selectivity. On the other hand, among the non-covalent interactions used to complex the anionic guest, the hydrogen bonding is particularly interesting. In contrast to merely electrostatic interactions, H-bonds are directional, a feature that allows the design of receptors capable of differentiating between anions with different geometries and hydrogen-bonding requirements. In this context, neutral anion receptors containing hydrogen bond donor groups, such as amides, ureas, thioureas, or synthetic imidazole, indole, carbazole, biindole and indolocarbazole-based receptors have been reported to be widely used in recognizing anions *via* forming H-bonds.[8] On the other hand, the guanidine function, due to its amphoteric nature, has a rich history in biological[9] and bio-inspired molecular recognition.[10] Such a guanidine moiety is present in the arginine side chains and is involved not only in the binding and recognition of ionic substrates but also in maintaining protein tertiary structure. The reason for the noncovalent strong interactions, especially with the oxy-anions, lies in the binding pattern featuring two parallel hydrogen bonds.

Among different types of chemosensors converting the anion recognition in physical recordable signals, colorimetric/chromogenic chemosensors are especially attractive because the anion recognition can be easily monitored by anion-complexation-induced changes in UV-vis absorption spectra, which would

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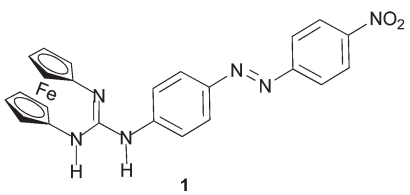
allow the so-called "naked eye" detection of anions, without the use of expensive equipment. Classical colorimetric chemosensors generally contain one or more chromophore groups both directly linked to an anion-binding moiety or through a spacer. The interaction of a special anion with the receptor binding site could affect the optical signals emitted by the chromophore leading to the colour variation of the system.[11] Among organic dyes used as signalling units in the development of chromogenic receptors, azo dyes have been widely used due to their well-known spectroscopic properties.[12] Moreover, such derivatives are also very interesting because they exhibit interesting electronic and optical properties which may be exploited as versatile precursors for the preparation of second harmonic generation chromophores.[13] On the other hand, ferrocene is one of the most favored building blocks in the construction of sensing platforms based on redox-active units due to the availability, stability and tailorability of most of its derivatives. The sensing behavior of these systems is mainly based on the potential shift shown upon their interaction with a variety of guest species. Thus, it is well-established that in ferrocene derivatives, anion binding at an adjacent receptor site induces a negative shift in the redox potential of the ferrocene/ferrocenium redox couple, which can then be used to evaluate the anion recognition properties of such derivatives.[14]

Despite the rich chemistry of guanidines, as the binding site, and ferrocene, as the redox signalling unit, their use as multichannel receptors of ions remains underdeveloped and ferrocenyl-guanidine derivatives are barely known and unexplored.[15] We wish to report here the synthesis of a highly preorganized system **1** and its anion recognition properties, in which a guanidine hydrogen-bond-donor unit is simultaneously linked to an electroactive ferrocene moiety and to an azobenzene-type chromophore, in order to establish the usefulness of both the recognition unit and the electrochemical and chromogenic signalling motifs for recognizing anionic species. 4-Nitrophenyldiazenyl substituents have been appended to the guanidine through a phenyl spacer for the following reasons. (i) Both the azo and *p*-nitrophenyl groups have already been reported as functional groups in molecular sensors.[6i,k,16] (ii) Although azo derivatives are a model of the photochromic compounds, they display enhancement of their chromogenic properties when attached to substituted aromatic rings. As a consequence, the optical properties of the receptor may be altered, following receptor–anion interaction, not only due to the presence of the azo group but also due to the presence of the additional chromogenic nitrophenyl fragment, thus providing a more efficient colorimetric and spectral sensing of the recognition event. (iii) The H-bonding donor ability of N–H groups can be increased by introducing electron-withdrawing substituents. So the presence of an $-NO_2$ group in the aryl azo substituent effectively polarises the N–H groups, thus favouring the formation of stable H-bonded receptor–anion adducts.[3b]



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Block 1

The insertion of a ferrocene subunit with redox characteristics within the guanidine core may represent an important "added value" to this type of receptor, because it could be used not only to bind the substrates but also to signal their presence in solution, thanks to quantifiable changes of its redox and colorimetric properties.

As a consequence, the recognition abilities of receptor **1** towards a set of anions were investigated by electrochemistry, UV-vis spectroscopic measurements, and ^{1}H NMR spectroscopy. Experimentally, it was found that this receptor presents higher selectivity to AcO^- than the other anions investigated.

Results and discussion

Synthesis

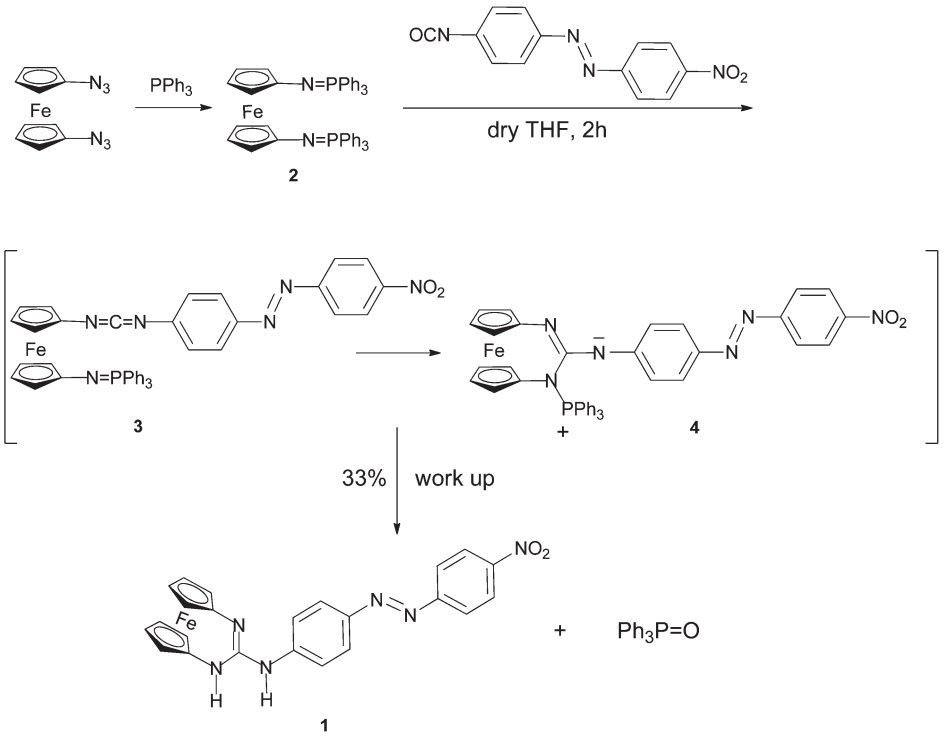
The preparation of receptor **1** was accomplished according to Scheme 1, following the aza-Wittig protocol.[17] Thus, reaction between the bis(iminophosphorane) **2**, readily available from 1,1′-diazidoferrocene and triphenylphosphine,[18] and (*E*)-1-(4-isocyanatophenyl)-2-(4-nitrophenyl)diazene[19] in dry THF at room temperature gave rise to the formation of **1** in moderate yield (33%), which was satisfactorily characterized by ^{1}H- and ^{13}C-NMR, EI MS and elemental analysis. Formation of the guanidine architecture in **1** can be explained by an initial aza-Wittig-type reaction between one iminophosphorane group of **2** and 1 equiv. of the isocyanate to give the carbodiimide **3**, which undergoes cyclization by nucleophilic attack of the nitrogen atom of the remaining iminophosphorane moiety on the central carbon atom of the carbodiimide functionality to give the zwitterionic compound **4**. This compound undergoes hydrolytic cleavage during the work-up to give **1** (Scheme 1). This mechanism is in agreement with previous results obtained from the aza-Wittig reaction of aryl, vinyl bis(iminophosphoranes) with aryl isocyanates substituted with an electron-withdrawing group.[20]

Anion sensing properties

The binding and recognition ability of receptor **1** toward a set of halide anions (F^-, Cl^-, Br^-) and oxoanions (AcO^-, CO_3^{2-}, ClO^-, NO_3^-, HSO_4^-, $H_2PO_4^-$, $HP_2O_7^{3-}$)[21] were evaluated by cyclic (CV) and Osteryoung square-wave voltammetry (OSWV),[22] UV-vis spectroscopic measurements, and ^{1}H NMR spectroscopy.

The CV response of **1** in CH_3CN ($c = 1 \times 10^{-4}$ M), also containing 0.1 M $TBAPF_6$ as the supporting electrolyte, showed a quasi-reversible one-electron oxidation process at E_p = 440 mV *versus* the ferrocenium/ferrocene (Fc^+/Fc) redox couple when the oxidation was carried out in the range of 0–700 mV (see the ESI†). However, working under the same electrochemical conditions but from 0 to 1000 mV, an additional non-reversible oxidation peak at E_p = 830 mV *versus* Fc^+/Fc also appeared (Fig. 1).

These results could be explained through the plausible two step oxidations shown in Scheme 2, previously reported for some amino-containing ferrocene derivatives.[23] Initially, oxidation of **1** occurs (E_p = 440 mV) at the Fe(II) centre to form a ferrocenium species, followed by fast electron transfer from the guanidine moiety of the receptor to the Fe(III) centre with



Scheme 1 Synthesis of receptor **1**.

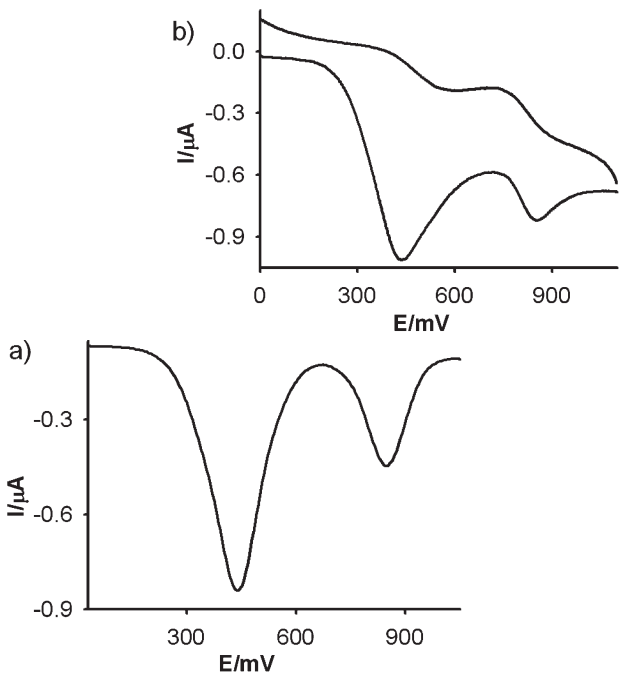
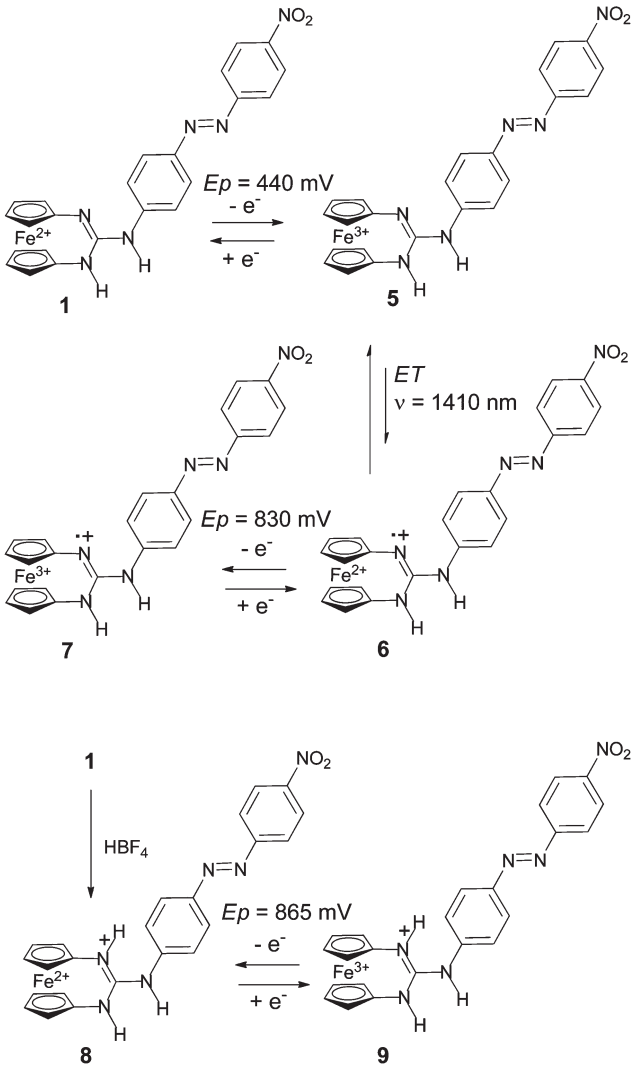


Fig. 1 (a) OSWV and (b) CV, from 0 to 1000 mV of compound **1** ($c = 1 \times 10^{-4}$ M in CH_3CN) using $[(n\text{-}C_4H_9)_4N]PF_6$ (0.1 M) as the supporting electrolyte, scanned at 0.1 V s^{-1}.

concomitant generation of an Fe(II) species and a radical cation centred at the nitrogen atom. The equilibrium between the two oxidized species favoured formation of the ferrocenium derivative. Then, in the second step, the radical cation species formed (**6**) should undergo a second electrochemical oxidation at higher potential (E_p = 830 mV).

This assumption is supported by two facts. (i) The OSWV of the protonated receptor **8**, obtained upon treatment with HBF_4, is almost identical to that of the radical cation **6**; in fact, the OSWV of the protonated species exhibited only an oxidation peak at E_p = 865 mV. (ii) The UV-visible/near infrared (NIR) absorption spectra of the mono-oxidized species, obtained by constant potential electrolysis 0.15 V above the E_p of the ferrocene redox couple, show a new weak band (half-height band width $\Delta\nu_{1/2}$ = 313 cm^{-1}), centred at 1410 nm, associated with the intramolecular electron transfer between the ferrocenium **5** and the radical cation **6**. In fact, when UV-visible/near infrared (NIR) absorption spectra were regularly recorded for different average number ($0 \leq n \leq 1$) of removed electrons such an absorption band increases continuously until complete formation of the mono-oxidized species (Fig. 2). However, on removing two electrons at a constant potential of 1.1 V the intensity of the band decreases until it disappears when the compound is fully oxidized. The appearance of two oxidation peaks has also been found by Plenio *et al.*[24] in other ferrocene derivatives with aminoalkyl substituents at a Cp ligand. As a consequence, a typical electron-transfer band due to the presence of an intramolecular electron-transfer process was also observed.[25]

The recognition ability of receptor **1** towards the above-mentioned set of anions, in the form of their corresponding tetrabutylammonium salts, as well as toward the sodium or potassium hypochlorite anion was evaluated by OSWV.[26] Titration studies with addition of those anions in CH_3CN ($c = 2.5 \times 10^{-2}$ M) to an electrochemical solution of the receptor **1** in the same solvent ($c = 1 \times 10^{-4}$ M) demonstrate that only the addition of AcO^- anions promotes remarkable responses while addition of Cl^-,



Scheme 2 Two step mechanism for explaining the electrochemical behaviour of receptor **1** and the effect of the protonation on the oxidation potential.

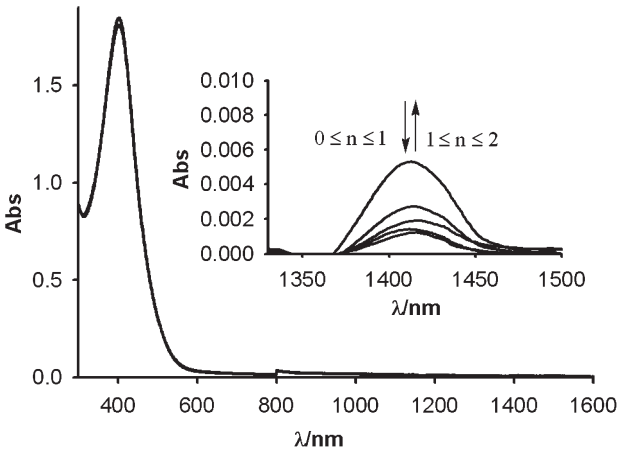


Fig. 2 Evolution of the vis-NIR spectra during the course of the oxidation of compound **1** ($c = 1 \times 10^{-4}$ M) in CH_3CN using $[(n\text{-}C_4H_9)_4N]PF_6$ (0.1 M) as the supporting electrolyte. Inset: near-IR region enlargement, showing the evolution of the spectra upon oxidation by removing from $0 \leq n \leq 1$ to $1 \leq n \leq 2$ electrons. Arrows indicate the increase and decrease of the absorption during the experiment.

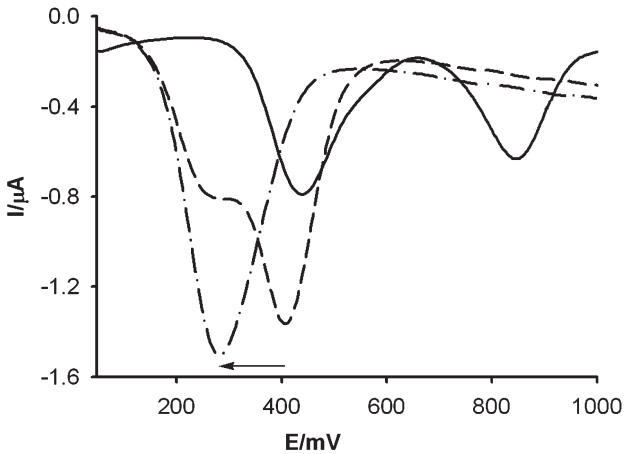


Fig. 3 Evolution of the OSWV of **1** ($c = 1 \times 10^{-4}$ M in CH_3CN), scanned at 0.1 V s^{-1} with $[(n\text{-}Bu)_4N]PF_6$ as the supporting electrolyte (solid line) and upon addition of 1 (dashed line) and 3 equiv. (dashed-dotted line) of AcO^- anions.

Br^-, CO_3^{2-}, NO_3^-, HSO_4^-, $H_2PO_4^-$ and $HP_2O_7^{3-}$ anionic species had no effect on the CV or OSWV of this receptor, even when present in a large excess. It is worth mentioning that addition of increasing amounts of the basic AcO^- anion to the free receptor promotes the complete disappearance of the oxidation peak at E_p = 830 mV. However, typical "two wave behavior" was observed for the evolution of the peak at E_p = 440 mV, which consists in the progressive appearance of a second oxidation peak at more negative potentials (ΔE_p = −182 mV), due to the anion complexed species, together with that corresponding to the free receptor, which completely disappeared when addition of 3 equiv. of anion was achieved (Fig. 3).

Titration with the most basic F^- anion also gave rise to the disappearance of the oxidation wave at E_p = 830 mV and the simultaneous appearance of a new oxidation wave at E_p = 250 mV, cathodically shifted (ΔE_p = −190 mV) with reference to that associated with the free receptor (E_p = 440 mV) (ESI). On the other hand, titration experiments carried out by using aqueous sodium or potassium hypochlorite solutions gave rise to similar behaviour, although the magnitude of the cathodic shift observed (ΔE_p = −55 mV) was significantly smaller than that caused by the more basic fluoride or hydroxide ions (ESI).

It is very well known that in solvents such as DMSO, $CHCl_3$ and CH_3CN deprotonation of the free receptor instead of a recognition process can also take place.[27] A way of solving the deprotonation–coordination dualism and elucidating the nature of the guanidine–anion interaction observed in this case implies to carry out the titration experiments under conditions that suppress the deprotonation process, which could be achieved by adding a small amount of acetic acid to the titration media.[27g,28] In preliminary experiments, we found that addition of up to 20 equiv. of acetic acid did not affect either CV or OSWV of receptor **1**. However, addition of the AcO^- anion to an electrochemical solution of receptor **1** in CH_3CN containing 20 equiv. of

acetic acid induced a cathodic shift of the oxidation peak (ΔE_p = −120 mV) similar to that observed in the absence of acid (ESI). These electrochemical data strongly support that the AcO^- anion induces formation of a hydrogen-bonded complex between receptor **1** and the AcO^- anion. By contrast, when the same experiment was carried out by using the F^- anion, a very different cathodic shift (ΔE_p = −53 mV) with reference to that observed in the absence of acetic acid (ΔE_p = −190 mV) was observed, demonstrating that the electrochemical response observed in the neutral media is only due to a deprotonation effect. Moreover, titrations carried out with the strong base *n*-Bu_4NOH, which definitely leads to deprotonation, induced a remarkable cathodic shift of the oxidation peak of receptor **1** (ΔE_p = −200 mV) of a magnitude similar to that observed in the case of the F^- anion (ΔE_p = −190 mV) (ESI). In connection with this behaviour, it is worth noting that the ΔE_p = −55 mV obtained when the hypochlorite anion was used should not be due to a deprotonation process but to a very slight recognition event, which, on the other hand, was not observed when other titration techniques were employed (ESI). It can be also mentioned that when the titration with ClO^- anion was followed by linear sweep voltammetry (LSV) a shift of the sigmoidal voltammetric wave toward more negative potentials was observed. This behaviour indicates that a recognition process is taking place to some extent and discounts the possibility of the oxidation of the free ligand by the ClO^- anion.[29]

The anion binding ability of receptor **1** has also been examined by UV-vis spectroscopy. Previous studies on ferrocene-based ligands have shown that their characteristic low energy (LE) bands in the absorption spectra are perturbed upon complexation.[30] Moreover, the azobenzene-type chromophore also provides a further advantage, allowing one to monitor complex formation through the distinctive changes of the receptor's absorbance in the UV-vis region. The UV-vis spectrum of receptor **1** in CH_3CN (c = 1 × 10^{-4} M) exhibits strong absorption bands at λ = 230 nm (ε = 14 140 M^{-1} cm^{-1}), 270 nm (ε = 9550 M^{-1} cm^{-1}), and 410 nm (ε = 18 400 M^{-1} cm^{-1}).

Titration experiments for CH_3CN solutions of this ligand (c = 1 × 10^{-4} M), and the corresponding anions in the same solvent (c = 2.5 × 10^{-2} M) were performed and analysed quantitatively.[31] It is worth mentioning that no changes were observed in the UV-vis spectrum of receptor **1** upon addition of Cl^-, Br^-, CO_3^{2-}, ClO^-, NO_3^-, HSO_4^-, $H_2PO_4^-$, and $HP_2O_7^{3-}$ anions, even in a large excess. However, significant modifications were observed upon addition of AcO^- anions. Thus, the addition of increasing amounts of AcO^- ions to a solution of **1** induced a progressive red-shift ($\Delta\lambda$ = 30 nm) of the low energy band from λ = 410 nm to λ = 440 nm (ε = 20 860 M^{-1} cm^{-1}). In this case, the yellow colour of the solution changes to pale orange which can be used for the "naked-eye" detection of this anion. Well-defined isosbestic points at λ = 330 nm and λ = 415 nm indicate that the acetate anion forms only a type of complex occurring as neat interconversion between the uncomplexed and complexed species (Fig. 4). The changes in the absorption spectrum were also found to be reversible upon addition of a competitive hydrogen bonding solvent such as H_2O. Binding assays using the method of continuous variations (Job's plot) suggest a 1 : 1 binding model with a K_a = 3.81 × 10^6 (±0.55) M^{-1}, determined by treatment of the spectrophotometric titration data using the non-linear regression analysis program Specfit/32. Additionally, the calculated detection limit[32] was 7.9 × 10^{-6} M.

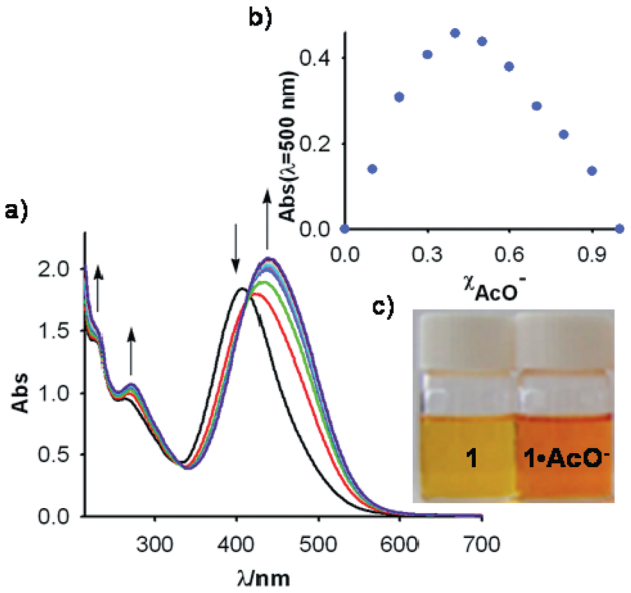


Fig. 4 (a) Variation of the UV-vis of receptor **1** (c = 1 × 10^{-4} M in CH_3CN) upon addition of increasing amounts of AcO^- anions, from 0 to 1.2 equiv. Arrows indicate the absorptions that increase (up) and decrease (down) during the experiments. (b) Job's plot evaluated from the absorption spectra of the titration solution exhibiting the inflection point at 0.5 (formation of a 1 : 1 complex): the total $[\mathbf{4}]^+$ $[AcO^-]$ = 10^{-4} M. (c) Visual changes observed upon acetate complexation.

The stoichiometry proposed was further confirmed by electrospray mass spectrometry. Thus, the ESI-MS spectrum of receptor **1** in the presence of AcO^- anions shows a peak at m/z = 524.9 corresponding to the 1 : 1 complex (Fig. 5). The relative abundance of the isotopic cluster was in good agreement with the simulated spectrum of the $[\mathbf{1}\cdot AcO^-]$ species.

The UV-vis spectral changes observed upon addition of F^- anions are identical to those promoted by addition of Bu_4NOH: the appearance of an additional low-energy band at 630 nm attributable to the deprotonated species, which is responsible for the development of a deep orange-red colour in the solution (ESI).

We have recently reported[15d] a related [3]ferrocenophane derivative in which a *p*-nitrophenyl group is appended to the 2 position of the metallocenophane ring, which allowed the sensing of AcO^-, $PhCO_2^-$, F^-, Cl^-, and Br^- anions through an unusual redox ratiometric method and spectroscopic measurements. However, the presence in **1** of an azophenyl bridge, connecting the *p*-nitrophenyl ring and the amino group linked to the 2 position of the 1,3-diaza-[3]ferrocenophane, offers more interesting properties in terms of selectivity and sensitivity because it can selectively sense the AcO^- anion through a colorimetric channel.

With a view to shedding light on the coordination modes and on the nature of the complexes formed by this ligand with the AcO^- anion, ^{1}H-NMR titration experiments were also performed. Fig. 6 shows the ^{1}H-NMR spectrum of **1** before and after addition of different amounts of AcO^- anions, where CD_3CN was chosen as the titration solvent to afford a

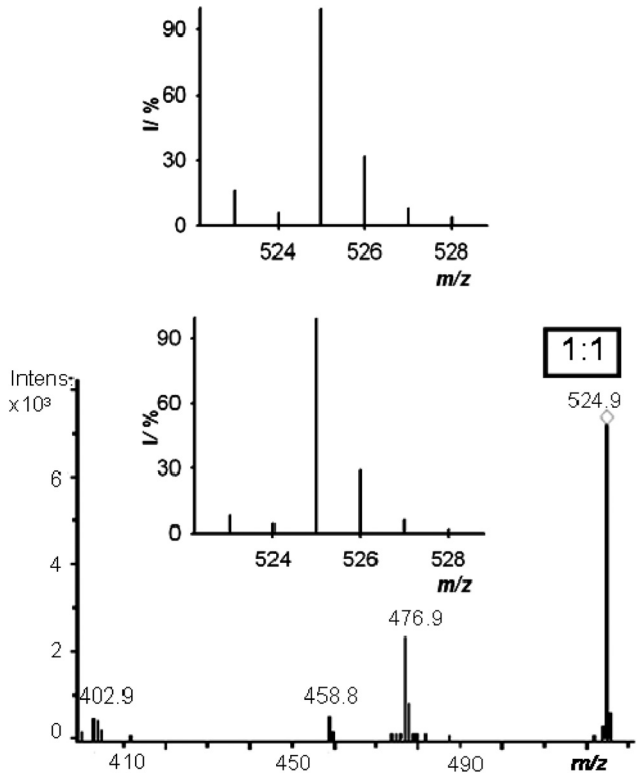


Fig. 5 ESI MS showing the 1 : 1 stoichiometry for the [**1**·AcO$^-$] complex formed. The inset shows the experimental (up) and simulated (down) relative abundance of the isotopic cluster for [**1**·AcO$^-$].

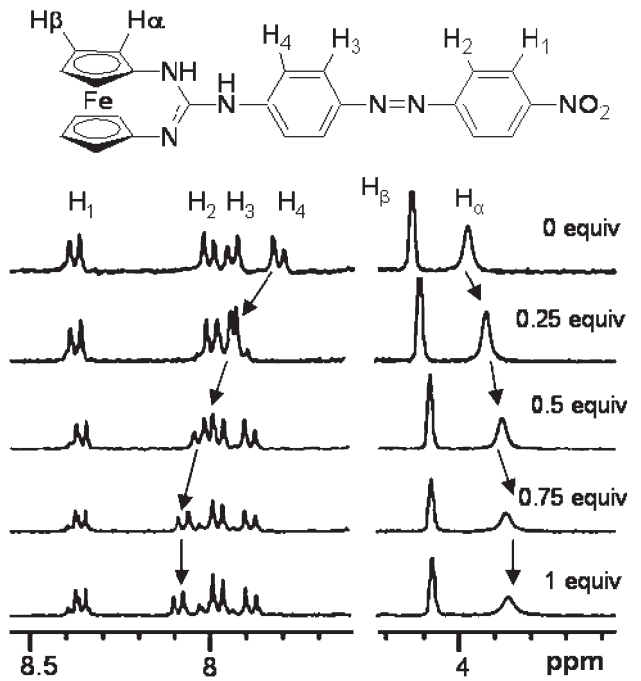


Fig. 6 Evolution of the ^{1}H NMR spectrum of **1** in CD_3CN, upon addition of increasing amounts of AcO$^-$, from 0 to 1 equiv.

concentration suitable for these spectroscopic studies (c = 2.5 × 10^{-2} M). The most significant features of the free ligand **1** are the following: (i) the presence of two sets of double doublets attributed to the two AB systems corresponding to the aromatic *p*-nitrophenyl moiety (H^1, δ = 8.37 ppm and H^2, δ = 8.00 ppm) and to the *p*-disubstituted phenyl ring (H^3, δ = 7.93 ppm and H^4, δ = 7.81 ppm) connecting the guanidine and azo units; (ii) two broad singlets corresponding to the H_α (δ = 3.97 ppm) and H_β (δ = 4.13 ppm) protons within the disubstituted cyclopentadienyl (Cp) units present in the ferrocene unit; (iii) it should be mentioned that the guanidine NH protons are not detected even when the spectrum was recorded up to 15 ppm, probably due to the existence of a fast tautomeric equilibrium.

It can be noticed that acetate complexation leads to a downfield shift of proton H^4 ($\Delta\delta$ = +0.27 ppm) whereas a highfield shift for proton H_α ($\Delta\delta$ = −0.12 ppm) is also observed. The other protons of the receptor were only very slightly affected. Taking into account these anion-induced chemical shift changes, it is plausible to suggest that the guanidine NH protons, placed in the vicinity of such most affected protons, should be involved in the interaction of this anion with the free receptor.

The chemosensor properties of the above mentioned protonated species [**1**·H$^+$] toward the same set of anions were also evaluated by using electrochemical, spectrophotometric and ^{1}H NMR titrations. The results obtained demonstrate that basic anions such as AcO$^-$, $H_2PO_4^-$ and $HP_2O_7^{3-}$ only promote the deprotonation of the [**1**·H$^+$] receptor. Thus, the characteristic oxidation peak at E_p = 865 mV in the OSWV evolves to the appearance of two peaks at the same oxidation potential as that observed in the deprotonated receptor **1** (ESI). Similarly, in the UV-vis and ^{1}H NMR titrations, the common features observed upon addition of these basic anions to the [**1**·H$^+$] receptor are the recovery of the corresponding spectra of the free receptor **1** (ESI).

By contrast, the less basic anions (Cl$^-$, Br$^-$, NO_3^- and HSO_4^-) are recognized by the [**1**·H$^+$] species. Thus, the oxidation peak at E_p = 865 mV in the OSWV is cathodically shifted in a magnitude ranging from ΔE = −107 mV (NO_3^- and HSO_4^-) to ΔE = −182 mV (Br$^-$) (Table 1 in the ESI†). On the other hand, the conversion of **1** into [**1**·H$^+$] results in a hypsochromic shift (λ = 344 nm, $\Delta\lambda$ = 66 nm) of the band appearing in the free ligand at λ = 410 nm; however, upon addition of these anions such a band (λ = 344 nm) undergoes a very slight bathochromic shift ranging from $\Delta\lambda$ = 6 nm (Br$^-$ and NO_3^-) to $\Delta\lambda$ = 8 nm (Cl$^-$ and HSO_4^-). The isosbestic points observed were indicative of the transition between the unbound and anion-complexed species (Table 1 in ESI†). Accordingly, the titration profiles could be fitted to a 1 : 1 model in the case of Br$^-$, NO_3^- and HSO_4^- and to 1 : 2 (receptor : anion) in the case of Cl$^-$, with the binding constant values shown in Table 1 in the ESI.† Moreover, the stoichiometries of the complexes formed have been further supported based on the molecular ion peaks observed in ESI MS titrations. The isotopic peak pattern provides an unambiguous assignment to these peaks by confirming the presence of such anions in the corresponding complexes (ESI).

Anion-induced chemical shift changes in the ^{1}H NMR spectra of [**1**·H$^+$] also support both the deprotonation (AcO$^-$, $H_2PO_4^-$ and $HP_2O_7^{3-}$) and recognition (Cl$^-$, Br$^-$, NO_3^- and HSO_4^-) processes previously described. ^{1}H NMR spectra of [**1**·H$^+$] are characterized by a pattern of signals identical to that described for the free receptor **1**, although in this case the chemical shifts of all protons on the two aromatic rings and the ferrocenyl unit

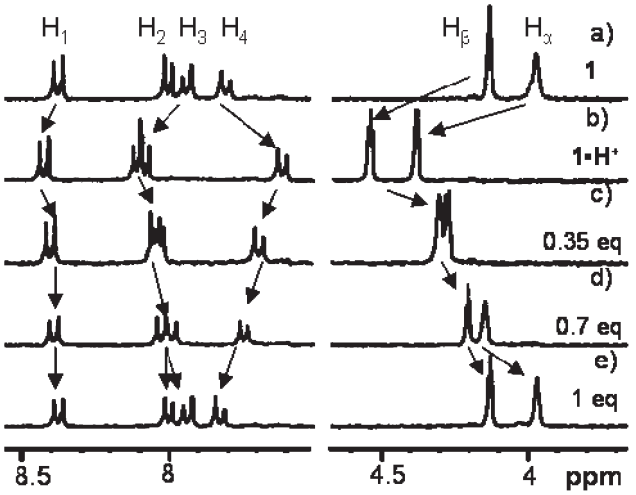


Fig. 7 Evolution of the ^{1}H NMR spectrum of **1** in CD_3CN (a), upon addition of 1 equiv. HBF_4 (b), and upon addition of increasing amounts of AcO^-, from 0.35 (c) to 1 equiv. (e), to the $[\mathbf{1}\cdot H]^+$ species showing the deprotonation effect promoted by the AcO^- on the protonated receptor.

are quite different. In general, all signals are downfield shifted except that corresponding to the protons placed at the *ortho* position to the guanidine substituent of the central phenyl group which is significantly upfield shifted ($\Delta\delta_{Hortho} = -0.20$ ppm). It is worth noting the significant downfield shift observed for the protons H_α ($\Delta\delta = 0.40$ ppm) and H_β ($\Delta\delta = 0.41$ ppm) of the ferrocenyl moiety as a consequence of the protonation on the guanidine bridge in **1** (Fig. 7).

Regarding the evaluation of the anion sensing properties of $[\mathbf{1}\cdot H^+]$ it should be commented that the registered ^{1}H NMR spectra upon addition of AcO^-, $H_2PO_4^-$ and $HP_2O_7^{3-}$ to a CD_3CN solution of $[\mathbf{1}\cdot H^+]$ were absolutely coincident with the spectrum of the free receptor **1**, demonstrating that deprotonation of $[\mathbf{1}\cdot H^+]$ is the dominant process taking place (Fig. 7). However, the same titration experiments performed using Cl^-, Br^-, NO_3^- and HSO_4^- anions did not produce such changes in the ^{1}H NMR of $[\mathbf{1}\cdot H^+]$, which remains almost unchanged. The only significant and general feature in these cases is the gradual appearance downfield of two different singlets attributed to the NH of the guanidine group.

Conclusion

We have prepared a highly preorganized system **1**, in which we combine the redox activity of the ferrocene unit with the chromogenic behaviour of the aryl azo functionality and the binding ability of the guanidine group, and examined its binding properties towards various guest anions using electrochemical, spectral and optical techniques. The guanidine derivative receptor **1** exhibits high binding affinity and sensitivity for the Y-shaped acetate anion in acetonitrile through a dual channel, electrochemical and chromogenic: the oxidation redox peak of the Fe(II)/Fe(III) couple is remarkably cathodically shifted ($\Delta E_p = -182$ mV) and the low energy band of the absorption spectrum is red-shifted ($\Delta\lambda = 30$ nm) upon complexation with this anion. This bathochromic shift gives rise to major colour changes from yellow to orange that are clearly visible to the naked eye. Its monoprotonated form is able to selectively sense the less basic Cl^-, Br^-, NO_3^-, and HSO_4^- anions: the oxidation redox peak at $E_p = 865$ mV is cathodically shifted (107–182 mV) and the low energy band of the absorption spectrum is red-shifted ($\Delta\lambda = 6$–8 nm) upon complexation.

Experimental

General methods

All reactions were carried out using solvents that were dried by routine procedures. The melting point was determined on a Kofler hot-plate melting point apparatus and is uncorrected. UV-vis-near IR spectra were taken on a Varian Cary 5000 spectrophotometer. ^{1}H and ^{13}C NMR spectra were recorded on Bruker 200 or 300 MHz spectrometers. Chemical shifts refer to signals of tetramethylsilane (TMS). The following abbreviations for stating the multiplicity of the signals have been used: d (doublet), st (pseudotriplet), q (quaternary carbon). The electron impact (EI) and electrospray (ESI) mass spectra were recorded on a Fisons AUTOSPEC 500 VG spectrometer. Microanalyses were performed on a Carlo-Erba 1108 instrument. The cyclic voltammetric measurements were performed on a QUICELTRON potentiostat/galvanostat controlled by a personal computer and driven by dedicated software. The cyclic voltammograms were recorded at a scan rate increasing from 0.05 to 1.00 V s^{-1}, while the OSWV were recorded at a scan rate of 100 mV s^{-1} with a pulse height of 10 mV and a step time of 50 ms. Deoxygenation of the solutions was achieved by bubbling nitrogen for at least 10 min and the working electrode was cleaned after each run. Typically, receptor (10^{-4} M) was dissolved in CH_3CN (5 mL) and the guest under investigation was then added as a 2.5×10^{-2} M solution in the same solvent using a microsyringe whilst the cyclic voltammetric properties of the solution were monitored. Ferrocene was used as an external and/or internal reference both for potential calibration and for reversibility criteria. Under similar conditions the Fc has $E = 0.39$ V *vs.* SCE and the anodic–cathodic peak separation is 67 mV.

Synthesis of 2{(*E*)-4-[2-(4-nitrophenyl)diazenyl]}phenylamino-1,3-diaza[3]ferrocenophane 1. To a solution of 4-isocyanate-4′-nitroazobenzene[18] (0.2 g, 0.74 mmol) in dry CH_2Cl_2 (15 mL) a solution of 1,1′-bis(triphenylphosphoranylidenamino)ferrocene[17] (0.2 g, 0.27 mmol) in dry THF (10 mL) was added dropwise and the solution was stirred for 2 h at room temperature. The solvent was removed under vacuum to give a residue which was chromatographed on a silica-gel column using ethyl acetate–*n*-hexane (1 : 1) as an eluent to give **1** in 33% yield, which was further crystallized from CH_2Cl_2–Et_2O (1 : 2). Mp: 160–162 °C (d). Found: C, 59.52; H, 3.60; N, 17.79. Calc. for $C_{23}H_{18}FeN_6O_2$: C, 59.25; H, 3.89; N, 18.02%. δ_H (200 MHz, $CDCl_3$) 4.17 (2H, st, Fc), 4.20 (2H, st, Fc), 7.46 (2H, d, J = 8.4 Hz), 7.95 (2H, d, J = 8.4 Hz), 7.99 (2H, d, J = 9.0 Hz), 8.35 (2H, d, J = 9.0 Hz). δ_H (300 MHz, CD_3CN) 3.97 (2H, st, Fc), 4.13 (2H, st, Fc), 7.81 (2H, d, J = 8.4 Hz), 7.93 (2H, d, J = 8.4 Hz), 8.00 (2H, d, J = 9.0 Hz), 8.37 (2H, d, J = 9.0 Hz); δ_C (50 MHz, $CDCl_3$) 68.4 (2 × CH, Fc), 70.2 (2 × CH, Fc), 91.6 (q, Fc), 122.1 (2 × CH), 123.3 (2 × CH), 124.7 (2 × CH), 125.3

(2 × CH), 143.4 (q), 148.4 (q), 148.6 (q), 155.7 (q), 156.2 (q). *m/z* (EI) 466 (M^+, 18), 316 (10), 149 (76), 91 (100).

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