Synthesis and Electrochemical Polymerisation of Calix[4]pyrroles Containing *N*-substituted Pyrrole Moieties

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Synthesis and Electrochemical Polymerisation of Calix[4]pyrroles Containing N-substituted Pyrrole Moieties

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The first examples of the synthesis of calix[4]pyrroles containing pendant N-substituted pyrrole moieties (in the *meso-* (2) and *β-* (1) positions) is reported. Attempts at the production of electropolymerised films containing (1) or (2) alone failed, however the electrochemical co-polymerisation of (1) and pyrrole and (2) and pyrrole has been achieved.

Keywords: Electropolymerisation; Calix[4]pyrrole; Polypyrrole; Modified electrode

INTRODUCTION

Calix[4]pyrroles (or *meso*-octalkylporphyrinogens) are a venerable class of macrocycle, first synthesised in 1886 by Baeyer [1] that have recently attracted much attention recently due to their interesting coordination properties. Floriani and co-workers have demonstrated that deprotonated calix[4]pyrroles act as ligands for various transition metals and shown that these transition metal complexes undergo oxidation to 'artificial porphyrin' structures [2] whilst Sessler and co-workers have shown that the array of pyrrolic NH groups present in these systems is capable of coordinating to anionic [3–5] and to a lesser extent neutral guest species [6].

In order to harness these macrocycles for uses in the field of chemical sensor technology it is advantageous to immobilise them onto an electrode surface. One way of doing this is by the production of an electropolymerised matrix consisting of the macrocycle bound to an electropolymerised moiety. In this note we report the synthesis of two new calix[4]pyrrole-N-substituted pyrrole conjugate compounds together with their electropolymerisation properties.

RESULTS AND DISCUSSION

Synthesis

Compounds **1** and **2** were synthesised by analogous methods (Scheme 1). The

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(a)

(b)
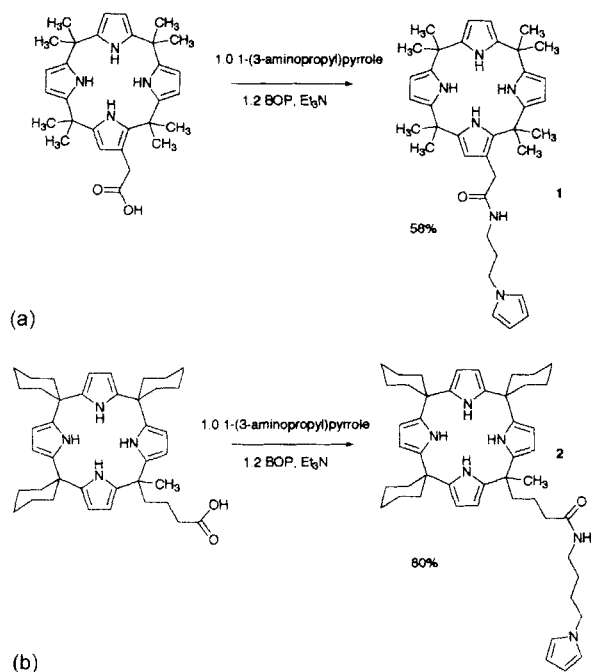
SCHEME 1   Synthesis of compounds 1 and 2.

meso-octamethylcalix[4]pyrrole-*β*-mono-acid [5] or *meso*-trispirocyclohexylcalix[4]pyrrole-*meso*-monoacid [4] and 3-aminopropylpyrrole were dissolved in 10ml of dry DMF. 1.2 Equivalents of benzotriazol-1-yloxy-tris(dimethylamino)phosphonium hexafluorophosphate (BOP) and an excess of Et_3N were added and the mixture was stirred in the dark for 3 days. The DMF was removed *in vacuo* and the residue purified by column chromatography on a silica column, eluting with CH_2Cl_2/MeOH.

Anion Complexation

The anion coordination properties of monomers 1 and 2 were studied using ^1H NMR titration techniques. In a typical experiment 5×10^{-6} mol of the receptor was dissolved in 0.5 ml acetonitrile-d_3 and shifts in the NH proton resonance sample were followed as a solution of the anion tetrabutylammonium salt was added. The stability constants of the receptor-anion complexes could then be found by fitting the shift of the NH proton resonance to a standard 1:1 host: guest binding model using the computer program EQNMR [7]. The results of this fitting procedure are shown in Table I and reveal that both receptors 1 and 2 form strong complexes with a variety of halide anions as well as dihydrogen phosphate in acetonitrile-d_3.

Electropolymerisation

Initial attempts to polymerise 1 or 2 alone were made using cyclic voltammetric (potential cycling) methods. Figures 1(a) and (b) show the first seven cyclic voltammograms obtained from consecutive potential cycling of acetonitrile solutions containing compounds 1 or 2 (5×10^{-4} mol dm^{-3}) between -1.0 V and $+0.9$ V vs. Ag/Ag^+. Within the applied anodic potential limit, the oxidation of the monomer 1 or 2 is characterised by two distinct irreversible electron transfer processes: one forms a small peak at about 0.45 V and another starts at about 0.6 V

TABLE I   Stability constants for compounds 1 and 2 with various anions measured in acetonitrile-d_3 at 25°C

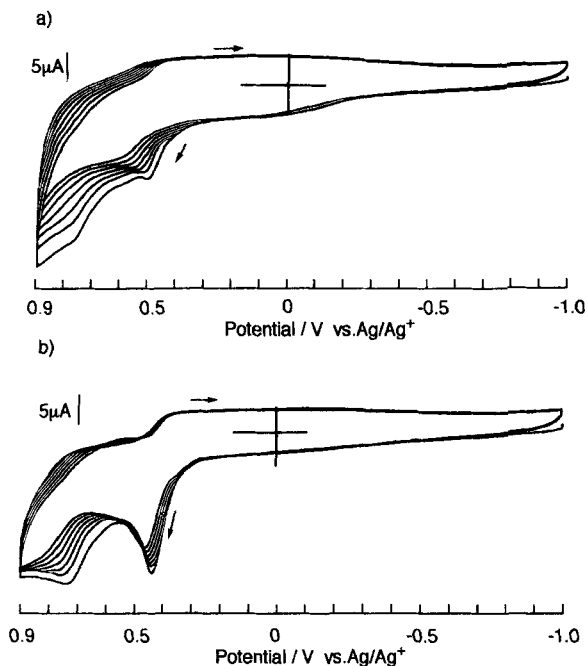| Anion	Stability constant (M^{-1}) with compound 2	Stability constant (M^{-1}) with compound 1
F^-	$> 10^4$	$> 10^4$
Cl^-	$> 10^4$	$> 10^4$
Br^-	174 ± 9	$> 10^4$
I^-	< 20	87 ± 12
NO_3^-	< 20	142 ± 28
HSO_4^-	< 20	199 ± 10
$H_2PO_4^-$	1120 ± 55	$> 10^4$
ReO_4^-	< 20	< 20

a)

b)

FIGURE 1   Consecutive CVs (a) of **1** $(5 \times 10^{-4}\,\mathrm{mol\,dm^{-3}})$ in CH_3CN solution cycled between $-1.0\,V$ and $+\,0.9\,V$ vs. Ag/ Ag^+ and (b) of **2** $(5 \times 10^{-4}\,\mathrm{mol\,dm^{-3}})$ in CH_3CN solution cycled between $-1.0\,V$ and $+0.9\,V$ vs. Ag/Ag^+, scan rate $50\,\mathrm{mVs^{-1}}$.

and gives rise to a sharp increase in current. While the sharp current increase obviously results from the oxidation of the N-substituted pyrrole, it is reasonable to attribute the small current peak to the oxidation of the calixpyrrole moiety [8].

Unfortunately, continuous potential cycling did not result in the growth of a conducting polymer film *i.e.*, increasing of current waves before the monomer oxidation with the number of cycles were not observed. Instead, the current

of both forward and backward potential scans decreases with each consecutive cycle as shown in Figures 1a and 1b. Attempts to use controlled potential electrolysis to grow the film also failed. While these results demonstrate the difficulty in the growing of the film, steric interactions may be responsible, as is often the case for large molecules with N-substituted pyrrole moieties.

In order to relieve these potential steric interactions, polymerisation of the calixpyrrole monomers was attempted in the presence of pyrrole. If steric interactions were preventing the formation of the polymer, the pyrrole may act as a spacer, increasing the distance between the calixpyrrole macrocycles in the film and allowing polymerization to occur (Scheme 2) [9]. The CVs recorded during potential cycling in a mixed solution of 1 + pyrrole and 2 + pyrrole respectively are shown in Figures 2a and 2b respectively. These voltammograms are indicative of the growth of a conducting polymer matrix (an increasing current is observed for each consecutive scan). In addition to this, a current shoulder was observed at 0.45 V, just before the sharp current increase corresponding to the oxidation of pyrrole, giving strong evidence of the participation of the calixpyrrole in the polymerisation process.

To confirm that co-polymerisation of pyrrole and calixpyrrole has occurred, the CVs of the copolymer were compared to those obtained from a solution of simple pyrrole, see Figure 3. Interestingly, it was found that the current at a given potential within the polymer redox region $(-0.2\,V$ to $0.6\,V)$ increases linearly with the
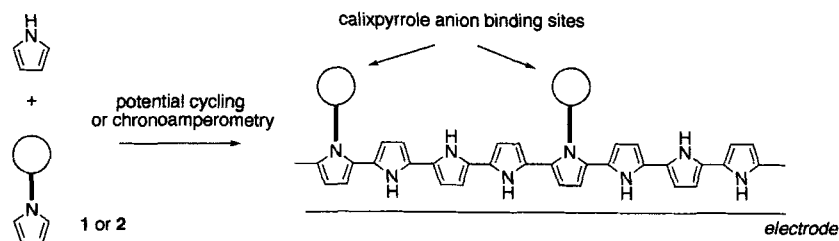
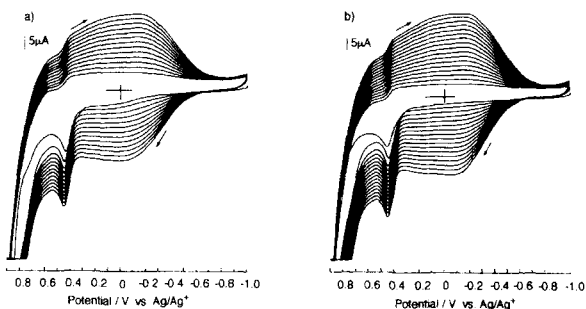SCHEME 2   Formation of a pyrrole–calixpyrrole copolymer.

FIGURE 2 Consecutive CVs of (a) 5×10^{-4} mol dm^{-3} **1** and 5.0×10^{-4} mol dm^{-3} pyrrole and (b) 5×10^{-4} mol dm^{-3} **2** and 5.0×10^{-4} mol dm^{-3} pyrrole in CH$_3$CN, scan rate 50 mVs^{-1}.
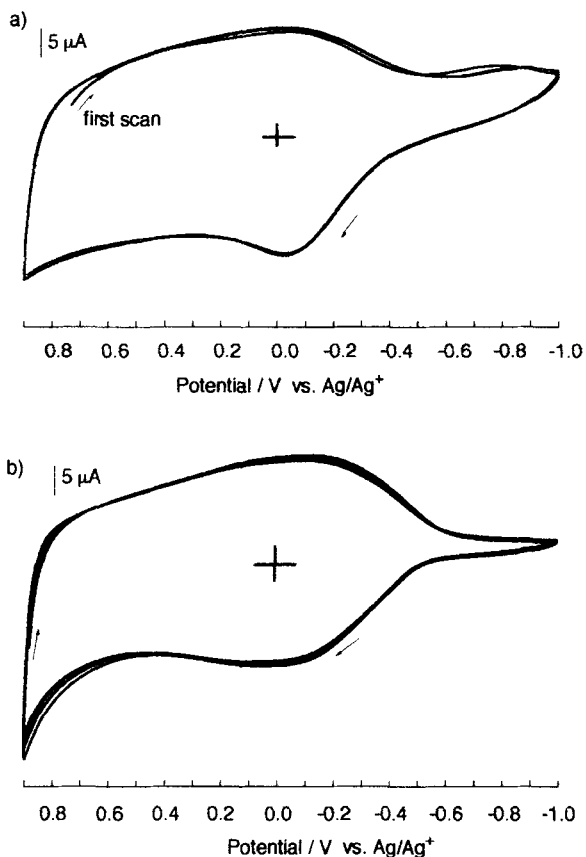

FIGURE 3 (a) CVs of polypyrrole and (b) the co-polymer film of compound **1** and pyrrole in CH$_3$CN, scan rate = 50 mVs^{-1}.

FIGURE 4 (a) Polymer oxidation current at 0.0 V against the number of potential cycles for pyrrole $(5 \times 10^{-4}$ mol dm$^{-3})$, pyrrole $(5 \times 10^{-4}$ mol dm$^{-3})$ + compound **1** $(5 \times 10^{-4}$ mol dm$^{-3})$ and pyrrole $(5 \times 10^{-4}$ mol dm$^{-3})$ + compound **2** $(5 \times 10^{-4}$ mol dm$^{-3})$ recorded in CH$_3$CN, scan rate 50 mVs^{-1} (b) Current-potential curves for the oxidation of mixtures of **1** or **2** with pyrrole and pyrrole alone.

number of potential cycles. Figure 4a plots such an example and demonstrates again the contribution of calixpyrrole to the polymerisation process.
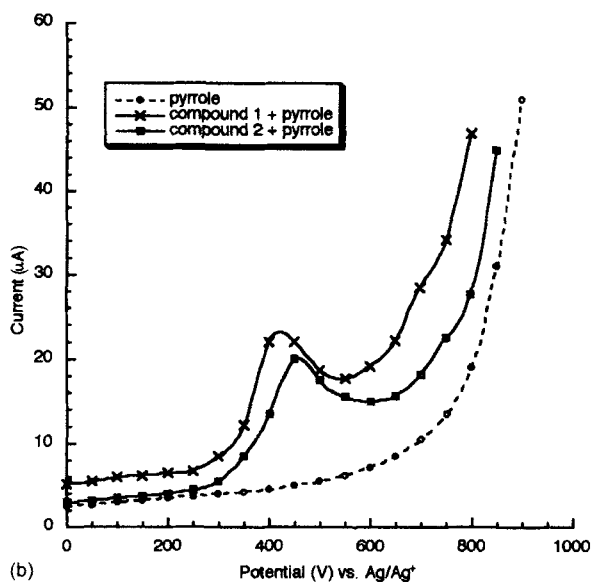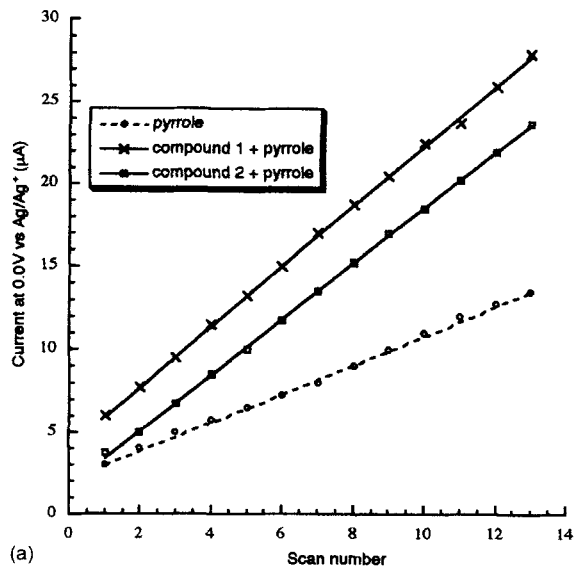
The anodic branches of the first cycle CV in pyrrole alone and the mixtures are shown in Figure 4b. Again, it can be seen that throughout

the scan the oxidation current of the mixture is greater than that of simple pyrrole alone.

Because the concentration of pyrrole in both solutions are identical, the higher initial oxidation current and the faster current increase with the number of cycles must have resulted from the participation of calixpyrrole in the polymerisation process. In other words, the CVs recorded from the mixture of pyrrole and calixpyrrole are the results of the co-polymerisation of the monomers.

After transfer the co-polymer coated electrode into the background electrolyte, the current peaks corresponding to the polypyrrole redox process are broader and less hysteresis-like than those observed in simple polypyrrole, indicating that different pyrrole units are present in the polymer chain [9]. On the other hand, the current peak corresponding to the oxidation of the monomeric calixpyrrole is almost completely obscured but still visible. This is not unexpected on the basis of previously published work on the electrochemistry of calixpyrroles [8]. It appears that oxidation of the calixpyrrole follows an EC mechanism, i.e., the electron transfer is followed by a chemical process that hinders the reduction of the oxidised macrocycle. This chemical process may be the formation of an ion pair between the oxidised calixpyrrole and the anions of the supporting electrolyte. Therefore the polymerised calixpyrrole could not undergo any electron transfer reaction at least within the explored potential window.

To investigate the use of this co-polymer film in sensing anions, the modified electrodes coated with simple polypyrrole or the co-polymer were immersed in solutions of supporting electrolyte (0.1 M) containing tetrabutylammonium salts of various anions at concentrations at least an order of magnitude lower than the supporting electrolyte.

For simple polypyrrole, when the electrode was immersed in a solution of the electrolyte containing tetrabutylammonium fluoride $(5 \times 10^{-4} \, M)$ the polymer redox waves shifted
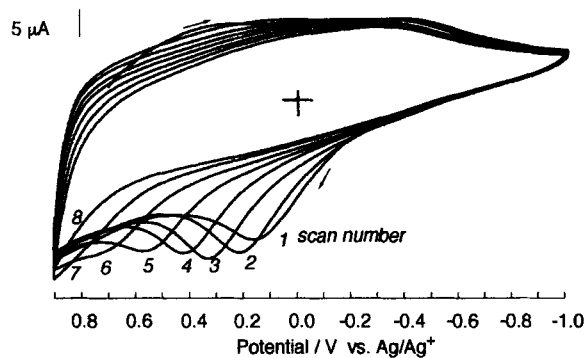

FIGURE 5 Consecutive potential scans for a polypyrrole film immersed in an acetonitrile solution containing $0.1 \, mol \, dm^{-3}$ n-Bu$_4$NBF$_4$ and $5 \times 10^{-4} \, mol \, dm^{-3}$ n-Bu$_4$NF, scan rate $50 \, mVs^{-1}$.

continuously to more positive potentials with the number of cycles (Fig. 5). At higher concentrations (0.1 M fluoride) the recorded CV showed no redox response. Similar behaviour was observed with dihydrogen phosphate and bromide but with a considerably smaller shift in the redox waves for each consecutive potential cycle. In previous work the anion effect was only studied in single anion solutions [10]. These studies produced stable CVs that did not change upon consecutive cycling. The same anion effect was observed in the co-polymer films of 1-pyrrole and 2-pyrrole. This effect masks any perturbation due to the formation of calixpyrrole anion complexes on the cyclic voltammogram.

CONCLUSIONS

Compounds 1 and 2 are the first examples of an electrochemically polymerisable calix[4]pyrrole containing N-substituted pyrrole moietiesand co-polymer films of 1 and pyrrole or 2 and pyrrole have been successfully produced. The polypyrrole anion effect has made it impossible to study the anion coordination properties of the immobilised calixpyrroles using voltammetric methods. Investigations of the co-polymer films are underway by other methods including spectroscopic, potentiometric and impedance

techniques. The results of these studies will be reported in due course.

EXPERIMENTAL

Compound (1): meso-octamethylcalix[4]pyrrole-β-mono-acid (298 mg, 0.612 mmol), 3-aminopropylpyrrole [11] (76 mg, 0.612 mmol), BOP (324 mg, 0.734 mmol) and Et$_3$N (149 mg, 1.468 mmol). Compound 1 was produced as a white foam (210 mg, 58% yield). ^{1}H NMR (300 MHz, CDCl$_3$); δ = 8.33 (s, 1H, NH(cp)), 7.59 (s, 1H, NH(cp)), 6.98 (1H, NH(cp)), 6.63 (d, 2H, CH(α free py)), 5.90–5.82 (m, 6H, CH(cp)), 5.66 (d, 1H, CH(cp)), 5.44 (t, 1H, NH(amide)), 3.94 (t, 2H, —NHCH$_2$—), 3.42 (s, 2H, —CH$_2$—CONH—), 3.32 (q, 2H, CH$_2$CH$_2$CH—), 1.97 (t, 2H, —NHCH$_2$CH$_2$CH$_2$—), 1.57–1.42 (m, 24H, CH$_3$(cp)).

^{13}C NMR (500 MHz, CDCl$_3$); δ: 173.1, 160.6, 139.2, 139.1, 138.6, 138.5, 138.3, 137.9, 137.2, 133.9, 124.6, 120.4, 109.8, 108.6, 106.6, 103.1, 103.0, 102.7, 102.4, 102.0, 47.5, 37.4, 35.6, 35.3, 31.3, 29.2, 29.1, 28.9, 28.7.

ESMS$^+$ C$_{37}$H$_{48}$N$_6$ONa$^+$ @ 615.38.

Microanalysis calcd. For C$_{37}$H$_{48}$N$_6$O–CH$_2$Cl$_2$ C, 67.34%; H, 7.44%, N, 12.40%. Found C, 67.30%; H, 7.11%; N, 12.32%.

Compound (2): meso-trispirocyclohexylcalix[4]pyrrole-meso-monoacid (140 mg, 0.209 mmol), 3-aminopropylpyrrole [11] (26 mg, 0.209 mmol), BOP (111 mg, 0.251 mmol) and Et$_3$N (49 mg, 0.484 mmol). Compound 2 was produced as a white foam (131 mg, 80% yield).

^{1}H NMR (500 MHz, CDCl$_3$); δ = 7.08 (s, 2H, NH(calixpyrrole)), 7.04 (s, 2H, NH(calixpyrrole)), 6.65 (d, 2H, NH(α free py)), 6.15 (d, 2H, NH(α free py)), 5.91 (br.s, 4H, 4CH(cp, py)), 5.88 (s, 4H, 4CH(cp, py)), 5.03 (s, 1H, NH(amide), 3.92 (t, 2H, CH$_2$), 3.20 (m, 2H, CH$_2$), 1.90 (m, 16H, 6CH$_2$(cyclohexyl), 2CH$_2$), 1.78 (m, 2H, CH$_2$), 1.46–1.19 (m, 23H, 9CH$_2$(cyclohexyl), CH$_2$, CH$_3$).

^{13}C NMR (500 MHz, CDCl$_3$); δ: 172.7, 137.1, 136.5, 136.3, 136.2, 120.4, 108.6, 103.6, 103.5, 103.2, 47.8, 39.8, 39.6, 39.4, 38.5, 37.2, 37.0, 36.5, 31.4, 31.2, 26.0, 25.9, 22.7, 22.6, 20.5.

ESMS$^+$ C$_{47}$H$_{62}$N$_6$ONa$^+$ @ 749.51

Microanalysis calcd. For C$_{47}$H$_{62}$N$_6$O–0.5CH$_2$Cl$_2$ C, 74.14%; H, 8.25%, N, 10.92%. Found C, 74.52%; H, 8.54%; N, 10.65%.

An EG&G 273 Potentio-/Galvanostat and a conventional three-electrode-one-compartment system, composed of a 5.0 mm diameter glassy carbon disk working, a Ag/Ag$^+$ $(1.0 \times 10^{-3}$ mol dm^{-3} AgNO$_3$/CH$_3$CN, 330 ± 10 mV vs. SCE) reference and a platinum gauze counter electrodes, were used to perform all the electrochemical experiments. Acetonitrile (CH$_3$CN) solutions were used for electropolymerisation, containing $0.1 \sim 0.2$ mol dm^{-3} NBu$_4$BF$_4$ as supporting electrolyte and $0.5 \sim 10.0$ mmol dm^{-3} monomer, either pyrrole or L or a mixture of the two. Cyclic voltammetric methods were employed for electropolymerisation studies with the starting potential ranging of -1.00 V vs. Ag/Ag$^+$ and the anodic limit potential from 0.90 to 1.10 V. Preliminary voltammetric investigations of the obtained polymer film coated electrode by cyclic voltammetry were conducted in the background solution, composed of 0.1 mol dm^{-3} n-Bu$_4$NBF$_4$ in CH$_3$CN. All experiments were conducted at 21°C under an argon atmosphere.

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