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## A ditopic calix[4]pyrrole amide derivative: highlighting the importance of fundamental studies and the use of NaPh<sub>4</sub>B as additive in the design and applications of mercury(II) ion selective electrodes†

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The use of calixpyrroles as cation monitoring systems is very limited. The importance of fundamental studies for providing the basis for the selection of an appropriate ionophore for use in the design of ion selective electrodes cannot be overemphasised. Thus a new ditopic receptor, namely *meso*-tetramethyl-tetrakis-(4*N,N*-diethylacetamide) phenoxymethylcalix[4]pyrrole (CPA), bearing cation and anion recognition sites has been synthesized and characterized using NMR measurements in acetonitrile. This new receptor interacts with Ca(II), Sr(II), Ba(II), Pb(II) and Cd(II) perchlorate salts and Hg(II) (nitrate as counter-ion). Among the cations tested, 1 : 1 complexes were found between CPA and the above mentioned cations except Hg(II) for which a 1 : 2 (ligand : metal cation) complex is found. These fundamental studies provided the basis for the design of a Hg(II) ion selective electrode (ISE). A detailed investigation on possible interactions between the analyte and the individual components of the membrane in solution as well as in membranes prepared in the absence of the receptor, revealed that NaPh<sub>4</sub>B, an additive frequently used in the preparation of mercury ion selective membranes, interacts with Hg(II). The implications of these findings on previously reported (Hg(II) ISE) are discussed. The optimum working conditions of the new electrode on its potentiometric response were established. Selectivity coefficients of Hg(II) relative to other cations were calculated. The advantages of this electrode relative to others reported in the literature are discussed. Analytical applications include its use as an indicator electrode as well as for the quantitative determination of this cation in an amalgam.

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## Introduction

Monitoring water quality is a process that requires sensors activated with materials capable of selectively recognising pollutants. The drive for a mercury(II) monitoring system is based on the following facts: (i) both inorganic as well as organic mercury species are strongly toxic and their presence in the food chain is undesirable. They are likely to be transferred to the global food chain where their concentration increases over time, a process known as bio-magnification, which has been observed for mercury species that result from common practices in industrial processes. (ii) Mercury can be released into the environment from different sources such as chloro-alkali, incineration of coal, dental, medical, gold mining, button cell battery manufacturing, other industrial waste and even natural sources (e.g. volcanoes) This means that mercury

can be present in different forms as an environmental pollutant, dominantly in the form of inorganic Hg(II), with atmospheric deposition being the dominant source of mercury over most of the landscape. Once it is in the environment it goes through a complex conversion cycle between atmosphere, ocean and land, resulting in the formation of different toxic mercury compounds.<sup>1–3</sup> Therefore, even though methyl-mercury is recognised as the most toxic form of mercury, it is mainly the product of the transformation of Hg(II). So in order to control or reduce the amount of methyl-mercury entering the food chain, it is critical to monitor the amount of Hg(II) in water.

Calixpyrroles or *meso*-substituted octamethyl porphyrinogens are generally crystalline stable materials which were first synthesized by Baeyer<sup>4,5</sup> in the 19th century by the condensation reaction involving pyrrole and acetone in the presence of HCl. This work was followed by Brown *et al.*<sup>6</sup> who proceeded with the production of modified calix[4]pyrroles, while Floriani *et al.*<sup>7,8</sup> investigated the metallation of such macrocycles. However, their anion binding properties were discovered by Sessler and co-workers.<sup>9–11</sup> Detailed thermodynamic studies on these systems and their anion complexes have

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been conducted by Danil de Namor and co-workers.<sup>12–19</sup> With the exception of the work by Floriani<sup>7,8</sup> on the complexation of iron with deprotonated *meso* octamethyl calix[4]pyrrole, which dates back to the early nineties, no other work can be tracked in the literature concerning the interaction of calix[4]pyrrole and its derivatives with cations. We have previously reported the thermodynamics of complexation of sulphur containing heterocalixpyrroles with the Hg(II) cation.<sup>13,16</sup> More recently an ion selective electrode based on one of these ligands has been reported based on research carried out at Surrey.<sup>20</sup>

Within this context we have now synthesised and characterised *meso*-tetramethyl-tetrakis-[(4*N,N* diethyl acetamide) phenoxyethyl]calix[4]pyrrole, CPA and its complexation properties with a variety of cations, mainly alkali, alkaline-earth and heavy metal cations. Fundamental studies were carried out to gain information on the sites of ligand–ion interaction through <sup>1</sup>H NMR measurements, while the composition of the complexes as well as qualitative information on the stability and therefore the selectivity or hosting ability of the receptor for the cation were obtained from conductance data. The outcome of this investigation was used to explore the capability of the receptor for the design of a Hg(II) ion selective electrode. Optimal working conditions for the potentiometric response of the electrode in terms of its membrane composition and the pH of the aqueous solution were investigated together with the characteristics of this electrode regarding linear working range, detection limit, lifetime and interferences. The advantages of this new electrode relative to those based on ionophores (such as crown ethers derivatives,<sup>21–26</sup> calixarene derivatives,<sup>27–29</sup> cryptand 22,<sup>30</sup> tetra-aza macrocycles<sup>31–33</sup> as well as other compounds<sup>34–53</sup>) are discussed.

## Experimental section

### Chemicals

Pyrrole (99.0%), 4-hydroxyacetophenone (99.0%), methane sulfonic acid (99.0%) potassium carbonate (≥99%), anhydrous MgSO<sub>4</sub> (≥99.5%), 18-crown-6 (≥99.0%), *N,N*-diethyl chloroacetamide (97.0%), dichloromethane (DCM, ≥99.5%), methanol (≥99.8%) and acetonitrile (99.9%), were purchased from Sigma-Aldrich. and tetrahydrofuran (99.9%), (Fisher Scientific) were first refluxed in a nitrogen atmosphere with calcium hydride (≥95%) (Sigma-Aldrich) for several hours and then distilled. *N,N*-Dimethylformamide (99.8%); HPLC grade, (Sigma Aldrich) was dried over 3 Å molecular sieves and the middle distilled fraction was collected. Cations (lithium (≥95.0%), sodium (≥98.0%), rubidium (≥99.0%), magnesium (≥99.99%), calcium (≥99.0%), strontium (≥99.0%), barium (≥97.0%), lead (≥99.99%), cadmium (99.0%), zinc (≥98.0%), nickel (≥98.0%)) perchlorates and mercury(II) nitrate (≥99.99%) (Aldrich) were dried over P<sub>4</sub>O<sub>10</sub> (≥99.99%) under vacuum for several days before use. The absence of a signal from residual water in the <sup>1</sup>H NMR spectra of CPA with the cations in CD<sub>3</sub>CN provided an indication that the cation salts used were anhydrous. TMS (≥97.0%), CD<sub>3</sub>CN (≥99.8%), CD<sub>3</sub>OD (≥99.8%), d<sub>6</sub>-acetone (≥99.9%), d<sub>6</sub>-DMSO (99.9%), CDCl<sub>3</sub> (≥99.9%) and d<sub>7</sub>-DMF (99.9%) were purchased from Cambridge Isotope Laboratories.

For the preparation of the ion selective membrane, polyvinyl chloride (PVC, 99.9%), diethyl sebacate (DOS) (≥97.0%), 2-nitrophenyl octyl ether (NPOE) (99.0%), sodium tetraphenylboron (NaPh<sub>4</sub>B) (≥99.5%) and oleic acid (OA) (≥99.0%), KCl (99.0%), NaCl (≥99.0%), silver wire (≥99.9%), HNO<sub>3</sub> (70.0%), NaOH (98.0%), oleic acid (≥99.0%), ethylenediaminetetraacetic acid, EDTA (≥99.0%), were purchased from Aldrich. Amalgam alloy (21.55% Ag, 13.05% Cu 15.4% Sn and 50% Hg) was purchased from Nordiska ental.

### Synthesis of *meso*-tetramethyl-tetrakis-[(4*N,N* diethylacetamide)phenoxyethylcalix[4]pyrrole, (CPA)

*Meso*-tetramethyl-tetrakis-(4-hydroxyphenyl)calix[4]pyrrole (1.7 g, 2.26 mmol), potassium carbonate (2.5 g, 18.1 mmol) and 18-crown-6 (0.125 g) were vigorously stirred and refluxed for 1 h in freshly refluxed MeCN (150 ml) under a nitrogen atmosphere. Then *N,N*-diethyl chloroacetamide (2.46 ml, 17.9 mmol) was added drop-wise and the reaction was refluxed overnight. The reaction was monitored by TLC using DCM/MeOH (9 : 1 mixture) as the developing solvent system. After cooling down the reaction, the solvent was removed under vacuum. The solid obtained was re-dissolved in DCM and extracted several times with water to remove the excess of potassium carbonate. The organic phase was separated and dried over anhydrous MgSO<sub>4</sub>, then filtered through a gravimetric funnel using a filter paper. The DCM was evaporated in a rota-evaporator and the oily product was recrystallized in MeCN to give white needle crystals (70% yield). These were dried under vacuum at 80 °C. Microanalysis was carried out (C<sub>72</sub>H<sub>88</sub>N<sub>8</sub>O<sub>8</sub>) with calculated %: wt C, 72.46; H, 7.43; N, 9.39; O, 10.72. Found %: C, 71.76; H, 7.47; N, 10.11. <sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>) (298 K), δ (ppm): 7.65 (s, broad, 4H, NH), 7.04 (d, 8H, ArH), 6.82 (d, 8H, ArH), 5.73 (d, 8H, pyrrole –H), 4.65 (s, 8H, O–CH<sub>2</sub>–CO), 3.41 (q, 16H, N(CH<sub>2</sub>–CH<sub>3</sub>)<sub>2</sub>), 1.94 (s, 12H, CH<sub>3</sub>-bridge), 1.24 (q, 12H, N(CH<sub>2</sub>–CH<sub>3</sub>)<sub>2</sub>), 1.15 (q, 12H, N(CH<sub>2</sub>–CH<sub>3</sub>)<sub>2</sub>). <sup>13</sup>C NMR (125.76 MHz), (298 K), δ (ppm): 167.43 (C1), 157.21 (C8), 137.04 (C5), 129.15 (C7), 114.25 (C6), 106.65 (C2), 68.04 (C4), 44.41 (C9), 42.08 (C11), 40.61 (C11'), 28.63 (C3), 14.90 (C12), 13.15 (C12') (see ESI† for C labelling).

### NMR measurements of the CPA–ion complexes

For these measurements, the macrocycle was dissolved in the deuterated solvent. This technique was used to characterise the ligand, provide information about the ion–ligand interaction and establish the sites of coordination of the ligand upon complexation with the ion. <sup>1</sup>H NMR, <sup>13</sup>C NMR, <sup>13</sup>C DEPT NMR, HSQCDEPT NMR and COSY NMR were recorded. To assess whether the ion complexes with the ligand or not, a known concentration of the ion salt (~8 × 10<sup>−3</sup> mol dm<sup>−3</sup>) was added to the NMR tube containing a 10 times lower concentration of the ligand, to ensure that the whole ligand has complexed with the appropriate anion or cation salt.

All NMR measurements were recorded at 298 K using a Bruker AC-500 E pulsed Fourier transform NMR spectrometer. Typical operating conditions for <sup>1</sup>H measurements involved a “pulse” or flip angle of 30°, spectral frequency (SF) of 500.25



MHz, delay time of 1.60 s, acquisition time (AQ) of 1.819 s, and line broadening of 0.55 Hz. Solutions of the samples of interest were prepared in the appropriate deuterated solvent, and then placed in 5 mm NMR tubes using TMS as the internal reference. For the  $^{13}\text{C}$  NMR measurements, the operating conditions were as follows: spectral frequency of 75.469 MHz, spectral width of 301 ppm, delay time of 0.279 s, acquisition time of 0.721 s and line-broadening of 1.4 Hz with TMS as internal reference. The same NMR equipment was used to establish possible analyte-additive and analyte-plasticizer interactions.

### Conductance measurements

For these measurements, a Wayne-Kerr Autobalance Universal Bridge (type B642) was used.<sup>54</sup> The conductivity cell constant was determined by the method of Jones and Bradshaw.<sup>55</sup> Conductometric titrations of the metal-cation salt (as perchlorates salts, except mercury where nitrate was the counter-ion used), with the ligand (CPA) were carried out in MeCN at 298.15 K. To perform these measurements, the conductometric cell was filled with accurately weighed amounts of the cation salt solution prepared in the appropriate solvent (25 ml) and left under stirring to reach thermal equilibrium. Then, a solution of the ligand prepared in the same solvent was stepwise added into the vessel. After each addition, stable conductivity readings were taken and molar conductance values were calculated. Molar conductances,  $\Lambda_{\text{m}}$  ( $\text{Scm}^2 \text{mol}^{-1}$ ) against the ligand-cation concentration ratio  $[\text{L}]/[\text{M}^{n+}]$ , were used to determine the stoichiometry of the complex.

### Preparation of the CPA based mercury(II) selective electrode

The Hg(II) selective membrane electrode based on the CPA ionophore was made using a procedure similar to that previously described in the literature.<sup>34,56</sup> The membrane electrode with different compositions of CPA (1 and 2%) were prepared by dissolving different amounts of PVC, using DOS or *o*-NPOE as plasticizers. Anion additives used were  $\text{NaPh}_4\text{B}$ , or OA, in freshly distilled THF (3  $\text{cm}^3$ ). Membranes without CPA were also prepared to assess possible interactions between the individual components of the membrane and the analyte. The composition ratios were changed within the range most commonly encountered in the literature (1–7% ionophore, 28–33% PVC, 60–69% plasticizer and 0.03–2% ionic additive).<sup>57</sup> The resulting mixture was poured to a glass dish ( $d = 30 \text{ mm}$ ). The solvent was evaporated off at room temperature. After 2 d, a resulting homogeneous PVC membrane (about 0.2 mm thickness) was cut in circles with a diameter of  $\sim 4 \text{ mm}$  and mounted into a PVC tube with a PVC paste (PVC dissolved in THF solvent as adhesive). An internal Ag/AgCl reference electrode was placed in the PVC tube which was filled with a solution of  $\text{Hg}(\text{NO}_3)_2$  ( $1.0 \times 10^{-2} \text{ mol dm}^{-3}$ ) and KCl, ( $0.1 \text{ mol dm}^{-3}$ ). The membrane electrochemical cell was set up as follows:

**Ag/AgCl | internal solution ( $\text{Hg}^{2+}$  in KCl) | PVC membrane.** The electrode was conditioned for 2–3 d with the same solution of  $\text{Hg}(\text{NO}_3)_2$  ( $1.0 \times 10^{-2} \text{ mol dm}^{-3}$ ) used as the filling internal solution. When the electrode was not in use, it was stored in  $\text{Hg}(\text{NO}_3)_2$ .

**Scanning electron microscopic experiments.** Micrographs of membrane surfaces were taken by S-3200 N microscope (Oxford instrument) equipped with an X-ray detector for EDAX analysis, a Back Scatter Robinson Detector for imaging, and a Secondary electron detector.

**Construction of the Hg(II)-ISE electrochemical cell.** A Ag/AgCl with a flexible connector (MF-2052, RE-5B) filled with a NaCl aqueous solution ( $3 \text{ mol dm}^{-3}$ ) was used as an external reference electrode while the silver wire coated with a thin layer of silver chloride was used as the internal electrode. The reference electrode was used in conjunction with the CPA based electrode.

**Preparation of standard solutions of the mercury(II) salt.** A stock solution of the mercury ion salt ( $1 \times 10^{-2} \text{ mol dm}^{-3}$ ) was freshly prepared by dissolving an accurate amount (0.171 g) of the salt (as nitrate) in deionized water ( $50 \text{ cm}^3$ ) while working solutions in the range  $5.0 \times 10^{-8}$  to  $5 \times 10^{-2} \text{ mol dm}^{-3}$  were prepared by appropriate dilution of the stock solution with deionized water.

**Potential measurements of Hg(II)-ISEs based on CPA.** The performance of the proposed CPA based Hg(II)-ISE was investigated by carrying out calibration curves. This procedure was followed in order to determine the composition which gives the best potential response. Different volumes of standard solution of the Hg(II) ion salt were successively added to a vessel containing deionized water ( $75 \text{ cm}^3$ ) to cover the concentration range from  $6.67 \times 10^{-8}$  to  $4.32 \times 10^{-2} \text{ mol dm}^{-3}$ . The additions of standard solutions were carried out from the low to the high concentration. The potential measurements were made in magnetically stirred solutions and stable potential readings were taken after a period of time after each addition. The ion activities of the metal salt solutions were calculated from the ion concentrations according to Debye–Huckel procedure.<sup>24,58</sup> Cell potential values  $E(\text{mV})$  were plotted as a function of the  $\log_{10}$  of the mercury ionic activity. The response characteristics of the ISE were evaluated from the calibration graph.

**Effect of soaking time on the response of Hg(II)-ISE.** The effect of soaking time on the performance of the CPA based Hg(II)-ISE was examined. The electrode was soaked in aqueous solution containing  $\text{Hg}(\text{NO}_3)_2$  ( $1 \times 10^{-2} \text{ mol dm}^{-3}$ ) the same as the test solution for different periods of time ranging from 6 to 48 h. The slope values obtained by plotting  $E(\text{mV})$  as a function of  $\log_{10}[\text{Hg(II)}]$  were also plotted as a function of soaking time. Thereafter, the optimum soaking time for the Hg(II)-ISE was determined.

**Effect of pH of the aqueous solution of the Hg(II) salt on the electrode response.** The effect of pH of the test solution on the response of the Hg(II)-ISE was examined. The potential was measured in the 2.0–12.0 pH range at two concentrations of Hg(II) solutions ( $1.0 \times 10^{-2}$  and  $1.0 \times 10^{-3} \text{ mol dm}^{-3}$ ). These experiments were achieved through following the variation of potential of the proposed electrode with the change in the solution pH for both concentrations used; the pH value was adjusted by the addition of a very small volume of  $\text{HNO}_3$  or  $\text{NaOH}$  (each  $0.1$ – $1.0 \text{ mol dm}^{-3}$ ). The potential readings were plotted against the corresponding pH values. The optimum pH



values obtained at both concentrations of Hg(II) solutions ( $1.0 \times 10^{-2}$  and  $1.0 \times 10^{-3}$  mol dm<sup>-3</sup>) were used for further studies.

**Determination of selectivity coefficients of ions relative to Hg(II).** In this work, potentiometric selectivity coefficients ( $K_{Hg,M}^{pot}$ ) of Hg(II) relative to other cations were determined by using two IUPAC recommended methods, namely, the separate solution method (SSM)<sup>59</sup> and the matched potential method (MPM).<sup>60</sup> These two methods were carried out under the following experimental conditions: for the SSM method, the concentration of the Hg(NO<sub>3</sub>)<sub>2</sub> (primary ion) was  $2.23 \times 10^{-4}$  mol dm<sup>-3</sup>; the same concentration was used for the interfering ions. For the MPM method, the concentration of Hg(NO<sub>3</sub>)<sub>2</sub> was  $1.0 \times 10^{-2}$  mol dm<sup>-3</sup> while  $1.0 \times 10^{-1}$  mol dm<sup>-3</sup> was the concentration of interfering ions.

**Assessment of the dynamic response time of the Hg(II)-ISE.** Measurements of the dynamic response time of the electrode were conducted at different Hg(NO<sub>3</sub>)<sub>2</sub> concentrations ( $1 \times 10^{-7}$ ,  $1 \times 10^{-6}$ ,  $1 \times 10^{-5}$ ,  $1 \times 10^{-4}$ ,  $1 \times 10^{-3}$  and  $1 \times 10^{-2}$  mol dm<sup>-3</sup>). Potentials resulting from the addition of each concentration of the primary ion (Hg(II)) solution (50 cm<sup>3</sup>) were plotted against dynamic response times of the electrode. The reversibility of the electrode was investigated by successive immersions of the Hg(II) ISE at two different concentrations of the Hg(II) salt solution from the lower to the higher concentration and *vice versa*. Finally, the potential values against response times were plotted.

**Determination of the lifetime of the Hg(II)-ISE.** The lifetime of the Hg(II)-ISE was monitored over a period of time by measuring the potential values of the calibration solutions of Hg(NO<sub>3</sub>)<sub>2</sub>. Calibration curves were obtained after each examined time in the  $6.67 \times 10^{-8}$  to  $4.32 \times 10^{-2}$  mol dm<sup>-3</sup> concentration range. The slope values obtained by plotting  $E$ (mV) as a function of log [Hg(II)] were also plotted against the period of time tested.

#### Analytical applications of the CPA based Hg(II)-ISE

**Determination of Hg(II) ion concentration with EDTA in aqueous solution.** The Hg(II)-ISEs (1%) with *o*-NPOE (68%) as plasticizer and OA as ionic additive (1%) were used as an indicator electrode in the potentiometric titration of the mercury(II) ion salt with EDTA at the standard temperature. The aqueous Hg(II) nitrate solution (60 cm<sup>3</sup>,  $1.0 \times 10^{-3}$  mol dm<sup>-3</sup>) was titrated with aliquots of EDTA (0.5 cm<sup>3</sup>,  $5.0 \times 10^{-3}$  mol dm<sup>-3</sup>). The amount of mercury(II) ion was accurately determined from the end point of the resulting titration by plotting  $E$ (mV) as a function of log [Hg(II)].

**Analysis of mercury(II) in a real sample.** The proposed Hg(II)-ISE as indicator electrode was tested for the potentiometric determination of mercury(II) in a dental amalgam filling. Thus an accurate weight of the dental amalgam alloy (43.1% Ag, 26.1% Cu and 30.8% Sn) (0.6 g) was dissolved in a minimum volume (20 ml) of HNO<sub>3</sub> (60%). The solution was intensely heated to near dryness. The acid treatment and the evaporation process of the solution were repeated at least three times. The residue obtained was dissolved in a small amount of water and filtered. The clear solution was quantitatively transferred into a volumetric flask (50 cm<sup>3</sup>) and filled to the mark with distilled water after adjusting the pH value of the solution to 5.6.

Thereafter, the standard addition method was applied where small increments (0.1 cm<sup>3</sup>) of the standard solution of Hg(NO<sub>3</sub>)<sub>2</sub> ( $3.0 \times 10^{-2}$  mol dm<sup>-3</sup>) were added to the dental amalgam solution (50 cm<sup>3</sup>) at the standard temperature. The changes in potential readings were recorded after each addition of the standard solution. The Hg(II) concentration in the dental amalgam solution was calculated. The results obtained with the CPA based electrode were compared with data obtained by atomic absorption spectrometry (AAS).

## Results & discussion

For the structural characterization of CPA, NMR experiments were carried out. In a first stage 1D <sup>1</sup>H NMR proton and <sup>13</sup>C NMR were run in CD<sub>3</sub>CN (Chemical shifts shown in the Experimental section). However the 1D <sup>1</sup>H NMR was not sufficient to attribute the protons of the different units, which become non-equivalent because of the loss of symmetry after substitution, therefore we proceeded with <sup>13</sup>C NMR-HBBD, <sup>13</sup>C NMR-DEPT and HMQC 2D NMR experiments to establish a correlation of <sup>1</sup>H and <sup>13</sup>C signals. Comparative analysis of <sup>13</sup>C NMR-HBBD and <sup>13</sup>C NMR-DEPT spectra given in ESI† help to identify the number of signals attributed to five quaternary carbons (one sp<sup>3</sup> and four sp<sup>2</sup>, including a carbonyl function at 166.01 ppm and another one integrating two carbons [C<sub>1</sub>-C<sub>4</sub> and C=O]), three methine [(CH)<sub>3</sub> all sp<sup>2</sup> all integrating two carbons each], three methylene one oxygenated and two link to a nitrogen atom [(CH<sub>2</sub>)<sub>2</sub>N(CH<sub>2</sub>-O)] and three methyl [(CH<sub>3</sub>)<sub>3</sub>]. The assignment of the N-H functionality was made directly from the <sup>1</sup>H NMR. Consequently the formula [C<sub>1</sub>-(C=O)<sub>4</sub>-(CO)-(CH)<sub>6</sub>-(CH<sub>2</sub>)<sub>2</sub>-(CH<sub>2</sub>-O)-(CH<sub>3</sub>)<sub>3</sub>-NH] = C<sub>18</sub>H<sub>22</sub>N<sub>2</sub>O<sub>2</sub> × 4 = C<sub>72</sub>H<sub>88</sub>N<sub>8</sub>O<sub>8</sub> was deduced, which was found to be in accord with the elemental analysis. However, the complete assignments, especially in the overlapped regions (<sup>1</sup>H at 3.35 ppm) had to be made from the 2D data. The <sup>1</sup>H-<sup>13</sup>C correlation (ESI†) was used for the assignment of hydrogens to carbons in a straight forward manner. The set of protons at 3.35 ppm showed correlation with two carbons C-11 (40.56 ppm) and C-11' (39.27 ppm), this indicates clearly that this set of protons integrates the two methylene of the acetamide arm group (2CH<sub>2</sub>-N). In addition the correlation of C-6 and C-7 to H-4 and H-5 benzene ring protons made the assignment of the pyrrole protons easy.

Having characterised the receptor, <sup>1</sup>H NMR measurements were carried out to assess cation-ligand interactions. These were carried out in CD<sub>3</sub>CN given that in this dipolar aprotic solvent ion salts are predominantly dissociated.

#### <sup>1</sup>H NMR measurements of CPA with metal cations and anions in CD<sub>3</sub>CN at 298 K

Hardly any chemical shift changes ( $\Delta\delta$  ppm) were observed in the <sup>1</sup>H NMR spectrum of CPA by the addition of alkali metal cations (Li(I), Na(I), K(I), Rb(I) and Cs(I)) as perchlorates in CD<sub>3</sub>CN at 298 K. The addition of Ag(I) salt to CPA also did not lead to significant chemical shift changes in any of the protons.





As far as the alkaline-earth metal cations are concerned, downfield chemical shift changes relative to the free ligand (ppm) were observed by the addition of Mg(II) (H-5, 0.14), Ca(II) (H-4, 0.15, H-5, 0.16), Sr(II) (H-4, 0.10, H-5, 0.15) and Ba(II) (H-5, 0.13) salts to CPA in CD<sub>3</sub>CN. Therefore, it can be concluded that these cations being of the hard Lewis acid type may interact with CPA through the phenolic and the carbonyl oxygens of the amide moiety (hard Lewis base).<sup>61</sup> As far as the heavy metal cations are concerned, the most significant downfield chemical shift changes for Pb(II) are observed in H-5 (0.21 ppm) and H-6 (0.20 ppm) while for Cd(II) the signal corresponding to H-6 disappeared. The addition of Hg(II) to the NMR tube containing a solution of CPA in CD<sub>3</sub>CN led to significant downfield chemical shift changes in the methylene protons (H-6, 0.16 ppm) between the phenolic oxygen and the carbonyl group of the acetamide arm group and the one next to the nitrogen atom of the acetamide nitrogen (H-7, 0.14 ppm, H-7', 0.16 ppm) as well as in the methyl terminal protons of acetamide arm (H-8', 0.13 ppm). Upfield chemical shift changes observed in the NH proton of the pyrrole units were found to be less significant and may result from the conformational changes of CPA upon complexation. These results suggest that the interaction of Hg(II) with CPA takes place through the amide functional group. We therefore conclude that Pb(II), Cd(II) and Hg(II) interact with the donor atoms of the acetamide functional groups.

Among the anions tested (halides, nitrate, hydrogen sulphate), dihydrogen phosphate, trifluoromethane sulphonate, thiocyanide strong interaction was found only with the fluoride ion where the most remarkable downfield chemical shift change was found for H-1 (4.52 ppm) as a result of the interaction of this anion with the NH functional groups of the pyrrole units. Preliminary studies in different dipolar aprotic solvents revealed a change in the composition of the anion complex in moving from one solvent to another. Therefore <sup>1</sup>H NMR titrations were carried out in three solvents: CD<sub>3</sub>CN, d<sub>6</sub>-DMSO and d<sub>7</sub>-DMF at 298 K.

### <sup>1</sup>H NMR titration of CPA with the fluoride anion in deuterated dipolar aprotic solvents

In an effort to study the behavior of the receptor in solution, <sup>1</sup>H NMR studies of CPA were carried out in CD<sub>3</sub>CN, d<sub>6</sub>-DMSO and d<sub>7</sub>-DMF in the absence and presence of the fluoride anion. Volumes of TBAF were added to the solution of CPA. The <sup>1</sup>H NMR spectrum (CD<sub>3</sub>CN, 500 MHz, 298 K) of CPA receptor showed one broad singlet at 7.98 ppm (integrating 4H) which was assigned to the four chemically equivalent NH protons' resonance. Addition of 0.5 equivalent of tetrabutylammonium fluoride (TBAF) to a solution of the receptor leads to an equilibrium favoring the cone-like conformation *via* the formation of the 1 : 1 fluoride–CPA complex. The conformational change of the receptor was easily observed in the <sup>1</sup>H NMR spectrum, where two different signals were observed for the NH protons, one at 7.98 ppm, corresponding to the free receptor, and the other at 12.00 ppm, corresponding to the fluoride complex. This finding was taken as evidence that the exchange between the complex and the free receptor is slow on the <sup>1</sup>H NMR timescale.

After the addition of 1.0 equivalent of TBAF, only the signals at 12 and 12.5 ppm, corresponding to the CPAF<sup>−</sup> complex were observed in the <sup>1</sup>H NMR spectrum under these conditions, as expected for a highly stable complex.

Surprisingly, the pyrrole NH resonance was found to split into two peaks in the presence of fluoride. It was considered that a likely cause for this splitting might be due to coupling between the NH protons and the <sup>19</sup>F nucleus of the bound fluoride anion. The coupling constant was found to be 49.5 Hz as was previously reported in the literature.<sup>62</sup> The stoichiometry of complexation was determined from plots of the integrals of the most significant downfield chemical shift changes in the

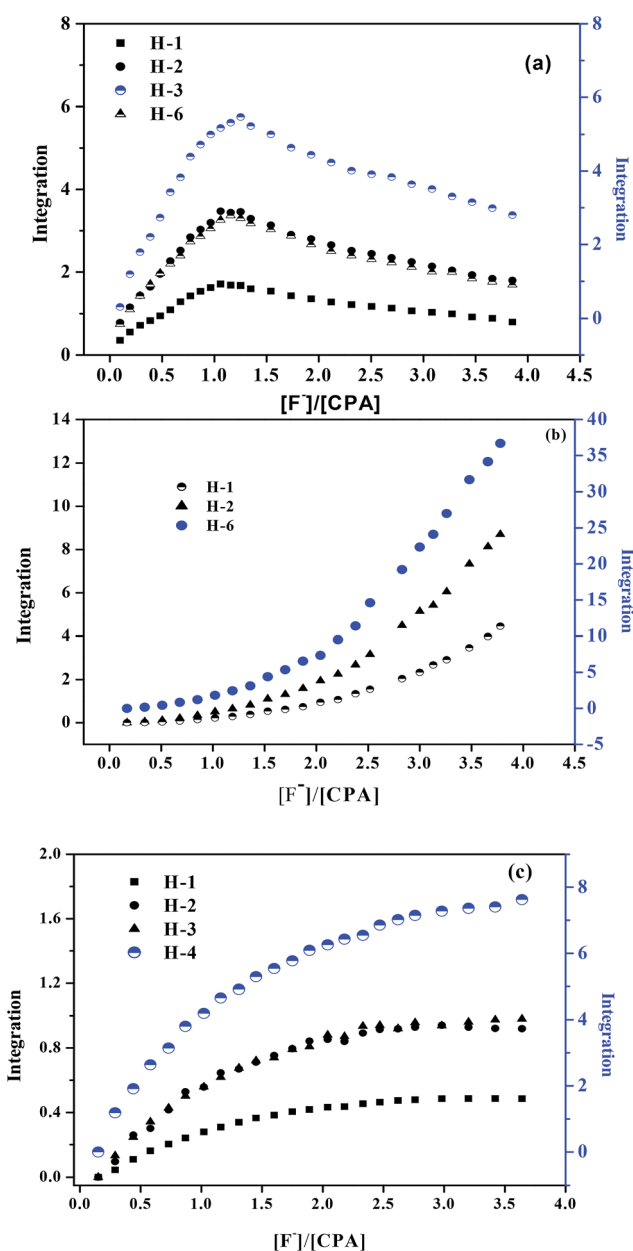


Fig. 1 (a) <sup>1</sup>H NMR titration of CPA with the fluoride anion in CD<sub>3</sub>CN at 298 K. (b) <sup>1</sup>H NMR titration of CPA with the fluoride anion in d<sub>6</sub>-DMSO at 298 K. (c) <sup>1</sup>H NMR titration of CPA with the fluoride anion in d<sub>7</sub>-DMF at 298 K.



protons of the anion complex (H-1, H-2, H-3, H-6) as shown in Fig. 1(a).

The results obtained from the  $^1\text{H}$  NMR titration of CPA with the fluoride anion salt in  $\text{d}_6$ -DMSO and  $\text{d}_7$ -DMF (Fig. 1(b) and (c)) clearly indicate that in the former solvent, CPA interacts with the anion with the formation of a 2 : 1 ( $\text{CPA} : \text{F}^-$ ) complex in the latter solvent the composition of the complex is 1 : 1.  $^1\text{H}$  NMR data for the free ligand in these solvents show that DMSO interacts with calixpyrrole through hydrogen bond formation between the basic oxygen atoms of the solvent and the NH moiety of the pyrrole ring. This was reflected in the significant downfield chemical shift changes observed in H-1 in moving from  $\text{CD}_3\text{CN}$  to  $\text{d}_6$ -DMSO (1.47 ppm) while insignificant upfield chemical shift changes were observed for the remaining protons. To a lesser extent  $\text{d}_7$ -DMF also interacts with CPA. A downfield shift in H-1 was observed (1.31 ppm) with additional ones in H-4 (0.10 ppm) and H-6 (0.11 ppm). Sessler and co-workers<sup>63</sup> reported the X-ray structure of the parent calix[4]pyrrole in a 1,2 alternate conformation in which two molecules of  $\text{d}_7$ -DMF are hydrogen bonded to two adjacent pyrrole units. However these authors found that in solution (benzene) only 1 : 1 complexes are formed. The same situation was found in DMSO. Apparent stability constants in benzene for the parent calix[4]pyrrole with  $\text{d}_6$ -DMSO ( $\log K_s = 1.21$ ) and with  $\text{d}_7$ -DMF ( $\log K_s = 1.05$ ) were reported. As far as CPA is concerned, a possible explanation of the different compositions of the fluoride complexes in these solvents must be attributed to their different molecular geometries. Thus DMSO is characterized by a pyramidal geometry ( $\text{sp}^3$  hybridization with a lone pair of electrons) while DMF has a planar structure ( $\text{sp}^2$  hybridization). It is also known that DMSO can be associated with the formation of head to tail dimers through dipole-dipole interactions.<sup>64,65</sup> As a result the binding sites of the receptor to enter interaction with the anion are reduced. Therefore two calixpyrrole units rather than one are required to enhance the number of binding sites required to enter complexation with the anion in  $\text{d}_6$ -DMSO.

In an attempt to test the ability of this receptor to interact simultaneously with  $\text{Hg}(\text{II})$  and  $\text{F}^-$ , the binding properties of CPA with  $\text{Hg}(\text{II})$  were examined by  $^1\text{H}$  NMR titration experiments in  $\text{CD}_3\text{CN}$  in the absence and the presence of  $\text{F}^-$  (Fig. 2).

From the results of this experiment the following conclusions can be drawn. As stated above, the addition of 1 equivalent of TBAF to CPA in  $\text{CD}_3\text{CN}$  caused a remarkable downfield chemical shift change of the NH protons and upfield shifts of the remaining protons (H-2; H-3; H-4,5; H-6, H-7,7' and H-8,8') of this receptor. Further addition of TBAF does not make any significant change in the chemical shifts of the protons, suggesting the formation of a 1 : 1 ( $\text{CPA} : \text{F}^-$ ) complex. In the first three additions of the  $\text{Hg}(\text{II})$  salt solution to the fluoride complex a substantial upfield chemical shift change of the NH protons of the complex ( $\sim 3.6$  ppm) was observed. Inspection of Fig. 2(a) shows the formation of a 2 : 1 ( $\text{Hg}(\text{II}) : \text{CPA}$ ) complex. The integrals of the NH protons of the 1 : 1 fluoride complex with the  $\text{Hg}(\text{II})$  salt is shown in Fig. 2(b). The break observed in this figure at the  $\text{Hg}(\text{II}) : \text{CPA}$  ratio of 0.5 clearly indicates that two units of the fluoride complex interacts with only one metal cation. These

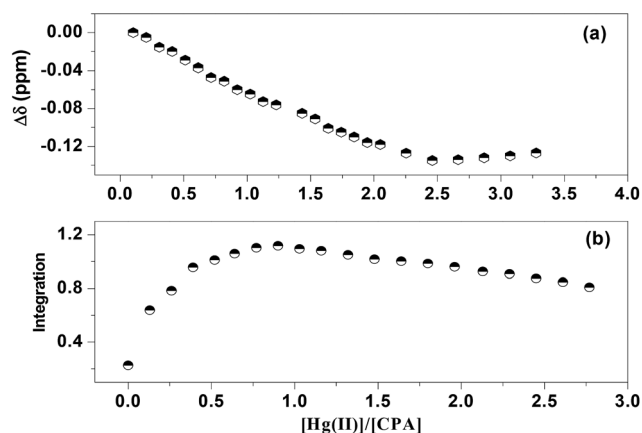


Fig. 2 Shifts and integrals of NH protons of the CPA/F (1 : 1) complex titrated with  $\text{Hg}(\text{II})$  in  $\text{CD}_3\text{CN}$  at 298 K.

may be the result of an exchange between the two  $\text{TBA}^+$  cations with the bivalent mercury ion. It is reasonable to assume that the  $\text{TBA}^+$  cations are large hydrophobic ions of low charge density relative to  $\text{Hg}(\text{II})$  and therefore these are likely to be easily displaced by the latter cation. In addition, ion-ion interactions are stronger than ion dipole interactions. Consequently  $\text{Hg}(\text{II})$  will be more attracted by the negatively charged fluoride complex than by the donor atoms of the amide functionality of the receptor.

### Conductometric titrations of ions with CPA in MeCN

Conductometric titrations of all metal cation salts (perchlorate as the counter-ion) investigated, except  $\text{Hg}(\text{II})$  (as nitrate), led to a defined change in the curvature at the 1 : 1 (ligand : metal ion) stoichiometry, suggesting the formation of complexes of moderate stability. As far as  $\text{Hg}(\text{II})$  is concerned. The conductometric titration curve (Fig. 3), which is a plot of the molar conductance,  $\Lambda_m$  against the ligand : metal cation ratio breaks at 0.5 indicating that two metal cations interact with one unit of receptor. A decrease in conductance due to the formation of the 1 : 2 complex (eqn (1)) is observed

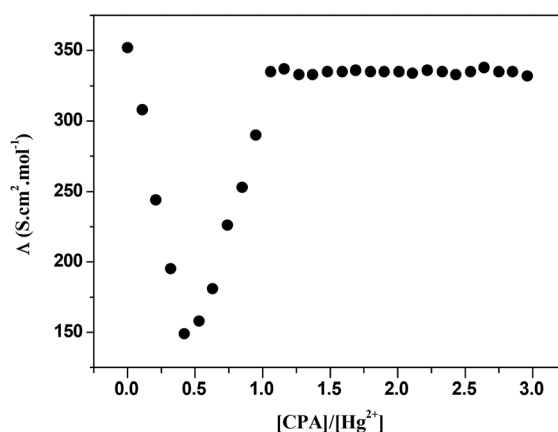
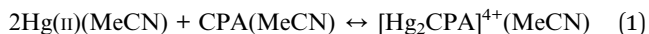
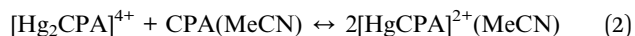


Fig. 3 Conductometric titration curve of  $\text{Hg}(\text{II})$  (as nitrate) with CPA in MeCN at 298.15 K.





In the presence of an excess of the ligand, it seems that one of the mercury cations in the complex is transported to the free ligand with the formation of a 1 : 1 complex (eqn (2)) as shown by the increase in conductance.



As far as the  $\text{F}^-$  anion is concerned, the conductometric titration curve consisted of a combination of two linear segments with a well-defined change in the curvature at the 1 : 1 ( $\text{CPA} : \text{F}^-$ ) molar ratio, suggesting the formation of a relatively strong complex.

Based on the evidence obtained from the fundamental studies described above, it is concluded that CPA has a higher hosting ability for  $\text{Hg(II)}$  relative to other ions investigated, therefore a  $\text{Hg(II)}$  selective liquid membrane electrode based on this receptor was designed. Before discussing the characteristics of the ISE we assessed whether or not interactions are found between the analyte and the individual components of the PVC based membrane (additive and plasticizer) in the absence of the receptor.

### Selection of additive and plasticizer for the preparation of the $\text{Hg(II)}$ ion selective membrane

Two additives (sodium tetraphenylboron,  $\text{NaPh}_4\text{B}$  and oleic acid, OA) were tested to find out whether or not these interact with the analyte and interfere in the selective behaviour of the ionophore for the analyte. Thus  $^1\text{H}$  NMR data obtained by the addition of  $\text{Hg(II)}$  (nitrate as counter-ion) shown in Table 1.

These results clearly indicate that there is a strong interaction between the cation and this additive. This is reflected in the significant downfield chemical shift changes observed in all the aromatic protons. In an attempt to observe the behaviour of  $\text{NaPh}_4\text{B}$ , this salt was introduced in a PVC based membrane in the absence of the receptor. Potentiometric measurements carried out demonstrated that the membrane responds to  $\text{Hg(II)}$  showing a Nernstian behaviour (slope  $29.1 \pm 0.6 \text{ mV/pHg(II)}$ ) in the  $3.25 \times 10^{-5}$  to  $2.5 \times 10^{-3} \text{ mol dm}^{-3}$  concentration range

with a response time of about 10 s). This was further corroborated by Scanning Electron Microscopy (SEM) carried out on the membrane with the aim of identifying the locations of the  $\text{Hg(II)}$  cation on the PVC membrane in the absence of the receptor and to understand the changes to the membrane morphology. Fig. 4(a1) and (a2) represent the SEM micrographs of the membrane surface before and after it has been used in the  $\text{Hg(II)}$  ISE.

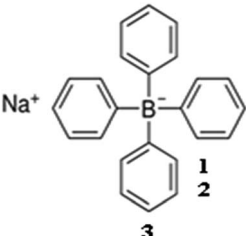
Fig. 4(a1) shows the typical clear and fibrous PVC membrane surface without exhibiting any dense areas or defects. The Fig. 4(a2) shows the  $\text{Hg(II)}$  as white dense patches on the membrane which have been detected in the EDAX spectrum in Fig. 4(b2), where the new peaks characteristic of Hg (compared to Fig. 4(b1) are noted and this indicates the binding of  $\text{Hg(II)}$  to the  $\text{Ph}_4\text{B}^-$  anion sites). A change in the morphology of the membrane as a function of the ageing time was also observed. It is therefore concluded that a PVC membrane containing  $\text{NaPh}_4\text{B}$  is able to detect  $\text{Hg(II)}$  in the absence of the CPA receptor. These findings as demonstrated below have implications on the working characteristics of the electrode in the presence of the receptor and open serious questions about whether or not the electrode responses that have been previously reported with this additive were due to the receptor or to the presence of  $\text{NaPh}_4\text{B}$  particularly when fundamental studies have not been carried out. No interaction was found between the mercury(II) cation and oleic acid by  $^1\text{H}$  NMR measurements. In addition, blank experiments in the absence of the receptor were carried out. It was found that when the membrane components were 68% *o*-NPOE, 30% PVC, and 1% OA, the electrode membrane displayed no response towards  $\text{Hg(II)}$  and therefore this was the additive selected for the preparation of the membrane containing the CPA receptor in the below experiments. In the same way, we tested two plasticizers, DOS and *o*-NPOE. Two PVC membranes were produced using OA as additive and either DOS or *o*-NPOE. No interaction was detected with the DOS plasticizer, in the concentration range  $1.3 \times 10^{-3}$  to  $1.5 \times 10^{-2} \text{ mol dm}^{-3}$ , and with *o*-NPOE in the concentration range of  $7.1 \times 10^{-4}$  to  $1.34 \times 10^{-3} \text{ mol dm}^{-3}$ .

### Effect of membrane composition on the potentiometric response characteristics of the CPA based $\text{Hg(II)}$ -ISE

The characteristics of the electrode such as its Nernstian behaviour, liner range (L-R), detection limit (D-L) and response time were investigated using five electrode membranes (E1–E5, composition electrode in Table 2) of varying compositions: two different plasticizers (*o*-NPOE or DOS) (E1 and E2) in the absence of additive (E3), in the presence of an increased amount of the receptor (E4). Also included data obtained in the presence of the receptor when  $\text{NaPh}_4\text{B}$  was used an additive (E5). Calibration curves for the five electrodes tested are shown in Fig. 5.

The nature of plasticizers used (*o*-NPOE and DOS) (E1 and E2) effects the characteristics of the  $\text{Hg(II)}$ -ISE. The results showed that the latter (E2) had a better response when compared with the former (E1). The linear working response was within a wide range of  $\text{Hg(II)}$  concentration from  $1.81 \times$

**Table 1**  $^1\text{H}$  NMR data for  $\text{NaPh}_4\text{B}$  and its interaction with the  $\text{Hg(II)}$  cation in  $\text{D}_2\text{O}$  at 298 K

$\text{NaPh}_4\text{B}$	H-1	H-2	H-3
			
$\text{NaPh}_4\text{B}$ free	6.99	7.26	6.85
$\text{Hg(II)}$ with $\text{NaPh}_4\text{B}$	7.37	7.60	7.14
$\Delta\delta$	0.38	0.34	0.29



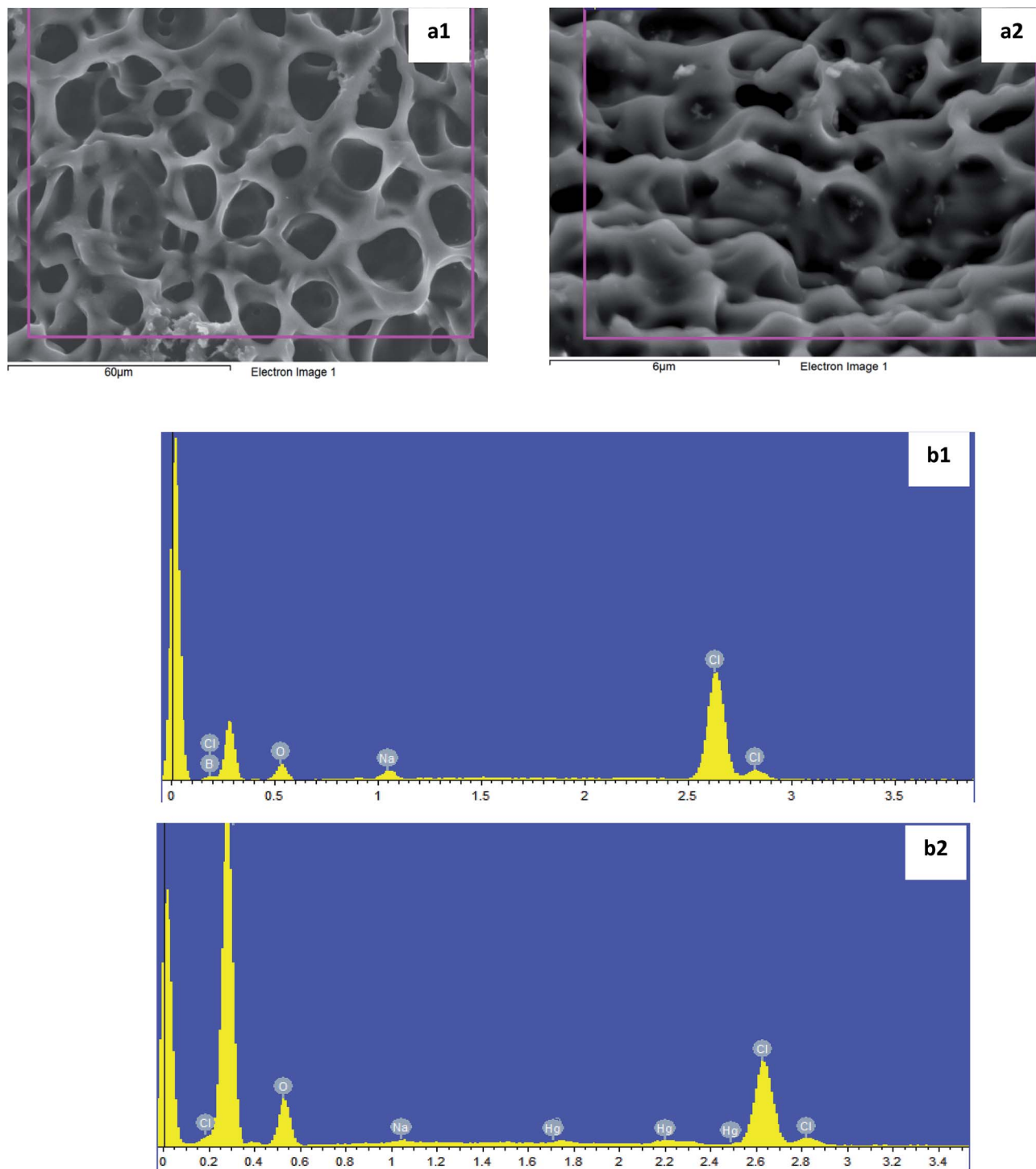


Fig. 4 (a1 & a2) PVC membrane (a1) prepared before being used in the electrode and (a2) after it has been used for several times in the ion selective electrode; (b1 & b2) EDAX spectra of the membranes showing the elemental analysis.

$10^{-7}$  to  $1.78 \times 10^{-3}$  mol dm $^{-3}$  with a detection limit of  $6.0 \times 10^{-8}$  mol dm $^{-3}$  and response time in about 10 s. In addition, the slope obtained for this electrode (E2) was found to be  $30 \pm 1$  mV dec $^{-1}$ , which is close to the Nernstian response (29.5 mV dec $^{-1}$  at 298 K). The difference in the response characteristics between E1 and E2 may be attributed to the dielectric constant of the plasticizers used which in turn may have an

effect on the membrane permittivity and the mobility of the ionophore molecules.<sup>24</sup> Accordingly, *o*-NPOE was chosen to be the optimum plasticizer for further studies with the CPA based electrode. Clearly in the absence of additive (E3) the response of the electrode in the presence of the receptor is indeed very weak.

Comparison of the potentiometric response characteristics of the membrane electrode E4 with respect to E2 revealed that the





Table 2 Composition of membranes and response characteristics of the CPA based ISE for Hg(II) at 298 K

Slope (mV/pHg)	L-R mol dm <sup>-3</sup>	D-L mol dm <sup>-3</sup>	Response time (s)
E1	1% CPA, 68% DOS, 30% PVC, 1% OA		
25 ± 1	$9.12 \times 10^{-7}$ to $1.78 \times 10^{-3}$	$4.46 \times 10^{-7}$	14
E2	1% CPA, 68% <i>o</i> -NPOE, 30% PVC, 1% OA		
30 ± 1	$1.81 \times 10^{-7}$ to $1.78 \times 10^{-3}$	$1.81 \times 10^{-7}$	10
E3	1% CPA, 68% <i>o</i> -NPOE, 30% PVC, no additive		
6 ± 1	$2.51 \times 10^{-5}$ to $1.58 \times 10^{-3}$	$1.78 \times 10^{-5}$	19
E4	2% CPA, 68% <i>o</i> -NPOE, 30% PVC, 1% OA		
25 ± 1	$3.98 \times 10^{-7}$ to $9.46 \times 10^{-4}$	$5.62 \times 10^{-7}$	<10
E5	1% CPA, 68% <i>o</i> -NPOE, 30% PVC, 1% NaPh <sub>4</sub> B		
26 ± 1	$1.6 \times 10^{-6}$ to $1.98 \times 10^{-3}$	$4.67 \times 10^{-6}$	~6.5

best performance was observed for the latter. The increase of the amount of ionophore led to a lower electrode response. This may be also ascribed to a decrease in the solubility of the ionophore in the membrane. As previously stated<sup>58</sup> the ionophore should be soluble in the membrane matrix and should be sufficiently lipophilic to avoid leaching from the membrane into the sample solution.<sup>24</sup> As far as E5 is concerned the data in Table 2 show that the presence of NaPh<sub>4</sub>B decreases the detection limit of the electrode by a factor higher than 10 which may be due to a possible interaction between this salt and the receptor. It is well established that the parent calix[4]pyrrole does not complex the tetraphenyl borate anion, but the possibility exists that its derivative containing aromatic group interacts with this anion through pi-pi interactions. From the above mentioned results, the membrane electrode E2 was chosen for further investigation under different experimental conditions.

The surface analysis of the PVC membrane casted with THF containing CPA, OA as additive and *o*-NPOE as plasticizer was characterised by SEM coupled with EDAX. Fig. 6(a) and (b) and 7(a) and (b) show SEM-EDAX of the PVC-CPA matrix before and after it has been in contact with Hg(NO<sub>3</sub>)<sub>2</sub>. A detectable transformation in the membrane shows the interaction with the cation. The EDAX analysis displays Hg(II) peaks, and this

depicts the selective recognition and binding of CPA to the Hg(II) cation.

### Effect of pH of the aqueous solution on the response of the CPA based Hg(II)-ISE

As can be seen from Fig. 8, the pH effect on the response of the electrode was investigated under the same conditions stated above over a 1.5–12.0 pH range of aqueous solutions of Hg(NO<sub>3</sub>)<sub>2</sub> ( $1.01 \times 10^{-3}$  and  $1.01 \times 10^{-2}$  mol dm<sup>-3</sup>). The results show that the electrode potential remains constant in the 4.3–8.5 pH range using  $1.01 \times 10^{-3}$  mol dm<sup>-3</sup> Hg(II) solution. At pH lower than 4.30, the increase of the acid nature of the solution gives rise to an increase in the electrode potential. At pH higher than 8.5, the potential values were found to decrease sharply due to the formation of hydroxyl-complexes of Hg(II) in solution. By altering the concentration of the mercury salt to  $1.01 \times 10^{-2}$  mol dm<sup>-3</sup>, a similar profile was observed. Therefore for further studies, an aqueous solution of Hg(NO<sub>3</sub>)<sub>2</sub> at pH 5.6 was used.

### Effect of the concentration of the internal solution on the response of Hg(II)-ISE based on CPA

The concentration of the internal reference solution has a remarkable influence on the electrode response (as shown in Fig. 9). The optimum concentration of Hg(NO<sub>3</sub>)<sub>2</sub> was found to be  $1 \times 10^{-2}$  mol dm<sup>-3</sup>. A slope value of  $29 \pm 1$  mV dec<sup>-1</sup> close to the theoretical Nernstian slope was found. However when the concentration was decreased to  $1 \times 10^{-3}$  mol dm<sup>-3</sup> Hg(NO<sub>3</sub>)<sub>2</sub> the electrolyte was unable to transfer the charge from the detected ion in the ISE membrane to the measuring system and as a result the electrode response decreased. Therefore, the concentration of  $1 \times 10^{-2}$  mol dm<sup>-3</sup> Hg(NO<sub>3</sub>)<sub>2</sub> was used for further studies reported in this paper.

### Effect of soaking time on the performance of Hg(II)-ISE based on CPA

Fig. 10 shows the effect of conditioning of the ISE for different periods of time on the slope values obtained by plotting  $E$ (mV) as a function of  $\log[Hg(II)]$ . These results revealed that the soaking time of the ISE has a considerable effect on its response characteristics. It was found that an optimum soaking time was 24 hours, the slope value ( $27 \pm 2$  mV dec<sup>-1</sup>) obtained is close to

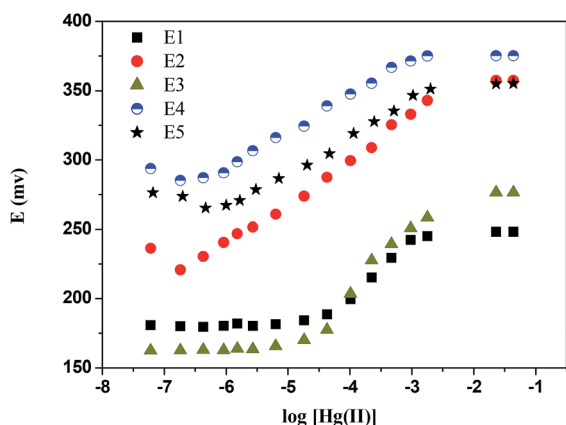


Fig. 5 Effect of membrane composition on the potentiometric response characteristics of the CPA based Hg(II)-ISE. Membrane compositions are in Table 2.



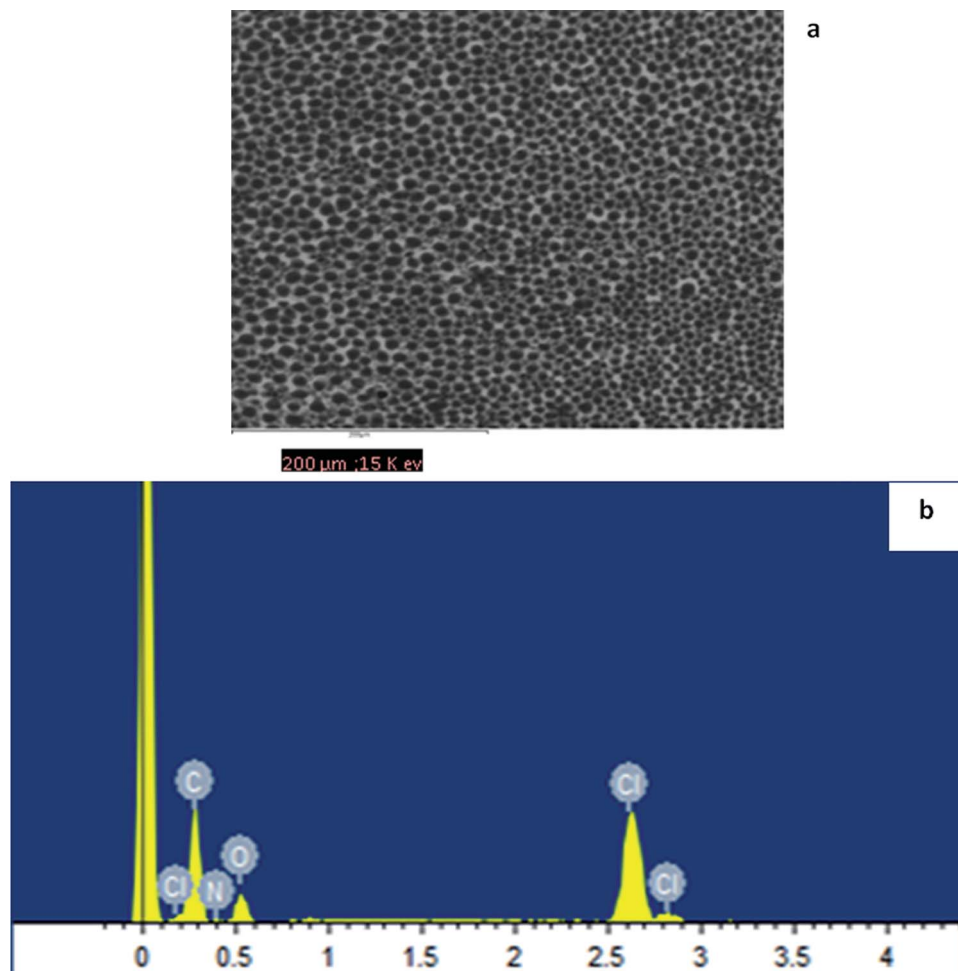


Fig. 6 (a) Scanning electron microscopy image of a CPA ionophore-PVC porous membrane; E2 (b) EDAX spectrum showing the membrane elemental composition.

the theoretical Nernstian slope ( $29.5 \text{ mV dec}^{-1}$ ). After longer periods of soaking, the  $\text{Hg(II)}$ -ISE did not show further improvements in response. Therefore, it can be seen that the conditioning for the proposed ( $\text{Hg(II)}$ -ISE) is a necessary step to increase the number of active sites of the ionophore used.

#### Response time and reversibility for $\text{Hg(II)}$ -ISE based on CPA

The response time for this ISE (E2) was tested with  $\text{Hg}(\text{NO}_3)_2$  solutions by changing from lower to higher concentrations within a range of  $1 \times 10^{-7}$  to  $1 \times 10^{-2} \text{ mol dm}^{-3}$ . The results (Fig. 11) showed that the response time of the CPA based  $\text{Hg(II)}$ -ISE was 10 s. The reversibility of the electrode was examined by alternatively dipping it in aqueous solutions of  $\text{Hg}(\text{NO}_3)_2$  at two different concentrations ( $1 \times 10^{-4}$  and  $1 \times 10^{-3} \text{ mol dm}^{-3}$ ). Results are shown in Fig. 12. It can be observed that the proposed electrode exhibited a satisfactory reversibility although the time required for attaining a stable potential (or equilibrium state) by changing from a low to a high concentration was longer than when changing from a higher to a lower concentration. Therefore, the response time was found to be about of 8 s when the concentration of  $\text{Hg}(\text{NO}_3)_2$  solution was

changed from  $1.0 \times 10^{-3}$  to  $1.0 \times 10^{-4} \text{ mol dm}^{-3}$ , but the response time increased to 13 s on the switch from  $1.0 \times 10^{-4}$  to  $1.0 \times 10^{-3} \text{ mol dm}^{-3}$ .

#### Lifetime of the CPA based $\text{Hg(II)}$ -ISE

The lifetime of the ISE was monitored with time as shown in Fig. 13. It was found that this electrode exhibited a good stability in the response up to a period of 68 d. Indeed the mean drift of slope observed over this period was found to be less than  $0.02 \text{ mV dec}^{-1}$ . Therefore, it can be concluded that the lifetime of the CPA based  $\text{Hg(II)}$ -ISE is 68 d.

#### Potentiometric selectivity coefficients of the CPA based $\text{Hg(II)}$ ion selective electrode

The potentiometric selectivity coefficients of the CPA based  $\text{Hg(II)}$ -ISE were determined for a variety of interfering metal ions such as  $\text{Na(I)}$ ,  $\text{K(I)}$ ,  $\text{Ag(I)}$ ,  $\text{Mg(II)}$ ,  $\text{Ca(II)}$ ,  $\text{Ba(II)}$ ,  $\text{Sr(II)}$ ,  $\text{Mn(II)}$ ,  $\text{Co(II)}$ ,  $\text{Ni(II)}$ ,  $\text{Cu(II)}$ ,  $\text{Zn(II)}$ ,  $\text{Cd(II)}$ ,  $\text{Pb(II)}$ ,  $\text{Fe(III)}$  and  $\text{Al(III)}$  using two methods: the Separate Solution Method (SSM)<sup>59</sup> and the Matched Potential Method (MPM).<sup>60</sup> The values of selectivity coefficients obtained under optimum experimental



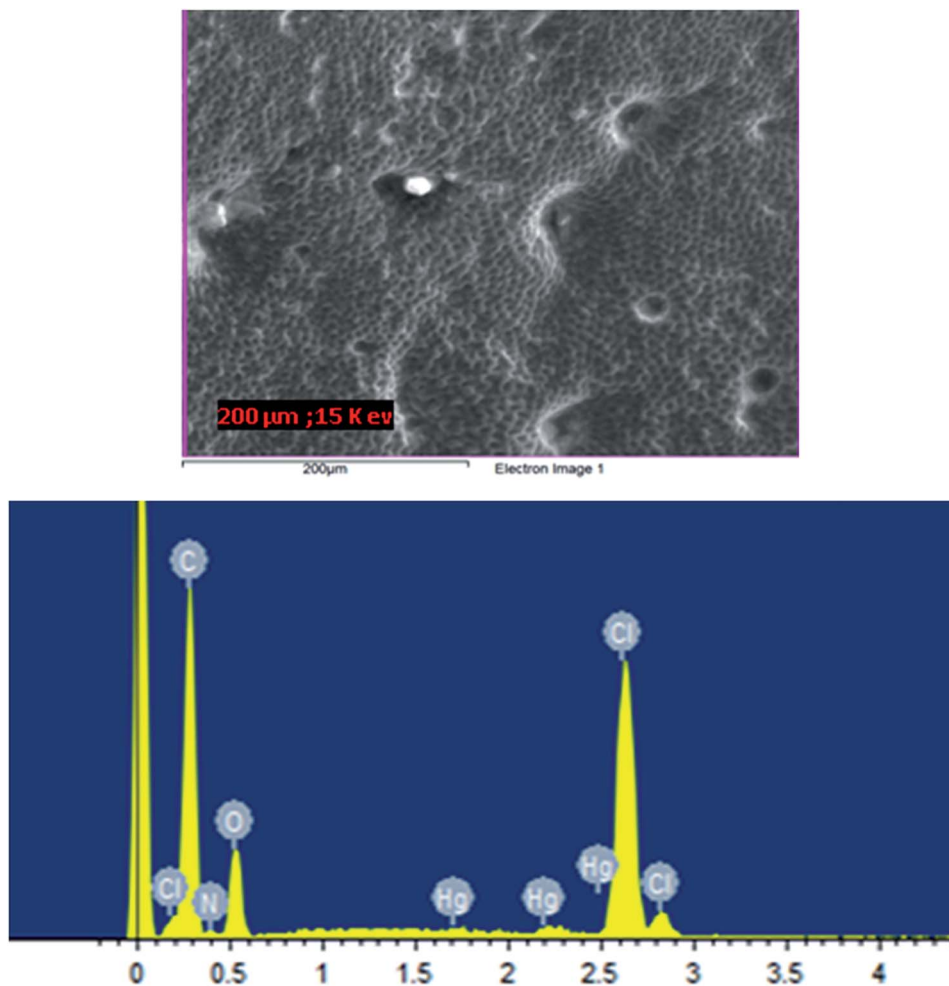


Fig. 7 (a) SEM of CPA ionophore-PVC membrane (E2) after it has been used in the ISE for Hg(II) selectivity; (b) EDAX analysis of the membrane showing the presence of Hg(II).

conditions are given in Table 3. Although the trend observed is the same for data derived from these two methods, the values differ given that different assumptions are made in these methods.

It can be seen from the  $\log K_{\text{Hg}^{2+}, \text{M}^{n+}}^{\text{plot}}$  values (by both methods) that the CPA based Hg(II) selective electrode is more selective towards mercury over all of the interfering ions

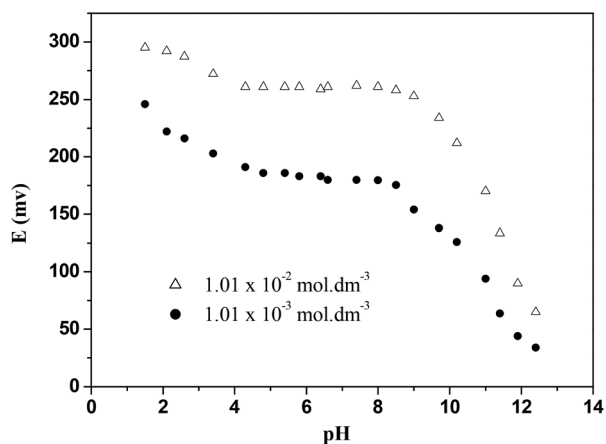


Fig. 8 Effect of the pH on the response of the CPA based electrode (E2).

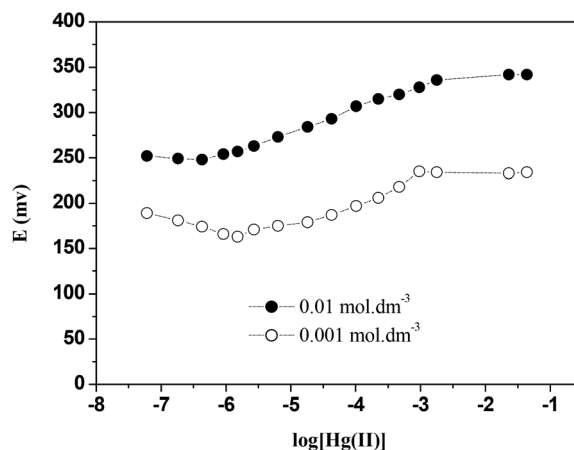


Fig. 9 Effect of internal solution concentration on the response of the ISE (E2).



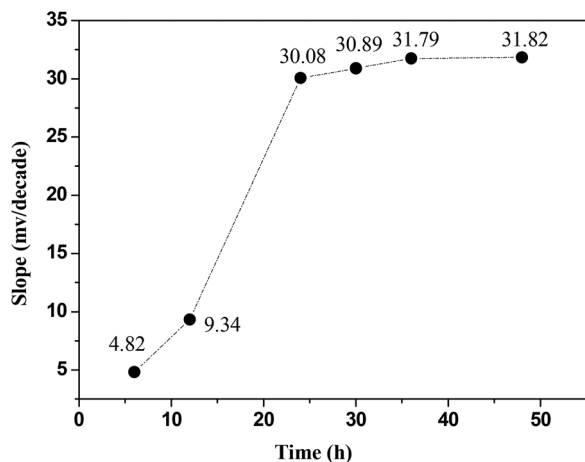


Fig. 10 Effect of soaking time on the Nernstian behaviour of the Hg ISE at 298 K.

studied. Also  $\log K_{\text{Hg}^{2+}, \text{M}^{n+}}^{\text{plot}}$  values for most ions examined except for the  $\text{Ag}(\text{I})$  ion were of the order of  $-1.38$  or smaller.

However, the  $\log K_{\text{Hg}^{2+}, \text{Ag}^+}^{\text{plot}}$  values for the  $\text{Ag}^+$  interfering ion obtained from the SSM and MPM methods were  $-0.46$  and  $-0.99$  respectively which does not seem to be a strong interference. The reliability of the electrode as an analytical tool was tested and this is now discussed.

#### Analytical applications of the CPA based Hg(II)-ISE

The CPA based Hg(II) ISE was used as (i) an indicator electrode for the potentiometric titration of Hg(II) with EDTA and (ii) the determination of mercury in an amalgam sample. Thus Fig. 14 shows the potentiometric titration curve resulting from the titration of an aqueous solution of  $\text{Hg}(\text{NO}_3)_2$  ( $1 \times 10^{-3} \text{ mol dm}^{-3}$ ) with EDTA ( $0.005 \text{ mol dm}^{-3}$ ) using the optimized electrode. A sharp end point was obtained.

Table 4 shows the results obtained for the determination of mercury(II) in a filling dental amalgam together with those obtained by atomic absorption spectrometry. An excellent

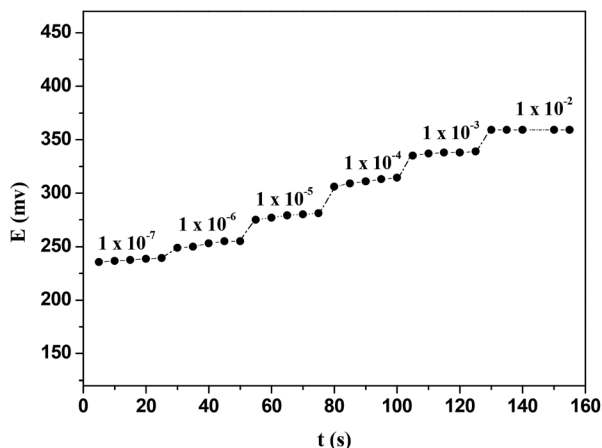


Fig. 11 Dynamic response of the CPA based Hg(II)-ISEs for step changes in mercury(II) concentration at 298 K.

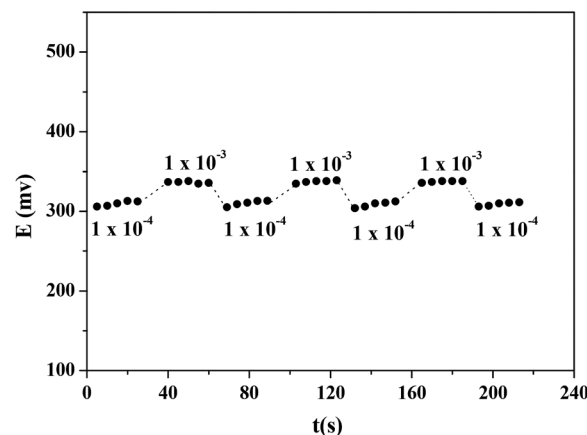


Fig. 12 Reversibility of the CPA based Hg(II)-ISE.

agreement is found between the two methods. Furthermore, the species such as  $\text{Cu}(\text{II})$ ,  $\text{Zn}(\text{II})$  and  $\text{Sn}(\text{II})$  present in the amalgam samples have no interfering effect. Therefore, it was concluded that the CPA based Hg(II)-selective electrode could be successfully employed for the quantitative determination of Hg in a real dental amalgam sample.

#### Advantages of the CPA based ISE relative to existing ionophore based Hg(II) electrodes

A great deal of the published material involves the use of the  $\text{NaPh}_4\text{B}$  (or related salts) as an additive,<sup>20–25,28,29,31,34–39,41,43,44,46–52,66–75</sup> which as shown in this paper interacts with Hg(II) and this has implications on the characteristics reported for these electrodes. In the absence of fundamental studies, the response of the electrode may result from the response of the additive rather than the ionophore (this may be occurring in the prior studies mentioned). Other ISEs for the detection of Hg(II) used plasticisers other than *o*-NPOE or DOS.<sup>40,42,45,53,76</sup> Given that a plasticizer may have an effect on the potential response of the electrode a comparison between the research carried out with

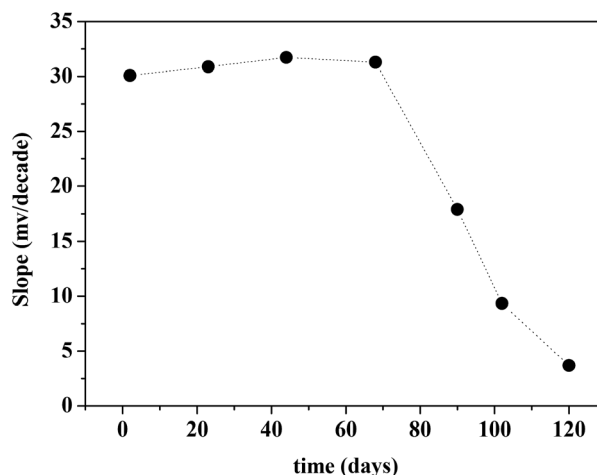


Fig. 13 Lifetime of the CPA based mercury(II) ion selective electrode.

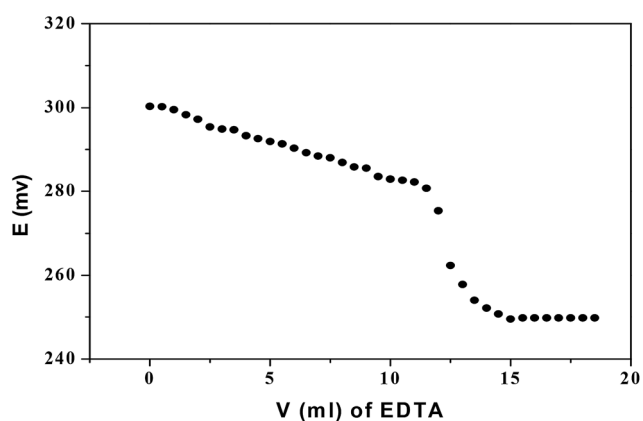




**Table 3** Selectivity coefficients of metal cations relative to mercury(II) at 298 K using two methods (for ISE E2)

Interferent ( $M^{n+}$ )	Values of $\left(\log K_{Hg^{2+},M^{n+}}^{plot}\right)$	
	Separate solution method <sup>a</sup> SSM	Matched potential method <sup>b</sup> MPM
Li <sup>+</sup>	-1.71	-1.38
Na <sup>+</sup>	-2.28	-2.20
K <sup>+</sup>	-2.30	-2.28
Rb <sup>+</sup>	-3.92	-3.07
Mg <sup>2+</sup>	-2.38	-2.40
Ca <sup>2+</sup>	-3.98	-3.37
Sr <sup>2+</sup>	-3.13	-2.91
Ba <sup>2+</sup>	-3.88	-2.99
Mn <sup>2+</sup>	-5.00	-4.16
Fe <sup>3+</sup>	-2.42	-2.68
Co <sup>2+</sup>	-4.26	-3.77
Ni <sup>2+</sup>	-1.89	-1.55
Cu <sup>2+</sup>	-3.17	-2.94
Ag <sup>+</sup>	-0.46	-0.99
Zn <sup>2+</sup>	-4.07	-3.63
Cd <sup>2+</sup>	-2.39	-2.55
Al <sup>3+</sup>	-3.03	-2.91
Pb <sup>2+</sup>	-2.61	-2.75

<sup>a</sup> Conditions: primary ion (A):  $2.23 \times 10^{-4}$  mol dm<sup>-3</sup> Hg(NO<sub>3</sub>)<sub>2</sub> interfering ions (B):  $2.23 \times 10^{-4}$  mol dm<sup>-3</sup>. <sup>b</sup> Conditions: reference solution:  $1.0 \times 10^{-4}$  mol dm<sup>-3</sup> Hg(NO<sub>3</sub>)<sub>2</sub> primary ions (A):  $1 \times 10^{-2}$  mol dm<sup>-3</sup> Hg(II); interfering ions (B):  $1 \times 10^{-1}$  mol dm<sup>-3</sup>.

**Fig. 14** Potentiometric titration of Hg(NO<sub>3</sub>)<sub>2</sub> with EDTA using the CPA based electrode as indicator electrode at 298 K.

different plasticiser is not strictly valid. The only reported Hg(II) ISE in which the same additive and plasticiser have been used is that reported by Somer and co-workers<sup>77</sup> using tridodecyl

methyl ammonium iodide as the ionophore. However the linear range for this electrode ( $5 \times 10^{-5}$  to  $1 \times 10^{-1}$  mol dm<sup>-3</sup>) with a DL of  $1 \times 10^{-5}$  mol dm<sup>-3</sup> is less sensitive than the one reported in this paper.

## Final remarks

Despite the efforts being made worldwide on the design of Hg(II) ISEs by the use of cyclic and acyclic ligands a comprehensive review at the state of the art in this particular area of research leads to the conclusion that an important drawback is the lack of a link between fundamental studies and their applications. This is clearly demonstrated in this paper where we show that the currently (and almost universally used) tetraphenyl borate additive salts (used in the design of Hg ISEs incorporating PVC membranes) act by themselves as selective detectors for this cation. It may well be that in some cases the additive and receptor can have a cooperative effect (offering an improvement in the characteristics of the electrode) but this need to be

**Table 4** Application of Hg(II)-ISEs based on the ionophores CPA determination of mercury ion a filling dental amalgam alloy sample mercury using an amalgam as a real sample

Sample	Supplier	Ionophore used	Mercury(II) content, mol dm <sup>-3</sup>		
			Practical con. using AAS	Practical con. using Hg-ISE	Compatibility (%)
Dental amalgam alloy	Nordiska Dental AB Industries, Sweden	CPA	$1 \times 10^{-5}$	$9.51 \times 10^{-6}$ M	95.1



investigated. Quite clearly this is not the case in the system investigated in this paper.

While calix[4]pyrroles and derivatives have been extensively used for the design of ISEs and chemically modified electrodes, most efforts have been directed to anions rather than cations.<sup>78</sup> However the possibility of altering the selectivity through structural modification (as demonstrated in this paper) opens the way for further developments on the use of these receptors for the design of cation selective electrodes. Further studies are being carried out to assess this electrode for monitoring fluoride in water as well as its selectivity in the presence of mercury(II) fluoride.

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