



Synthesis of Tetra-*N*-substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes and their Application as Lead (II) Selective Electrodes. X-ray Crystal Structure of 4,7,13,16-tetrathenoyl- 1,10-dioxa-4,7,13,16-tetraazacyclooctadecane

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Abstract. Tetra-*N*-substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes (tetraazacrown ethers) (**1-5**) have been synthesised. Each compound was incorporated in a PVC membrane that provided the basis for a lead-selective potentiometric electrode. The electrode based on the 4,7,13,16-tetrathenoyl-1,10-dioxa-4,7,13,16-tetraazacyclooctadecane (**5**) ionophore bearing four thenoyl functional subunits exhibited excellent lead (II) ion selectivity with only Ag^+ and Hg^{2+} significantly interfering. The crystal structure of this host (**5**) has been determined by single crystal X-ray analysis. *Crystal data.* $\text{C}_{32}\text{H}_{36}\text{N}_4\text{O}_6\text{S}_4$, M 700.9, monoclinic, space group $\text{P}2_1/c$, a , 10.315(4), b , 13.635(2), c , 14.357(6) Å, β 124.63(2)°, V 1661.6(9) Å³, D_c 1.40 g cm⁻³, Z 2, μ_{Cu} 29.90 cm⁻¹. Final residuals R , R_w were 0.054, 0.082 for the observed data.

Key words: ion-selective membrane electrodes, ionophores, crystal structure, tetraazacrown ethers

Supplementary Data relating to this article are deposited with the British Library as Supplementary Publication No. 82247 (13 pages).

1. Introduction

In the past decade, various macrocyclic and non-macrocyclic ligands have been synthesised and studied as ion-selective ionophores for sensing heavy metal ions such as lead (II) and mercury (II) for applications in industry and environment pollution monitoring. In particular, macrocyclic ionophores such as pendant diaza-crown ethers bearing heterocyclic ligating groups [1–7] have attracted attention as noble-metal molecular receptors. The heteroatoms present in the side arms of these host ligands cooperate in binding to the guest cations. The diaza crowns have complexation properties that lie between oxygen crown ethers which bind strongly to

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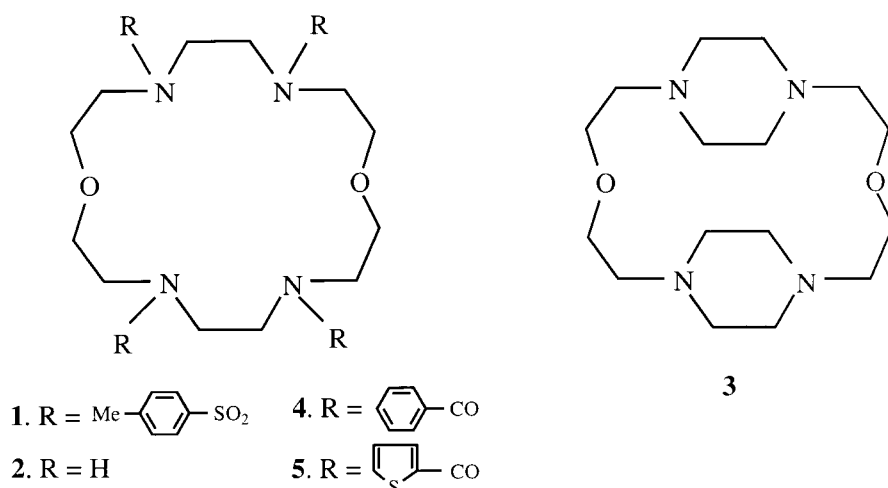


Figure 1. Structures of macrocycles.

alkali metals and nitrogen cyclams which bind very strongly to the transition metals [8]. These complexation properties make these ionophores ideal candidates for heavy metal ion sensing studies where strong binding of the cation to the ionophore is not desirable. We have recently synthesised a series of ionophores derived from 1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (diazacrown ether) bearing pendant benzoyl, thenoyl, thenyl and 2-thiopheneacetyl groups on nitrogen atoms and studied their ion complexing properties [7]. These ionophores when used in ion-selective electrodes showed very good selectivity for lead (II) compared with other divalent cations (except mercury (II)). The alkali metal ions, in particular K⁺, however, still interfered with these electrodes. In order to improve the selectivity of these ionophores we decided to replace the two electronegative oxygen atoms in the diazacrown with two soft, basic amidic nitrogens. The resulting tetrazacrown cavity should be less favourable to alkali metal ions.

A series of tetraacyl substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes (**1–5**) have been synthesised and their properties as ionophores in ion-selective membrane electrodes are described. We have also carried out an X-Ray crystal structure determination of uncomplexed tetrathenoylaza crown **5** and herein report the result of this study.

2. Experimental

2.1. MATERIALS FOR SYNTHESIS

All chemicals for the synthesis of the ionophores e.g. ethylenediamine, 4-methylphenylsulfonyl chloride, 1, 2-dibromoethane and 2-chloroethyl ether, 2-thiophenecarbonyl chloride, benzoyl chloride etc. were purchased from Aldrich

Chemical Company (Sydney, Australia). The solvents used in the reactions were dried prior to their use.

2.2. ANALYTICAL PROCEDURES

Melting points are uncorrected and were determined using a Kofler hot stage micro-melting apparatus. ^1H NMR spectra were obtained in the designated solvent on a Bruker AC300F (300 MHz) spectrometer. Ultraviolet spectra were measured on a Hitachi U-3200 spectrometer and refer to solution in methanol. Infrared spectra were recorded as paraffin mulls on a Perkin-Elmer 298 spectrometer. The electron impact mass spectra were recorded on a VG Quattro mass spectrometer at 70 eV ionisation voltage and 200 °C ion source temperature.

2.3. SYNTHETIC PROCEDURES

Compounds **1**, **2** and **3** were synthesised according to the procedures described previously [10, 11].

2.3.1. Preparation of 4,7,13,16-tetra(4-methylphenylsulfonyl)-1,10-dioxo-4,7,13,16-tetraazacyclooctadecane (**1**)

A mixture of ditosyl ethylenediamine [9] (14.75 g, 40 mmol), K_2CO_3 (8 g) and 2-chloroethyl ether (5.3 mL, 45 mmol) in dimethylformamide (16 mL) was heated in an oil bath at 160 °C for 5 hr. After cooling to room temperature, water (50 mL) was added to the reaction mixture. The resulting sticky precipitate was washed thoroughly several times with water. The residual product was suspended in acetone (50 mL), filtered and washed with a small amount of acetone. The crude product was recrystallized from DMF to give the tetra(4-methylphenylsulfonyl)crown (**1**) as white needles. M.p. 244-246 °C (Lit [10]: m.p. 245 °C); Yield 6.1 g (35%); ν_{SO} 1340, 1150 cm^{-1} ; $^1\text{H-NMR}$ (CDCl_3) δ : 2.44 (s, 12H, CH_3), 3.22, (bt, 8H, CH_2), 3.32, (s, 8H, CH_2), 3.54, (bt, 8H, CH_2), 7.32, (d, $J_{\text{H-H}} = 8.2$ Hz, 8H, ArH), 7.71, (d, $J_{\text{H-H}} = 8.2$ Hz, 8H, ArH).

2.3.2. Preparation of 1,10-dioxo-4,7,13,16-tetraazacyclooctadecane (**2**)

A solution of tetra(4-methylphenylsulfonyl)tetraazacrown (**1**) (3.75g, 4.3 mmol) in conc. H_2SO_4 (5 mL) was heated at 100 °C for 3 days. The reaction mixture was cooled in an ice bath and neutralised with sodium hydroxide pellets to pH 7–8. The resulting product was extracted with chloroform, dried over anhydrous sodium sulfate and evaporated. The residual oil was recrystallized from light petroleum (60-80 °C) to yield the tetraazacrown (**2**) as colourless prisms. M.p. 58 °C (Lit [10]: m.p. 58–60 °C); Yield 25%; $^1\text{H-NMR}$ (CDCl_3) δ : 2.45–2.75, (bs, 4H, NH), 2.75–2.90, (bs, 16H, CH_2), 3.59–3.66, (bt, 8H, OCH_2); mass spectrum m/z : 261 (MH^+ , 100%).

2.3.3. *Preparation of 4,13-dioxo-1,7,10,16-tetraazatricyclo [14.2.2.2^{7,10}] docosane (3)*

Tetraaza crown (**2**) (0.2 g, 0.77 mmol) was reacted with 1,2-dibromoethane (0.65 g, 3.4 mmol) in 10 mL of ethanol according to the procedure previously described [11]. After evaporation of the solvent the oily product was purified by chromatography on silica gel [eluent, CH₂Cl₂/CH₃OH (19 : 1)] to yield the tetraaza crown (**3**) as a light yellow oil which solidified on keeping. Yield (25 mg, 11%); ¹H-NMR (CDCl₃) δ: 2.4–2.9 (m, 24H, —CH₂N), 3.5–3.7 (m, 8H, —CH₂O); mass spectrum m/z: 313 (MH⁺, 100%).

2.3.4. *Preparation of 4,7,13,16-tetrabenzoyl-1,10-dioxo-4,7,13,16-tetraaza cyclooctadecane (4)*

A solution of benzoyl chloride (0.1 mmol) in acetonitrile (2 mL) was added with stirring to a solution of tetraazacrown (**2**) (50 mg, 0.19 mmol) in acetonitrile (5 mL) containing anhydrous Na₂CO₃ (0.02 g). The mixture was stirred at 60 °C for 24 hours. After cooling to room temperature the solid was filtered and the solvent was evaporated to dryness. The oily residue was chromatographed on silica gel using CH₂Cl₂/CH₃OH (19 : 1) as the eluent. The crude product was recrystallized from CHCl₃ to yield the tetrabenzoyl crown (**4**) as a white solid. Yield 75%; M.p. 172–174 °C; ν_{CO} 1610 cm⁻¹; λ_{max} 223.5 nm (ε 16390); ¹H NMR (CDCl₃) δ: 3.00–4.10 (m, 24H, CH₂), 7.38 (bs, 20H, ArH); mass spectrum m/z: 676 (M⁺, 10%), 571 (16), 486 (10), 460 (8), 394 (12), 339 (20), 295 (30), 247 (80), 173 (100), 148 (60).

2.3.5. *Preparation of 4,7,13,16-tetrathenoyl-1,10-dioxo-4,7,13,16-tetraaza cyclooctadecane (5)*

A solution of 2-thiophene carbonyl chloride (0.32 g, 2.16 mmol) in dry tetrahydrofuran (2 mL) was added with stirring to a solution of tetraaza crown (**2**) (70.2 mg, 0.27 mmol) in dry THF (5 mL) containing pyridine (0.05 mL). After refluxing overnight, the solvent was evaporated and the residue was extracted with dichloromethane. The organic phase was washed with aqueous HCl (1M, 20 mL), water, dried over Na₂SO₄ and evaporated. The crude product was recrystallized by dichloromethane/methanol to yield tetrathenoyl crown (**5**) as colourless needles. Yield (80 mg, 45%); M.p. 199–201 °C; ν_{CO} 1605 cm⁻¹; λ_{max} 266 (ε 22215), 242 nm (ε 30594); ¹H-NMR (CDCl₃) δ: 3.5–3.7 (bs, 16H, —CH₂N), 3.74–4.0 (bs, 8H, —CH₂O), 6.8–6.95 (bs, 2H, thiophene H), 7.5 (m, 2H, thiophene H); mass spectrum m/z 701 (MH⁺, 100%).

2.4. X-RAY DATA COLLECTION, STRUCTURE DETERMINATION AND REFINEMENT

The title compound **5** was crystallized from dichloromethane to yield colourless prisms. Crystal data. C₃₂H₃₆N₄O₆S₄, M 700.9, monoclinic, space group P2₁/c, *a* 10.315(4), *b* 13.635(2), *c* 14.357(6) Å, β 124.63(2) °, V 1661.6(9) Å³, D_c 1.40 g cm⁻³, Z 2, μ_{Cu} 29.90 cm⁻¹. Crystal size 0.14 by 0.21 by 0.25 mm, 2θ_{max} 140°, min. and max. transmission factors 0.58 and 0.72. The number of reflections was 2511 considered observed out of 3148 unique data, with R_{merge} 0.019 for 111 pairs of equivalent hk0 reflections. Final residuals R, R_w were 0.054, 0.082 for the observed data.

Reflection data were measured with an Enraf-Nonius CAD-4 diffractometer in θ/2θ scan mode using graphite monochromatized copper radiation (λ 1.5418 Å). Data were corrected for absorption using the analytical method of de Meulenaer and Tompa [12]. Reflections with I > 3σ(I) were considered observed. The structure was determined by direct phasing and Fourier methods. Hydrogen atoms were included in calculated positions and were assigned thermal parameters equal to those of the atom to which they were bonded. Positional and anisotropic thermal parameters for the non-hydrogen atoms were refined using full matrix least squares.

Reflection weights used were 1/σ²(F₀), with σ(F₀) being derived from σ(I₀) = [σ²(I₀) + (0.04I₀)²]^{1/2}. The weighted residual is defined as R_w = (ΣwΔ²/ΣwF₀²)^{1/2}. Atomic scattering factors and anomalous dispersion parameters were from International Tables for X-ray Crystallography [13]. Structure solution was by SIR92 [14] and refinement used BLOCKLS, a local version of ORFLS [15]. ORTEP-II [16] running on a Power Macintosh was used for the structural diagram, and a DEC Alpha-AXP workstation was used for calculations.

2.5. MEMBRANE ELECTRODES AND EMF MEASUREMENTS

2.5.1. Chemicals

Poly(vinyl chloride) (PVC; high molecular weight type) used as the electrode membrane material, 2-nitrophenyl octyl ether (NPOE) used as the membrane solvent (plasticiser), and potassium tetrakis(p-chlorophenyl)borate (KTPCIPB) used as the anionic additive, were purchased from Aldrich Chemical Co. Lead nitrates and other metal nitrates were AR grade and aqueous solutions were prepared using Millipore deionised water.

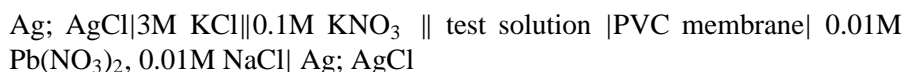
2.5.2. Membrane and Electrode Preparation

PVC membranes for ion selective electrodes were prepared as described before [7]. Typical membrane components (3w/w% ionophore, 30w/w% PVC, 67w/w% NPOE and 50 mol% KTPCIPB relative to the ionophore content), about 200 mg in total, were dissolved in 2 mL of freshly distilled and dried THF. A clear solution was poured into a glass ring (25 mm) resting on a glass plate and left overnight

at room temperature while the solvent evaporated. The resulting membrane was peeled off from the glass ring and a disc of 5 mm i.d. was cut out and fixed, on to the base of a 5 mm i.d. PVC tube, using a small amount of THF, to form the ion-selective electrode body. The internal reference electrode was a silver chloride-coated silver wire (anodised in 1M HCl for 5 min), and the internal filling solution was 0.01M $\text{Pb}(\text{NO}_3)_2$, 0.01M NaCl. The electrodes were conditioned in 0.01 M $\text{Pb}(\text{NO}_3)_2$ solution overnight.

2.5.3. EMF Measurements

E.m.f. measurements were made with a Orion model SA 720 digital pH / mV meter equipped with a cell amplifier at 25 ± 0.5 °C using the following electrochemical cell system as previously described.



All sample solutions were prepared with metal nitrate salts and potential measurements were carried out at pH 4.5–5.0, adjusting the pH of the solutions with very dilute nitric acid or sodium hydroxide as necessary. The activities of metal ions were based on activity coefficients calculated from the Debye-Hückel equation [17]. Selectivity coefficients $K_{\text{Pb},\text{M}}^{\text{Pot}}$ for ions were determined by the separate solution method (SSM) [18], using 0.01 M solutions of the metal nitrates at pH 4 except mercury and iron (III) nitrate which were measured at pH 2 and 3 respectively. The slope of the calibration graph of E_{cell} against $\log(a_{\text{Pb}^{2+}})$ and the detection limit (from 3 times the standard deviation of the voltage in a number of blank solutions) of each electrode were also determined.

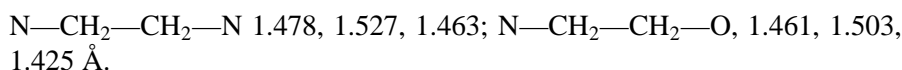
3. Results and Discussion

3.1. SYNTHESIS OF IONOPHORES

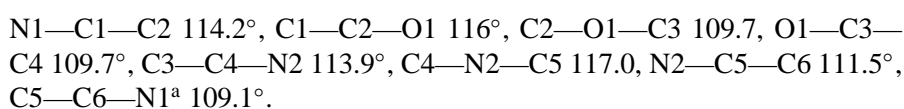
The chemical structures of the synthesised ionophores are indicated in Figure 1. The structures of the synthesised compounds were confirmed by ^1H NMR, infrared and mass spectroscopic analysis. The macrocyclic free base 1,4,10,13-tetraaza-7,16-dioxacyclooctadecane **2** was prepared by the condensation of *N, N'*-ditosylethylenediamine with 2-chloroethyl ether in dimethylformamide containing potassium carbonate [10]. Deprotection of the *N*-tosyl group with concentrated sulfuric acid followed by basification afforded the parent macrocycle in 25% yield. The four acyl groups were introduced by acylation of the free base with benzoyl chloride or 2-thiophene carbonyl chloride in tetrahydrofuran in the presence of pyridine.

3.2. CRYSTAL STRUCTURE

Crystals of **5** suitable for single crystal X-ray diffraction studies were obtained by slow crystallization from dichloromethane. A representation of the structure is presented in Figure 2 and selected atomic coordinates, bond lengths, bond angles and torsion angles are reported in Tables I–III. The macrocycle has a crystallographic centre of symmetry and an approximate twofold axis of symmetry with one axis passing through the C1 and C1^a atoms and the other through the N2 and N2^a atoms. The bond distances in the 18-member crown have the following average values:



and endocyclic angles:



The macrocycle **5** clearly has the following two important features: (i) a base tetraazacrown ring, which offers a hydrophilic site for the cation and (ii) four amide side chains which offer effective binding sites for divalent cations. In the solid state, this combination of tetraazacrown and pendant amide groups represent what could be described as a preorganised three dimensional host. Additionally, the four thenoyl groups in the molecule are in a 1,2-alternate conformation with the two thenoyl groups being above the plane of the tetraazacrown ring and the other two below it. This is in contrast to the structure of tetra *N*-substituted cyclams where four functional groups have been proposed to be oriented on the same side of the ring [19]. Supplementary material deposited comprises atomic and thermal parameters, interatomic distances and angles, torsional angles and structure factors.

3.3. EMF MEASUREMENTS

Figure 3 shows plot of E_{cell} against $\log a_{\text{Pb}}^{2+}$ for electrodes prepared with each of the synthesised ionophores (**1–5**). Even though all the ionophore molecules have the same cavity size, molecules containing tetraamide pendant groups (**4–5**) showed the best response to lead ions. In general, their slopes were in agreement with the expected Nernstian value (30 mV/decade change in activity) and the linear ranges followed tetrathenoyl (**5**) (slope 32.0 mV/decade) > tetrabenzoyl (**4**) (slope 23.5 mV/decade). The corresponding ionophore containing sulfonamide pendant groups, tetra(4-methylphenylsulfonyl)tetraazacrown ether (**1**), showed a very poor response to lead ions and an insignificant linear range (slope 14.7 mV/decade). The 4-methylphenylsulfonyl group being a strongly electron-withdrawing group, causes a significant decrease in the electronegativities of the four nitrogen atoms thereby decreasing their complexing ability for Pb (II) ions. It is also possible that

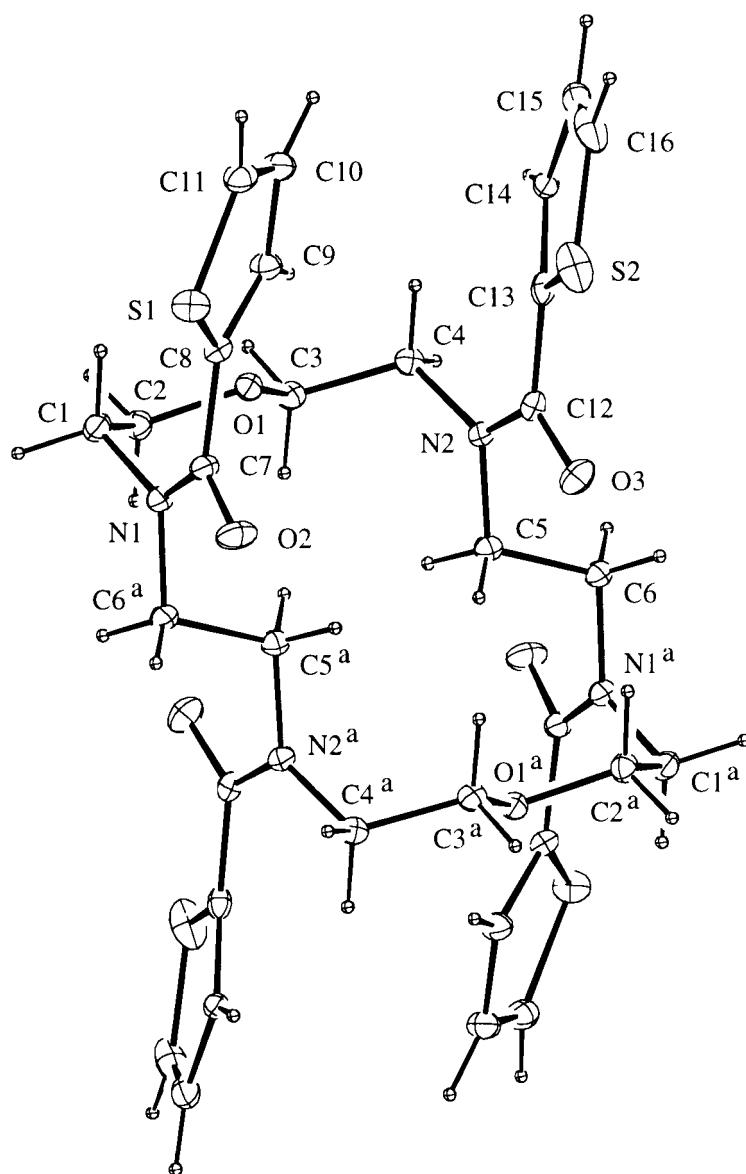


Figure 2. Molecular structure of **5**: top view showing the symmetrical nature of the molecule.

the orientation of the bulky 4-methylphenylsulfonyl group hinders the approach of lead (II) ions into the macrocyclic cavity. Moreover, the ionophores containing the 4-methylphenylsulfonyl groups have poor solubility in organic solvents which results in the formation of inhomogeneous membranes.

In comparison, the unsubstituted parent ionophore (**2**) and tetraaza tricyclo ionophore (**3**) showed very poor cation response, which can be attributed to the

Table I. Final fractional atomic coordinates for non-hydrogen atoms of **5** (e.s.d.s are in parentheses)

Atom	x	y	z	(U ₁₁ + U ₂₂ + U ₃₃)/3
S1	0.2169(1)	0.5592(1)	0.1303(1)	0.071(1)
S2	0.7072(1)	0.7646(1)	0.1808(1)	0.100(1)
O1	0.8001(2)	0.4087(1)	0.2676(2)	0.047(1)
O2	0.4831(3)	0.5376(2)	0.3790(2)	0.080(2)
O3	0.9603(3)	0.7012(2)	0.4045(2)	0.076(1)
N1	0.5934(3)	0.4118(2)	0.3465(2)	0.049(1)
N2	1.0382(3)	0.5663(2)	0.3600(2)	0.048(1)
C1	0.5889(3)	0.3381(2)	0.2705(2)	0.054(1)
C2	0.7460(4)	0.3207(2)	0.2875(3)	0.054(1)
C3	0.9551(3)	0.3946(2)	0.2951(2)	0.049(1)
C4	1.0163(3)	0.4896(2)	0.2812(2)	0.050(1)
C5	1.1511(4)	0.5465(2)	0.4808(2)	0.059(1)
C6	1.3008(3)	0.6075(2)	0.5307(2)	0.055(1)
C7	0.4964(3)	0.4895(2)	0.3122(2)	0.052(1)
C8	0.4073(3)	0.5213(2)	0.1926(2)	0.048(1)
C9	0.4580(4)	0.5395(2)	0.1228(3)	0.058(2)
C10	0.3366(4)	0.5851(3)	0.0196(3)	0.066(2)
C11	0.2016(4)	0.5982(3)	0.0129(3)	0.067(2)
C12	0.9507(3)	0.6490(2)	0.3307(2)	0.050(1)
C13	0.8491(3)	0.6814(2)	0.2109(3)	0.051(1)
C14	0.8540(3)	0.6681(2)	0.1141(2)	0.052(1)
C15	0.7419(5)	0.7299(3)	0.0247(3)	0.087(2)
C16	0.6560(4)	0.7818(3)	0.0483(4)	0.103(3)

basicity of the nitrogen atoms in the ionophores [7]. Ionophores containing basic groups form highly stabilised complexes with cations and the resulting positively charged complexes lead to anionic response. In addition, the strong proton affinity of the basic ionophores interferes with their ion-sensitivity under acidic conditions.

The selectivity coefficients for the electrodes (**1–5**), using sixteen different cations are presented in Figure 4 and expressed as $\log K_{\text{Pb},\text{M}}^{\text{pot}}$. The conditioned membrane electrodes containing tetrathenoyltetraazacrown ether (**5**) are, with the exception of silver and mercury, selective to lead. Electrodes derived from tetrabenzoyletetraazacrown ether (**4**), on the other hand, are more potassium selective and the selectivity coefficients for Na^+ , Li^+ , Ca^{2+} and Ba^{2+} are very close to that of lead. Similarly, ionophores **1–3** are poorly selective and show strong interference with the alkali metal ions and transition metal cations.

Table II. Selected bond distances (Å) involving non-hydrogen atoms of **5** (e.s.d.s are in parentheses)

N1-C1	1.464(4)	C9-C10	1.429(5)
C1-C2	1.514(4)	C10-C11	1.352(5)
C2-O1	1.420(3)	C11-S1	1.687(4)
O1-C3	1.425(3)	S1-C8	1.711(3)
C3-C4	1.503(4)	N2-C12	1.352(4)
C4-N2	1.461(4)	C12-O3	1.234(3)
N2-C5	1.463(4)	C12-C13	1.483(4)
C5-C6	1.527(4)	C13-C14	1.430(4)
C6-N1 ^a	1.478(3)	C14-C15	1.417(5)
N1-C7	1.344(4)	C15-C16	1.320(7)
C7-O2	1.232(3)	C16-S2	1.678(6)
C7-C8	1.479(4)	S2-C13	1.703(3)
C8-C9	1.390(4)		

Table III. Selected bond angles (°) involving non-hydrogen atoms of **5** (e.s.d.s are in parentheses)

N1-C1-C2	114.2(2)	C8-C9-C10	111.0(3)
C1-C2-O1	110.0(2)	C9-C10-C11	113.0(3)
C2-O1-C3	109.7(2)	C10-C11-S1	112.4(2)
O1-C3-C4	109.7(2)	C11-S1-C8	92.6(2)
C3-C4-N2	113.9(2)	C4-N2-C12	125.0(2)
C4-N2-C5	117.0(2)	C5-N2-C12	117.6(2)
N2-C5-C6	111.5(2)	N2-C12-O3	120.0(3)
C5-C6-N1 ^a	109.1(2)	N2-C12-C13	121.0(3)
C1-N1-C7	124.5(2)	O3-C12-C13	118.9(3)
C6 ^a -N1-C7	118.0(2)	C12-C13-C14	134.2(3)
N1-C7-O2	121.5(3)	C12-C13-S2	115.6(2)
N1-C7-C8	119.9(3)	S2-C13-C14	109.7(2)
O2-C7-C8	118.5(3)	C13-C14-C15	110.1(3)
C7-C8-C9	130.5(3)	C14-C15-C16	114.1(4)
C7-C8-S1	117.8(2)	C15-C16-S2	113.0(3)
S1-C8-C9	111.0(2)	C16-S2-C13	93.0(2)

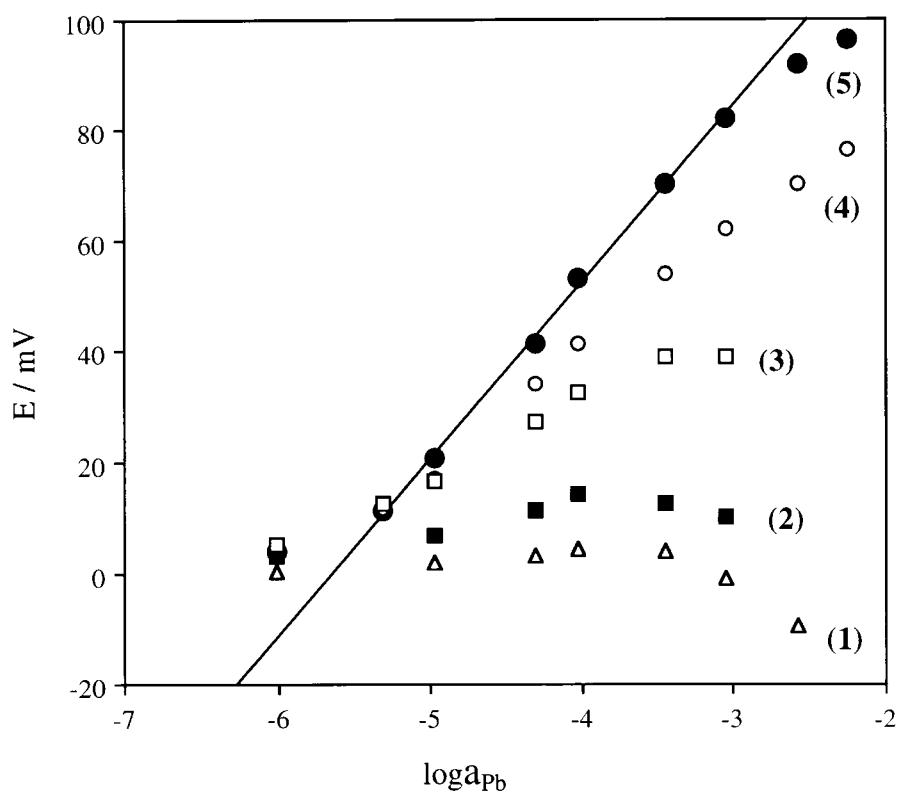


Figure 3. Lead (II) calibration curves for membrane electrodes based on tetra-*N*-substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes 1-5.

The complexation of 1,10-dioxa-4,7,13,16-tetraazacyclooctadecane **2** and related compound **3** with various metal ions including Pb (II) has been reported [11]. It has been proposed on the basis of size-match selectivity that the tetraazacrown cavity should show a strong preference for Pb^{2+} which more nearly matches the size of the cavity. However, poor size selectivity of the unsubstituted crown- and aza-crown ethers has been attributed to the flexibility of the macrocycles. It has been shown by Hancock et al. [11] that successive insertion of ethylene bridges into the 1,4-diamino units in tetraazacrown **3** increases its rigidity, which in turn leads to better selectivity. Unfortunately, the crystal structure of this free ligand **3** [11] showed that the piperazine rings responsible for making the ligand more size selective assume an energetically lower chair conformation rather than the boat conformation necessary for complexation. It is also known that complexation rates of macrocycles with pendent donor groups are higher than for the parent macrocycles. Therefore the tetrathenoyl ionophore **5** is expected to show faster complexation rate and higher selectivity. Recently a crystal structure [20] of a manganese complex of 1,10-dioxa-4,7,13,16-tetraazacyclooctadecane bearing four 2-pyridylmethyl pendent groups has been reported. In the solid state two man-

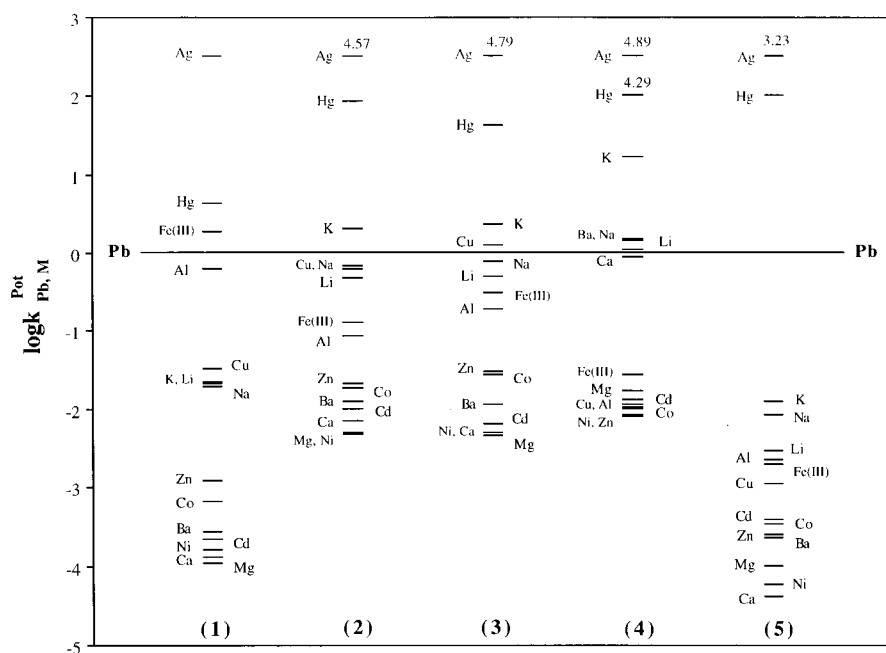


Figure 4. Values of selectivity coefficients $\log K_{Pb,M}^{dot}$ for membrane electrodes based on tetra-*N*-substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes **1–5**.

ganese (II) atoms are surrounded by four nitrogens (two from the pyridine ligand and two from the macrocycle) and two oxygen atoms, one from a bridging hydroxo ligand, the other from an ether function. Such a scenario is unlikely in the case of **5** because of the size of the Pb (II) cation and the nature of the thiophene amide group, which is not as strongly coordinating as a pyridine ring. We attempted to obtain crystals of the Pb–(**5**) complex but without success. A low formation constant of this complex is not necessarily a problem in membrane electrode applications where rapid complexation and decomplexation of the ligand is an essential prerequisite of an efficient (ie Nernstian) membrane electrode.

Although the tetrathenoyl ligand **5** is likely to be flexible in solution, it may not be completely free in a membrane environment. Our X-Ray crystallography results clearly show that the tetrathenoyl ligand **5** is highly symmetrical with the four amide groups strategically placed to take part in coordination with the metal ions. The selectivity of the tetrathenoyl (**5**) membrane towards lead (II) ions was significantly better than that of tetrabenzoyl (**4**). This could be attributed to the presence of thiophene ligating groups that might provide an initial affinity for the lead (II) ions.

It is interesting to note that 4,7,13,16-tetrathenoyl-1,10-dioxa-4,7,13,16-tetraazacyclooctadecane electrodes (**5**) demonstrate higher selectivity for lead (II) cations than the corresponding 7,16-dithenoyl-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane membrane electrodes [7]. For example the selectivity values

$\log K_{\text{Pb,M}}^{\text{pot}}$ of the tetrathenoyl ionophore (**5**) are -1.90 , -2.07 , -4.38 and -4.01 for $M = \text{K}$, Na , Mg and Ca respectively, which may be compared with previously reported values of -0.12 , -0.31 , -1.52 and -2.64 for the dithenoyl diazacrown ether ionophore [7].

4. Conclusions

The tetra-substituted 1,10-dioxa-4,7,13,16-tetraazacyclooctadecanes represent a unique class of host molecules, which combine properties of the parent tetraaza crown ether with those of arm-donor groups in cooperation. This cooperative participation clearly results in increased metal-recognition ability. Ion selective electrodes based on tetrathenoyl-1,10-dioxa-4,7,13,16-tetraazacyclooctadecane (**5**) exhibit rapid response, high selectivity and sensitivity for Pb^{2+} ions. A number of applications of these electrodes for measurement of lead in environmental monitoring, for example lead in contaminated soils, is now being studied in our laboratory.

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