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Ligand modifications for tailoring the binuclear microenvironments in Schiff-base calixpyrrole Pacman complexes**‡

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Graphical abstract:

Synopsis:
Two strategies to modify the bimetallic microenvironment in Schiff-base calixpyrrole Pac-man complexes are described and result in either laterally-twisted or vertically-elongated binuclear compounds.
Abstract

The synthesis and structures of two new octadentate, Schiff-base calixpyrrole macrocycles are presented in which modifications at the meso-substituents (L^1) or the aryl spacer between the two pyrrole-imine donor compartments (L^2) are introduced. The outcomes of these changes are highlighted in the structures of binuclear Pacman complexes of these macrocycles, [M_2(L^1)] and [M_2(L^2)]. Both palladium and cobalt complexes of the fluorenyl-meso-substituted macrocycle H_4L^1 adopt rigid, but laterally-twisted geometries with enclosed bimetallic microenvironments; a consequence of this spatial constraint is an exo-exo-bonding mode of pyridine in the dicobalt complex [Co_2(py)_2(L^1)]. In contrast, the use of an anthracenyl backbone between the two donor compartments (H_4L^2) generates a binuclear palladium complex in which the two PdN_4 environments are approximately cofacial and separated by 5.3 Å, so generating a bimetallic complex that is structurally very similar to binuclear compounds of cofacial diporphyrins.

Introduction

Strategies for the development of new catalysts suitable for multielectron redox reactions of small molecules that are fundamental to nascent energy technologies such as solar fuel and fuel cells often take inspiration from Nature where such reactions are catalysed by metalloenzymes that contain precisely-organised bi- or multimetallic reaction sites. As such, the design of ligands that can promote the construction of bi- and multimetallic complexes that imitate or surpass enzymes as catalysts in these processes have both a long held fascination and increasing strategic significance. In particular, numerous studies have been carried out on binuclear complexes of cofacial and Pacman diporphyrins and their corrole relatives as they have been shown to manage the multiple electron and proton inventory for a variety of redox reactions of small molecules including O_2, H_2O, N_2, and CO_2. These binucleating ligands provide precisely-controlled primary coordination environments for the metals, coupled with the ability to organize their intraspatial separation, which results in a well-defined bimetallic reaction microenvironment. However, the multi-step synthetic routes to these compounds are challenging, and, as an alternative, we, and Sessler and co-workers, reported independently synthetic procedures to a series of straightforwardly-prepared, binucleating Schiff-base calixpyrrole macrocycles (H_4L) that adopt “double-pillared” Pacman geometries on metal coordination. In relation to the chemistry of small molecules, binuclear Fe(II) complexes of these macrocycles were shown to react with oxygen to form the oxo-bridged compounds [Fe_2(μ-O)(L)], while binuclear Co(II) complexes reduce and retain dioxygen within the macrocyclic cleft to form mixtures of the peroxo complex [Co_2(μ-O_2)(L)] and the superoxo cation [Co_2(μ-O_2)(L)]^+. Significantly, these latter cobalt Pacman complexes were shown to catalyse selectively the four-electron, four-proton reduction of dioxygen and furthermore, the mechanism of this reaction is thought to be similar to that for the cobalt diporphyrin analogues, in that the superoxo cation [Co_2(O_2)(L)]^+ is believed to be the catalytically-relevant species. Disappointingly, it was
found that the rate of catalysis was very low with limited turnover, and it was reasoned that this was a consequence of the formation of the redox inactive peroxo complex and single-atom bridged species such as $[\text{Co}_2(\mu-\text{OH})(\text{L})]^+$. 

In order to access more catalytically-active binuclear complexes, it therefore appears important that the design of the bimetallic microenvironment should favour the formation of diatom-bridged intermediates over single-atom-bridged species. This rationale has been used to good effect in binuclear diporphyrin chemistry, in particular that related to oxo-atom transfer and oxygen evolution, where the use of bulky meso-mesityl substituents on the porphyrin rings causes the two metalloporphyrin units to ‘spring’ apart and to disfavour the formation of inhibitory oxo- and hydroxo-bridges.\(^9,10\) In our case, we reasoned that two complementary ligand design approaches could be used to overcome the problems associated with mono-atom bridged complexes and to favour the formation of diatom-bridged complexes: (i) the incorporation of more sterically-hindering meso-substituents that would promote both a lateral twist and open the mouth of the cleft, and (ii) the use of elongated aryl hinges between the two N\(_4\)-donor compartments (Chart 1). These approaches make use of the intrinsic modularity of our ligand synthesis in that it is straightforward to modify the meso-substituents and aryl backbone as these components are derived from readily-available ketones and aromatic diamines.

**Chart 1.** Ligand design strategies to disfavour single-atom-bridged binuclear complexes.

Herein we describe our initial research into two new macrocyclic ligand designs that use sterically-rigid fluorenyl meso-substituents or anthracenyl aryl backbones to generate new classes of binuclear macrocyclic Pacman complexes.

**Experimental Section**

**General**

The syntheses of diethyl-2,2’-dipyrrmethane,\(^11\) 2,2’-dipyrrro-9-fluorene,\(^12\) 1,8-diaminoanthracene,\(^13,14\) \([\text{PdCl}_2(\text{PhCN})_2]\),\(^15\) and \([\text{Co}(\text{THF})\langle\text{N(SiMe}_3\rangle_2\rangle\),\(^16\) were carried out as described in the literature, with the
final reduction step of 1,8-diaminoanthracene carried out in the dark to avoid decomposition. Pyrrole was distilled under reduced pressure prior to use. All other chemicals were used as purchased. The synthesis of the macrocycle H₄L² was carried out in the dark. The palladium complex [Pd₂(L²)], and the cobalt compounds [Co₂(L¹)] and [Co₂(py)₂(L¹)] were synthesised under nitrogen using Schlenk and glovebox techniques. Dry solvents (THF, CH₂Cl₂ and toluene) were purified by passage through Vacuum Atmospheres solvent drying towers, pyridine was distilled from potassium and stored over molecular sieves, CDCl₃ was stirred over activated alumina and trap-to-trap vacuum distilled, and d₈-THF and d₅-pyridine were dried over potassium, trap-to-trap vacuum distilled, and freeze-pump-thaw degassed three times. ¹H NMR spectra were recorded at 298 K on a Bruker ARX250, DPX360, DMX500 or AVA600 spectrometer at 250.13, 360.13, 500.13 and 599.81 MHz respectively; ¹³C{¹H} NMR spectra were recorded at 298 K on a Bruker ARX250, DPX360 or DMX500 at 62.90, 90.55 and 125.77 respectively. All ¹H NMR spectra were referenced internally to residual protio-solvent resonances. EPR spectra were recorded on a Bruker ER200D spectrometer operating at 9.14 GHz, and IR spectra were recorded on a JASCO FT/IR 460 Plus spectrometer in the range 4000-400 cm⁻¹. Electrospray mass spectra were recorded using a Thermo LCQ instrument and electron impact mass spectra using a Thermo MAT 900XP spectrometer. Elemental analyses were carried out by Mr. Stephen Boyer at the London Metropolitan University. UV-vis spectra were recorded in THF or CH₂Cl₂ on a PerkinElmer Lambda 900 UV/VIS/NIR Spectrophotometer.

Synthesis of 9,9-bis(5-formylpyrrole-2-yl)fluorene, 2 - Neat POCl₃ (0.69 mL, 7.41 mmol) was added dropwise to a stirred solution of 9,9-bis(pyrrole-2-yl)fluorene (1.00 g, 3.38 mmol) in DMF (10 mL) at 0°C, during which the colour changed from red to red-brown. The mixture was stirred for 1 h at room temperature, after which the solution was cooled down to 0°C and quenched by addition of H₂O (20 mL). Aqueous KOH (2M) was added slowly until the solution became strongly basic and colourless solids had precipitated. The solution was then boiled for 1 h, the solids collected by filtration, washed with water (3 × 50 mL) and dried under vacuum to yield 1.01 g, 85% of 2 as a colourless powder.

¹H NMR (CDCl₃, 360.13 MHz): δH 11.38 (br, N-H, 2H), 8.90 (s, 2H, CHO), 7.92 (m, 2H, fluorenyl), 7.73 (m, 2H, fluorenyl), 7.35 (m, 4H, fluorenyl), 6.61 (d, 2H, pyrrole), 5.65 (d, 2H, pyrrole); ¹³C{¹H} NMR (CDCl₃, 90.55 MHz): δC 178.6 (s, CHO), 147.4 (s, quaternary), 143.4 (s, quaternary), 139.8 (s, quaternary), 132.9 (s, quaternary), 128.5 (s, CH₆fluorenyl), 128.4 (s, CH₆fluorenyl), 126.1 (s, CH₆fluorenyl), 121.6 (s, CH₆pyrrole), 120.2 (s, CH₆fluorenyl), 110.7 (s, CH₆pyrrole), 56.1 (s, quaternary); IR (nujol): ν 3120 (N-H), 1656 (C=O), 1634 (C=N) cm⁻¹; Analysis. Found: C, 78.17; H, 4.67; N, 8.15. C₂₃H₁₈N₂O₂ requires: C, 78.39; H, 4.58; N, 7.95 %; UV-Vis (CH₂Cl₂): λ max 289 nm (log ε 10.9 mol⁻¹.L.cm⁻¹).

Synthesis of H₄L¹ - A mixture of 2 (0.50 g, 1.42 mmol) and 4,5-dimethyl-2,3-phenylenediamine (0.19 g, 1.42 mmol) in methanol (20 mL) was warmed until some part of the solids were dissolved, giving a yellow suspension. Neat TFA (0.32 g, 2.8 mmol) was added dropwise, causing the entire residual solid to dissolve
and yield a red solution. The mixture was stirred for 15 min, and then solid KOH was added slowly in portions causing the immediate precipitation of yellow solids. The solids were collected by filtration, washed with methanol (3 x 10 mL) and dried under vacuum to yield 0.60 g, 93% of H$_4$L$^1$ as a yellow powder. A sample of H$_4$L$^1$ was recrystallized from CHCl$_3$/hexane solution for elemental analysis, while single crystals suitable for X-ray diffraction were grown by Et$_2$O diffusion into a CH$_2$Cl$_2$ solution.

$^1$H NMR (CDCl$_3$, 360.13 MHz): $\delta$$_H$ 9.05 (br, NH, 4H), 8.20 (s, 4H, imino), 7.81 (d, 4H, $J$=7.60 Hz , fluorenyl Ar$H$), 7.57 (d, 4H, $J$=7.60 Hz, fluorenyl Ar$H$), 7.43 (t, $J$=7.3 Hz, 4H, fluorenyl Ar$H$), 7.32 (t, $J$=7.3 Hz, 4H, fluorenyl Ar$H$), 6.84 (d, 4H, phenyl Ar$H$), 6.54 (d, 4H, $J$=3.3 Hz, pyrrole CH$_2$), 6.06 (d, 4H, $J$=3.3 Hz, pyrrole CH$_2$), 2.20 (s, 12H, C$_6$H$_{12}$); $^{13}$C ($^1$H) NMR (CDCl$_3$, 90.55 MHz): $\delta$$_C$= 151.4 (s, imino), 148.4 (s, quaternary), 141.9 (s, quaternary), 140.9 (s, quaternary), 139.0 (s, quaternary), 135.2 (s, quaternary), 132.7 (s, quaternary), 129.6 (s, fluorenyl CH), 129.2 (s, fluorenyl CH), 126.6 (s, fluorenyl CH), 124.5 (s, phenyl CH), 121.6 (s, fluorenyl CH), 117.4 (s, pyrrole CH), 110.9 (s, pyrrole CH), 57.3 (s, quaternary), 20.2 (s, CH$_3$); IR (nujol): $\nu$ 3441 (N-H), 1616 (C=N), 1554 (C=C) cm$^{-1}$; UV-Vis (CH$_2$Cl$_2$): $\lambda$$_{max}$ 310 nm (ln $\varepsilon$ 11.7 mol$^{-1}$.L.cm$^{-1}$); ESI-MS: m/z 905.4 (M$^+$+1$^+$, 76 %); Analysis. Found: C, 68.43; H, 4.39; N, 10.04 %.

Synthesis of the binuclear palladium complex [Pd$_2$(L$^1$)] - To a stirred solution of H$_4$L$^1$ (0.100 g, 0.11 mmol) in CH$_2$Cl$_2$ (15 mL) was added a solution of [PdCl$_2$(PhCN)$_2$] (0.085 g, 0.22 mmol) in CH$_2$Cl$_2$ (10 mL). The resulting solution was stirred for 10 min at RT during which the solid dissolved and the colour changed to light red. Then NEt$_3$ (0.2 mL) was added dropwise, and the resulting deep red solution was stirred for 16 h, reduced in volume and the crude product precipitated by addition of hexane. The solid was extracted into toluene and filtered. The filtrate was evaporated and the solids recrystallized from CH$_2$Cl$_2$/hexane at room temperature yielding 0.066 g, 54 % of [Pd$_2$(L$^1$)] as a brown/red powder. Single crystals suitable for X-ray diffraction were grown by slow evaporation of a Et$_2$O solution.

$^1$H NMR (CDCl$_3$, 360.13 MHz): $\delta$$_H$ 7.78 (d, 2H, fluorenyl Ar$H$), 7.49 (m, 2H, fluorenyl Ar$H$), 7.44 (m, 2H, fluorenyl Ar$H$), 7.41(m, 2H, fluorenyl Ar$H$), 7.39 (s, 4H, CHN), 7.31 (m, 2H, fluorenyl Ar$H$), 6.72 (m, 2H, fluorenyl Ar$H$), 6.68(s, 4H, phenyl Ar$H$),6.60 (m, 2H, fluorenyl Ar$H$) 6.53 (d, 4H, $J$=3.90 Hz, pyrrole CH$_2$), 6.01 (m, 2H, fluorenyl Ar$H$), 5.45 (d, 4H, $J$=3.90 Hz, pyrrole CH$_2$), 2.10 (s, 12H, CH$_3$); $^{13}$C ($^1$H) NMR (CDCl$_3$, 90.55 MHz): $\delta$$_C$= 160.2 (s, imine), 149.7 (s, quaternary), 148.8 (s, quaternary), 148.2 (s, quaternary), 143.0 (s, quaternary), 141.8 (s, quaternary), 139.6 (s, quaternary), 139.1 (s, quaternary), 135.2 (s, quaternary), 129.9 (s, fluorenyl CH), 129.0 (s, fluorenyl CH), 128.6 (s, fluorenyl CH), 127.3 (s, fluorenyl CH), 126.9 (s, fluorenyl CH), 126.3 (s, fluorenyl CH), 125.1 (s, phenyl), 120.8 (s, fluorenyl CH), 120.1 (s, fluorenyl CH), 119.7 (s, pyrrole CH), 109.7 (s, pyrrole CH), 62.6 (s, quaternary), 20.3 (s, CH$_3$); IR (nujol): $\nu$ 1547 (C=N) cm$^{-1}$; UV-Vis (CH$_2$Cl$_2$): $\lambda$$_{max}$ 311 nm (ln $\varepsilon$ 10.63 mol$^{-1}$.L.cm$^{-1}$); 415 (ln $\varepsilon$ 10.06); ESI-MS: m/z 1115.4 (M$^+$+2, 6 %); Analysis. Found: C, 66.53; H, 4.41; N, 9.94. C$_{62}$H$_{44}$N$_8$Pd$_2$ requires: C, 66.85; H, 4.39; N, 10.01 %
Synthesis of $[\text{Co}_2(\text{L}^1)]$ and its pyridine adduct $[\text{Co}_2(\text{exo-py})_2(\text{L}^1)]$ - A solution of $[\text{Co}($THF$)_2\{\text{N(SiMe}_3)_2\}_2]$ (1.82 g, 4.00 mmol) in THF (25 mL) was added dropwise to a suspension of $\text{H}_4\text{L}^1$ (1.81 g, 2.00 mmol) in THF (30 mL) at -78 °C. The mixture was stirred for 16 h at room temperature, after which it was evaporated to dryness under vacuum. The dark residues were extracted into warm toluene (ca. 50 °C, total 50 mL), filtered by cannula, and the filtrate evaporated to dryness under vacuum, yield 1.52 g, 75.0 %. Dark-red crystals of $[\text{Co}_2(\text{L}^1)]$ were grown by hexane diffusion into toluene. Addition of pyridine to the same crystallisation mixture generated dark red prisms of the bis(pyridine) adduct $[\text{Co}_2(\text{exo-py})_2(\text{L}^1)]$ that were suitable for X-ray crystallography.

$^1\text{H}$ NMR (CDCl$_3$, 360.13 MHz): $\delta$ 74.6 (br.s, 4H), 39.5 (s, 4H), 1.44 (s, 2H), 1.13 (s, 2H), 0.60 (s, 2H), -2.40 (s, 2H), -3.16 (s, 2H), -24.5 (s, 2H), -32.2 (br.s, 4H), -43.4 (br.s, 2H), -51.2 (s, 2H); $\mu_{\text{eff}}$(CDCl$_3$, 298 K) 3.24 $\mu_B$; IR (nujol): $\nu$ 1551 (C=N) cm$^{-1}$; UV-Vis (THF): $\lambda_{\text{max}}$ 332 nm (ln $\varepsilon$ 11.12 mol$^{-1}$Lcm$^{-1}$), 257 (11.29), 221 (11.4); Analysis: Found: C, 73.16; H, 4.16; N, 10.93. C$_{62}$H$_{44}$N$_8$Co$_2$ requires: C, 73.14; H, 4.35; N, 10.98 %

$[\text{Co}_2(\text{py})_2(\text{L}^1)]$ EPR (131 K, CHCl$_3$): $g$ 2.217

Synthesis of dialdehyde 4 – Neat POCl$_3$ (40.4 mL, 0.16 mol) was added dropwise to a stirred, cooled solution of 3 (40.0 g, 0.20 mol) in DMF (400 mL) at 0 °C. The cherry red reaction mixture was stirred at this temperature for 1 h and allowed to warm up to RT. The mixture was quenched with H$_2$O (400 mL) and 2M KOH (1000 mL) which caused the precipitation of light pink solids. The suspension was warmed at 70°C for 50 min, allowed to cool, and the solid filtered, washed with water until washings were neutral, and dried under vacuum to yield 40.0 g, 89 % of 4 as a pale pink solid.

$^1\text{H}$ NMR (CDCl$_3$, 250.13 MHz): $\delta$ 10.36 (s, 2H, NH), 9.05 (s, 2H, CHO, s), 6.76 (d, 2H, $J = 4.0$ Hz, pyrrole CH), 6.19 (d, 2H, $J = 4.0$ Hz, pyrrole CH), 1.98 (q, 4H, $J = 7.4$ Hz, CH$_2$), 0.65 (t, 6H, $J = 7.4$ Hz, CH$_3$); $^{13}$C($^1\text{H}$) NMR (CDCl$_3$, 62.90 MHz): $\delta_C$ 179.2 (s, CHO), 146.6 (s, quaternary), 132.6 (s, quaternary), 122.4 (s, CH), 111.1 (s, CH), (s, quaternary), 29.6 (s, CH$_2$), 8.7 (s, CH$_3$); Analysis: Found: C, 69.72; H, 7.04; N, 10.75. C$_{15}$H$_{18}$N$_2$O requires: C, 69.74; H, 7.02; N, 10.84 %

Synthesis of 1,8-diaminoanthracene - 1,8-diaminoanthracene was prepared as reported in the literature from 1,8-dinitroquinone,$^{13,14}$ except the quinone reduction step was carried out in the dark and the diamine product was kept away from light at all times. The diamine was isolated as a bright yellow solid by filtration, washed with hexane and recrystallized from methanol at -80°C to yield pale yellow needles in an overall 81 % yield. The $^1\text{H}$ NMR data are identical to those reported previously.

$^1\text{H}$ NMR (d$_8$-THF, 599.81 MHz): $\delta$ 8.65 (s, 1H, ArH), 8.18 (s, 1H, ArH), 7.26 (d, $J = 8.4$ Hz, 2H, ArH), 7.16 (t, $J = 7.8$ Hz, 2H, ArH), 6.58 (d, $J = 7.1$ Hz, 2H ArH), 5.21 (s, 4H, NH); IR (nujol): $\nu$ 3427 (NH), 3373 (NH), 1583 (C=N), 1549 (C=C) cm$^{-1}$; UV-Vis (THF): $\lambda_{\text{max}}$ 356 nm (ln $\varepsilon$ = 8.35 mol$^{-1}$Lcm$^{-1}$), 375
Synthesis of the anthracenyl-macrocycle $H_4L^2$ - The reaction and work up were carried out in the dark. A suspension of diethyl-5,5'-diformyl-2,2'-dipyrrromethane (2.46 g, 79.6 mmol) in MeOH (40 mL) was warmed until a clear solution was obtained and added to a suspension of 1,8-diaminoanthracene (2.00 g, 9.6 mmol) in MeOH (40 mL). Neat (CF$_3$CO)$_2$O (1.60 mL, 11.5 mmol) was added dropwise at room temperature, the reaction mixture was stirred at a ambient temperature for 30 min during which a bright orange precipitate formed. NEt$_3$ was added dropwise until the precipitate turned bright yellow. The mixture was stirred for a further 15 min, the solid filtered, washed with methanol, and dried under vacuum to yield 2.80 g, 68% of $H_4L^2$ as a yellow solid that was stored under N$_2$.

$^1$H NMR (CDCl$_3$, 250.13 MHz): $\delta$H 9.28 (s, 2H, NH), 9.22 (s, 2H, ArH), 8.42 (s, 2H, ArH), 8.37 (s, 4H, imino), 7.82 (d, 4H, $J$ = 8.4 Hz, ArH), 7.43 (t, 4H, $J$ = 7.3 Hz, ArH), 6.95 (d, 4H, $J$ = 7.0 Hz, ArH), 6.68 (d, 4H, $J$ = 3.6 Hz, pyrrole CH), 6.23 (d, 4H, $J$ = 3.7 Hz, pyrrole CH), 2.05 (q, 8H, $J$ = 7.4 Hz, CH$_2$), 0.81 (t, 12H, $J$ = 7.3 Hz, CH$_3$); $^{13}$C{$^1$H} NMR (CDCl$_3$, 62.90 MHz): $\delta$C 150.6 (s, imine), 150.1 (s, quaternary), 140.83 (s, quaternary), 132.5 (s, quaternary), 125.8 (s, CH), 125.2 (s, CH), 118.9 (s, C), 116.9 (s, CH), 112.8 (s, CH), 110.0 (s, CH), 45.5 (s, meso-C-pyrrole quaternary), 32.2 (s, CH$_2$), 9.1 (s, CH$_3$); IR (nujol): $\nu$ 3250 (N-H), 1613 (C=N), 1550 (C=C) cm$^{-1}$; UV-Vis (THF): $\lambda_{max}$ 322 nm ($\ln \varepsilon$ = 9.6 mol$^{-1}$Lcm$^{-1}$), 370 (shoulder), 420 (shoulder); EI-MS: 860.5 (M$^+$, <1%), 831.5 (M$^+$-29, <1%, Et loss), 448.2 (M/2+18, 2%, water adduct), 430.2 (M/2, 100%) 401.1 (M/2-28, 86%, Et loss); ESI-MS: 897.27 (M+37, 28%), 861.74 (M$, 40%)$, 431.72 (M/2+2, 40%); TLC: DCM/MeOH 97:3, Rf = 0.81, 0.62 (product); Analysis. Found: C, 80.48; H, 6.13; N, 12.94. C$_{58}$H$_{52}$N$_8$ requires: C, 80.90; H, 6.09; N, 13.01 %

Synthesis of the potassium salt [K$_4$(THF)$_2$.65$(L$_2$)] - To a stirred mixture of $H_4L^2$ (0.50 g, 0.58 mmol) and KH (0.12 g, 2.90 mmol) was added THF at -78°C under nitrogen. The resulting solution was stirred for 1 h at -78°C, allowed to reach room temperature and stirred for a further 4 h. The deep red solution was decanted from the excess KH and the solvent was removed under reduced pressure to yield 0.70 g, 74% of the potassium salt as a red solid.

$^1$H NMR (d$_5$-pyridine, 500.13 MHz): $\delta$H 10.02 (s, ArH), 8.55 (s, ArH), 8.41 and 8.34 (br.s, ArH), 7.73 and 7.69 (br.d, $J$ = 7.7 Hz, ArH), 7.41 and 7.31 (br.t, $J$ = 7.0 Hz, ArH), 7.22 (m, ArH + pyridine ArH), 6.80 (m, pyrrole CH), 3.67 (m, THF), 3.49 and 3.14 (br, CH$_2$), 2.79 and 2.73 (br, CH$_3$), 1.63 (m, THF), 1.28 (br, CH$_3$); IR (nujol): $\nu$ 1583 (C=N), 1549 (C=C) cm$^{-1}$; Analysis. Found: C, 68.41; H, 5.66; N, 9.54. C$_{68}$H$_{62}$N$_8$K$_4$O$_2$ requires: C, 68.40; H, 5.79; N, 9.30 %

Synthesis of the binuclear palladium complex [Pd$_2$(L$_2$)] - A mixture of $H_4L^2$ (0.13 g, 0.015 mmol) and
KH (0.03 g, 0.075 mmol) was combined in THF at -78 °C, allowed to warm to room temperature, and stirred for a further 4 h. The resulting mixture was transferred by filter cannula into a solution of [PdCl₂(PhCN)₂] (0.15 g, 38.8 mmol) in THF shielded from light, and stirred for 20 days, after which the mixture was filtered, the solvent reduced under vacuum, and recrystallized at -78°C to yield a yellow microcrystalline solid. Yield: 0.04 g, 23 %

¹H NMR (d₈-THF, 500.13 MHz): δH 9.28 (s, 2H, ArH), 7.80 (s, 2H, ArH), 7.74 (s, 4H, imino), 7.34 (d, J = 8.8 Hz, 4H, ArH), 6.93 (dd, J = 7.0 Hz, J = 1.0 Hz, 4H, ArH), 6.84 (dd, J = 8.4 Hz, J = 7.0 Hz, 4H, ArH), 6.81 (d, J = 4.0 Hz, 4H, pyrrole CH), 2.15 (q, J = 7.2 Hz, 4H, C₂H₂), 1.89 (q, J = 7.3 Hz, 4H, C₂H₂), 0.51 (t, J = 7.2 Hz, 6H, C₃H₃), 0.27 (t, J = 7.3 Hz, 6H, C₃H₃); ¹³C{¹H} NMR (d₈-THF, 125.77 MHz) δC 160.6 (s, imine), 145.0 (s, quaternary), 146.9 (s, quaternary), 138.2 (s, quaternary), 132.8 (s, quaternary), 127.9 (s, CH), 126.8 (s, CH), 126.6 (s, CH), 125.1 (s, CH), 120.7 (s, pyrrole CH), 119.4 (s, CH), 116.8 (s, CH), 109.0 (s, pyrrole CH), 40.0 (s, CH₂), 36.6 (s, CH₂), 11.2 (s, CH₃), 10.4 (s, CH₃). The poor solubility of the compound prevented the assignment of the quaternary meso-carbon; IR (nujol): ν 1616 (w), 1570 (C=N), 1552 (C=C) cm⁻¹; UV-Vis (THF): λmax 314 nm (ln ε = 11.0 mol⁻¹Lcm⁻¹), 411 (10.1), 433 (9.9); ESI-MS: 1095.21 (M+2+23, 44%, Na⁺ adduct), 1094.23 (M+1+23, 46%, Na⁺ adduct), 1093.16 (M+23, 64%, Na⁺ adduct), 1092.19 (M-1+23, 57%, Na⁺ adduct), 1091.12 (M-2+23, 63%, Na⁺ adduct), 1090.2 (M-3+23, 52%, Na⁺ adduct). 1072.3 (M+2, 29%), 1071.2 (M+1, 34%), 1070.2 (M, 34%), 1069.2 (M-1, 31%), 1068.2 (M-2, 31%), 1067.1 (M-3, 24%); Analysis. Found: C, 64.89; H, 4.86; N, 9.93. C₅₈H₄₈N₈Pd₂ requires: C, 65.11; H, 4.52; N, 10.47 %.

Alternative synthesis of [Pd₂(L²⁻)] - A solution of [PdCl₂(PhCN)₂] (0.02 g, 0.06 mmol) in THF (1 mL) was added to a solution of H₄L²⁻ (0.05 g, 0.06 mmol) in THF (4 mL) and stirred at room temperature for 30 min. A few drops of NEt₃ were added and the reaction mixture was stirred for a further 3 days at room temperature. The mixture was treated with toluene and solvent was removed under reduced pressure. The crude mixture was analysed by ¹H NMR spectroscopy in CDCl₃ from which crystals suitable for X-ray diffraction deposited.

¹H NMR (CDCl₃, 250.13 MHz): δH 9.08 (s, 2H, ArH), 8.27 (s, 2H, ArH), 8.22 (s, 4H, ArH), 7.67 (d, 4H, J = 8.70 Hz, ArH), 7.27 (m, 4H, ArH), 6.78 (m, 4H, ArH), 6.58 (d, 4H, J = 3.72 Hz, pyrrolic CH), 6.10 (d, 4H, J = 3.73 Hz, pyrrolic CH), 1.54 (m, 4H CH₃CH₂).

Crystallographic details

X-Ray diffraction data from single crystals of H₄L¹ and [Co₂(exo-py)₂(L¹⁻)] were collected at 93.15 K using graphite monochromated Mo Kα radiation (λ = 0.71073 Å) on a Rigaku MM007 diffractometer equipped with a high brilliance Saturn 70 CCD detector. The data for [Pd₂(L¹⁻)], [Co₂(L¹⁻)], H₄L²⁻ and [Pd₂(L²⁻)] were collected at 150 K on a Bruker SMART APEX diffractometer equipped with a CCD
detector. Details of the individual data collections and refinements are given in Table 1. All structures were solved by direct methods and refined using full-matrix least square refinement on $|F|^2$ using SHELXL-97. All non-hydrogen atoms were refined with anisotropic displacement parameters while hydrogen atoms were placed at calculated positions and included as part of a riding model. The X-ray data for H$_4$L$^1$ was collected on a weakly diffracting crystal although the macrocycle is well defined in the model. The solvent of crystallisation in H$_4$L$^2$ was diffuse and disordered and could not be modelled accurately so the corresponding electron density was accounted for using the SQUEEZE routine of PLATON. Three voids were found which was equated to 2 molecules of CH$_2$Cl$_2$ and 6.5 molecules of MeOH in the unit cell. Similarly, the Et$_2$O solvent of crystallisation in the structure of [Pd$_2$(L$^1$)] could not be modelled accurately, and two voids were found using the SQUEEZE routine of PLATON that equate to 2.5 molecules of Et$_2$O per asymmetric unit. The high residual electron densities seen in the structure of [Pd$_2$(L$^1$)] are located close to the Pd centres and are not due to unidentified solvent atoms. The data for [Co$_2$(L$^1$)] were weak and resulted in a model with high residual electron density. The data for [Co$_2$(py)$_2$(L$^1$)] were also weak, and 0.25 molecules of PhMe per asymmetric unit were modelled isotropically, while the remaining unidentified solvent of crystallisation was accounted for using the SQUEEZE routine of PLATON and modelled as 3.5 molecules of PhMe in the unit cell. In the asymmetric unit of the structure of [Pd$_2$(L$^2$)], one molecule of chloroform was disordered about an inversion centre and what appeared to be one molecule of disordered triethylamine was modelled using the SQUEEZE routine of PLATON. Two distinct voids were found with electron density appropriate for one molecule of NEt$_3$ per asymmetric unit.
**Table 1. Crystal data**

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<th>Compound</th>
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<th>Cell setting, space group</th>
<th>a, b, c (Å)</th>
<th>α, β, γ (°)</th>
<th>V (Å³)</th>
<th>Z</th>
<th>Dₐ (Mg m⁻³)</th>
<th>Crystal size (mm)</th>
<th>Absorption correction</th>
<th>Tmin</th>
<th>Tmax</th>
<th>No. of measured, independent and observed reflections</th>
<th>θ max (°)</th>
<th>R(F² &gt; 2σ(F²)), wR(F²), S</th>
<th>No. of parameters</th>
<th>H-atom treatment</th>
<th>Δρ max, Δρ min (e Å⁻³)</th>
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<tr>
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<tr>
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“CCDC 730679-730684 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif

**Results and discussion**

**Synthesis and structures of H₄L₁ and H₄L₂**

Although the synthesis of dipyromethanes from bulky ketones can be problematic, we reported recently that the acid-catalyzed condensation reaction between pyrrole and 3,3,5,5-tetramethylecyclohexanone...
formed the corresponding dipyrrmethane;\textsuperscript{17,18} furthermore, we found that it was possible to use this dipyrrmethane as a precursor to the [2+2] Schiff-base pyrrole macrocycle. As an alternative, we reasoned that planar aromatic substituents would provide excellent steric hindrance that would promote a laterally-twisted conformation in [M\textsubscript{2}(L)] structures, and noted that the \textit{meso}-fluorenyl-dipyrrmethane \textsuperscript{19} 1 had been used in the synthesis of calixpyrroles and in conformational studies of calix[4]phyrins.\textsuperscript{12,19} As such, \textsuperscript{19}I was prepared as described in the literature by reacting fluorenone with pyrrole under acidic conditions,\textsuperscript{12} and was formylated in the 5, 5\textsuperscript{'}-positions using a POCl\textsubscript{3}/DMF Vilsmeier-Haack procedure described by us previously (Scheme 1);\textsuperscript{20} the resulting dialdehyde \textsuperscript{29}2 displayed a resonance at 8.90 ppm in the \textsuperscript{1}H NMR spectrum that is characteristic of the C(H)=O group. Using the method described by us,\textsuperscript{21} and independently by Sessler and co-workers,\textsuperscript{22} we found that the reaction between \textsuperscript{29}2 and 3,4-Me\textsubscript{2}-1,2-diaminobenzene in the presence of CF\textsubscript{3}CO\textsubscript{2}H in methanol resulted in the sole formation of the acid salt of the [2+2] macrocycle H\textsubscript{4}L\textsuperscript{1}(CF\textsubscript{3}CO\textsubscript{2}H)\textsubscript{n} as an orange solid. Neutralisation of this salt with KOH in MeOH caused the rapid precipitation of the macrocycle H\textsubscript{4}L\textsuperscript{1} as an analytically-pure yellow solid in high yield.

\begin{center}
\textbf{Scheme 1.} The synthesis of the fluorenyl and anthracenyl Schiff-base calixpyrroles H\textsubscript{4}L\textsuperscript{1} and H\textsubscript{4}L\textsuperscript{2} and their binuclear Pd and Co complexes
\end{center}

The \textsuperscript{1}H NMR spectrum of H\textsubscript{4}L\textsuperscript{1} displays resonances consistent with the formation of a symmetric Schiff-base calixpyrrole, with the resonance at 8.20 ppm characteristic of the C(H)=N imine proton. The electrospray mass spectrum showed a parent ion at \textit{m/z} 905 that supports the formation of the [2+2] condensation product, and there was no indication of any other lower or higher order condensation products.
In order to synthesise a macrocycle in which the two N₄-donor compartments were more separated vertically, we chose to use 1,8-diaminoanthracene as the hinge component as this would be liable to act as a rigid double-pillar in the resulting [M₂(L)] complexes. While not reported in the literature, we found that 1,8-diaminoanthracene was light sensitive and decomposed rapidly in solution to an intractable dark solid, presumably as a result of radical polymerisation. As such, the synthesis and recrystallization of this diamine was carried out in the dark to afford analytically-pure, pale yellow crystals of the diamine from methanol in good yield. Furthermore, to enhance the solubility of the macrocyclic product in non-polar solvents, the new dialdehyde 4 was generated in good yield by the Vilsmeier-Haack formylation of meso-diethyldipyrrromethane 3. In a similar manner to above, dialdehyde 4 reacts with 1,8-diaminoanthracene in MeOH in the presence of acid (in this case generated from trifluoroacetic anhydride) to form the [2+2] macrocyclic orange acid salt H₄L²(TFA)n, that, upon neutralisation with NEt₃, yields H₄L² as an analytically pure bright yellow solid. Due to the potential reversibility of the imine bond formation in a wet environment, the synthesis of H₄L² was carried out in the dark to prevent the formation of the diaminoanthracene and subsequent light-induced decomposition. However, once dry, the ligand can be stored indefinitely under a dry nitrogen atmosphere in the presence of light. The ¹H NMR spectrum of H₄L² supports the formation of a single, symmetric macrocycle and displays a single resonance at 8.34 ppm characteristic of imine bond formation and a broad resonance at 9.28 ppm integrating for the four pyrrolic N-H groups. In the electrospray mass spectrum of H₄L², a parent ion was seen at m/z 861 and also a doubly-charged base peak at m/z 430; these data support the sole formation of the [2+2] macrocycle, and not any lower or higher order macrocyclic products.

X-ray quality crystals of H₄L¹ and H₄L² were grown by diffusion of Et₂O into a solution of CH₂Cl₂, and MeOH into CH₂Cl₂, respectively, and the crystal structures determined (Figure 1). Crystal data are displayed in Table 1 and selected bond lengths and angles are detailed in Table 2.

Figure 1. X-ray crystal structures of H₄L¹(CH₂Cl₂)₂ (left) and H₄L²(CH₂Cl₂)(MeOH)₃.₂₅ (right). For clarity, all hydrogen atoms, except those bound to the pyrrolic nitrogens, and solvent of crystallisation are omitted (displacement ellipsoids are drawn at 50% probability).
Table 2. Selected bond lengths [Å] and angles [°] for: H$_4$L$_1$(CH$_2$Cl)$_2$; H$_4$L$_2$(CH$_2$Cl)$_2$(MeOH)$_{3.25}$; [Pd$_2$(L$_1$)][(Et$_2$O)$_{2.5}$; [Co$_2$(L$_1$)](PhMe)$_2$; [Co$_2$(py)$_2$(L$_1$)](PhMe)$_{1.125}$ and [Pd$_3$(L$_2$)][(NEt$_3$)(CDCl$_3$)

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<th>H$_4$L$_1$(CH$_2$Cl)$_2$</th>
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<th><a href="PhMe">Co$_2$(L$_1$)</a>$_2$</th>
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In the solid state, the fluorenyl-macrocycle H$_4$L$_1$ adopts a shallow bowl-shaped structure which hinges at the meso-carbons, with the fluorenyl groups essentially orthogonal to the macrocyclic plane. The pyrrole-imine units alternate exo- and endo- within the macrocyclic framework and are involved in hydrogen-bonding interactions with the CH$_2$Cl$_2$ solvent of crystallisation (e.g. N2-M1-C1 3.783 Å) and π-π stacking interactions with neighbouring molecules. Similarly, the anthracenyl macrocycle adopts a wedge shape that is also hinged at the meso-carbons in the solid state with ill-defined solvent molecules present within the cleft; both of these structures are consistent with the propensity of this class of ligand to act as both hydrogen bond donor and acceptors. All the bond distances and angles in H$_4$L$_2$ are similar to those observed in related ligands, although the bond angle at the imine nitrogen in H$_4$L$_2$ is slightly more contracted than in previous structures and in H$_4$L$_1$ (average C1-N1-Caryl 116.1° cf. 120.8°).
**Synthesis and structure of [Pd₂(L¹)]**

The reaction between H₄L¹ and [PdCl₂(PhCN)₂] in the presence of NEt₃ resulted in the formation of the dark red, binuclear palladium complex [Pd₂(L¹)] in good yield (Scheme 1). The presence of eight fluorenyl hydrogens in the ¹H NMR spectrum of [Pd₂(L¹)] suggests that a C₂-symmetric Pacman geometry is present in solution with one half of the fluorenyl group endo- to the molecular cleft, and the other half exo. Furthermore, the lack of NH resonances, and a decrease in the C=N vibration from 1616 in the IR spectrum of H₄L¹ to 1547 cm⁻¹ in [Pd₂(L¹)] are consistent with the coordination of the metal. This structure is retained in the solid state, as shown in the X-ray crystal structure of [Pd₂(L¹)] (Figure 2); crystal data are shown in Table 1 and selected bond lengths and angles in Table 2.

![Figure 2. Solid state structure of [Pd₂(L¹)](Et₂O)₂.5 (left: side-on; right: face-on). For clarity, all hydrogen atoms and solvent of crystallisation are omitted (displacement ellipsoids are drawn at 50% probability).](image)

In [Pd₂(L¹)], the two metals Pd1 and Pd2 sit in approximately square-planar N₄-pyrrole-imine donor environments, in which the sum of the angles at Pd1 is 359.8° and at Pd2 is 359.9°, with out-of-plane distances 0.086 and 0.073 Å respectively. As seen by us previously in similar complexes,⁵ the presence of the aryl groups between the two donor compartments results in a Pacman geometric arrangement. As such, the aryl groups act as hinges and π-stack with a shortest interatomic distance of 3.56 Å, and converge towards the metals with an interplanar angle of 11.2°. The pseudo-porphyrinic cavities are not entirely planar due to the flexibility of the N₄-donor set at the sp³-hybridised meso-carbons which results in dihedral angles between the pyrrole-imine planes of 20.6° at Pd1 and 15.5° at Pd2. Gross structural parameters including the M•••M separation, lateral twist, and vertical bite angles for [Pd₂(L¹)] can be compared to those of similar complexes.
described by us previously, in the particular with the binuclear palladium complexes \([\text{Pd}_2(L^{\text{Me8}})]\) and \([\text{Pd}_2(L^{\text{Ph4Me4}})]\) which differ only in their meso-substitution pattern, \textit{i.e.} \([\text{Pd}_2(L^{\text{Me8}})]\) has methyl meso-substituents while those in \([\text{Pd}_2(L^{\text{Ph4Me4}})]\) are phenyl (Table 3). While crystal packing does appear to have an effect on these structural parameters, for example as seen in the series of complexes \([\text{Cu}_2(L)]\), they remain useful as a way of gaining some comparative insight into a series of interrelated compounds. As a result of avoiding a steric clash between the \textit{endo}-substituents both aryl-meso-substituted complexes display more twisted structures than the Me-substituted complex and results in shorter Pd•••Pd separations and a decrease in the bite angle. In \([\text{Pd}_2(L')]\), it is clear that a \(\pi\)-stacking interaction between the \textit{endo}-fluorenyl-substituents occurs (shortest interatomic separation 3.46 Å) and that these substituents are locked into a more sterically-congested conformation, which contrasts to that seen with meso-Ph substituents that can undergo free rotation about the aryl-meso-C bond. In order to evaluate further the structural effects of the meso-fluorenyl substituents in these binuclear Pacman complexes, the cobalt complex \([\text{Co}_2(L']\)) and its bis(pyridine) adduct \([\text{Co}_2(\text{py})_2(L')\]) were synthesised.

\textit{Table 3.} Comparison of geometric parameters derived from the X-ray crystal structures of a series of Pacman complexes of Schiff-base calixpyrrole ligands (*two molecules in the asymmetric unit*).

<table>
<thead>
<tr>
<th>Compound</th>
<th>(\text{M} \cdot \text{M} [\text{Å}])</th>
<th>Twist [°]</th>
<th>Bite [°]</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{Pd}_2(L')])</td>
<td>3.72</td>
<td>27.8</td>
<td>56.4</td>
<td>This work</td>
</tr>
<tr>
<td>([\text{Pd}_2(L^{\text{Me8}})])</td>
<td>4.11/4.12(^a)</td>
<td>11.1</td>
<td>62.1</td>
<td>17</td>
</tr>
<tr>
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<td>3.94</td>
<td>28.5</td>
<td>59.7</td>
<td>17</td>
</tr>
<tr>
<td>([\text{Co}_2(L')])</td>
<td>3.64/3.64(^a)</td>
<td>34.2</td>
<td>54.7</td>
<td>This work</td>
</tr>
<tr>
<td>([\text{Co}_2(\text{exo-py})_2(L')])</td>
<td>4.12</td>
<td>25.9</td>
<td>62.3</td>
<td>This work</td>
</tr>
<tr>
<td>([\text{Co}_2(L^{\text{Me8}})])</td>
<td>4.08/4.12(^a)</td>
<td>31.3</td>
<td>62.6</td>
<td>8</td>
</tr>
<tr>
<td>([\text{Co}_2(\text{endo-py})(\text{exo-py})(L^{\text{Me8}})])</td>
<td>4.30/4.33(^a)</td>
<td>2.9</td>
<td>64.8</td>
<td>7</td>
</tr>
</tbody>
</table>

\textbf{Synthesis and structure of \([\text{Co}_2(L')\]) and \([\text{Co}_2(\text{py})_2(L')\])}

The transamination reaction between \(\text{H}_4L^{\text{L'}}\) and \([\text{Co}({\text{THF}})[\text{N(SiMe}_3]_2\text{]}_2\]) in THF was carried out and generated the dark red, air-sensitive dicobalt complex \([\text{Co}_2(L')]\) in good yield (Scheme 1). The paramagnetic \(^1\text{H}\) NMR spectrum of \([\text{Co}_2(L')]\) displayed 13 resonances between 74 and -51 ppm that support the adoption of a cleft-like structure in solution, and the room temperature magnetic moment of 3.24 \(\mu_B\) by Evans’ method is appropriate for an S = 1 spin ground state (\(\mu_{\text{calc}}=2.83 \mu_B\)). Metal coordination is corroborated further by a shift in the C=N stretch from 1616 cm\(^{-1}\) in \(\text{H}_4L^{\text{L'}}\) to 1551 cm\(^{-1}\) in \([\text{Co}_2(L')]\). The X-band EPR spectrum of \([\text{Co}_2(\text{exo-py})_2(L')]\) in frozen CHCl\(_3\) consisted of a single, broad
feature centred at $g = 2.217$. Dark-red crystals of $[\text{Co}_2(L^1)]$ were grown by hexane diffusion into toluene, and furthermore, addition of pyridine to the same crystallisation solvent mixture generated dark red prisms of the bis(pyridine) adduct $[\text{Co}_2(\text{exo-py})_2(L^1)]$ that were suitable for X-ray crystallography; the solid state structures of $[\text{Co}_2(L^1)]$ and $[\text{Co}_2(\text{exo-py})_2(L^1)]$ were determined (Figure 3) and crystal data are shown in Table 1 with selected bond lengths and angles in Table 2.

**Figure 3.** Solid state structures of $[\text{Co}_2(L^1)]$(PhMe)$_2$ and $[\text{Co}_2(\text{exo-py})_2(L^1)]$(PhMe)$_1$25. For clarity, all hydrogen atoms and toluene solvent of crystallisation are omitted (displacement ellipsoids are drawn at 50% probability for $[\text{Co}_2(L^1)]$ and 25% probability for $[\text{Co}_2(\text{exo-py})_2(L^1)]$).

In a manner similar to $[\text{Pd}_2(L^1)]$, the Co(II) cations in $[\text{Co}_2(L^1)]$ are co-ordinated in a square planar geometry by the two N$_4$-donor compartments (sum of the angles: Co1 is 359.7°; Co2 359.5°), and in an overall Pacman geometry. The lateral twist of the two donor compartments allows the two fluorenyl-substituents to interact to form a face-to-face π-stack (interplanar separation 3.77 Å) which results in a significantly shorter Co•••Co separation and bite angle than in the meso-methyl-substituted analogue $[\text{Co}_2(L^\text{Me}_4)]$ (see Table 3). All other bond distances and angles are similar to those seen in previously reported examples.\textsuperscript{7, 8} The addition of pyridine to form the bis(pyridine) adduct $[\text{Co}_2(\text{py})_2(L^1)]$ has a significant effect on the gross structure. While a Pacman geometry is still observed, the macrocycle is less twisted than in $[\text{Co}_2(L^1)]$ and results in a larger bite angle and an increase in the Co•••Co separation. Surprisingly, both pyridine molecules are coordinated exogenously to the cleft, which suggests that this bimetallic microenvironment is spatially-constrained, even though the mouth of the cleft has opened slightly on exo-pyridine complexation. Furthermore, the exo-fluorenyl groups interact with the pyridines in an edge-to-face π-stacking manner (C(H)•••pyridine centroid 3.63 Å), with the pyridines arranged
orthogonal to the fluorenyl-substituents. This structure contrasts to that of the meso-methyl-substituted analogue [Co₂(endo-py)(exo-py)(L₄Me⁴)] in which one of the pyridine molecules binds to a Co(II) cation within the cleft, a mode that is stabilised by π-stacking interactions with the opposing pyrrole-imine compartment and also by a hydrogen-bonding interaction between the meso-methyl group and the orthogonal pyridine π-cloud. The presence of this endo-pyridine also results in a significant decrease in the molecular twist angle, from 31.3° in [Co₂(L₄Me⁴)], to 2.9° in [Co₂(endo-py)(exo-py)(L₄Me⁴)]. As such, it is clear that the presence of the fluorenyl-meso-substituent in H₄L¹ has a significant effect on the structural parameters of its complexes, resulting in compounds that retain a lateral twist and a more spatially-constrained bimetallic cleft environment.

**Synthesis and structure of [Pd₂(L²)]**

The most straightforward route to the binuclear palladium complex of [Pd₂(L²)] was to form the potassium salt [K₄(L²)] *in situ* and to carry out a salt elimination reaction with [PdCl₂(PhCN)₂] (Scheme 1). Alternatively, [K₄(L²)] could be isolated as the THF adduct [K₄(THF)₂.65(L²)], as demonstrated by elemental analysis and NMR data, and reacted separately with the Pd salt. The ¹H NMR spectrum of [K₄(L²)] shows very broad signals that can be assigned in general but are difficult to interpret. As such, the number of THF molecules per macrocycle was determined by quenching the potassium salt with wet d₅-pyridine which resulted in the recovery of H₄L² and 2.65 molecules of free THF by integration.

The reaction between [PdCl₂(PhCN)₂] and [K₄(L²)] prepared *in situ* in THF in the dark formed, after 20 days, the binuclear complex [Pd₂(L²)] which crystallised from THF as a poorly soluble yellow solid in low yield; reactions for shorter time periods gave lower yields of the desired product. The ¹H NMR spectrum of [Pd₂(L²)] shows two sets of ethyl-meso-substituent resonances at 2.15/1.89 (CH₂) and 0.51/0.27 (CH₃) ppm that are characteristic of two non-equivalent ethyl groups and suggests that a cofacial ligand geometry has been adopted in solution. This feature is corroborated in the ¹³C{¹H} NMR spectrum which displays ethyl group resonances at 40.0/36.6 (CH₂) and 11.2/10.4 (CH₃) ppm; the quaternary meso-carbon could not be located in the ¹³C NMR spectrum due to the poor solubility of the compound. No N-H peak (v = 3250 cm⁻¹ in H₄L²) was observed in the IR spectrum of [Pd₂(L²)], and a shift in the C=N stretch to lower energies (from 1613 in H₄L² to 1570 cm⁻¹) supports the coordination of the metal by the macrocycle. The electrospray mass spectrum of [Pd₂(L²)] showed a molecular ion [Pd₂(L²)]⁺ at m/z 1070 and its sodium adduct Na[Pd₂(L²)]⁺ at m/z 1093 with the expected isotopic pattern, and elemental analysis further supported the proposed molecular formula. As an alternative synthetic procedure, [Pd₂(L²)] can also be accessed by the reaction between H₄L² and [PdCl₂(PhCN)₂] in presence of triethylamine, although yields from this route were generally lower and the complex more difficult to isolate. However, the ¹H NMR spectrum of the product from this route is identical to that described
above, and yellow crystals of the binuclear palladium complex $\text{[Pd}_2(L^2)\text{]}\text{NEt}_3\text{CDCl}_3$ were grown from a CDCl$_3$ solution. The X-ray crystal structure was determined and the solid state structure is shown in Figure 4 with crystal data in Table 1 and selected bond lengths and angles detailed in Table 2.

![Figure 4. Solid state structure of $\text{[Pd}_2(L^2)\text{]}\text{NEt}_3\text{CDCl}_3$ (Left: side-on view; right: face on view).](image)

For clarity, all hydrogen atoms and solvents of crystallisation are omitted (displacement ellipsoids are drawn at 50% probability). The two palladium atoms Pd1 and Pd1' are related by the symmetry operation -x, y, $\frac{1}{2}$-z.

As with $\text{[Pd}_2(L^1)\text{]}$, each N$_4$-donor compartment offers a pseudo-square-planar environment to the metal (sum of angles at Pd1 359.4°) and the palladium is located 0.122 Å out of the N$_4$ mean plane. In contrast however, the presence of the anthracenyl groups between the two metal-compartments in $\text{[Pd}_2(L^2)\text{]}$ has resulted in the formation of a double-pillared cofacial complex in which the two metal coordination planes are almost planar and show a slight divergence away from coplanarity (interplanar angle 15.3°); this slight deviation from co-planarity is likely attributable to a steric clash between the ethyl meso-substituents. The two anthracenyl backbones π-stack in a face-to-face manner (interatomic separation 3.43 Å) and are coplanar (interplanar angle 7.6°). Overall, the complex adopts a lateral twist of 29.4°, again due likely to sterically-hindered interactions between the ethyl meso-substituents.

The structural parameters for $\text{[Pd}_2(L^2)\text{]}$ can be compared to related cofacial diporphyrin and corrole systems. Indeed, this ligand with its anthracenyl backbone proffers a geometric arrangement very similar to DPA (diporphyrinanthracene) and DCA (dicorroleanthracene),$^{24}$ and $\text{[Pd}_2(L^2)\text{]}$ can be viewed as a double-pillared analogue of the series of well-known single-pillared complexes $\text{[M}_2\text{(DPA)}\text{]}$. As the solid state structures of $\text{[Pd}_2\text{(DPA)}\text{]}$ and $\text{[Pd}_2\text{(DCA)}\text{]}$ are, to the best of our knowledge, unknown, the
structurally-characterised cofacial diporphyrin H₄DPA and its metal complexes [Co₂(DPA)] and [Ni₂(DPA)] are used for comparison (Table 4), along with the related dicorrole complexes [Cu₂(DCA)] and [Ni₂(DCA)]. While the twist angle for [Pd₂(L²)] is similar to those seen in the structures of H₄(DPA), [Co₂(DPA)], and [Ni₂(DPA)], the interplanar angle for [Pd₂(L²)] is larger than the diporphyrin analogues which suggests that the mouth of the cleft can expand vertically. This results in a Pd•••Pd separation of 5.38 Å which is appreciably longer (by ca. 1.3 Å) than those seen in the 1,2-aryl-hinged complexes [Pd₂(L¹)], [Pd₂(L⁷⁷⁸)], and [Pd₂(L⁷⁴⁶⁴)] and similar to those observed for the related anthracenyl porphyrinic complexes (Table 4). Of the various binuclear DPA and DCA compounds that have been characterised structurally, the M•••M separations (range: DPA 3.49 to 6.17; DCA 4.68 to 7.46 Å)²⁷ show that these ligands allow considerable vertical flexibility. In particular, the presence of endogenous solvent or ligands (e.g. MeOH) causes vertical expansion while single-atom bridging ligands (e.g. O or OH) promote closer interaction of the metallo-porphyrinic compartments. In our case, it is anticipated that the combination of the longer M•••M separations and the presence of the very rigid double-anthracenyl pillars in [M₂(L²)] complexes will limit the stability of single-atom bridged complexes and so favour diatom binding.

Table 4. Comparison between the X-ray structural data of the anthracenyl-based cofacial diporphyrin and dicorrole complexes, and [Pd₂(L²)]. a Angle between the best mean planes of the N₄-donor compartments; b distance between the centroids of the two N₄-binding sites; c a molecule of PhMe is sandwiched within the bimetallic cleft

<table>
<thead>
<tr>
<th>Compound</th>
<th>M•••M [Å]</th>
<th>Twist [°]</th>
<th>Interplanar Angle a</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>[Pd₂(L²)]</td>
<td>5.38</td>
<td>29.4</td>
<td>15.3</td>
<td>This work</td>
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<td>[Co₂(DPA)]</td>
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<td>-10.2</td>
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</tr>
<tr>
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<td>18.9</td>
<td>29</td>
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<td>[Ni₂(DCA)]</td>
<td>4.68</td>
<td>22.4</td>
<td>9.4</td>
<td>30</td>
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</tbody>
</table>

Conclusions

We have shown that both the meso-fluorenyl-substituted and the anthracenyl-based Schiff-base calixpyrroles H₄L¹ and H₄L² can be prepared and that complexes of these macrocycles exhibit properties intrinsic to their design. The metal-metal separations in complexes derived from the meso-fluorenyl-substituted ligand H₄L¹ are comparable to, or larger than those found in complexes of the less bulky analogues due to an increased lateral twist, and, furthermore, the sterically-hindering fluorenyl substituent prevents coordinating solvent from accessing the bimetallic cavity in the pyridine adduct [Co₂(exo-py)(L¹)]; presumably, this aspect will be important in preventing the formation of overly stable single-atom bridged complexes. As for the anthracenyl-
based ligand H$_4$L$_2$, the metal-metal separation in [Pd$_2$(L$^2$)] is increased significantly compared to the analogues derived from 1,2-diaminobenzene; as such, the metals should be sufficiently distant to favour the formation of diatom-bridged complexes. Significantly, the two N$_4$-donor compartments adopt a cofacial conformation in the solid state as a result of the π-stacked double-pillared arrangement of the anthracenyl hinges. We are currently investigating the formation of transition metal and f-element complexes of these new ligands and the effect that these designs have on their structural and catalytic chemistry.
References


