

## Synthesis and X-Ray Crystal Structure of a New Redox-active Calix[5]arene Containing a Totally Included Ethanol Molecule

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A novel *p*-*tert*-butylcalix[5]arene trisferrocenoyl ester molecule **L** has been prepared; the X-ray crystal structure of the ethanol complex of **L** reveals the guest molecule bound deep in the cavity of the calix[5]arene.

Calix[*n*]arenes are macrocyclic molecules composed of *n* phenol rings linked by methylene groups. The chemistry of calix[4,6 and 8]arenes is well represented in the literature due to the ease with which these molecules can be synthesised.<sup>1</sup> Calix[5]arenes can only be synthesised in relatively small yields,<sup>2,3</sup> however they may possess a greater propensity to completely include small organic molecules than analogous calix[4]arenes due to their larger cavity size.<sup>4</sup> The chemistry of the calix[5]arenes is still relatively unexplored and there are few papers detailing modification via lower rim substitution.<sup>5,6</sup> While this work was in progress a report of the synthesis of a number of ester and ether derivatised calix[5]arenes was published.<sup>7</sup> As part of a research programme aimed at the construction of redox-active host molecules designed to electrochemically sense neutral guests,<sup>8–12</sup> we report here the synthesis, structure and electrochemical properties of a novel *p*-*tert*-butylcalix[5]arene tris ferrocenyl ester receptor **L**.

*p*-*tert*-Butylcalix[5]arene **1** was synthesised according to a modification of the method of Ninagawa<sup>2</sup> which has been refined by Gutsche and Stewart.<sup>13</sup> Compound **1** (0.38 g, 0.47 mmol) was dissolved in dichloromethane in the presence of excess triethylamine and a solution of excess chlorocarbonylferrocene (0.82 g, 3.3 mmol) in dichloromethane added dropwise to the stirred reaction mixture under a nitrogen atmosphere. The solution was then heated at reflux for 12 h. The crude product **L** was purified by column chromatography on silica gel eluting with petroleum ether–dichloromethane–acetone (20:20:1 v/v) affording **L** as an orange powder in 16% yield (Fig. 1). **L** was characterised by <sup>1</sup>H and <sup>13</sup>C NMR, microanalysis and FAB MS all of which gave results consistent with a tri-substituted product. The 1,3,4- pattern of substitution is expected on steric grounds, as analogous reactions carried out on several calix[4]arenes have produced 1,3-substituted products.<sup>11†</sup>

Crystals suitable for X-ray structure determination were grown from a dichloromethane–ethanol solvent mixture of **L**.<sup>‡</sup> The structure of **L**.ethanol inclusion complex is shown in Fig. 1. Overall the geometry is similar to that of calix[5]arenes which are unsubstituted at the lower rim, taking up the cone conformation.<sup>14–17</sup> In the structure (Fig. 1) hydrogen bonds are formed to a totally included ethanol molecule. The oxygen atom [O(800)] is lying within hydrogen bonding distance of both unsubstituted oxygen atoms at the bottom of the cone [*e.g.*

O(350) 2.81, O(550) 2.82 Å] and at larger distances from the other oxygen atoms O(150) 3.47, O(250) 3.13, O(450) 3.72 Å. This contrasts with the crystal structure of the ethanol complex of 1,3-diethoxy-*p*-*tert*-butylcalix[4]arene,<sup>18</sup> the first ethanol–calix[4]arene complex, which includes an ethanol at the very top of the cavity with no interaction between the included ethanol hydroxy group and the lower rim phenolic groups of the calixarene.

Electrochemical studies of the behaviour of **L** ( $5 \times 10^{-4}$  mol dm<sup>-3</sup> in dichloromethane solution containing 0.1 mol dm<sup>-3</sup> [NBu<sub>4</sub>]BF<sub>4</sub> as supporting electrolyte) have been carried out using cyclic and square wave<sup>19</sup> voltammetric techniques. The receptor itself undergoes two quasi-reversible oxidations at  $E_{p1} = +350$  mV and  $E_{p2} = +450$  mV referenced to Ag/Ag<sup>+</sup>. Rotating disk electrode electrochemistry<sup>20</sup> was used to resolve the two oxidation processes. It is possible to express the instantaneous current in terms of the limiting current and the potential applied. Fig. 2 illustrates this for **L**. It can be seen that the limiting current of the first oxidation process is half that of the second. This corresponds to one ferrocene being oxidised at 350 mV and the other two at the larger anodic potential of 450 mV.<sup>21</sup>

Preliminary electrochemical investigations on the effects of addition of potential neutral guests (DMF, DMSO, ethanol) to an electrochemical solution of **L** in CH<sub>2</sub>Cl<sub>2</sub> show an interesting electrochemical effect. For example Fig. 3 which shows the CV of **L** in CH<sub>2</sub>Cl<sub>2</sub> background solution upon addition of progressive amounts of DMF. Clearly the presence of DMF causes the two redox couples to merge. Similar effects were also observed on addition of DMSO or ethanol. However on addition of toluene to the electrochemical solution no shifts in the redox couples were observed.

These preliminary electrochemical results tentatively suggest that there may be an association between **L** and the added neutral polar guest species which is detectable using electrochemical techniques. The decrease in the separation between the redox potentials of the ferrocene moieties upon addition of the higher dielectric constant solvent guest species implies that the guest molecules are interposing themselves between the

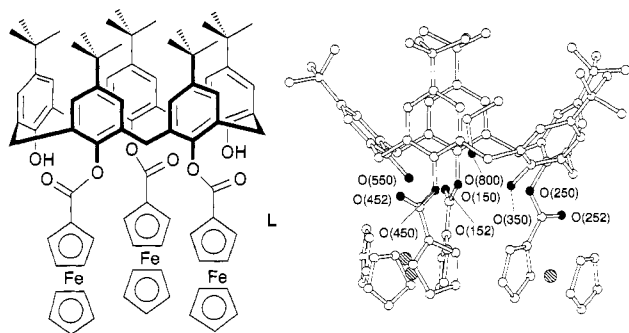


Fig. 1 Structure and side view with oxygen numbering scheme of the molecular structure of the ethanol inclusion complex of **L**.

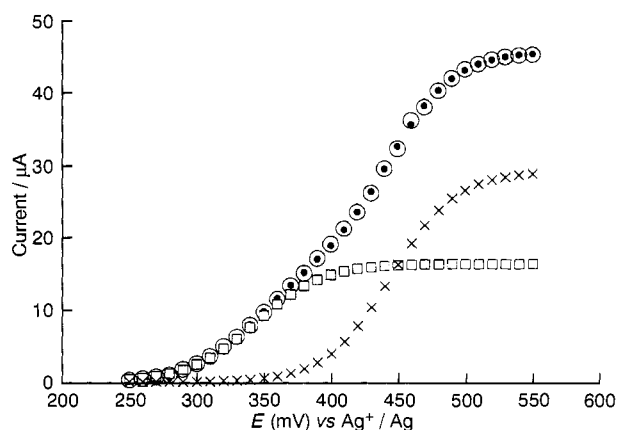


Fig. 2 Computer fit of the Nernst equation to the rotating disk electrode electrochemistry, at 121 rpm, of **L** ( $5 \times 10^{-4}$  mol dm<sup>-3</sup>) in CH<sub>2</sub>Cl<sub>2</sub> with [Bu<sub>4</sub>N]BF<sub>4</sub> (0.1 mol dm<sup>-3</sup>) as supporting electrolyte

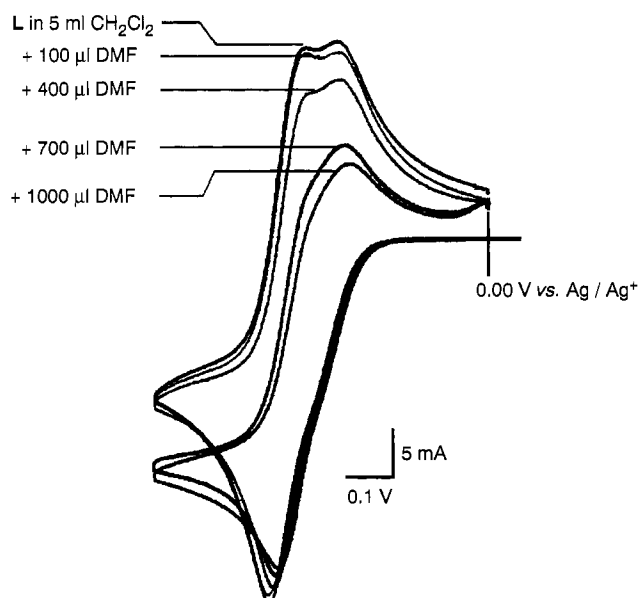


Fig. 3 The two redox processes tend towards equivalence upon addition of DMF to the electrochemical solution of L ( $5 \times 10^{-4}$  mol dm $^{-3}$ ) in CH $_2$ Cl $_2$  with [Bu $_4$ N]BF $_4$  (0.1 mol dm $^{-3}$ ) as supporting electrolyte

redox-active groups and consequently shielding the mutual electrostatic influences of the ferrocene centres. The ferrocene moieties therefore exhibit more independent electrochemical behaviour tending towards that of a single three electron oxidation wave.

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### Footnotes

† The low yield of this reaction is attributed to the production of other substituted calix[5]arenes, for example small quantities of a 1,3-substituted *p*-*tert*-butylcalix[5]arene bisferrocenoyl ester in the cone conformation have been obtained, however the possibility also exists for the formation of substituted calix[5]arenes in other conformations (partial cone, 1,3-alternate *etc.*). Unfortunately this mixture of products has to date proved to be inseparable using various column chromatographic techniques.

‡ Crystal Data for L, 2EtOH, 3H $_2$ O, C $_{92}$ H $_{112}$ Fe $_3$ O $_{13}$ ,  $M = 1593.4$ , Mo-K $\alpha$  radiation, triclinic space group  $P\bar{1}$ ,  $a = 14.004(6)$ ,  $b = 14.482(6)$ ,  $c = 22.511(6)$  Å,  $\alpha = 79.61(1)^\circ$ ,  $\beta = 82.09(1)^\circ$ ,  $\gamma = 79.06(1)^\circ$ ,  $V = 4384(3)$  Å $^3$ ,  $Z = 2$ ,  $d_m = 1.207$  mg m $^{-3}$ . Data were collected with Mo-K $\alpha$  radiation using the MARresearch Image Plate System. The crystal was positioned at 75 mm from the Image Plate. 95 frames were measured at 2° intervals with a counting time of 5 mins. Data analysis was carried out with the XDS program.<sup>22</sup> The structure was solved using direct methods with the SHELXS-86 program.<sup>23</sup> The structure showed some disorder. In L, two of

the *tert*-butyl groups were disordered and both were refined in two different orientations such that the sum of the occupancies was 1.0. Two ethanol molecules were located, one in the cavity of the calixarene and one positioned between calix[5]arene molecules and not involved in hydrogen bonding. In addition there were several molecules of water with low occupancies. All non-hydrogen atoms except those affected by disorder were refined with anisotropic thermal parameters. Hydrogen atoms were included in the substituted calixarenes in calculated positions but not on the disordered *tert*-butyl groups. The structure was then refined using SHELXL-93<sup>24</sup> to an  $R$  of 0.0945 for data with  $I > 3\sigma(I)$  and an  $R$  of 0.1335 for all data. All calculations were carried out on a Silicon Graphics R4000 Workstation at the University of Reading.

Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

### References

- 1 C. D. Gutsche, *Calixarenes: Monographs in Supramolecular Chemistry*, ed. J. F. Stoddart, RSC, Cambridge and London, 1989.
- 2 A. Ninagawa and H. Matsuda, *Makromol. Chem., Rapid Commun.*, 1982, **3**, 65.
- 3 K. Iwamoto, K. Araki and S. Shinkai, *Bull. Chem. Soc. Jpn.*, 1994, **67**, 1499.
- 4 C. D. Gutsche and I. Alam, *Tetrahedron*, 1988, **44**, 4689.
- 5 G. Barrett, M. A. McKervey, J. F. Malone, A. Walker, F. Arnaud-Neu, L. Guerra, M.-J. Schwing-Weill, C. D. Gutsche and D. R. Stewart, *J. Chem. Soc., Perkin Trans. 2*, 1993, 1475.
- 6 D. Kraft, R. Arnecke, V. Böhmer and W. Vogt, *Tetrahedron*, 1993, **49**, 6019.
- 7 D. R. Stewart, M. Krawiec, R. P. Kashyap, W. H. Watson and C. D. Gutsche, *J. Am. Chem. Soc.*, 1995, **117**, 586.
- 8 P. D. Beer, A. D. Keefe and M. G. B. Drew, *J. Organomet. Chem.*, 1988, **353**, C10.
- 9 P. D. Beer, M. G. B. Drew, A. Ibbotson and E. L. Tite, *J. Chem. Soc., Chem. Commun.*, 1988, 1498.
- 10 P. D. Beer and E. L. Tite, *Tetrahedron Lett.*, 1988, 2349.
- 11 P. D. Beer, A. D. Keefe and M. G. B. Drew, *J. Organomet. Chem.*, 1989, **378**, 437.
- 12 P. D. Beer, A. D. Keefe, A. M. Z. Slawin and D. J. Williams, *J. Chem. Soc., Dalton Trans.*, 1990, 3675.
- 13 D. R. Stewart and C. D. Gutsche, *Org. Prep. Proc. Intl.*, 1993, **25**, 137.
- 14 M. Coruzzi, G. D. Andreetti, V. Bocchi, A. Pochini and R. Ungaro, *J. Chem. Soc., Perkin Trans. 2*, 1982, 1133.
- 15 R. K. Juneja, K. D. Robinson, G. W. Orr, R. H. Dubois, K. A. Belmore, J. L. Atwood, J. A. Ripmeester and C. I. Ratcliffe, *J. Inc. Phenom. Mol. Recognit. Chem.*, 1992, **13**, 93.
- 16 J. F. Gallagher and G. Ferguson, *Acta Crystallogr.*, 1994, **C50**, 73.
- 17 M. Perrin and S. Lecocq, *J. Inc. Phenom. Mol. Recognit. Chem.*, 1991, **11**, 171.
- 18 K.-E. Bugge, W. Verboom and D. N. Reinhoudt, *Acta Crystallogr.*, 1992, **C48**, 1848.
- 19 J. Osteryoung and J. J. O'Dea, in *Electroanalytical Chemistry*, ed. A. J. Bard and M. Dekker, New York, vol. 14, 1987, pp. 209–308.
- 20 Southampton Electrochemistry Group, *Instrumental Methods in Electrochemistry*, Wiley, New York, 1985, pp. 113–148.
- 21 For an explanation of apparent simultaneous multielectron transfer see: A. J. Bard and L. R. Faulkner, *Electrochemical Methods, Fundamentals and Applications*, Wiley, New York, 1980, pp. 232–235.
- 22 W. Kabsch, *J. Appl. Cryst.*, 1988, **21**, 916.
- 23 SHELXS-86, G. M. Sheldrick, *Acta Crystallogr.*, 1990, **A46**, 467.
- 24 SHELXL-93 package for crystal structure refinement, G. M. Sheldrick, *J. Appl. Cryst.*, 1995, in the press.