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Synthesis and applications of copillar[5]arene dithiols

Raghuram Reddy Kothur^a, Flavia Fucassi^a, Gennaro Dichello^a, Ludovic Doudet^{a,b}, Wafa Abdalaziz^a, Bhavik Anil Patel^a, Gareth W. V. Cave^c, Ian A. Gass^a, Dipak K. Sarker^a, Sergey V. Mikhalovsky^{a,d} and Peter J. Cragg^a

^aSchool of Pharmacy and Biomolecular Sciences, University of Brighton, Brighton, UK; ^bEcole Supérieure de Chimie Organique et Minérale, Compiègne, France; ^cSchool of Science & Technology, Nottingham Trent University, Nottingham, UK; ^dNazarbayev University, Astana, Kazakhstan

ABSTRACT

A novel copillar[4+1]arene incorporating alkylthiol substituents was synthesised in three steps and structurally characterised as the first example of a pillar[n]arene to incorporate two terminal thiols on the same aromatic ring. The macrocycle was attached to gold electrodes through a standard dipping technique. Cyclic voltammetry demonstrated selectivity for Li⁺ over other alkali metal cations. The copillar[4+1]arene was also used as a capping agent in the preparation of 3 nm gold nanoparticles.

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Pillar[5]arenes; macrocycles; gold nanoparticles; surface modification

1. Introduction

Pillar[5]arenes are macrocycles belonging to the broad class of cyclophanes and are comprised of five aromatic rings linked by methylene bridges in the 2,5-positions with O-alkyl substituents in the 1,4-positions. The first example, 1,4-dimethoxypillar[5]arene (1,4-DMP[5]A, 1), was reported in 2008 (1). Many other derivatives have since been prepared and shown to have a range of interesting properties from recognition of linear alkyl diamines to the formation of channels that act as conduits for protons (2-11). The cyclopentameric macrocycles are tubular, with a central cavity approximately 4.7 Å wide by 7.8 Å long for 1,4-DMP[5]A, possessing D_{sh} symmetry and have been shown to act as hosts for a range of neutral and charged chemical guests (3). The rings of oxygen atoms at each orifice provide good binding sites for guest species such as metal cations, planar aromatic species and linear alkyl molecules. The simplest derivative, 1,4-DMP[5]A, even without further functionalisation, can be used as an electrode modifier to detect Na⁺ across the entire physiological range (*12*).

It is possible to introduce different groups during the initial macrocyclisation by using two monomers to form so called 'copillar[5] arenes' that incorporate the monomer in a 4:1 ratio (copillar[4+1] arene) or a 3:2 ratio (copillar[3+2] arene) (*13, 14*). Other reactions of monomers leading to copillar[2+3] arene and copillar[1+4] arene are theoretically possible although, to date, the focus has been on the higher yielding [4+1] and [3+2] derivatives (Scheme 1).

Copillar[5] arenes such as **2** and **3** (Figure 1) can undergo further reactions so that functional groups can be introduced as in dithiol **4**. An alternative stratagem involves partial or total demethylation of **1** with BBr_3 followed by the reduction of the resulting quinones to phenols by





Scheme 1. (Colour online) Copillar[5]arene synthesis.



1: $R_1 = R_2 = R_3 = R_4 = CH_3$ 2: $R_1 = R_3 = R_4 = CH_3$, $R_2 = -CH_2CH_2Br$ 3: $R_1 = CH_3$, $R_2 = R_3 = R_4 = -CH_2CH_2Br$ 4: $R_1 = R_3 = R_4 = CH_3$, $R_2 = -CH_2CH_2SH$ 5: $R_1 = R_2 = R_3 = R_4 = CH_2CH_2(N-methylimidizolium)^+ Br^-$ 6: $R_1 = R_2 = R_3 = R_4 = CH_2CO_2^- Na^+$ 7: $R_1 = R_2 = R_3 = R_4 = CH_3$, $R_4 = -CH_2CH_2CH_2CH_2SH$ 8: $R_1 = R_2 = R_3 = R_4 = CH_2CO_2H$ 9: $R_1 = R_2 = R_3 = R_4 = CH_2CO_2(N-pyrrolidine)$ 10: $R_1 = R_2 = R_3 = R_4 = CH_2CO_2(N-morpholine)$

Figure 1. (Colour online) Copillar[5] arenes described in the text.

sodium dithionite (15). O-Alkylation can then be used to introduce a range of substituents (16).

Recently, several groups have employed pillar[5]arenes in the synthesis of functionalised nanoparticles prepared from gold (AuNPs) and silver (AgNPs). The imidazolium derivative, **5**, was shown by Huang to promote the formation of AuNPs from HAuCl₄ in aqueous solution following the addition of NaBH₄ with sizes controlled by the concentration of pillar[5]arene added (*17*). The carboxylate derivative, **6**, was employed by Yang and Weiss to prepare AuNPs. They proposed that strong carboxyl-gold-binding interactions stabilised the AuNPs during their formation and that, furthermore, growth of the AuNPs during the reduction step was suppressed (*18*). Compound **6** has also been shown by Xue to control the size of AgNPs (*19*). Other examples where pillar[n]arenes have been used as

nanoparticle capping agents or for surface functionalisation can be found in the work of Li (20), Diao (21), and Jia (22). In these cases, the pillar[5] arene attaches to the metal surface through one of its functionalised rims. This results in the nanoparticles being covered in macrocyclic receptors that can be exploited to respond to particular guest molecules. For example, Zhou treated sodium citrate stabilised AuNPs with monothiolated derivative, 7, and was able to demonstrate attachment through a combination of Fourier transform infrared (FTIR) and UV-vis spectroscopy (23). The modified AuNPs reversibly assembled as a consequence of the photocycloaddition of anthracene quest species. Other applications of pillar[n]arene-coated nanoparticles include pillar[5]- and [6]arene-capped nanoparticles to detect alkylpolyamines (24), hybrid AuNPs that form from responsive pillar[5]arene-containing polymers (25), carboxylated pillar[5]arene-coated AuNPs with peroxidase activity (26), pH- and NIR-triggered controlled release by pillar[6]arene-modified AuNPs and nanorods (27) and the use of cationic pillar[5]arene-coated AuNPs to detect pyrene by surface-enhanced Raman scattering spectroscopy (28).

In our pillar[5] arene-based cation (12) and pH sensors (11), the guest species are able to enter the macrocycle from either end and be trapped within the central aromatic annulus. Examples such as Stoddart's fluorescent copillar[5]arene (9) demonstrate that it is important for linear guests to thread through the macrocycle in order to differentiate between alkyl amines and diamines with varying lengths and distances between amine groups. The same phenomenon has since used to form pseudorotaxanes (29-33) and, in an elegant extension of this, to synthesise a [1] rotaxane (34). We wished to broaden the application of this threading mechanism to develop pillar[5] arene-based sensors, such as gold microelectrodes and acoustic wave sensors, where the macrocycles are covalently bound to surfaces and respond to changes electrical conductance upon guest binding. To achieve this, a thiol derivative of pillar[5]arene seemed appropriate due to the well-known affinity of sulfur for gold. Indeed, the same idea underpinned Zhou's synthesis and use of 7 as a capping agent for AuNPs. The strategy that we adopted was to use copillar[5]arene precursors that allow thiols to be introduced in the 1,4-positions of one or two aromatic moieties of a copillar[4+1]arene or copillar[3+2]arene. In particular, we aimed to synthesise a copillar[4+1]arene with only two thiols, both on the same ring, so that when it was attached to a gold surface the cavity of the copillar[4+1] arene would lie parallel, rather than perpendicular, to the surface and allow guests to pass through this channel. We also required short linkers between the pillar[5]arene and the terminal thiols to bind the macrocycle close to the gold surface so that, in the case of electrochemical applications, the effect



Figure 2. (Colour online) X-ray structure of $2 \cdot DMF \cdot 0.5 H_2O$ (hydrogen atoms removed for clarity).



Figure 3. Cyclic voltammetry during copillar[4+1]arene attachment: (a) the effect of attachment time with **4** on a gold electrode and (b) the oxidation peak current decrease with time $(0.01 \text{ M K}_{a}[\text{Fe}(\text{CN})_{6}] \text{ in } 0.1 \text{ M HCl supporting electrolyte}).$

of guest inclusion could be transmitted directly to the electrode. By contrast, Zhou's monothiol has a single four carbon spacer which allows the macrocycle to lie further from the metal surface which is ideal for the promotion of particle aggregation but less amenable to electrochemical guest detection. As proof of principle, **4** was attached to a gold electrode and demonstrated a selectivity for Li⁺ over other alkali metal cations. To investigate whether the derivative could have applications in AuNP chemistry, **4**

was used to displace tetracoctylammonium bromide to stabilise AuNPs resulting in particles with a diameter of 2.9 ± 0.9 nm.

2. Results and discussion

2.1. Copillar[4+1]- and [3+2] arene dithiol synthesis

Using Huang's method, 1,4-bis(bromoethoxy)benzene was prepared in 80% yield from 1,4-bis(hydroxyethoxy) benzene (17). It was noticeable that both the yield and purity of the product were reduced if powdered, rather than crystalline, 1,4-bis(hydroxyethoxy)benzene was used. The alkyl bromide copillar[4+1]- and [3+2] arenes were prepared using Meier's iron-catalysed method (35) to give 2 and 3 which were isolated in 33 and 10% yields, respectively, following column chromatography. Using other reaction conditions, we have seen mass spectrometric evidence for [2+3] and [1+4] regioisomers but they were not observed under these conditions. The yield of 2 compares favourably with the 19% reported by Zhang and Yang for the same copillar[4+1] arene prepared with trifluoromethanesulfonic acid as the catalyst (36). An alternative approach using $BF_3 \cdot O(C_2H_5)_2$ in dry 1,2-dichloroethane was attempted but the yield of 2 was only 18%. No formation of 3 was observed by this method (see Supplementary Information). Using the low temperature approach of Hu and Fox (37), compound 2 was treated with hexamethyldisilathiane to give dithiol 4 in 85% yield.

2.2. X-ray crystallography

Derivatives 2 and 3 could be crystallised from methanol:DMF (1:1). The single crystal X-ray structure of 2 showed that it crystallises as the DMF solvate with a single solvent quest in the macrocyclic cavity. The structure was solved in the $P2_1/n$ space group with one bromine atom disordered over two sites, with occupancies of 92 and 8%, and a water molecule modelled at 50% occupancy. Simple pillar[5] arenes crystallise out in racemic planar chiral forms and consequently the unit cell of 2 contains two molecules with Sp and two with Rp chirality. For simplicity, only the Rp form is illustrated in Figure 2. The structure of copillar[5]arene 3 was problematic to solve and could only be resolved as a 4:1 cocrystallised mixture of 3.DMF and 2.DMF.CH2CI2. Cocrystallisation is consistent with the appearance of both 2 and 3 in the mass spectrum of chromatographic fractions that gave an apparent single spot by TLC. The structure could not be resolved satisfactorily however, although the R-factor was 9.87%, the connectivity is unequivocal and shows -CH2CH2Br substituents on the A and C rings, not the A and B rings, in agreement with NMR data (see Supplementary Information). Furthermore, the crystal structure indicates that the macrocycles are in



Figure 4. Changes observed in the capacitance signal on bare gold electrodes and gold electrodes coated with **4** (data shown as mean \pm st. dev., where **p* < 0.05, ***p* < 0.05 and ****p* < 0.001 vs. the bare gold electrode).

the expected pseudo- D_{5h} geometry observed for other alkylated pillar[5]arene derivatives.

2.3. Electrode modification

Cyclic voltammetry was used to determine whether **4** could be successfully attached to gold electrodes and function as an electrode modifier. The standard dipping method was adopted to attach **4** to the surface of a gold electrode and cyclic voltammograms of the redox couples of $K_4[Fe(CN)_6]$ before and during the process were compared (Figure 3). Both the capacitive and faradic current were attenuated with increasing time (Figure 3(a)), consistent with a coating of the macrocycle on the conductive gold surface. After 4 h, no significant oxidation or reduction peak current for $K_4[Fe(CN)_6]$ was observed on the gold electrode, suggestive of maximum coverage by **4** within this time (Figure 3(b)).

2.4. Assessment of copillar[4+1]arene-coated gold electrodes for alkali metal detection

Figure 4 shows how the capacitive responses varied for bare gold electrodes and gold electrodes coated with **4**. Cyclic voltammetry was utilised to characterise the capacitive signal on 10 mM solutions of alkali metal cations. In

the presence of these cations, significant differences in the capacitive signal were observed for Li⁺, Na⁺, and K⁺ salts with the greatest reduction was observed for Li⁺. Although not statistically significant, some reduction in the capacitive signal was also observed with Rb⁺ and Cs⁺. The decrease in the capacitance is due to changes in the double layer in the vicinity of the electrode which alters the capacitive current at the electrode surface. If Li⁺ is held within the pillar[5] arene the electrode surface is less accessible to the free ions in solution, which are repelled, thus the double-layer profile is influenced and the net capacitance is reduced. The electrochemical response follows the unusual Eisenman sequence XI in which transport follows the order of ionic radii ($Li^+ > Na^+ > K^+ > Rb^+ > Cs^+$) rather than the order of dehydration (38). In previous work on pillar[5]arene immobilised in composite electrodes, we have seen that Rb⁺ and Cs⁺ are excluded from the pillar[5] arene cavity based on their ionic radii, K⁺ binds strongly, Na⁺ binds reversibly and Li⁺ does not bind at all (12). We ascribed the selectivity to a combination of cation size and complementarity to the cavity of the pillar[5] arene when locked into a rigid pentagonal geometry. When the macrocycle is attached to a surface through substituents on one aromatic ring, as is the case for 4, the remaining rings are free to change conformation. They can therefore adopt the coordination geometry preferred by each cation. As a consequence, Li⁺ could be bound effectively without the need to be completely dehydrated which is energetically unfavourable. This is consistent with the observations of Shurpik who reported the binding constants for the Li⁺, Na⁺, K⁺, and Cs⁺ with 8, 9, and 10 in methanol. In all cases log K_{ass} was highest for Li⁺ over the other cations (39). Selectivity for the lightest alkali metal is of note as Li⁺ detection remains a challenge in analytical chemistry.

2.5. Preparation of copillar[4+1]arene-coated gold nanoparticles

As an indication of the range of analytical methods that could benefit from thiol-substituted **4**, AuNPs were prepared using the Brust–Schiffrin method (40) as modified



Figure 5. AuNPs capped by 4. (a)–(c) show TEM images and (d) a frequency histogram.

3. Conclusions

A novel copillar[4+1]arene derivative has been synthesised and attached to the gold surfaces of electrodes. It has also been used as a capping agent to prepare gold nanoparticles. Unlike other examples where pillar[5]arenes interact through substituents at one end of the macrocyclic cavity, attachment to a gold surface by two thiol groups allows **4** to lie parallel to the surface so that guest species can pass through. The electrochemical response to alkali metal salts by **4** indicates selectivity for Li⁺ over the other cations.

4. Experimental

All chemicals, solvents and reagents were purchased commercially and used without further purification. All solvents used were of at least reagent plus grade (>98.5%). Compounds were synthesised according to the literature with amendments as described. For nanoparticle synthesis, hydrogen tetrachloroaurate(III) trihydrate (HAuCl₄·3H₂O, 99.9%), tetraoctylammonium bromide (TOAB, $[CH_3(CH_2)_7]_4$ N⁺Br⁻, >98%) and sodium borohydride (NaBH, >98%) were purchased from Sigma-Aldrich. TEM images of AuNPs were collected on a Hitachi-7100 Gatan Ultrascan 1000 CCD camera at 100 kV accelerating voltage. Compounds were characterised by NMR and infrared spectroscopy, melting point and high-resolution mass spectrometry (HRMS) to confirm their identities. NMR data were collected by a Bruker Avance DMX-400 spectrometer at 400 MHz for ¹H and 90 MHz for ¹³C with tetramethylsilane (TMS) as the internal reference. Chemical shifts are reported in parts per million (ppm) downfield from TMS (0 ppm) as the internal standard. Multiplicities in the ¹H NMR spectra are reported as (s) singlet, (d) doublet and (t) triplet. Electrospray ionisation mass spectra were recorded by a Bruker Daltonics microTOF spectrometer operating in the positive mode. Infrared absorption spectra were recorded on a Nicolet Avatar 320 FT-IR fitted with a Smart Golden Gate®. Melting points were determined on a BI Barnstead Electrothermal Ltd melting point apparatus and are uncorrected. Gold electrodes (3.0 mm diameter) were mechanically polished and coated with a self-assembled monolayer of copillar[4+1]arene 4. Electrochemical data were collected with an Ag/AgCl reference electrode using

CH instruments software. X-ray data were collected on a Bruker X8 Apex II CCD diffractometer using a Mo K_{α} radiation source ($\lambda = 0.71073$ Å).

4.1. Ligand synthesis

1,4-Bis(bromoethoxy)benzene

1,4-Bis(hydroxyethoxy)benzene (5.00 g, 25.2 mmol) and triphenylphosphine (15.00 g, 60 mmol) were stirred in CH₃CN and cooled to 0 °C. Carbon tetrabromide (20.00 g, 60 mmol) was slowly added in small portions to a solution with stirring while maintaining 0 °C. The reaction mixture was then left to warm to room temperature and the resulting clear solution was stirred for a further 4 h under a nitrogen atmosphere. Cold distilled water (100 ml) was added to precipitate a white solid that was collected by vacuum filtration and recrystallised from hot methanol (200 mL). 1,4-Bis(bromoethoxy)benzene was isolated as white flake-like crystals following vacuum filtration. Yield: 6.54 g (80%); m.p.: 112.7-115.6 °C; ¹H NMR (400 MHz, CDCl₂) δ (ppm): 6.85 (s, 4H, ArH), 4.23 (t, 4H, –CH₂O), 3.59 $(t, 4H, -CH_3Br)$; ¹³C NMR (90 MHz, CDCl₃) δ (ppm): 152.89, 116.17, 68.81, 29.19. HRMS (*m/z*): calcd for C₁₀H₁₂Br₂O₂·Na C₂HO₂, 391.9063; found, 391.9195. Note: the molecular ion could not be detected for this compound and was always observed as the sodium orthoformate complex.

1,4-Bis(bromoethyoxy)copillar[5]arenes

1,4-Dimethoxybenzene (11.96 g, 86.56 mmol) and 1,4-bis(bromoethoxy)benzene (1.75 g, 5.41 mmol) were dissolved in dry CH₂Cl₂ (350 mL). Paraformaldehyde (7.80 g, 259.68 mmol) was added and the mixture sirred under a nitrogen atmosphere. After cooling to 0 °C, FeCl₃ (2.19 g, 13.53 mmol) was added with stirring. The temperature was maintained at 0 °C for a further 30 min, during which time the solution turned light green, before being allowed to warm to room temperature, whereupon it was stirred for a further 3 h, turning dark green in the process. After completion of the reaction, distilled water (100 mL) was added. The organic layer was isolated, washed with distilled water (100 mL), saturated brine (100 mL) and dried over Na2SO4. After filtration the solvent was removed under vacuum and purified by column chromatography (silica, 230–400 mesh, 3.0 cm \times 25.5 cm column), using a mixture of petroleum ether and CH₂Cl₂ (initially 2:1 then decreasing to 1:1) as the eluent. Two products (2 and 3) were obtained as white solids.

1,4-Bis(bromoethyoxy)copillar[4+1]arene (**2**): yield 1.56 g (33%); R_f : 0.66 (petroleum ether:CH₂Cl₂ 1:1; silica 40–70 Å); m.p.: 127.5 °C; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 6.79 (d, J = 5.6 Hz, 4H, -ArH), 6.77 (s, 4H, -ArH), 6.73 (s, 2H, -ArH), 4.06 (t, J = 6.2 Hz, 4H, CH₂O), 3.79 (s, 4H, ArCH₂Ar), 3.78 (s, 6H, ArCH₂Ar), 3.69 (s, 18H, OCH₃), 3.74 (s, 6H, OCH₃), 3.55 (*t*, 4H, $-CH_2Br$); ¹³C NMR (90 MHz, CDCl₃) δ (ppm): 150.85, 150.78, 150.74, 149.74, 129.11, 128.57, 128.24, 128.15, 127.82, 115.83, 114.39, 114.03, 113.93, 68.74, 56.05, 55.82, 55.79, 55.76, 34.00, 29.88, 29.80, 29.56; IR (ν , cm⁻¹): 2929.4, 2100.2, 1721.4, 852.2, 696.4; HRMS (*m/z*): calcd for C₄₇H₅₂Br₂NaO₁₀, 959.1804; found, 959.2048. Data are in agreement with literature values (*36*).

1,4-Bis(bromoethyoxy)copillar[3+2]arene (**3**): yield: 607 mg (10%); $R_{\rm f}$: 0.80 (petroleum ether:CH₂Cl₂ 1:1; silica 40–70 Å); m.p.: 140.24 °C; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 6.90–6.91 (*m*, 6H, –ArH), 6.85 (*d*, 4H, –ArH), 3.93–3.97 (*m*, 8H, ArCH₂Ar), 3.78–3.81 (*m*, 28H, ArCH₂Ar+ –OCH₃), 3.49–3.52 (m, 8H, –CH₂Br); ¹³C NMR (90 MHz, CDCl₃) δ (ppm): 150.82, 150.80, 150.73, 149.73, 129.26, 128.55, 127.95, 115.78, 115.73, 114.34, 113.92, 68.83, 68.74, 56.05, 55.79, 39.7, 31.84, 31.53, 29.95, 29.67, 29.59, 28.97; IR (ν , cm⁻¹): 2932.1, 1910.2, 1781.2, 1730.3, 850.1, 692.3; HRMS (*m/z*): calcd for C₄₉H₅₄Br₄NaO₁₀, 1145.0308; found, 1144.9071.

1,4-Bis(thioethyoxy)copillar[4+1]arene

1,4-Bis(bromoethoxy)copillar[4+1]arene (2) (0.200 g, 0.213 mmol) was dissolved in dry THF (10 mL) at -30 °C under nitrogen. S(SiMe₃)₂ (0.09 mL, 0.426 mmol) and tetrabutylammonium fluoride trihydrate (TBAF·3H₂O) (0.296 g, 0.941 mmol) were added and the resulting light green reaction mixture was stirred overnight and allowed to warm to room temperature. THF was removed under vacuum from the resulting colourless mixture and a mixture of distilled water (20 mL) and CH₂Cl₂ (20 mL) were added. The organic layer was isolated and washed with distilled water (3 mL × 20 mL). The organic layer was dried with Na₂SO₄, filtered, and the solvent removed under vacuum to give the crude product as a pale yellow solid. Recrystallisation from methanol gave 1,4-bis(thioethyoxy) copillar[4+1]arene (4) as a pale yellow solid. Yield: 155 mg (85%); m.p.: 188.0–192.0 °C; ¹H NMR (400 MHz, CDCl₃) δ (ppm): 6.77–6.73 (m, 10H, –ArH), 4.12 (t, 4H, –CH₂O), 3.77 (s, 10H, ArCH₂Ar), 3.65 (*d*, 24H, –OCH₃), 3.02 (*m*, 4H, –CH₂SH), 1.42 (*m*, 2H, –S*H*); ¹³C NMR (90 MHz, CDCl₂) δ (ppm): 150.93, 150.87, 128.66, 128.44, 128.20, 114.39, 114.23, 65.79, 56.06, 55.91, 55.84, 50.80, 29.73, 15.23. IR (ν , cm⁻¹): 2930.3, 1497.3, 1397.5, 1272.6, 908.3, HRMS (m/z): calcd for $C_{47}H_{54}NaO_{10}S_{7}$, 865.3056; found, 865.3141.

4.2. Nanoparticle synthesis

Direct synthesis of AuNPs was based on a modification of a previously reported method (32). HAuCl₄·3H₂O (7.75 mg, 19.7 μ mol) was dissolved in distilled water (0.7 mL) and added immediately to TOAB (10 mL, 0.215 g, 20 equiv.) dissolved in toluene. The biphasic mixture was stirred for 30 min at room temperature and the aqueous phase

subsequently discarded to leave gold(III) in toluene solution. Compound 4 (6.4 mg, 6.8 µmol, equivalent to a thiol concentration of 0.14 mM) was added to the mixture with vigorous stirring which was continued for a further 30 min. Freshly prepared aqueous 0.4 M NaBH₄ (0.5 mL, 7.44 mg, 10 equiv.) was added dropwise at a rate of approximately 20 µl every 15 s with vigorous stirring. The gold(III) solution turned brown over 90 s whereupon the remainder of the NaBH, solution was added. The mixture was stirred for 4 h and the aqueous phase was subsequently discarded. The final toluene solution (10 mL) contained ~0.2 mM of gold and 40 mM of TOAB and was stored in a glass container in the dark for characterisation using UV-vis spectroscopy and TEM. A control experiment was carried out using the same procedure but in the absence of 4. FTIR following the attachment of 4 showed the characteristic absorbance at 3200 and 1600 cm⁻¹ indicative of aromatic compounds and used by Zhou to prove attachment of 7 to AuNPs (23) (supplementary information, Figure S10). UV-vis scans of the AuNPs show subtle changes around 520 nm which indicate that replacement of TOAB by 4 though the peaks are too broad to be used to extrapolate changes in AuNP sizes as a consequence of TOAB replacement (supplementary information, Figure S11).

4.3. Attachment of copillar[4+1]arenes to gold electrodes

The gold electrode (2.0 mm diameter) was mechanically polished with two micropolish alumina suspensions of 0.3 and 0.5 μ , respectively, for 3 min each and washed with distilled water. Subsequent ultrasonic cleaning with absolute ethanol removed the residual alumina powder. After mechanical cleaning, the gold electrode was immersed in piranha solution (H_2SO_4/H_2O_2 , 1:3 v/v) for 10 min at room temperature and finally washed with distilled water. Prior to sensor fabrication, a gold working electrodes was electrochemically cleaned by cycling between -0.3 and 1.5 V at a scan rate 0.1 V s vs. Ag AgCl in 0.5 M sulfuric acid until gold oxide formation was detected in the voltammogram. The electrodes were washed thoroughly with distilled water and dried in a nitrogen stream to obtain a clean gold surface. The modified electrodes were characterised by cyclic voltammetry. All cyclic voltammetric measurements were taken using of Ag|AgCl as a reference electrode and platinum wire as a counter electrode. A solution of 10 mM K₄[Fe(CN)₆ in 1 M KCl (pH 7.0) was used as a redox probe and scanned at 0.1 V s^{-1} from -0.2 to +0.6 V.

Electrode modification was carried out in a glass tube, where only the gold surface was in contact with organic reagent. The gold electrode was dipped in a solution of **4** (20 mg in 2 mLTHF) for varying durations (20 min to 6 h) at ambient temperature before being washed several times with pure ethanol and then with double-distilled water. The modified gold electrodes were kept in double-distilled water.

4.4. Surface analysis

Attachment of **4** to gold electrodes was assumed to be complete after 4 h as shown in Figure 3(b) as no further changes in peak current were observed. To confirm this, unmodified and modified electrodes were imaged by SEM and surface composition determined by energy dispersive X-ray spectroscopy (EDX). SEM images show a broadly smooth gold surface, with a little pitting, which becomes uniformly uneven following addition of **4** (Supplemental material, Figure S12). No sulfur is evident on the surface prior to attachment of **4** but EDX shows it to be present after addition. The theoretical ratio of carbon to sulfur in **4** is 1:0.114; the ratio from EDX is 1.00 (\pm 0.024):0.095 (\pm 0.03) which falls within the expected range and proves that **4** has bound to the electrode surface.

4.5. Electrochemical assessment of alkali metals using pillar[5]ene attached gold electrodes

Voltammetric scans were carried out in 10 mM solutions of alkali metal cations (Li⁺, Na⁺, K⁺, Rb⁺, Cs⁺) were prepared from their PF_6^- salts. Recordings were carried out between -0.3 and +0.3 V at 0.1 V s⁻¹ scan rate. Between all recordings the electrodes were rinsed in distilled water. In order to measure the effect of cation salts on the voltammetric response, the change in the capacitive signal was monitored on both a gold electrode attached with **4** and a bare gold electrode. The capacitance was measured as the difference in the current observed at 0 V over the scan rate. All experiments were conducted in triplicate.

4.6. X-ray crystallography

Single crystals of **2** and **3** were grown from solutions in DMF/methanol and DMF/CH₂Cl₂, respectively. The crystal structures were solved by direct methods and refined based on full-matrix least-squares methods on F^2 with SHELX-97 (42). All non-hydrogen atoms were refined with anisotropic displacement parameters, all hydrogen atoms with free positional parameters and isotropic displacement parameters. For **2**·DMF·0.5 H₂O, the occupancies of the terminal bromine were refined to 0.921(2) for Br1 and 0.079(2) for Br1'. Selected data: $C_{50}H_{60}Br_2NO_{11.50'}$ M = 1017.80, monoclinic, space group $P2_1/n$ (No. 14), a = 11.956(2), b = 24.061(5), c = 16.901(3) Å, $\alpha = 90$, $\beta = 93.72(3)$, $\gamma = 90^\circ$, V = 4851.8(17) Å³, Z = 4, $\rho = 1.393$ g cm⁻³, $\mu = 1.732$ mm⁻¹, temperature = 100(2) K, $F(0 \ 0 \ 0) = 2112$, 11517 reflections ($2\theta_{max} = 58.80^\circ$) measured (5887 unique, $R_{int} = 0.0193$),

completeness = 85.8% (2θ = 58.8°), 97.3% (2θ = 55°), R_1 ($l > 2\sigma(l)$) = 0.0750, wR_2 ($l > 2\sigma(l)$) = 0.1652, R_1 = 0.1550, wR_2 (all data) = 0.2117. GOF = 1.027 for 606 parameters and 0 restraints, largest diff. peak and hole 0.849/-1.023 eÅ³. CCDC: 1404413.

Supplemental material

Supplemental data for this article can be accessed here: http://dx.doi.org/10.1080/10610278.2015.1111375

Disclosure statement

No potential conflict of interest was reported by the authors.

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