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Self-assembled monolayers of different conformers of *p*-*tert*-butylcalix[4]crown-6 derivatives and their metal cation recognition properties

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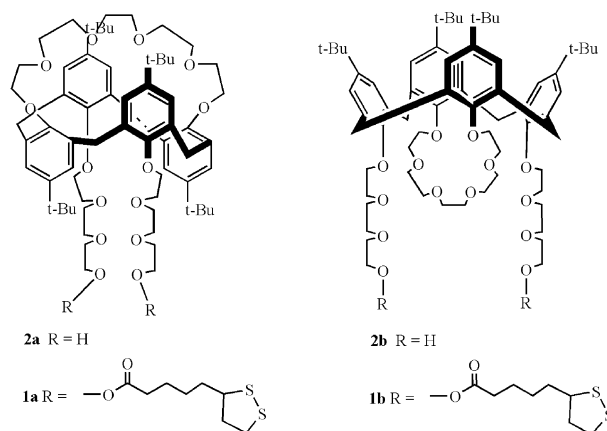
Abstract—Two isomers of *p*-*tert*-butylcalix[4]crown-6 derivatives form stable self-assembled monolayers (SAMs) by taking advantage of the adsorption of bis-thioctic ester on gold electrodes, and their Cs⁺ recognition is completely dependent on the conformational orientation of the compounds.

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Self-assembled monolayers (SAMs) that possess molecular recognition motifs can be used to design chemical sensors,¹ nonlinear optical materials² and molecular switches.³ Currently, extensive efforts have been made to modify surfaces by self-assembled monolayers.⁴ The first reports involving the incorporation of crown-ether groups into SAMs and their use as metal cation sensors were published almost simultaneously by Bryce et al.⁵ and Reinhoudt et al.⁶ We have recently prepared and investigated remarkably stable SAMs of bis-thioctic ester derivatives of oligoethylene glycols⁷ and crown ether-annelated TTFs.⁸ Also, we demonstrated for the first time that potassium cations can be imprinted into SAMs when the monolayer is formed in the presence of this metal cation.⁹

The first example of a calixarene-crown ether conjugate compound, *p*-*tert*-butylcalix[4]crown-6, was reported by Alfieri et al.¹⁰ The highly selective complexation of calix[4]crown-6 with alkali and alkaline-earth metal ions have been extensively investigated. The calix[4]crown-6 in its 1,3-alternate conformation is particularly attractive because it exhibits remarkable efficiency to extract cesium ion from nuclear waste.¹¹ The selective removal of ¹³⁷Cs from radioactive waste is an important environmental and technological issue. For this purpose, a number of cesium ion selective sensors based on 1,3-alternate-calix[4]crown-6 were prepared and their behavior in solution was reported.¹² To fully realize the practical application of these molecules,

however, they need to be organized on surfaces. The incorporation of calix[4]crown-6 derivatives into SAMs to study their ion recognition properties has been reported only by Ji et al.¹³ They reported a selective cesium ion sensor based on a SAM coated micro-cantilever modified by a 1,3-alternate calix[4]benzo-crown-6 derivative. A few other articles of calixarene derivatives on self-assembled monolayers has also been reported.¹⁴ In this letter, we report the preparation of two conformational isomers of bis-thioctic ester derivatives of *p*-*tert*-butylcalix[4]crown-6, **1a** and **1b**, which form stable SAMs on gold and show reversible and selective complexation of metal ions. SAMs derived from **1a** bind Cs⁺ while those from the cone isomer **1b** do not.



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Two derivatives, (**1a**, **1b**) were synthesized in moderate yields by reacting the corresponding bis-alcohols (**2a**, **2b**) with thioctic acid in CH_2Cl_2 in the presence of DCC and DMAP.¹⁵ Treatment of *p*-tert-butylcalix[4]crown-6¹⁶ with triethylene glycol monotosylate in the presence of Cs_2CO_3 in refluxing acetonitrile afforded **2a**. Bis-alcohol **2b** was obtained by the reaction of *p*-tert-butylcalix[4]crown-6 with NaH and triethylene glycol monotosylate in refluxing DMF/THF (9: 1). It should be emphasized that slow addition of the DMF solution of triethylene glycol monotosylate was crucial to the success of this reaction.

SAMs of **1a** and **1b** were prepared by immersing glass-sealed gold bead electrodes made from gold wire (99.9999%, diameter 250 μm) for 24 h in an acetonitrile solution of **1a** or **1b** (3 mM), respectively. After rinsing with copious acetonitrile and drying under a stream of Ar, these SAM modified electrodes were placed into 0.1 M aqueous Et_4NCl and their cyclic voltammograms were recorded using a platinum mesh as counter and a Ag/AgCl as reference electrodes. Impedance measurements were performed using an aqueous solution of Et_4NCl (0.1 M) and $[\text{Ru}(\text{NH}_3)_6]\text{Cl}_3$ (1 mM) at the formal redox potential of the $[\text{Ru}(\text{NH}_3)_6]^{3+/2+}$ redox couple at frequencies between 1 kHz and 0.1 Hz.

Figure 1(a) (dotted line) shows the CV response for the $\text{Ru}(\text{NH}_3)_6^{3+/2+}$ redox couple at a SAM modified gold electrode with **1a**. Apparently, the blocking effect of the

monolayer is poor, since a large cathodic current was observed, indicating fast electron transfer at the interface. This is either due to poor surface coverage or good electron permeability through the monolayer. Interestingly, addition of 45 mM CsCl to the electrolyte results in a drastically reduced cathodic current and in the almost complete disappearance of the corresponding anodic current (shown in Fig. 1(a) solid line). This observation is ascribed to the inhibition of electron transfer at the interface caused by strong repulsion between the calixcrown bound cations and the positively charged $\text{Ru}(\text{NH}_3)_6^{3+/2+}$ redox couple.^{6,7,11} In contrast, the CV response at a **1b** modified gold electrode shows almost no change when CsCl was added to the electrolyte. This means that cone-calix[4]crown-6 isomer **1b** cannot bind Cs^+ , but the 1,3-alternate isomer **1a** can recognize cesium cations very efficiently.

Impedance spectroscopy was employed to investigate further the interfacial ion recognition process because both the guest cations and the host SAM are electrochemically inactive. The R_{ct} (charge transfer resistance) of the monolayer is highly dependent on the metal cations added to the electrolyte solution. The complex plane impedance response of SAMs of **1b** upon addition of increased $[\text{Cs}^+]$ shows very little effect on the charge transfer resistance of the monolayer, corroborating that cesium ions cannot bind significantly to the surface [shown in Fig. 1(b)]. Interestingly, the SAM modified gold electrode with **1a** shows a completely

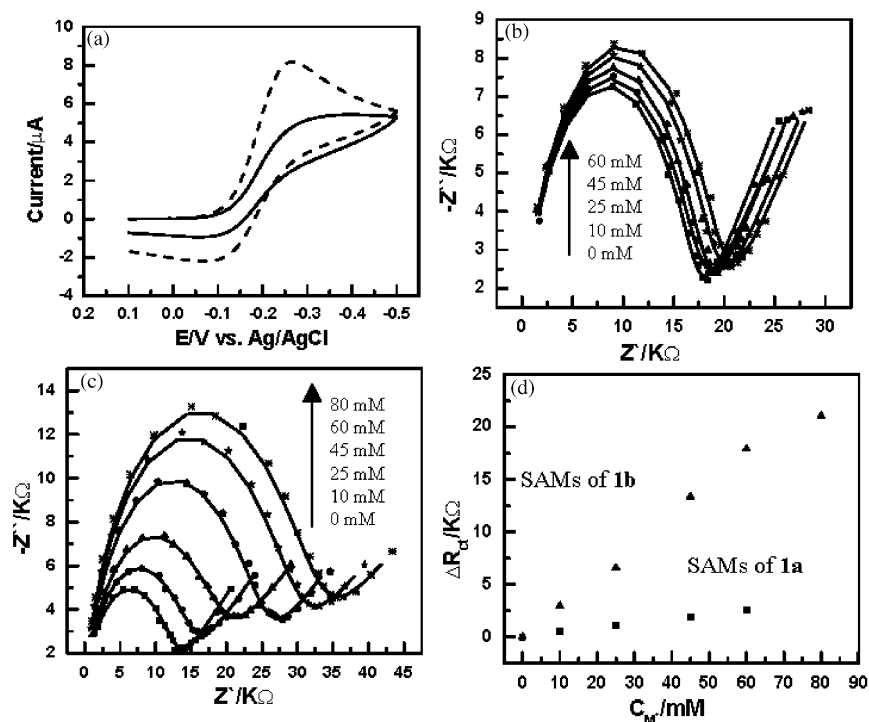


Figure 1. (a) Cyclic voltammogram of $\text{Ru}(\text{NH}_3)_6^{3+/2+}$ in 0.1 M Et_4NCl at a SAM of **1a** modified gold electrode before (dashed line) and after (solid line) addition of Cs^+ to the electrolyte at a scan rate of 100 mV/s. (b) Impedance response of the electrode modified by SAM of **1b** in the absence and presence of increasing $[\text{Cs}^+]$. The solid lines represent the fits of the experimental points. (c) Impedance response of SAMs of **1a** modified gold electrode in the absence and presence of increasing Cs^+ . (d) Comparative plot of ΔR_{ct} versus concentrations of $[\text{Cs}^+]$ for SAMs of **1a** and **1b**.

different response towards cesium ions when compared to the SAMs of cone-isomer **1b**. Figure 1(c) shows that addition of Cs^+ to the electrolyte gives rise to an increase in the value of R_{ct} , from 13.3 k Ω in the absence of Cs^+ to 34.4 k Ω in the presence of 80 mM Cs^+ . This indicates complexation of Cs^+ at the interface and the repulsion of the positively charged redox probe, in perfect agreement with the CV observations. The system was found to be fully reversible since replacing the cesium chloride containing solution with a metal cation free electrolyte leads to the initially determined value of R_{ct} . The totally different impedance responses for Cs^+ of SAMs of **1a** and **1b** confirm that Cs^+ binds strongly to the 1,3-alternate isomer **1a**, but essentially not at all to the corresponding cone-isomer **1b**. This Cs^+ selectivity must be controlled by two factors: the size fit of the crown ether with the ion, and a cation- π interaction between the Cs^+ and the two rotated aromatic rings.¹⁷ Thus the calix(4)arene, which can assume four different conformations, plays a key role in the selectivity of calix[4]crown-6 derivatives for the metal cations. In comparison with the cone-*p*-*tert*-butylcalix[4]crown-6 derivative **1b**, the 1,3-alternate isomer **1a** exhibits a much more favorable conformation to recognize Cs^+ . The conformation of **1a** couples the complexation ability of the crown ether with the metal cations with the interaction between the aromatic centers and Cs^+ . Some derivatives of 1,3-alternate-calix[4]crown-6 have been shown to possess high selectivity towards Cs^+ in both alkaline and acidic media.¹¹ This is the first report of the self-assembly of different conformers of *p*-*tert*-butylcalix[4]crown-6 derivatives on gold electrodes and their conformationally-controlled Cs^+ recognition. This research further demonstrates the potential use of 1,3-alternate calix[4]crown-6 derivatives as potential sensors for Cs^+ .

The sensing ability of SAMs of **1a** and **1b** for other metal cations was also determined. In both instances, however, only small changes in the value of R_{ct} were observed for Na^+ and K^+ , respectively, suggesting that both Na^+ and K^+ cannot form stable complexes with SAMs of either **1a** or **1b**. These observations reveal that the SAMs of **1a** instead of the SAMs of **1b** can, in a way, serve as a reversible and selective sensor for Cs^+ over Na^+ and K^+ . Further investigation into the sensing capacity of the SAMs with other metal cations shows that the selectivity for Cs^+ of SAMs of **1a** is not that good, since both SAMs of **1a** and SAMs of **1b** on gold electrodes can recognize calcium cations. Placing the gold electrode modified by SAMs of **1b** in an electrolyte solution containing increasing concentrations of Ca^{2+} leads to an increase in the R_{ct} value, from 16.7 k Ω in the absence of Ca^{2+} to 60.8 k Ω in the presence of 80 mM Ca^{2+} . Similarly, binding of calcium cations to the SAMs of **1a** increases its resistance from 13.3 k Ω to 44.2 k Ω at a concentration of 80 mM. The latter observation demonstrates that SAMs of **1a** have an even higher affinity for Ca^{2+} than for Cs^+ , showing a lack for good selectivity. The poor selectivity of SAMs of **1a** for Cs^+ is probably due to the introduction of oligoethylene glycol (OEG) chains in the lower rim.

The fitting of all the impedance data were done by the program EQUIVALENT CIRCUIT. Figure 1(d) shows a plot of ΔR_{ct} versus $[\text{Cs}^+]$ for SAMs of **1a** and **1b**. The SAMs of **1a** show a linear increase in R_{ct} with increased concentration of $[\text{Cs}^+]$. This is in contrast to the lack of a response to Cs^+ for the SAMs of **1b**. In addition, both monolayers show a linear increase in the value of R_{ct} with increased concentration of $[\text{Ca}^{2+}]$. There are two molecular domains where Ca^{2+} can bind with *p*-*tert*-butylcalix[4]crown-6 derivatives **1a** and **1b**: with the crown ether ring or with the OEG chains. Further work is underway to determine the relative contributions of these Ca^{2+} binding motifs in order to improve the selectivity for Cs^+ .

In summary, remarkably stable monolayers of two conformational isomers of *p*-*tert*-butylcalix[4]crown-6 derivatives have been prepared and their metal cation recognition properties were detected by impedance spectroscopy and cyclic voltammetry. The selectivity of calixcrown SAMs is modulated by the change of conformation. Only the conformationally suitable compound, 1,3-alternate isomer is able to recognize cesium cations.

Acknowledgements

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15. All new compounds were fully characterized by spectroscopic techniques.
Selected data for 1a: pale-yellow sticky solid, yield 71%; mp 93.4–95.1°C; IR (film on quartz): 2931, 2904, 2846, 1738, 1624, 1480, 1122, 843, 731, 559 cm⁻¹. ¹H NMR: δ 7.03 (8H, s, broad), 4.21 (4H, t, $J=4.8$), 3.85 (8H, s, broad), 3.44–3.68 (30H, m), 3.08–3.16 (8H, m), 2.95–2.99 (8H, m), 2.42–2.46 (2H, m), 2.34 (4H, t, $J=7.4$), 1.86–1.93 (2H, m), 1.45–1.70 (12H, m), 1.34 (18H, s), 1.29 (18H, s); ¹³C NMR: δ 173.29, 154.34, 154.01, 144.56, 143.91, 133.21, 133.02, 125.88, 125.73, 71.32, 71.15, 70.42, 69.26, 69.00, 68.18, 67.90, 63.47, 56.34, 40.10, 38.94, 38.37, 34.48, 33.91, 33.81, 31.63, 31.58, 28.62, 24.49; m/z (MALDI): 1528.7 (M⁺+K).
- For 1b*: pale-yellow solid, yield 64%; mp 194.2–195.3°C; IR (film on quartz): 2933, 2897, 2847, 1735, 1624, 1480, 1457, 1260, 1121, 750, 559 cm⁻¹. ¹H NMR: δ 7.03 (4H, s), 6.47 (4H, s), 4.38–4.44 (4H, d, $J=12.5$), 4.15–4.23 (12H, m), 3.99 (4H, t, $J=4.8$), 3.69–3.86 (28H, m), 3.53–3.58 (2H, m), 3.08–3.18 (8H, m), 2.42–2.46 (2H, m), 2.33 (4H, t, $J=7.4$), 1.89–1.92 (2H, m), 1.44–1.70 (12H, m), 1.31 (18H, s), 0.83 (18H, s); ¹³C NMR: δ 73.35, 151.89, 144.97, 144.21, 135.24, 132.06, 125.37, 124.48, 73.67, 72.23, 71.18, 70.83, 70.57, 70.35, 70.21, 69.78, 69.15, 63.44, 56.24, 40.13, 38.40, 34.51, 33.92, 33.82, 33.51, 31.63, 31.06, 30.86, 28.64, 24.52; m/z (MALDI): 1513.2 (M⁺+Na), 1529.2 (M⁺+K).
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