Pergamon

Polyhedron Vol. 14, No. 19, pp. 2631–2635, 1995
Elsevier Science Ltd
Printed in Great Britain
0277-5387/95 $9.50+0.00

0277-5387(95)00129-8

POTASSIUM CATIONS ALLOSTERICALLY SWITCH OFF THE HALIDE ANION RECOGNITION PROPERTIES OF A NEW COBALTICINIUM BIS BENZO CROWN ETHER RECEPTOR*

PAUL D. BEER† and SALLY E. STOKES

Inorganic Chemistry Laboratory, University of Oxford, South Parks Road, Oxford OX1 3QR, U.K.

Abstract—The synthesis of a new cobalticinium bis benzo crown ether receptor (**3**) is described whose halide anion recognition properties can be switched on or off via the absence or presence of co-bound potassium cations.

The design and synthesis of abiotic allosteric receptor molecules that can exhibit positive or negative binding cooperatively of guest species is an area of ever increasing interest of relevance to the future development of switchable device technology.[1] For example, the chelation of transition metal cations by various elegantly designed molecular hinges have been shown to enhance or decrease the binding strengths of co-bound charged substrates.[2] We report here the synthesis of a new cobalticinium bis benzo crown ether receptor (**3**) whose halide anion recognition properties are "switched off" via conformational changes induced by the presence of crown ether complexed potassium cations.

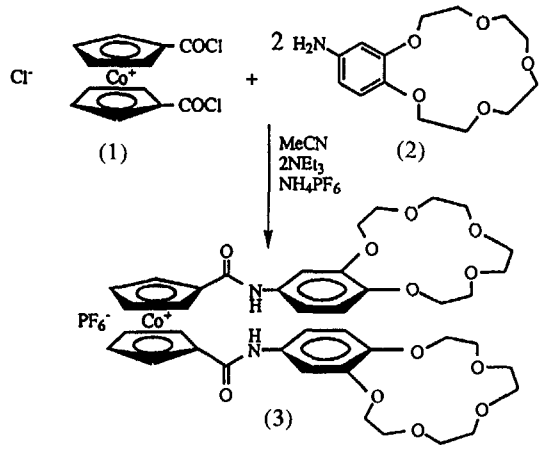
RESULTS AND DISCUSSION

Ligand synthesis

The condensation of 1,1′-bis(chlorocarbonyl) cobalticinium chloride (**1**)[3] with 2 equivalents of 4-aminobenzo-15-crown-5 (**2**)[4] in the presence of triethylamine in dry acetonitrile gave a crude orange/red powder. This material was dissolved in water and on addition of excess ammonium hexafluorophosphate the desired product (**3**) was isolated as a fine brick red solid in 56% yield (Scheme 1). Proton and ^{13}C NMR spectroscopic, and fast atom bombardment mass spectrometric data were in accordance with the receptor's proposed structure (see Experimental).

Cation coordination chemistry of **3**

The crown ether moiety is notorious for its ability to complex a variety of group 1 metal cations of differing stoichiometries dependent upon the relative sizes of the crown ether cavity to metal cation diameter.[5] Typically bis crown ethers in addition to forming 2:1 metal:ligand complexes readily form



Scheme 1.

* Dedicated to Professor E. W. Abel, a dear friend and colleague, on the occasion of his retirement.

† Author to whom correspondence should be addressed.

1 : 1 sandwich type complexes with metal cations of a size larger than the single crown ether cavity.[6]

The coordination chemistry of **3** with sodium and potassium cations was investigated by preparing the respective alkali metal complexes. The cobalticinium bis crown ether receptor was refluxed with aqueous solutions of $NaBPh_4$ and $KBPh_4$ and on cooling the respective metal complexes were isolated as orange powders in quantitative yields. Elemental analyses and fast atom bombardment mass spectrometry suggested **3** forms a 1 : 2 ligand to metal cation complex with sodium cations, indicating that the two benzo crown ether moieties are acting independently, each complexing a sodium cation; whereas the larger potassium cation forms a 1 : 1 intramolecular sandwich complex in which the two crown ether sub-units act cooperatively (Scheme 2). Similar potassium cation bis crown ether complexes have been reported with a variety of bis-benzo-15-crown-5 crown ethers.[7]

Anion coordination chemistry of **3** *and of its sodium and potassium complexes*

We have recently shown that simple acyclic cobalticinium receptors containing the amide CO—NH linkage can coordinate and electrochemically sense a variety of anionic guest species.[8] It was envisaged that the incorporation of additional centres of positive charge into the cobalticinium ligand framework, in the form of crown ether co-bound metal cations, may amplify the strength of the anion recognition process.[9] In order to study this possible cooperative anion binding effect, anion coordination chemical studies were undertaken with the free ligand **3** and with its alkali metal cation complexes.

The addition of chloride and bromide anions to ^1H NMR deuterated acetonitrile solutions of **3** all produced significant perturbations of the receptors amide and cyclopentadienyl protons. As can be seen from the resulting titration curves (Fig. 1) the stoichiometries of complexation are 1 : 1 with each anion. Using the non-linear curve fitting programme EQNMR,[10] stability constant values were determined from the ^1H NMR titration data. Within experimental error the calculated stability constants, Log Ks = 3.1 (Cl^-), Log Ks = 3.0 (Br^-) are of similar magnitudes, suggesting there is very little selectivity for either halide anionic guest.

Analogous ^1H NMR halide anion complexation investigations with the sodium and potassium cation complexes of **3** revealed contrasting results. With $[3 \cdot 2Na]^{3+}(BPh_4^-)_3$ in CD_3CN the calculated stability constants [Log Ks = 3.0 (Cl^-), 3.0 (Br^-)] were, within experimental error, disappointingly the same as those determined with the free ligand

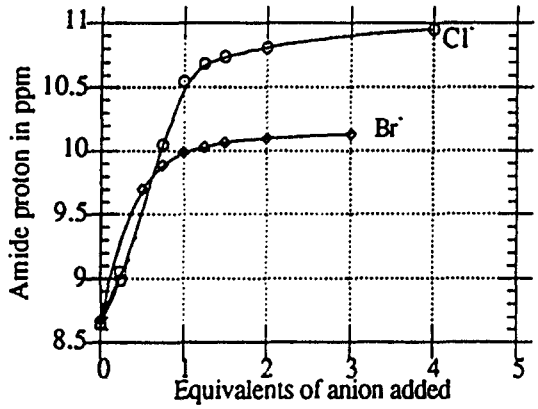
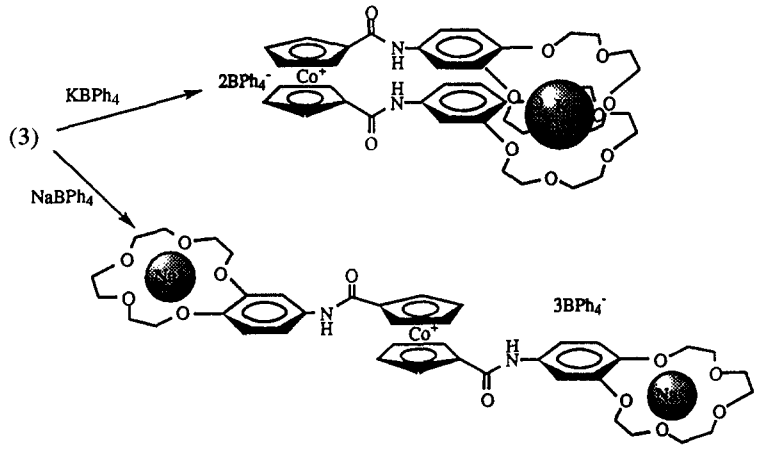


Fig. 1. Proton NMR titration curves of the perturbation of the amide proton of **3** on addition of halide anions in CD_3CN.



Scheme 2.

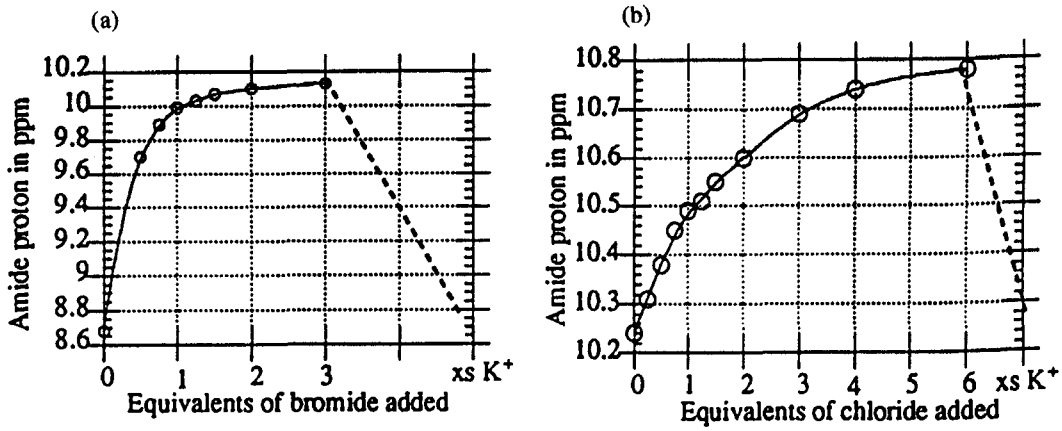


Fig. 2. The effect of added potassium cations on the proton NMR titration curves of (a) $Br^-(CD_3CN)$ and (b) $Cl^-(DMSO-d_6)$.

3, indicating the presence of the additional two positively charged benzo crown ether complexed sodium cations has very little effect on the anion complexation process. Titrating either $[3\cdot K]^{2+}(BPh_4^-)_2$ or **3** in the presence of an excess amount of $KBPh_4$, in CD_3CN with Br^- or Cl^- resulted in unexpectedly *no* significant downfield shifts ($\Delta\delta \leqslant 0.05$ ppm) of the amide or cyclopentadienyl protons of the receptor, suggesting the potassium complex does not coordinate anions. This surprising observation was further investigated by adding an excess amount of potassium cations at the end of ^1H NMR halide anion titration experiments of the free ligand. Figures 2(a) and 2(b) clearly show that the addition of potassium cations to the **3** anion titration CD_3CN and DMSO-d_6 NMR solutions had a dramatic effect on the anion complexing properties of the receptor. Following the amide proton's downfield shift on the stepwise addition of halide, there was significant upfield perturbation of the amide proton signal to a chemical shift value close to that of the free ligand on the addition of excess K^+. This observation suggests the amide protons are no longer involved in favourable hydrogen-bonding interactions with the halide anionic guest species.

It may be postulated that the potassium cations added to the respective bromide-**3** and chloride-**3** ^1H NMR solutions form a 1 : 1 potassium bis benzo crown ether intramolecular sandwich complex which causes the spatial arrangement of the anion binding site within the receptor to alter leading to less efficient or even the termination of anion complexation. The relatively rigid structure of the potassium complex perhaps sterically hinders the approach of the anionic guest to the amide CO—NH hydrogen bonding vicinity of the cobalticinium receptor (Fig. 3). Indeed the solid-state structure of the potassium complex of the analogous ferrocene bis benzo-15-crown-5 ligand (**4**) supports this postulation.[11]

Electrochemical studies

The electrochemical properties of **3** and of its alkali metal complexes were investigated in acetonitrile using cyclic voltammetry and the results are summarized in Table 1. The receptor **3** exhibited a reversible one-electron redox reduction wave which is anodically shifted in the alkali metal complexes. This is a result of the electrostatic inductive effect of the crown ether bound metal cations withdrawing electron density from the cobalticinium redox centre. Cyclic voltammograms were also recorded after progressively adding stoichiometric equivalents of Cl^- and Br^- anions to the electrochemical solutions (Table 1). Significant one-

Table 1. Electrochemical data

Compound	$E_{\frac{1}{2}}^{1}$(V)[a]	$\Delta E(Cl^-)$[b] (mV)	$\Delta E(Br^-)$[b] (mV)
3	−0.85	60	30
$[3\cdot 2Na][BPh_4]_3$	−0.79	60	25
$[3\cdot K][BPh_4]_2$	−0.78	<5	<5

[a] Obtained in acetonitrile solution containing $NBu_4^nBF_4$ (0.2 mol dm^{-3}) as supporting electrolyte. Solutions were *ca* 2×10^{-3} mol dm^{-3} in compound and potentials were determined with reference to the SCE.

[b] Cathodic shift in reduction potential produced by the presence of anions (up to 4 equivalents) added as their tetrabutylammonium salts.

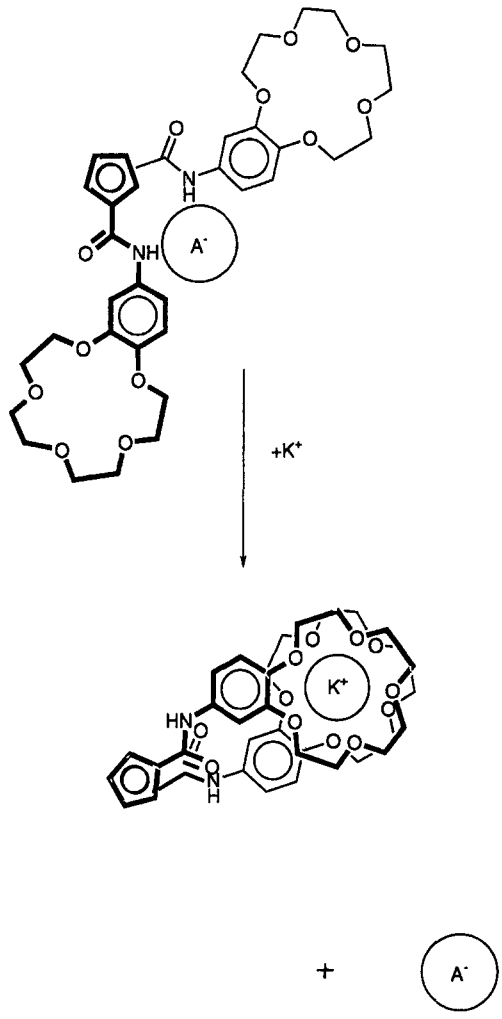


Fig. 3. Proposed negative binding cooperation effect of K^+ complexation on the halide recognition properties of 3.

wave cathodic perturbations were observed with **3** and with its bis sodium complex. However, the potassium complex exhibited negligible cathodic shifts suggesting, in agreement with the results obtained from ^1H NMR anion complexation experiments, that anion binding was not apparent. It is noteworthy that the addition of potassium cations to electrochemical solutions of **3** in the presence of excess chloride caused the redox reduction wave that had initially shifted cathodically with Cl^- to undergo an *anodic* perturbation back to a potential value similar to that of the free receptor, suggesting the competitive complexation of K^+ metal cations can "switch off" the binding and consequently the electrochemical recognition of the chloride anion.

Conclusions

The synthesis of a new cobalticinium bis benzo crown ether receptor **3** has been achieved and shown to coordinate alkali metal cations forming a bis sodium complex and a 1:1 intramolecular sandwich complex with the potassium cation. The free receptor complexes and electrochemically recognizes halide anions. Disappointingly, the introduction of sodium cations, as judged from stability constant determinations had little effect on strengthening the halide anion complexing properties of the receptor. However, the potassium complex did not apparently complex anions. This difference in anion binding capability may be attributed to the conformation of the relatively rigid receptor's bis benzo-15-crown-5 potassium cation intramolecular sandwich complex sterically inhibiting access to the amide CO—NH moieties, negating the possibility of favourable hydrogen bonding with the anionic guest species. Therefore, a novel potential molecular switch has been developed whereby the binding of halide anionic guest species by **3** can be switched on or off via the absence or presence of potassium cations (Fig. 3).

EXPERIMENTAL

Instrumentation

NMR spectra were obtained on a Bruker AM300 instrument using the solvent deuterium signal as an internal reference. Fast atom bombardment (FAB) mass spectrometry was performed by the SERC mass spectrometry service at University College, Swansea. Electrochemical measurements were carried out using an E.G. and G. Princeton Applied Research 362 scanning potentiostat. Elemental analyses were performed at the Inorganic Chemistry Laboratory, University of Oxford.

Solvent and reagent pre-treatment

Where necessary, solvents were purified prior to use and stored under nitrogen. Acetonitrile was predried over class 4 Å molecular sieves (4–8 mesh) and then distilled from calcium hydride. 1,1′-Bis(chlorocarbonyl)cobalticinium chloride (**1**)[3] and 4-amino-benzo-15-crown-5 (**2**)[4] were prepared according to literature procedures.

1,1′ - Bis(3,4 - benzo - 1,4,7,10,13 - pentaoxacyclo - pentadeca-2-ene aminocarbonyl)cobalticinium hexafluorophosphate (**3**)

A solution of 3,4-aminobenzo-1,4,7,10,13-pentaoxacyclopentadeca-2-ene (**2**) (1.35 g, 4.8 mmol) and triethylamine (0.6 g, 5.9 mmol) was made up in dry CH_3CN (50 cm^3) and stirred under nitrogen at room temperature. To this was added a solution

of 1,1′-bis(chlorocarbonyl)cobalticinium hexafluorophosphate (**1**) (1.09 g, 2.4 mmol) in CH_3CN (30 cm^3) via a cannula dropwise and under nitrogen. On addition, a red/orange precipitate formed and the mixture was allowed to stir for 24 h. The solvent was removed by rotary evaporation to yield the crude product as a red/orange powder (3.47 g, 3.5 mmol).

To purify, the solid product was dissolved in hot H_2O and excess NH_4PF_6 was added. The solution was allowed to cool to room temperature and the product was isolated by filtration and washed with cold water to yield a fine brick red powder (1.28 g, 1.34 mmol, yield: 56%).

^{1}H NMR (300MHz,CD_3CN): δ: 3.36–4.06 (m,32H,OCH_2),5.91 (t, J = 2 Hz, 4H, CpH), 6.30 (t, J = 2 Hz, 4H, CpH), 6.38 (d, J = Hz, 2H, ArH), 6.99 (d, J = 8 Hz, 2H, ArH), 7.15 (s, 2H, ArH), 8.71 (s, 2H, NH). ^{13}C NMR (75.42 MHz, DMSO): δ: 68.3, 68.7, 69.7, 70.3 (OCH_2CH_2O), 85.2 (Cp *C* H), 86.6 (Cp *C* H), 95.7 (Cp *C* CO), 107.6, 113.4, 113.7, 131.6, 145.6, 148.1 (Ar *C*), 158.5 (*C* = O). FTIR (cm^{-1}): 1656 (C=O), 1549 (CONH), 844 (PF_6^-). Analysis: Found: C, 50.2; H, 5.97; N, 3.60. Calc. for $C_{40}H_{48}N_2O_{12}CoPF_6$: C, 50.4; H, 5.08; H; N, 2.94. FAB-MS m/z: 807 $(M\text{-}PF_6)^+$.

1,1′ - *Bis*(3,4 - *benzo* - 1,4,7,10,13 - *pentaoxacyclo* - *pentadeca-2-ene aminocarbonyl)cobalticinium bis tetraphenylborate potassium* [**3**·K]$(BPh_4)_2$

Crude 1,1′-bis(3,4-benzo-1,4,7,10,13-pentaoxacyclopentadeca-2-ene aminocarbonyl)cobalticinium hexafluorophosphate was taken up in hot H_2O. To this solution was added $KBPh_4$ and the mixture was reheated for 30 min. The solution was then allowed to cool to room temperature and the product was isolated by filtration as an orange powder in quantitative yield.

^{1}H NMR (300 MHz, CD_3CN): δ: 3.4–4.10 (m, 32H, OCH_2), 5.88 (t, J = 2 Hz, 4H, CpH), 6.38 (t, J = 2 Hz, 4H, CpH), 6.80–7.40 (m, 66H, BPh_4 and ArH), 9.18 (s, 2H, NH). FTIR (cm^{-1}): 1676(C=O). Analysis: Found: C, 68.58; H, 5.45; N, 2.51. Calc. for $C_{88}H_{88}N_2O_{12}CoB_2K \cdot 2H_2O$: C, 69.47; H, 6.05; N, 1.89%. FAB-MS m/z: 807 $(M\text{-}2BPh_4 - K^+)^+$, 846 $(M\text{-}2BPh_4 + K^+)^{2+}$.

1,1′ - *Bis*(3,4 - *benzo* - 1,4,7,10,13 - *pentaoxacyclo* - *pentadeca-2-ene aminocarbonyl)cobalticinium tris tetraphenylborate bis sodium* [**3**·2Na]$(BPh_4)_3$

Crude 1,1′-bis(3,4-benzo-1,4,7,10,13-pentaoxacyclopentadeca-2-ene aminocarbonyl)cobalticinium hexafluorophosphate was taken up in hot H_2O. To this solution was added $NaBPh_4$ and the mixture was reheated for 30 min. The solution was then allowed to cool to room temperature and the product was isolated by filtration as an orange powder in quantitative yield.

^{1}H NMR (300 MHz, CD_3CN): δ: 3.35–4.10 (m, 32H, OCH_2), 5.85 (t, J = 2 Hz, 4H, CpH), 6.25 (t, J = 2 Hz, 4H, CpH), 6.80–7.40 (m, 66H, BPh_4 and ArH), 9.21 (s, 2H, NH). FTIR (cm^{-1}): 1680 (C=O). Analysis: Found: C, 70.9; H, 6.11; N, 1.97. Calc. for $C_{112}H_{108}N_2O_{12}CoB_3Na_2 \cdot 4H_2O$: C, 71.5; H, 6.18; N, 1.55% FAB-MS$m/z$: 807 $(M\text{-}3BPh_4 - 2Na^+)^+$, 831 $(M\text{-}3BPh_4 + Na^+)^{2+}$.

Acknowledgements—We thank the EPSRC for an earmarked studentship to S.E.S. and for use of the mass spectrometry service at University College Swansea.

REFERENCES

1. J. Rebek Jr, *Accts. Chem. Res.* 1984, **17**, 258; J. Rebek Jr, *Science* 1987, **235**, 1478.
2. P. D. Beer and A. S. Rothin, *J. Chem. Soc., Chem. Commun.* 1988, 52; H. J. Schneider and F. Werner, *J. Chem. Soc., Chem. Commun.* 1992, 490 and refs therein.
3. J. E. Sheats and M. D. Rausch, *J. Org. Chem.* 1970, **35**, 3245.
4. R. Ungaro, B. El. Hay and J. Smid, *J. Am. Chem. Soc.* 1976, **98**, 5198.
5. C. J. Pedersen, *J. Am. Chem. Soc.* 1970, **92**, 386.
6. K. Kikukawa, G-X. He, A. Abe, T. Groto, R. Arata, T. Ikeda, F. Wada and T. Matsuda, *J. Chem. Soc., Perkin Trans* 2 1987, 135 and refs therein.
7. P. D. Beer, Z. Chen, A. Grieve and J. Haggitt, *J. Chem. Soc., Chem. Commun*, 1994, 2413.
8. P. D. Beer, C. Hazelwood, D. Hesek, J. Hodacova and S. E. Stokes, *J. Chem. Soc., Dalton Trans.* 1993, 1327; P. D. Beer, M. G. B. Drew, A. R. Graydon, D. K. Smith and S. E. Stokes, *J. Chem. Soc., Dalton Trans*, 1995, in press.
9. P. D. Beer and A. R. Graydon, *J. Organomet. Chem.* 1994, **466**, 241.
10. M. J. Hynes, *J. Chem. Soc., Dalton Trans.* 1993, 311.
11. P. D. Beer, H. Sikanyika, A. M. Z. Slawin and D. J. Williams, *Polyhedron* 1989, **8**, 879.