BF_2 complexes of α-alkyl-substituted dipyrrolyldiketones as acyclic anion receptors†‡

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α-Alkyl-substituted dipyrrolyldiketones have exhibited anion binding behaviours with pyrrole rotations, whose rates depend on the alkyl chain lengths.

Conformation changes by external stimuli can potentially be used as strategies to realize the formation of molecular machines and devices.[1] As subunits comprising stimuli-responsive molecules, acyclic systems with binding abilities appear to be more appropriate than cyclic systems for exhibiting flexible transformations that are controlled by guest species.[2] Among the various available external stimuli, inorganic and biotic anions such as halides, acetates and phosphates, ubiquitous in biology, are essential for aspects such as the activity of enzymes, transport of hormones, protein synthesis and DNA regulation.[3,4] Acyclic anion receptors, potential building subunits for macromolecular systems, are required to dynamically change their conformations for binding.[5,6] As π-conjugated 'binding sites' responsive to anions, boron complexes (*e.g.*, **1a–d**, Fig. 1)[7–9] based on 1,3-dipyrrolyl-1,3-propanediones[10–12] act as efficient acyclic anion receptors by the 'inversion' of pyrrole rings from the most stable conformations. For example, α-aryl-substituted receptors with long aliphatic chains constitute anion-responsive supramolecular organogels.[9] Therefore, the chemical modification of the periphery would control the anion binding properties and behaviours related to the transformation of π-conjugated systems. The synthesis and anion binding properties of α-alkyl-substituted receptors (**2a1–16**, Fig. 1) are reported in this communication, wherein we also focus on the rate constants, estimated by stopped-flow measurements, for anion binding depending on the alkyl chain lengths.

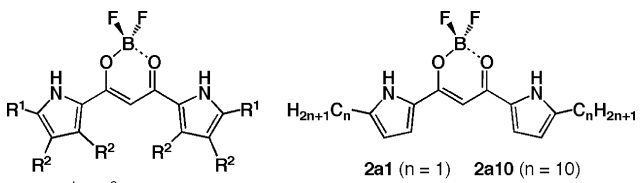

Fig. 1 Structures of BF_2 complexes of dipyrrolyldiketones as acyclic anion receptors.

Similar to the synthesis procedures for **1a–d**, α-alkyl-substituted receptors **2a1–16** have been synthesized in modest yields by the condensation of α-alkylpyrroles[13,14] and malonyl chloride followed by treatment with $BF_3{\cdot}OEt_2$. As compared to the UV–vis absorption maximum of **1a** (432 nm), those of **2a1**, **2a2** and **2a4–16** in CH_2Cl_2 are observed at 453, 455 and 457 nm, respectively, suggesting that the alkyl chains slightly red-shift each absorption maximum. Emissions in the same solvent are observed at, for example, 473 (**2a1**), 475 (**2a2**) and 477–478 (**2a4–16**) nm, excited at each absorption maximum, with high quantum yields (**2a1–16**) within the range of 0.92–0.98. Cylic voltammetry (CV) analyses of **2a1** and **2a2** in CH_3CN with $TBAClO_4$ as an electrolyte reveal a reversible reduction potential at −1.65 ($E_{1/2}$) V (Fc^+/Fc) and irreversible oxidation potential at 0.77 (E_p) V, which are comparable to the potentials of β-ethyl **1c** at −1.74 ($E_{1/2}$) and irreversible 0.85 (E_p) V, suggesting that the oxidation process may afford oligomeric compounds possibly linked at the free pyrrole position(s).

The solid-state structures of **2a1**, **2a2** and **2a4** have been determined by single-crystal X-ray analysis (Fig. 2).§ Similar to other derivatives,[8,9] each molecule shows the conformation with two pyrrole NH facing the carbonyl oxygen. Among these α-alkyl-substituted derivatives, **2a4** locates two butyl chains unsymmetrically, suggesting flexible side alkyl chains. Molecular assemblies using hydrogen bonding between N–H···F–B were observed in these cases: the distances between N(–H)···F are 2.863–2.871 Å

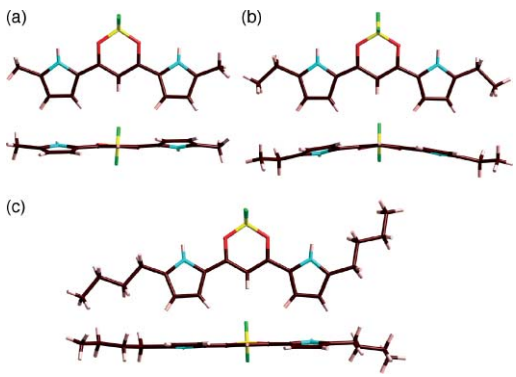

Fig. 2 Single-crystal X-ray structures (top and side views) of (a) **2a1**, (b) **2a2** and (c) **2a4**. One of the independent molecules is represented in (a) and (b). Atom colour code: brown, blue, pink, red, yellow and green represent carbon, nitrogen, hydrogen, oxygen, boron and fluorine, respectively.

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† Electronic supplementary information (ESI) available: Synthetic procedures, analytical data, optimized structures and anion binding behaviours for **2a1–16** and **2b4** and CIF files for the X-ray structural analysis of **2a1**, **2**, **4**, and **2a2**·Cl^-. See DOI: 10.1039/b718317h

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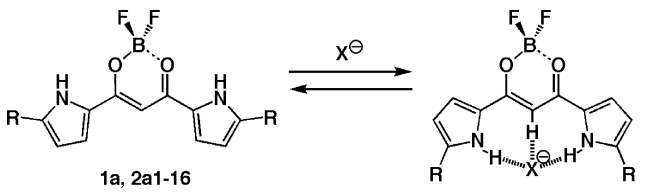
for **2a1**, 2.844–2.964 Å for **2a2** and 2.896–2.980 Å for **2a4**. In addition to the 'flat' dimers observed in **2a1** and **2a4** as well as **1a** and **1d**, α-ethyl **2a2** also forms edge-to-face assemblies. The self-assemblies using NH and BF that are observed in these molecules are found to form supramolecular organized structures as crystals and soft materials. These α-alkyl-substituted **2a1**, **2a2** and **2a4** also construct slipped π–π stacking structures that are essential for the derivatives with long aliphatic chains to fabricate supramolecular organogels.[9] Further, the absorption spectra of solid **1a**, **2a1** and **2a2** crystallised from CH_2Cl_2–hexane dispersed in nujol, which partially dissolves other receptors **2a4–16** to give complicated spectra, are observed at 440 nm (with a minor peak at 480 nm), 458 nm (with a shoulder at 488 nm) and 458 nm, respectively. These electronic situations in the solid state are consistent with *various* packing diagrams from the single-crystals of **1a**, **2a1** and **2a2**.

The anion binding of BF_2 complexes of dipyrrolyldiketones (Scheme 1) was suggested by the ^{1}H NMR spectral changes of, for example, **2a2** upon the addition of Cl^- as a tetrabutylammonium salt in CD_2Cl_2, wherein the signals of NH and bridging CH at 9.38 and 6.42 ppm vanish and the corresponding signals of the complexes newly emerge at 11.92 and 8.30 ppm, respectively. In this case, the interaction of α-alkyl chains with anion was not observed even at −50 °C. The binding constants (K_a) of unsubstituted **1a** and α-substituted **2a1–16** summarized in Table 1 have been determined by the UV–vis absorption spectral changes in CH_2Cl_2; λ_{max} of **2a2** at 455 nm is shifted to 456 and 459 nm upon the addition of Cl^- and $CH_3CO_2^-$, respectively, with the smaller absorbances. The K_a values depend on the alkyl chain lengths; K_a of **1a** are comparable to those of β-fluorinated **1d** (26 000, 1700, 960 000 and 190 000 mol^{-1} dm^3 for Cl^-, Br^-, $CH_3CO_2^-$ and $H_2PO_4^-$) and are larger than that of **2a1** and other receptors. The effects of alkyl chains were observed remarkably in the binding of large anions such as $CH_3CO_2^-$ and $H_2PO_4^-$; for example, K_a of **1a** for $CH_3CO_2^-$ is 930 000 mol^{-1} dm^3, which is 4.2 and 5.5 times larger than those of **2a1** (220 000 mol^{-1} dm^3) and **2a2** (170 000 mol^{-1} dm^3), respectively. These observations suggest that side alkyl chains could interfere with the anion binding possibly due to the electron donating properties.



Scheme 1 Anion binding of BF_2 complexes of dipyrrolyldiketones.

Table 1 Binding constants (K_a, mol^{-1} dm^3) of **1a** and **2a1–16** for anions in CH_2Cl_2 and the ratios to that of **1a** (in the parentheses)

	Cl^-	Br^-	$CH_3CO_2^-$	$H_2PO_4^-$
1a	15 000	2100	930 000	270 000
2a1	6000 (0.40)	1200 (0.57)	220 000 (0.24)	150 000 (0.56)
2a2	4700 (0.31)	870 (0.41)	170 000 (0.18)	76 000 (0.28)
2a4	3500 (0.23)	790 (0.38)	160 000 (0.17)	30 000 (0.11)
2a6	3600 (0.24)	690 (0.33)	170 000 (0.18)	35 000 (0.13)
2a8	3200 (0.21)	690 (0.33)	140 000 (0.15)	27 000 (0.10)
2a10	3900 (0.26)	760 (0.36)	140 000 (0.15)	33 000 (0.12)
2a12	3900 (0.26)	750 (0.36)	130 000 (0.14)	29 000 (0.11)
2a14	3300 (0.22)	730 (0.35)	120 000 (0.13)	24 000 (0.09)
2a16	4000 (0.27)	680 (0.32)	110 000 (0.12)	20 000 (0.07)

In contrast to the 1-D chains bridged by anions that are observed in the solid state structures of **1a**·Cl^- (Fig. 3a) and **1d**·Cl^-,[8] α-aryl receptors have exhibited 'pentacoordinated' binding by using the *o*-CH of the aryl rings as well as pyrrole NH and bridging CH sites (Fig. 3b).[9] In the case of α-unsubstituted **1a**,**d**, the binding modes in the solid state are quite different from the 'tricoordinated' fashions in the solution as well as the optimized structures by DFT calculations. Similarly to the α-aryl-substituted receptors, the single-crystal X-ray structure of **2a2**·Cl^- exhibits the '*syn*' form with tricoordinated geometry (Fig. 3c); the lengths of N(H) $\cdots$ Cl and C(H) $\cdots$ Cl are 3.305–3.346 and 3.521 Å for **2a2**·Cl^-, possibly due to the supportive interactions of the side ethyl chains for the anion.¶ Cl^- anions are located near the side CH_2 moiety at C $\cdots$ Cl distances of 4.195–4.324 Å. Further, the neighbouring Cl^- anions are located at a distance of 5.881 Å, associated with the two cavities of the receptors, and they are 'covered' by two TBA cations, possibly due to the less bulky ethyl moieties. The binding modes in the solid state were also observed in the solution state and were also supported by the optimized structures. These observations in X-ray analysis have revealed that the peripheral alkyl substituents such as α-aryl moieties could stabilize the anion complex using two pyrrole NH and bridging CH under the conditions without solvents.

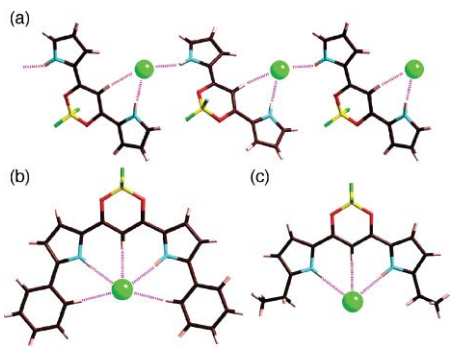


Fig. 3 (a) 1-D infinite chains bridged by anions of **1a**·Cl^-,[8] (b) penta-coordinated geometry of Cl^- complex of phenyl-substituted receptors[9] and (c) tricoordinated geometry of **2a2**·Cl^- in the solid state (Cl anion is represented by yellow-green spheres). In all cases, counter cations (Bu_4N^+ (a,c) and Pr_4N^+ (b)) and solvents are omitted for clarity.

DFT studies also estimated the relative stabilities of the 'preorganized' conformations, adequate for anion binding, with two 'inverted' pyrrole rings.[15] The preorganized structures of **2a1**, **2a2**, **2a3** (α-propyl-substituted receptor, not synthesized), **2a4**, **2a6** and **2a8** are estimated to be less stable than the structures with two pyrrole NH facing carbonyl oxygens at 9.19, 9.12, 9.27, 9.16, 9.17 and 9.10 kcal mol^{-1}, which are almost similar to the α-free **1a** (9.08 kcal mol^{-1}). These calculations suggest that the smaller K_a values in the derivatives with longer alkyl chains are possibly due to their electron-donating properties located next to the binding NH sites. Furthermore, the optimized structures of the Cl^- complexes of **2a1–4**, **2a6** and **2a8** suggest that the interaction between the anion and aliphatic moieties is not so significant.

The acyclic receptors shown in this report are required to invert their pyrrole rings to the same side in order to bind anions; this characteristic point would affect the binding kinetics according to the peripheral substituents. Therefore, we have attempted to estimate the rate constants of the anion binding process by stopped-flow measurements.[9,16] The rate constants of anion binding cannot be determined by ^{1}H NMR exchange studies readily due to the equilibrium of the host–guest complexation. As derived *via* pseudo first order k' with excess Cl^-, the second order rate constants k (mol dm^{-3} s^{-1}) of Cl^- binding in CH_2Cl_2 at r.t. have been determined to be 6.7×10^5 (**1a**), 2.5×10^5 (**2a1**), 1.9×10^5 (**2a2**) and 1.3×10^5 (**2a4–16**), respectively. The k values are smaller depending on the alkyl chain lengths, although they appear to be saturated in the receptors **2a4–16**. The rate constants for anion binding would be affected by the electron-donating properties of alkyl chains, to afford more rigid C(sp^2)–C(sp^2) linkage between pyrrole and boron-diketone units, as well as their bulkiness. In fact, correlations between the 'gradients' in k and K_a (Table 1) are observed.

The anion binding behaviours have also been investigated in α-perfluorobutyl-substituted receptor **2b4**, synthesized by the *n*-C_4F_9 substitution of **1a** using C_4H_9I, H_2O_2 and $FeSO_4$.[17] The binding constants (K_a) of **2b4** and the ratios to α-butyl **2a4** (parentheses) for Cl^-, Br^-, $CH_3CO_2^-$ and $H_2PO_4^-$ in CH_2Cl_2 are 56 000 (16), 4700 (5.9), 270 0000 (16) (with *ca.* 40% error due to an extremely large K_a value) and 560 000 (19) mol^{-1} dm^3, respectively. The affinities of **2b4** for anions are about twice as large as those of β-fluorinated **1d**. These K_a augmentations in **2b4** as compared to **1d** are possibly derived from the effective electron-withdrawing effect at α-substituents as well as the relatively preferable preorganized structure of **2b4** as compared to **1d** as seen in the less stable values of 7.59 (**2b4**) and 15.04 (**1d**) kcal mol^{-1}.

In summary, we have controlled anion binding properties such as rate constants (k) as well as binding constants (K_a) by introducing alkyl chains at the periphery. Furthermore, an effective binding system with electron-withdrawing perfluoroalkyl moieties has also been obtained. α-Substituents such as alkyl chains, which interfere with the extension to the covalently-linked oligomeric systems, would afford more stable receptors due to the 'lack' of reactive free α-positions. Long aliphatic chains would enable the incorporation of these acyclic anion receptors into functional materials systems. This is currently being investigated.

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Notes and references

§ Crystal data for **2a1** (from CH_2Cl_2–hexane): $C_{13}H_{13}BF_2N_2O_2$, M_w = 258.06, triclinic, $P\bar{1}$ (no. 2), a = 8.336(5), b = 11.777(9), c = 12.965(11) Å, α = 84.71(3), β = 83.95(3), γ = 87.53(3)°, V = 1259.7(16) Å^3, T = 123(2) K, Z = 4, D_c = 1.466 g cm^{-3}, μ(Mo-Kα) = 0.118 mm^{-1}, 12042 reflections measured, 5530 unique (R_{int} = 0.0376). R_1 = 0.0447, wR_2 = 0.1431, GOF = 0.918 ($I > 2\sigma(I)$). CCDC 666247. Crystal data for **2a2** (from CH_2Cl_2–hexane): $C_{15}H_{17}BF_2N_2O_2$, M_w = 306.12, triclinic, $P\bar{1}$ (no. 2), a = 9.272(11), b = 11.368(17), c = 16.05(3) Å, α = 98.48(5), β = 104.48(6), γ = 109.80(3)°, V = 1491(4) Å^3, T = 123(2) K, Z = 4, D_c = 1.364 g cm^{-3}, μ(Mo-Kα) = 0.107 mm^{-1}, 12504 reflections measured, 6399 unique (R_{int} = 0.1074). R_1 = 0.0744, wR_2 = 0.1738, GOF = 0.995 ($I > 2\sigma(I)$). CCDC 666248. Crystal data for **2a4** (from CH_2Cl_2–hexane): $C_{19}H_{25}BF_2N_2O_2$, M_w = 362.22, monoclinic, *P*c (no. 7), a = 8.526(6), b = 12.160(6), c = 8.797(3) Å, α = 90, β = 93.64(3), γ = 90°, V = 910.2(10) Å^3, T = 123(2) K, Z = 4, D_c = 1.322 g cm^{-3}, μ(Mo-Kα) = 0.098 mm^{-1}, 8741 reflections measured, 3728 unique (R_{int} = 0.0386). R_1 = 0.0376, wR_2 = 0.0781, GOF = 1.056 ($I > 2\sigma(I)$). CCDC 666249.

¶ Crystal data for **2a2**·Cl^- (from CH_2Cl_2–hexane): $C_{15}H_{17}BF_2N_2O_2 \cdot C_{16}H_{36}NCl$, M_w = 584.02, monoclinic, $C2/c$ (no. 15), a = 27.621(8), b = 13.498(3), c = 22.643(6) Å, β = 128.066(10)°, V = 6647(3) Å^3, T = 123(2) K, Z = 8, D_c = 1.167 g cm^{-3}, μ(Mo-Kα) = 0.157 mm^{-1}, 31576 reflections measured, 7573 unique (R_{int} = 0.0430). R_1 = 0.1199, wR_2 = 0.3261, GOF = 1.083 ($I > 2\sigma(I)$). CCDC 666250.

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