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Simple acyclic molecules containing a single charge-assisted O–H group can recognize anions in acetonitrile : water mixtures†

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Hydroxypyridinium and hydroxyquinolinium compounds containing acidic O–H groups attached to a cationic aromatic scaffold were synthesized, *i.e.* *N*-methyl-3-hydroxypyridinium (**1**⁺) and *N*-methyl-8-hydroxyquinolinium (**2**⁺). These very simple compounds are capable of binding to chloride very strongly in CD₃CN and with moderate strength in 9 : 1 CD₃CN : D₂O. Comparison with known association constants reveals that **1**⁺ and **2**⁺ bind chloride in CD₃CN or CD₃CN : D₂O with comparable affinities to receptors containing significantly more hydrogen bond donors and/or higher positive charges. Crystal structures of both compounds with coordinating anions were obtained, and feature short O–H...anion hydrogen bonds. A receptor containing two hydroxyquinolinium groups was also prepared. While the low solubility of this compound caused difficulties, we were able to demonstrate chloride binding in a competitive 1 : 1 CD₃CN : CD₃OD solvent mixture. Addition of sulfate to this compound results in the formation of a crystallographically-characterised solid state anion coordination polymer.

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Introduction

The development of anion recognition and its application in a range of fields has been an ongoing research target within supramolecular chemistry.^{1,2} Many of the initial receptors bound anions through N–H...anion interaction, although more recently C–H...anion hydrogen bonding,³ as well as halogen bonding⁴ and other sigma-hole interactions⁵ have been developed as recognition motifs. While O–H...anion interactions have been studied intermittently for several decades, they have received relatively little attention, particularly given their potential ease of synthesis and strong hydrogen bond character.⁶

Early studies revealed that simple O–H-containing molecules such as sugars, catechol and alizarin can bind anions in polar organic solvents.^{7–9} More recently, it has been demonstrated that incorporating O–H hydrogen bond donors into more complex scaffolds such as foldamers^{10,11} or metal organic frameworks¹² can achieve impressive guest reco-

gnition, while using O–H hydrogen bonds in conjunction with a Lewis acidic boron centre can give selective fluoride binding in THF : water mixtures.¹³ As the field of anion supramolecular chemistry has expanded beyond simple anion recognition to applications,^{14,15} so O–H...anion interactions have been used in a range of applications including self-assembly,^{16,17} anion transport,^{18–20} and organocatalysis.^{21–23}

It would appear that the development of strong O–H...anion binding motifs would facilitate further applications in these fields. Given that even relatively simple neutral O–H containing molecules can be surprisingly potent anion receptors,^{8,9,24,25} it is likely that cationic hosts containing strong O–H hydrogen bond donors may be able to achieve high anion affinities in competitive solvent media, although very few such receptors have been prepared. Alfonso has reported di- and tricationic O–H containing receptors that can function in acetonitrile/methanol mixtures,²⁶ while we have recently reported simple cationic acyclic receptors containing amide and phenol hydrogen bond donors that can function in 9 : 1 acetonitrile : water.²⁷ In the current work, we describe the anion recognition properties of a family of simple cationic molecules that contain very strong O–H hydrogen bond donors (Fig. 1). These molecules can be prepared in one step from commercially-available and cheap 3-hydroxypyridine or 8-hydroxyquinoline. While they are prone to deprotonation by basic anions, we show that they are able to bind anions in acetonitrile : water mixtures.

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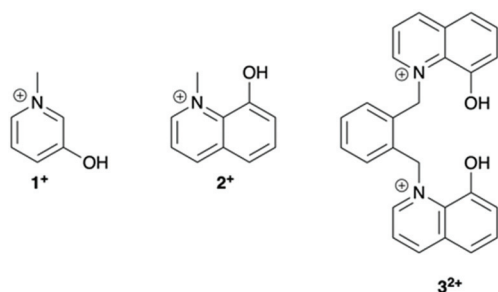


Fig. 1 Cationic molecules containing strong O–H hydrogen bond donors used in this work.

Results

Synthesis

Synthesis of 1⁺, 2⁺ and 3²⁺. Compounds **1⁺** and **2⁺** were prepared as their iodide salts by alkylation of commercially-available 3-hydroxypyridine or 8-hydroxyquinoline using methyl iodide.^{28,29} Alkylation of **1⁺** proceeds quantitatively, while a side-product is produced during the alkylation of **2⁺**. However, this is not troublesome as **2-I** precipitates from the acetonitrile reaction solution (see ESI† for an optimized preparation of **2-I** on a multi-gram scale).

The bis-hydroxyquinolinium compound **3²⁺** was synthesized from commercially available 8-hydroxyquinoline and 1,2-bis(bromomethyl)benzene (Scheme 1). The reaction of ten equivalents of hydroxyquinoline with bis(bromomethyl)benzene in refluxing acetonitrile gave a yellow precipitate in approximately 55% yield, which ¹H NMR spectroscopy showed was **3-Br₂** of ~90% purity (see ESI† for more details). Purification by column chromatography eluting with a basic DCM/MeOH/NEt₃ mixture and then precipitating using HBr_(aq) gave pure **3-Br₂**. It appears that several side-products form during the

reaction resulting from *O*-alkylation reactions: one of these, **4-Br** could be isolated from the reaction mixture and was characterized crystallographically and by NMR spectroscopy (Scheme 1 and ESI†). A “tidier” synthesis of **3-Br₂** may well be possible starting from 8-methoxyquinoline and bis(bromomethyl)benzene followed by demethylation, however given that the starting materials used in our synthesis are cheap, and purification relatively simple, this was not investigated.

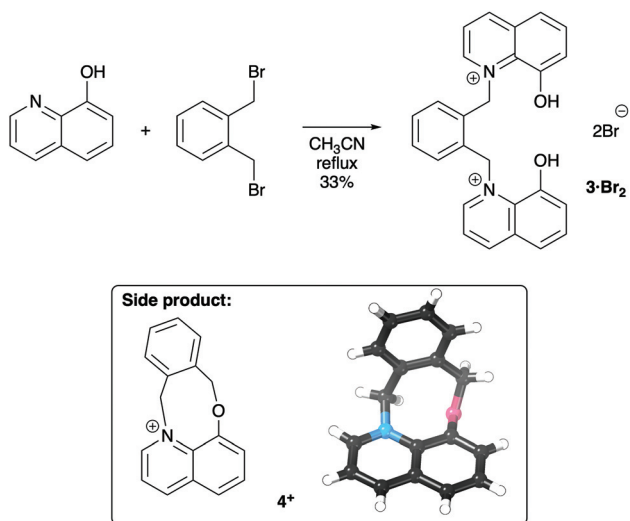
Anion exchange. We exchanged the potentially coordinating halide anions in **1-I**, **2-I** and **3-Br₂** for non-coordinating hexafluorophosphate or tetraphenylborate anions by precipitation in good yields (86–93%). We prepared the hexafluorophosphate salt of **3²⁺** and found that it was best to add a few drops of 1% HPF_{6(aq)} to avoid the products having an orange colour, which we attribute to traces of deprotonated species (see later).

In the case of **1⁺**, we could not isolate the PF₆[−] salt as this did not precipitate from water. In the case of **2⁺**, it was possible to isolate a crystalline solid when a concentrated aqueous solution of hot **2-I** was mixed with aqueous NH₄PF₆ and allowed to cool. SCXRD studies of one of these crystals showed that it was **2-PF₆**, and ¹H and ¹³C NMR analyses of the bulk material were satisfactory. However, quantitative ¹⁹F NMR spectroscopy³⁰ revealed a lower amount of PF₆[−] than expected (approximately one half) suggesting that anion exchange was incomplete and the material was a mixture of the I[−] and PF₆[−] salt. Mixing a solution of this material in acetone with AgBF₄ in acetone resulted in the formation of cloudy precipitate (presumably AgI), supporting this hypothesis.

Given that we could not satisfactorily isolate PF₆[−] salts of **1⁺** or **2⁺**, these compounds were instead isolated as the tetraphenylborate salts by precipitation from methanol. Integration of the ¹H NMR spectrum confirmed that complete anion exchange had been achieved in these cases, and integration of the quantitative ¹⁹F NMR spectrum³⁰ of **3-(PF₆)₂** indicated complete conversion to the hexafluorophosphate salt.

Deprotonation. We initially attempted to convert **2⁺** and **3²⁺** to their PF₆[−] salts using a relatively old bottle of NH₄PF₆. This resulted in deep orange-coloured solutions or precipitates; an intense orange-red colour is known to result from deprotonated hydroxyquinolinium groups, which display significant solvatochromic effects.²⁸ Analysis of this bottle of NH₄PF₆ using ¹⁹F NMR spectroscopy revealed that it contained a significant amount of F[−], which presumably acted as a base to partially deprotonate the compounds resulting in the deeply-coloured zwitterionic form. Adding small amounts of triethylamine to solutions of the compounds produced similar colours, and we were able to obtain single crystals of **3^{−H}-PF₆** suitable for X-ray diffraction studies in this way. X-ray crystallography reveals a very short O–H...O[−] distance, with a distance of 2.414(2) Å between the two oxygen atoms.³¹ This hydrogen bond links the structure into a one-dimensional hydrogen bonded chain (Fig. 2).

To investigate this further, we attempted to measure the pK_a of **3-Br₂** in water to allow comparison with that of **2⁺**, which is 6.8.³³ Unfortunately precipitation meant we were



Scheme 1 Synthesis of **3-Br₂**, structure of side product **4-Br**, and X-ray crystal structure of cation **4⁺**.

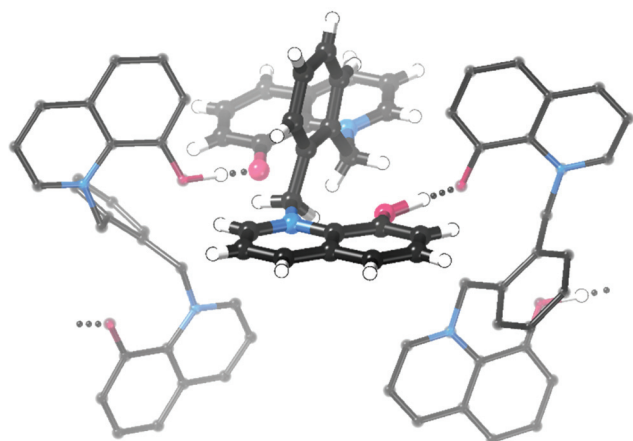
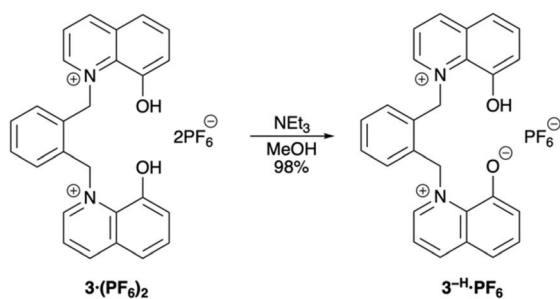


Fig. 2 X-ray crystal structure of $3\text{-H}\cdot\text{PF}_6$ (PF_6^- anions and some C–H hydrogen atoms are omitted for clarity). Note: PLATON-SQUEEZE was used (see ESI† for details).³²



Scheme 2 Synthesis of $3\text{-H}\cdot\text{PF}_6$.

unable to do so quantitatively, but qualitatively, the pK_a of 3^{2+} appears to be broadly similar to that of 2^+ , suggesting the acidity of each O–H group is relatively independent of the other.³⁴ Due to the low solubility of $3\text{-H}\cdot\text{PF}_6$ in polar solvents, it was possible to isolate it as a crystalline solid by adding one equivalent of triethylamine to a methanol solution of $3\text{-(PF}_6)_2$ (Scheme 2). NMR spectroscopy, including integration of the ^1H NMR and quantitative ^{19}F NMR spectrum³¹ against a standard confirmed that $3\text{-H}\cdot\text{PF}_6$ was isolated selectively.

Anion binding of 1^+ and 2^+

NMR titrations. A preliminary qualitative screen of anion binding was conducted by adding one equivalent of anion to 1.0 mM solutions 2^+ in either CH_3CN or 9 : 1 $\text{CH}_3\text{CN}:\text{H}_2\text{O}$. This revealed that H_2PO_4^- caused precipitation, while OAc^- caused deprotonation in both solvent systems and so these anions were not studied quantitatively (Fig. S25 and S26†). Instead we focused on Cl^- and SO_4^{2-} and studied guest binding using quantitative ^1H NMR titration experiments. Addition of chloride anion to either 1^+ or 2^+ in CD_3CN resulted in significant downfield shifts of hydrogen atoms adjacent to the O–H group (Fig. 3 and Fig. S29–S34†).³⁵ Fitting the peak movement to a 1 : 1 binding isotherm using *Bindfit*,³⁶ revealed that association of chloride with both of these receptors was

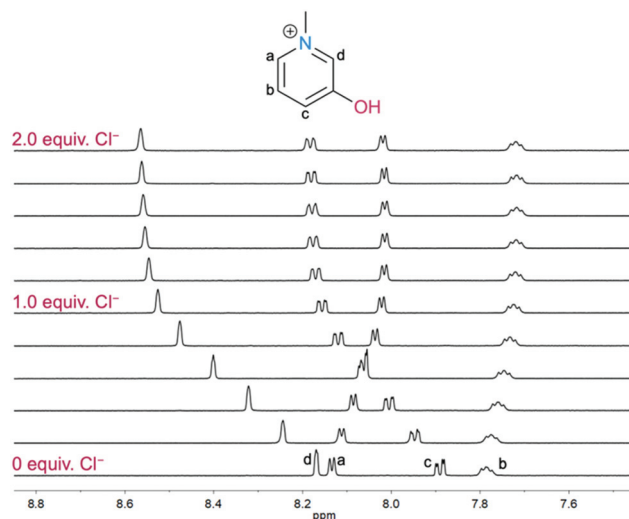


Fig. 3 Partial ^1H NMR spectra of 1-BPh_4 upon addition of $\text{TBA}\cdot\text{Cl}$ (CD_3CN , 600 MHz, 298 K). The 11 spectra represent 0–2.0 equivalents of Cl^- at intervals of 0.2 equivalents.

too high to be determined by NMR titration experiments ($>10^4 \text{ M}^{-1}$). Addition of sulfate resulted in precipitation.

Given the very strong binding in CD_3CN , we next studied binding in the highly competitive mixed organic/aqueous system 9 : 1 $\text{CD}_3\text{CN}:\text{D}_2\text{O}$. Interestingly, chloride caused small downfield shifts in C–H protons adjacent to the O–H group, while sulfate caused upfield shifts. We do not know the reason for this upfield peak movement, although it does not appear to be due to deprotonation.³⁷ In this competitive solvent mixture, binding was significantly weaker than in pure acetonitrile, but moderate binding was still observed by 1^+ , with very weak binding observed by 2^+ (Table 1). The stronger binding observed for 1^+ compared to 2^+ is not unexpected as 1^+ is known to have a more acidic O–H group than 2^+ (the pK_a values in water are 5.0³⁸ and 6.8,³³ respectively).

X-ray crystal structures. We were able to obtain several crystal structures of 1^+ and 2^+ with various anions: the structures of 1-I , 2-Cl and 2-SO_4 are presented in Fig. 4, while additional structures (1-BPh_4 , 2-PF_6) are discussed in the ESI.† As shown, H···anion distances are short ranging from as little as 64% of the sum of the van der Waals radii⁴⁰ (Σ_{vdw}) in the structure of 2-SO_4 to 71% of Σ_{vdw} in 2-Cl , to 76–80% of Σ_{vdw}

Table 1 Association constants (M^{-1}) for 1-BPh_4 and 2-BPh_4 with anions^a

Receptor, solvent	Cl^-	SO_4^{2-}
1-BPh_4 , CD_3CN	$>10^4$	Precipitation
2-BPh_4 , CD_3CN	$>10^4$	Precipitation
1-BPh_4 , 9 : 1 $\text{CD}_3\text{CN}:\text{D}_2\text{O}$	65(3)	77(8)
2-BPh_4 , 9 : 1 $\text{CD}_3\text{CN}:\text{D}_2\text{O}$	13(1)	Negligible

^a Anions added as TBA salts, 1 : 1 binding constants calculated using *Bindfit*,³⁶ the asymptotic error³⁹ is provided at the 95% confidence interval in parentheses.

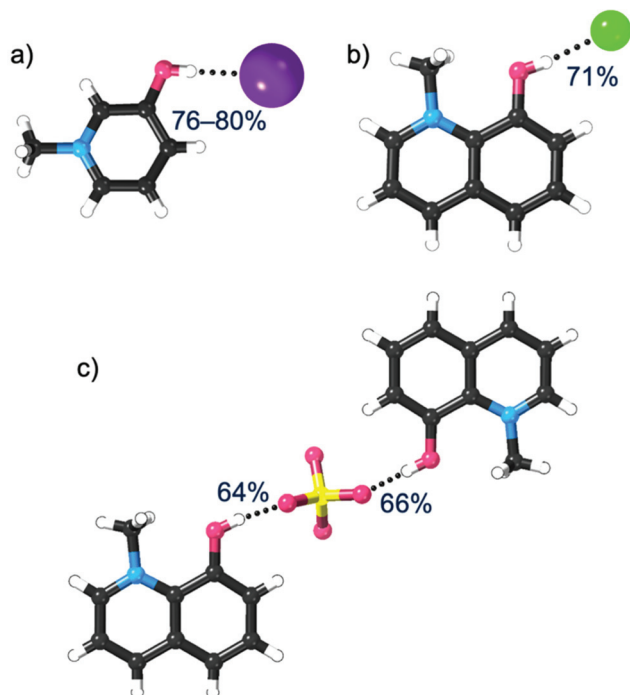


Fig. 4 X-ray crystal structures of (a) $1 \cdot \text{I}$, (b) $2 \cdot \text{Cl}$, and (c) $2 \cdot \text{SO}_4$. H...acceptor distances for hydrogen bonds are given as Σ_{vdw} .⁴⁰ A range is given for $1 \cdot \text{I}$ as this structure has $Z' = 5$ so there are several different H...I[−] distances. Positional disorder of the anion in $2 \cdot \text{SO}_4$ is omitted for clarity.

in $2 \cdot \text{I}$. In the structures of $1 \cdot \text{BPh}_4$ and $2 \cdot \text{PF}_6$, no O–H...anion interactions shorter than Σ_{vdw} are observed, consistent with the non-coordinating nature of these anions. We note that the 71% of Σ_{vdw} in $2 \cdot \text{Cl}$ is similar to the 72% Σ_{vdw} observed in the previously-reported structure of $1 \cdot \text{Cl}$.^{41,42}

Anion binding of 3^{2+}

NMR titrations. $3 \cdot (\text{PF}_6)_2$ suffers from poor solubility, and is not appreciably soluble in a range of polar organic solvents, including acetonitrile and acetonitrile/water mixtures. We were therefore not able to conduct binding studies in the same solvent mixture used for 1^+ and 2^+ . Instead, anion recognition was studied using ^1H NMR titration experiments in competitive 1 : 1 $\text{CD}_3\text{CN} : \text{CD}_3\text{OD}$. As was the case for 1^+ and 2^+ , a preliminary screen (Fig. S23†) revealed that H_2PO_4^- caused precipitation, while OAc^- caused deprotonation and so these anions were not studied quantitatively.

Addition of chloride to 3^{2+} resulted in small but significant downfield shifts in the C–H proton resonances close to the hydroxy groups and the peak movement was fitted to a 1 : 1 binding isotherm using *Bindfit*.³⁶ This revealed that chloride bound with moderate strength in this polar solvent mixture [$K_a = 76(2) \text{ M}^{-1}$]. Addition of sulfate to 3^{2+} caused precipitation and so we were unable to calculate an association constant.

X-ray crystal structures. We were able to obtain several crystal structures of 3^{2+} , which are shown in Fig. 5.

Interestingly, when there are no coordinating anions available in the structure of $3 \cdot (\text{PF}_6)_2$ the receptor adopts an *anti* configuration where the two O–H groups point in opposite directions and form short hydrogen bonds (66, 71% Σ_{vdw} ⁴⁰) to acetonitrile solvent molecules. Another structure of $3 \cdot (\text{PF}_6)_2$ was obtained from a different solvent mixture and has a similar structure (see ESI†). In the structure of $3 \cdot \text{Br}_2$, an *anti* configuration of the cation is also observed, presumably to facilitate hydrogen bonding to each anion. When $3 \cdot (\text{PF}_6)_2$ was crystallised in the presence of one equivalent of either Cl^- or Br^- , crystals of $3 \cdot \text{Cl} \cdot \text{PF}_6$ and $3 \cdot \text{Br} \cdot \text{PF}_6$ were obtained (Fig. 5c and d). In these structures, the receptor adopts a *syn* configuration with both O–H groups forming relatively short hydrogen bonds to the halide anion. Hydrogen bonds are slightly shorter as Σ_{vdw} with chloride than with bromide. Very small crystals of $3 \cdot \text{SO}_4$ were obtained, which required the use of synchrotron radiation.⁴³ In this case, the molecule adopts an *anti* configuration and short hydrogen bonds between 3^{2+} and sulfate (64, 65% Σ_{vdw}) result in the formation of a one-dimensional hydrogen bonded polymer assembled by anion coordination.^{44–46} Two methanol solvent molecules also hydrogen bond to the sulfate anion, although these hydrogen bonds are longer (70, 74% Σ_{vdw}).

Colourimetric “anion” sensing by 2^+ , 3^{2+} and 3^{-H^+}

As noted above, pale yellow solutions of $2 \cdot \text{BPh}_4$ take on a deep orange-red colour in the presence of OAc^- (Fig. S25 and S26†), which we attribute to deprotonation of 2^+ to form the zwitterionic form, which is a known chromophore.²⁸ A similar phenomenon is observed when OAc^- is added to 3^{2+} (Fig. S27†). Additionally, red solutions of $3^{-\text{H}^+} \cdot \text{PF}_6$ partially decolourise upon addition of HSO_4^- (Fig. S28†), which we attribute to partial protonation of 3^{-H^+} by the acidic HSO_4^- anion ($\text{p}K_a = 2.0$).⁴⁷ While these colourimetric responses suggest an anion sensing response (and similar responses are sometimes reported in the literature as such⁶), this is not really an accurate description of what is occurring, and the compounds are instead simply responding to base/acid.

$\text{p}K_a$ measurements of 2^+

We investigated the effect of solvent and anion on the $\text{p}K_a$ values of these highly acidic O–H groups. Unfortunately, the low solubility of 3^{2+} prohibited the determination of quantitative $\text{p}K_a$ measurements and so we focused attention on 2^+ .

Solvent effects. We conducted measurements in 9 : 1 $\text{MeOH} : \text{H}_2\text{O}$ and DMF to complement the known value in H_2O .³³ Unsurprisingly, moving towards less polar solvents increases the $\text{p}K_a$ of 2^+ , with this value increasing from 6.8 in water, to 7.5 in $\text{MeOH} : \text{H}_2\text{O}$ and 9.5 in DMF (Table 2).

Anion effects. We were interested to see whether the anion present affected the $\text{p}K_a$ of the O–H group in 2^+ . To investigate this we prepared $2 \cdot \text{Cl}$ in good yield by precipitation from acetone (see Experimental section). We reasoned that a favourable O–H...Cl[−] hydrogen bond might favour the protonated form of 2^+ and thus increase the $\text{p}K_a$ of $2 \cdot \text{Cl}$ relative to

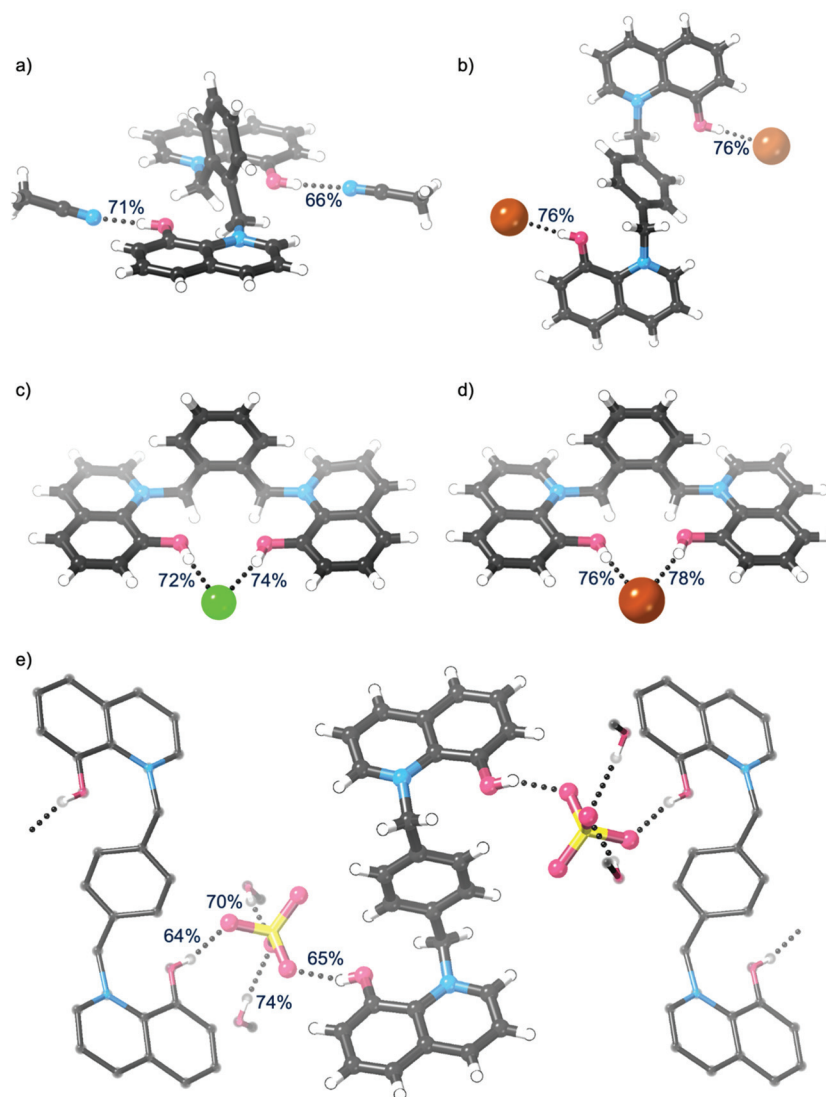


Fig. 5 X-ray crystal structures of (a) **3**·(PF₆)₂, (b) **3**·Br₂, (c) **3**·Cl·PF₆, (d) **3**·Br·PF₆ and (e) **3**·SO₄. H...acceptor distances for hydrogen bonds are given as Σ_{vdW}^{40} . The structure of **3**·(PF₆)₂ has $Z' = 2$, only part of the unit cell is shown for clarity. Most solvent molecules and the PF₆[−] anions are omitted for clarity.

Table 2 pK_a values of **2-Cl** and **2-BPh₄** in different solvents, with the estimated 95% confidence interval of the mean^a

Solvent	pK_a for 2-Cl	pK_a for 2-BPh₄
H ₂ O	6.8 ³³	—
9 : 1 MeOH : H ₂ O ^b	7.4 ± 0.1	7.5 ± 0.1
DMF ^c	9.5 ± 0.2	9.5 ± 0.1

^a ±2 standard errors (SE) of the mean, which were estimated as $SE = \sigma/\sqrt{n}$. ^b Determined by potentiometric titrations using NaOH as base. ^c Determined by potentiometric titrations using DBU as base.

2-BPh₄,⁴⁸ which cannot form a strong hydrogen bond, and so measured the pK_a s of these compounds in both 9 : 1 MeOH : H₂O and DMF. Unsurprisingly, in 9 : 1 MeOH : H₂O, no difference in pK_a is observed between **2-Cl** and **2-BPh₄**, which we attribute to negligible hydrogen bonding between **2**⁺ and Cl[−] in this very competitive solvent mixture. We were also not

able to obtain evidence of a difference in pK_a s between **2-Cl** and **2-BPh₄** in DMF, which is perhaps somewhat surprising. More details of these experiments and the rationale behind them are provided in the ESI.†

Computational studies and discussion

Compounds **1**⁺ and **2**⁺ each appear to have only one significant hydrogen bond donor, *i.e.* the O–H group. In the crystal structures, these groups are the only ones that form short hydrogen bonds, although contacts slightly shorter than the sum of the vdW radii are also observed on some occasions between the anion and the C–H group adjacent to the O–H group.⁴⁹ To investigate the energetic contributions of these possible interactions, we conducted density functional theory calculations at the M06-2X/6-311+G(d,p) level of theory.⁵⁰ We minimised the

structures of **1-Cl** and **2-Cl** using an SMD continuum solvent model⁵¹ to account for solvent effects, and then used Natural Bond Orbital (NBO) analysis to calculate the relative contributions of the possible interactions (see the ESI† for full details). These calculations reveal that 88–90% of the binding energy is accounted for by O–H...Cl[−] interactions, *i.e.* that other contributions are minimal and this single hydrogen bond is responsible for the vast majority of the binding (Tables S13–S15†).

Despite the fact that **1⁺** and **2⁺** each contain only one significant hydrogen bond donor, they are able to bind anions strongly, with association constants for chloride >10⁴ M^{−1} in acetonitrile, and respectable values obtained in competitive 9:1 acetonitrile:water mixtures. To put this in context, we have compared these association constants with known receptors that have been reported to bind Cl[−] in acetonitrile or 9:1 acetonitrile:water. Unsurprisingly, **1⁺** and **2⁺** bind chloride more strongly than neutral molecules containing a single O–H group. Interestingly, this is true even for molecules with similarly acidic O–H groups, suggesting that electrostatic attraction is important as well as the acidity of the O–H hydrogen bond. For example, 4-nitrophenol has a very similar pK_a to **2⁺** (7.1⁵² compared with 6.8³³ for **2⁺**), but binds chloride with an association constant of only 560 M^{−1} in CD₃CN.⁵³ It is notable that

1⁺ and **2⁺** also bind chloride more strongly than similarly acidic molecules containing more O–H donors: for example, 4-nitrocatechol which has two highly acidic O–H groups (pK_a = 6.7,⁵⁴ K_a = 4400 M^{−1} for Cl[−] in CD₃CN).⁹

While the electrostatic attraction for anions in **1⁺** and **2⁺** is presumably important, it is clearly not the only factor. For example, **1⁺** displays similar chloride binding affinities in 9:1 CD₃CN:D₂O to charged receptors containing a pyridinium group and two phenolic O–H and two amide groups (65 M^{−1} for **1⁺** vs. 61–170 M^{−1}).^{27,55} Indeed, the association constant between **1⁺** and Cl[−] in 9:1 CD₃CN:D₂O (65 M^{−1}) is within one order of magnitude of those reported for a di-cationic bis-imidazolium macrocycle **4²⁺** (structure provided in Fig. 6, K_a 163 M^{−1}),⁵⁶ tetra-cationic tetra-imidazolium macrocycles⁵⁷ and tetra-imidazolium catenanes (binding constants and structures for these compounds are provided in Fig. S69†).⁵⁶

To investigate the effects of the various contributions to guest binding, we used Energy Decomposition Analysis based on Absolutely Localised Molecular Orbitals within a continuum solvent model [ALMO-EDA(solv)],⁵⁸ to tease apart the respective contributions to binding energies. It should be noted that these calculations isolate the contributions to the solution phase electronic energy and do not consider entropy, which would be expected to have a relatively consistent contri-

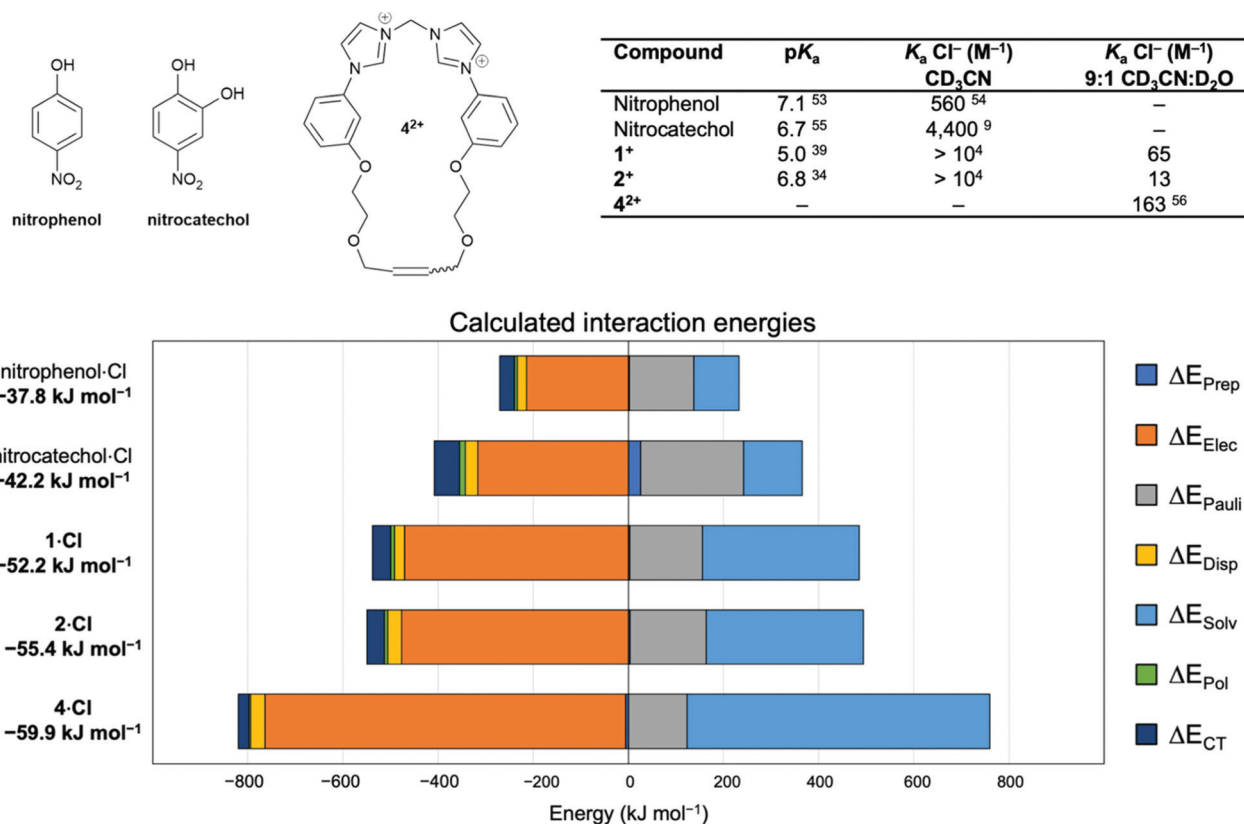


Fig. 6 Structures of molecules investigated computationally, their association constants for chloride, and ALMO-EDA(solv.) contributions to calculated interaction energies. The overall interaction energies are given to the left of the chart. ΔE_{Prep} is preparation energy, ΔE_{Elec} is the electrostatic component, ΔE_{Pauli} is the Pauli repulsion energy, ΔE_{Disp} is the dispersion energy, ΔE_{Solv} is the solvation energy contribution, ΔE_{Pol} is the polarisation contribution and ΔE_{CT} is the charge transfer energy.

bution as the same anion and solvent are being compared in all cases. The calculations suggest that in acetonitrile binding of chloride to any of 1^+ , 2^+ or the macrocycle 4^{2+} is significantly stronger than binding to nitrocatechol, which is itself significantly stronger than chloride binding to nitrophenol (as expected based on measured association constants). In 9 : 1 MeCN:H₂O, binding of chloride to macrocycle 4^{2+} is more favourable than binding to 1^+ , but not by a huge amount.

As would be expected and as shown graphically in Fig. 6, dicationic 4^{2+} has a significantly more favourable electrostatic component (-758 kJ mol^{-1}) than mono-cationic 1^+ and 2^+ (-471 to -477 kJ mol^{-1}) or neutral nitrocatechol and nitrophenol (-214 to -316 kJ mol^{-1}). This favourability is largely counteracted however, by a significantly higher solvation penalty for 4^{2+} (636 kJ mol^{-1} for 4^{2+} , 329 – 330 kJ mol^{-1} for 1^+ and 2^+ , 95 – 123 kJ mol^{-1} for the neutral molecules). A more detailed data breakdown, including a similar analysis for 1^+ and 4^{2+} in 9 : 1 CH₃CN : H₂O is provided in the ESI.†

Clearly recognition of chloride by more complex anion receptors is complicated by preorganisation effects, *i.e.* it is non-trivial to design a receptor where all donors can interact with the anion without significant reorganisation. Nevertheless, it is remarkable that 1^+ and 2^+ can effect chloride recognition in aqueous acetonitrile using a single charge-assisted O–H group, and that the strength of this is broadly comparable to receptors with a much higher charge and/or far more hydrogen bond donors. Calculations suggest that the combination of electrostatic attraction for the anion, coupled with an acidic hydrogen bond donor, and a relatively low solvation energy penalty drive the favourable binding of chloride to 1^+ and 2^+ . Taken together, our results suggest that receptors with few binding sites may bind guests more strongly than would otherwise be expected, due to their lower solvation penalties.

Conclusions

We have investigated the anion recognition capability of the simple molecules 1^+ and 2^+ , which contain a single strong O–H hydrogen bond donor. These molecules display strong chloride binding in CD₃CN ($K_a > 10^4 \text{ M}^{-1}$), and moderate chloride binding in 9 : 1 CD₃CN : D₂O ($K_a = 65$ and 13 M^{-1} , respectively). These association constants are much higher than neutral compounds containing similarly acidic O–H groups, and are comparable to highly charged receptors. Computational studies suggest this is due to a favourable balance of electrostatic attraction with a relatively low degree of solvation.

While it is clear that these types of molecules are prone to deprotonation, it seems likely that hosts incorporating two or more hydroxypyridinium or hydroxyquinolinium groups would be very potent anion receptors. Unfortunately our first attempts to investigate such systems in the form of 3^{2+} were hampered by this compound's low solubility. This compound is also apparently poorly preorganised such that 3^{2+} has to rearrange from an *anti* to *syn* conformation to bind anions.

Nevertheless, we suggest that future receptors containing well-designed charged O–H groups would be worthy targets of further investigation.

Experimental

Characterisation data, details of instrumentation, anion binding experiments, p*K*_a measurements, X-ray crystallography and computational studies are provided in the ESI.†

General remarks

The reaction of 3-hydroxypyridine and methyl iodide in *n*-propanol afforded **1·I** quantitatively, as previously reported.^{29,59} **2·I** was prepared on a multi-gram scale by a slight modification of a previously reported procedure²⁸ (see ESI†). The synthesis of DBU^H·PF₆ from DBU is described in the ESI.†

1·BPh₄. A solution of **1·I** (0.237 g, 1.00 mmol) in MeOH (10 mL) was added to a solution of NaBPh₄ (0.411 g, 1.20 mmol) in MeOH (10 mL) resulting in the immediate formation of a white precipitate. The suspension was allowed to stand for 30 minutes, and then filtered. The resulting white microcrystalline solid was washed with MeOH (3 × 5 mL) and then thoroughly air-dried to give **1·BPh₄**. Yield: 0.367 g (0.856 mmol, 86%). ¹H NMR (CD₃CN): 8.15 (br. s, 1H), 8.10 (d, *J* = 7.8 Hz, 1H), 7.88 (dd, *J* = 8.8, 1.8 Hz, 1H), 7.73–7.78 (m, 1H), 7.24–7.30 (m, 8H), 6.99 (dd, *J* = 7.4, 7.4 Hz, 8H), 6.84 (t, *J* = 7.4 Hz, 4H). ¹³C NMR (d₆-DMSO): 162.6–164.1 (m), 156.7, 136.3, 135.5, 133.7, 130.8, 128.2, 125.3, 121.5, 47.8. HRESI-MS (pos.): 110.0608, calc. for $1^+ [\text{C}_6\text{H}_6\text{NO}]^+ = 110.0606 \text{ Da}$. HRESI-MS (neg.): 319.1661, calc. for $\text{BPh}_4^- [\text{C}_{24}\text{H}_{20}\text{B}]^- = 319.1658 \text{ Da}$.

2·BPh₄. A solution of **2·I** (0.718 g, 2.50 mmol) in MeOH (25 mL) was added to a solution of NaBPh₄ (1.03 g, 3.00 mmol) in MeOH (25 mL) giving a pale yellow solution. After about 15 seconds, pale crystals began to form, and the reaction was left to stand at room temperature for an hour, and then in a freezer for an hour. After this time, the pale yellow crystals were isolated by filtration, washed with MeOH (3 × 5 mL), and thoroughly air-dried to give **2·BPh₄**. Yield: 1.04 g (2.17 mmol, 87%). ¹H NMR (d₆-DMSO): 9.16 (d, *J* = 5.7 Hz, 1H), 9.05 (d, *J* = 8.1 Hz, 1H), 7.95 (dd, *J* = 8.4, 8.4 Hz, 1H), 7.75–7.80 (m, 2H), 7.51–7.56 (m, 1H), 7.12–7.21 (m, 8H), 6.92 (dd, *J* = 7.4, 7.2 Hz, 8H), 6.78 (t, *J* = 7.2 Hz, 4H), 4.80 (s, 3H). ¹³C NMR (d₆-DMSO) 162.8–164.2 (m), 151.2, 150.0, 147.1, 135.7, 132.0, 130.6, 129.5, 125.5, 121.73, 121.70, 120.7, 119.7, 51.5. HRESI-MS (pos.): 160.0764, calc. for $2^+ [\text{C}_{10}\text{H}_{10}\text{NO}]^+ = 160.0762 \text{ Da}$. HRESI-MS (neg.): 319.1663, calc. for $\text{BPh}_4^- [\text{C}_{24}\text{H}_{20}\text{B}]^- = 319.1658 \text{ Da}$. ESI-MS (pos.): 639.3, calc. for $[\text{2·BPh}_4]^+ \text{ i.e. } [\text{C}_{44}\text{H}_{40}\text{BN}_2\text{O}_2]^+ = 639.3 \text{ Da}$.

2·Cl. A solution of **2·BPh₄** (0.240 g, 0.500 mmol) in acetone (10 mL) was added to a solution of TBA·Cl (0.167 g, 0.600 mmol) in acetone (10 mL) resulting in the immediate formation of a pale yellow precipitate. The suspension was swirled briefly, left to stand for 30 minutes and then the solid was isolated by filtration, washed with acetone (3 × 3 mL) and thoroughly air-dried to give **2·Cl** as a yellow powder. Yield:

0.096 g (0.049 mmol, 98%). ^1H NMR (d_6 -DMSO): 12.20 (s, 1H), 9.30 (d, $J = 5.6$ Hz, 1H), 9.10 (d, $J = 8.4$ Hz, 1H), 8.00 (dd, $J = 8.4, 5.7$ Hz, 1H), 7.75–7.82 (m, 3H), 4.83 (s, 3H). ^{13}C NMR (d_6 -DMSO): 151.1, 150.2, 146.9, 131.8, 130.3, 129.4, 121.5, 120.2, 119.7, 51.2. HRESI-MS (pos.): 160.0764, calc. for 2^+ $[\text{C}_{10}\text{H}_{10}\text{NO}]^+ = 160.0762$ Da.

3-Br₂. 8-Hydroxyquinoline (2.90 g, 20.0 mmol) was dissolved in acetonitrile (50 mL) and the solution heated to reflux. Solid 1,2-bis(bromomethyl)benzene (0.528 g, 2.00 mmol) was added and the solution heated at reflux for 24 hours under a nitrogen atmosphere, during which time the colourless solution turned yellow and a yellow precipitate developed. The reaction was concentrated under reduced pressure and acetonitrile (20 mL) was added, the suspension was sonicated for 15 minutes, refluxed for 15 minutes and then cooled to room temperature. It was filtered, and the resulting yellow powder washed with acetonitrile (3×5 mL) and air-dried. Analysis by ^1H NMR spectroscopy indicated that the compound was approximately 90% pure at this point, and the yield at this point was 0.615 g (~55%, see Fig. S7† for ^1H NMR spectrum of this material).

The crude product was dry-loaded onto silica (~10 mL) and added to the top of a column of silica (~25 mL) in 9:1 DCM:MeOH. Approximately 250 mL of 9:1 DCM:MeOH was eluted to remove an orange impurity, and then the eluent was switched to 88:10:2 DCM:MeOH:NEt₃, which caused the yellow compound at the top of the column to turn purple. The column was eluted with 200 mL of this solvent to remove a small purple band and then the eluent switched to 83:15:2 DCM:MeOH:NEt₃ (~250 mL) to remove a large purple band. This was concentrated *in vacuo* to give a purple solid. This was dissolved in 9:1 DCM:MeOH (20 mL) to give a deep purple solution, to which was added dropwise conc. HBr_(aq). Addition of HBr initially caused a colour change from deep purple to bright red-orange and the development of a precipitate. Continued addition of HBr_(aq) caused the colour to change to a bright yellow colour, at which point addition was stopped (0.3–0.4 mL HBr_(aq) was added in total). The yellow suspension was left to stand for 30 minutes, and then filtered to give a lemon-yellow powder, which was washed with 9:1 DCM:MeOH (3×5 mL), DCM (3×5 mL), and then dried *in vacuo*. Yield of **3-Br₂**: 0.368 g (0.664 mmol, 33%). ^1H NMR (d_6 -DMSO): 11.88 (br. s, 2H), 9.45 (d, $J = 5.7$ Hz, 2H), 9.23 (d, $J = 8.3$ Hz, 2H), 8.10–8.15 (m, 2H), 7.87 (d, $J = 7.9$ Hz, 2H), 7.79 (dd, $J = 7.9, 7.9$ Hz, 2H), 7.48 (d, $J = 7.9$ Hz, 2H), 7.13 (s, 4H), 6.56 (s, 4H). ^{13}C NMR (d_6 -DMSO): 151.8, 148.8, 148.4, 136.4, 132.4, 130.7, 128.4, 126.7, 122.1, 121.2, 120.2, 63.6. HRESI-MS (pos.): 197.0840, calc. for 3^{2+} *i.e.* $[\text{C}_{26}\text{H}_{20}\text{N}_2\text{O}_2]^{2+} = 197.0835$ Da. ESI-MS (pos.): 473.1, calc. for $[\text{3-Br}]^+ \text{i.e. } [\text{C}_{26}\text{H}_{22}\text{N}_2\text{O}_2\text{Br}]^+ = 473.1$ Da.

This reaction to produce **3-Br₂** also produced **4-Br**, which we were able to isolate in small quantities (see ESI†).

3-(PF₆)₂. A solution of **3-Br₂** (0.277 g, 0.500 mmol) in 3:1 H₂O:MeOH (30 mL) was added to a solution of NH₄PF₆ (0.196 g, 1.20 mmol) in H₂O (10 mL) containing 10 drops of 1% HPF_{6(aq)} resulting in the immediate formation of a precipitate. The suspension was left to stand for 30 minutes and then filtered to give a very pale yellow powder, which was washed

with water (3×5 mL), air-dried and then dried thoroughly *in vacuo* (<10 mbar, 50 °C). Yield: 0.318 g (0.464 mmol, 93%). ^1H NMR (d_6 -DMSO): 11.90 (br. s, 2H), 9.43 (d, $J = 5.4$ Hz, 2H), 9.22 (d, $J = 8.0$ Hz, 2H), 8.11–8.14 (m, 2H), 7.87 (d, $J = 7.7$ Hz, 2H), 7.79 (dd, $J = 7.9, 7.9$ Hz, 2H), 7.47 (d, $J = 7.7$ Hz, 2H), 7.13 (s, 4H), 6.55 (s, 4H). ^{13}C NMR (d_6 -DMSO): 151.8, 149.0, 148.4, 136.5, 132.4, 130.7, 128.5, 126.7, 122.0, 121.1, 120.3, 63.7. ^{19}F NMR (d_6 -DMSO): -70.2 (d, $J = 711$ Hz). ^{31}P NMR (d_6 -DMSO): -144.2 (sept., $J = 711$ Hz). HRESI-MS (pos.): 197.0840, calc. for 3^{2+} *i.e.* $[\text{C}_{26}\text{H}_{20}\text{N}_2\text{O}_2]^{2+} = 197.0835$ Da. ESI-MS (pos.): 931.4, calc. for $[\text{3-}^-\text{H}_2\text{PF}_6]^+ \text{i.e. } [\text{C}_{52}\text{H}_{42}\text{N}_4\text{O}_4\text{F}_6\text{P}]^+ = 931.3$ Da. ESI-MS (neg.): 145.0, calc. for $\text{PF}_6^- = 145.0$ Da.

3-^H-PF₆. **3-(PF₆)₂** (0.127 g, 0.200 mmol) was dissolved in MeOH (20 mL) with gentle heating. NEt₃ (28 μL, 20 mg, 0.20 mmol) was added to the hot yellow solution resulting in a change to a deep red colour. Within a few seconds, a bright orange precipitate developed. The suspension was cooled to room temperature and then left to stand for 10 minutes. It was then filtered to isolate a bright orange precipitate, which was washed with MeOH (3×3 mL), Et₂O (3×3 mL), air-dried and then dried thoroughly *in vacuo*. Yield: 0.106 g (0.196 mmol, 98%). ^1H NMR (d_6 -DMSO): 9.15 (d, $J = 5.5$ Hz, 2H), 8.97 (d, $J = 8.3$ Hz, 2H), 7.86–7.90 (m, 2H), 7.48 (dd, $J = 7.9, 7.9$ Hz, 2H), 7.30 (d, $J = 7.6$ Hz, 2H), 7.18 (s, 4H), 6.99 (d, $J = 7.9$ Hz, 2H), 6.80 (s, 4H). ^{13}C NMR (d_6 -DMSO): 154.8, 149.5, 148.0, 136.9, 132.9, 131.1, 129.6, 127.3, 121.2, 120.9, 116.1, 62.6. ^{19}F NMR (d_6 -DMSO): -70.2 (d, $J = 711$ Hz). ^{31}P NMR (d_6 -DMSO): -144.2 (sept., $J = 711$ Hz). HRESI-MS (pos.): 393.1609, calc. for $3^{-\text{H}}$ *i.e.* $[\text{C}_{26}\text{H}_{21}\text{N}_2\text{O}_2]^+ = 393.1603$ Da. ESI-MS (neg.): 144.8, calc. for $\text{PF}_6^- = 145.0$ Da.

Conflicts of interest

There are no conflicts to declare.

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