Electronic Supplementary Material (ESI) for New Journal of Chemistry.

Electronic Supplementary Information for

A pyrrole-containing cleft-type halogen bonding receptor for oxoanion recognition and sensing in aqueous solvent media

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S1. Synthesis of Compounds

S1.1 General Information

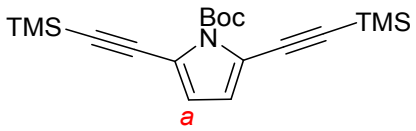
All commercially available chemicals and solvents were used as received without further purification. All dry solvents were thoroughly degassed with N_2, dried through a Mbraun MPSP-800 column and used immediately. Water used was deionized and passed through a Milli-Q® Millipore machine for microfiltration. TBTA (tris(benzyltriazolemethyl)amine) was prepared according to reported procedures.[1] Chromatography was undertaken using silica gel (particle size: 40-63 μm) or preparative TLC plates (20 × 20 cm, 1 cm silica thickness).

NMR spectra were recorded on Bruker AVIII HD Nanobay 400 MHz, Bruker AVIII 500 MHz and Bruker AVIII 500 MHz (with ^{13}C cryoprobe) spectrometers. Low resolution electrospray ionisation mass spectrometry (ESI-MS) was performed using the Waters Micromass LCT for characterisation of compounds previously reported in the literature, and high resolution ESI-MS was recorded using Bruker microTOF spectrometer for novel compounds.

S1.2 Synthetic Procedures

*N*Boc-protected pyrrole[2] and 2,5-dibromo-*N*Boc-pyrrole were prepared according to reported procedures.[3]

2,5-bis(TMS-ethynyl)-*N*Boc-pyrrole (compound 3)



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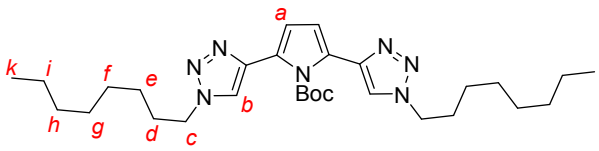
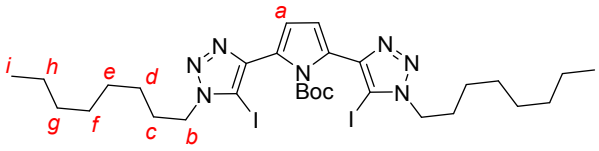
2,5-dibromo-*N*Boc-pyrrole (200 mg, 0.62 mmol) was dissolved in thoroughly-degassed 1,4-dioxane (1.2 mL) in a microwave vial. To this solution was added $Pd(PPh_3)_2Cl_2$ (44 mg, 0.062 mmol), copper(I) iodide (12 mg, 0.062 mmol), anhydrous triethylamine (0.60 mL, 4.3 mmol) and TMS-acetylene (0.26 mL, 1.86 mmol) sequentially and the mixture was sonicated for 2 minutes. The reaction was heated in the microwave reactor at 120 °C for 1 hour to give a dark brown suspension which was filtered through celite. After washing the celite with diethyl ether, the solvent was removed in vacuo and the brown crude mixture purified by silica gel column chromatography (1 % ethyl acetate in hexane) to give the product as a yellow oil (142 mg, 64 %). **^{1}H-NMR** (400 MHz, $CDCl_3$) δ 6.46 (2H, s, H_a), 1.64 (9H, s, Boc-^{t}Bu), 0.24 (18H, s, TMS-CH_3); **^{13}C-NMR** (100 MHz, CD_3OD) δ 147.6, 119.4, 98.8, 95.6, 85.3, 26.8, -1.4, -1.5; **MS** (ESI +ve) *m/z* 382.1625 ($[M + Na]^+$, $C_{19}H_{29}NO_2Na^{28}Si_2$, calc. 382.1629).

Neutral *n*-octyl HB Receptor Precursor 5.HB



To a thoroughly-degassed solution of compound **3** (30 mg, 0.083 mmol) in THF (1 mL) was added tetrabutylammonium fluoride trihydrate (54 mg, 0.21 mmol) portionwise and the reaction stirred for 1 hour under N_2 to give a brown solution. Octyl azide (32 mg, 0.21 mmol), $[Cu(CH_3CN)_4]PF_6$ (10 mg, 0.033 mmol), TBTA (18 mg, 0.034 mmol) and DIPEA (0.060 mL, 0.033 mmol) were then added portionwise to the reaction which was then stirred for 2 days. Thereafter, the solvent was removed *in vacuo*, chloroform (20 mL) was added and the organic solution washed with 1 M NH_4Cl (aq.) (2 x 10 mL), water (5 x 10 mL) and dried with $MgSO_4$. Solvent removal gave a brown oil which was purified by silica gel column chromatography (30 % ethyl acetate in hexane) to yield the product as a yellow solid (20 mg, 45 %). **^{1}H-NMR** (400 MHz, $CDCl_3$) δ 7.77 (2H, s, H_b), 6.60 (2H, s, H_a), 4.39 (4H, t, ^3J = 7.2 Hz, H_c), 1.95 (4H, quint. ^3J = 7.1 Hz, H_d), 1.27-1.39 (29H, m, $H_{e\text{-}i}$ + *N*Boc-^{t}Bu), 0.88 (6H, t, ^3J = 6.8 Hz, H_k); **^{13}C-NMR** (100 MHz, CD_3OD) δ 149.4, 140.4, 126.1, 122.2, 113.8, 84.4, 50.4, 31.7, 30.3, 29.0, 28.9, 27.2, 26.5, 22.6, 14.0; **MS** (ESI +ve) *m/z* 526.3853 ($[M + H]^+$, $C_{29}H_{48}N_7O_2$, calc. 526.3864).

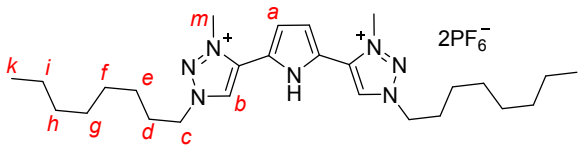
Neutral *n*-octyl XB Receptor Precursor 5.XB



Tetrabutylammonium fluoride trihydrate (66 mg, 0.25 mmol) was added to a solution of compound **3** (36 mg, 0.10 mmol) in THF/ acetonitrile 1:1 (1 mL) and the resulting purple-brown solution stirred for 45 minutes. In a separate round bottom flask charged with the same solvent mixture (1 mL) was added sodium iodide (121 mg, 0.808 mmol), copper(II) perchlorate hexahydrate (150 mg, 0.404 mmol) and octyl azide (35 mg, 0.22 mmol) portionwise. After stirring for 5 minutes, DBU (0.028 mL, 0.19 mmol), TBTA (5.4 mg, 0.010 mmol) and the deprotected bis-alkyne solution were added, and the reaction stirred in the dark under N_2 for 24 hours. Thereafter, the solvent was removed *in vacuo* and the resulting brown tar was partitioned between chloroform (25 mL) and 10 % aqueous ammonia solution (10 mL). The aqueous layer was separated and back-extracted with chloroform (2 x 10 mL) and the combined organics were washed with water (10 mL), brine (10 mL) and dried with $MgSO_4$. Silica gel column chromatography (25 % ethyl acetate in hexane) afforded the product as a bright yellow liquid (50 mg, 63 %). **^{1}H-NMR** (400 MHz, $CDCl_3$) δ 6.47 (2H, s, H_a), 4.40 (4H, t, ^3J = 7.2 Hz, H_b), 1.95 (4H, quint. ^3J = 7.2 Hz, H_c), 1.28-1.41 (20H, m, $H_{d\text{-}h}$), 1.22 (9H, s, *N*Boc-^{t}Bu), 0.88 (6H, t, ^3J = 6.8 Hz, H_k); **^{13}C-NMR** (100 MHz, CD_3OD) δ 148.1, 145.9, 125.1, 115.3, 83.9, 81.2, 51.1, 31.7, 30.0,

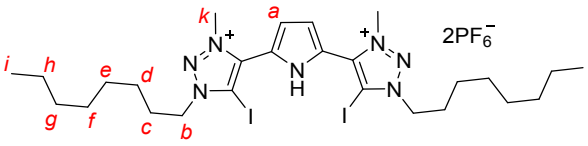
29.1, 29.0, 27.3, 26.5,22.6, 14.1; **MS** (ESI +ve) *m/z* 778.1776 ([M + H]$^+$, $C_{29}H_{46}N_7O_2{}^{127}I_2$, calc. 778.1797).

Dicationic *n*-octyl HB Receptor 1.HB



To a solution of the neutral receptor precursor **5.HB** (24 mg, 0.046 mmol) in dry dichloromethane (1.5 mL) was added trimethyloxonium tetrafluoroborate (20 mg, 0.14 mmol) and the reaction was stirred overnight under N_2. ESI-MS analysis showed that double methylation and *in-situ* deprotection of the *N*Boc group had occurred, and the reaction was quenched with one drop of methanol and stirred for 15 minutes. After solvent removal *in vacuo*, the resulting brown solid was purified by preparatory TLC (9 % methanol in dichloromethane) to give the product as a yellow solid. Anion exchange was performed by washing a chloroform solution (30 mL) of the purified receptor with 0.1 M NH_4PF_6 (aq.) (8 x 10 mL) followed by water (2 x 10 mL). Drying the organic phase with $MgSO_4$ and solvent removal afforded **5.19H**, as its $2PF_6^-$ salt, as a yellow solid (18 mg, 53 %). **^{1}H-NMR** (400 MHz, CD_3OD) δ 8.77 (2H, s, H_b), 7.08 (2H, s, H_a), 4.67 (4H, t, ^3J = 7.3 Hz, H_c), 4.41 (6H, s, H_m), 2.08 (4H, quint. ^3J = 7.2 Hz, H_d), 1.29-1.43 (20H, m, H_{e-i}), 0.91 (6H, t, ^3J = 6.8 Hz, H_k); **^{13}C-NMR** (100 MHz, CD_3OD) δ 137.2, 128.5, 119.5, 116.2, 55.5, 39.8, 33.0, 30.4, 30.3, 30.1, 27.3, 23.8, 14.5; **^{19}F-NMR** (470 MHz, CD_3OD) δ -74.4 (d, $^1J_{F-P}$ = 706 Hz); **^{31}P-NMR** (162 MHz, CD_3OD) δ -144.7 (sep., $^1J_{P-F}$ = 706 Hz); **MS** (ESI +ve) *m/z* 227.6858 ($[M]^{2+}$, $C_{26}H_{45}N_7$, calc. 227.6863).

Dicationic *n*-octyl XB Receptor 1.XB



Identical procedure as that reported for **1.HB**, but using precursor compound **5.XB** (49 mg, 0.063 mmol) and trimethyloxonium tetrafluoroborate (28 mg, 0.19 mmol) in dry dichloromethane (1.0 mL) for 2 days. Purification by preparatory TLC (10 % methanol in dichloromethane) and anion exchange by repeated washing with 0.1 M NH_4PF_6 (aq.) afforded the target compound as a yellow solid (23 mg, 42 %). **^{1}H-NMR** (400 MHz, CD_3OD) δ 7.05 (2H, s, H_a), 4.70 (4H, t, ^3J = 7.3 Hz, H_b), 4.36 (6H, s, H_k), 2.08 (4H, quint. ^3J = 7.2 Hz, H_c), 1.29-1.51 (20H, m, H_{d-h}), 0.92 (6H, t, ^3J = 6.8 Hz, H_i); **^{13}C-NMR** (100 MHz, CD_3OD) δ 140.5, 117.5, 116.1, 90.1, 54.8, 38.6, 31.7, 31.6, 29.4, 29.2, 28.8, 28.7, 25.8, 22.4, 13.1;

^{19}F-NMR (470 MHz, CD_3OD) δ -74.4 (d, $^1J_{F\text{-}P}$ = 706 Hz); **^{31}P-NMR** (162 MHz, CD_3OD) δ -144.7 (sep., $^1J_{P\text{-}F}$ = 706 Hz); **MS** (ESI +ve) *m/z* 353.5824 ($[M]^{2+}$, $C_{26}H_{43}N_7{}^{127}I_2$, calc. 353.5829).

S2. Spectral Characterisation of Compounds

XB Receptor **1.XB**

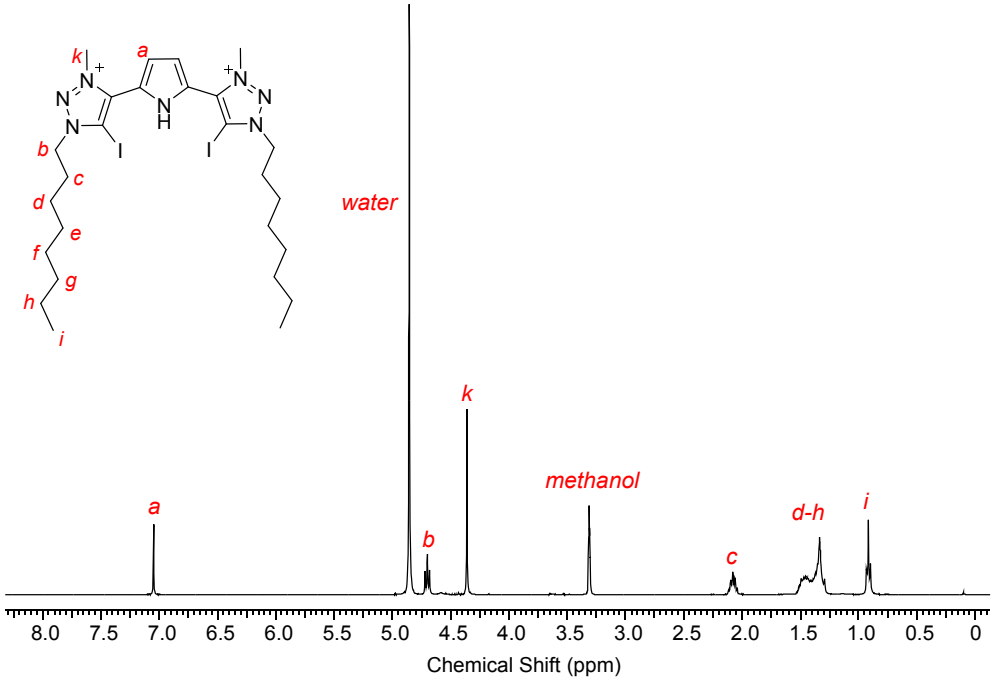


Fig. S1. ^{1}H NMR spectrum of receptor **1.XB** (CD_3OD).

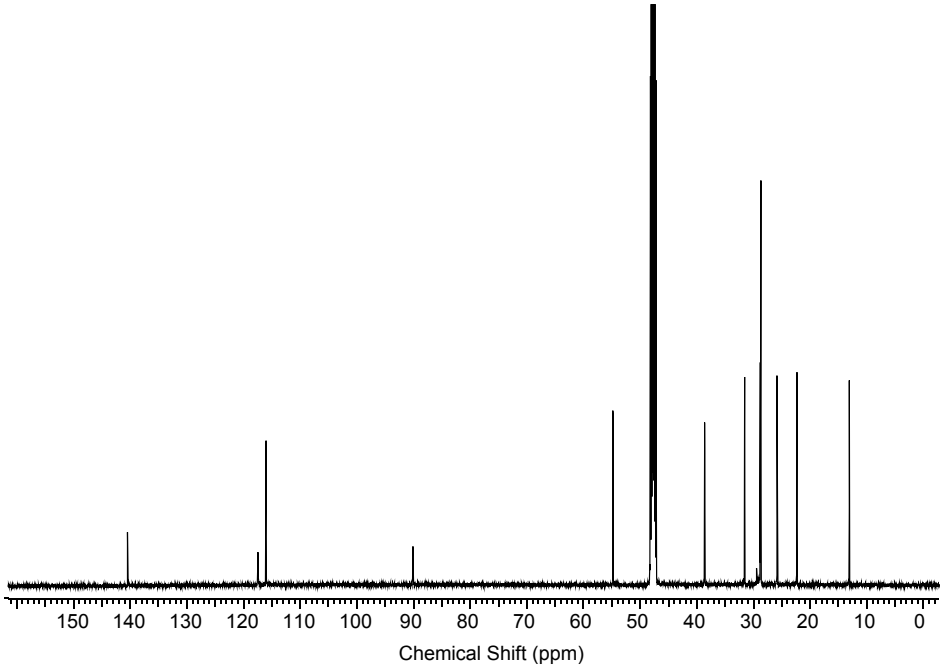


Fig. S2. ^{13}C NMR spectrum of receptor **1.XB** (CD_3OD).

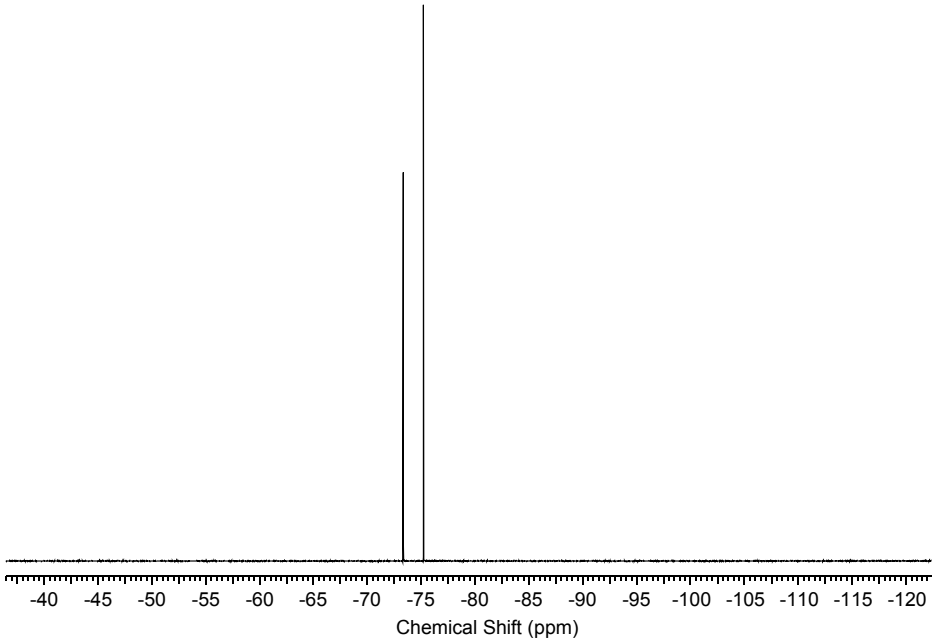


Fig. S3. ^{19}F NMR spectrum of receptor **1.XB** (CD_3OD).

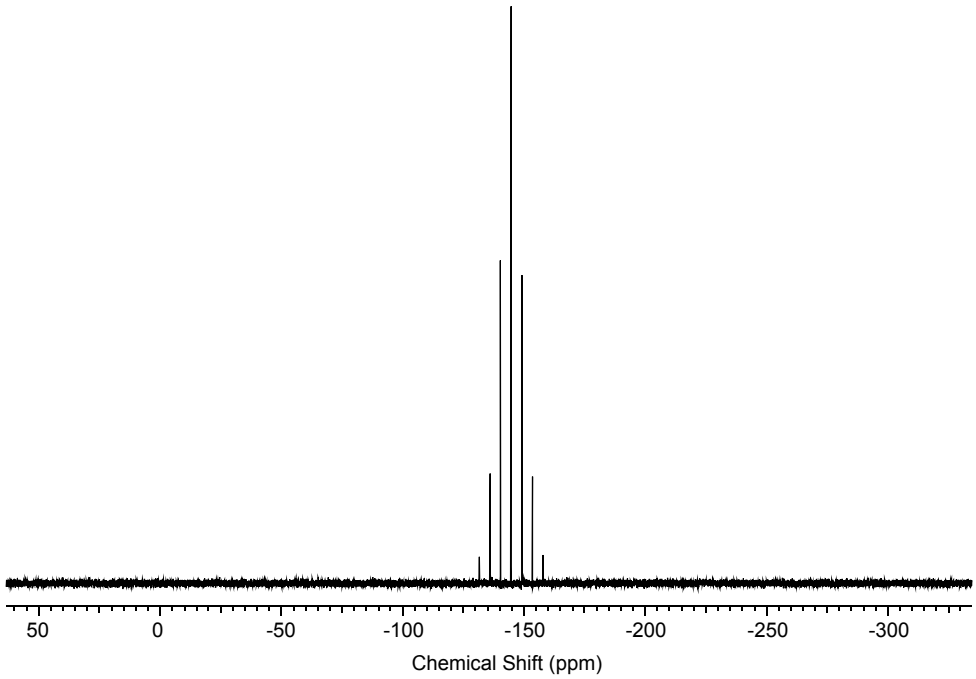


Fig. S4. ^{31}P NMR spectrum of receptor **1.XB** (CD_3OD).

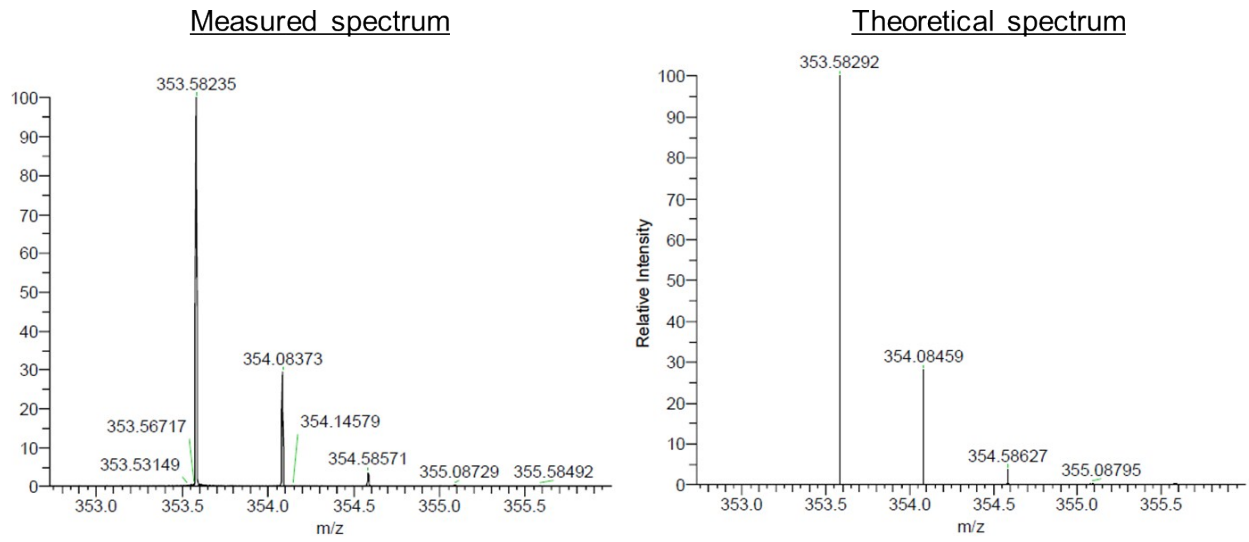


Fig S5. High-resolution ESI mass spectrum of receptor **1.XB** (left) and its theoretical calculated spectrum (right).

HB Receptor **1.HB**

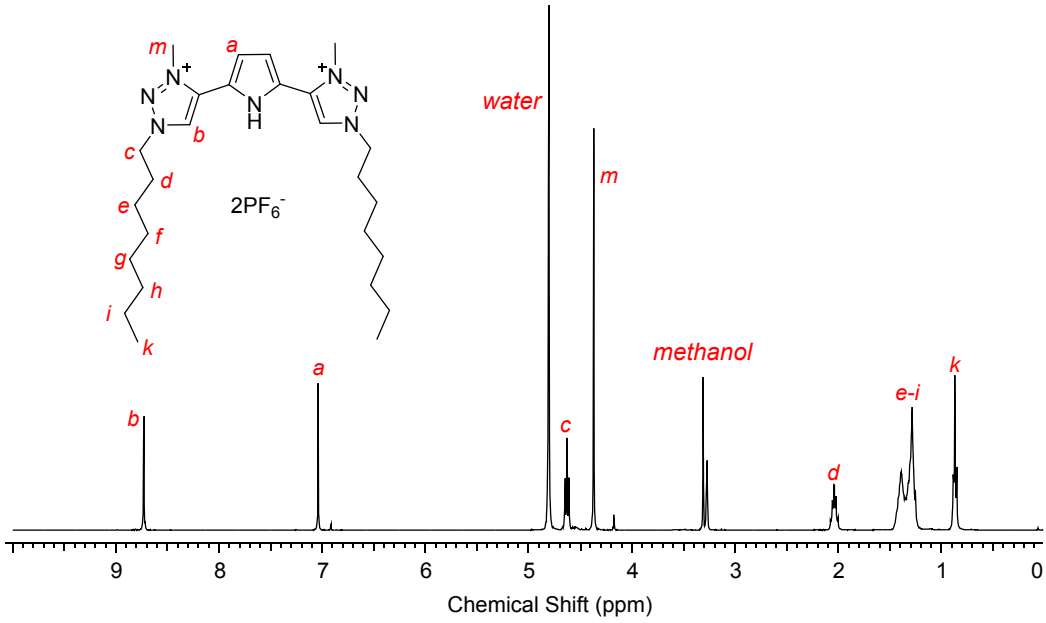


Fig. S6. ^{1}H NMR spectrum of receptor **1.HB** (CD_3OD).

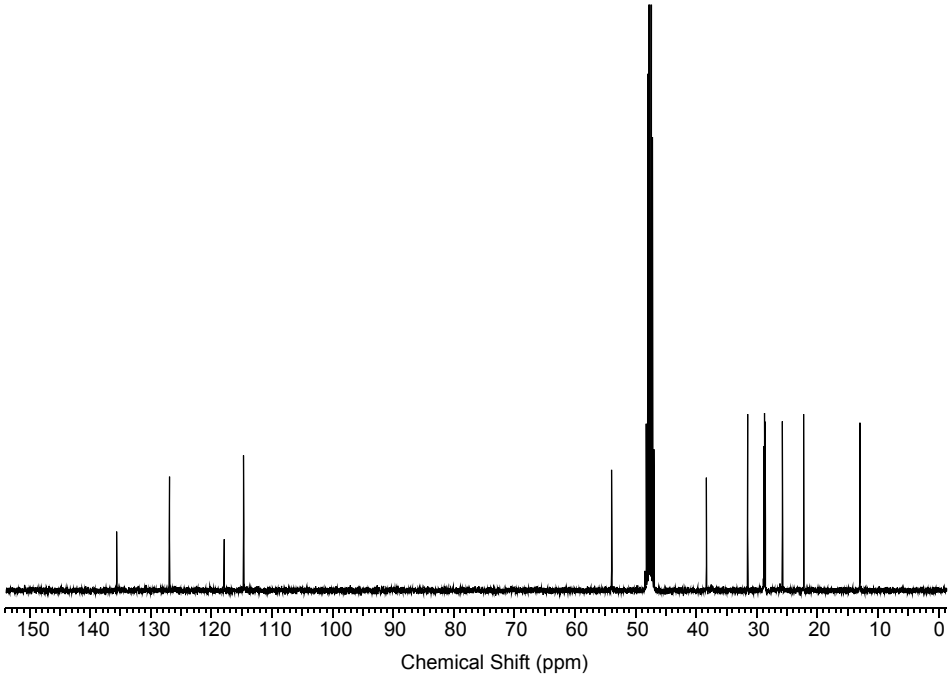


Fig. S7. ^{13}C NMR spectrum of receptor **1.HB** (CD_3OD).

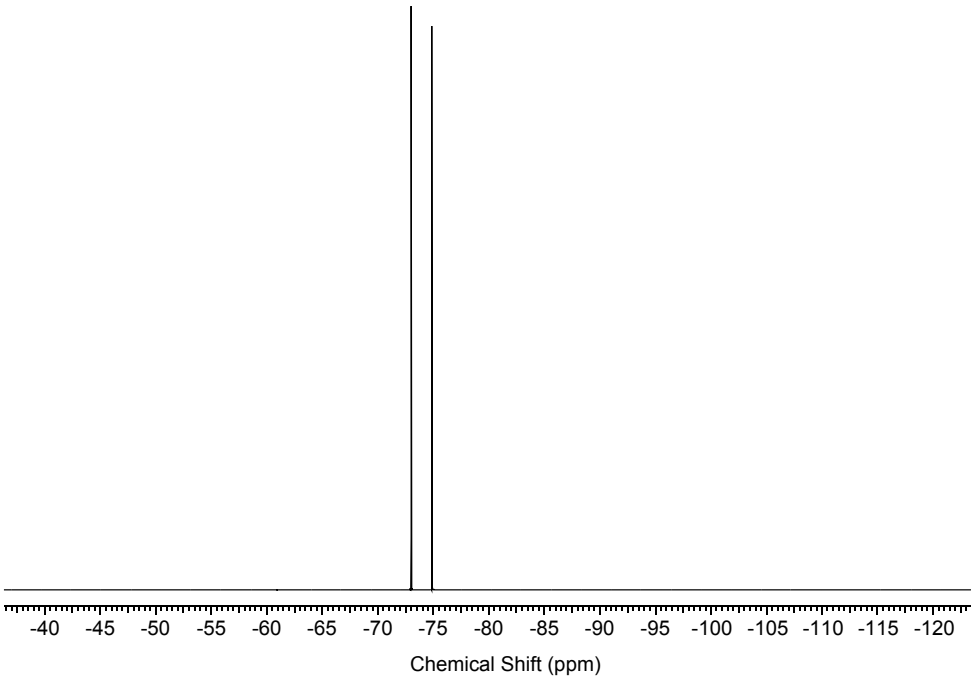


Fig. S8. ^{19}F NMR spectrum of receptor **1.XB** (CD_3OD).

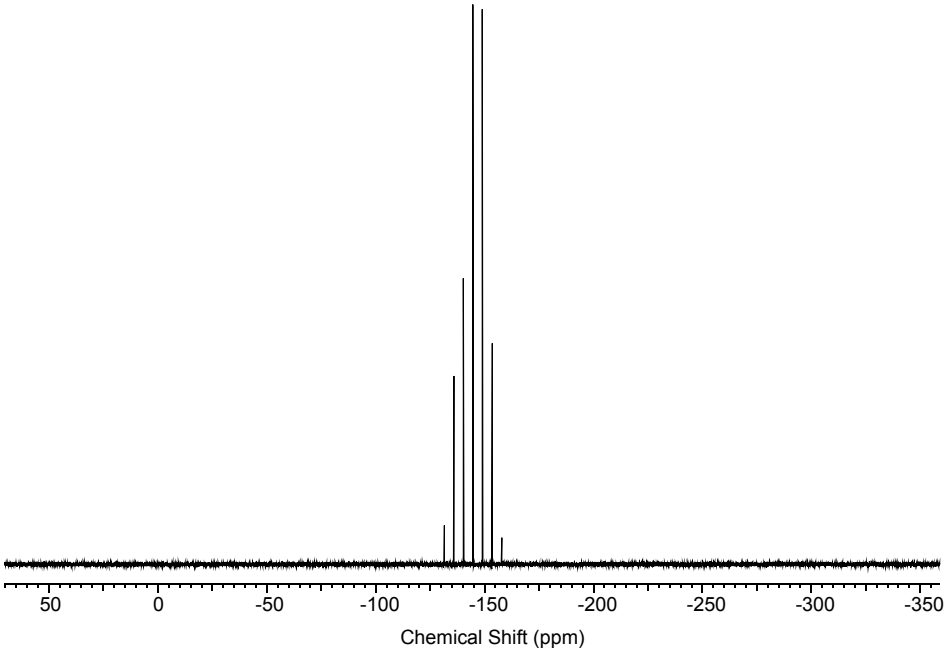


Fig. S9. ^{31}P NMR spectrum of receptor **1.XB** (CD_3OD).

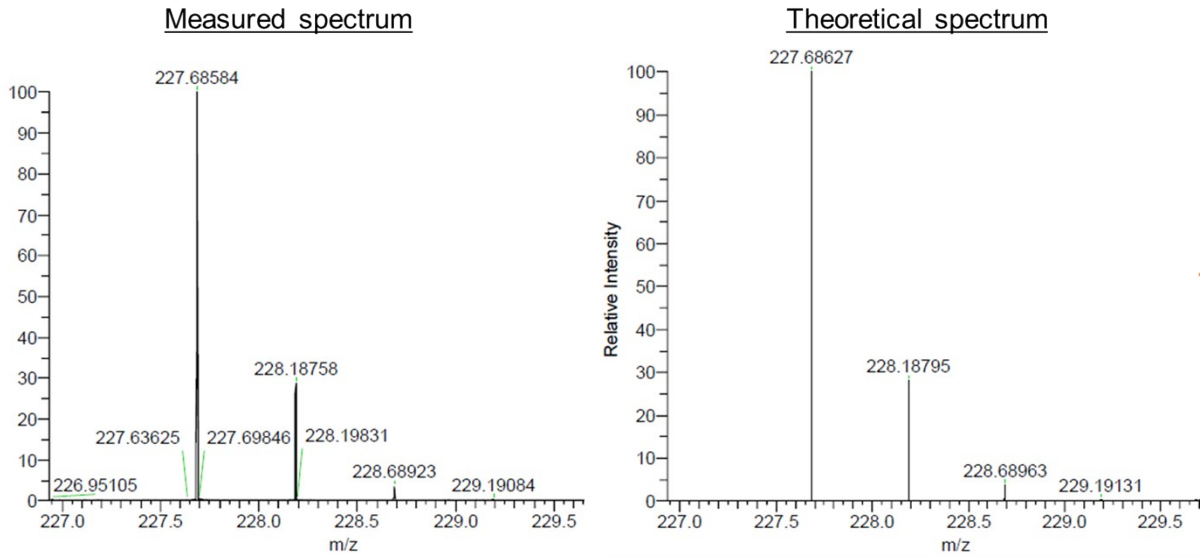


Fig S10. High-resolution ESI mass spectrum of receptor **1.HB** (left) and its theoretical calculated spectrum (right).

S3. Anion binding studies by ^{1}H NMR Titrations

General procedure

^{1}H NMR titration experiments were performed on a Bruker AVIII 500 MHz spectrometer. In a typical experiment, a solution of the appropriate tetrabutylammonium (TBA) salt was added to a solution of the receptor molecule at 298 K in $CDCl_3$/ CD_3OD/ D_2O 45:45:10 *v/v/v*. Both TBA salt and receptor were dissolved in the same solvent. TBA was chosen as the counter-cation due to its non-coordinating nature. A 0.075 M solution of the salt was added to 0.50 mL of a 1.5 mM solution of receptor, where 1.0 equivalent of salt added corresponds to 10.0 µL of the salt solution. 17 data points corresponding to 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0, 7.0 and 10.0 equivalents of added guest anion were obtained.

The binding of anions with receptors **1.HB** and **1.XB** were found to be fast on the NMR timescale, and the external pyrrolic proton H_a was monitored for all titrations. While H_a of **1.HB** showed detectable perturbations, those for **1.XB** moved negligibly (see Figure S11 below). As none of the proton environments were directly flanking the anion binding cavity and thus could provide a reliable probe for anion binding, ^{1}H NMR titrations were deemed unsuitable for studying the anion binding properties of **1.HB** and **1.XB**.

^{1}H NMR titration data

Receptor 1.XB

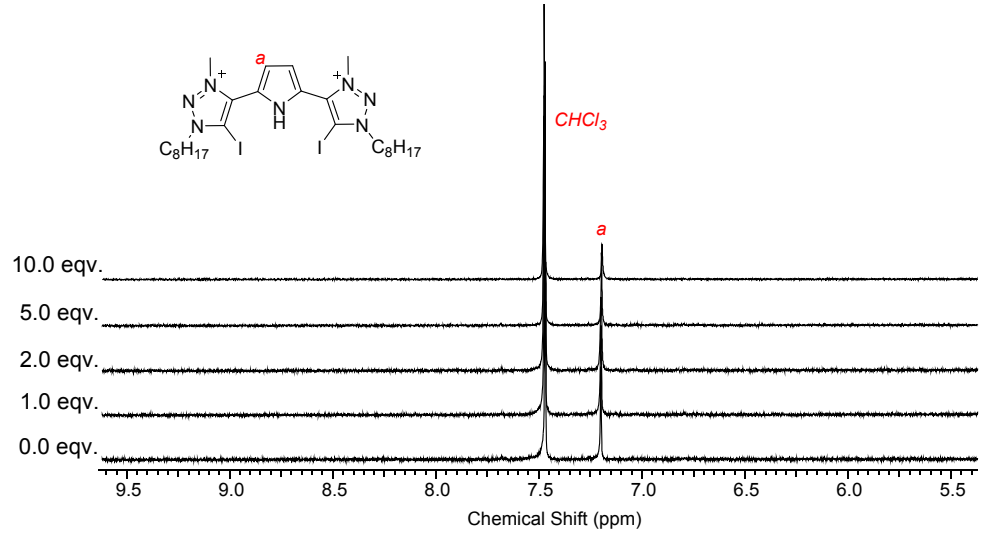


Figure S11. Partial ^{1}H NMR spectra of receptor **1.XB** in the presence of 0.0, 1.0, 2.0, 5.0 and 10.0 equivalents of TBACl ([**1.XB**] = 1.5 mM, *T* = 298 K, $CDCl_3$/ CD_3OD/ D_2O = 45:45:10 *v/v/v*).

S4. UV-Vis Titrations

UV-Vis titrations were performed on a T60U (PG Instruments Ltd) spectrophotometer and the data was processed using the OriginPro software. In each case, the host molecule (**1.XB** or **1.HB**) were dissolved in CH_3CN/ H_2O 9:1 *v/v* to give a concentration of 50 μM. The TBA salt of the anion was dissolved in a solution of the host molecule to give a concentration of 50 mM for F^- and OAc^-; 100 mM for Cl^-, Br^- and I^-; and 200 mM for $H_2PO_4^-$, SO_4^{2-}, NO_3^- and ClO_4^-. Aliquots of the anion solution were added to 2.0 mL of the host solution in a quartz cuvette, where the sample was then thoroughly mixed before the absorbance spectra were recorded. Stability constants were obtained by global analysis where the largest spectral changes were observed (305 - 340 nm for the halides and 340 - 390 nm for the oxoanions) using BindFit[4] using the host-guest binding model which gave the best and most sensible fit. In all cases, the theoretical binding isotherms and calculated concentration profiles of the complexes were compared with the experimental data to ensure validity of the model used.

For the anion titrations, the recorded spectra during the titration are shown, with arrows denoting the direction of spectral changes for each receptor following anion addition. The binding isotherms shown below (at selected wavelengths) are representative of the quality of the non-linear data fit. Filled dots represent the experimental data, while the solid lines show the fitted data (calculated isotherm).

Receptor 1.XB

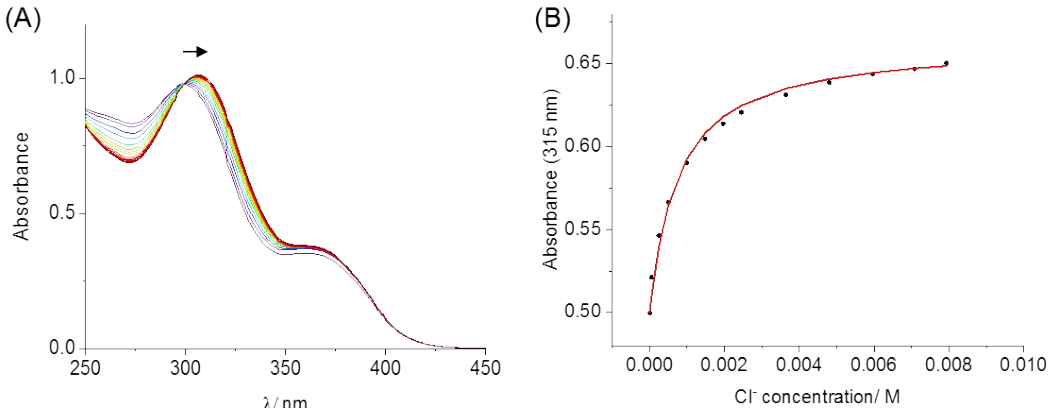


Fig. S12. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of TBACl; (B) Experimental and calculated binding isotherms at 315 nm.

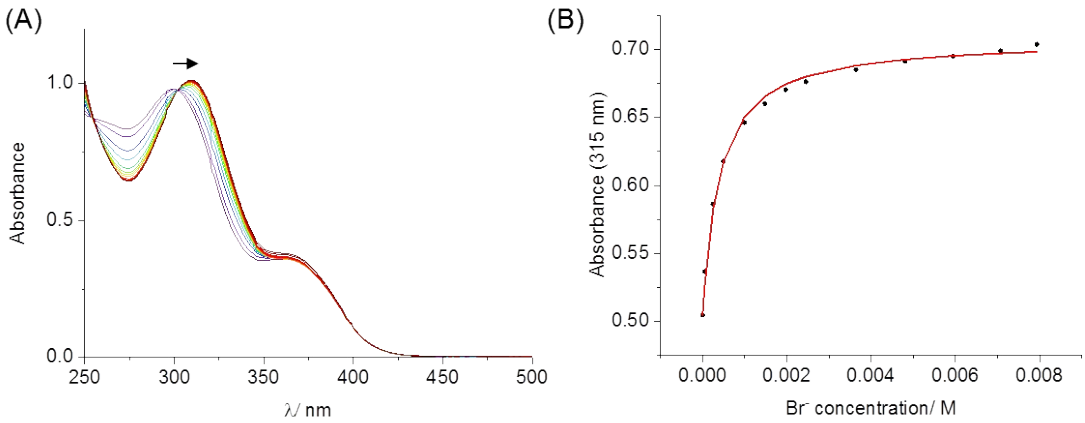


Fig. S13. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of TBABr; (B) Experimental and calculated binding isotherms at 315 nm.

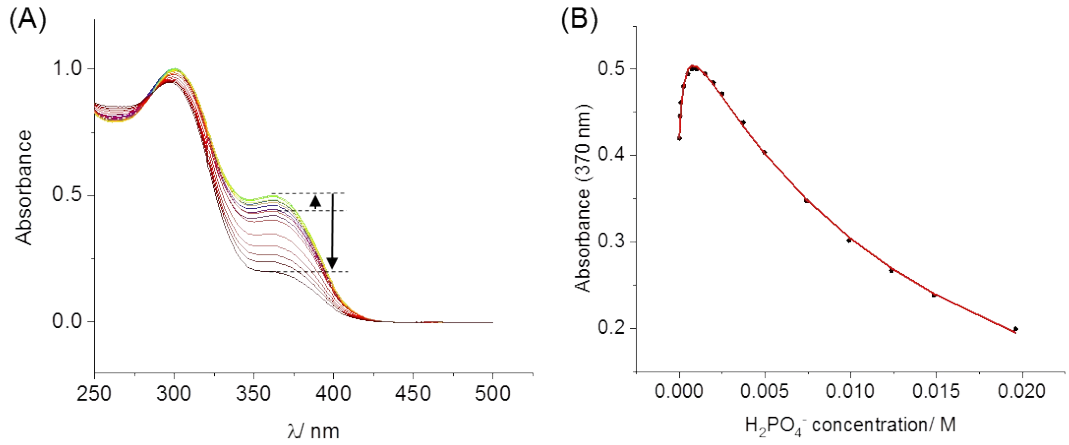


Fig. S14. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of $(TBA)(H_2PO_4)$; (B) Experimental and calculated binding isotherms at 370 nm.

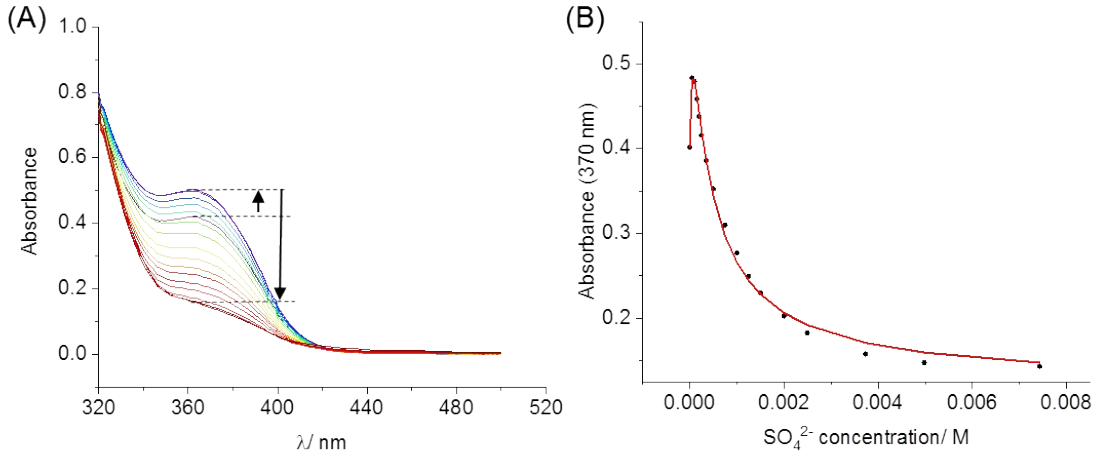


Fig. S15. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of $(TBA)_2(SO_4)$; (B) Experimental and calculated binding isotherms at 370 nm.

A note on the host-guest 2:1 association constants determined for SO_4^{2-} binding

Fitting the titration data to an alternative host-guest 1:2 stoichiometric binding model yielded K_{11} = 136 000 ± 19 000 M^{-1} and K_{12} = 1980 ± 20 M^{-1}. Notably, the 14 % error in K_{11} showed that the HG 1:2 model was inappropriate for SO_4^{2-} binding, in contrast to the host-guest 2:1 model used to determine K values mentioned in the manuscript. Nonetheless, while (**1.XB**)$_2$(SO_4) and (**1.XB**)(SO_4) complexes (host-guest 2:1 and 1:1 complexes respectively) are expected to be dominantly present within the anion concentration regime investigated, some host-guest 1:2 complexes [(**1.XB**)(SO_4)$_2$] are likely to be present as well upon addition of large excess of anions relative to host **1.XB**. This results in the K_{21} and K_{11} values thus reported being inevitable estimates.

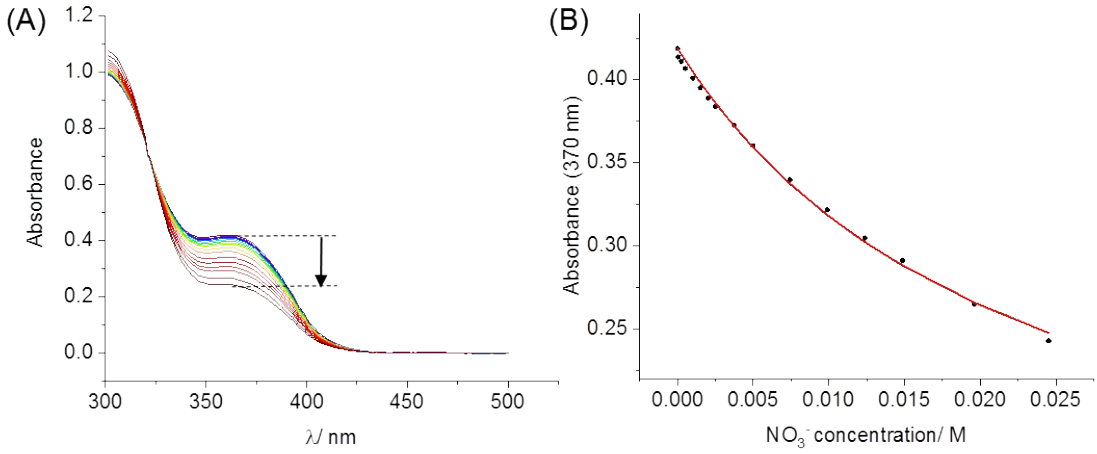


Fig. S16. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of (TBA)(NO_3); (B) Experimental and calculated binding isotherms at 370 nm.

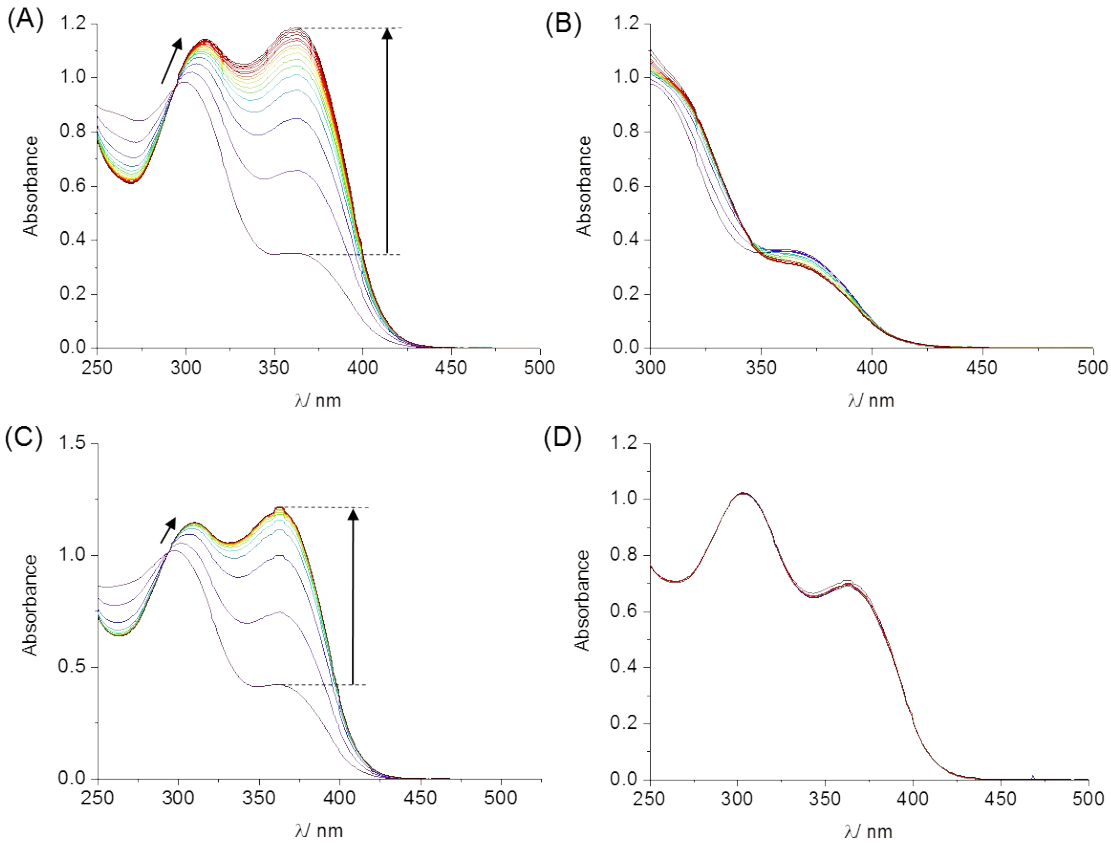


Fig. S17. (A) Recorded emission spectra of **1.XB** in the presence of increasing quantities of (A) TBAF; (B) TBAI; (C) (TBA)(OAc) and (D) (TBA)(ClO_4).

Receptor 1.HB

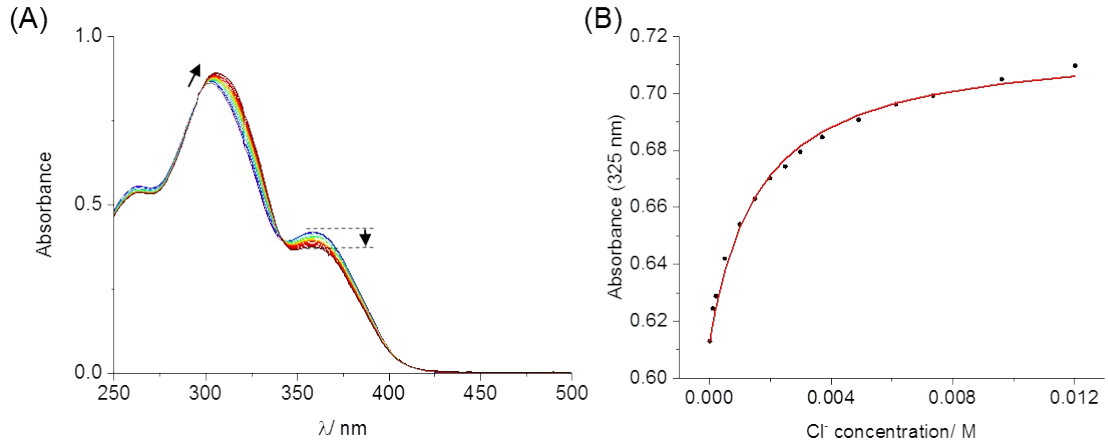


Fig. S18. (A) Recorded emission spectra of **1.HB** in the presence of increasing quantities of TBACl; (B) Experimental and calculated binding isotherms at 325 nm.

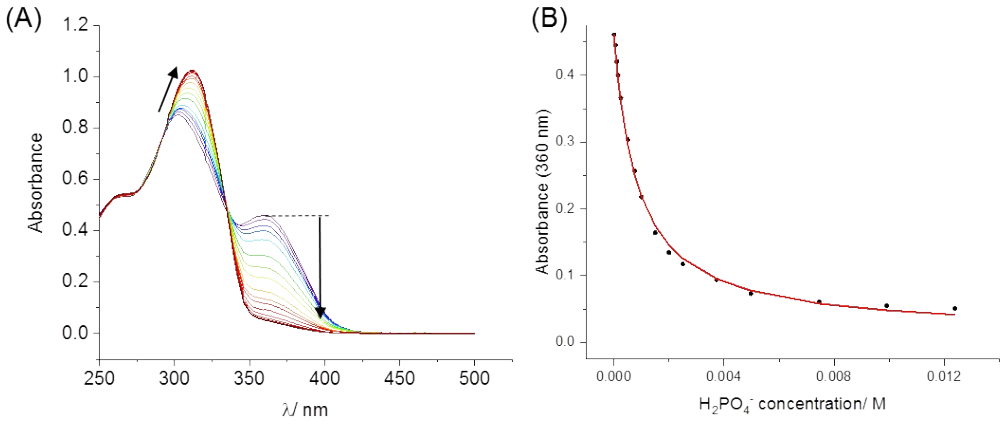


Fig. S19. (A) Recorded emission spectra of **1.HB** in the presence of increasing quantities of $(TBA)(H_2PO_4)$; (B) Experimental and calculated binding isotherms at 370 nm.

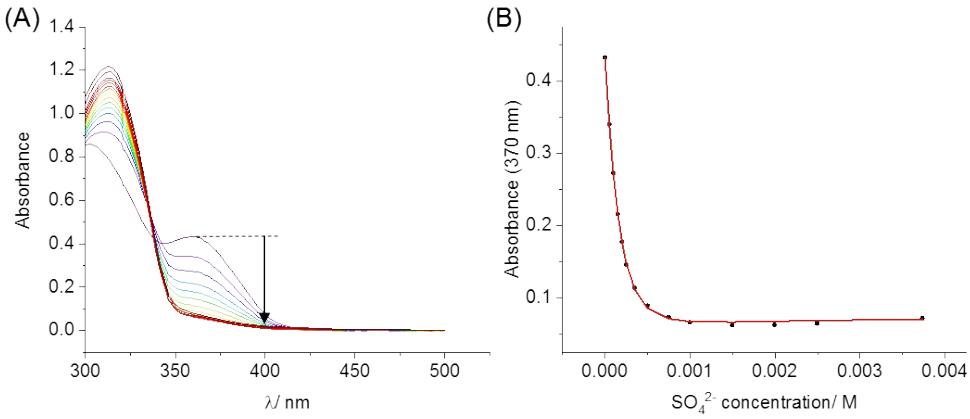


Fig. S20. (A) Recorded emission spectra of **1.HB** in the presence of increasing quantities of $(TBA)_2(SO_4)$; (B) Experimental and calculated binding isotherms at 370 nm.

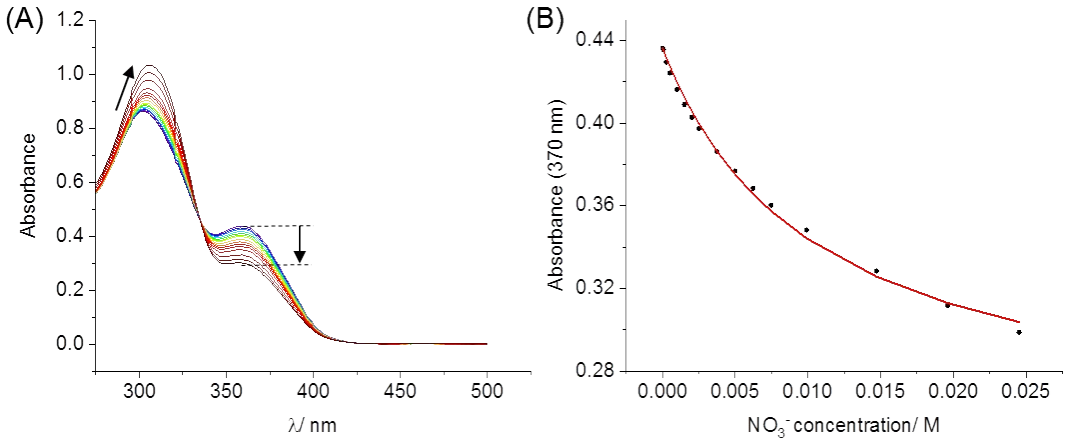


Fig. S21. (A) Recorded emission spectra of **1.HB** in the presence of increasing quantities of (TBA)(NO_3); (B) Experimental and calculated binding isotherms at 370 nm.

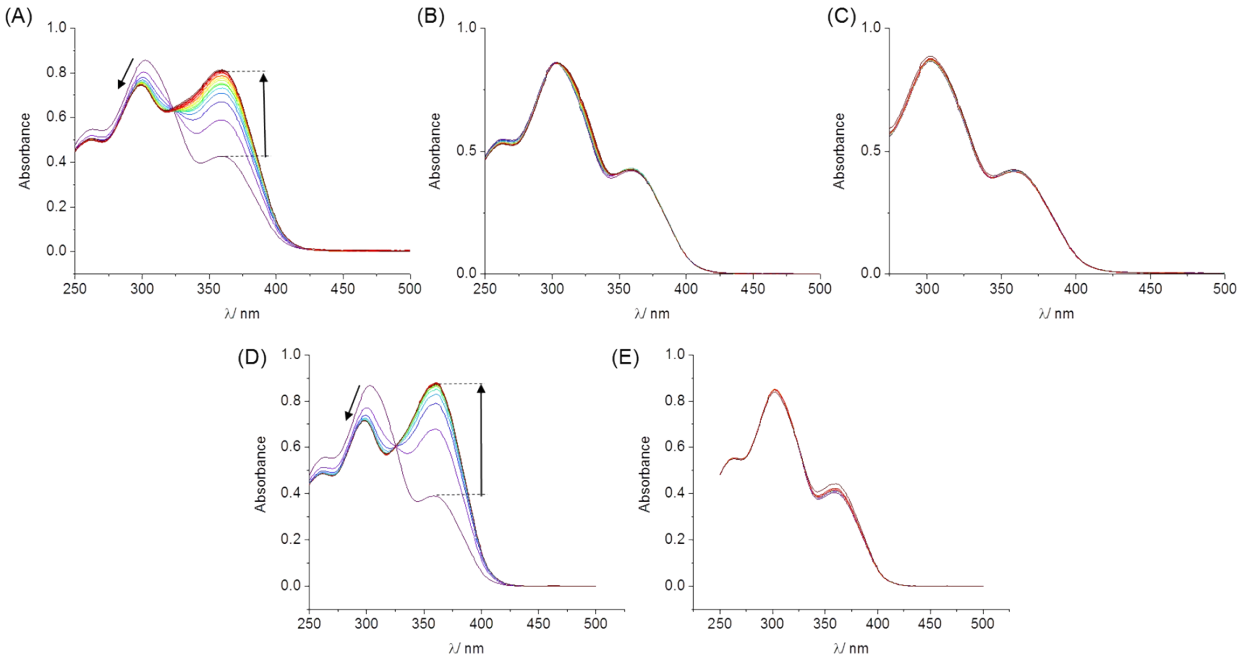


Fig. S22. (A) Recorded emission spectra of **1.HB** in the presence of increasing quantities of (A) TBAF; (B) TBABr; (C) TBAI; (D) (TBA)(OAc) and (E) (TBA)(ClO_4).

S5. References

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