# From Isolated *1H*-Pyrazole Cryptand Anion Receptors to Hybrid Inorganic-Organic 1D Helical Polymeric Anion Receptors.

*Javier Pitarch-Jarque, Raquel Belda, Laura García-España, José M. LLinares, FangFang Pan, Kari Rissanen, Pilar Navarro and Enrique García-España.**

## Suplementary Information.

## Synthesis.

### Synthesis and characterization of 1.

The cryptand **1** was prepared as previously reported.[1] 3,5-Pyrazoledicarbaldehyde (0.375 g, 3 mmol) was dissolved in warm methanol (120 mL) and added drop wise during 2 h under an argon atmosphere to a stirred solution of tris(2-aminoethyl)amine (0.292 g, 2 mmol) in methanol (80 mL). After stirring overnight at room temperature, sodium borohydride (228 mg, 6 mmol) was added portion wise, and after 2 h the solvent was evaporated to dryness under reduced pressure. The residue was directly recrystallized from water (15 mL).

Yield (0.380 g, 65%); mp 245 °C. $^1$H NMR (400 MHz, $CD_3OD$): δ 5.85 (s, 3 H, H4), 3.72 (s, 12 H, H6), 2.80-2.83 (m, 12 H, Hα), 2.68-2.71 (m, 12 Hβ). $^{13}$C NMR (100.58 MHz, $CD_3OD$): δ 147.92 (br s, C3,5), 103.28 (C4), 52.86 (Cβ), 48.54 (Cα), 46.47 (C6). FAB-MS (m/z, %): 569 $[M + H]^+$ (60), 307 (17), 154 (100), 136 (83). Anal. Calcd (%) for $C_{27}H_{48}N_{14}$, $H_2O$ (586.8): C, 55.27; H, 8.59; N, 33.42. Found: C, 55.42; H, 8.91; N, 33.70.

### Synthesis of the complexes4 and 5.

**$[H_6(1)Cl(H_2O)_2]Cl_5·6\ H_2O$ (4).** Working under argon atmosphere, a solution of **1** (10 mg, 17 mmol) in water (2 mL) was acidified with hydrochloric acid until pH = 2. A slow evaporation of the solution in a vessel afforded the formation of colorless crystals suitable for X-ray diffraction in 95% yield. Anal. Calcd.for $C_{27}H_{70}Cl_6N_{14}O_8$: C, 34.90; H, 7.59; N, 21.11. Found: C, 34.8; H, 7.7; N, 21.1

**$(5H_2O, 2Cl@[Cu_3(H_61)_2Cl_9])\ Cl_7·14.25H_2O$ (5):** Working under argon atmosphere, a solution of $Cu(ClO_4)_2$ **6**$H_2O$ (9.45 mg, 25.5 mmol) in water (2 mL) was added with stirring to a solution of **1** (10 mg, 17 mmol) in 2 mL in water acidified with HCl acid until pH 4. The blue solution was adjusted to pH = 1.5 with a concentrated solution of HCl. The pale green solution formed by means of a slowly evaporation at room temperature, affords green crystals in 95% yield. Anal. Calcd. for $C_{54}H_{149.5}Cl_{18}Cu_3N_{28}O_{20.75}$: C, 27.68; H, 6.43; N, 16.74. Found:C, 27.4; H, 6.6; N, 16.5.

## Experimental Section.

### X-Ray Analysis

A single crystal of **4** was measured in an Enraf Nonius KappaCCD using MoKα radiation ($\lambda = 0.71073$ Å) at 293 K. A single crystal of **5** was measured in an Oxford diffraction Supernova diffractometer using $CuK_\alpha$ ($\lambda = 1.5418$ Å) radiation at 123 K. Structures were solved by direct methods using SIR97[2] and refined by full-matrix least-squares on all $F^2$ using SHELXL97[3] with the Olex2[4] suite. Molecular drawings were produced with Mercury.[5]

Compound **5** contains voids with scattered electron density which could not be modelled and was treated with the solvent masking protocol inside Olex2. The electron count / cell is 62.4 and it could be assigned to 6 water molecules. For more details see _smtbx_masks_special_details at the end of the cif file.

Cifs of **4** and **5** are deposited in CCDC with numbers 1030676 and 983275. These data can be obtained free of charge from The Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

### Electromotive Force Measurements.

The potentiometric titrations were carried out at 298.1±0.1 K using NaCl 0.15 M as supporting electrolyte. The experimental procedure (burette, potentiometer, cell, stirrer, microcomputer, etc.) has been fully described elsewhere.[6] The acquisition of the emf data was performed with the computer program PASAT.[7] The reference electrode was an Ag/AgCl electrode in saturated KCl solution. The glass electrode was calibrated as an hydrogen-ion concentration probe by titration of previously standardized amounts of $HCF_3SO_3$ with $CO_2$-free NaOH solutions and determining the equivalent point by the Gran's method,[8] which gives the standard potential, $E^{o\prime}$, and the ionic product of water (pKw = 13.73(1)).

The computer program HYPERQUAD[9] was used to fit the protonation and stability constants. Solutions containing the ligand and the ligand + NaCl, with concentrations $1 \times 10^{-3}$ M were titrated with NaOH. The different titration curves for each ligand were treated as separated curves without significant variations in the values of the stability constants. Finally, the sets of data were merged together and treated simultaneously to give the final stability constants.

### MALDI-TOF spectrometry

#### -Sample preparation

The samples of **4** and **5** were prepared in water with a final concentration $1\times 10^{-3}$ M. The sample was dissolved in water at acidic pH. 1 μL of sample spotted onto the MALDI plate, after the droplets were air-dried at room temperature 0.75 μL of sample matrix was spotted and allowed to dry. Matrix (5 mg/mL CHCA (Bruker) in 0.1% TFA-ACN/$H_2O$ (7:3, v/v).

## Mass spectrometry analysis

The resulting mixtures were analyzed in a 5800 MALDI TOFTOF (ABSciex) in reflectror linear mode (3000 shots every position) in a mass range of 350-35000 m/z; and in linear mode in a mass range of 3500-25000 Da.

Previously, the Plate and the acquisition method were calibrated with 1 μL the TOFTOF calibration mixture (ABSciex), in 13 positions. Only the reflector mode gives signal. The analysis was carried out in the SCSIE-University of Valencia Proteomics Unit, a member of ISCIII ProteoRedProteomics Platform".

## NMR Measurements.

The $^1$H and $^{13}$C NMR spectra were recorded on a Bruker Advance DPX 400 MHz spectrometer operating at 399.95 MHz for $^1$H and at 100.58 MHz for $^{13}$C. $^{19}$F spectra were recorded on a DPX 500 Bruker spectrometer operating at 470.47MHz. $^1$H-NMR studies were done in $D_2O$ using 3-(Trimethylsilyl) propionic acid sodium salt as a reference standard ($\delta = 0$ ppm for $^1$H and $\delta = 1.7$ ppm for $^{13}$C). Adjustments to the desired pH were made using drops of trifluoromethanesulfonic acid or NaOD solutions. The pD was calculated from the measured pH values using the correlation, pH = pD - 0.4.[10]

## X-Ray Analysis

**Table S1**. Crystallographic data for complexes **4** and **5**.

| **Compound** | **4** | **5** |
|---|---|---|
| **Empirical formula** | $C_{27}H_{70}Cl_6N_{14}O_8$ | $C_{216}H_{484}Cl_{72}Cu_{12}N_{112}O_{77}$ |
| **Formula weight** | 931.67 | 2346.07 |
| **Temperature** | 293.0(2) K | 123.0(1) K |
| **Crystal system** | Monoclinic | Monoclinic |
| **Space group** | P 21/c | P 21/c |
| **Unit cell dimensions** | | |
| **a(Å)** | 14.1190(8) | 20.6746(7) |
| **b(Å)** | 15.1510(5) | 18.6770(3) |
| **c(Å)** | 24.8700(11) | 40.0092(14) |
| **α(°)** | 90 | 90 |
| **β(°)** | 121.047(2) | 132.674(6) |
| **γ(°)** | 90 | 90 |
| **Volume $Å^3$** | 4558.0(4) | 11358.5(10) |
| ***Z*** | 4 | 1 |
| **Density calc ($g/cm^3$)** | 1.358 | 1.345 |
| **Crystal size (mm)** | 0.3× 0.2 ×0.2 | 0.35×0.17×0.06 |
| **Wavelength** | 0.71073 | 1.5418 |
| **F(000)** | 1984 | 4752 |
| **μ ($mm^{-1}$)** | 0.435 | 5.084 |
| **Absorption. correction** | None | Multi-scan |
| **Θ range** | 1.91° to 25° | 1.41° to 27.48° |
| **reflns collected** | 14111 | 49666 |
| **indep reflns** | 7709 | 20216 |
| **R(int)** | 0.0579 | 0.024 |
| **data/restr/param** | 7709/38/530 | 20216/281/1254 |
| **Final R indices** | $R1 = 0.0626$; | $R1 = 0.0975$; |
| **[I >2 sigma(I)]** | $wR^2 = 0.1266$; | $wR^2 = 0.3214$; |
| **R indices all data** | $R1 = 0.1369$; | $R1 = 0.1049$; |
| | $wR^2 = 0.1711$; | $wR^2 = 0.3382$; |
| **GOF ($F^2$)** | 1.036 | 1.542 |

**Table S2.** Hydrogen Bonding Contacts for **4.**

| D | H | A | D-H | D-H..A | D-H..A | Angle |
|---|---|---|---|---|---|---|
| N2 | H2A | Cl1 | 0.97 | 2.32 | 3.194(4) | 149.9 |
| N2 | H2B | O7(#1) | 0.97 | 1.83 | 2.773(5) | 164 |
| N7 | H7A | Cl4 | 0.97 | 2.18 | 3.126(4) | 166.4 |
| N7 | H7B | OW2 | 0.97 | 1.8 | 2.755(5) | 168.9 |
| N11 | H11A | Cl1 | 0.97 | 2.46 | 3.350(4) | 152.1 |
| N10 | H10A | Cl1 | 0.97 | 2.41 | 3.257(4) | 146.1 |
| N10 | H10B | Cl3 | 0.97 | 2.19 | 3.155(4) | 175.7 |
| N5 | H5A | OW1 | 0.97 | 1.87 | 2.796(5) | 159.8 |
| N5 | H5B | Cl4 | 0.97 | 2.2 | 3.155(4) | 166.5 |
| N14 | H14A | OW2 | 0.97 | 1.9 | 2.825(5) | 158 |
| N14 | H14B | OW1 | 0.97 | 2.56 | 3.051(5) | 111.1 |
| N14 | H14B | O5(#1) | 0.97 | 1.85 | 2.777(5) | 157.8 |
| O7 | H7E | Cl4 | 0.84 | 2.44 | 3.143(4) | 141.2 |
| O7 | H7F | Cl3 | 0.77 | 2.34 | 3.104(4) | 173.9 |
| OW1 | HW1A | Cl3(#1) | 0.77 | 2.54 | 3.302(3) | 167 |
| OW1 | HW1B | Cl1 | 0.85 | 2.4 | 3.210(3) | 159.8 |
| OW2 | HW2A | Cl1 | 0.77 | 2.41 | 3.179(3) | 174.3 |
| O5 | H5C | Cl3 | 0.77 | 2.44 | 3.199(4) | 166.6 |
| O9 | H9D | Cl5 | 0.89 | 2.24 | 3.105(7) | 164 |
| O3 | H3D | N8 | 0.86 | 2.04 | 2.886(6) | 165.3 |
| N9 | H9 | N3(#2) | 0.95(7) | 2.00(7) | 2.943(6) | 171(6) |

Symmetry operations : (#1) = 1-x, y-1/2, -z; (#2) = 1-x,1/2+y,1/2-z

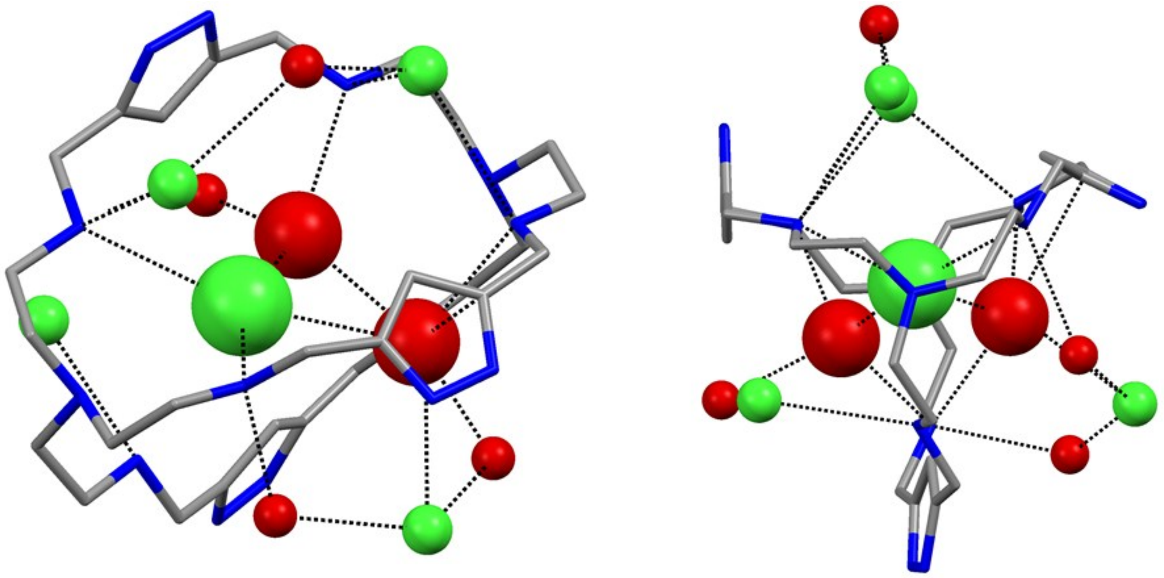


**Figure S1.** Views of the coordination sphere of **4**. Hydrogen bonds represented by dotted lines.

## Electromotive Force Measurements.

| Reaction[a] | Log K |
|---|---|
| $L + H \leftrightarrows HL$ | 9.65(2)[b] |
| $HL + H \leftrightarrows H_2L$ | 9.04(2) |
| $H_2L + H \leftrightarrows H_3L$ | 8.75(2) |
| $H_3L + H \leftrightarrows H_4L$ | 7.55(2) |
| $H_4L + H \leftrightarrows H_5L$ | 5.85(1) |
| $H_5L + H \leftrightarrows H_6L$ | 5.13(2) |

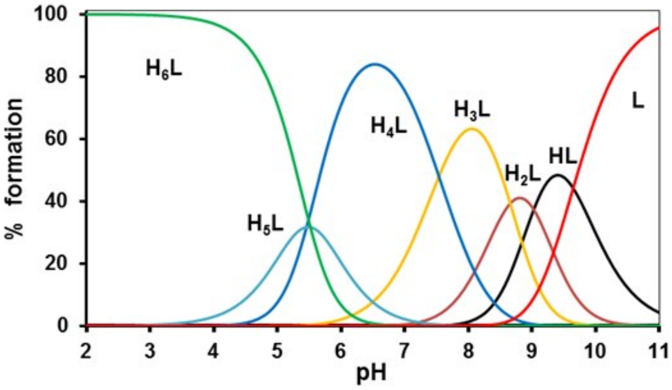


**Figure S2.** Stepwise protonation constants for receptor **1** determined in 0.15 mol dm$^{-3}$ NaTFMS at 298.1 K ([a] Charges omitted. [b] Values in parentheses are standard deviations in the last significant figure).

| Reaction[a] | Log K |
|---|---|
| $H_2L + A \leftrightarrows H_2LA$ | 2.58(4)[b] |
| $H_3L + A \leftrightarrows H_3LA$ | 2.81(3) |
| $H_4L + A \leftrightarrows H_4LA$ | 3.47(2) |
| $H_5L + A \leftrightarrows H_5LA$ | 4.51(2) |
| $H_6L + A \leftrightarrows H_6LA$ | 4.83(2) |

[a] Charges omitted. [b] Values in parentheses are standard deviations in the last significant figure.

**Table S3.** Stepwise stability constants for the complexes of receptor **1** with Cl$^-$ determined in 0.15 mol dm$^{-3}$ NaTFMS at 298.1 K

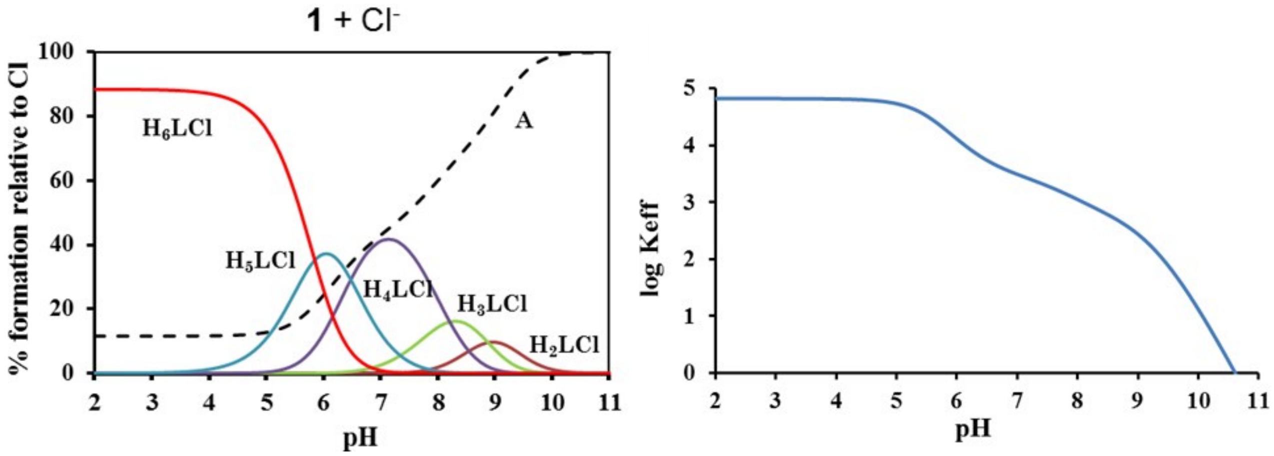
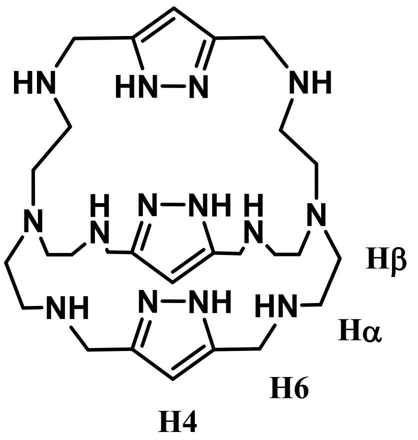


**Figure S3**. a) Plot of the distribution diagram of the system **1 :** Cl in 1:1 molar ratio (charges omitted). b) Plot of log $K_{eff}$ vs. pH.

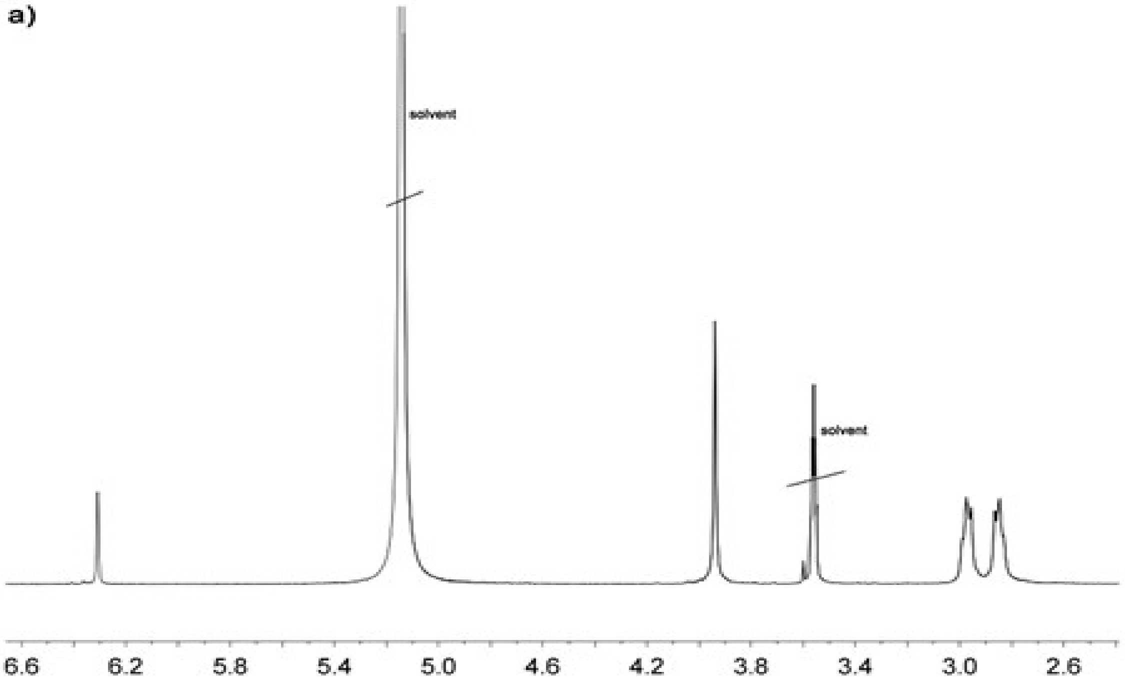
The Effective constant (**$K_{eff}$**) was calculated using the formulae:

$$K_{eff} = \frac{\Sigma[AH_{i+j}L]}{\Sigma[AH_j] \cdot \Sigma[H_jL]}$$

**NMR Measurements.**



**Scheme S1.** Assignation of $^{1}$H NMR signals of **1**.



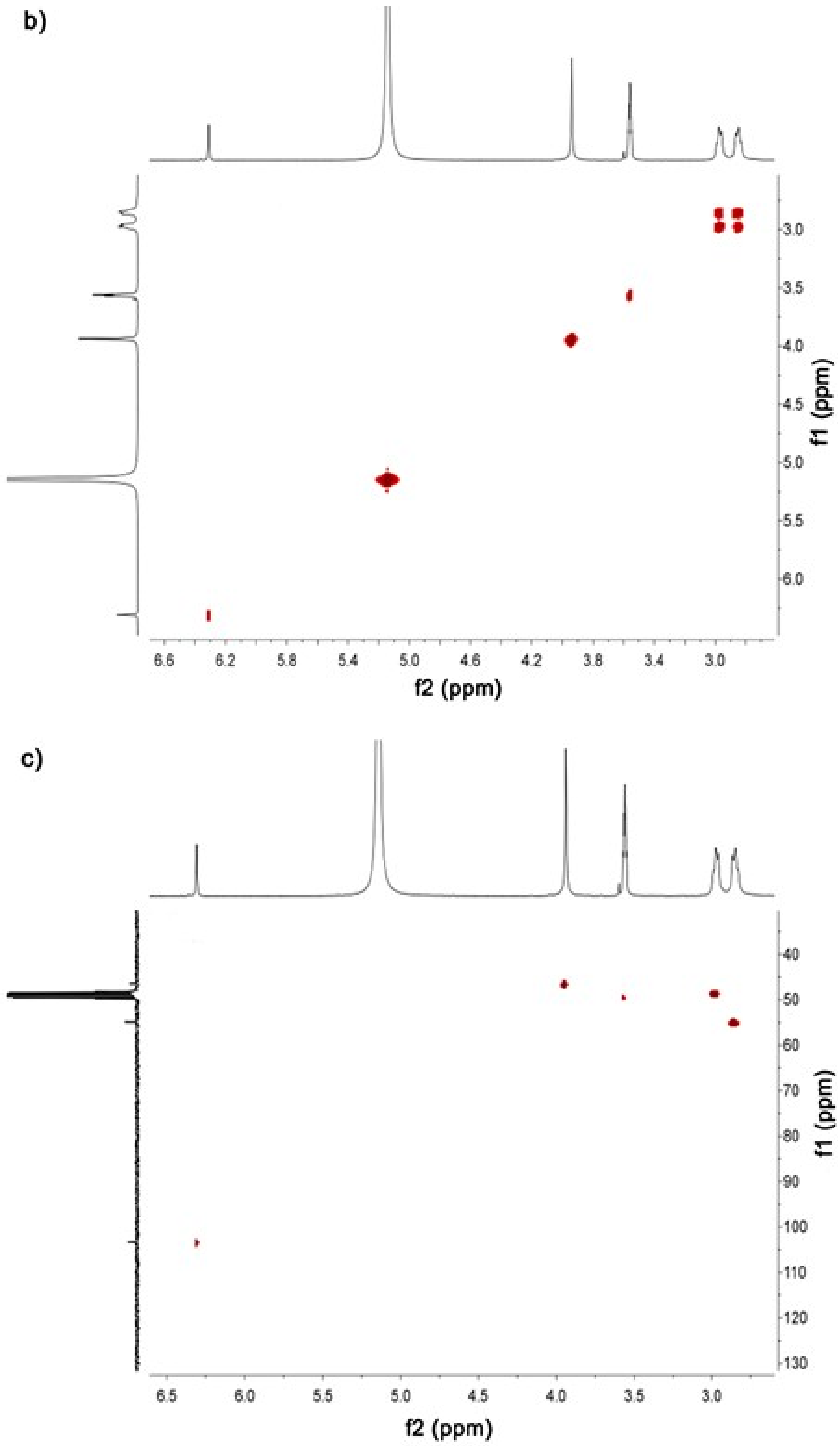


**Figure S4.** a) $^{1}$H NMR (400 MHz, $CD_3OD$) spectrum of **1**. b) Cosy spectrum of **1** and c) HSQC spectrum of **1**.

**Chloride tritation $^{1}$H NMR experiments.**

The study was done adding Cl$^{-}$ amounts added to a solution of **1**. The spectra recorded are shown in figure S6. The pH and concentration of **1** were kept constant during the titration.

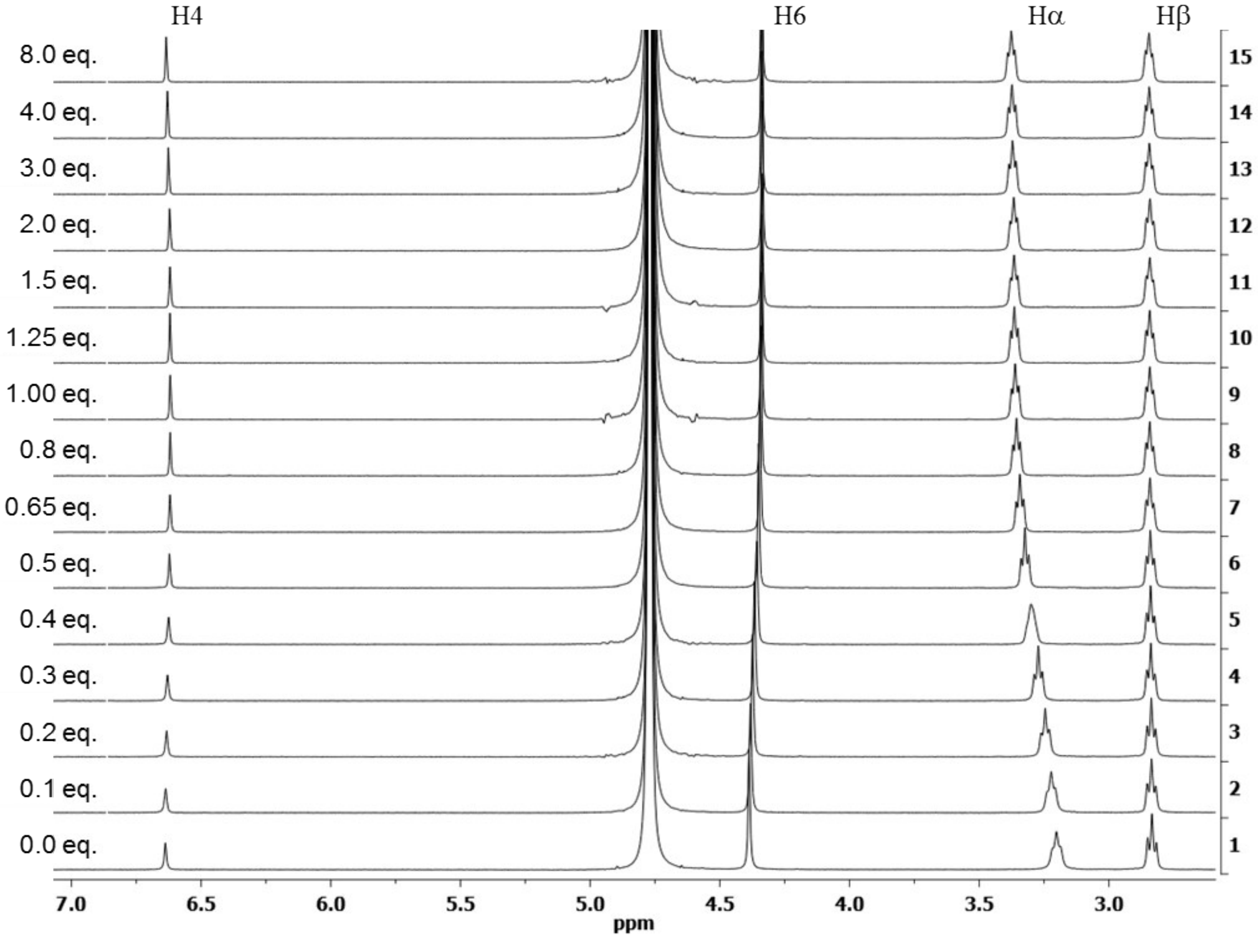


**Figure S5.** $^{1}$H NMR titration of **1** with Cl$^{-}$ in D$_2$O at pH=2. Numbers at the left side indicate the equivalent amounts of Cl$^{-}$ added.

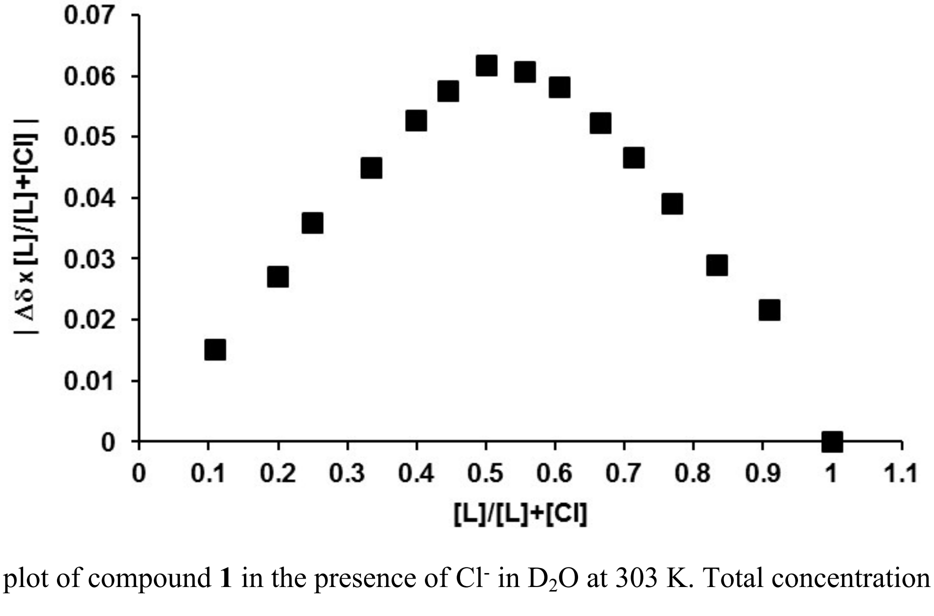


**Figure S6.** Job plot of compound **1** in the presence of Cl$^{-}$ in D$_2$O at 303 K. Total concentration [**1**+Cl] = 5 mM. (■ = Hα)

**Fluoride tritation: $^{19}$F NMR experiments.**

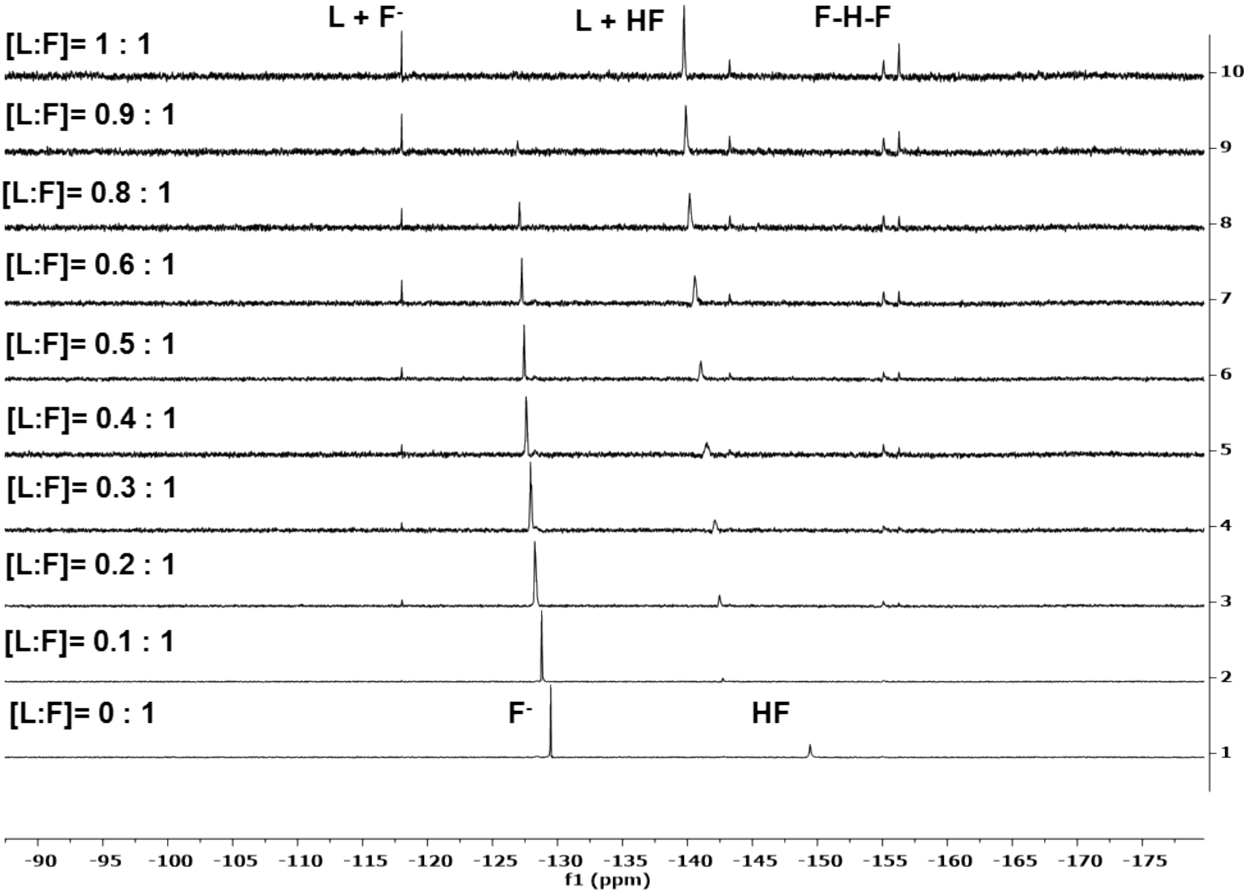


**Figure S7**. $^{19}$F NMR titration of **1** in the presence of $F^-$ in $D_2O$ at pH=2. Numbers at the left side indicate the **1**:$F^-$ molar ratios.

### $^{19}$F NMR titration of complex [1:F]=[1:1] with Cl$^-$.

The study was done adding amounts of concentrated Cl$^-$ solution to a solution that contains the complex **[1:F$^-$]** in 1:1 molar ratio in $D_2O$ at pH 2. Concentration of **1** and F$^-$ and pH were maintained during the study.

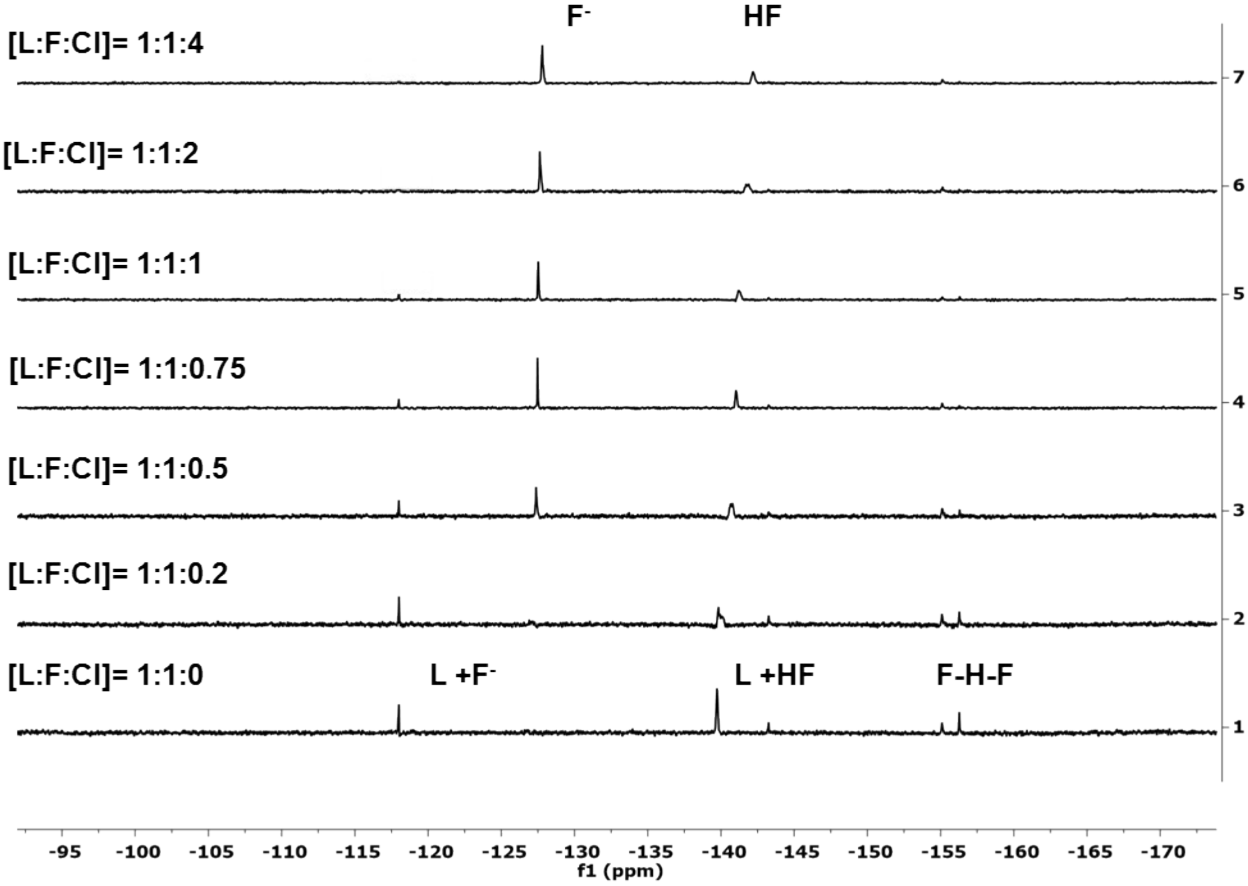


**Figure S8**. $^{19}$F NMR titration of the complex [**1**:F] (in 1:1 molar ratio) in the presence of Cl$^-$ in $D_2O$ at pH=2. Numbers at the left side indicate the **1**:F:Cl$^-$ molar ratios.

## MALDI-TOF spectrometry

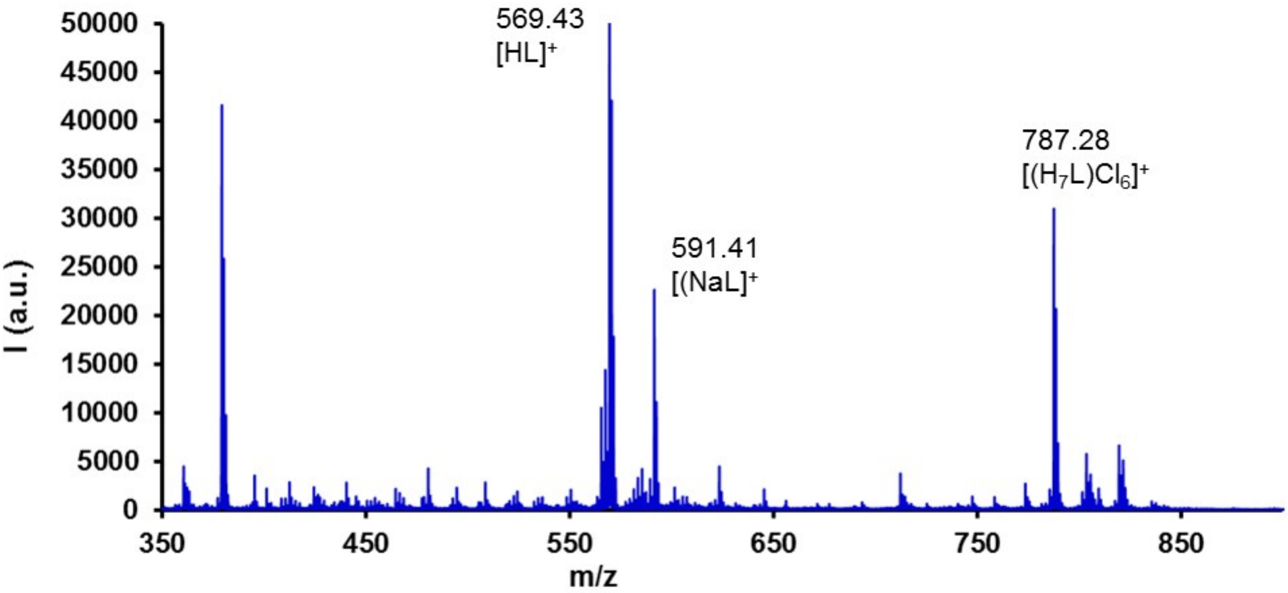


**Figure S9.** MALDI-TOF spectrum of aqueous solution of **4** at pH =2.

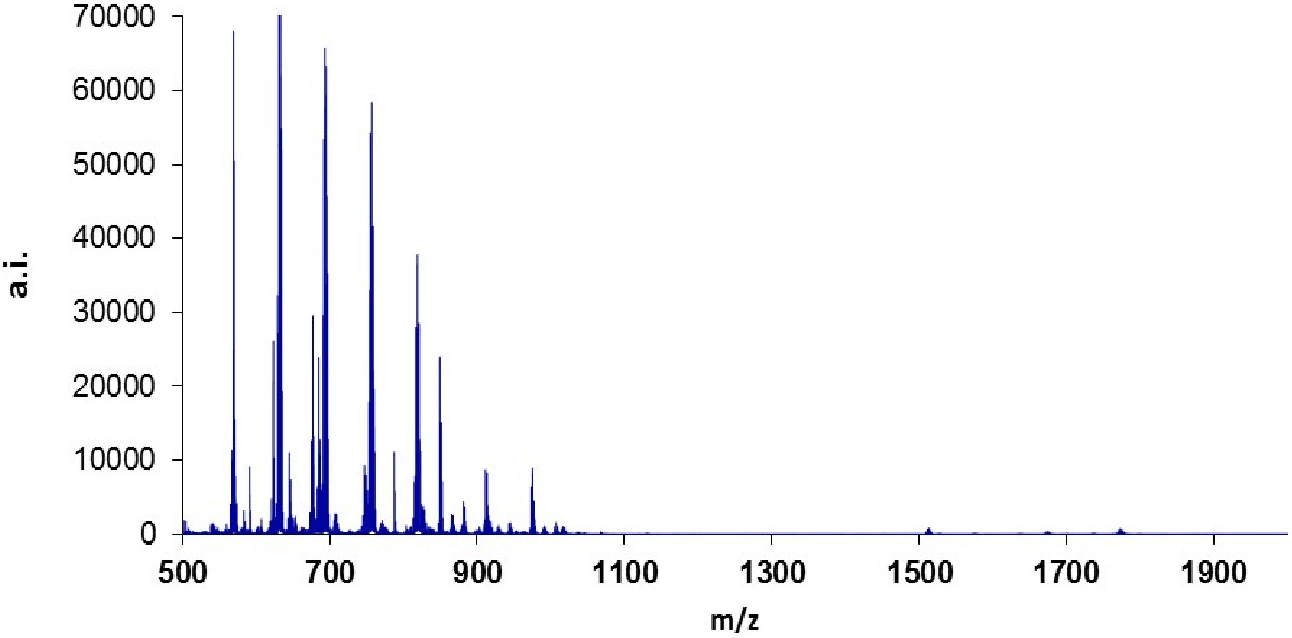


**Figure S10.** MALDI-TOF spectrum of aqueous solution of **5** at pH =1.5.

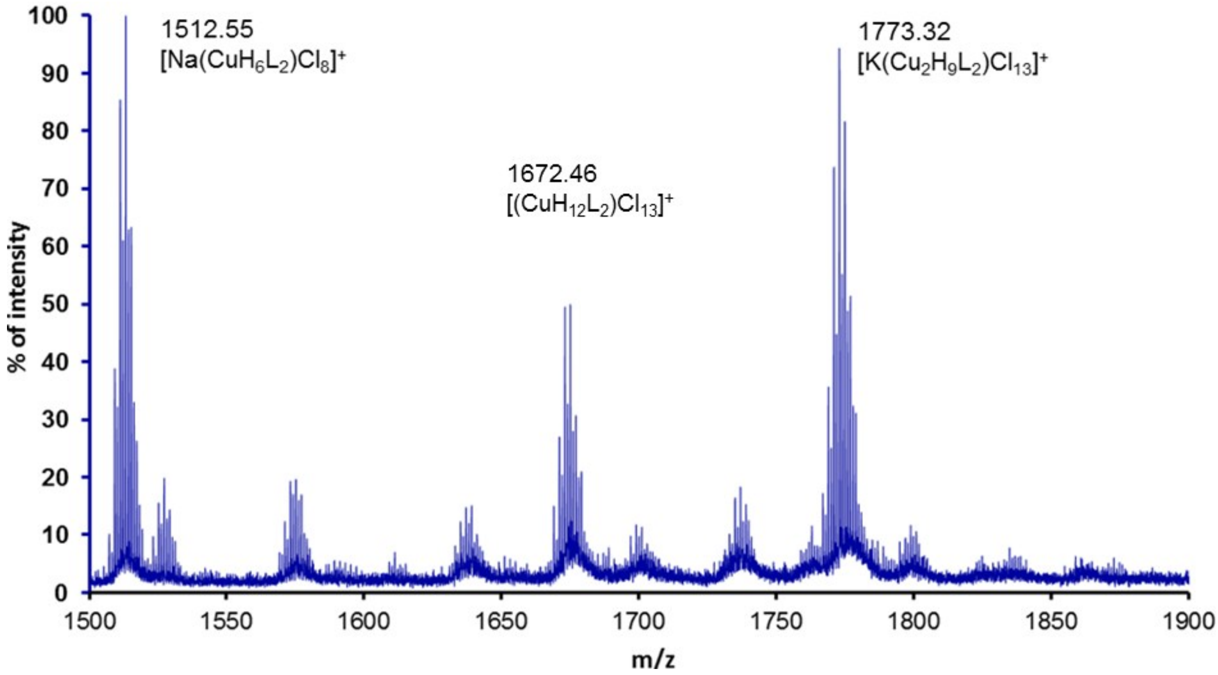


**Figure S11.** MALDI-TOF spectrum of **5** in the m/z = 1500 – 1850 range.

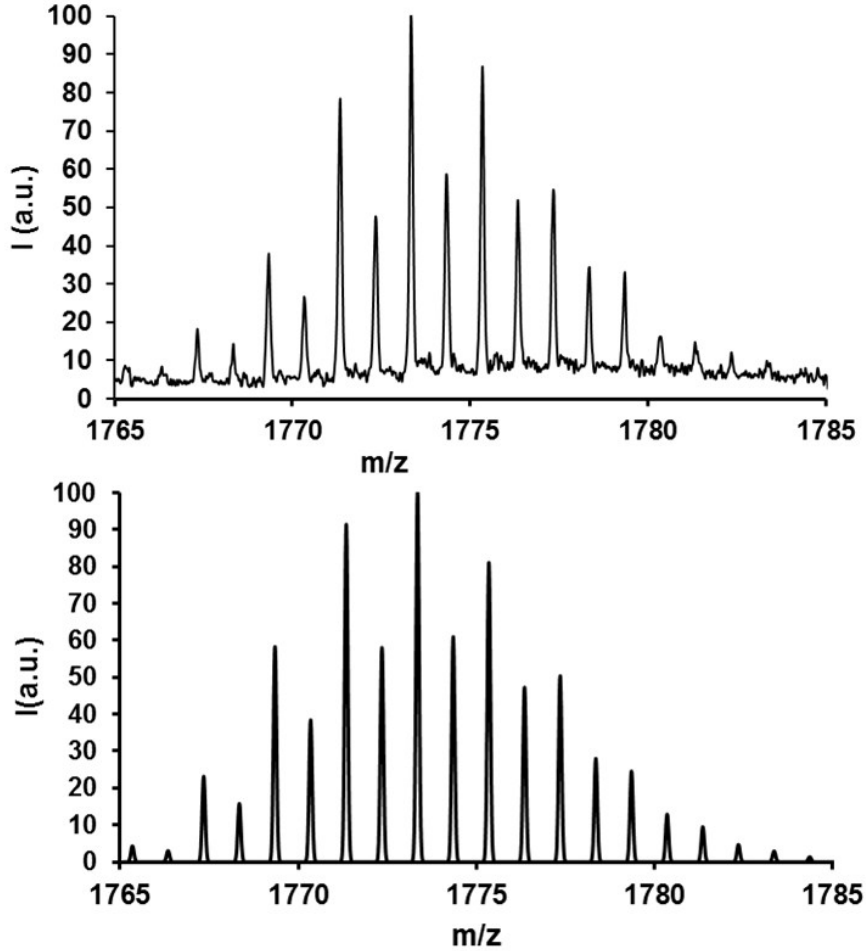


**Figure S12.** Simulated (top) and experimental (bottom) MALDI-TOF spectrum of peaks for $[K(Cu_2H_9L_2)Cl_{13}]^+$.

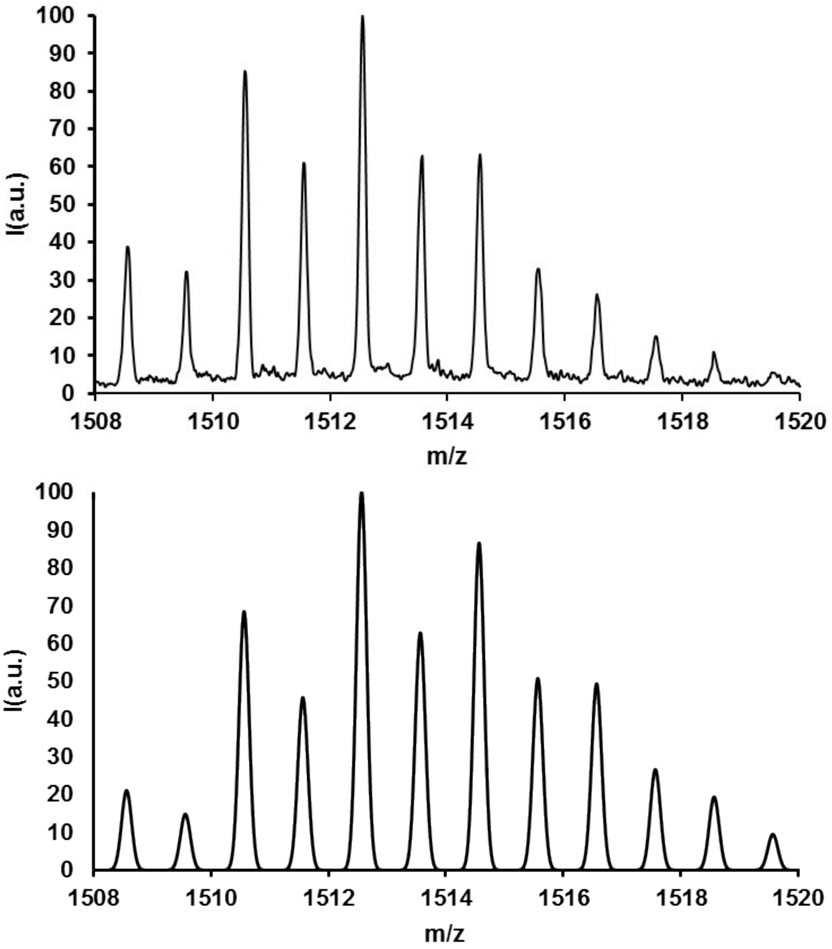


**Figure S13.** Simulated (top) and experimental (bottom) MALDI-TOF spectrum of peaks for $[Na(Cu_2H_6L_2)Cl_8]^+$.

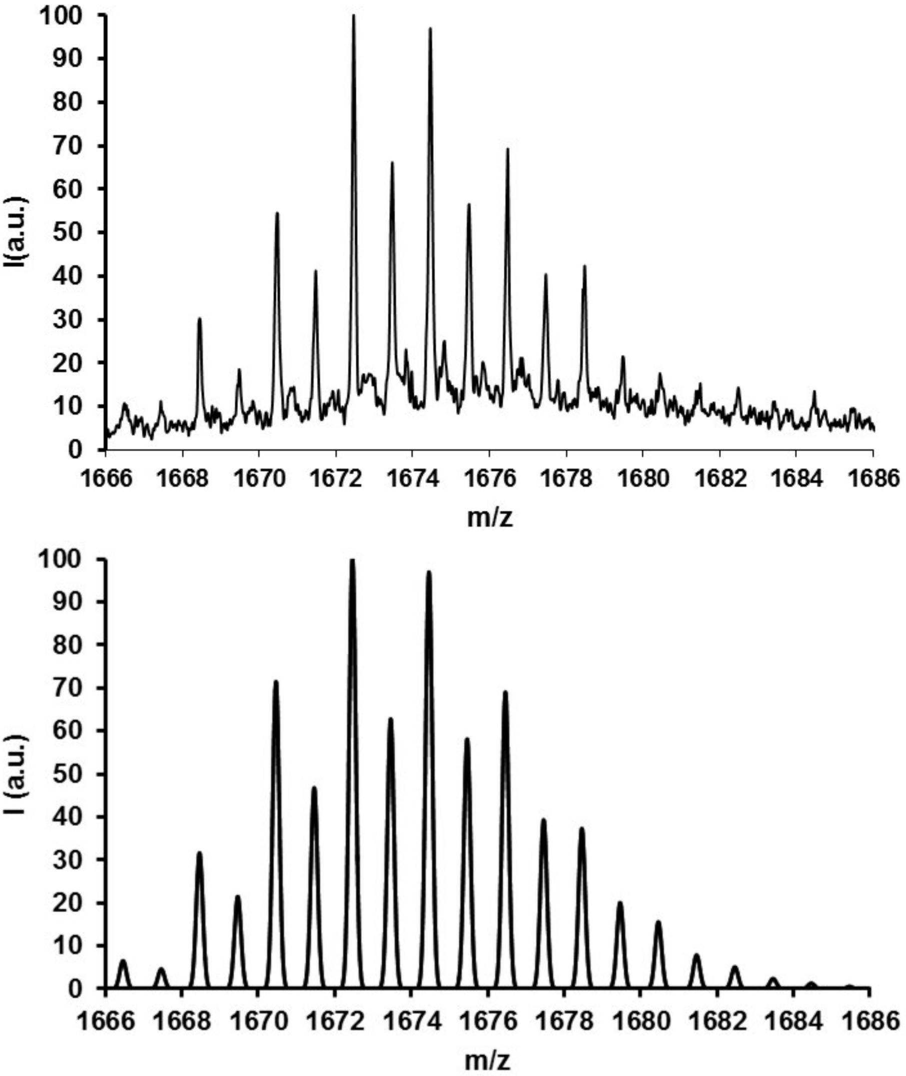


**Figure S14.** Simulated (top) and experimental (bottom) MALDI-TOF spectrum of peaks for $[(Cu_2H_{12}L_2)Cl_{13}]^+$.

## Infrared Spectra.

Infrared spectra of solids were recorded in the region 400 - 4000 cm$^{-1}$ on a Nicolet NICOLET 5700 Fourier-Transform Infrared Spectrophotometer using KBr pellets.

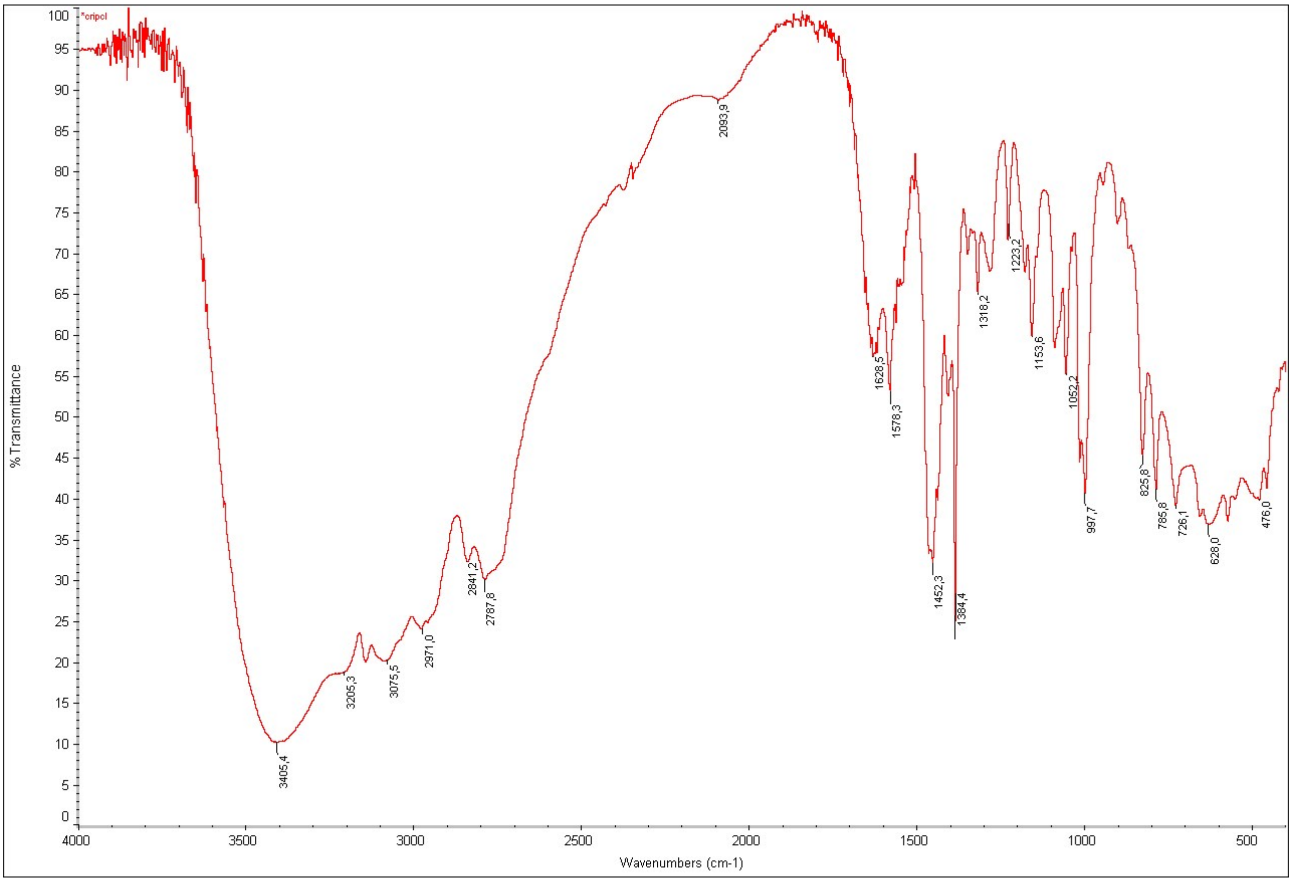


**Figure S15**. IR spectrum of **4** in KBr.

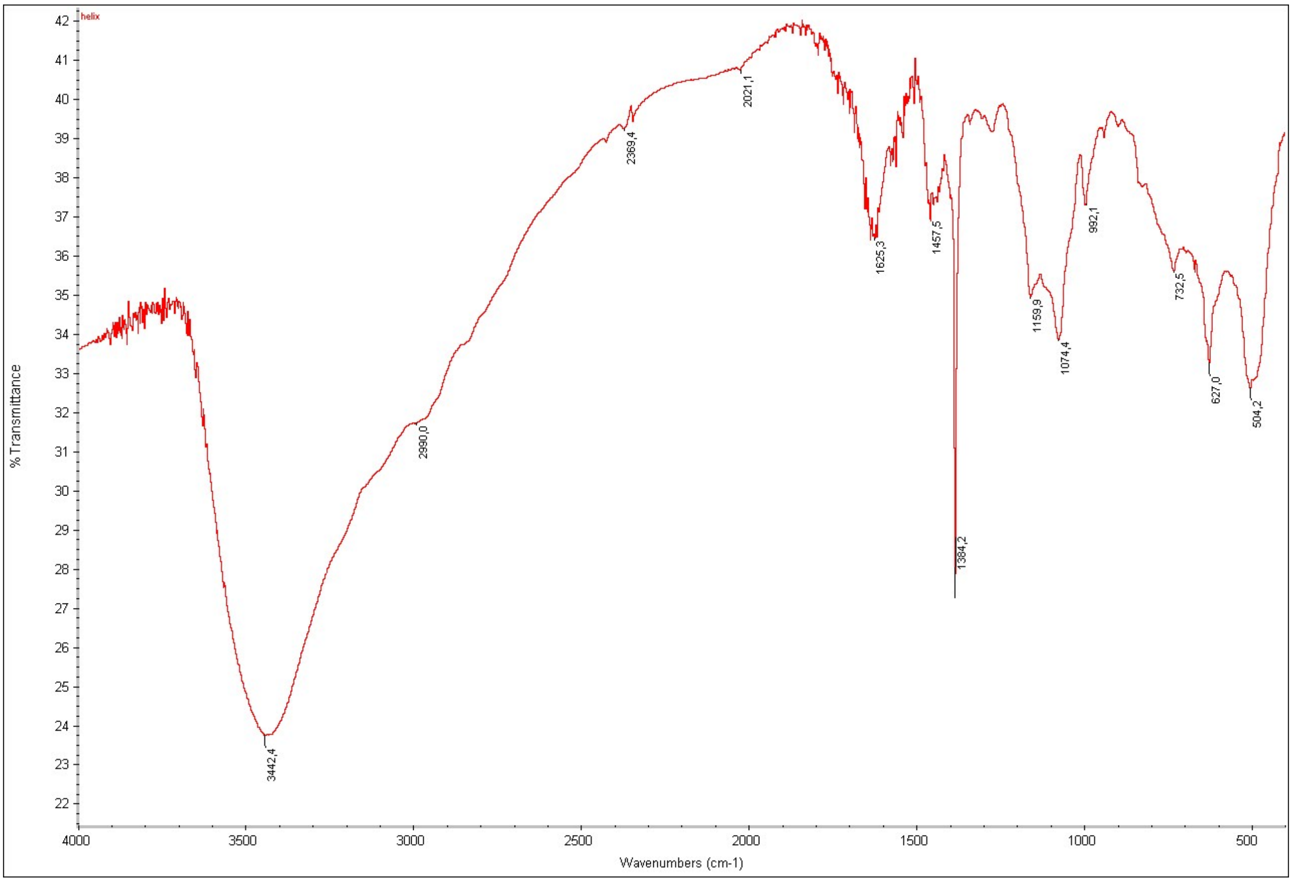


**Figure S16**. IR spectrum of **5** in KBr.

## Thermal decomposition (TG) analysis.

Thermal decomposition (TG) analysis was obtained by a model (TG-DTA) Pyris Diamond, PerkinElmer. The experiment was performed in air atmosphere at a heating rate of 5˚C $min^{-1}$ in the temperature range 30˚C - 800˚C.

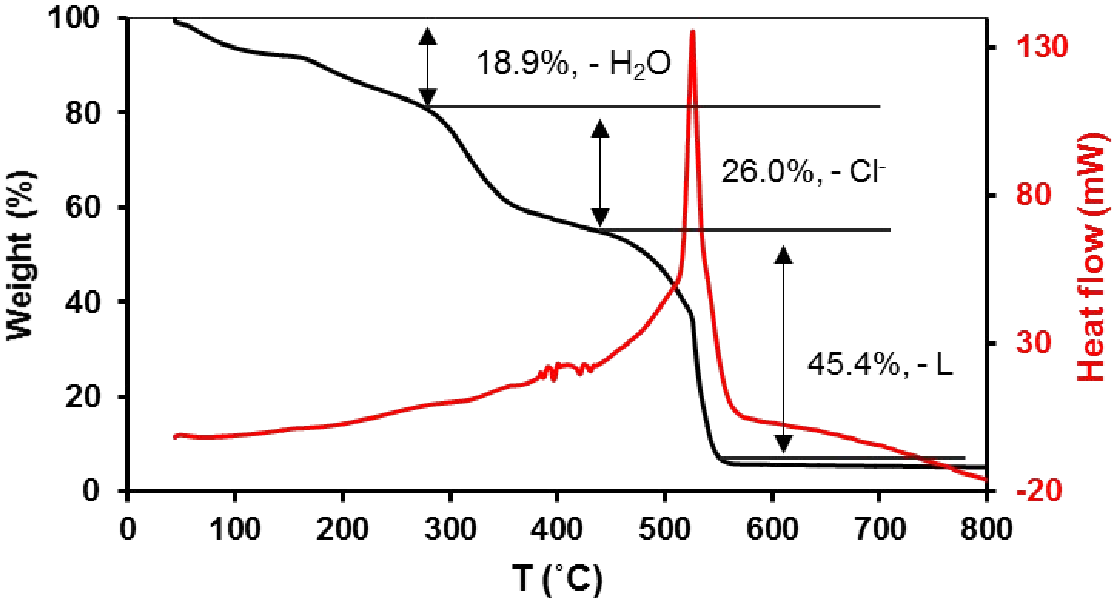


**Figure S17.** Thermogravimetric analysis (TGA) (black) and Differential thermal analysis (DTA) (red) of **5**.

# References

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