

Electronic Supplementary Information

Synthesis and Structural Studies of Copper(II) Complex With N₂S₂ Based *N*-Substituted Pendant Phosphonic Acid Arms

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Procedures:

((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonic acid) (N₂S₂-POH). A nitrogen flushed pressure vessel equipped with a magnetic stir bar was charged with 1,8-dithia-4,11-diazacyclotetradecane (0.100 g, 0.427 mmol), phosphonic acid (0.110 g, 1.28 mmol), 37% formaldehyde (0.10 mL, 1.28 mmol), water (1 mL) and 12 M HCl (0.11 mL, 1.28 mmol). The pressure flask was then submersed into an oil bath at 120 °C for 1 h and the solution was cooled to room temperature. An additional 37% formaldehyde (0.10 mL, 1.28 mmol) was added and the pressure vessel was again submersed in an oil bath at 120 °C for an additional 1 h. The reaction was cooled to room temperature, solvent removed *in vacuo*, and the residue loaded onto Dowex ion exchange resin 50W-X12 (H⁺ form) and flushed with water, 0.5 M HCl, 1 M HCl, and the desired compound was eluted off with 2 M HCl. The 2 M HCl fractions were concentrated *in vacuo* to afford ((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonic acid) as a white residue in 38% yield (0.804 g, 0.162 mmol). ¹H NMR (400 MHz, Deuterium Oxide, 25 °C) δ 3.48 (bs, 4H), 3.37 (bt, *J* = 7.9 Hz, 4H), 3.27 (d, *J* = 12.7 Hz, 4H), 2.86 (t, *J* = 7.8 Hz, 4H), 2.60 (bs, 4H), 1.94 (bp, *J* = 7.9 Hz, 4H). ¹³C NMR (101 MHz, Deuterium Oxide, 25 °C) δ 52.18, 52.14, 52.01, 51.97, 50.64, 26.82, 22.83, 22.43. ¹H NMR (400 MHz, Deuterium Oxide, 65 °C) δ 3.95 (t, *J* = 7.5 Hz, 1H), 3.86 (t, *J* = 7.9 Hz, 1H), 3.71 (d, *J* = 12.6 Hz, 1H), 3.36 (t, *J* = 7.4 Hz, 1H), 3.11 (t, *J* = 7.1 Hz, 1H), 2.44 (p, *J* = 6.8, 6.3 Hz, 1H). ¹³C NMR (101 MHz, Deuterium Oxide, 65 °C) δ 53.49, 53.37, 51.64, 28.13, 24.57, 23.37. IR ν_{\max} 3363, 2496, 2367, 2296, 1646, 1456, 1211 cm⁻¹. HRMS (ESI) *m/z* [M-H] calcd for C₁₂H₂₇O₆N₂P₂S₂ 421.0791, found 421.0785.

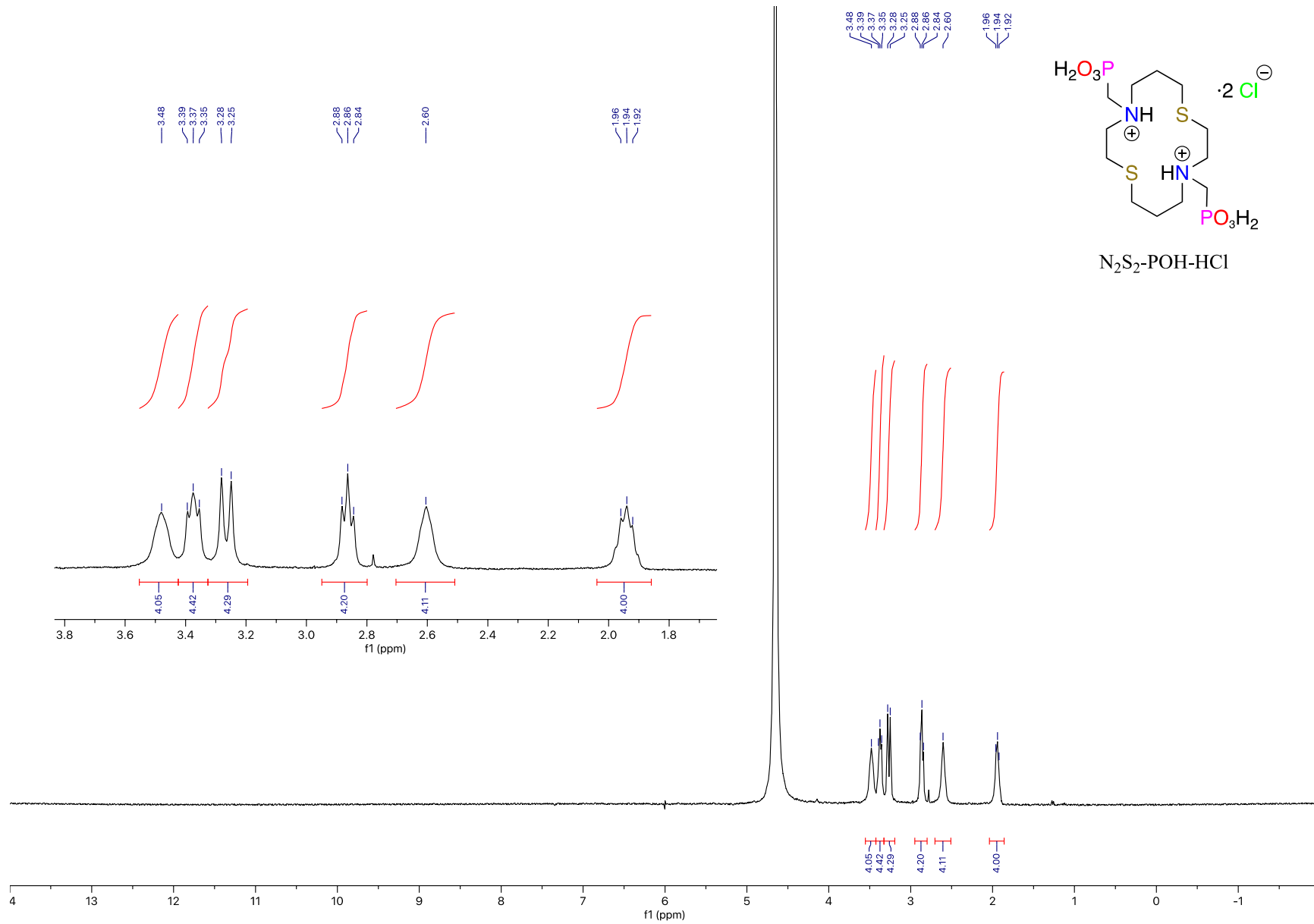
tetraethyl((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonate) (N₂S₂-POEt). A 10 mL flame dried round bottom flask equipped with a magnetic stir bar, rubber septum and nitrogen inlet was charged with 1,8-dithia-4,11-diazacyclotetradecane (0.100 g, 0.427 mmol), THF (degassed, 1.4 mL), paraformaldehyde (2.5 equiv., 0.033 g) and triethyl phosphite (0.18 mL, 1.02 mmol). The solution was stirred at 23 °C for 4 days then concentrated *in vacuo*. The crude residue was basified to pH ~ 12 with 6 M NaOH and extracted with CHCl₃ (5 x 10 mL). The combined organic layers were dried with sodium sulfate, filtered, concentrated *in vacuo* and subjected to column chromatography (EtOAc → EtOAc:10 % MeOH) to afford tetraethyl((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonate) in a 72% yield (165 mg, 0.307 mmol) as a clear oil. *R_f* = 0.1, EtOAc. ¹H NMR (400 MHz, Chloroform-d) δ 4.15 – 3.97 (m, 8H), 2.83 (d, *J* = 9.8 Hz, 4H), 2.73 (td, *J* = 6.6, 4.3 Hz, 8H), 2.67 – 2.45 (m, 8H), 1.72 (p, *J* = 6.7 Hz, 4H), 1.26 (t, *J* = 7.1 Hz, 12H). ¹³C NMR (101 MHz, Chloroform-d) δ 61.85, 61.78, 53.92, 53.83, 53.64, 53.59, 51.34, 49.76, 28.99, 28.80, 27.32, 16.54, 16.48. IR ν_{\max} 3446, 3274, 2979, 2926, 2911, 2810, 1651, 1443, 1391, 1224, 1020, 959 cm⁻¹. HRMS (ESI) *m/z* [M+H] calcd for C₂₀H₄₅O₆N₂P₂S₂ 535.2189, found 535.2189. HRMS (ESI) *m/z* [M+Na] calcd for C₂₀H₄₄O₆N₂NaP₂S₂ 557.2008, found 557.2008.

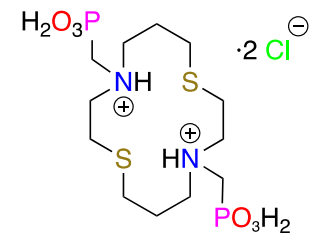
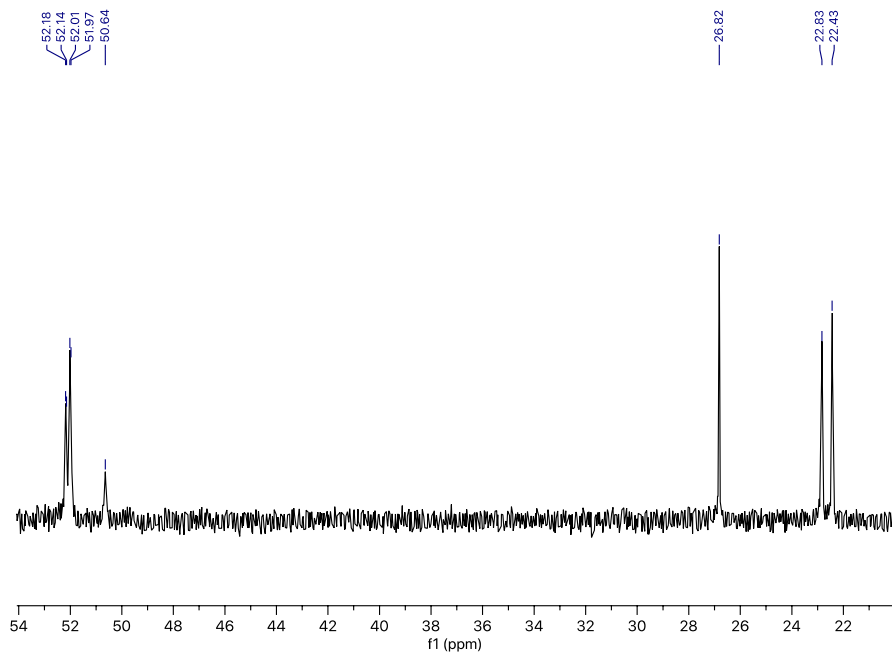
Triethyl ammonium ((11-((hydroxyoxidophosphoryl)methyl)-1,8-dithia-4,11-diammoniocyclotetradeca-4,11-dium-4-yl)methyl)phosphonate (N₂S₂-PON). A nitrogen flushed pressure vessel equipped with a magnetic stir bar was charged with 1,8-dithia-4,11-diazacyclotetradecane (0.100 g, 0.427 mmol), phosphonic acid (0.110 g, 1.28 mmol), 37% formaldehyde (0.10 mL, 1.28 mmol), water (1 mL) and 12 M HCl (0.11 mL, 1.28 mmol). The pressure flask was then submersed into an oil bath at 120 °C for 1 h and the solution was cooled to room temperature. An additional 37% formaldehyde (0.10 mL, 1.28 mmol) was added and the pressure vessel was again submersed in an oil bath at 120 °C for an additional 1 h. The reaction was cooled to room temperature, solvent removed in vacuo, and the residue loaded onto Dowex ion exchange resin 50W-X12 (H⁺ form) and flushed with two column lengths of water, 0.5 M HCl, and three column lengths 2 M HCl. The 2 M HCl fractions were concentrated in vacuo to afford ((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonic acid) as a white residue in 62% yield (0.131 g, 0.265 mmol). The product was dissolved in 2 M NEt₃ (2 mL) and precipitated out as the mono-ammonium salt with methanol (~2 mL). ¹H NMR (400 MHz, Deuterium Oxide) δ 3.48 (t, *J* = 7.8 Hz, 4H), 3.37 (t, *J* = 7.8 Hz, 4H), 3.06 (q, *J* = 7.4 Hz, 6H), 3.03 (s, 4H), 2.87 (t, *J* = 7.7 Hz, 4H), 2.62 (t, *J* = 7.3 Hz, 4H), 1.96 (p, *J* = 6.8, 6.4 Hz, 4H), 1.14 (t, *J* = 7.3 Hz, 9H). ¹³C NMR (101 MHz, Deuterium Oxide) δ 52.92 (d, *J* = 126.5 Hz), 52.14 (d, *J* = 3.8 Hz), 51.98 (d, *J* = 3.8 Hz), 46.58, 26.96, 23.14, 22.62, 8.16. IR ν_{max} 3342, 2501, 1644, 1455, 607, 580, 569 cm⁻¹. HRMS (ESI) *m/z* [M]⁻ calcd for C₁₂H₂₇O₆N₂P₂S₂ 421.0791, found 421.0785.

Dicesium((11-((hydroxyoxidophosphoryl)methyl)-1,8-dithia-4,11-diammoniocyclotetradeca-4,11-dium-4-yl)methyl)phosphonate (N₂S₂-POCs). A nitrogen flushed pressure vessel equipped with a magnetic stir bar was charged with 1,8-dithia-4,11-diazacyclotetradecane (0.100 g, 0.427 mmol), phosphonic acid (0.110 g, 1.28 mmol), 37% formaldehyde (0.10 mL, 1.28 mmol), water (1 mL) and 12 M HCl (0.11 mL, 1.28 mmol). The pressure flask was then submersed into an oil bath at 120 °C for 1 h and the solution was cooled to room temperature. An additional 37% formaldehyde (0.10 mL, 1.28 mmol) was added and the pressure vessel was again submersed in an oil bath at 120 °C for an additional 1 h. The reaction was cooled to room temperature, solvent removed in vacuo, and the residue loaded onto Dowex ion exchange resin 50W-X12 (H⁺ form) and flushed with two column lengths of water, 0.5 M HCl, and three column lengths 2 M HCl. The 2 M HCl fractions were concentrated in vacuo to afford ((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonic acid) as a white residue in 62% yield (0.131 g, 0.265 mmol). The product was dissolved in 2 M Cs₂CO₃ (2 mL) and precipitated out as the dicesium salt with methanol (~2 mL). ¹H NMR (400 MHz, Deuterium Oxide) δ 2.95 (t, *J* = 8.6 Hz, 4H), 2.84 (t, *J* = 7.9 Hz, 4H), 2.67 (t, *J* = 11.3 Hz, 4H), 2.62 (d, *J* = 11.7 Hz, 4H), 2.47 (t, *J* = 7.8 Hz, 4H), 1.81 – 1.66 (m, 4H). ¹³C NMR (101 MHz, Deuterium Oxide) δ 53.63 (d, *J* = 132.6 Hz), 51.81 (d, *J* = 3.6 Hz), 51.75 (d, *J* = 3.5 Hz), 27.38, 24.12, 24.00. IR ν_{max} 3201, 2941, 2588, 2281, 1620, 1311, 1368, 1233, 1171, 1121, 1100, 1025, 1002, 970, 916, cm⁻¹. HRMS (ESI) *m/z* [M-H]⁻ calcd for C₁₂H₂₇O₆N₂P₂S₂ 421.0791, found 421.0784.

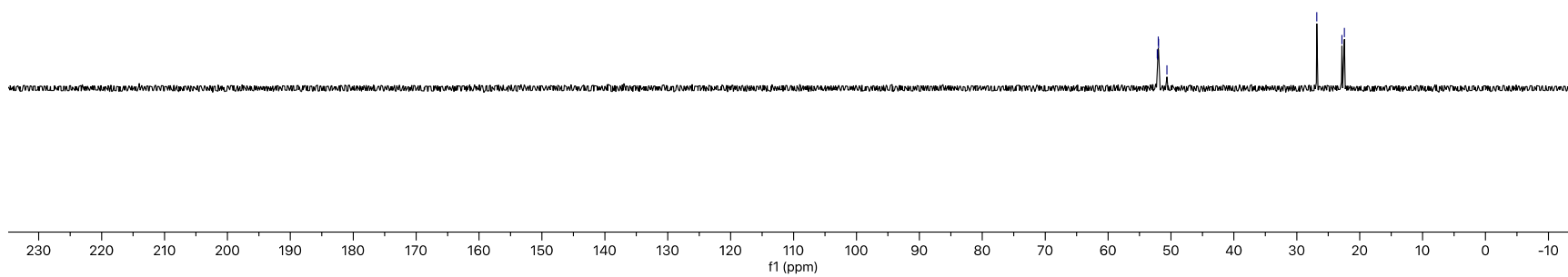
Dipotassium((11-((hydroxyoxidophosphoryl)methyl)-1,8-dithia-4,11-diammoniocyclotetradeca-4,11-diium-4-yl)methyl)phosphonate (N₂S₂-POK). A nitrogen flushed pressure vessel equipped with a magnetic stir bar was charged with 1,8-dithia-4,11-diazacyclotetradecane (0.100 g, 0.427 mmol), phosphonic acid (0.110 g, 1.28 mmol), 37% formaldehyde (0.10 mL, 1.28 mmol), water (1 mL) and 12 M HCl (0.11 mL, 1.28 mmol). The pressure flask was then submersed into an oil bath at 120 °C for 1 h and the solution was cooled to room temperature. An additional 37% formaldehyde (0.10 mL, 1.28 mmol) was added and the pressure vessel was again submersed in an oil bath at 120 °C for an additional 1 h. The reaction was cooled to room temperature, solvent removed in vacuo, and the residue loaded onto Dowex ion exchange resin 50W-X12 (H⁺ form) and flushed with two column lengths of water, 0.5 M HCl, and three column lengths 2 M HCl. The 2 M HCl fractions were concentrated in vacuo to afford ((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis(phosphonic acid) as a white residue in 62% yield (0.131 g, 0.265 mmol). The product was dissolved in 2 M K₂CO₃ (2 mL) and precipitated out as the dipotassium salt with ethanol (~2 mL). ¹H NMR (400 MHz, Deuterium Oxide) δ 3.45 (t, *J* = 7.6 Hz, 4H), 3.34 (t, *J* = 8.2, 7.5 Hz, 4H), 2.97 (d, *J* = 11.4 Hz, 4H), 2.87 (t, *J* = 7.8 Hz, 4H), 2.62 (t, *J* = 7.8 Hz, 4H), 1.95 (p, *J* = 7.8 Hz, 4H). ¹³C NMR (101 MHz, Deuterium Oxide) δ 53.36 (d, *J* = 125.3 Hz), 52.12 (d, *J* = 4.2 Hz), 51.93 (d, *J* = 4.2 Hz), 27.07, 23.37, 22.92. IR ν_{max} 3206, 2937, 2588, 2295, 1622, 1394, 1368, 1176, 1143, 1090, 1037, 1004, 970, 916, 829 cm⁻¹. HRMS (ESI) *m/z* [M+K]⁺ calcd for C₁₂H₂₈O₆N₂KP₂S₂ 461.0496, found 461.0495.

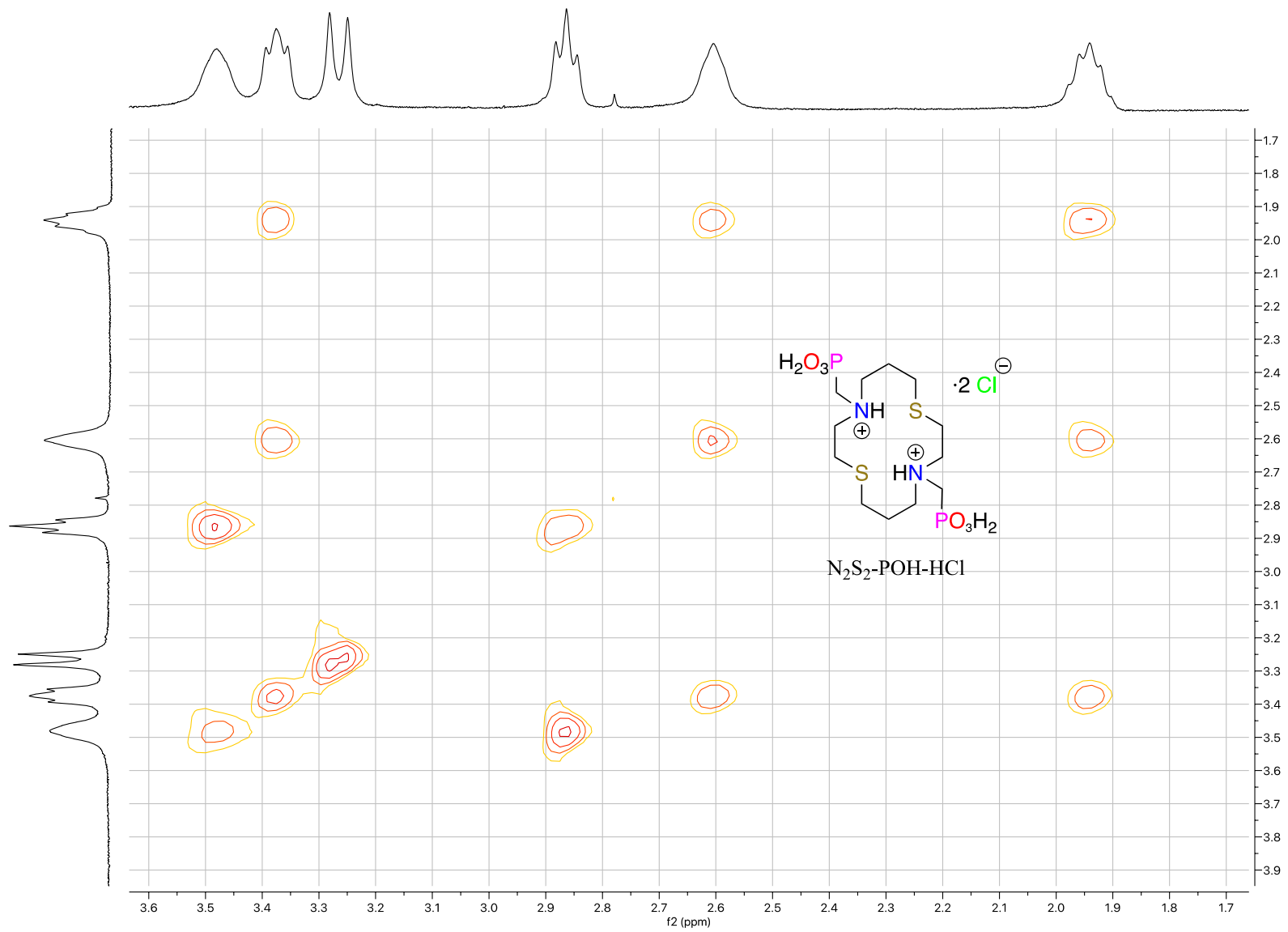
((1,8-dithia-4,11-diazacyclotetradecane-4,11-diyl)bis(methylene))bis-phosphonate copper(II) acetate (N₂S₂-POK-Cu). A 10 mL round bottom flask equipped with a magnetic stir bar, rubber septa and nitrogen inlet was charged with 1,8-dithia-4,11-diazacyclotetradecane (20.00 mg, 0.036 mmol) and acetonitrile (1 mL) and allowed to stir at room temperature for 5 min. After, a solution of copper(II) acetate·H₂O (7.19 mg, 0.036 mmol) in 18 MΩ water (1 mL) was added in one portion and the mixture was stirred at 23 °C for 5 min. Once copper(II) was added the solution turned bright green. The solution was then filtered through glass wool and concentrated in vacuo affording a green solid in quantitative yield (20.6 mg). IR ν_{max} 3396, 2920, 2858, 1654, 1562, 1541, 1415, 1069, 966 cm⁻¹. HRMS (ESI) *m/z* [M]⁺ calcd for C₁₂H₂₅O₆N₂CuK₂P₂S₂ 559.9194, found 559.9192.

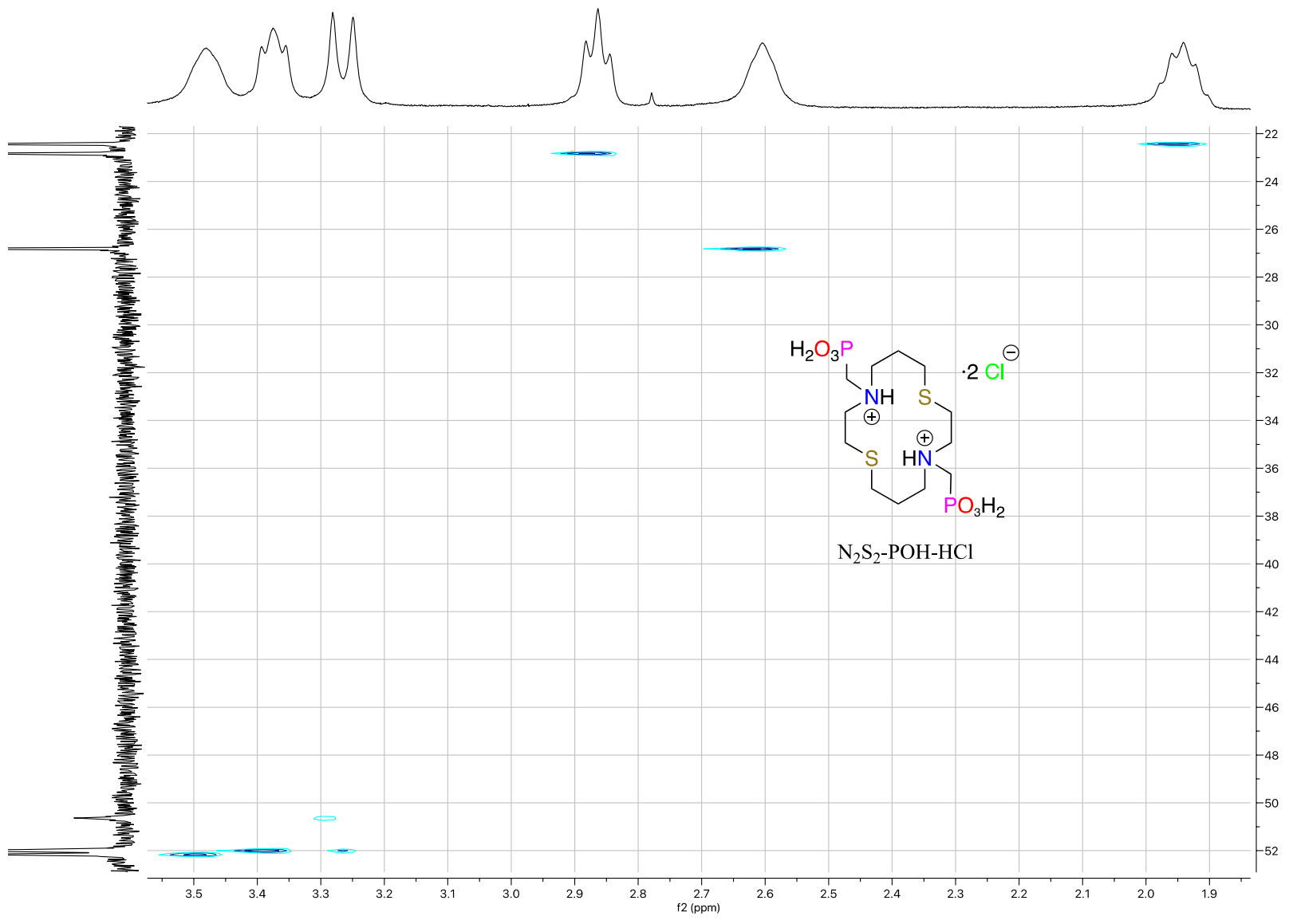


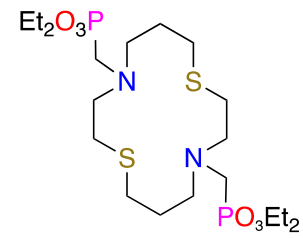


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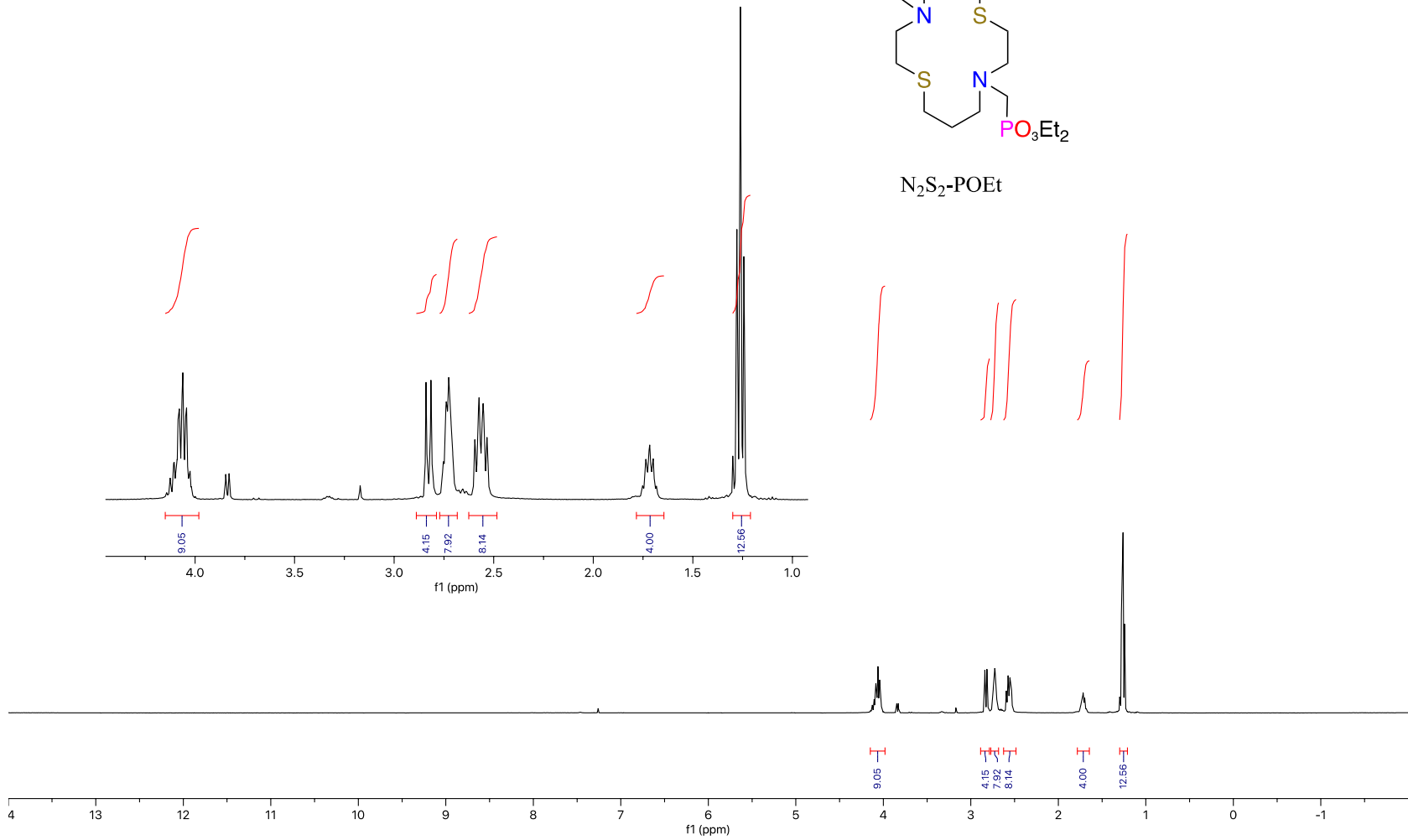




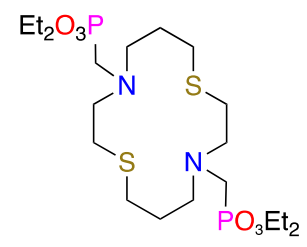




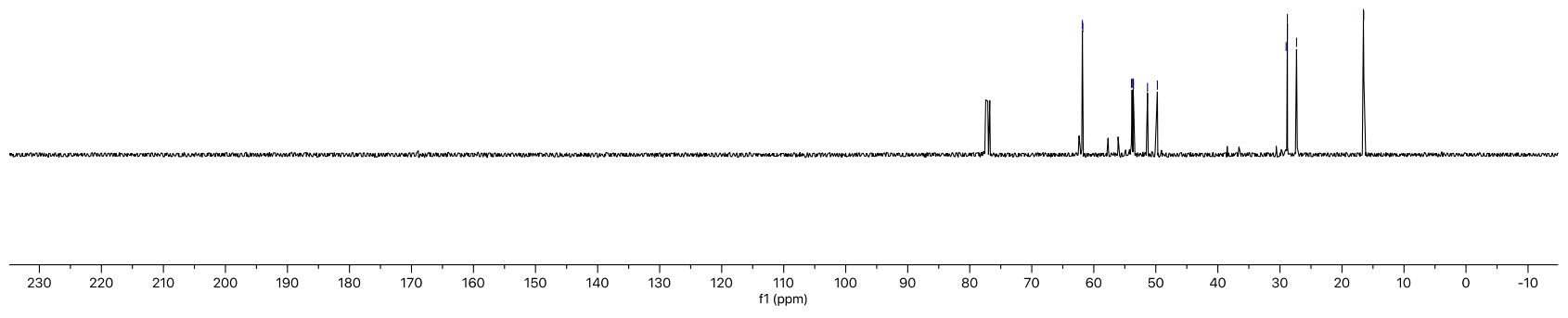
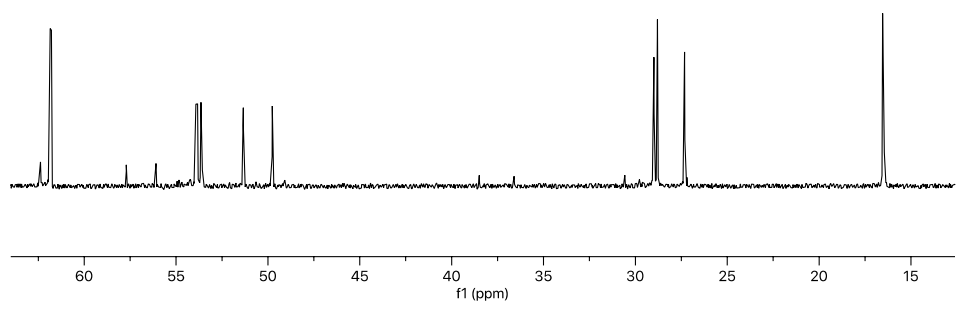
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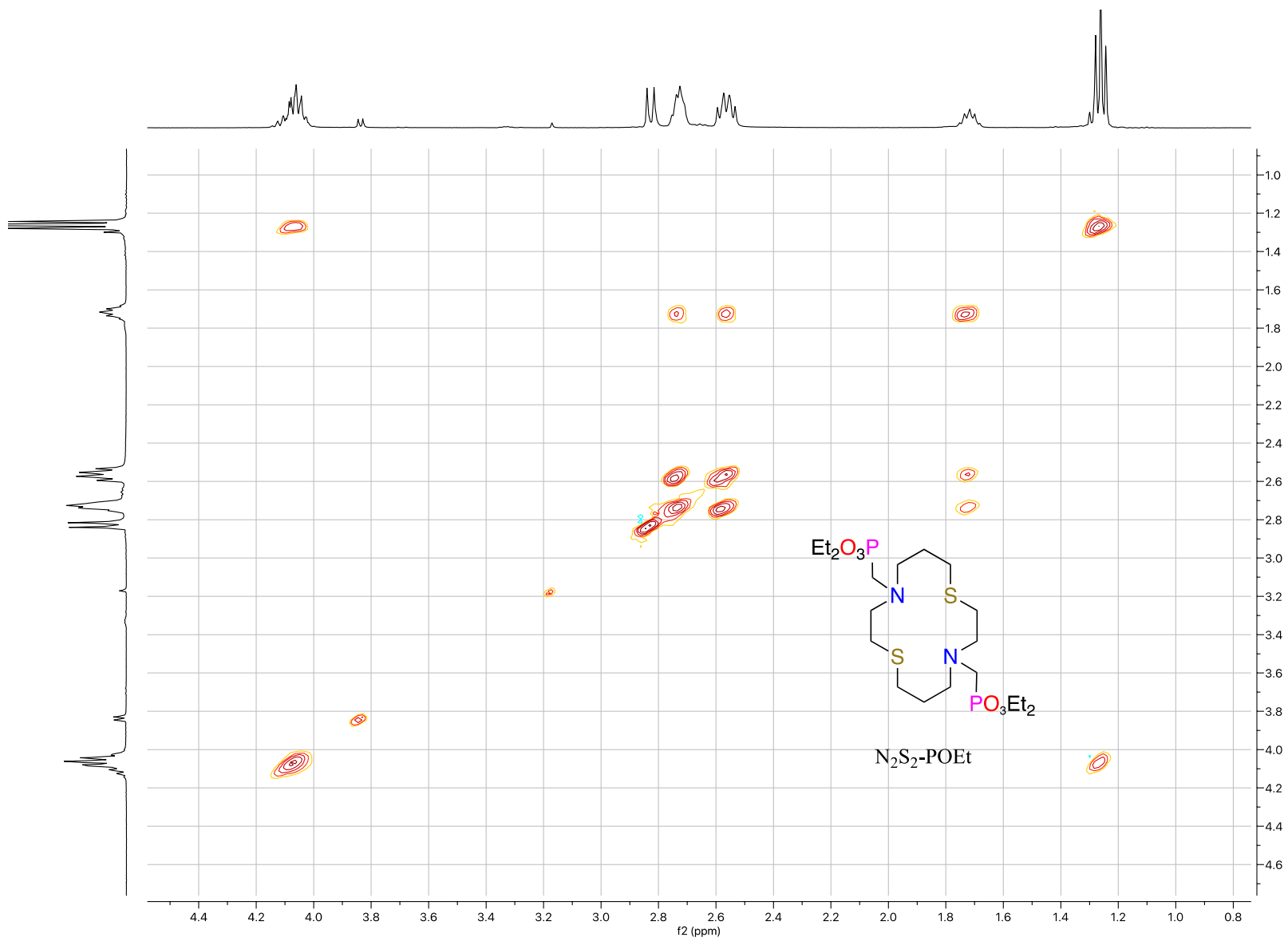


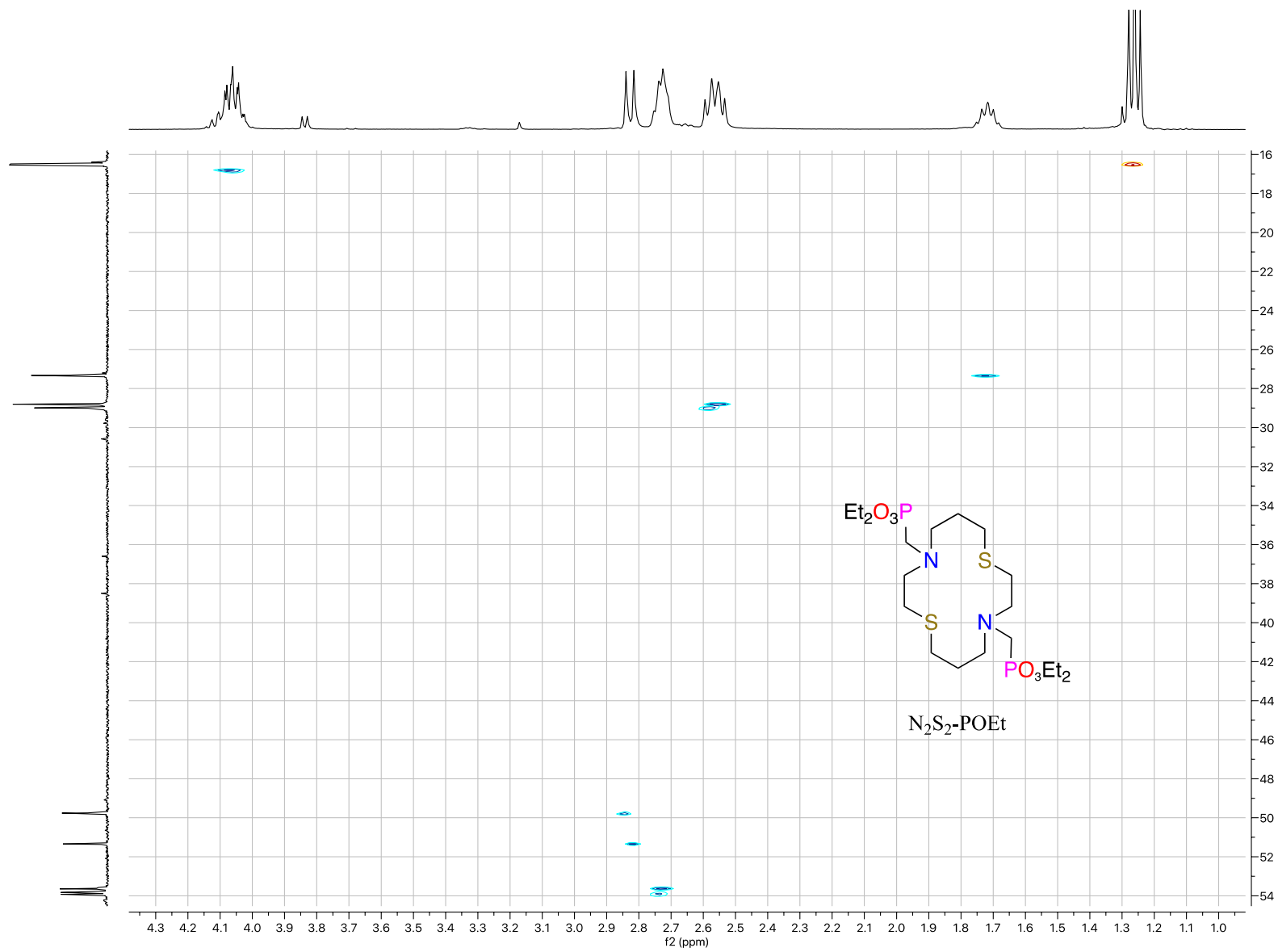
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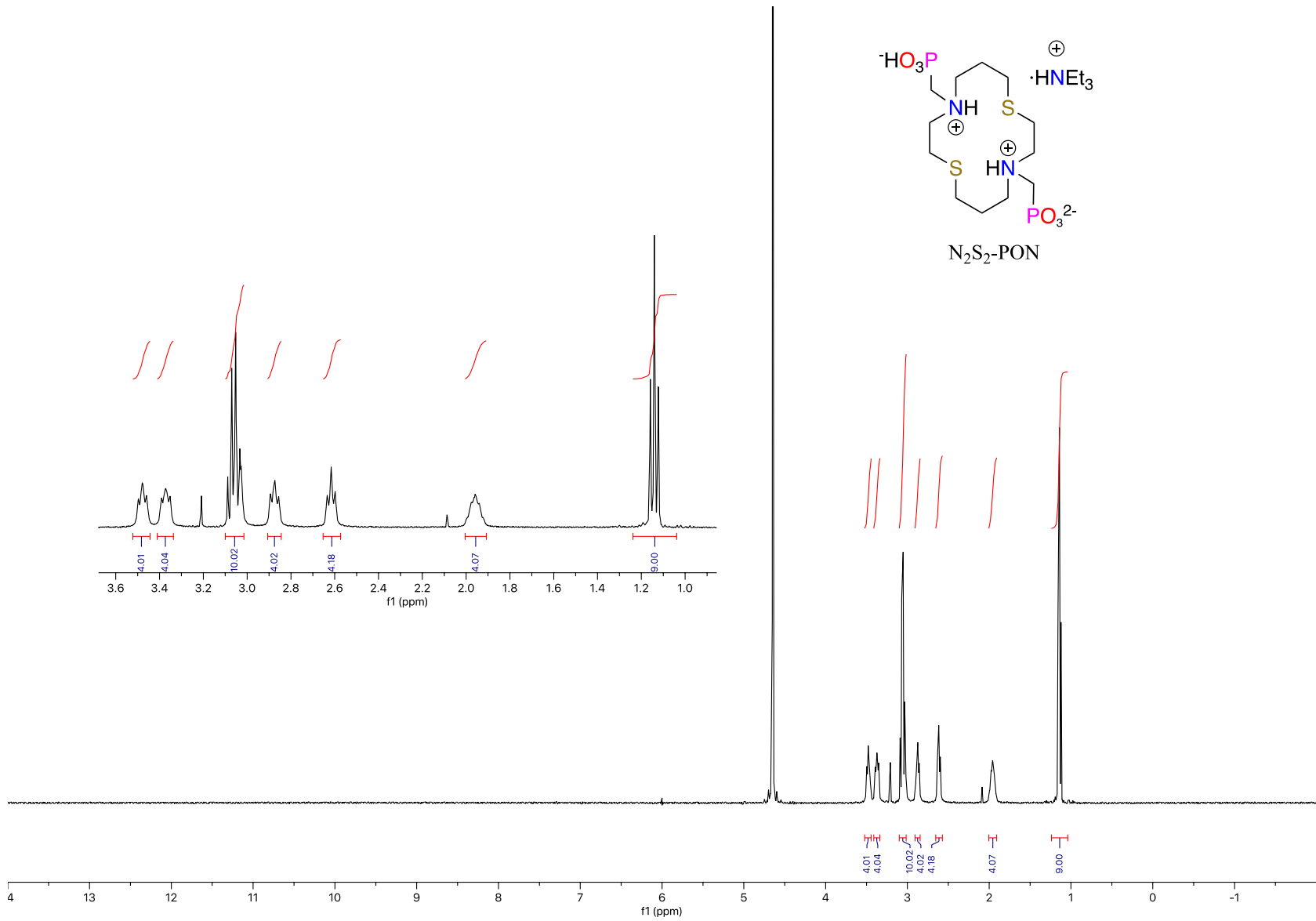


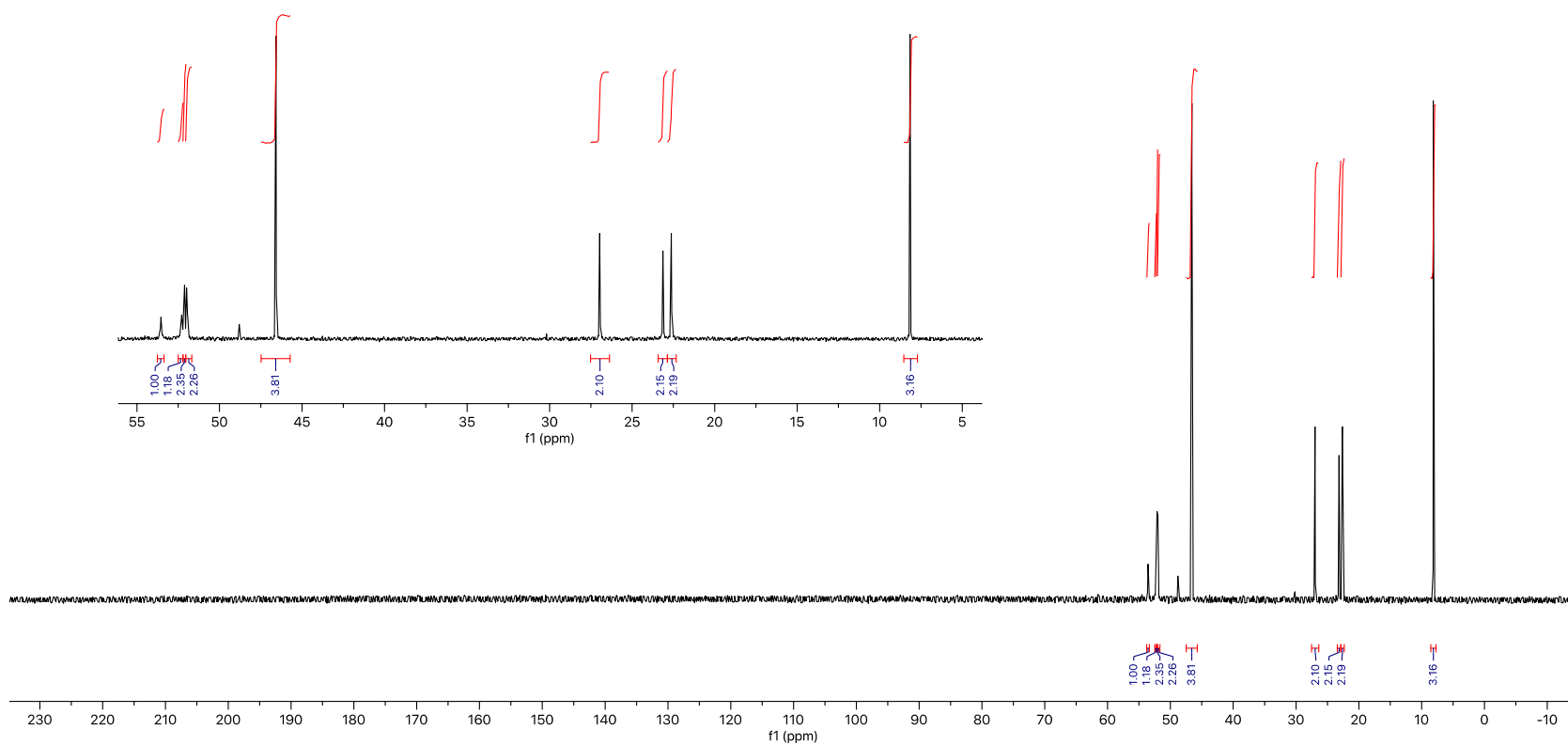
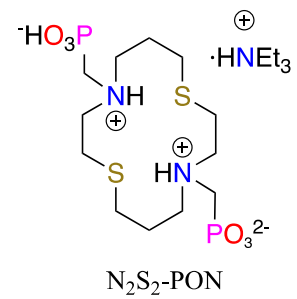
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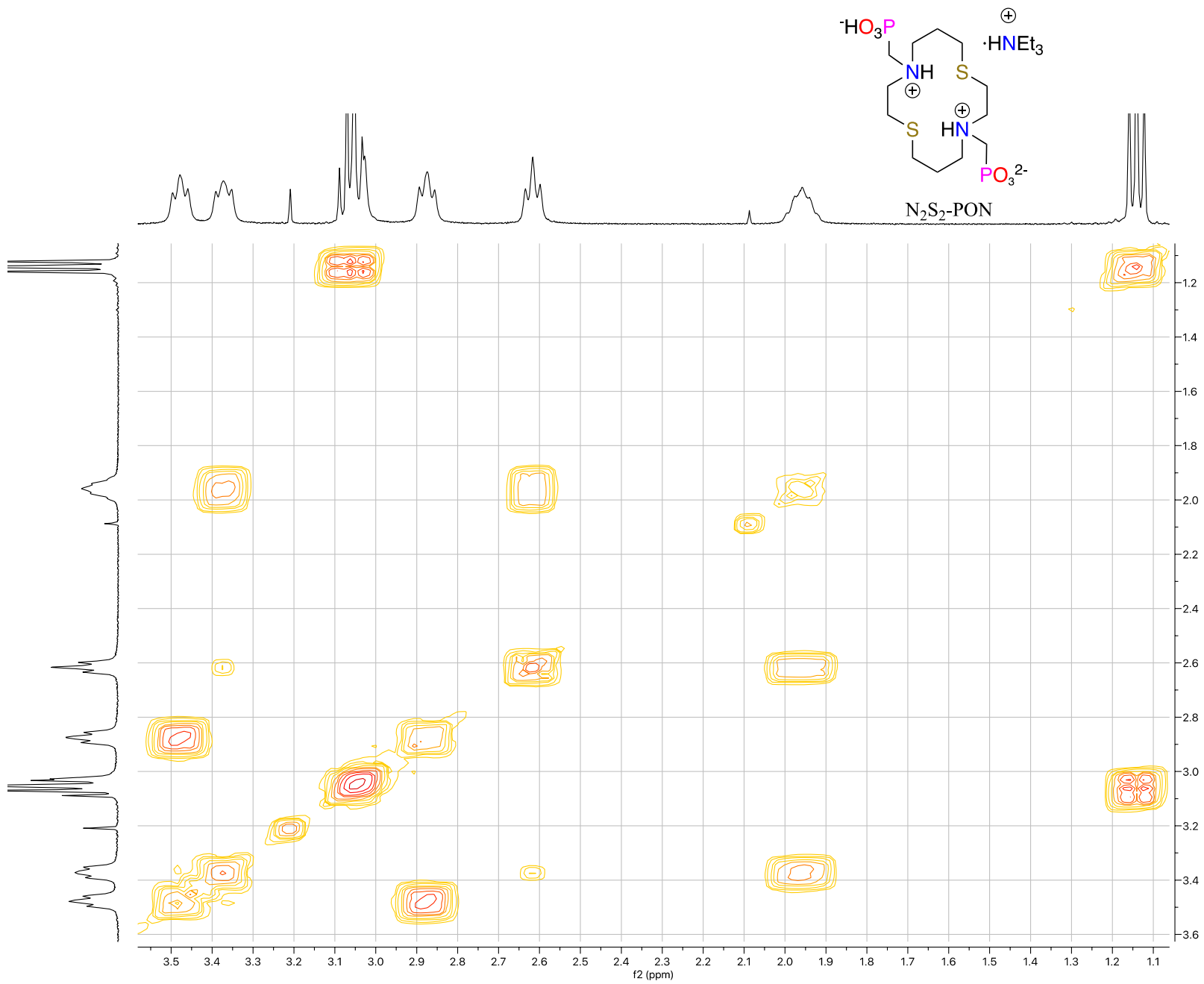


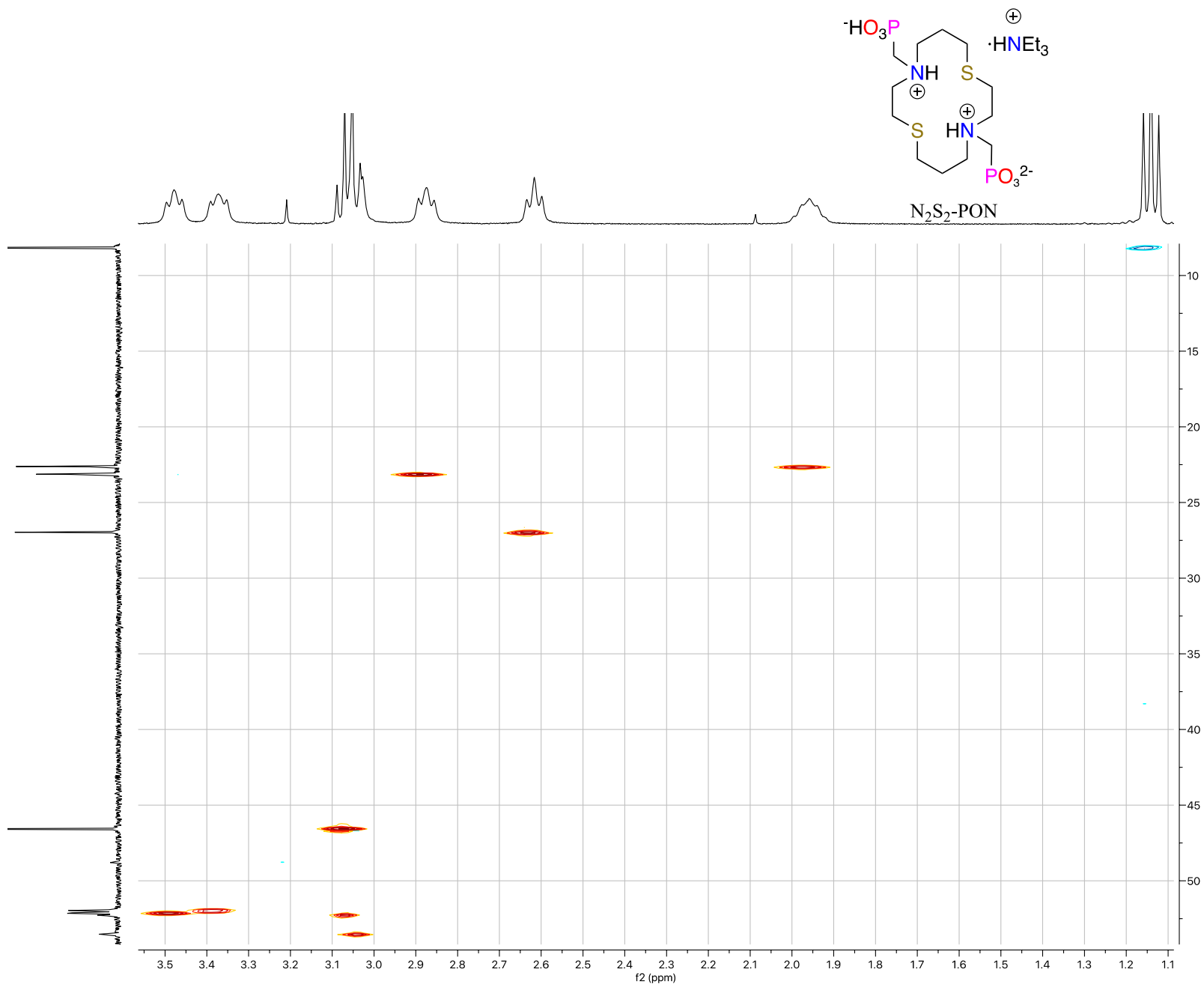


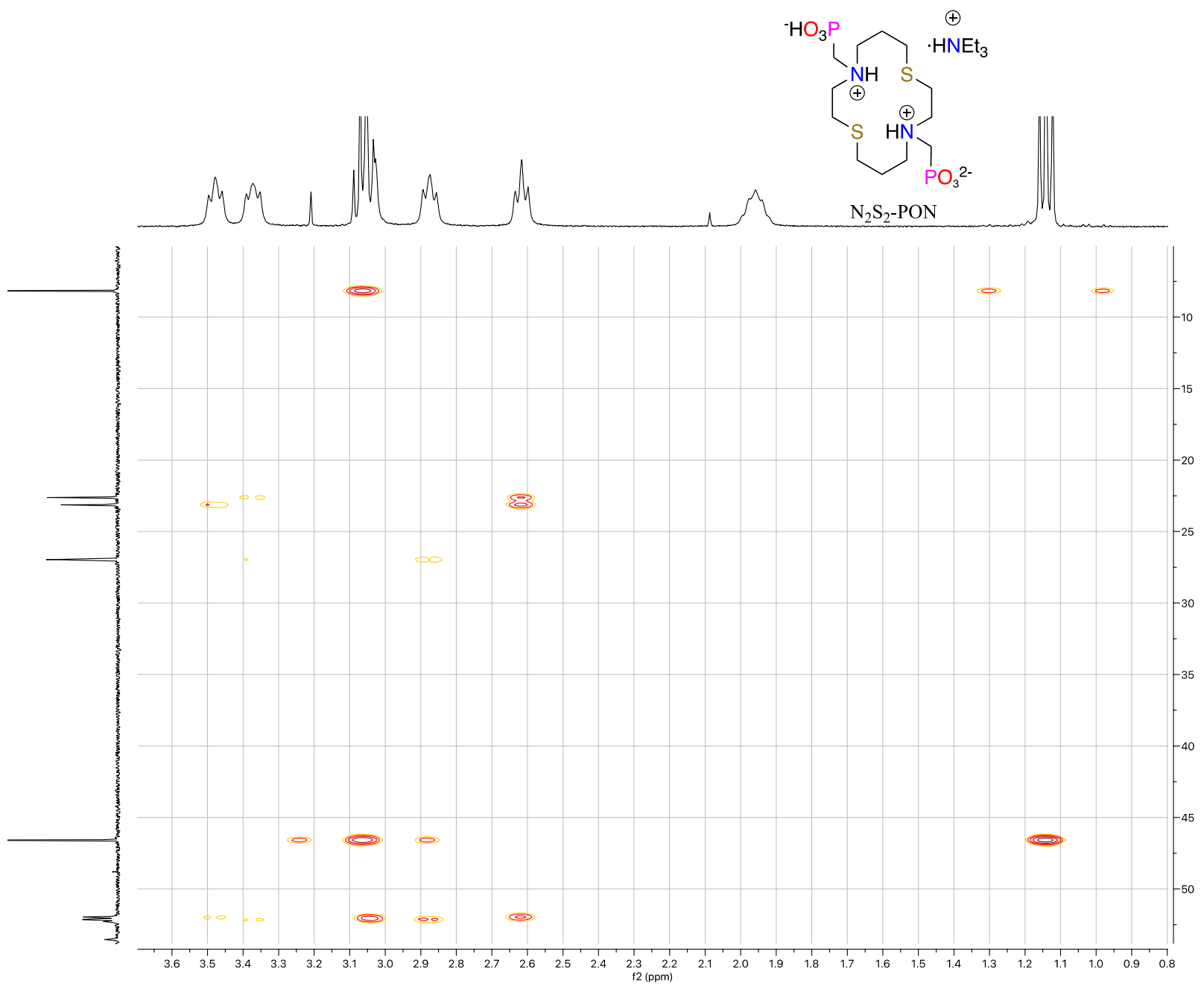


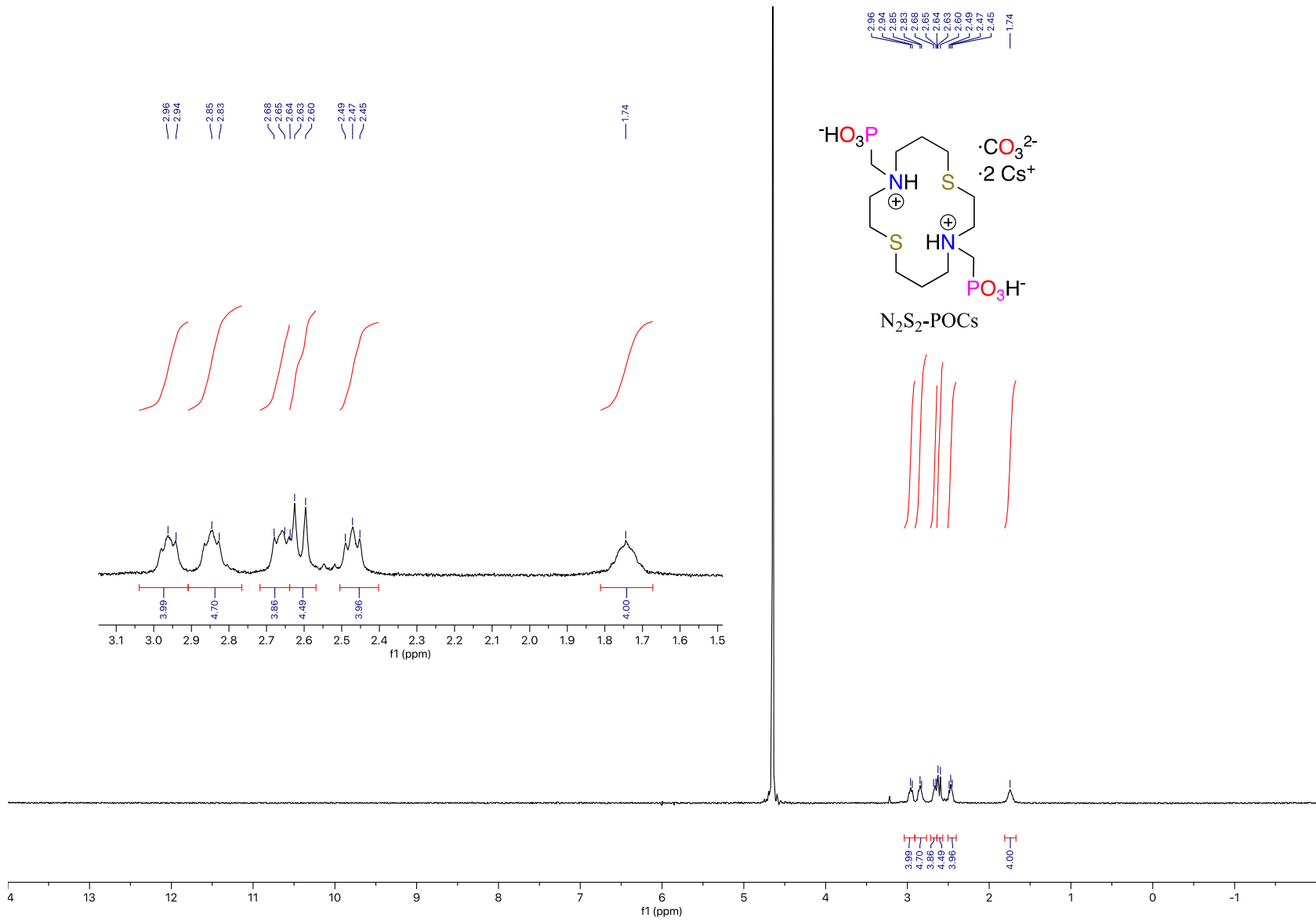


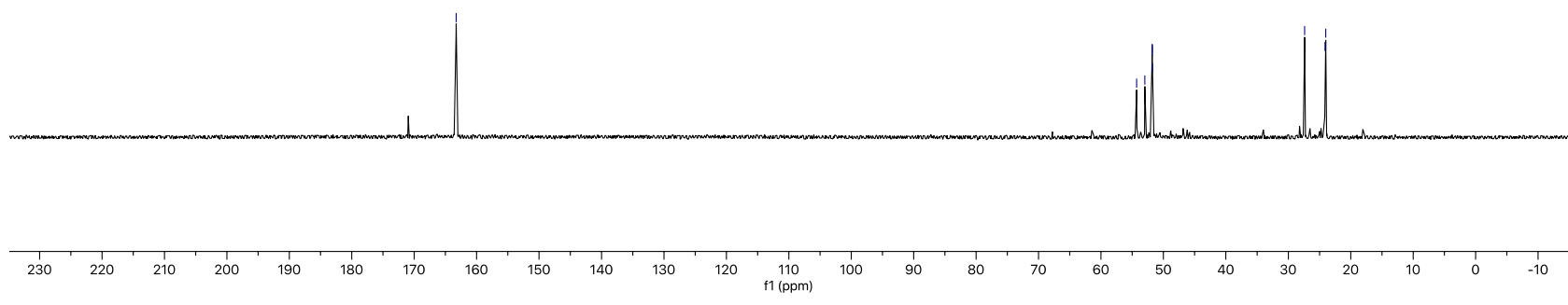
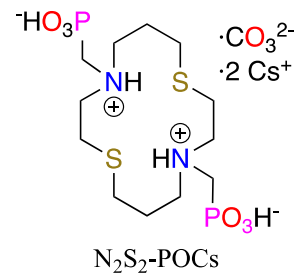
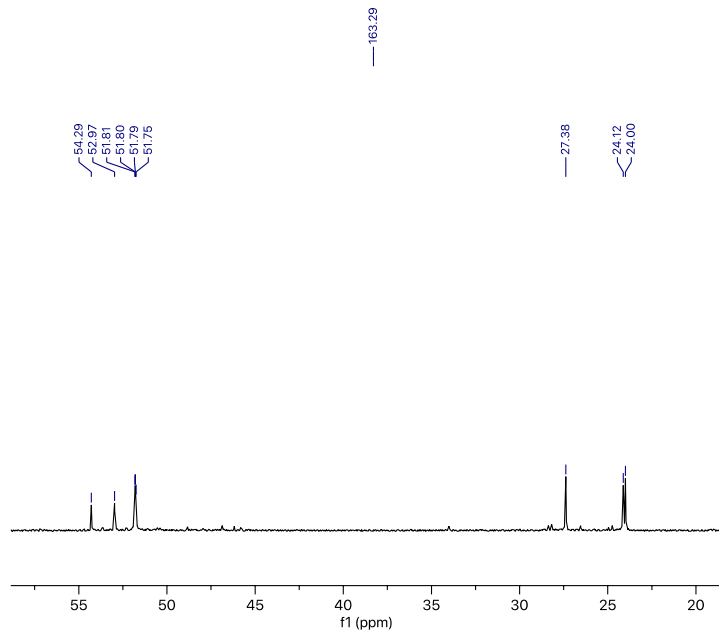


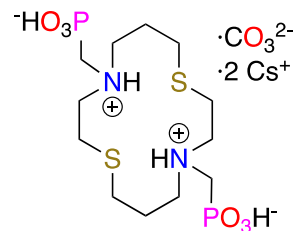




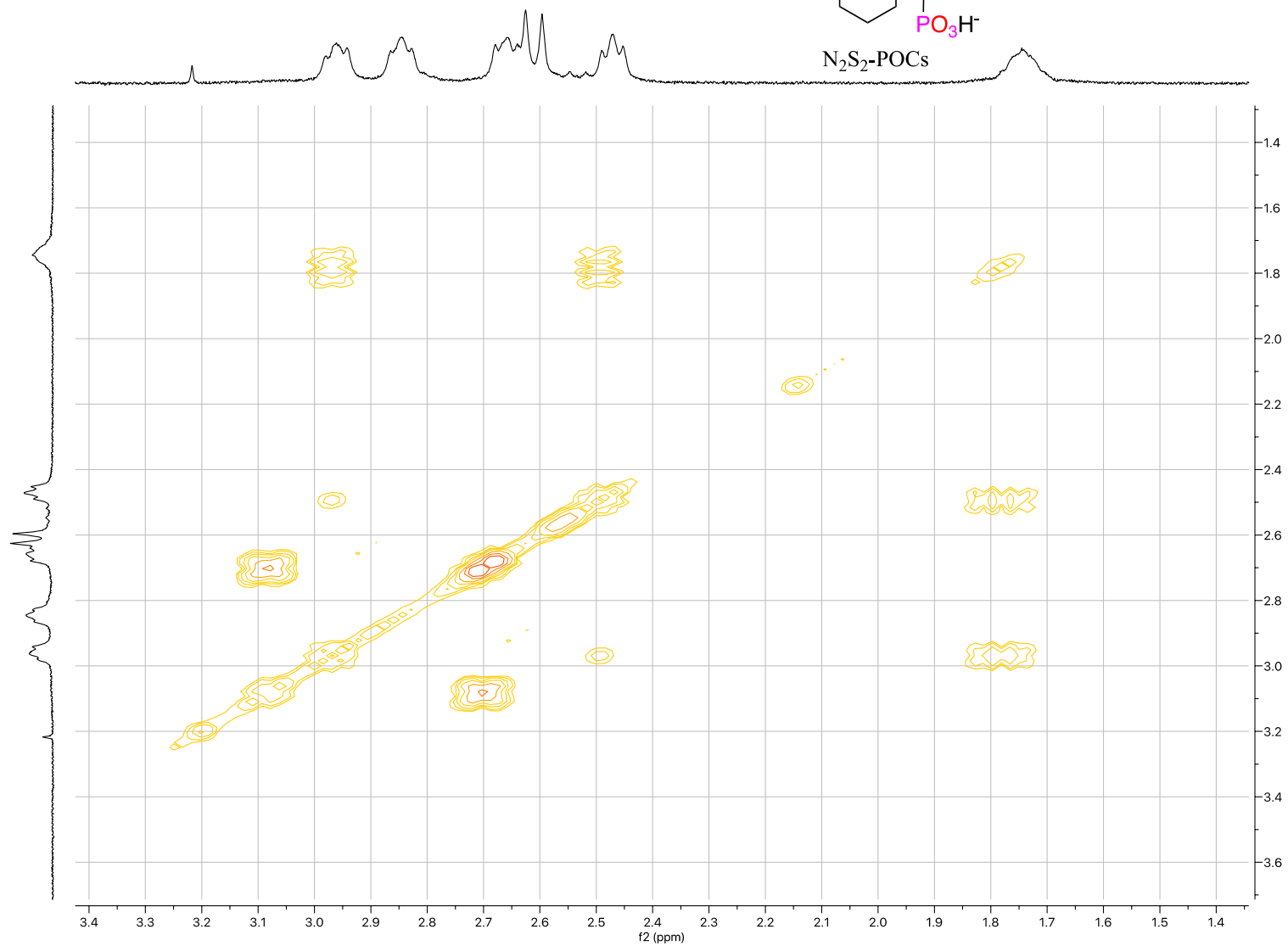


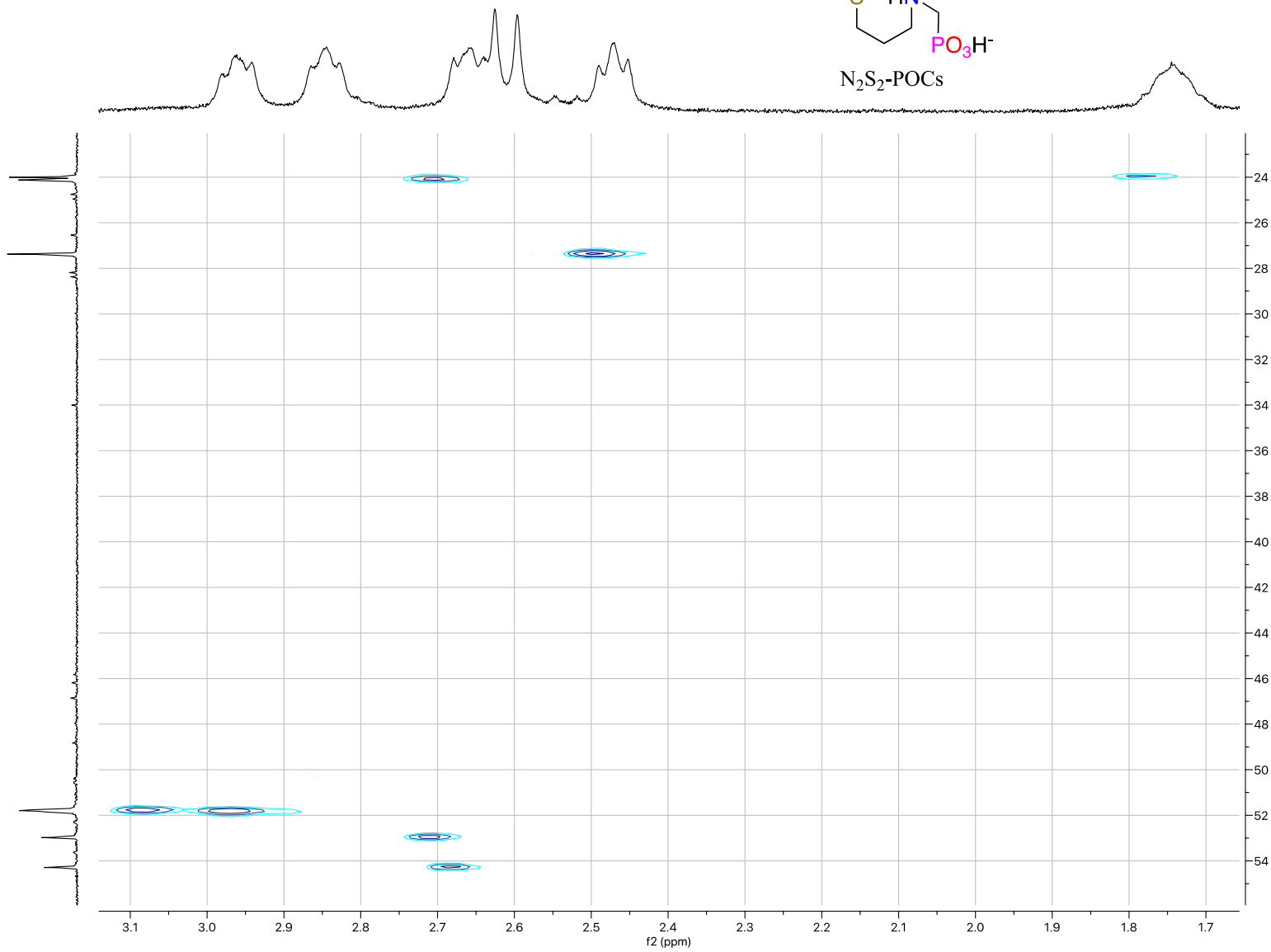
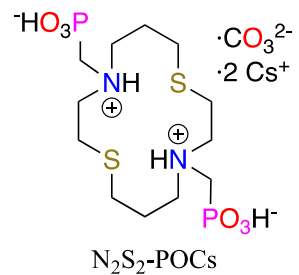


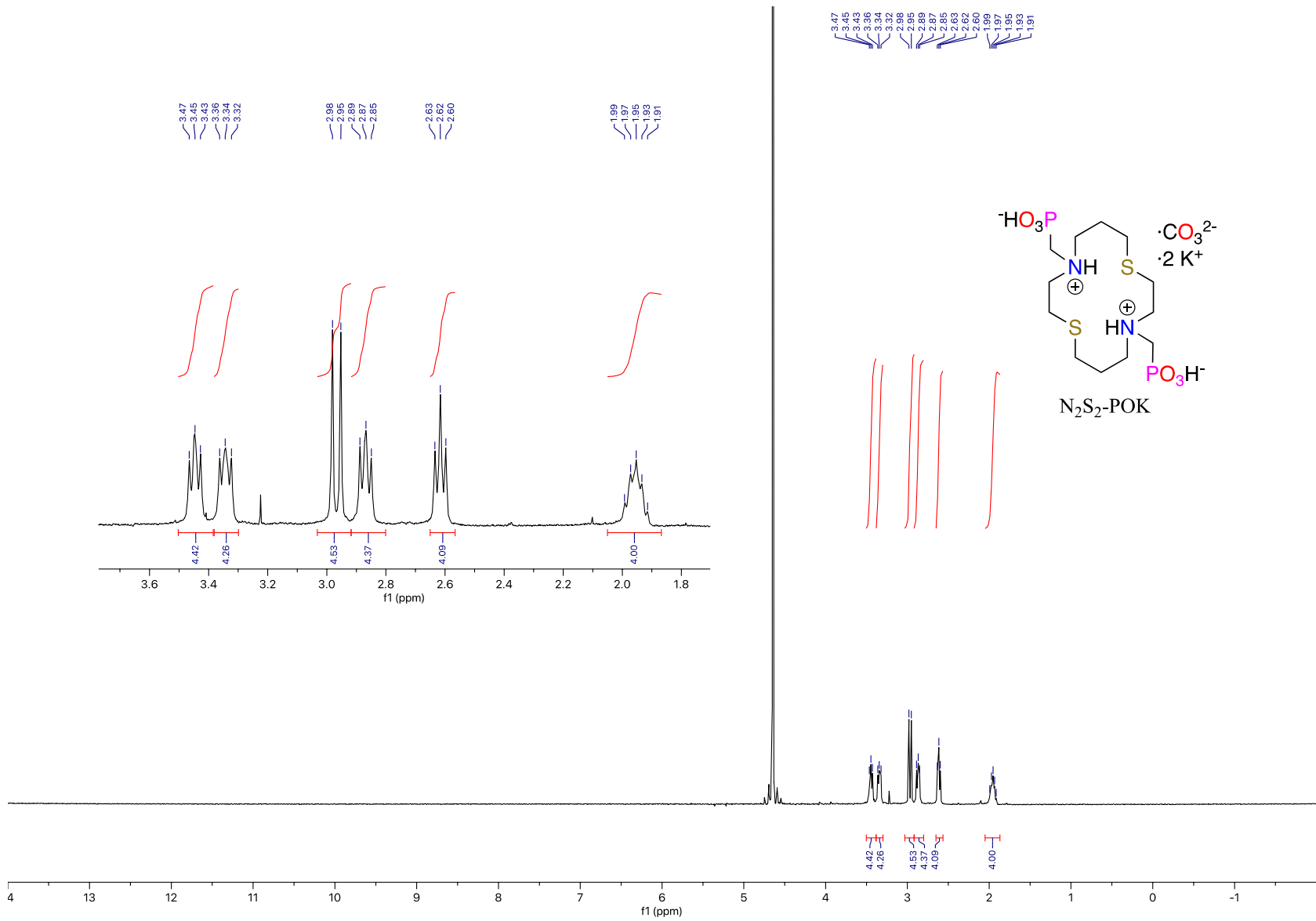


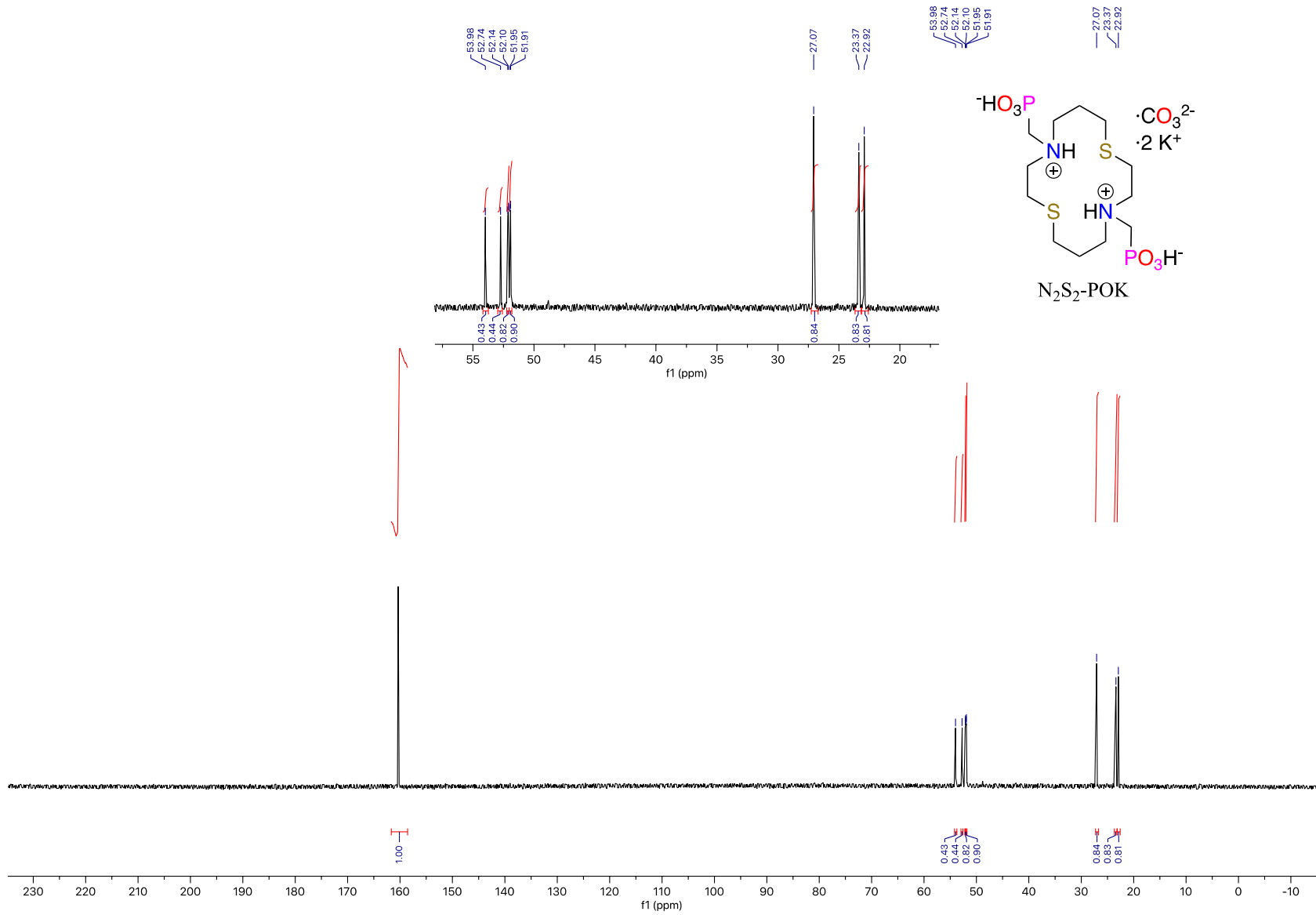


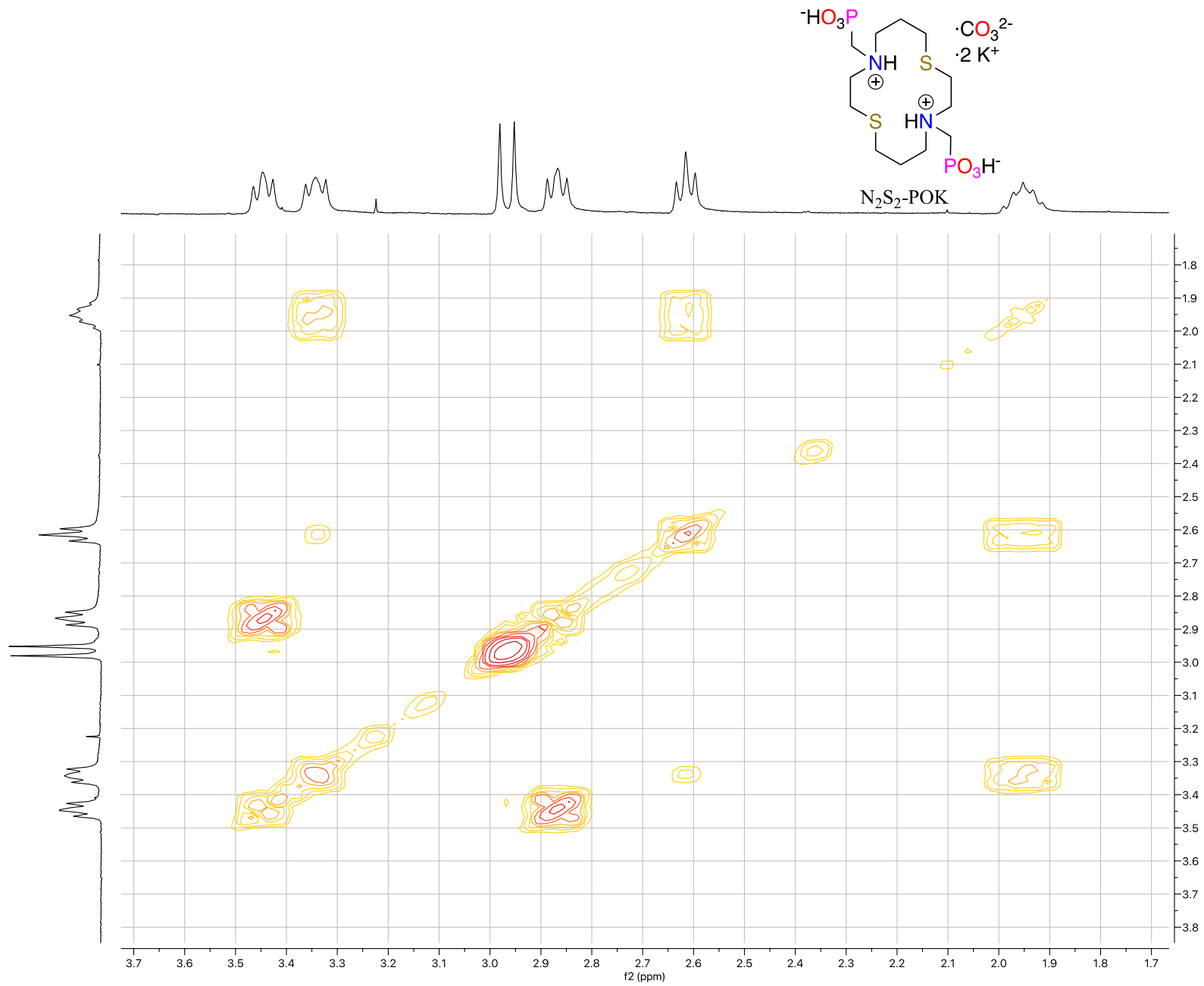
N₂S₂-POCs

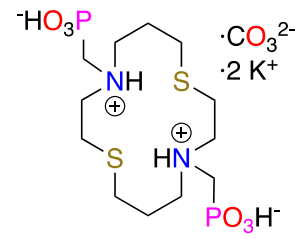




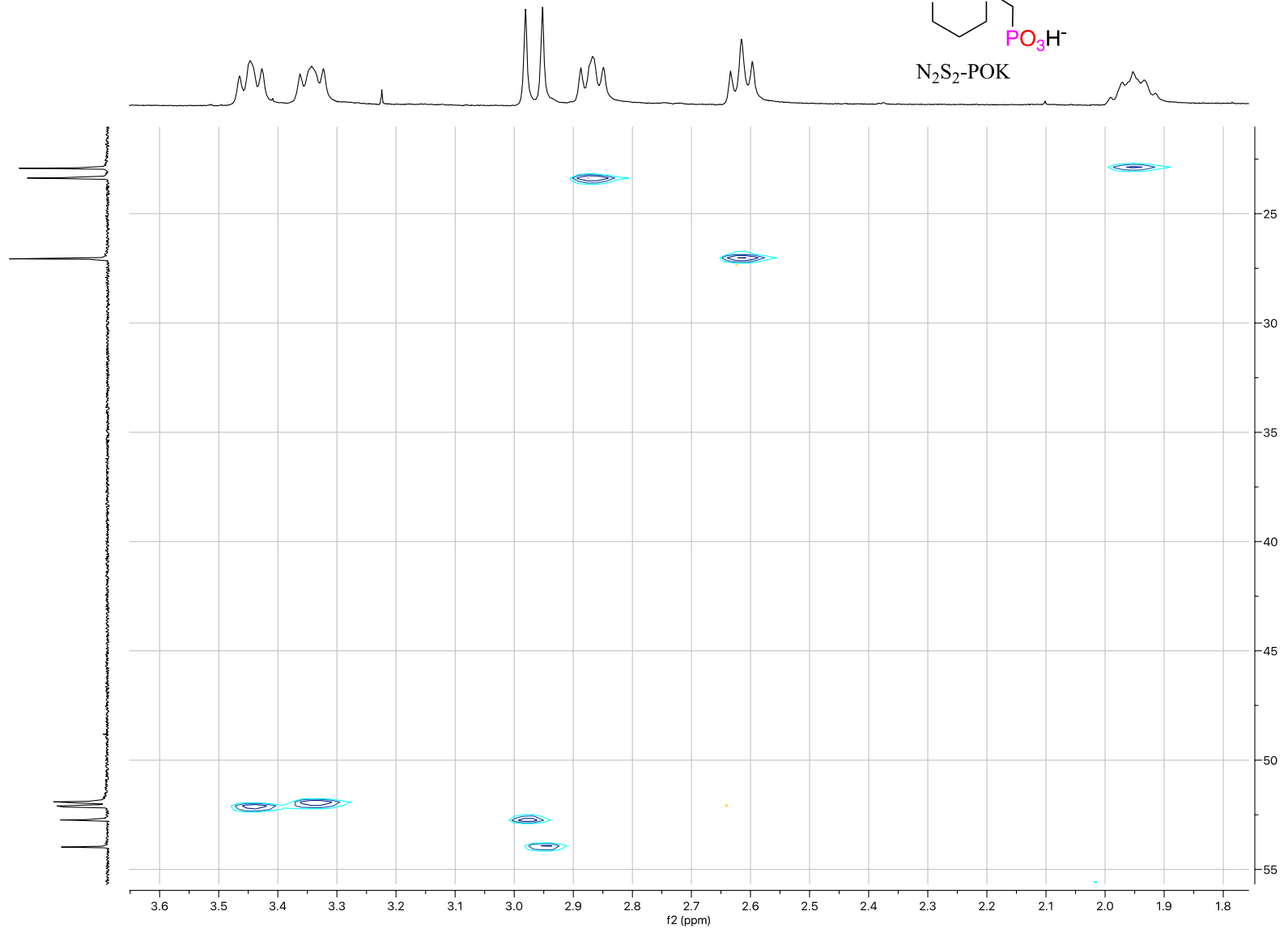


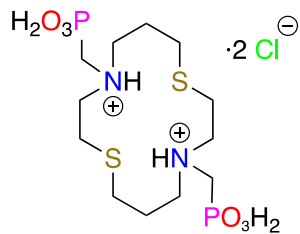






N₂S₂-POK

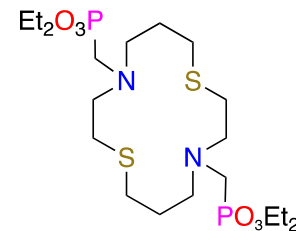
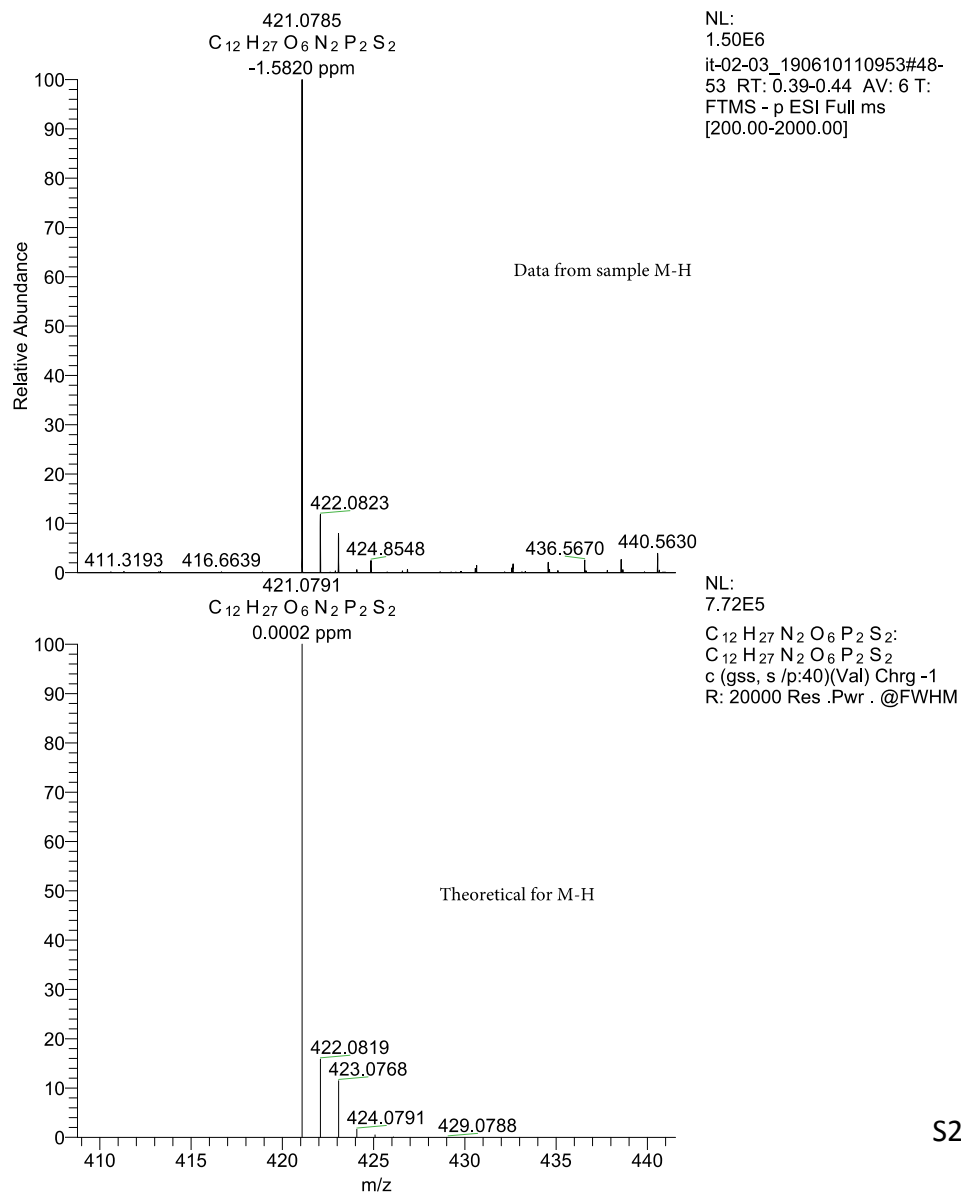




N_2S_2 -POH-HCl

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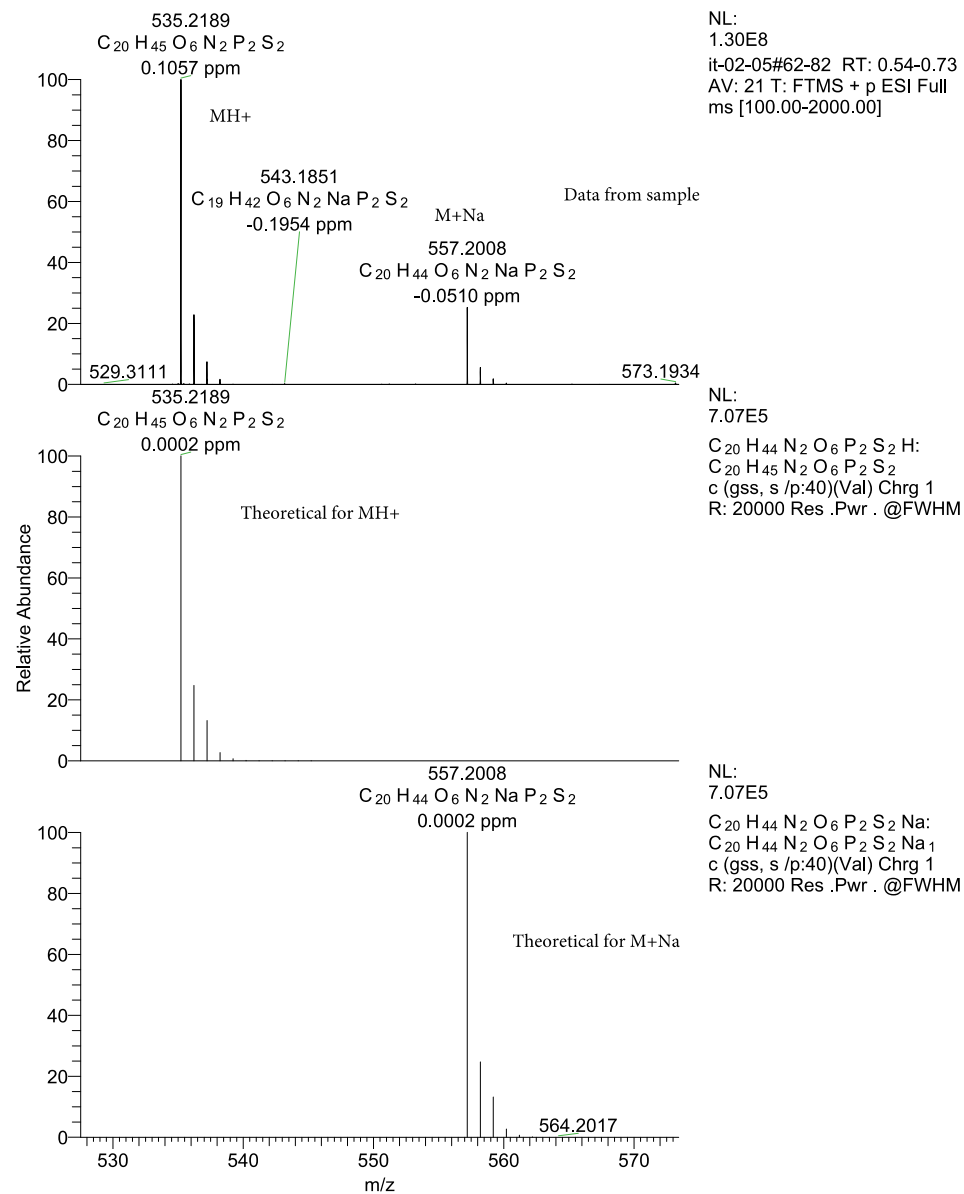
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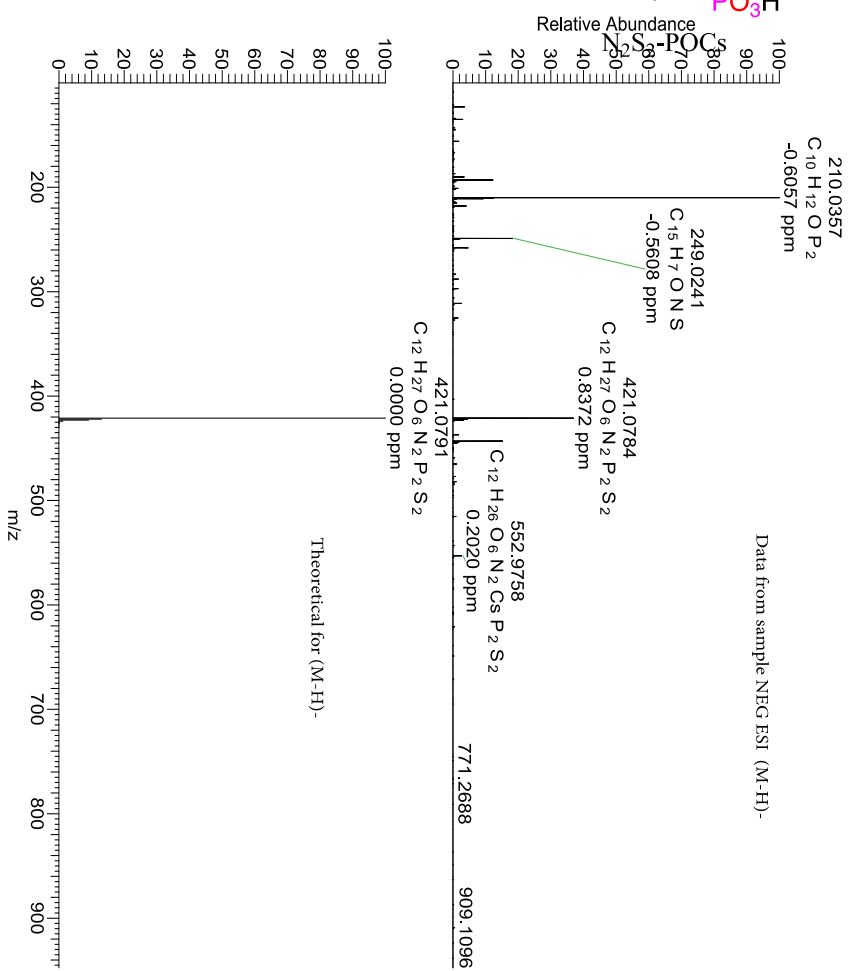
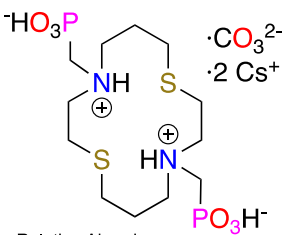


N_2S_2 -POEt

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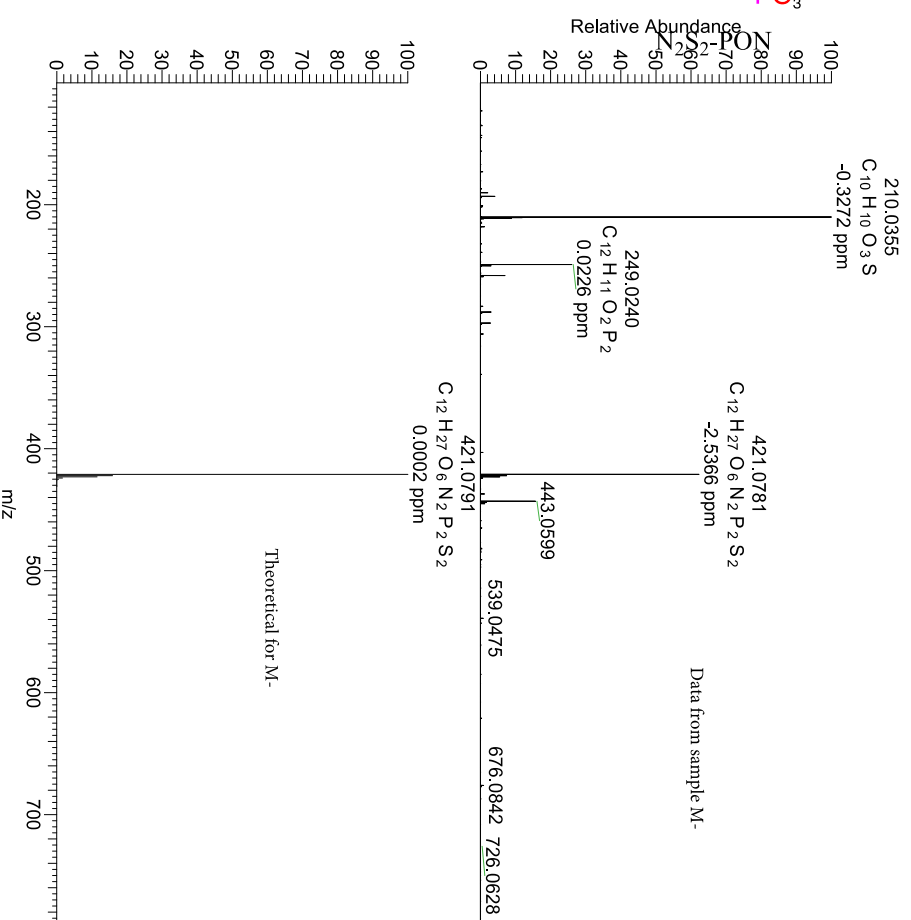
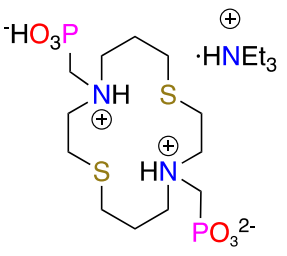
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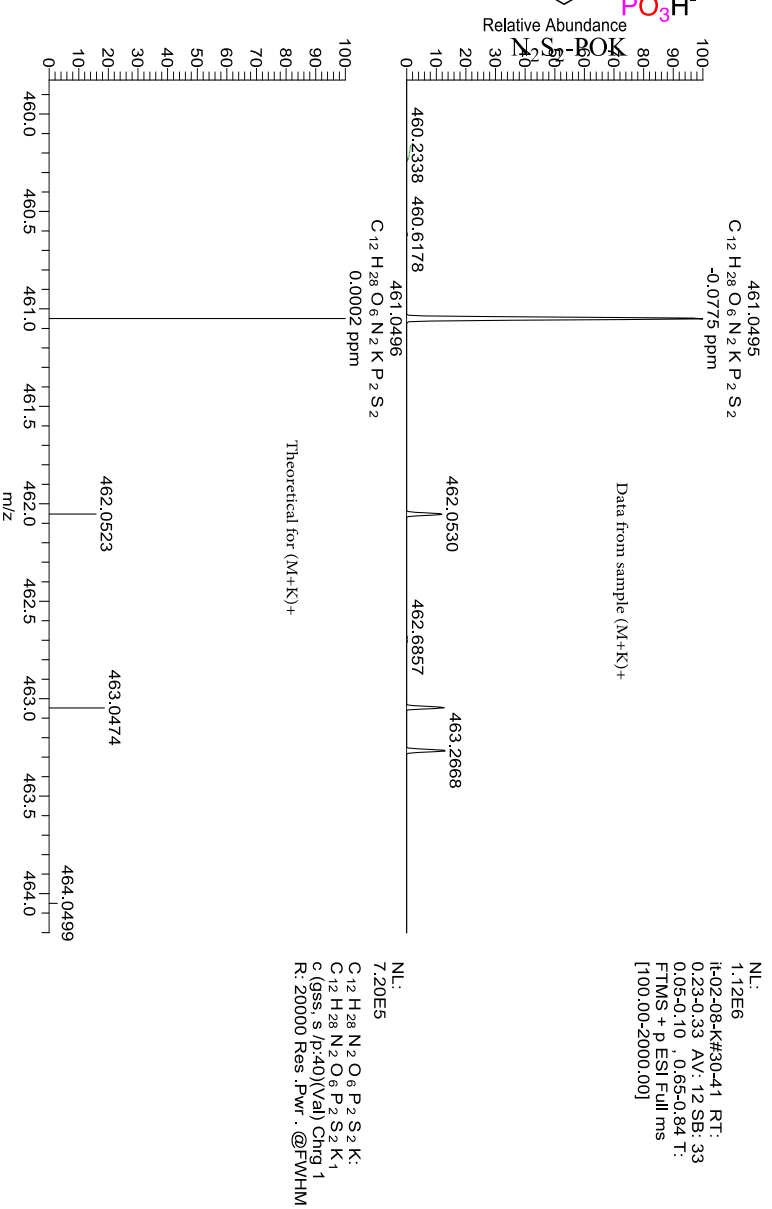
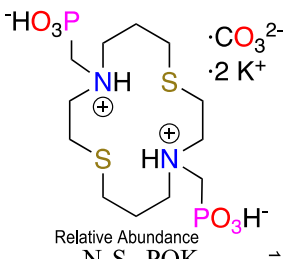
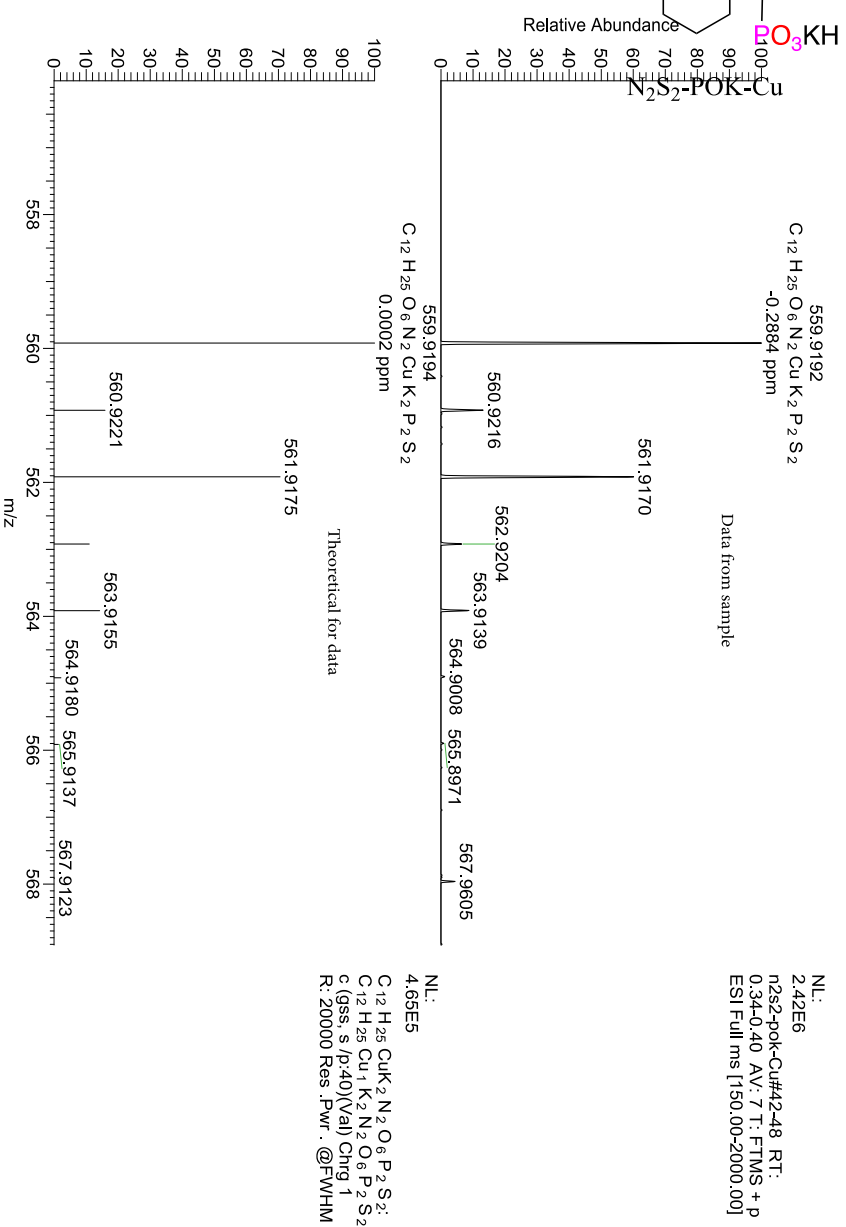
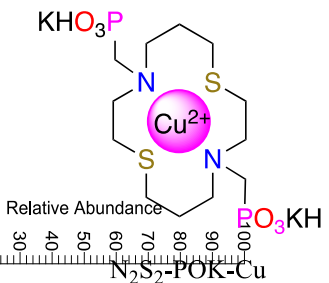
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pa Chrg -1



NL:
3.94E7
it-02-08-NEI3_190813164040#31-
40 RT: 0.24-0.31 AV: 10 SB: 52
0.02-0.09 , 0.74-1.07 T: FTMS -p
ESI Full ms [100.00-2000.00]

NL:
7.7ZE5
C₁₂H₂₇N₂O₆P₂S₂:
C₁₂H₂₇N₂O₆P₂S₂:
c (gss, s /p:40)(Val) Chrg -1
R: 20000 Res. Pwr. @FWHM



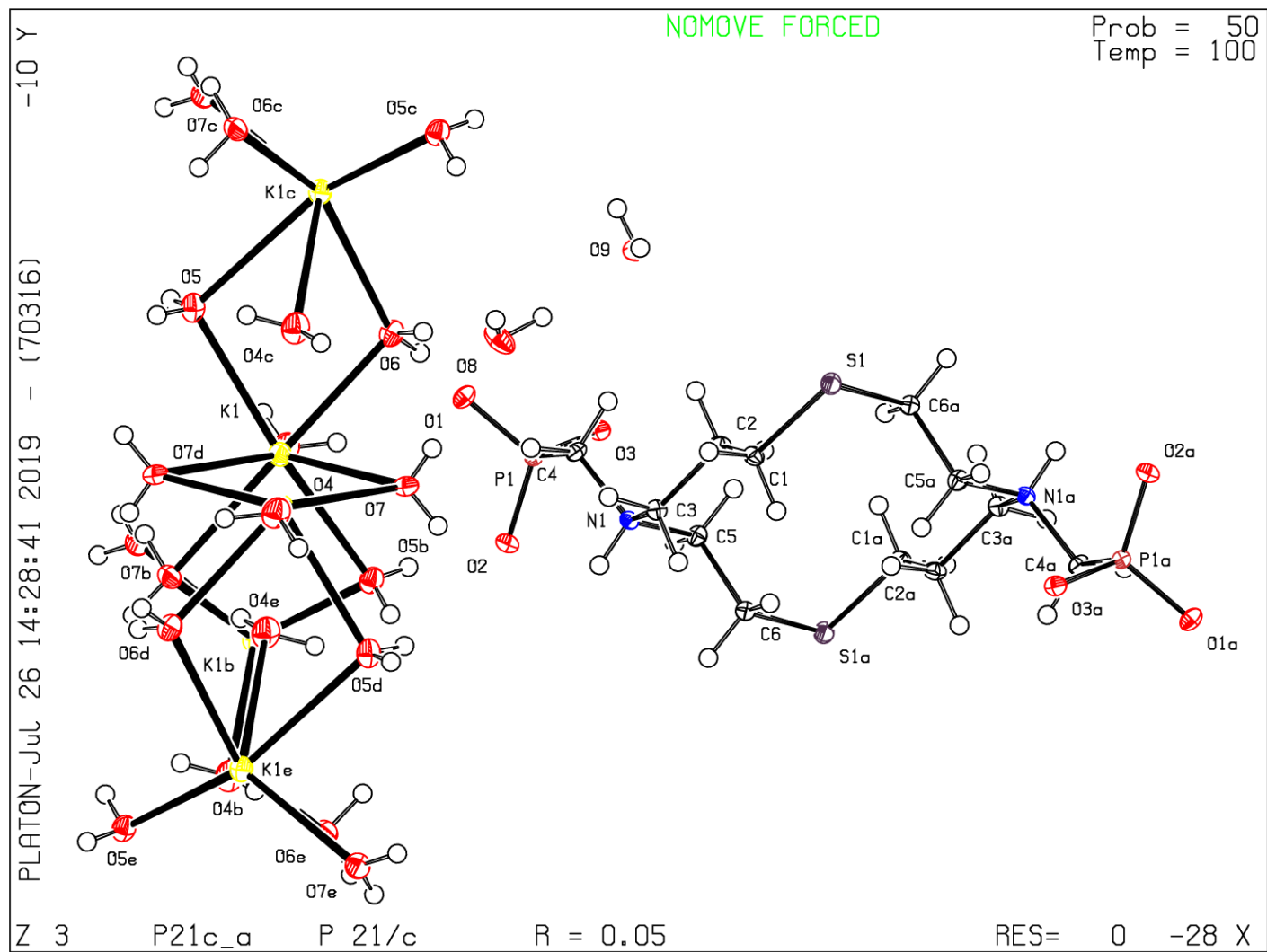


Figure S1. Ellipsoid plot for compound L1 with ellipsoid contour at 50% probability

Table S1. Crystal data and structure refinement parameters for N₂S₂-POK

Compound	N₂S₂-POK
Empirical formula	C ₆ H ₂₅ KNO ₉ PS
Formula weight	357.40
Crystal system	Monoclinic
Space group	P2 ₁ /c
a/ Å	18.4319(11)
b/ Å	8.4812(5)
c/ Å	10.0288(5)
α(°)	90
β(°)	100.191(4)
γ(°)	90
Volume (Å ³)	1543.01(15)
Z	4
D _c (Mg/m ³)	1.538
μ (mm ⁻¹)	0.619
F(000)	760
reflns collected	14493
indep. reflns	3854
GOF on F ²	1.018
R1 (on F _o ² , I > 2σ(I))	0.0452
wR2 (on F _o ² , I > 2σ(I))	0.0880
R1 (all data)	0.0743
wR2 (all data)	0.1008

Table S2. Selected bond angles and bond lengths for N₂S₂-POK and N₂S₂-HCl.

Bond lengths, Å	N ₂ S ₂ -POK	N ₂ S ₂ -HCl
S-C	1.808(2), 1.811(3)	1.807(2), 1.820(3), 1.807(2), 1.817(2)
N-C	1.502(3), 1.511 (3), 1.497(3)	1.501(3), 1.497(3), 1.491(3), 1.501(3)
Bond Angles°		
C-S-C	102.39(12)	102.5(12), 102.1(12)
C-N-C	112.84(18), 110.9(2), 114.00(18)	117.2(19), 116.3(19)
C-C-S	112.17(16), 114.16(17)	113.3(17), 114.4(17), 112.3(16), 114.9(17)
C-C-C	108.17(19)	110.0(2), 109.4(2)
N-C-C	115.52(19), 112.12(19)	111.3(19), 112.8(2), 110.9(19), 112.2(19)

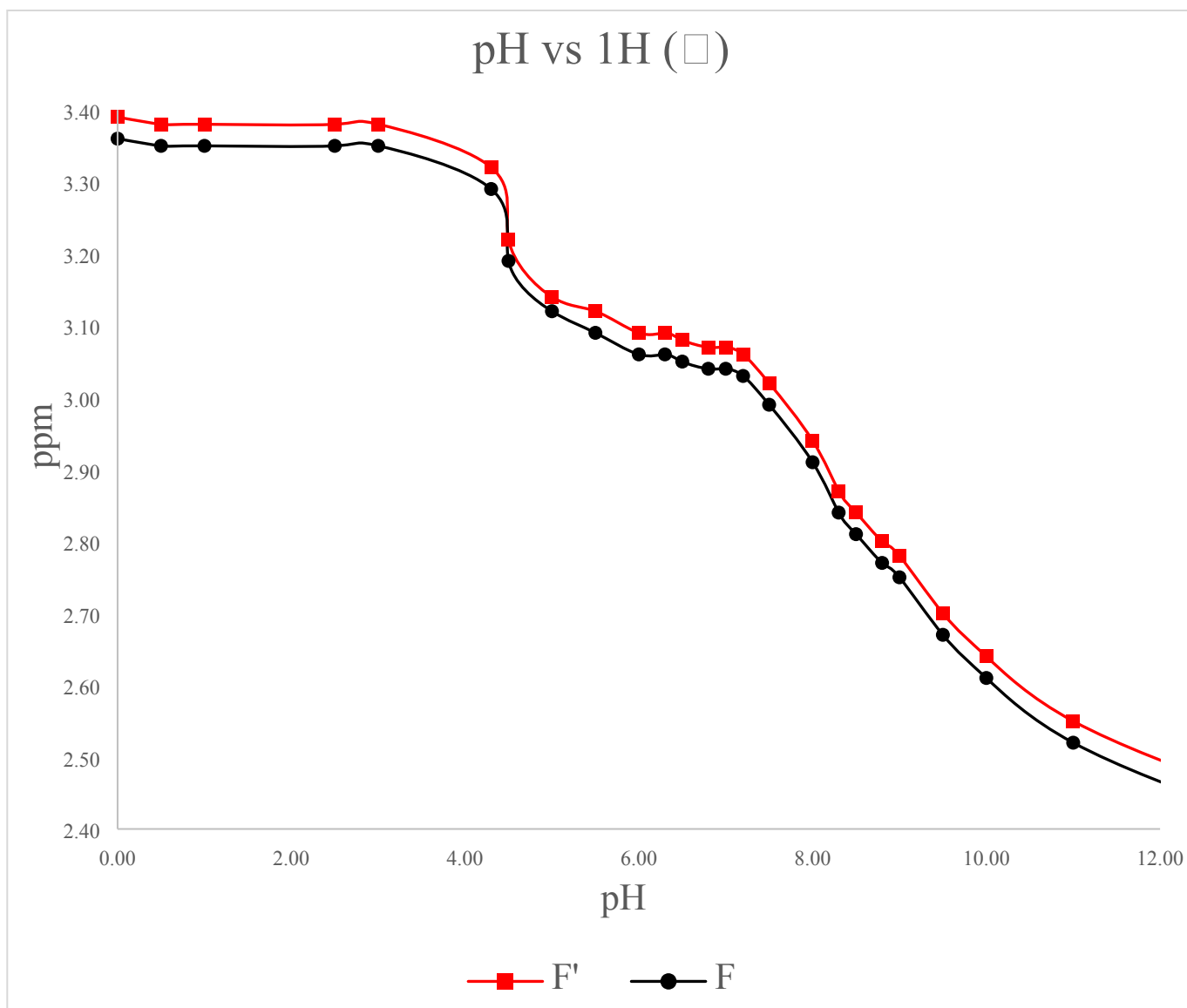


Figure S2. pH dependence on chemical shift (ν) of phosphorus nuclei

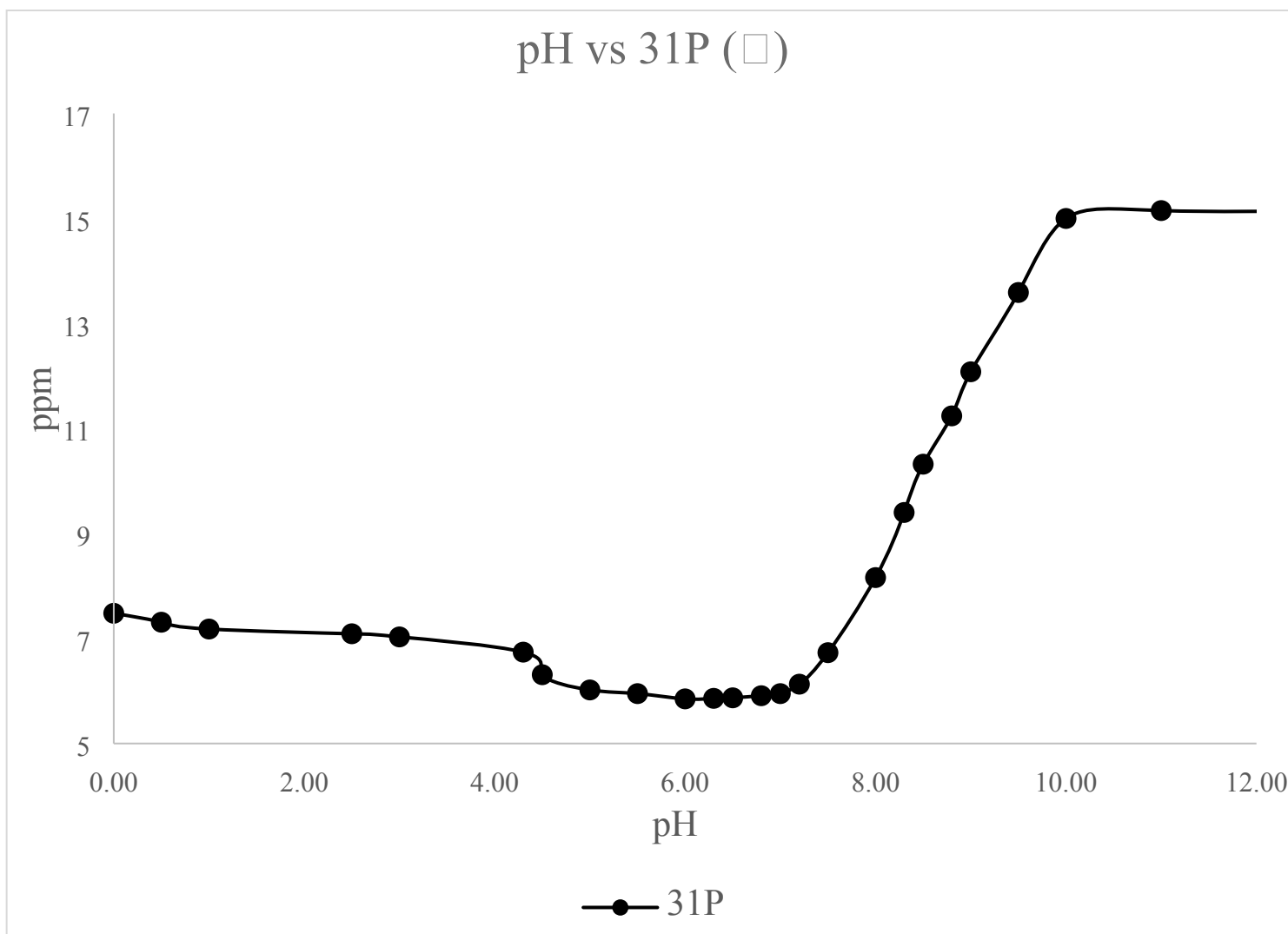


Figure S3. pH dependence on chemical shift (ν) of ^1H 's f and f'

Benesi-Hildebrand Procedure:

All thermodynamic studies were performed using UV-Vis spectroscopy from 200-1100 nm at 25 °C in an aqueous buffer (0.1 M KCl, pH = 5). All solutions were made in 5 mL volumetric flasks maintaining a constant copper perchlorate concentration ($c_{Cu} = 3 \times 10^{-3}$ M). **N₂S₂-POK** stock solution ($c_{N_2S_2POK} = 3 \times 10^{-2}$ M) was made with copper perchlorate solution made above. Concentration ranges for **N₂S₂-POK** ranged from 0 – 9.9×10^{-3} and the absorption band utilized for determination of the conditional stability constant was $\lambda_{max} = 635$ nm. Derivations for final fitting of data are provided below:

• Derivation and to afford K_{therm} :

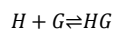
$$K_{therm}^{HG} = K_{cond}^{HG} \alpha_H$$

$$\alpha_H = \frac{K_1 K_2 [H_3O^+]^2}{1 + K_1 [H_3O^+] + K_1 K_2 [H_3O^+]^2 + K_1 K_2 K_3 [H_3O^+]^3 + K_1 K_2 K_3 [H_3O^+]^3 + K_1 K_2 K_3 K_4 [H_3O^+]^4 + K_1 K_2 K_3 K_4 K_5 [H_3O^+]^5 + K_1 K_2 K_3 K_4 K_5 K_6 [H_3O^+]^6}$$

Where: K_{therm}^{HG} : Thermodynamic stability Constant

K_{cond}^{HG} : Conditional Stability Constant

• Derivation to fit K_{cond}^{HG} to the UV-Vis data:



$$K = \frac{[HG]}{[H][G]}$$

$$[H] = [H]_o - [HG]$$

$$[G] = [G]_o - [HG]$$

$$K = \frac{[HG]}{([H]_o - [HG])([G]_o - [HG])}$$

$$[HG]^2 - ([H]_o + [G]_o)[HG] + [H]_o[G]_o = \frac{[HG]}{K}$$

$$[HG]^2 - \left([H]_o + [G]_o + \frac{1}{K}\right)[HG] + [H]_o[G]_o = 0$$

Quadratic Equation Solving for [HG]:

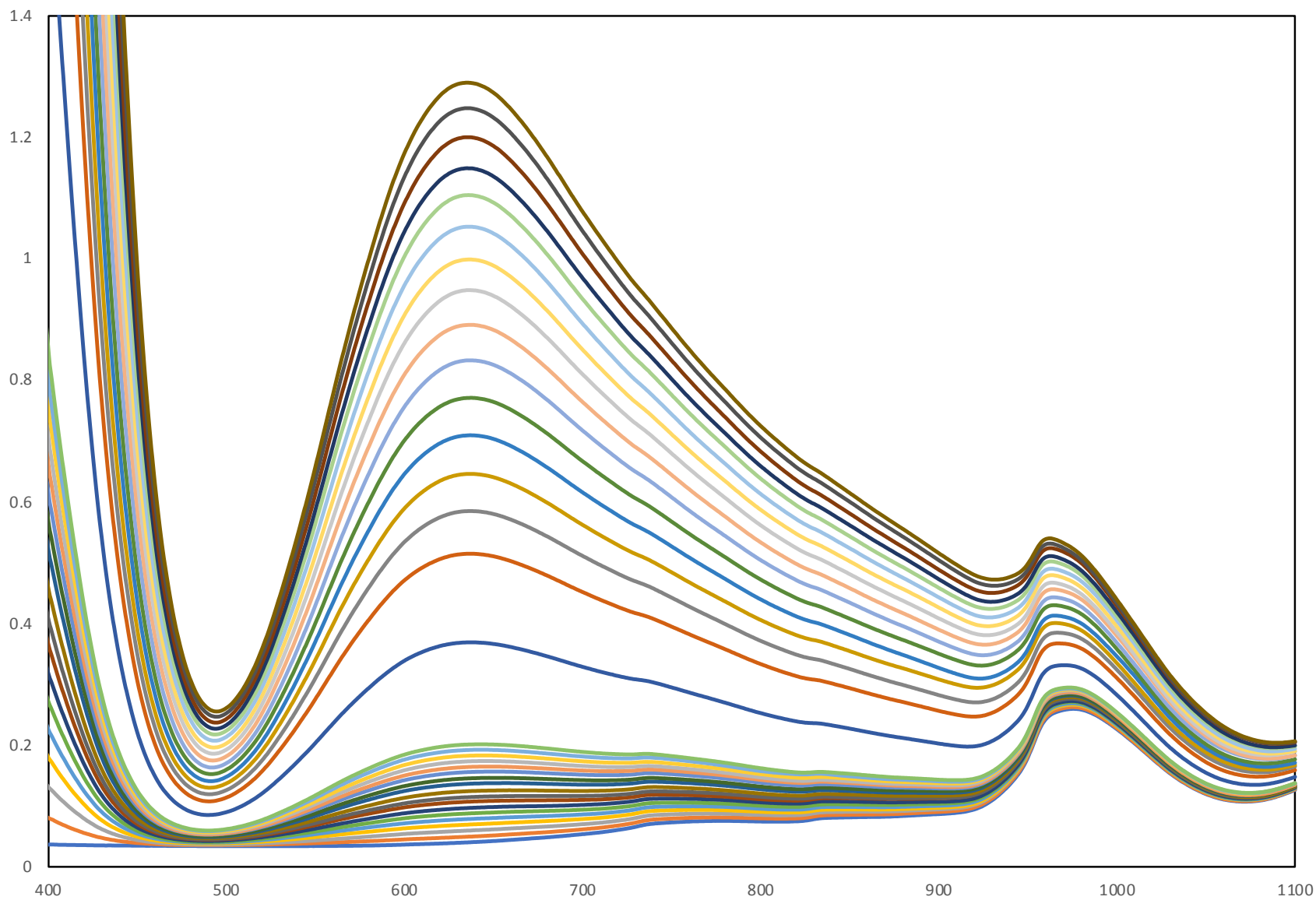
$$[HG] = \frac{1}{2} \left[\left([H]_o + [G]_o + \frac{1}{K} \right) \pm \sqrt{\left([H]_o + [G]_o + \frac{1}{K} \right)^2 - 4[H]_o[G]_o} \right]$$

$$\Delta A = \epsilon_{HG}[HG] - \epsilon_G \Delta[G] - \epsilon_H \Delta[H] = \epsilon_{HG}[HG] - \epsilon_G [HG] - \epsilon_H [HG]$$

$$\Delta A = (\epsilon_{HG} - \epsilon_G - \epsilon_H)[HG] = \Delta \epsilon [HG]$$

$$\Delta A = \frac{\Delta \epsilon}{2} \left[\left([H]_o + [G]_o + \frac{1}{K} \right) \pm \sqrt{\left([H]_o + [G]_o + \frac{1}{K} \right)^2 - 4[H]_o[G]_o} \right]$$

UV-Vis



S35