Conformation of N,N′-bis(3-pyridylformyl)piperazine and spontaneous formation of a saturated quadruple stranded metallohelicate

Himansu S. Sahoo and Dillip K. Chand[*]

Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India

Supporting Information

NMR spectra were obtained at room temperature with a BRUKER AVANCE-400 spectrometer. The ^{1}H NMR spectra were recorded at 400 MHz, and ^{13}C NMR was recorded at 100 MHz by using TMS in $CDCl_3$ as external standard. Mass spectra were recorded on a MICROMASS Q-TOF mass spectrometer equipped with standard electrospray source. The samples were dissolved in water and introduced into the ESI source through a syringe pump at the rate 5 µL per minute. The ESI capillary was set at 3.5 kV, the cone voltage was 5 – 15 V.

Synthesis of *N,N′*-bis(3-pyridylformyl)piperazine, L$_1$: Nicotinyl chloride hydrochloride (0.858 g, 4.82 mmol) was taken in a 100 mL round bottom flask and 15 mL of CH_2Cl_2 was added to it under nitogen atmosphere. The suspension was stirred vigorously for 10 minute followed by addition of piperazine solution (0.186 g, 2.16mmol) dissolved in 20 mL of CH_2Cl_2. Triethylamine (1.3 mL) was added dropwise over a period of 30 minute at 0 - 5 °C . The mixture was stirred at room temparature for 24 hour under nitrogen atmosphere. To this mixture $NaHCO_3$ solution (10% w/v) was added slowly to neutralize the acid until the evolution of CO_2 has ceased. The organic layer was washed with distilled water, separated and dried over sodium sulfate. Evaporation of the solvent gave a yellow solid as the product (0.452 g, 70%). m.p. 469 K. Anal.Calcd for $C_{16}H_{16}N_4O_2$: C, 64.85; H, 5.44; N, 18.91. Found: C, 64.92; H, 5.64; N, 19.08%. ^{1}H NMR (δ, CDCl$_3$, 400 MHz, 293 K): 8.71 (s, 2H, H_a), 8.70 (s, 2H, H_b), 7.78 (td, J = 8.0 and 1.8 Hz, 2H, H_c), 7.40 (dd, J = 7.6 and 4.8 Hz, 2H, H_d), 3.69 (broad d, 8H, H_{pip}). ^{13}C NMR (δ, CDCl$_3$, 100MHz): 168.09, 151.29, 147.94, 135.18, 130.83, 123.67, 47.59, 42.38 ppm. ESI MS (CHCl$_3$): m/z 297 (100%), [(**L$_1$**+H)]$^+$.
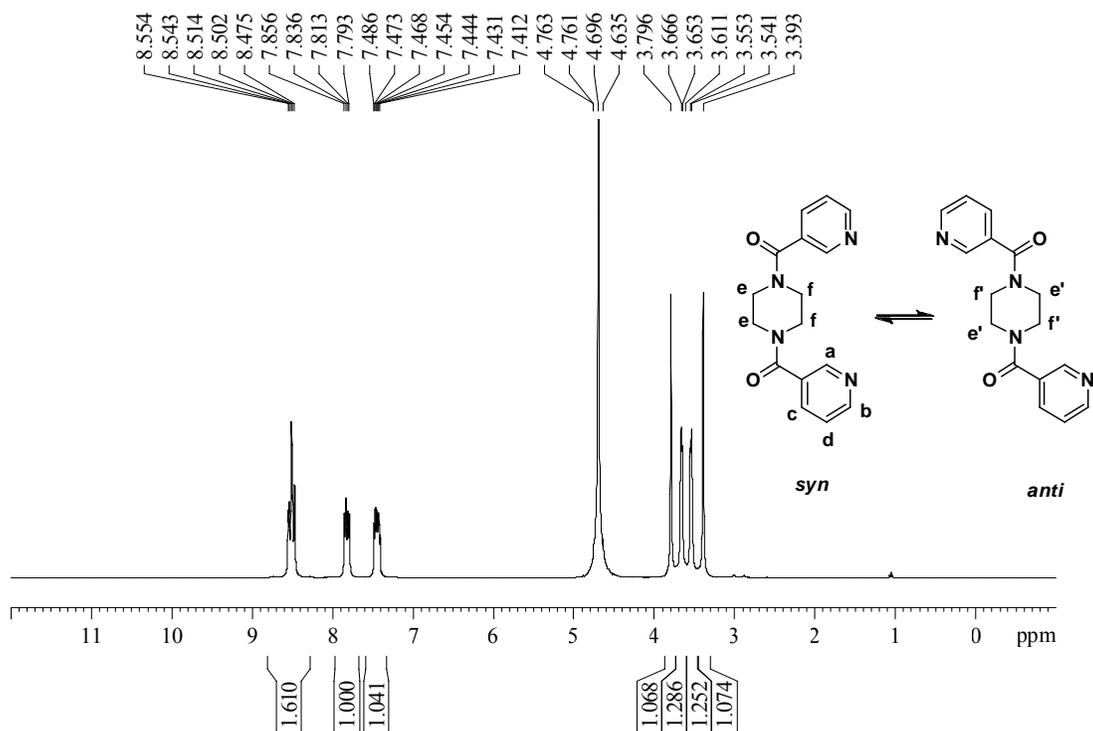
^{1}H NMR (δ, D_2O, 400 MHz, 293 K): 8.60-8.40 (m, 4H, H_a, H_b), 7. 83-7.79 (m, 2H, H_c), 7.50-7.40 (m, 2H, H_d), 3.79 (s, 4H, H_e, *syn* form), 3.65 (t, 4H, $H_{e'}$, *anti* form), 3.55 (t, 4H, $H_{f'}$, *anti* form), 3.39 (s, 4H, H_f, *syn* form). ^{13}C NMR (δ, D_2O, 100 MHz, 293 K): 170.03, 150.77, 146.92, 146.56, 136.34, 130.89, 124.60, 47.73, 47.10, 42.71 and 42.11.
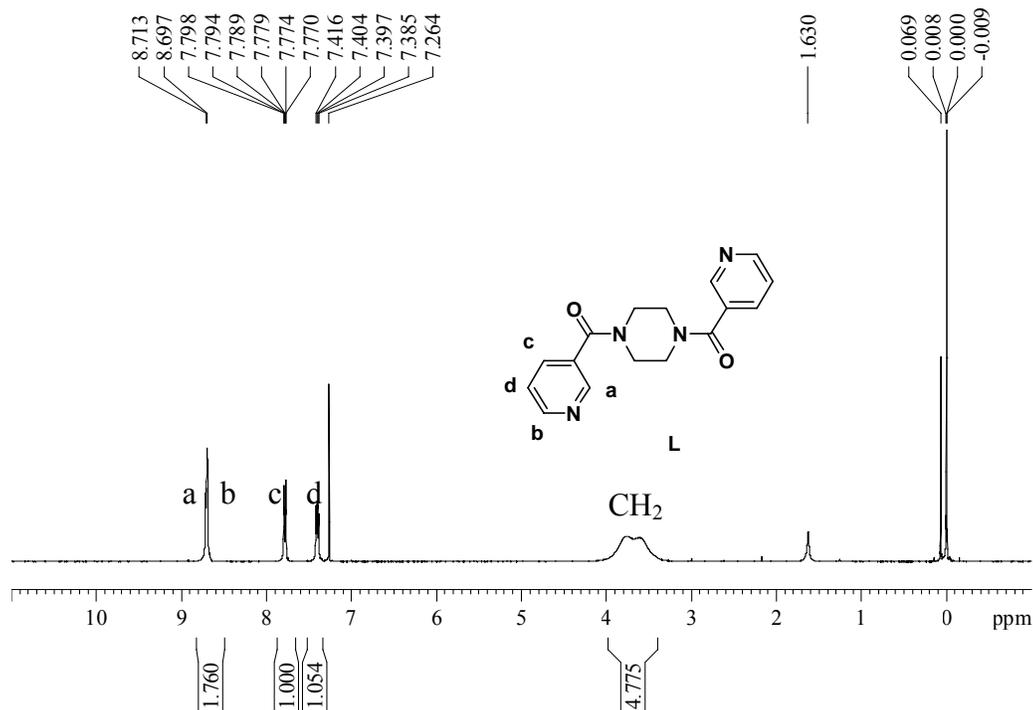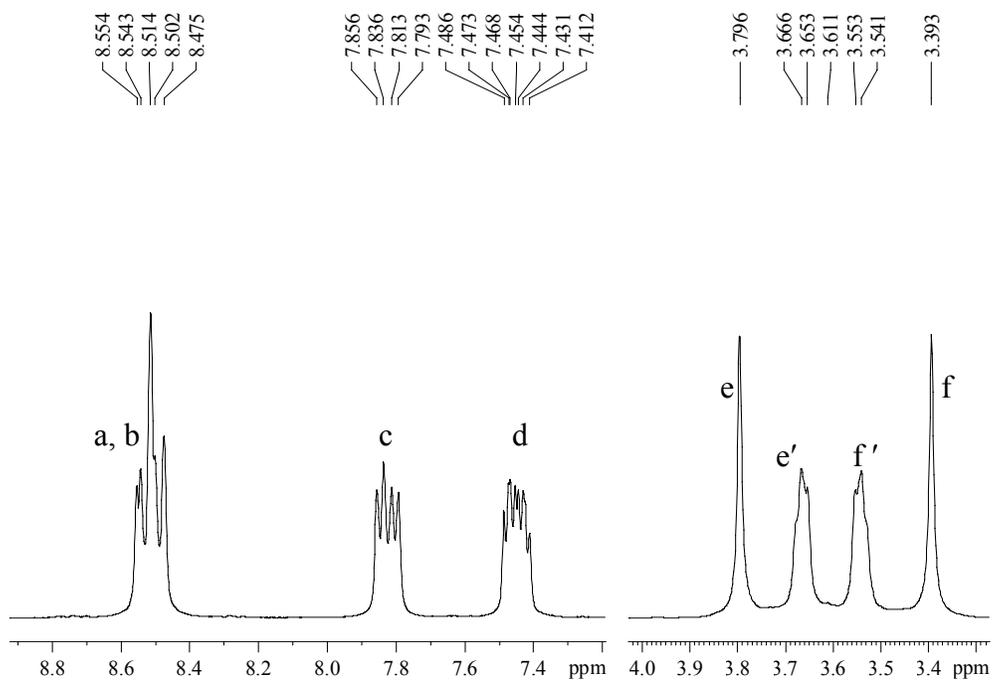
400 MHz ^{1}H NMR spectrum of ligand L_1 in $CDCl_3$

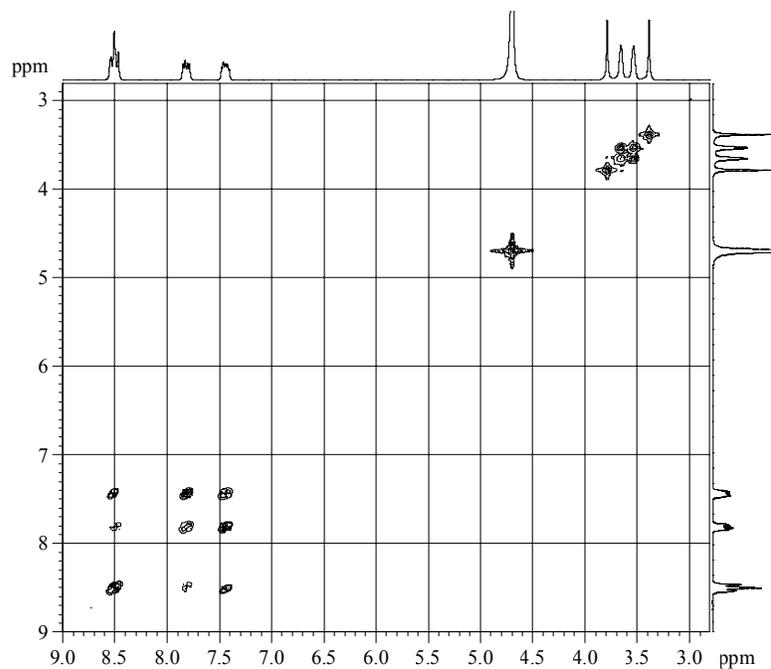^{13}C NMR spectrum of ligand L_1 in $CDCl_3$.

S3
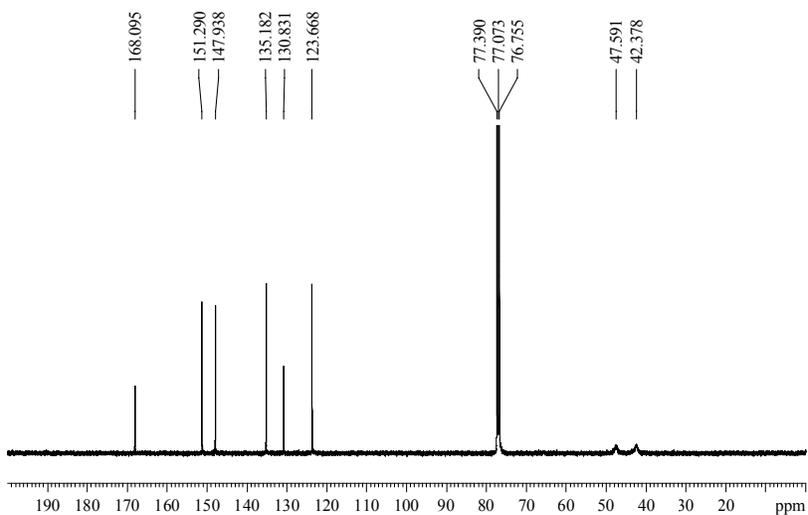
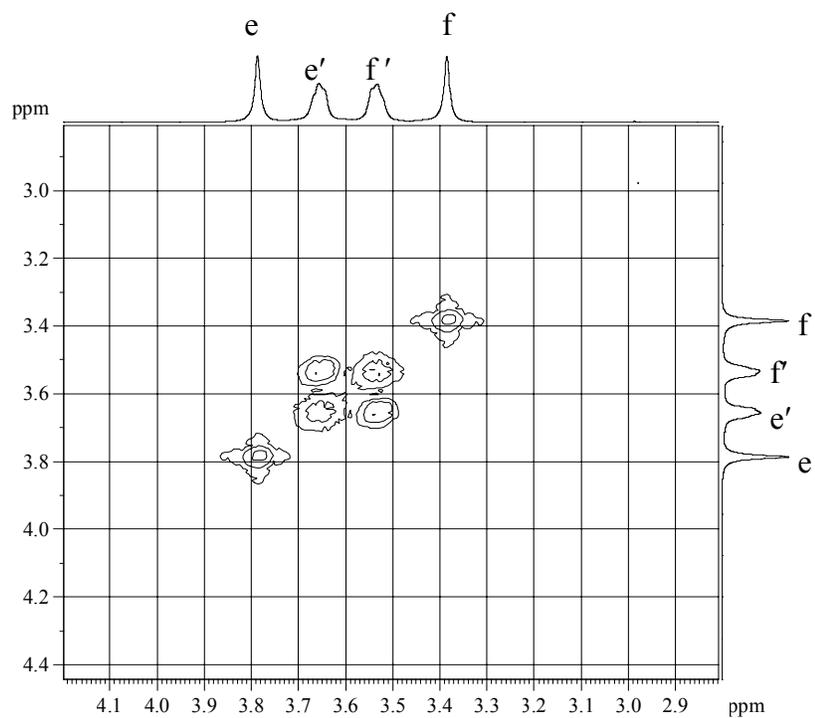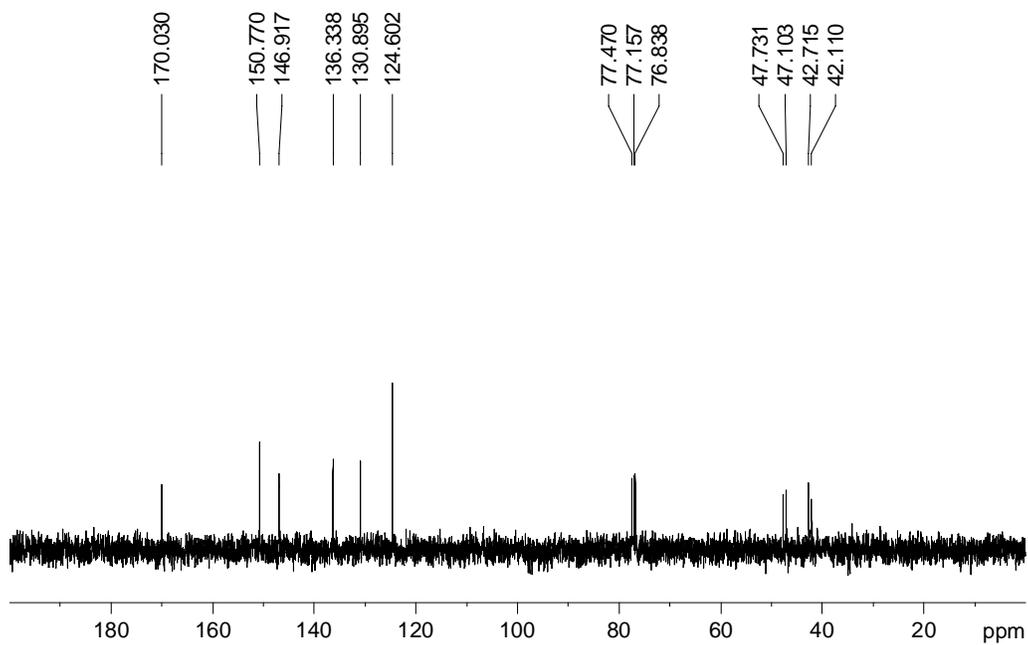400 MHz ^{1}H NMR spectrum of ligand **L$_1$** in D$_2$O.

400 MHz ^{1}H NMR spectrum of ligand **L$_1$** in D$_2$O (expanded)

S4
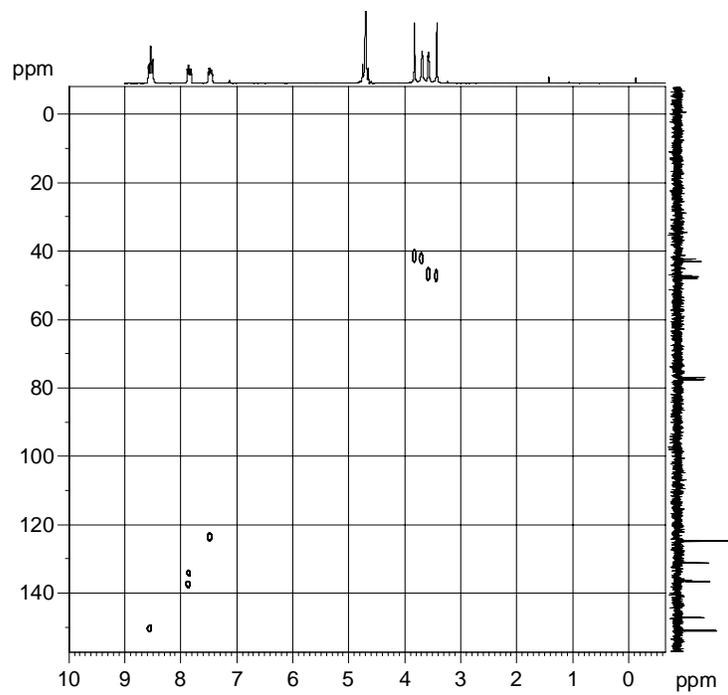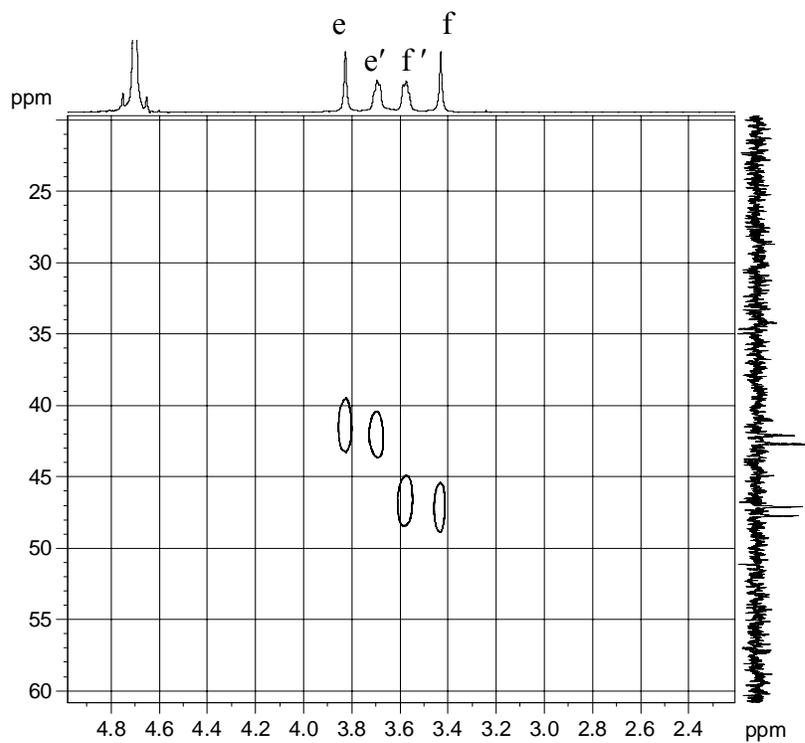
H-H COSY of ligand L_1 in D_2O

H-H COSY of ligand L_1 in D_2O (expanded)

^{13}C NMR spectrum of ligand **L$_1$** in D$_2$O.

C-H COSY of ligand **L$_1$** in D$_2$O

C-H COSY of ligand **L₁** in D₂O (expanded)

Calculation of the free energy of activation ($\Delta G^{\ddagger}$) for the hindered C-N bond rotation

From this coalescence temperature, the rate of inversion of conformation at that temperature can be calculated using the following relation.

$$k = 2.22\ \Delta v$$

In the equation, k is the rate constant for inversion from one conformer to the other and Δv is the difference in the chemical shift values of the protons in Hz *cis* and *trans* with respect to the oxygen atom.

The energy of activation ($\Delta G^{\ddagger}$) for free rotation of the C-N bond can be calculated by Eyring equation,

$$k = x \frac{k_B T}{h} e^{-\Delta G^{\ddagger}/RT}$$

Assuming the value of transmission coefficient (x) to be unity and putting the values of the constants above equation can be written as ($\Delta G^{\ddagger}$ in kJmol^{-1})

$$\Delta G^{\ddagger} = 19.14\ T_C (9.97 + log(T_C/\Delta v))$$

From the VT NMR spectra, it was found that the peaks for the methylene protons in piperazine slowly merges and gives a broad singlet at 70 °C. The peaks for the pyridine rings showed four well separated signals. The coalescence temperature for C-N bond rotation in L is 70 °C. The difference in chemical shift value between the protons *cis* and *trans* to the oxygen (Δv) was

found to be 105.60 Hz, so using Eyring equation, the energy of activation ($\Delta G^{\ddagger}$) for free rotation

of the C-N bond is $\approx$16.45 kcalmol^{-1}.
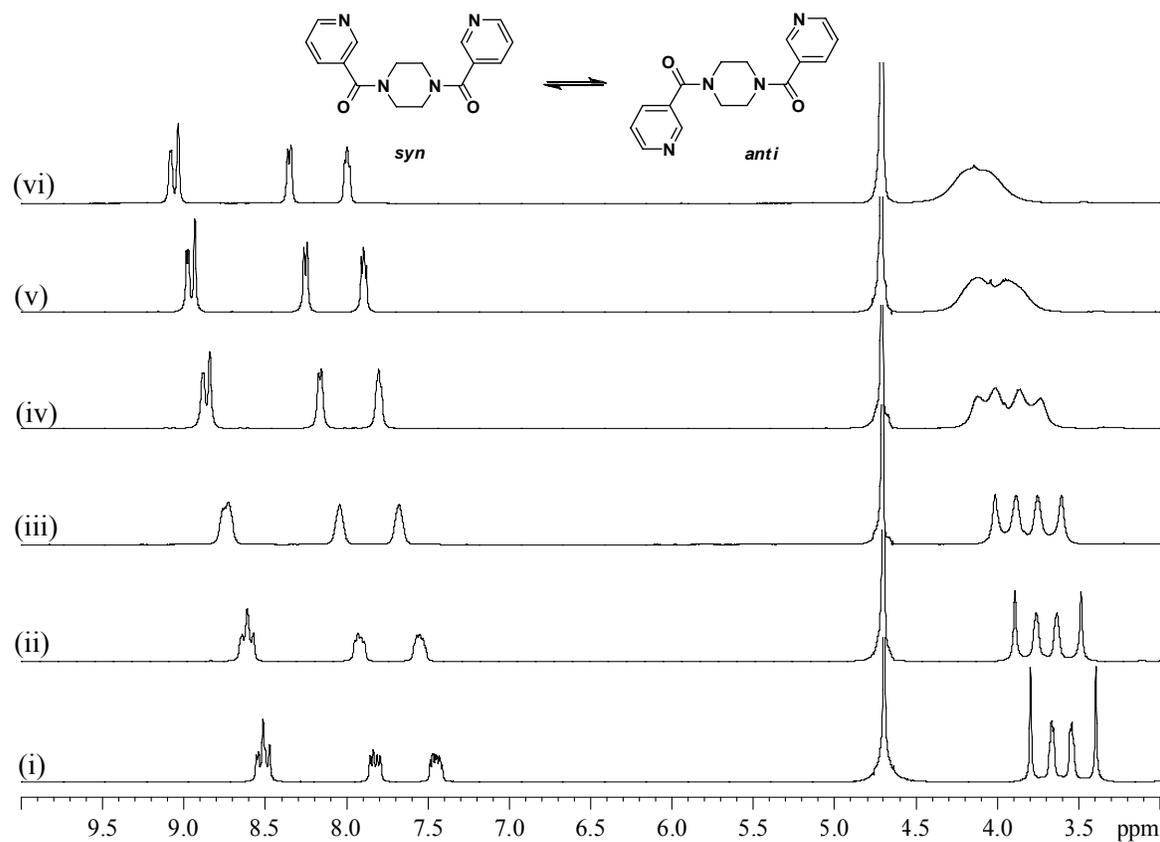
400 MHz ^{1}H NMR spectra of $\mathbf{L_1}$ in D$_2$O recorded at various temperatures, (i) 25 °C; (ii) 30 °C; (iii) 40 °C; (iv) 50 °C; (v) 60 °C and (vi) 70 °C.

Computational study for L$_1$
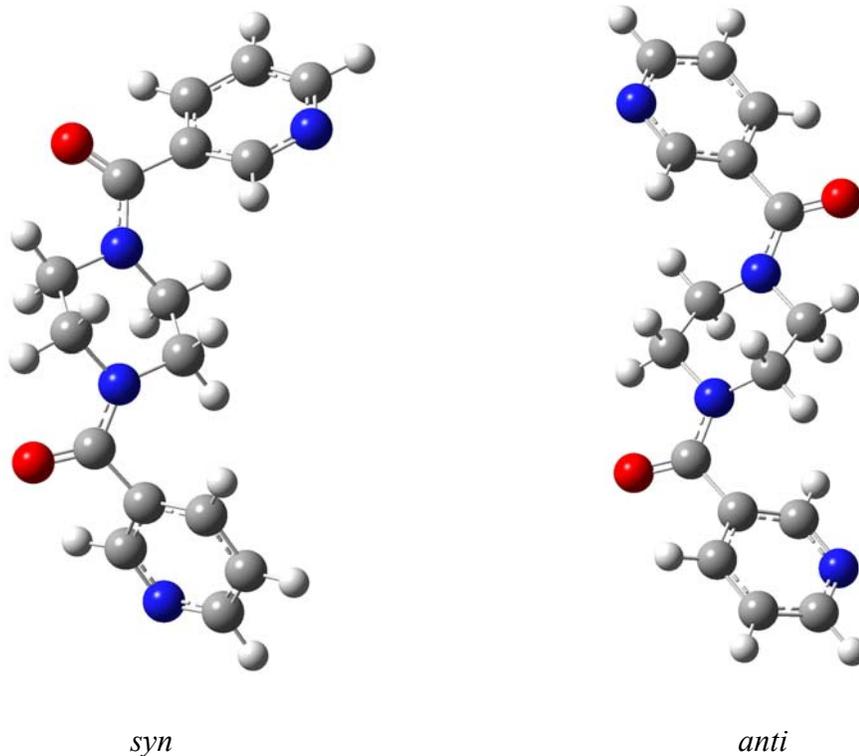
syn   anti

DFT studies on both *syn* and *anti* were undertaken using the GAUSSIAN 03 set of algorithms. The hybrid Becke-3–Lee–Yang–Parr (B3LYP) exchange correlation functional was applied for DFT calculations. Geometries were optimised at the B3LYP level of theory using 6-311G* basis sets.
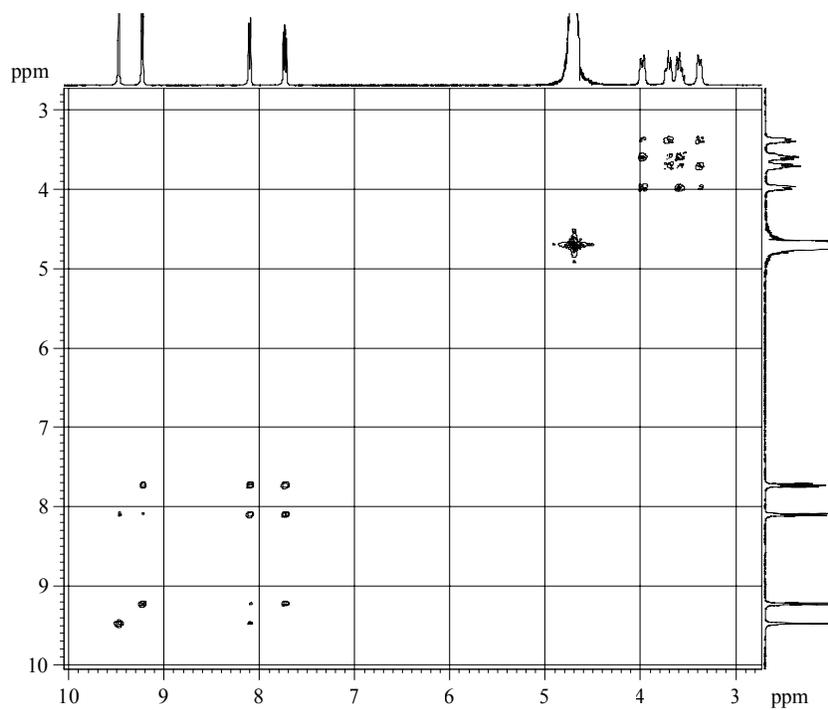
Energy for syn conformer: - 988.80069414 Hartree

Energy for trans conformer: - 988.80183874 Hartree

Synthesis of [Pd$_2$(L$_1$)$_4$](NO$_3$)$_4$, 1: Ligand L (0.032 g, 0.10 mmol) was added to a previously prepared Pd(NO$_3$)$_2$ solution in CH$_3$CN (5 mL of 10 mM, 11 mmol) at room temperatute, the solution became colorless immediately along with the formation of an off white precipitate, the resulting mixture was stirred for 30 minute. The clear solution was centrifuged and filtered, the preipitate was dissolved in water and the solution was kept for evaporation to get a colourless solid. The clear solution of the centriguged part was also kept for evaporation to get the product as a colourless solid; the two parts collected and found to be 0.038 g (yield 86%). m. p. 535 K (decomposed). Anal.Calcd for C$_{64}$H$_{64}$N$_{20}$O$_{20}$Pd$_2$: C, 46.70; H, 3.92; N, 17.02. Found: C, 46.98; H, 3.82; N, 17.28%. ^{1}H NMR (δ, D$_2$O, 400 MHz, 293 K): 9.62 (s, 8H, H_a), 9.37 (dd, J = 5.6 and 0.8 Hz, 8H, H_b), 8.24 (d, J = 8.0 Hz, 8H, H_c), 7.87 (dd, J = 7.8 and 5.8 Hz, 8H, H_d), 4.15-4.10 (m, 8H, CH_2pip), 3.86-3.81 (m, 8H, CH_2pip), 3.77-3.70 (m, 8H, CH_2pip), 3.54-3.50 (m, 8H, CH_2pip). ^{13}C NMR (δ, D$_2$O, 100 MHz, 293 K): 166.96, 153.71, 146.52, 140.96, 134.80, 129.48, 47.05 and 41.58 ppm. ESI MS (H$_2$O): *m/z* 761 [(**1**-2NO$_3$)]$^{2+}$, 487 [(**1**-3NO$_3$)]$^{3+}$.
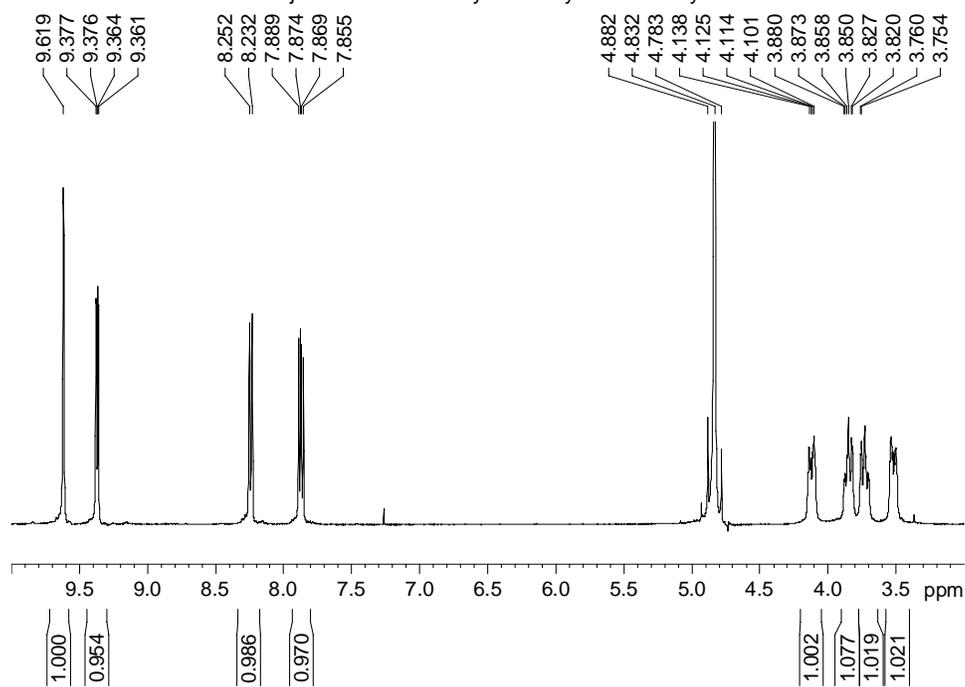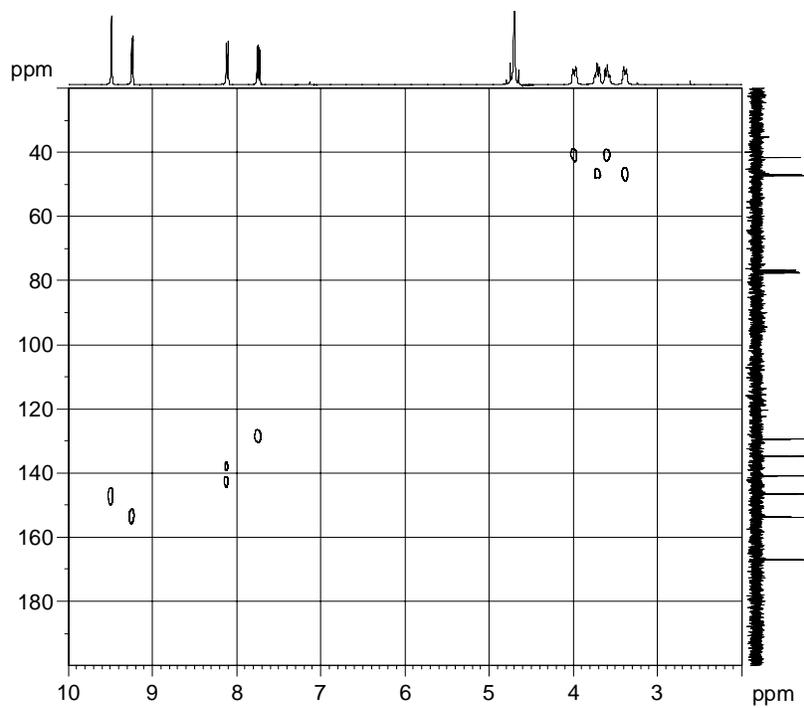
400 MHz ^{1}H NMR spectrum in D$_2$O for [Pd$_2$(**L$_1$**)$_4$](NO$_3$)$_4$, **1**.

H-H COSY for **1** in D$_2$O.

H-H COSY for **1** in D$_2$O (expanded).

^{13}C NMR for compound **1**.
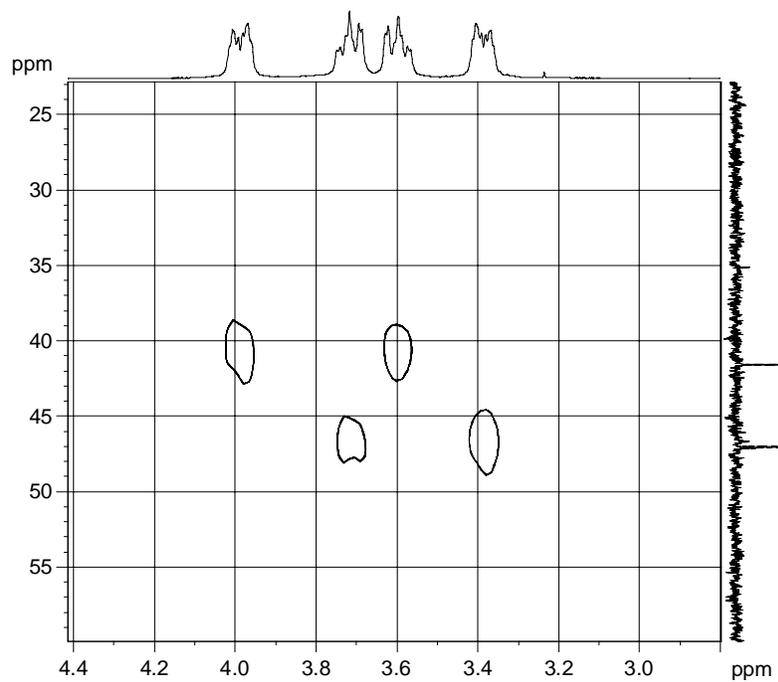
C-H COSY of $[Pd_2(\mathbf{L_1})_4](NO_3)_4$, **1**

C-H COSY of $[Pd_2(\mathbf{L_1})_4](NO_3)_4$, **1** (expanded)

M W of **18** = 1644

$[18\text{-}3NO_3]^{3+}$

$[18\text{-}2NO_3]^{2+}$
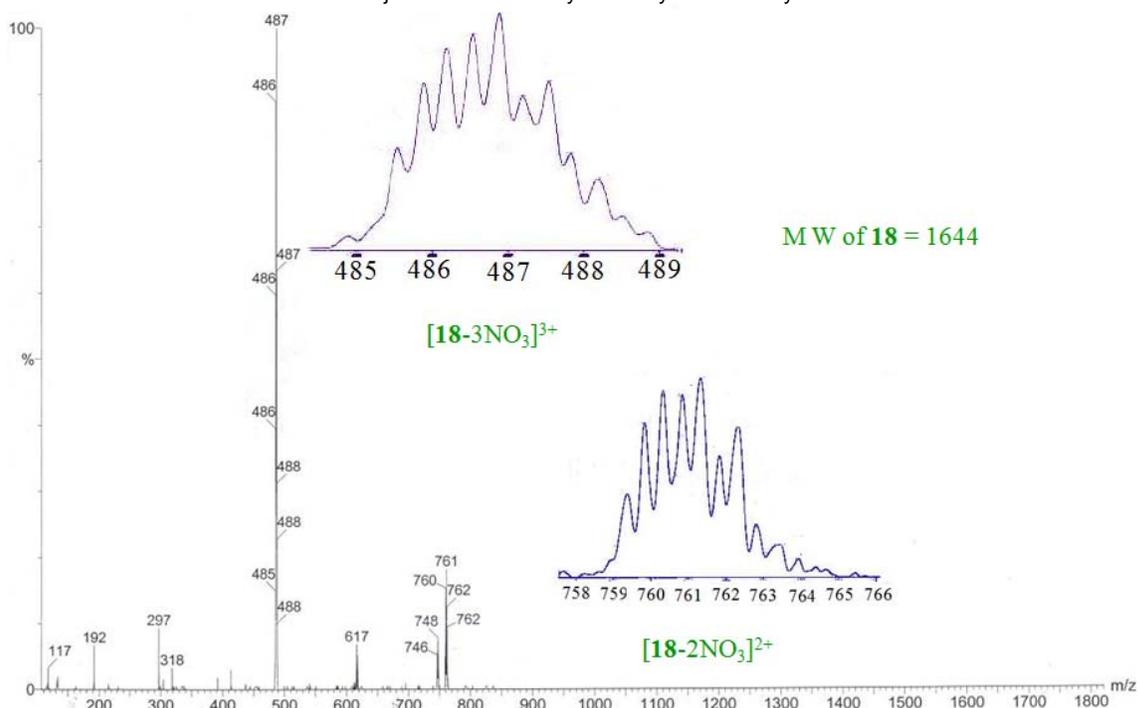
ESI MS of compound **1**.

X-ray crystal structure of $[Pd_2(L_1)_4](NO_3)_4$, 1

X-ray quality single crystals of **1** were obtained by the slow evaporation of its solution in water at room temperature. Crystallographic data was collected by Bruker X8 KAPPA APEX II and Mo Kα radiation was used. The structure was solved by direct methods and refined by full-matrix least square methods on all reflections (SHELXL-97).
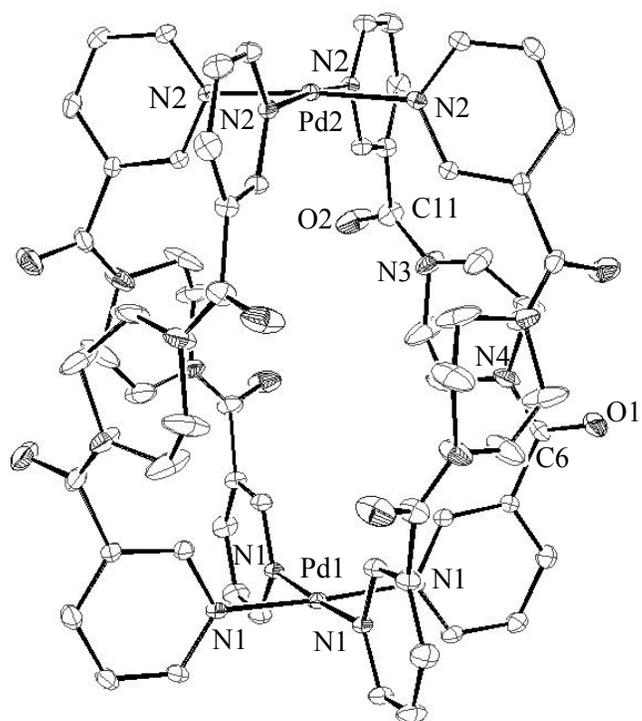
ORTEP plot of the complexed cation $[Pd_2(\mathbf{L_1})_4]^{4+}$.
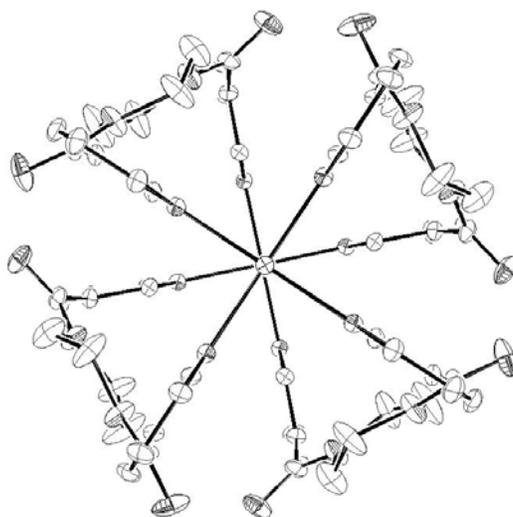
View of $[Pd_2(\mathbf{L_1})_4](NO_3)_4$, **1** along Pd-Pd axis.

Selected bond distances (Å) and bond angels (°) of compound **1**

Pd1-N1	2.010(6)	N1-Pd1-N1 (*cis*)	89.935(13)
Pd2-N2	2.013(7)	N1-Pd1-N1 (*trans*)	176.2(4)
C6-O1	1.212(12)	N2-Pd2-N2 (*cis*)	89.906(16)
C11-O2	1.214(11)	N2-Pd2-N2 (*trans*)	175.4(4)
N3-C11	1.291(13)	O1-C6-N4	122.7(10)
N4-C6	1.285(13)	O1-C6-C4	118.6(10)
Pd1-Pd2 (non bonded)	9.445(2)	N4-C6-C4	118.6(9)
		O2-C11-N3	122.8(10)
		O2-C11-C12	118.0(10)
		N3-C11-C12	119.0(9)

Crystal structural and refinement parameters for [Pd$_2$($\mathbf{L_1}$)$_4$](NO$_3$)$_4$, **1**

Parameter	[Pd$_2$($\mathbf{L_1}$)$_4$](NO$_3$)$_4$, **1**
Diffractometer	CCD-Bruker Apex II
X-ray source	Mo(Kα)
λ, Å	0.71073
MF	C$_{64}$H$_{96}$N$_{20}$O$_{48}$Pd$_2$
Fwt (g mol^{-1})	2126.41
T, K	293(2)
Crystal system	tetragonal
Space group	P4/n
a, Å	17.0336(7)
b, Å	17.0336(7)
c, Å	17.5784(9)
α, deg	90.00
β, deg	90.00
γ, deg	90.00
V, Å^3	5100.3(4)
Z	2
F(000)	2192
D$_c$ g/cm^3	1.385
Reflections measured	6354
Reflections used	3006
Abs. coeffi	0.450
No. of refined parameters	296
GOF	0.998
^{a}R (>2σ)	0.0844
^{b}Rw	0.2131

^{a}R=$\sum$| |F$_o$|−|F$_c$| |$/\sum$|F$_o$|, ^{b}R$_w$=[$\sum$w(|F$_o$|^2−|F$_c$|^2)$/\sum$w(F$_o$^{2})^2]$^{1/2}$

w =1/[σ^2(F$_o$^{2})+(0.1303P)^2+19.5464P] where P=(F$_o$^{2}+2F$_c$^{2})/3 (**1**)

For ligand exchange reactions, the ^{1}H NMR spectra were recorded at 400 MHz, and the chemical shifts were reported relative to those of the residual protons of DMSO-d_6 fixed at 3.04 ppm by using TMS in CDCl$_3$ as external standard. The compounds are prepared in DMSO-d_6 and the concentration was kept 10 mmol with respect to Pd(II); samples were heated at 60 °C/90 °C in NMR tubes. The desired temperature was achieved by immersing the tubes in a constant temperature bath. The sample tubes were taken out of the bath at chosen intervals of time, and ^{1}H NMR spectra were recorded at room temperature.
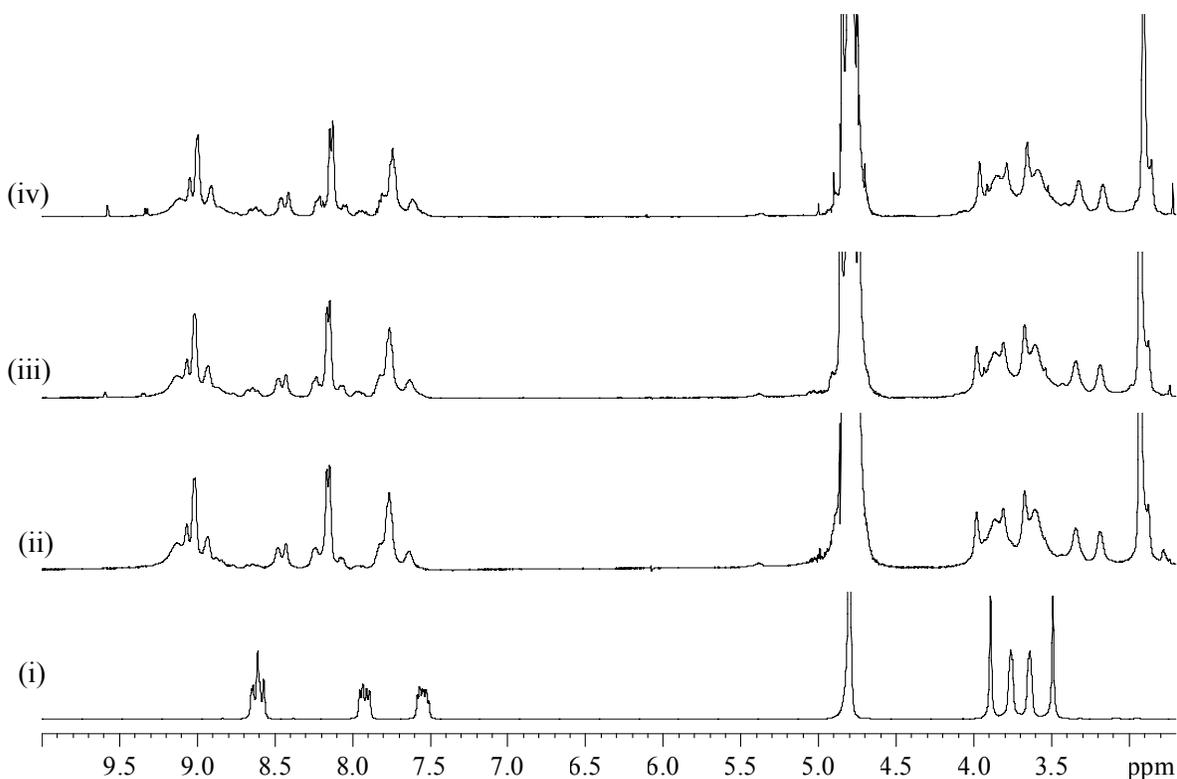
400 MHz ^{1}H NMR spectra in D$_2$O for (i) ligand $\mathbf{L_1}$; (ii) unidentified [{cis-Pd(en)}$_x$($\mathbf{L_1}$)$_y$](NO$_3$)$_{2x}$ type complex(es) at room temperature. Spectra showing formation of a small amount of **1** after heating a solution of [{cis-Pd(en)}$_x$($\mathbf{L_1}$)$_y$](NO$_3$)$_{2x}$ in D$_2$O for (iii) 12 hr and (iv) 60 hr at 60 °C.
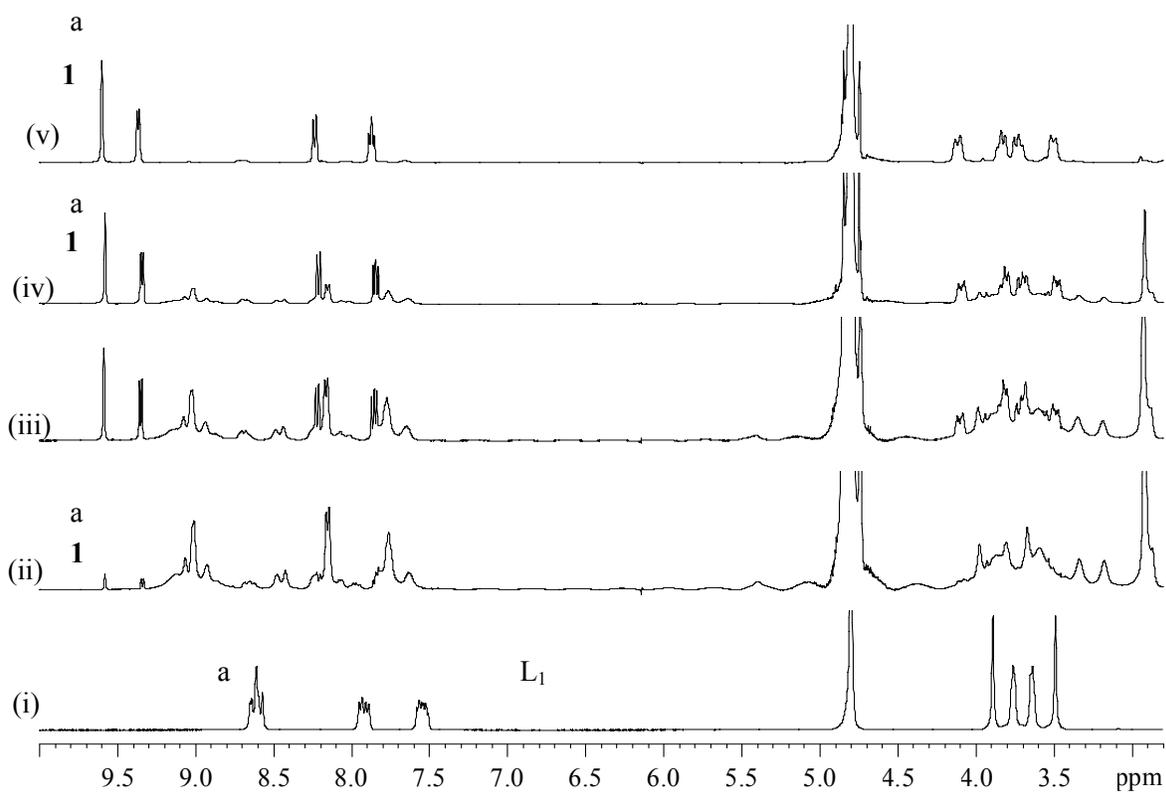
400 MHz ^{1}H NMR spectra (i) $\mathbf{L_1}$ (in D_2O); (ii) unidentified [{cis-Pd(en)}$_x$($\mathbf{L_1}$)$_y$](NO$_3$)$_{2x}$ complex(es) in D_2O: DMSO-d_6 (4:1) at r. t. Spectra showing formation of $\mathbf{1}$ after heating the cis-Pd(II) compounds for (iii) 36 hr; (iv) 75 hr and (v) 260 hr at 60 °C.