Electronic Supplementary Material (ESI) for Chemical Communications

Urea-based Constructs Readily Amplify and Attenuate Nonlinear Optical Activity in Response to H-bonding and Anion Recognition

Deepak Asthana,[a] Ravindra Pandey[b] and Pritam Mukhopadhyay*[a]

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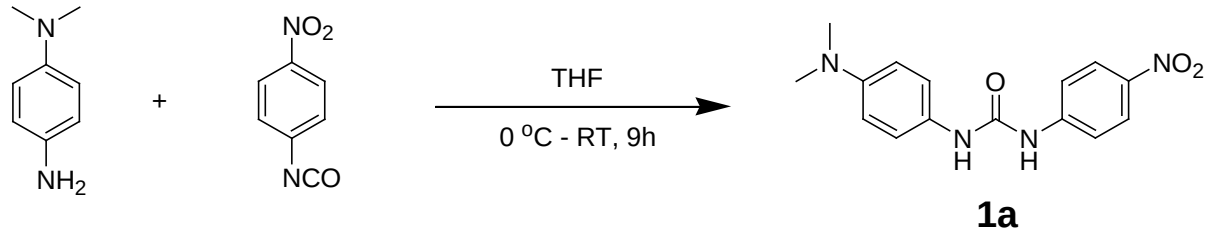
Experimental Details:

General: Starting materials 4-Nitrophenyl isocyanate, 4-Nitrophenylisothiocyanate and *N*,*N*′-dimethyl-*p*-phenylenediamine were supplied from Aldrich Chemicals and were used as received. 4-Amino-4′-(*N*,*N*-dimethylamino)stilbene was obtained from Tokyo Chemical Industries (TCI) and $COCl_2$ as 20% in toluene was purchased from Spectrochem India. The solvents tetrahydrofuran (THF) and dichloromethane (DCM) were obtained from Fisher Scientific and were freshly dried before use. Thin layer chromatography (TLC) was carried out on aluminium plates coated with silica gel mixed with fluorescent indicator having particle size of 25 µm and was sourced from Sigma Aldrich. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker 500 MHz spectrometer in DMSO-d_6 and $CDCl_3$ with TMS as an internal standard. Coupling constants (*J* values) are given in terms of Hz and chemical shifts are reported in parts per million (ppm). Splitting patterns are designated as s (singlet), d (doublet). Infra Red spectra were recorded in KBr pellet using Varian 7000 FT-IR instrument. The UV-Vis spectra were recorded on a JASCO V-670 or Shimadzu UV-2401 PC model spectrophotometer. Elemental analysis was performed on a Perkin Elmer CHN analyzer. MALDI-TOF mass spectral data were obtained by using a Bruker made Autoflex TOF/TOF instrument and α-Cyano-4-hydroxycinnamic acid as the matrix.

NLO Measurements: The NLO properties were studied using Hyper-Rayleigh Scattering (HRS) technique in THF solvent. The HRS measurements were performed using fundamental (1064 nm) output from a Q-switched Nd:YAG laser (Spectra Physics - Prolab 170, 10 Hz, 10 ns) as the incident light source. The laser beam was focused by a plano-convex lens to a point 2-3 cm away from the center of the cylindrical sample cell of diameter 2.5 cm and volume ~ 15 cc. The incident laser power was kept at < 10 mJ/pulse so that the dielectric breakdown, self focusing or defocusing etc., could be avoided. The scattered second harmonic (SH) photons (532 nm) were collected at 90° with respect to incident beam direction, using a photomultiplier tube (PMT). The PMT output signal was digitized and averaged over 512 shots on a 500 MHz digital storage oscilloscope. The solute concentrations were kept in the range of 10^{-3} to 10^{-5} M.

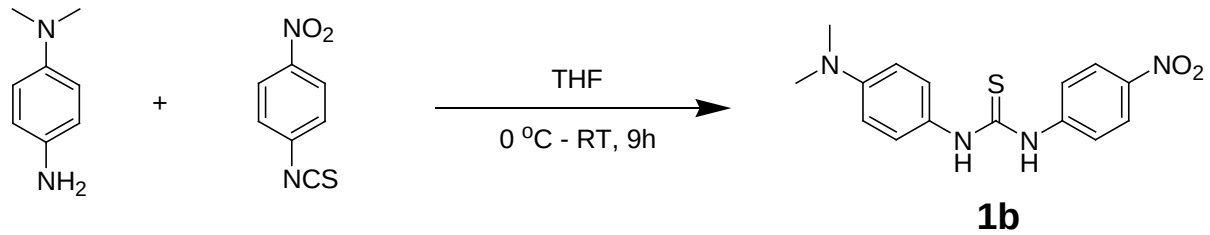
Synthesis of 1a:



1a

Synthetic procedure: In a 50 ml round bottomed (RB) flask containing 18 ml freshly dried THF, 4-Nitrophenylisocyanate (3.3 mmol) was taken and stirred for 10 min. at 0 °C. Subsequently *N*,*N*′-dimethyl-*p*-phenylenediamine (2.2 mmol) was added to ice cooled RB and stirred for 9 h with gradual heating to room temperature. Solvent was evaporated using a rotary evaporator and residue was purified by washing it with DCM.[1] Yield: 70%. R_f = 0.51 (9:1 $CHCl_3$/MeOH). Melting Point: 240 °C. ^{1}H NMR (500 MHz, DMSO-d_6, 300K): δ= 9.31 (s, 1H, NH), 8.56 (s, 1H, N*H*), 8.17 (d, 2H, *J* = 9.0 Hz, Ar), 7.67 (d, 2H, *J* = 9.0 Hz, Ar), 7.28 (d, 2H, *J* = 9.0 Hz, Ar), 6.71 (d, 2H, *J* = 9.0 Hz, Ar), 2.84 (s, 6H, N(C*H*$_3$)$_2$). ^{13}C NMR (125 MHz, DMSO-d_6, 300K): δ= 152.56, 147.36, 141.14, 129.00, 125.62, 121.10, 118.46, 117.65, 113.48, 41.06. MS (MALDI-TOF, matrix- α-cyano-4-hydroxycinnamic acid): 299.3 (m/z). FTIR (KBr): 3310 (υ_{NH}), 2895, 1644 (υ_{CO}), 1608, 1549, 1406, 1335. Anal. calcd. for $C_{15}H_{16}N_4O_3$: C 59.99, H 5.37, N 18.66; Found for C 59.89, H 5.30, N 18.78.

Synthesis of 1b:

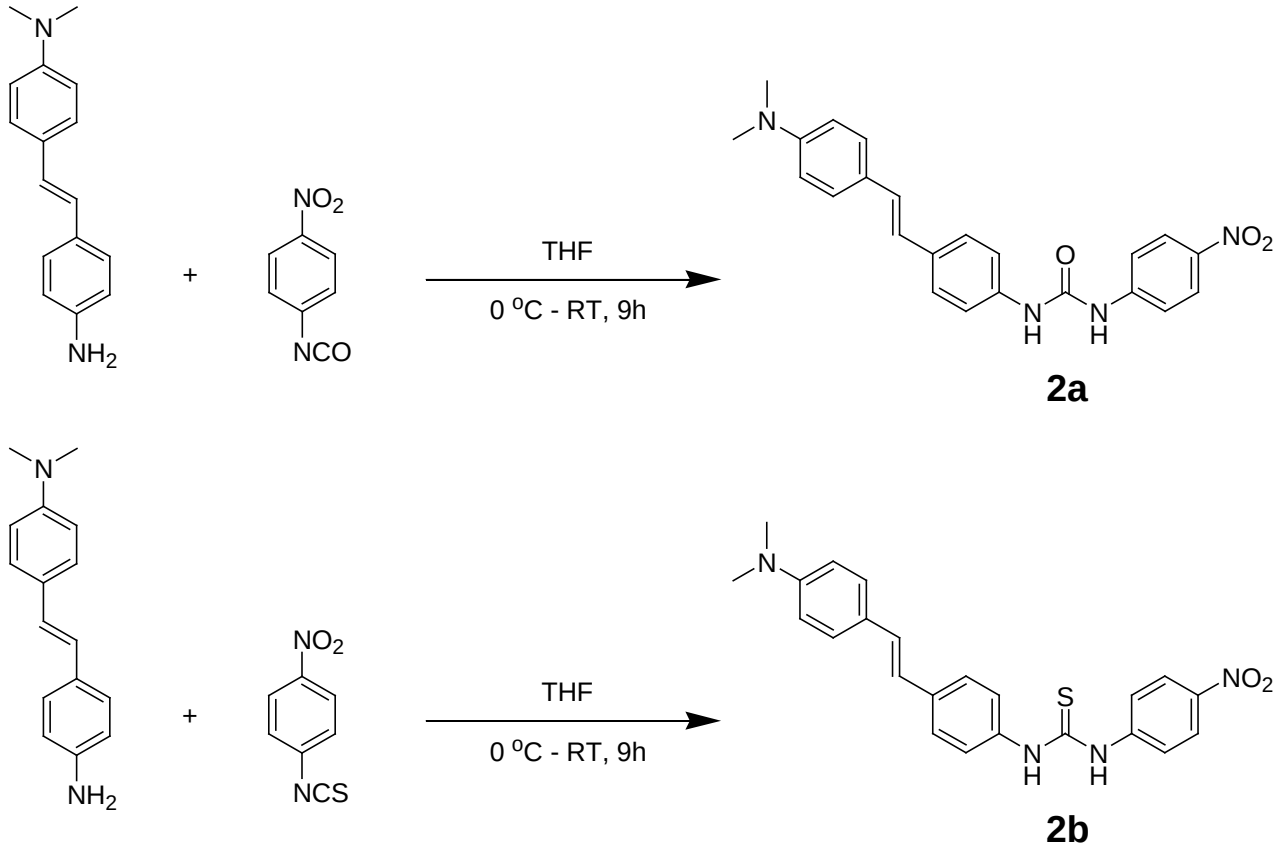


1b

Synthetic procedure: In a 50 ml round bottomed flask containing 18 ml dry THF, 4-Nitrophenyl isothiocyanate (6.6 mmol) was taken and stirred for 10 min. at 0 °C. To this solution *N*,*N*′-dimethyl-*p*-phenylenediamine (4.4 mmol) was added and stirred for 9 h with gradual warming to RT. The solvent was evaporated using a rotary evaporator and residue was purified by washing it with DCM. Yield: 71%. R_f = 0.76 (9:1 $CHCl_3$/MeOH). Melting Point: 208 °C. ^{1}H NMR (500 MHz, DMSO-d_6, 300K): δ= 10.08 (s, 1H, NH), 9.99 (s, 1H, NH), 8.18 (d, 2H, *J* = 9.0 Hz, Ar), 7.84 (d, 2H, *J* = 9.0 Hz, Ar), 7.24 (d, 2H, *J* = 9.0 Hz, Ar), 6.71 (d, 2H, *J* = 9.5 Hz, Ar), 2.89 (s, 6H, N(C*H*$_3$)$_2$). ^{13}C NMR (125 MHz, DMSO-d_6, 300K): δ= 179.51, 148.90, 147.11, 142.45, 128.19, 125.94, 124.75, 121.77, 112.72, 40.76. MS

(MALDI-TOF, matrix- α-cyano-4-hydroxycinnamic acid): 316.2 (m/z). FTIR (KBr): 3262, 3225 (υ_{NH}), 2895, 1595, 1516, 1421, 1339. Anal. calcd. for $C_{15}H_{16}N_4O_2S$: C 56.94, H 5.10, N 17.71; Found for C 56.87, H 5.18, N 17.80.

Synthesis of 2a and 2b:

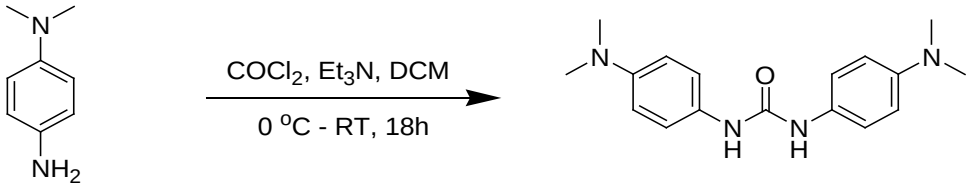


Synthetic procedures for 2a and 2b: Compounds **2a** and **2b** were synthesized in good yields by reacting 4-amino-4′-(*N*,*N*-dimethylamino)stilbene with 4-Nitrophenylisocyanate and 4-Nitrophenylisothiocyanate following the procedures similar to **1a** and **1b** respectively.

2a: R_f = 0.57 (9:1 $CHCl_3$/MeOH). Melting Point: 262 °C. ^{1}H NMR (500 MHz, DMSO-d_6, 300K): δ= 9.32 (s, 1H, NH), 8.83 (s, 1H, NH), 8.18 (d, 2H, *J* = 9.5 Hz, Ar), 7.69 (d, 2H, *J* = 9.0 Hz, Ar), 7.45 (d, 4H), 7.39 (d, 2H, *J* = 9.0 Hz, Ar), 7.04 - 6.87 (2H), 6.71 (d, 2H, *J* = 8.5 Hz, Ar), 2.94 (s, 6H, N(CH_3)$_2$). ^{13}C NMR (125 MHz, DMSO-d_6, 300K): δ= 152.30, 150.26, 146.85, 141.46, 138.13, 132.81, 127.74, 127.63, 126.85, 125.63, 123.75, 119.23, 118.46, 117.93, 112.77, 40.51 MS (MALDI-TOF, matrix- α-cyano-4-hydroxycinnamic acid): 402 (m/z). FTIR (KBr): 3308 (υ_{NH}), 2804, 1651 (υ_{CO}), 1605, 1551, 1502, 1344. Anal. calcd. for $C_{23}H_{22}N_4O_3$: C 68.64, H 5.51, N 13.92; Found for C 68.53, H 5.43, N 14.10.

2b: R_f = 0.77 (9:1 $CHCl_3$/MeOH). Melting Point: 212 °C. ^{1}H NMR (500 MHz, DMSO-d_6, 300K): δ= 10.35 (s, 1H, NH), 10.29 (s, 2H, NH), 8.21 (d, 2H, *J* = 7.5 Hz, Ar), 7.84 (d, 2H, *J* = 8.0 Hz, Ar), 7.52-7.41 (m, 6H), 7.11-6.94 (2H), 6.72 (d, 2H, *J* = 7.5 Hz, Ar), 2.93 (s, 6H, N(CH_3)$_2$). ^{13}C NMR (125 MHz, DMSO-d_6, 300K): δ= 179.36, 150.43, 147.11, 142.73, 137.84, 135.19, 128.84, 127.94, 126.45, 125.46, 124.85, 124.08, 123.44, 121.99, 112.72, 40.60. MS (MALDI-TOF, matrix- α-cyano-4-hydroxycinnamic acid): 418.3 (m/z). FTIR (KBr): 3298 (υ_{NH}), 2895, 1598, 1525, 1441, 1331. Anal. calcd. for $C_{23}H_{22}N_4O_2S$: C 66.01, H 5.30, N 13.39, O 7.65, S 7.66. Found for C 66.12, H 5.43, N 13.12.

Synthesis of 3:



Synthetic procedure: In a 50 ml round bottomed flask containing 15 ml dry DCM, *N*,*N*′-dimethyl-*p*-phenylenediamine (14.6 mmol) was taken and stirred with Et_3N (36.6 mmol) for 10 min. The mixture was cooled to 0 °C and $COCl_2$ (7.3 mmol) was added to this solution. The reaction mixture was stirred for 18 h and gradually brought to room temperature. The precipitate obtained after filtration was purified by washing it with MeOH.[2] Yield: 55%. R_f = 0.50 (9:1 $CHCl_3$/MeOH). Melting Point: 250 °C. ^{1}H NMR (500 MHz, DMSO-d_6, 300K): δ= 8.11 (s, 2H, NH), 7.23 (d, 4H, *J* = 8.5 Hz, Ar), 6.67 (d, 4H, *J* = 9.0 Hz, Ar), 2.81 (s, 12H, N(CH_3)$_2$). ^{13}C NMR (125 MHz, DMSO-d_6, 300K): δ= 153.60, 146.72, 130.46, 120.42, 113.7, 41.24. MS (MALDI-TOF, matrix- α-cyano-4-hydroxycinnamic acid): 298.6 (m/z). FTIR (KBr): 3315 (υ_{NH}), 2882, 2797, 1649, 1603, 1516, 1445, 1313. Anal. calcd. for $C_{17}H_{22}N_4O$: C 68.43, H 7.43, N 18.78; Found for C 68.35, H 7.32, N 18.89.

Measurement of β by HRS experiment:

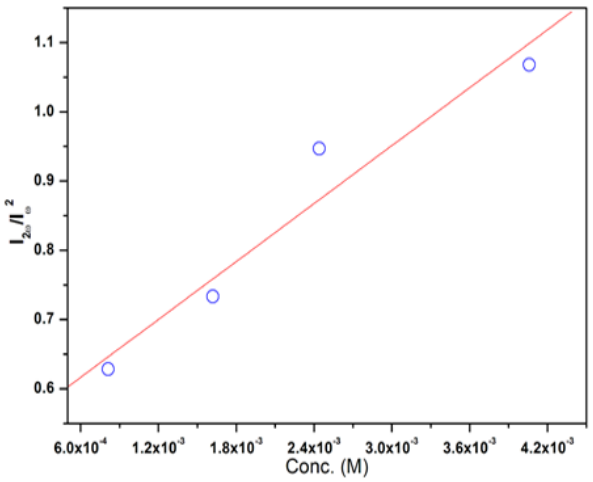
The β values were calculated using the p-NA as external reference (21.4 x 10^{-30} esu) using the following relation.[3]

$$\frac{\langle \beta^2_R \rangle}{\langle \beta^2_S \rangle} = \frac{(\text{Slope})_R}{(\text{Slope})_S}$$

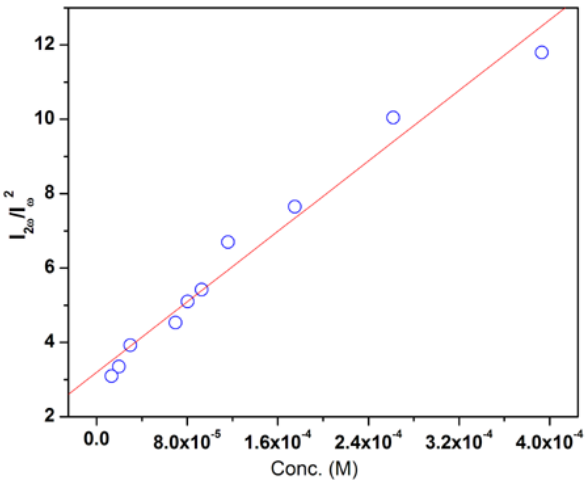
Where, the subscripts R and S denote the reference and sample respectively. The slopes are obtained by plotting the SH intensity as a function of concentration which results in a straight line showing the linear dependence of SH signal on number of molecules present in solution.

Figures S1 (a – h) show the plots of second harmonic intensities as a function of solute concentrations.

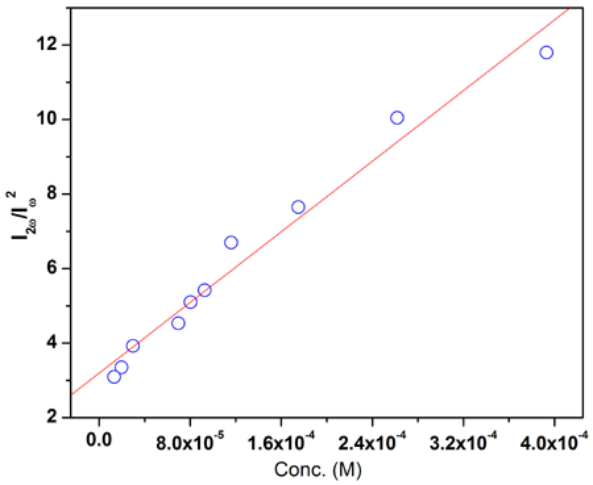
a) **p-NA** in THF, Slope = 139.46



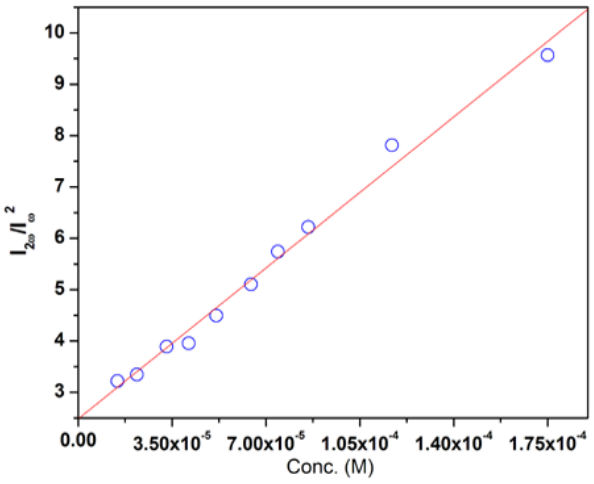
b) **1a** in THF, Slope = 23701



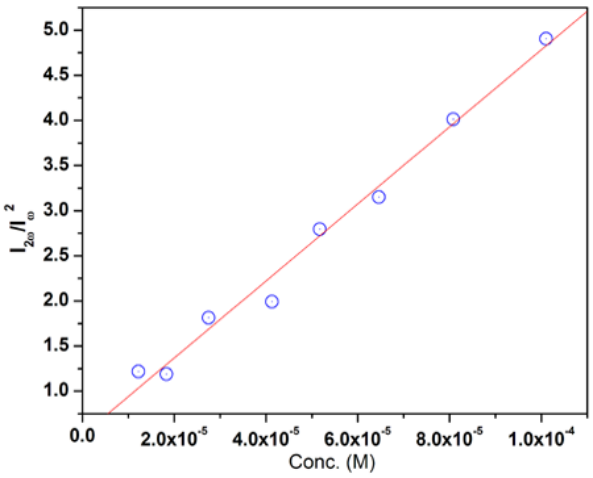
c) **1b** in THF, Slope = 14071.7



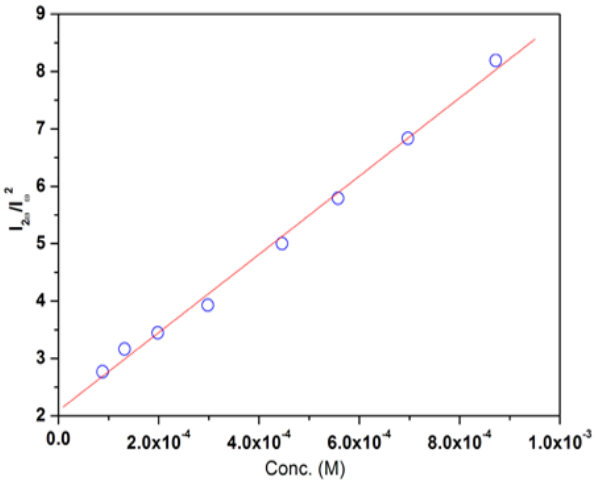
d) **2a** in THF, Slope = 41993.8



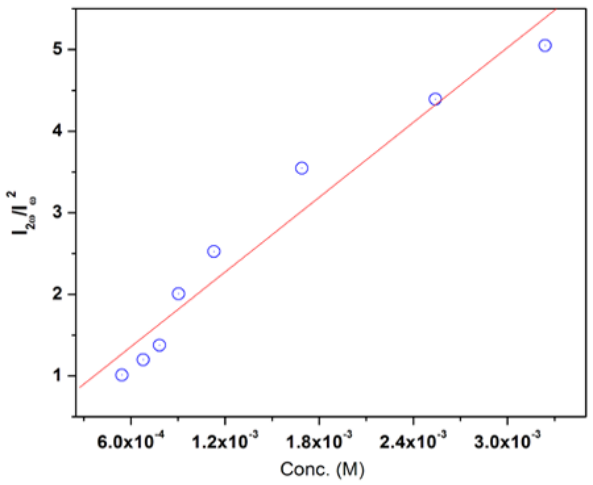
e) **2b** in THF, Slope = 42690.8



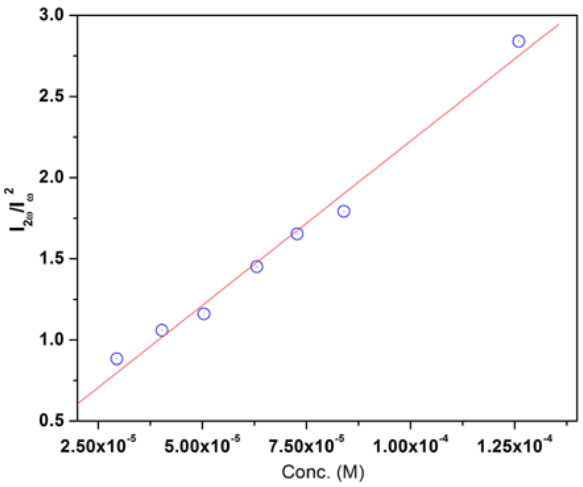
f) **3** in THF, Slope = 6813



g) **p-NA** in MeOH, Slope = 1528



h) **1a** in MeOH, Slope = 20243



^{1}H NMR titration of 1b in $CDCl_3$:

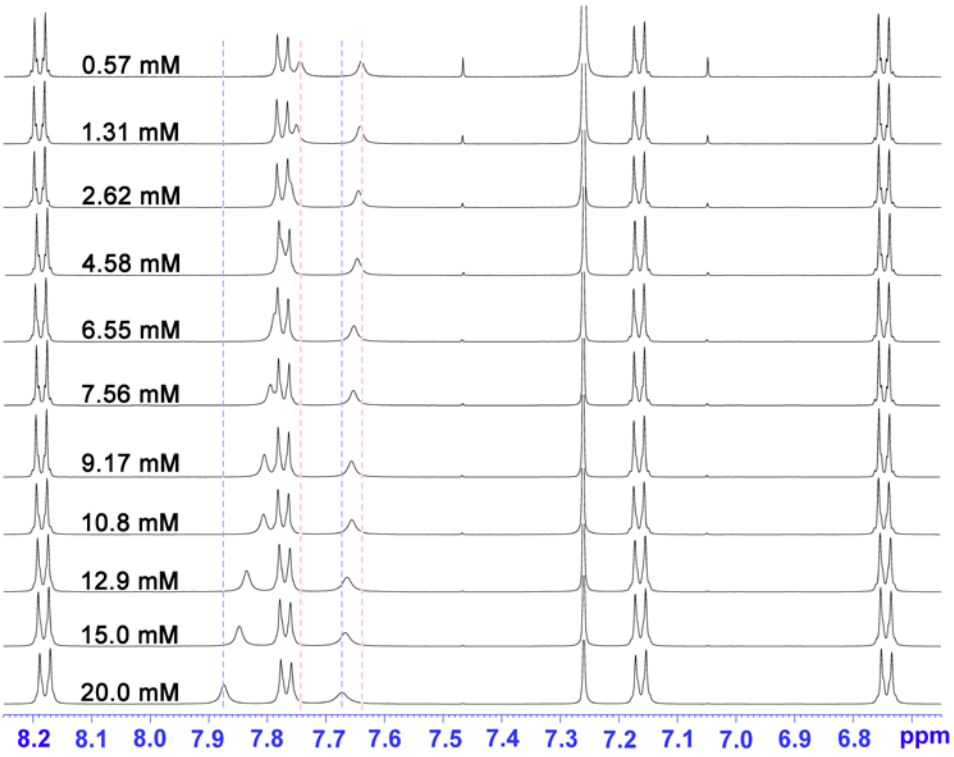


Figure S2: ^{1}H NMR spectra of **1b** in $CDCl_3$ at different concentrations at 298 K.

Calculation of Association Constant by concentration dependent ^{1}H NMR titration of 1b:

The self-association constant of **1b** in $CDCl_3$ was found to be 38.3 M^{-1}, calculated by fitting the plot obtained by plotting the chemical shift of NH proton against the concentration using a nonlinear least-squares analysis according to a three parameter isodesmic self-association model following equation given below: [4b,c]

Considering an isodesmic infinite reversible polymerization of monomer A ($\mathbf{K_2} = \mathbf{K_3} = \ldots\mathbf{K_i}\ \ldots = \mathbf{K}$) in solution:

$$A + A \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} A_2 \qquad K_2 = \frac{k_2}{k_{-2}} = \frac{[A_2]}{[A]^2}$$

$$A_2 + A \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} A_3 \qquad K_3 = \frac{k_3}{k_{-3}} = \frac{[A_3]}{[A][A_2]}$$

$$\vdots \qquad\qquad \vdots$$

$$A_{i-1} + A \underset{k_{-i}}{\overset{k_i}{\rightleftharpoons}} A_i \qquad K_i = \frac{k_i}{k_{-i}} = \frac{[A_i]}{[A][A_{i-1}]}$$

Free monomer concentration **[A]** can be written as,

$$[A] = \frac{1}{2}\frac{2CK + 1 - (4CK + 1)^{1/2}}{CK^2}$$

Where, **C** is initial total concentration of monomer.

Under fast exchange process the observed chemical shift can be given as:

$$\delta_{obs} = f_a\delta_a + f_b\delta_b + f_c\delta_c$$

Where, f_a, f_c and f_b represent the mole fraction of monomer, mole fraction of molecules at stack ends and mole fraction of molecules in a stack interior and corresponding **δ** values denote the chemical shifts.

With the help of above parameters the mole fractions can be written as:

$$f_a = \frac{1}{2}\frac{2CK + 1 - (4CK + 1)^{1/2}}{C^2K^2}$$

$$f_b = \frac{K^2A^3}{(1-KA)^2 C}$$

And,

$$f_c = \frac{2KA^2}{(1-KA)\,C}$$

Assuming that chemical shift of molecule at stack end to equal to average of monomer and interior stacks and combining above equations results in following expression:

$$\delta_{obs} = \delta_a + (\delta_b - \delta_a)\left(1 + \frac{1}{2}\frac{1 - (4CK + 1)^{1/2}}{CK}\right)$$

Where, δ_{obs} is the shift observed at a particular concentration, δ_a is the shift corresponding to monomer when there is no association at very low concentration, δ_b is the shift of stacked or associated molecules, **K** is the association constant and **c** is the concentration.

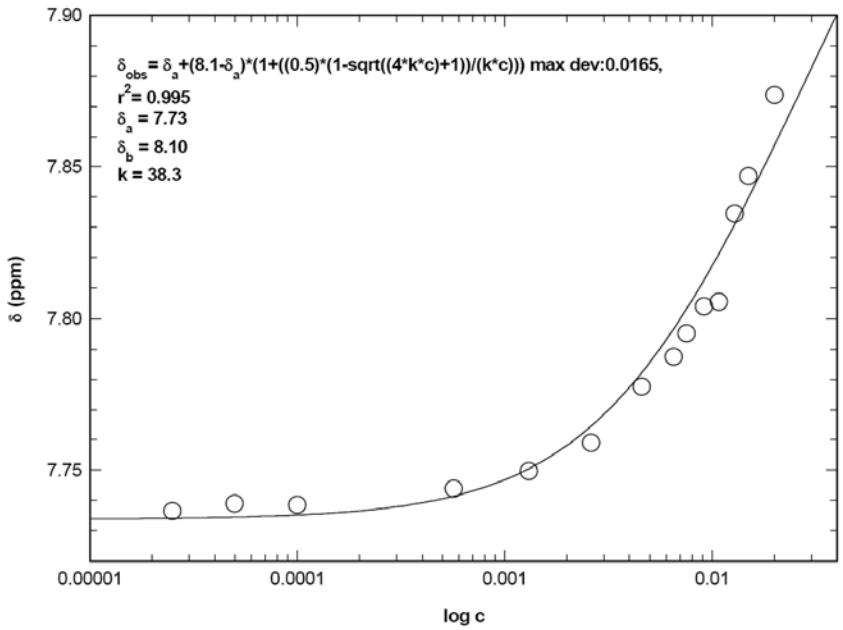


Figure S3: Curve showing the nonlinear least-squares fitting of chemical shift against concentration to obtain self association constant of **1b**.

Temperature dependent ^{1}H NMR spectra of 1b ($CDCl_3$):

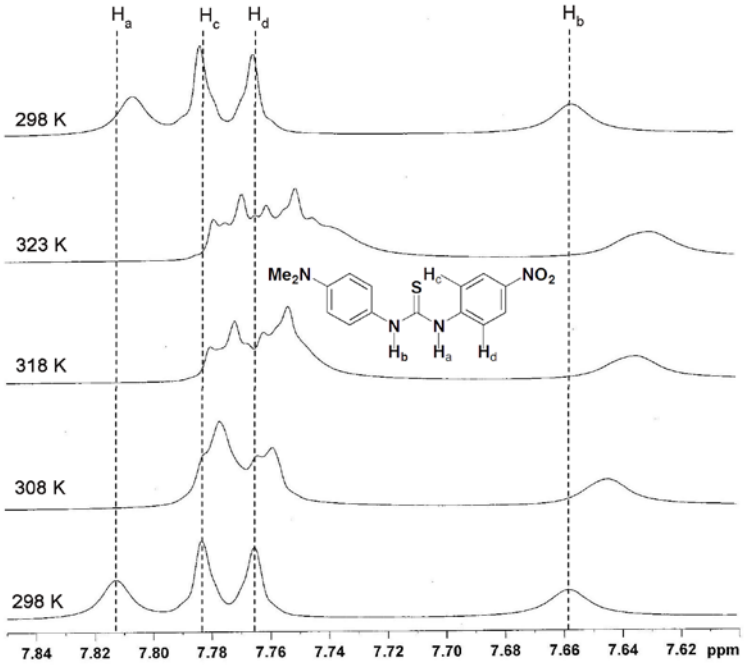
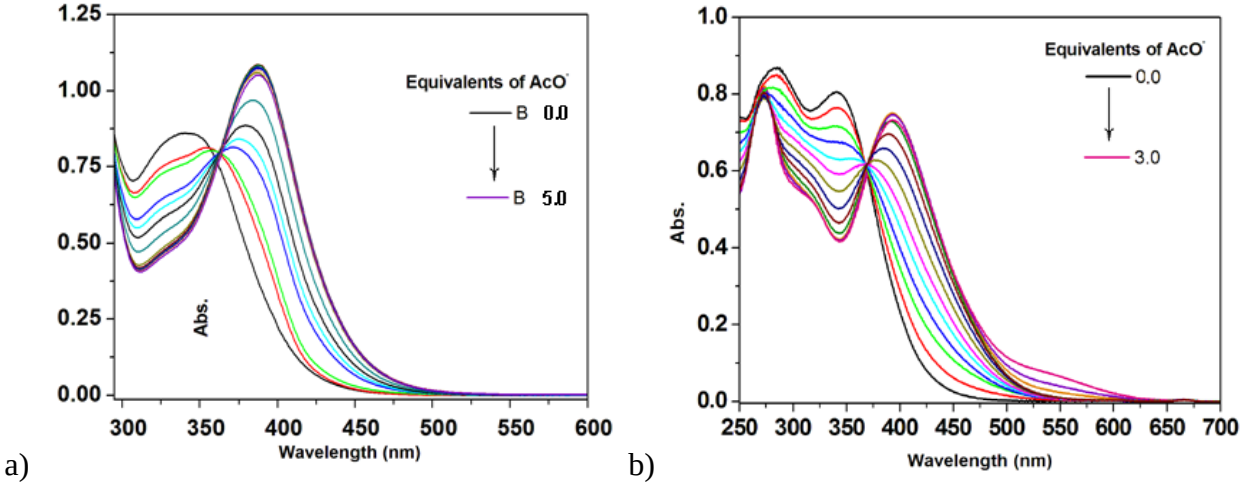


Figure S4: Temperature dependent ^{1}H NMR spectra of **1b** in $CDCl_3$.

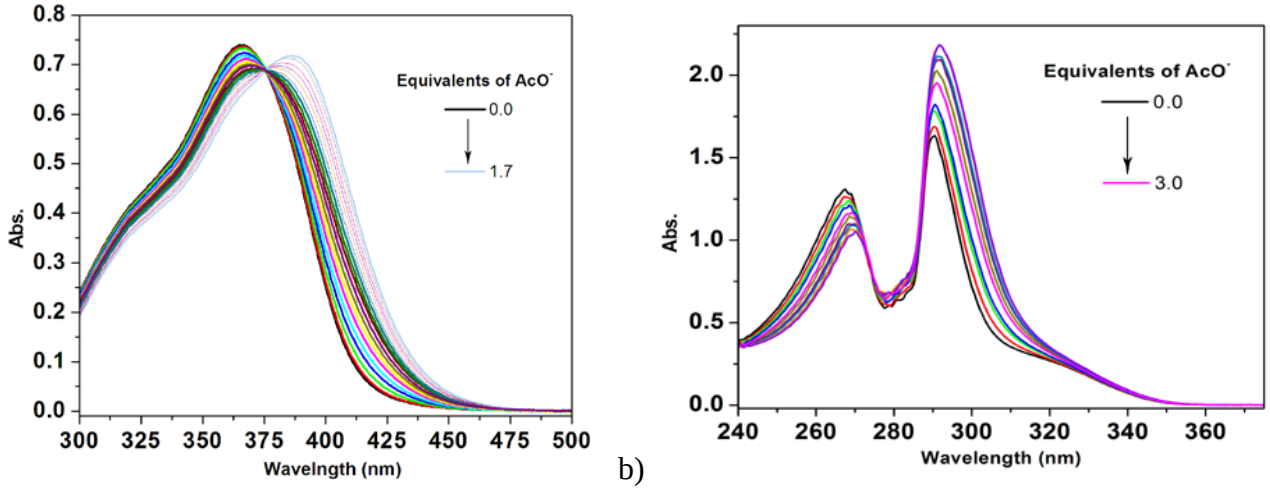
UV-Vis titrations:

The UV-Vis absorption experiments were performed in THF solvent. Anions were used as their tetrabutylammonium salts and AcO^- was dried before use.



a) b)

Figure S5: (a) UV-Vis titration of compound **1a** (5×10^{-5} M) with AcO^- (5×10^{-3} M) in THF; (b) UV-Vis titration of compound **1b** (5×10^{-5} M) with AcO^- (5×10^{-3} M) in THF.



a) b)

Figure S6: (a) UV-Vis titration of compound **2a** (1×10^{-5} M) with AcO^- (0.86×10^{-3} M) in THF; (b) UV-Vis titration of compound **3** (5×10^{-5} M) with AcO^- (5.5×10^{-3} M) in THF.

Calculation of Anion Binding Constant by UV-Vis titration:

The binding constant of AcO^- with **1a** in THF was determined to be 5.3×10^4 M^{-1} from measurements of absorbance as a function of AcO^- concentration using the following equation[4a]

$$\frac{\Delta A}{L} = \frac{[D_1]\, K\, \Delta\varepsilon\, [M]}{1 + K\, M}$$

Where, ΔA is the absorbance difference at 387 nm between only **1a** solution and **1a** + AcO^-, L is path length, D_1 is total **1a** concentration, M is concentration of excess AcO^-, $\Delta\varepsilon$ is the change in excitation coefficient at 387 nm between **1a** and **1a**+AcO^-.

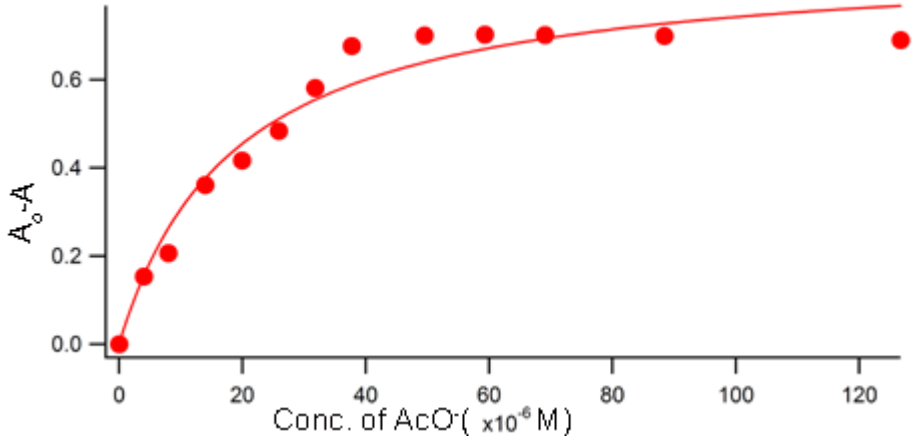


Figure S7: Calculation of binding constant by UV-Vis titration.

Diffusion Constant (D) Measurement by NMR:

Diffusion constants, D of **1b** and **1b + AcO**$^-$ (2.1 equivalents) were obtained by performing DOSY experiments in $CDCl_3$ using a Bruker 500 MHz spectrometer. During DOSY experiments the temperature was set at 15 ^oC and a 15 mM solution was used in both cases. In a 5 mm NMR tube 600 µl solution of **1b** or **1b + AcO**$^-$ was taken for each experiment. Pulse sequence ledbpgp2s was used keeping diffusion time (D20) 60 ms, gradient length (P30) equal to 3 ms. Diffusion data were collected using a linear gradient ramp from 2 – 95 % of the maximum gradient strength. The diffusion coefficients were calculated using available T1/T2 relaxation module.

Molecule	**D** (x 10^{-9} m^2/s)
1b	1.24
1b + AcO$^-$	1.38

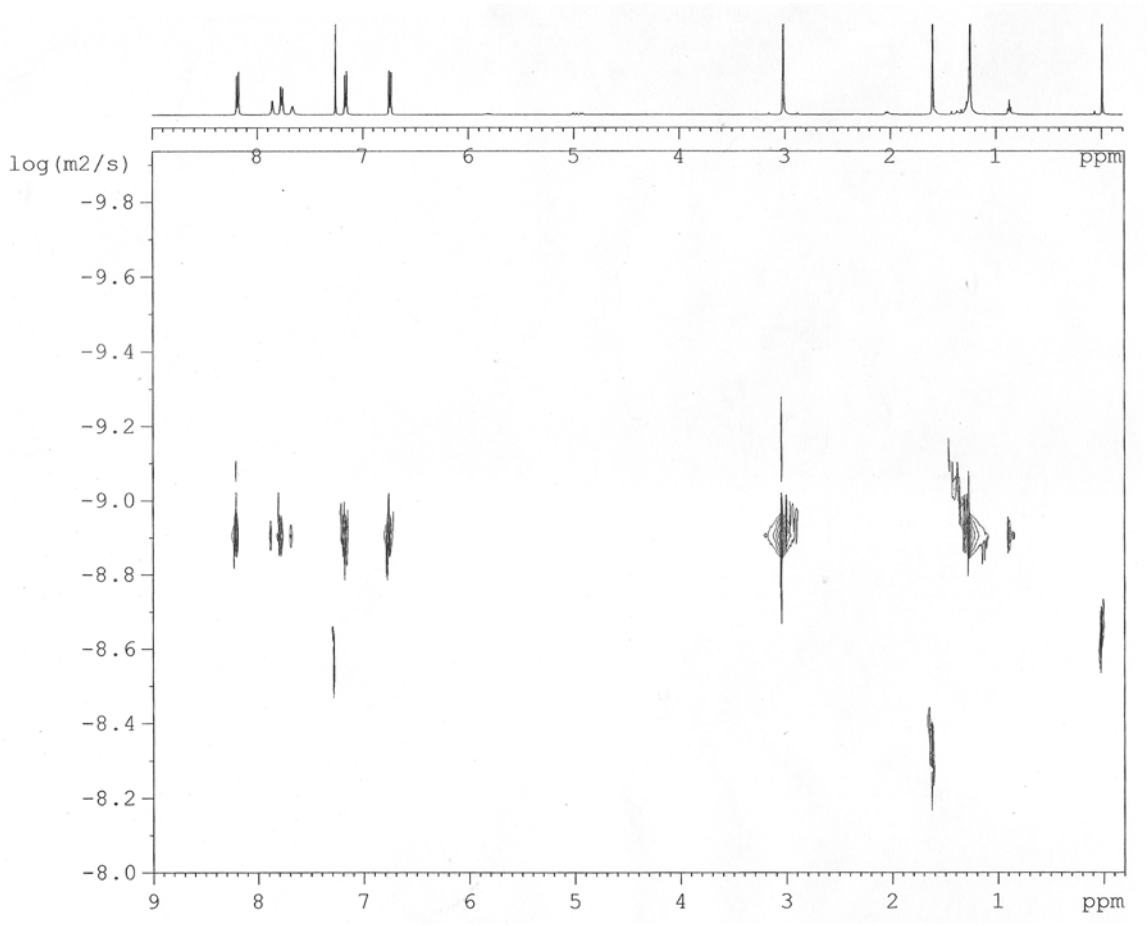


Figure S8: DOSY NMR spectrum (500 MHz) of **1b** (15 mM) and ^1H NMR spectrum at top in $CDCl_3$ at 15 ^0C temperature.

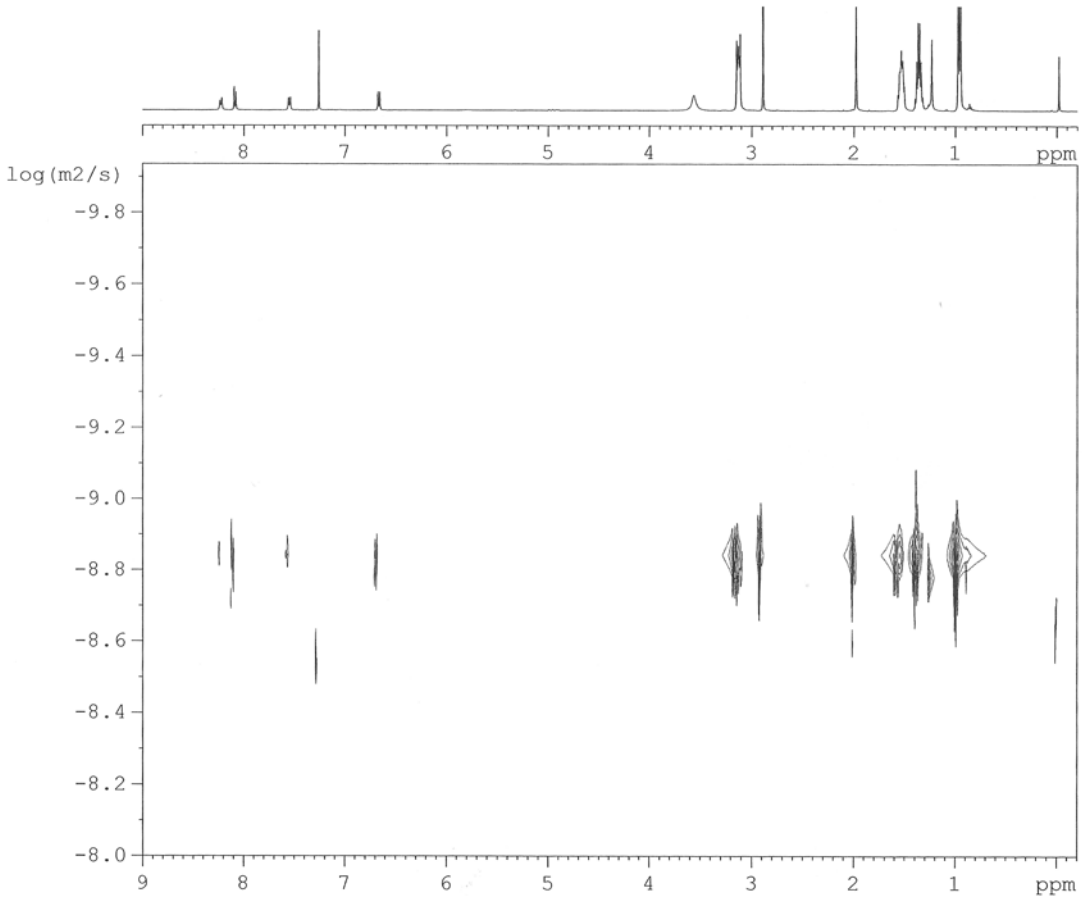
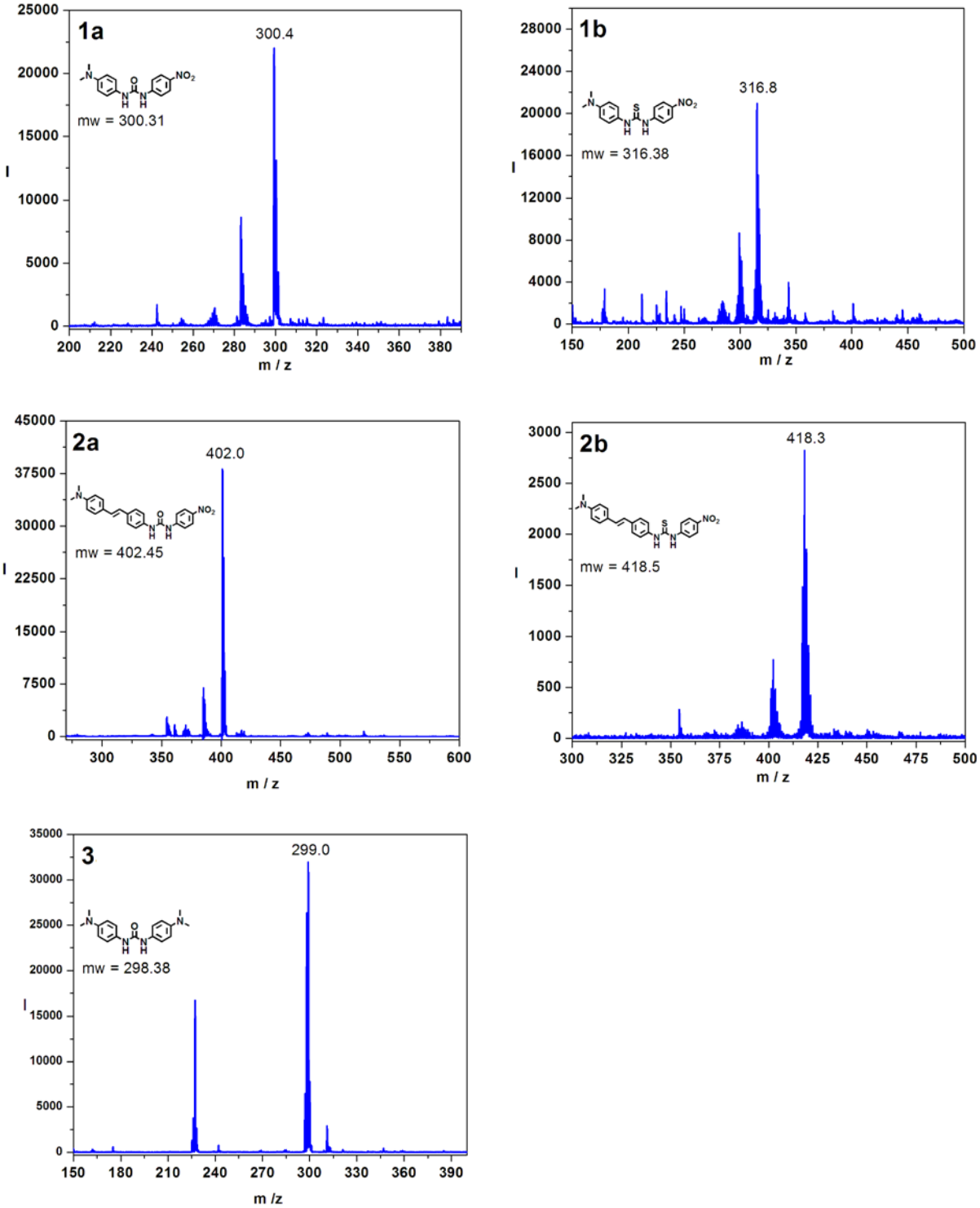


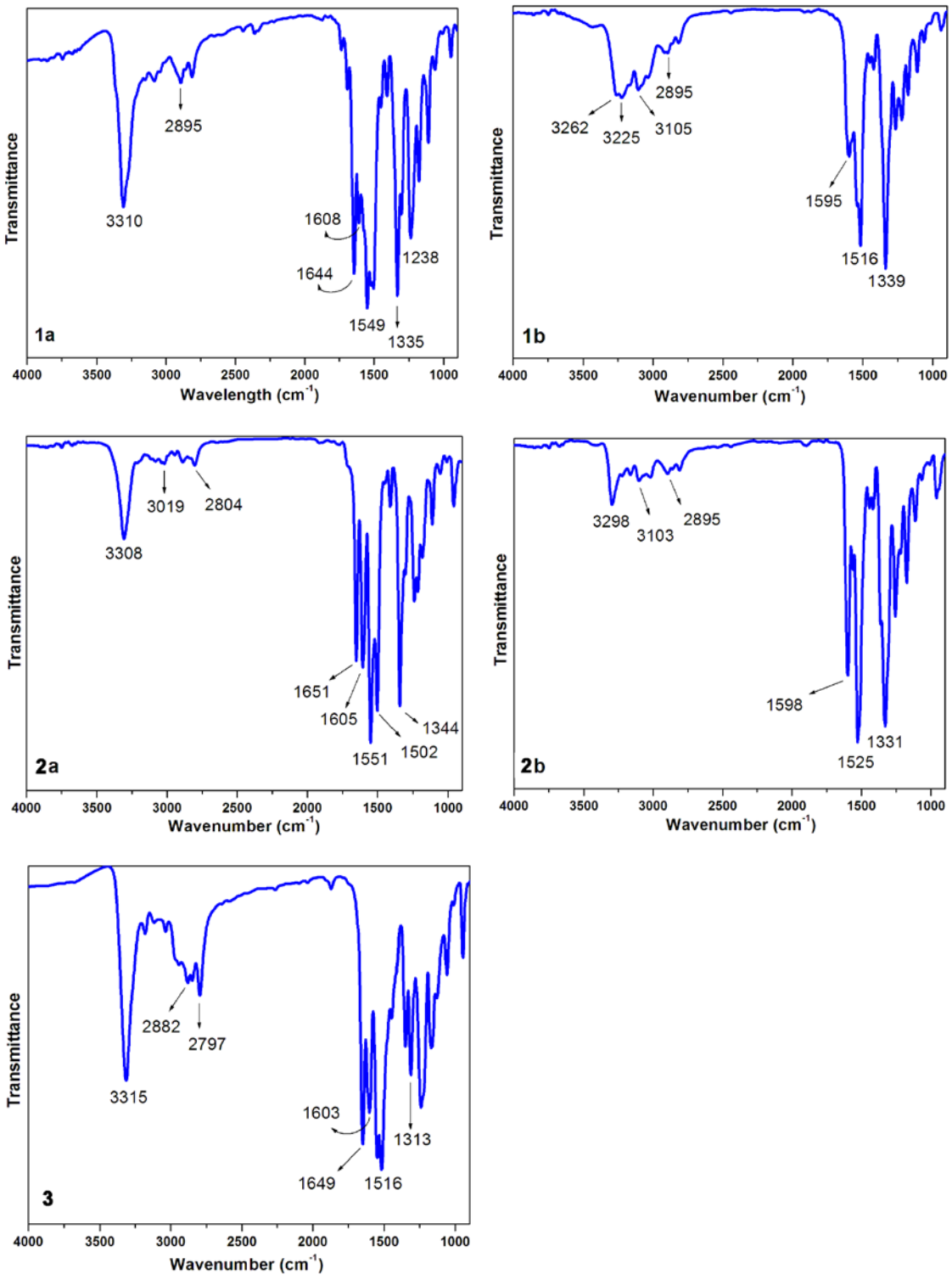
Figure S9: DOSY NMR spectrum (500 MHz) of **1b** + **AcO**$^-$ (15 mM, 2.1 eqv) and ^{1}H NMR spectrum (showed only up to δ=9 ppm) at top in $CDCl_3$ at 15 ^{0}C temperature.

MALDI-TOF Mass Spectra: MALDI-TOF mass spectra of compounds **1a- 3**.

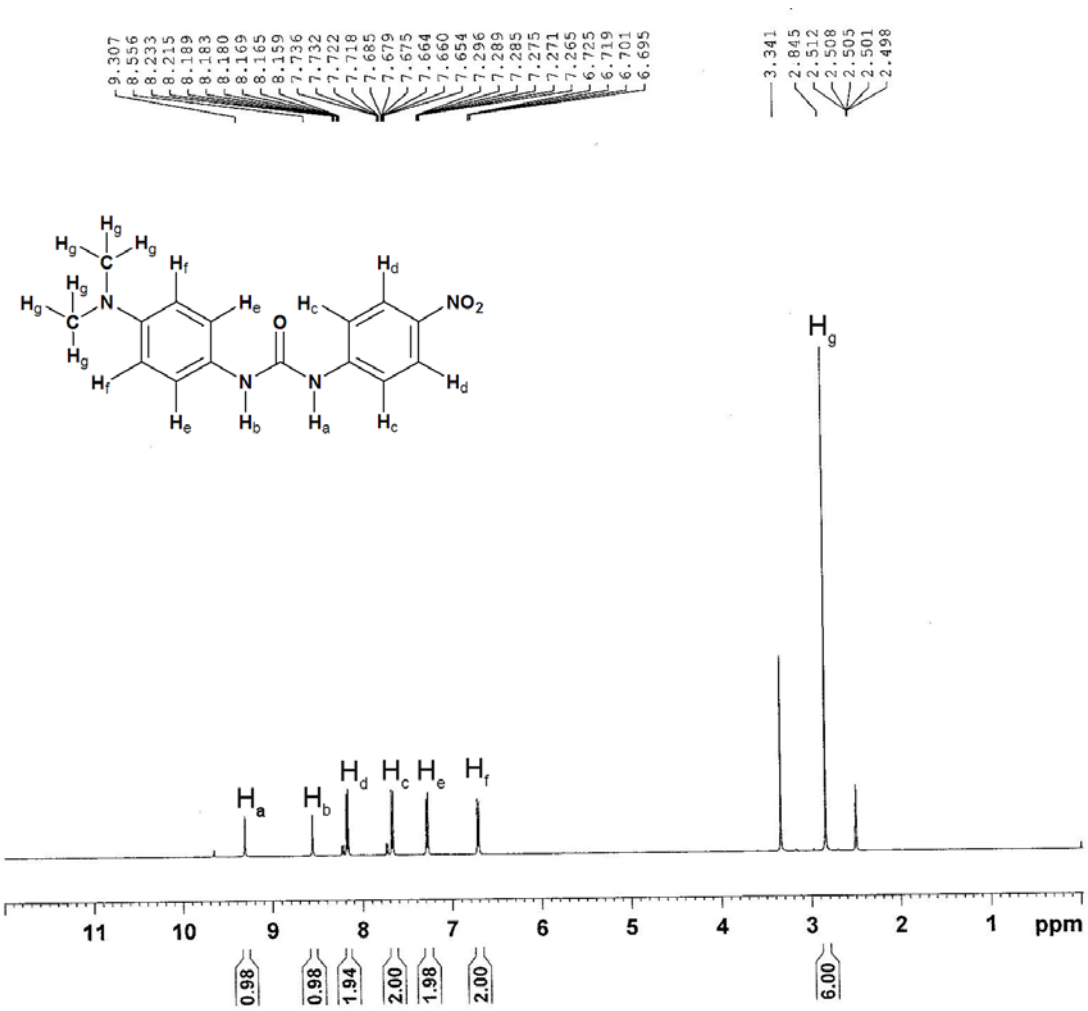


IR Spectra:

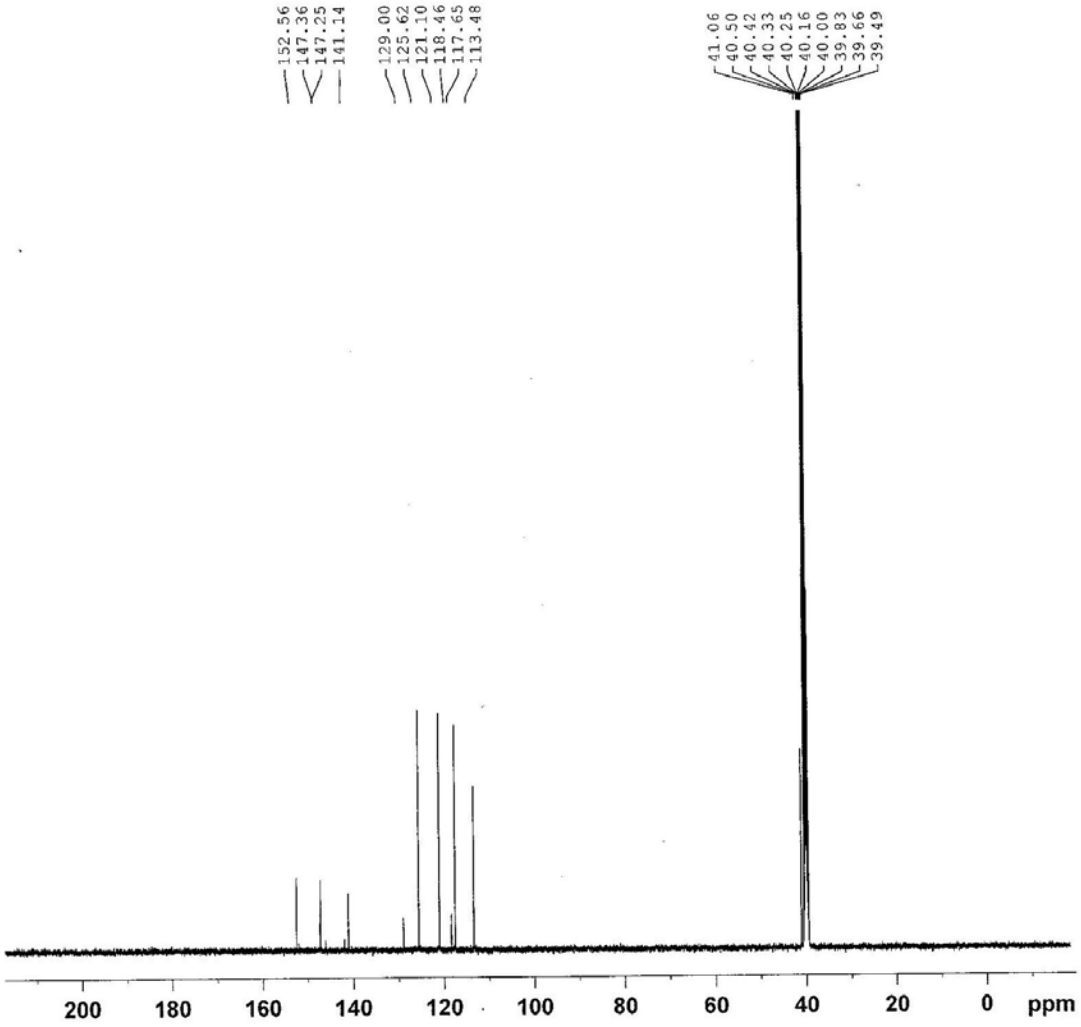
The FTIR spectra of compounds **1a**-**3** were recorded in solid state using KBr pellets.



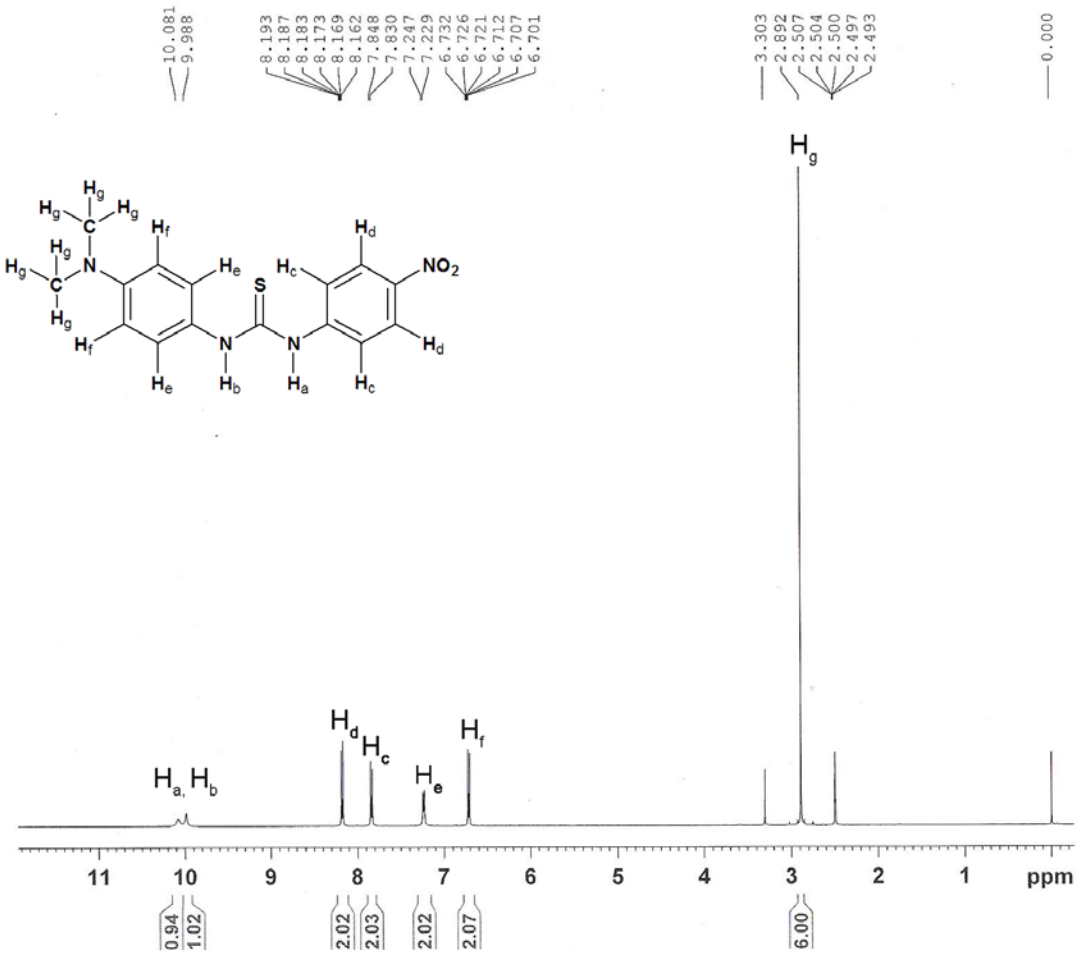
500 MHz ^{1}H NMR spectrum of 1a (DMSO-d_6):



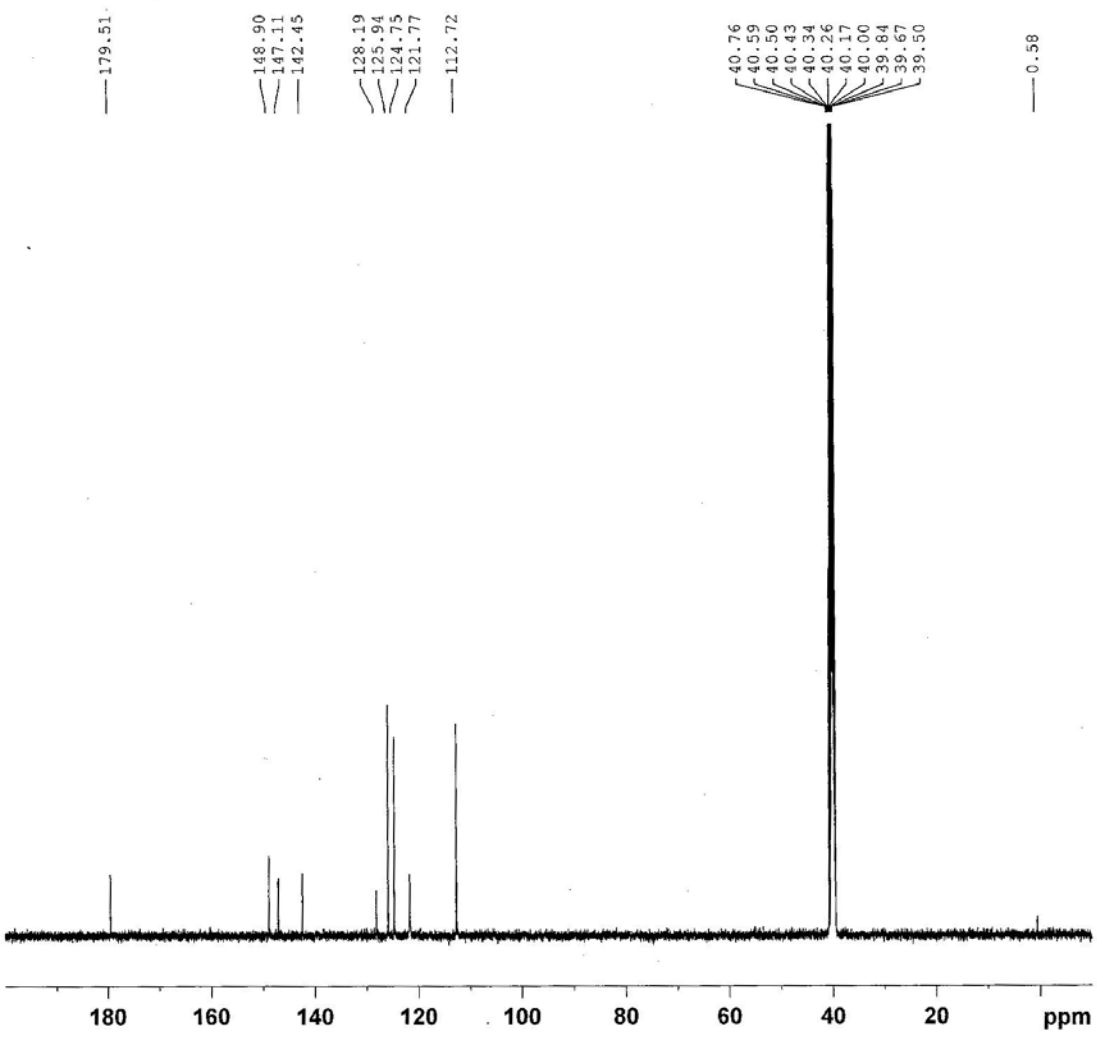
125 MHz ^{13}C NMR spectrum of 1a (DMSO-d_6):



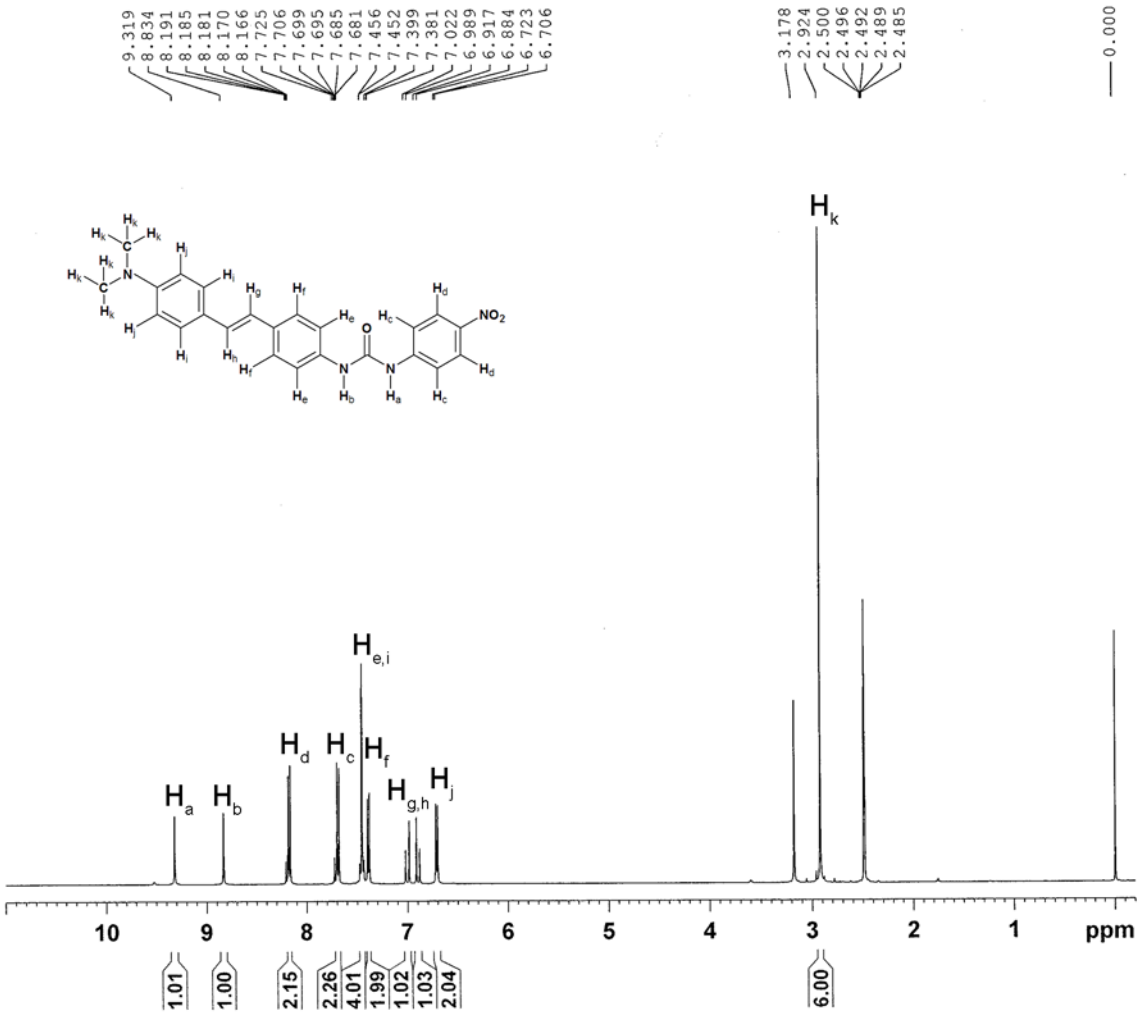
500 MHz ^{1}H NMR spectrum of 1b (DMSO-d_6):



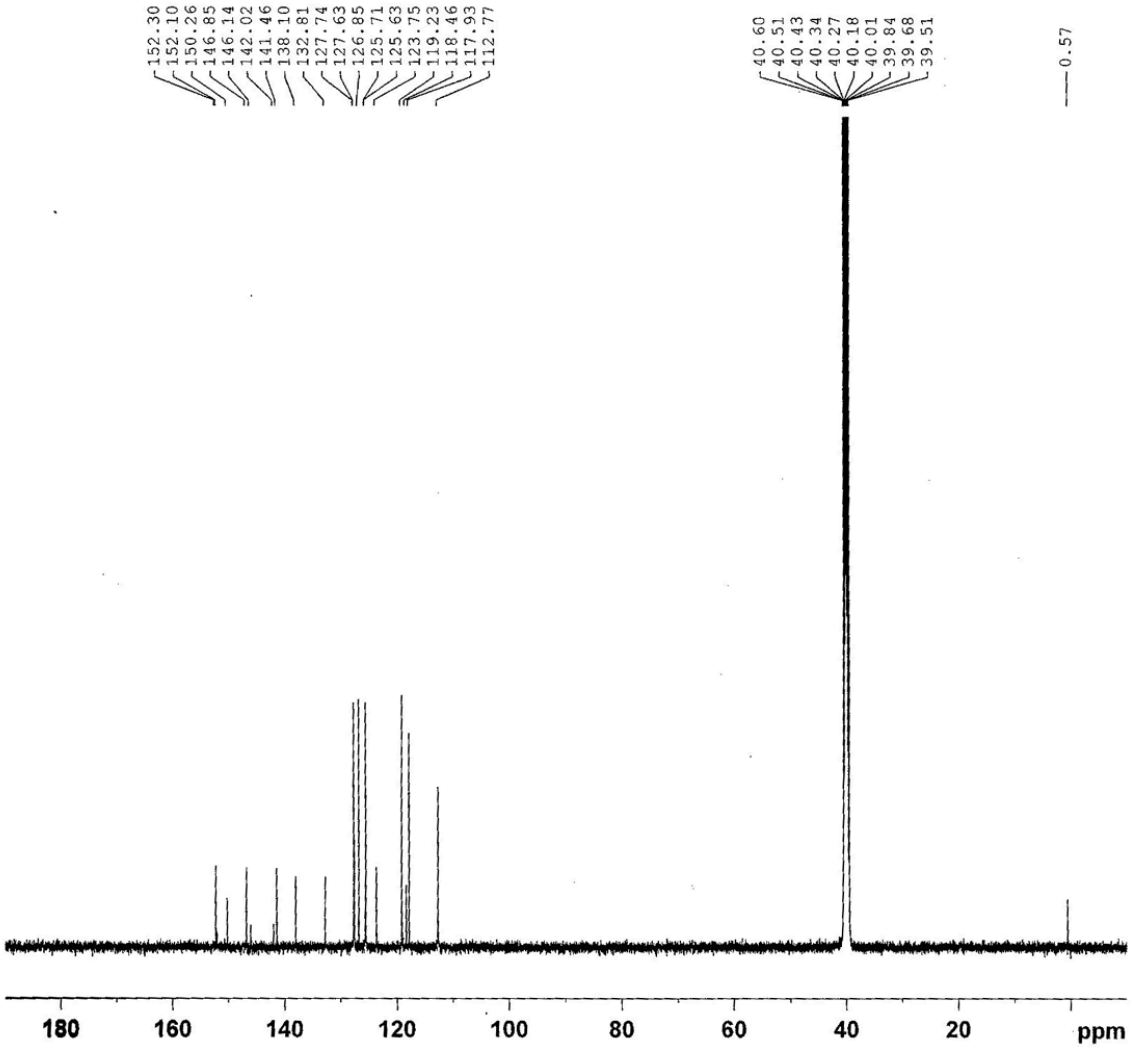
125 MHz ^{13}C NMR spectrum of 1b (DMSO-d_6):



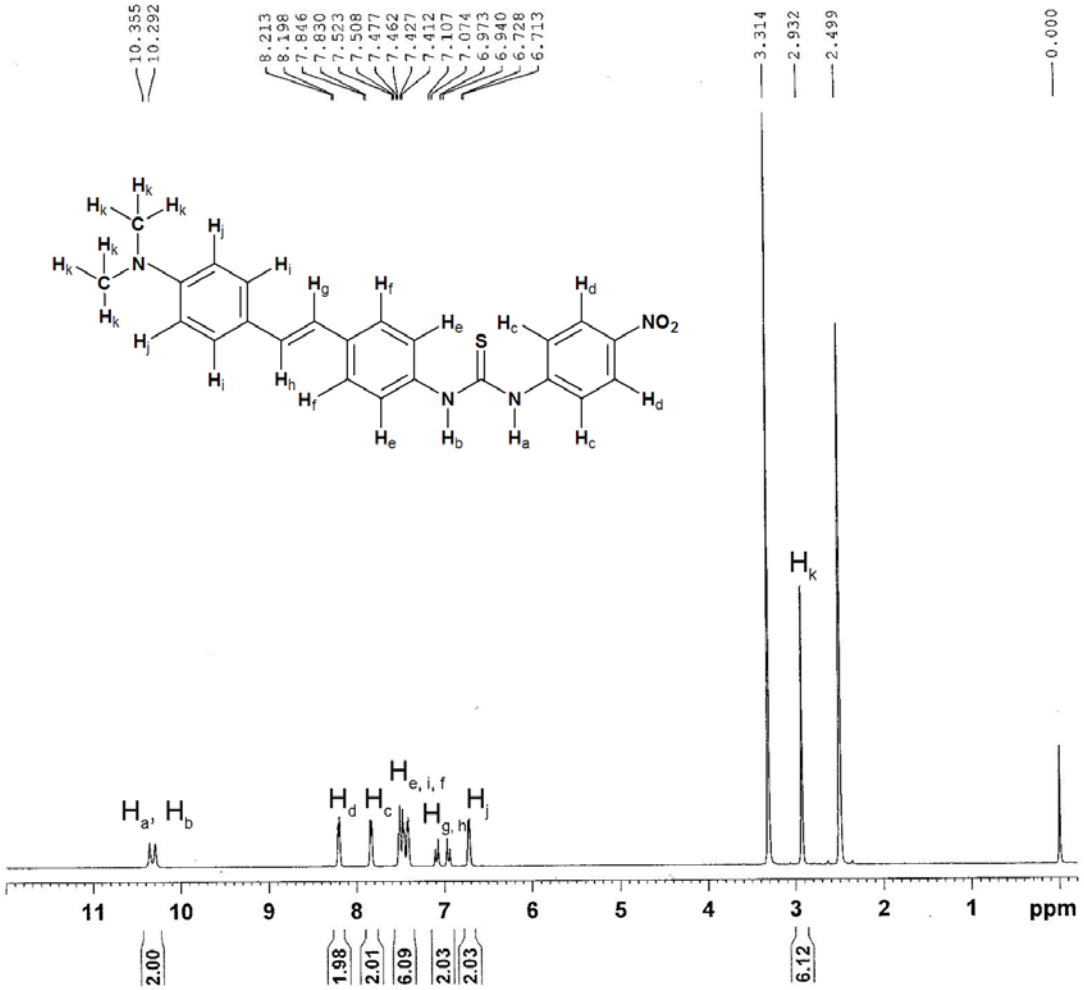
500 MHz ^{1}H NMR spectrum of 2a (DMSO-d_6):



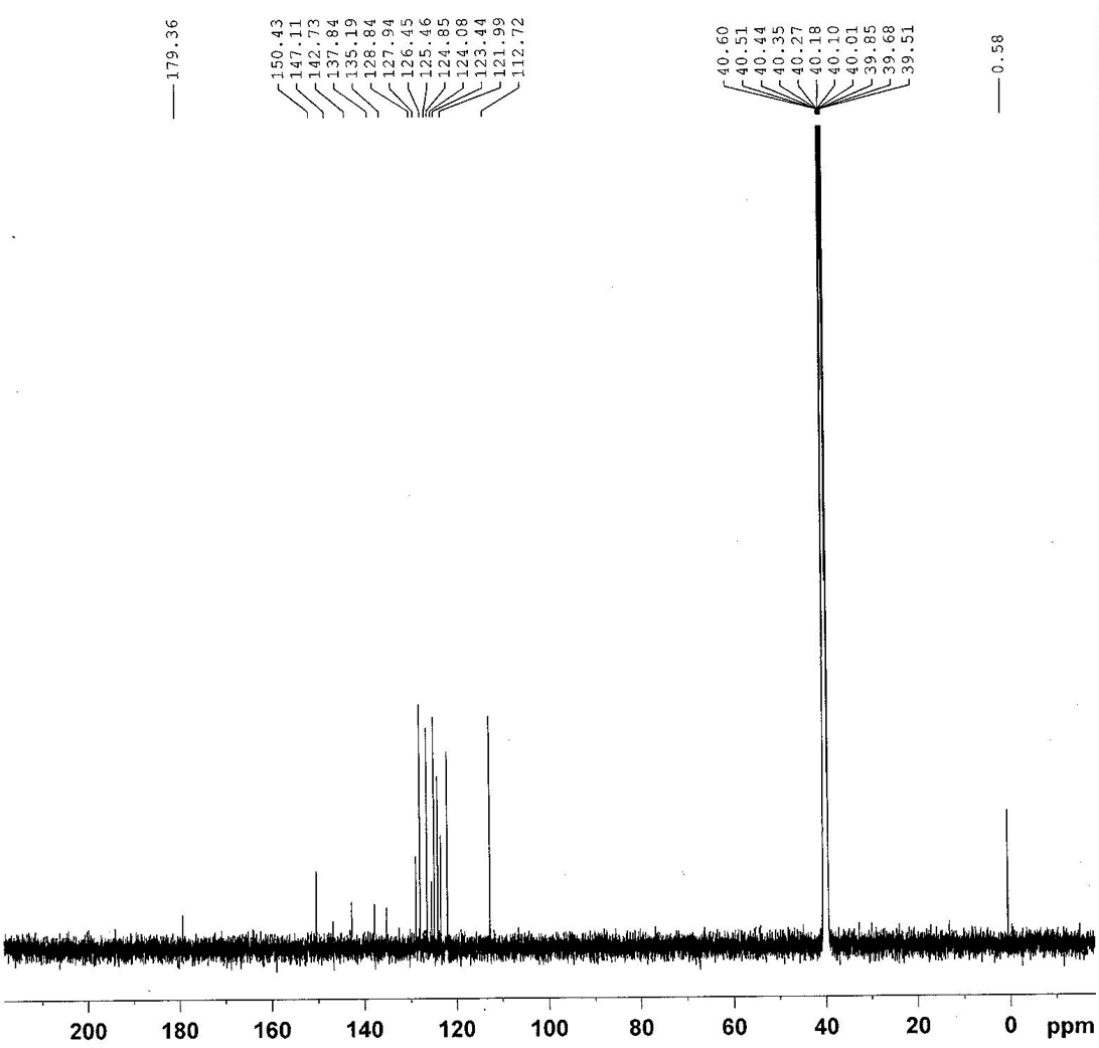
125 MHz ^{13}C NMR spectrum of 2a (DMSO-d_6):



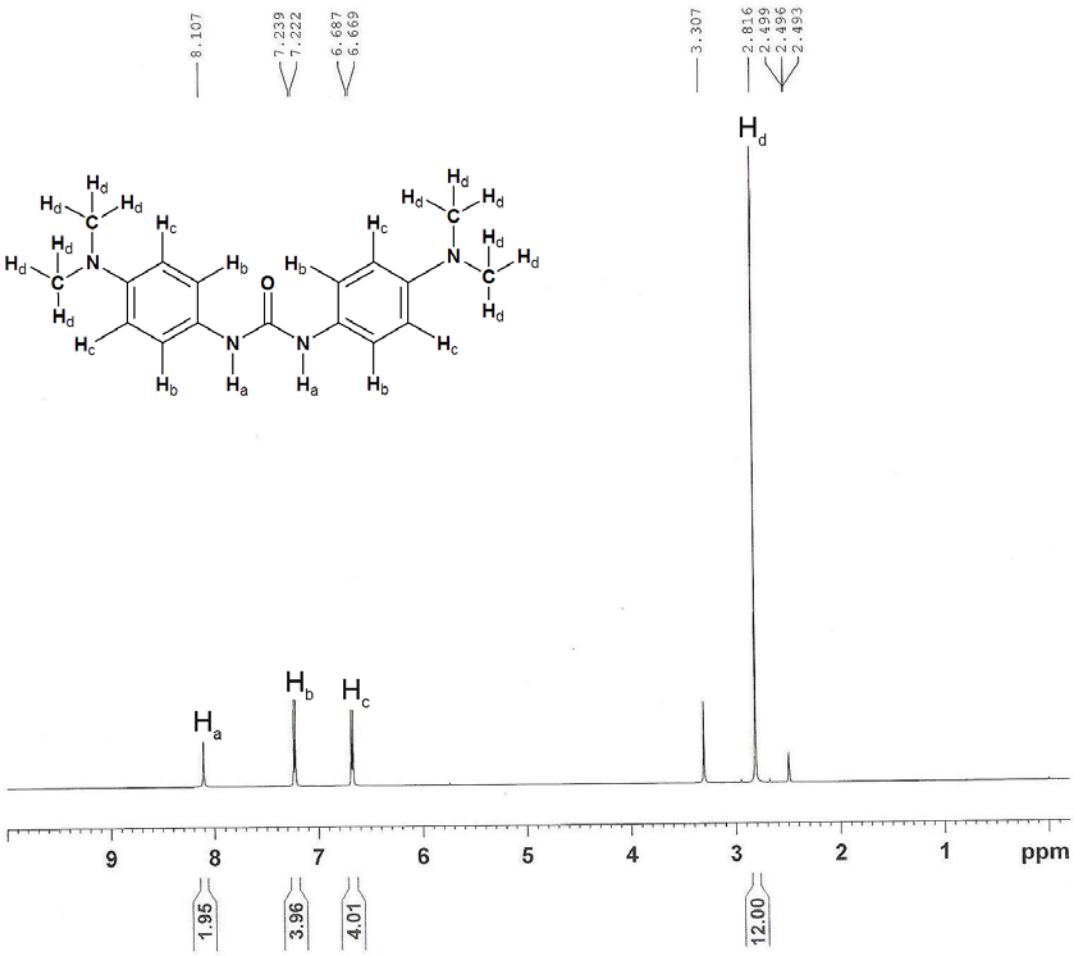
500 MHz ^{1}H NMR spectrum of 2b (DMSO-d_6):



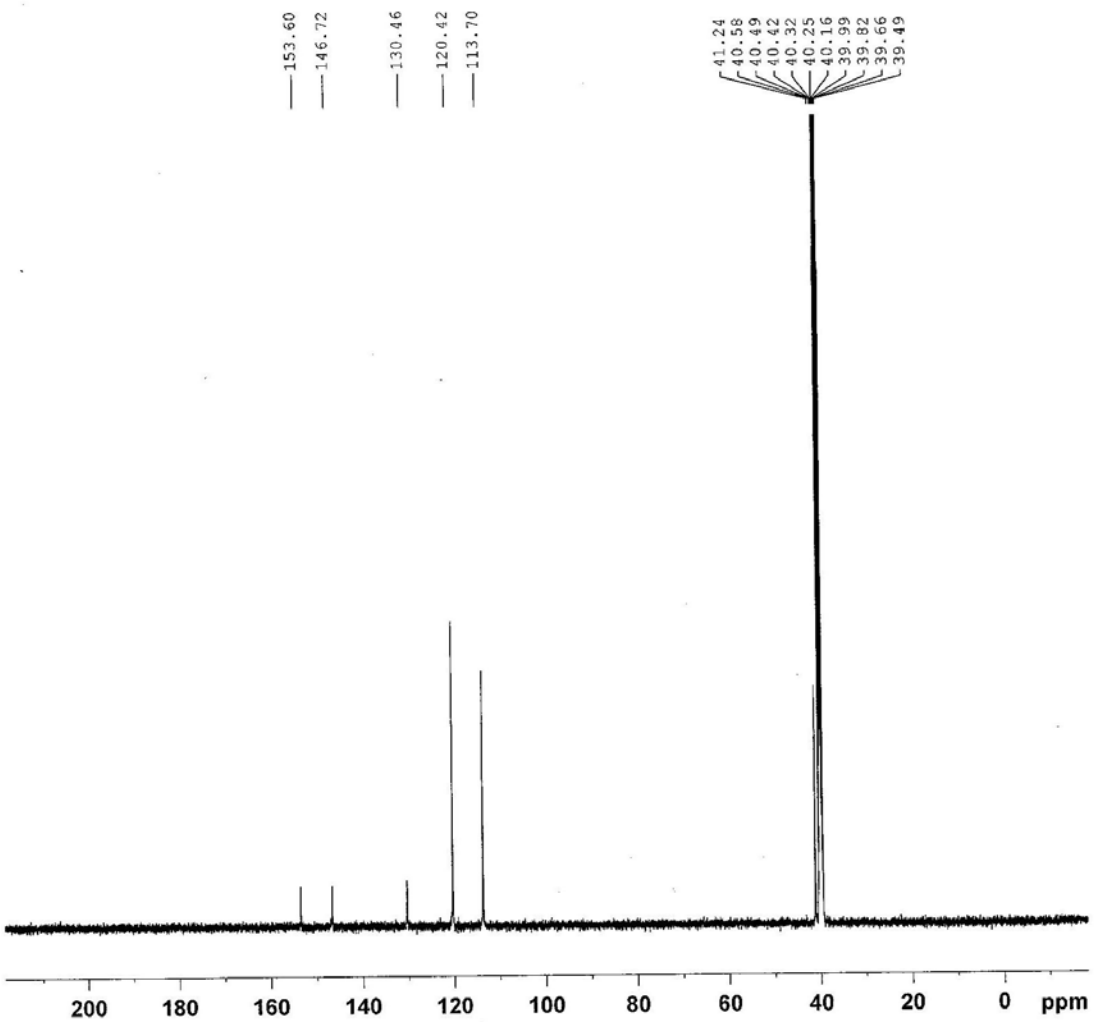
125 MHz ^{13}C NMR spectrum of 2b (DMSO-d_6):



500 MHz ^{1}H NMR spectrum of 3 (DMSO-d_6):



125 MHz ^{13}C NMR spectrum of 3 (DMSO-d_6):



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