Supplementary Material (ESI) for Organic & Biomolecular Chemistry


# Supplementary Information

# Chirality at Phosphorus in Pentacoordinate Spirophosphoranes: Stereochemistry by X-ray Structure and Spectroscopic Analysis

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## 1. General information

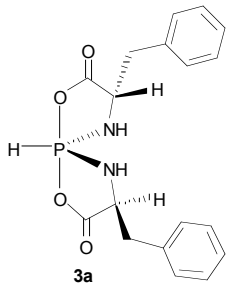
The solvents and reagents were dried and purified by standard methods before use. Triethylamine was refluxed and then distilled over KOH, tetrahydrofuran was refluxed then distilled over sodium, phosphorus trichloride was distilled directly. Melting points were determined (uncorrected) on a Yanaco MP-500 micro-melting point apparatus. Optical rotation were recorded using AUTOMATIC Polarimeter of RUDOLPH Research Analytical (AUTOPOL-IV) at 19.5 ˚C, 589 nm. Infrared (IR) spectra (film) were recorded on a Nicolet Avatar 360 FT-IR spectrometer in the range of 400 - 4000 $cm^{-1}$. NMR experiments were performed at rt on a 400 or 500 MHz NMR spectrometer. $^{1}H$ NMR spectra were recorded at 400 MHz using DMSO-$d_6$ as solvent, $^{13}C$ NMR spectra were determined at 100 MHz using DMSO-$d_6$ or $CDCl_3$ as solvent, $^{31}P$ NMR spectra were determined at 162 MHz using DMSO-$d_6$ as solvent, $^{15}N$ NMR spectra were determined at 40.5 MHz using DMSO-$d_6$ as solvent, $^{1}H$-$^{1}H$ COSY spectra were recorded at 400 or 500 MHz using DMSO-$d_6$ as solvent. $^{1}H$ NMR, $^{1}H$-$^{1}H$ COSY, $^{13}C$ NMR chemical shifts are relative to DMSO, $Me_4Si$ or $CDCl_3$, $^{31}P$ NMR chemical shifts are relative to 85% $H_3PO_4$ and $^{15}N$ NMR chemical shifts are relative to the saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent). Solid-State circular dichroism (CD) spectra were recorded using a JASCO J-810 spectropolarimeter at rt. Disks were prepared by manually mixing and grinding a crystal sample (approximately 0.3 mg) KCl (approximately 200 mg). Approximately 30 mg of the mixture was collected and weighed before pressing for 0.5 min at 20 ton into a disk (13 mm dia). Reverse-phase HPLC experiments were carried out on a Agilent model 1100 series HPLC system (Agilent1100 Technologies, Wilmington, DE). Methanol of HPLC quality were obtained from Tedia (Fairfleld, USA). Deionized water was from a Milli-Q (Millipore, USA) system. The HPLC used an Agilent, TC-$C_{18}$ column, 5 μm (4.6 x 250 mm, Agilent, Co., USA). Mobile phases for HPLC were filtered through a 0.45 μm membrane filter (Millipore, USA) and degassed before use. Sample solutions were filtered before analysis through 0.45 μm membrane filters (Millipore, USA). Samples were introduced into the columns using a model injection valve with a 20 μL sample loop at rt (~25 ˚C). The mobile phase consisted of methanol (Solvent A) and deionized water (Solvent B) (3:2 v/v) as eluent. The flow rate was 0.8 mL/min. The UV detection was at 215 nm. High Resolution MS data used an APEX

III 7.0 TESLA FT-MS (Bruker Daltonics, Inc.), while the ESI-MS data was determined with a Bruker ESQYIRE~3000 plus. The crystal of intensity data were collected on an Oxford Gemini S Ultra CCD Area Detector, using graphite-monochromated Mo $K_\alpha$ radiation ($\lambda$ = 0.71073 Å) at 173(2) K.

## 2. Experimental procedures

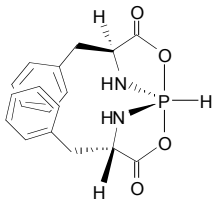
Following a general procedure,[S1] phosphorus trichloride (60 mmol) was added to a stirred solution of *L*- or *D*-phenylalanine (120 mmol) in 200 mL anhydrous tetrahydrofuran under nitrogen atmosphere at rt over 0.5 h. After stirring at rt for 0.5 h, triethylamine (3 equiv., 180 mmol) was added dropwise to the solution (~1 mL/min) at -10 ˚C to induce the reaction. Then the solution was stirred for 2 h. Solvent was removed under reduced pressure by rotary evaporation and the residue was washed rapidly with a sufficient quantity of water. The yields of crude product are near 75 %. The crude product was purified and separated by silica gel (300 - 400 mesh) column chromatography [$CH_2Cl_2$/$CH_3OH$ (v/v) = 100:1] to give white solid. **3a**/**3b** were synthesized from *L*-phenylalanine, and **4a**/4**b** were synthesized from *D*-phenylalanine, respectively. The relative yields of isomers **a** and **b** were 40:60 %. Compounds **3b** and **4b** were crystallized from a solution in acetone and petroleum ether (1:1 v/v).

## 3. Characterization data for 3a-4b



**3a**

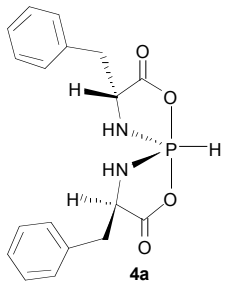
**(3*S*,5*Λ*,8*S*)-3,8-dibenzyl-1,6-dioxa-4,9-diaza-5λ$^5$-phosphaspiro[4.4]-nonane-2,7-dione (3a).** $R_f$ = 0.3 [TLC (silica gel); $CH_2Cl_2$/$CH_3OH$ (v/v) = 100:1]; separating efficiency 21.0 %; white solid; mp > 217 ˚C (decomposition); $[\alpha]_D^{20}$ + 50.0 (*c* 1.0, DMSO); $\nu_{max}$(film)/cm$^{-1}$ 3346, 3085, 3066, 3028, 2961, 2932, 2856, 2467, 1738, 1455, 1288 and 846; $\delta_H$(400 MHz; DMSO-$d_6$; DMSO) 7.24 - 7.08 (10 H, m, 2 × C*H* of Ph), 5.79 (2 H, d, *J* 20.0, 2 × N*H*), 5.64 (1 H, dt, *J* 810.2 and 2.4, P*H*), 4.11 - 4.09 (2 H, m, 2 × α-C*H*), 2.88 (2 H, dt, *J* 13.6 and 2.7, 2 × β-C$H_{2(a)}$), 2.81 (2 H, dd, *J* 13.6 and 4.9, 2 × β-C$H_{2(b)}$); $\delta_C$(100 MHz; DMSO-$d_6$; DMSO) 171.0 (d, *J* 6.4), 135.6, 130.0, 128.0, 126.7, 54.7 (d, *J* 3.9), 37.6 (d, *J* 4.4); $\delta_P$(162 MHz; DMSO-$d_6$; 85% $H_3PO_4$) – 60.02; $\delta_N$[40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)] 61.88 (d, *J* 33.7); *m/z* (ESI): 359.1 (25%), 381.0 (100); HRMS *m/z* (ESI) 359.1161 ($C_{18}H_{20}N_2O_4P^+$ requires 359.1161).



**3b**

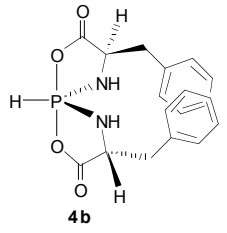
**(3*S*,5*Λ*,8*S*)-3,8-dibenzyl-1,6-dioxa-4,9-diaza-5λ$^5$-phosphaspiro[4.4]-nonane-2,7-dione (3b).** $R_f$ = 0.4 [TLC (silica gel), $CH_2Cl_2$/$CH_3OH$ (v/v) = 100:1]; separating efficiency 26.4 %; white solid; mp > 210 ˚C (decomposition); $[\alpha]_D^{20}$ – 40.4 (*c* 1.0, DMSO); $\nu_{max}$(film)/cm$^{-1}$ 3329, 3082, 3062, 3027, 2928, 2890, 2848, 2458, 1735, 1454, 1288 and 854; $\delta_H$(400 MHz; DMSO-$d_6$; $Me_4Si$) 7.30 - 7.10 (10 H, m, 2 × C*H* of Ph), 7.09 (1 H, d, *J* 804.9, P*H*), 5.56 (2 H, d, *J* 20.8, 2 × NH), 4.02 - 3.96 (2 H, m, 2 × α-C*H*), 2.77 (2 H, dd, *J* 13.9 and 5.8, 2 × β-C$H_{2(a)}$), 2.65 (2 H, dd, *J* 13.9 and 5.4, 2 * β-C$H_{2(b)}$); $\delta_C$(100 MHz; $CDCl_3$; $CDCl_3$) 169.9 (d, *J* 6.4), 136.0, 129.4, 128.9, 127.5, 55.7 (d, *J* 6.2), 40.0 (d, *J* 1.8); $\delta_P$(162 MHz; DMSO-$d_6$; 85%

$H_3PO_4$) – 63.03; $\delta_N$[40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)] 62.38 (d, *J* 34.5); *m/z* (ESI): 359.0 (25%), 381.0 (100); HRMS *m/z* (ESI) 359.1161 ($C_{18}H_{20}N_2O_4P^+$ requires 359.1161).



**4a**

**(3*R*,5*Λ*,8*R*)-3,8-dibenzyl-1,6-dioxa-4,9-diaza-5λ$^5$-phosphaspiro[4.4]-nonane-2,7-dione (4a).** $R_f$ = 0.3 [TLC (silica gel), $CH_2Cl_2$/$CH_3OH$ (v/v) = 100:1]; separating efficiency 17.4 %; white solid; mp > 218 ˚C (decomposition); $[\alpha]_D^{20}$ – 50.2 (*c* 1.0, DMSO); $\nu_{max}$(film)/cm$^{-1}$ 3347, 3085, 3054, 3027, 2960, 2935, 2906, 2466, 1739, 1454, 1303 and 847; $\delta_H$(400 MHz; DMSO-$d_6$; $Me_4Si$) 7.24 - 7.08 (10 H, m, 2 × C*H* of Ph), 5.80 (2 H, d, *J* 20.0, 2 × N*H*), 5.64 (1 H, dt, *J* 810.2 and 2.4, P*H*), 4.11 - 4.09 (2 H, m, 2 × α-C*H*), 2.88 (2 H, dt, *J* 13.3 and 2.6, 2 × β-C$H_{2(a)}$), 2.81 (2 H, dd, *J* 13.6 and 4.9, 2 × β-C$H_{2(b)}$); $\delta_C$(100 MHz; DMSO-$d_6$; DMSO) 170.9 (d, *J* 6.4), 135.6, 130.0, 128.0, 126.7, 54.7 (d, *J* 4.0), 37.6 (d, *J* 4.2); $\delta_P$(162 MHz; DMSO-$d_6$; 85% $H_3PO_4$) – 60.03; $\delta_N$[40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)] 61.58 (d, *J* 33.6); *m/z* (ESI): 359.1 (24%) 381.1 (100); HRMS *m/z* (ESI) 359.1154 ($C_{18}H_{20}N_2O_4P^+$ requires 359.1161).



**4b**

**(3*R*,5*Λ*,8*R*)-3,8-dibenzyl-1,6-dioxa-4,9-diaza-5λ$^5$-phosphaspiro[4.4]-nonane-2,7-dione (4b).** $R_f$ = 0.4 [TLC (silica gel), $CH_2Cl_2$/$CH_3OH$ (v/v) = 100:1]; separating efficiency 27.8 %; white solid; mp > 210 ˚C (decomposition); $[\alpha]_D^{20}$ + 41.0 (*c* 1.0, DMSO); $\nu_{max}$(film)/cm$^{-1}$ 3327, 3082, 3061, 3027, 2928, 2895, 2848, 2459, 1735, 1454, 1289 and 855 cm$^{-1}$; $\delta_H$(400 MHz; DMSO-$d_6$; $Me_4Si$) 7.30 - 7.10 (10 H, m, 2 × C*H* of Ph), 7.09 (1 H, d, *J* 805.0, P*H*), 5.56 (2 H, d, *J* 20.8, 2 × N*H*), 4.02 - 3.96 (2 H, m, 2 × α-C*H*), 2.77 (2 H,

dd, *J* 13.9 and 5.8, 2 × β-C$H_{2(a)}$), 2.65 (2 H, dd, *J* 13.9 and 5.4, 2 × β-C$H_{2(b)}$); $\delta_C$(100 MHz; $CDCl_3$; $CDCl_3$) 169.9 (d, *J* 6.4), 136.0, 129.4, 128.9, 127.5, 55.7 (d, *J* 6.2), 40.0 (d, *J* 2.0); $\delta_P$(162 MHz; DMSO-$d_6$; 85% $H_3PO_4$) – 63.04 ppm; $\delta_N$[40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)] 62.32 (d, *J* 34.6); *m/z* (ESI): 359.1 (46%), 381.1 (100); HRMS *m/z* (ESI) 359.1155 ($C_{18}H_{20}N_2O_4P^+$ requires 359.1161).

## 4. X-ray Crystallography data for 3b and 4b

Crystals of **3b** and **4b** suitable for X-ray diffraction were grown from acetone and petroleum ether (1:1 v/v). Light white block crystal of **3b** and 4**b** were mounted on top of glass fibers and transferred into a cold stream of nitrogen. Intensity data were collected on an Oxford Gemini S Ultra CCD Area Detector, using graphite-monochromated Mo $K_\alpha$ radiation (λ = 0.71073 Å) at 173(2) K. The structures were solved by direct methods with the program SHELXS-97.[S2] CCDC-721774 (**3b**) and CCDC-721775 (**4b**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

**Table S1** Crystallographic data for compounds ($\Lambda_P$,$S_C$,$S_C$)-**3b** and ($\Lambda_P$,$R_C$,$R_C$)-**4b**.

| | ($\Lambda_P$,$S_C$,$S_C$)-**3b** | ($\Lambda_P$,$R_C$,$R_C$)-**4b** |
|---|---|---|
| Empirical formula | $C_{18}H_{19}N_2O_4P$ | $C_{18}H_{19}N_2O_4P$ |
| Formula weight | 358.32 | 358.32 |
| *T*, K | 173(2) | 173(2) |
| radiation (Mo $K_\alpha$), Å | 0.71073 | 0.71073 |
| Cryst syst | Orthorhombic | Orthorhombic |
| Space group | $P2_12_12_1$ | $P2_12_12_1$ |
| *a*, Å | 6.0491(4) | 6.0474(2) |
| *b*, Å | 8.3323(5) | 8.3290(3) |
| *c*, Å | 34.349(3) | 34.270(2) |
| *α*, deg | 90 | 90 |
| *β*, deg | 90 | 90 |

| | | |
|---|---|---|
| $\gamma$, deg | 90 | 90 |
| $V$, Å$^3$ | 1731.3(2) | 1726.14(14) |
| $Z$ | 4 | 4 |
| $d_{calcd}$, mg/mm$^3$ | 1.375 | 1.379 |
| abs coeff, mm$^{-1}$ | 0.184 | 0.185 |
| $F$(000) | 752 | 752 |
| Cryst size, mm$^3$ | 0.36 x 0.16 x 0.10 | 0.40 x 0.20 x 0.20 |
| $\theta$ range, deg | 3.56-25.00 | 2.52-25.00 |
| no. of reflns collected | 6300 | 5918 |
| no. of indep reflns | 2821 [$R$(int) = 0.0405] | 2917 [$R$(int) = 0.0276] |
| no. of data/restraints/ params | 2821/0/230 | 2917/12/227 |
| final $R$ indices [$I > 2\sigma(I)$] | $R_1$ = 0.0411, $wR_2$ = 0.0629 | $R_1$ = 0.0625, $wR_2$ = 0.1442 |
| $R$ indices (all data) | $R_1$ = 0.0698, $wR_2$ = 0.0696 | $R_1$ = 0.0675, $wR_2$ = 0.1457 |
| Flack parameter | -0.07(12) | 0.0(2) |
| peak and hole [e Å$^3$] | 0.178 and -0.248 | 0.378 and -0.441 |

**Table S2** Selected angles [$^o$] of compounds ($\Lambda_P$,$S_C$,$S_C$)-**3b** and ($\Delta_P$,$R_C$,$R_C$)-**4b**.

| | ($\Lambda_P$,$S_C$,$S_C$)-3b | ($\Delta_P$,$R_C$,$R_C$)-4b |
|---|---|---|
| **N(4)-P(5)-N(9)** | **125.79(13)** | **125.9(2)** |
| **N(4)-P(5)-O(6)** | **89.94(10)** | **90.00(19)** |
| **N(9)-P(5)-O(6)** | **89.54(11)** | **89.4(2)** |
| **N(4)-P(5)-O(1)** | **89.29(10)** | **89.16(19)** |
| **N(9)-P(5)-O(1)** | **90.82(10)** | **91.00(19)** |
| O(6)-P(5)-O(1) | 179.22(10) | 179.15(19) |
| C(2)-O(1)-P(5) | 114.67(18) | 115.3(3) |
| C(3)-N(4)-P(5) | 118.93(17) | 119.0(3) |
| O(2)-C(2)-O(1) | 121.6(3) | 122.3(4) |

| | | |
|---|---|---|
| O(2)-C(2)-C(3) | 125.1(3) | 126.0(4) |
| O(1)-C(2)-C(3) | 113.2(2) | 111.7(4) |
| C(8)-N(9)-P(5) | 118.43(18) | 118.9(3) |
| N(4)-C(3)-C(2) | 103.6(2) | 104.5(4) |
| N(4)-C(3)-C(10) | 114.6(2) | 114.4(4) |
| C(2)-C(3)-C(10) | 113.0(2) | 112.4(4) |
| C(7)-O(6)-P(5) | 115.4(2) | 116.1(3) |
| O(7)-C(7)-O(6) | 123.8(3) | 123.8(5) |
| O(7)-C(7)-C(8) | 123.8(3) | 125.0(5) |
| O(6)-C(7)-C(8) | 112.4(3) | 111.2(4) |
| N(9)-C(8)-C(7) | 104.1(2) | 104.4(4) |
| N(9)-C(8)-C(17) | 114.1(2) | 114.3(4) |
| C(7)-C(8)-C(17) | 110.9(2) | 110.1(4) |

**Table S3** Hydrogen-bond geometry (Å, °) of compounds ($\Lambda_P$,$S_C$,$S_C$)-**3b** and ($\Lambda_P$,$R_C$,$R_C$)-**4b**.

| Comp. | D-H···A | D-H | H···A | D···A | D-H···A |
|---|---|---|---|---|---|
| **3b** | N(9)-H(9A)···O(7)$^{i}$ | 0.86 | 2.52 | 3.048(3) | 120 |
| | C(12)-H(12A)···O(7)$^{ii}$ | 0.93 | 2.49 | 3.189(4) | 131 |
| | N(4)-H(4A)···O(2)$^{iii}$ | 0.86 | 2.15 | 2.965(3) | 158 |
| | C(22)-H(22A)···CgA$^{iv}$ | 0.93 | 3.34 | 4.145(3) | 146 |
| **4b** | N(9)-H(10A)···O(7)$^{v}$ | 0.86 | 2.53 | 3.049(6) | 120 |
| | C(12)-H(12A)···O(7)$^{vi}$ | 0.93 | 2.49 | 3.187(7) | 131 |
| | N(4)-H(4A)···O(2)$^{vii}$ | 0.86 | 2.15 | 2.963(5) | 158 |
| | C(22)-H(22A)···CgA$^{viii}$ | 0.93 | 3.33 | 4.135(3) | 145 |

Symmetry codes: (i) x + 1, y, z; (ii) x + 1, y - 1, z; (iii) x - 1, y, z; (iv) -x + 1, y + 1/2, -z + 3/2; (v) x + 1, y, z; (vi) x + 1, y + 1, z; (vii) x - 1, y, z; (viii) -x, y - 1/2, -z + 3/2. Cg is the centroid of the $C_{18}$-$C_{23}$ phenyl ring.

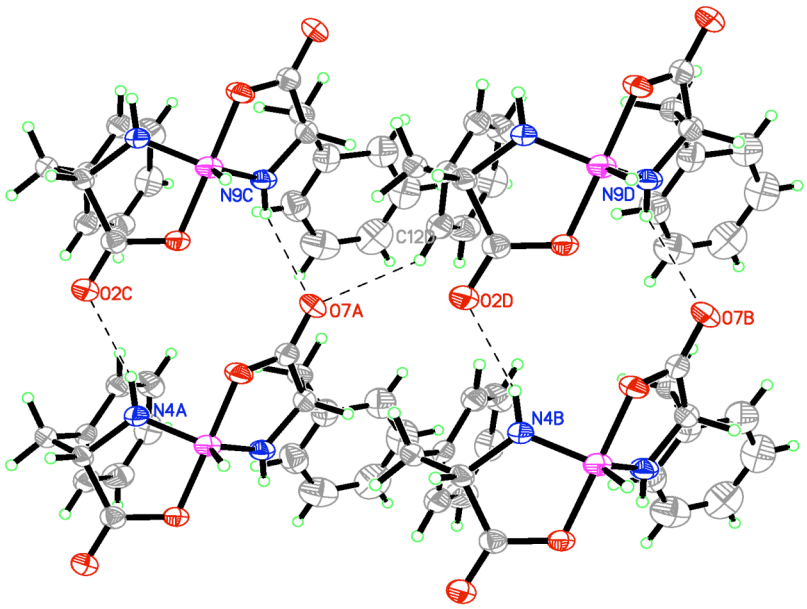



**Figure S1** The hydrogen-bonded motif of compound **3b**, hydrogen bonds are shown as dashed lines.

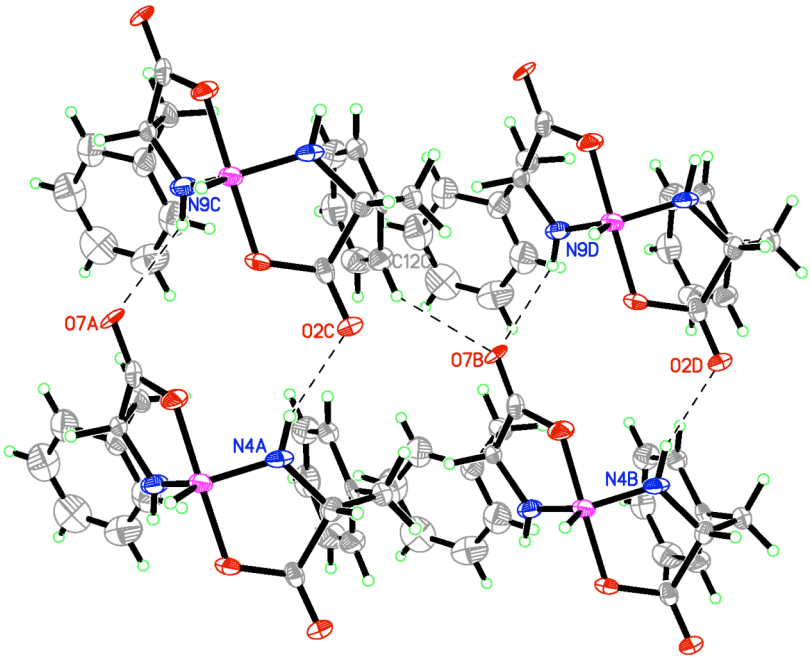



**Figure S2** The hydrogen-bonded motif of compound **4b**, hydrogen bonds are shown as dashed lines.

## 5. Supplementary information references

(S1) L. Yu, Z. Liu, H. Fang, Q. L. Zeng and Y. F. Zhao, *Amino Acid*, 2005, **28**, 369.

(S2) (*a*) G. M. Sheldrick, *Acta Crystallogr.*, 1990, **A46**, 467; (*b*) G. M. Sheldrick, *SHELXL-97, Program for Crystal Structure Refinement from Diffraction Data,* University of Göttingen: Germany, 1997.

## 6. $^{1}$H NMR, $^{13}$C NMR, $^{31}$P NMR, $^{15}$N NMR, HPLC, IR, and CD spectra of 3a, 3b, 4a and 4b.

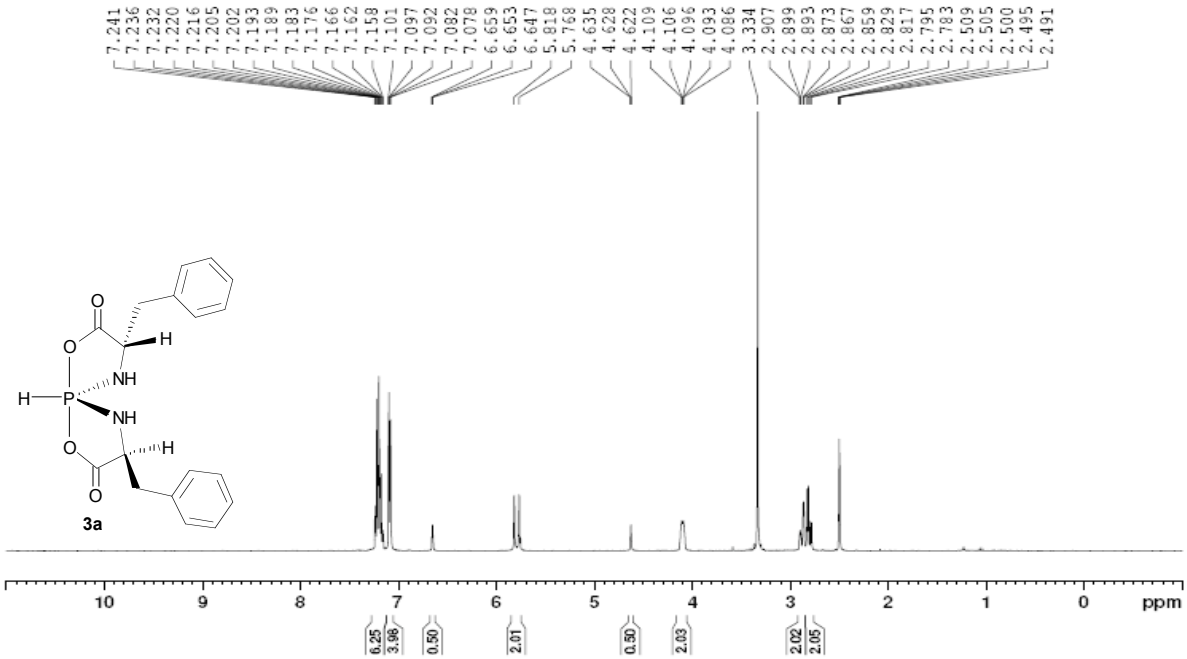



**Figure S3** $^{1}$H NMR spectrum of compound **3a** (400 MHz; DMSO-$d_6$; DMSO).

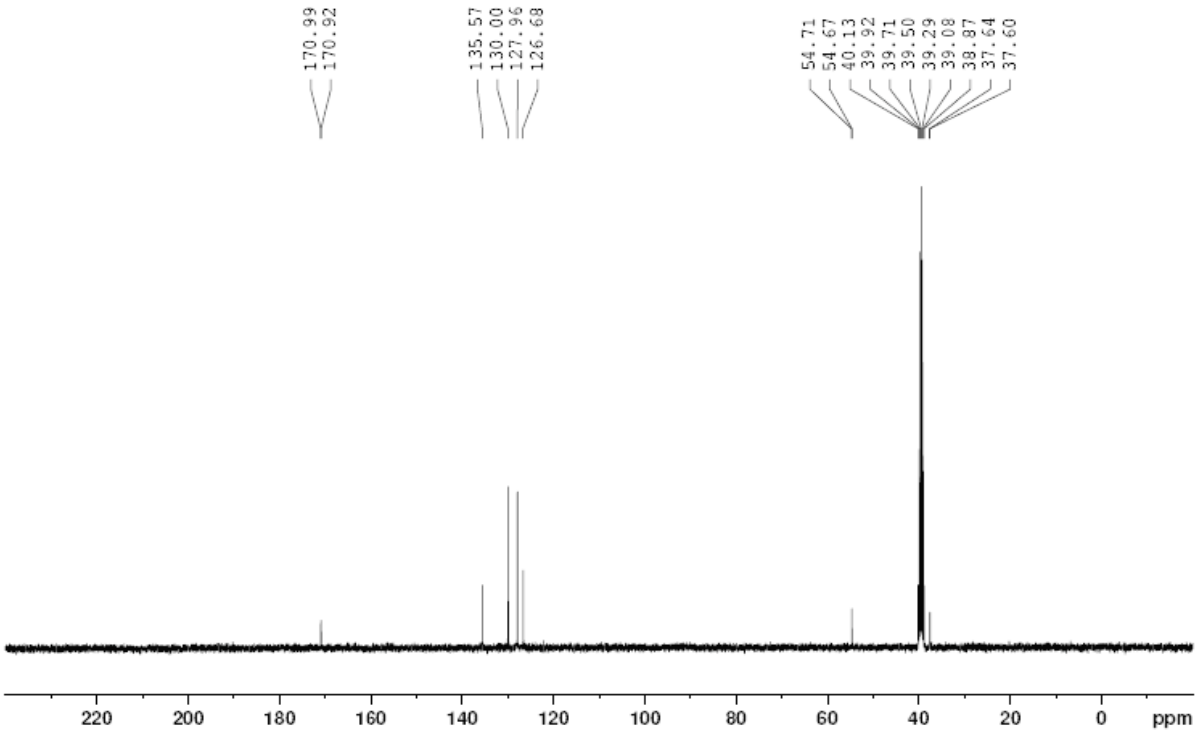



**Figure S4** $^{13}$C NMR spectrum of compound **3a** (100 MHz; DMSO-$d_6$; DMSO).

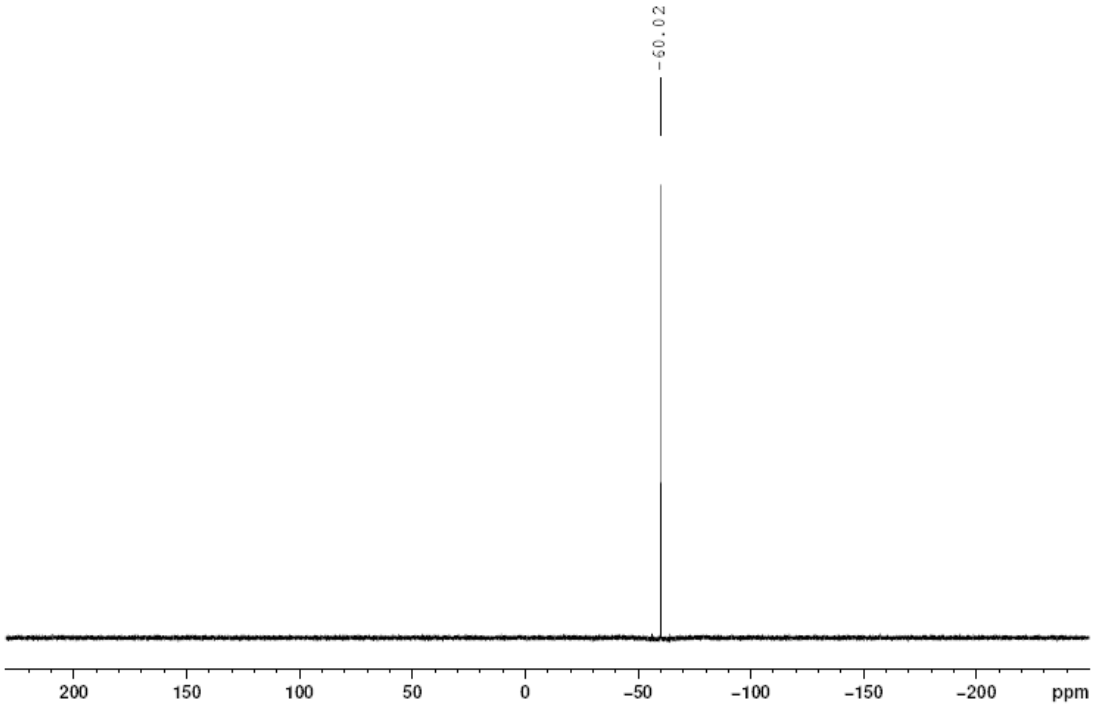



**Figure S5** $^{31}P$ NMR spectrum of compound **3a** (162 MHz; DMSO-$d_6$; 85% $H_3PO_4$).

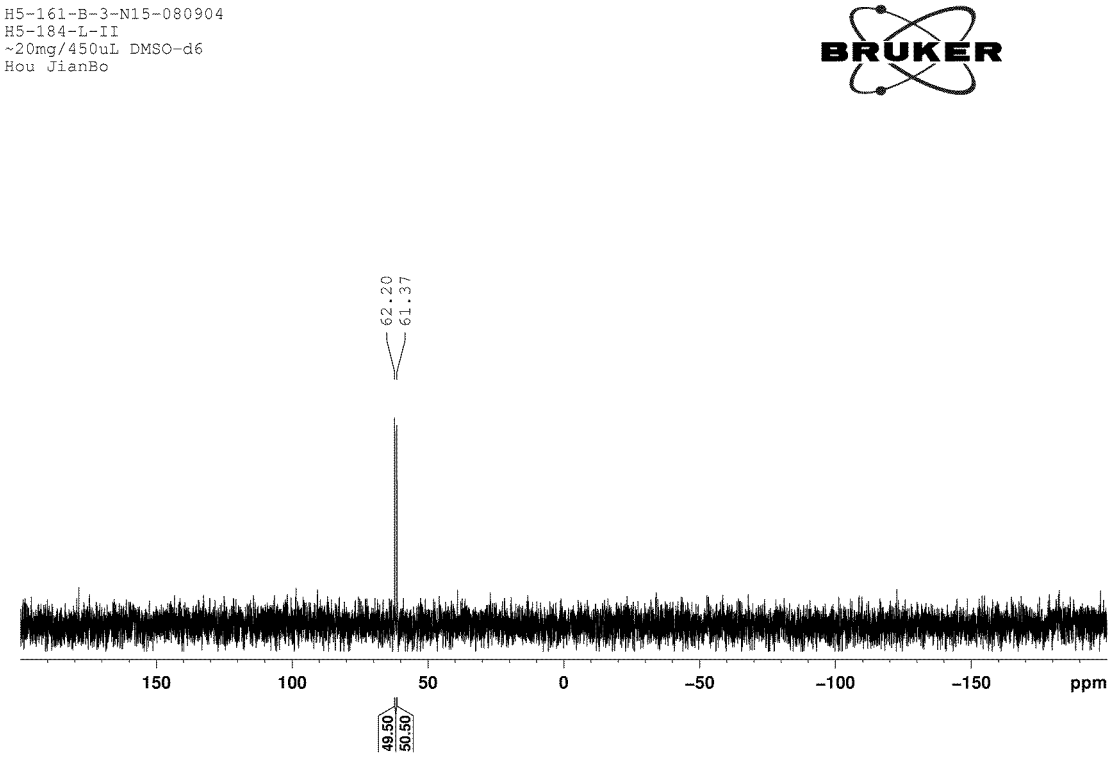



**Figure S6** $^{15}N$ NMR spectrum of compound **3a** [40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)].

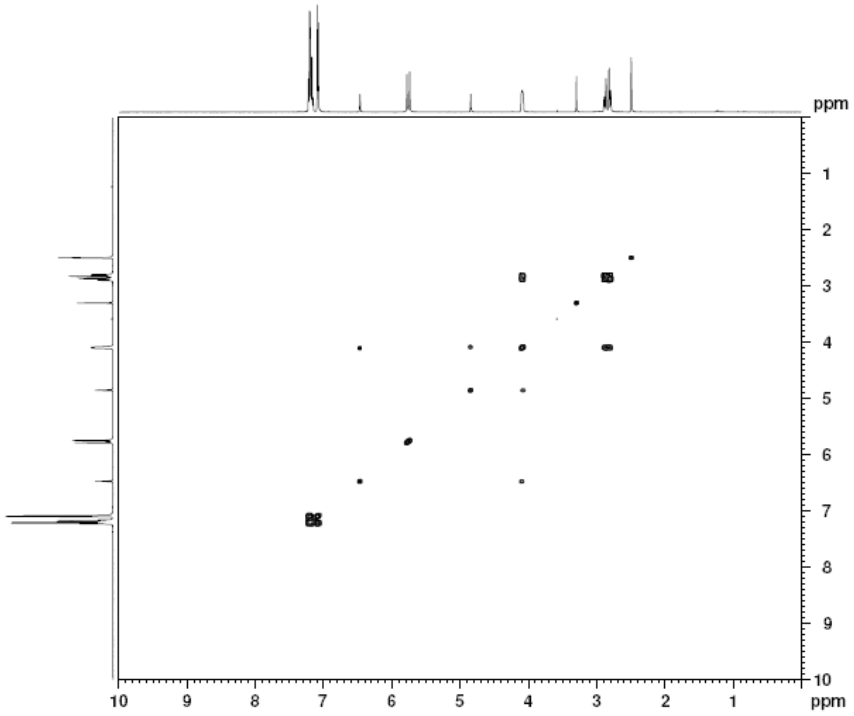



**Figure S7** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **3a** (500 MHz; DMSO-$d_6$; DMSO).

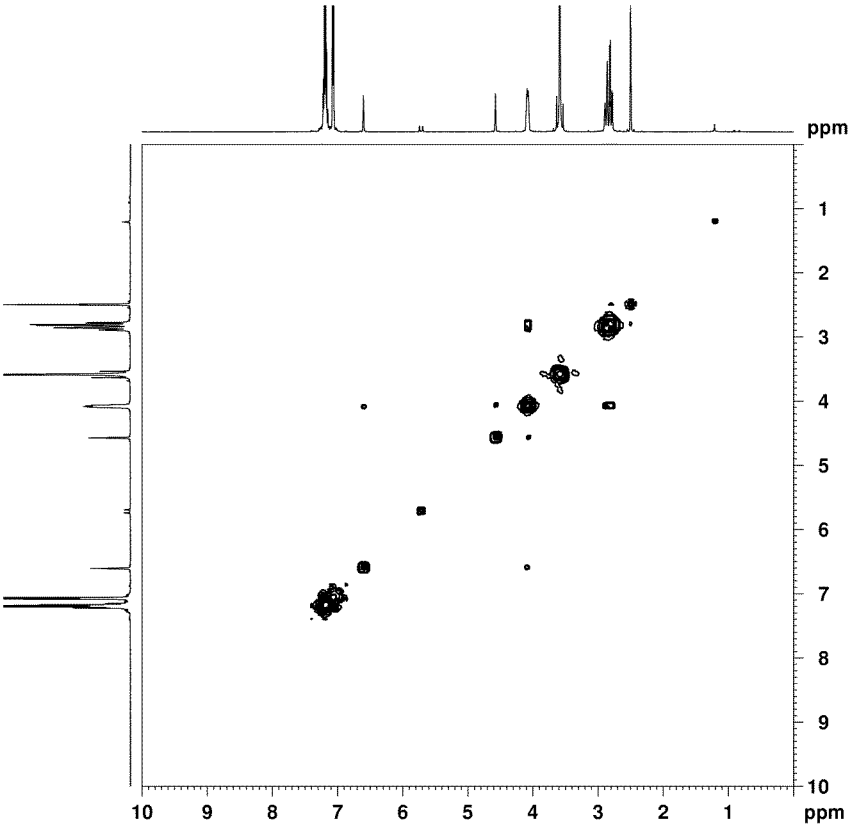



**Figure S8** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **3a** (400 MHz; DMSO-$d_6$ + $D_2O$; DMSO).

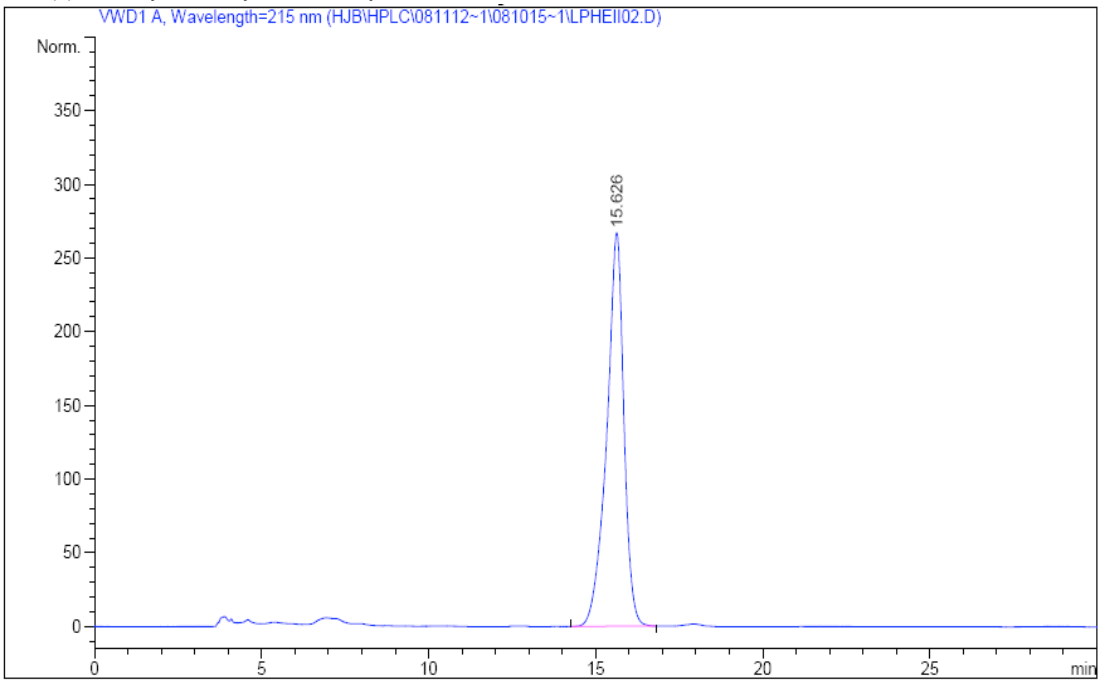



**Figure S9** HPLC spectrum of compound **3a** [(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

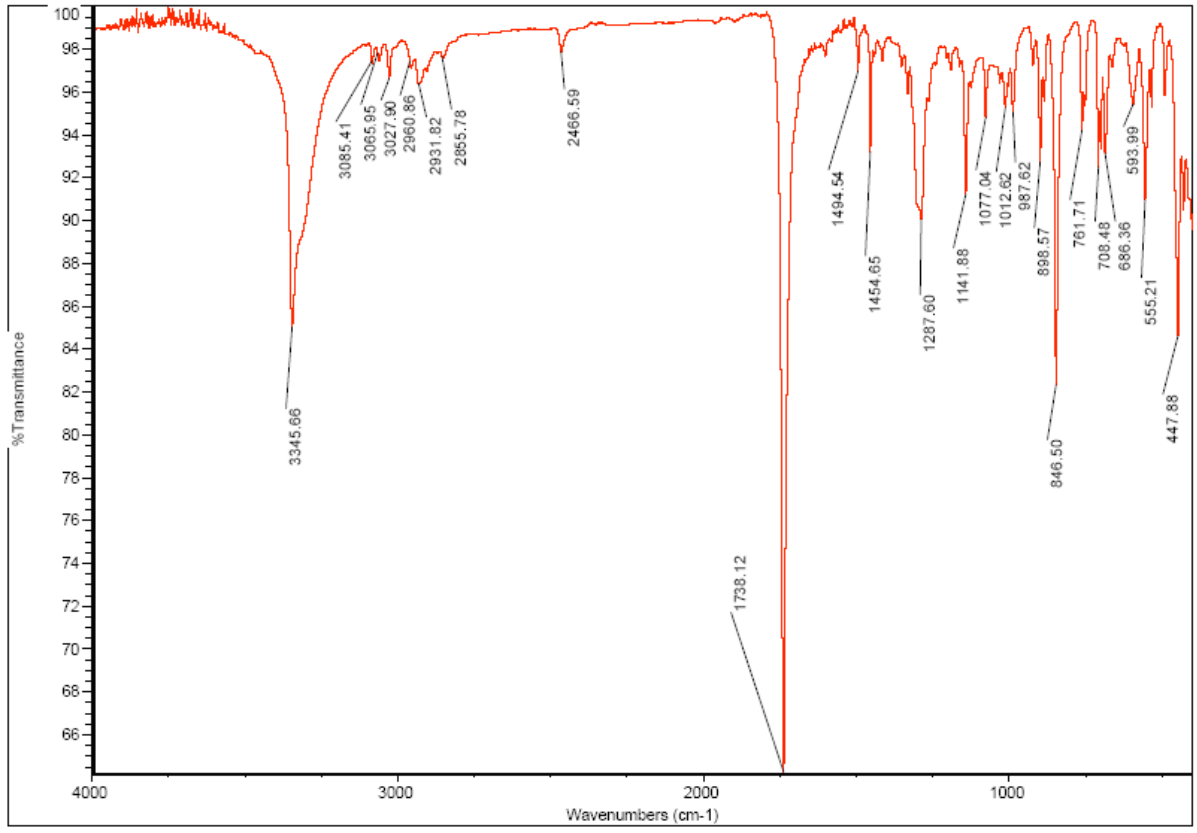



**Figure S10** IR spectrum of compound **3a** (film).

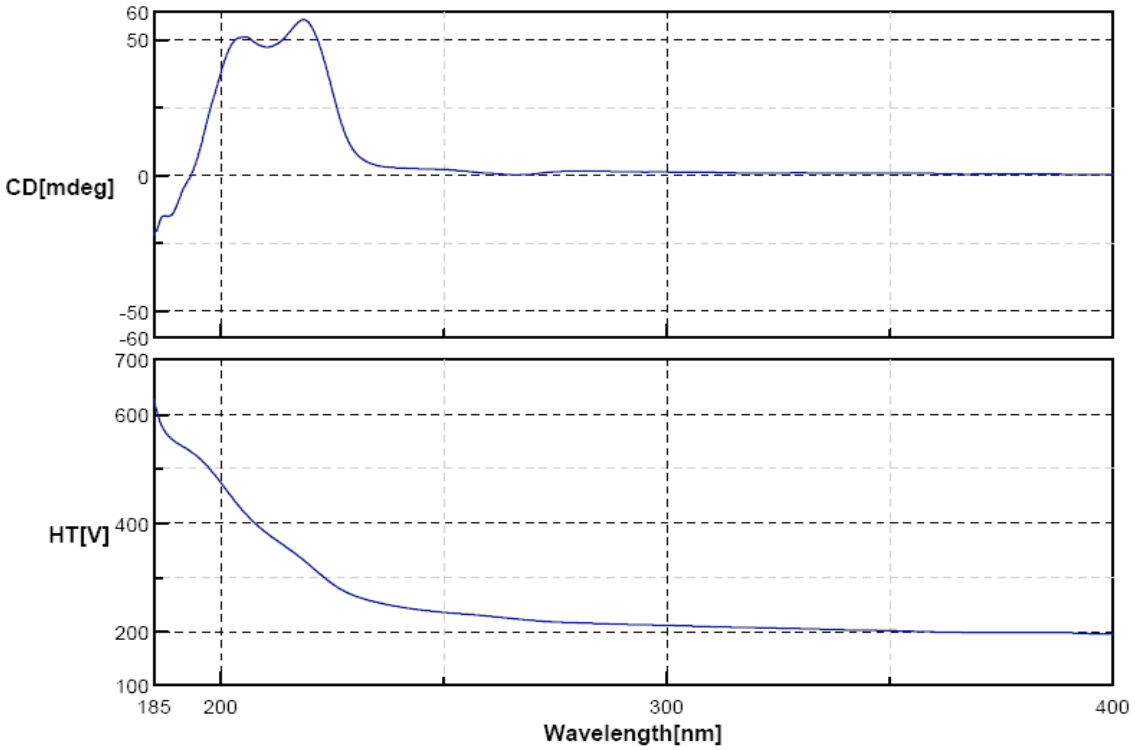



**Figure S11** Solid-state CD spectrum of compound **3a** (KCl disk).

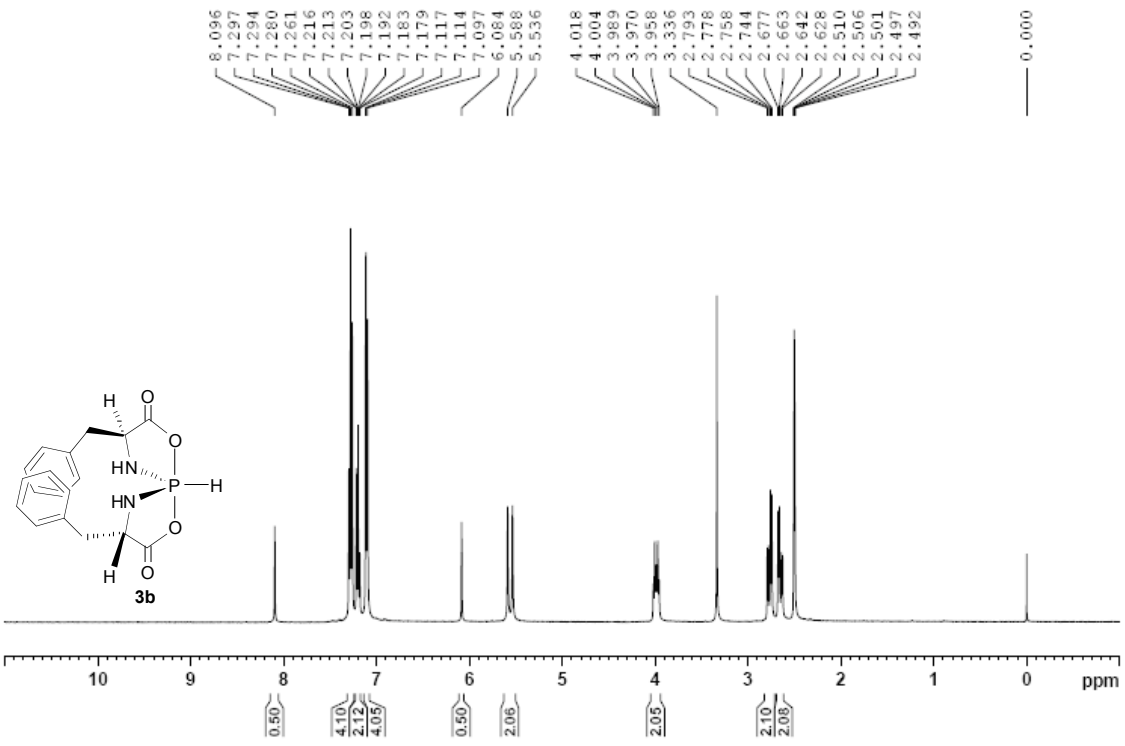



**Figure S12** $^{1}$H NMR spectrum of compound **3b** (400 MHz; DMSO-$d_6$; $Me_4Si$).

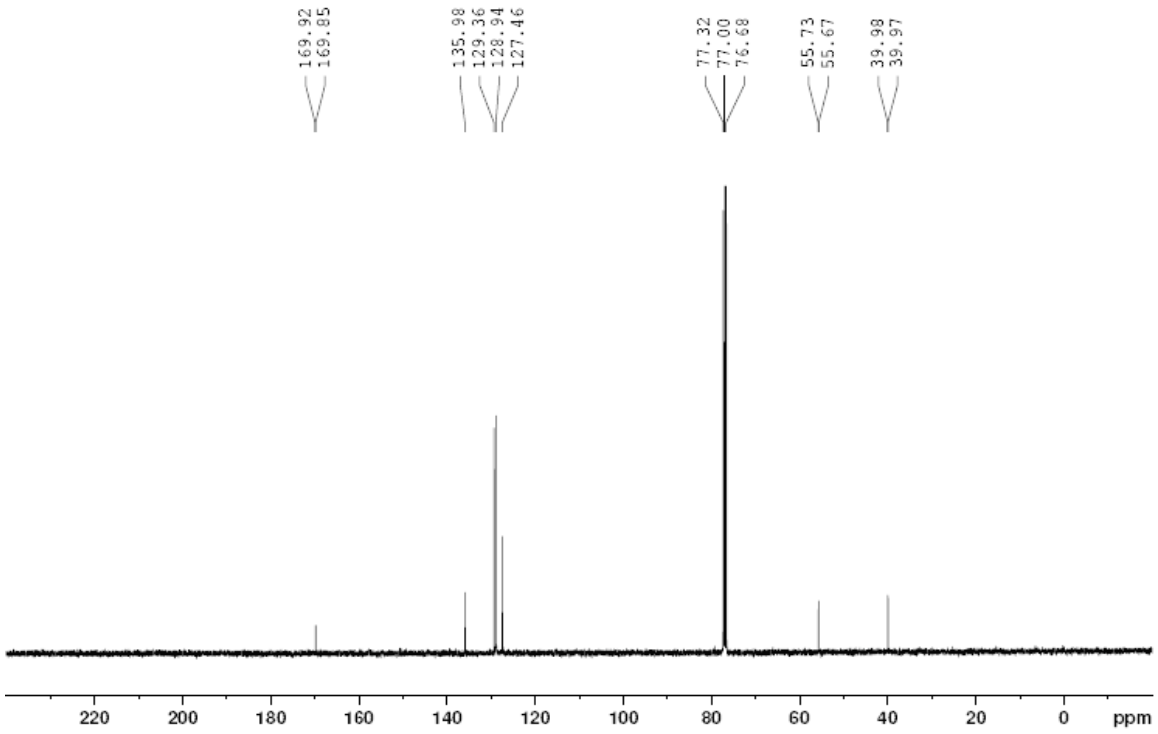



**Figure S13** $^{13}C$ NMR spectrum of compound **3b** (100 MHz; $CDCl_3$; $CDCl_3$).

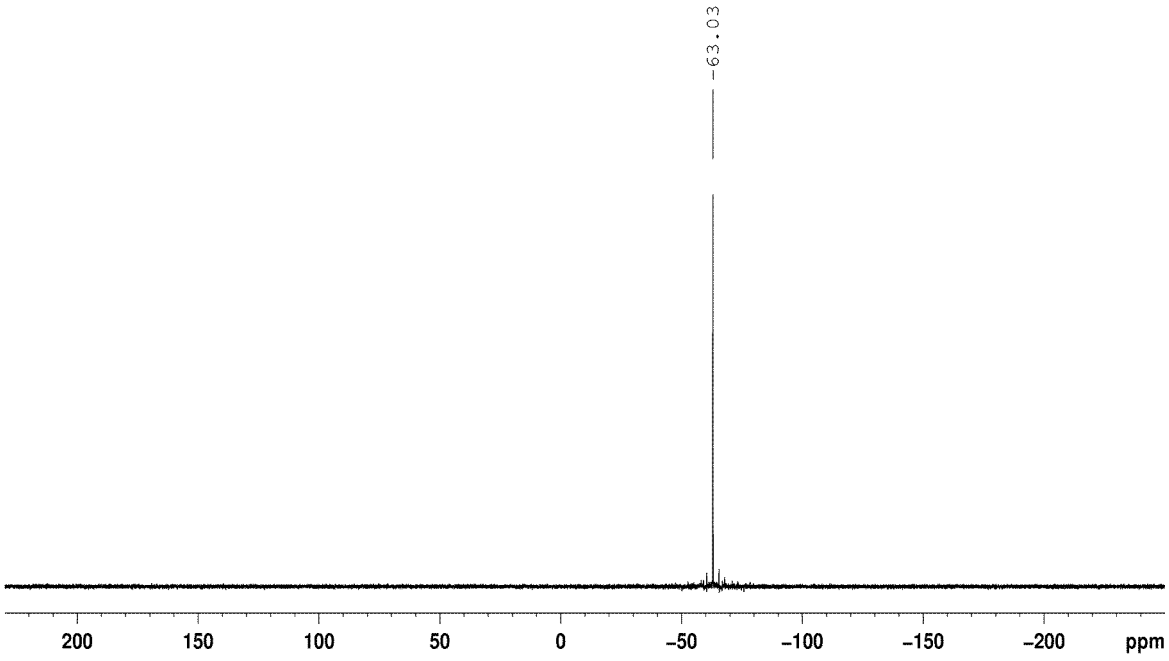



**Figure S14** $^{31}P$ NMR spectrum of compound **3b** (162 MHz; DMSO-$d_6$; 85% $H_3PO_4$).

H5-161-B-1-N15-080903
H5-184-L-I
~20mg/450uL DMSO-d6
Hou JianBo

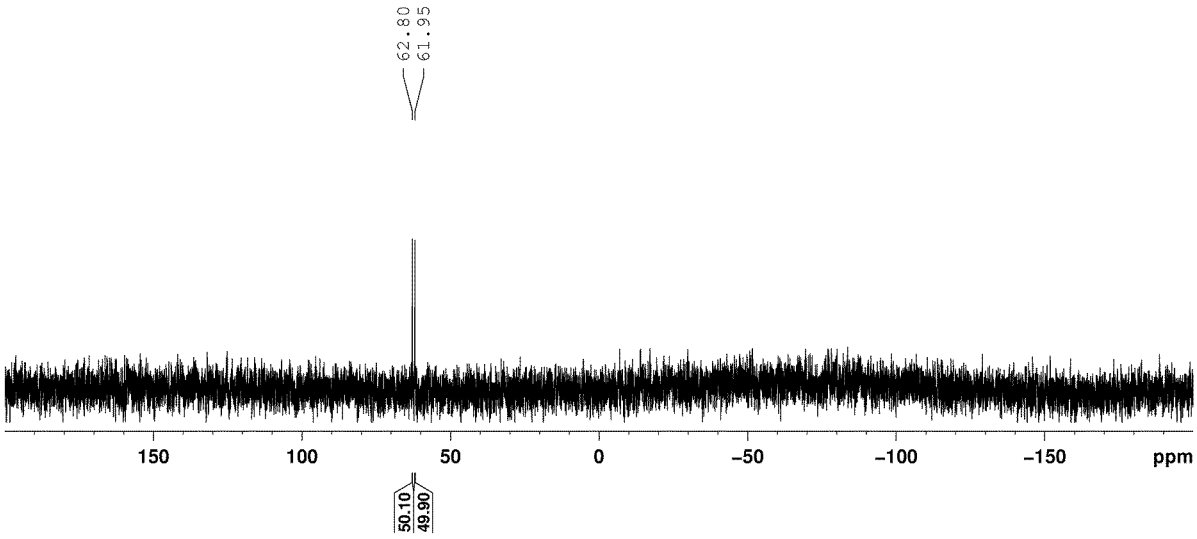



**Figure S15** $^{15}N$ NMR spectrum of compound **3b** [40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)].

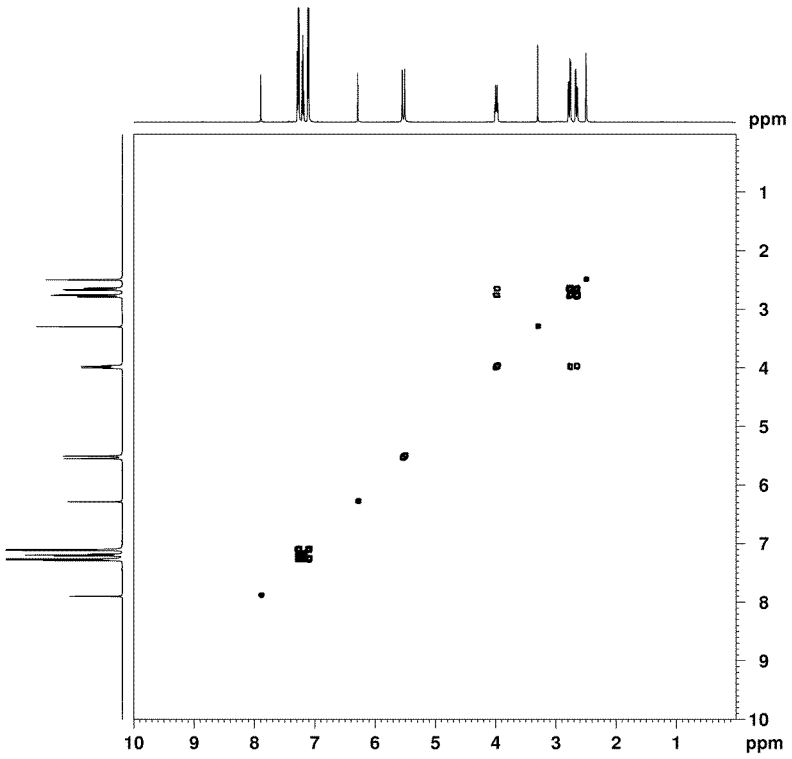



**Figure S16** $^1H$ - $^1H$ COSY NMR spectrum of compound **3b** (500 MHz; DMSO-$d_6$; DMSO).

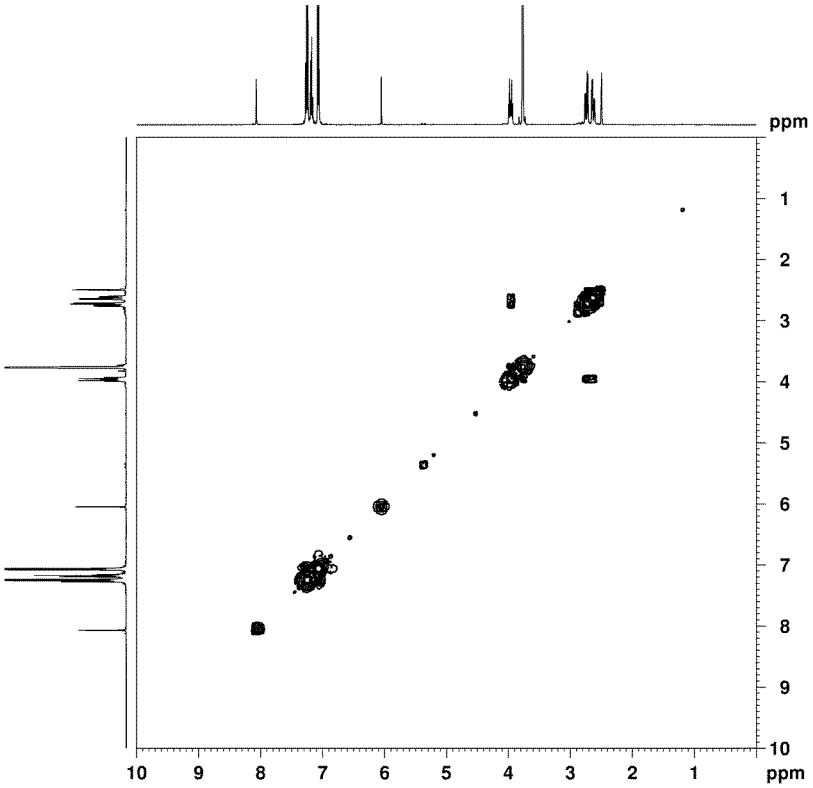



**Figure S17** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **3b** (400 MHz; DMSO-$d_6$ + $D_2O$; DMSO).

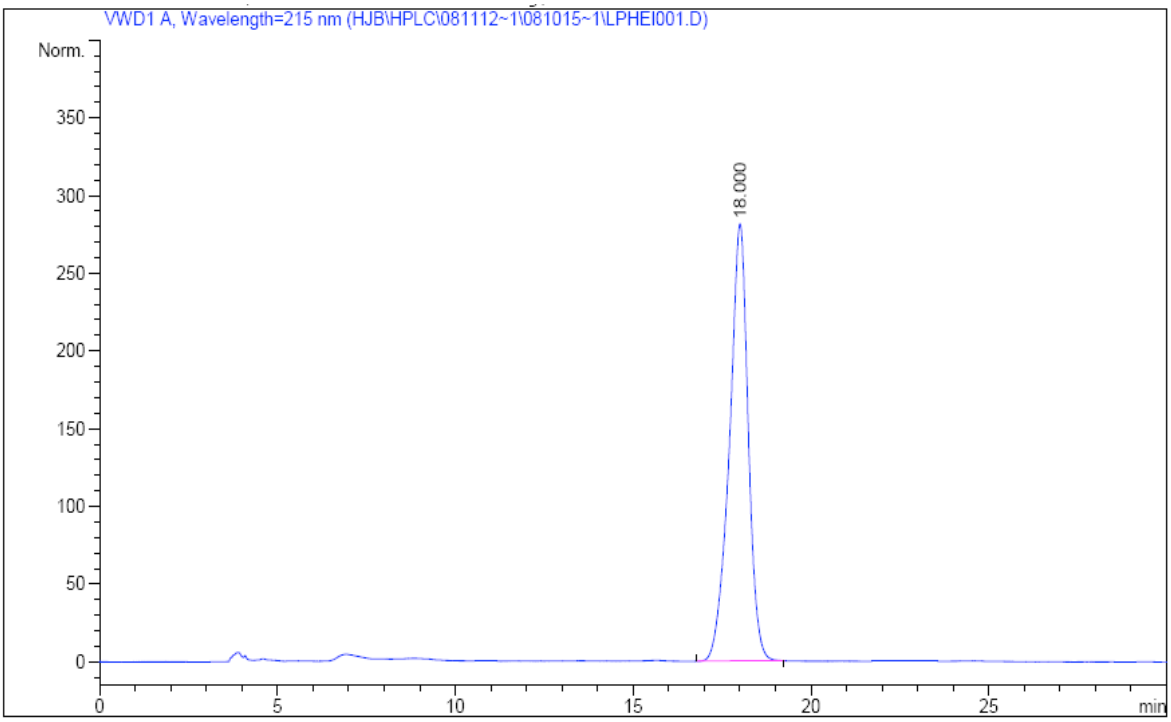



**Figure S18** HPLC spectrum of compound **3b** [(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

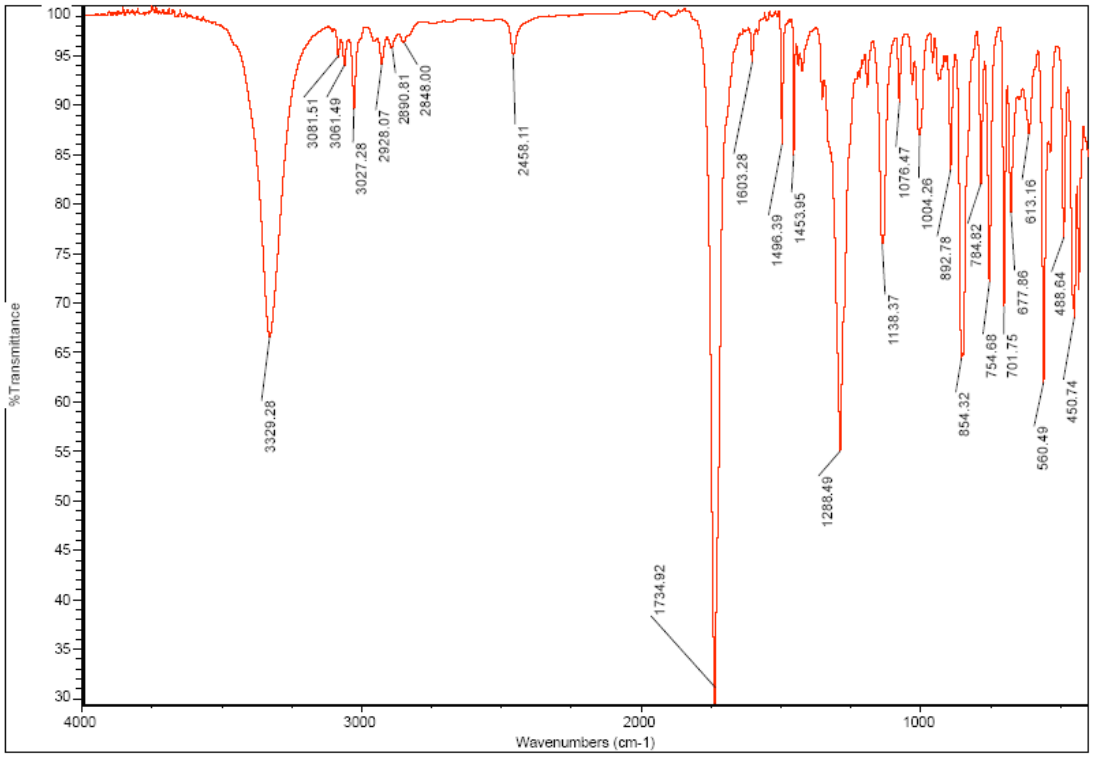



**Figure S19** IR spectrum of compound **3b** (film).

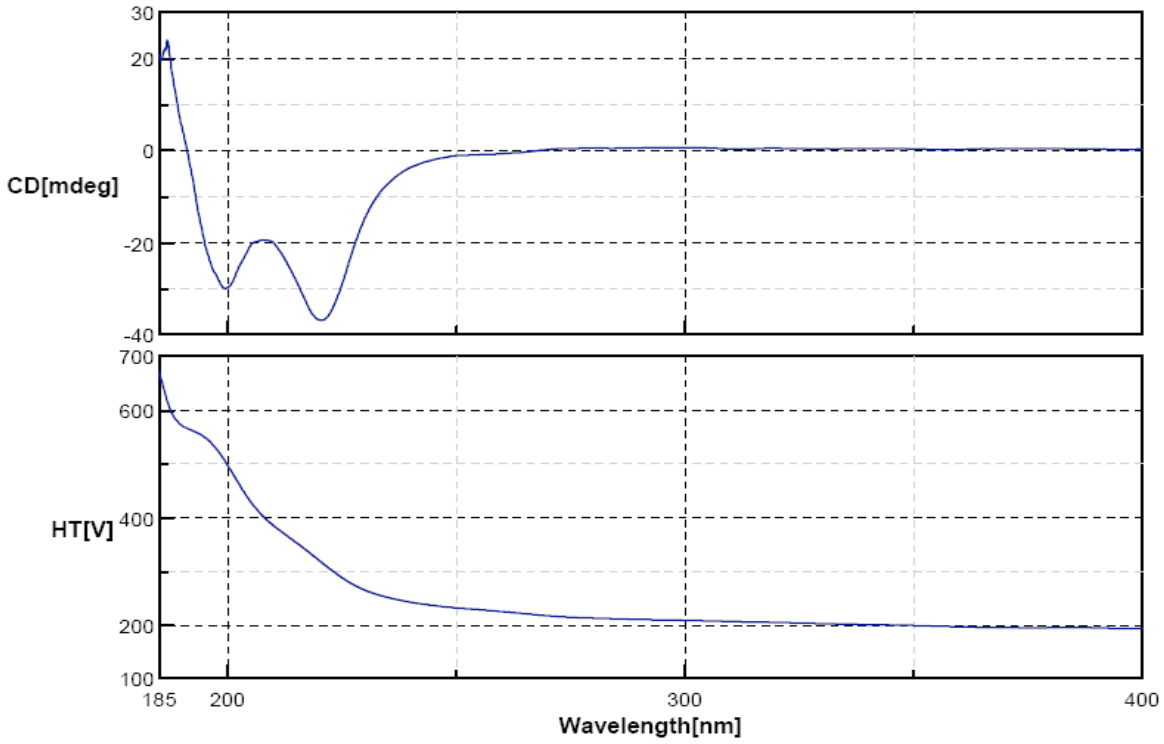



**Figure S20** Solid-state CD spectrum of compound **3b** (KCl disk).

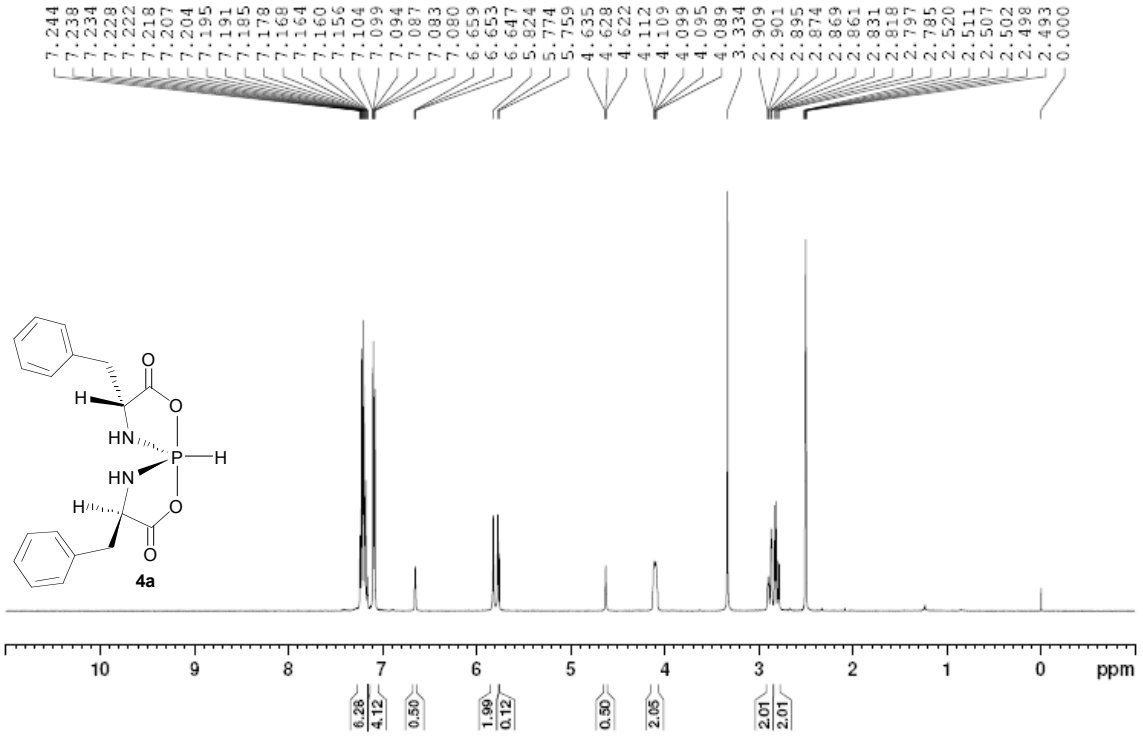



**Figure S21** $^{1}$H NMR spectrum of compound **4a** (400 MHz; DMSO-$d_6$; $Me_4Si$).

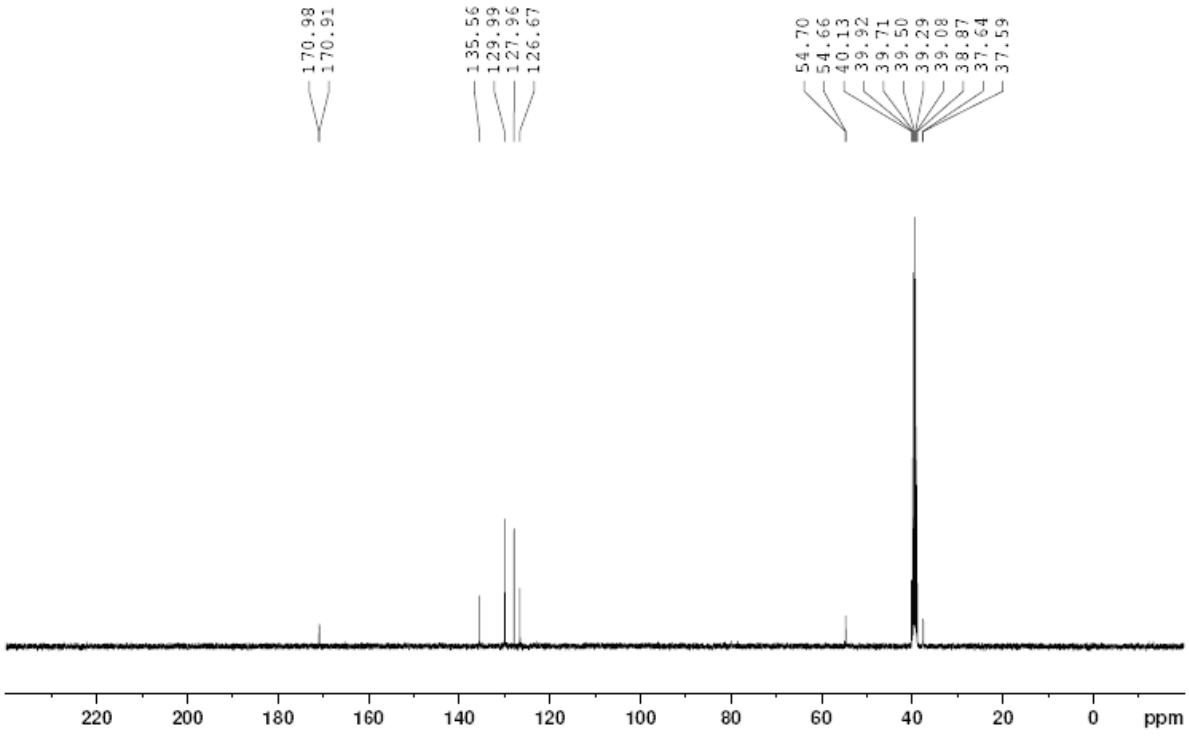



**Figure S22** $^{13}$C NMR spectrum of compound **4a** (100 MHz; DMSO-$d_6$; DMSO).

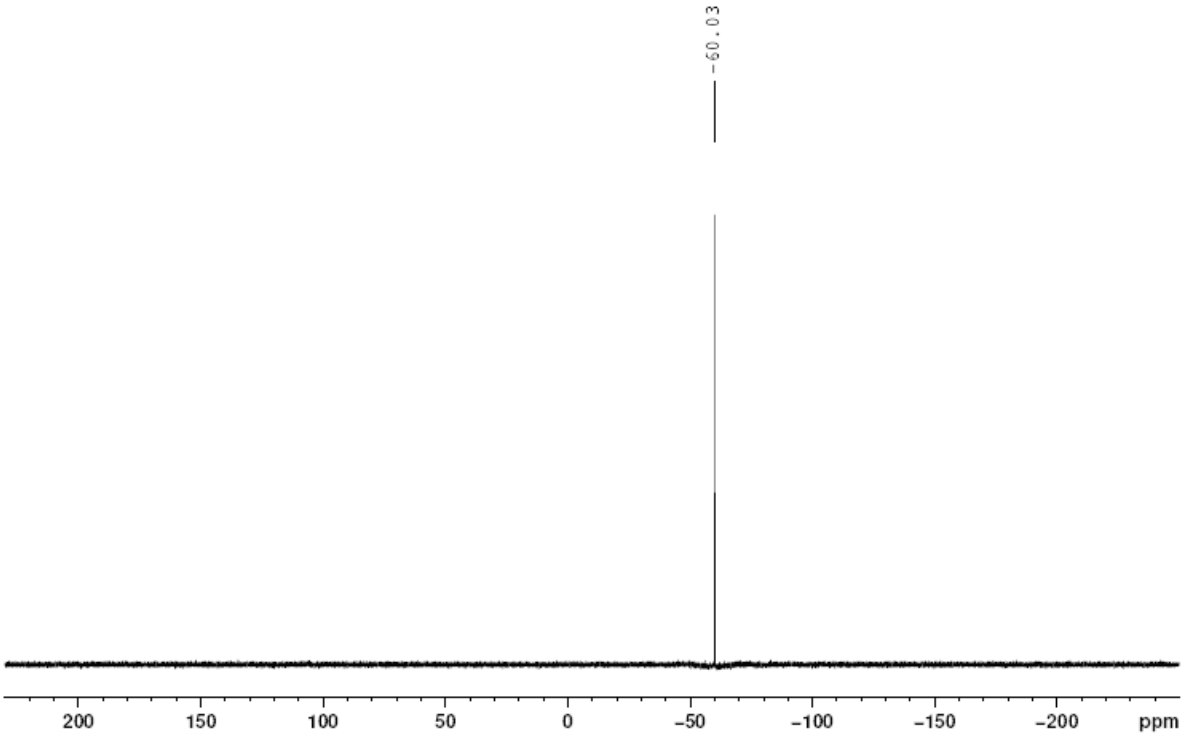



**Figure S23** $^{31}P$ NMR spectrum of compound **4a** (162 MHz; DMSO-$d_6$; 85% $H_3PO_4$).

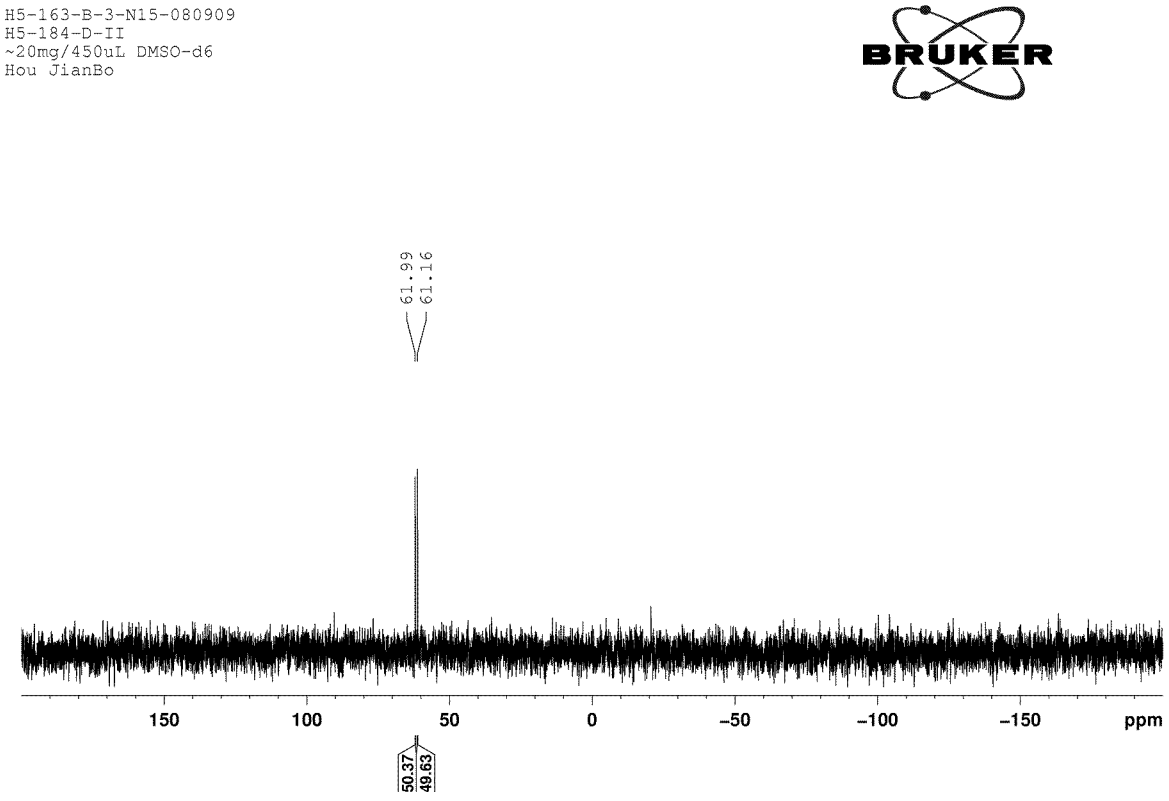



**Figure S24** $^{15}N$ NMR spectrum of compound **4a** [40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)].

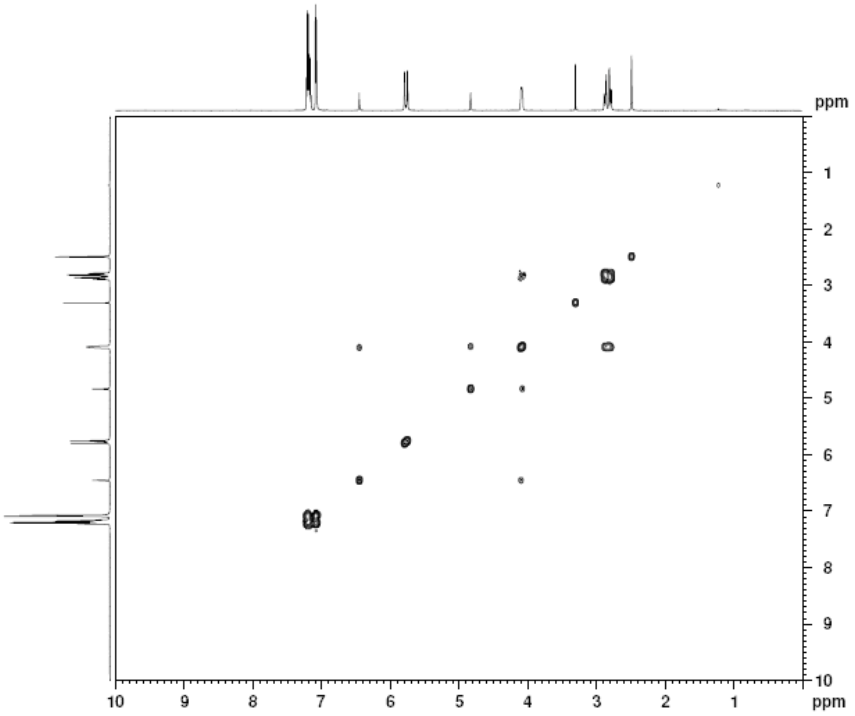



**Figure S25** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **4a** (500 MHz; DMSO-$d_6$; DMSO).

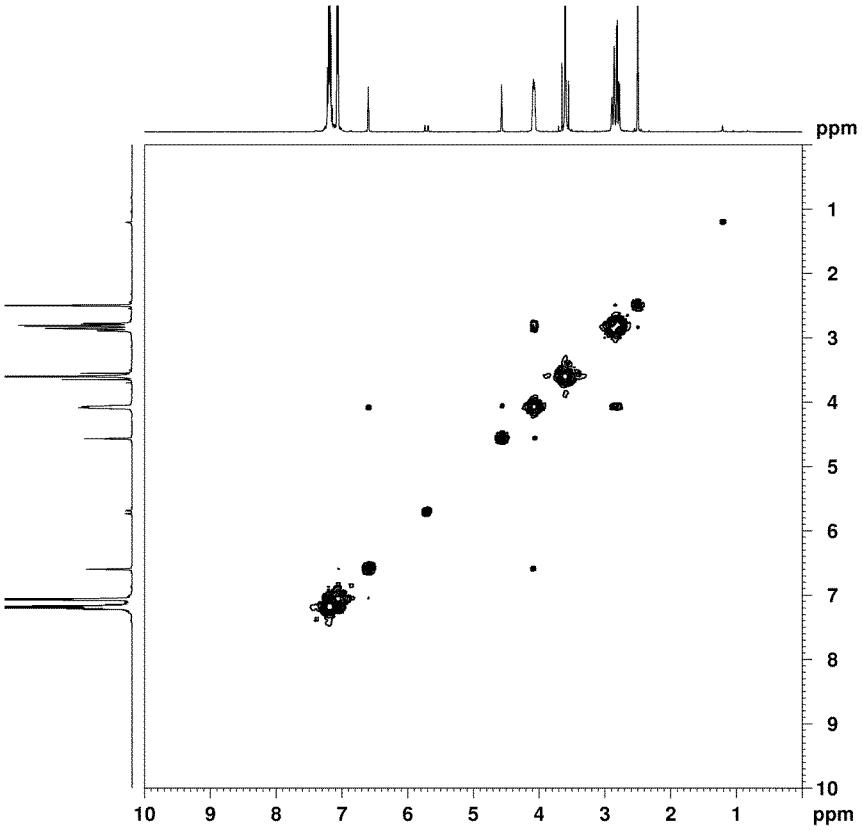



**Figure S26** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **4a** (400 MHz; DMSO-$d_6$ + $D_2O$; DMSO).

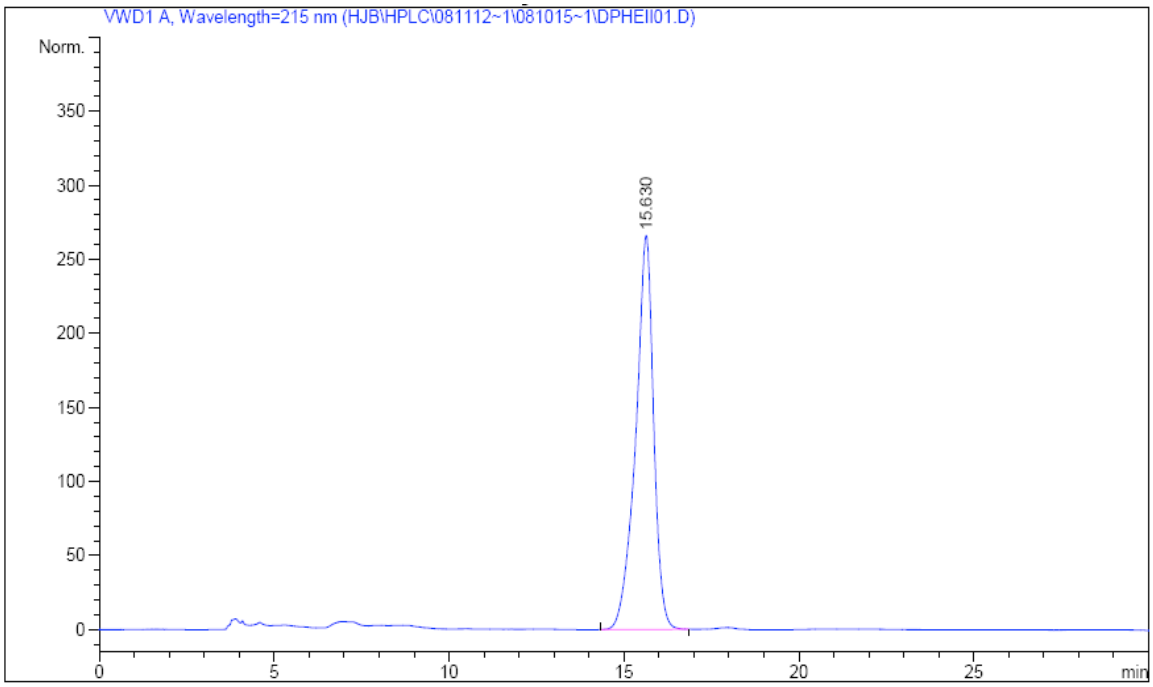



**Figure S27** HPLC spectrum of compound **4a** [(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

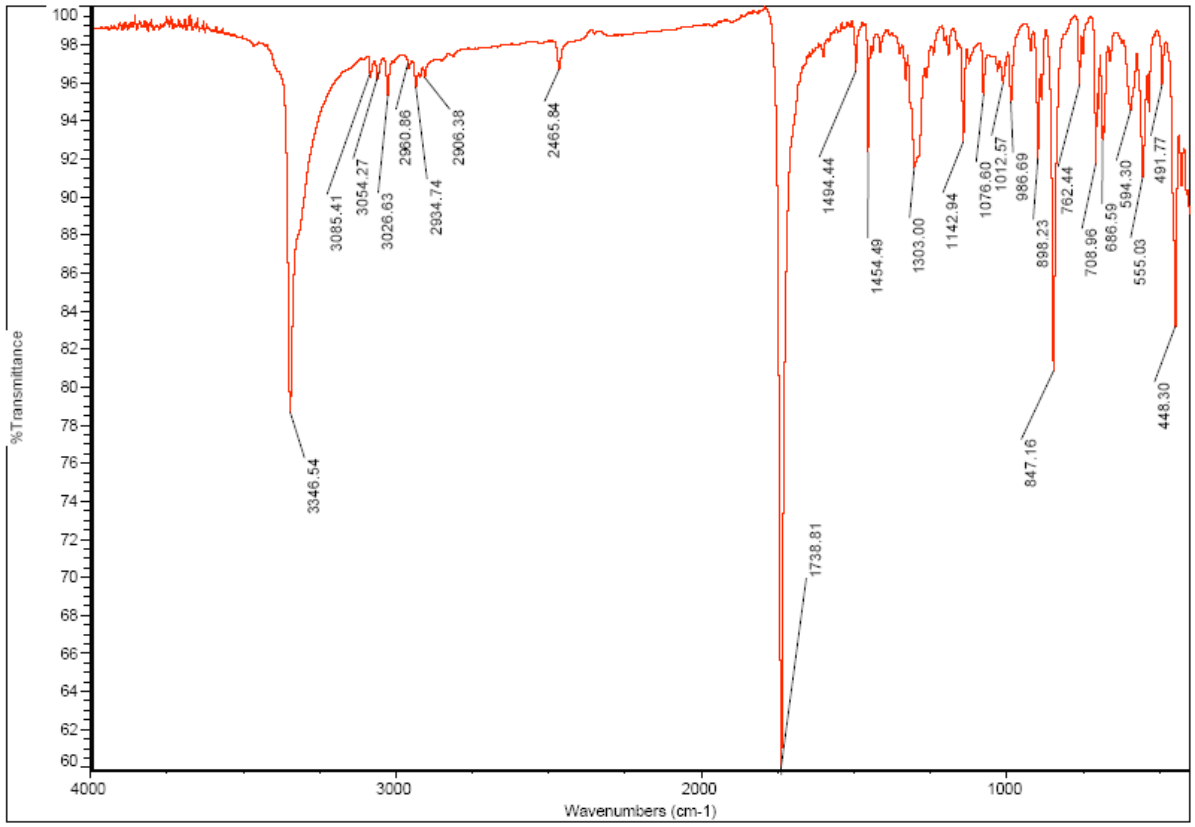



**Figure S28** IR spectrum of compound **4a** (film).

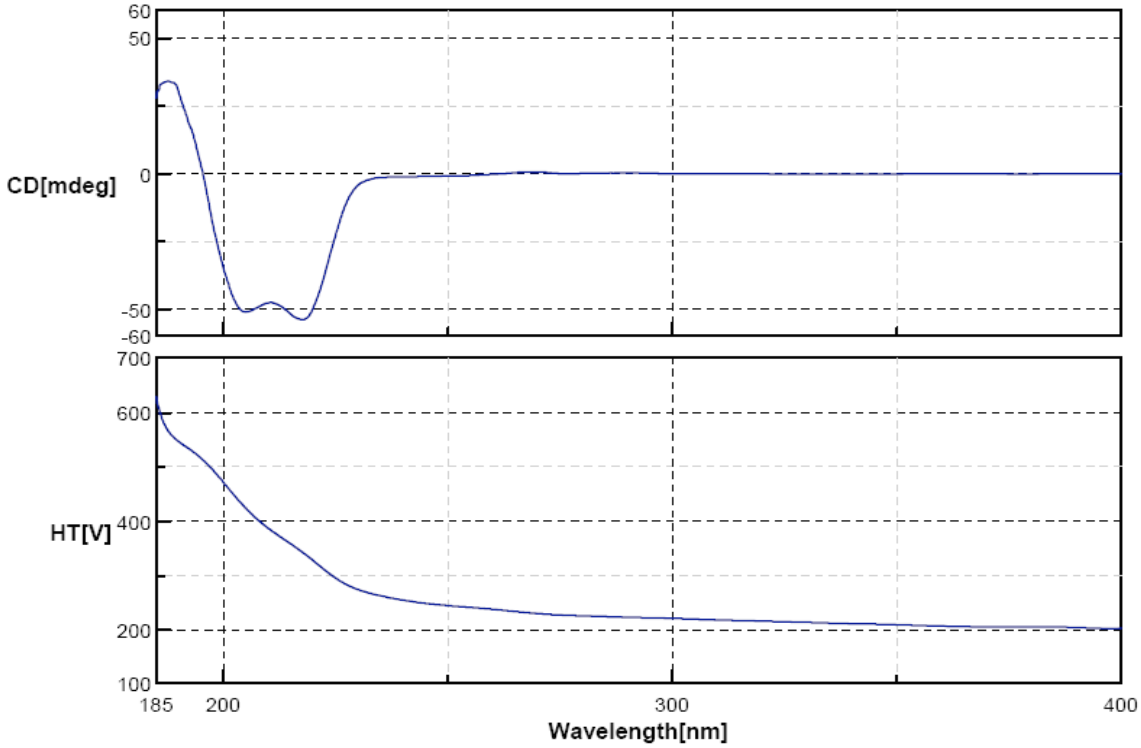



**Figure S29** Solid-state CD spectrum of compound **4a** (KCl disk).

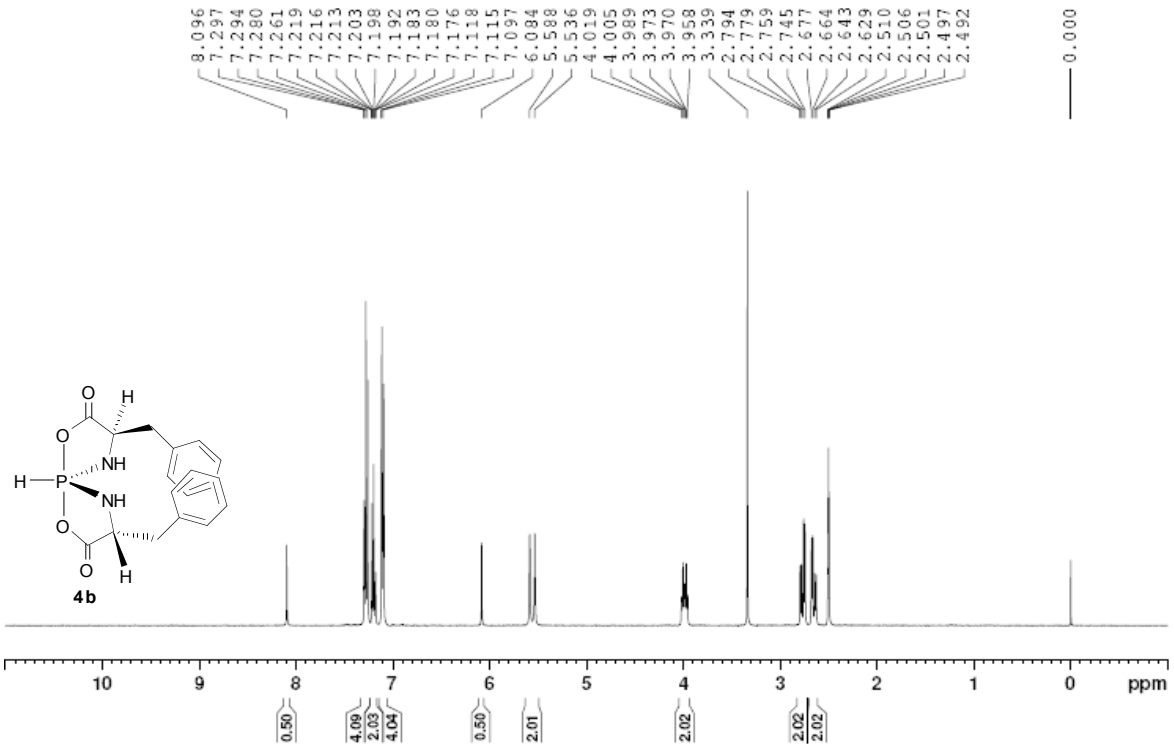



**Figure S30** $^{1}$H NMR spectrum of compound **4b** (400 MHz; DMSO-$d_6$; $Me_4Si$).

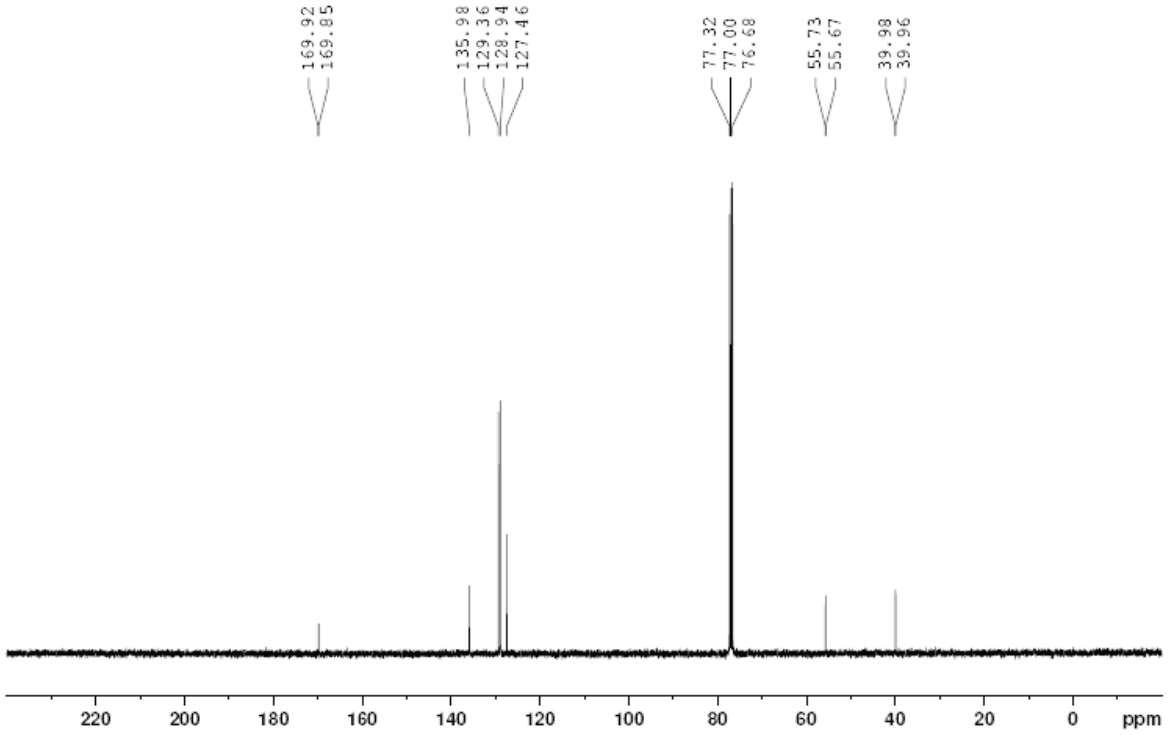



**Figure S31** $^{13}C$ NMR spectrum of compound **4b** (100 MHz; $CDCl_3$; $CDCl_3$).

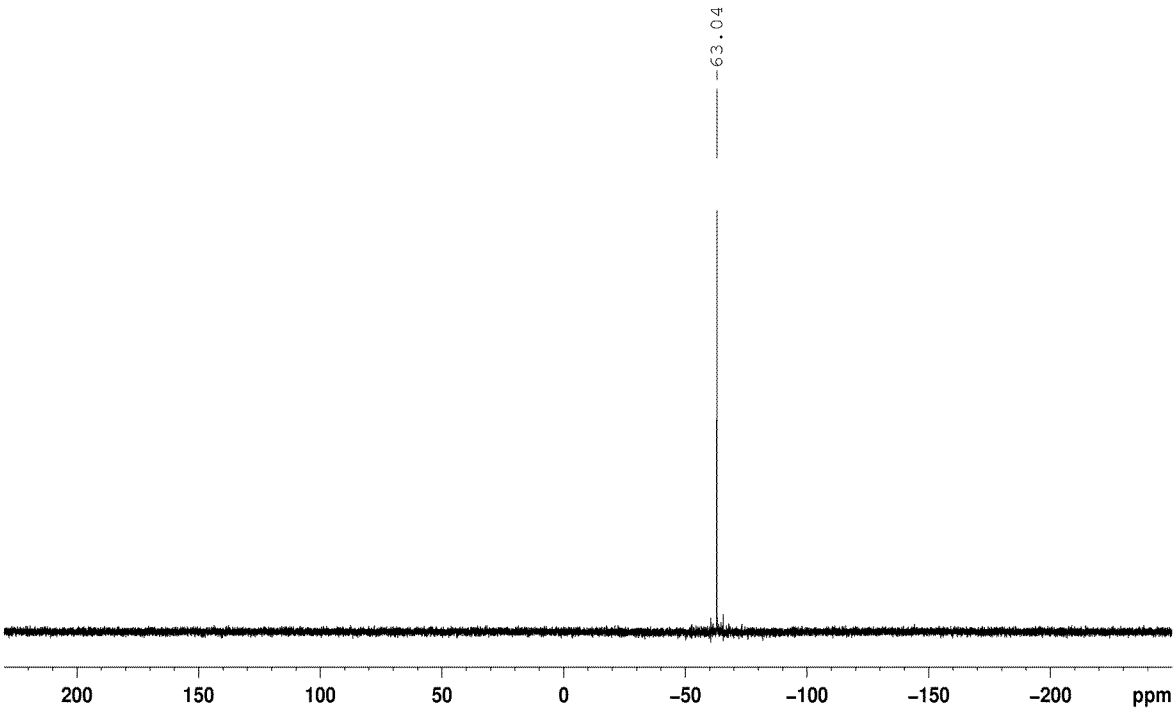



**Figure S32** $^{31}P$ NMR spectrum of compound **4b** (162 MHz; DMSO-$d_6$; 85% $H_3PO_4$).

H5-163-B-1-N15-080906
H5-184-D-I
~20mg/450uL DMSO-d6
Hou JianBo

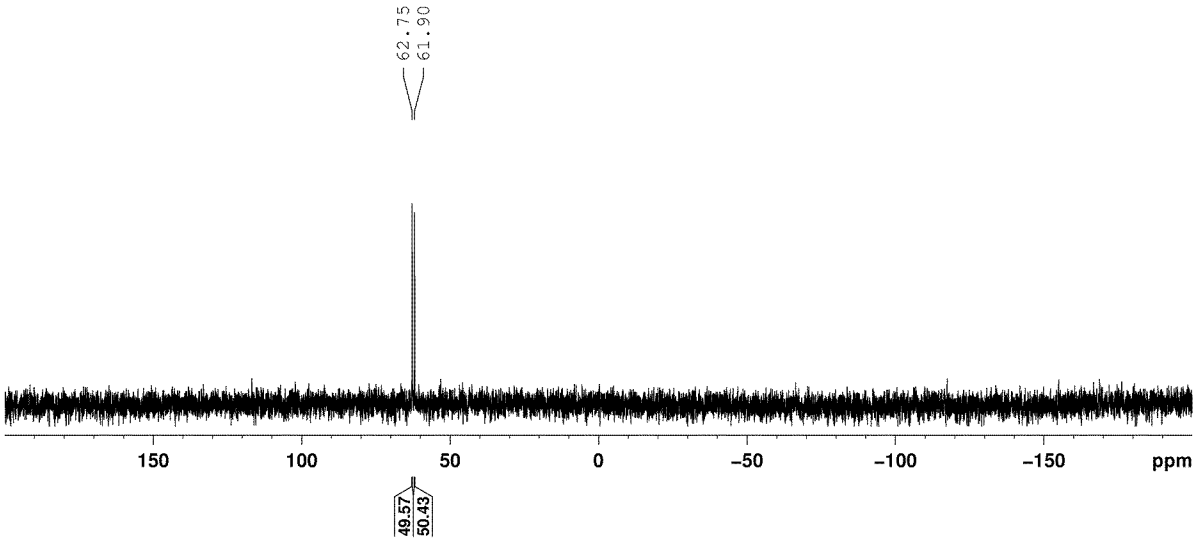



**Figure S33** $^{15}$N NMR spectrum of compound **4b** [40.5 MHz; DMSO-$d_6$; saturated solution of $^{15}NH_4Cl$ ($D_2O$ as solvent)].

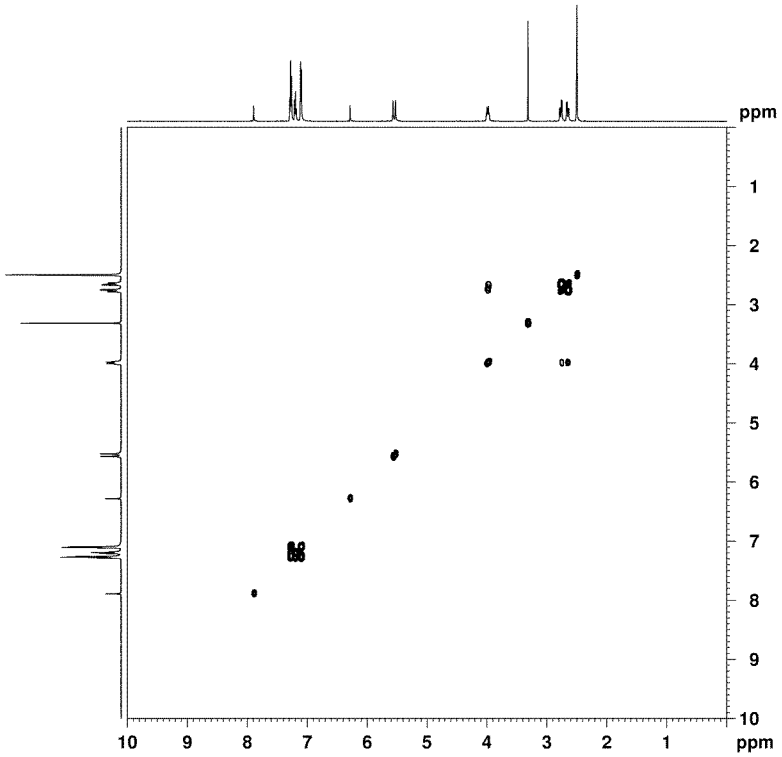



**Figure S34** $^1$H - $^1$H COSY NMR spectrum of compound **4b** (500 MHz; DMSO-$d_6$; DMSO).

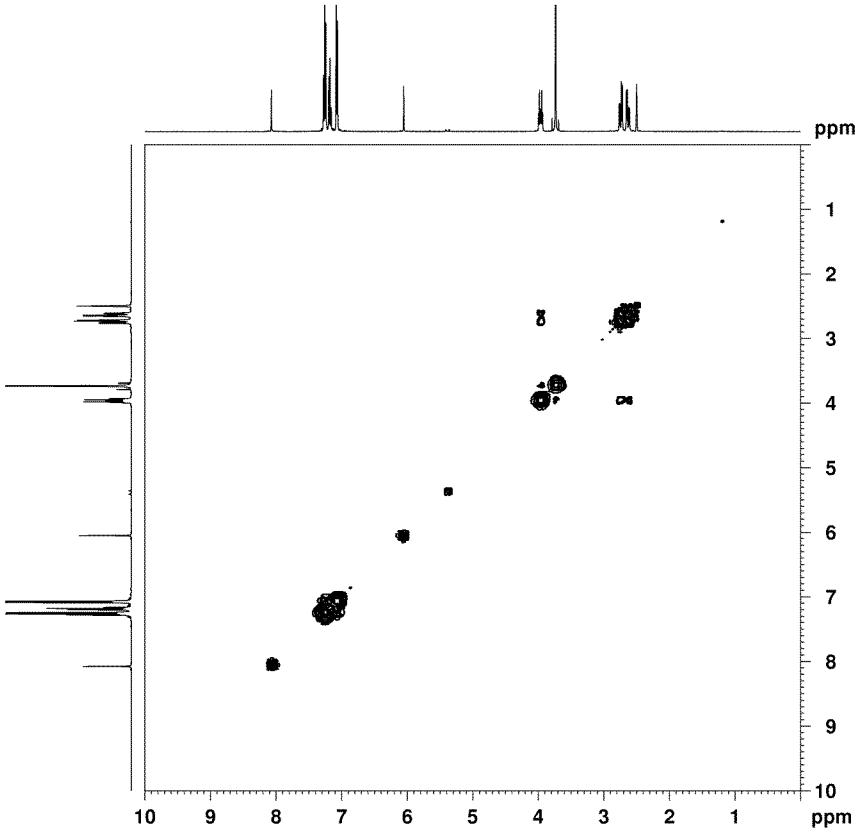



**Figure S35** $^{1}H$ - $^{1}H$ COSY NMR spectrum of compound **4b** (400 MHz; DMSO-$d_6$ + $D_2O$; DMSO).

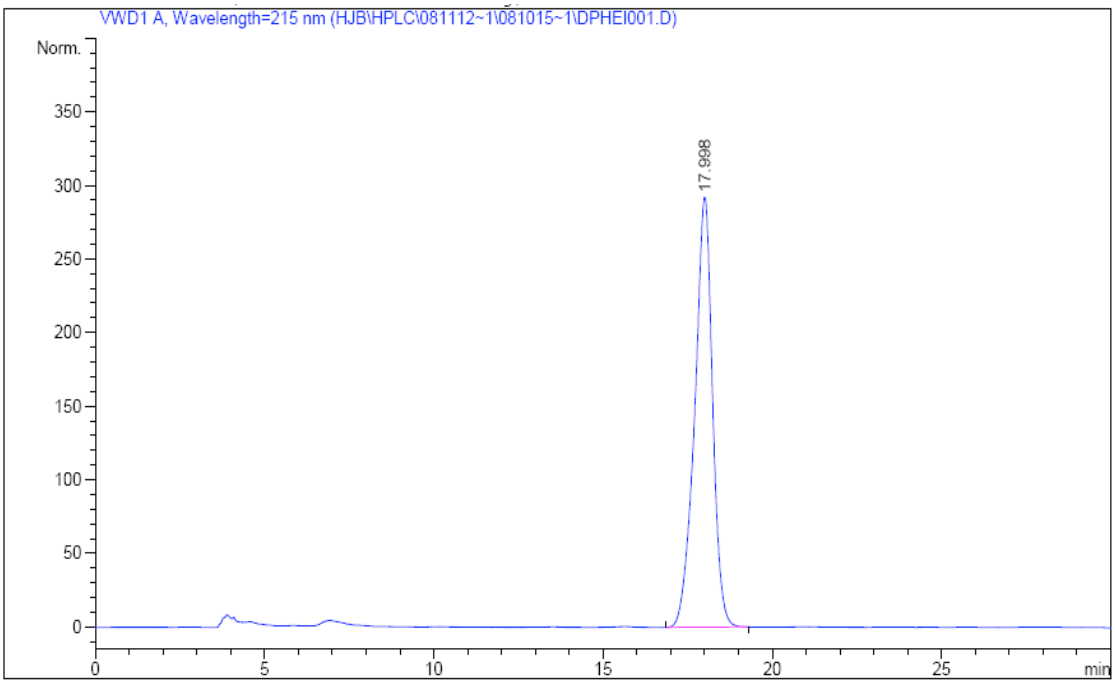



**Figure S36** HPLC spectrum of compound **4b** [(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

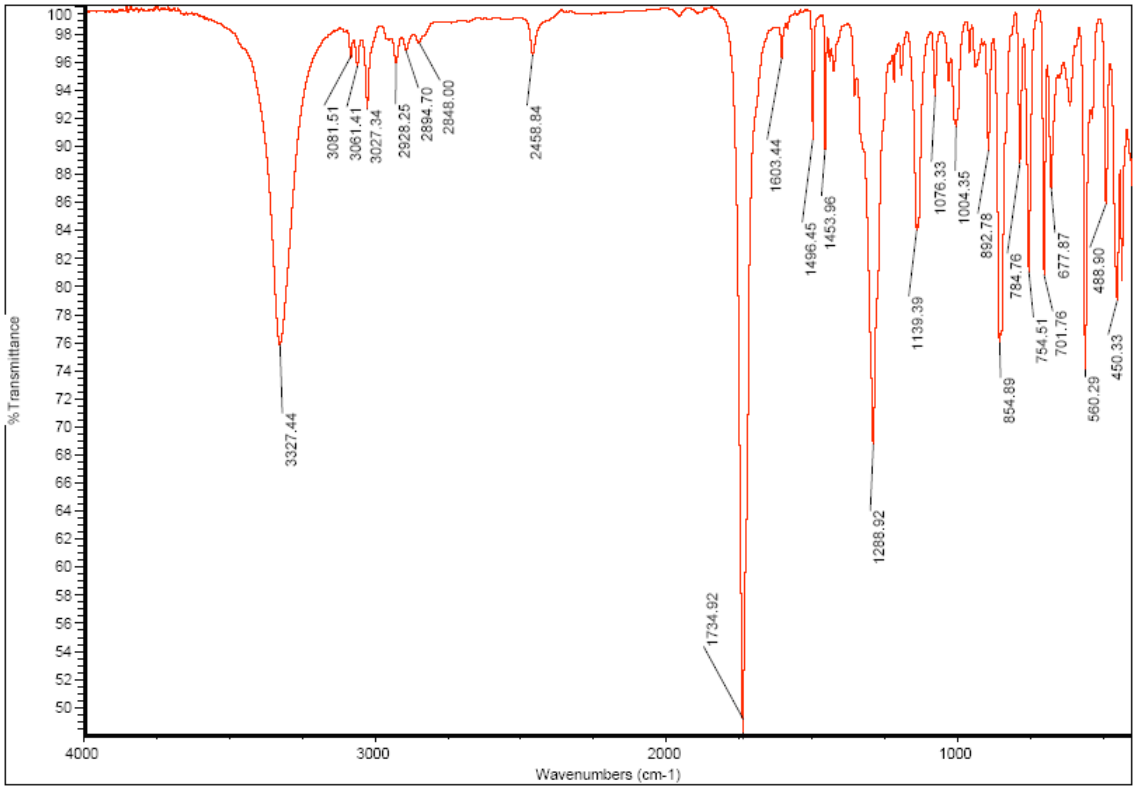



**Figure S37** IR spectrum of compound **4b** (film).

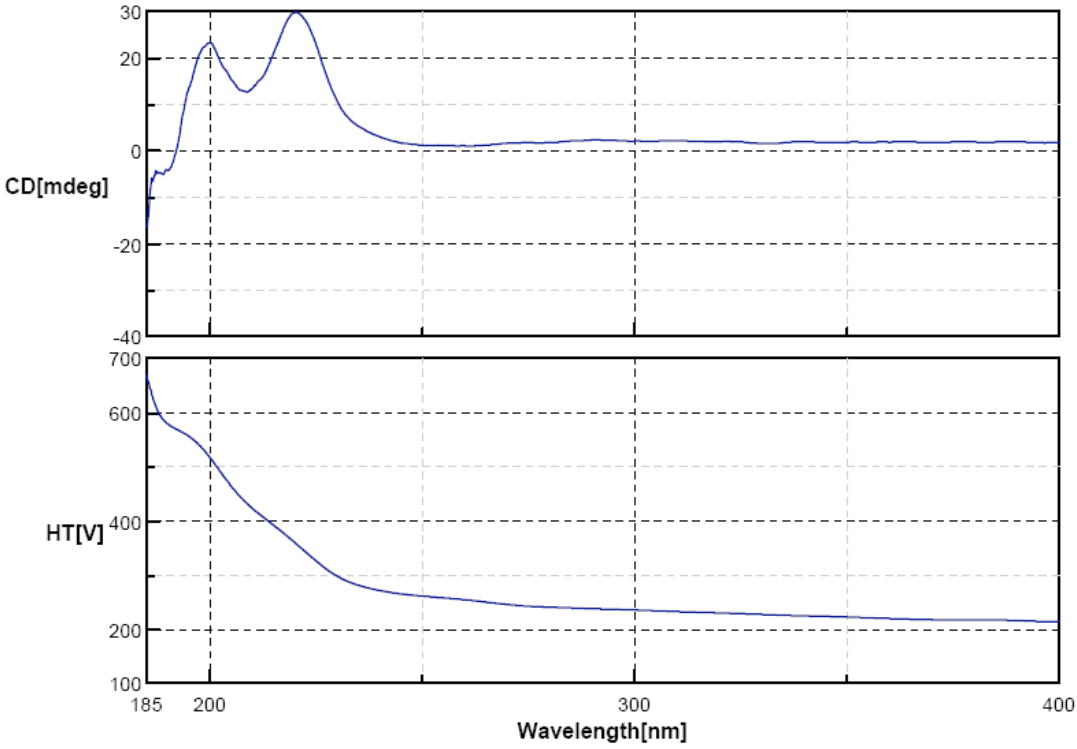



**Figure S38** Solid-state CD spectrum of compound **4b** (KCl disk).

## 7. HPLC spectra of 3a/3b and 4a/4b

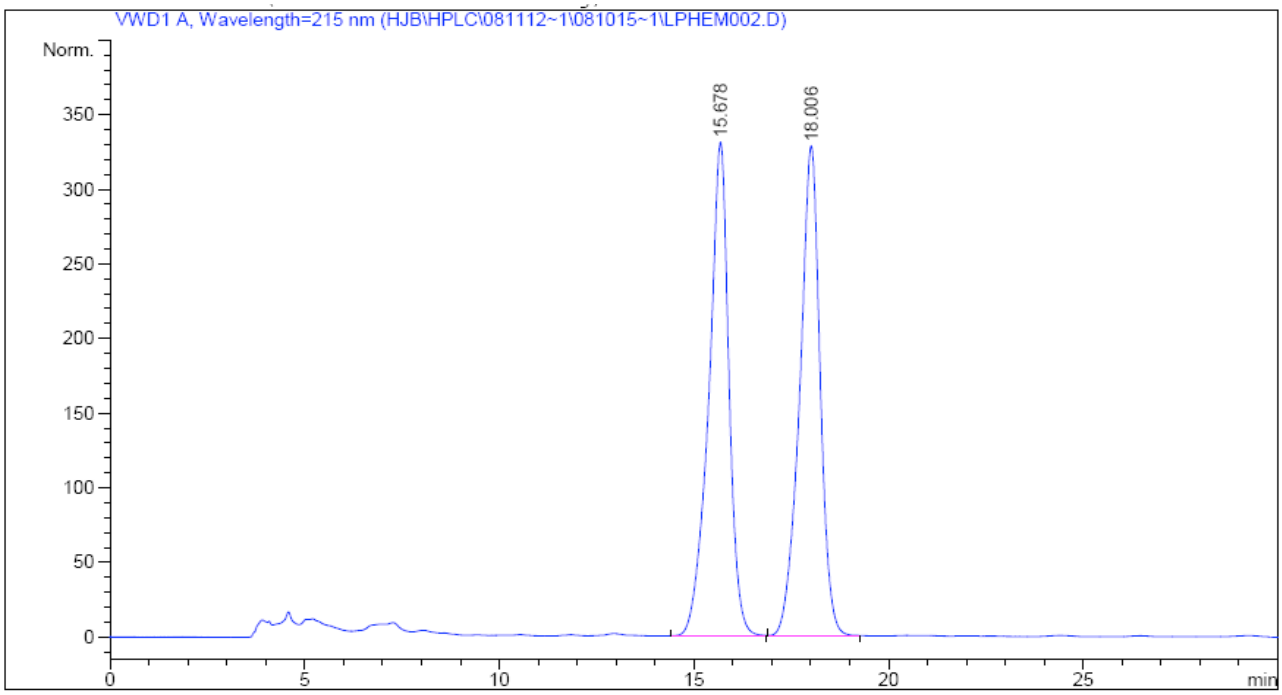



**Figure S39** HPLC spectrum of compounds **3a** (15.678 min) and **3b** (18.006 min). [(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

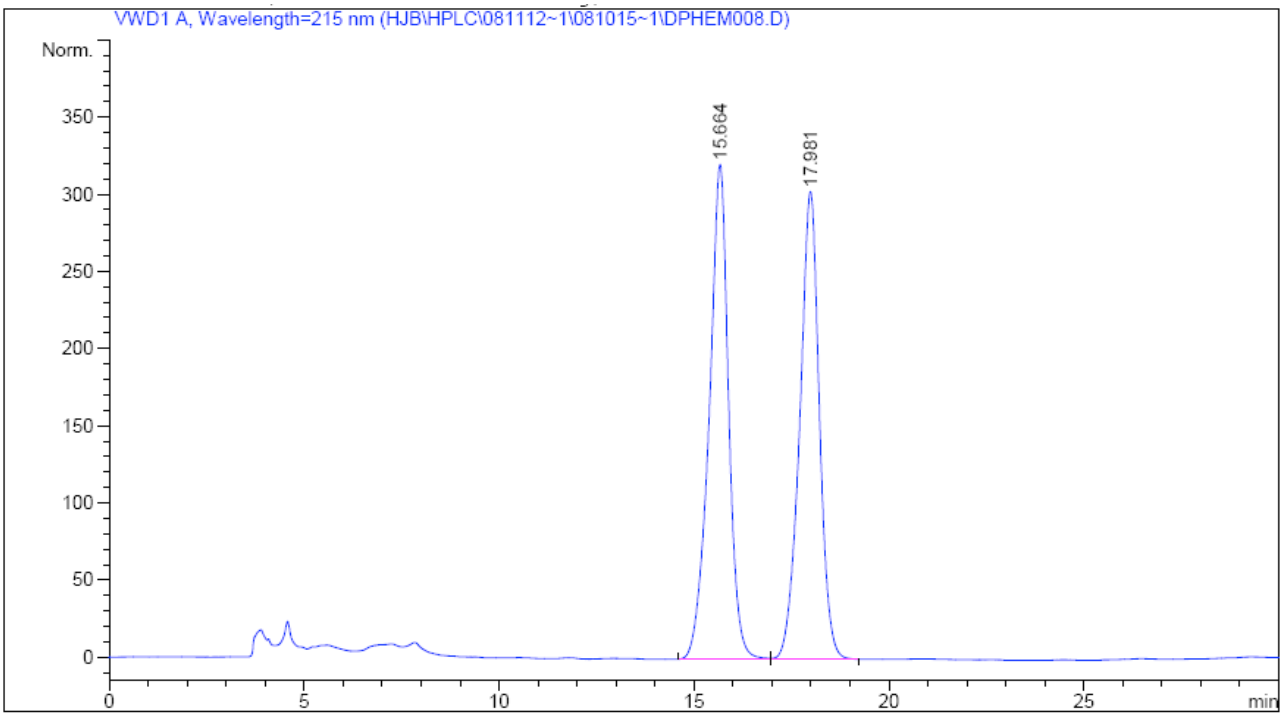



**Figure S40** HPLC spectrum of compounds **4a** (15.664 min)and **4b** (17.981 min).[(Agilent, TC-$C_{18}$ column, 5 μm, 4.6 x 250 mm), mobile phase: elute $CH_3OH/H_2O$ (v/v) = 3:2, 0.8 mL/mins; rt (25 ˚C); injection volume 20.0 μL; detection absorption at 215 nm.]

## 8. Solid-state CD spectrum of 3a-4b

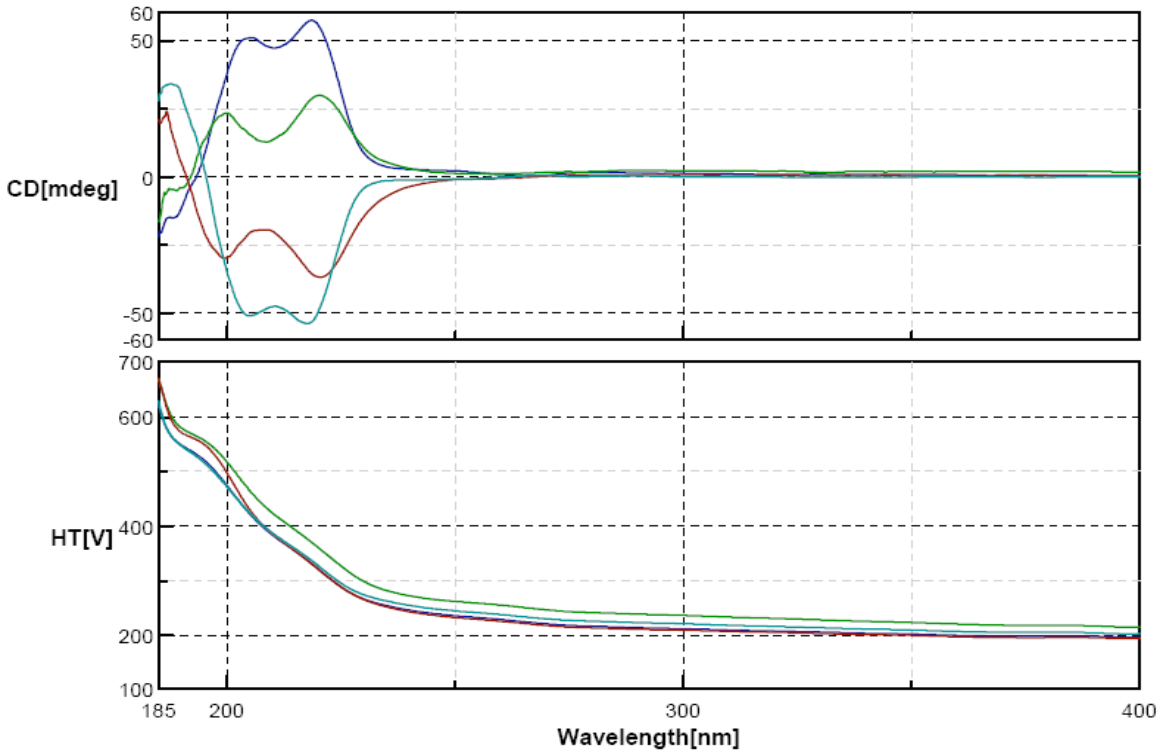



**Figure S41** Solid-state CD spectra of compounds **3a**-**4b** (KCl disk).