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Supporting Information (SI) for:

Asymmetric 1,3-dipolar cycloaddition reaction of chiral 1-alkyl-1,2-diphospholes with diphenyldiazomethane

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Calculation details

The quantum chemical calculations were performed with the Gaussian 03 software package.[1] Full geometry optimizations have been carried out within the framework of DFT (PBE0) method using 6-31+G(d) basis sets. Chemical shifts were calculated at the PBE0/6-311G(2d,2p) level of theory. ^{13}C chemical shifts were referred to TMS. ^{31}P chemical shifts were referred to H_3PO_4, and a linear scaling procedure was applied.[2]

References: see S37

Details of structure elucidation by NMR

The structures of compounds **3a, 3b** and **5a** were established by verity of 1D/2D NMR correlation methods. Namely, starting from the group with well known "finger prints" structure of whole compound can be established practically directly.

For example, for **3a** we can start from the P2-CH_2O protons with characteristic ABXY type spin system (at 3.95 and 3.62 ppm).

As to the menthyl fragment: There is ^{1}H-^{13}C HMBC correlation from the P2-CH_2O protons to C1' (80.52 ppm). Then from ^{1}H-^{13}C HSQC experiment the H1' (3.01 ppm) proton can be established. Next there are ^{1}H-^{13}C HMBC connectivity's from the H1' proton to C2' (48.91 ppm), to C5' (31.56 ppm), to C7' (24.76 ppm) and to P2-$\underline{C}H_2O$ (64.79 ppm) carbons. There are also NOE's from the P2-CH_2O protons to H1', to H6eq' and to H7' protons. Then combination of ^{1}H-^{1}H COSY, ^{1}H-^{13}C HSQC and ^{1}H-^{13}C HMBC experiments allows to assign all signals in ^{1}H and ^{13}C spectra of the menthyl moiety. The most important connectivity's are from H7' to Me-8' and Me-9' (^{1}H-^{1}H COSY and ^{1}H-^{13}C HMBC); and from H5' to Me-10' (^{1}H-^{1}H COSY and ^{1}H-^{13}C HMBC).

As to the bicyclic phosphirane fragment: There are ^{1}H-^{31}P HMBC correlations from the P2-CH_2O protons to P1 (-121.4 ppm) and to P2 (6.2 pm). There is also ^{1}H-^{13}C HMBC connectivity from the P2-CH_2O protons to C3 (144.52 ppm). ^{13}C DEPT experiments help to distinguish protonated carbons from not protonated ones (CH *versus* C) in low field region. Then, four less intense signals of protonated carbons can be assigned to *para*-carbons of phenyl rings. Doublets in low field region of the ^{1}H spectra are due to *ortho*-protons. Then there is correlation from the *o*-Ph3 (d, 6.3 ppm) protons to C3 (^{1}H-^{13}C HMBC), to P2 (^{1}H-^{31}P HMBC) and to the P2-CH_2O protons (NOE). There are correlations from the *o*-Ph6 (d, 7.65 ppm) and the *o*-Ph6' (d, 6.9 ppm) protons to C6 (54.09 ppm, ^{1}H-^{13}C HMBC) and P1 (^{1}H-^{31}P HMBC). The *o*-Ph6 *versus* *o*-Ph6' protons can be distinguished upon NOE between the *o*-Ph6 and the *o*-Ph3 protons. There is also NOE between the *o*-Ph3 and the *o*-Ph4 protons. There is ^{1}H-^{13}C HMBC correlation from the *o*-Ph4 protons to C4 (151.12 ppm). Unfortunately, there is no ^{1}H-^{13}C HMBC connectivity's to C5 (73.08 ppm) due to: 1) the *o*-Ph5 protons are broadened due to sterical hindrance; 2) there is no other protons in close proximity. But it's characteristic chemical shift and ^{1}JCP (37.8 Hz) allows assign the signal to C5. This is also in good agreement with results of calculations. Finally, starting from the ortho-protons all other signals in ^{13}C and ^{1}H spectra can be well assigned upon ^{1}H-^{13}C HMBC, ^{1}H-^{13}C HSQC and ^{1}H-^{1}H COSY connectivity's.

In similar way structures of **3b** and **5a** were established.

In the case of compound **5b** the bicyclic phosphirane fragment signals in ^{1}H and ^{13}C NMR spectra cannot be resolved (except C4-*o*-Ph and C3-*o*-Ph) due to intensive overlap with the main isomer (**5a**) signals therefore only the data for the neomenthyl fragment is given. In this case ^{1}H-^{31}P HMBC, ^{1}H-^{1}H COSY and ^{1}H-^{13}C HSQC spectra are particularly helpful. The ^{1}H-^{31}P HMBC spectra allows to reveal the protons coupled with minor phosphorus signals, while the ^{1}H-^{1}H COSY and ^{1}H-^{13}C HSQC spectra helps to resolve ^{1}H and ^{13}C signals of neomenthyl fragment. But no information about exact multiplet structure of the ^{1}H and ^{13}C spectra can be obtained in this way for some of the protons.

Table S1. Energies (PBE0/6-31+G(d)) of main forms due to rotation around P2-CH_2 bond in the model of compound **3** (**3'**, methyl instead of menthyl).

Energy	-g*	**trans**	+g
hartree	-2145.8153312	-2145.8190703	-2145.8169151
kcal/mol	**2.3**	**0**	**1.4**

* orientation with respect to the lone pair of electrons at phosphorus, C-O with lone pair of electrons; "+" – clockwise;

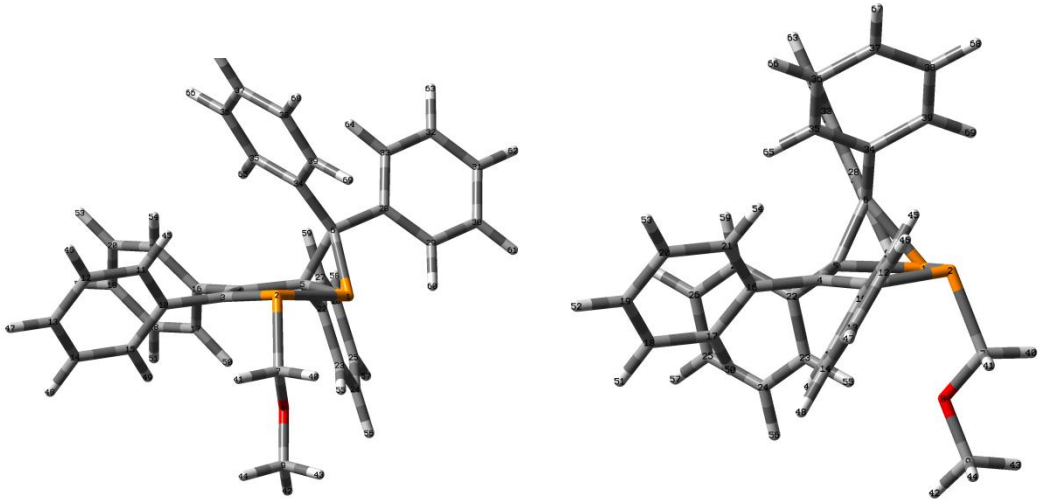

Figure S1. The major form of the model compound **3'** (methyl instead of menthyl): front and side views.

Table S2. Energies (PBE0/6-31+G(d)) and some key ^{13}C and ^{31}P NMR chemical shifts (GIAO PBE0/6-31+G(d)//PBE0/6-311G(2d,2p)) calculated for **3a** and **3b**.

	3a	**3b**
Energy, hartree	-2498.0263604	-2498.026385
Energy, kcal/mol	**0.015**	**0**
P1	-105.7	-102.4
P2	13.6	16.1
C3	156.0	156.9
C4	158.5	157.7
C5	80.3	80.3
C6	58.2	58.4

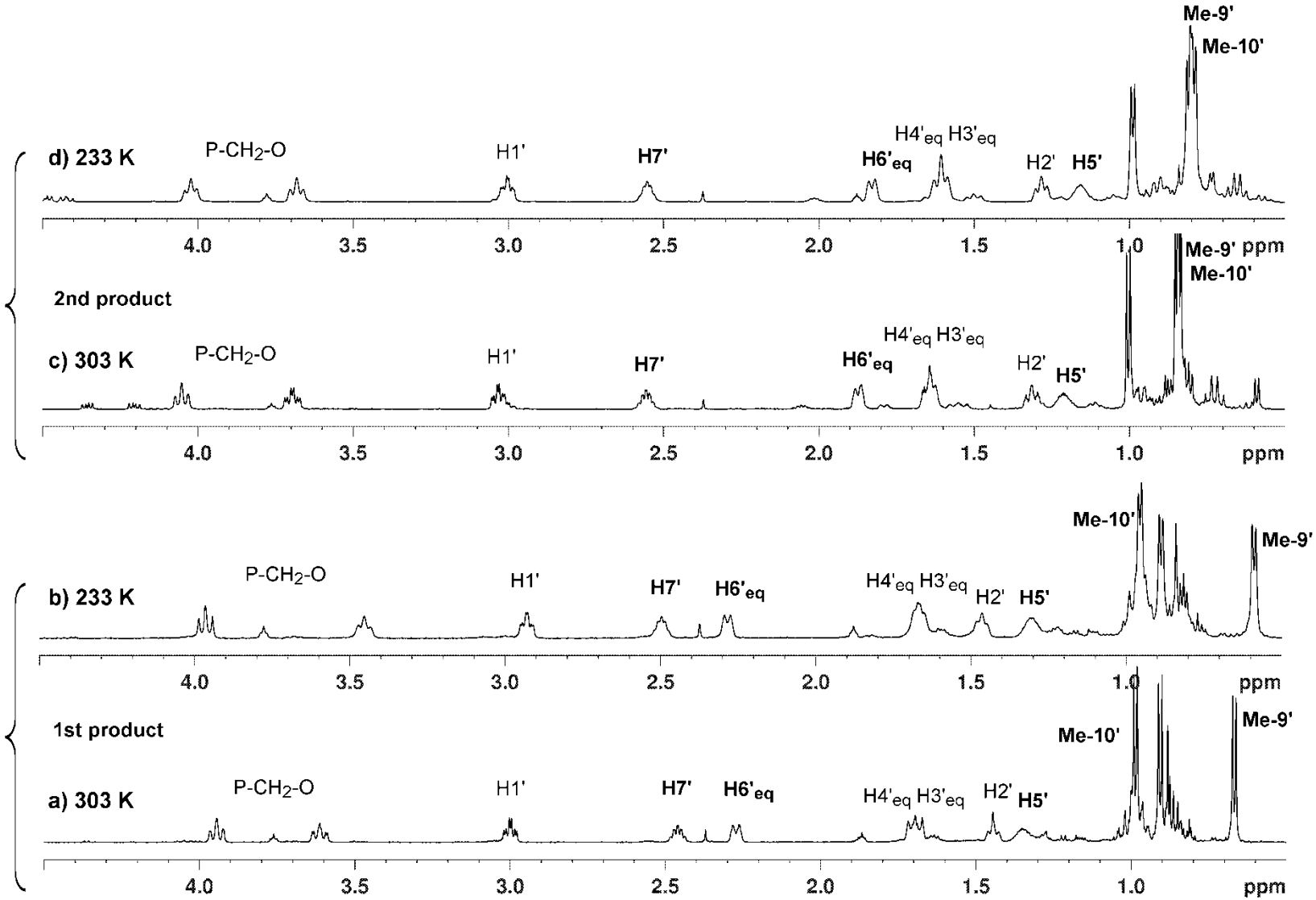

Figure S2. High field sections of the ^{1}H NMR spectra of **3a** (a, b) and **3b** (c, d) in $CDCl_3$ at room and low temperatures.

Table S3. Energies (PBE0/6-31+G(d)) and some key ^{13}C and ^{31}P NMR chemical shifts (GIAO PBE0/6-31+G(d)//PBE0/6-311G(2d,2p)) calculated for **5a** and **5b**.

	5a	**5b**
Energy,	-2383.6206784	-2383.6181352
Energy, kcal/mol	**0**	**1.6**
P1	-85.7	-104.7
P2	22.3	15.5
C3	159.5	155.6
C4	156.8	159.5
C5	82.7	80.8
C6	60.0	58.0

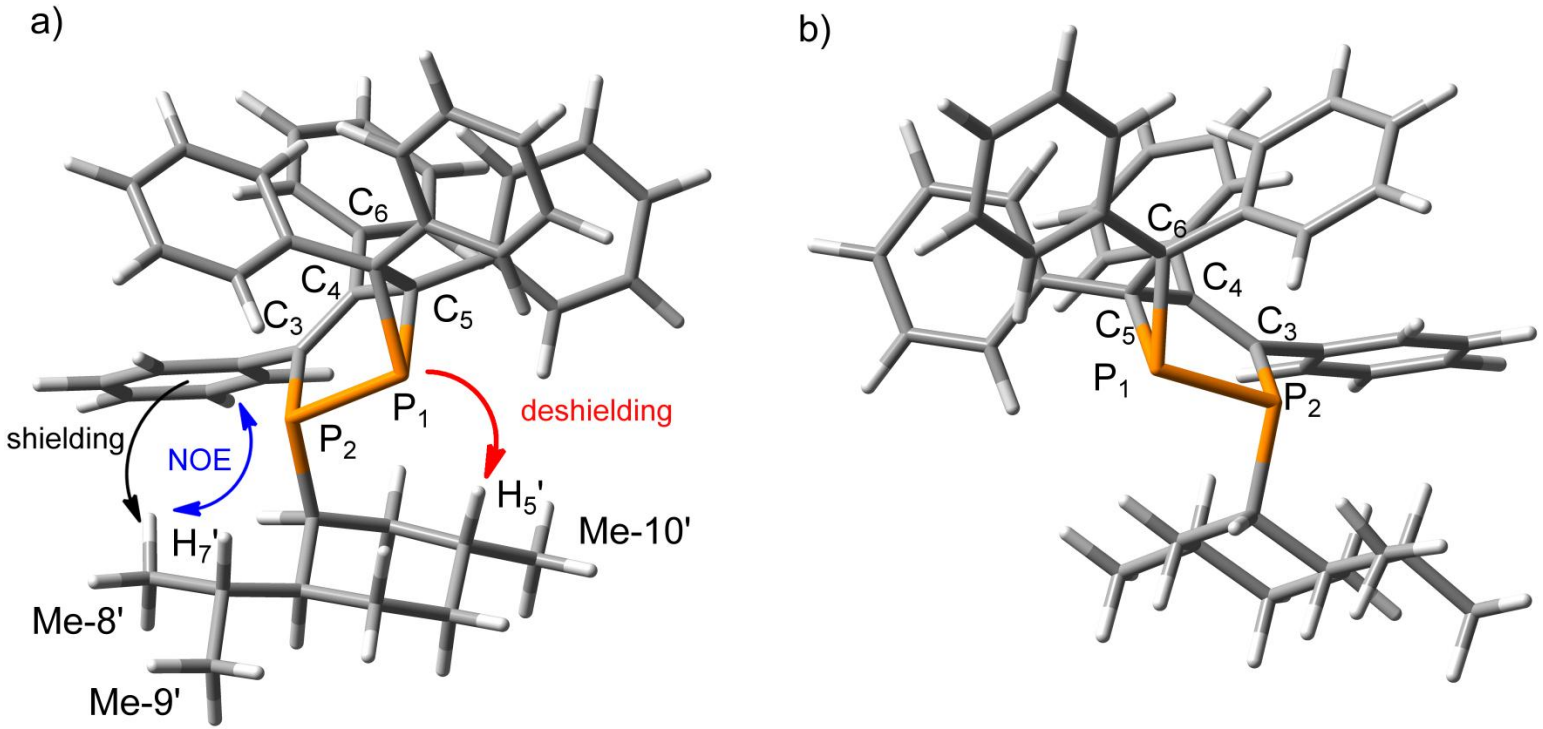

Figure S3. Structures of isomers **5a** (a) and **5b** (b) with indicative NMR effects.

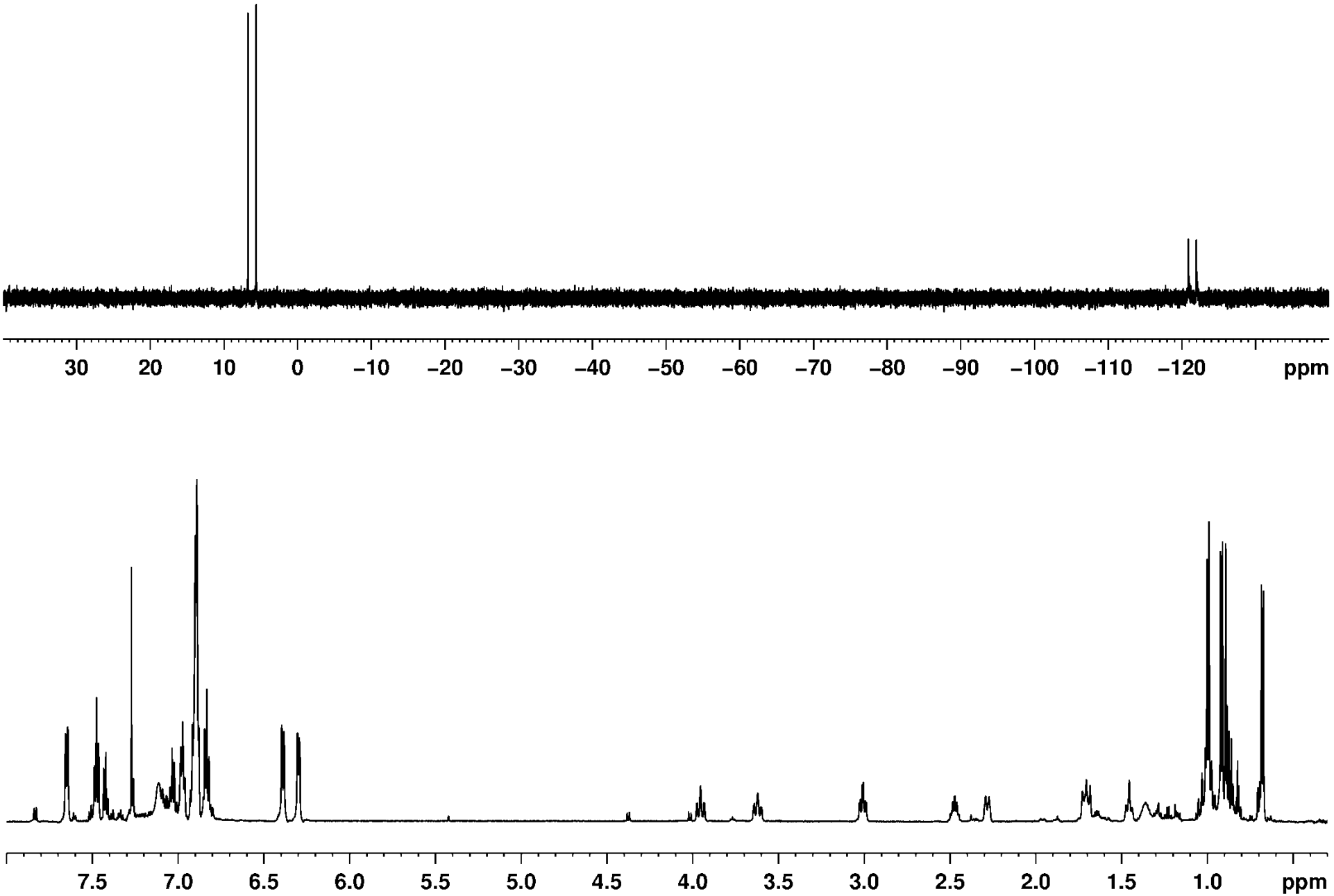

Figure S4. 1D ^{1}H and $^{31}P\{^{1}H\}$ NMR spectra of **3a** in $CDCl_3$ at T = 303 K.

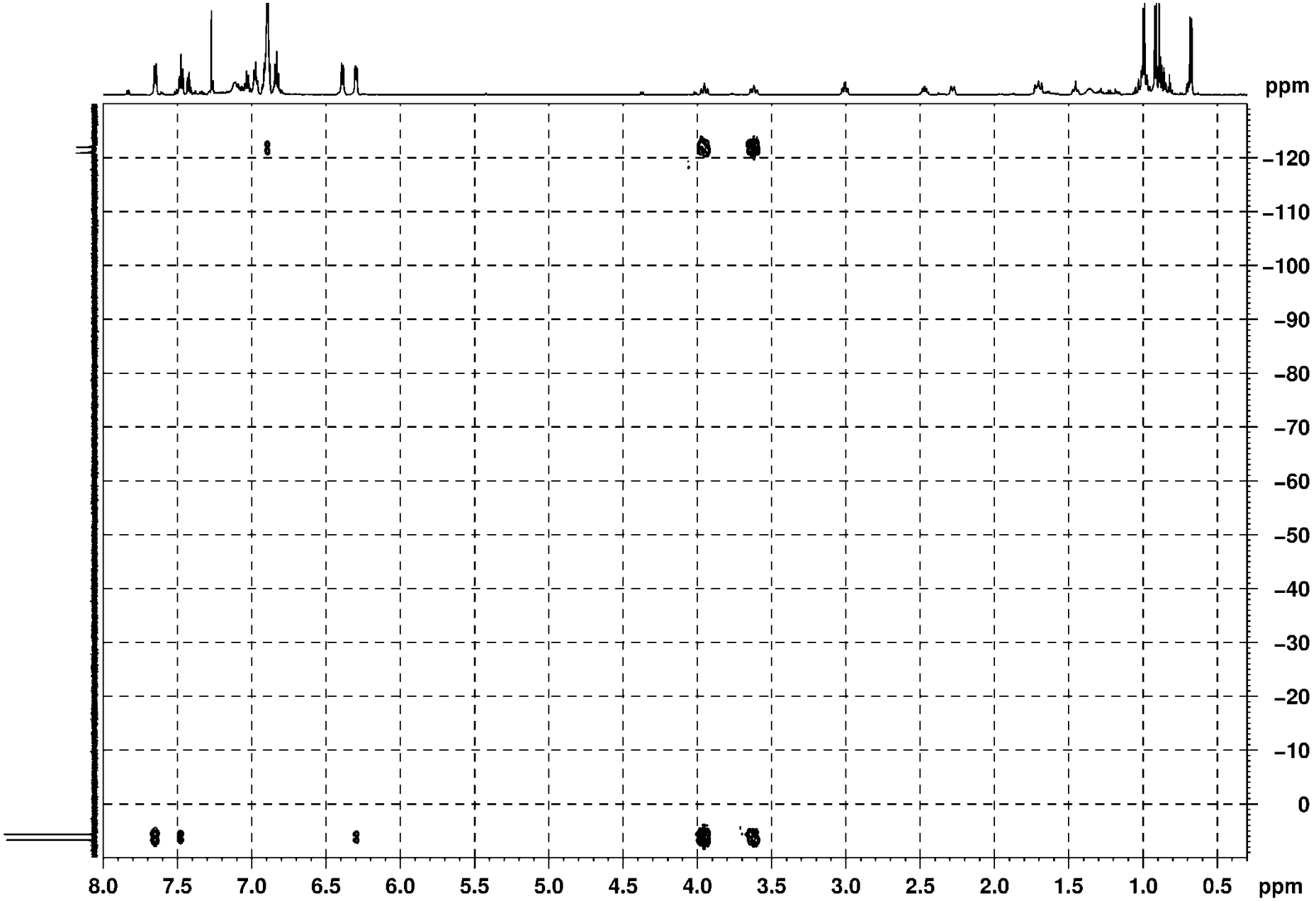

Figure S5. 2D ^{1}H-^{31}P HMBC NMR spectrum of **3a** in $CDCl_3$ at T = 303 K.

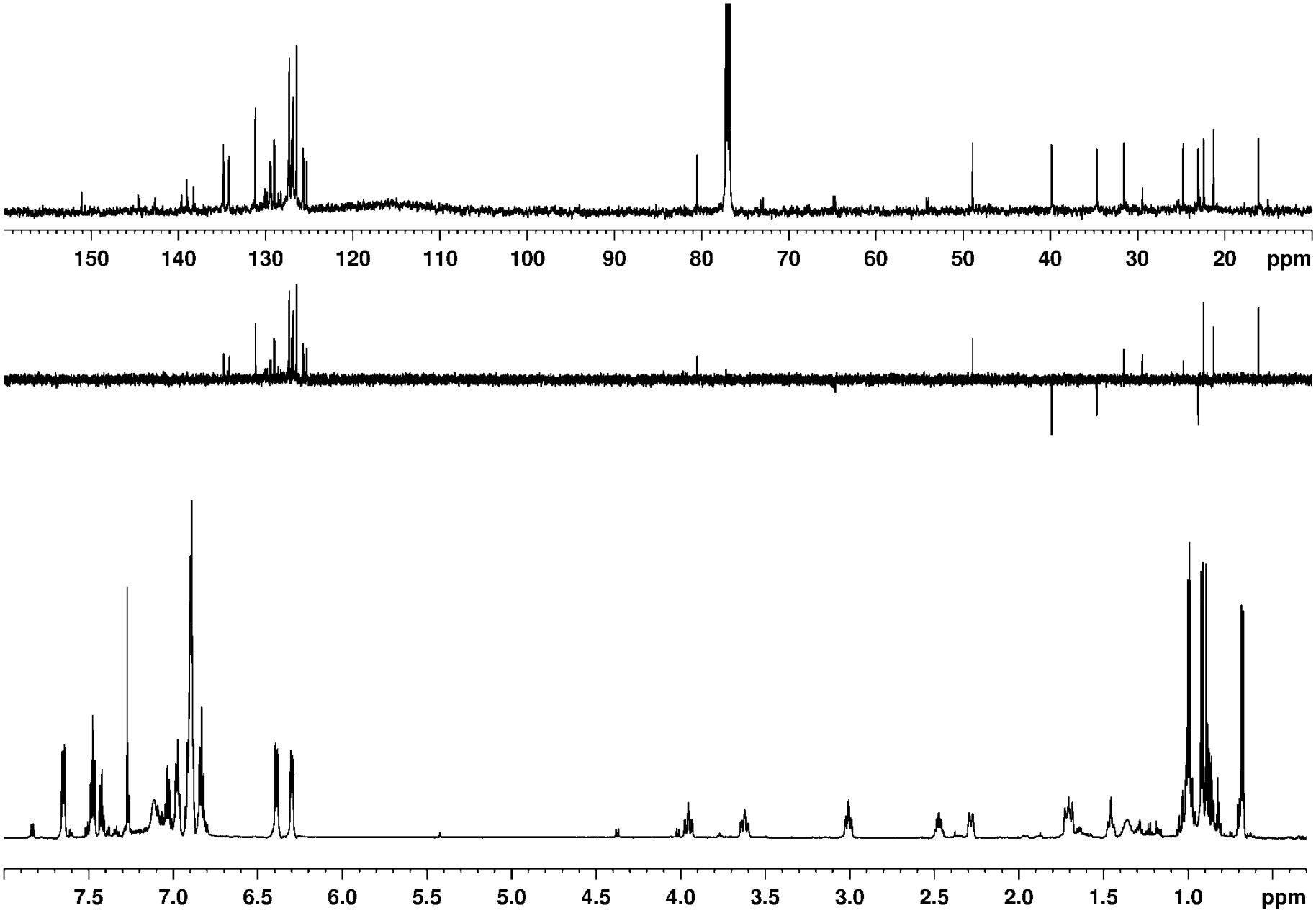

Figure S6. 1D ^{1}H, ^{13}C DEPT and $^{13}C\{^{1}H\}$ NMR spectra of **3a** in $CDCl_3$ at T = 303 K.

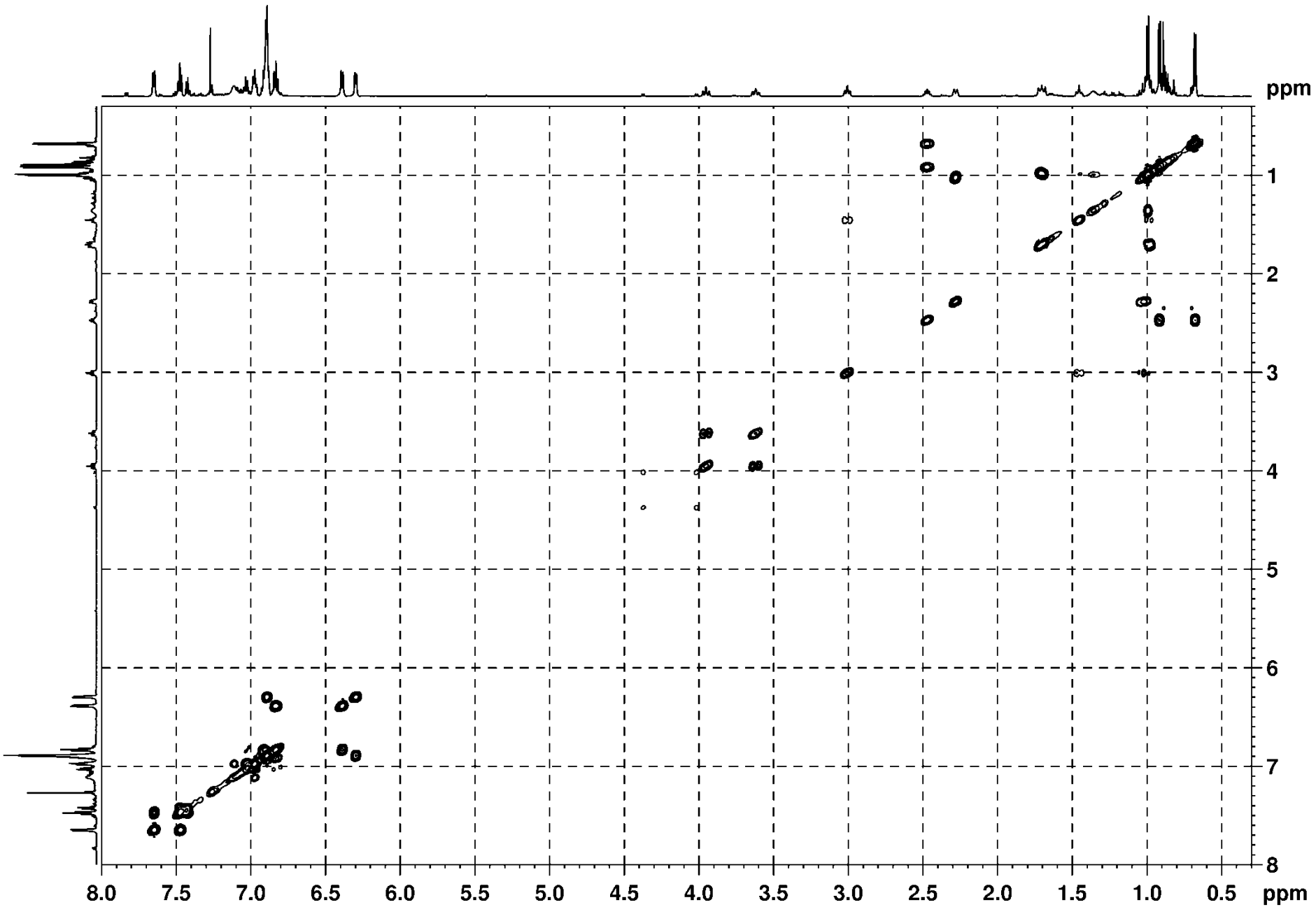

Figure S7. 2D ^{1}H-^{1}H COSY NMR spectrum of **3a** in $CDCl_3$ at T = 303 K.

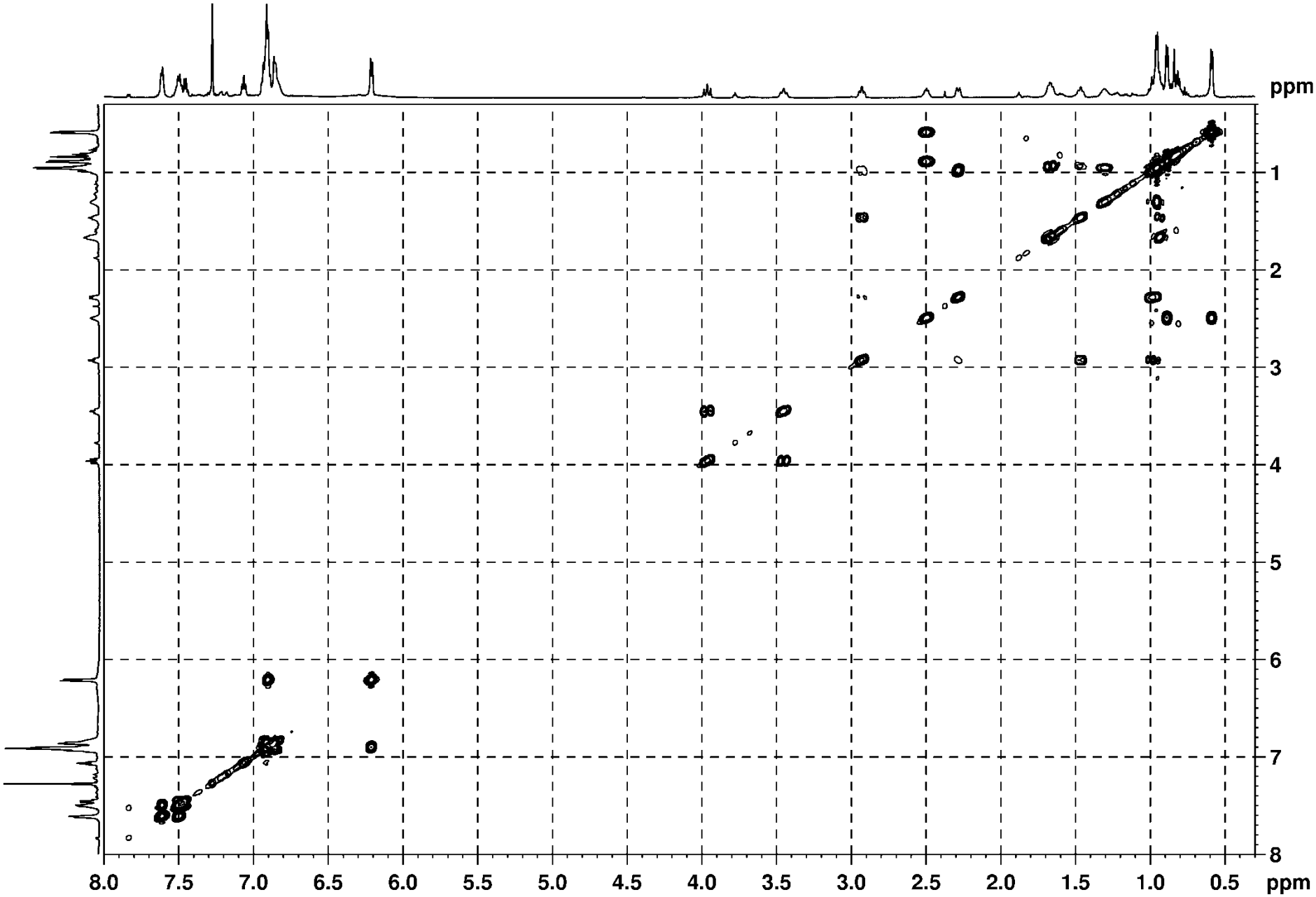

Figure S8. 2D ^{1}H-^{1}H COSY NMR spectrum of **3a** in $CDCl_3$ at T = 233 K.

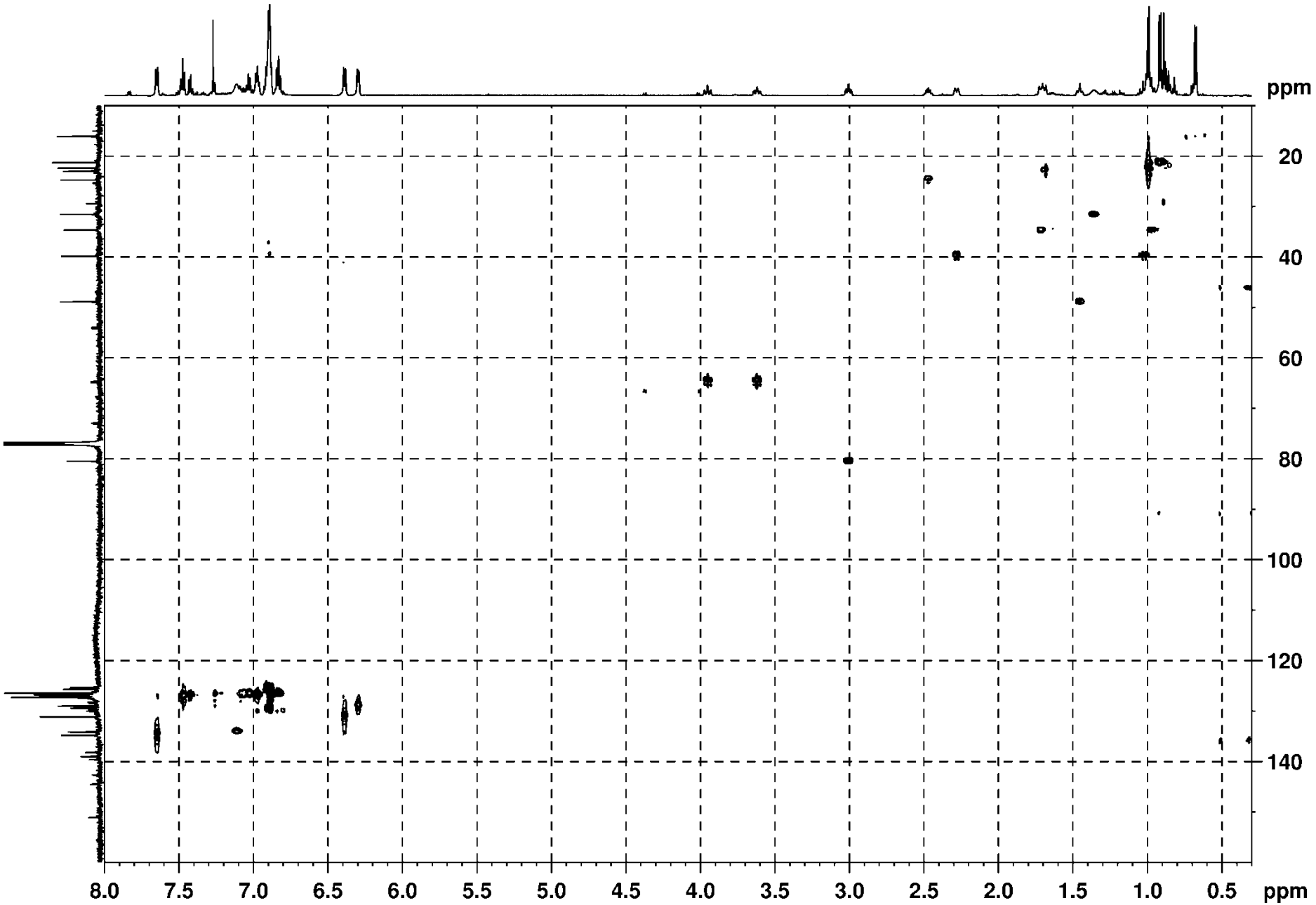

Figure S9. 2D ^{1}H-^{13}C HSQC NMR spectrum of **3a** in $CDCl_3$ at T = 303 K.

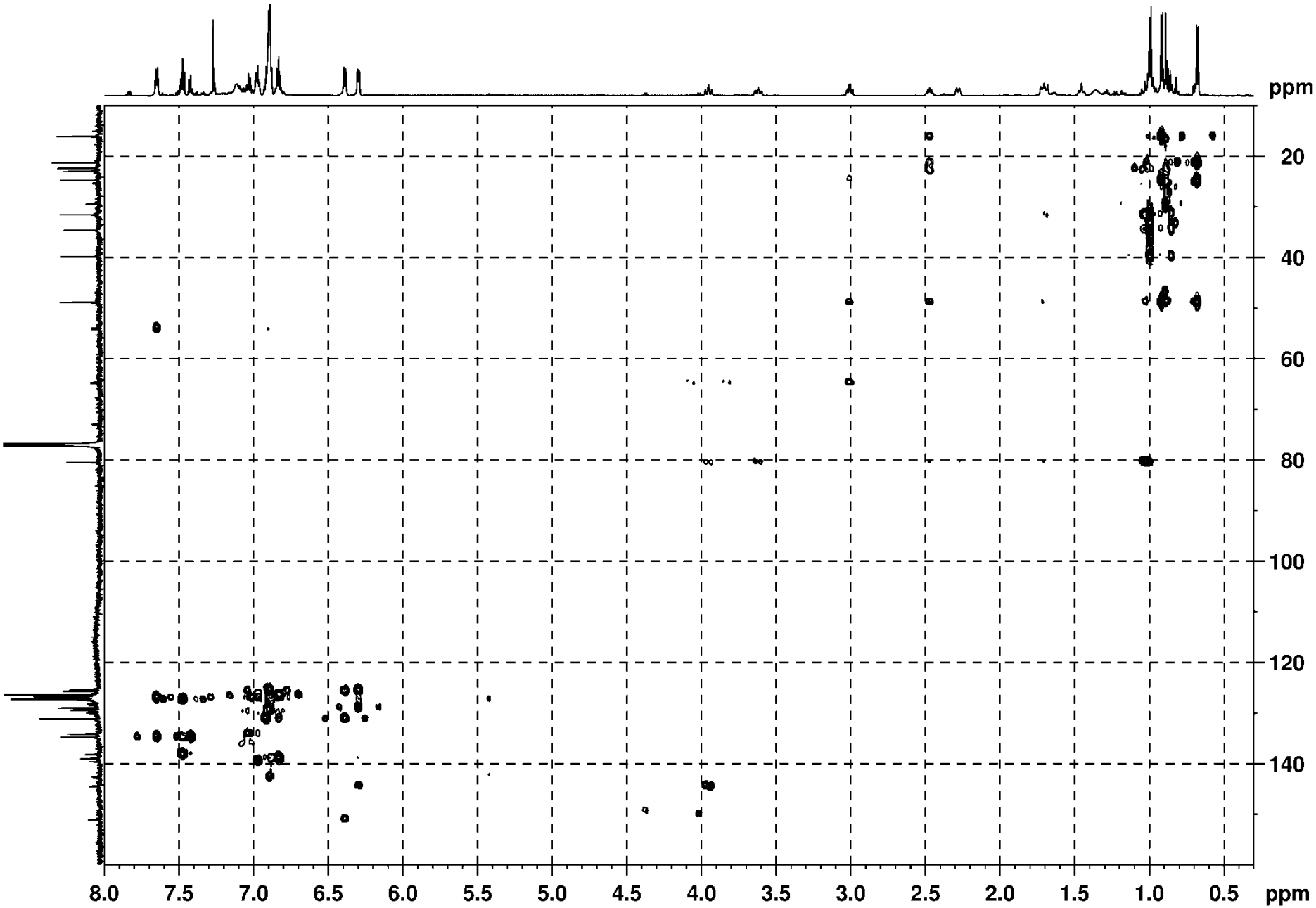

Figure S10. 2D ^{1}H-^{13}C HMBC NMR spectrum of **3a** in $CDCl_3$ at T = 303 K.

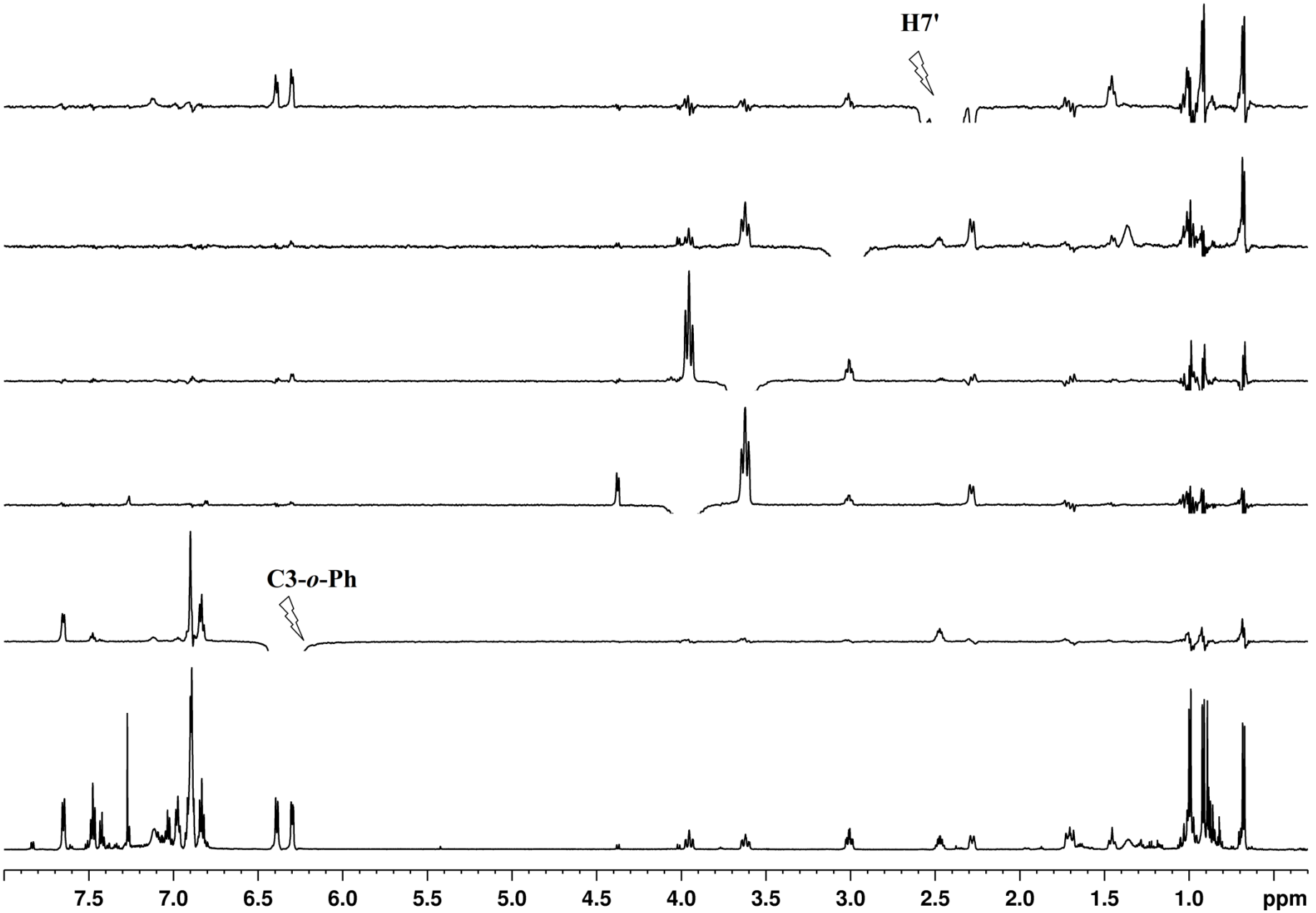

Figure S11. 1D ^{1}H and ^{1}H NOESY NMR spectra of **3a** in $CDCl_3$ at T = 303 K.

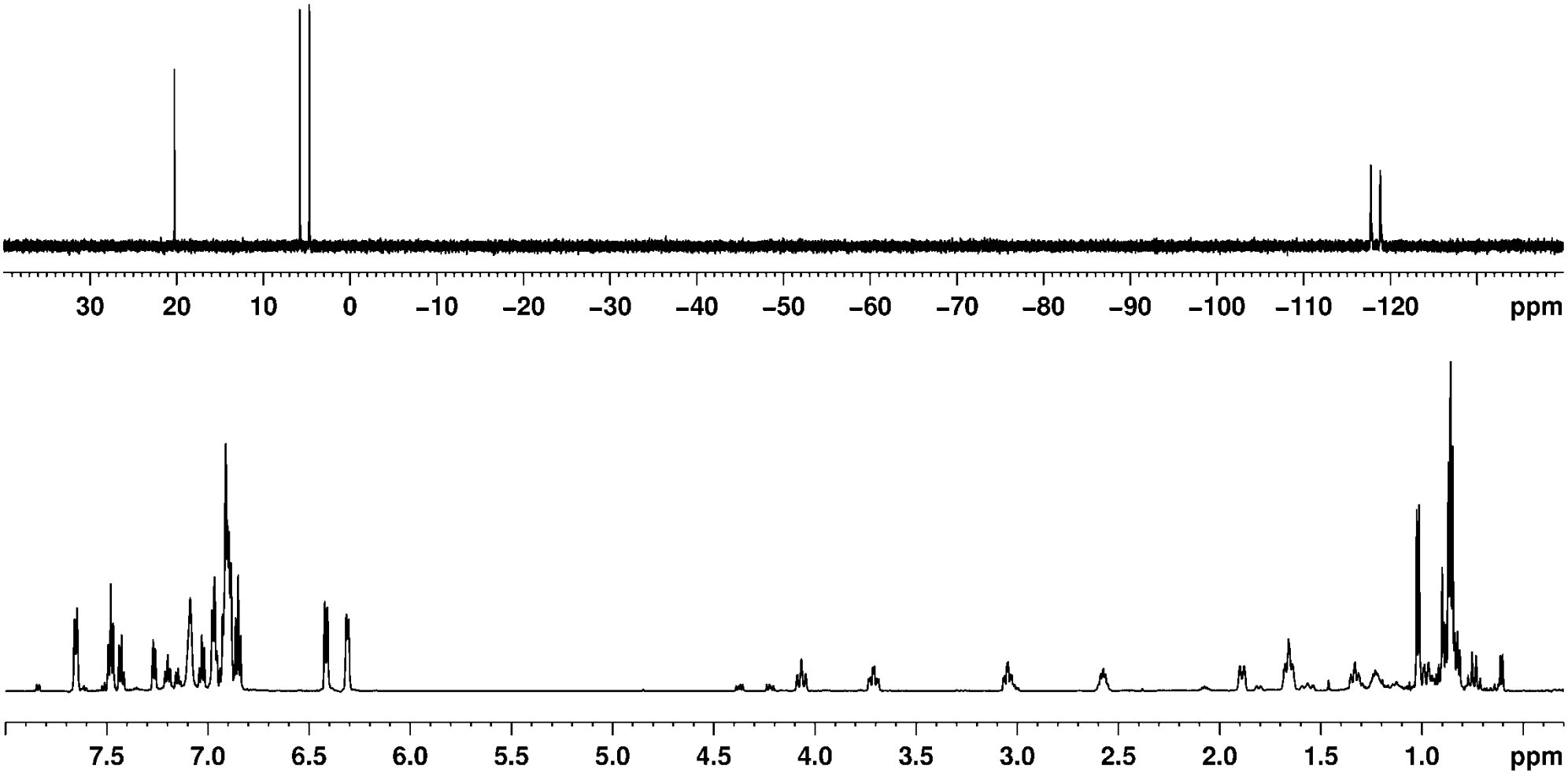

Figure S12. 1D ^{1}H and $^{31}P\{^{1}H\}$ NMR spectra of **3b** in $CDCl_3$ at T = 303 K.

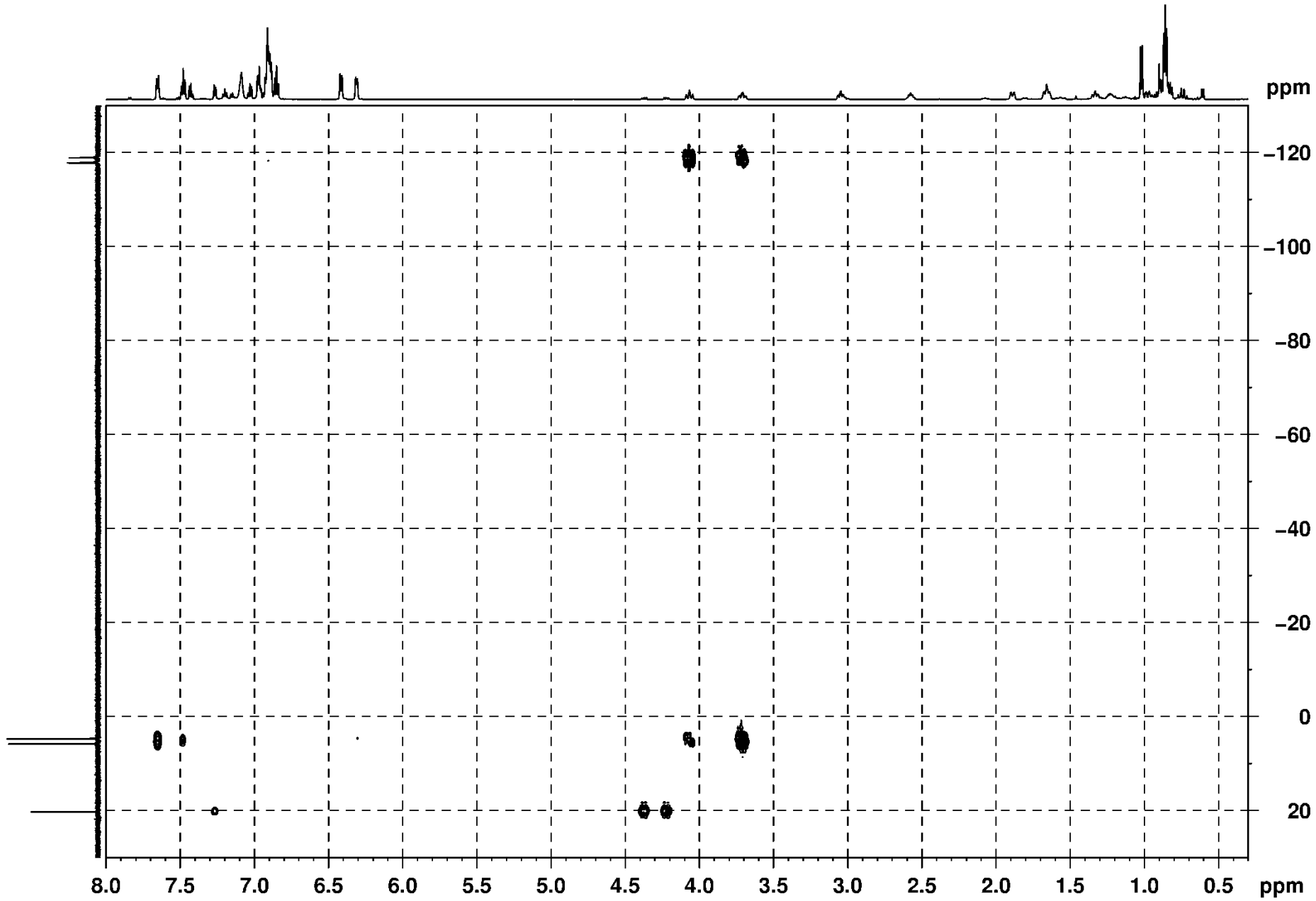

Figure S13. 2D ^{1}H-^{31}P HMBC NMR spectrum of **3b** in $CDCl_3$ at T = 303 K.

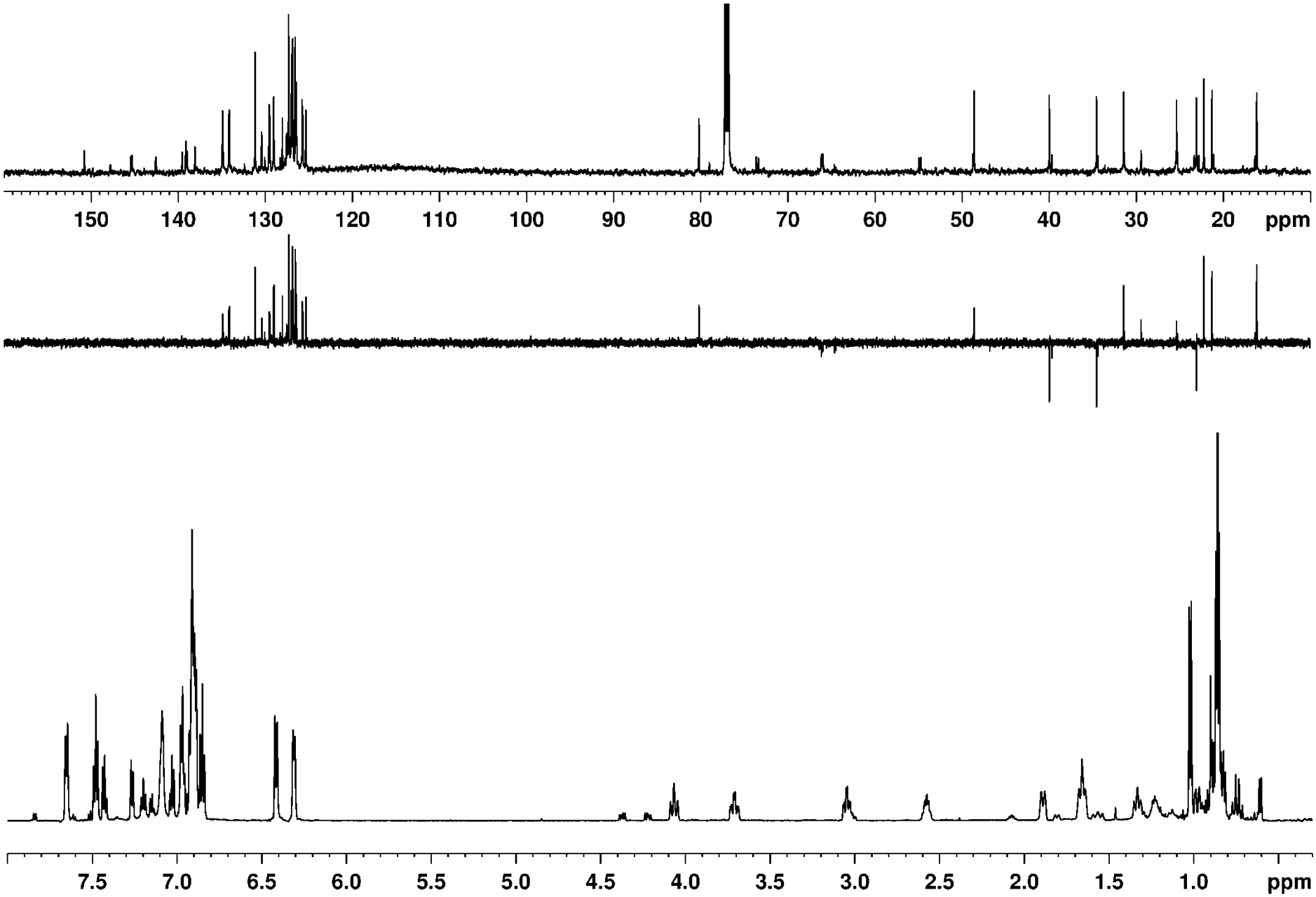

Figure S14. 1D ^{1}H, ^{13}C DEPT and $^{13}C\{^{1}H\}$ NMR spectra of **3b** in $CDCl_3$ at T = 303 K.

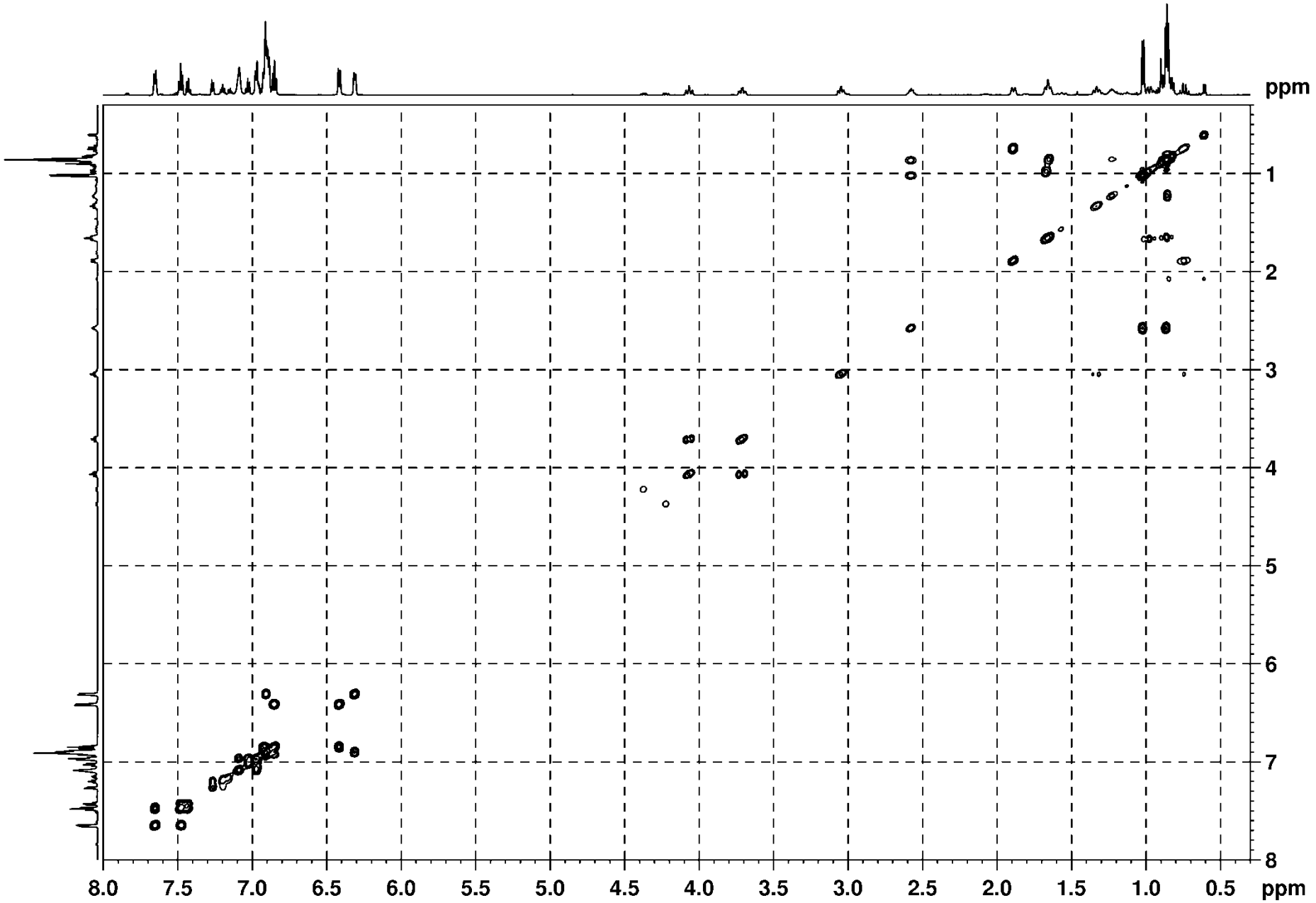

Figure S15. 2D ^{1}H-^{1}H COSY NMR spectrum of **3b** in $CDCl_3$ at T = 303 K.

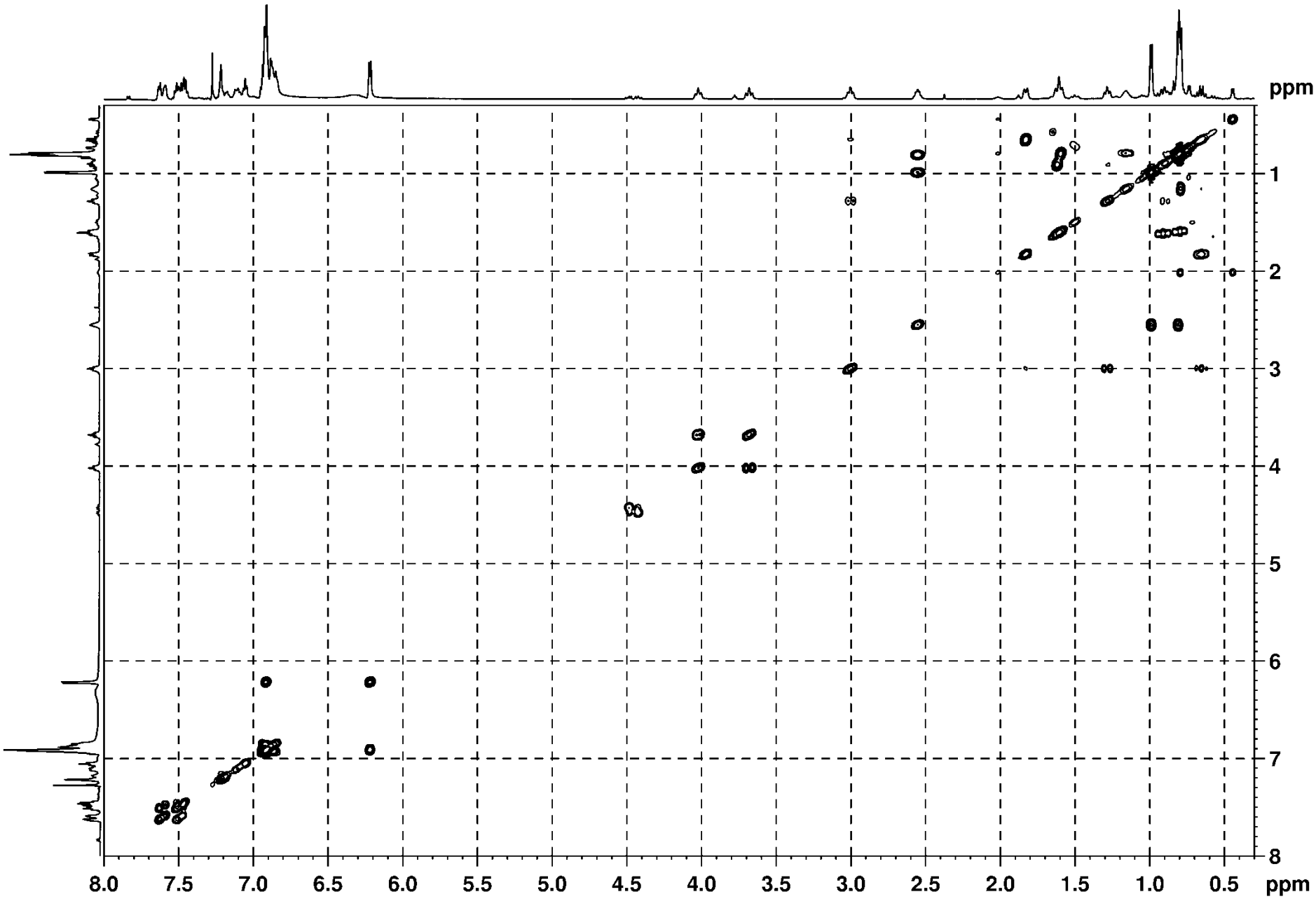

Figure S16. 2D ^{1}H-^{1}H COSY NMR spectrum of **3b** in $CDCl_3$ at T = 233 K.

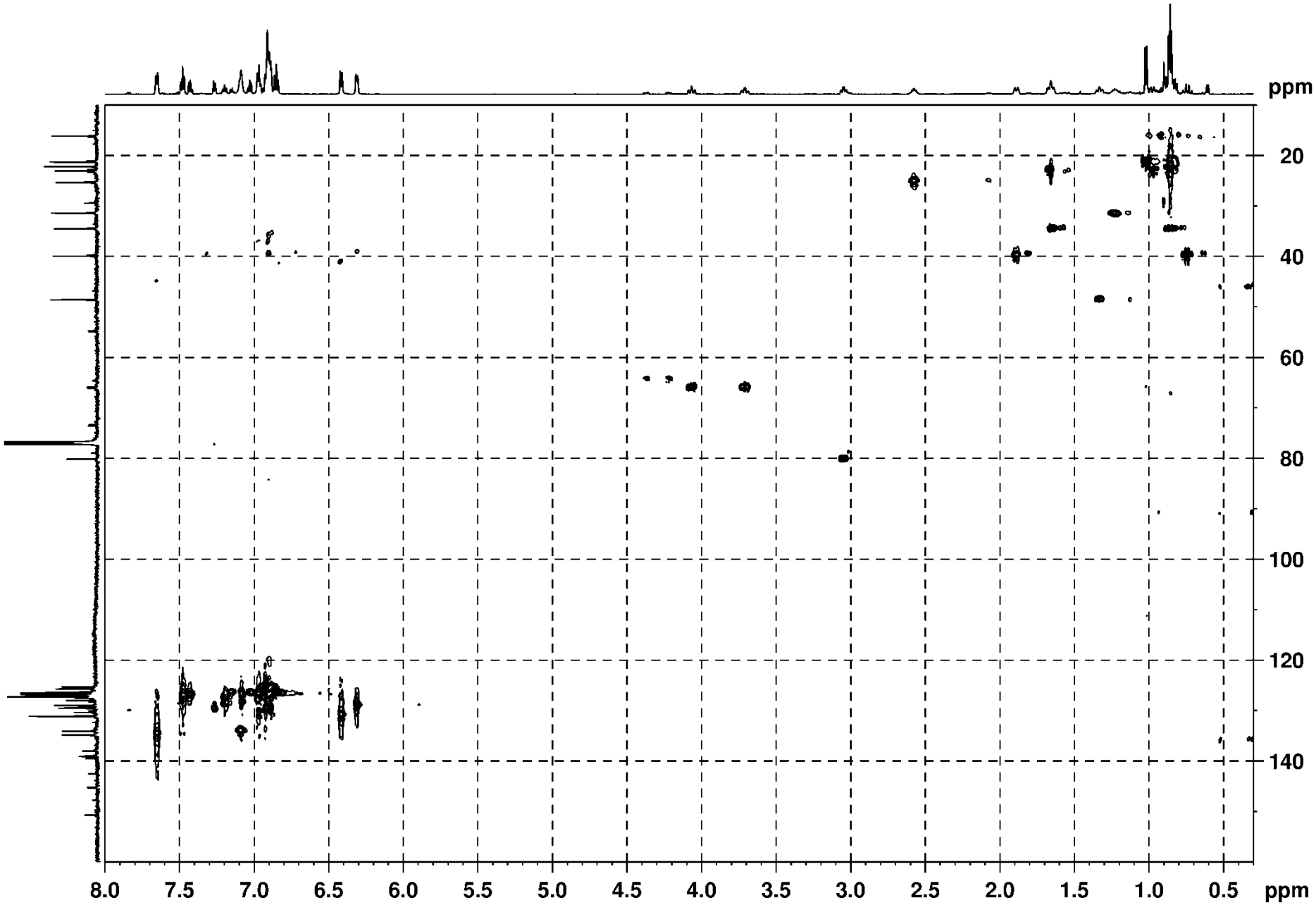

Figure S17. 2D ^{1}H-^{13}C HSQC NMR spectrum of **3b** in $CDCl_3$ at T = 303 K.

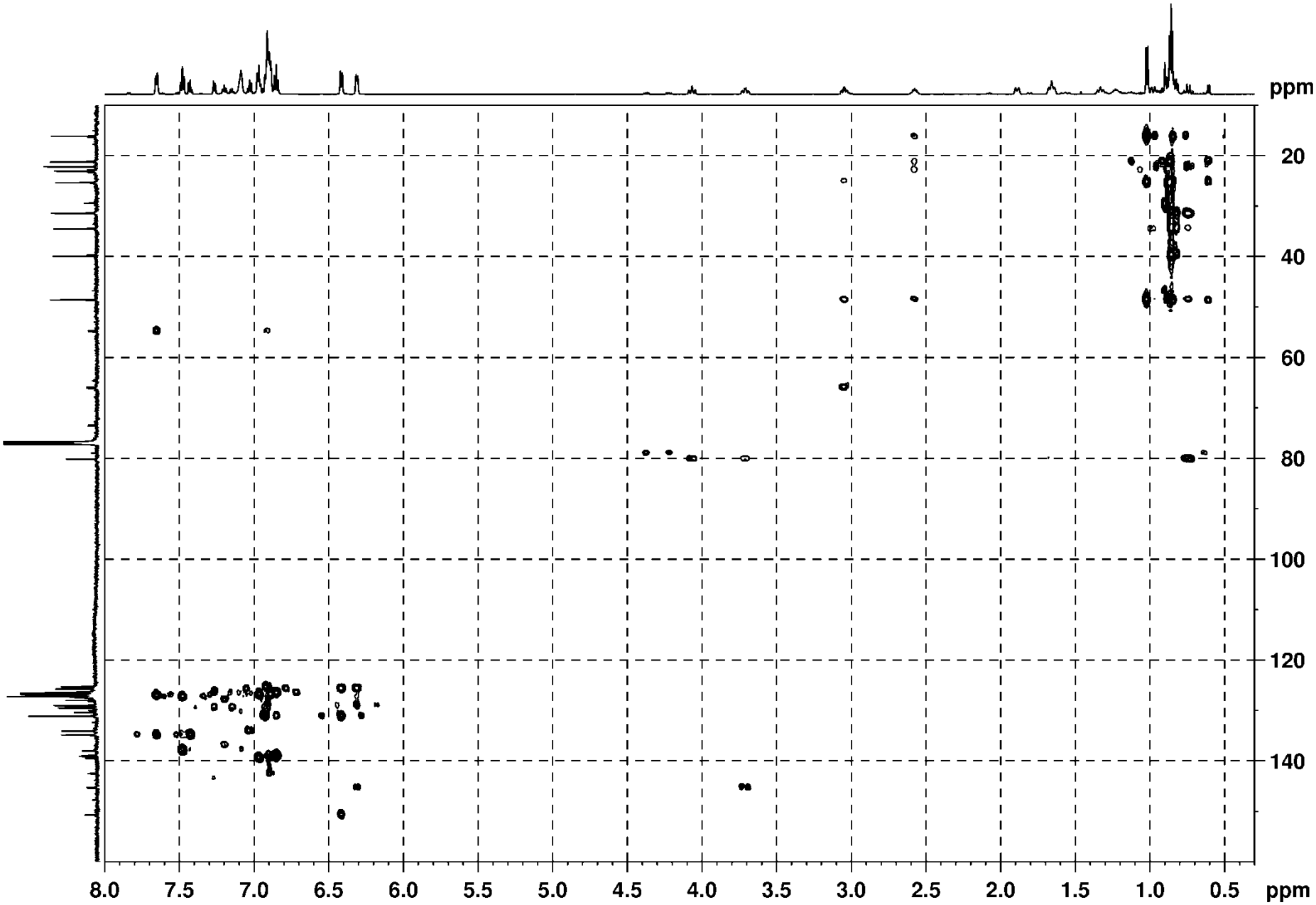

Figure S18. 2D ^{1}H-^{13}C HMBC NMR spectrum of **3b** in $CDCl_3$ at T = 303 K.

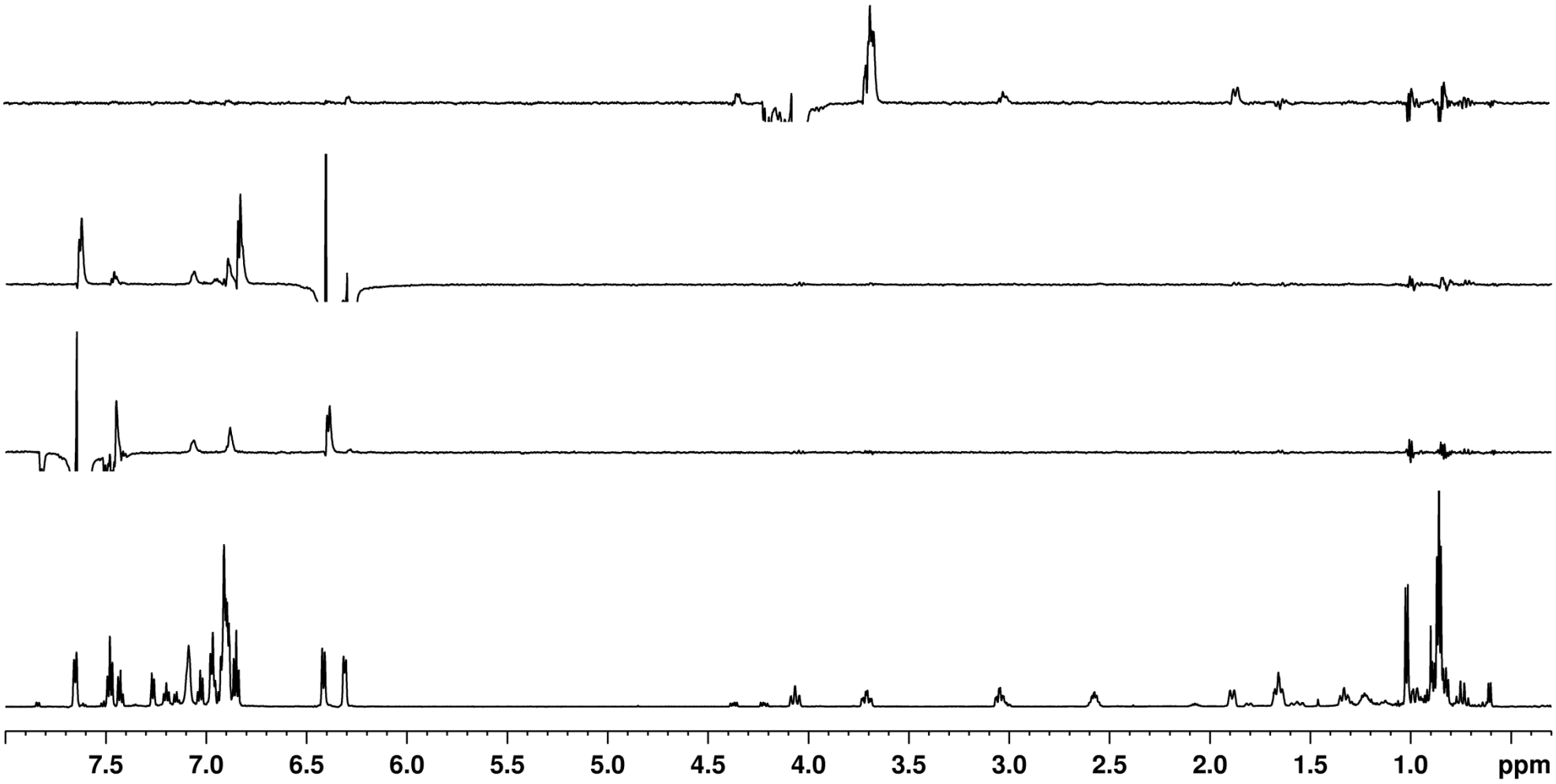

Figure S19. 1D ^{1}H and ^{1}H NOESY NMR spectra of **3b** in $CDCl_3$ at T = 303 K.

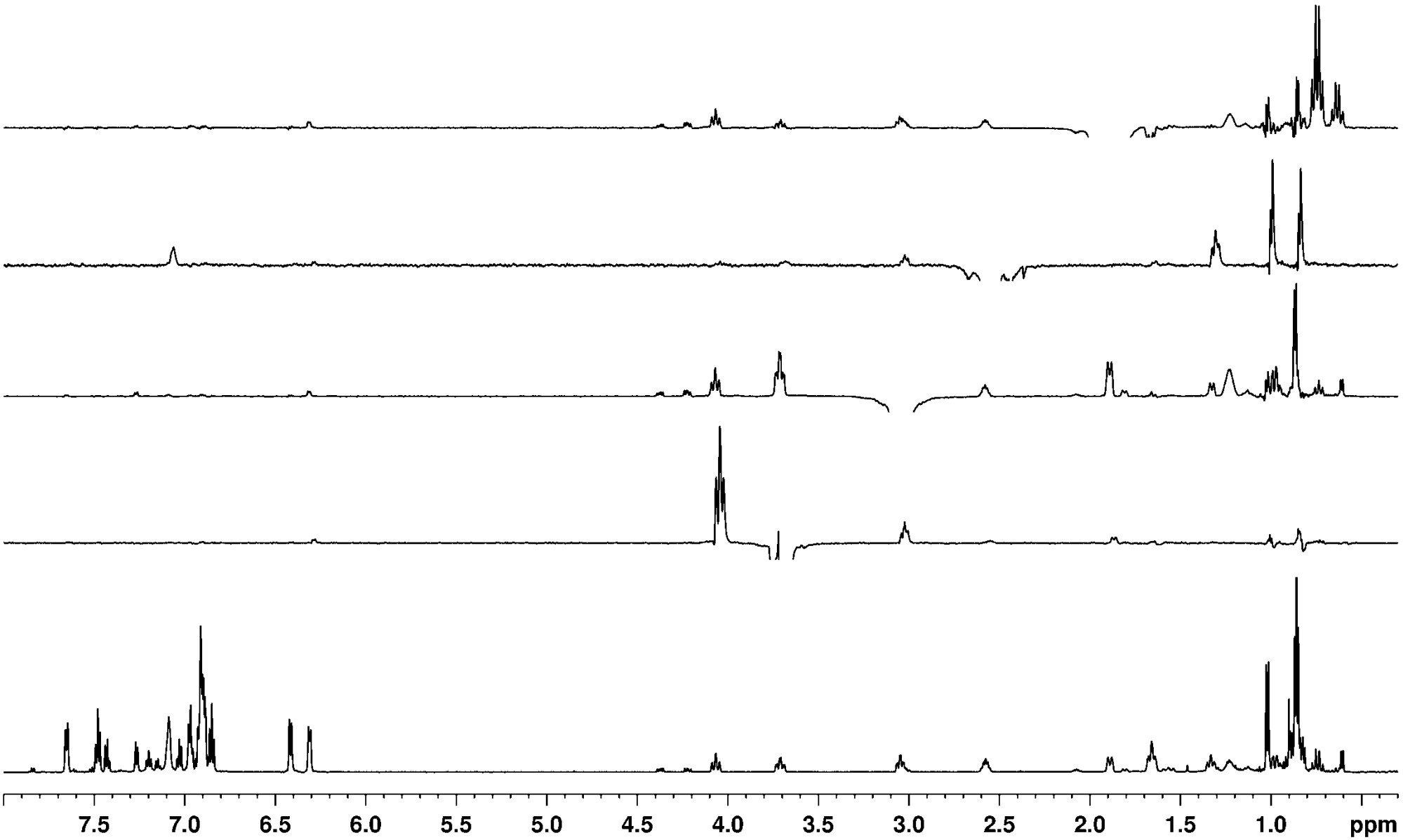

Figure S20. 1D ^{1}H and ^{1}H NOESY NMR spectra of **3b** in $CDCl_3$ at T = 303 K.

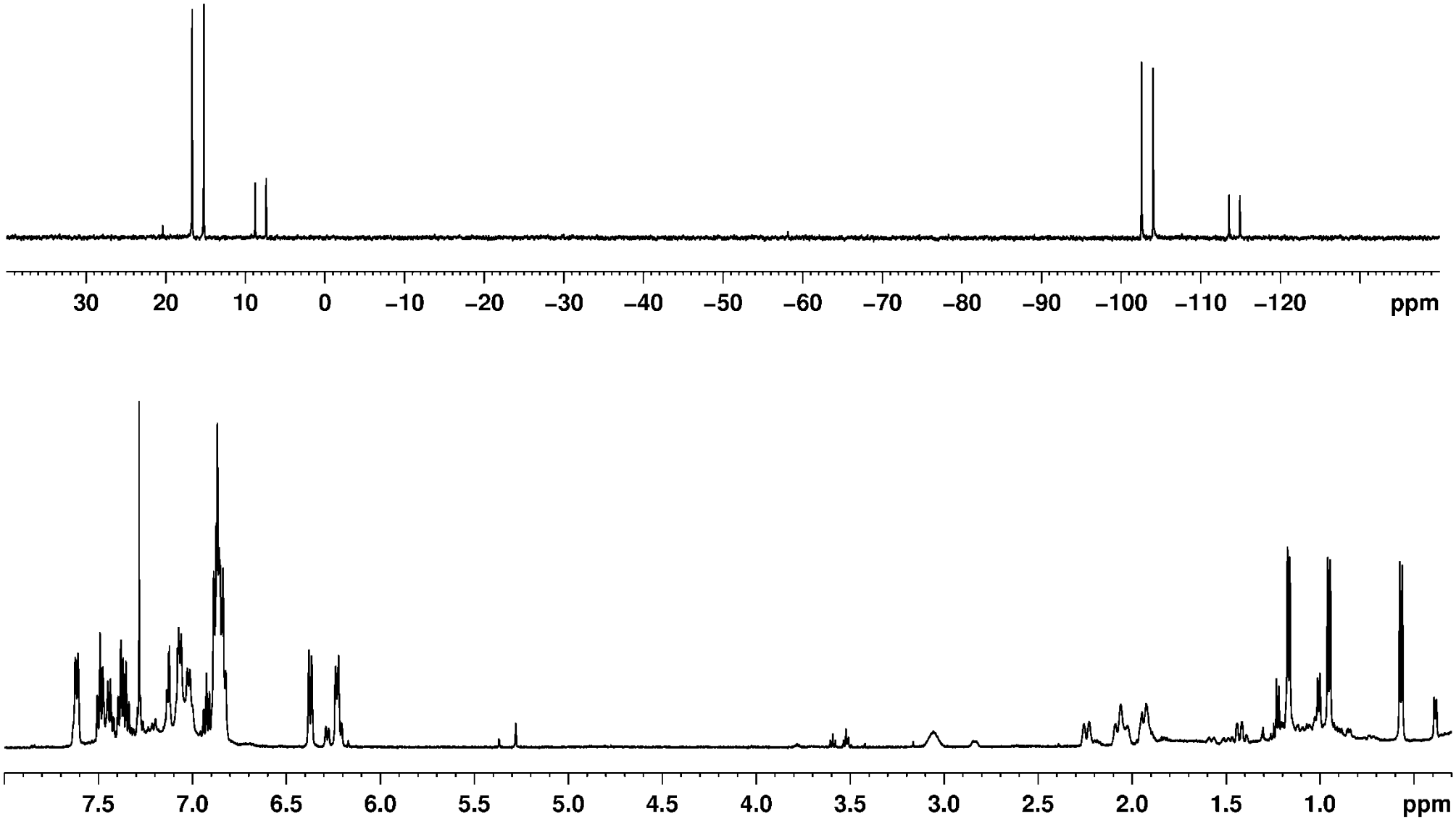

Figure S21. 1D ^{1}H and $^{31}P\{^{1}H\}$ NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

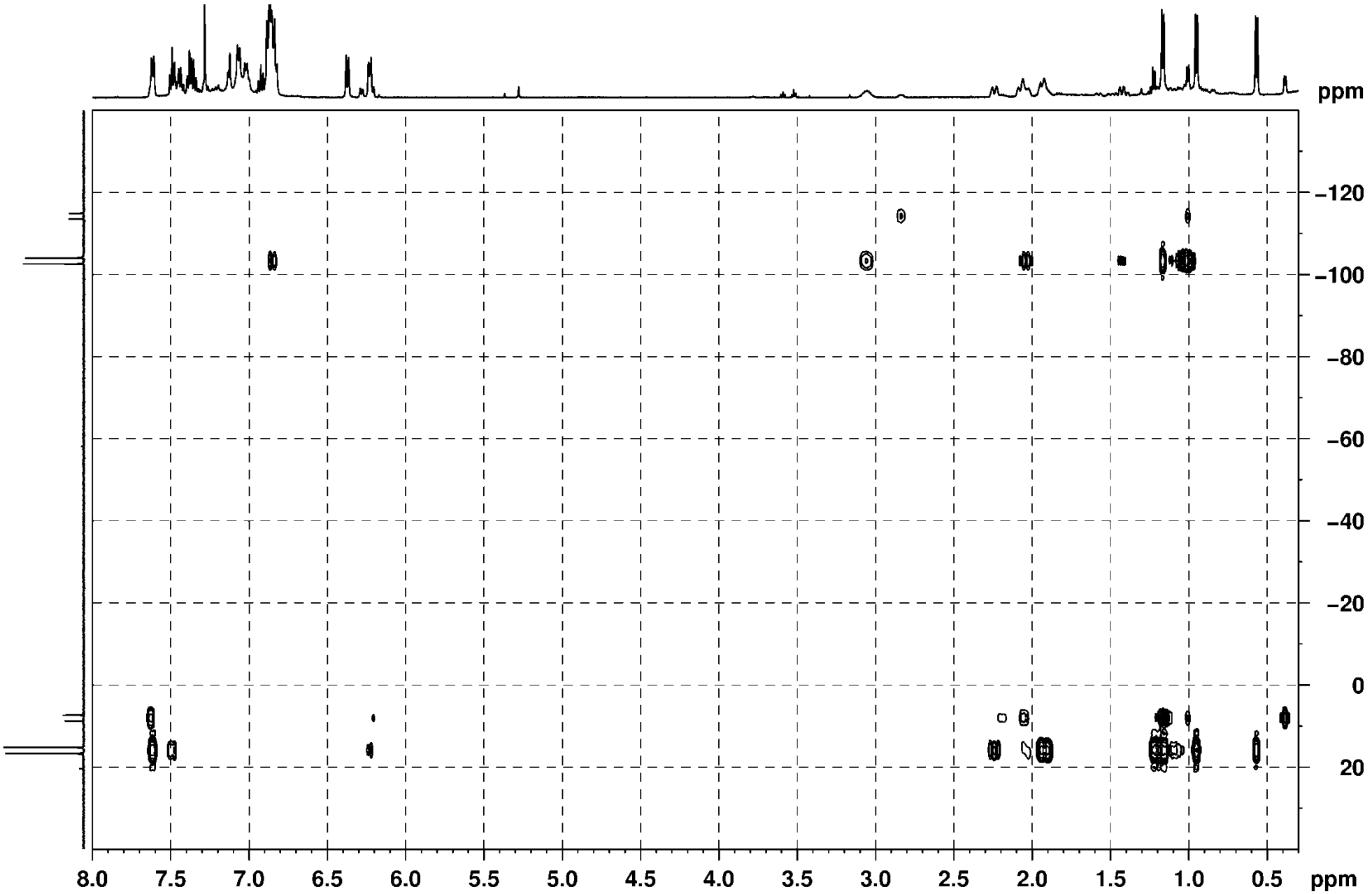

Figure S22. 2D ^{1}H-^{31}P HMBC NMR spectrum of **5a** and **5b** in $CDCl_3$ at T = 303 K.

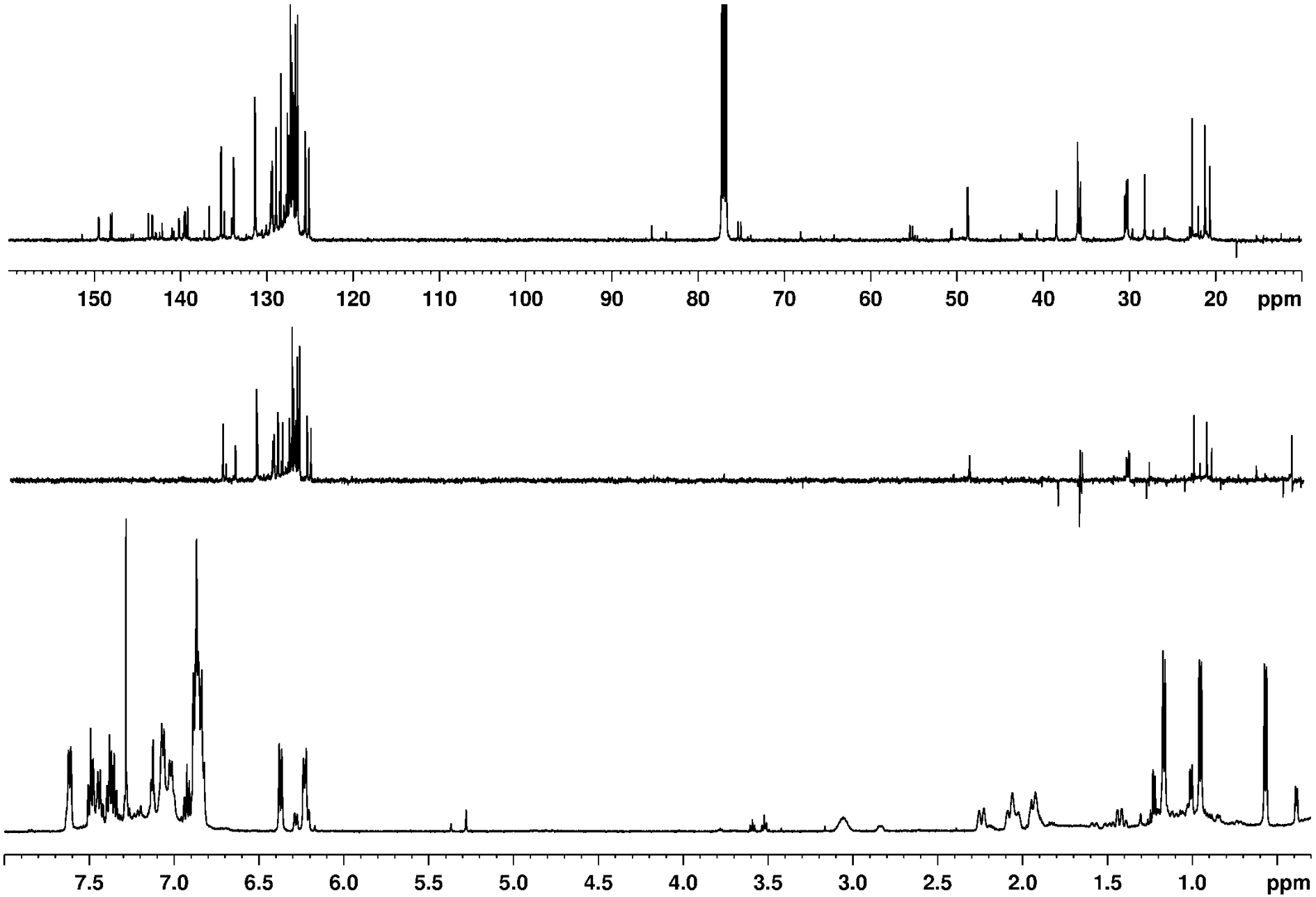

Figure S23. 1D ^{1}H, ^{13}C DEPT and $^{13}C\{^{1}H\}$ NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

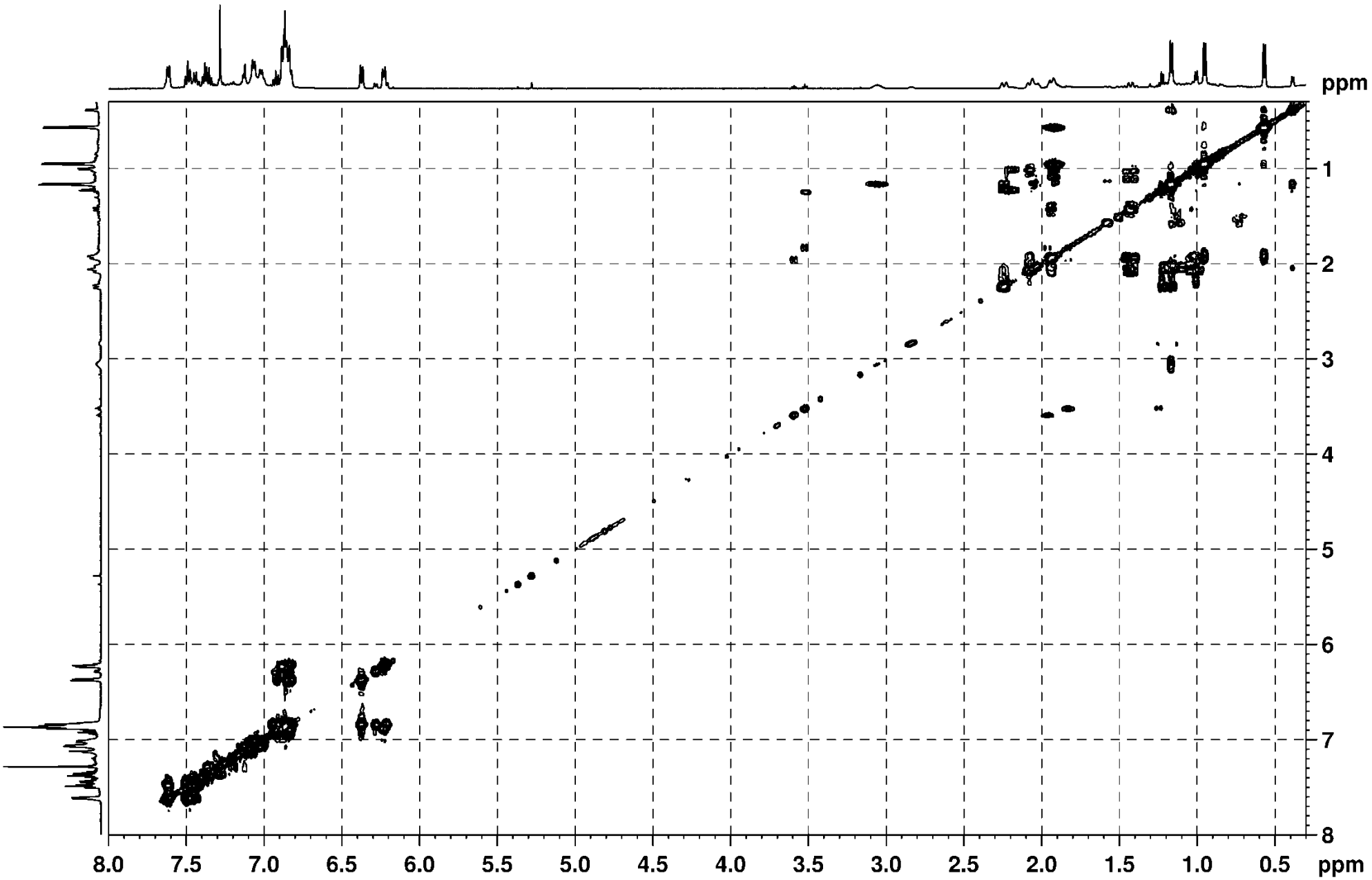

Figure S24. 2D ^{1}H-^{1}H COSY NMR spectrum of **5a** and **5b** in $CDCl_3$ at T = 303 K.

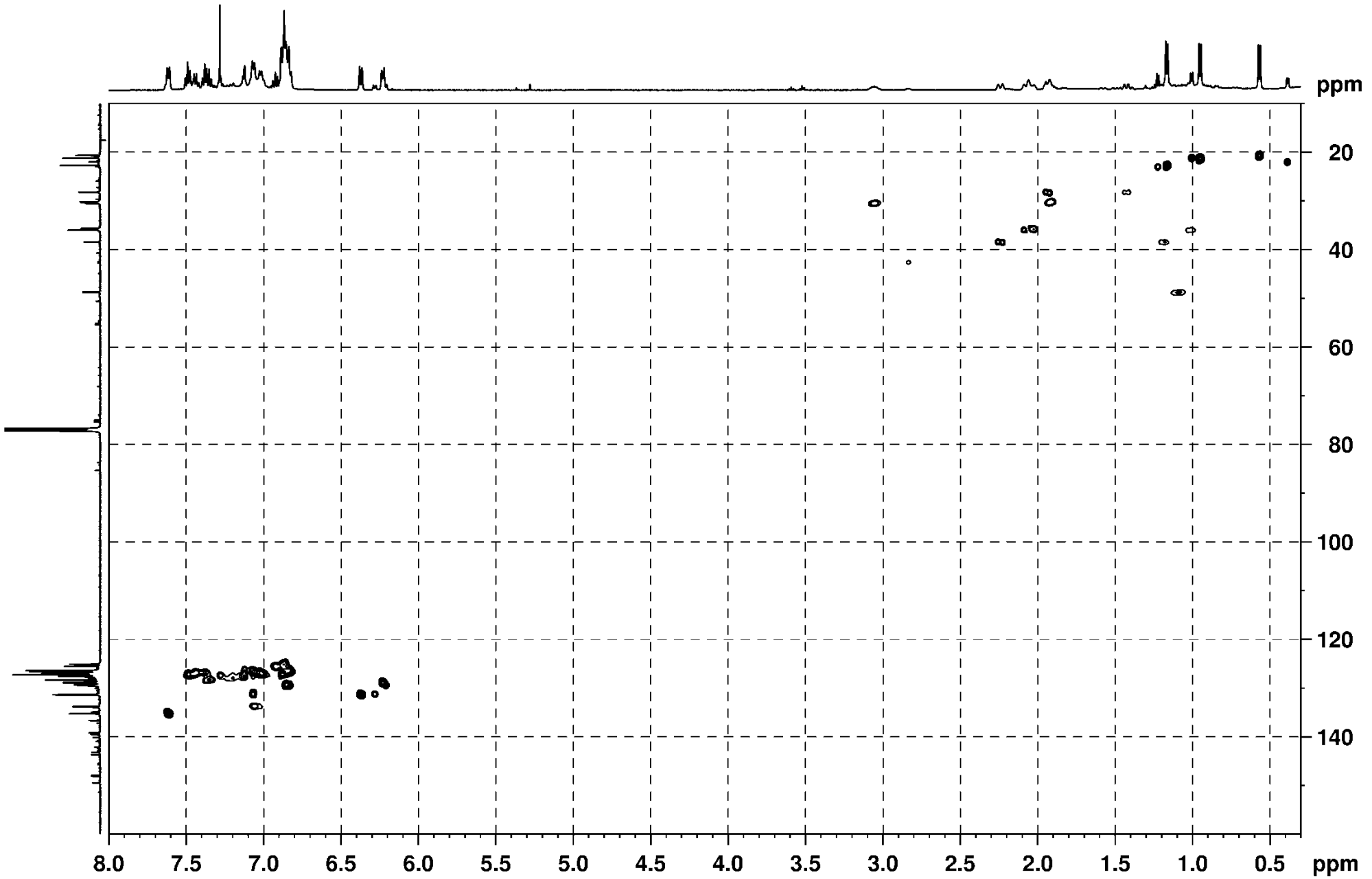

Figure S25. 2D ^{1}H-^{13}C HSQC NMR spectrum of **5a** and **5b** in $CDCl_3$ at T = 303 K.

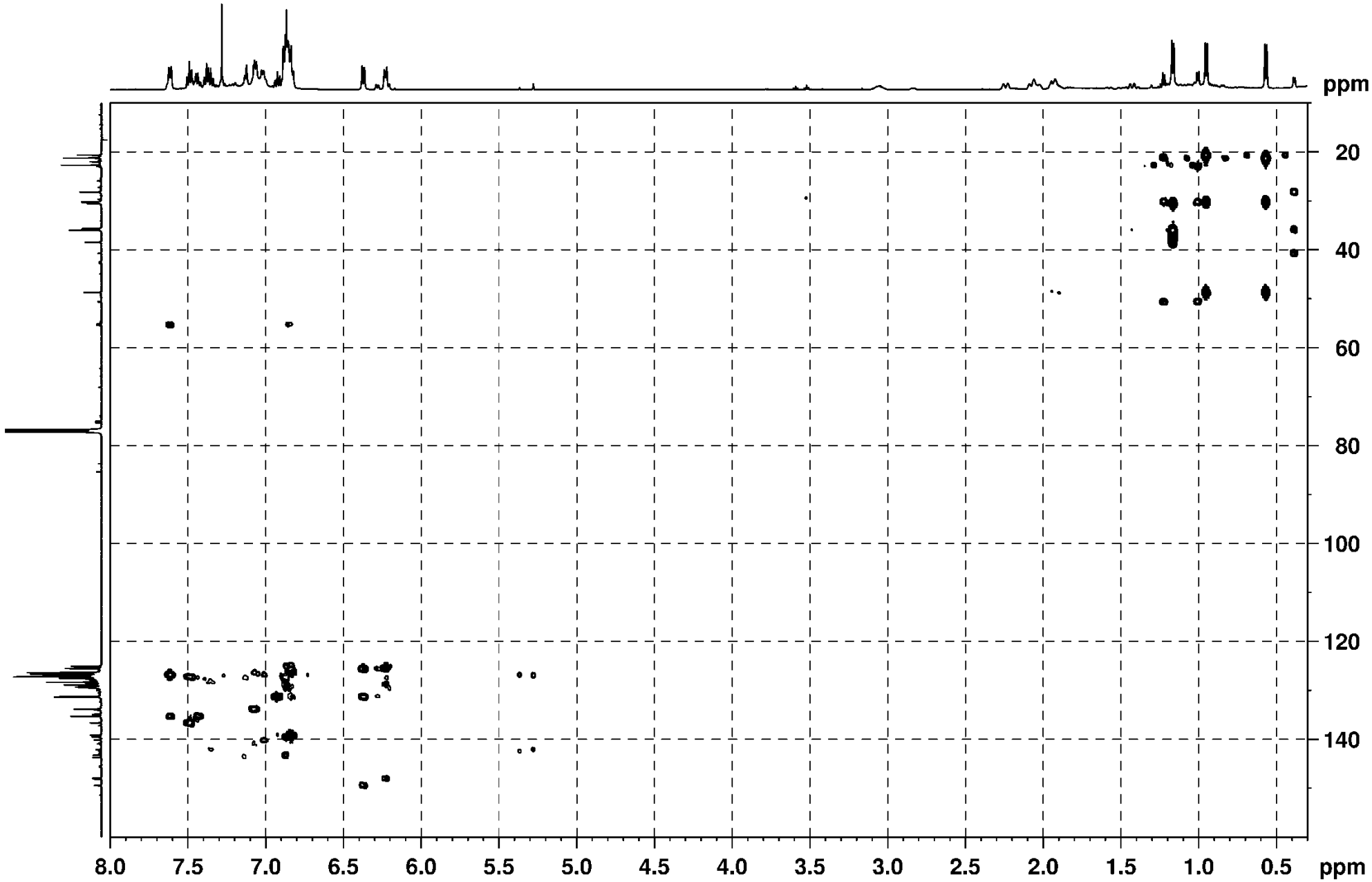

Figure S26. 2D ^{1}H-^{13}C HMBC NMR spectrum of **5a** and **5b** in $CDCl_3$ at T = 303 K.

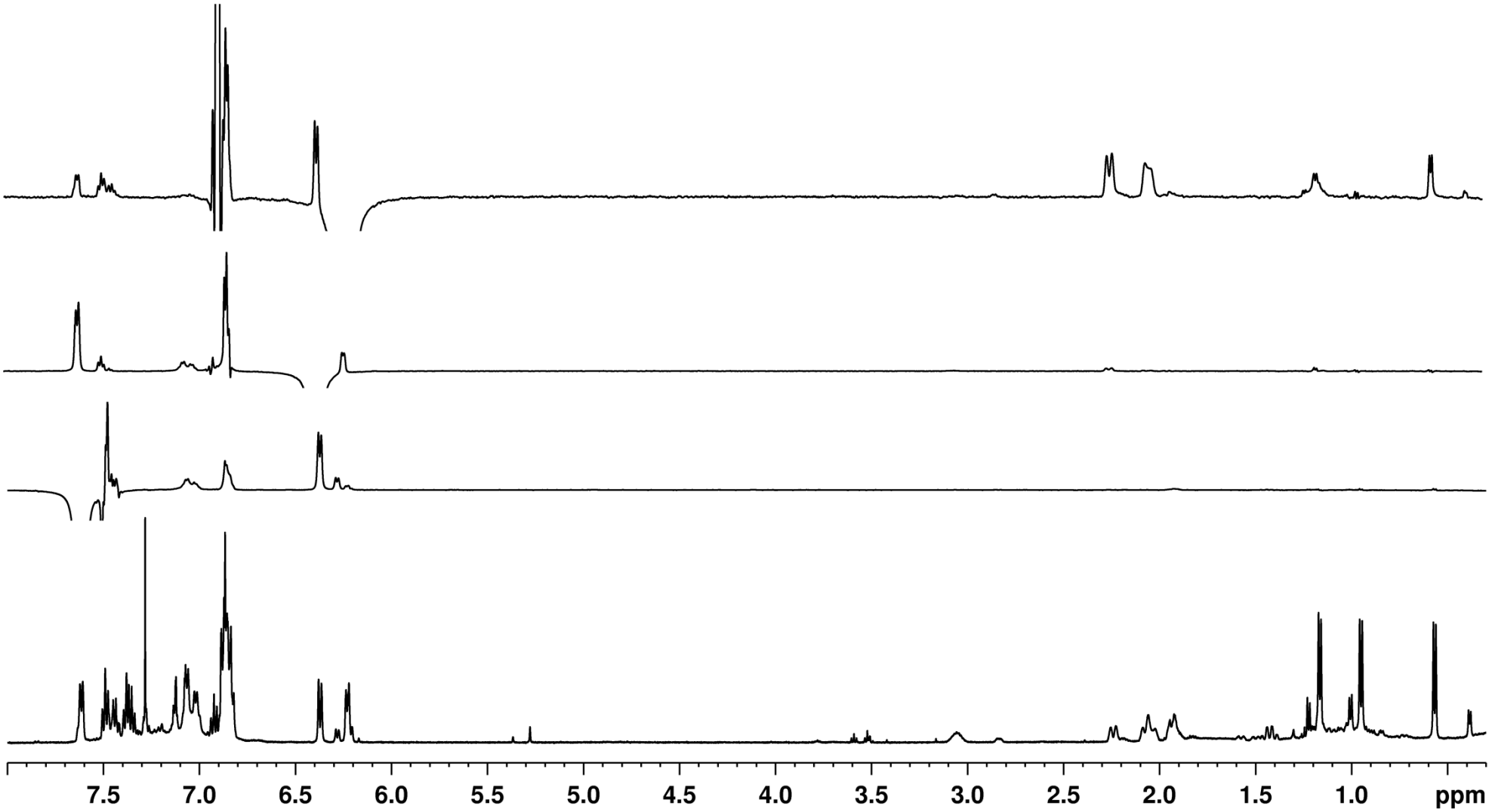

Figure S27. 1D ^{1}H and ^{1}H NOESY NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

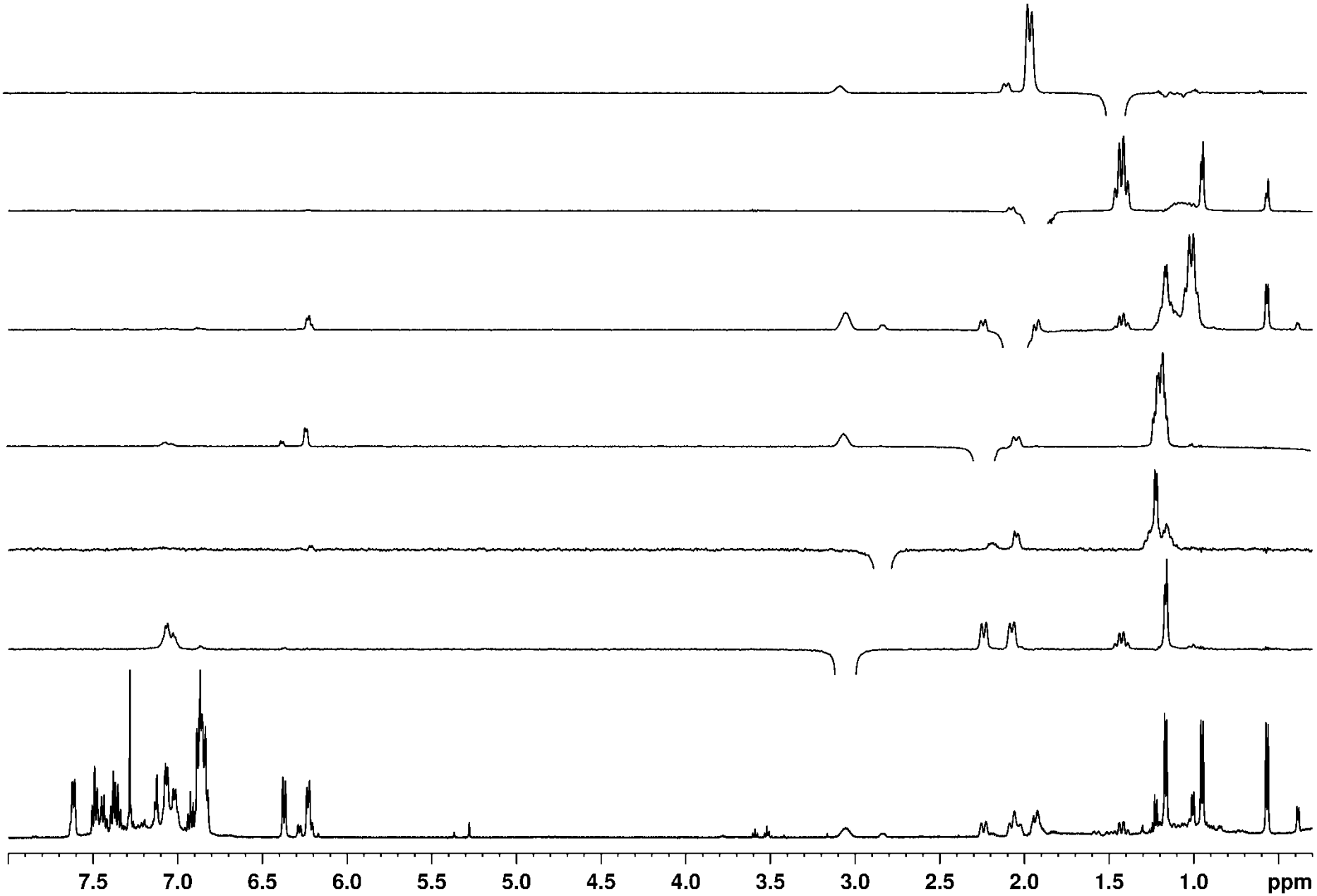

Figure S28. 1D ^{1}H and ^{1}H NOESY NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

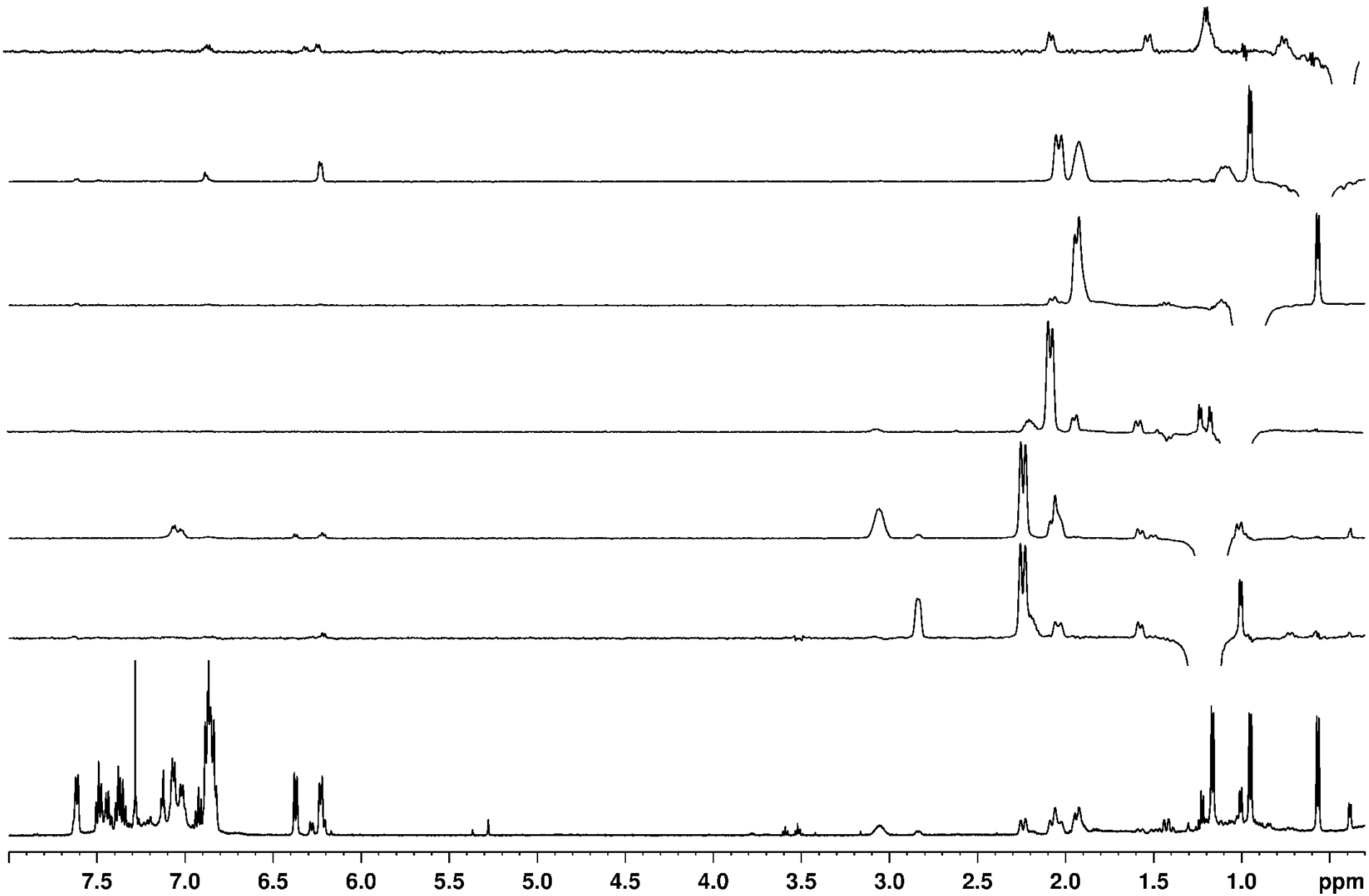

Figure S29. 1D ^{1}H and ^{1}H NOESY NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

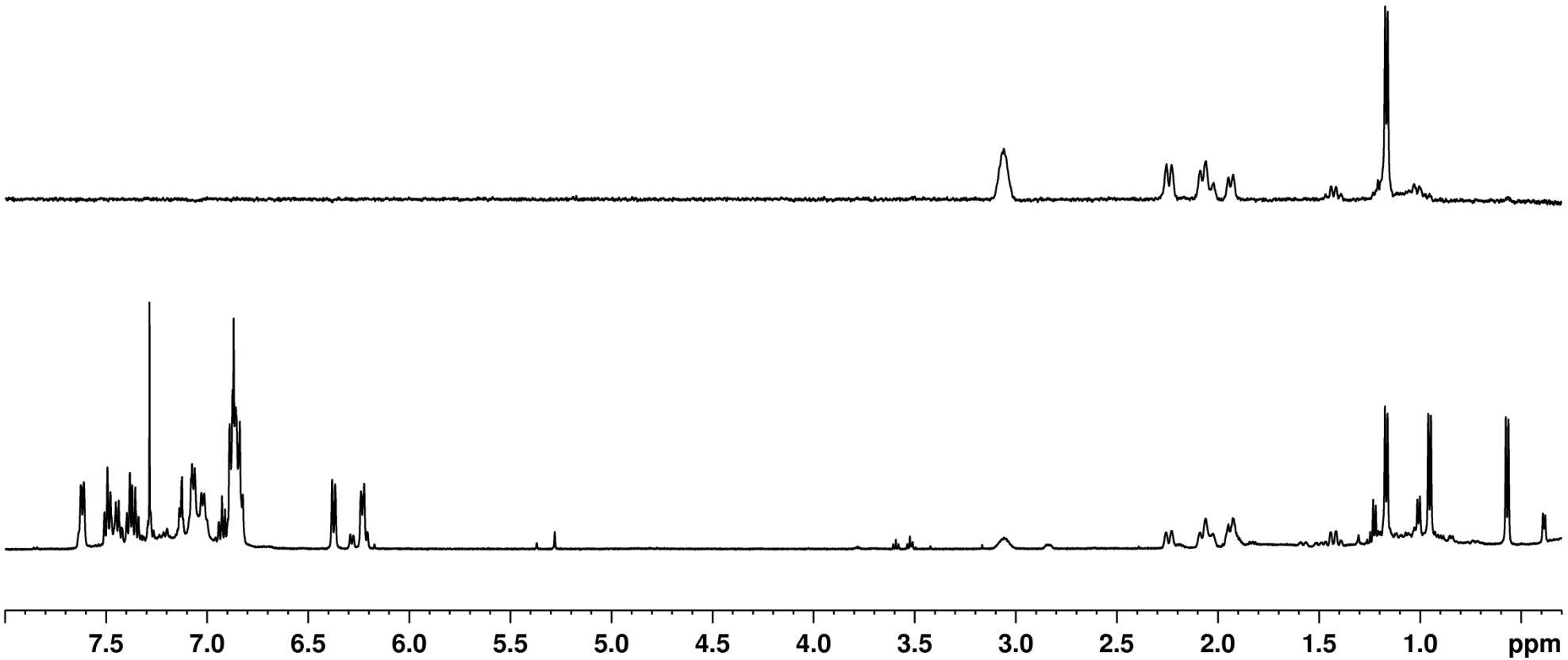

Figure S30. 1D ^{1}H and ^{1}H TOCSY NMR spectra of **5a** and **5b** in $CDCl_3$ at T = 303 K.

X-Ray Structure Determination

The data was collected on a Gemini diffractometer (Rigaku Oxford Diffraction) using Mo-Kα radiation (λ = 0.71073 Å) and ω-scan rotation. Data reduction was performed with CrysAlisPro [3] including the program SCALE3 ABSPACK for empirical absorption correction. The structure was solved by direct methods (SIR-92) [4] and the refinement was performed with SHELXL-2018.[5] Except disordered solvent THF molecules, all non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms for methyl substituents and disordered molecules were calculated on idealized positions using the riding model, whereas all other H atoms were located on difference Fourier maps calculated at the final stage of the structure refinement. Structure figures were generated with DIAMOND-4.[6] Both THF solvent molecules are disordered in the vicinity of a twofold axis. CCDC 1988239 (**5a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via https://summary.ccdc.cam.ac.uk/structure-summary-form (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44)1223-336-033; or deposit@ccdc.cam.uk).

References: see S37

Table S4. Basic crystallographic structure parameters for **5a**.

Molecular formula	$C_{44}H_{44}P_2 \cdot THF$	Crystal size	0.35 x 0.24 x 0.06 mm^3
Empirical formula	$C_{48}H_{52}OP_2$	Theta range for data collection	2.311 to 30.508°
Formula weight	706.83	Index ranges	$-24 \leq h \leq 24$, $-14 \leq k \leq 14$, $-32 \leq l \leq 32$
Temperature	130(2) K	Reflections collected	26465
Wavelength	0.71073 Å	Independent reflections	12072 [R(int) = 0.0360]
Crystal system	Monoclinic	Completeness to theta = 25.242°	99.9 %
Space group	*C*2	Absorption correction	Semi-empirical from equivalents
Unit cell dimensions	a = 17.2172(4) Å	Max. and min. transmission	1.00000 and 0.99370
	b = 10.3390(3) Å	Refinement method	Full-matrix least-squares on F^2
	c = 22.6719(5) Å	Data / restraints / parameters	12072 / 39 / 590
	β= 101.889(2)°	Goodness-of-fit on F^2	1.006
Volume	3949.2(2) $Å^3$	Final R indices [I>2sigma(I)]	R1 = 0.0524, wR2 = 0.1224
Z	4	R indices (all data)	R1 = 0.0745, wR2 = 0.1356
Density (calculated)	1.189 Mg/m^3	Absolute structure parameter	-0.01(3)
Absorption coefficient	0.146 mm^{-1}	Residual electron density	0.531 and -0.387 $e \cdot Å^{-3}$
F(000)	1512		

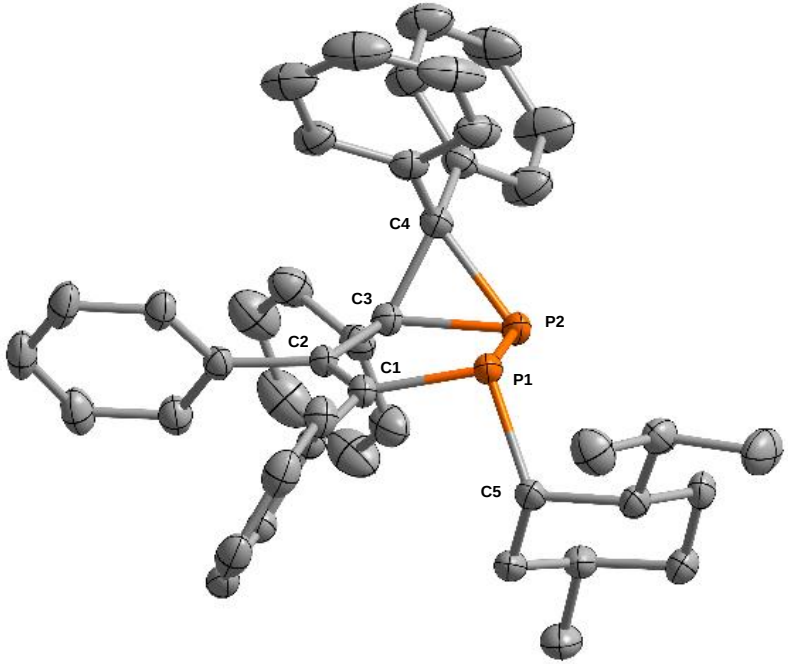

Figure S31. Molecular structure of 2-((+)-neomenthyl)-3,4,5,6,6-pentaphenyl-1,2-(P1$_R$P2$_R$C3$_S$)-diphosphabicyclo[3.1.0]hex-3-ene **(5a)**. Hydrogen atoms are omitted for clarity. Configuration of chiral atoms in the five-membered ring: P1:(*R*), P2:(*R*), C3:(*S*). Selected bond lengths [Å] and angles [°]: P1-C1 1.818(3); P1-C5 1.888(3); P1-P2 2.194(1); P2-C4 1.877(3); P2-C3 1.879(3); C1-C2 1.354(4); C2-C3 1.513(4); C3-C4 1.554(4); C1-P1-C5 99.9(1); C1-P1-P2 93.4(1); C4-P2-C3 48.9(1); C4-P2-P1 100.8(1); C3-P2-P1 94.4(1).

A crystal structure analysis of **5a** showed that only one diastereomer was obtained with the neomenthyl group in an *anti* orientation to the 3-membered P2-C3-C4(Ph$_2$) fragment. Compound **5a** crystallizes in the monoclinic space group C_2 with a Flack parameter of -0.01(3). There are 6 chiral centers in **5a**, each phosphorus atom has a typical pyramidal environment and the menthyl fragment has the configuration of (+)-neomenthol or (1*S*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexanol.

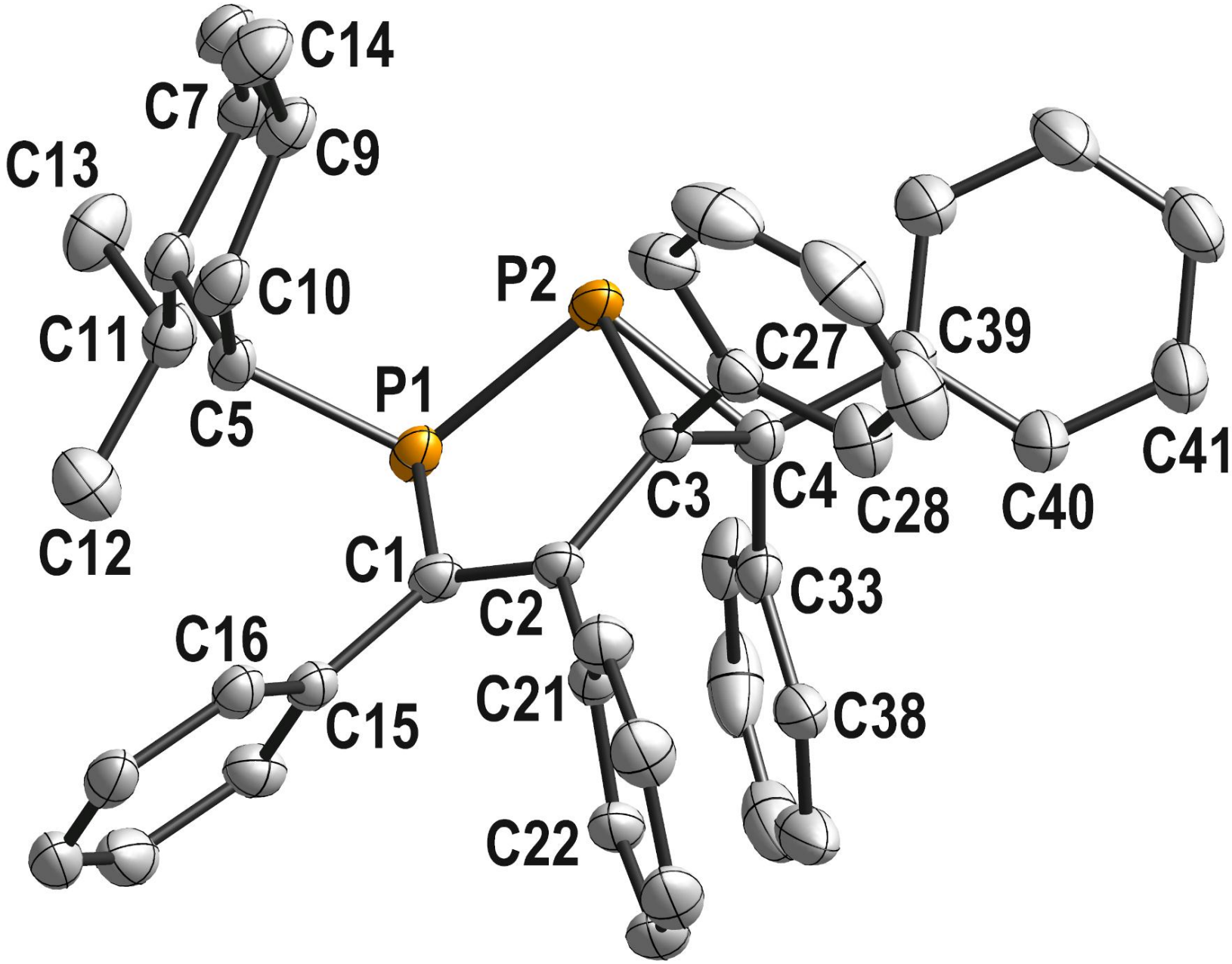

Figure S32. Atom-labeling scheme of **5a**. Displacement ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity.

References

(1) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. *Gaussian 03, Revision B.04*; Gaussian, Inc., Pittsburgh, PA, 2003.
(2) Latypov, Sh.K.; Polyancev, F.M.; Yakhvarov, D.G.; Sinyashin, O.G. Quantum Chemical Calculations of 31 P NMR Chemical Shifts: Scopes and Limitations. *Phys. Chem. Chem. Phys*. **2015**, *17*, 6976–6987.
(3) CrysAlisPro: Data reduction software package, Rigaku Oxford Diffraction, Oxford, UK.

(4) SIR92: A. Altomare, G. Cascarano, C. Giacovazzo and A. Guagliardi, J. Appl. Crystallogr. 1993, 26, 343-350

(5) SHELXL: G. M. Sheldrick, Acta Cryst. C71 (2015) 3 – 8

(6) DIAMOND 4: K. Brandenburg, Crystal Impact GbR, Bonn, Germany