Electronic Supplementary Material (ESI) for Organic & Biomolecular Chemistry.

Supporting information

Synthesis of 3-(2-Thiopyridiyl)indoles *via* Ruthenium Catalyzed [2+2+2] Cycloaddition of Diynes and 3-Thiocyanatoindoles

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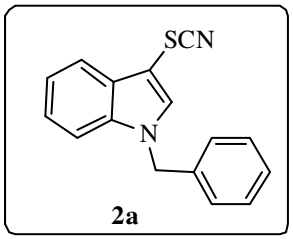
1. General information

Chemicals and reagents were purchased from commercial suppliers and used without further purification. Freshly distilled solvent was used for column chromatography. Thin layer chromatography (TLC) was performed using pre-coated plates purchased from E. Merck (silica gel 60 PF254, 0.25 mm). Column chromatography was performed using E. Merck silica gel 60 (100–200 mesh). NMR spectra were recorded in $CDCl_3$, on JEOL JNM-ECS spectrometer at operating frequencies of 400 MHz (^1H) or 100 MHz (^{13}C) as indicated in the individual spectrum. Chemical shifts (δ) are given in ppm relative to residual solvent (chloroform, δ= 7.26 for ^1H and 77.16 for proton decoupled ^{13}C NMR) and coupling constants (*J*) in Hz. Multiplicity is tabulated as s for singlet, bs for broad singlet, d for doublet, dd for doublet of doublet, t for triplet, q for quatrate, and m for multiplet. High-resolution mass spectra (HRMS) were recorded using electron spray ionization (ESI) methods on waters mass spectrometer. Melting points were determined using BIBBY-SMP30 melting point meter and IR data were recorded on a Bruker spectrophotometer in the region 600–4000 cm^{-1}. Single crystal X-ray structural data of all the three compounds were collected on a CMOS based Bruker D8 Venture PHOTON 100 diffractometer equipped with a INCOATEC micro-focus source with graphite monochromated Mo Kα radiation (λ = 0.71073 A) operating at 50 kV and 30 mA.

The symmetrical (**1a-g**)[1] and unsymmetrical diynes (**4a-c**)[1] are prepared according to the reported literature procedure.

References:

1. V. Richard, M. Ipouck, D. S. Me´rel, S. Gaillard, R. J. Whitby, B. Witulskia, J.-L. Renaud, *Chem. Commun.,* 2014, **50**, 593.



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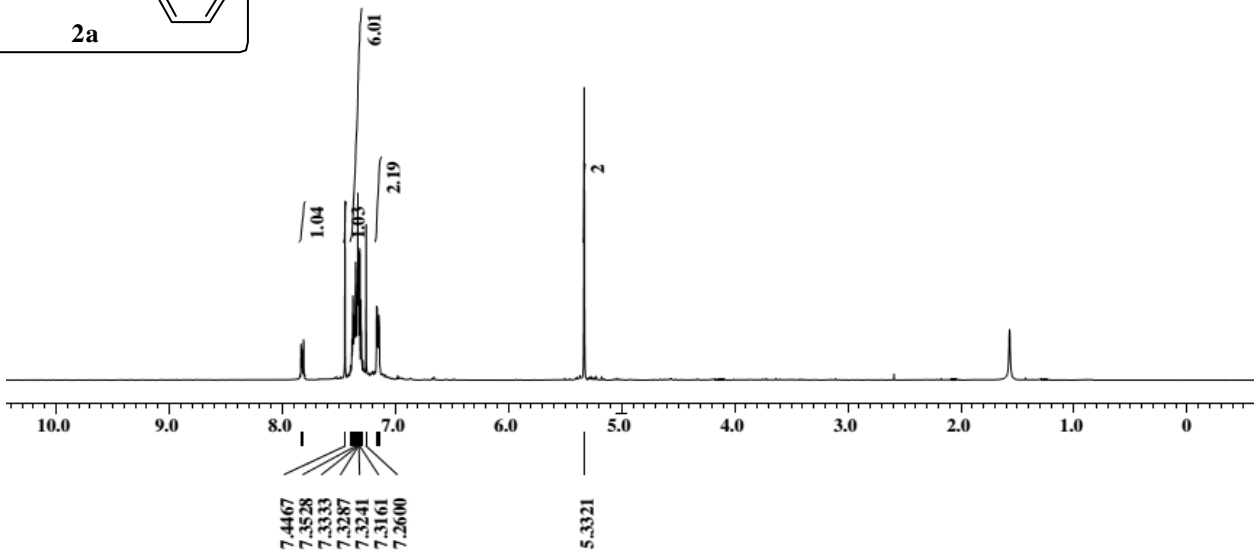

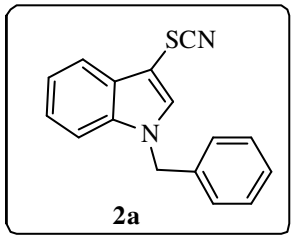

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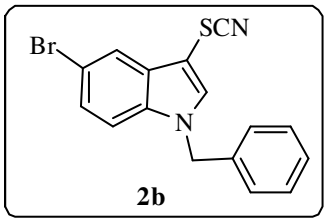

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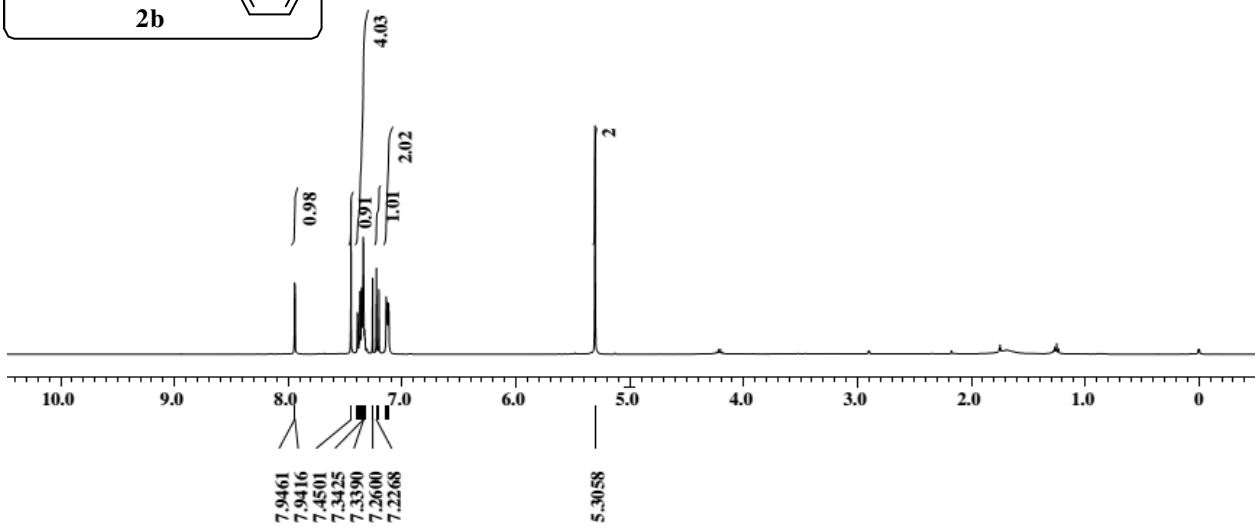

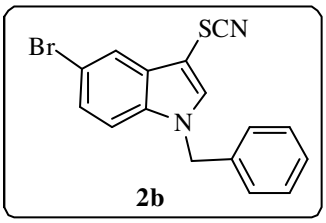

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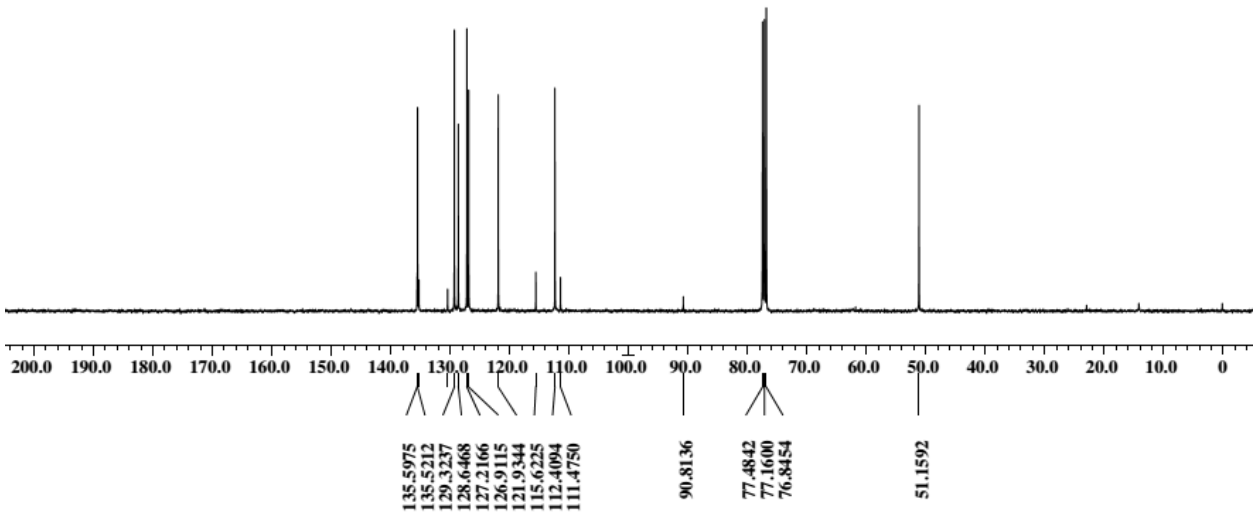

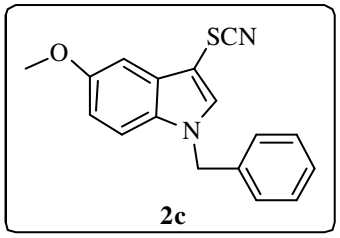

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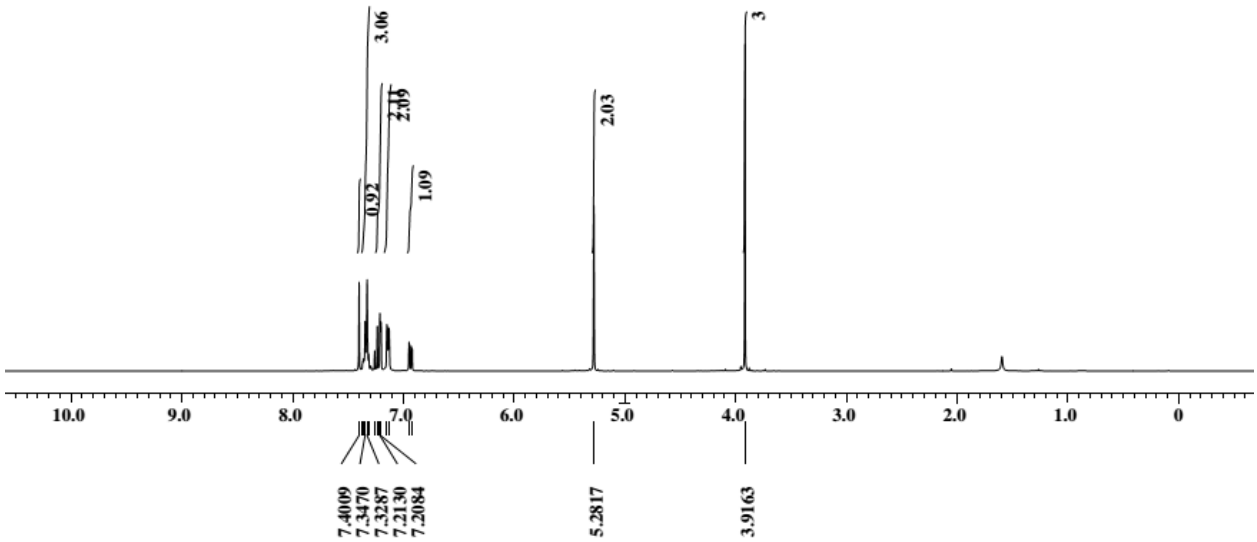

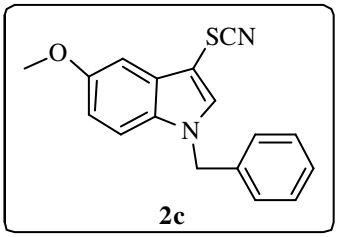

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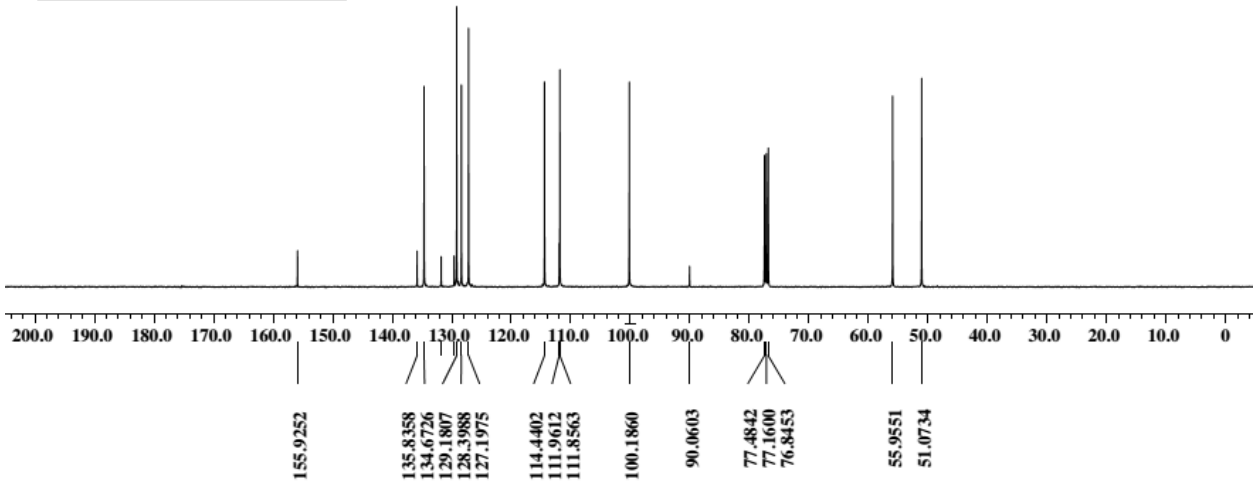

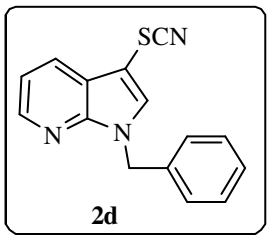

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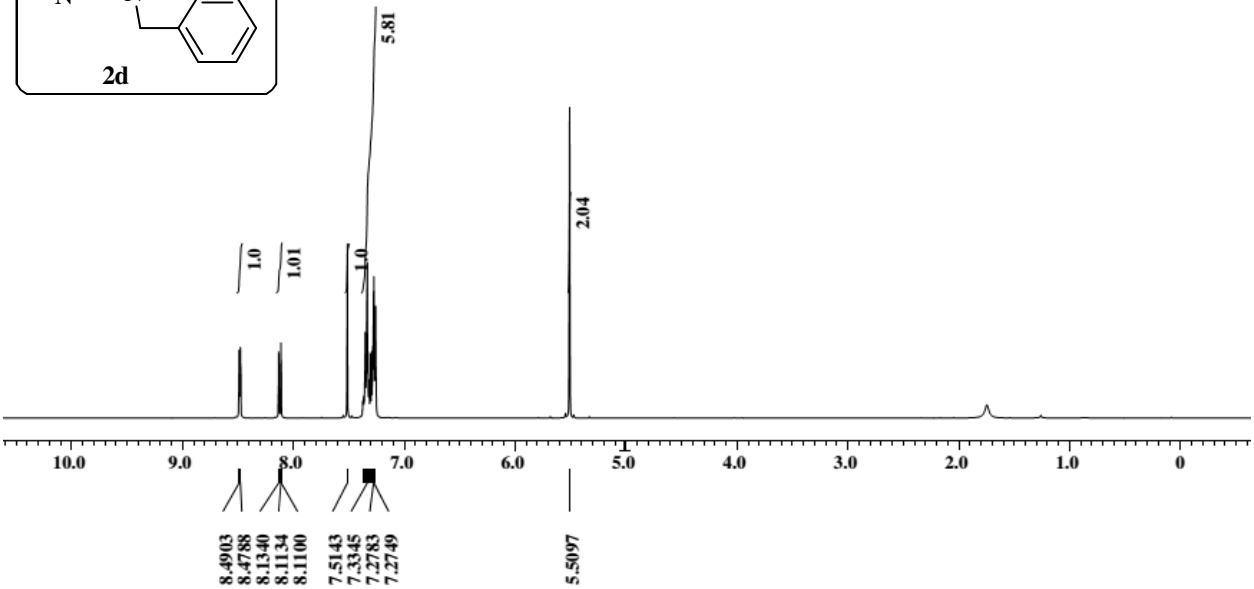

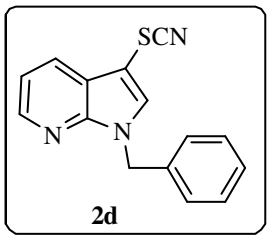

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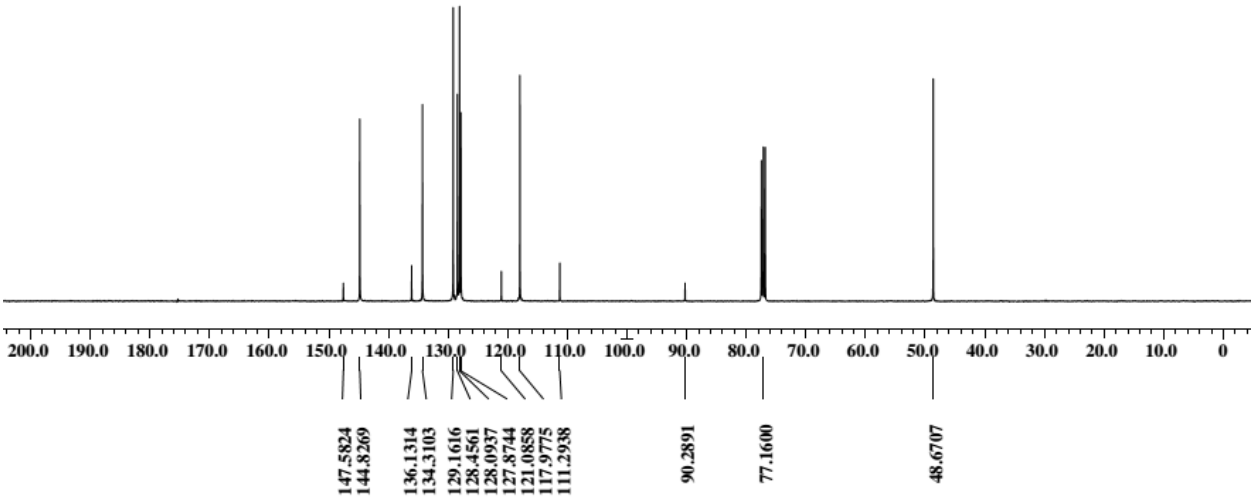

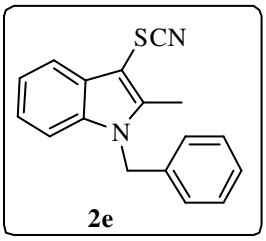

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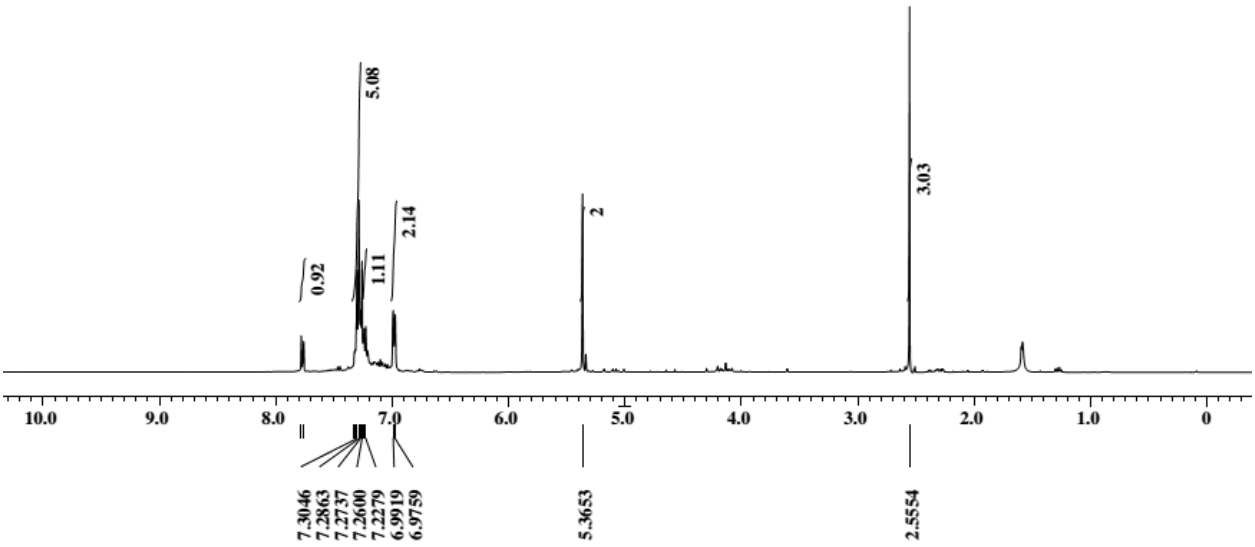

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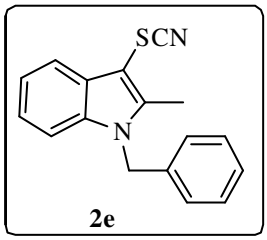

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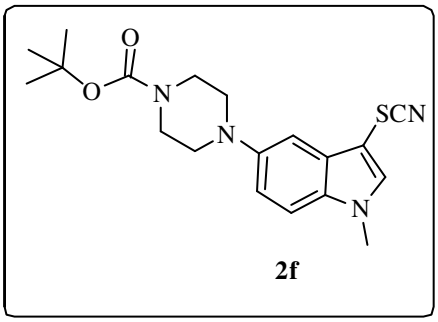

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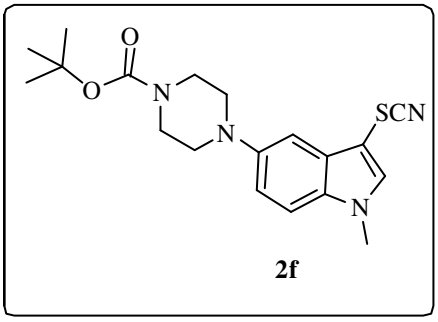

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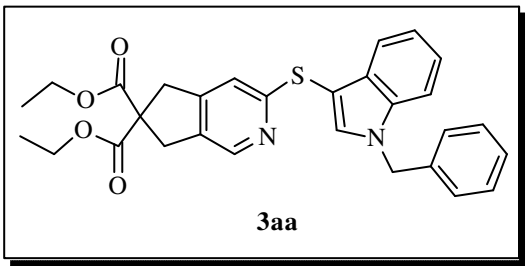

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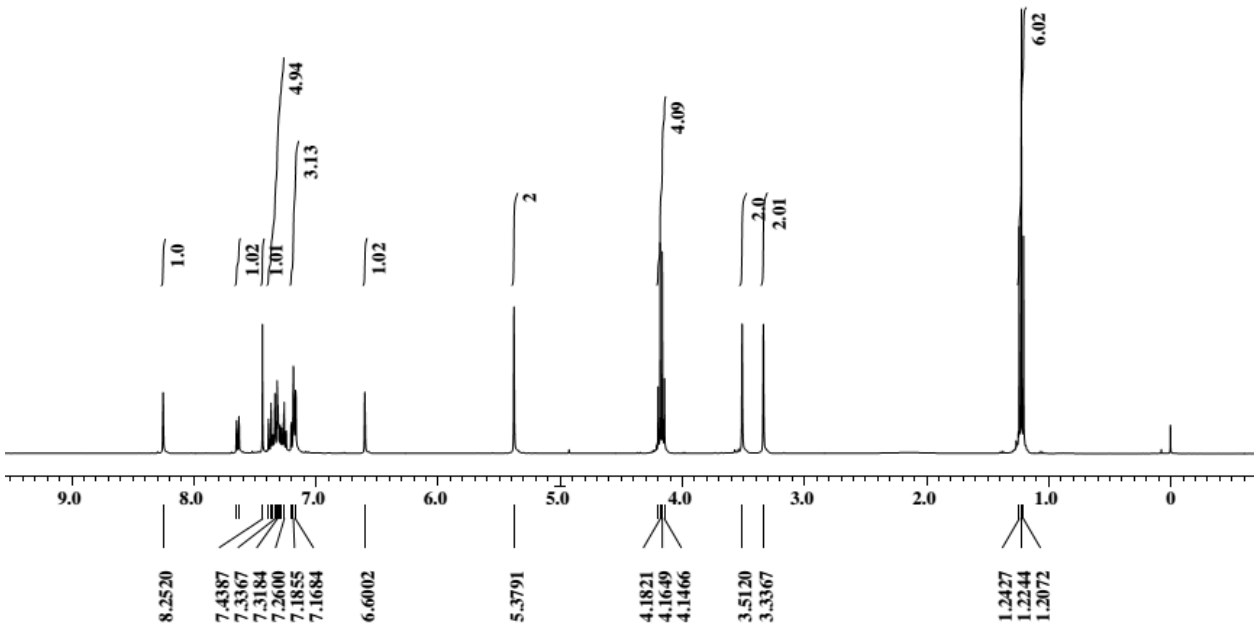

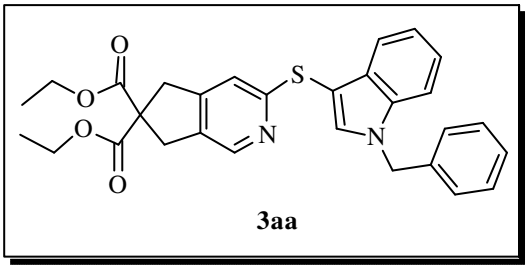

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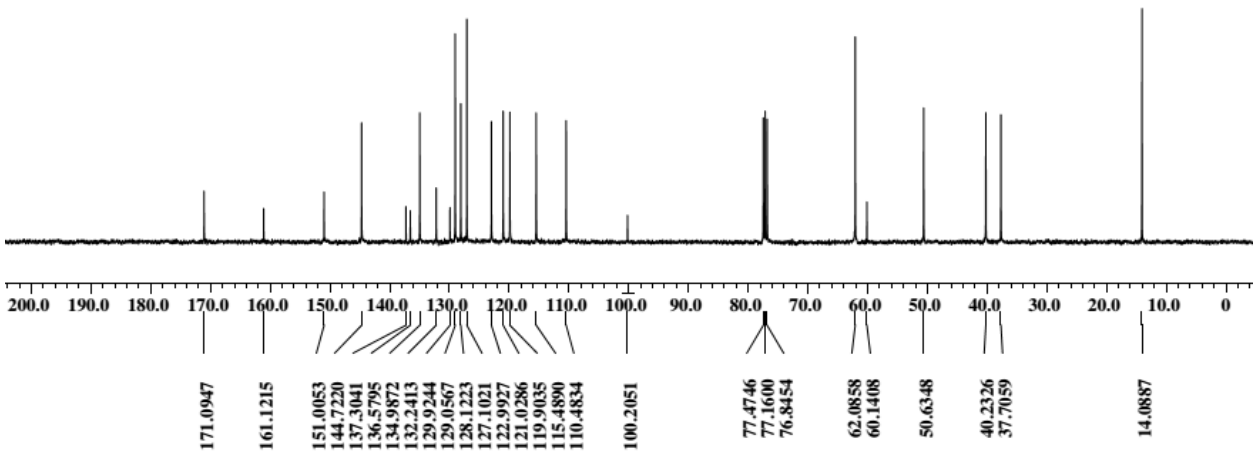

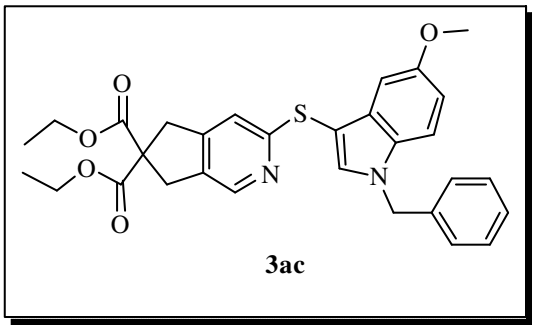

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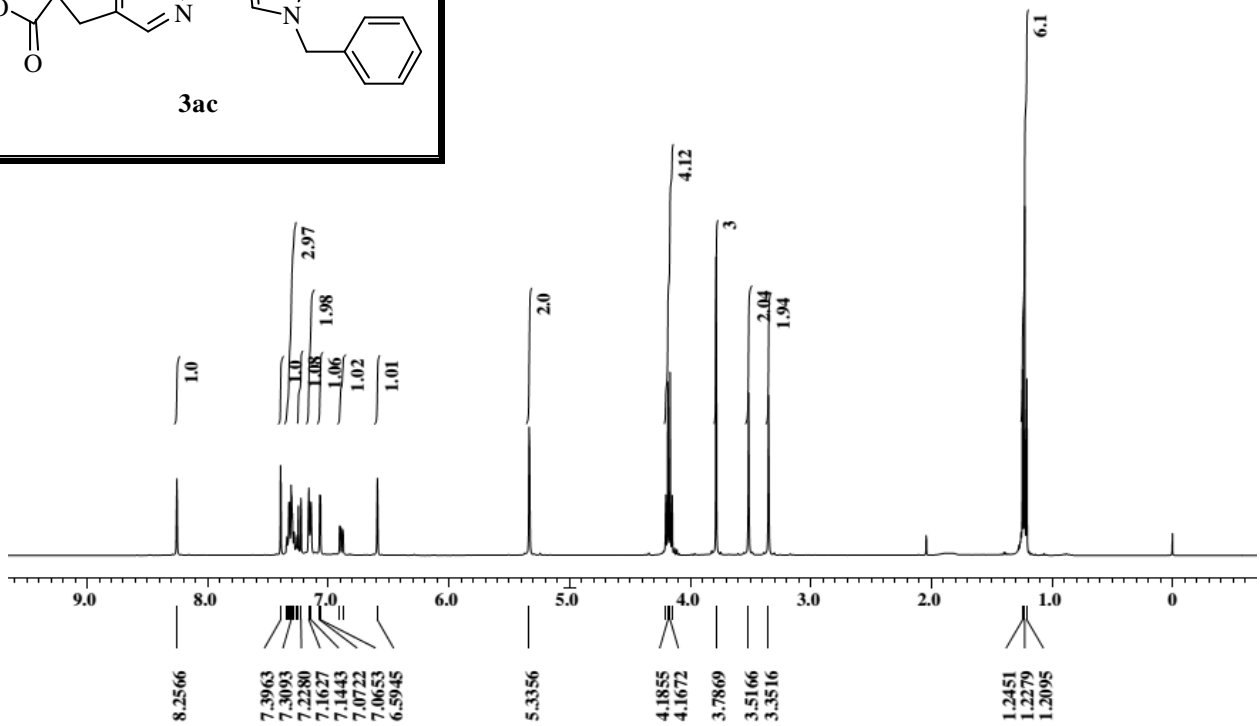

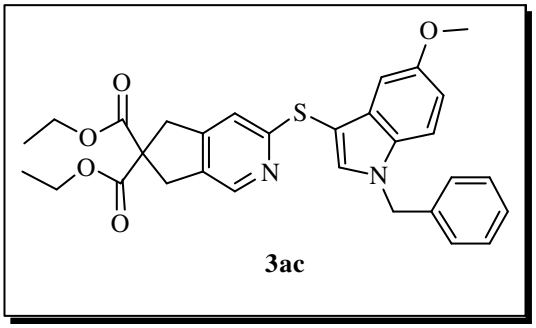

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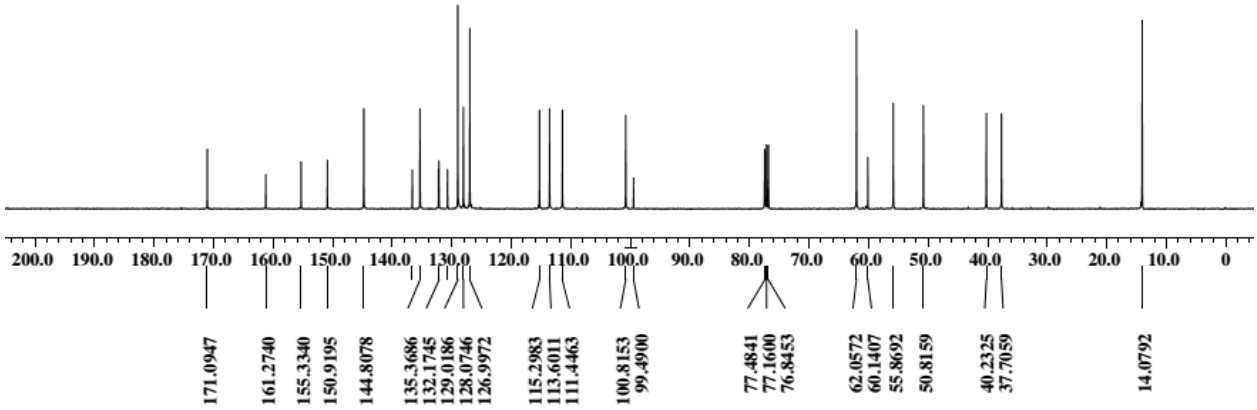

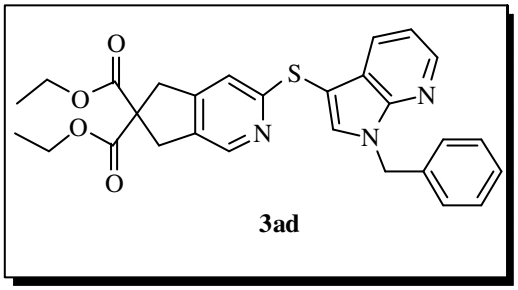

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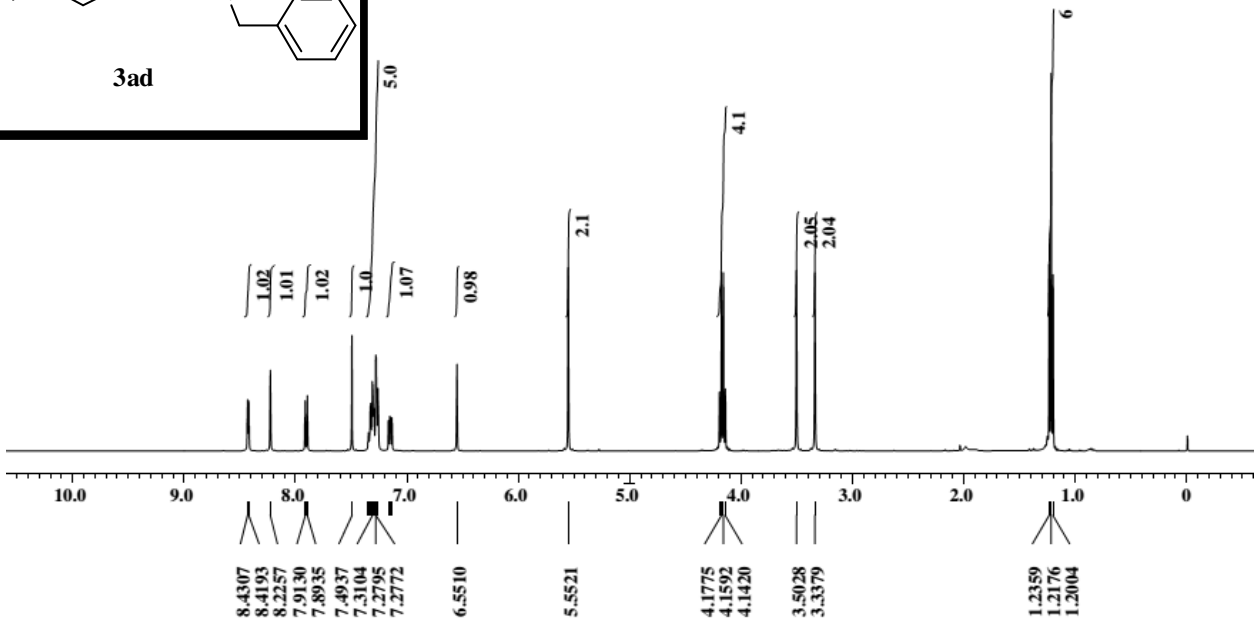

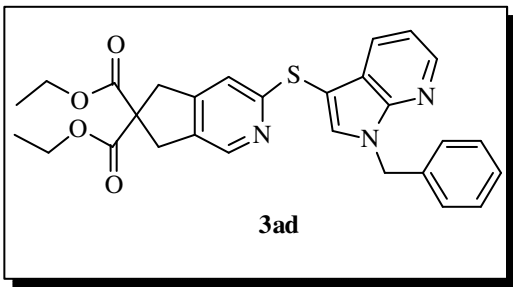

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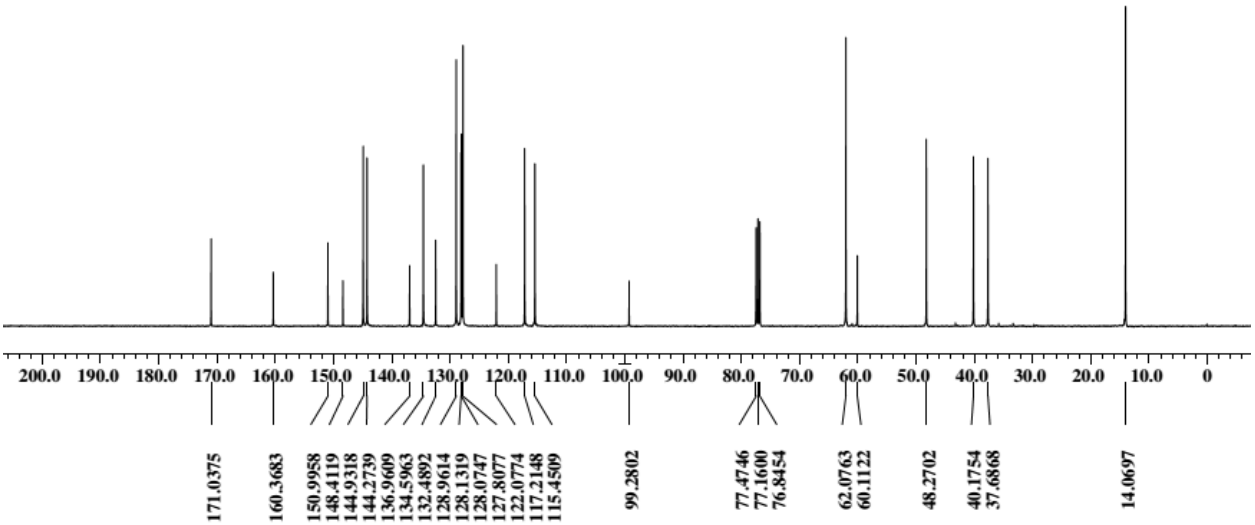

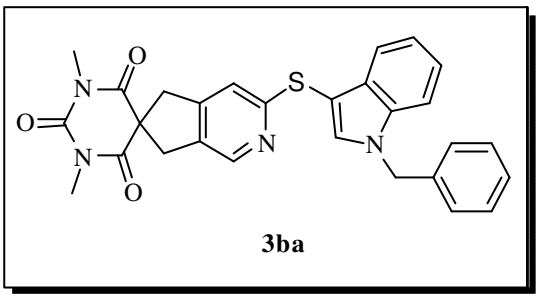

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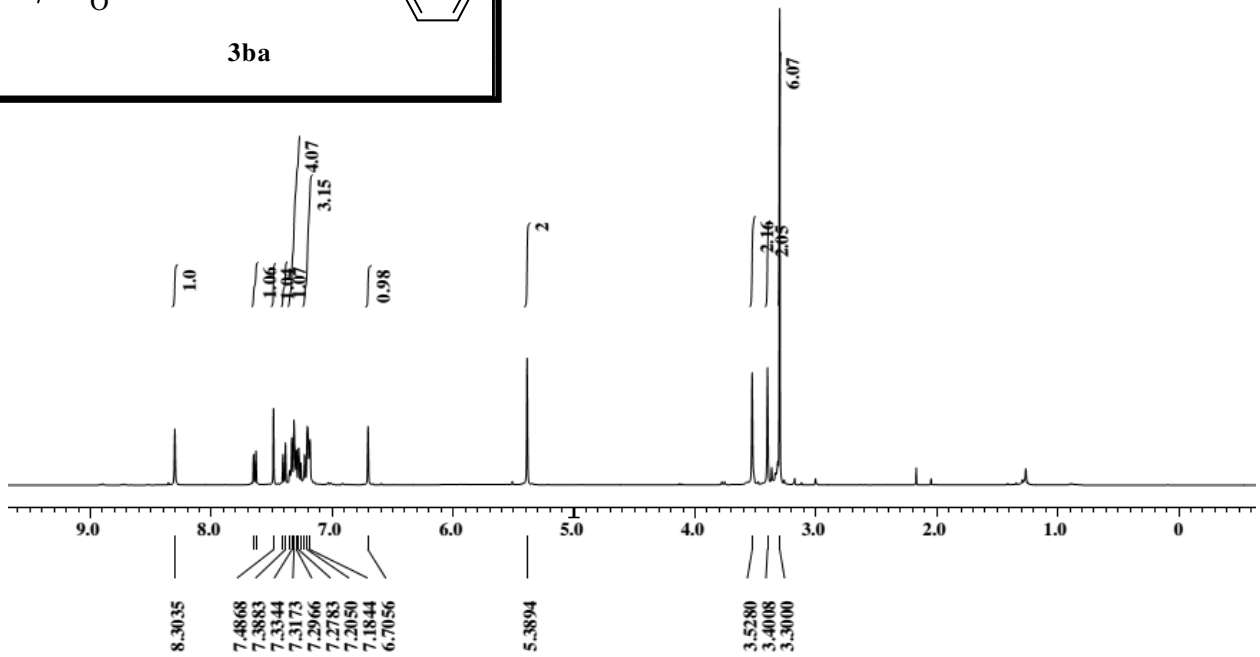

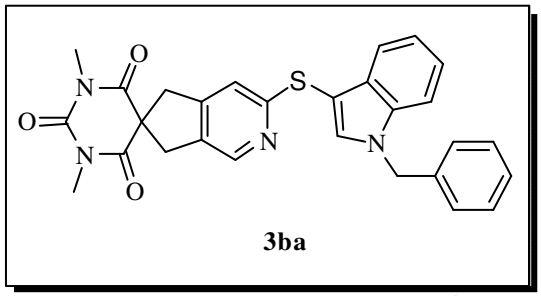

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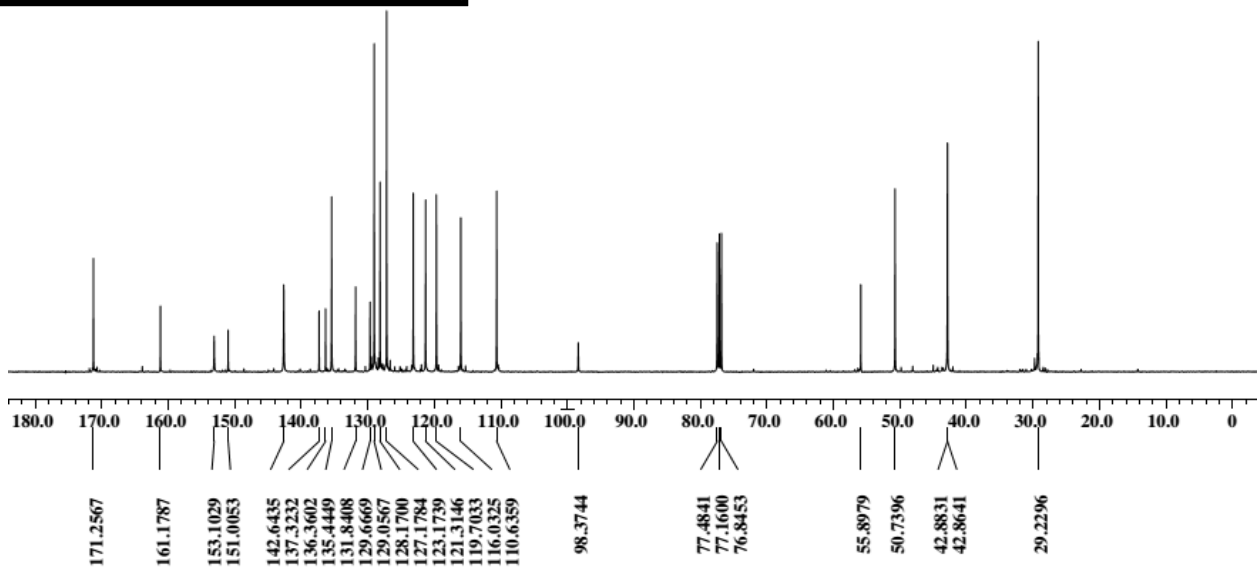

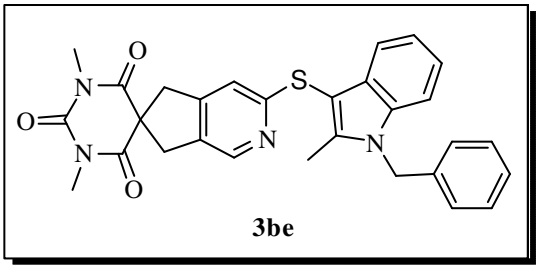

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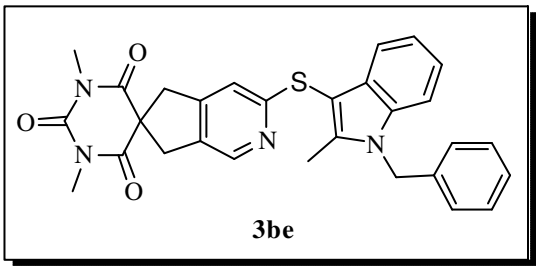

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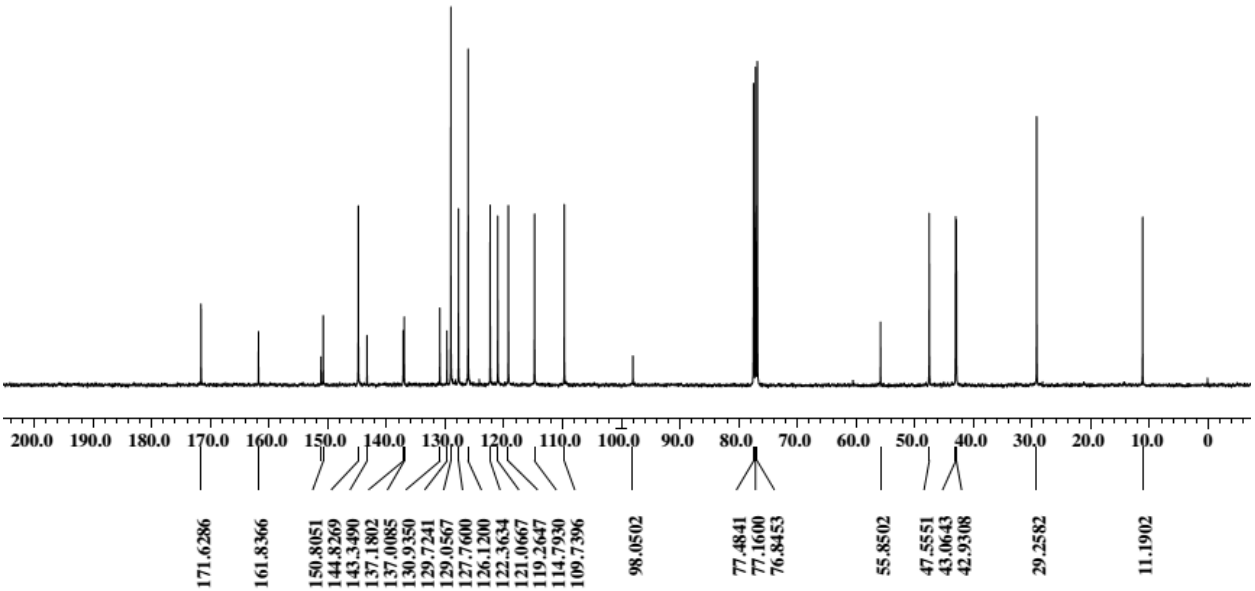

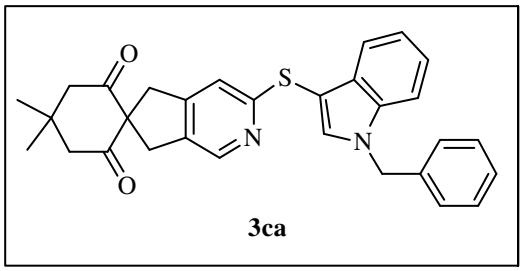

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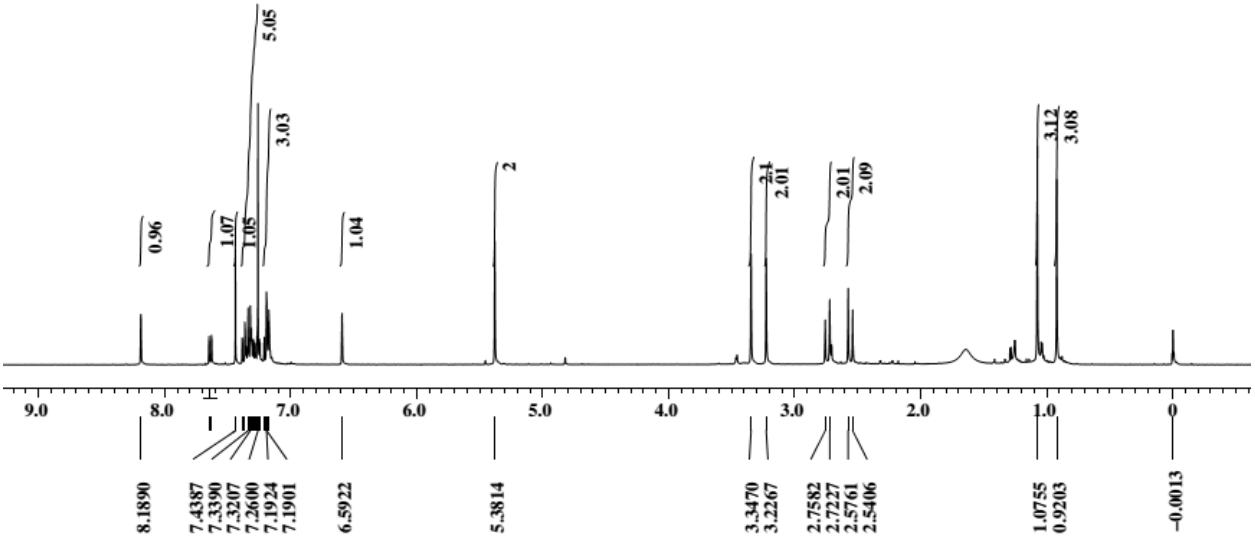

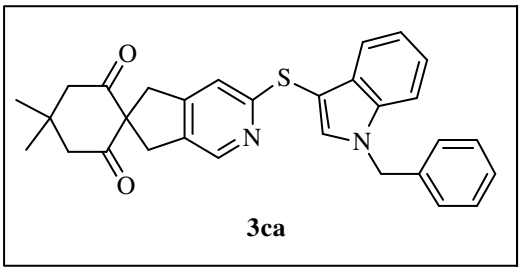

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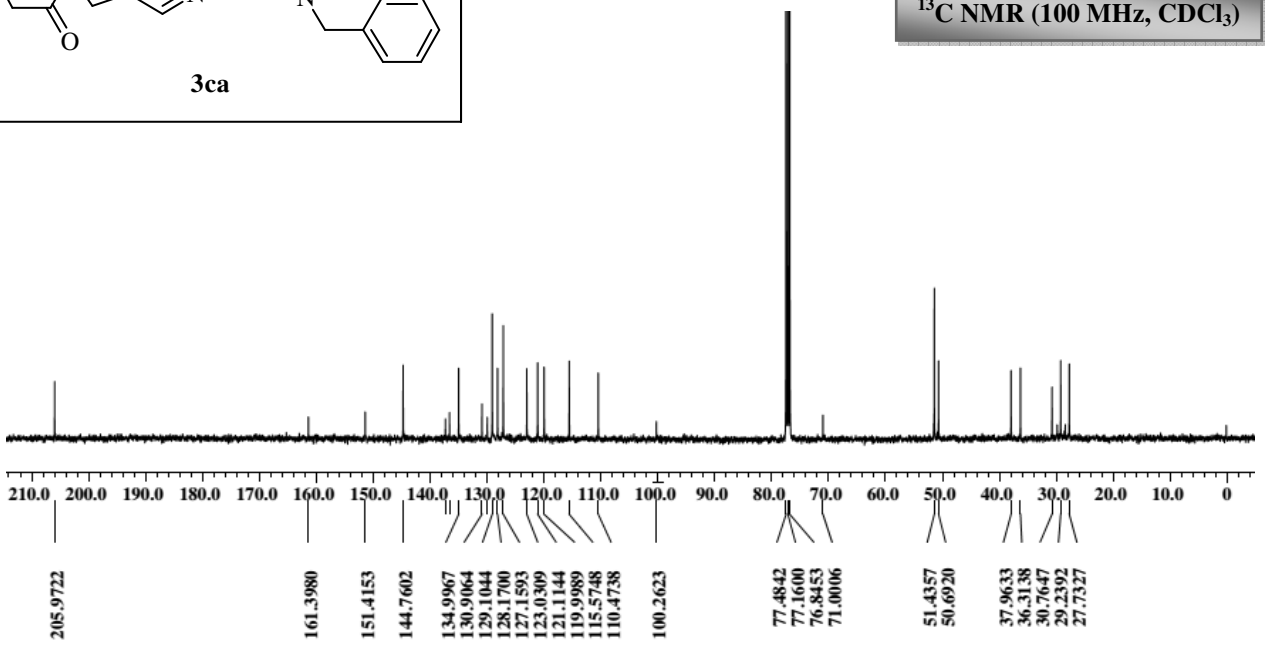

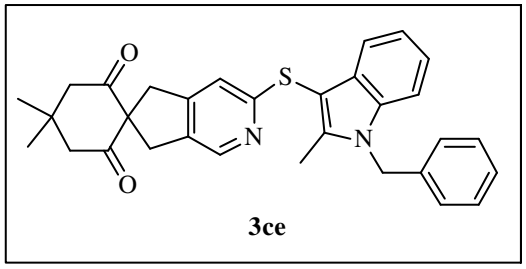

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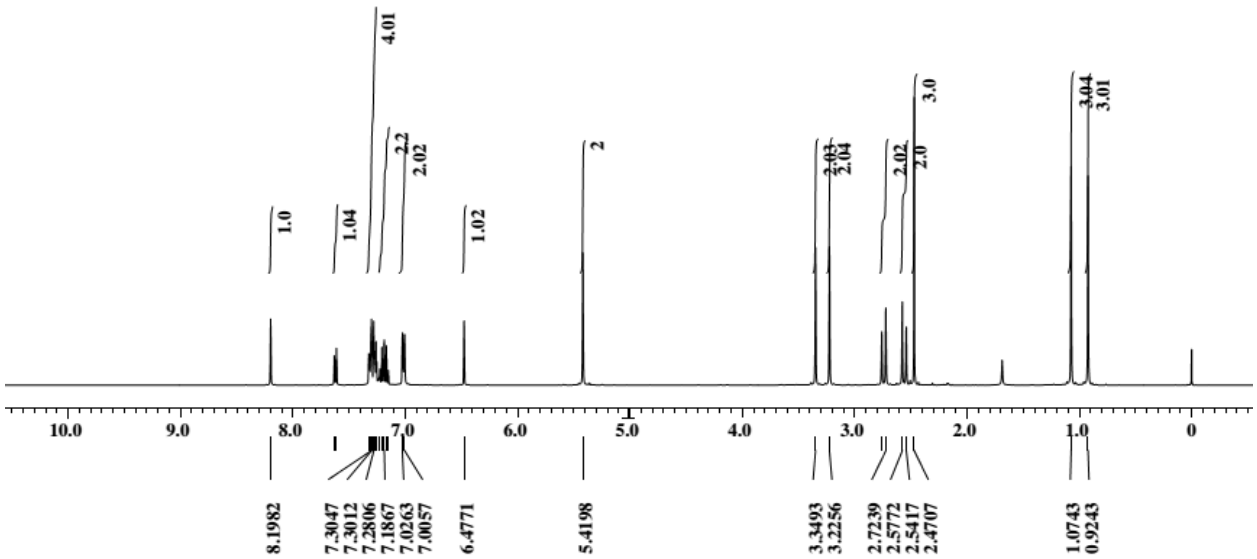

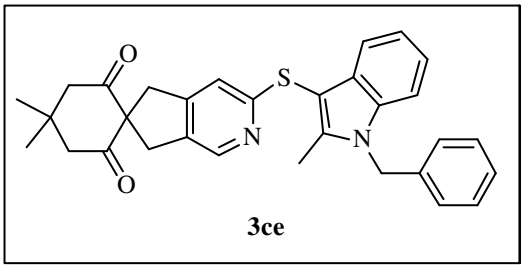

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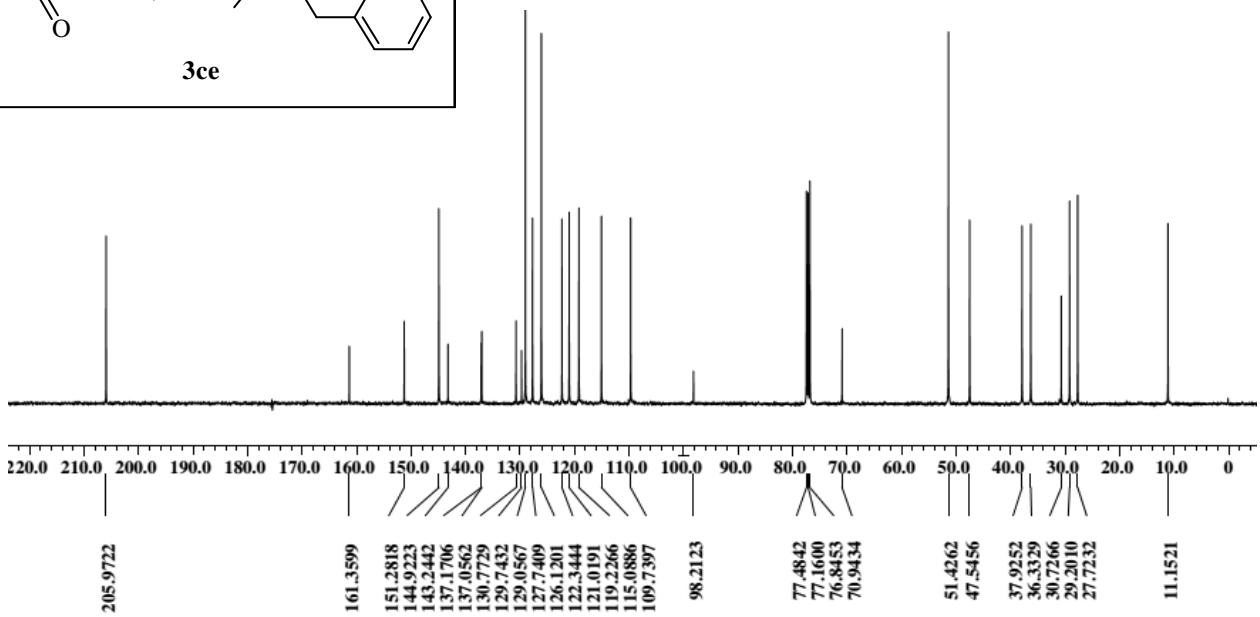

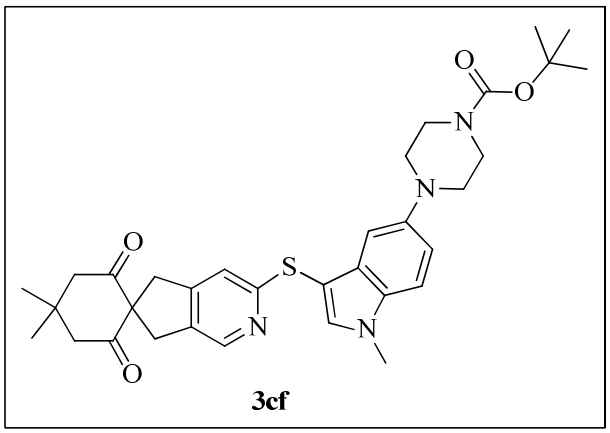

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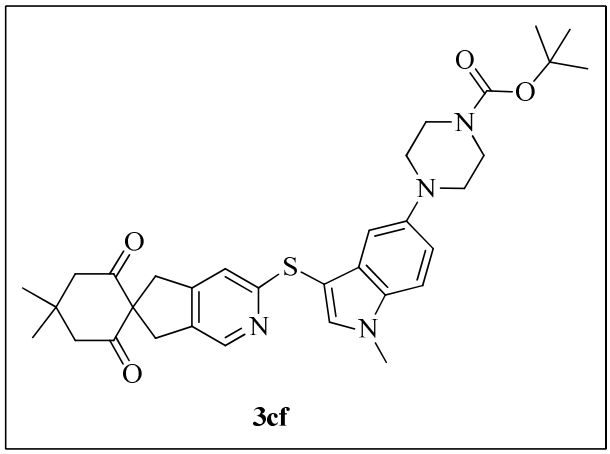

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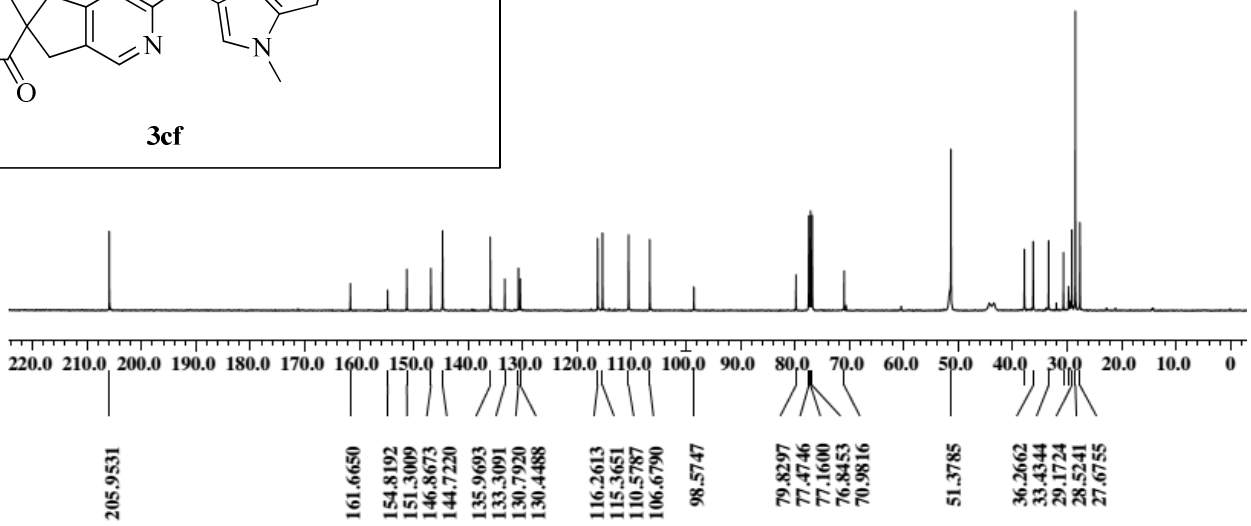

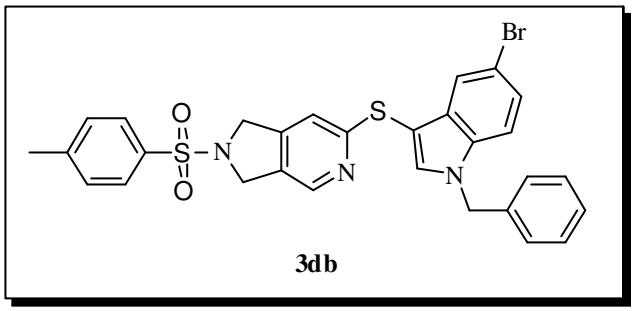

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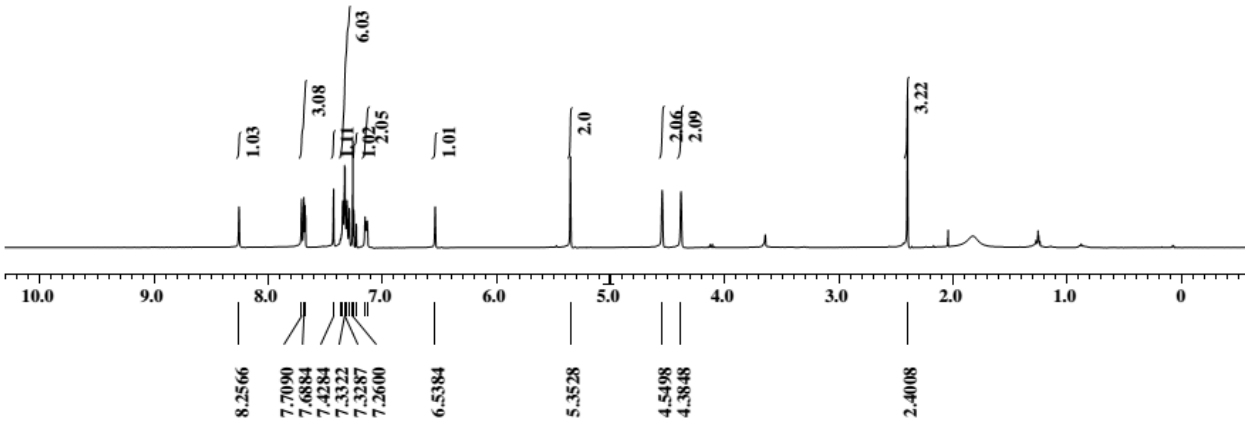
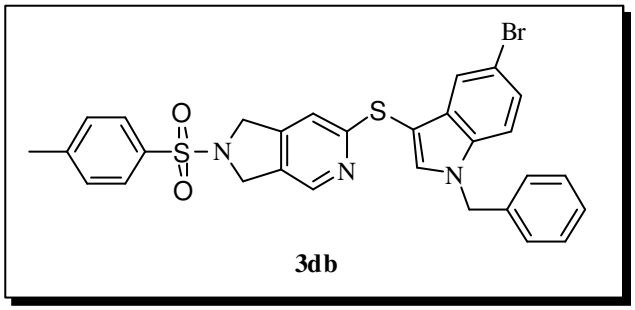
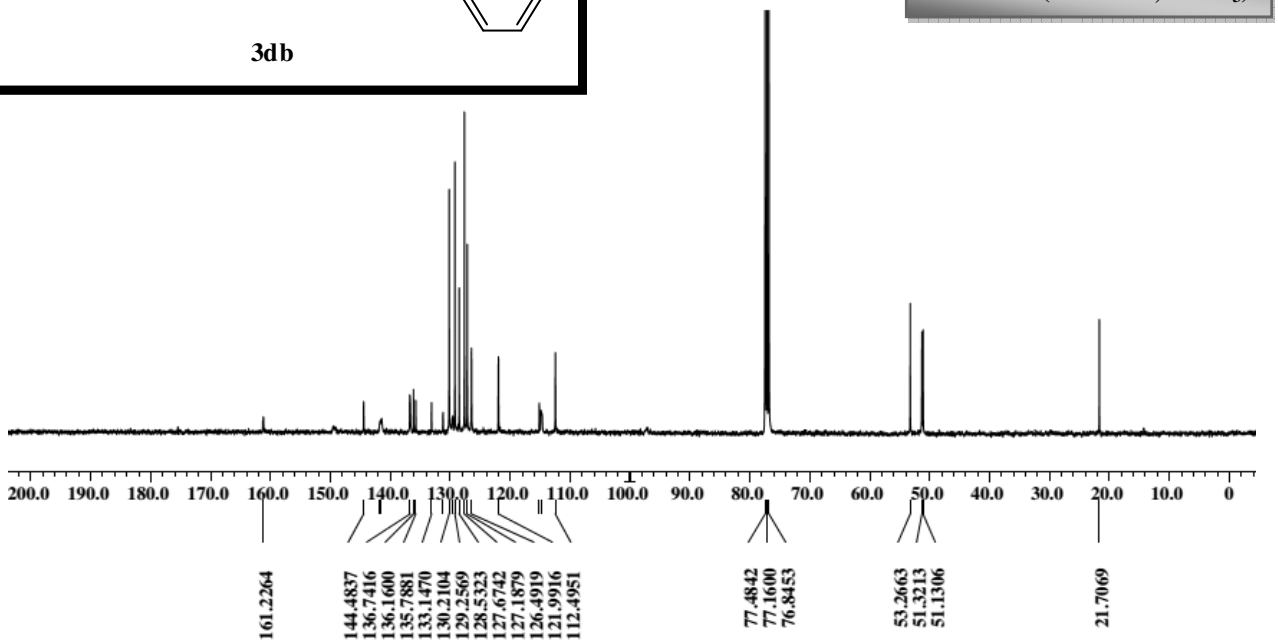
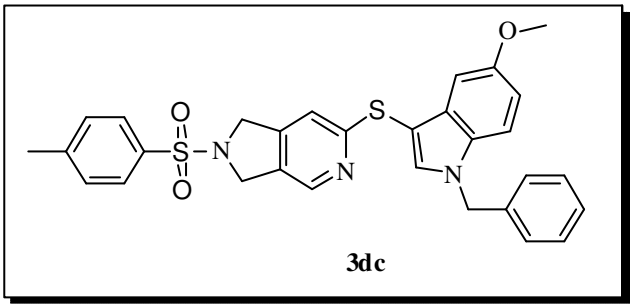




3db

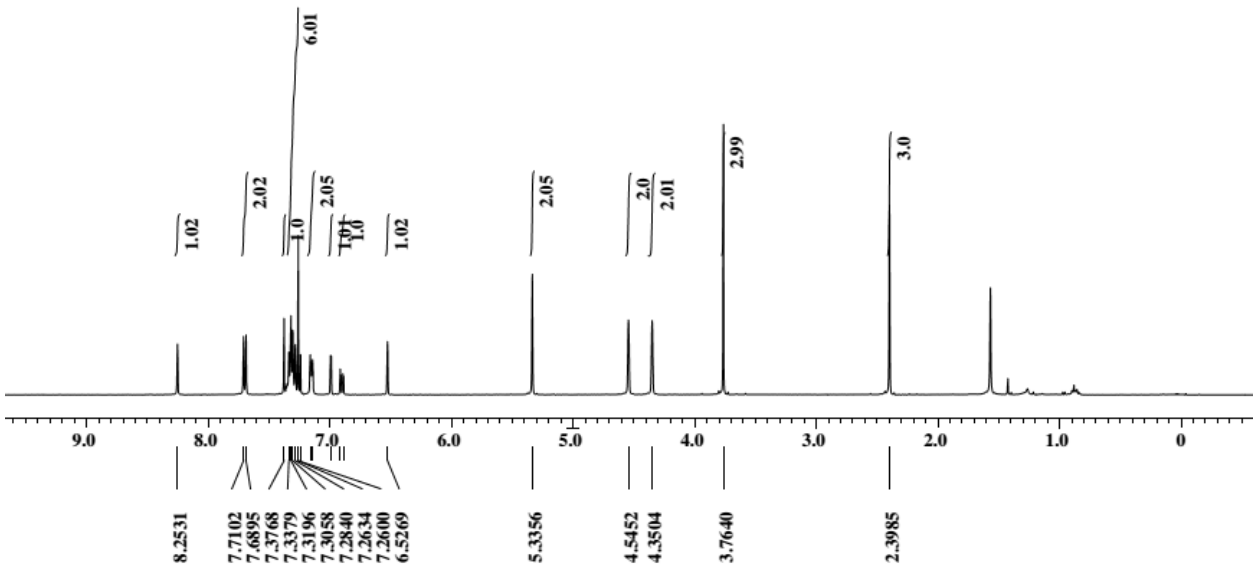
^{13}C NMR (100 MHz, $CDCl_3$)

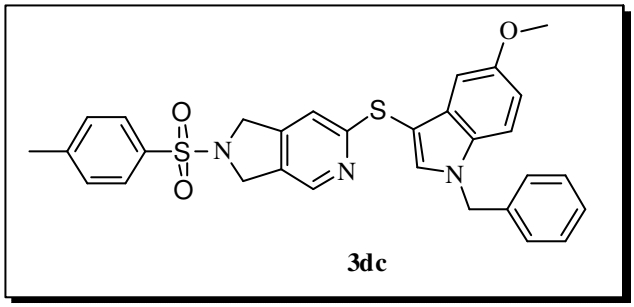




3dc

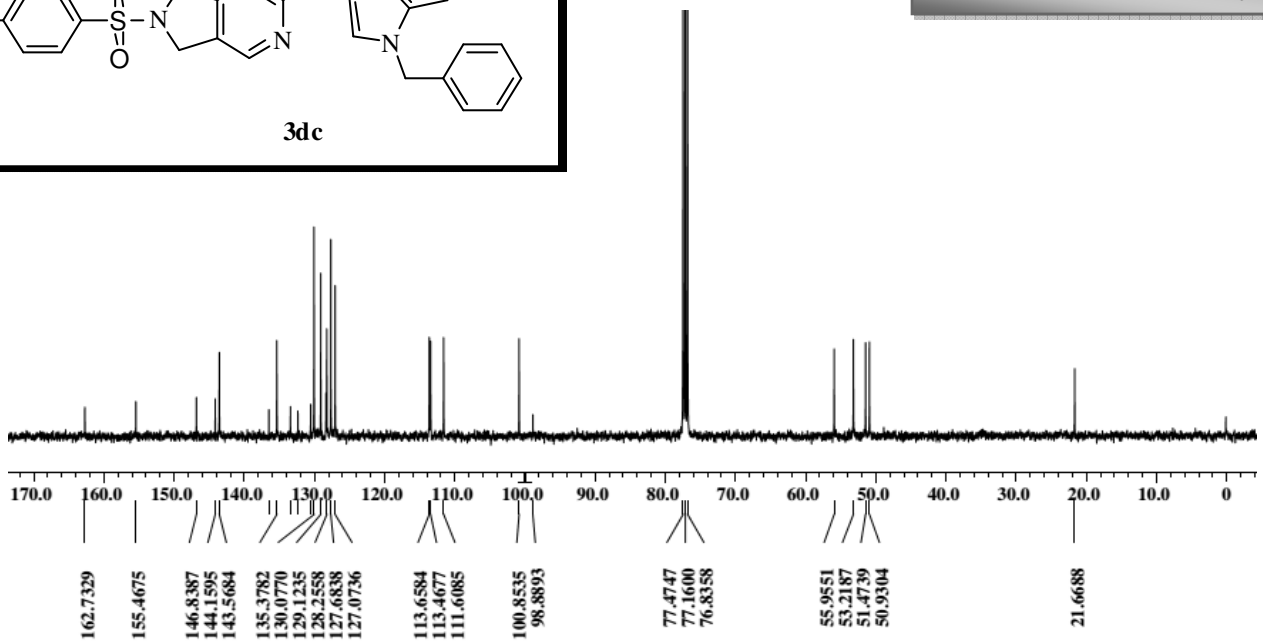
^{1}H NMR (400 MHz, $CDCl_3$)

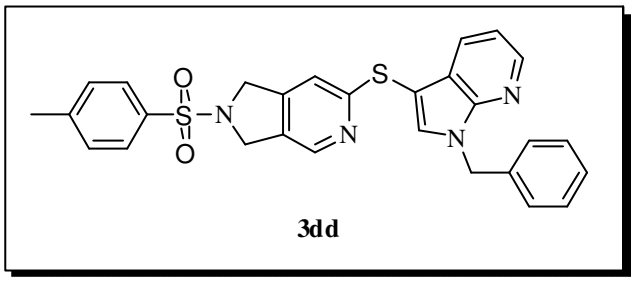




3dc

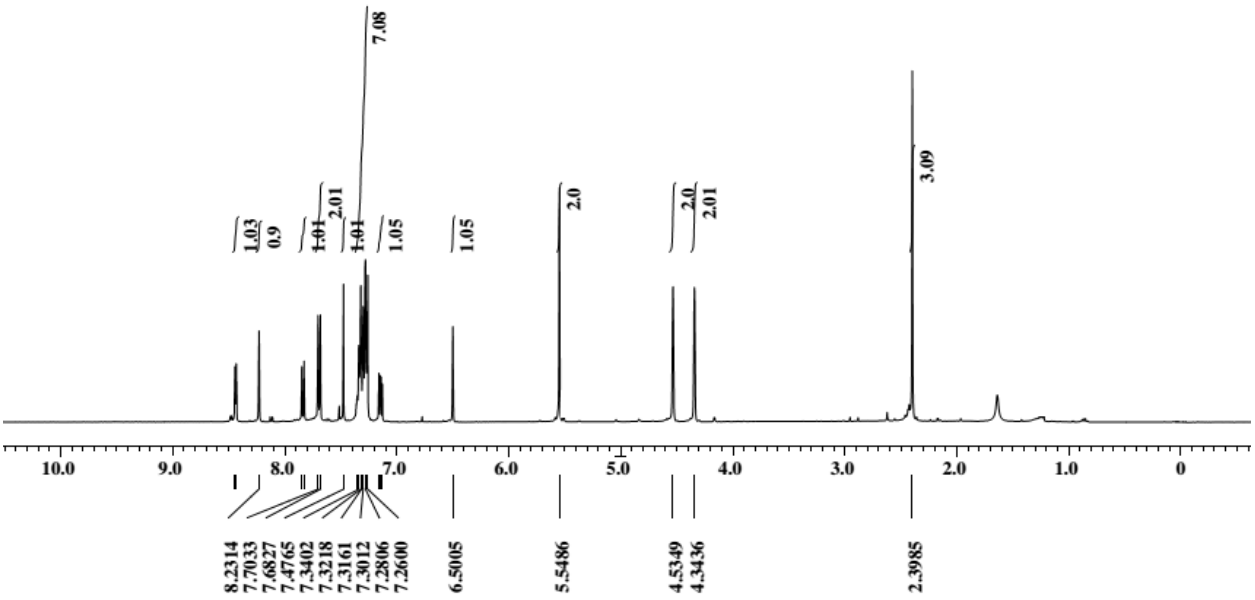
^{13}C NMR (100 MHz, $CDCl_3$)

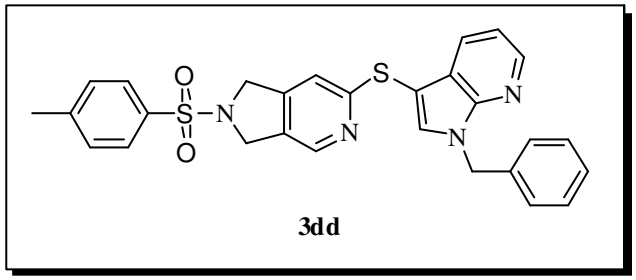




3dd

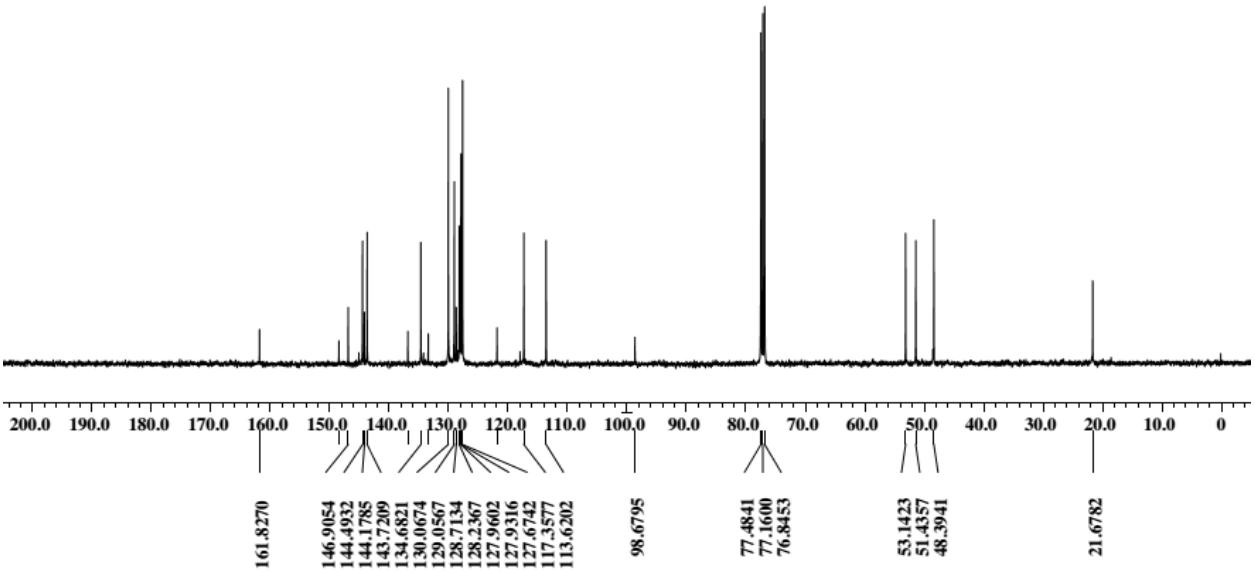
^{1}H NMR (400 MHz, $CDCl_3$)

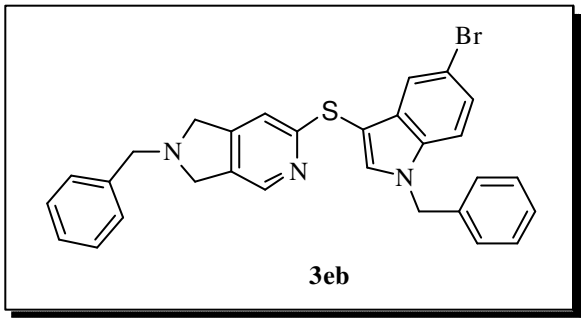




3dd

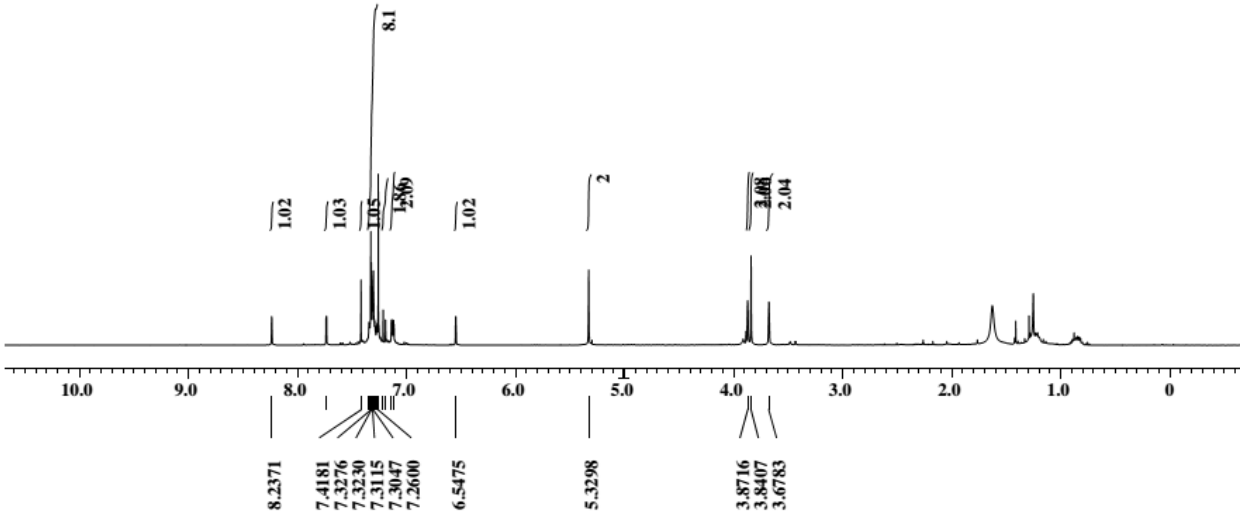
^{13}C NMR (100 MHz, $CDCl_3$)

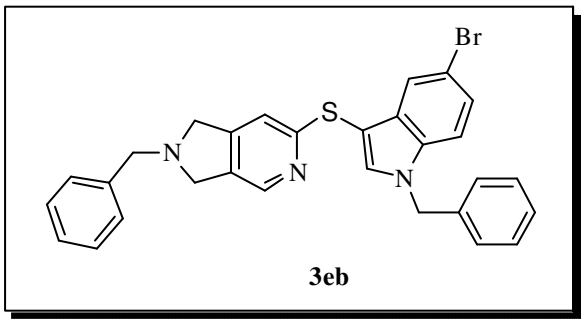




3eb

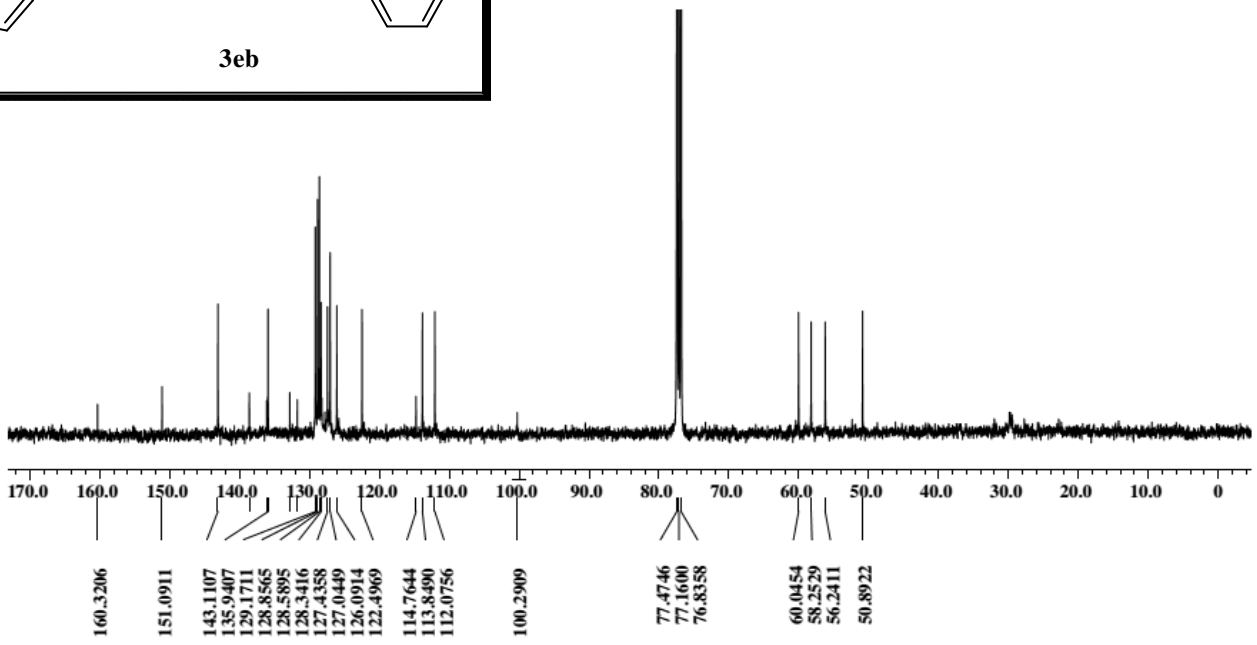
^{1}H NMR (400 MHz, $CDCl_3$)

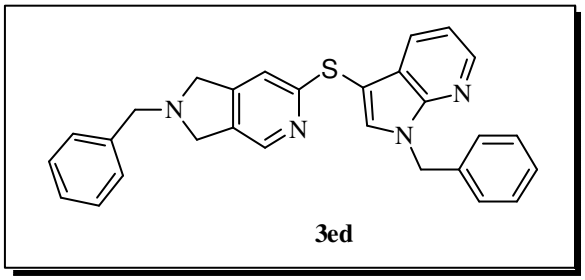




3eb

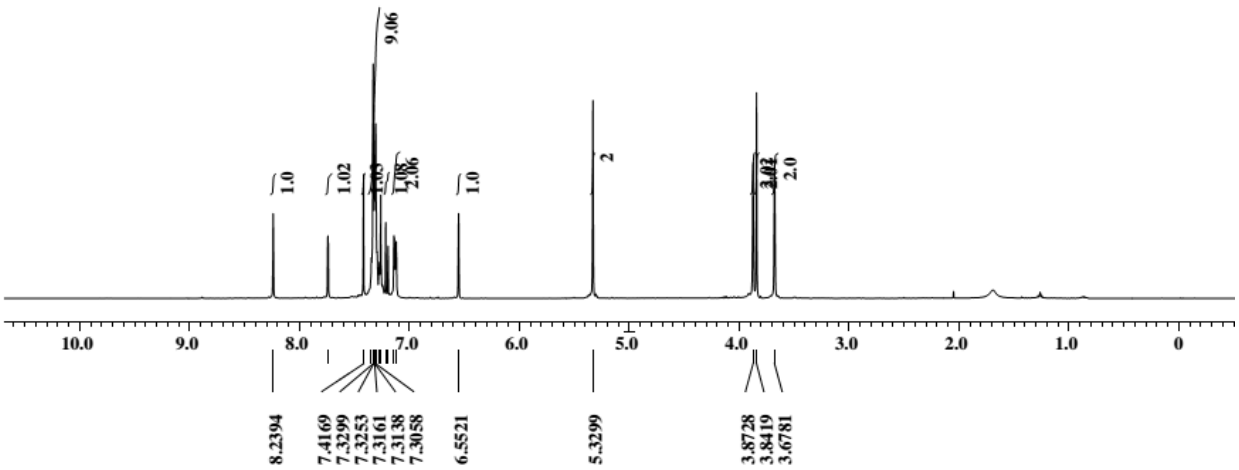
^{13}C NMR (100 MHz, $CDCl_3$)

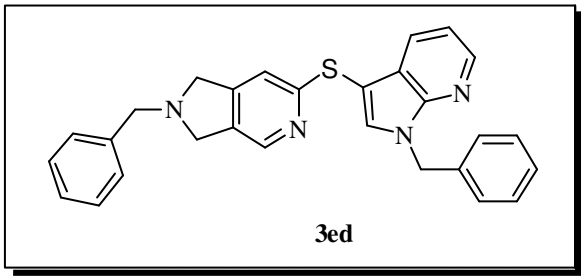




3ed

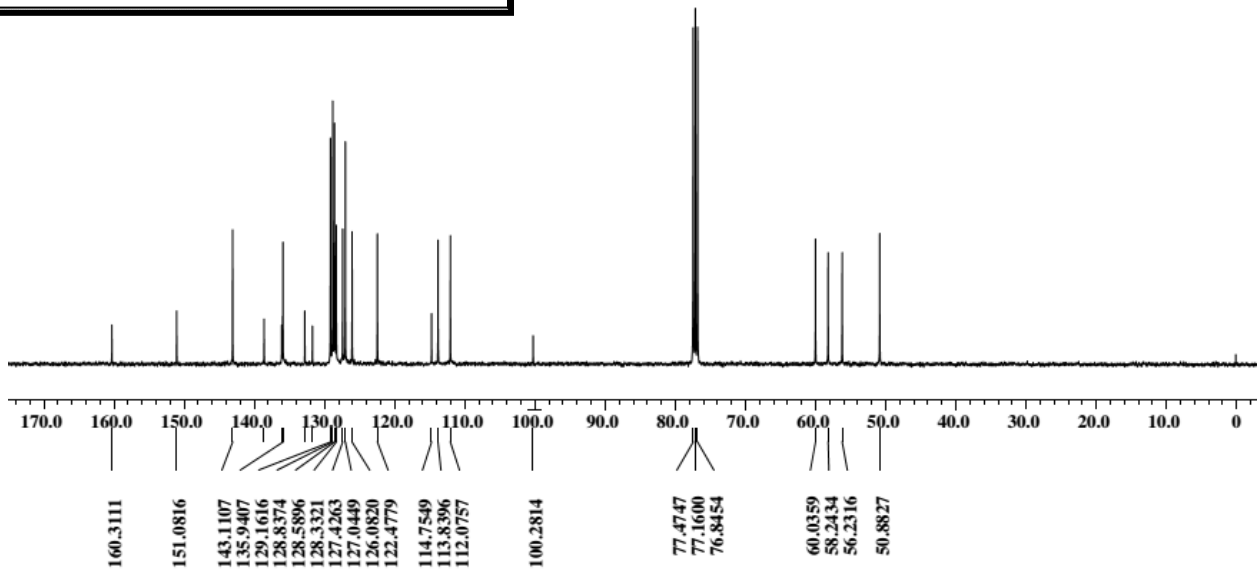
^{1}H NMR (400 MHz, $CDCl_3$)

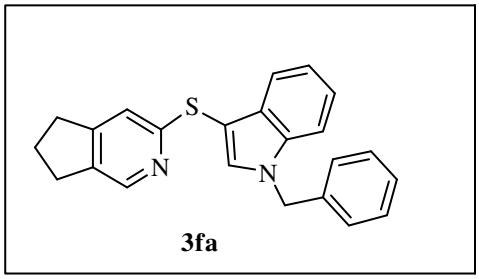




3ed

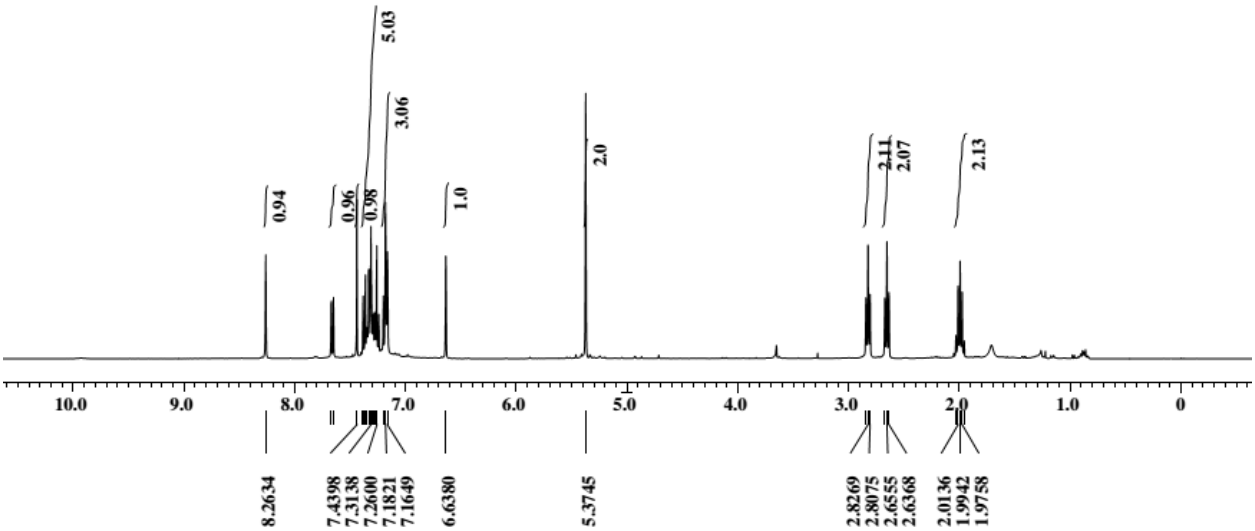
^{13}C NMR (100 MHz, $CDCl_3$)

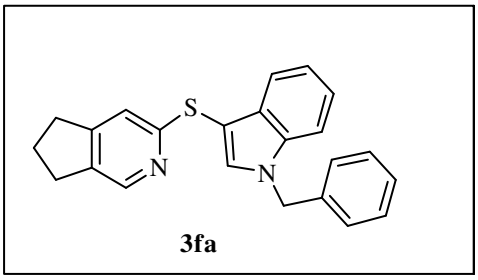




3fa

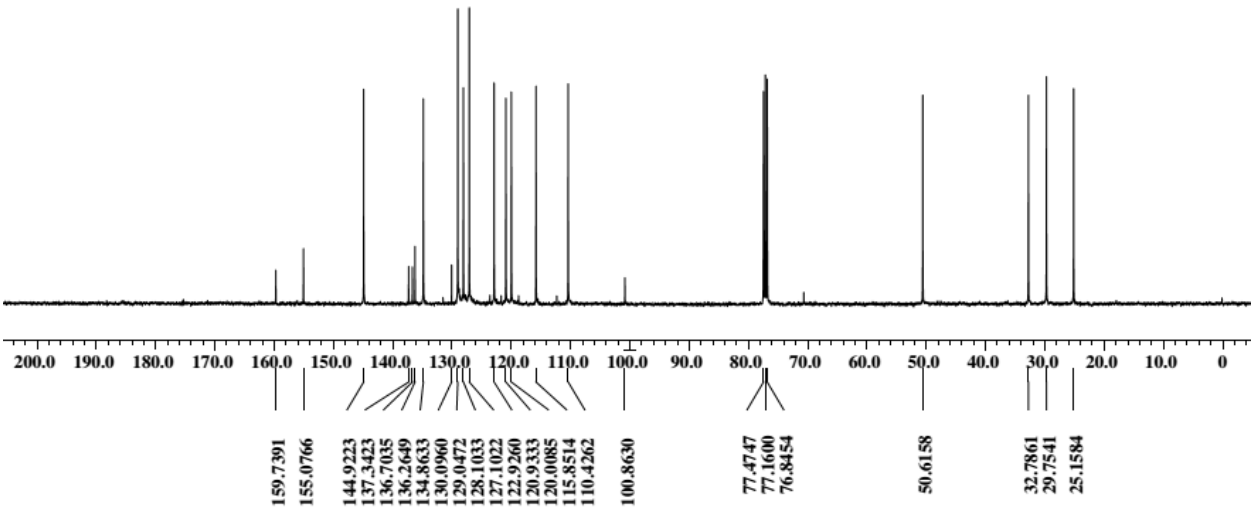
^{1}H NMR (400 MHz, $CDCl_3$)

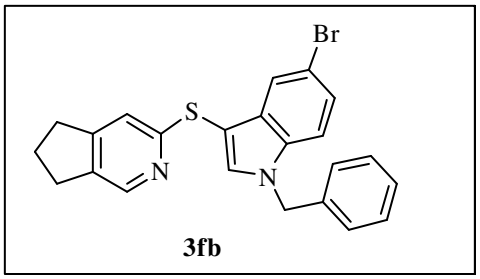




3fa

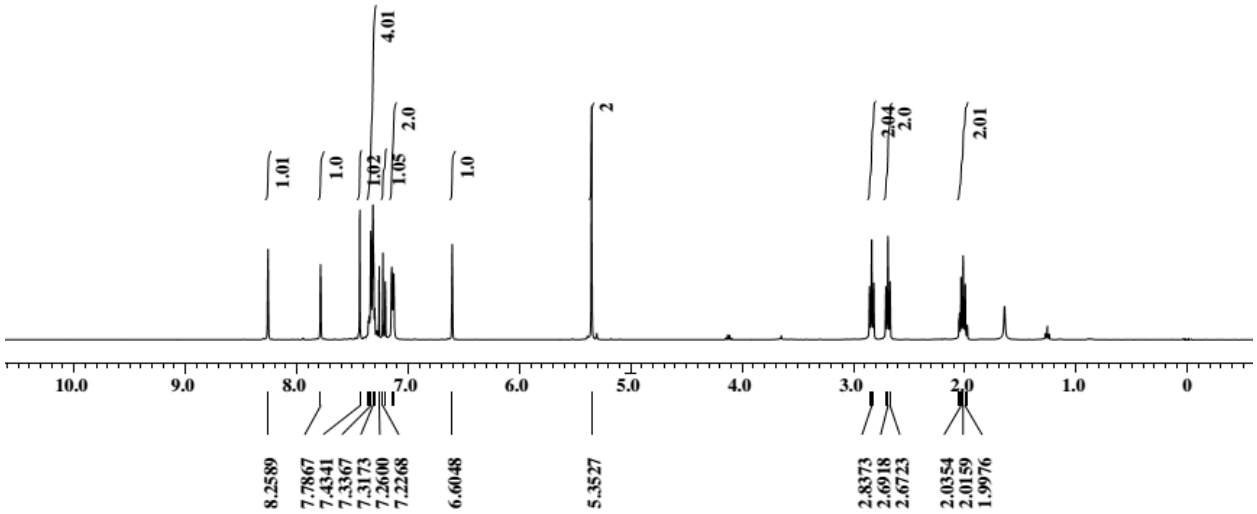
^{13}C NMR (100 MHz, $CDCl_3$)

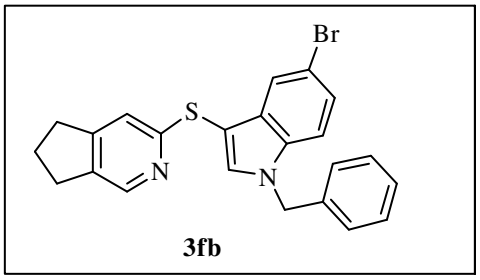




3fb

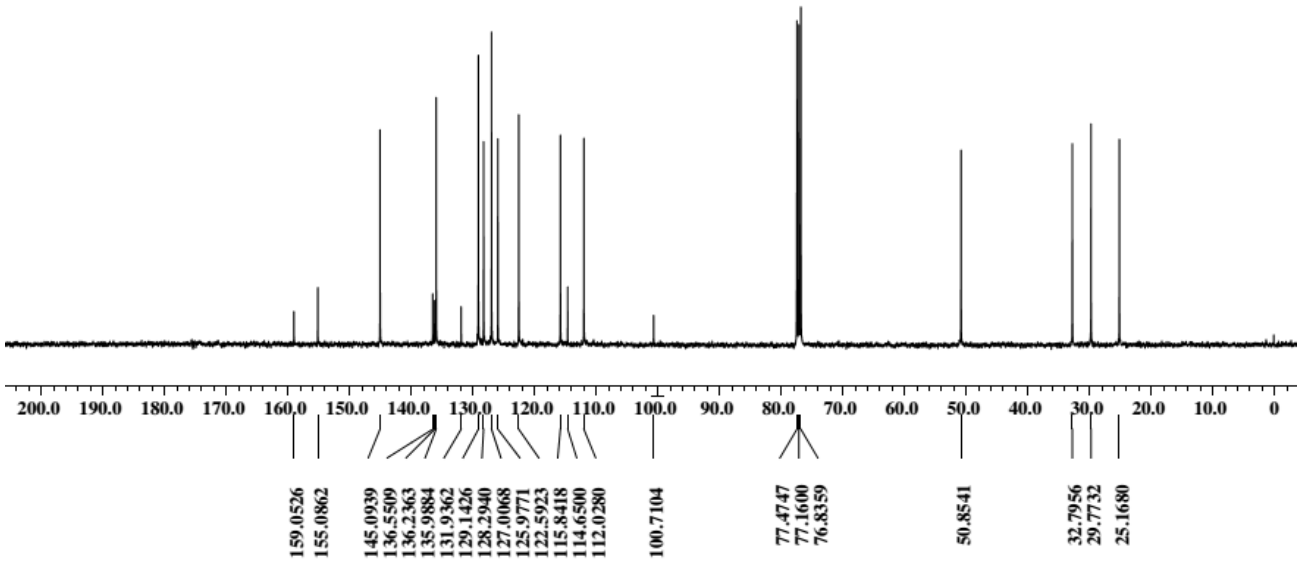
^{1}H NMR (400 MHz, $CDCl_3$)

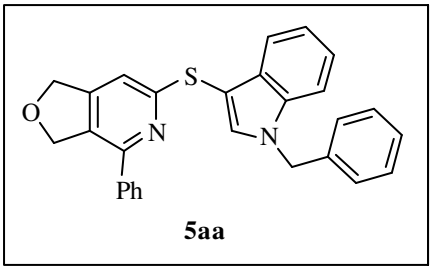




3fb

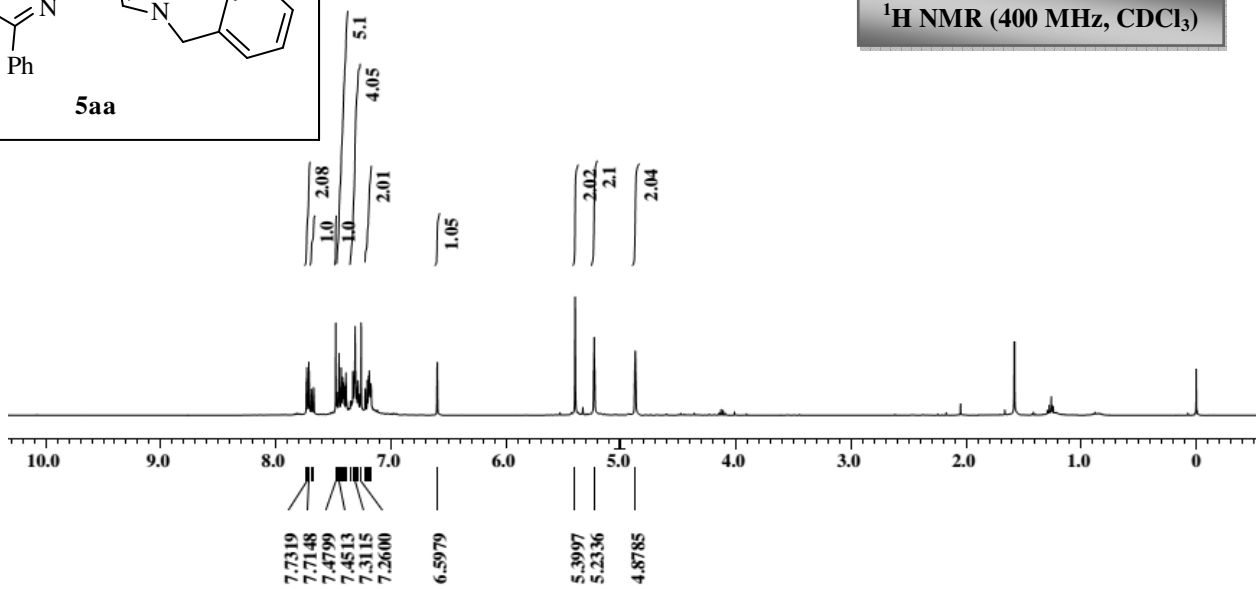
^{13}C NMR (100 MHz, $CDCl_3$)

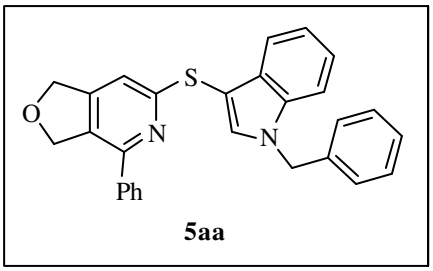




5aa

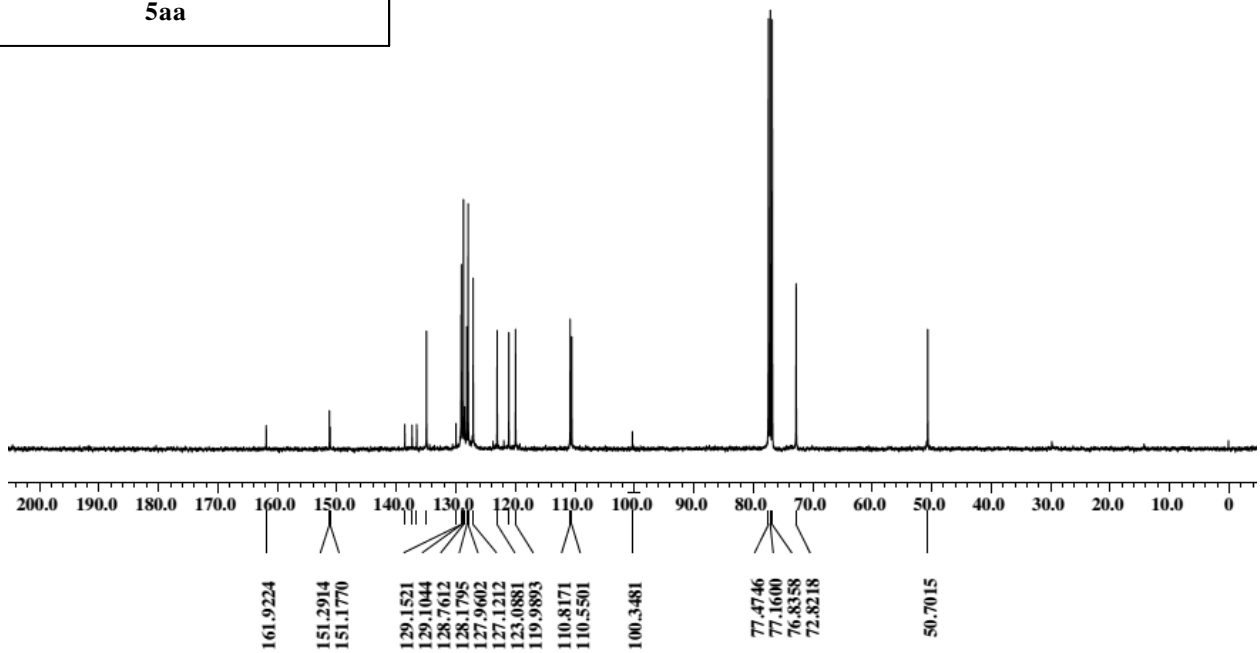
^{1}H NMR (400 MHz, $CDCl_3$)

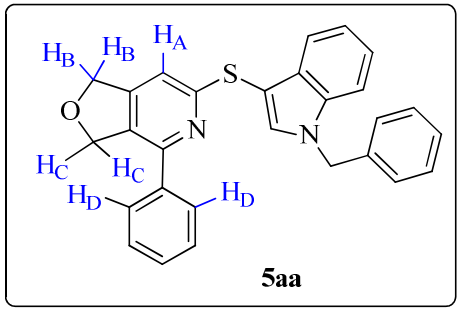




5aa

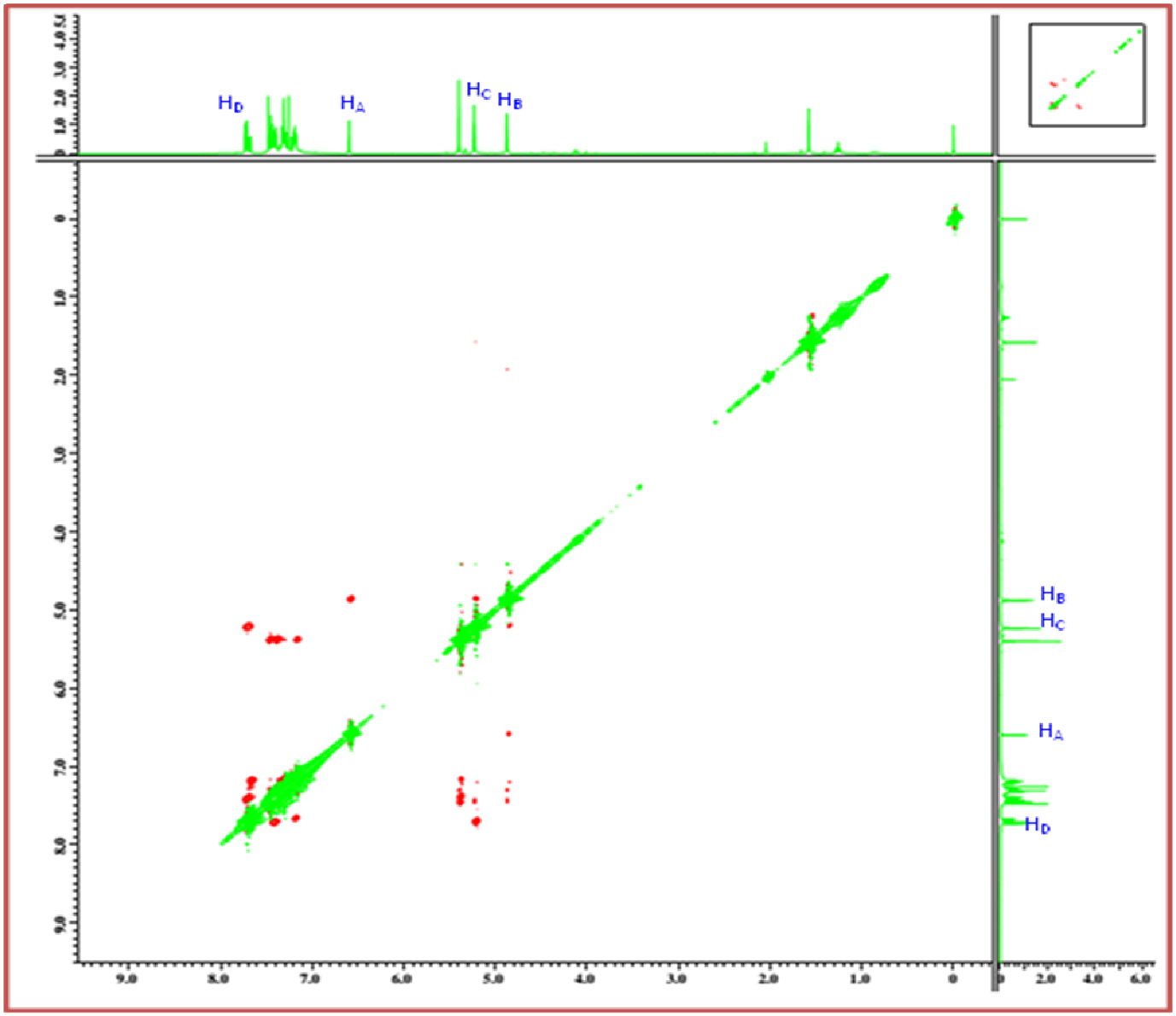
^{13}C NMR (100 MHz, $CDCl_3$)

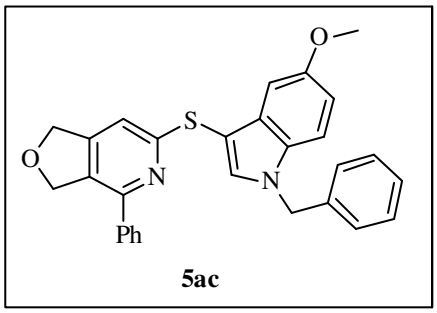




5aa

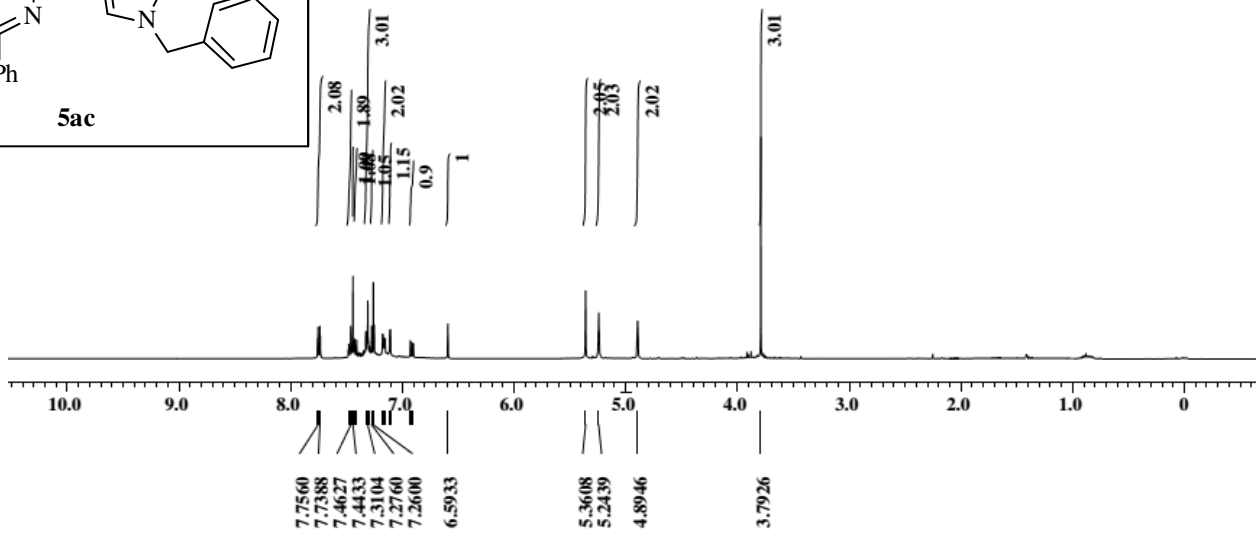
NOESY NMR (400 MHz, $CDCl_3$)

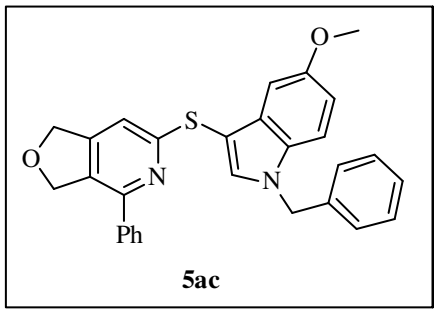




5ac

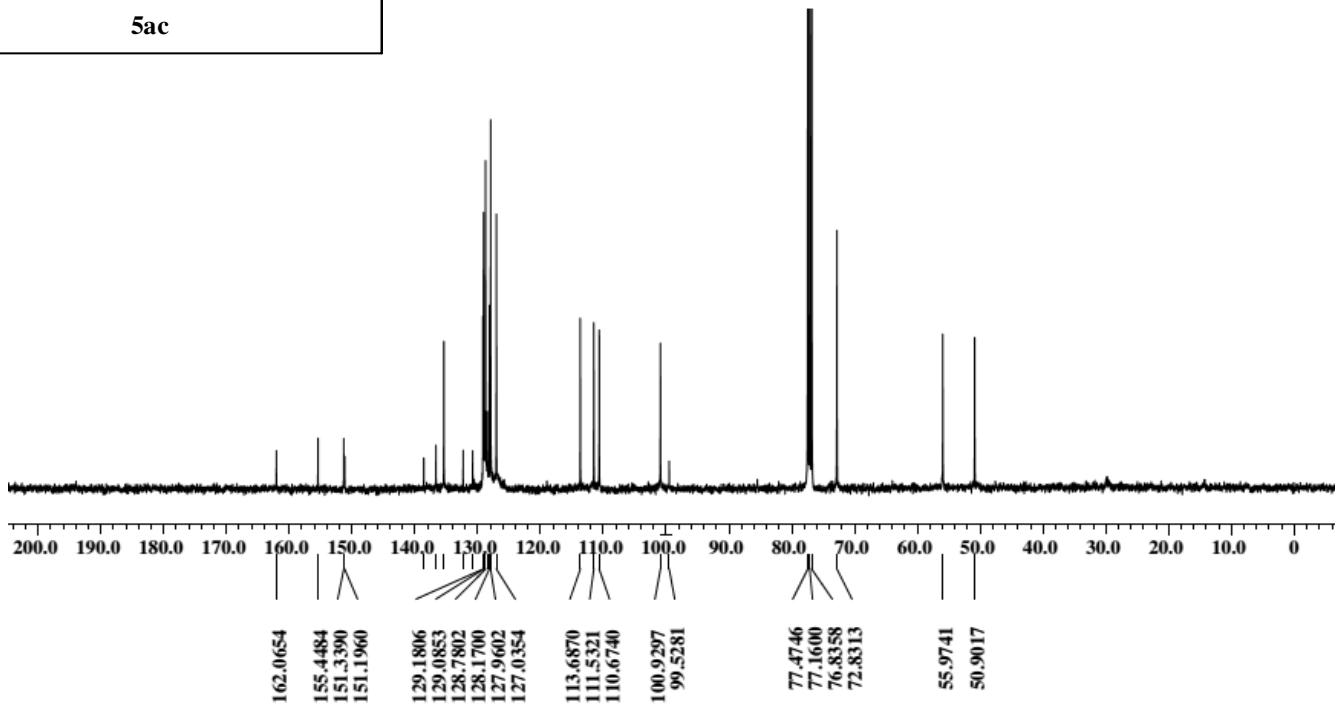
^{1}H NMR (400 MHz, $CDCl_3$)

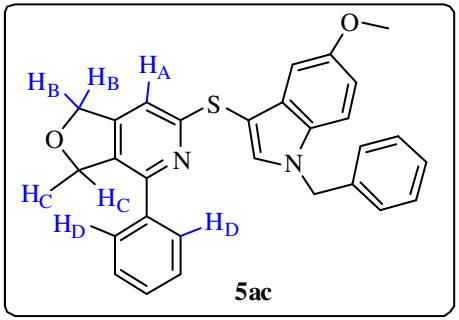




5ac

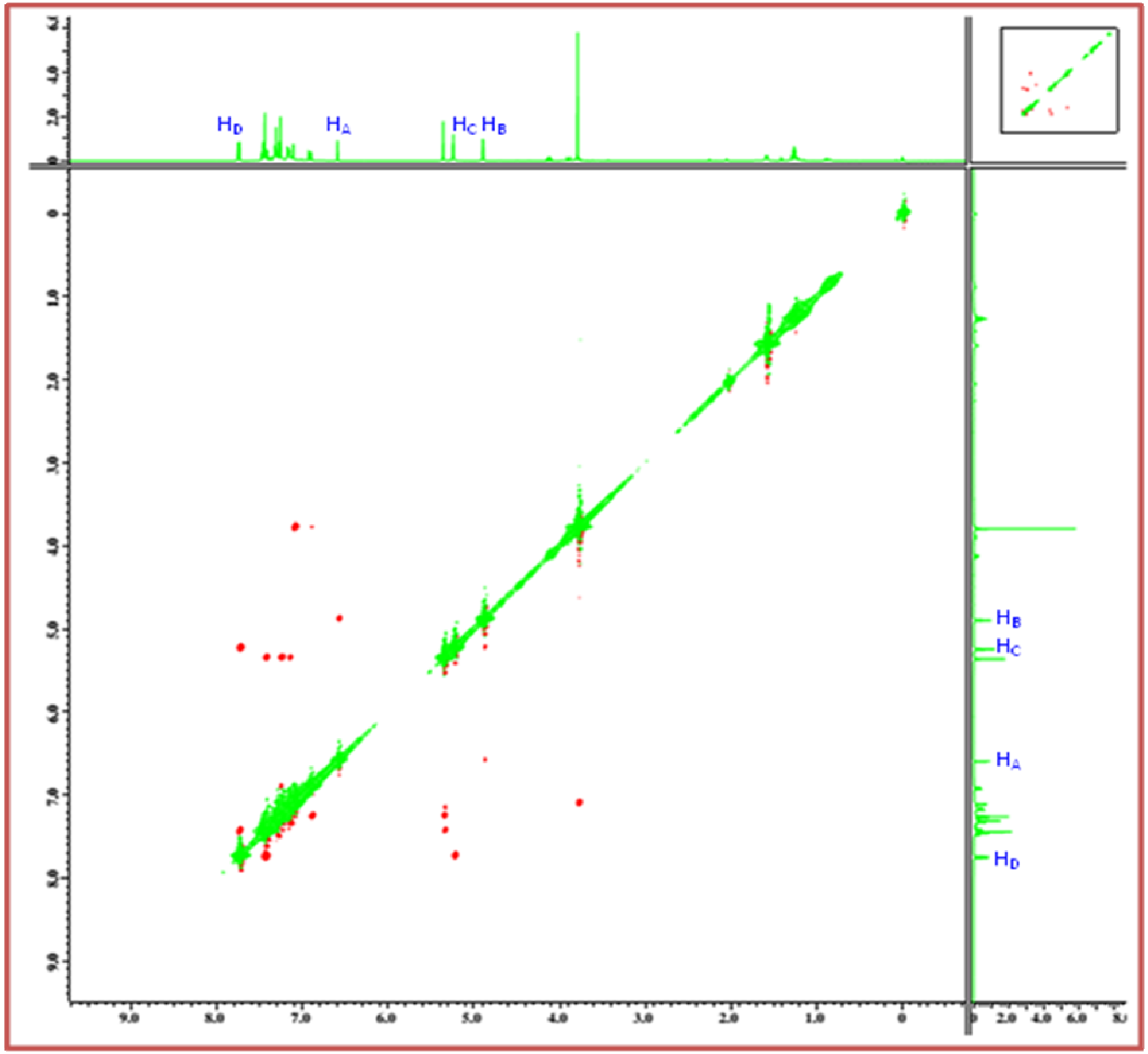
^{13}C NMR (100 MHz, $CDCl_3$)

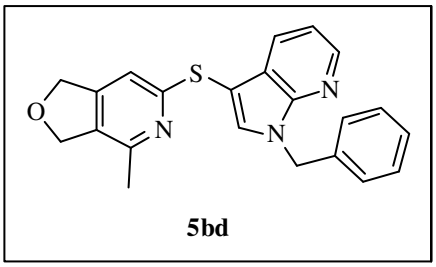




5ac

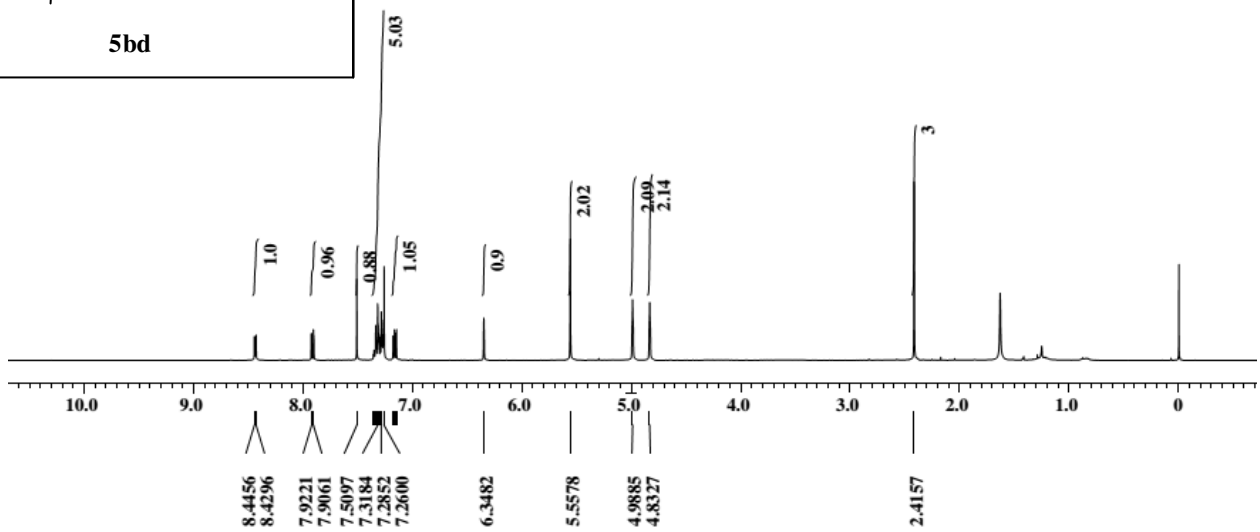
NOESY NMR (400 MHz, $CDCl_3$)

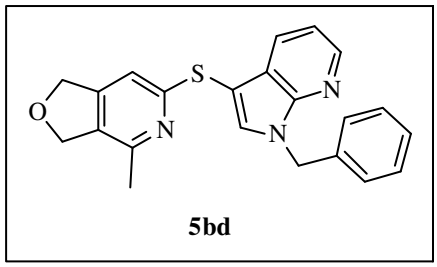




5bd

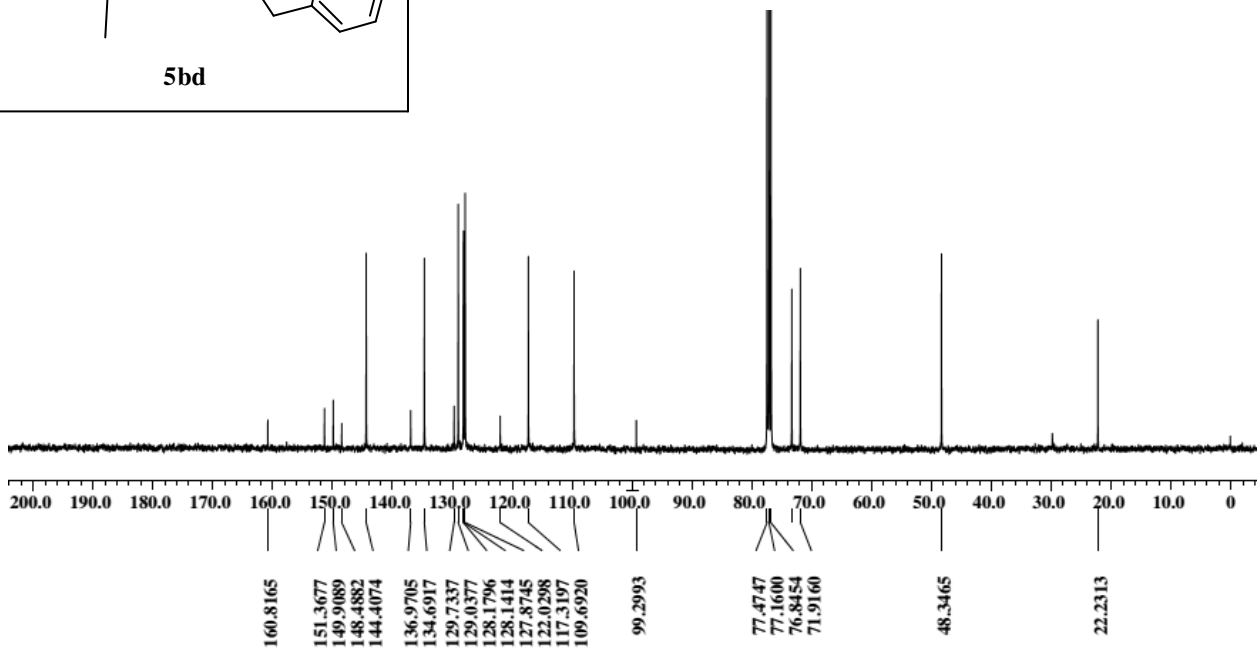
^{1}H NMR (400 MHz, $CDCl_3$)

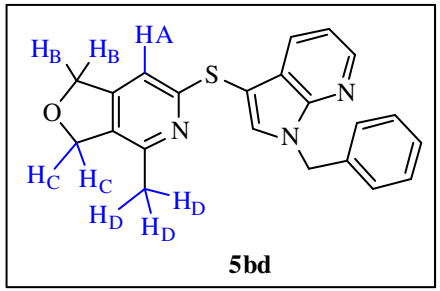




5bd

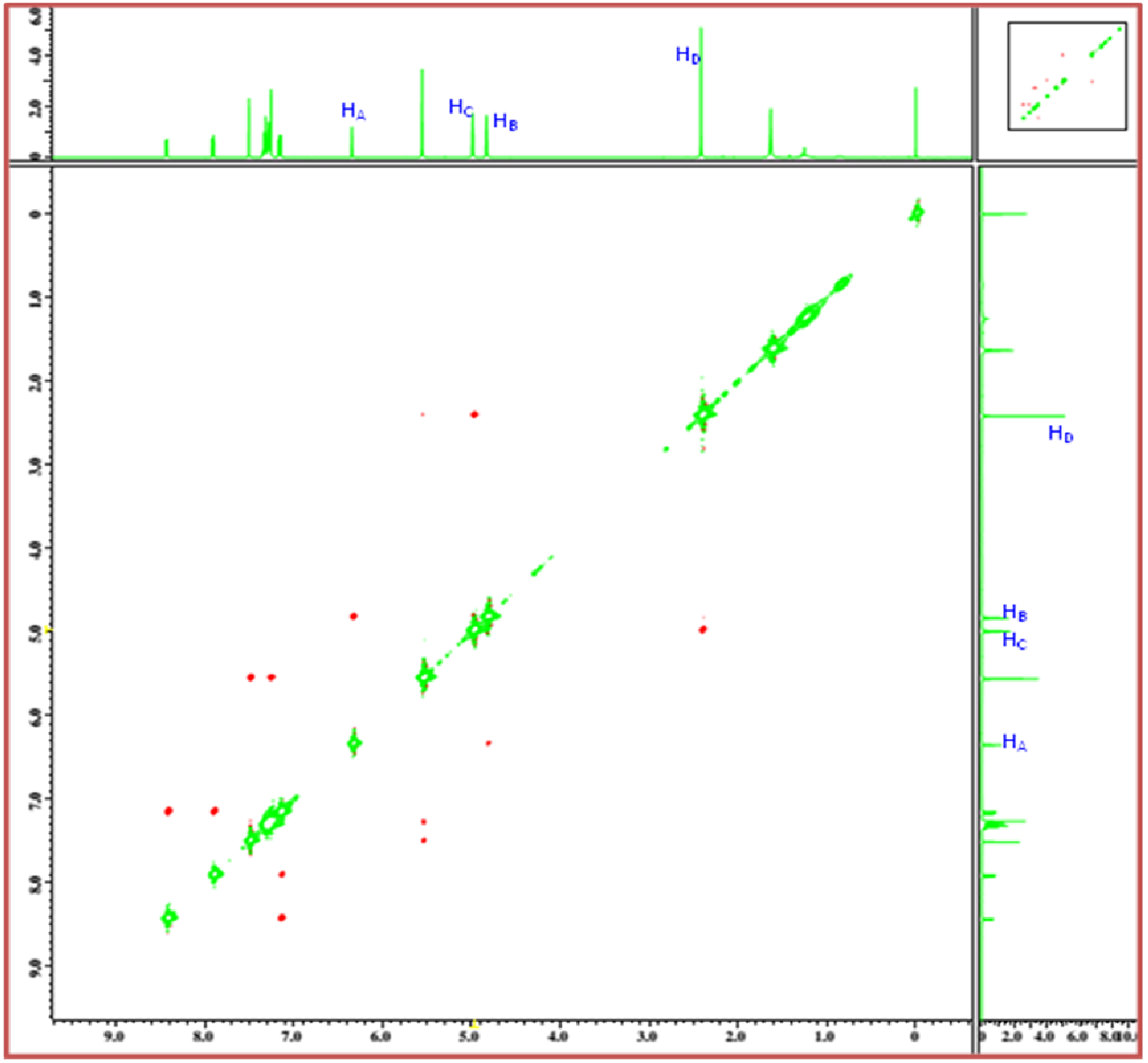
^{13}C NMR (100 MHz, $CDCl_3$)

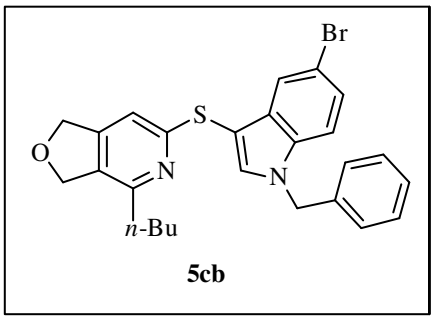




5bd

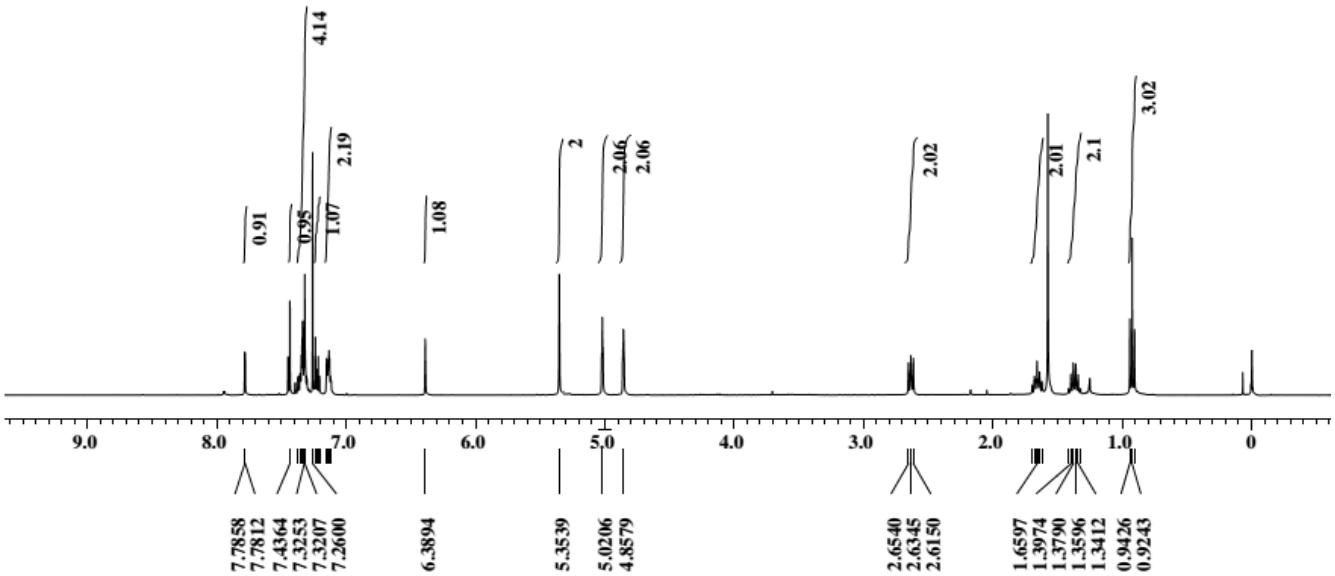
NOESY NMR (400 MHz, $CDCl_3$)

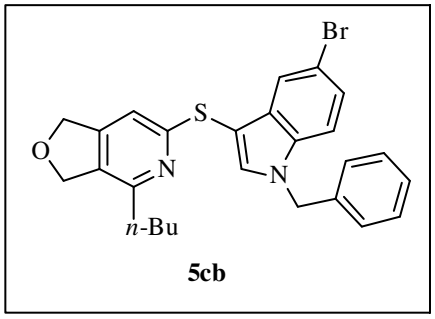




5cb

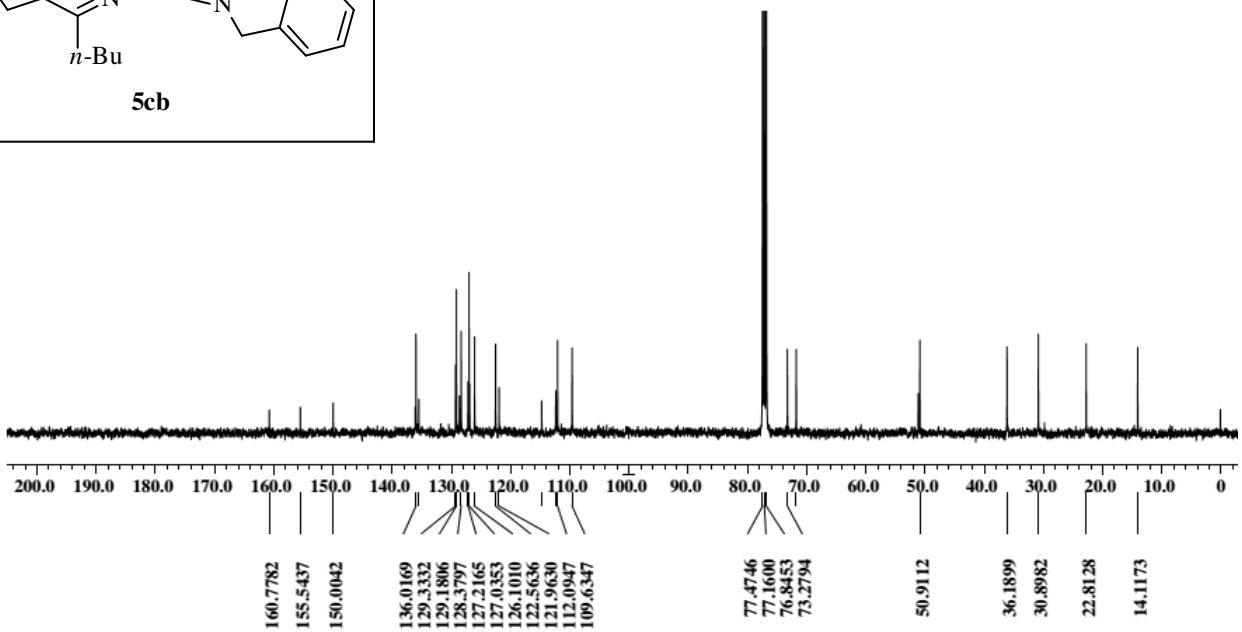
^{1}H NMR (400 MHz, $CDCl_3$)

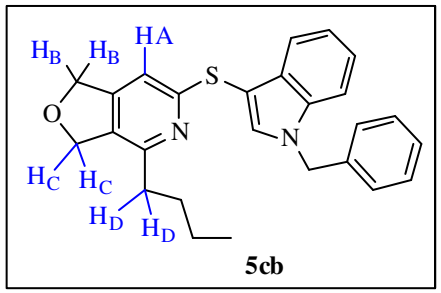




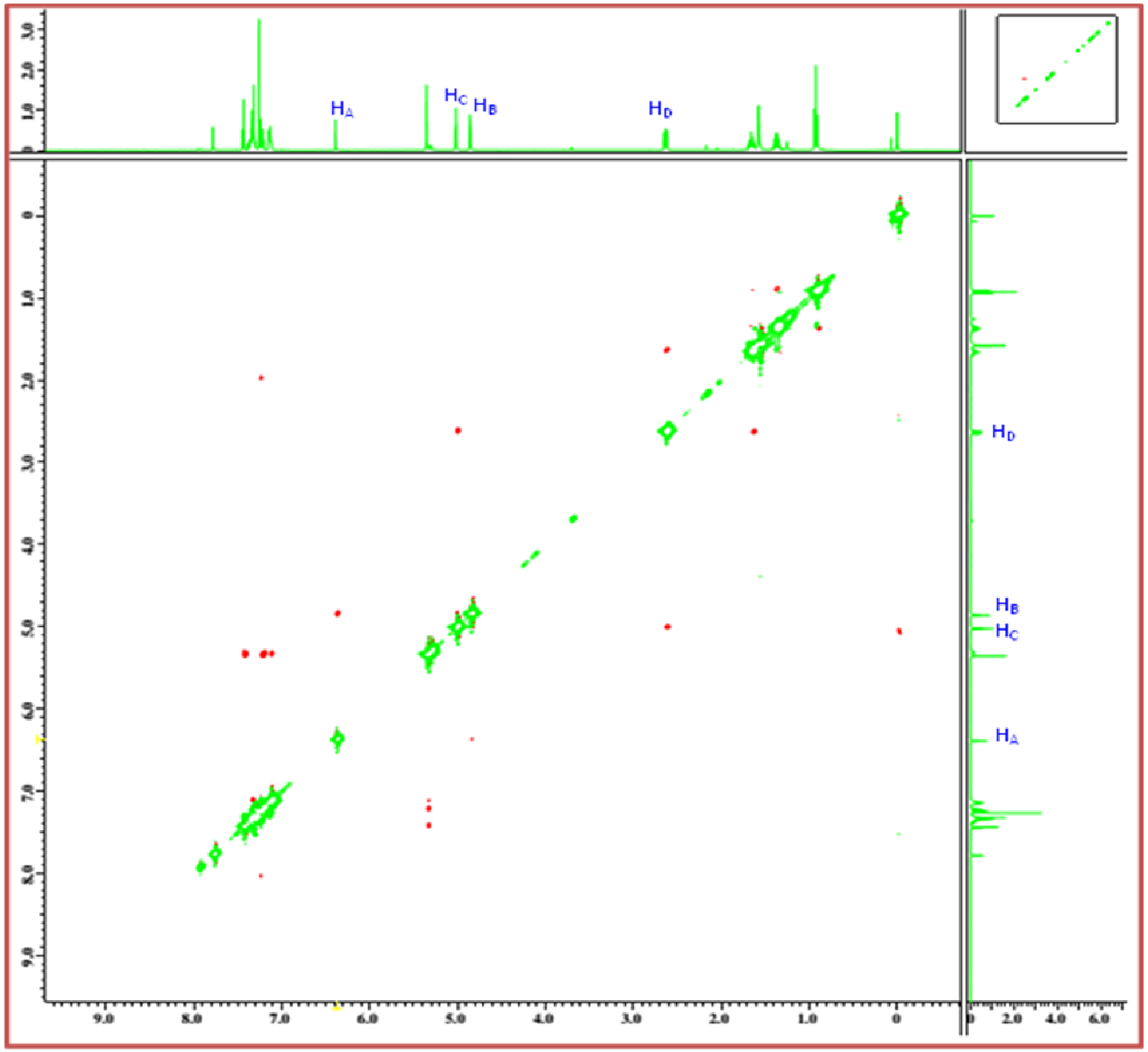
5cb

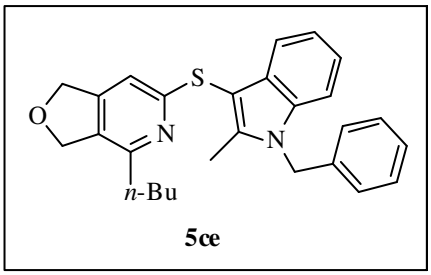
^{13}C NMR (100 MHz, $CDCl_3$)



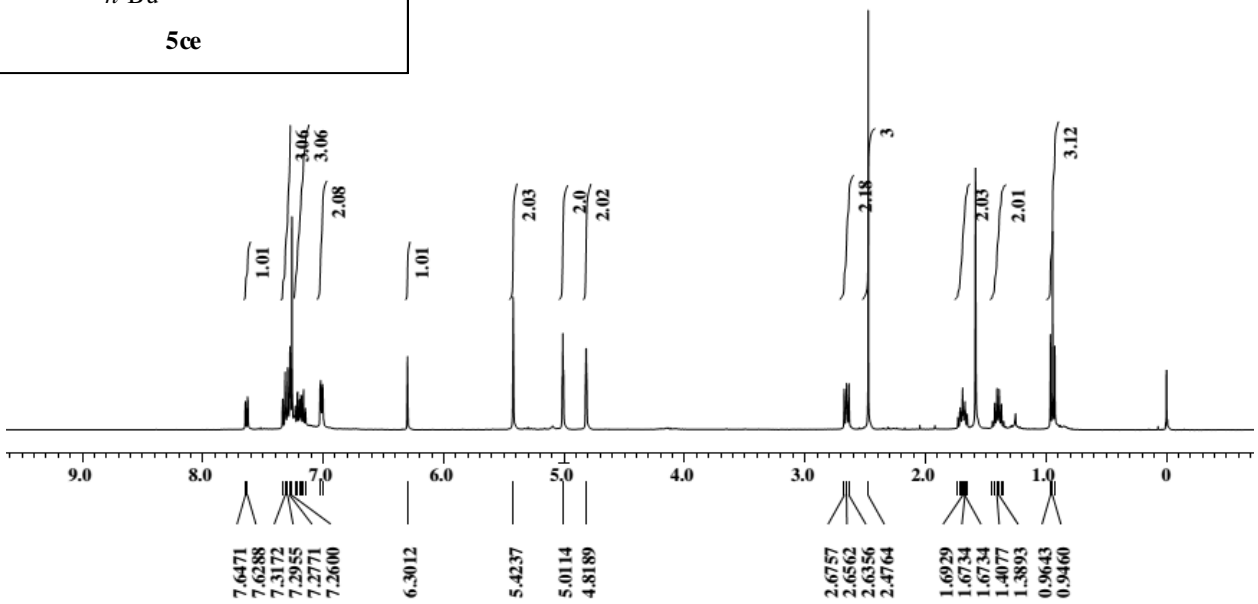


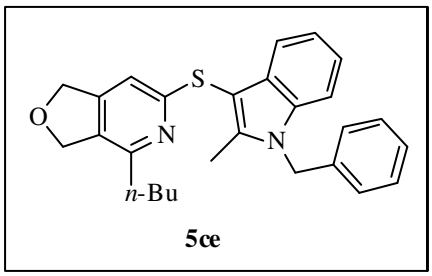
NOESY NMR (400 MHz, $CDCl_3$)





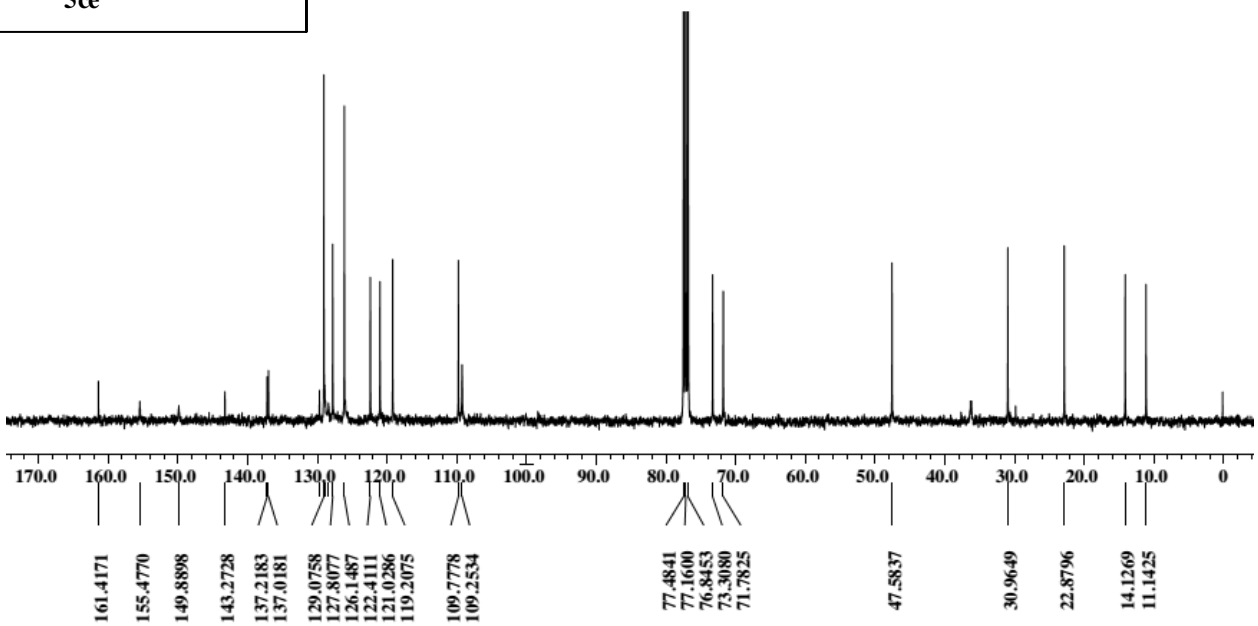
5ce

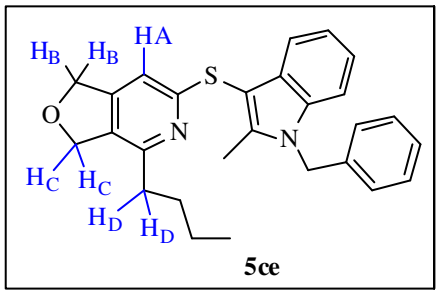




5ce

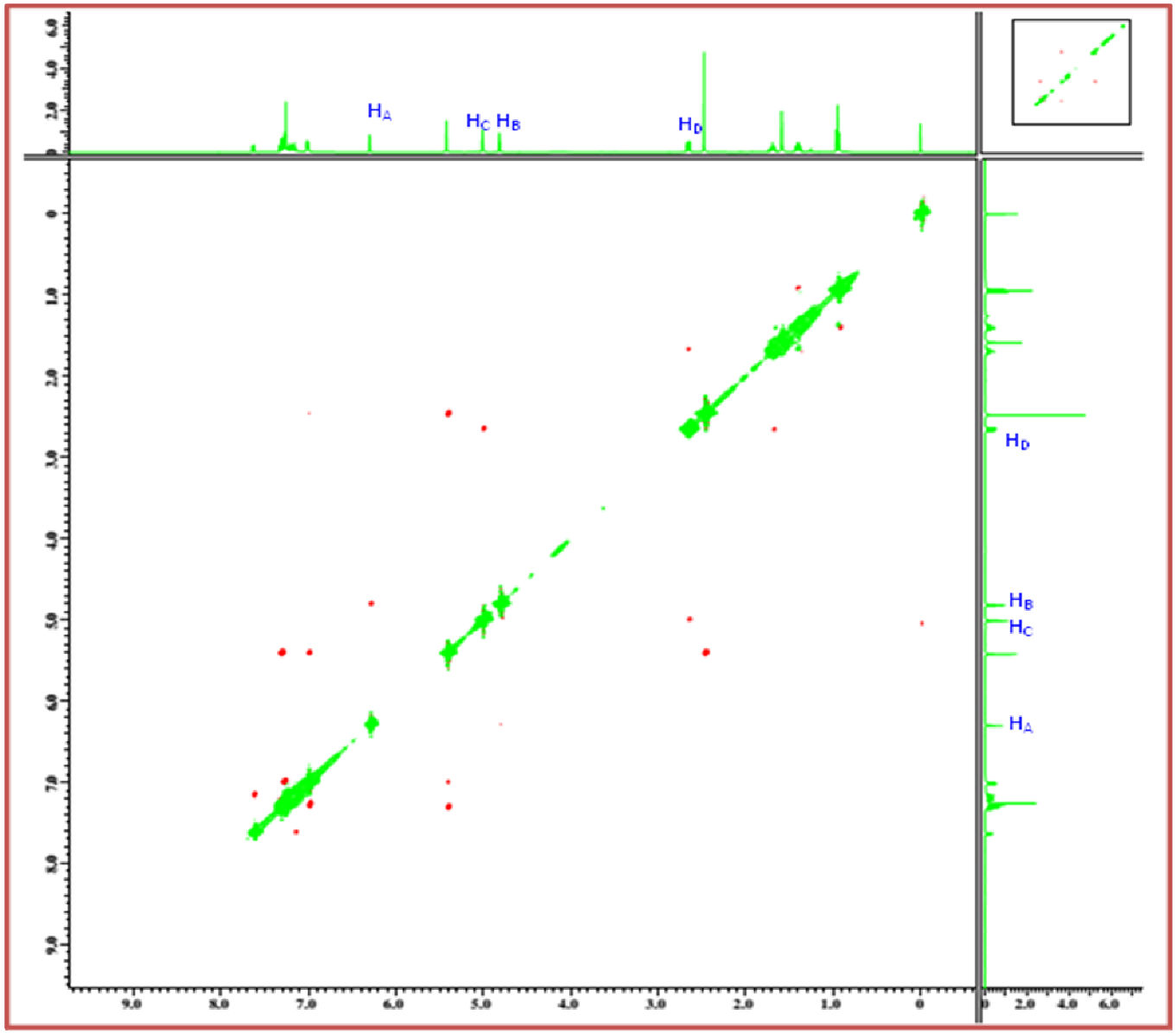
^{13}C NMR (100 MHz, $CDCl_3$)





5ce

NOESY NMR (400 MHz, $CDCl_3$)



3. X-Ray diffraction:

For the determination of X-ray crystal structures of **2c, 3ce, 3fa, 5aa** single crystals were selected and mounted with paratone oil on a glass fiber using gum. The data were collected at 293K on a CMOS based Bruker D8 Venture PHOTON 100 diffractometer equipped with a INCOATEC micro-focus source with graphite monochromated Mo Kα radiation (λ = 0.71073 Å) operating at 50 kV and 30 mA. For the integration of diffraction profiles SAINT program[1] was used. Adsorption correction was done applying SADABS program[2]. The crystal structure was solved by SIR 92[3] and refined by full matrix least square method using SHELXL-97[4] WinGX system, Ver 1.70.01[5]. All the non-hydrogen atoms in the structure were located from the Fourier map and refined anisotropically. The hydrogen atoms were fixed by HFIX in their ideal positions and refined using riding model with isotropic thermal parameters. The crystal structure has been deposited to Cambridge Crystallographic Data Centre and allotted deposition numbers are 1516419, 1516418, 1516417 and 1524672.

Crystal structure of 2c:

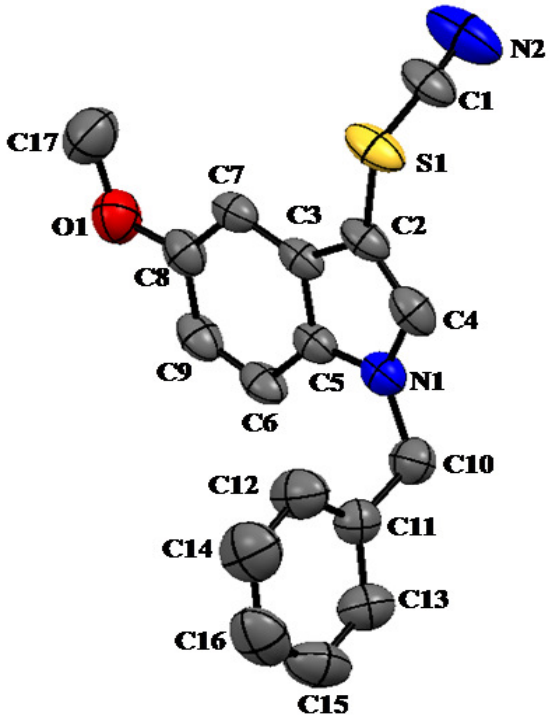


Table 1: Crystal data and structure refinement of 2c

CCDC number:	1516419	
Empirical formula:	C17H14N2OS	
Formula weight:	294.36	
Temperature:	293 (K)	
Wavelength:	0.71073Å	
Crystal System:	Monoclinic	
Space group:	P21/c	
Unit cell dimensions:	a = 10.825 (5) Å	α = 90
	b = 8.969 (5) Å	β = 101.245 (5)
	c = 15.960 (5) Å	γ = 90
Volume:	1519.8(12) $Å^3$	
Z	4	
Density (calculated):	1.286 g /cm^3	
Absorption coefficient	0.213mm^{-1}	
F (000)	616	
Crystal size	0.12 x 0.20 x 0.26 mm^3	
Theta range for data collection:	2.6 ^{o} to 28.4 ^{o}	
Index ranges:	-14 < = h < = 14, -11 < = k < = 11, -21 < = l < = 21	
Reflections collected:	63161	
Independent reflections:	3778 [R_{int} = 0.041]	
Completeness to theta = 28.4 ^{o}	99.7%	
Absorption correction:	MULTI-SCAN	
Min.and max. transmission:	0.694 and 0.746	
Refinement method:	Full-matrix-least-Squares on F^2	
Goodness of fit on F^2:	1.049	
Data [I>2σ (I)]:	2808	

R indices (all data):	$R = 0.0458$, $wR_2 = 0.1227$
Largest diff. peak and hole:	-0.29 and 0.18e.Å^{-3}

Table 2: Selected bond lengths [Å] of 2c

Atoms	Bond lengths [Å]
S1- C1	1.688(2)
S1- C2	1.7444(19)
O1 – C8	1.367(2)
O1- C17	1.417(3)
N1- C4	1.355(2)
N1- C5	1.382(2)
N2- C1	1.135(3)

Table 3: Selected bond angles [^{o}] of 2c

Atoms	Bond angles[^{o}]
C1 –S1-C2	102.23(9)
C8 –O1-C17	117.33(17)
C4-N1-C5	108.46(14)
C4-N1-C10	126.37(15)
C5-N1-C10	124.90(14)
S1-C2-C3	127.11(14)
S1-C2-C4	124.84(13)
N1-C4-C2	109.82(15)
N1-C5 -C3	108.50(13)
N1-C5-C6	129.96(15)
O1-C8-C7	124.89(16)
O1-C8-C9	114.07(15)
N1-C10-C11	113.90(14)

Table 4: Selected hydrogen bonding geometry [Å, °] for compound 2c

D–H···A	D···H	H···A	D···A	D–H···A
C9 - H9…S1	0.9300	2.8400	3.590(3)	139.00[i]
C2-H12…N1	0.9300	2.5300	2.859(3)	101.00

Symmetry code: i = x, 1+y, z

Crystal structure of 3ce:

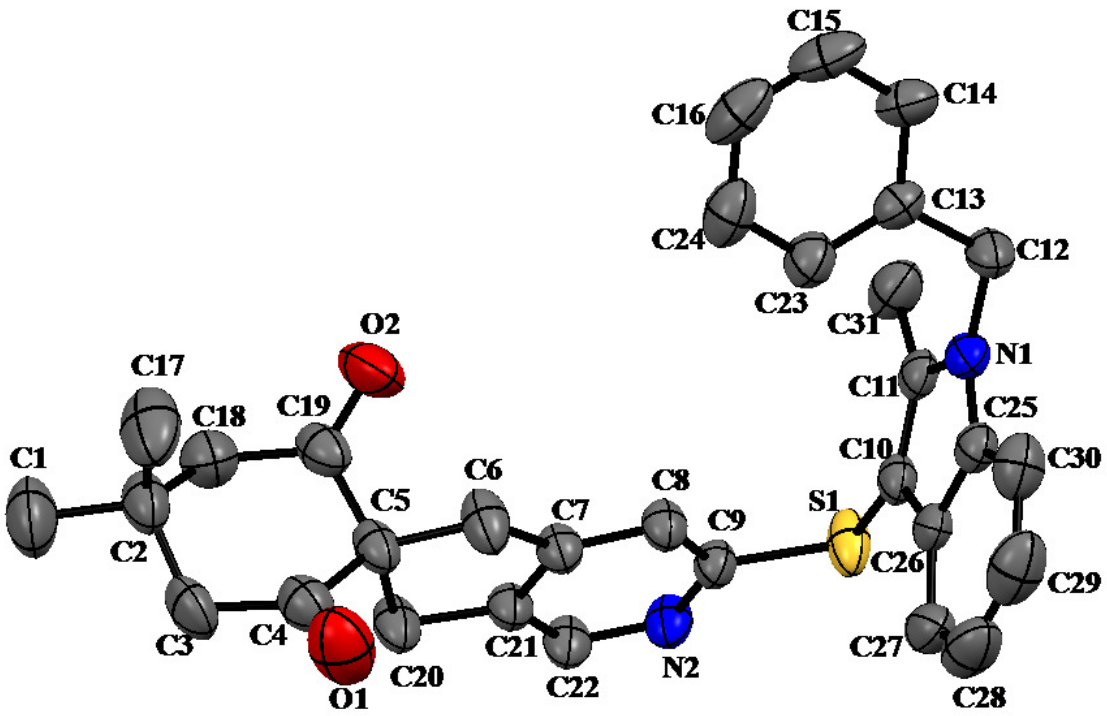


Table 1: Crystal data and structure refinement of 3ce

CCDC number:	1516418
Empirical formula:	C31H30N2O2S
Formula weight:	494.63

Temperature:	298 (K)	
Wavelength:	0.71073Å	
Crystal System:	Monoclinic	
Space group:	Pca21	
Unit cell dimensions:	a = 17.5208(9) Å	α = 90
	b = 12.0966(7) Å	β = 94.984(2)
	c = 12.4375(6) Å	γ = 90
Volume:	2626.1(2) $Å^3$	
Z	4	
Density (calculated):	1.251 g /cm^3	
Absorption coefficient	0.154 mm^{-1}	
F (000)	1048	
Crystal size	0.16 x 0.24 x 0.28 mm^3	
Theta range for data collection:	2.3 ^{o} to 28.4 ^{o}	
Index ranges:	-23 < = h < = 23, -16 < = k < = 16, -16 < = l < = 16	
Reflections collected:	56690	
Independent reflections:	6565 [R_{int} = 0.037]	
Completeness to theta = 28.363^o	99.9 %	
Absorption correction:	MULTI-SCAN	
Max. and min. transmission:	0.746 and 0.685	
Refinement method:	Full-matrix-least-Squares on F^2	
Goodness of fit on F^2:	1.049	
Data [I>2σ (I)]:	4893	
R indices (all data):	R = 0.0533, wR_2 = 0.1400	
Largest diff. peak and hole:	-0.41 and 0.34 e.$Å^{-3}$	

Table 2: Selected bond lengths [Å] of 3ce

Atoms	Bond lengths [Å]
S1-C9	1.7703(17)
S1-C10	1.7425(17)
O1-C4	1.207(3)
O2-C19	1.205(3)
N1-C11	1.375(2)
N1-C12	1.454(2)
N1-C25	1.379(2)
N2-C9	1.473(8)
N2-C22	1.332(2)

Table 3: Selected bond angles [^{o}] of 3ce

Atoms	Bond angles[^{o}]	Atoms	Bond angles[^{o}]
C9 –S1-C10	104.41(8)	N1 -C11 -C31	121.90(16)
C11–N1-C12	125.33(16)	N1 -C12 -C13	113.42(14)
C11-N1-C25	109.60(14)	O2 -C19 -C5	120.83(19)
C12-N1-C25	124.28(16)	O2 -C19 -C18	122.0(2)
C9-N2-C22	117.67(14)	N2 -C22 -C21	122.64(16)
O1-C4-C3	122.3(2)	N1 -C25 -C26	107.52(15)
O1-C4-C5	121.1(2)	N1 -C25 -C30	130.18(17)
S1-C9-N2	111.58(12)		
S1-C9 –C8	124.26(13)		
N2-C9-C8	124.15(15)		
S1-C10-C11	125.39(14)		
S1-C10-C26	126.46(13)		
N1-C11-C10	108.44(16)		

Table 4: Selected hydrogen bonding geometry [Å, °] for compound 3ce

D–H···A	D···H	H···A	D···A	D–H···A
C15 - H14…N2	0.9300	2.6100	3.447(3)	151.00[i]
C23-H16…N1	0.9300	2.5200	2.856(2)	102.00
C6 – H25…O2	0.9700	2.3900	2.754(3)	102.00
C6 - H26… O1	0.9700	2.3600	2.807(3)	107.00

Symmetry code: i = x, y, 1+z

Crystal structure of 3fa:

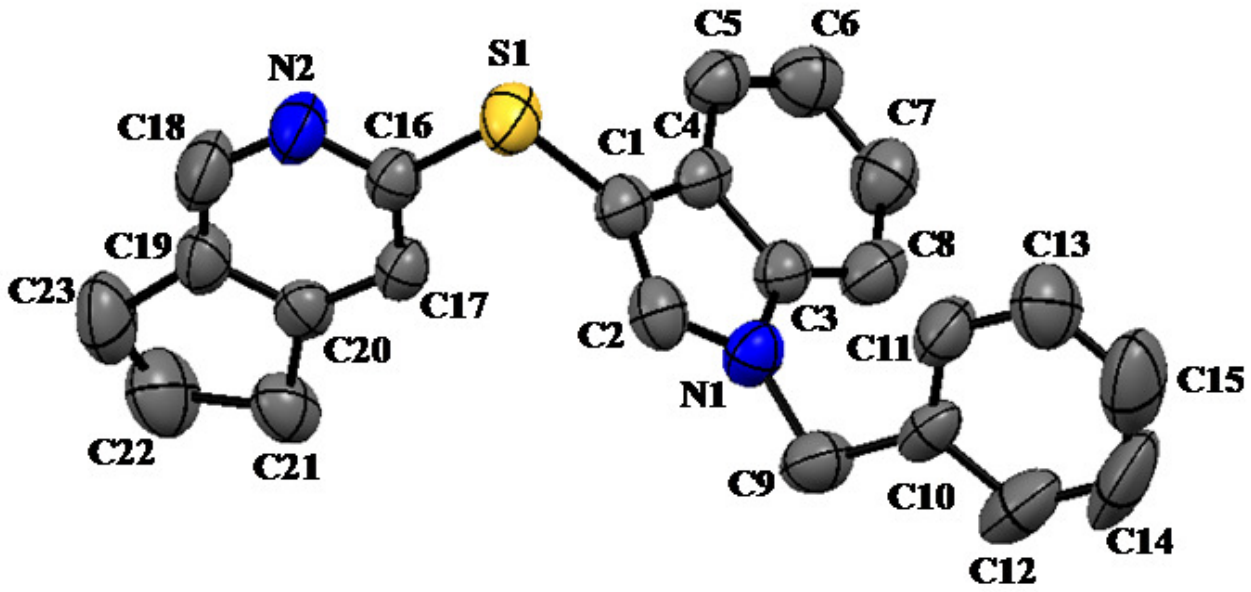


Table 1: Crystal data and structure refinement of 3fa

CCDC number:	1516417
Empirical formula:	C23H20N2S
Formula weight:	356.47
Temperature:	298 (K)

Wavelength:	0.71073Å	
Crystal System:	Monoclinic	
Space group:	P21/n	
Unit cell dimensions:	a = 14.207(5) Å	α = 90
	b = 5.497(5) Å	β = 106.065(5)
	c = 24.708(5) Å	γ = 90
Volume:	1854.2(18) $Å^3$	
Z	4	
Density (calculated):	1.277 g /cm^3	
Absorption coefficient	0.183 mm^{-1}	
F (000)	752	
Crystal size	0.14 x 0.24 x 0.28 mm^3	
Theta range for data collection:	2.6 ^{o} to 28.4 ^{o}	
Index ranges:	-18 < = h < = 18, -7 < = k < = 7, -33 < = l < = 33	
Reflections collected:	35666	
Independent reflections:	4793 [R_{int} = 0.173]	
Completeness to theta = 28.363^o	98.7 %	
Absorption correction:	MULTI-SCAN	
Max. and min. transmission:	0.746 and 0.685	
Refinement method:	Full-matrix-least-Squares on F^2	
Goodness of fit on F^2:	0.984	
Data [I>2σ (I)]:	1736	
R indices (all data):	R = 0.0690, wR_2 = 0.1534	
Largest diff. peak and hole:	-0.19 and 0.17 e.$Å^{-3}$	

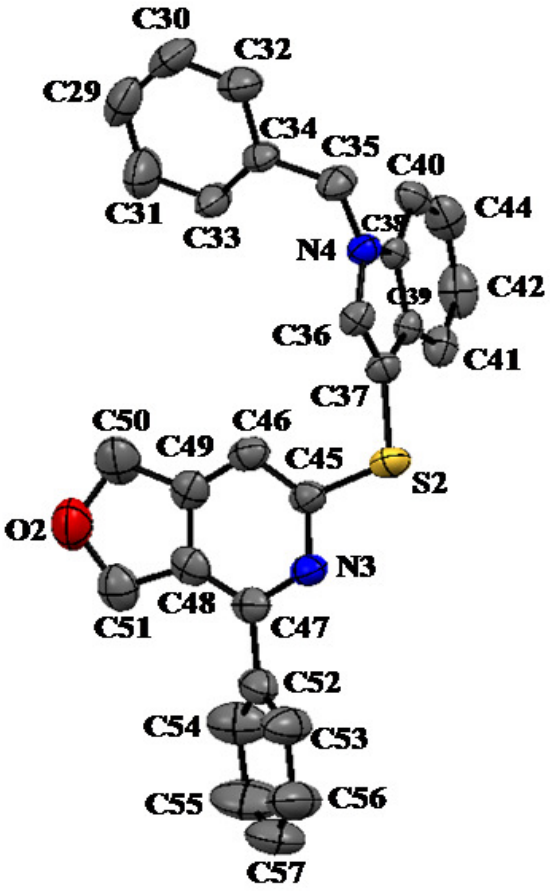
Table 2: Selected bond lengths [Å] of 3fa

Atoms	Bond lengths [Å]
S1-C1	1.748(3)
S1-C16	1.777(3)
N1-C2	1.366(4)
N1-C3	1.373(4)
N1-C9	1.466(4)
N2-C16	1.329(4)
N2-C18	1.348(5)

Table 3: Selected bond angles [^{o}] of 3fa

Atoms	Bond angles[^{o}]
C1 –S1-C16	104.22(13)
C2–N1-C3	108.8(2)
C2-N1-C9	125.3(2)
C3-N1-C9	125.8(3)
C16-N2-C18	115.7(3)
S1-C1-C2	125.9(2)
S1-C1-C4	127.3(2)
N1-C2 –C1	110.1(3)
N1-C3-C4	107.7(3)
N1-C3-C8	130.2(3)
N1-C9-C10	112.2(3)
S1 -C16 –N2	121.90(16)
S1 -C16 -C17	113.42(14)
N2 -C16 –C17	120.83(19)

Crystal structure of 5aa:



CCDC number:	1524672	
Empirical formula:	C28H22 N2OS	
Formula weight:	434.53	
Temperature:	298 (K)	
Wavelength:	0.71073Å	
Crystal System:	Triclinic	
Space group:	P-1	
Unit cell dimensions:	a = 10.1014(7) Å	α = 80.723(3)
	b = 11.8755(8) Å	β = 80.515(4)

	c = 19.3441(14) Å γ = 89.777(4)
Volume:	2258.2(3) (18) $Å^3$
Z	4
Density (calculated):	1.278 g /cm^3
Absorption coefficient	0.166 mm^{-1}
F (000)	912
Crystal size	0.20 x 0.24 x 0.32 mm^3
Theta range for data collection:	2.2 ^{o} to 28.4 ^{o}
Index ranges:	-13 < = h < = 13, -15 < = k < = 15, -25 < = l < = 25
Reflections collected:	56592
Independent reflections:	11246 [R_{int} = 0.145]
Completeness to theta = 28.363^o	98.7 %
Absorption correction:	MULTI-SCAN
Max. and min. transmission:	0.746 and 0.576
Refinement method:	Full-matrix-least-Squares on F^2
Goodness of fit on F^2:	1.083
Data [I>2σ (I)]:	5322
R indices (all data):	R = 0.0533, wR_2 = 0.1400
Largest diff. peak and hole:	-0.25 and 0.43 e.$Å^{-3}$

Table 2: Selected bond lengths [Å] of 5aa

Atoms	Bond lengths [Å]	Atoms	Bond lengths [Å]
S1-C1	1.745(4)	O2-C51	1.413(8)
S1-C16	1.773(5)	N1-C7	1.453(6)
S2-C37	1.743(4)	N1-C8	1.356(5)
S2-C45	1.771(4)	N1-C11	1.379(5)
O1-C21	1.434(7)	N2 -C16	1.332(6)

O1-C22	1.411(8)	N2-C20	1.346(6)
O2-C50	1.411(7)	N3-C45	1.340(6)
N3-C47	1.348(5)	N4-C36	1.353(5)
N4-C35	1.459(6)	N4-C38	1.364(5)

Table 3: Selected bond angles [^{o}] of 5aa

Atoms	Bond angles[^{o}]	Atoms	Bond angles[^{o}]
C9-S1-C16	103.7(2)	C35-N4-C36	125.7(4)
C37-S2-C45	103.6(2)	N1-C7-C6	113.2(4)
C21-O1-C22	110.0(4)	N1-C8-C9	110.4(3)
C50-O2-C51	111.0(4)	S1-C9-C8	126.4(3)
C8-N1-C11	108.4(3)	S1-C9-C10	126.6(3)
C7-N1-C8	125.9(4)	N1-C11-C10	108.3(3)
C7-N1-C11	125.5(4)	N1-C11-C12	130.2(4)
C16-N2-C20	119.9(4)	N2-C16-C17	123.4(4)
C45-N3-C47	119.9(4)	S1-C16-N2	112.1(3)
C35-N4-C38	125.4(4)	S1-C16-C17	124.4(4)
C36-N4-C38	108.7(3)	N2-C20-C23	116.2(4)
O1-C21-C19	105.5(4)	N2-C20-C19	120.2(4)
O1-C21-C18	104.7(4)	S2-C45-C46	124.8(3)
N4-C35-C34	112.6(4)	N3-C45-C46	123.1(4)
N4-C36-C37	110.3(3)	N3-C47-C48	120.1(4)
S2-C37-C36	126.4(3)	N3-C47-C52	115.6(4)
S2-C37-C39	127.0(3)	O2-C50-C49	104.7(4)
N4-C38-C39	108.2(3)	O2-C51-C48	104.4(4)
N4-C38-C40	130.4(4)		
S2-C45-N3	112.0(3)		

Table 4: Selected hydrogen bonding geometry [Å, °] for compound 5aa

D–H···A	D···H	H···A	D···A	D–H···A
C5-H5... N1	0.9300	2.5200	2.849(6)	101.00
C8-H8... N3	0.9300	2.4900	3.402(5)	168.00
C33-H33... N4	0.9300	2.5600	2.889(6)	101.00
C36-H36...N2	0.9300	2.5700	3.489(5)	170.00
C51-H51A …O1	0.9700	2.5500	3.452(7)	155.00

Symmetry code: i = -1+x, y, z, ii = 1-x, 1-y, 1-z

References:

(1) Bruker, SAINT V7.68A, Bruker AXS Inc., Madison (WI, USA), 2005.

(2) Sheldrick, G. M. SADABS 2008/2, Göttingen, 2008.

(3) A. Altomare, G. Cascarano, C. Giacovazzo, A. Guagliardi, *J. Appl. Cryst.* 1993, **26**, 343.

(4) Sheldrick, G. M. SHELXL-97, Program for Crystal Structure Solution and Refinement; University of Göttingen, Göttingen, Germany, 1997.

(5) L. Farrugia, WinGX-A Windows Program for Crystal Structure Analysis, *J. Appl. Cryst.* 1999, **32**, 837.