Pd-Catalyzed Double C–H Bond Activations of Diaryl Ketones for the Synthesis of Fluorenones

*Parthasarathy Gandeepan, Chen-Hsun Hung and Chien-Hong Cheng**

Department of Chemistry, National Tsing Hua University, Hsinchu 30013, Taiwan.

chcheng@mx.nthu.edu.tw

Supporting Information

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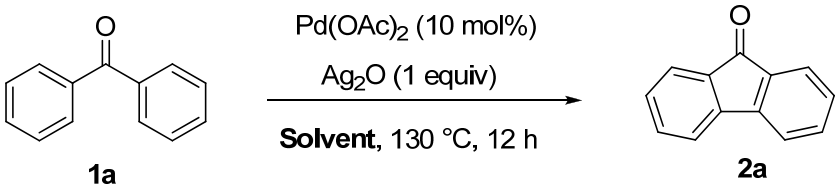
General. All reactions were conducted under nitrogen atmosphere on a dual-manifold Schlenk line unless otherwise mentioned and in oven-dried glass wares. All solvents were dried according to known methods and distilled prior to use.[1] Other reagents were commercially available and used as purchased.

Table 1. Solvent Optimization for the Synthesis of Fluorenone by Pd-Catalysed Intramolecular Oxidative Cyclization[a]

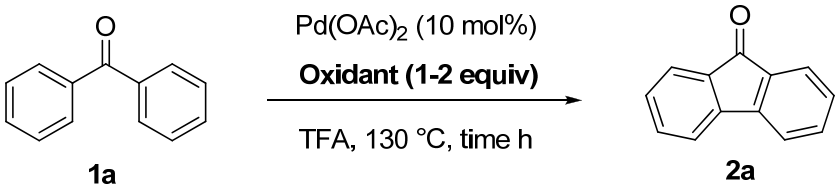


Entry	Oxidant/equiv	Solvent	Temperature	Time	Yield (%)[b]
1	Ag_2O/1	AcOH	130	12	15
2	Ag_2O/1	TFA	130	12	60
3	Ag_2O/1	PivOH	130	12	34
4	Ag_2O/1	DCE	130	12	-
5	Ag_2O/1	toluene	130	12	-
6	Ag_2O/1	dioxane	130	12	-
7	Ag_2O/1	butanol	130	12	-
8	Ag_2O/1	DMF	130	12	-
9	Ag_2O/1	DMSO	130	12	-

[a]All reactions were carried out using benzophenone **1a** (1.0 mmol), $Pd(OAc)_2$ (10 mol %), Ag_2O (1 equiv) and solvent (2.0 mL) at 130 ºC for 12 h.

[b]Yields were measured by ^1H NMR using mesitylene as an internal standard.

Table 2. Oxidant Optimization for the Synthesis of Fluorenone by Pd-Catalysed Intramolecular Oxidative Cyclization[a]



1a 2a

Entry	Oxidant/equiv	Solvent	Temperature	Time/h	Yield (%)[b]
1	$K_2S_2O_8$	TFA	130	12	-
2	Oxone	TFA	130	12	-
3	$Cu(OAc)_2$	TFA	130	12	-
4	O_2	TFA	130	12	-
5	BQ	TFA	130	12	-
6	Ag_2O/1	TFA	130	24	85
7	AgOAc/2	TFA	130	24	70
8	Ag_2CO_3/1	TFA	130	24	74
9	Ag_2O/2	TFA	130	24	96
10	Ag_2O/1.5	TFA	130	24	93
11	-	TFA	130	24	trace
12	Ag_2O/1.5	TFA	130	24	-[c]
13	Ag_2O/1.5	TFA	120	24	81

[a]All reactions were carried out using benzophenone **1a** (1.0 mmol), $Pd(OAc)_2$ (10 mol %), Oxidant (1-2 equiv) and TFA (2.0 mL) at 130 ºC for 12 h.

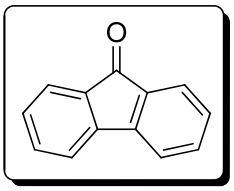
[b]Yields were measured by ^1H NMR using mesitylene as an internal standard.

[C] $Pd(OAc)_2$ is not used.

General Procedure for Pd-Catalyzed Oxidative Cyclization of Diaryl Ketones to form Fluorenone Derivatives: A seal tube (15 mL) initially fitted with a septum containing $Pd(OAc)_2$ (0.055 mmol) Ag_2O (0.825 mmol) and diaryl ketone **1** (0.550 mmol) was evacuated and purged with nitrogen gas three times. Trifluoroacetic acid (2 mL) was added to the system and the reaction mixture was stirred at 130 °C for 24-36 h. After completion of the reaction, the reaction mixture was cooled and filtered through a short Celite pad and was washed several times with dichloromethane. The combined filtrate was then concentrated and separated on a silica gel column using hexane/EtOAc as eluent gave the corresponding pure fluoren-9-one product.

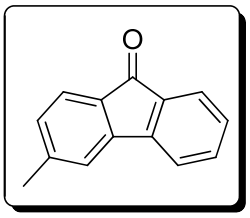
The ^{1}H and ^{13}C NMR, IR and HRMS data of these fluoren-9-one products are listed below.

9*H*-Fluoren-9-one (2a)



Pale yellow solid; m.p. 82-84 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.58 (d, J = 7.6 Hz, 2 H), 7.41 (s, 4 H), 7.24-7.21 (m, 2 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 193.6 (*C*O), 144.2 (2 C), 134.5 (2 *C*H), 133.9 (2 C), 128.8 (2 *C*H), 124.0 (2 *C*H), 120.1 (2 *C*H); **HRMS** (FAB^{+}) calcd for $C_{13}H_8O$ 180.0575, found 180.0574; IR (neat, cm^{-1}) ν: 1712, 1450, 1295, 956.

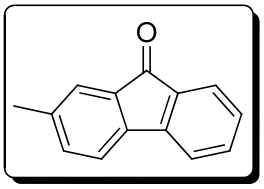
3-Methyl-9*H*-fluoren-9-one (2b)



Pale yellow solid; m.p. 65-67 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.60 (dt, J = 0.8 Hz, J = 7.2 Hz, 1 H), 7.51 (d, J = 7.2 Hz, 1 H), 7.45-7.42 (m, 2 H), 7.28 (s, 1 H), 7.26-7.22 (m, 1 H), 7.05 (d, J = 7.6 Hz, 1 H), 2.39 (s, 3 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 193.6 (*C*O), 145.7 (C),

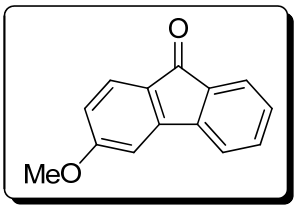
144.7 (C), 144.2 (C), 134.6 (C), 134.3 (*C*H), 131.8 (C), 129.5 (*C*H), 128.9 (*C*H), 124.2 (*C*H), 124.1 (*C*H), 121.1 (*C*H), 120.0 (*C*H), 22.1 (*C*H$_3$); **HRMS** (FAB$^+$) calcd for $C_{14}H_{10}O$ 194.0732, found 194.0736; IR (neat, cm^{-1}) ν: 3046, 1704, 1596.

2-Methyl-9*H*-fluoren-9-one (2c)



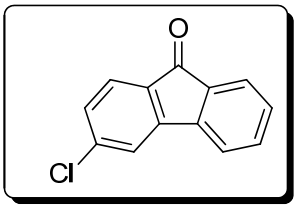
Pale yellow solid; m.p. 90-92 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.57 (d , *J* = 7.2 Hz , 1 H), 7.40-7.39 (m , 3 H), 7.32 (d , *J* = 7.2 Hz , 1 H), 7.22-7.20 (m , 2 H), 2.32 (s , 3 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 194.0 (*C*O), 144.5 (C), 141.7 (C), 139.1 (C), 135.0 (*C*H), 134.5 (*C*H), 134.3 (C), 134.1 (C), 128.4 (*C*H), 124.9 (*C*H), 124.1 (*C*H), 120.6 (*C*H), 119.9 (*C*H), 21.2 (*C*H$_3$); **HRMS** (EI$^+$) calcd for $C_{14}H_{10}O$ 194.0732, found 194.0738; IR (neat, cm^{-1}) ν: 1712, 1612, 1457, 952.

3-Methoxy-9*H*-fluoren-9-one (2d)



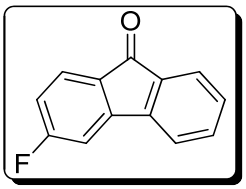
Pale yellow solid; m.p. 94-96 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.59 (t, *J* = 5.6 Hz, 2 H), 7.44 (d, *J* = 3.2 Hz, 2 H), 7.29-7.26 (m, 1 H), 6.98 (s, 1 H), 6.71 (dd, *J* = 2.0 Hz, *J* = 8.0 Hz, 1 H), 3.88 (s , 3 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 192.4 (*C*O), 165.3 (C), 146.9 (C), 143.2 (C), 135.2 (C), 134.0 (*C*H), 129.2 (*C*H), 127.0 (C), 126.2 (*C*H), 123.7 (*C*H), 120.0 (*C*H), 112.9 (*C*H), 107.0 (*C*H), 55.7 (*C*H$_3$); **HRMS** (EI$^+$) calcd for $C_{14}H_{10}O_2$ 210.0681, found 210.0685; **HRMS** (EI$^+$) calcd for $C_{14}H_{10}O_2$ 210.0681, found 210.0678; IR (neat, cm^{-1}) ν:1704, 1612, 1295, 1226.

3-Chloro-9*H*-fluoren-9-one (2e)



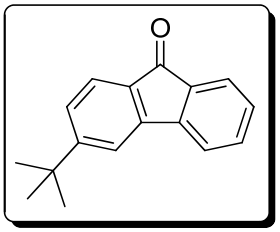
Pale yellow solid; m.p. 159-161 °C; **^{1}H NMR** (500 MHz, $CDCl_3$): δ 7.63 (d, *J* = 7.0 Hz, 1 H), 7.54 (d, *J* = 7.0 Hz, 1 H), 7.49-7.44 (m, 3 H), 7.30 (t, *J* = 6.5 Hz, 1 H), 7.23 (d, *J* = 7.5 Hz, 1 H); **^{13}C NMR** (125 MHz, $CDCl_3$): δ 192.3 (*C*O), 146.0 (C), 143.0 (C), 140.9 (C), 134.7 (*C*H), 134.2 (C), 132.3 (C), 129.7 (*C*H), 128.9 (*C*H), 125.3 (*C*H), 124.4 (*C*H), 120.9 (*C*H), 120.5 (*C*H); **HRMS** (EI^+) calcd for $C_{13}H_7OCl$ 214.0185, found 214.0190; IR (neat, cm^{-1}) ν: 1712, 1597, 1080.

3-Fluoro-9*H*-fluoren-9-one (**2f**)



Pale yellow solid; m.p. 121-123 °C; **^{1}H NMR** (500 MHz, $CDCl_3$): δ 7.63 (t, *J* = 6.7 Hz, 2 H), 7.48 (q, *J* = 7.33 Hz, 2 H) 7.32-7.30 (m, 1 H), 7.17 (d, *J* = 5.5 Hz, 1 H), 6.94-6.90 (m, 1 H); **^{13}C NMR** (125 MHz, $CDCl_3$): δ 192.0 (*C*O), 168.2 (d, $J_{C\text{-}F}$ = 254.0 Hz, C), 147.4 (d, $J_{C\text{-}F}$ = 10.0 Hz, C), 142.7 (C), 134.6 (C H), 134.6 (C), 130.1 (d, $J_{C\text{-}F}$ = 3.4 Hz, C), 129.7 (C H), 126.4 (d, $J_{C\text{-}F}$ = 9.9 Hz, C H), 124.2 (C H), 120.5 (C H), 115.5 (d, $J_{C\text{-}F}$ = 23.3 Hz, C H), 108.5 (d, $J_{C\text{-}F}$ = 24.4 Hz, C H); **HRMS** (FAB^+) calcd for $C_{13}H_7FO$ 198.0481, found 198.0482; IR (neat, cm^{-1}) *v:* 1712.

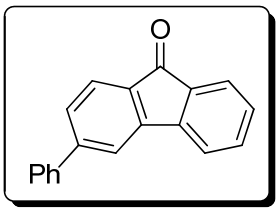
3-*Tert*-butyl-9*H*-fluoren-9-one (2g)



Yellow liquid; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.60 (d, *J* = 7.6 Hz, 1 H), 7.56 (d, *J* = 8.0 Hz, 1H),7.52-7.49 (m, 2 H), 7.43 (t, *J* = 7.2 Hz, 1 H), 7.28 (d, *J* = 7.6 Hz, 1 H), 7.23 (t, *J* = 7.6

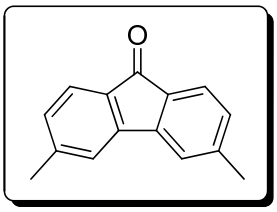
Hz, 1 H), 1.36 (s, 9 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 193.4 (*C*O), 158.8 (C), 144.4 (C), 144.3 (C), 134.5 (C), 134.2 (CH), 131.6 (C), 128.7 (*C*H), 125.8 (*C*H), 123.9 (*C*H), 123.9 (*C*H), 119.9 (*C*H), 117.4 (*C*H), 35.3 (C), 30.9 (3 *C*H_3); **HRMS** (EI^+) calcd for $C_{17}H_{16}O$ 236.1201, found 236.1199; IR (neat, cm^{-1}) ν: 1712, 1612.

3-Phenyl-9*H*-fluoren-9-one (2h)



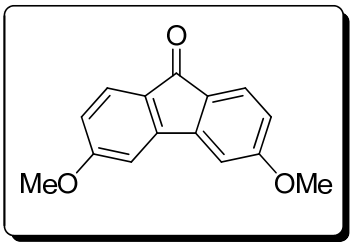
Yellow viscous liquid; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.71-7.69 (m, 2 H), 7.67-7.63 (m, 3 H), 7.55 (d, *J* = 7.2 Hz, 1 H), 7.50-7.46 (m, 4 H), 7.44-7.42 (m, 1 H), 7.32-7.28 (m, 1 H); **^{13}C NMR** (100 MHz, $CDCl_3$) : δ 193.4 (*C*O), 147.8 (C), 145.1 (C), 144.0 (C), 140.1 (C), 134.6 (*C*H), 134.5 (C), 132.9 (C), 129.1 (*C*H), 128.9 (2 *C*H), 128.4 (*C*H), 127.8 (*C*H), 127.1 (2 *C*H) , 124.6 (*C*H), 124.2 (*C*H), 120.2 (*C*H), 119.1 (*C*H); **HRMS** (FAB^+) calcd for $C_{19}H_{12}O$ 256.0888, found 256.0885; IR (neat, cm^{-1}) ν: 3054, 1704, 840.

3,6-Dimethyl-9*H*-fluoren-9-one (2i)



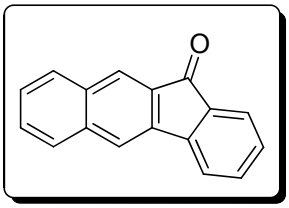
Pale yellow solid; m.p. 108-110 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 7.6 Hz, 2 H), 7.22 (s, 2 H), 7.02 (d, *J* = 7.6 Hz , 2 H), 2.37 (s, 6 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 186.2 (CO), 138.3 (2 C), 137.5 (2 C), 125.2 (2 C), 122.3 (2 *C*H), 116.9 (2 *C*H), 113.9 (2 *C*H), 15.0 (2 CH_3); **HRMS** (EI^+) calcd for $C_{15}H_{12}O$ 208.0888, found 208.0880;IR (neat, cm^{-1}) ν: 2915, 1712, 1612.

3,6-Dimethoxy-9*H*-fluoren-9-one (2j)



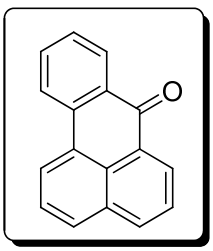
Pale yellow solid; m.p. 137-139 °C; **^{1}H NMR** (500 MHz, $CDCl_3$): δ 7.56 (d, *J* = 7.5 Hz, 2 H), 6.97 (d, *J* = 2.5 Hz, 2 H), 6.72 (dd, *J* = 2.5 Hz, *J* = 8.5 Hz, 2 H), 3.88 (s, 6 H); **^{13}C NMR** (125 MHz, $CDCl_3$): δ 191.2 (*C*O), 164.9 (2 C), 145.8 (2 C), 128.3 (2 C), 125.7 (2 *C*H), 112.9 (2 *C*H), 107.0 (2 *C*H), 55.7 (2 *C*H_3); **HRMS** (FAB^+) calcd for $C_{15}H_{12}O_3$ 240.0786, found 240.0789; IR (neat, cm^{-1}) ν: 2923, 1697, 1249, 1226.

11*H*-Benzo[*b*]fluoren-11-one (2k)



Yellow solid; m.p. 141-142 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 8.16 (s, 1 H), 7.89-7.86 (m, 2 H), 7.82 (d, *J* = 8.0 Hz, 1 H), 7.75 (d, *J* = 7.6 Hz, 1 H), 7.71 (d, *J* = 7.6 Hz, 1 H), 7.57-7.53 (m, 2 H), 7.46 (t, *J* = 7.6 Hz, 1 H), 7.34 (t, *J* = 7.6 Hz, 1 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 193.1 (*C*O), 144.8 (C), 138.3 (C), 136.9 (C), 136.1 (C), 135.0 (*C*H), 133.6 (C), 132.7 (C), 130.8 (*C*H), 129.1 (*C*H), 128.9 (*C*H), 128.7 (*C*H), 126.9 (*C*H), 125.6 (*C*H), 124.4 (*C*H), 120.9 (*C*H), 119.0 (*C*H); **HRMS** (FAB^+) calcd for $C_{17}H_{10}O$ 230.0732, found 230.0728; IR (neat, cm^{-1}) ν: 1709, 894.

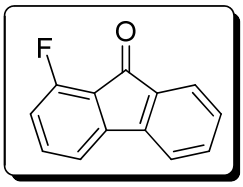
7*H*-Benzo[*de*]anthracen-7-one (2l)



Yellow solid; m.p. 162-164 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 8.77 (d, *J* = 7.6 Hz, 1 H), 8.51 (d, *J* = 7.2 Hz, 1 H), 8.46 (d, *J* = 7.2 Hz, 1 H), 8.35 (d, *J* = 8.0 Hz, 1 H), 8.22 (d, *J* = 8.0

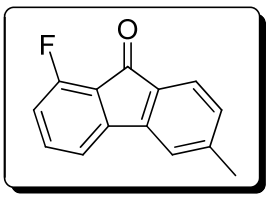
Hz, 1 H), 8.01 (d, *J* = 8.0 Hz, 1 H), 7.80-7.72 (m, 2 H), 7.69 (t, *J* = 8.0 Hz, 1 H), 7.56 (t, *J* = 7.6 Hz, 1 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 183.8 (*C*O), 136.1 (C), 135.1 (*C*H), 133.3 (*C*H), 133.0 (C), 131.1 (C), 130.1 (*C*H), 129.8 (*C*H), 128.5 (C), 128.2 (*C*H), 128.1 (*C*H), 127.9 (C), 126.8 (C), 126.5 (*C*H), 126.5 (*C*H), 124.1 (*C*H), 123.0 (*C*H); **HRMS** (FAB^+) calcd for $C_{17}H_{10}O$ 230.0732, found 230.0728; IR (neat, cm^{-1}) ν: 1650, 1596.

1-Fluoro-9*H*-fluoren-9-one (2m)



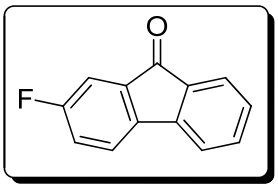
Yellow solid; m.p. 112-115 °C; **^{1}H NMR** (500 MHz, $CDCl_3$): δ 7.63 (d, *J* = 6.0 Hz, 1 H), 7.41-7.15 (m, 3 H), 7.31-7.24 (m, 2 H), 6.90 (t, *J* = 9.0 Hz, 1 H); **^{13}C NMR** (125 MHz, $CDCl_3$): δ 190.0 (*C*O), 159.3 (d, $J_{C\text{-}F}$ = 210.2 Hz, C), 146.3 (C), 143.3 (C), 137.0 (d, $J_{C\text{-}F}$ = 17.1 Hz, *C*H), 134.5 (*C*H), 133.9 (C), 129.6 (*C*H), 124.4 (*C*H), 120.5 (*C*H), 119.8 (d, $J_{C\text{-}F}$ = 10.7 Hz, C), 117.4 (d, $J_{C\text{-}F}$ = 16.9 Hz, *C*H), 116.3 (d, $J_{C\text{-}F}$ = 2.7 Hz, *C*H); **HRMS** (FAB^+) calcd for $C_{13}H_7OF$ 198.0481, found 198.0486; IR (neat, cm^{-1}) ν:1712, 1480.

1-Fluoro-6-methyl-9*H*-fluoren-9-one (2n)



Yellow solid; m.p. 118-119 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.54 (d, *J* = 7.6 Hz, 1 H), 7.46-7.41 (m, 1 H), 7.31 (s, 1 H), 7.26 (d, *J* = 7.2 Hz, 1 H), 7.11 (d, *J* = 8.4 Hz, 1 H), 6.90 (t, *J* = 8.8 Hz, 1 H) 2.41 (s, 3 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 190.0 (*C*O), 159.2 (d, $J_{C\text{-}F}$ = 261.5 Hz, C), 146.2 (d, $J_{C\text{-}F}$ = 3.0 Hz, C), 145.7 (2 C), 143.7 (d, $J_{C\text{-}F}$ = 2.0 Hz, C), 136.7 (d, $J_{C\text{-}F}$ = 8.3 Hz, *C*H), 131.6 (C), 130.2 (*C*H), 124.4 (*C*H), 121.4 (*C*H), 117.4 (d, $J_{C\text{-}F}$ = 21.2 Hz, *C*H), 116.1 (d, $J_{C\text{-}F}$ = 3.1 Hz, *C*H), 22.0 (CH_3); **HRMS** (FAB^+) calcd for $C_{14}H_9FO$ 212.0637, found 212.0631; IR (neat, cm^{-1}) ν:1712, 1480.

2-Fluoro-9*H*-fluoren-9-one (2o)

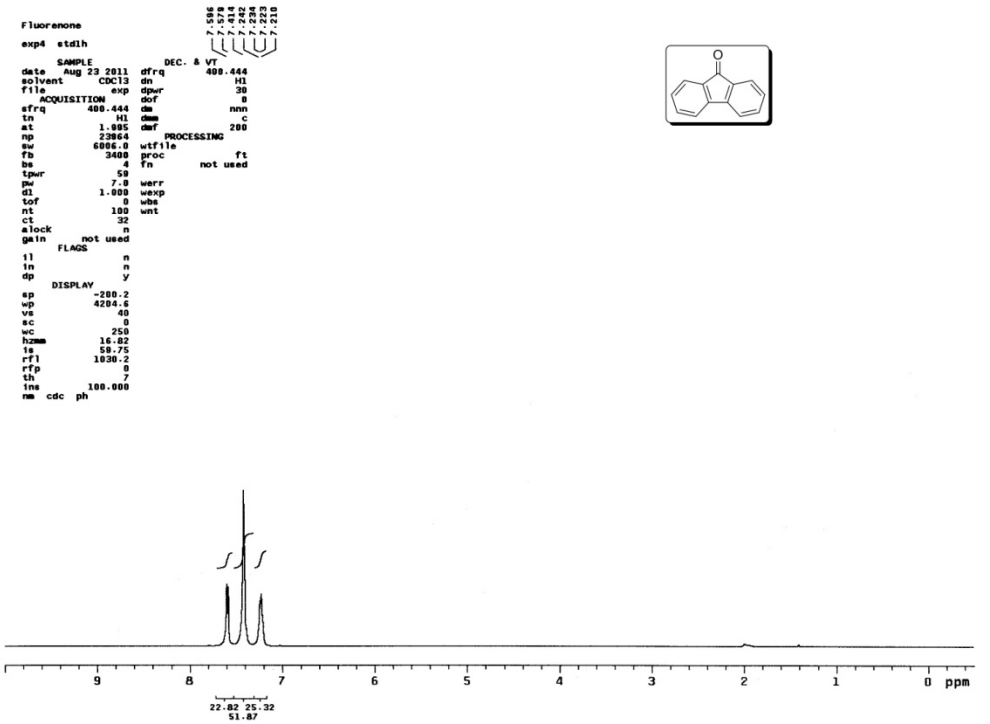


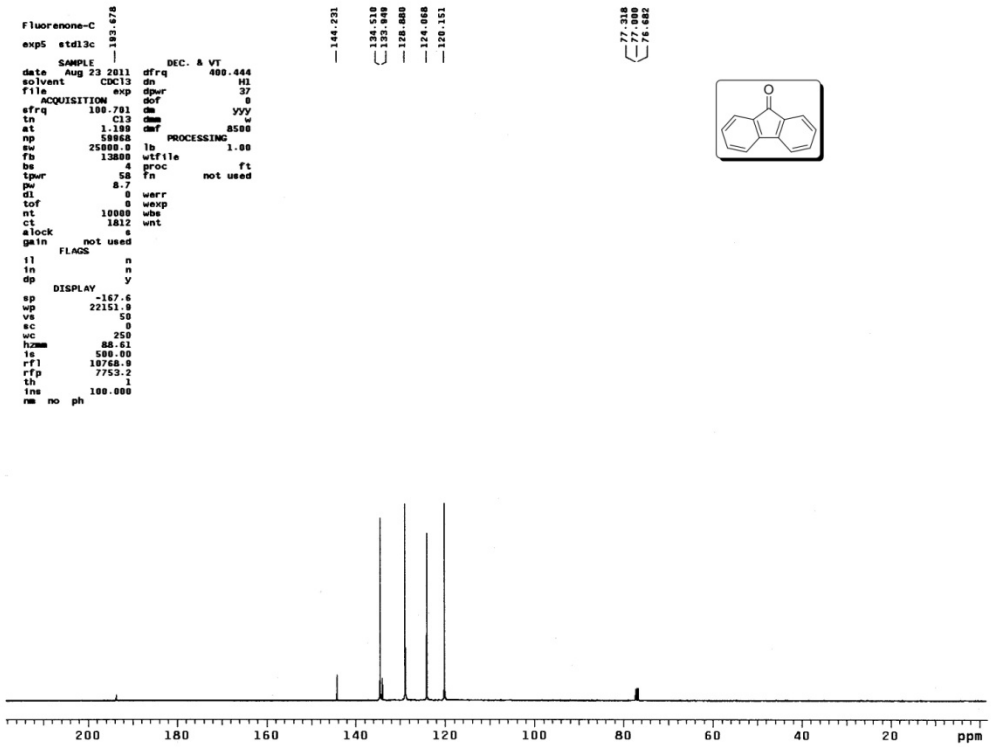
Yellow solid; m.p. 103-105 °C; **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.60 (d, J = 7.2 Hz, 1 H), 7.46-7.39 (m, 3 H), 7.29-7.22 (m, 2 H), 7.14-7.09 (m, 1 H); **^{13}C NMR** (100 MHz, $CDCl_3$): δ 192.3 (CO), 163.4 (d, $J_{C\text{-}F}$ = 248.2 Hz, C), 143.7 (C), 140.0 (d, $J_{C\text{-}F}$ = 2.9 Hz, C), 136.3 (d, $J_{C\text{-}F}$ = 6.6 Hz, C), 135.0 (CH), 134.3 (d, $J_{C\text{-}F}$ = 2.2 Hz, C), 128.7 (CH), 124.5 (CH), 121.5 (d, $J_{C\text{-}F}$ = 7.2 Hz, CH), 120.5 (d, $J_{C\text{-}F}$ = 60.2 Hz, CH), 120.1 (CH) 111.9 (d, $J_{C\text{-}F}$ = 23.4 Hz, C); **HRMS** (FAB^{+}) calcd for $C_{13}H_7FO$ 198.0481, found 198.0482; IR (neat, cm^{-1}) ν: 1712, 1480.

References:

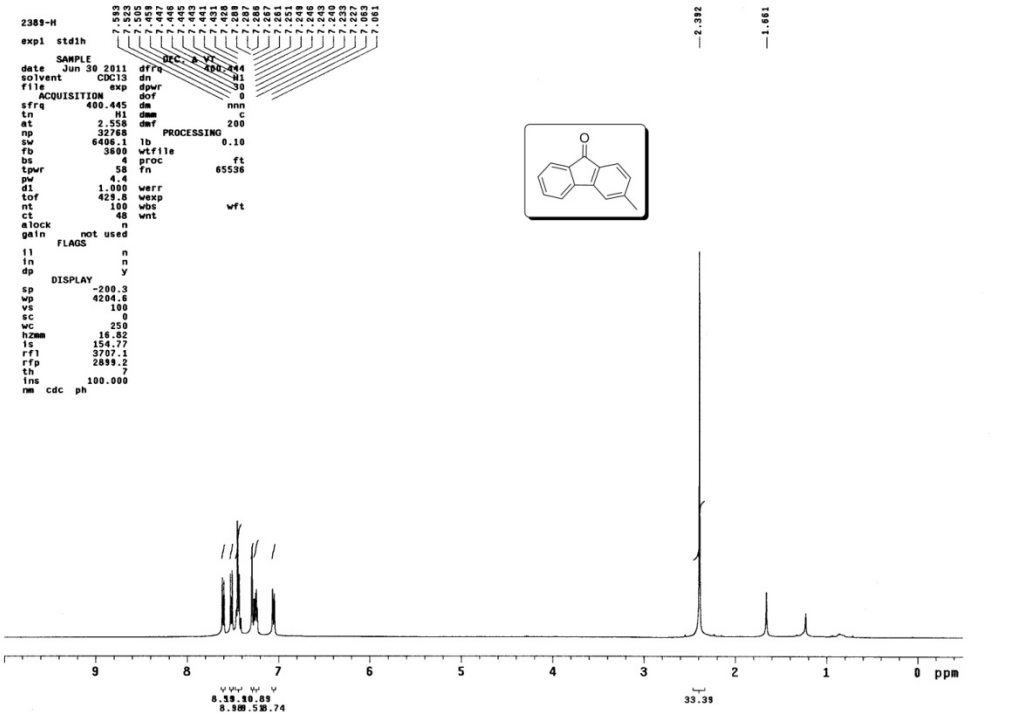
1. D. D. Perrin, W. L. F Armarego. *In Purification of Laboratory Chemicals*, 3rd ed.; Pergamon Press: New York, **1988**.

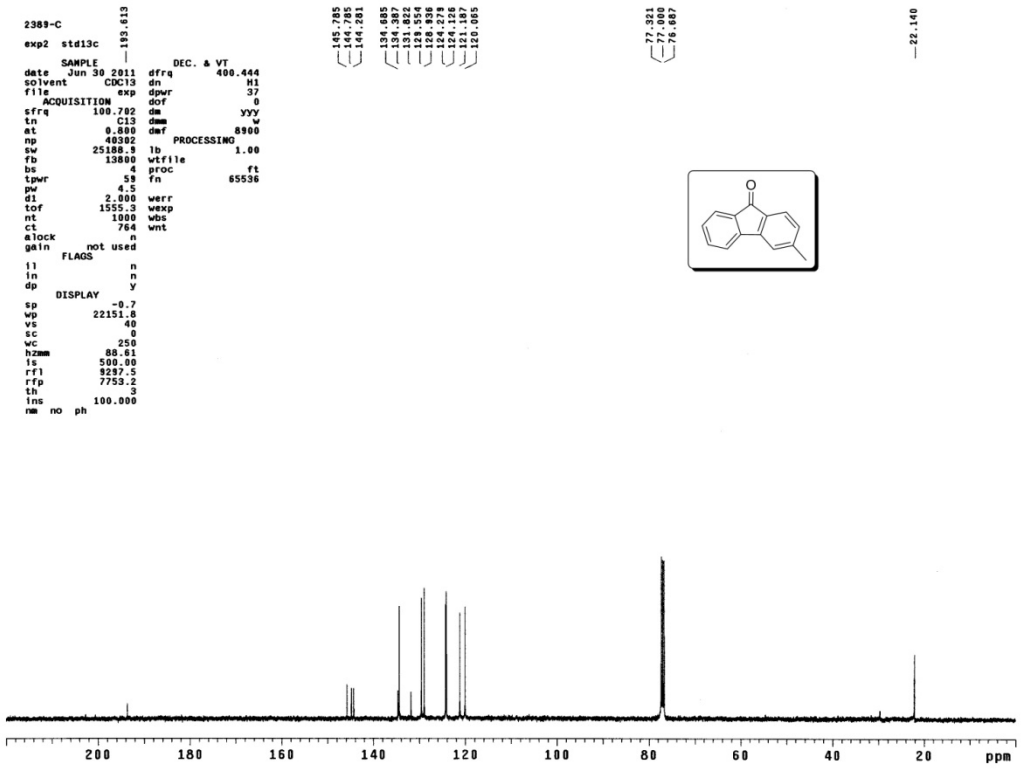
^{1}H and ^{13}C NMR spectra of compound **2a**.



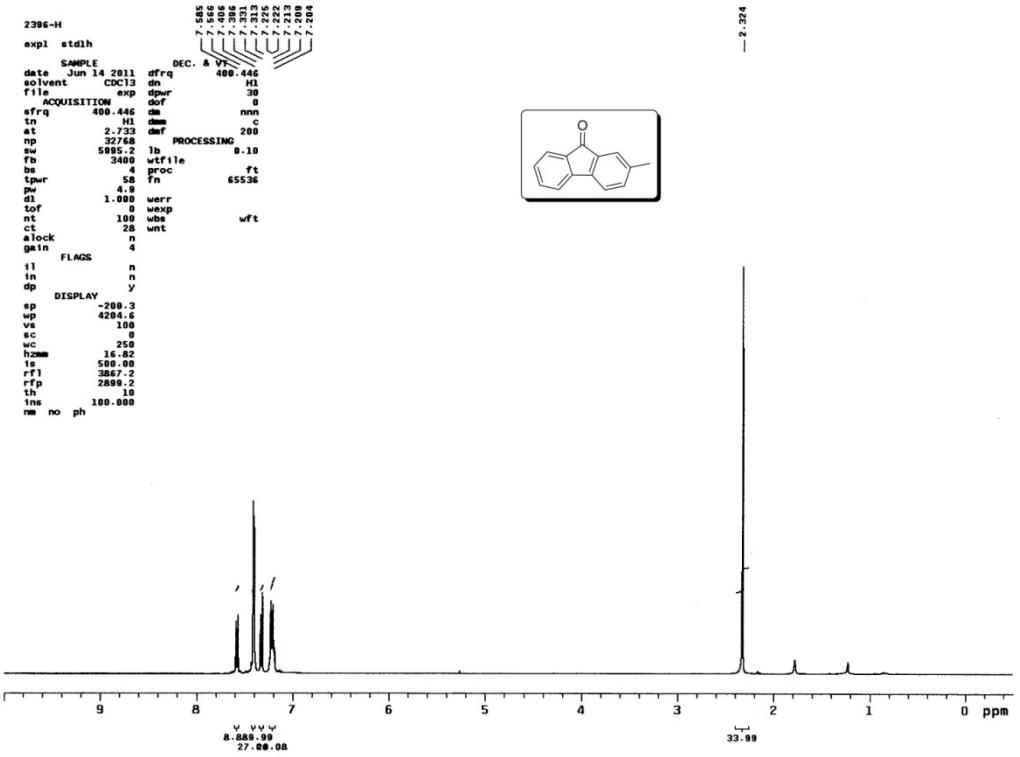


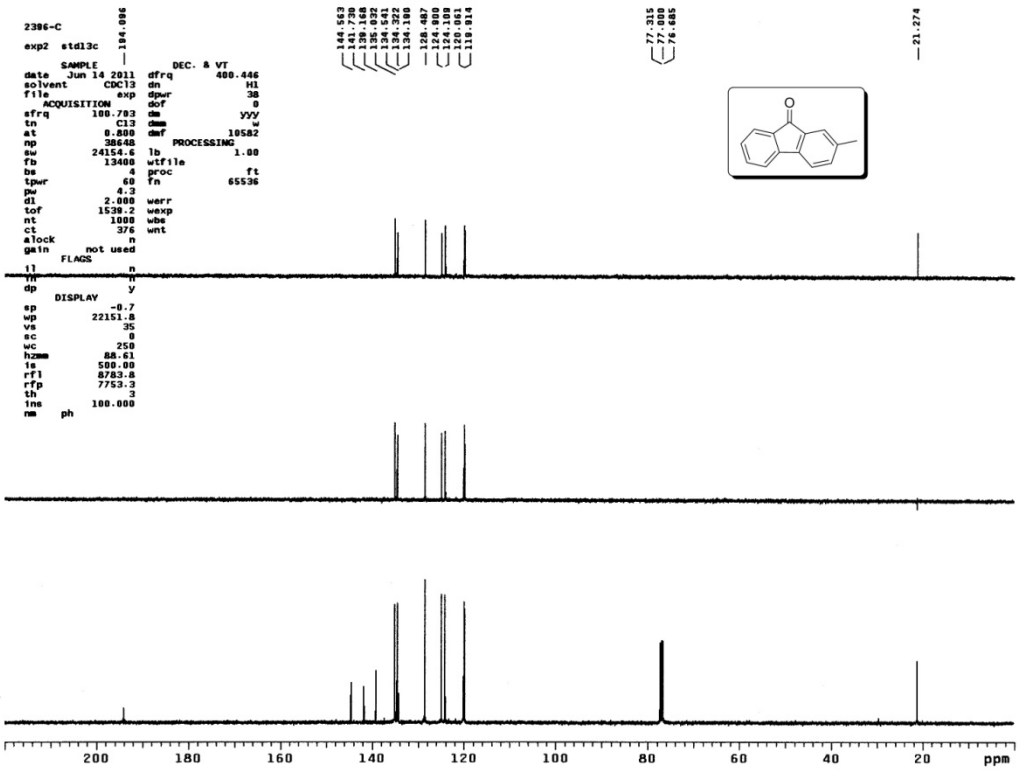
^{1}H and ^{13}C NMR spectra of compound **2b**.



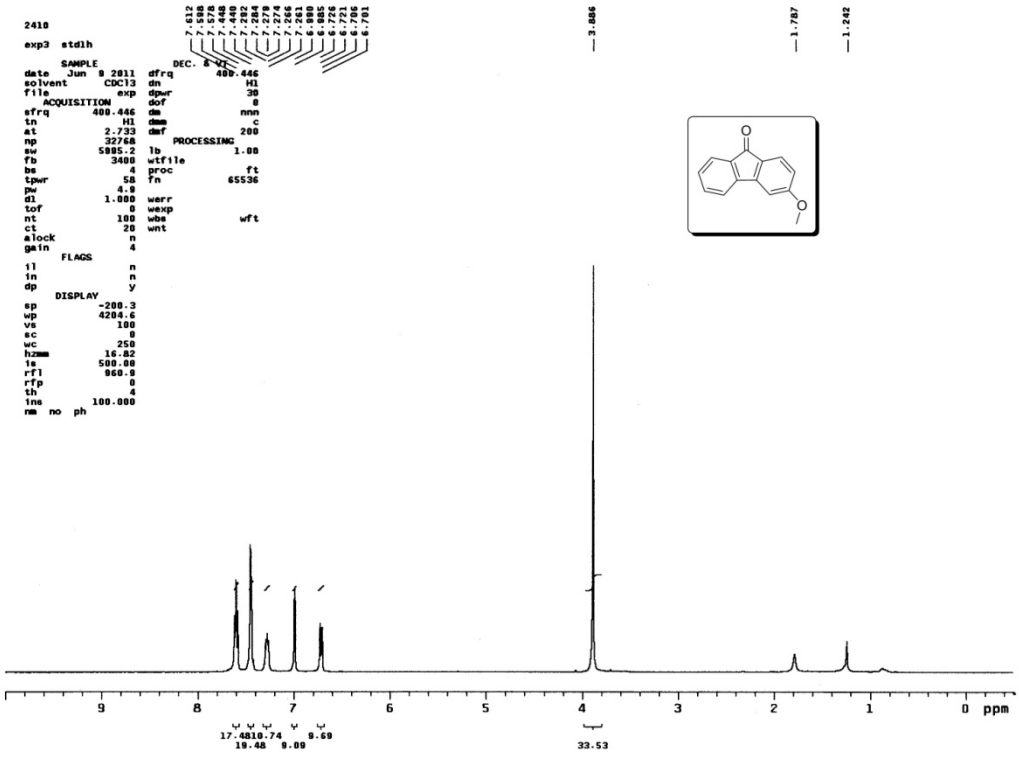


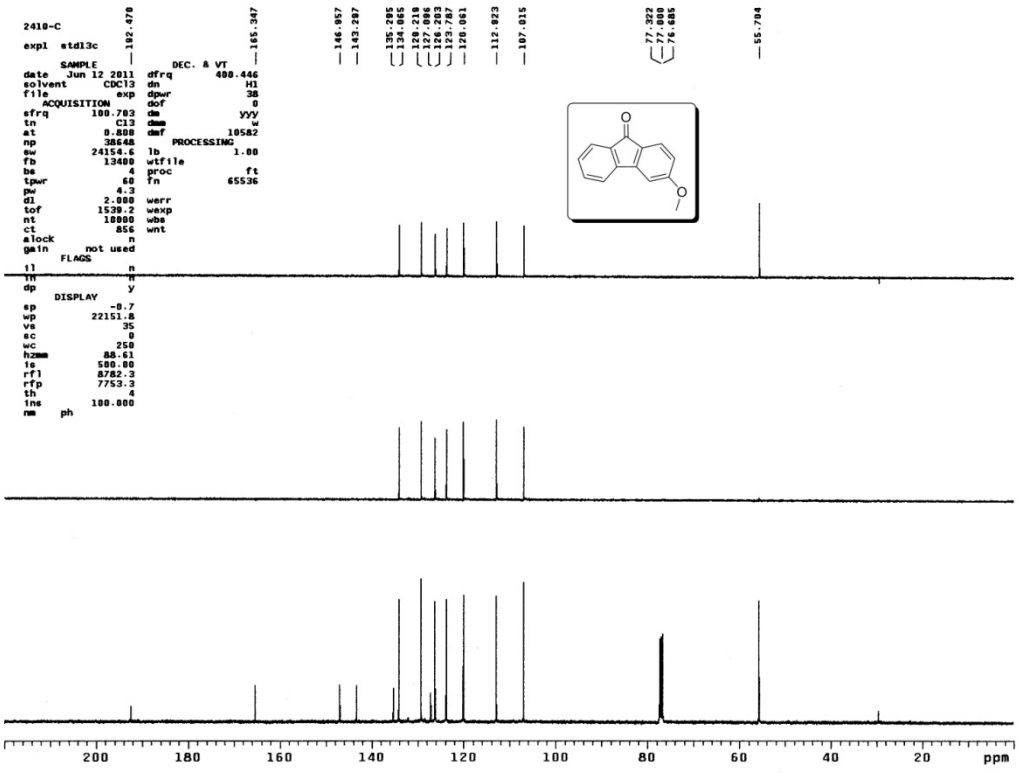
^{1}H and ^{13}C NMR spectra of compound **2c**



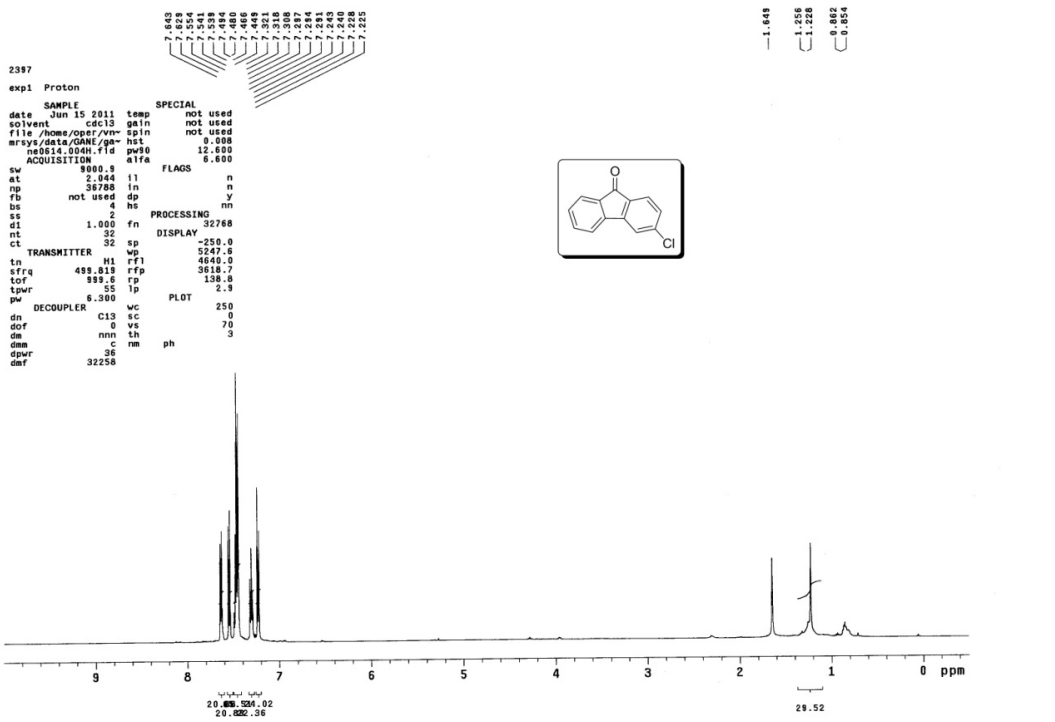


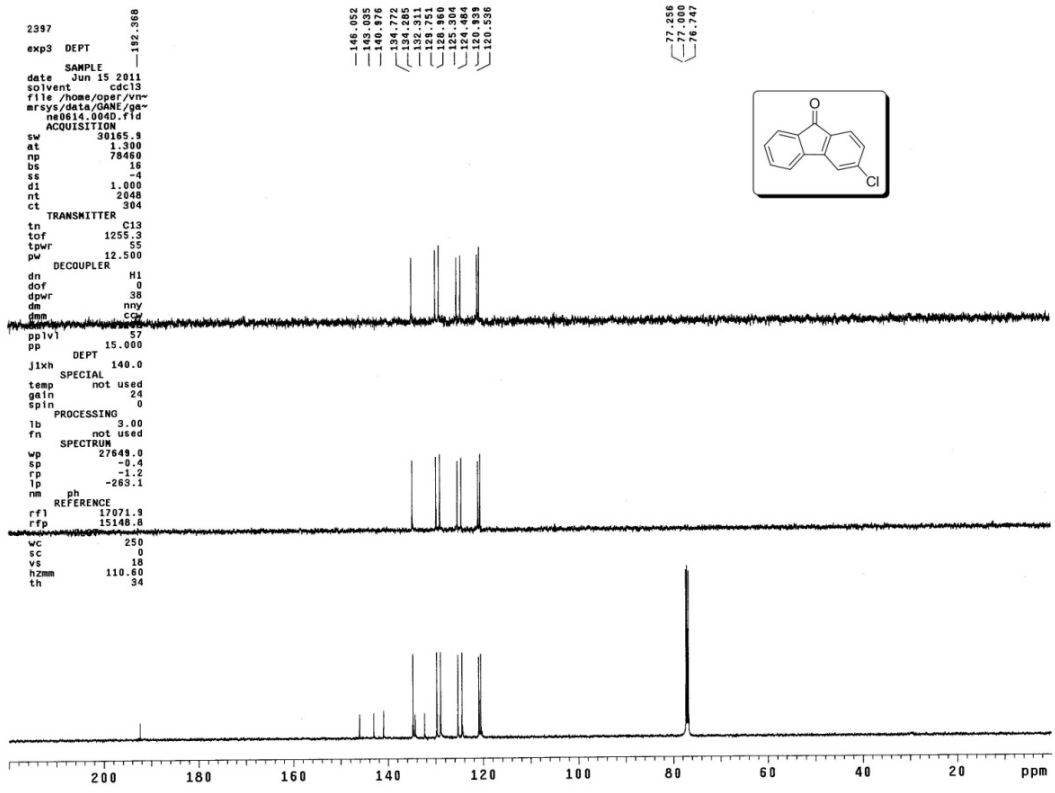
^{1}H and ^{13}C NMR spectra of compound **2d**



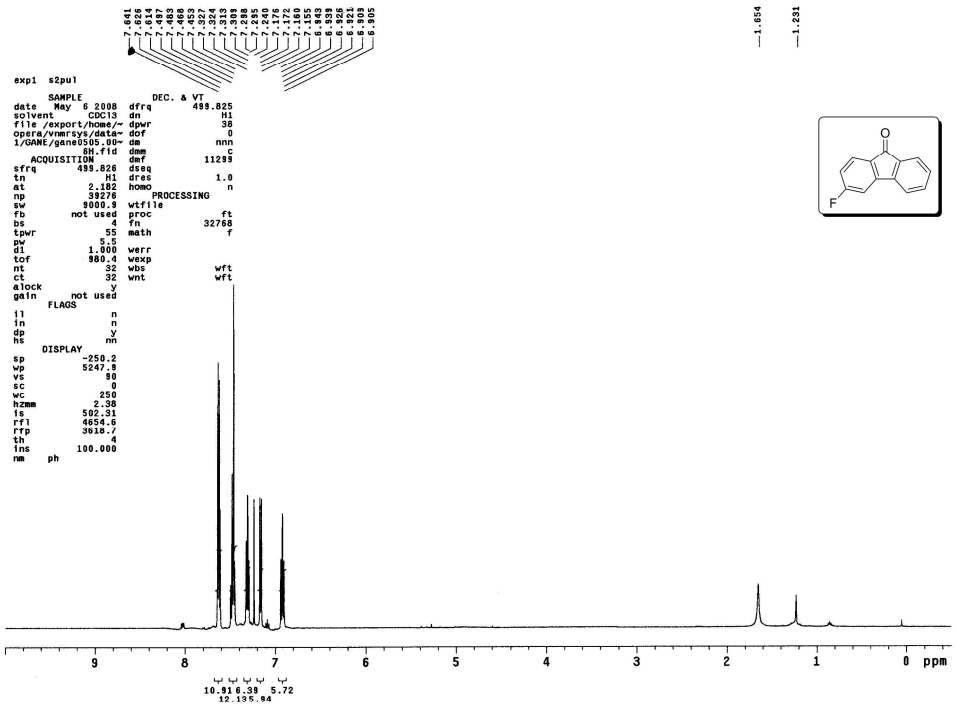


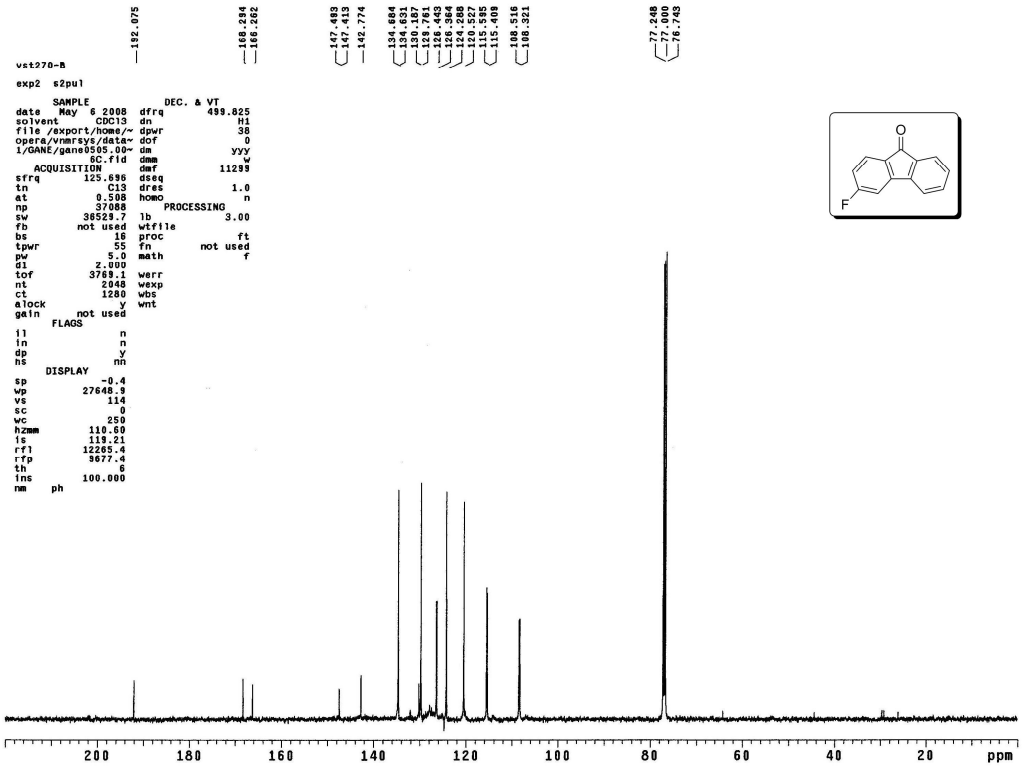
^{1}H and ^{13}C NMR spectra of compound **2e**



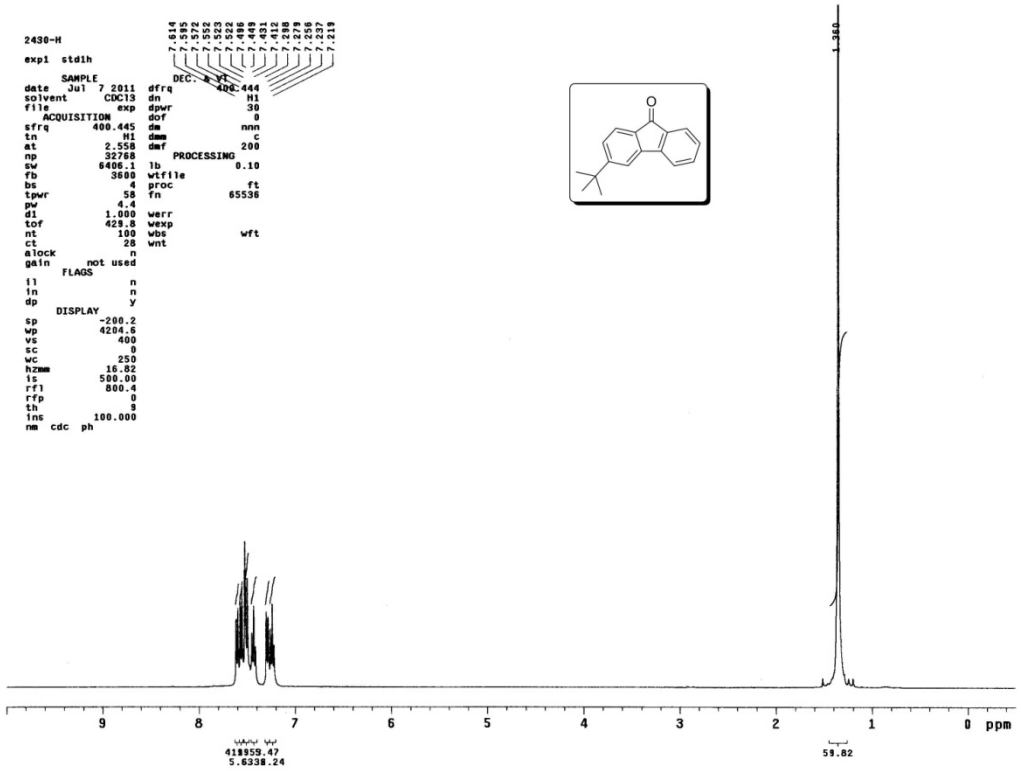


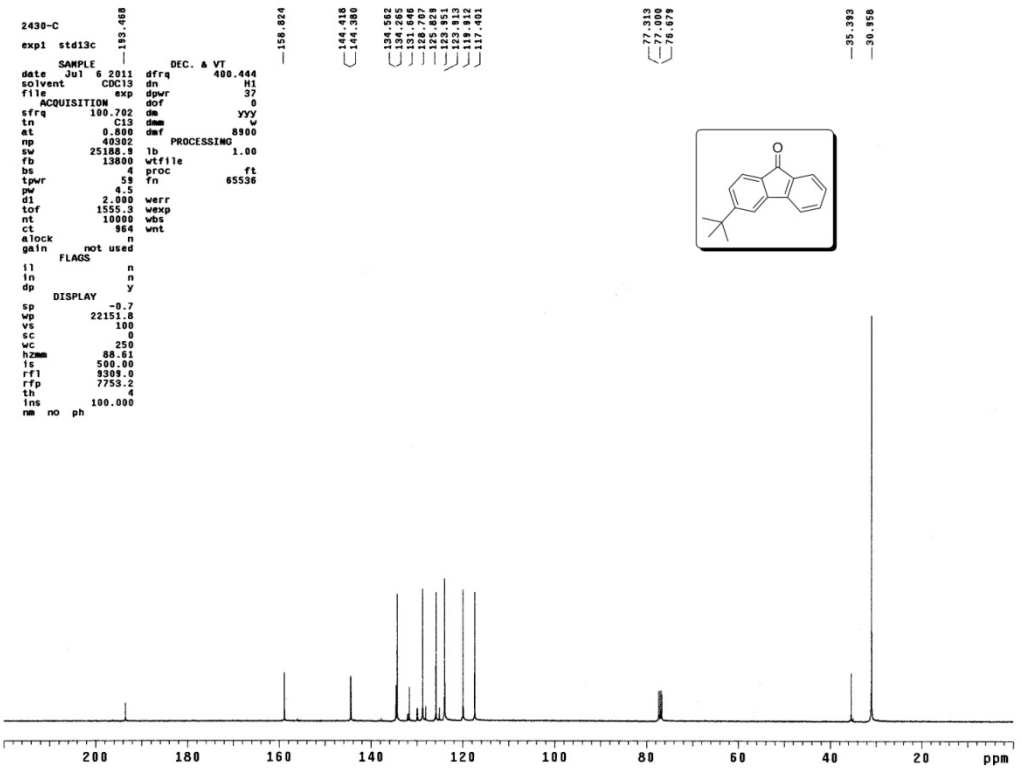
^{1}H and ^{13}C NMR spectra of compound **2f**



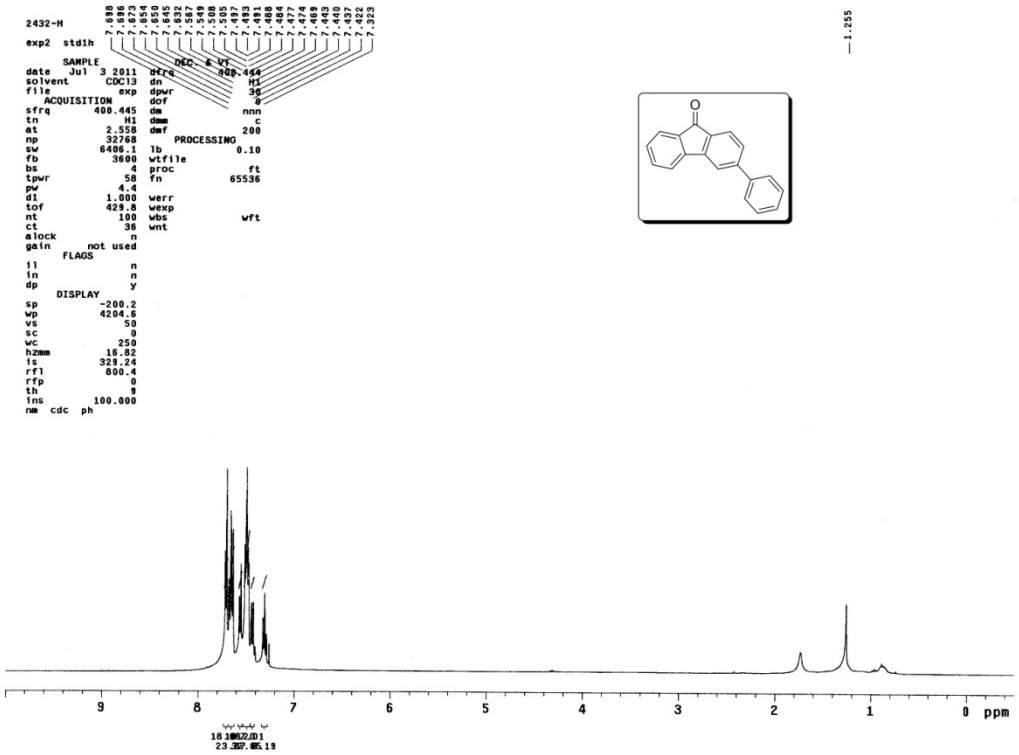


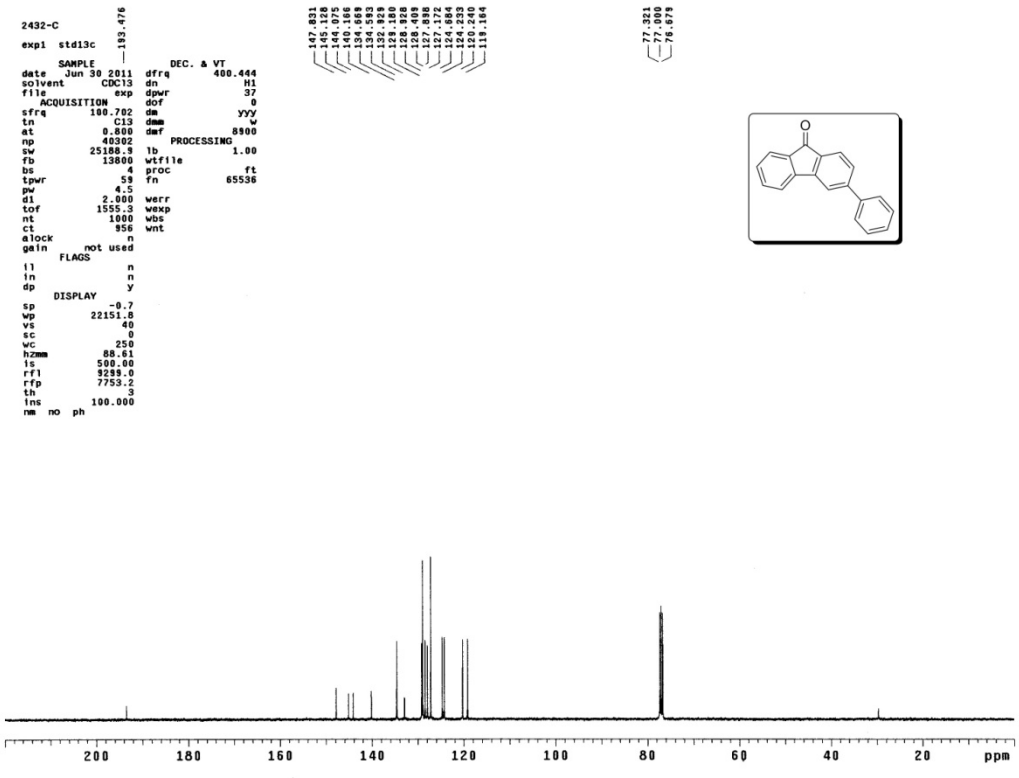
^{1}H and ^{13}C NMR spectra of compound **2g**



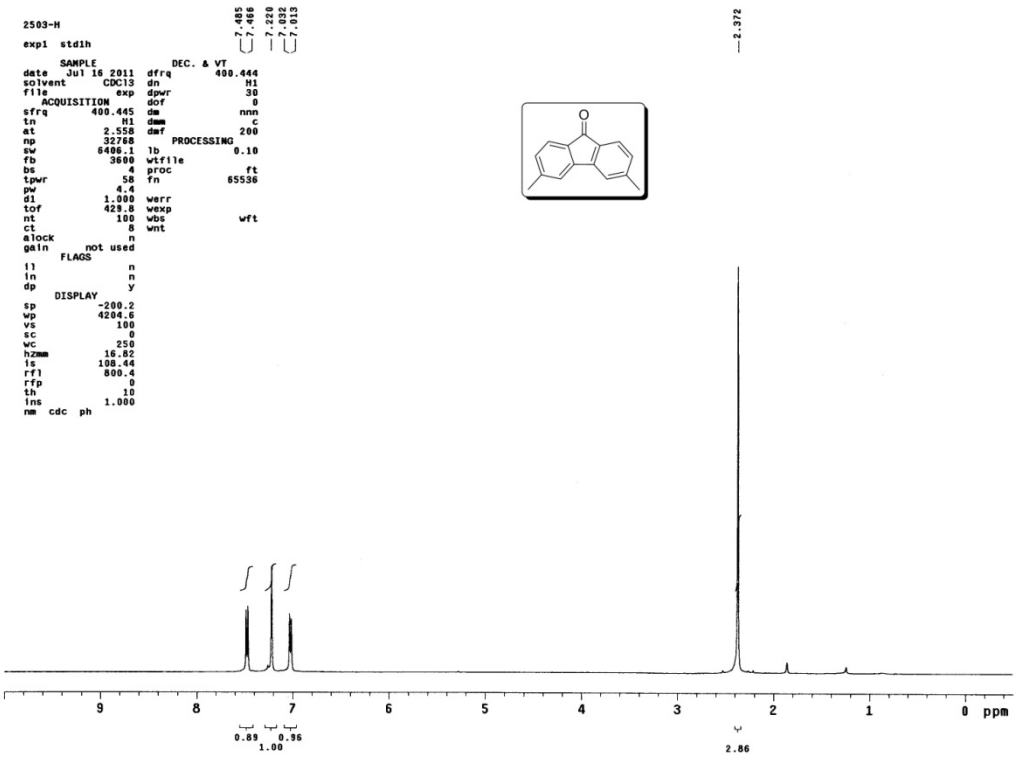


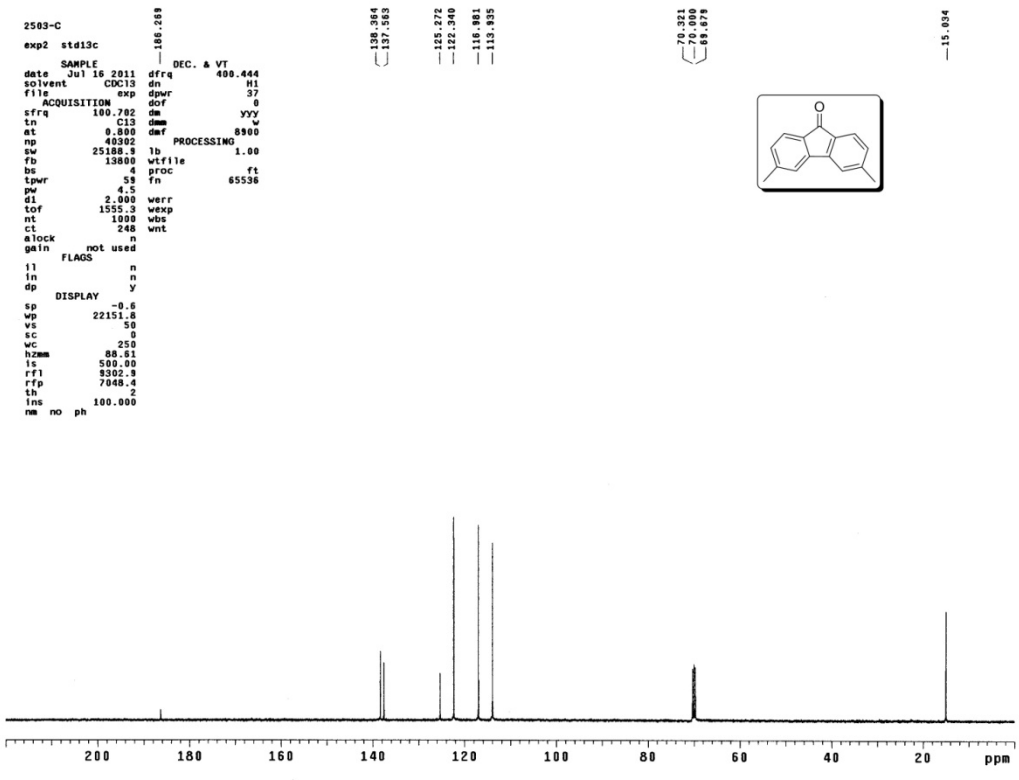
^{1}H and ^{13}C NMR spectra of compound **2h**



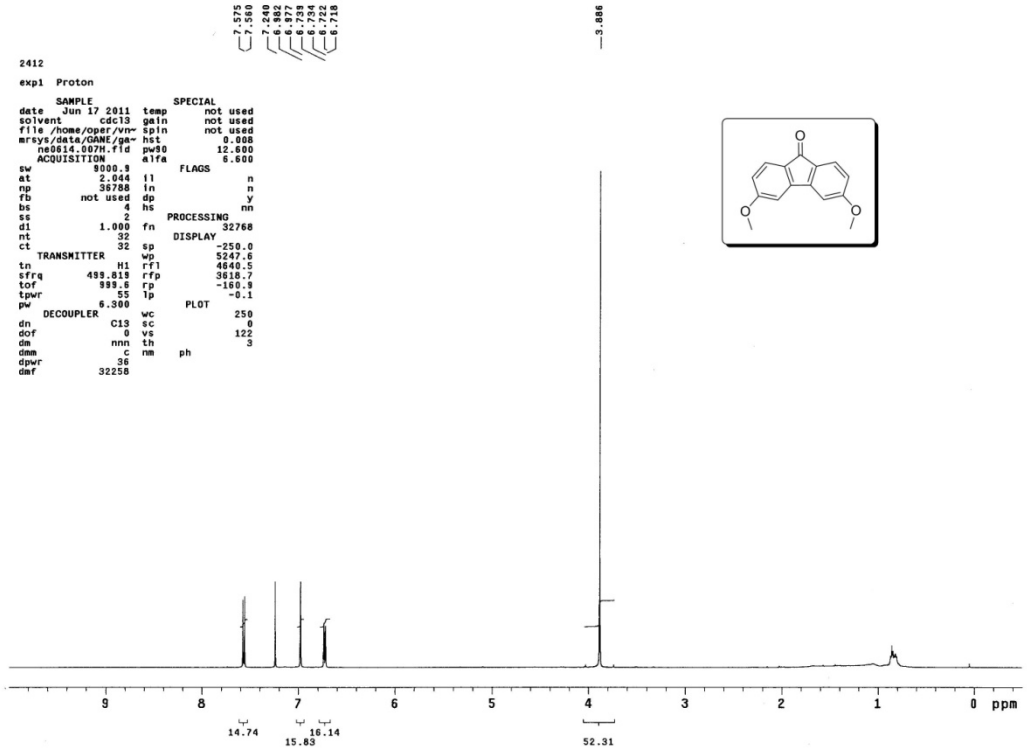


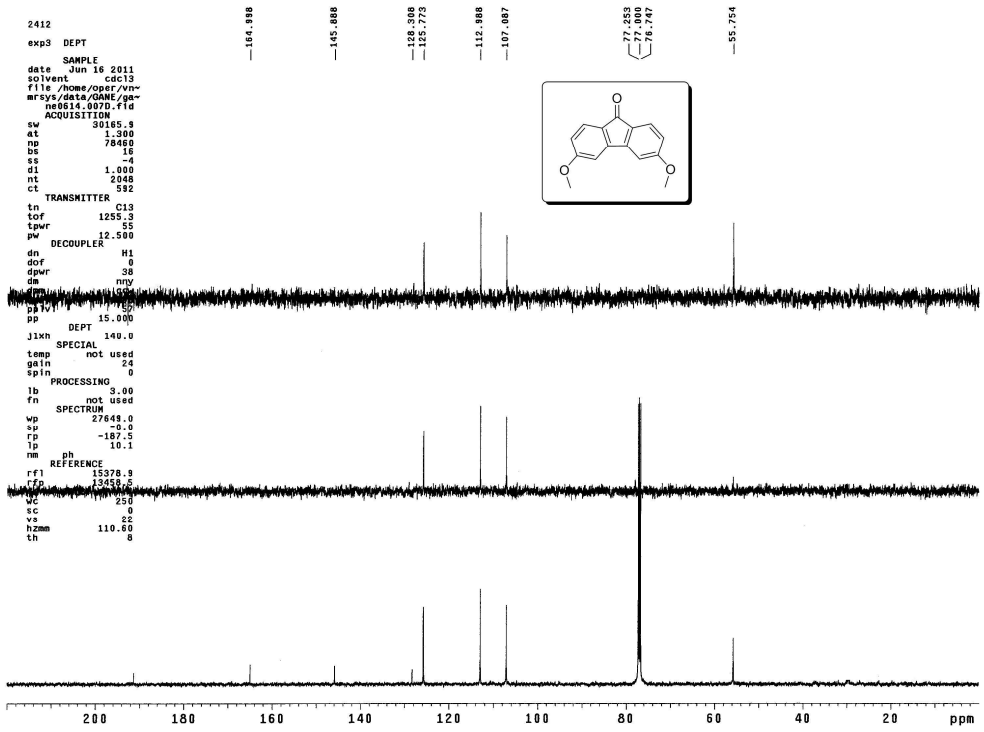
^{1}H and ^{13}C NMR spectra of compound **2i**



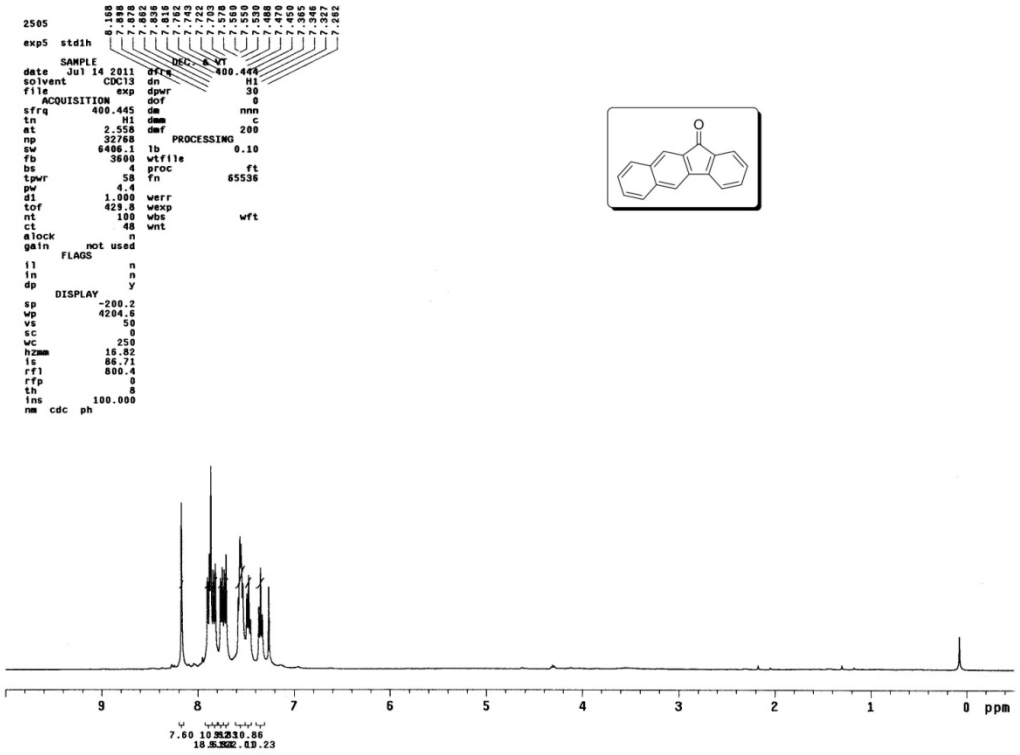


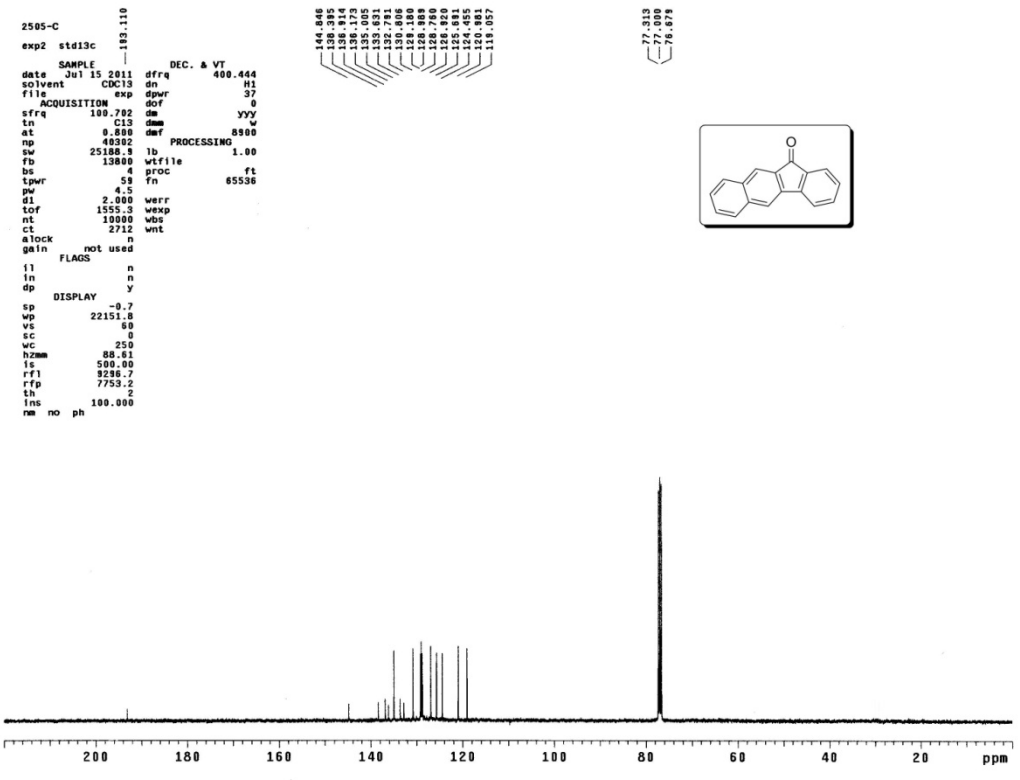
^{1}H and ^{13}C NMR spectra of compound **2j**



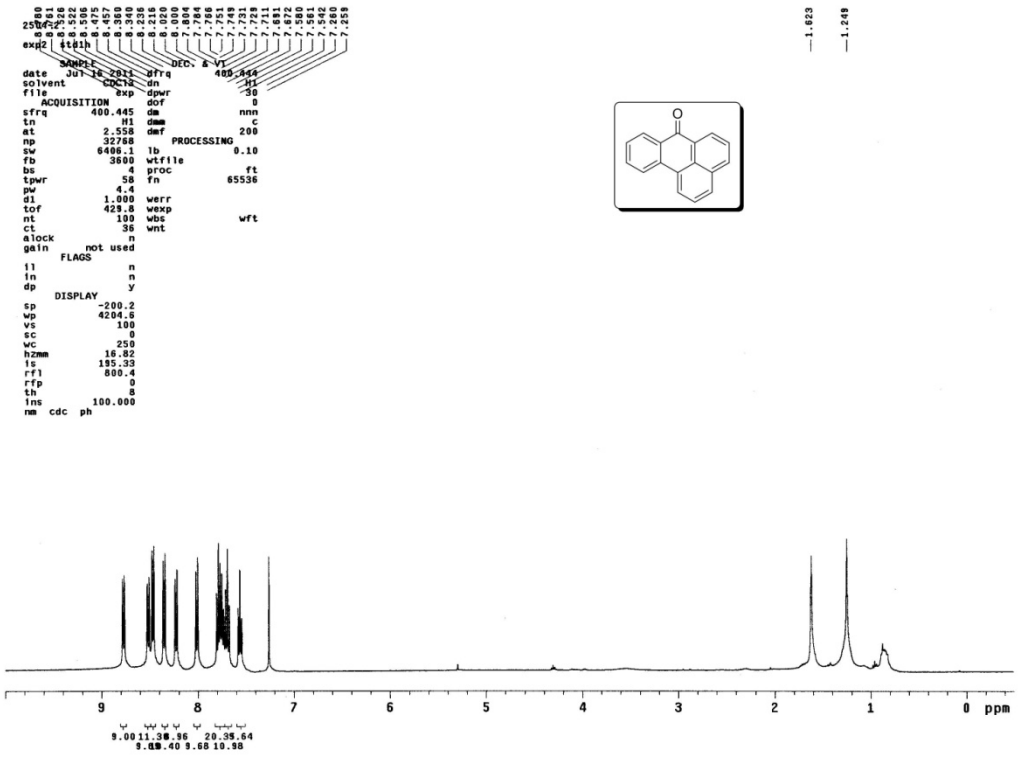


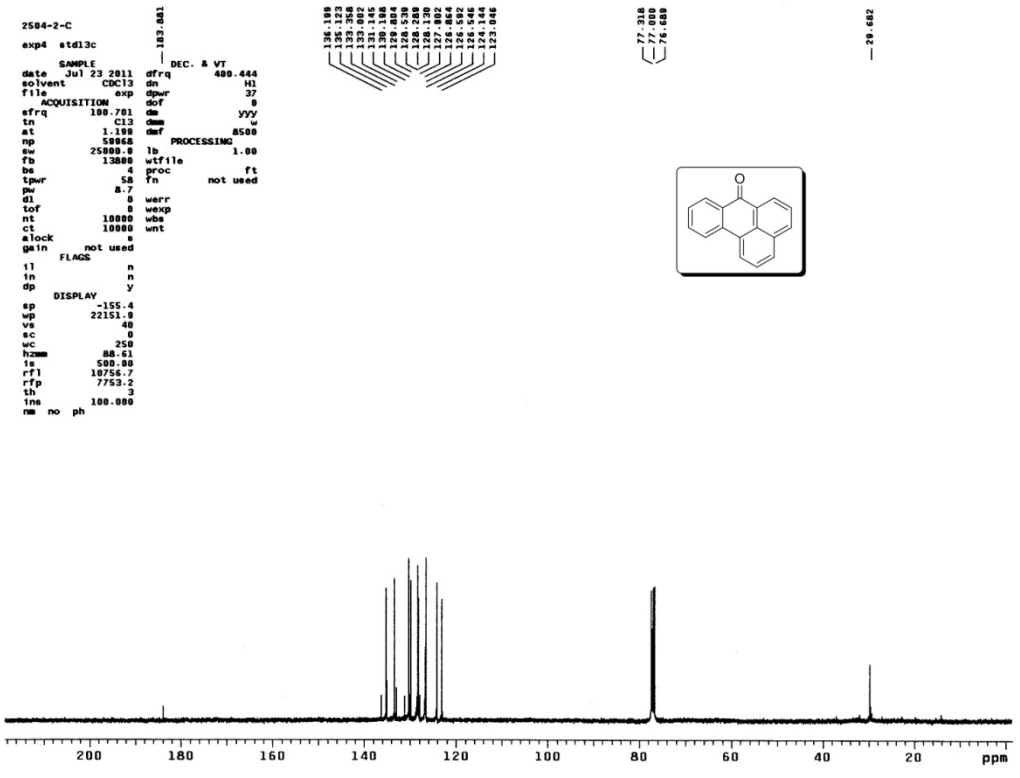
^{1}H and ^{13}C NMR spectra of compound **2k**



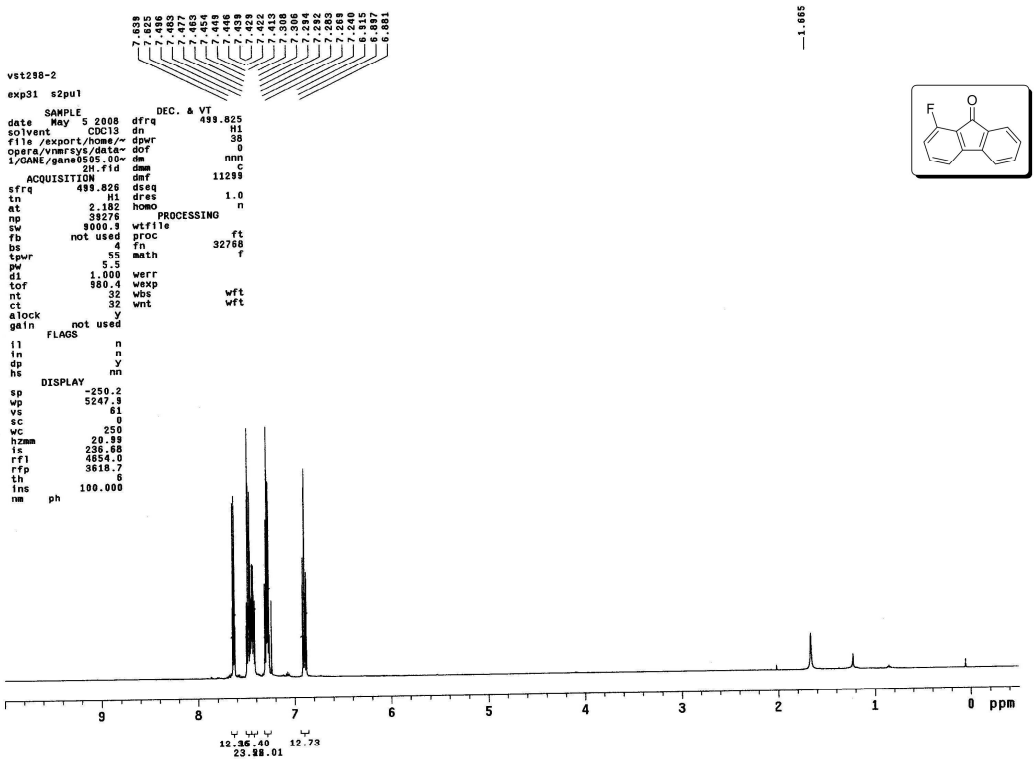


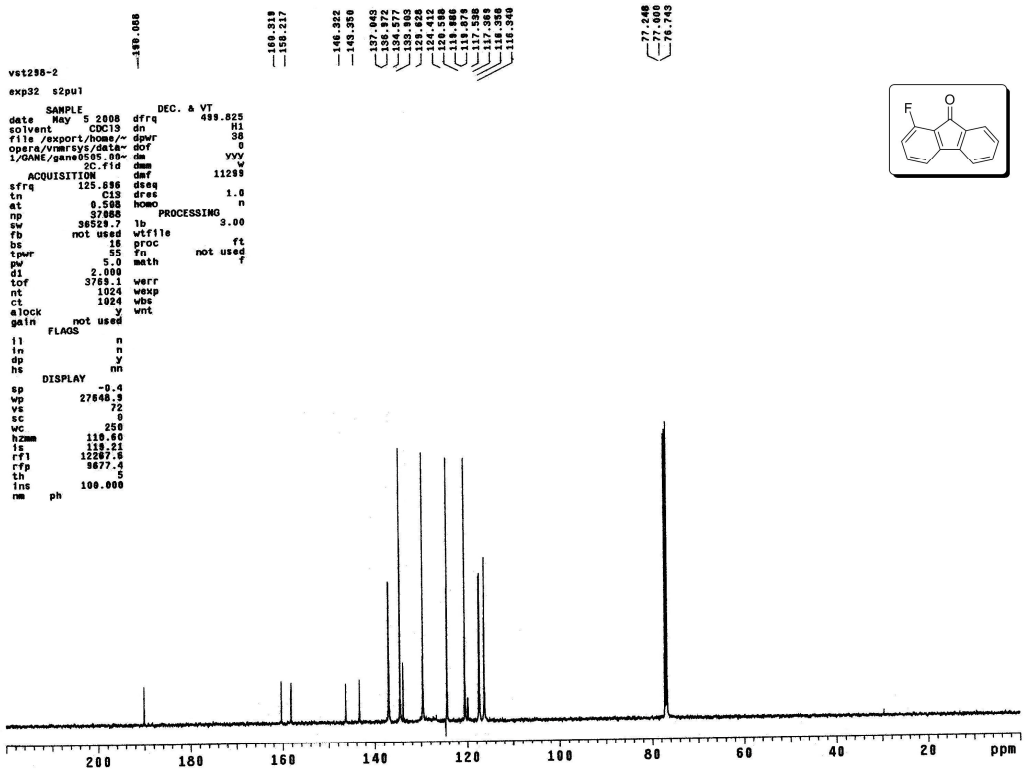
^{1}H and ^{13}C NMR spectra of compound **2l**



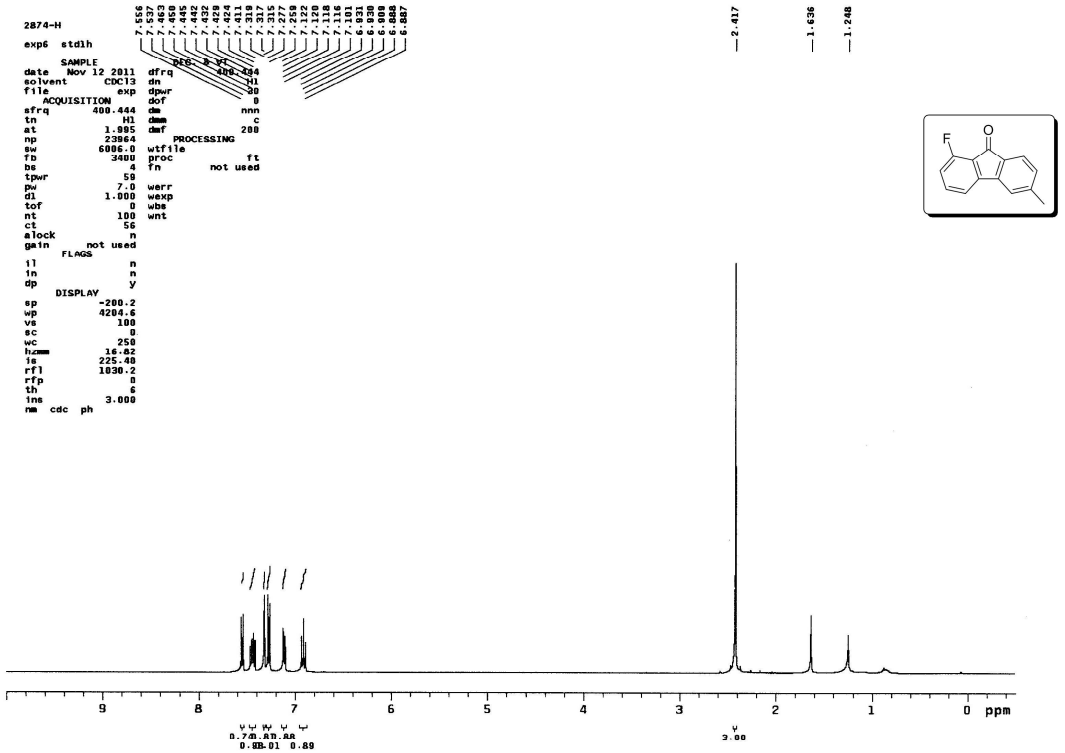


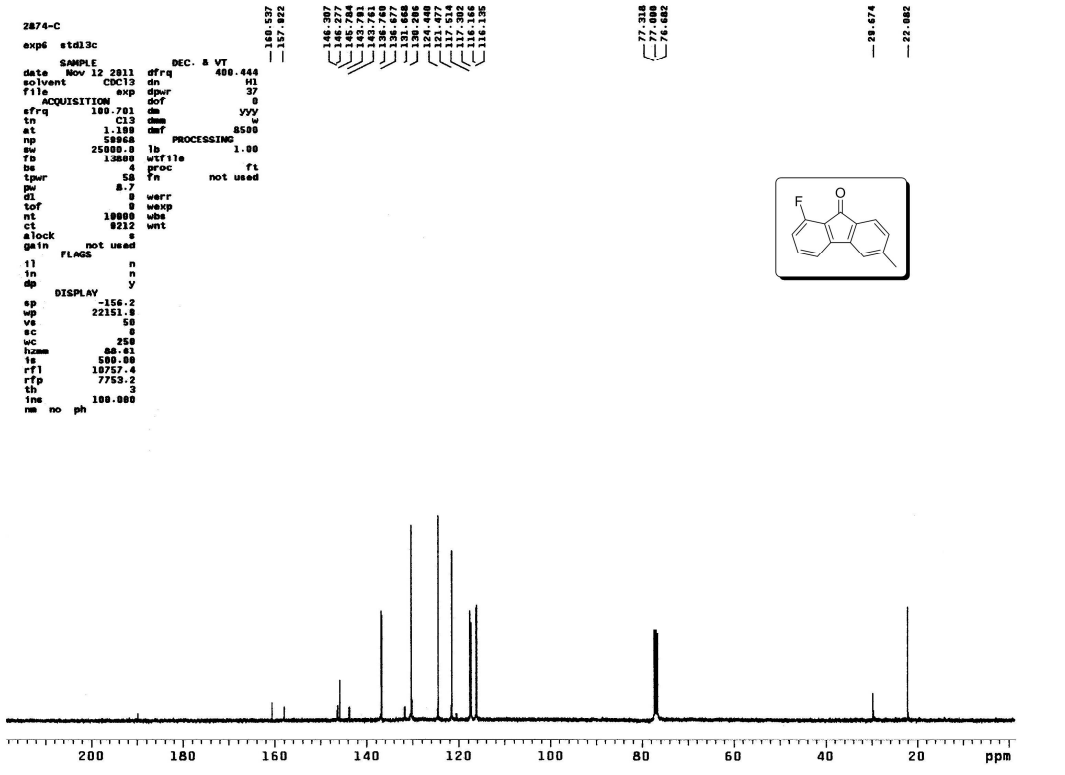
^{1}H and ^{13}C NMR spectra of compound **2m**





^{1}H and ^{13}C NMR spectra of compound **2n**





^{1}H and ^{13}C NMR spectra of compound **2o**