Supplementary Information

Facile Aerobic Photooxidation of Methyl Group in the Aromatic Nucleus in the Presence of an Organocatalyst under VIS Irradiation

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1. General Information SI-2
2. Facile Aerobic Photooxidation of Methyl Group in the Aromatic Nucleus in the Presence of an Organocatalyst under VIS Irradiation
2.1 Optimization of the Reaction Conditions (Supplementary data for Table 1) SI-2
2.2 Optimization of the Reaction Conditions (Supplementary data for Table 2) SI-4
2.3 Aerobic Photooxidation under Lower Concentration of Oxygen SI-5
2.4 Time Course of the Aerobic Photooxidation SI-5
2.5 Measurement of Peroxide by Iodometry SI-7
2.6 General Procedure SI-8

Appendix: ^{1}H and ^{13}C NMR spectra SI-10

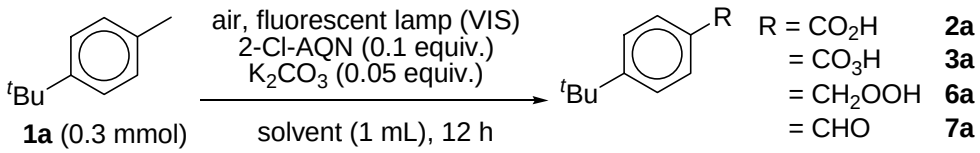
1. General Information.

All dry solvents were obtained from Kanto Kagaku Co., Ltd. Other chemicals used were of reagent grade and were obtained from Aldrich Chemical Co., Tokyo Kasei Kogyo Co., Ltd. and Wako Pure Chemical Industries, Ltd. ^{1}H NMR and ^{13}C NMR spectra were obtained on a JEOL ECA 500 spectrometer or JEOL AL 400 spectrometer or JEOL EX 400 spectrometer (500 or 400 MHz for ^{1}H NMR and 125 or 100 MHz for ^{13}C NMR). Chemical shifts (δ) are reported in parts per million (ppm) downfield from internal Me_4Si. Mass spectra (MS) were obtained on a JEOL JMS-SX102A instrument. Preparative thin-layer chromatography (TLC) was carried out on precoated plates of silica gel (MERCK, silica gel F-254).

2. Facile Aerobic Photooxidation of Methyl Group in the Aromatic Nucleus in the Presence of an Organocatalyst under VIS Irradiation

2.1. Optimization of the Reaction Conditions (Supplementary data for Table 1)

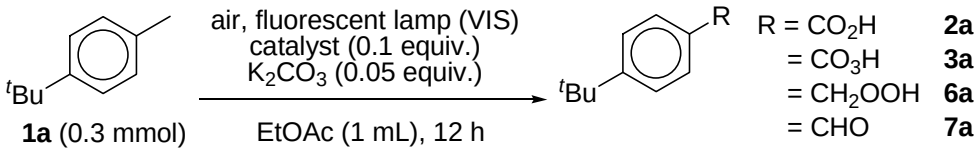
Table S1. Study of Solvent under Air



entry	solvent	yield (%)[a]				
		2a	**3a**	**6a**	**7a**	**s.m. (1a)[b]**
1	EtOAc	85	0	0	0	0
2	acetone	20	0	50	26	6
3	MeCN	0	0	49	21	11
4	MeOH	0	0	0	30	70
5	EtOH	0	0	0	28	72
6	^{i}PrOH	0	0	18	0	63
7	$^{i}Pr_2O$	0	0	trace	trace	92
8	PhH	42	10	4	13	13
9	hexane	0	0	trace	trace	78
10[c]	EtOAc	0	0	20	6	56
11[d]	EtOAc	0	0	0	0	100

[a] Yields were determined by ^{1}H-NMR. [b] Since the starting material is somewhat volatile, it is difficult to recover it perfectly even by careful work-up.[c] Under N_2. [d] In the dark.

Table S2. Study of Catalyst under Air



1a (0.3 mmol) EtOAc (1 mL), 12 h

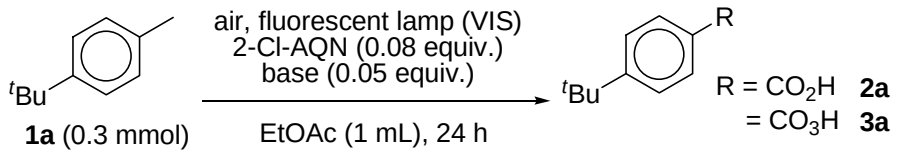
R = CO_2H **2a**
= CO_3H **3a**
= CH_2OOH **6a**
= CHO **7a**

entry	catalyst	yield (%)[a]				
		2a	**3a**	**6a**	**7a**	**s.m.(1a)[b]**
1	AQN	29	0	14	5	32
2	2-Me-AQN	54	0	11	3	19
3	2-^{t}Bu-AQN	78	0	7	3	8
4	AQN-2-CO_2H	6	0	7	3	68
5	2-Cl-AQN	85	0	0	0	0
6	1-Cl-AQN	33	0	7	4	49
7	DCA	0	0	0	0	100
8	anthracene	0	0	3	0	80
9	benzophenone	0	0	0	0	96
10	Rose bengal	0	0	0	0	89
11	Methylene blue	0	0	0	0	77

[a] Yields were determined by ^{1}H-NMR. [b] Since the starting material is somewhat volatile, it is difficult to recover it perfectly even by careful work-up.

2.2. Optimization of the Reaction Conditions (Supplementary data for Table 2)

Table S3. Study of Additive (Base) under Air

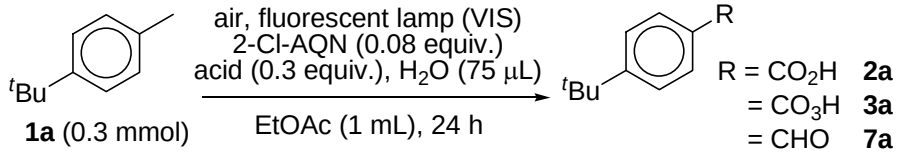


1a (0.3 mmol)

entry	base	solubility (g /100g of H_2O at 25 °C)	yield (%)[a]	
			2a	**3a**
1	Li_2CO_3	1.3	92	6
2	Na_2CO_3	29.4	55	24
3[b]	Na_2CO_3	29.4.	91	0
4[c]	Na_2CO_3	29.4	85	8
5	$NaHCO_3$	10.3	55	31
6[b]	$NaHCO_3$	10.3	88(86)[d]	0
7[c]	$NaHCO_3$	10.3	60	35
8	K_2CO_3	112.0	100(94)[d]	0
9	$CaCO_3$	0.8	38	61
10[b]	$CaCO_3$	0.8	83	17
11[c]	$CaCO_3$	0.8	76	15
12	$Ca(OH)_2$	0.2	33	60
13[b]	$Ca(OH)_2$	0.2	94(87)[d]	36
14[c]	$Ca(OH)_2$	0.2	53	36
15[e]	KOAc	256.0	84	16
16[b]	K_2CO_3	112.0	83	0

[a] Yields were determined by ^{1}H-NMR. [b] H_2O (75 μL) was used. [c] For 72 h. [d] Isolated yields. [e] For 15 h.

Table S4. Study of Additive (Acid) under Air



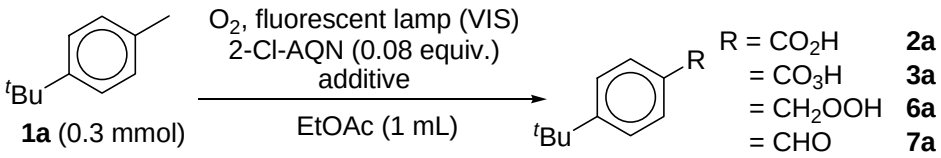
1a (0.3 mmol)

entry	acid	pKa	yield (%)[a]		
			2a	**3a**	**7a**
1	$TfSO_3H$	H_0 = -15	52	14	trace
2[b]	$TfSO_3H$	H_0 = -15	78	22	0
3	H_2SO_4	H_0 = -12	75	18	0
4	p-$TsOHH_2O$	-2.8	76	18	0
5	HBF_4	-0.4	92	0	0
6[b]	TFA	0.23	100 (99)[c]	0	0
7	CCl_3CO_2H	0.77	94	0	0
8	F_2CHCO_2H	1.24	64	32	0
9	AcOH	4.74	42	53	0
10[b]	AcOH	4.74	83	10	0
11[d]	TFA	0.23	81	12	0

[a] Yields were determined by ^{1}H-NMR. [b] For 72 h. [c] Isolated yields. [d] H_2O was not added.

2.3. Aerobic Photooxidation under Low Concentration of Oxygen

Table S5. Aerobic Photooxidation under Low Concentration of O_2



entry	additive	O_2 (%)	time (h)	yield (%)[a] 2a	3a	6a	7a
1	TFA (0.3 equiv.) / H_2O (75 μL)	10	24	93 (93)	0	0	0
2	TFA (0.3 equiv.) / H_2O (75 μL)	5	24	87	5	0	trace
3	TFA (0.3 equiv.) / H_2O (75 μL)	5	30	96 (100)	0	0	0
4	K_2CO_3 (0.05 equiv.)	10	12	83 (79)	2	7	10
5	K_2CO_3 (0.05 equiv.)	10	15	100 (88)	0	0	0
6	K_2CO_3 (0.05 equiv.)	10	18	(95)	0	0	0
7	K_2CO_3 (0.05 equiv.)	5	18	67	0	13	15
8	K_2CO_3 (0.05 equiv.)	5	24	99 (95)	0	0	0

[a] Yields were determined by ^{1}H-NMR. Numbers in parentheses were isolated yields.

2.4. Time Course of the Aerobic Photooxidation

Figure 1. Without Additive

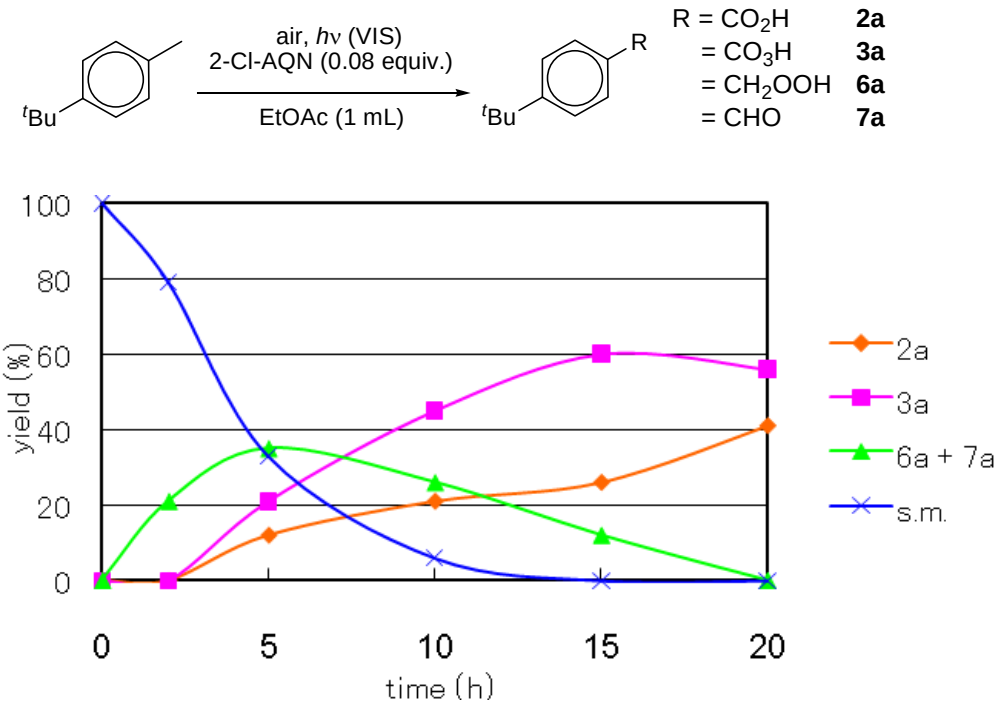


Figure 2. With TFA / H_2O

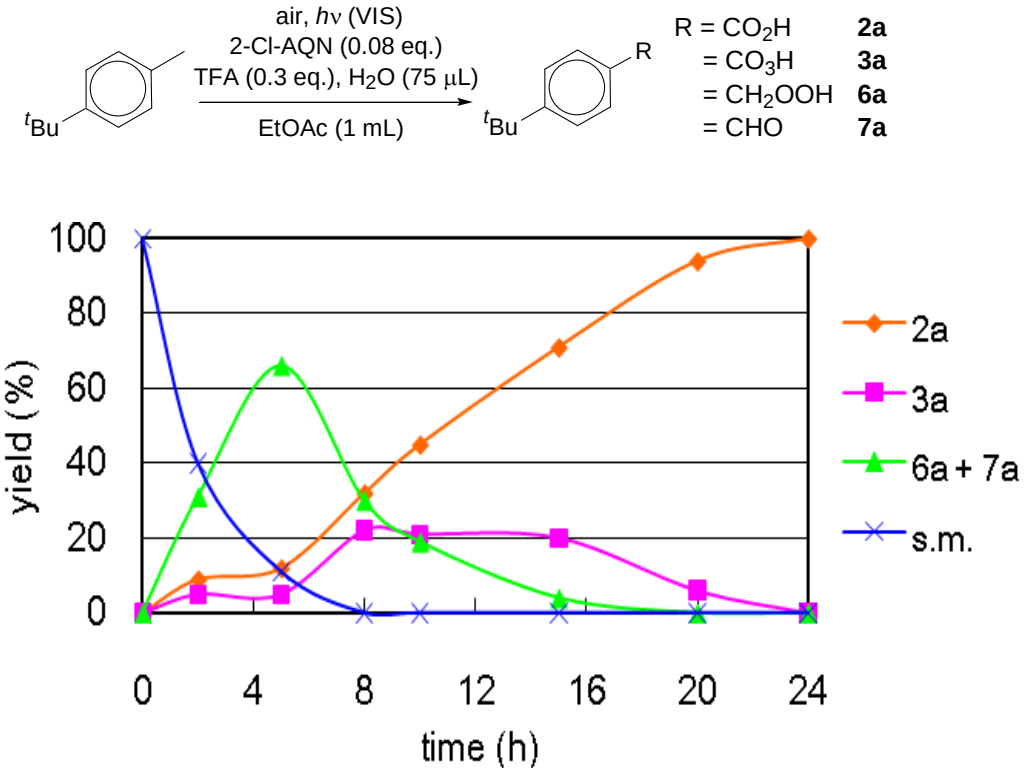
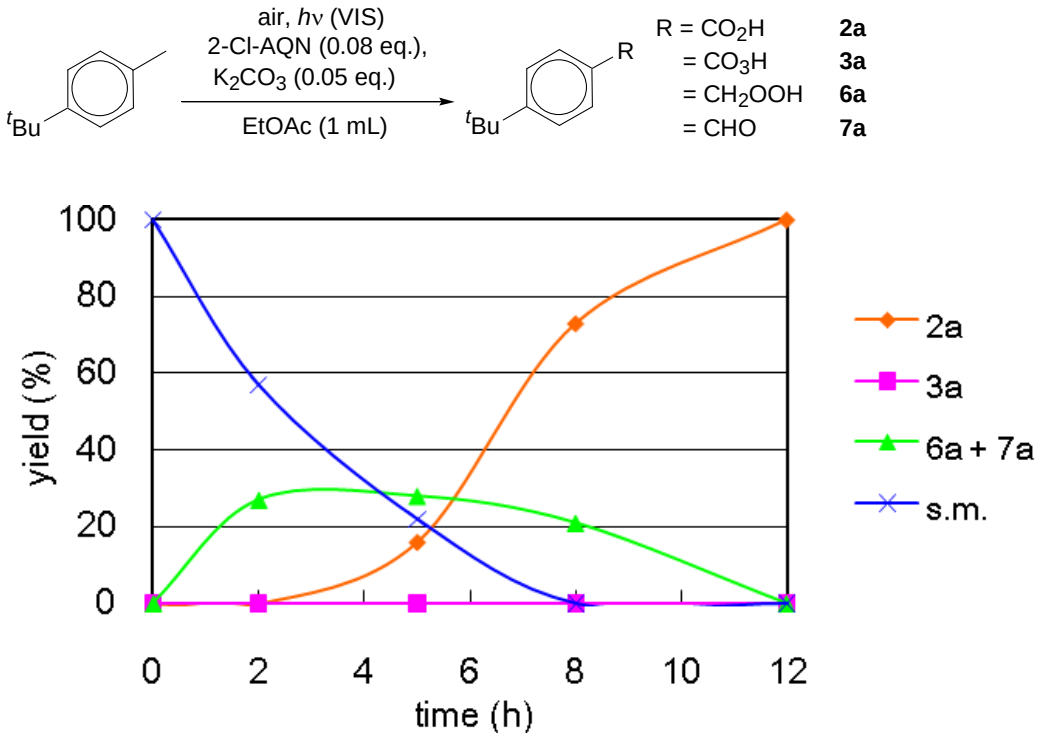


Figure 3. With K_2CO_3



2.5. Measurement of Peroxide by Iodometry

Typical procedure is as follows; 4-*tert*-butyltoluene (0.3 mmol) is oxidized with 2-Cl-AQN (0.08 equiv.), TFA (0.3 equiv.) and H_2O (75 μL) in EtOAc (1 mL) under irradiation of VIS from fluorescent lamp (22w x 4) in an air atmosphere for 24 h, which usually gives 4-*tert*-butylbenzoic acid quantitatively. The residue is mixed with saturated aq. KI (3 mL), AcOH (1 mL) and *i*-PrOH (10 mL), and warmed at 100°C for 5 min. The result solution is titrated by 0.1 M aq. $Na_2S_2O_3$, and the volumes of required 0.1 M aq. $Na_2S_2O_3$ are 5.9 and 5.5 mL for two trials. These results correspond to 0.18 and 0.16 mmol of peroxides respectively after subtracting the required volume of 0.1 M aq. $Na_2S_2O_3$ for blank experiment.

2.6. General Procedure

Aerobic photooxidation: A solution of substrate (0.3 mmol), 2-Cl-AQN (0.08 equiv) and additive in dry EtOAc (1 mL) in a Pyrex test tube under an air atmosphere is stirred and irradiated externally with four 22W fluorescent lamps for indicated time. The product is extracted with 10% aq. $NaHCO_3$. Then the aq. solution is acidified with 2N aq. HCl and extracted with Et_2O. The product is purified by PTLC.

4-*tert*-Butylbenzoic acid (2a): colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.06 (d, *J* = 8.7 Hz, 2H), 7.49 (d, *J* = 8.7 Hz, 2H), 1.35 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.6, 157.7, 130.2, 126.7, 125.6, 35.3, 31.2; MS m/z 178 (M^+), 163, 135, 91; CAS Registry Number: 98-73-7

***p*-Toluic acid (2b)**: colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.00 (d, *J* = 8.6 Hz, 2H), 7.27 (d, *J* = 8.6 Hz, 2H), 2.43 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.5, 144.7, 130.4, 129.3, 126.7, 21.9; MS m/z 136 (M^+), 119, 91; CAS Registry Number: 99-94-5

***m*-Toluic acid (2c)**: colorless solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (s, 1H), 7.93 (d, *J* = 8.2 Hz, 1H), 7.41 (d, *J* = 7.3 Hz, 1H), 7.38-7.34 (m, 1H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.6, 138.3, 134.6, 130.7, 129.2, 128.4, 127.4, 21.2; MS m/z 136 (M^+), 119, 91; CAS Registry Number: 99-04-7

***o*-Toluic acid (2d)**: colorless solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09-8.07 (m, 1H), 7.47-7.43 (m, 1H), 7.30-7.25 (m, 2H), 2.67 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 141.4, 132.9, 131.9, 131.6, 128.3, 125.8, 22.1; MS m/z 136 (M^+), 118, 91; CAS Registry Number: 118-90-1

***p*-Methoxybenzoic acid (2e)**: colorless solid; ^{1}H NMR (400 MHz, acetone-d_6) δ 7.96 (d, *J* = 9.2 Hz, 2H), 7.0 (d, *J* = 9.2 Hz, 2H), 3.85 (s, 3H); ^{13}C NMR (100 MHz, acetone-d_6) δ 167.5, 164.4, 132.5, 123.7, 114.5, 55.8; MS m/z 152 (M^+), 135, 107; CAS Registry Number: 100-09-4

***p*-Bromobenzoic acid (2f)**: colorless solid; ^{1}H NMR (500 MHz, acetone-d_6) δ 7.93 (d, *J* = 8.6 Hz, 2H), 7.67 (d, *J* = 8.6 Hz, 2H); ^{13}C NMR (100 MHz, acetone-d_6) δ 166.9, 132.6, 132.3, 130.7, 128.1; MS m/z 200 (M^+), 183, 155; CAS Registry Number: 586-76-5

***p*-Chlorobenzoic acid (2g)**: colorless solid; ^{1}H NMR (500 MHz, acetone-d_6) δ 8.01 (d, *J* = 8.6 Hz, 2H), 7.53 (d, *J* = 8.6 Hz, 2H); ^{13}C NMR (100 MHz, acetone-d_6) δ 166.7, 139.5, 132.1, 130.3, 129.5; MS m/z 156 (M^+), 139, 111; CAS Registry Number: 74-11-3

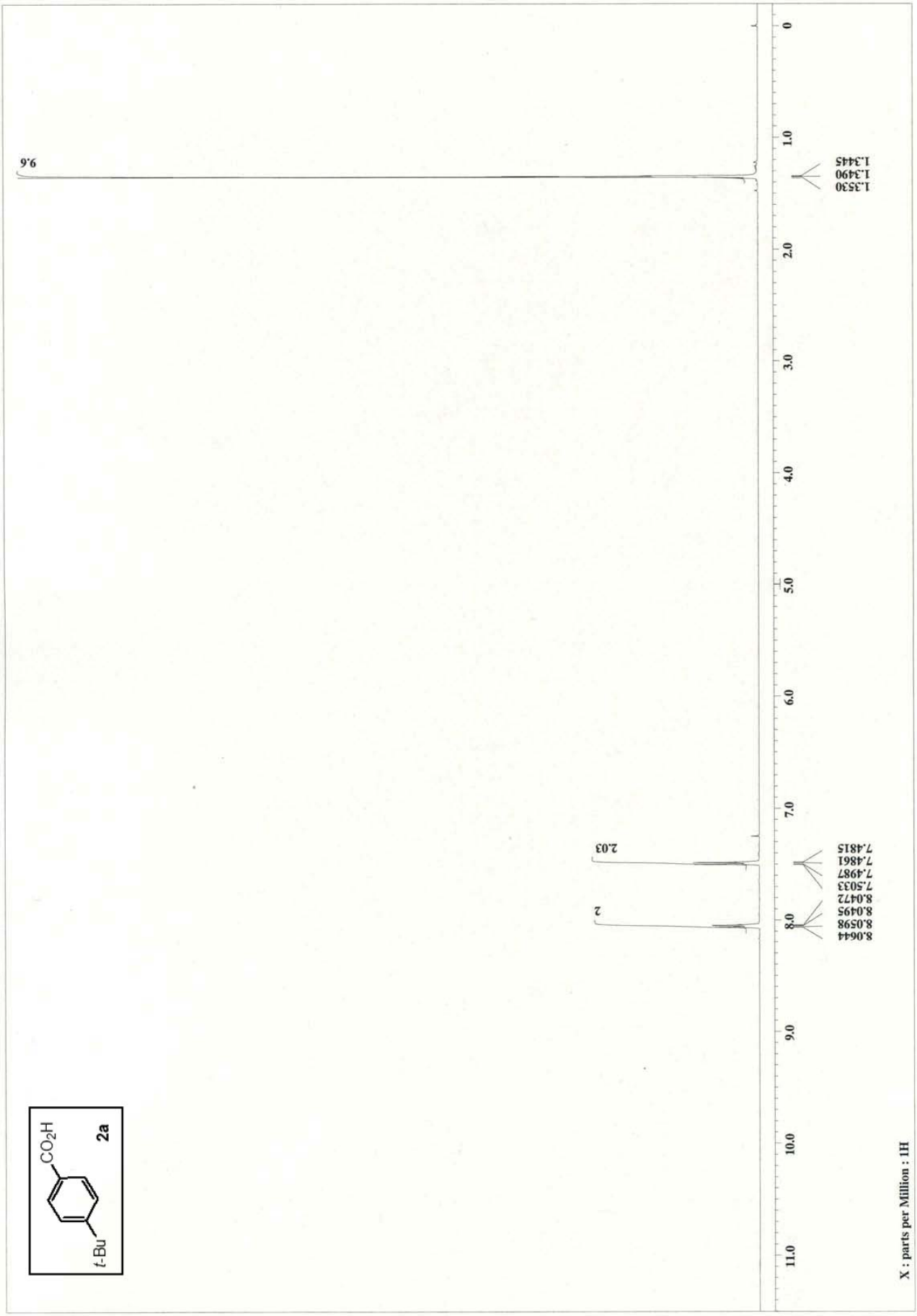
Benzoic acid (2h): colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.13 (d, *J* = 7.4 Hz, 2H), 7.62 (t, *J* = 7.4 Hz, 1H), 7.48 (t, *J* = 7.4 Hz, 2H); ^{13}C NMR (125 MHz, acetone-d_6) δ 172.6, 133.9, 130.3, 129.4, 128.6; MS m/z 122 (M^+), 105, 77; CAS Registry Number: 65-85-0

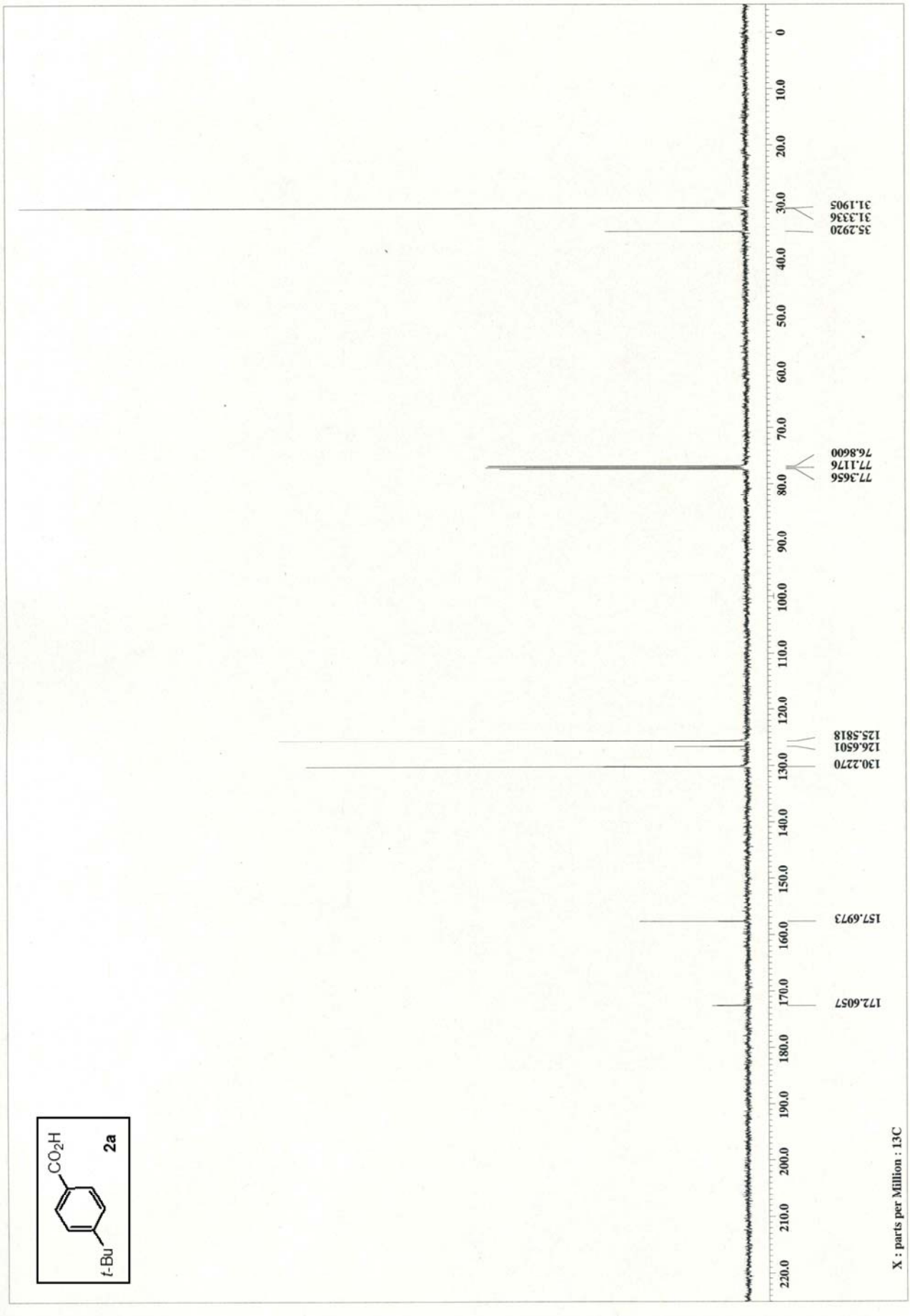
***p*-Phenylbenzoic acid (2i)**: colorless solid; ^{1}H NMR (500 MHz, acetone-d_6) δ 8.10 (d, *J* = 8.6 Hz, 2H), 7.78 (d, *J* = 8.6 Hz, 2H), 7.71 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.40 (t, *J* = 7.5 Hz, 1H); ^{13}C

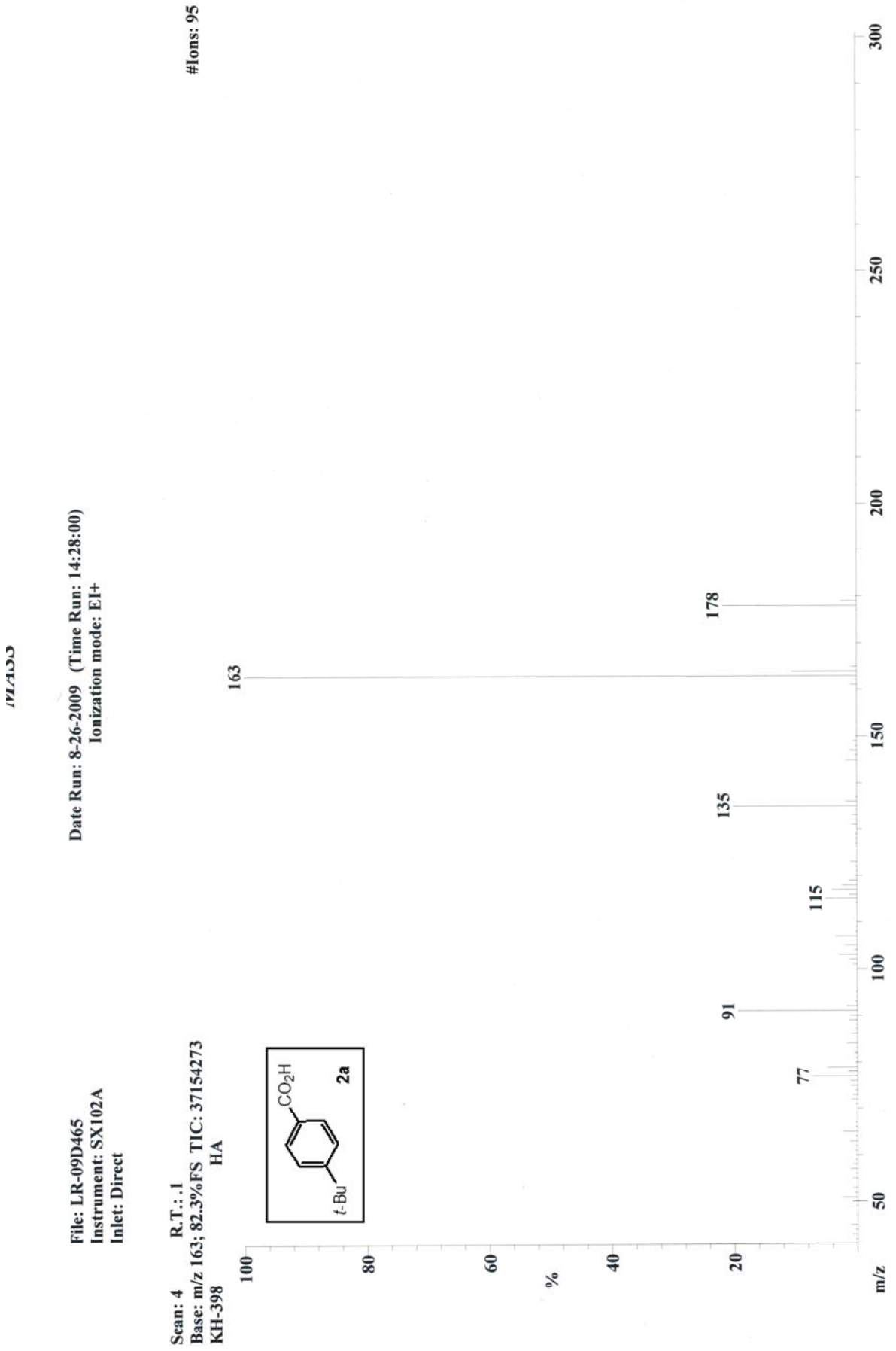
NMR (100 MHz, acetone-d_6) δ 167.5, 146.1, 140.7, 131.0, 130.4, 129.9, 129.0, 128.0, 127.7; MS m/z 198 (M^+), 181, 152; CAS Registry Number: 92-92-2

***p*-Benzoylbenzoic acid (2j)**: colorless solid; ^{1}H NMR (500 MHz, acetone-d_6) δ 8.19 (d, J = 8.6 Hz, 2H), 7.86 (d, J = 8.6 Hz, 2H), 7.79 (d, J = 7.4 Hz, 2H), 7.68 (t, J = 7.4 Hz, 1H), 7.56 (t, J = 7.4 Hz, 2H); ^{13}C NMR (125 MHz, acetone-d_6) δ 195.3, 166.3, 141.4, 137.2, 133.8, 132.9, 129.9, 129.7, 128.6; MS m/z 226 (M^+), 181, 149, 105; CAS Registry Number: 611-95-0

4,4'-Oxybis-benzoic acid (2k): white powder; ^{1}H NMR (500 MHz, DMSO-d_6) δ 7.96 (d, J = 9.2 Hz, 2H), 7.11 (d, J = 9.2 Hz, 2H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 167.2, 160.0, 132.3, 126.9, 119.2; MS m/z 258 (M^+), 241; CAS Registry Number: 2215-89-6.



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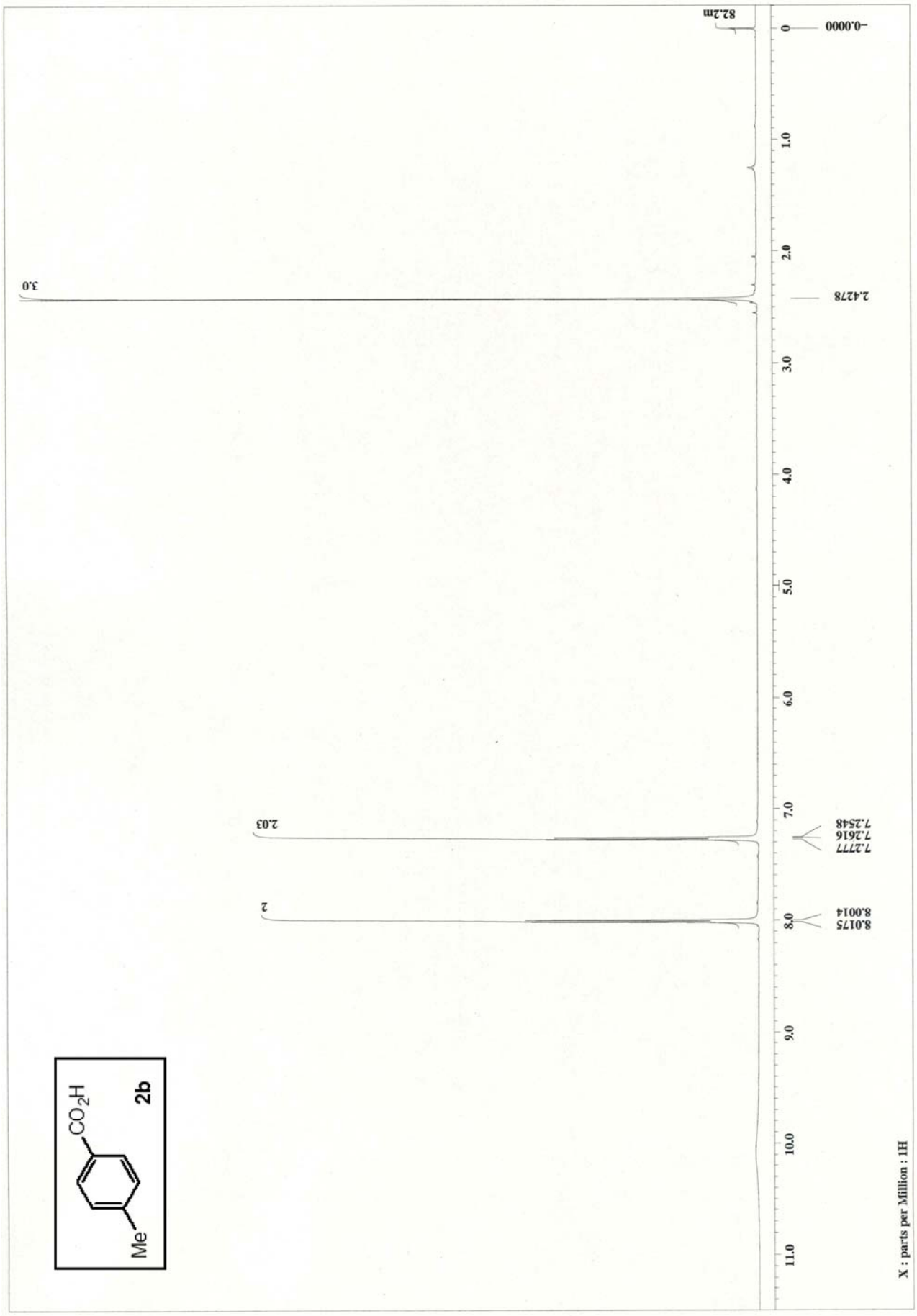

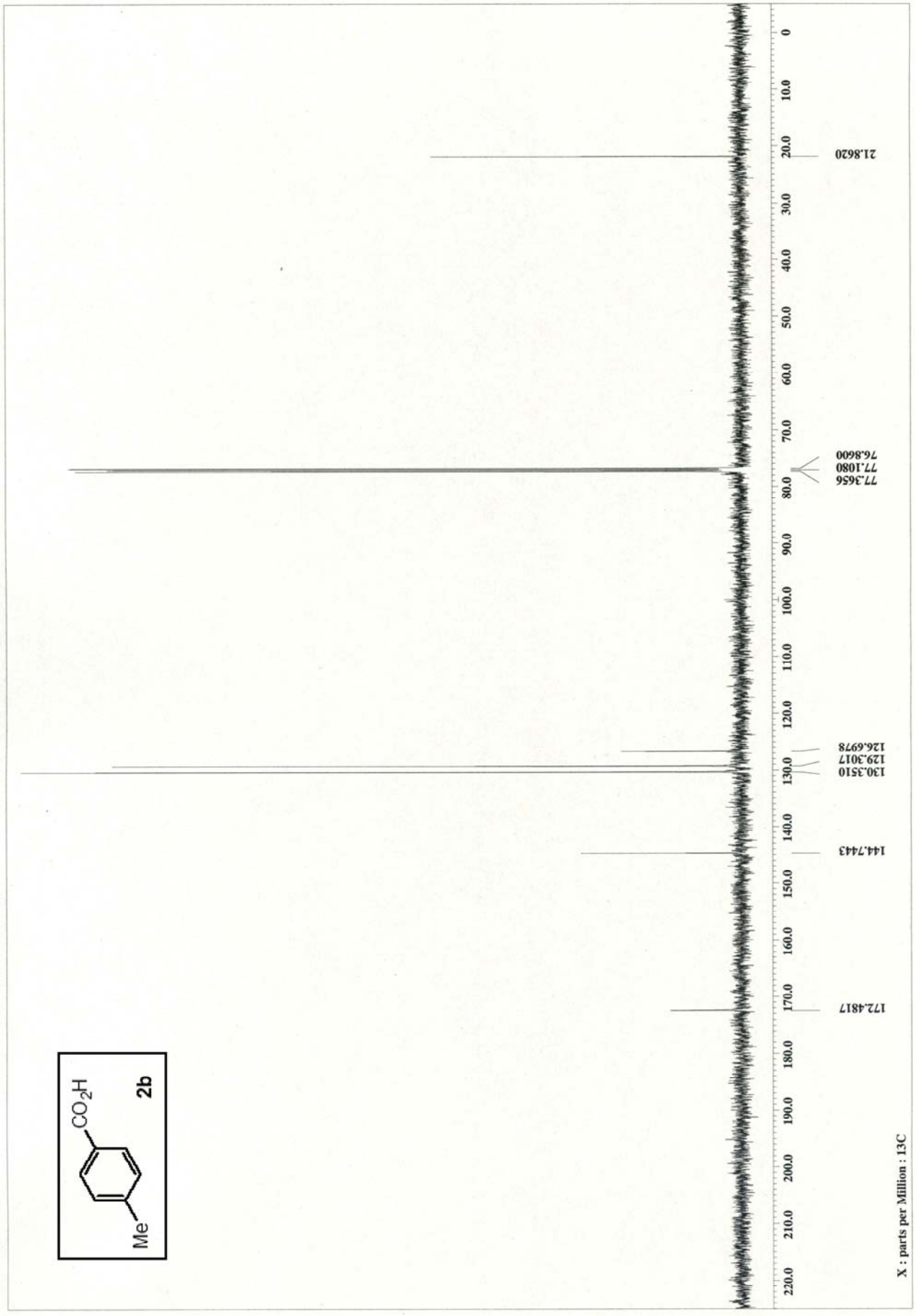

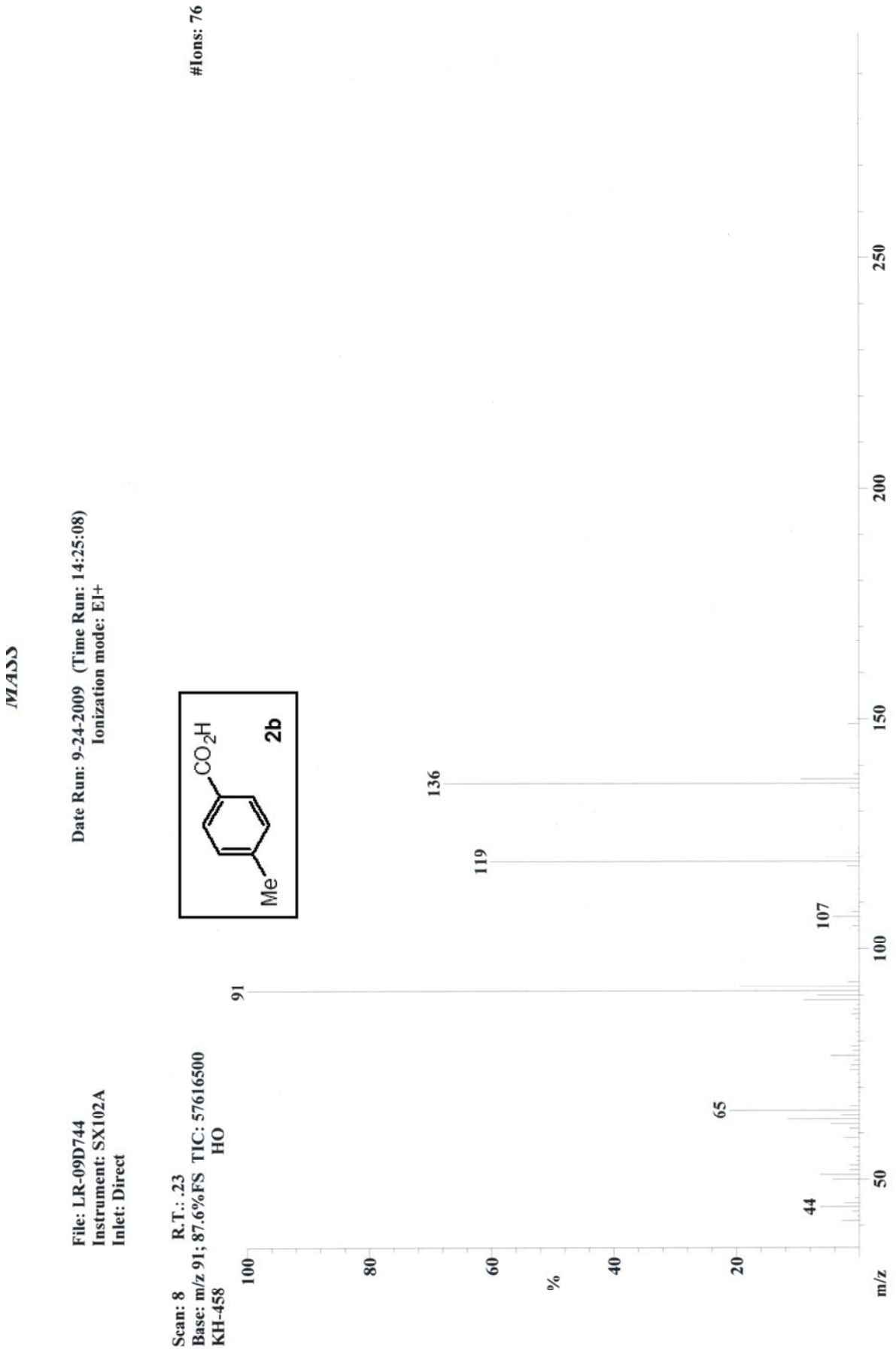

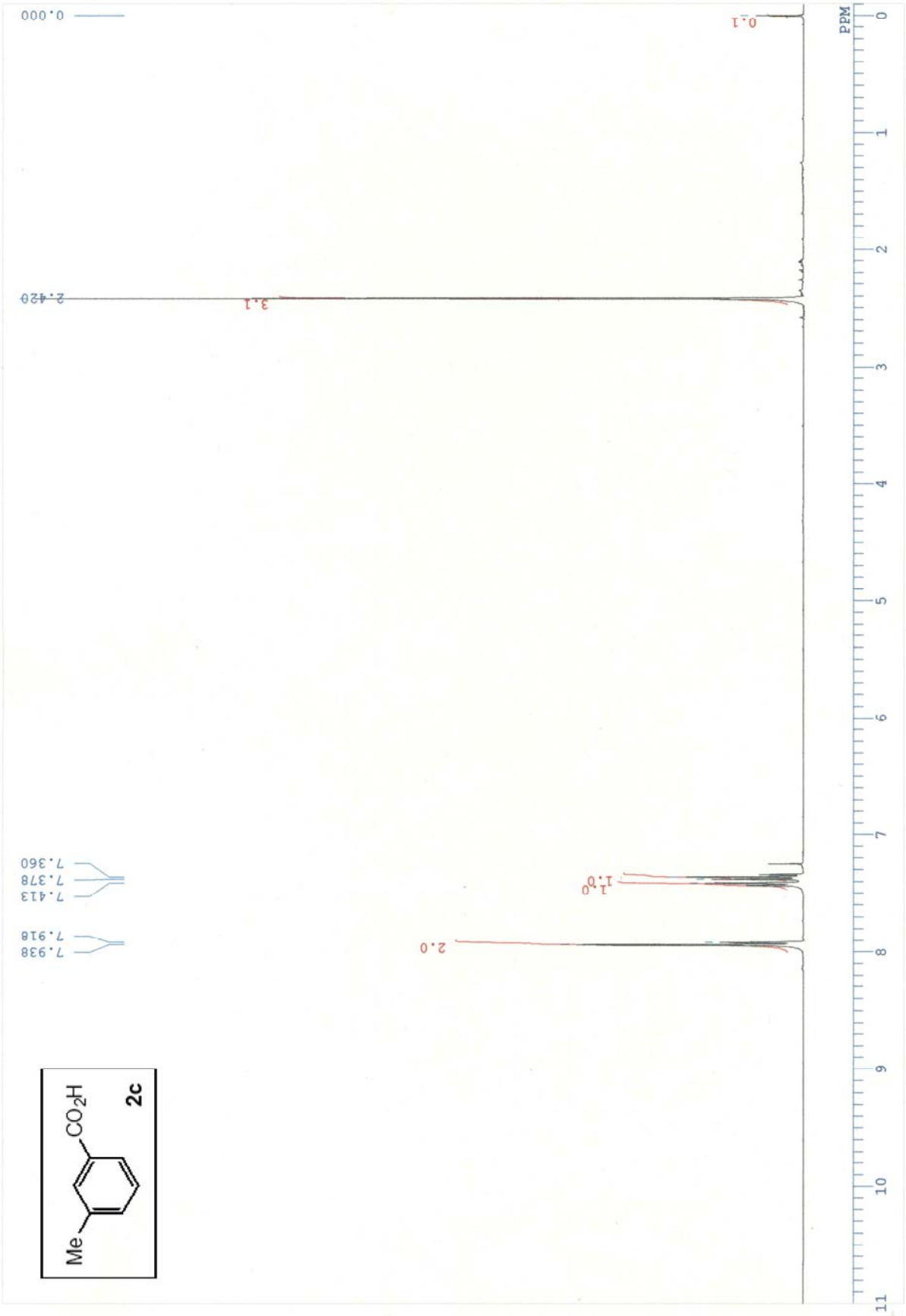

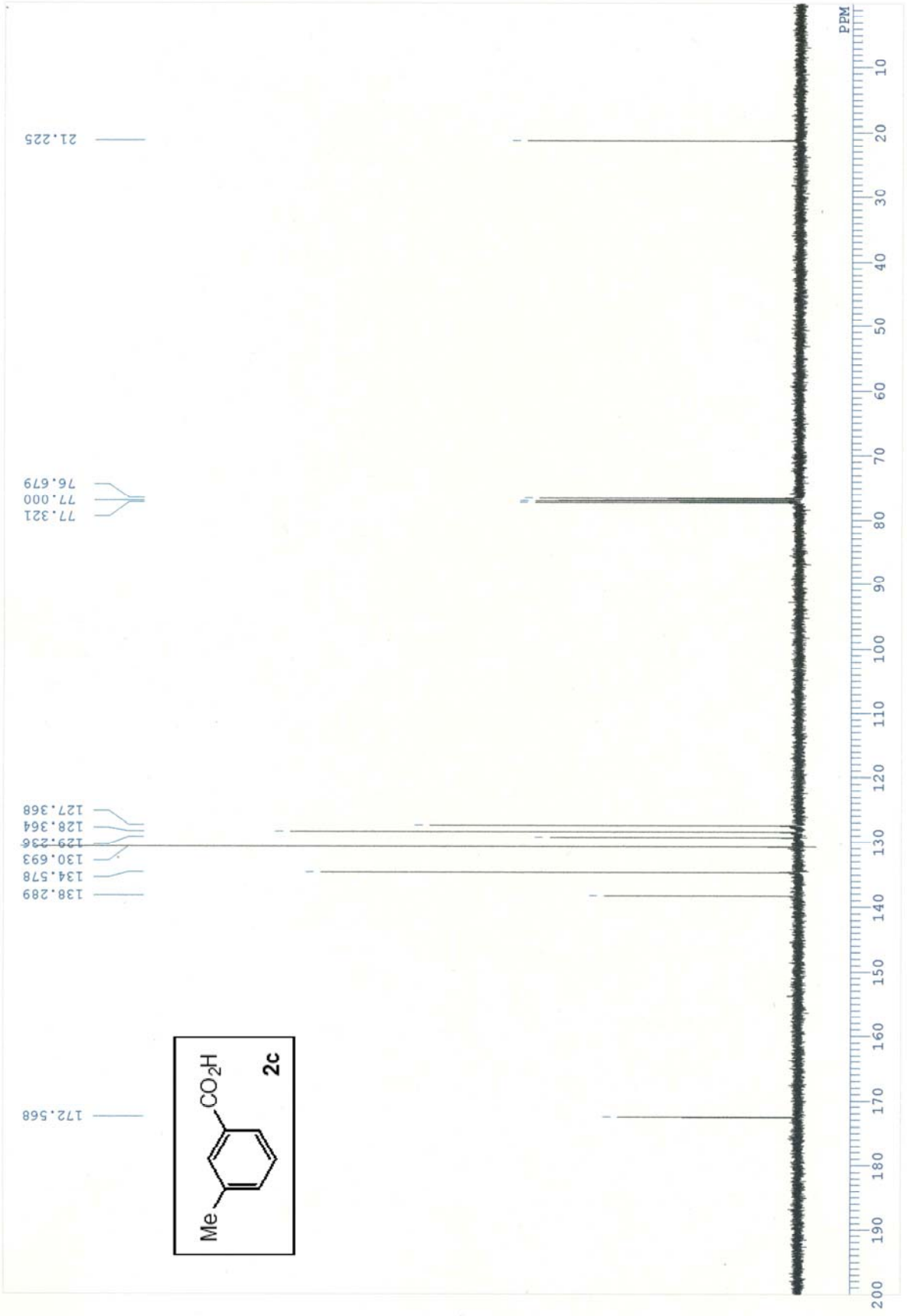

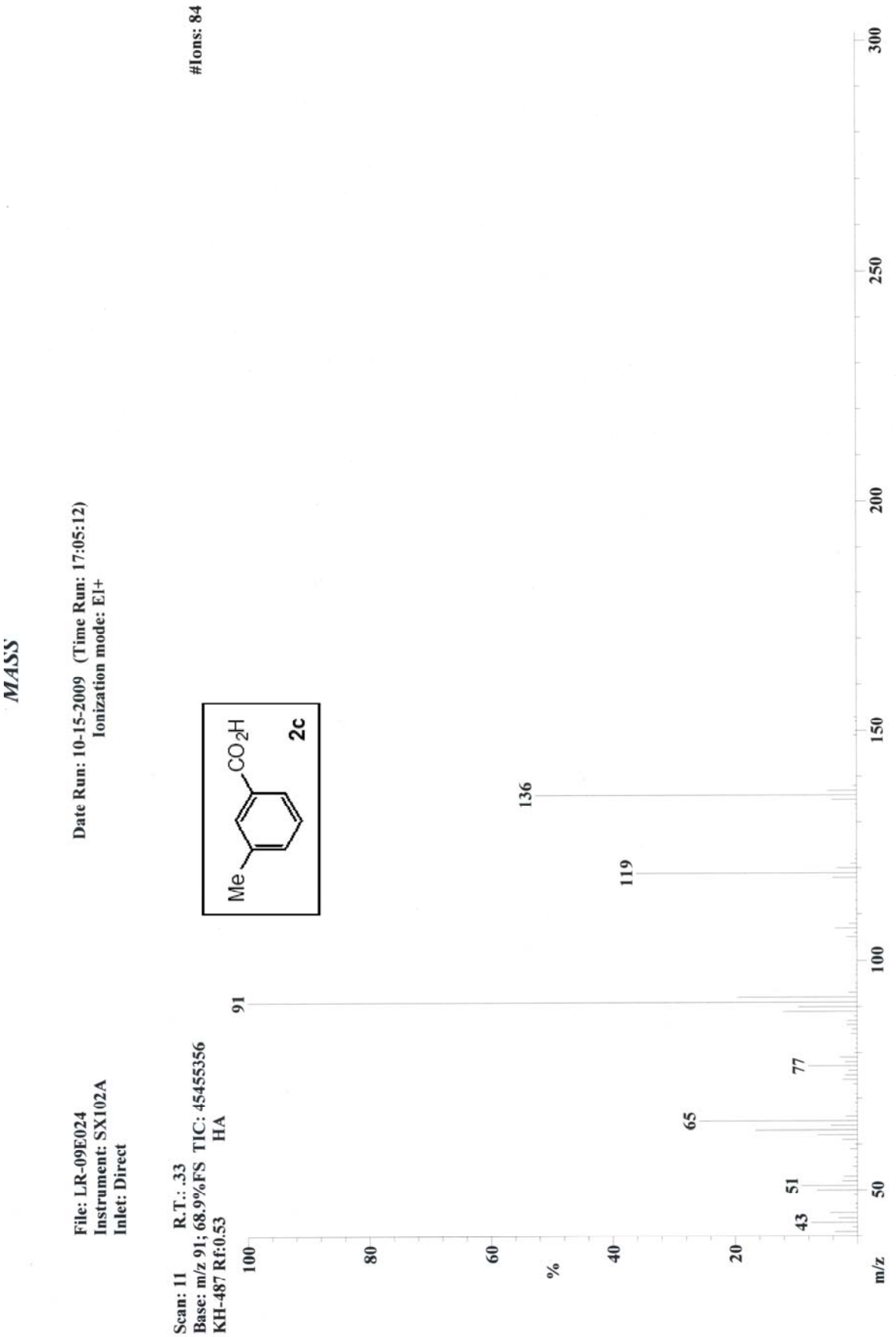
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2c
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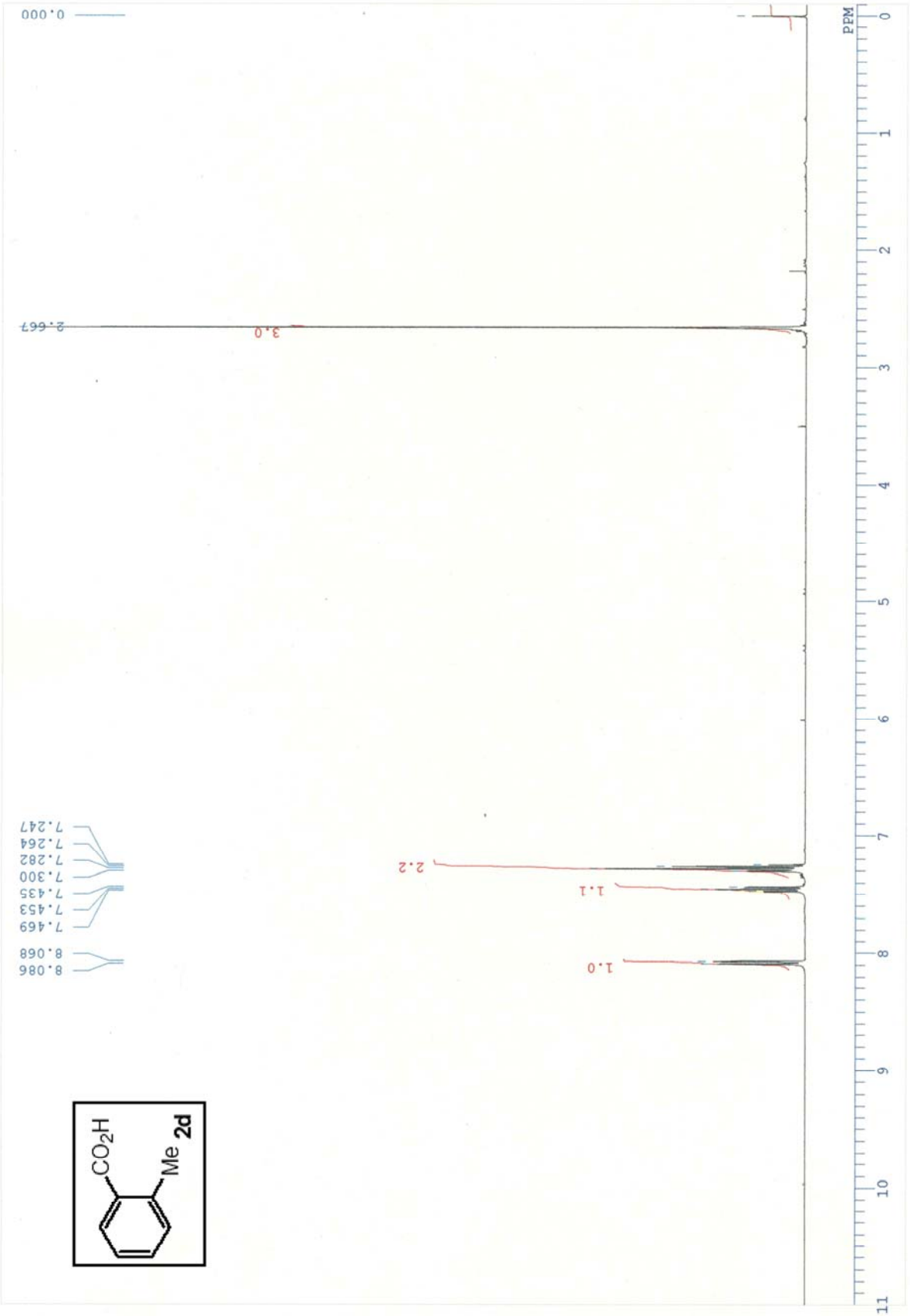

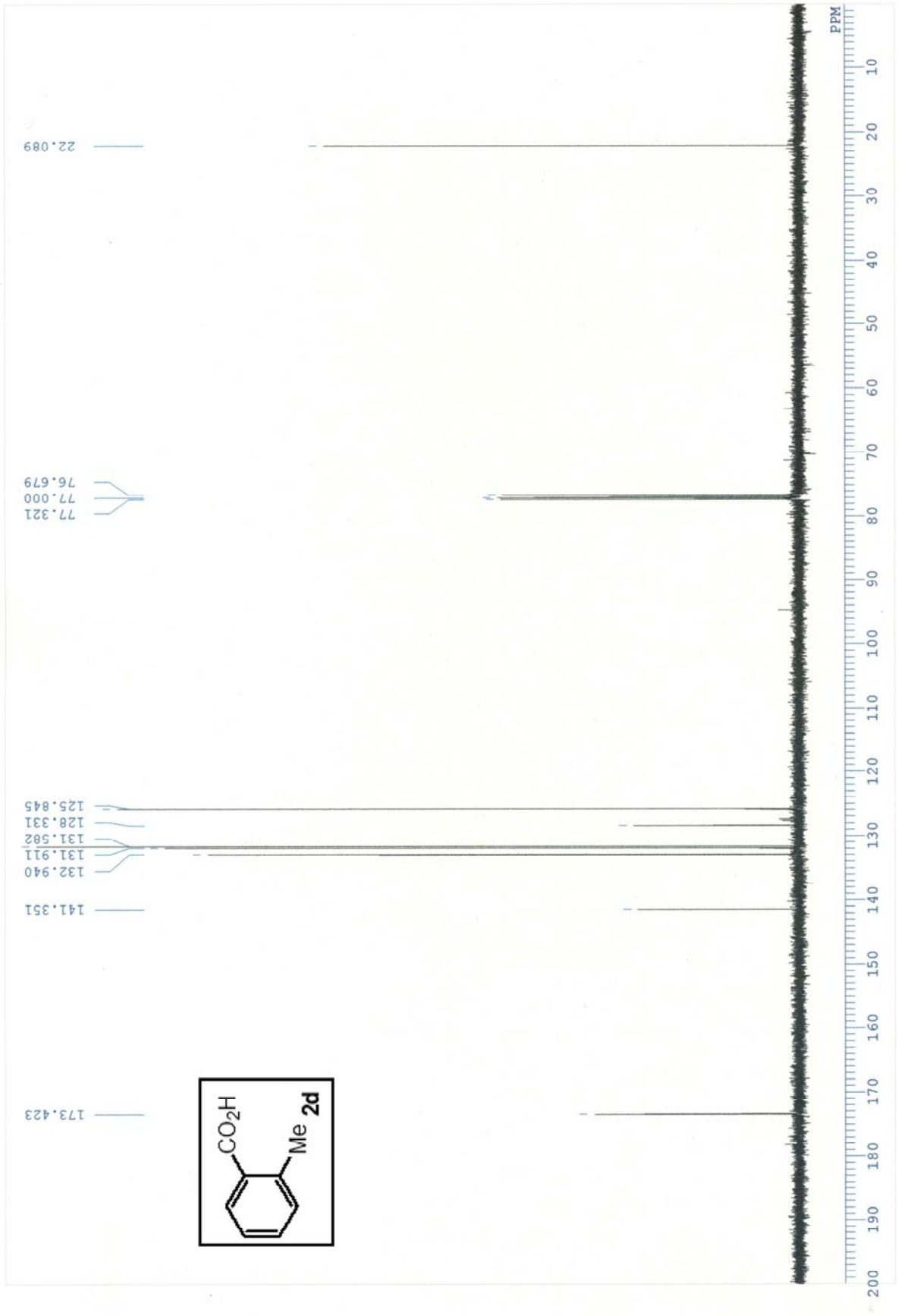

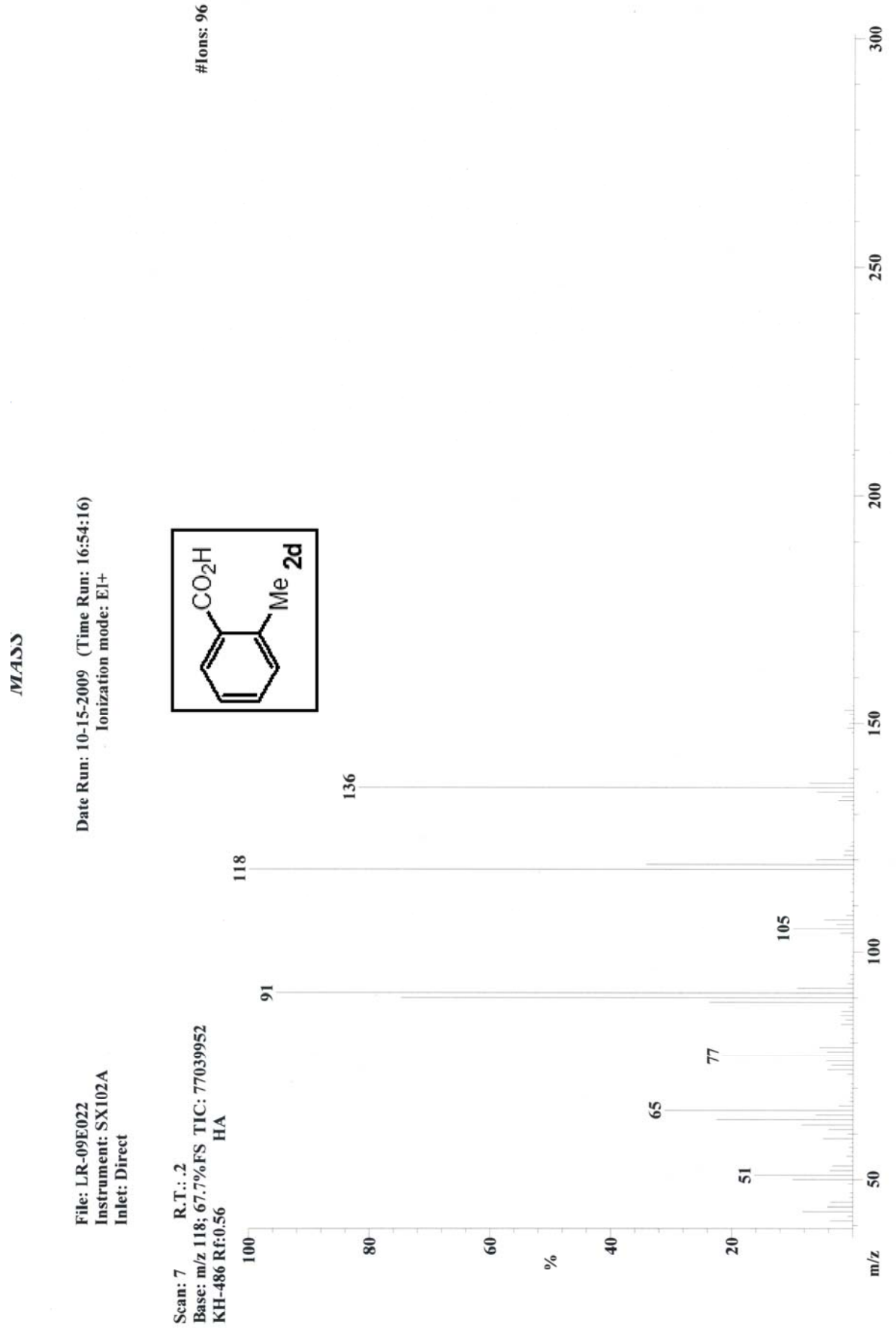
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91
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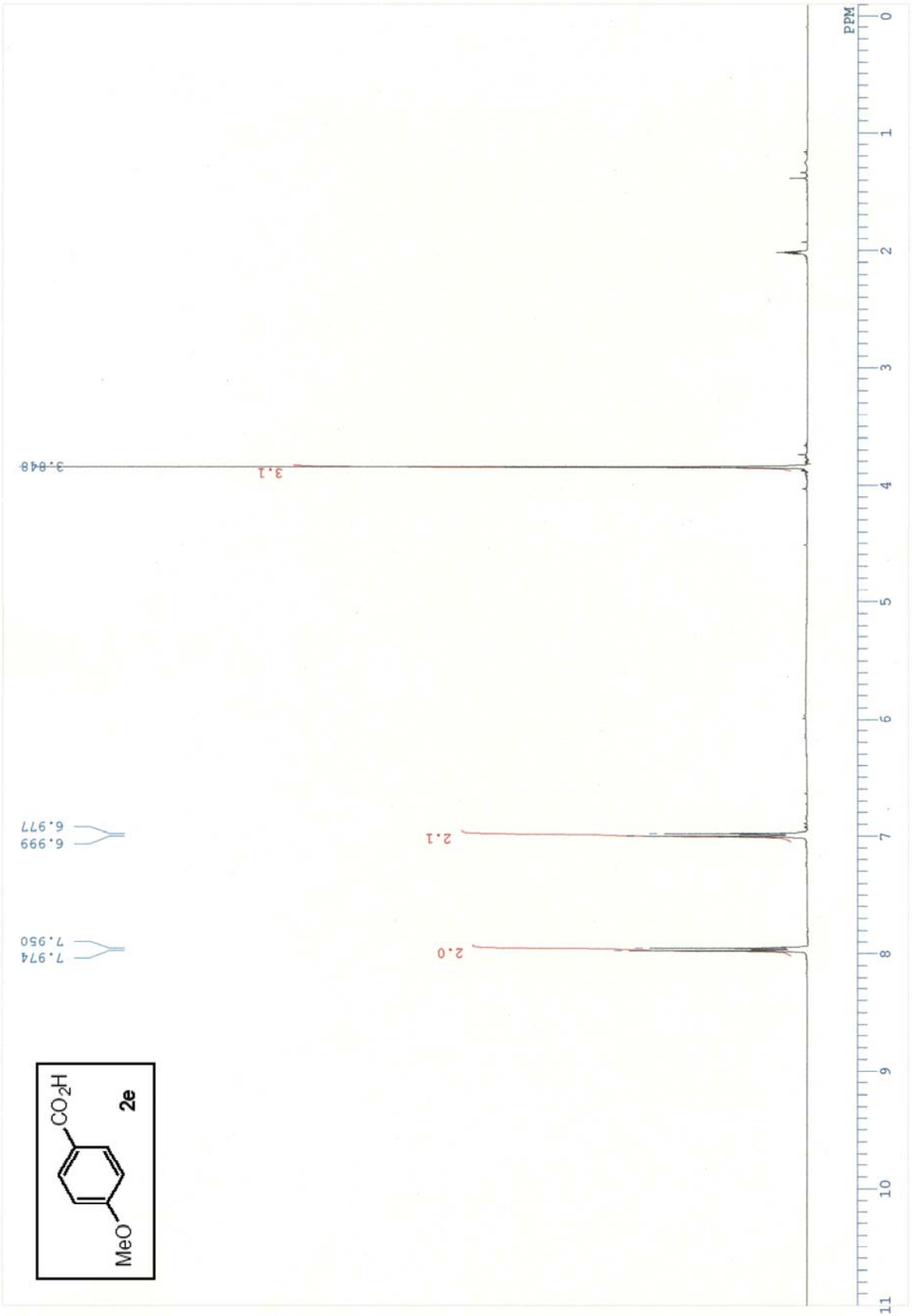
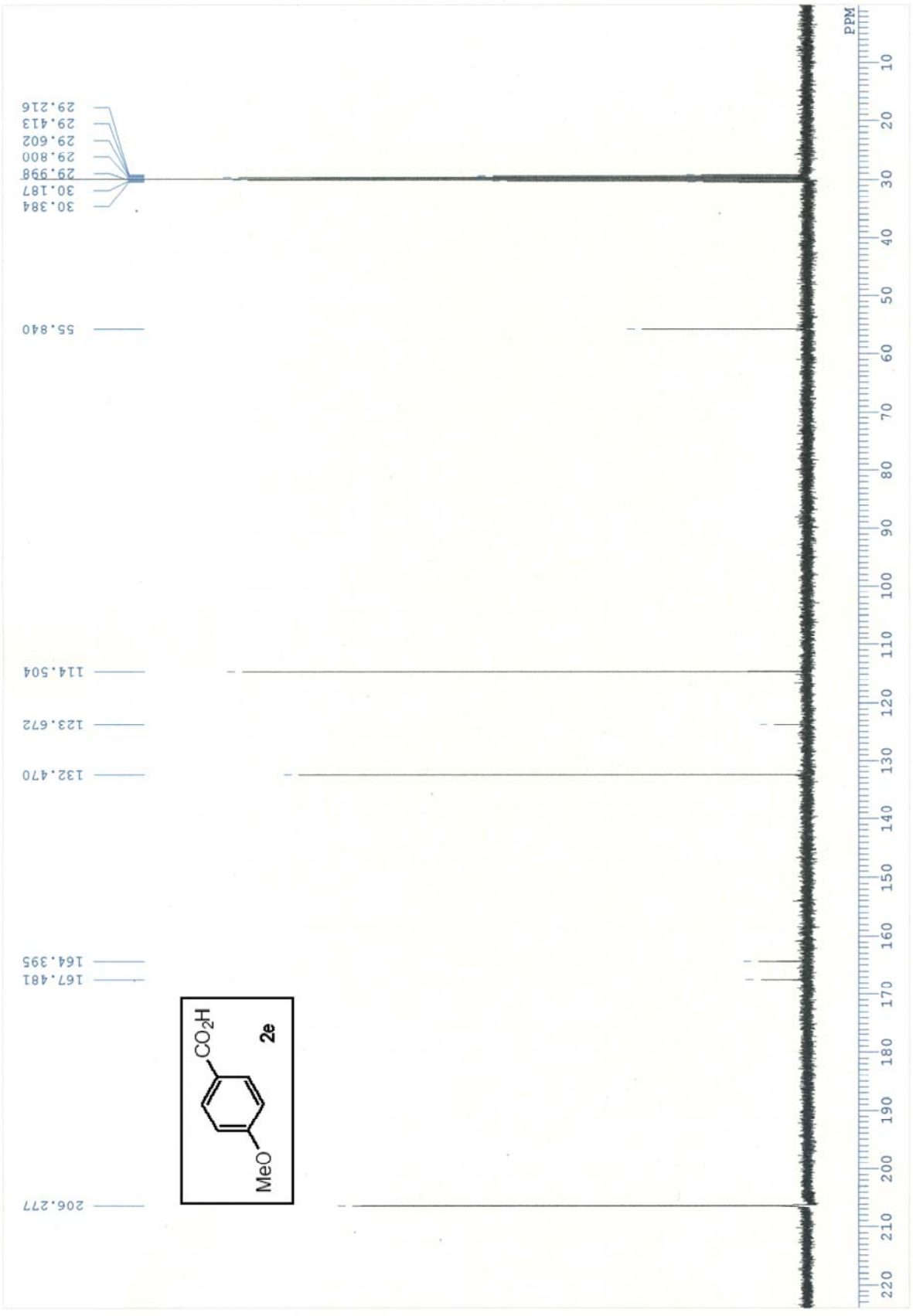
136





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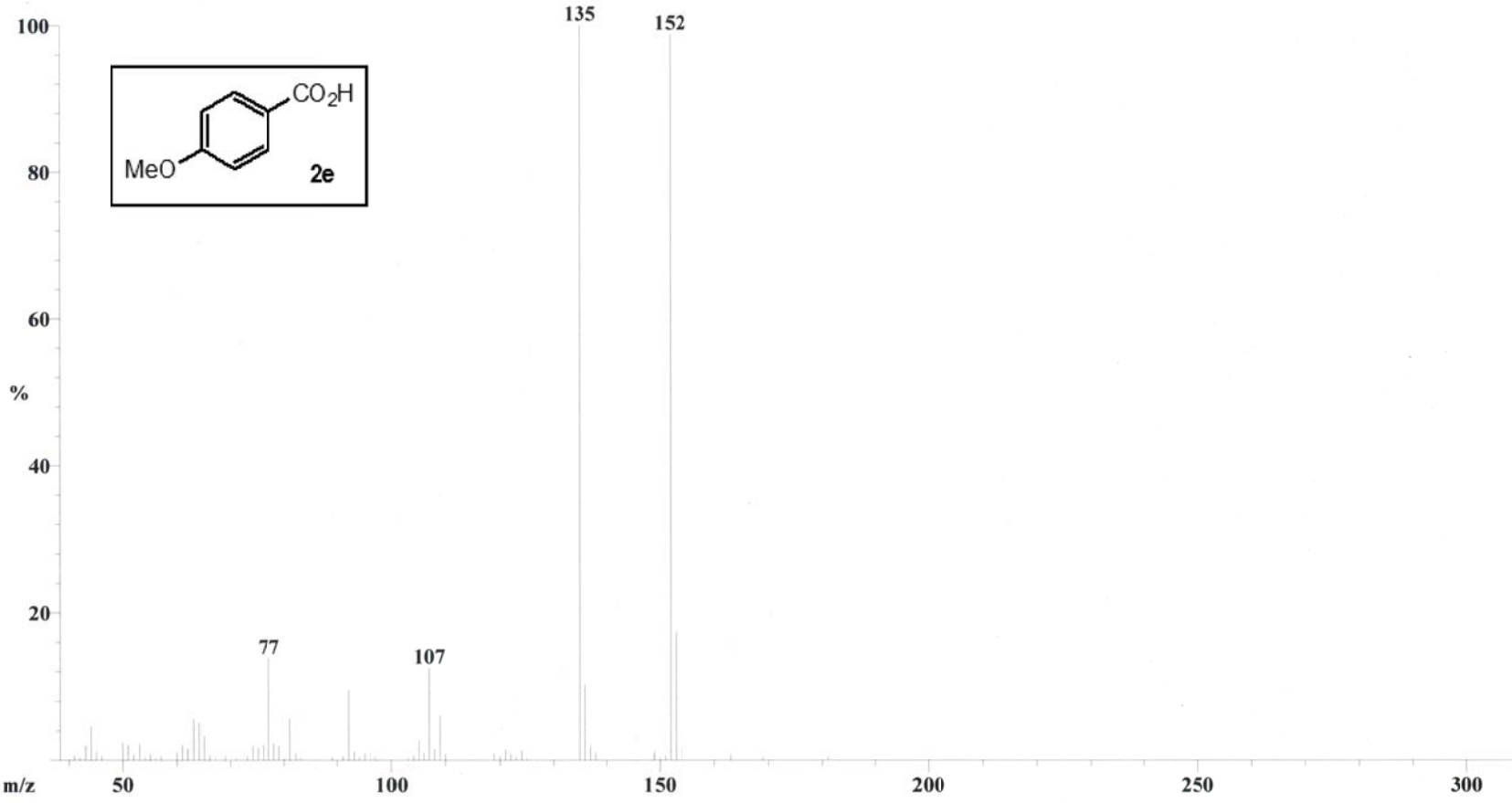
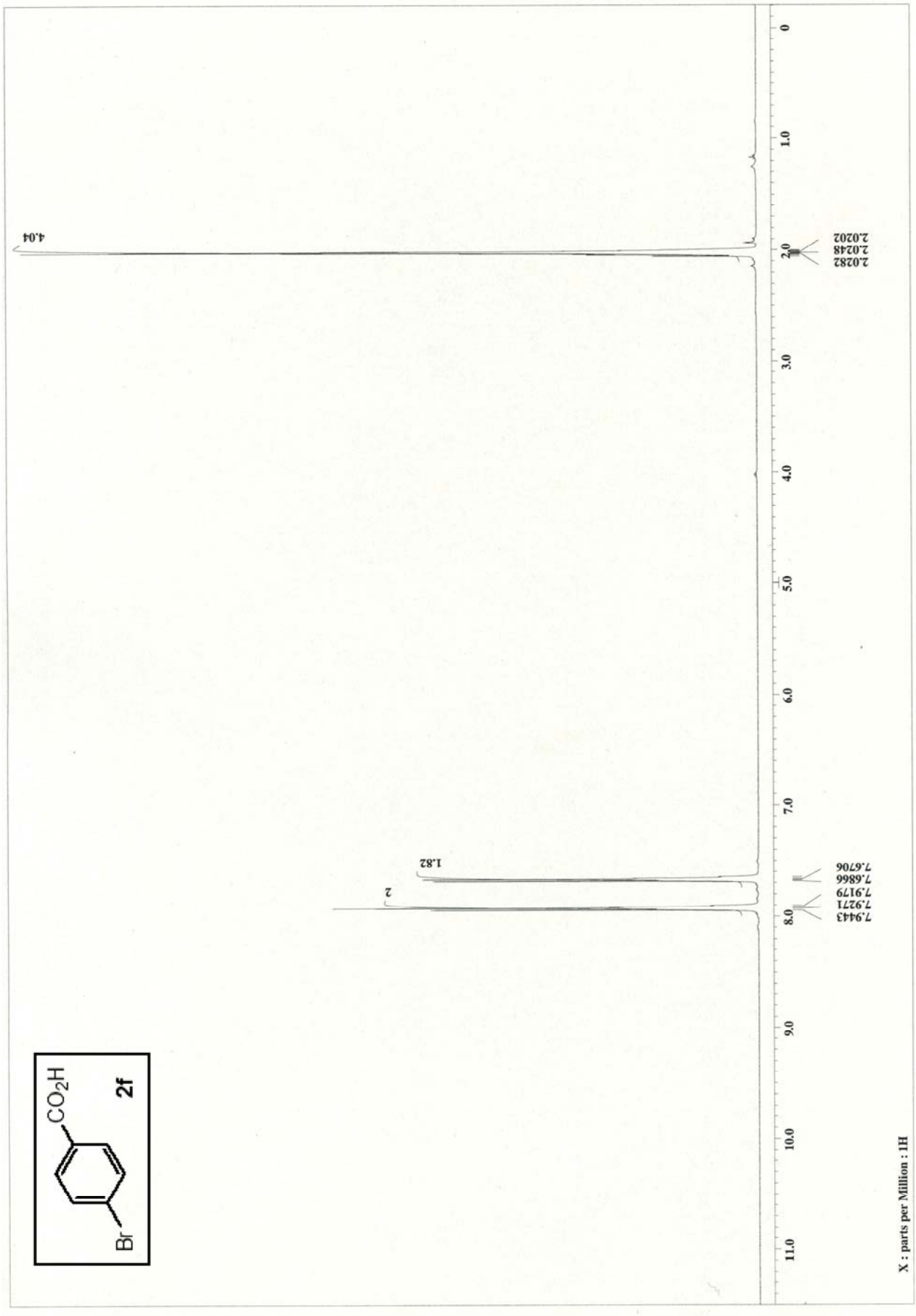
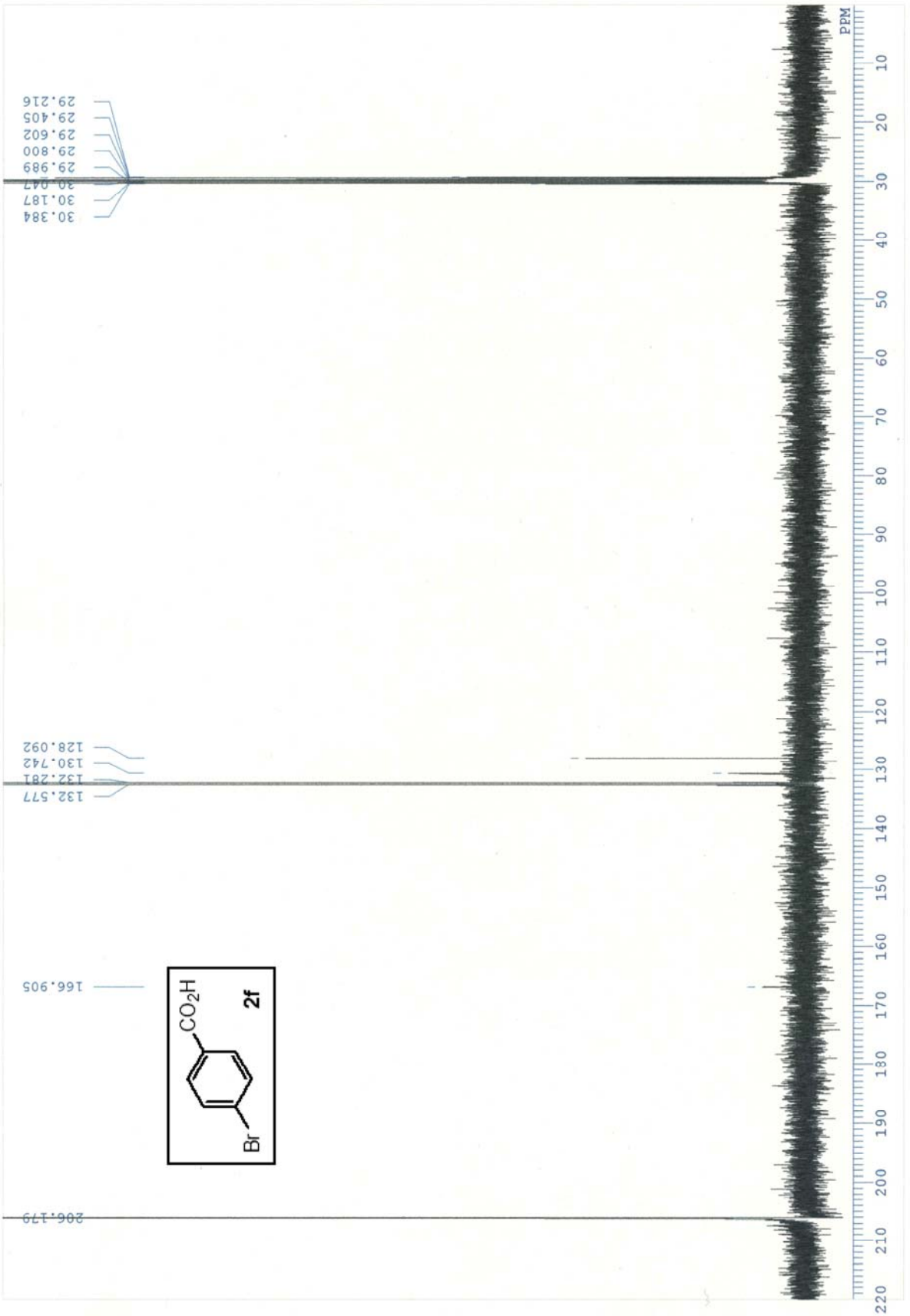
KH-451 HO

#Ions: 72





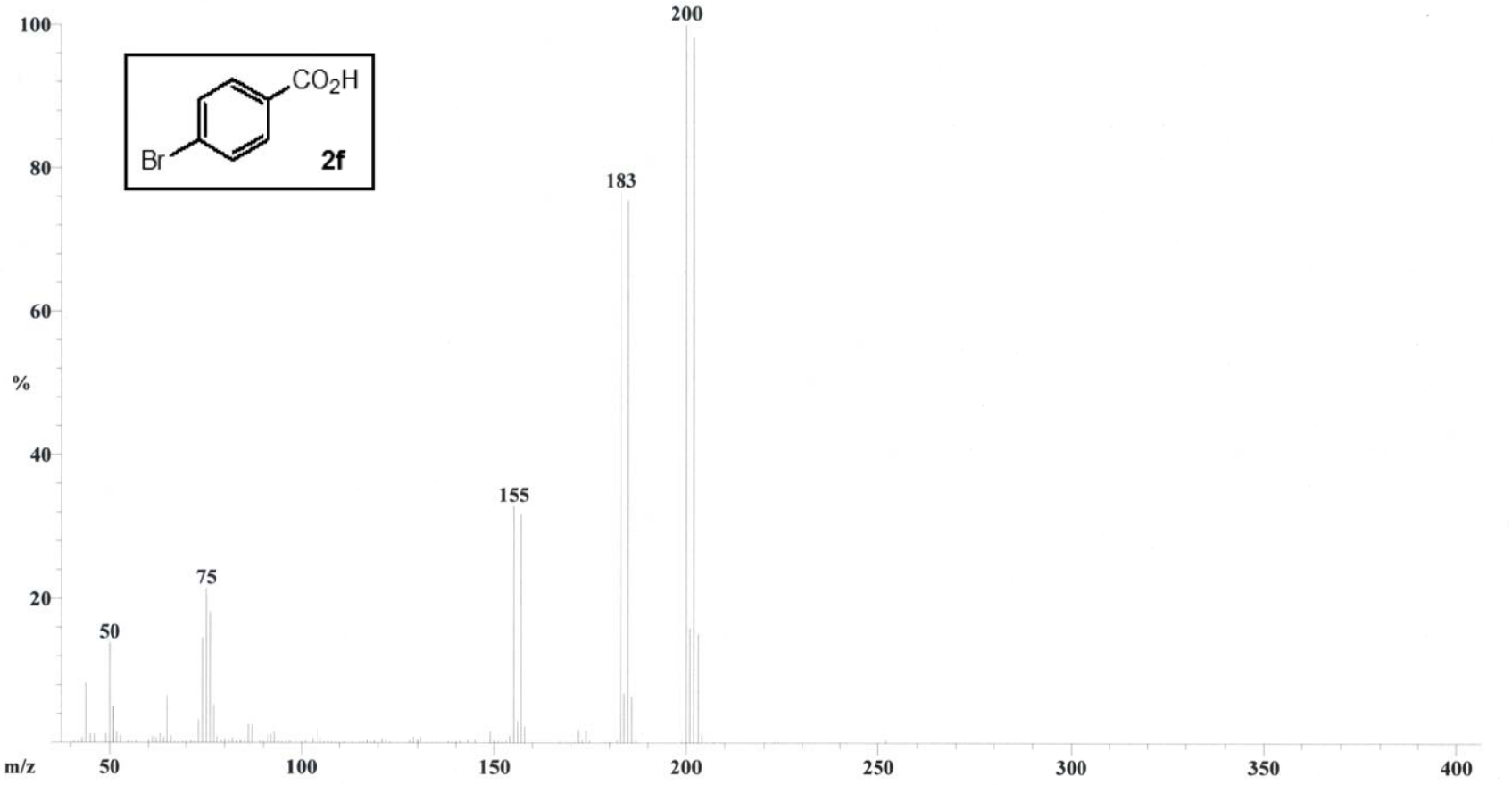


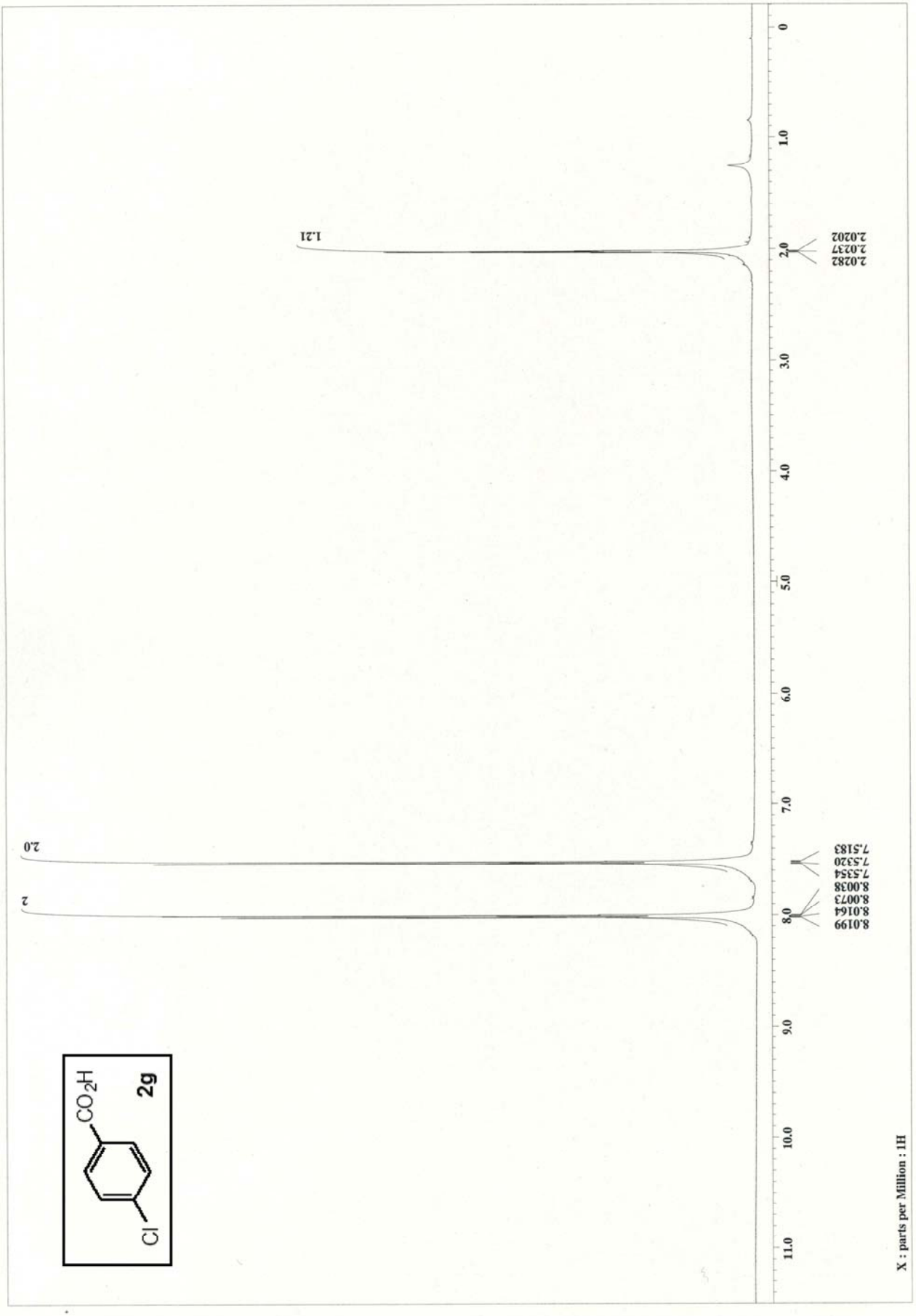
File: LR-09D738
Instrument: SX102A
Inlet: Direct

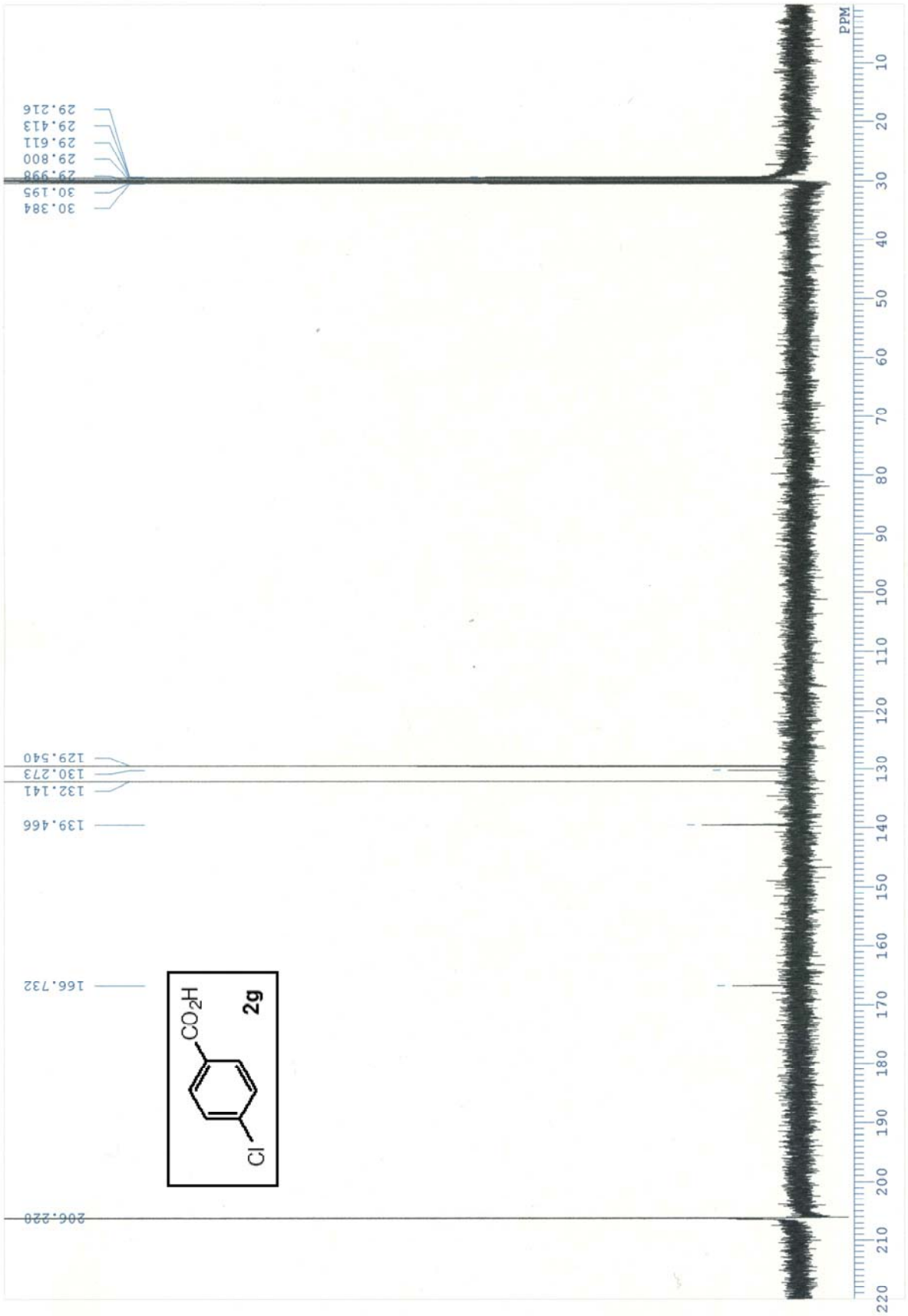
Date Run: 9-24-2009 (Time Run: 13:41:05)
Ionization mode: EI+

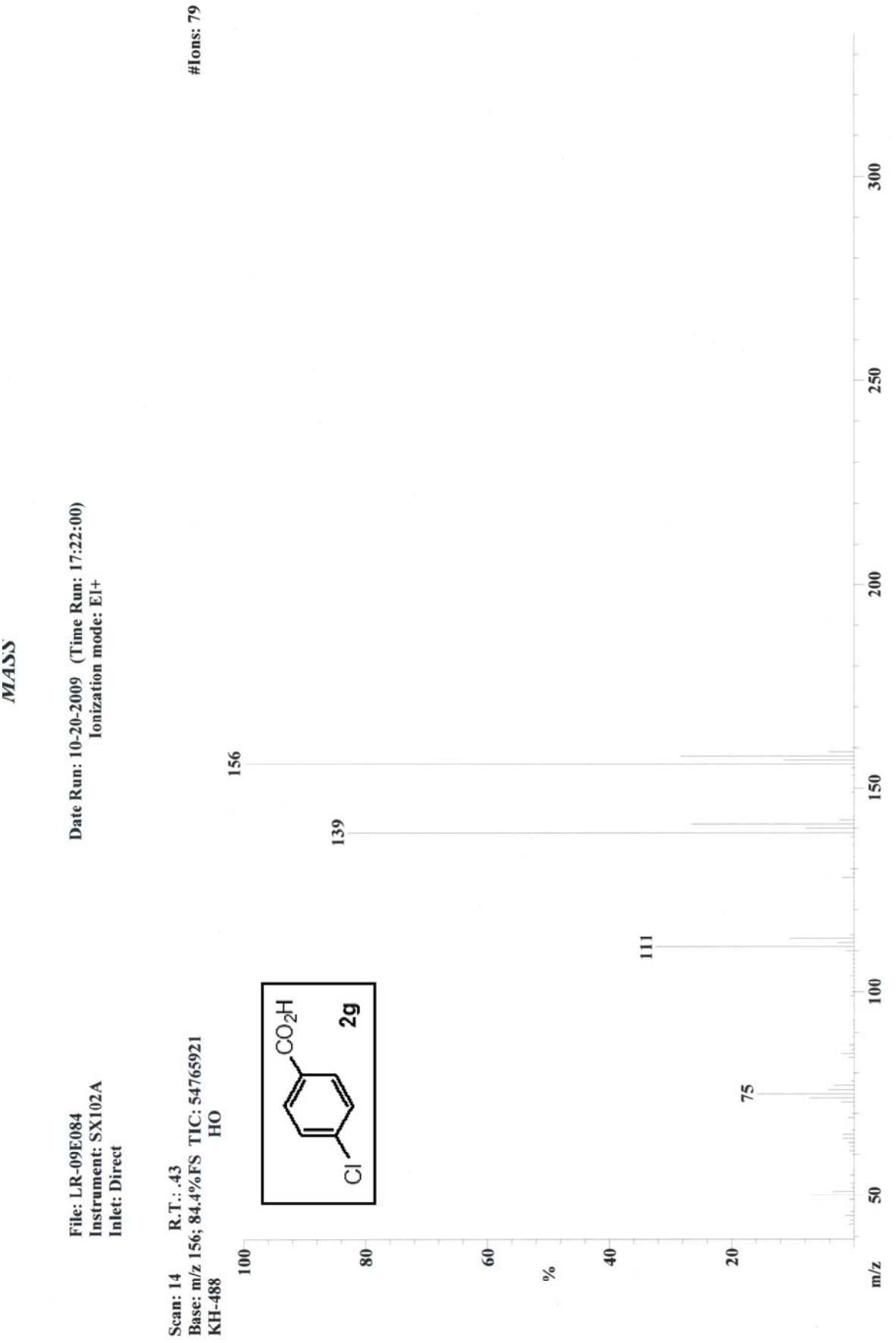
Scan: 26 R.T.: .83
Base: m/z 200; 94.3%FS TIC: 97282090
KH-453 HO

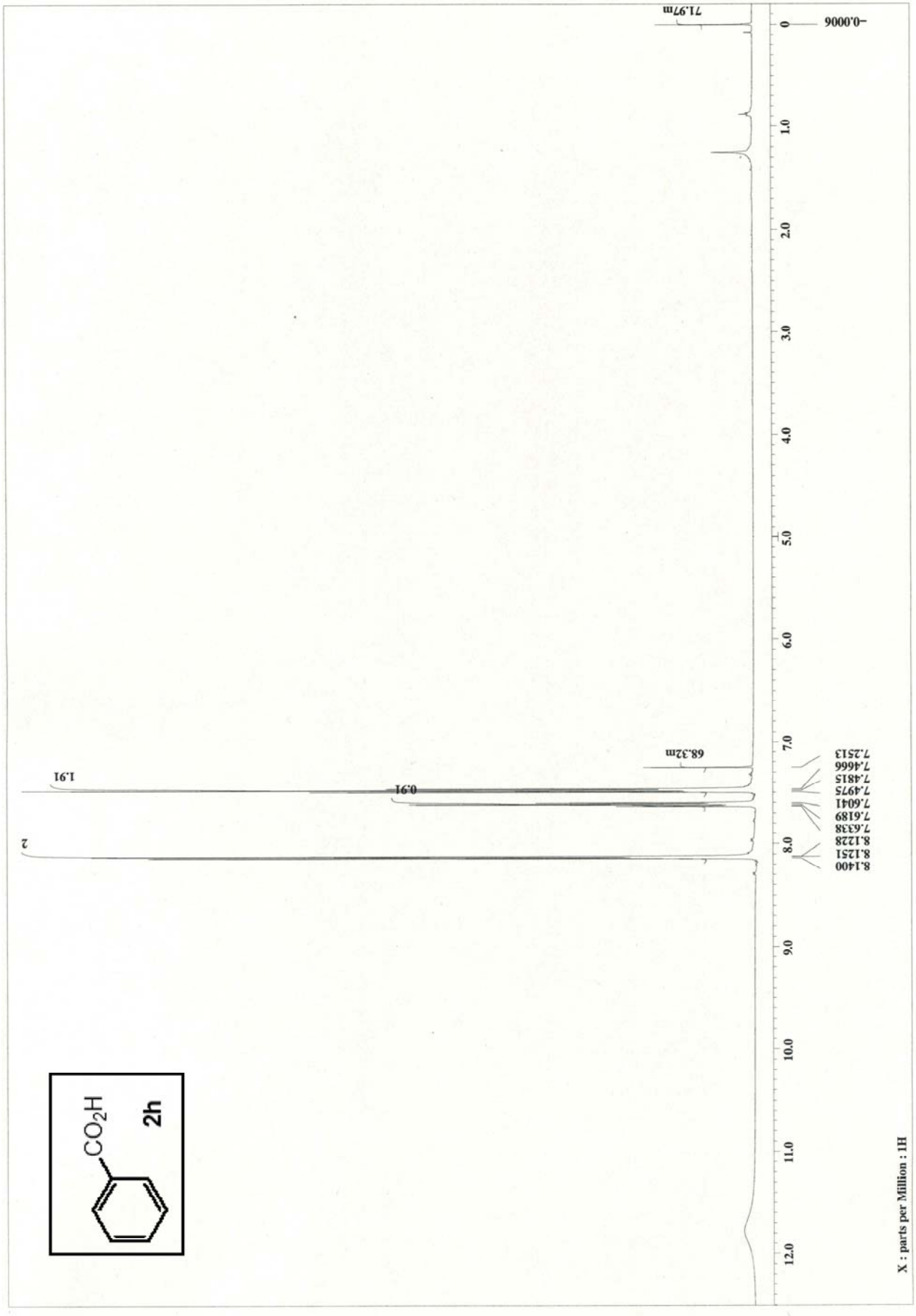
#Ions: 118

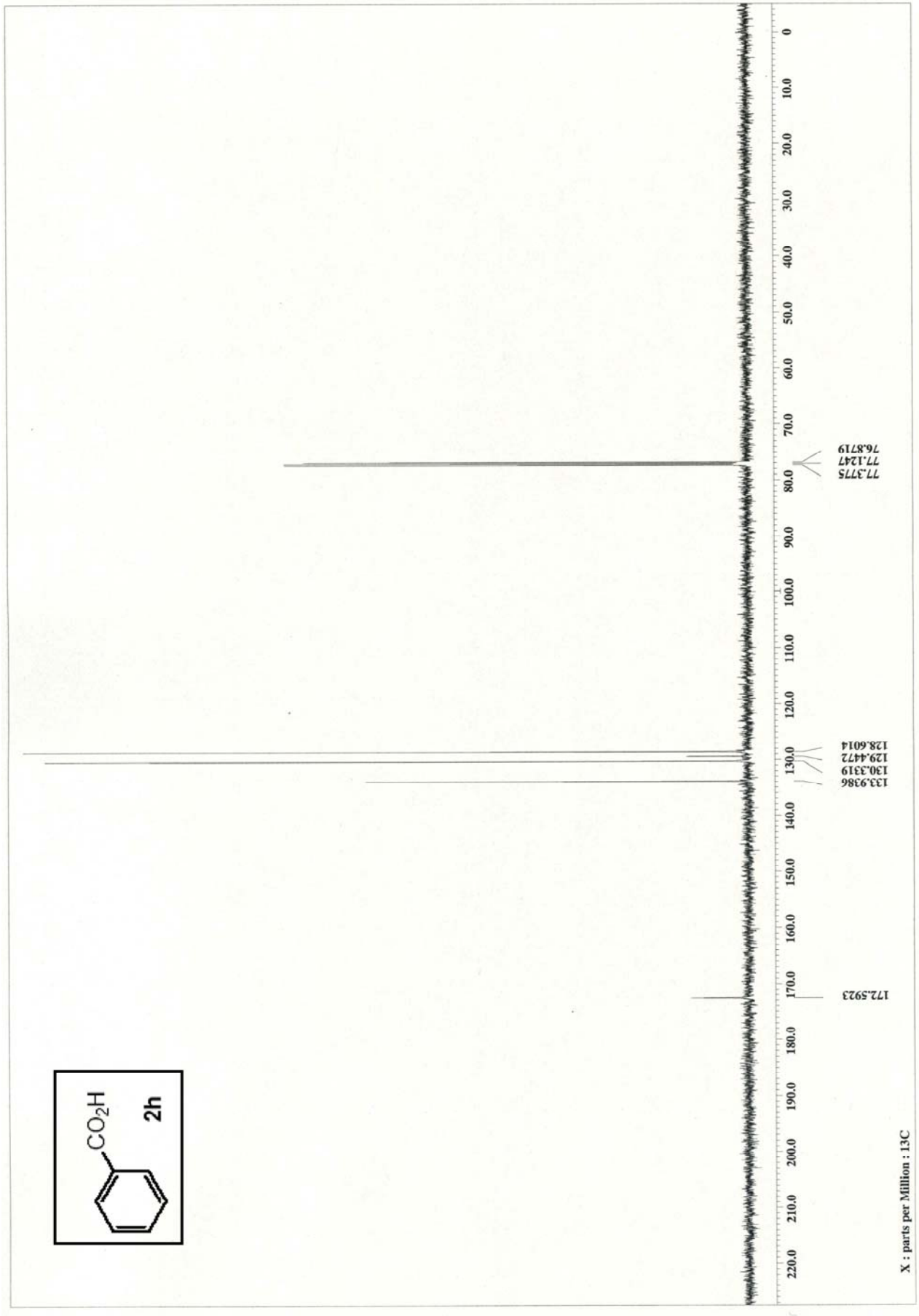


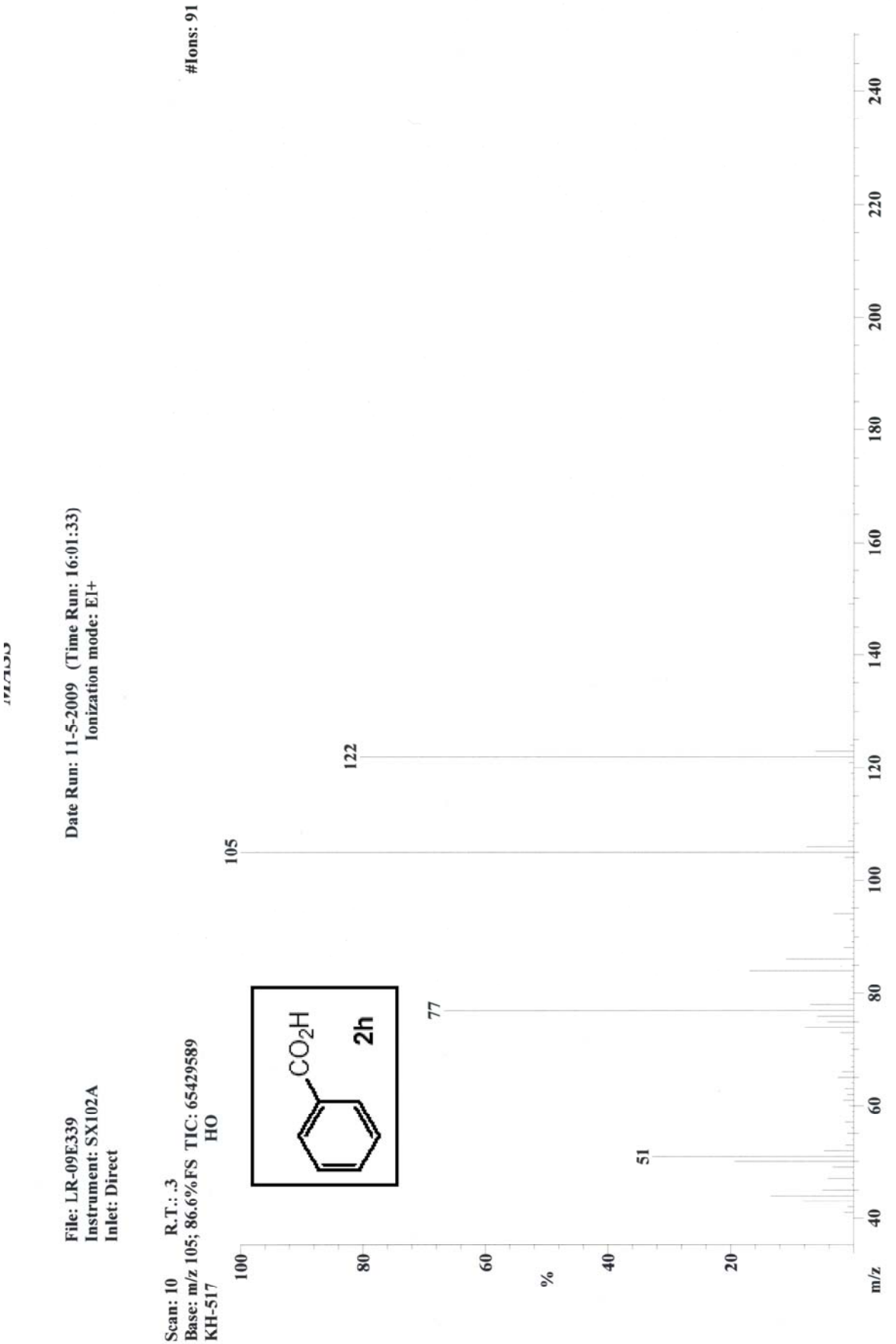


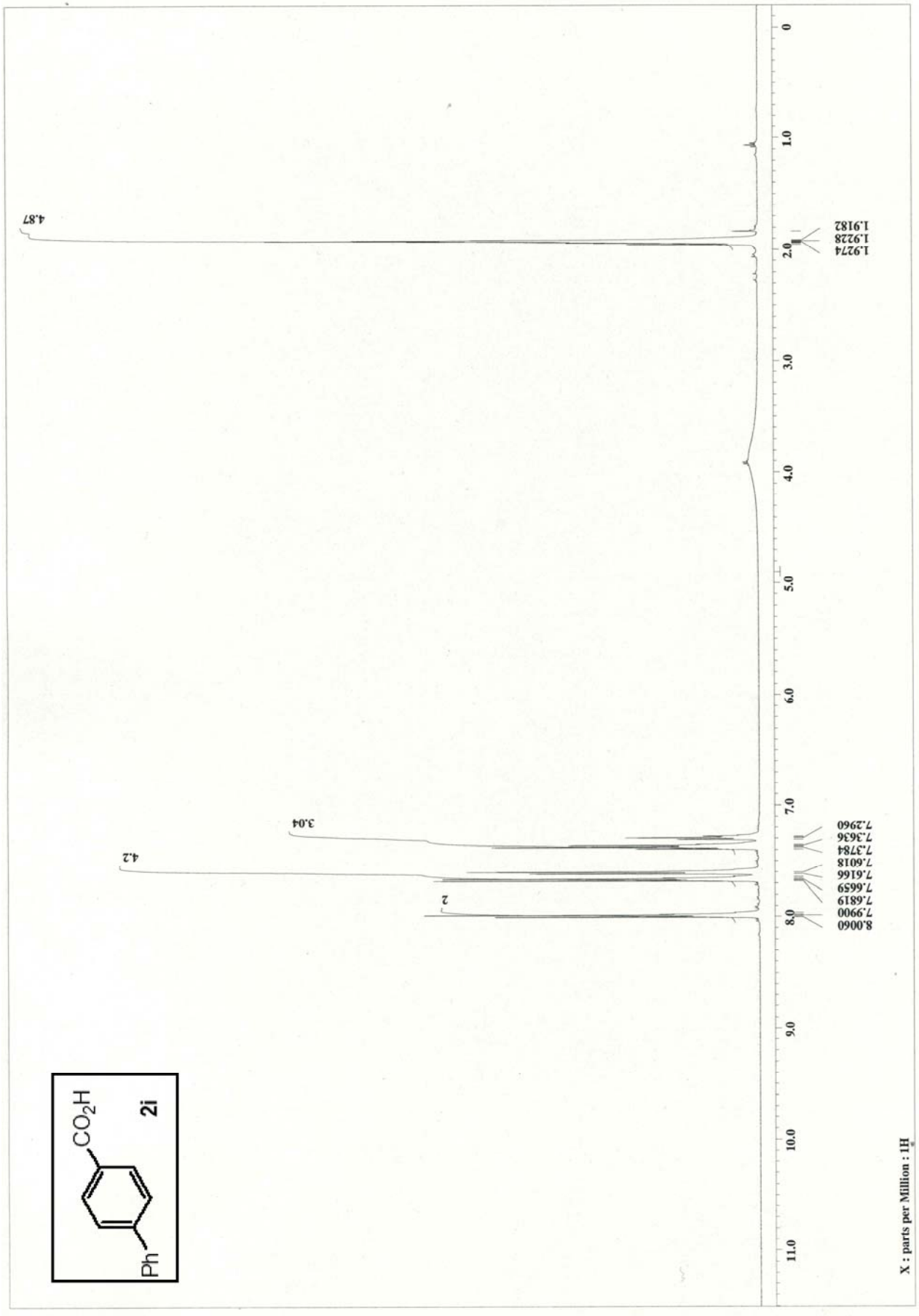


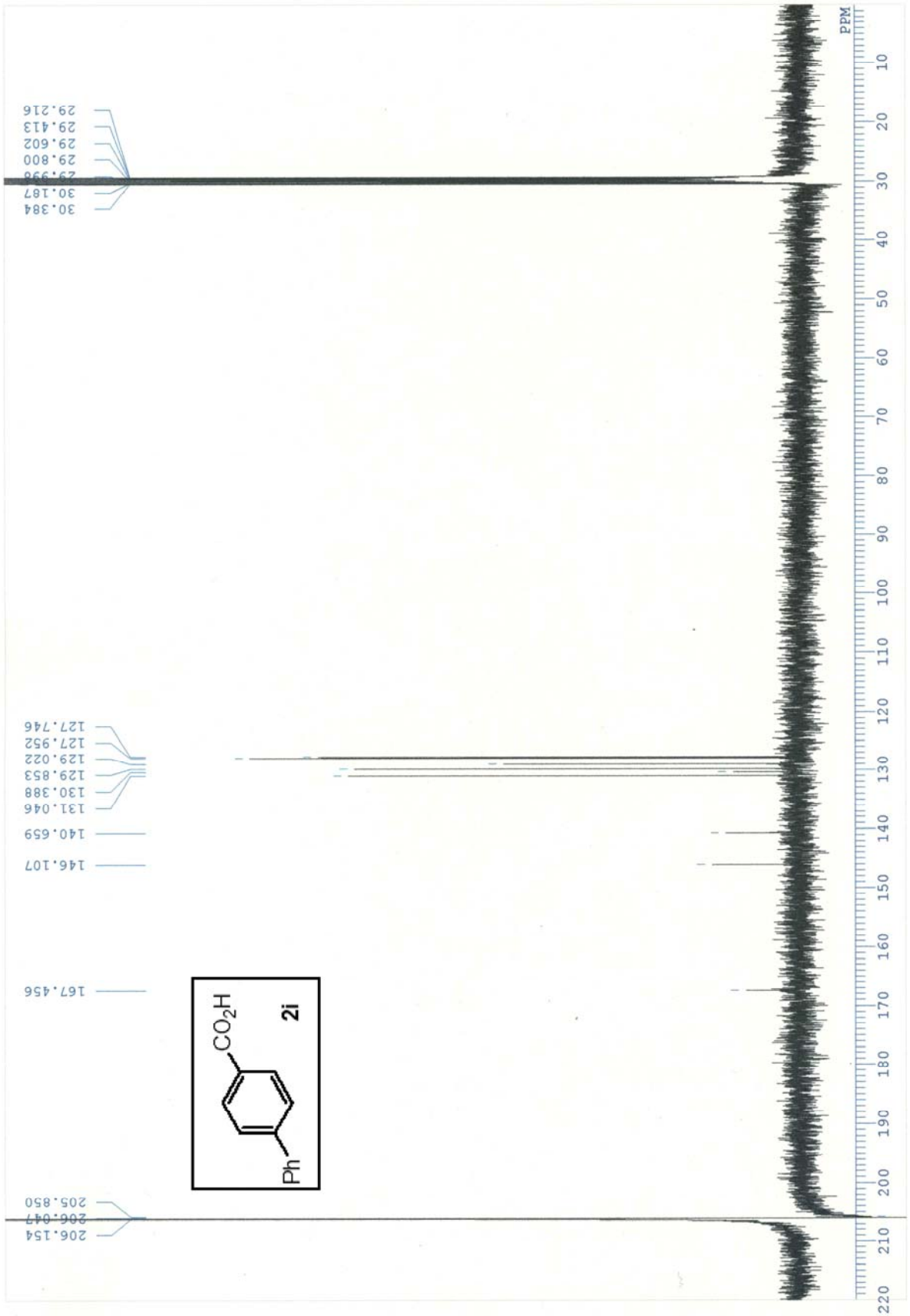


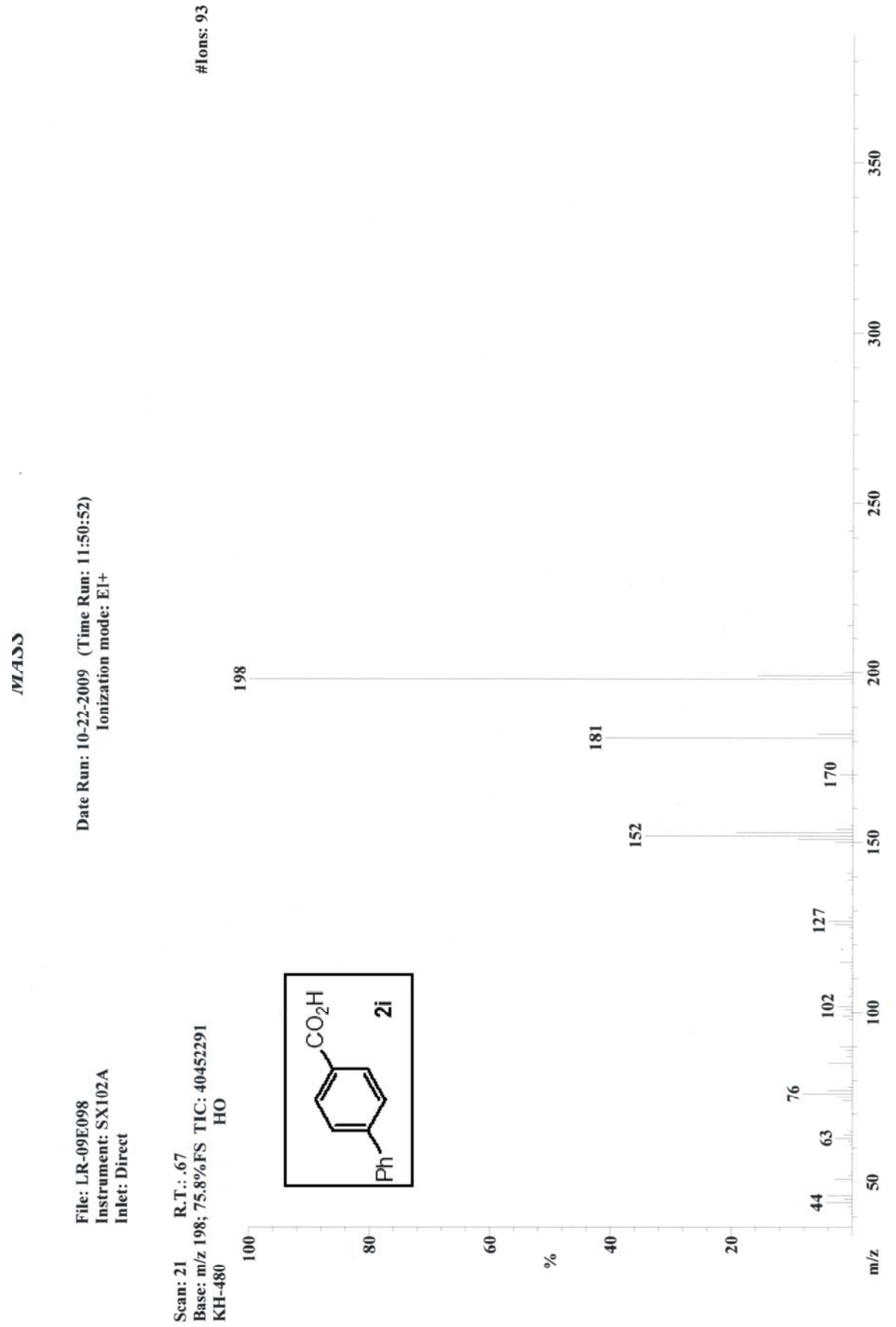


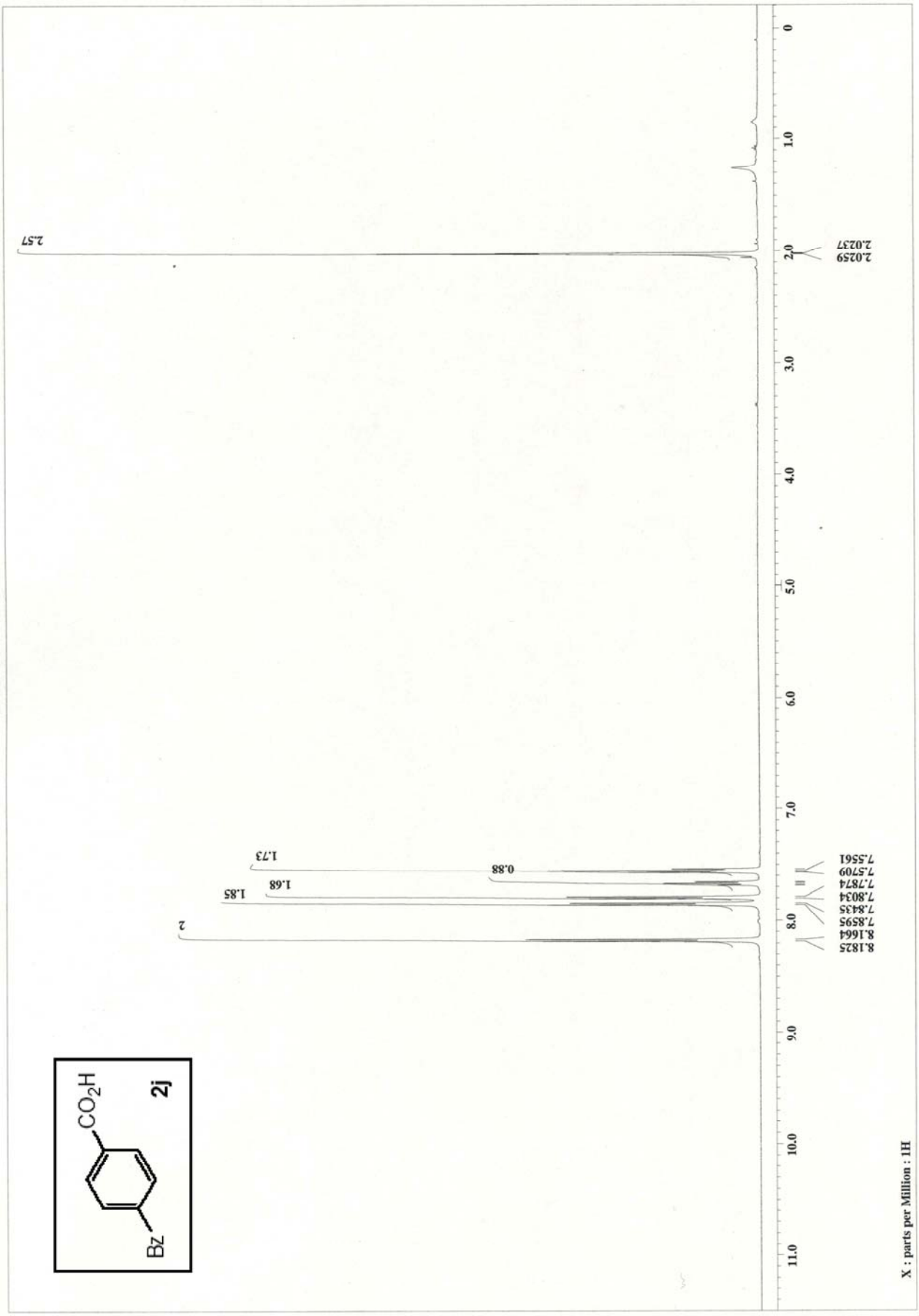

CO2H
2h
172.5923
133.9386
130.3319
129.4472
128.6014
77.3775
77.1247
76.8719
X : parts per Million : 13C

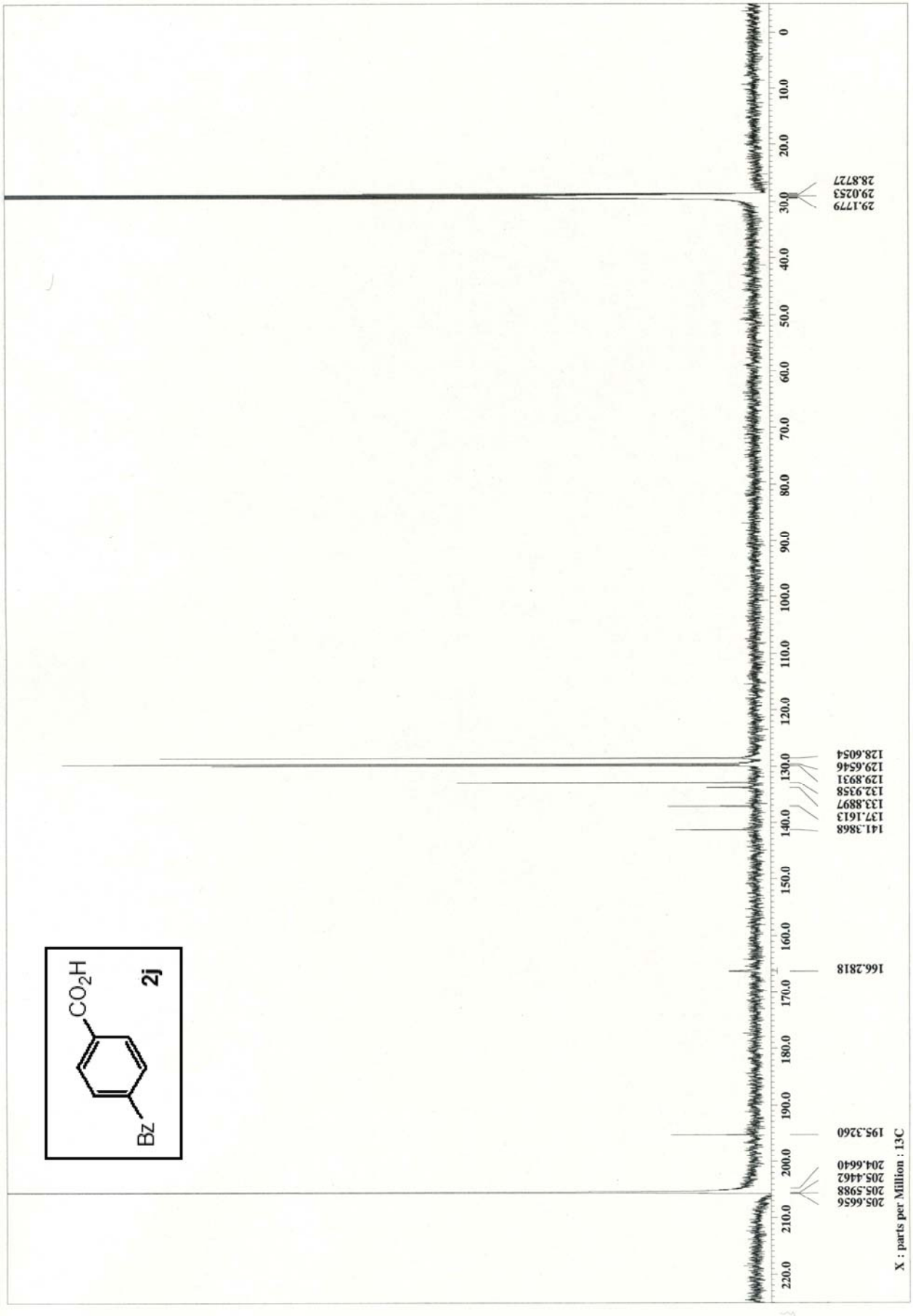

File: LR-09E339
Instrument: SX102A
Inlet: Direct
Date Run: 11-5-2009 (Time Run: 16:01:33)
Ionization mode: EI+
#Ions: 91
Scan: 10 R.T.: .3
Base: m/z 105; 86.6%FS TIC: 65429589
KH-517
HO
2h
CO2H
105
122
77
51
%
m/z









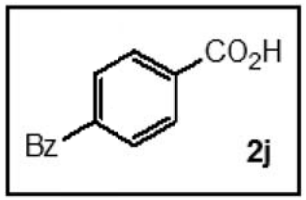

CO2H
Bz
2j
28.8727
29.0253
29.1779
128.6054
129.6546
129.8931
132.9358
133.8897
137.1613
141.3868
166.2818
195.3260
204.6640
205.4462
205.5988
205.6656
X : parts per Million : 13C

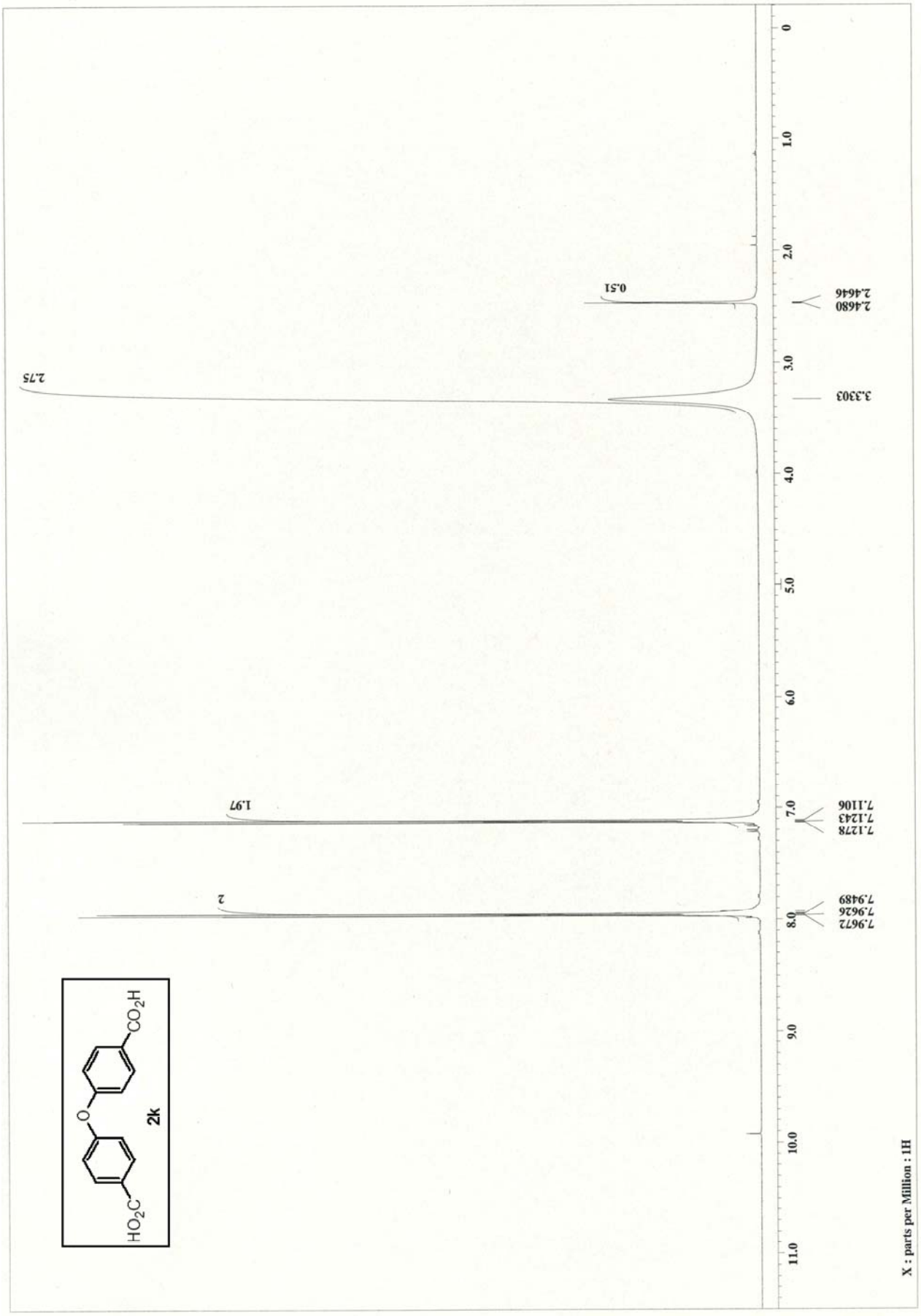
File: LR-09E427
Instrument: SX102A
Inlet: Direct

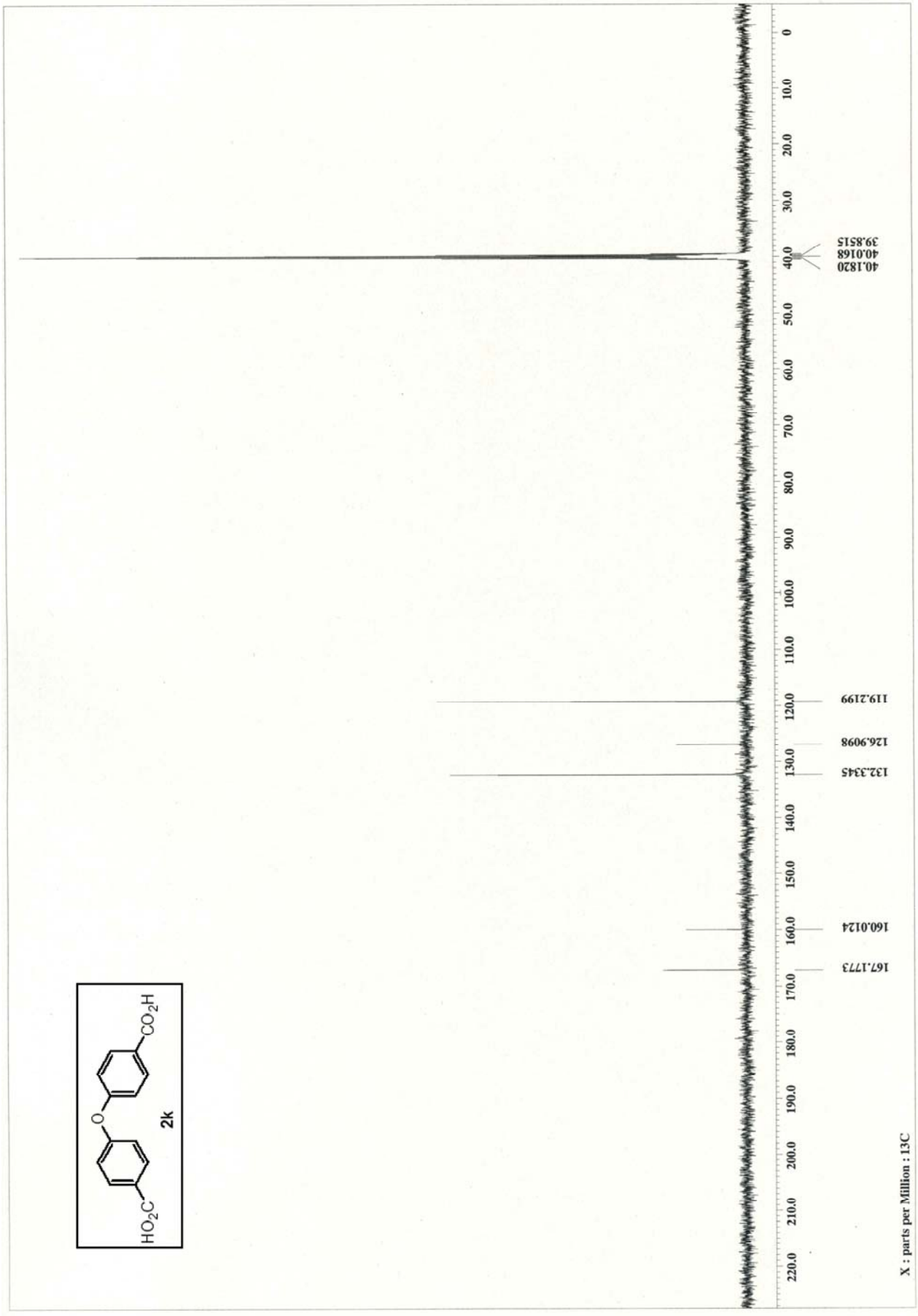
Date Run: 11-9-2009 (Time Run: 17:27:23)
Ionization mode: EI+

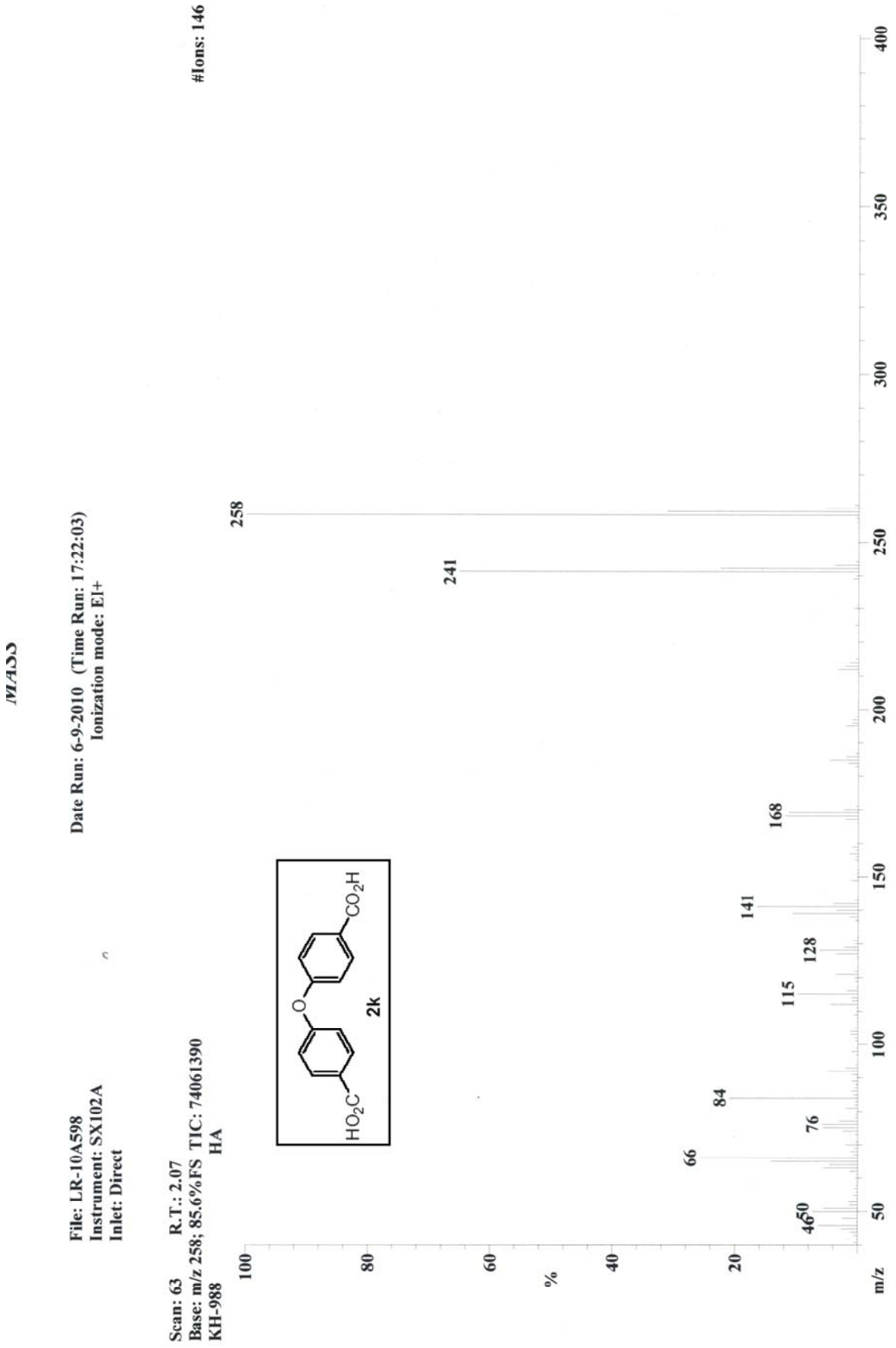
Scan: 17 R.T.: .53
Base: m/z 105; 88.7%FS TIC: 65871975
KH-510 HA

#Ions: 169




2k
CO_2H
HO_2C
O
0.51
2.75
1.97
2
2.4680
2.4646
3.3303
7.1278
7.1243
7.1106
7.9672
7.9626
7.9489
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
X : parts per Million : 1H




MASS
File: LR-10A598
Instrument: SX102A
Inlet: Direct
Date Run: 6-9-2010 (Time Run: 17:22:03)
Ionization mode: EI+
#Ions: 146
Scan: 63 R.T.: 2.07
Base: m/z 258; 85.6% FS TIC: 74061390
KH-988 HA
2k
258
241
168
141
128
115
84
76
66
46
50
100
150
200
250
300
350
400
m/z
%
100
80
60
40
20