Electronic Supplementary Material (ESI) for ChemComm.

O-Transfer-facilitated Cyclizations of Propargylamides with TMSN$_3$: Selective Synthesis of Tetrazoles and Dihydroimidazoles

Supporting Information

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1. General information

Unless otherwise stated, all manipulations and reactions were performed under argon atmosphere using standard Schlenk techniques or in an argon-filled glove-box. All chemicals were obtained from commercial sources and were used as received without further purification. Solvents were treated prior to use according to the standard methods. Column chromatography was carried out on silica gel (300–400 mesh) using a forced flow of eluent at 0.3–0.5 bar pressure. NMR Spectra were recorded at room temperature in $CDCl_3$ or CD_3COCD_3 on 400 or 500 MHz spectrometers. The chemical shifts for ^1H NMR were recorded in ppm downfield from tetramethylsilane (TMS) with $CDCl_3$ (7.26 ppm), CD_3COCD_3 (2.05 ppm) or CD_2Cl_2 (5.32 ppm) as the internal standard. The chemical shifts for ^{13}C NMR were recorded in ppm downfield using the central peak of $CDCl_3$ (77.16 ppm), CD_3COCD_3 (29.84 ppm) or CD_2Cl_2 (53.84 ppm) as the internal standard. Coupling constants (J) are reported in hertz and refer to apparent peak multiplications.

2. *Caution!*

Although we have experienced no hazards during the course of this work, but all reactions with azides should be conducted behind a blast shield in a fume hood with care. Personal protective equipment must be worn, including a lab coat, safety glasses, and gloves with adequate chemical resistance. Keep the hood clear of any unnecessary chemicals and equipment. Other safety issues for handling of azides, please see the following precautions:

Sodium azide is toxic (LD50 oral for rats = 27 mg/kg) and can be absorbed through the skin. Appropriate gloves are necessary when using it. It decomposes explosively upon heating to above 275 °C. Avoid water and strong acids which can lead to the formation of HN_3, which is highly toxic, volatile, and explosive. Do not use metal spatulas for weighing and transferring NaN_3. Do not use halogenated solvents (such as DCM or $CHCl_3$) for sodium azide reactions, as this can result in the formation of potentially explosive azides.

Organic azides are potentially explosive substances that can decompose with introduction of external energy (heat, light, pressure, etc).[1] When designing new organic azides, we keep in mind the following equation.[2] It is noted that this equation takes into account all nitrogen atoms in the organic azide, not just those in the azido group.

$$\frac{N_C + N_O}{N_N} \geq 3 \quad \text{N: nubmber of atom}$$

Use of azidotrimethylsilane ($TMSN_3$) should be performed in a fume hood since it is a flammable liquid with toxic properties with route of inhalation. Organic azide waste should be placed in a separate, explicitly-labeled container designated solely for azide waste.

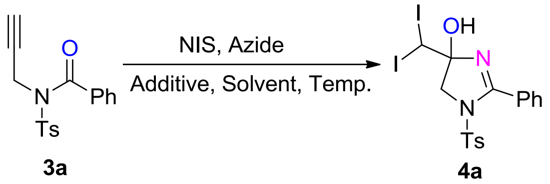
Notes: Although we experienced no hazards when using $TMSN_3$ as nucleophile source in DCE, further experiment of reactions using azides (especially, sodium azide) as a nucleophile in DCM and $CHCl_3$ solvents must be avoided since it forms potentially explosive diazomethane and triazomethane respectively.[3]

3. Optimization of reaction conditions[a]

1a **2a**

Entry	Azide	H_2O (eq)	Solvent	Temp. (°C)	Yield (%)[b]
1	$TMSN_3$	2.0	DCE	60	26
2	$TMSN_3$	2.0	1,4-Dioxane	60	Trace
3	$TMSN_3$	2.0	CH_3CN	60	Trace
4	$TMSN_3$	2.0	THF	60	Trace
5	$TMSN_3$	2.0	CH_3CN	60	Trace
6	$TMSN_3$	2.0	DCE	80	58[c]
7	$TMSN_3$	2.0	DCE	80	32[d]
8	$TMSN_3$	-	DCE	80	54[c]
9	$TMSN_3$	1.2	DCE	80	81[e]
10	NaN_3	1.2	DCE	80	36[e]
11	$TMSN_3$	1.2	DCE	80	48[e,f]
12	$TMSN_3$	1.2	DCE	80	53[e,g]

[a] 0.20 mmol of **1a**, 2.4 equiv of NIS, 3.6 equiv of azide, 3.0 mL of solvent, 12 h. [b] Isolated yield. [c] 2 h. [d] 1.2 equiv of NIS, 2.0 equiv of $TMSN_3$, 80 °C for 2 h. [e] RT for 10 min, 80 °C for 2 h. [f] 2.4 equiv of ICl was employed. [g] 2.4 equiv of I_2 was employed.



Entry	Azide	Solvent	Temp. (°C)	Yield (%)[b]
1	$TMSN_3$	DCE	80	81[c]
2	$TMSN_3$	DCE	60	86
3	$TMSN_3$	CH_3CN	60	35
4	$TMSN_3$	Toluene	60	Trace
5	$TMSN_3$	MeOH	60	-
6	$TMSN_3$	1,4-Dioxane	60	72
7	NaN_3	DCE	60	23
8	$TMSN_3$	DCE	60	40[d]
9	$TMSN_3$	DCE	60	49[e]

[a] 0.20 mmol of **3a**, 2.4 equiv of NIS, 3.6 equiv of azide, 2.0 equiv of additive, 3.0 mL of solvent, 12 h.

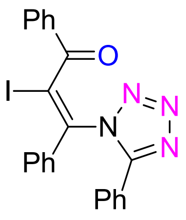
[b] Determined by HPLC. Naphthalene was used as internal standard.

[c] 6 h, 1.2 equiv of H_2O.

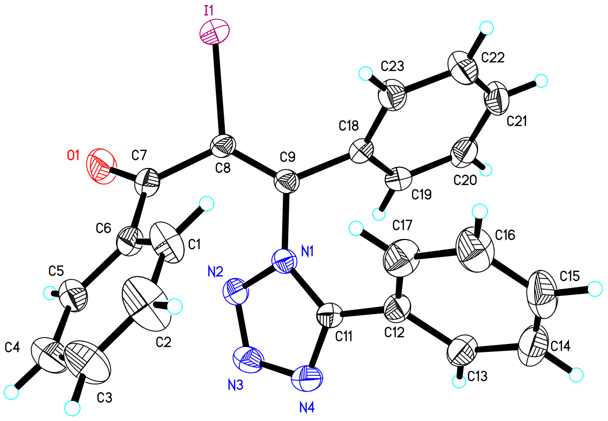
[d] 2.4 equiv of ICl was employed.

[e] 2.4 equiv of I_2 was employed.

4. X-ray structure of 2a

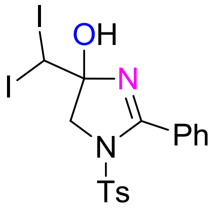


2a

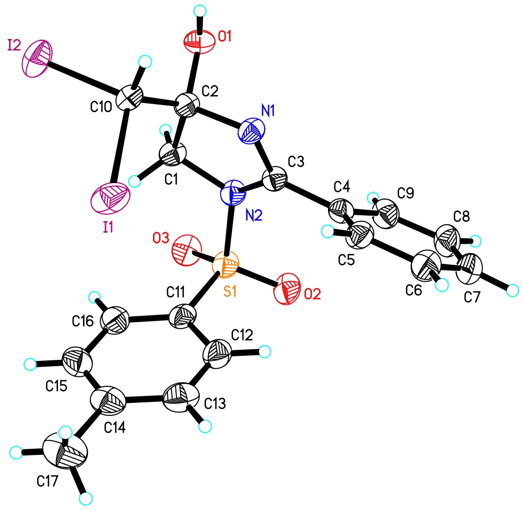


CCDC 1026405 (**2a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

5. X-ray structure of 4a



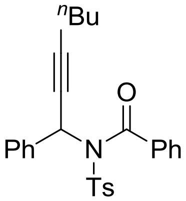
4a



CCDC 1026409 (**4a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

6. Characterization of starting materials

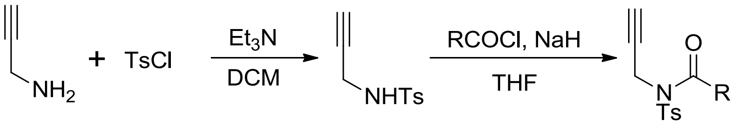
The internal *N*-sulfonyl propargylamides **1** were prepared following the procedure described in the reported literature.[4] **1l** new compound, the others are known compounds[4].



1l

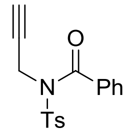
Colorless oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.71 (d, *J* = 8.3 Hz, 2H), 7.52–7.41 (m, 2H), 7.41–7.32 (m, 3H), 7.31–7.18 (m, 7H), 6.30 (s, 1H), 2.41 (s, 3H), 2.30 (td, *J* = 7.0, 2.2 Hz, 2H), 1.64–1.50 (m, 2H), 1.50–1.41 (m, 2H), 0.95 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, CDCl$_3$) δ 171.4, 144.6, 136.7, 136.5, 135.2, 131.6, 129.3, 129.0, 128.3, 128.1, 127.97, 127.91, 88.6, 75.6, 54.5, 30.7, 22.1, 21.7, 18.7, 13.7; HRMS (ESI-TOF) m/z calcd for $C_{27}H_{28}NO_3S$ [M + H]$^+$ 446.1784, found 446.1785.

General procedure for the preparation of terminal propargylic amides:



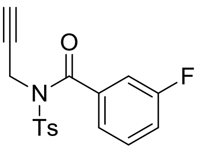
Propargylamine (30.0 mmol) was added to a mixture of TsCl (1.3 equiv), Et_3N (2.5 equiv), and DCM slowly at 0 °C. The resulting yellow solution was then stirred at room temperature for 4 h and quenched with $NH_3 \cdot H_2O$. The aqueous layer was extracted with ethyl acetate and the combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Recrystallization in EtOH and pentane afforded the expected product.

To a suspension of NaH (60% dispersion in mineral oil, 4.8 mmol) in THF (40.0 mL) at 0 °C was added *N*-tosyl propargylamine (4.0 mmol) and stirred for 40 min. The resulting mixture was then treated with acyl chloride (6.0 mmol) and stirred at room temperature for 3 h. The reaction was quenched with water, and the layers were separated. The aqueous layer was extracted with ethyl acetate and the combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Recrystallization from EtOH and pentane afforded terminal propargylamides.



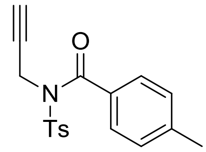
3a

White solid, m.p. 146–147 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, *J* = 8.3 Hz, 2H), 7.58–7.47 (m, 3H), 7.38 (t, *J* = 7.7 Hz, 2H), 7.30 (d, *J* = 8.2 Hz, 2H), 4.58 (d, *J* = 2.3 Hz, 2H), 2.43 (s, 3H), 2.36 (t, *J* = 2.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 145.2, 135.6, 134.0, 131.9, 129.5, 129.0, 128.5, 128.0, 78.5, 73.3, 37.7, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{16}NO_3S$ [M + H]$^+$ 314.0845, found 314.0852.



3b

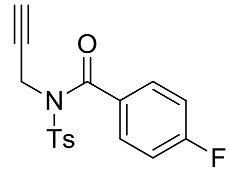
Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (d, *J* = 8.3 Hz, 2H), 7.44–7.27 (m, 4H), 7.18 (m, 2H), 4.58 (d, *J* = 2.3 Hz, 2H), 2.44 (s, 3H), 2.38 (t, *J* = 2.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.1 (d, *J* = 2.6 Hz), 162.2 (d, *J* = 248.8 Hz), 145.5, 136.0 (d, *J* = 7.1 Hz), 135.3, 130.3 (d, *J* = 7.9 Hz), 129.6, 128.9, 123.6 (d, *J* = 3.2 Hz), 118.9 (d, *J* = 21.1 Hz), 115.1 (d, *J* = 23.6 Hz), 78.3, 73.5, 37.5, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{15}FNO_3S$ [M + H]$^+$ 332.0751, found 332.0758.



3c

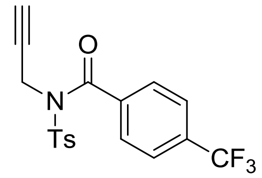
Yellow solid, m.p. 88–89 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.4 Hz, 2H), 7.48 (d, *J* = 8.1 Hz, 2H), 7.30 (d, *J* = 8.1 Hz, 2H), 7.20 (d, *J* = 7.9 Hz, 2H), 4.56 (d, *J* = 2.4 Hz, 2H), 2.43 (s, 3H), 2.39 (s, 3H), 2.34 (t, *J* = 2.4 Hz, 1H); ^{13}C

NMR (100 MHz, $CDCl_3$) δ 170.8, 145.1, 142.8, 135.7, 131.2, 129.5, 129.2, 129.0, 128.3, 78.6, 73.3, 37.9, 21.8, 21.7; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{18}NO_3S$ $[M + H]^+$ 328.1002, found 328.1008.



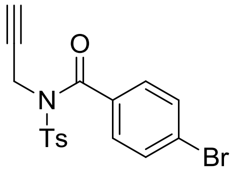
3d

White solid, m.p. 87–88 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8.4 Hz, 2H), 7.64–7.50 (m, 2H), 7.31 (d, *J* = 8.1 Hz, 2H), 7.18–6.97 (m, 2H), 4.56 (d, *J* = 2.4 Hz, 2H), 2.44 (s, 3H), 2.35 (t, *J* = 2.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.7, 164.9 (d, *J* = 253.7 Hz), 145.4, 135.5, 130.9 (d, *J* = 9.0 Hz), 129.6, 128.9, 128.6, 115.7 (d, *J* = 22.1 Hz), 78.4, 73.4, 37.7, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{15}FNO_3S$ $[M + H]^+$ 332.0751, found 332.0750.



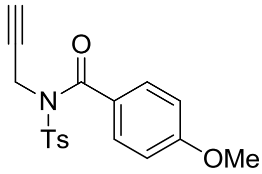
3e

White solid, m.p. 110–111 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.81 (d, *J* = 8.2 Hz, 2H), 7.62 (q, *J* = 8.3 Hz, 4H), 7.30 (d, *J* = 8.1 Hz, 2H), 4.59 (d, *J* = 2.2 Hz, 2H), 2.44 (s, 3H), 2.37 (t, *J* = 2.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.3, 145.6, 137.6, 135.3, 133.3 (q, *J* = 32.9 Hz), 129.7, 128.8, 128.3, 125.4 (q, *J* = 3.7 Hz), 123.6 (q, *J* = 272.6 Hz), 78.2, 73.5, 37.3, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{15}F_3NO_3S$ $[M + H]^+$ 382.0719, found 382.0724.



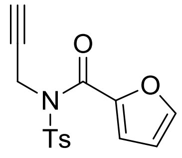
3f

White solid, m.p. 92–93 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8.4 Hz, 2H), 7.61 – 7.49 (m, 2H), 7.44–7.38 (m, 2H), 7.31 (d, *J* = 8.1 Hz, 2H), 4.56 (d, *J* = 2.4 Hz, 2H), 2.44 (s, 3H), 2.34 (t, *J* = 2.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.8, 145.4, 135.5, 133.1, 131.8, 129.8, 129.7, 128.9, 126.8, 78.3, 73.4, 37.6, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{15}BrNO_3S$ $[M + H]^+$ 391.9951, found 391.9949.



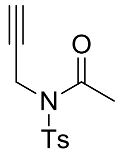
3g

White solid, m.p. 96–97 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.88 (d, *J* = 8.3 Hz, 2H), 7.62 (d, *J* = 8.7 Hz, 2H), 7.30 (d, *J* = 8.1 Hz, 2H), 6.89 (d, *J* = 8.7 Hz, 2H), 4.54 (d, *J* = 2.2 Hz, 2H), 3.85 (s, 3H), 2.43 (s, 3H), 2.33 (t, *J* = 2.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.4, 163.0, 145.0, 135.6, 130.9, 129.5, 128.9, 126.1, 113.8, 78.6, 73.3, 55.6, 38.0, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{18}NO_4S$ [M + H]$^+$ 344.0951, found 344.0949.



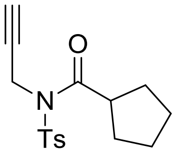
3h

Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 (d, *J* = 8.3 Hz, 2H), 7.57 (s, 1H), 7.44–7.29 (m, 3H), 6.53 (dd, *J* = 3.5, 1.6 Hz, 1H), 4.93 (d, *J* = 2.3 Hz, 2H), 2.43 (s, 3H), 2.32 (t, *J* = 2.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.4, 146.4, 146.0, 145.1, 135.9, 129.5, 129.1, 120.6, 112.4, 78.6, 73.3, 36.8, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{15}H_{14}NO_4S$ [M + H]$^+$ 304.0638, found 304.0636.



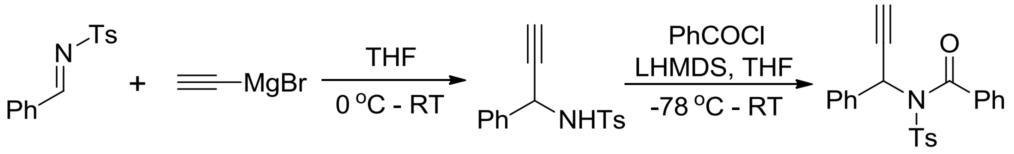
3i

Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.4 Hz, 2H), 7.35 (d, *J* = 8.0 Hz, 2H), 4.67 (d, *J* = 2.4 Hz, 2H), 2.45 (s, 3H), 2.35–2.28 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.5, 145.3, 136.0, 129.9, 128.1, 78.4, 72.6, 35.5, 24.5, 21.7; HRMS (ESI-TOF) m/z calcd for $C_{12}H_{14}NO_3S$ [M + H]$^+$ 252.0689, found 252.0689.



3j

Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.2 Hz, 2H), 7.33 (d, *J* = 8.0 Hz, 2H), 4.70 (s, 2H), 3.44–2.98 (m, 1H), 2.44 (s, 3H), 2.34 (s, 1H), 1.69 (m, 6H), 1.51 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.4, 144.9, 136.6, 129.7, 128.0, 78.7, 72.7, 44.0, 35.3, 30.8, 26.2, 21.7; HRMS (ESI-TOF) m/z calcd for $C_{16}H_{20}NO_3S$ [M + H]$^+$ 306.1158, found 306.1168.

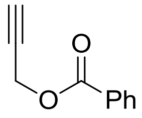


3k

To a solution of *N*-Ts imine (10.0 mmol) in THF (40.0 mL) at 0 °C was added ethynylmagnesium bromide (12.0 mmol) and stirred overnight. The reaction was quenched with water and extracted with Et_2O. The combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Recrystallization from EtOH and pentane afforded *N*-Ts propargylamine.

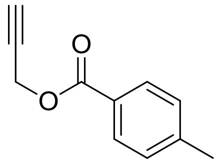
LiHMDS in THF (1.0 M, 2.3 mmol) was added to a mixture of *N*-Ts propargylamine (2.0 mmol) and THF (10.0 mL) carefully at -78 °C. The resulting solution was stirred at -78 °C for 40 min, treated with benzyl chloride (3.0 mmol), and warmed to RT. After 4 h, the reaction was quenched with saturated NH_4Cl and extracted with Et_2O. The combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Recrystallization from EtOH and pentane afforded the desired product.

White solid, m.p. 126–127 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 (d, *J* = 8.3 Hz, 2H), 7.55–7.47 (m, 2H), 7.42 (m, 3H), 7.29 (m, 5H), 7.21 (d, *J* = 8.2 Hz, 2H), 6.33 (d, *J* = 2.3 Hz, 1H), 2.71 (d, *J* = 2.5 Hz, 1H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 144.9, 136.1, 135.4, 134.9, 131.8, 129.4, 128.9, 128.5, 128.4, 128.1, 127.9, 79.3, 75.8, 53.7, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{23}H_{20}NO_3S$ [M + H]$^+$ 390.1158, found 390.1161.



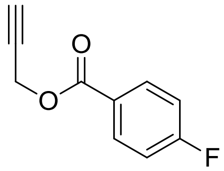
3l

Known compound.[5]



3m

Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 8.2 Hz, 2H), 7.24 (d, *J* = 8.0 Hz, 2H), 4.90 (d, *J* = 2.5 Hz, 2H), 2.50 (t, *J* = 2.5 Hz, 1H), 2.41 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.0, 144.2, 130.0, 129.3, 126.8, 78.0, 75.0, 52.4, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{11}H_{11}O_2$ [M + H]$^+$ 175.0754, found 175.0749.



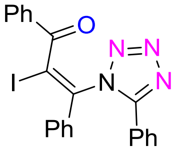
3n

Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.31–7.86 (m, 2H), 7.39–6.85 (m, 2H), 4.91 (d, *J* = 2.5 Hz, 2H), 2.56 (t, *J* = 2.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.0 (d, *J* = 254.4 Hz), 164.8, 132.4 (d, *J* = 9.4 Hz), 125.7 (d, *J* = 3.0 Hz), 115.6 (d, *J* = 22.1 Hz), 77.7, 75.2, 52.6; HRMS (ESI-TOF) m/z calcd for $C_{10}H_8FO_2$ [M + H]$^+$ 179.0503, found 179.0510.

7. O-transfer facilitated formal [3+2] annulation of propargylamides with $TMSN_3$

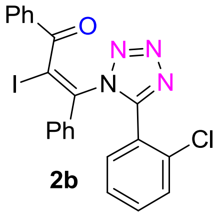
Representative procedure:

Internal propargylamide **1** (0.20 mmol) and NIS (108.0 mg) were dissolved in 3 mL of dry and degassed DCE. Subsequently, $TMSN_3$ (95.0 μL) and H_2O (4.3 μL) were added. The resulting yellow solution was stirred at room temperature for 10 min, then 80 °C for 2-8 h. Direct purification by flash chromatography on silica gel (petroleum ether/EtOAc: 10/1) afforded tetrazole **2**.



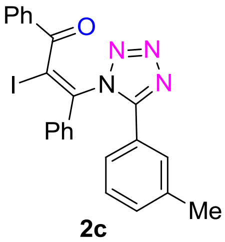
2a

White solid, m.p. 108–109 °C; ^1H NMR (400 MHz, Acetone-d_6) δ 8.09–7.93 (m, 2H), 7.87–7.75 (m, 2H), 7.68 (t, *J* = 7.4 Hz, 1H), 7.60–7.46 (m, 7H), 7.39 (m, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.4, 154.7, 139.3, 135.24, 135.17, 134.1, 132.4, 131.6, 130.8, 130.4, 129.8, 129.7, 129.6, 129.5, 124.1, 102.7; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{16}IN_4O$ $[M + H]^+$ 479.0363, found 479.0376.



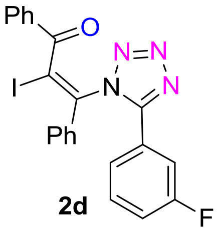
2b

White solid, m.p. 122–123 °C; ^1H NMR (400 MHz, Acetone-d_6) δ 8.09 (m, 2H), 7.72 (t, *J* = 7.4 Hz, 1H), 7.62 (t, *J* = 7.6 Hz, 2H), 7.57–7.41 (m, 4H), 7.38–7.21 (m, 6H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.2, 152.6, 138.4, 135.1, 135.0, 134.3, 133.6, 132.5, 131.4, 131.1, 130.7, 130.3, 129.7, 129.4, 128.0, 124.3, 101.3; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}ClIN_4O$ $[M + H]^+$ 512.9974, found 512.9974.



2c

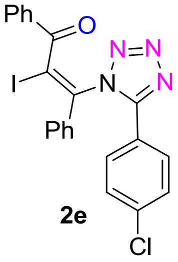
Colorless oil; ^1H NMR (400 MHz, Acetone-d_6) δ 7.99 (m, 2H), 7.72–7.64 (m, 1H), 7.61–7.48 (m, 6H), 7.45–7.39 (m, 3H), 7.35 (m, 2H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.2, 154.7, 139.6, 135.3, 135.2, 134.1, 133.1, 131.6, 130.8, 130.4, 130.0, 129.7, 129.6, 129.5, 126.7, 124.0, 102.6, 21.2; HRMS (ESI-TOF) m/z calcd for $C_{23}H_{18}IN_4O$ $[M + H]^+$ 493.0520, found 493.0536.



2d

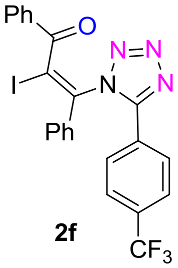
Yellow solid, m.p. 96–97 °C; ^1H NMR (400 MHz, Acetone-d_6) δ 8.01 (m, 2H), 7.72–7.62 (m, 2H), 7.61–7.50 (m, 5H), 7.50–7.46 (m, 1H), 7.44–7.38 (m, 3H), 7.38–7.31 (m, 1H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.4, 163.2 (d, *J* = 246.3

Hz), 153.7, 138.9, 135.3, 134.9, 134.0, 132.2 (d, J = 8.4 Hz), 131.8, 130.8, 130.3, 129.7, 129.6, 126.1 (d, J = 8.7 Hz), 125.8 (d, J = 3.2 Hz), 119.4 (d, J = 21.1 Hz), 116.3 (d, J = 24.4 Hz), 102.9; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}FIN_4O$ $[M + H]^+$ 497.0269, found 497.0279.



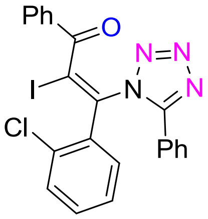
2e

Yellow oil; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.00 (d, J = 8.3 Hz, 2H), 7.87–7.74 (m, 2H), 7.67 (t, J = 7.4 Hz, 1H), 7.55 (dd, J = 9.3, 3.3 Hz, 6H), 7.46–7.35 (m, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.4, 153.8, 139.0, 138.2, 135.3, 134.9, 134.0, 131.8, 131.2, 130.8, 130.4, 130.1, 129.7, 129.6, 122.8, 102.9; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}ClIN_4O$ $[M + H]^+$ 512.9974, found 512.9981.



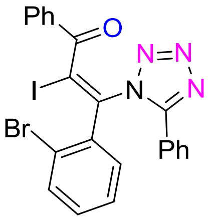
2f

Yellow oil; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.04–7.98 (m, 4H), 7.87 (d, J = 8.2 Hz, 2H), 7.72–7.64 (m, 1H), 7.60–7.50 (m, 4H), 7.47–7.36 (m, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.4, 153.6, 138.9, 135.4, 134.9, 134.0, 133.4 (q, J = 32.6 Hz), 131.8, 130.8, 130.5, 129.7, 129.6, 128.0, 126.8 (q, J = 3.8 Hz), 124.7 (q, J = 271.9 Hz), 103.1; HRMS (ESI-TOF) m/z calcd for $C_{23}H_{15}F_3IN_4O$ $[M + H]^+$ 547.0237, found 547.0246.



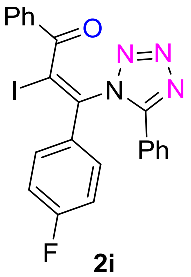
2g

Yellow oil; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.14–7.98 (m, 2H), 7.76–7.66 (m, 1H), 7.64–7.53 (m, 5H), 7.52–7.34 (m, 5H), 7.29–7.20 (m, 1H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 192.0, 154.7, 137.7, 135.2, 134.4, 134.2, 134.0, 133.9, 133.1, 132.3, 131.2, 130.7, 129.9, 129.8, 129.7, 127.9, 124.4, 106.9; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}ClIN_4O$ $[M + H]^+$ 512.9974, found 512.9977.



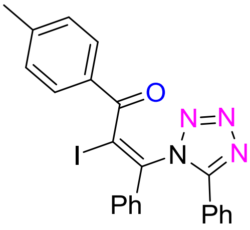
2h

Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12–8.03 (m, 2H), 7.61 (t, J = 7.4 Hz, 1H), 7.55–7.45 (m, 6H), 7.42–7.35 (m, 2H), 7.16 (td, J = 7.7, 1.8 Hz, 1H), 7.09 (td, J = 7.5, 1.2 Hz, 1H), 7.03 (dd, J = 7.7, 1.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.7, 154.0, 138.0, 135.5, 134.5, 133.8, 133.2, 132.9, 131.9, 131.4, 130.4, 129.4, 128.85, 128.82, 127.3, 123.6, 123.2, 105.3; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}BrIN_4O$ $[M + H]^+$ 556.9468, found 556.9468.



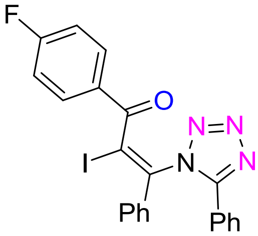
2i

Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07–7.97 (m, 2H), 7.78–7.67 (m, 2H), 7.46 (dt, *J* = 2.5, 2.1 Hz, 1H), 7.43–7.37 (m, 2H), 7.37–7.26 (m, 5H), 7.19–7.12 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.5, 166.6 (d, *J* = 257.8 Hz), 154.3, 138.7, 134.0, 133.4 (d, *J* = 9.8 Hz), 131.7, 131.0, 129.5, 129.0 (d, *J* = 2.9 Hz), 128.93, 128.90, 128.7, 123.1, 116.2 (d, *J* = 22.3 Hz), 100.0; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}FIN_4O$ $[M + H]^+$ 497.0269, found 497.0279.



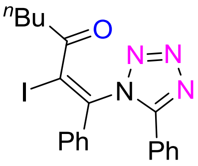
2j

White solid, m.p. 111–112 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.03–7.87 (m, 2H), 7.83–7.77 (m, 2H), 7.66–7.46 (m, 5H), 7.44–7.25 (m, 5H), 2.44 (d, *J* = 2.5 Hz, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 191.9, 154.7, 146.5, 138.9, 135.2, 132.4, 131.6, 131.4, 131.1, 130.4, 130.3, 129.8, 129.6, 129.5, 124.2, 102.8, 21.8; HRMS (ESI-TOF) m/z calcd for $C_{23}H_{18}IN_4O$ $[M + H]^+$ 493.0520, found 493.0531.



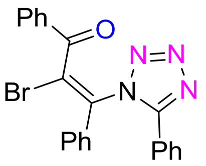
2k

White solid, m.p. 114–115 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.12–8.08 (m, 2H), 7.79 (d, *J* = 8.0 Hz, 2H), 7.65–7.44 (m, 5H), 7.42–7.38 (m, 3H), 7.31 (t, *J* = 8.7 Hz, 2H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 190.9, 167.1 (d, *J* = 255.0 Hz), 154.7, 139.4, 135.0, 133.9 (d, *J* = 9.9 Hz), 132.5, 131.7, 130.6 (d, *J* = 2.9 Hz), 130.4, 129.8, 129.54, 129.47, 124.0, 116.8 (d, *J* = 22.5 Hz), 102.1; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{15}FIN_4O$ $[M + H]^+$ 497.0269, found 497.0275.



2l

Yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72–7.61 (m, 2H), 7.46–7.34 (m, 3H), 7.30–7.27 (m, 1H), 7.25–7.17 (m, 4H), 2.96 (t, *J* = 7.3 Hz, 2H), 1.66–1.58 (m, 2H), 1.45 – 1.26 (m, 2H), 0.92 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.7, 154.3, 137.2, 134.2, 131.5, 130.8, 129.4, 128.9, 128.8, 128.5, 123.2, 103.1, 39.6, 25.8, 22.2, 13.9; HRMS (ESI-TOF) m/z calcd for $C_{20}H_{20}IN_4O$ $[M + H]^+$ 459.0676, found 459.0682.



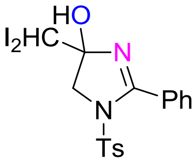
2m

White solid, m.p. 97–98 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 8.05–7.94 (m, 2H), 7.86–7.78 (m, 2H), 7.70 (t, *J* = 7.5 Hz, 1H), 7.60–7.47 (m, 7H), 7.44–7.36 (m, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 190.2, 155.1, 136.5, 135.5, 134.4, 133.1, 132.5, 131.9, 130.7, 130.2, 129.9, 129.8, 129.58, 129.56, 123.9, 122.7; HRMS (ESI-TOF) m/z calcd for $C_{22}H_{16}BrN_4O$ [M + H]$^+$ 431.0502, found 431.0502.

8. O-transfer facilitated cyclizations of terminal propargylamides with $TMSN_3$

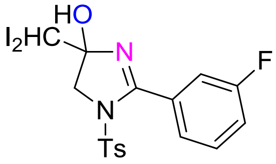
Representative procedure for the synthesis of dihydroimidazoles:

Terminal propargylamide **3** (0.20 mmol) and NIS (108.0 mg) were dissolved in 3 mL of dry and degassed DCE. Subsequently, $TMSN_3$ (95.0 µL) and H_2O (7.0 µL) were added. The resulting yellow solution was stirred at 60 °C for 8-18 h, and quenched with sodium thiosulfate solution. The aqueous layer was extracted with DCM and the combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Purification by flash chromatography on silica gel (petroleum ether/EtOAc: 3/1) afforded the expected product.



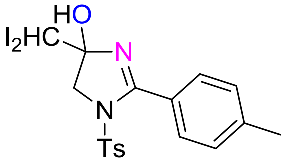
4a

Light yellow solid, m.p. 148–149 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.56 (m, 3H), 7.52–7.36 (m, 6H), 5.76 (s, 1H), 5.33 (s, 1H), 4.27 (d, *J* = 11.9 Hz, 1H), 4.15 (d, *J* = 11.9 Hz, 1H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 161.4, 146.1, 136.0, 131.8, 131.0, 130.8, 130.5, 128.7, 128.4, 96.6, 58.9, 21.5, -11.8; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{17}I_2N_2O_3S$ [M + H]$^+$ 582.9044, found 582.9058.



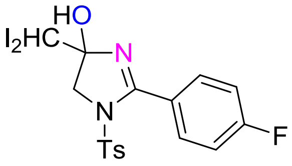
4b

Yellow solid, m.p. 168–169 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.56–7.48 (m, 3H), 7.41 (m, 3H), 7.38–7.32 (m, 1H), 7.31–7.25 (m, 1H), 5.83 (s, 1H), 5.35 (s, 1H), 4.28 (d, *J* = 11.9 Hz, 1H), 4.16 (d, *J* = 11.9 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 162.6 (d, *J* = 244.7 Hz), 160.0 (d, *J* = 2.9 Hz), 146.3, 135.8, 133.1 (d, *J* = 8.4 Hz), 130.9, 130.6 (d, *J* = 8.2 Hz), 128.7, 126.5 (d, *J* = 3.1 Hz), 118.6 (d, *J* = 21.2 Hz), 117.3 (d, *J* = 23.9 Hz), 96.8, 58.9, 21.5, -12.3; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{16}FI_2N_2O_3S$ [M + H]$^+$ 600.8950, found 600.8960.



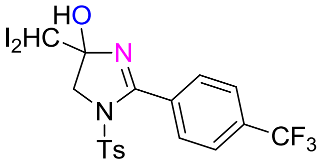
4c

Yellow solid, m.p. 162–163 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.48 (t, *J* = 7.9 Hz, 4H), 7.39 (d, *J* = 8.4 Hz, 2H), 7.25 (d, *J* = 7.9 Hz, 2H), 5.68 (s, 1H), 5.29 (s, 1H), 4.25 (d, *J* = 12.0 Hz, 1H), 4.13 (d, *J* = 12.0 Hz, 1H), 2.42 (s, 3H), 2.41 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 161.6, 146.0, 142.2, 135.9, 130.8, 130.6, 129.0, 128.7, 128.1, 96.6, 58.9, 21.5, -11.6; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{19}I_2N_2O_3S$ [M + H]$^+$ 596.9200, found 596.9213.



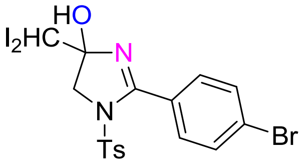
4d

Yellow solid, m.p. 169–170 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.70–7.59 (m, 2H), 7.51 (d, *J* = 8.4 Hz, 2H), 7.41 (d, *J* = 8.1 Hz, 2H), 7.26–7.14 (m, 2H), 5.78 (s, 1H), 5.32 (s, 1H), 4.26 (d, *J* = 12.0 Hz, 1H), 4.15 (d, *J* = 12.0 Hz, 1H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ165.2 (d, *J* = 249.2 Hz), 160.5, 146.2, 135.8, 133.0 (d, *J* = 8.9 Hz), 130.9, 128.7, 127.2 (d, *J* = 3.1 Hz), 115.5 (d, *J* = 22.2 Hz), 96.6, 59.0, 21.5, -12.0; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{16}FI_2N_2O_3S$ [M + H]$^+$ 600.8950, found 600.8960.



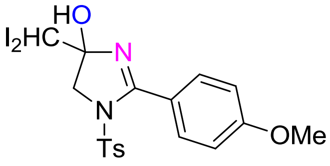
4e

Light yellow solid, m.p. 182–183 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.80 (q, *J* = 8.5 Hz, 4H), 7.55 (d, *J* = 8.3 Hz, 2H), 7.43 (d, *J* = 8.3 Hz, 2H), 5.88 (s, 1H), 5.37 (s, 1H), 4.28 (d, *J* = 11.9 Hz, 1H), 4.15 (d, *J* = 11.9 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 160.1, 146.4, 135.7, 135.1, 132.8 (q, *J* = 32.3 Hz), 131.1, 131.0, 128.7, 125.5 (q, *J* = 3.8 Hz), 125.0 (q, *J* = 271.7 Hz), 97.0, 58.7, 21.5, -12.5; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{16}F_3I_2N_2O_3S$ [M + H]$^+$ 650.8918, found 650.8940.



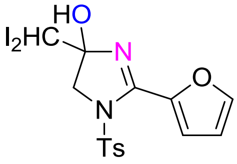
4f

Yellow solid, m.p. 177–178 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.72–7.62 (m, 2H), 7.57–7.49 (m, 4H), 7.43 (d, *J* = 8.1 Hz, 2H), 5.76 (s, 1H), 5.33 (s, 1H), 4.26 (d, *J* = 11.9 Hz, 1H), 4.13 (d, *J* = 11.9 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 160.5, 146.3, 135.8, 132.3, 131.7, 131.0, 130.3, 128.7, 125.8, 96.8, 58.8, 21.5, -12.2; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{16}BrI_2N_2O_3S$ [M + H]$^+$ 660.8149, found 660.8166.



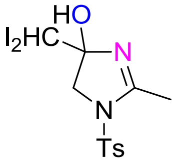
4g

Yellow solid, m.p. 143–144 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.56 (d, *J* = 8.7 Hz, 2H), 7.47 (m, 2H), 7.38 (d, *J* = 8.1 Hz, 2H), 7.21–6.85 (m, 2H), 5.70 (s, 1H), 5.24 (s, 1H), 4.23 (d, *J* = 12.1 Hz, 1H), 4.13 (d, *J* = 12.1 Hz, 1H), 3.89 (s, 3H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 163.0, 161.4, 146.0, 135.9, 132.5 130.8, 128.7, 122.8, 113.8, 96.4, 59.0, 55.8, 21.5, -11.4; HRMS (ESI-TOF) m/z calcd for $C_{18}H_{19}I_2N_2O_4S$ [M + H]$^+$ 612.9149, found 612.9166.



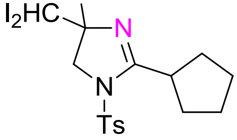
4h

Yellow solid, m.p. 159–160 °C; ^{1}H NMR (400 MHz, CD$_2$Cl$_2$) δ 7.67 (s, 1H), 7.60 (d, *J* = 8.3 Hz, 2H), 7.45 (d, *J* = 3.5 Hz, 1H), 7.34 (d, *J* = 8.1 Hz, 2H), 6.61 (dd, *J* = 3.5, 1.6 Hz, 1H), 5.08 (s, 1H), 4.27 (s, 2H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, CD$_2$Cl$_2$) δ 152.6, 147.1, 146.2, 134.9, 130.5, 128.1, 120.4, 112.4, 95.8, 58.8, 21.9, -13.4; HRMS (ESI-TOF) m/z calcd for $C_{15}H_{15}I_2N_2O_4S$ [M + H]$^+$ 572.8836, found 572.8849.



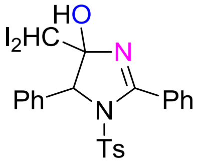
4i

Yellow solid, m.p. 156–157 °C; ^{1}H NMR (400 MHz, CD$_2$Cl$_2$) δ 7.81 (d, *J* = 8.2 Hz, 2H), 7.41 (d, *J* = 8.1 Hz, 2H), 5.14 (s, 1H), 4.05 (d, *J* = 11.4 Hz, 1H), 3.96 (d, *J* = 11.4 Hz, 1H), 2.45 (s, 3H), 2.33 (s, 3H); ^{13}C NMR (100 MHz, Acetone) δ 159.2, 146.1, 136.6, 131.2, 128.4, 96.2, 57.9, 21.5, 16.8, -11.2; HRMS (ESI-TOF) m/z calcd for $C_{12}H_{15}I_2N_2O_3S$ [M + H]$^+$ 520.8887, found 520.8897.



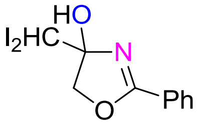
4j

White solid, m.p. 149–150 °C; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ 7.90 (d, *J* = 8.4 Hz, 2H), 7.51 (d, *J* = 8.1 Hz, 2H), 5.54 (s, 1H), 5.34 (s, 1H), 4.09 (d, *J* = 11.3 Hz, 1H), 3.91 (d, *J* = 11.3 Hz, 1H), 3.57–3.33 (m, 1H), 2.46 (s, 3H), 1.98–1.80 (m, 4H), 1.79–1.65 (m, 2H), 1.65–1.46 (m, 2H); ^{13}C NMR (100 MHz, Acetone-d$_6$) δ 166.8, 145.9, 136.9, 131.1, 128.3, 95.8, 58.3, 39.3, 33.0, 32.2, 26.4, 26.4, 21.5, -10.8; HRMS (ESI-TOF) m/z calcd for $C_{16}H_{21}I_2N_2O_3S$ [M + H]$^+$ 574.9357, found 574.9369.



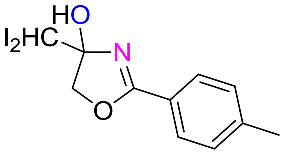
4k

Yellow solid, m.p. 164–165 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 7.78–7.70 (m, 2H), 7.68–7.58 (m, 1H), 7.56–7.47 (m, 4H), 7.44–7.32 (m, 7H), 5.45 (s, 1H), 5.40 (s, 1H), 4.48 (s, 1H), 2.46 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 161.2, 146.3, 136.9, 136.3, 132.3, 131.3, 130.9, 130.7, 129.4, 128.8, 128.7, 128.6, 98.1, 69.4, 21.5, -9.8; HRMS (ESI-TOF) m/z calcd for $C_{23}H_{21}I_2N_2O_3S$ $[M + H]^+$ 658.9357, found 658.9363.



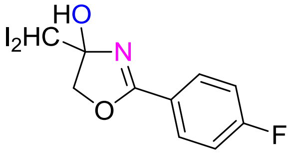
4l

White solid, m.p. 150–151 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.15–7.90 (m, 2H), 7.66–7.57 (m, 1H), 7.50 (m, 2H), 5.75 (s, 1H), 5.58 (s, 1H), 4.66 (d, J = 10.1 Hz, 1H), 4.51 (d, J = 10.1 Hz, 1H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 166.8, 133.1, 129.45, 129.41, 128.3, 100.8, 76.8, -11.7; HRMS (ESI-TOF) m/z calcd for $C_{10}H_{10}I_2NO_2$ $[M + H]^+$ 429.8795, found 429.8806.



4m

Yellow solid, m.p. 142–143 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 7.86 (d, J = 8.2 Hz, 2H), 7.32 (d, J = 8.0 Hz, 2H), 5.71 (s, 1H), 5.56 (s, 1H), 4.64 (d, J = 10.1 Hz, 1H), 4.48 (d, J = 10.1 Hz, 1H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 166.9, 143.7, 130.1, 129.4, 125.4, 100.8, 76.7, 21.6, -11.4; HRMS (ESI-TOF) m/z calcd for $C_{11}H_{12}I_2NO_2$ $[M + H]^+$ 443.8952, found 443.8963.



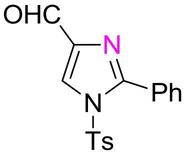
4n

Yellow solid, m.p. 158–159 °C; ^{1}H NMR (400 MHz, Acetone-d_6) δ 8.22–7.81 (m, 2H), 7.43–7.01 (m, 2H), 5.80 (s, 1H), 5.57 (s, 1H), 4.67 (d, J = 10.1 Hz, 1H), 4.52 (d, J = 10.1 Hz, 1H); ^{13}C NMR (100 MHz, Acetone-d_6) δ166.1 (d, J = 250.9 Hz), 165.8, 132.0 (d, J = 9.2 Hz), 124.8 (d, J = 3.0 Hz), 116.5 (d, J = 22.3 Hz), 100.8, 76.9, -11.9; HRMS (ESI-TOF) m/z calcd for $C_{10}H_9FI_2NO_2$ $[M + H]^+$ 447.8701, found 447.8729.

9. Reactions for the synthesis of heterocyclic carbaldehydes

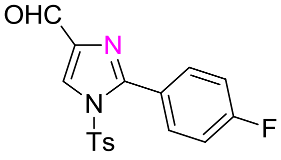
Representative procedure:

The resulting product **4** (0.2 mmol) was dissolved in 2.0 mL $CDCl_3$, and then added 0.4 mmol Martin's sulfurane dehydrating agent. The resulting solution was stirred at room temperature for 12-18 h. Direct purification by flash chromatography on silica gel (petroleum ether/EtOAc: 10/1) afforded the desired product **5**.



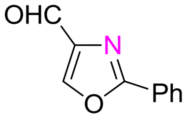
5a

White solid, m.p. 106–107 °C; ^1H NMR (400 MHz, Acetone-d_6) δ 9.89 (d, *J* = 1.6 Hz, 1H), 8.50 (d, *J* = 1.6 Hz, 1H), 7.62–7.52 (m, 1H), 7.51–7.24 (m, 8H), 2.40 (d, *J* = 1.2 Hz, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 185.5, 149.9, 148.1, 141.2, 134.6, 131.3, 131.2, 131.1, 130.0, 128.8, 128.7, 127.9, 21.6; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{15}N_2O_3S$ $[M + H]^+$ 327.0798, found 327.0815.



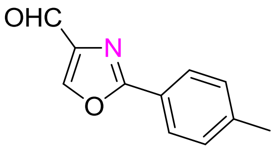
5d

Yellow solid, m.p. 112–113 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 9.92 (s, 1H), 8.28 (s, 1H), 7.50–7.36 (m, 2H), 7.31 (d, *J* = 8.5 Hz, 2H), 7.19 (d, *J* = 8.1 Hz, 2H), 7.13–7.03 (m, 2H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.5, 164.3 (d, *J* = 251.8 Hz), 148.4, 147.2, 139.9, 133.6, 132.9 (d, *J* = 8.8 Hz), 130.3, 128.1, 125.8, 124.7 (d, *J* = 3.3 Hz), 115.3 (d, *J* = 22.0 Hz), 21.9; HRMS (ESI-TOF) m/z calcd for $C_{17}H_{14}F\ N_2O_3S$ $[M + H]^+$ 345.0704, found 345.0703.



5l

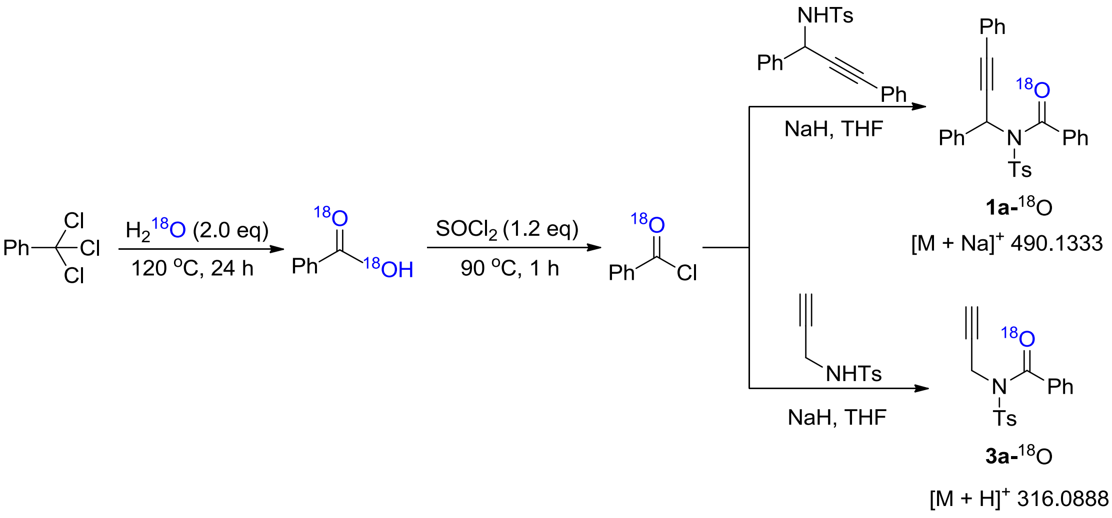
White solid, m.p. 84–85 °C; ^1H NMR (400 MHz, Acetone-d_6) δ 10.00 (d, *J* = 5.3 Hz, 1H), 8.80 (d, *J* = 5.9 Hz, 1H), 8.27–7.68 (m, 2H), 7.92–7.16 (m, 3H); ^{13}C NMR (100 MHz, Acetone-d_6) δ 184.52, 163.36, 147.46, 143.03, 132.29, 130.03, 127.55, 127.43; HRMS (ESI-TOF) m/z calcd for $C_{10}H_8NO_2$ $[M + H]^+$ 174.0550, found 174.0550.



5m

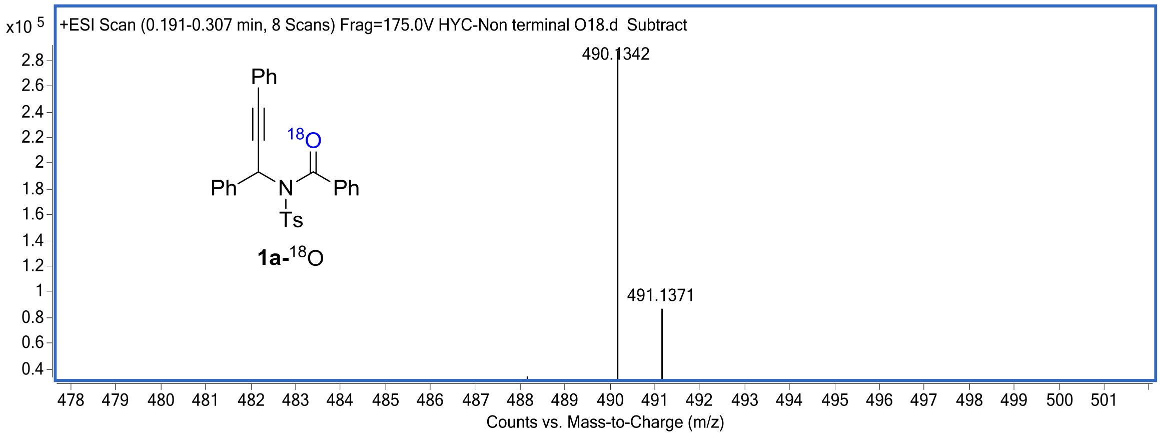
Yellow solid, m.p. 102–103 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 10.00 (s, 1H), 8.29 (s, 1H), 8.00 (d, *J* = 8.2 Hz, 2H), 7.30 (d, *J* = 8.1 Hz, 2H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 184.3, 163.4, 144.2, 142.2, 142.0, 129.8, 127.1, 123.6, 21.7; HRMS (ESI-TOF) m/z calcd for $C_{11}H_{10}NO_2$ [M + H]$^+$ 188.0706, found 188.0714.

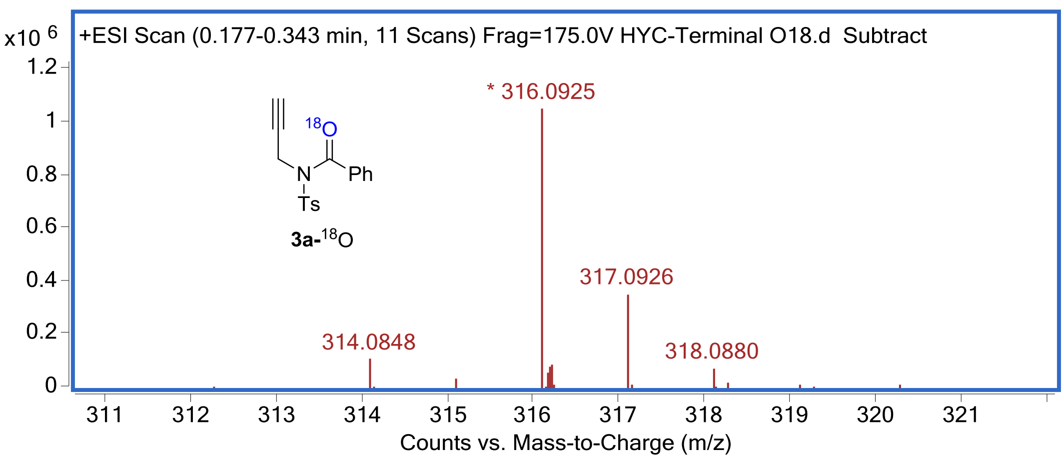
10.Mechanistic studies

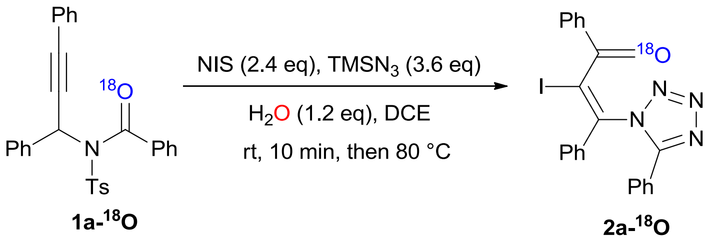


Synthesis of [^{18}O]-benzoyl chloride:[6] α,α,α-Trichlorotoluene (0.98 mL, 5.0 mmol) and $H_2{}^{18}O$ (200 μL, 10.0 mmol) were placed in a sealed tube and stirred at 120 °C for 24 h. The resulting HCl gas was removed after cooling the sealed tube to room temperature. Recrystallization from acetone and pentane afforded the white crystalline product [^{18}O]-benzoic acid. [^{18}O]-Benzoic acid (0.3528 g, 2.5 mmol) and thionyl chloride (0.3 mL, 1.2 eq) were placed in a sealed tube, stirred at 90 °C for 1 h, and subsequently removing the excessive $SOCl_2$ by distillation.

Synthesis of ^{18}O-labelled propargylamide **1a** or **3a**: To a suspension of NaH (60% dispersion in mineral oil, 2.4 mmol) in THF (10.0 mL) at 0 °C was added *N*-tosyl propargylamine (2.0 mmol) and stirred for 40 min. The resulting mixture was then treated with [^{18}O]-benzoyl chloride (2.5 mmol) and stirred at room temperature for 3 h. The reaction was quenched with water, and the layers were separated. The aqueous layer was extracted with ethyl acetate and the combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Purification by flash chromatography on silica gel (petroleum ether/EtOAc: 10/1) afforded the desired ^{18}O-labelled propargylamide **1a** or **3a**.

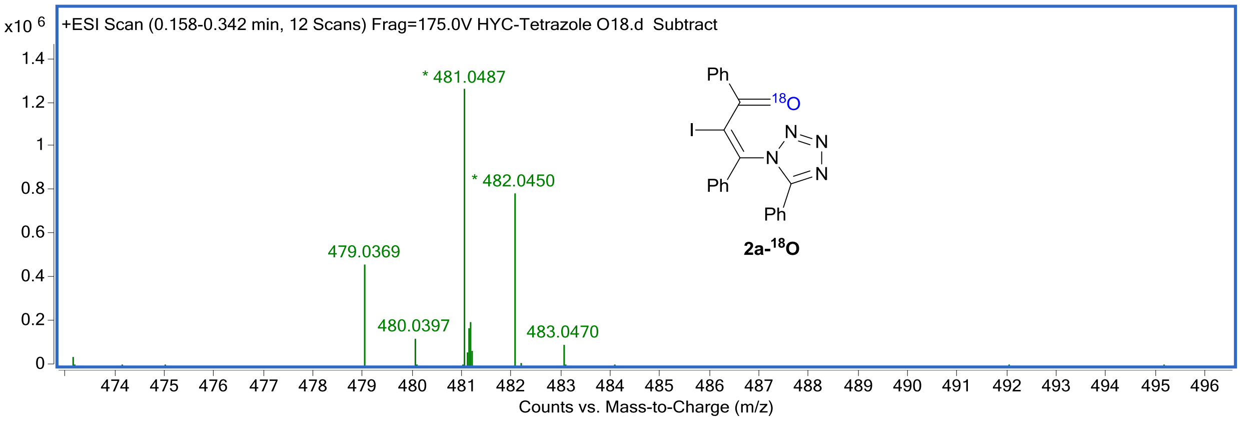


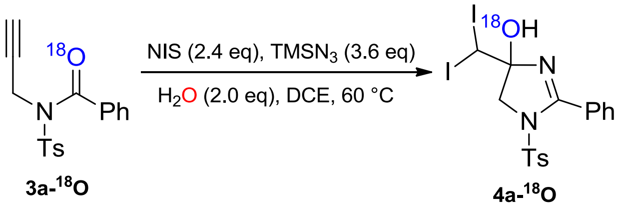




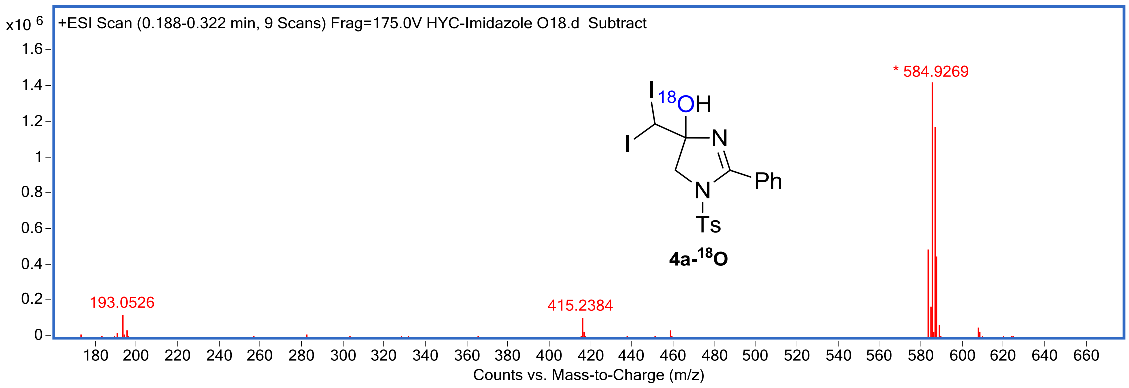
1a-^{18}O **2a-^{18}O**

$[M + H]^+$ 481.0406

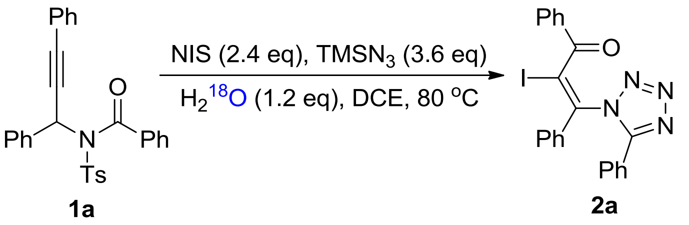




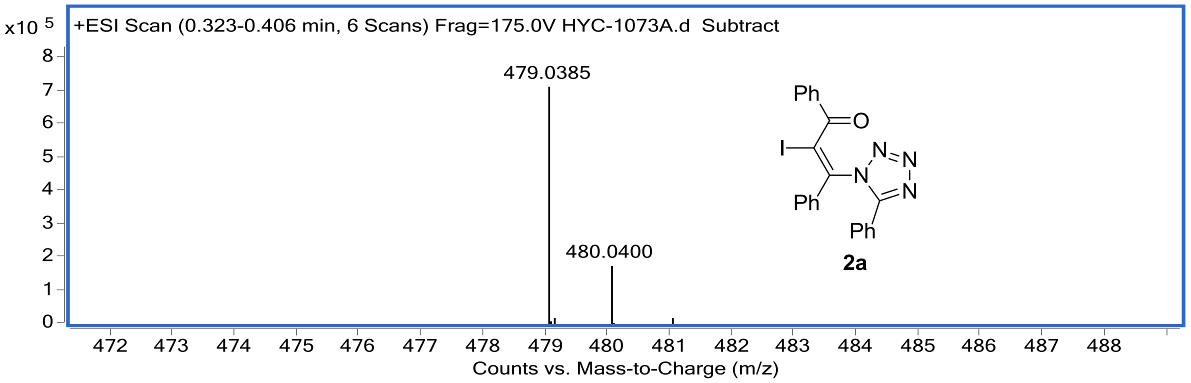
$[M + H]^+$ 584.9086

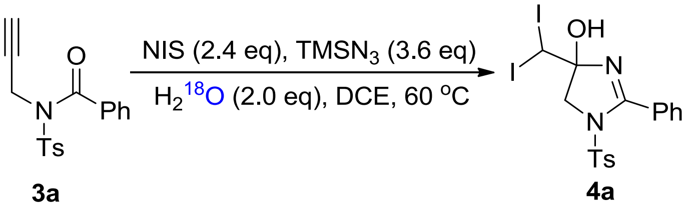


$H_2{}^{18}O$ was employed in the reactions, no ^{18}O-labeled products were observed.

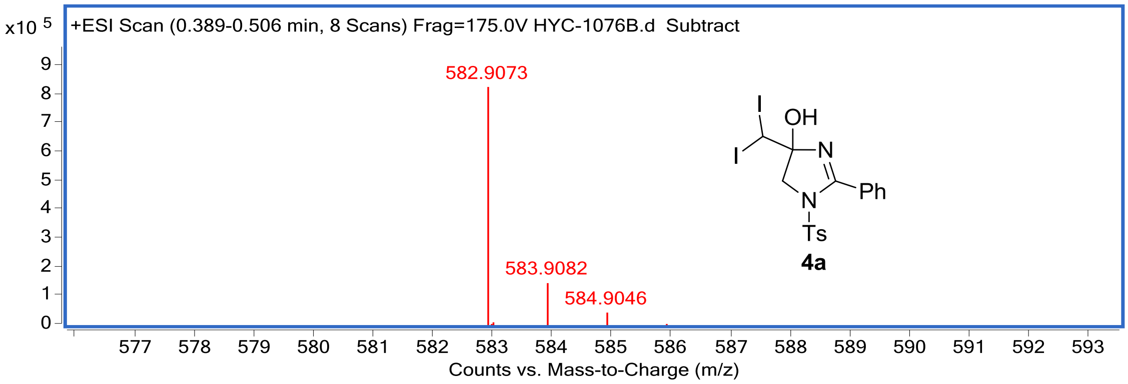


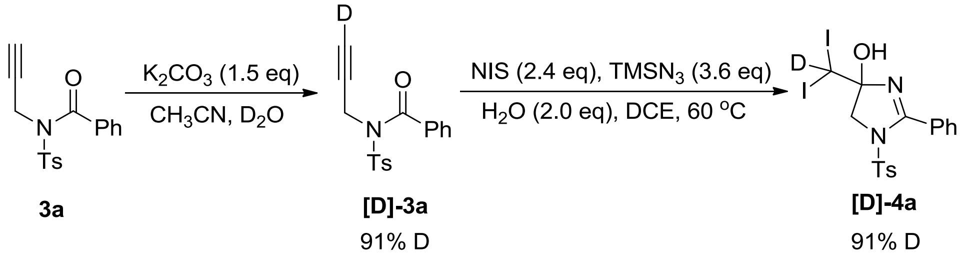
$[M + H]^+$ 479.0363



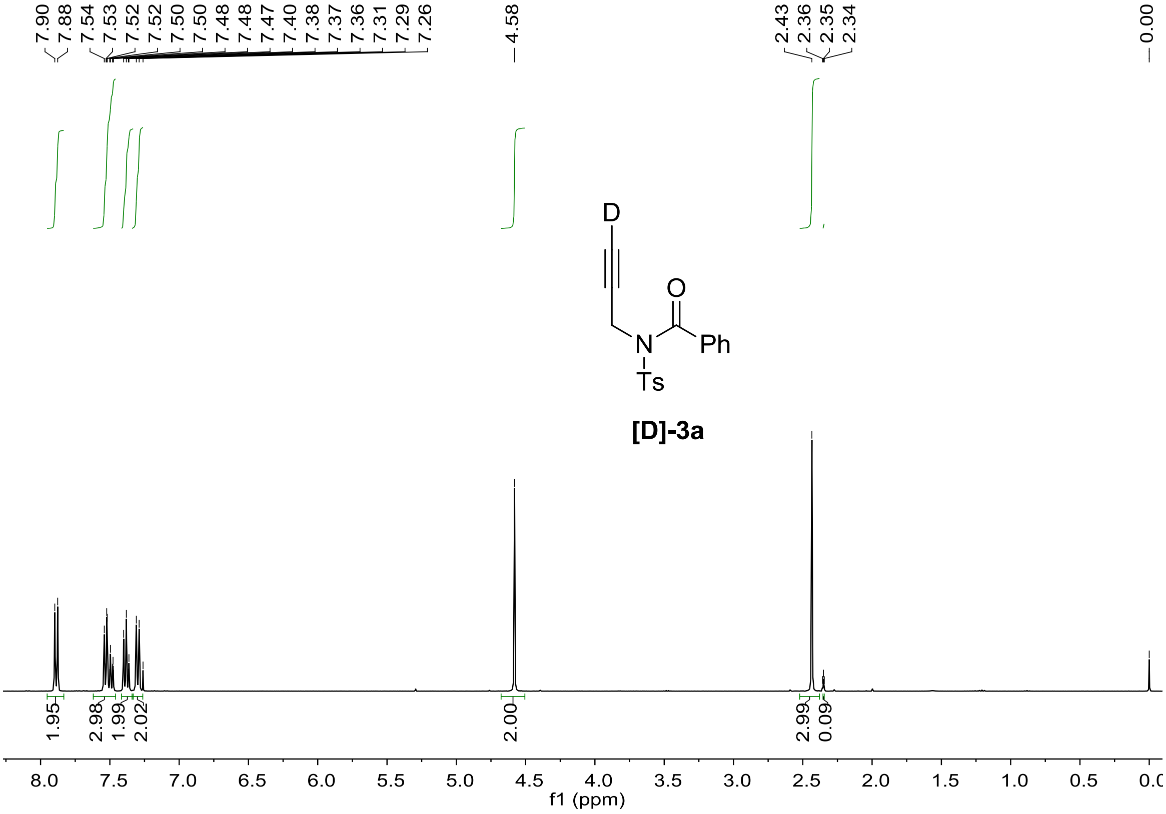


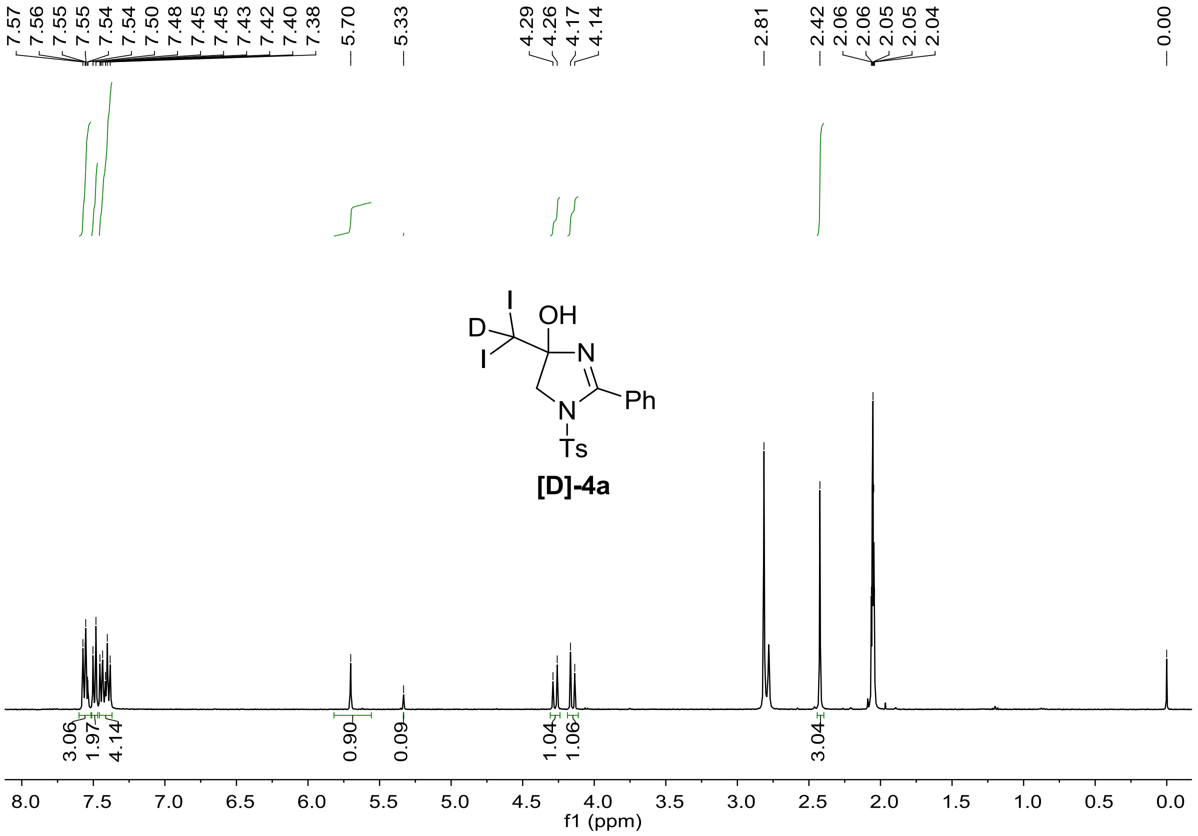
$[M + H]^+$ 582.9044

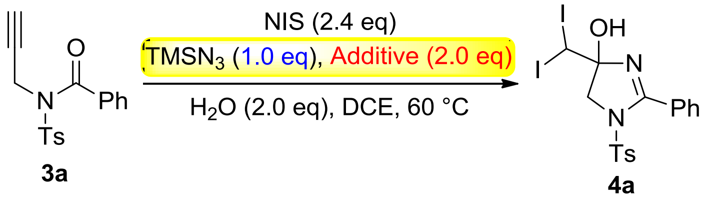




N-Ts propargylamide **3a** (0.40 mmol) and K_2CO_3 (0.60 mmol) were dissolved in 5.0 mL of dry and degassed CH_3CN. The resulting solution was stirred at room temperature for 30 min and then added D_2O (0.80 mmol). After 3 h, the reaction was quenched with water and extracted with Et_2O. The combined organic layers were washed twice with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Recrystallization from EtOH and pentane afforded [D]-**4a**.







Entry	Additive	Yield of **4a**
A	none	trace (<5%)
B	NaI	39%
C	KBr	58%
D	$PhSO_2Na$	15%
E	NaN_3	23%
F	$TMSN_3$	78%

N-Ts propargylamide **3a** (0.20 mmol) and NIS (0.48 mmol) were dissolved in 3.0 mL of dry and degassed DCE. Subsequently, $TMSN_3$ (0.20 mmol, 25.0 µL), H_2O (7.0 µL) and additive (0.40 mmol) were added and the resulting solution was stirred at 60 °C for 12 h. The reaction was quenched with sodium thiosulfate solution and detected by HPLC.

11. References

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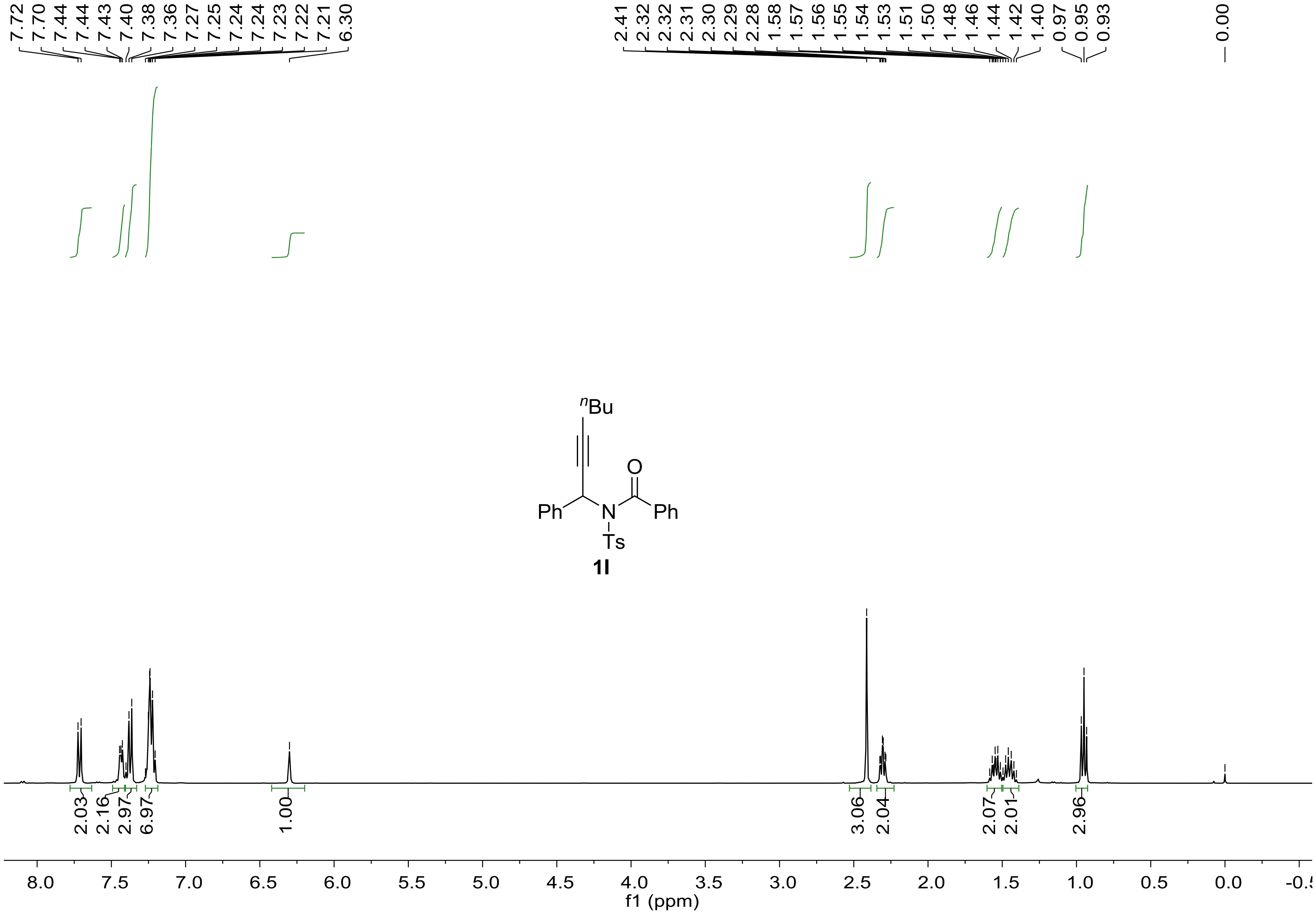
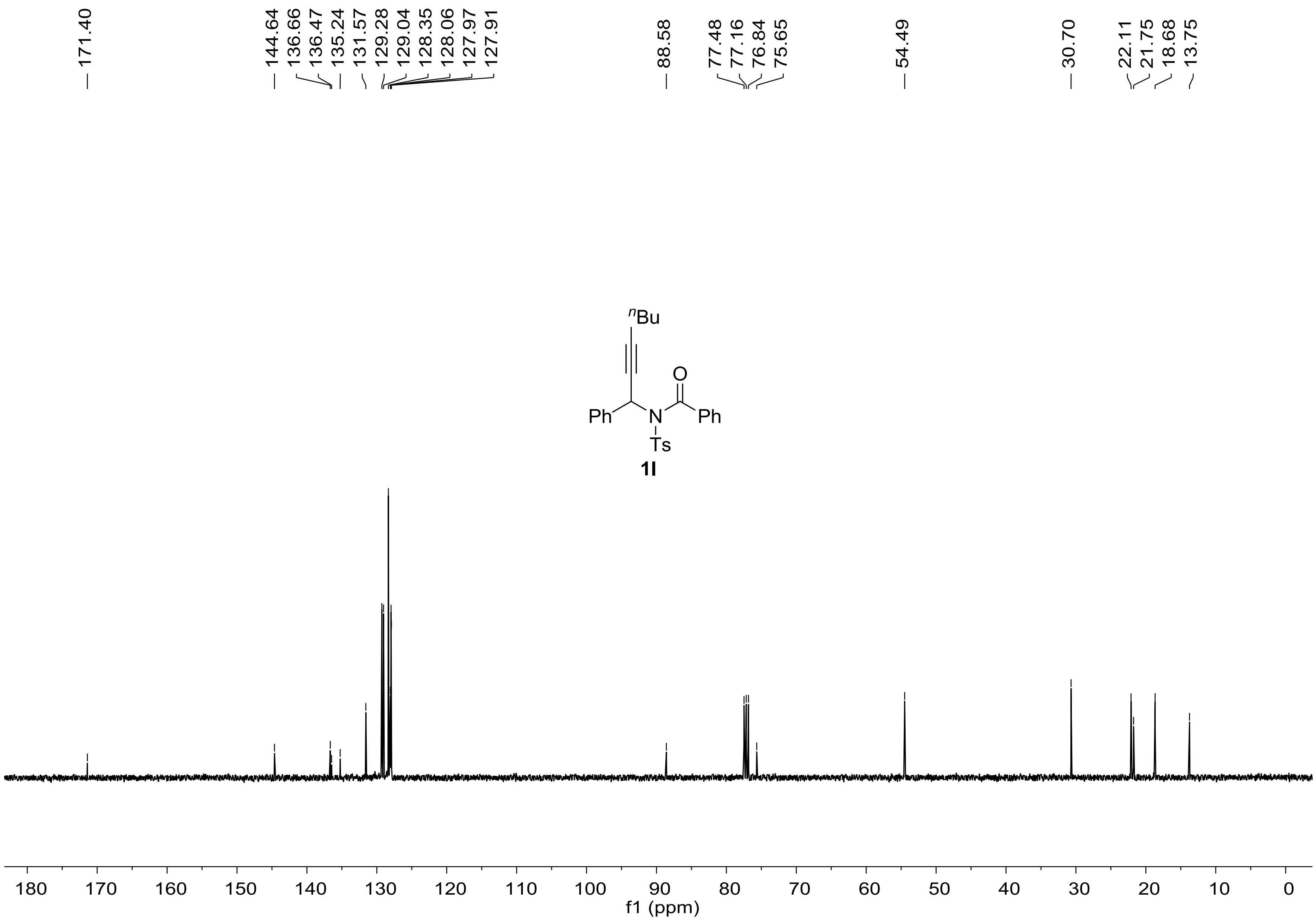
5. B. Zhou, H. Chen, C. Wang, *J. Am. Chem. Soc.* **2013**, *135*, 1264.
6. K. Yamada, S. Dong, G. Wu, *J. Am. Chem. Soc.* **2000**, *122*, 11602.

12. NMR spectra

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128.35
128.06
127.97
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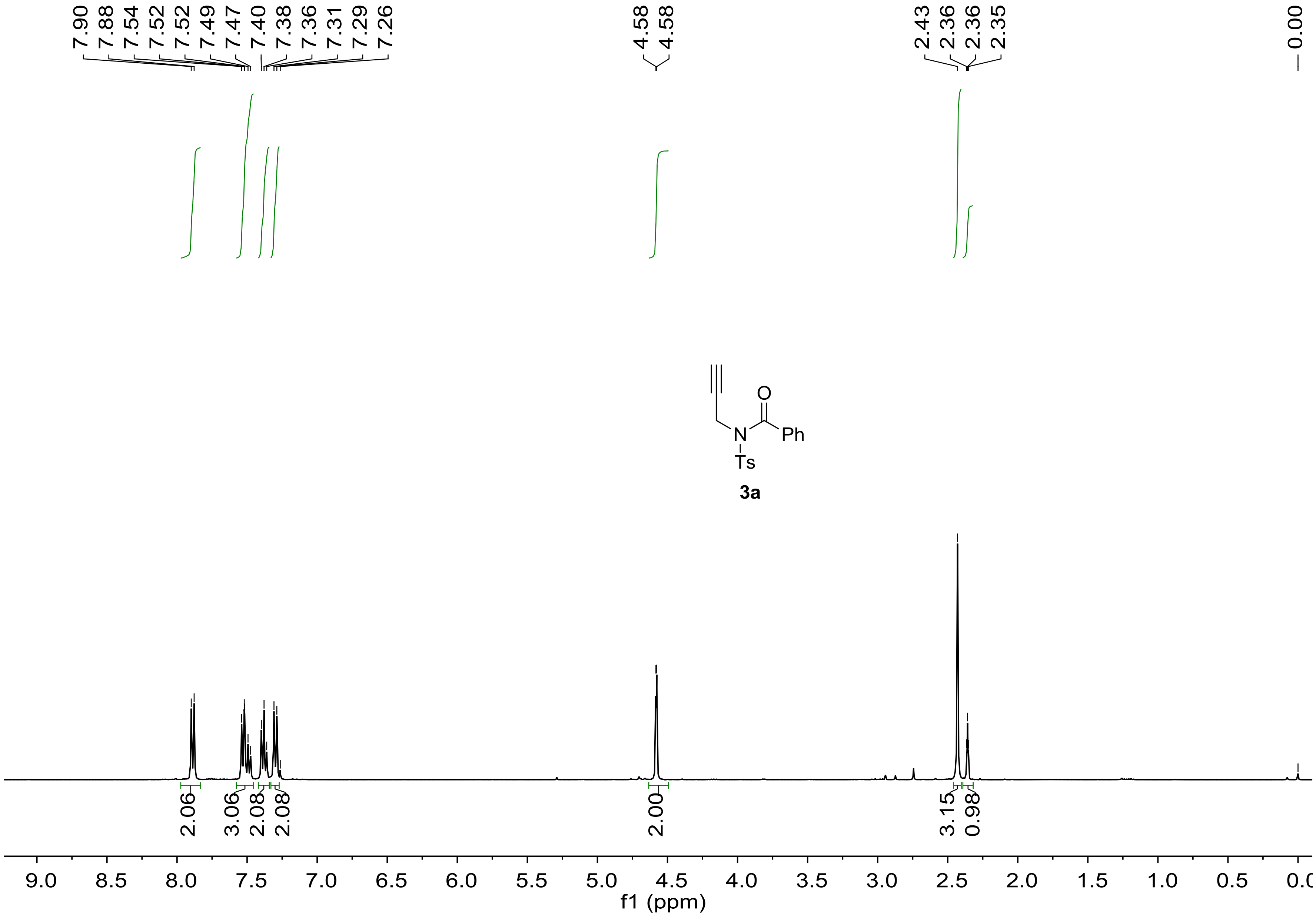
88.58
77.48
77.16
76.84
75.65
54.49
30.70
22.11
21.75
18.68
13.75
^{n}Bu
O
Ph
N
Ph
Ts
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

1l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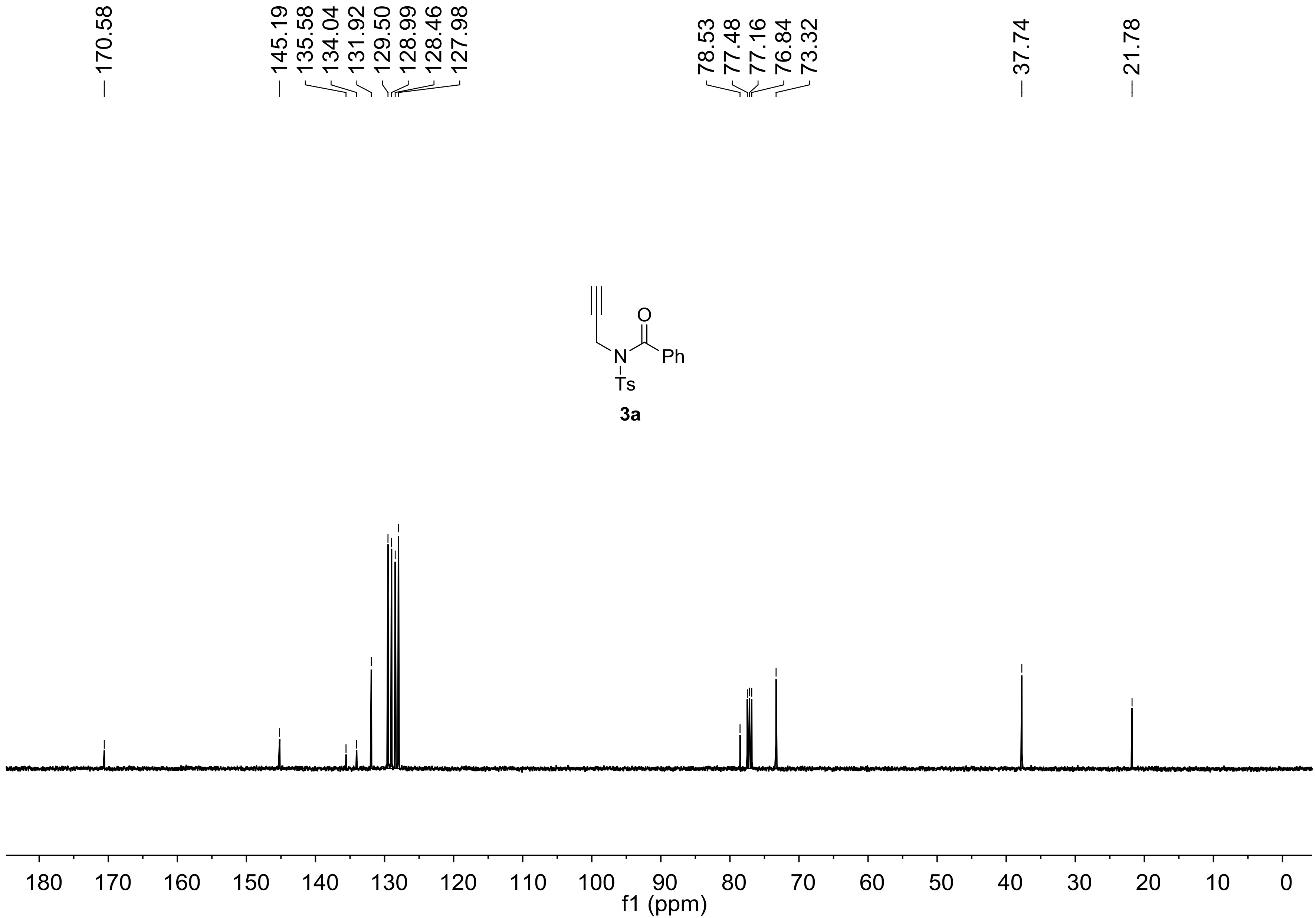
2.36
2.35
0.00
O
N
Ph
Ts
3a
2.06
3.06
2.08
2.08
2.00
3.15
0.98
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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N
Ph
Ts
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170
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90
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30
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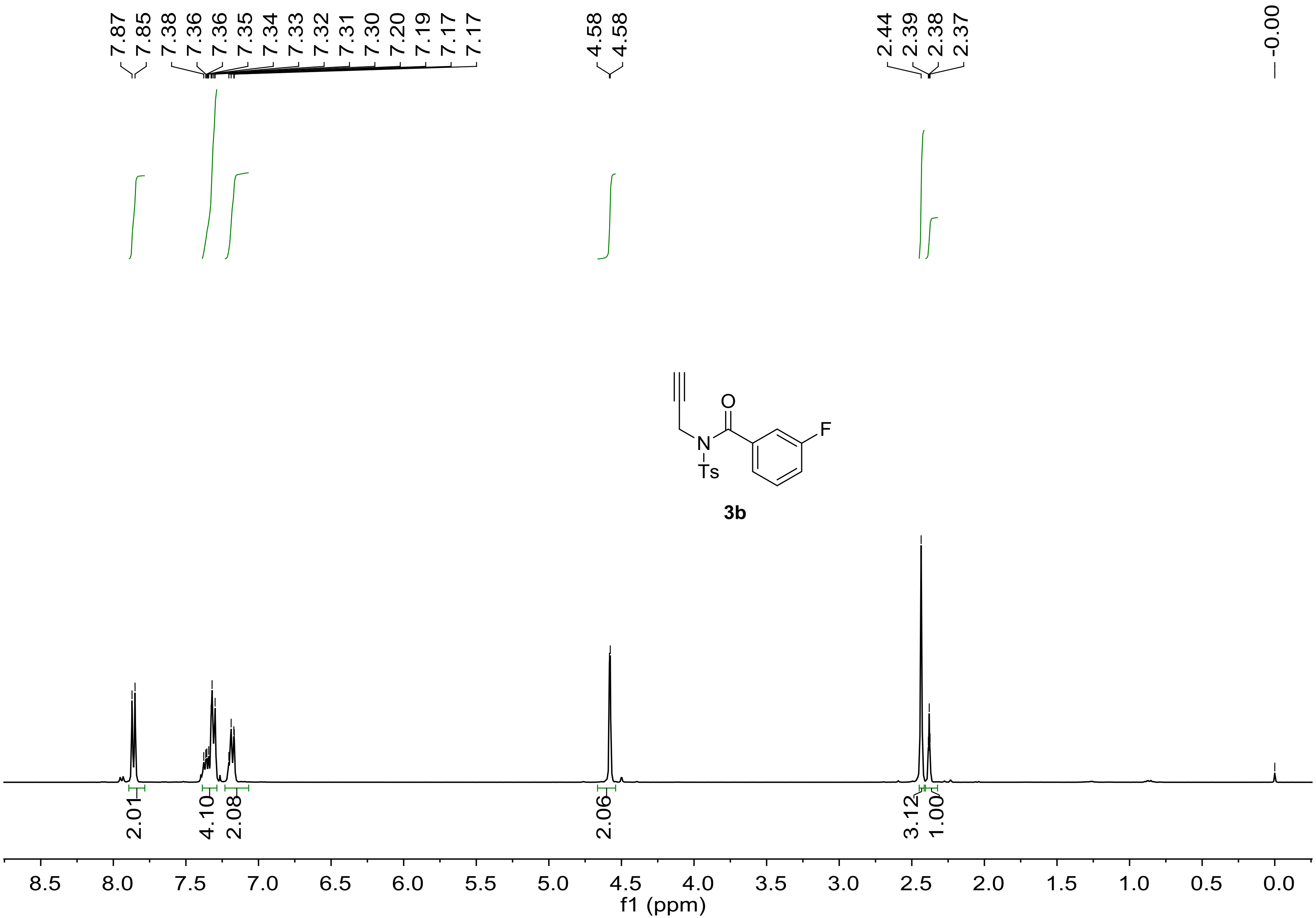
f1 (ppm)

3a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7.17
7.17
4.58
4.58
2.44
2.39
2.38
2.37
-0.00
O
F
N
Ts
3b
2.01
4.10
2.08
2.06
3.12
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
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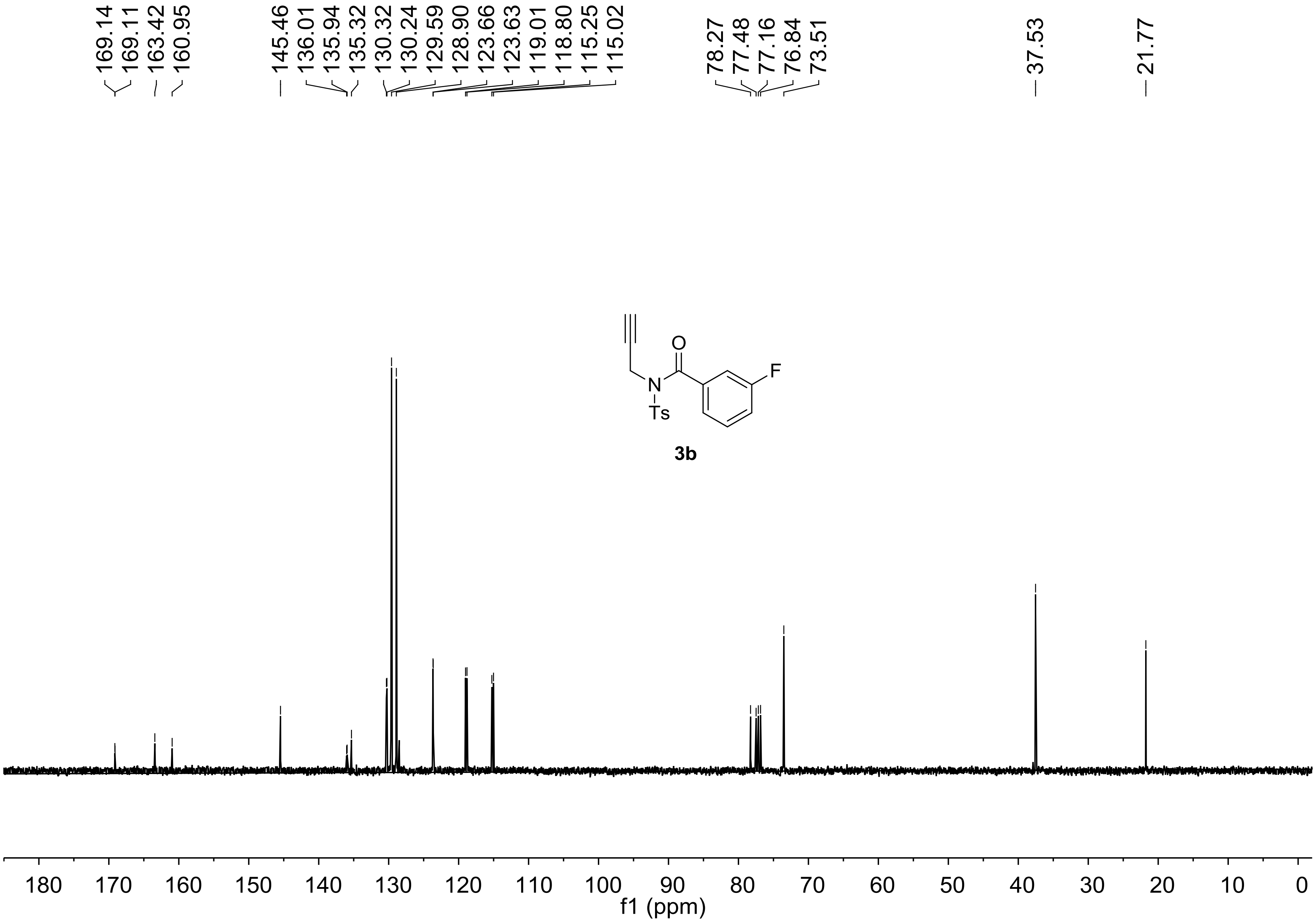
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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169.11
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160.95
145.46
136.01
135.94
135.32
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130.24
129.59
128.90
123.66
123.63
119.01
118.80
115.25
115.02
78.27
77.48
77.16
76.84
73.51
37.53
21.77
O
F
N
Ts
3b
180
170
160
150
140
130
120
110
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90
80
70
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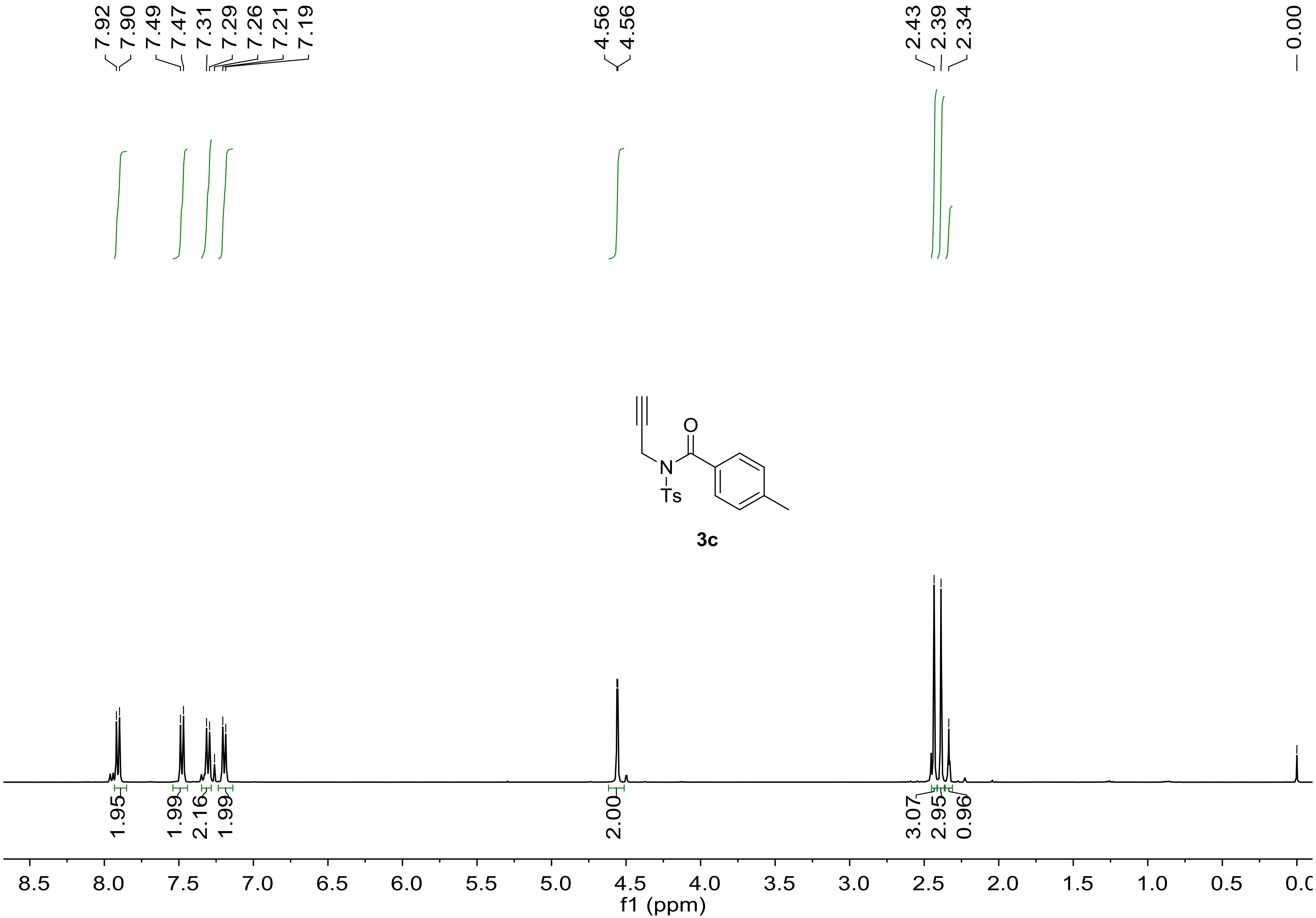
50
40
30
20
10
0
f1 (ppm)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7.21
7.19
4.56
4.56
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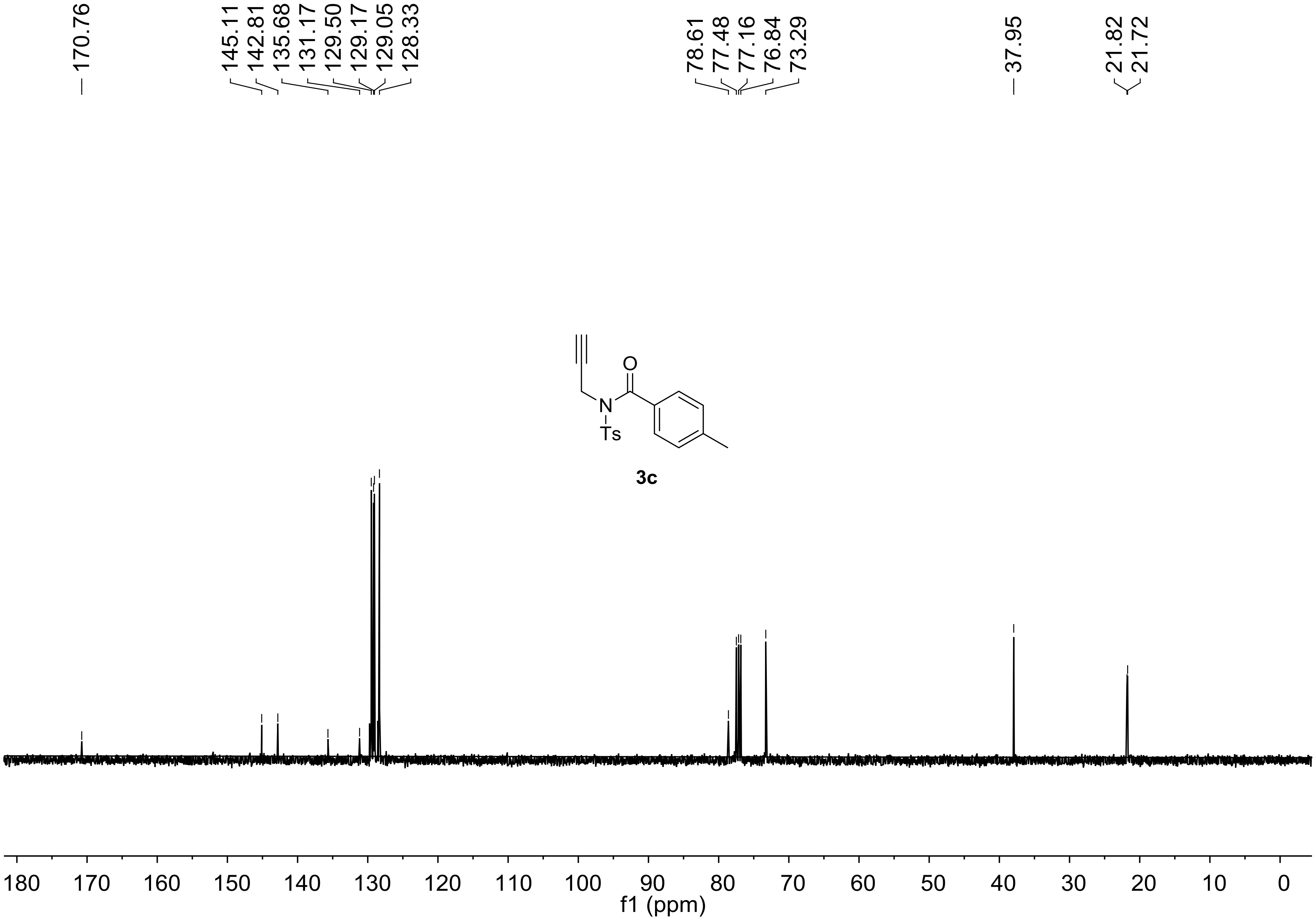
2.39
2.34
0.00
O
N
Ts
1.95
1.99
2.16
1.99
2.00
3.07
2.95
0.96
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

3c


170.76
145.11
142.81
135.68
131.17
129.50
129.17
129.05
128.33
78.61
77.48
77.16
76.84
73.29
37.95
21.82
21.72
O
N
Ts
180
170
160
150
140
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110
100
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80
70
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50
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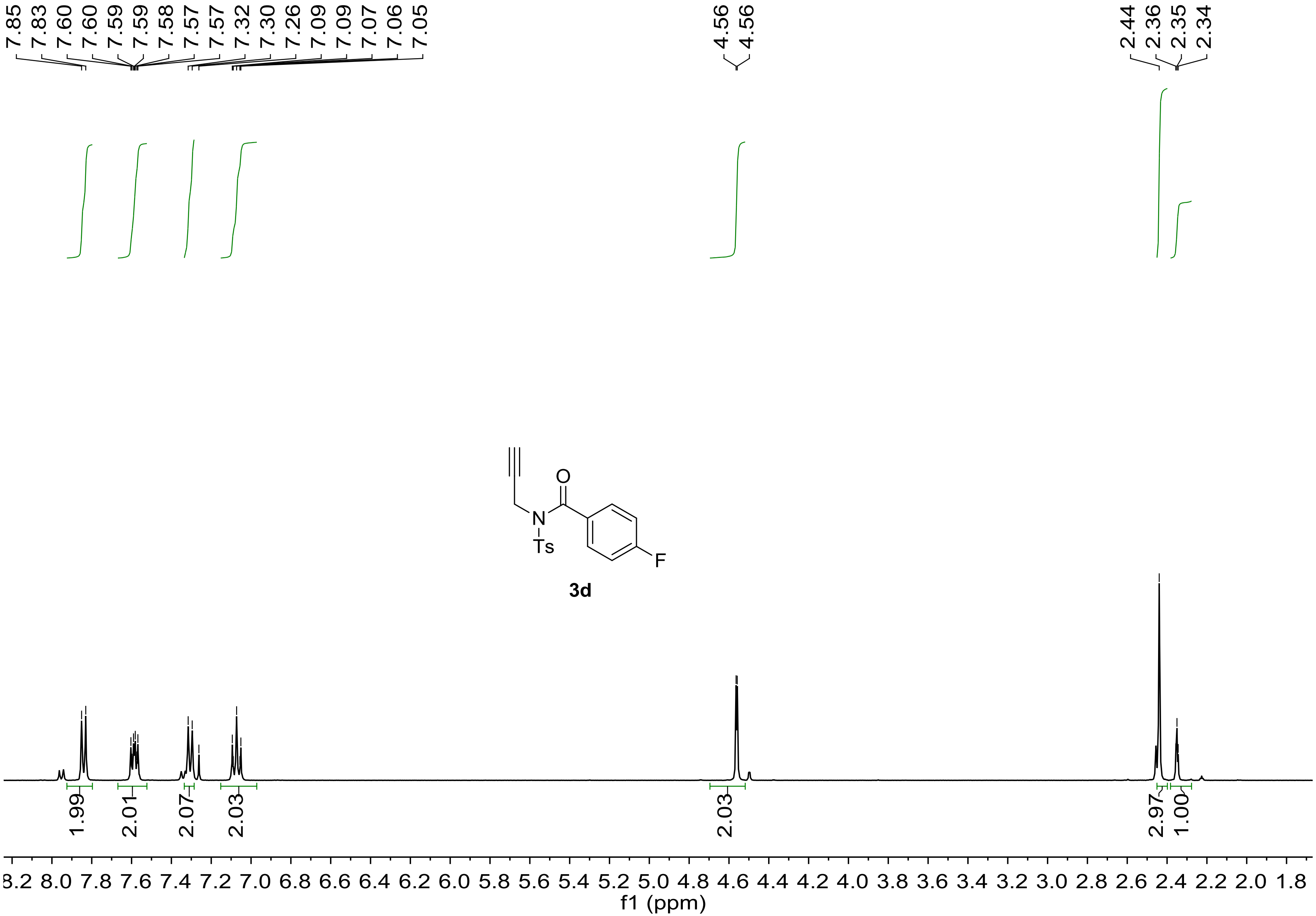
30
20
10
0
f1 (ppm)

3c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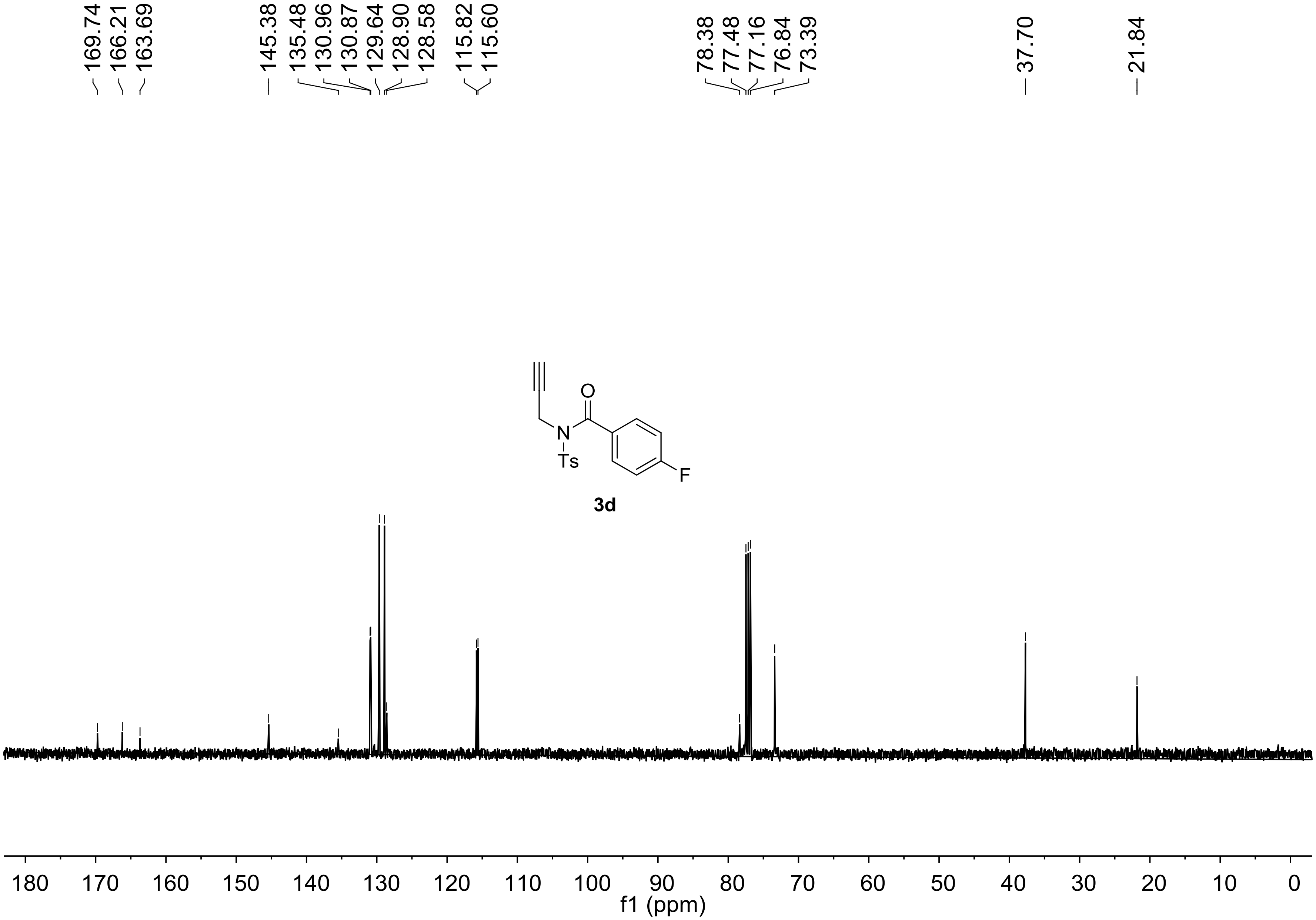
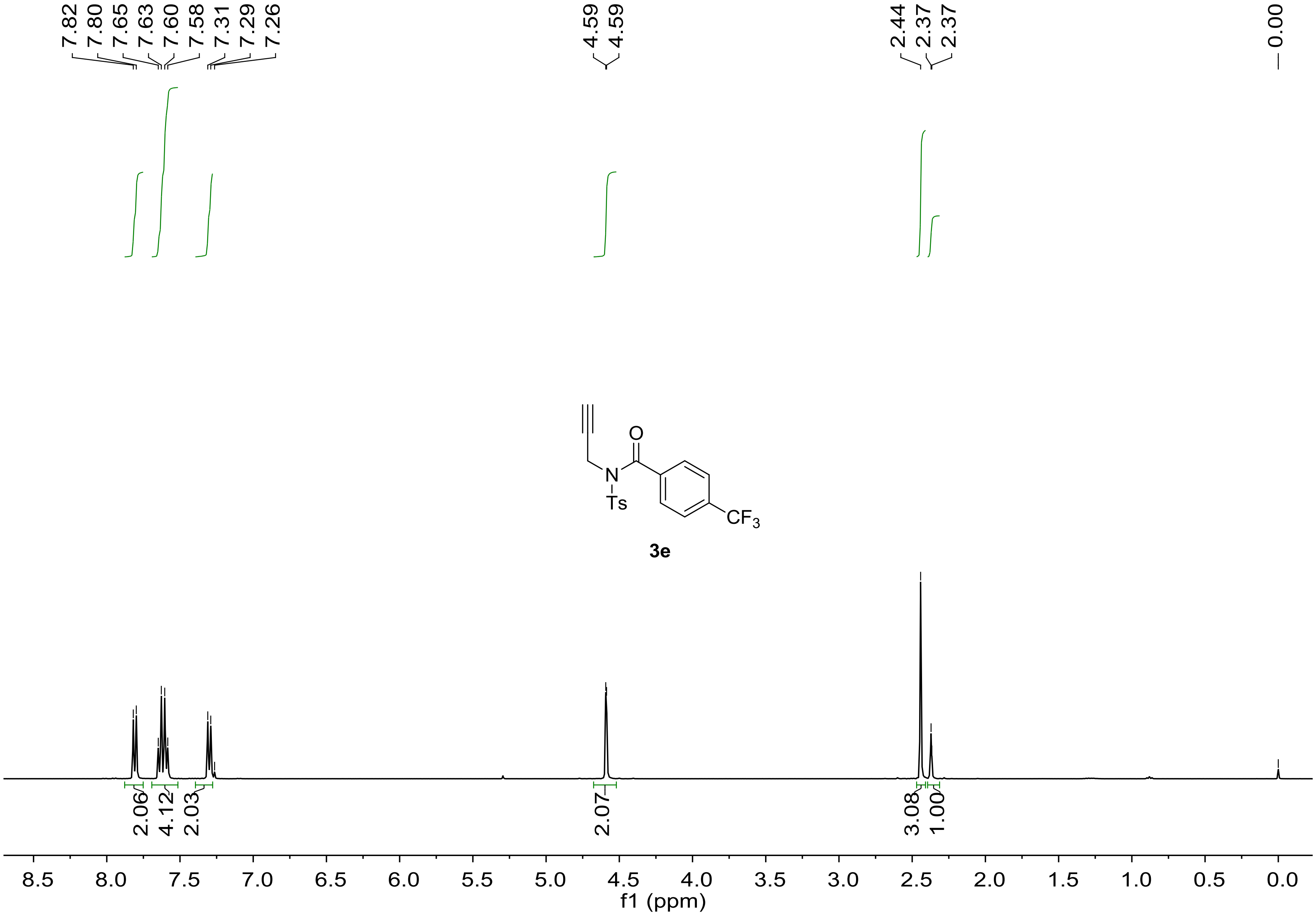
7.59
7.59
7.58
7.57
7.57
7.32
7.30
7.26
7.09
7.09
7.07
7.06
7.05
4.56
4.56
2.44
2.36
2.35
2.34
O
N
Ts
F
3d
1.99
2.01
2.07
2.03
2.03
2.97
1.00
8.2 8.0 7.8 7.6 7.4 7.2 7.0 6.8 6.6 6.4 6.2 6.0 5.8 5.6 5.4 5.2 5.0 4.8 4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6 2.4 2.2 2.0 1.8
f1 (ppm)


3d

169.74
166.21
163.69
145.38
135.48
130.96
130.87
129.64
128.90
128.58
115.82
115.60
78.38
77.48
77.16
76.84
73.39
37.70
21.84
O
N
Ts
F
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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7.80
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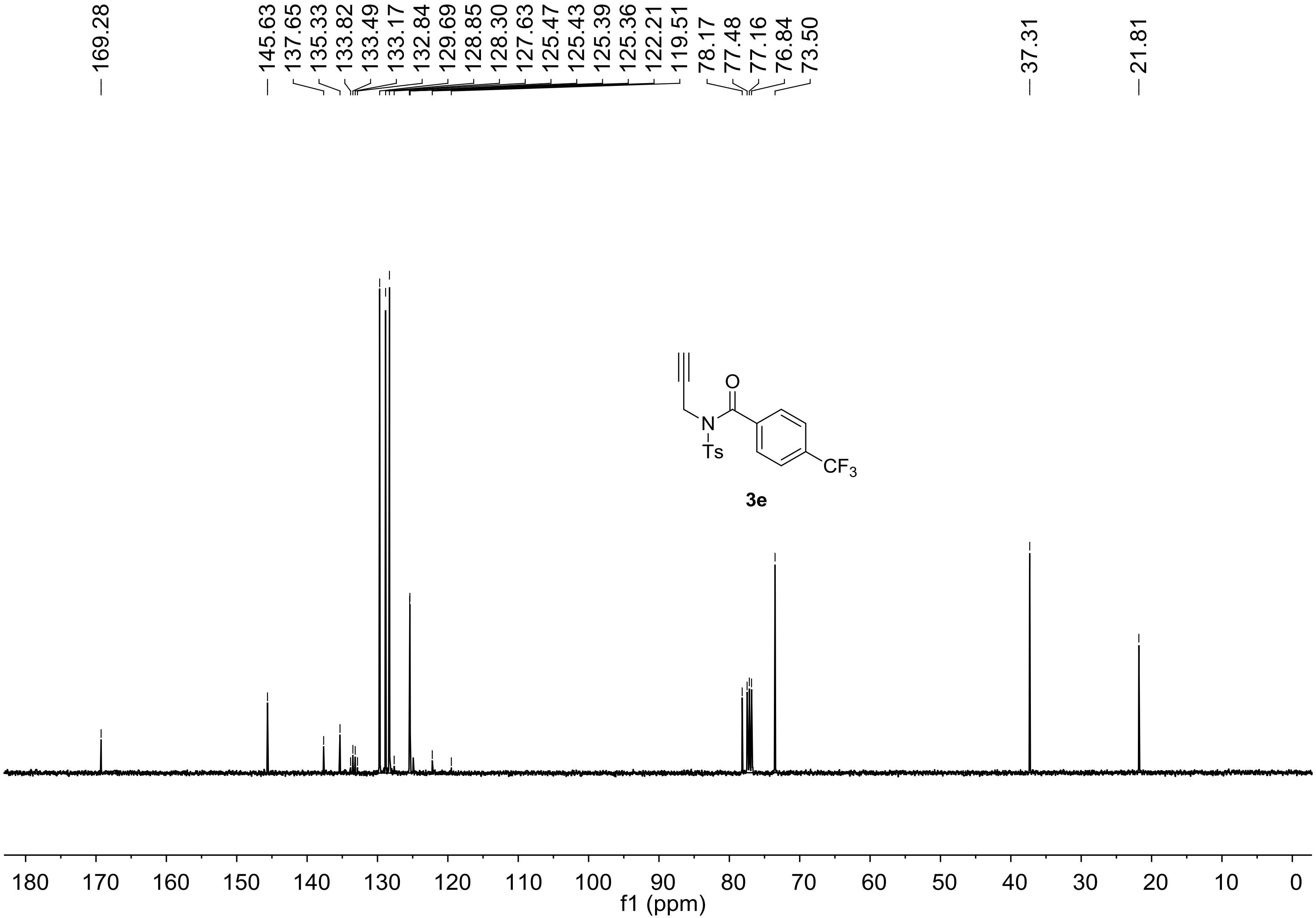
7.58
7.31
7.29
7.26
4.59
4.59
2.44
2.37
2.37
0.00
O
N
Ts
CF3
3e
2.06
4.12
2.03
2.07
3.08
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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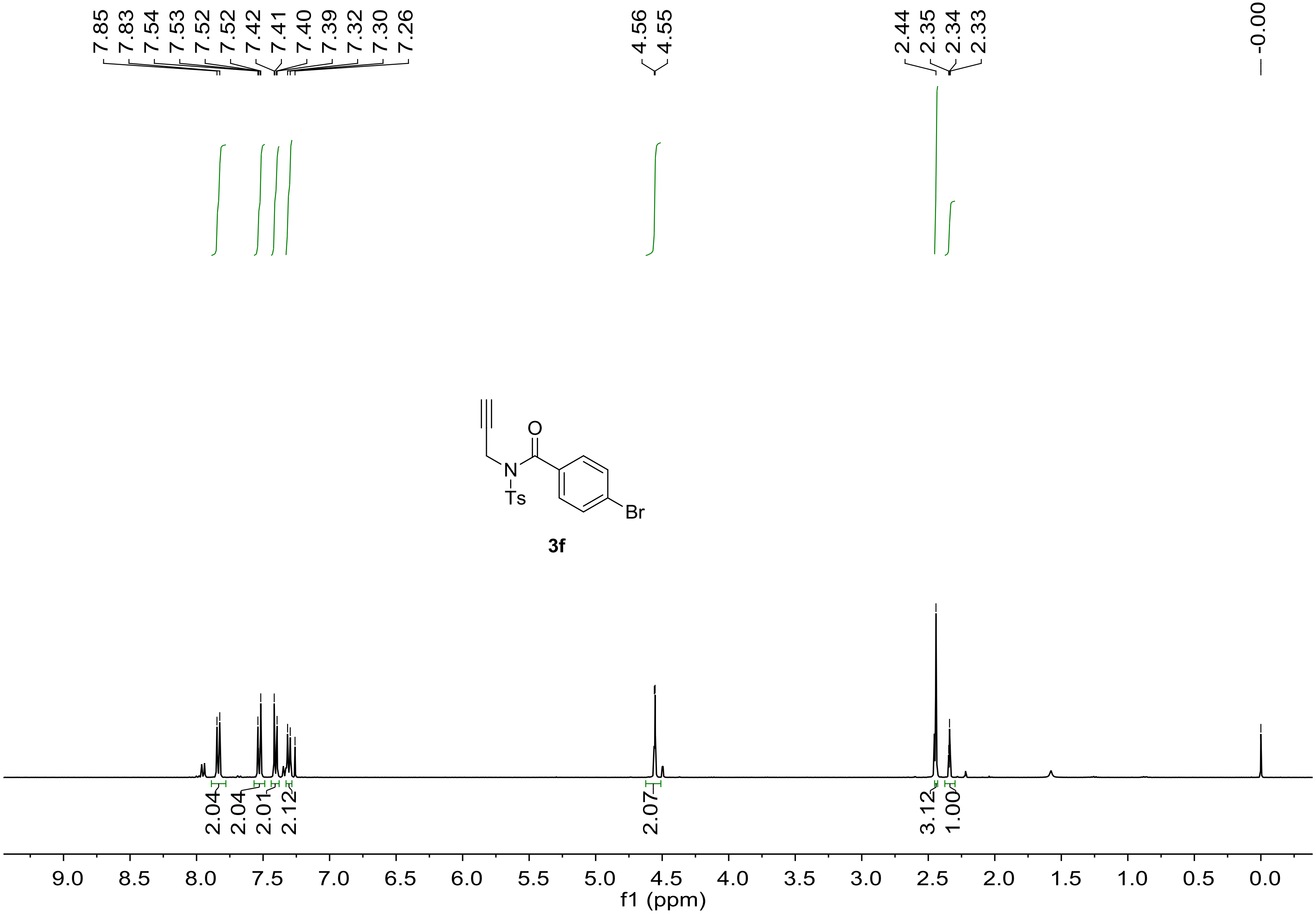
129.69
128.85
128.30
127.63
125.47
125.43
125.39
125.36
122.21
119.51
78.17
77.48
77.16
76.84
73.50
37.31
21.81
O
N
Ts
CF3
3e
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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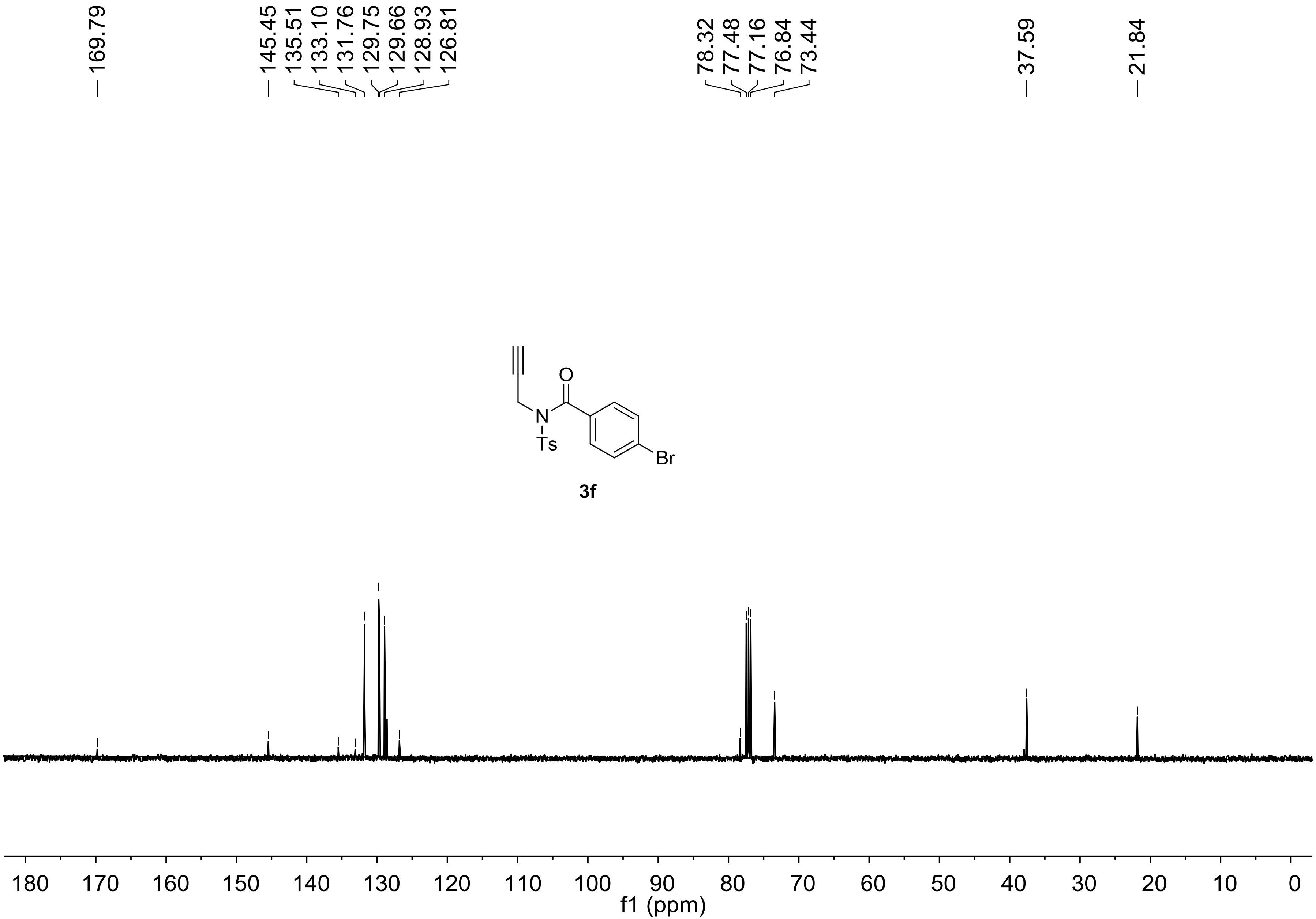
7.83
7.54
7.53
7.52
7.52
7.42
7.41
7.40
7.39
7.32
7.30
7.26
4.56
4.55
2.44
2.35
2.34
2.33
-0.00
O
N
Ts
Br
2.04
2.04
2.01
2.12
2.07
3.12
1.00
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

3f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133.10
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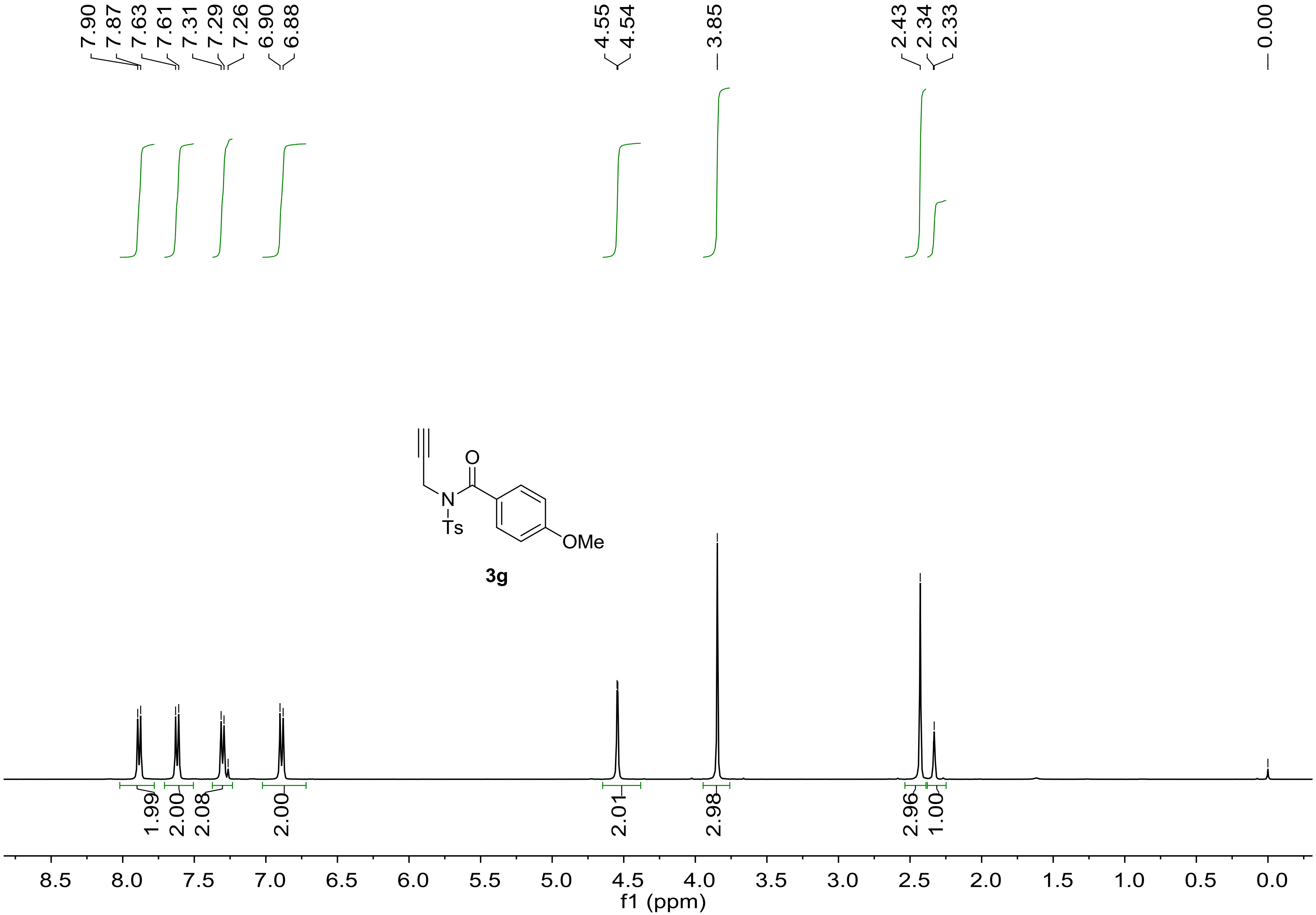
129.75
129.66
128.93
126.81
78.32
77.48
77.16
76.84
73.44
37.59
21.84
O
N
Ts
Br
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

3f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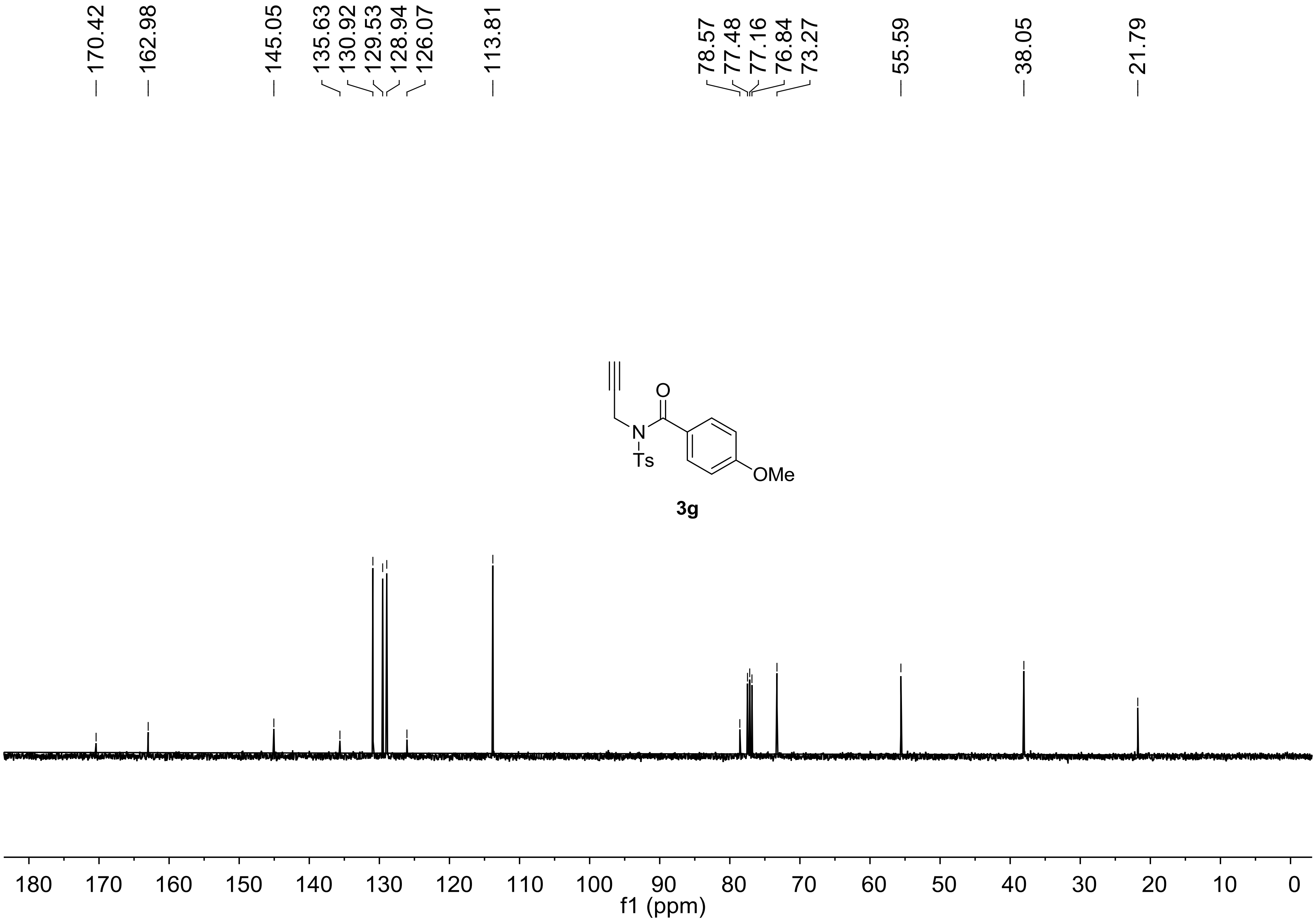
7.87
7.63
7.61
7.31
7.29
7.26
6.90
6.88
4.55
4.54
3.85
2.43
2.34
2.33
0.00
O
N
Ts
OMe
3g
1.99
2.00
2.08
2.00
2.01
2.98
2.96
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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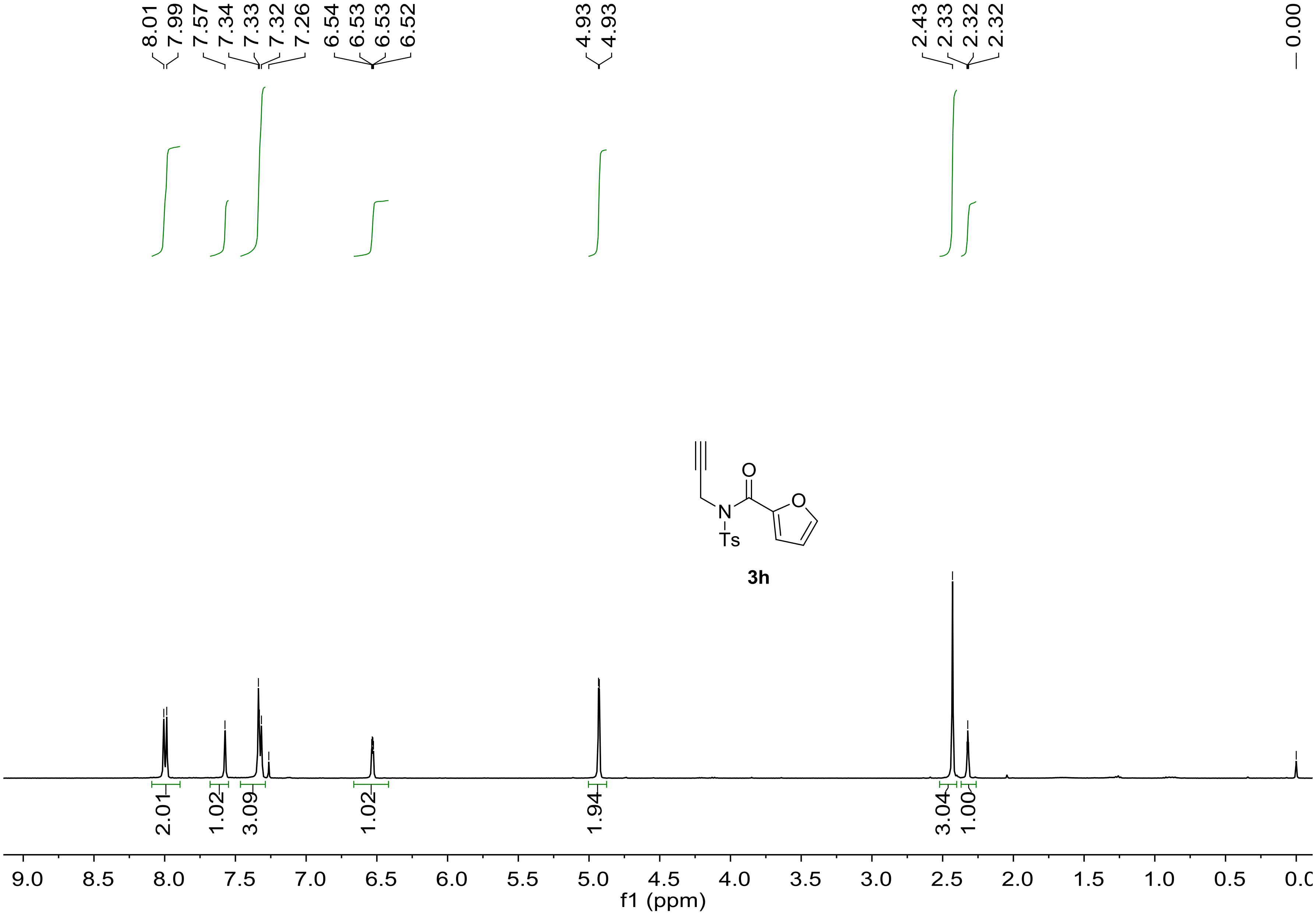
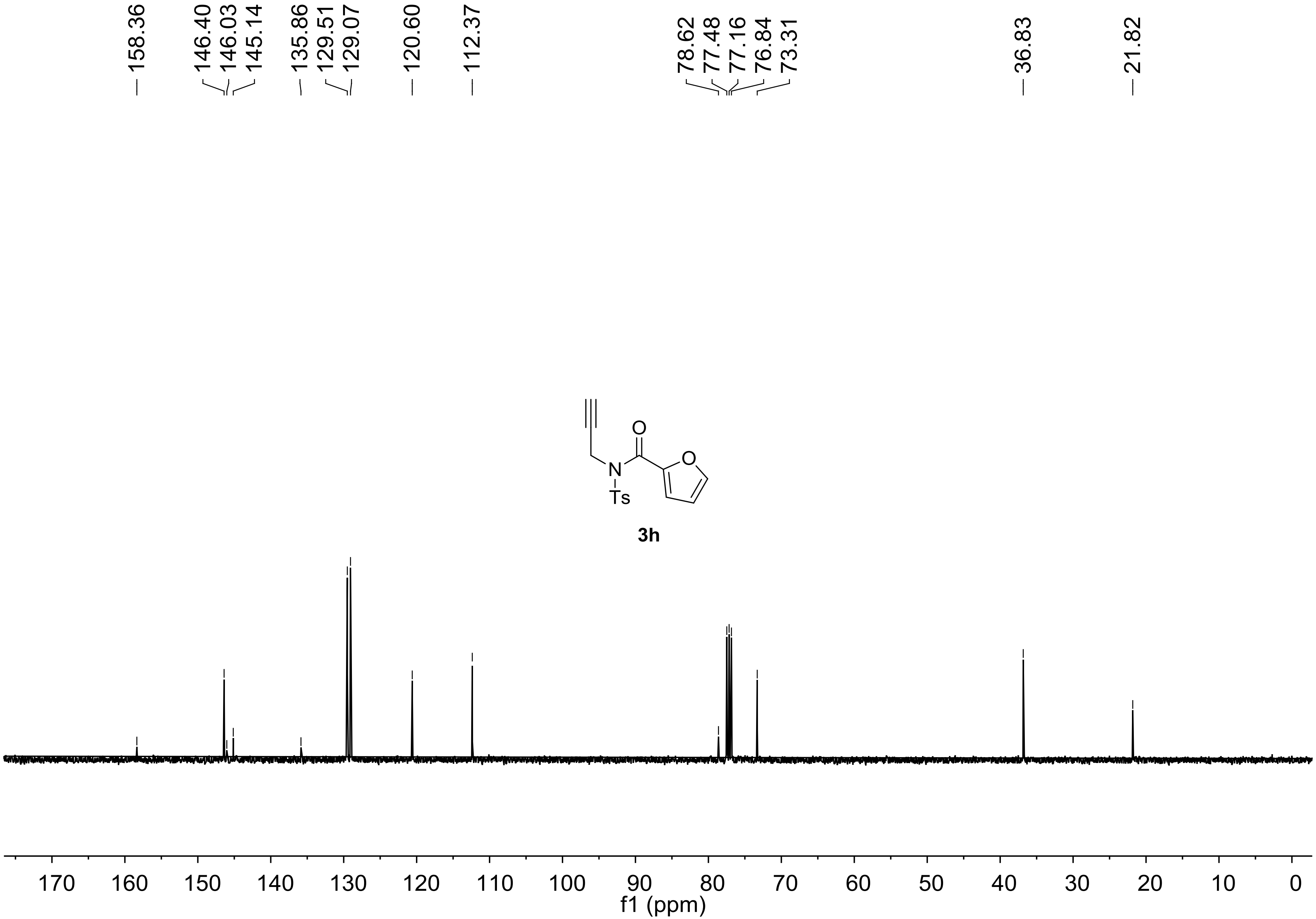
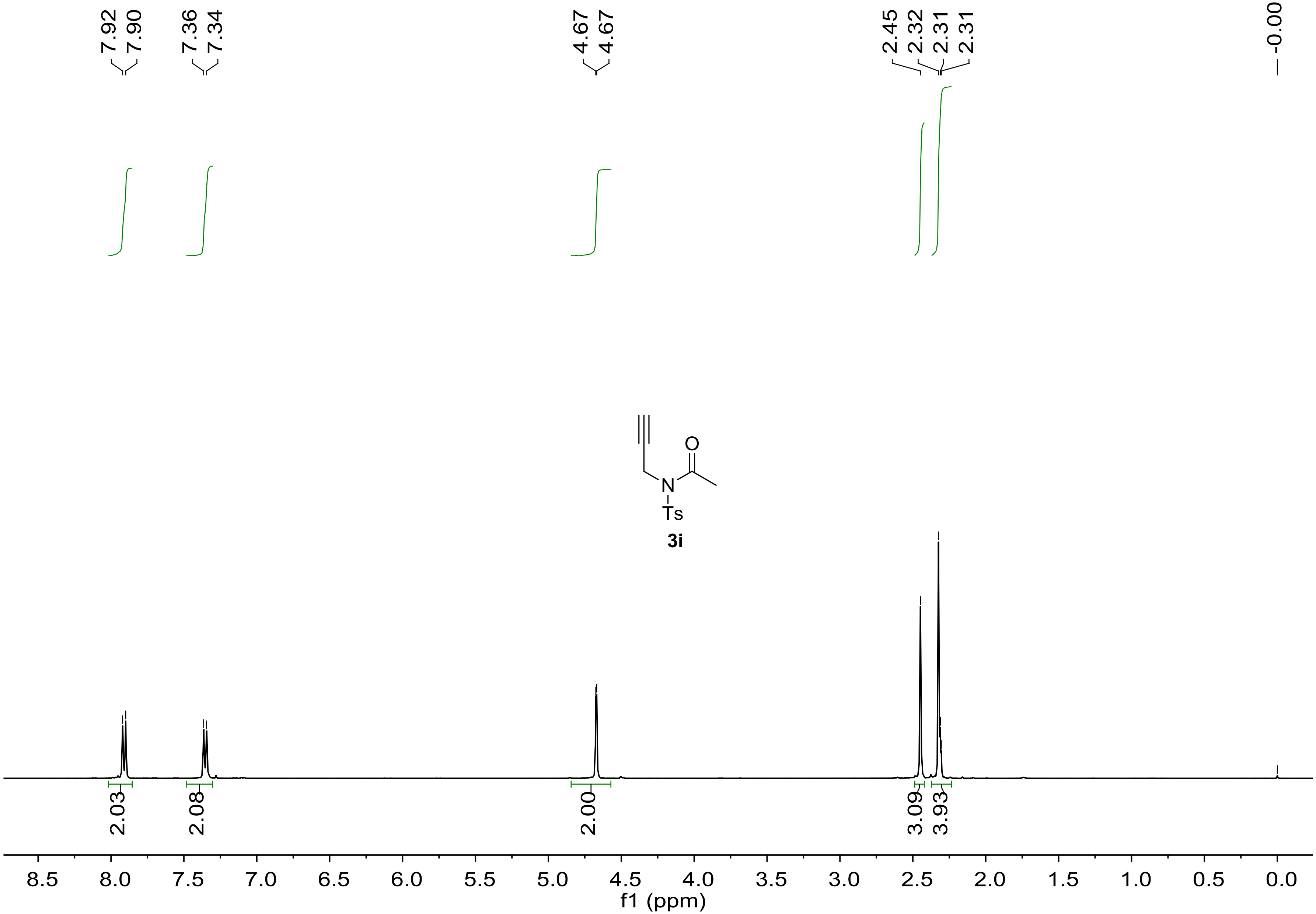
128.94
126.07
113.81
78.57
77.48
77.16
76.84
73.27
55.59
38.05
21.79
O
N
Ts
OMe
3g
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


8.01
7.99
7.57
7.34
7.33
7.32
7.26
6.54
6.53
6.53
6.52
4.93
4.93
2.43
2.33
2.32
2.32
0.00
O
N
Ts
O
3h
2.01
1.02
3.09
1.02
1.94
3.04
1.00
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

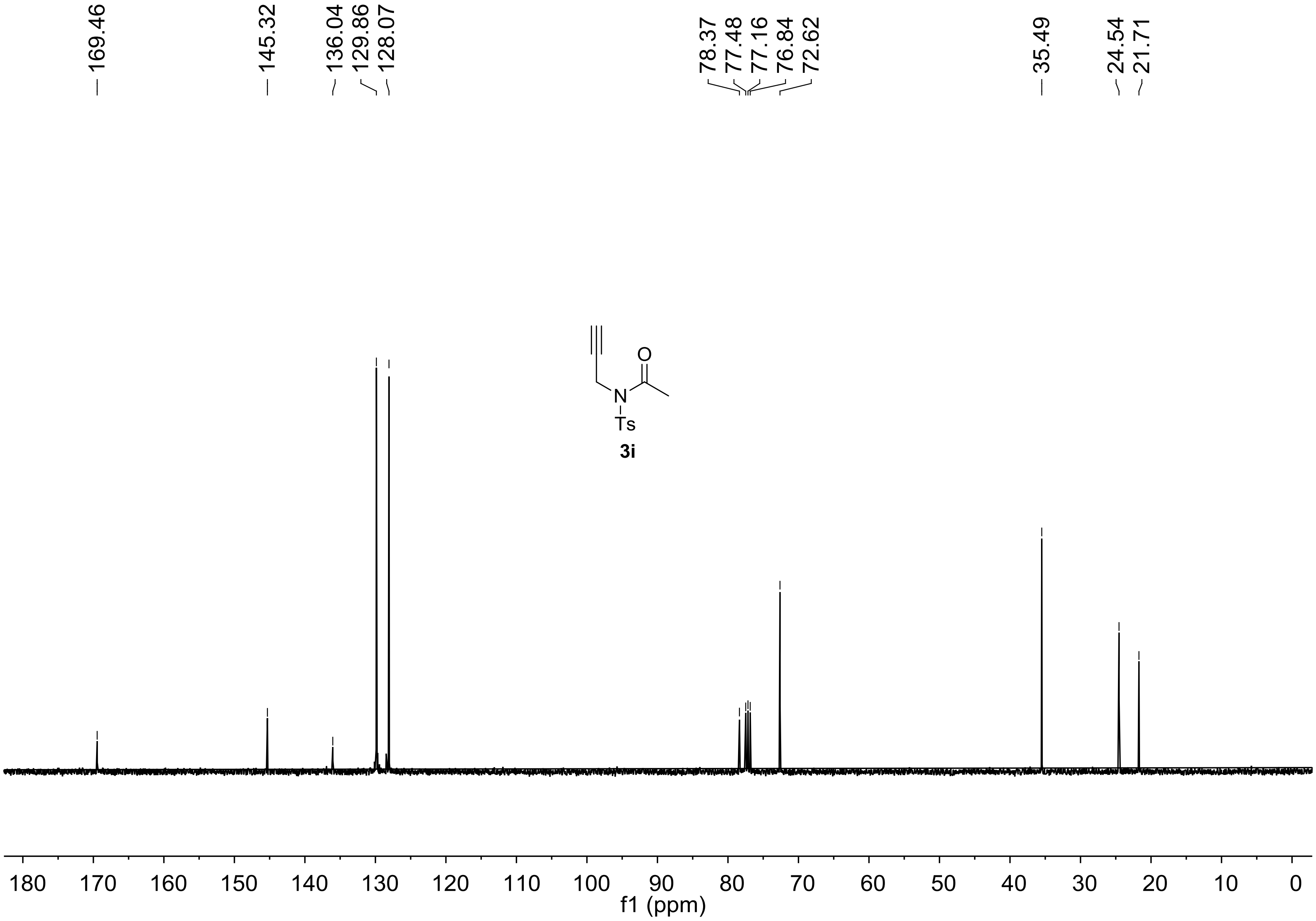


3h

158.36
146.40
146.03
145.14
135.86
129.51
129.07
120.60
112.37
78.62
77.48
77.16
76.84
73.31
36.83
21.82
O
O
N
Ts
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


3i

7.92
7.90
7.36
7.34
4.67
4.67
2.45
2.32
2.31
2.31
-0.00
O
N
Ts
2.03
2.08
2.00
3.09
3.93
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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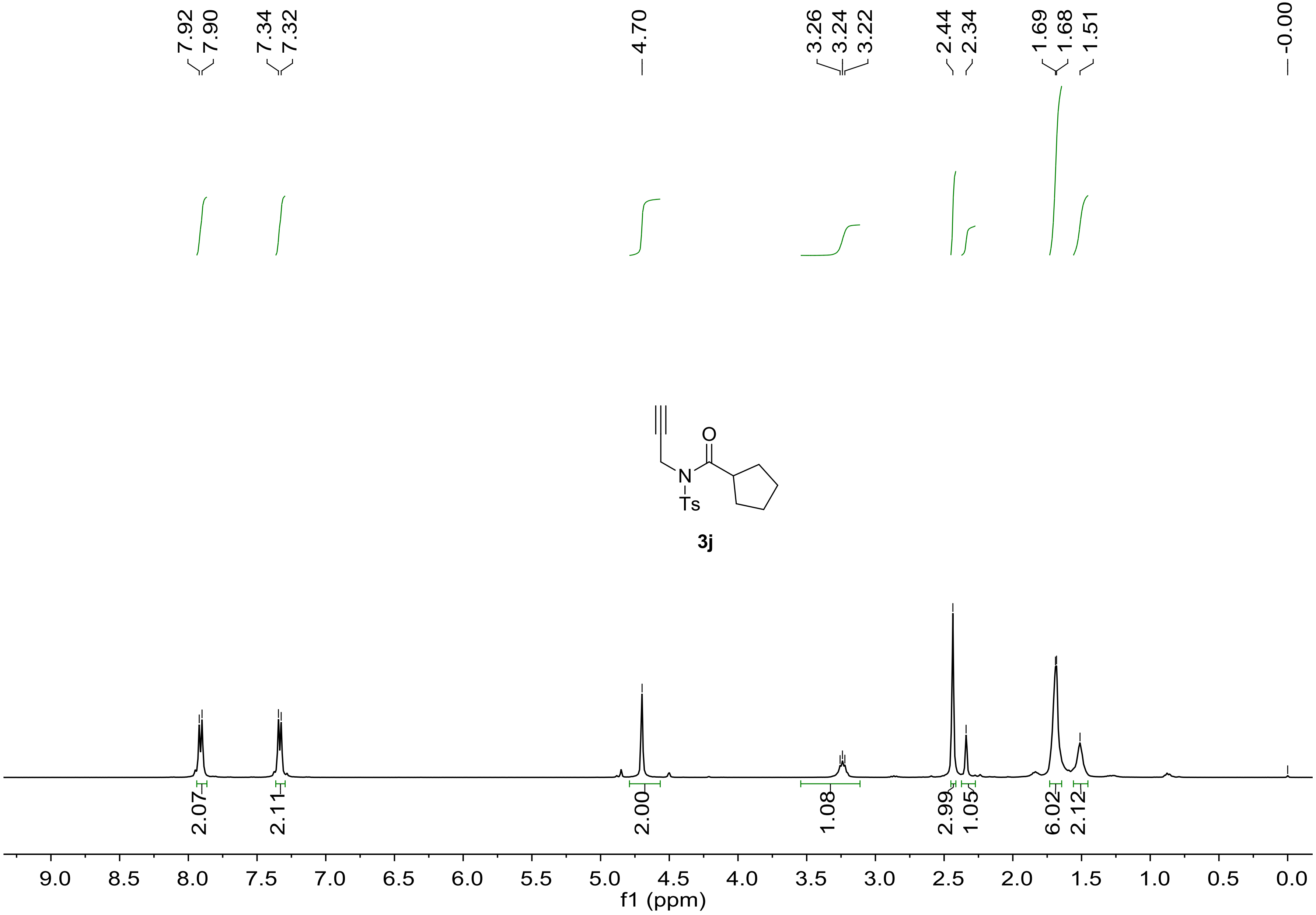
145.32
136.04
129.86
128.07
78.37
77.48
77.16
76.84
72.62
35.49
24.54
21.71
O
N
Ts
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

3i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7.90
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3.26
3.24
3.22
2.44
2.34
1.69
1.68
1.51
-0.00
O
N
Ts
2.07
2.11
2.00
1.08
2.99
1.05
6.02
2.12
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
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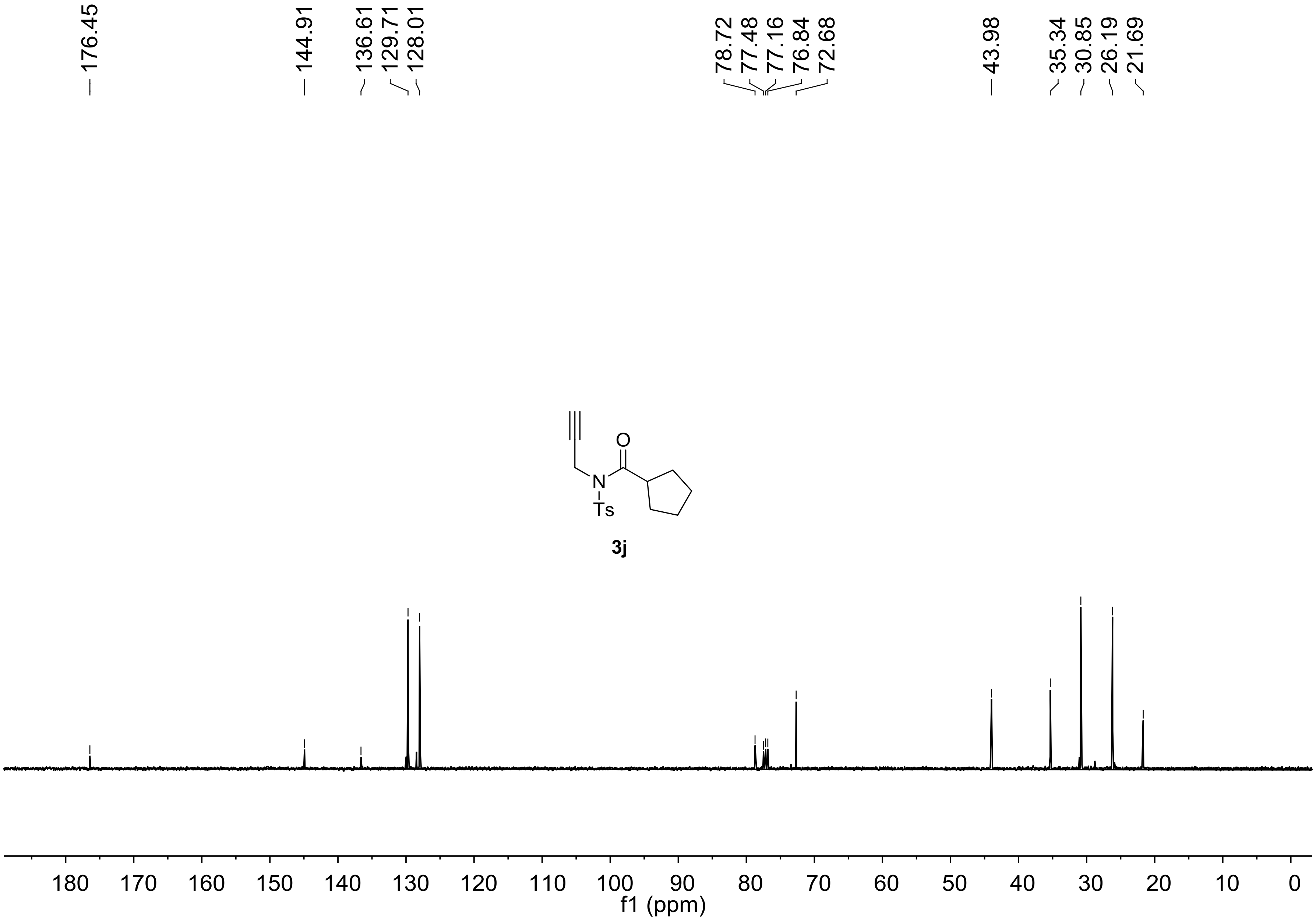
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

3j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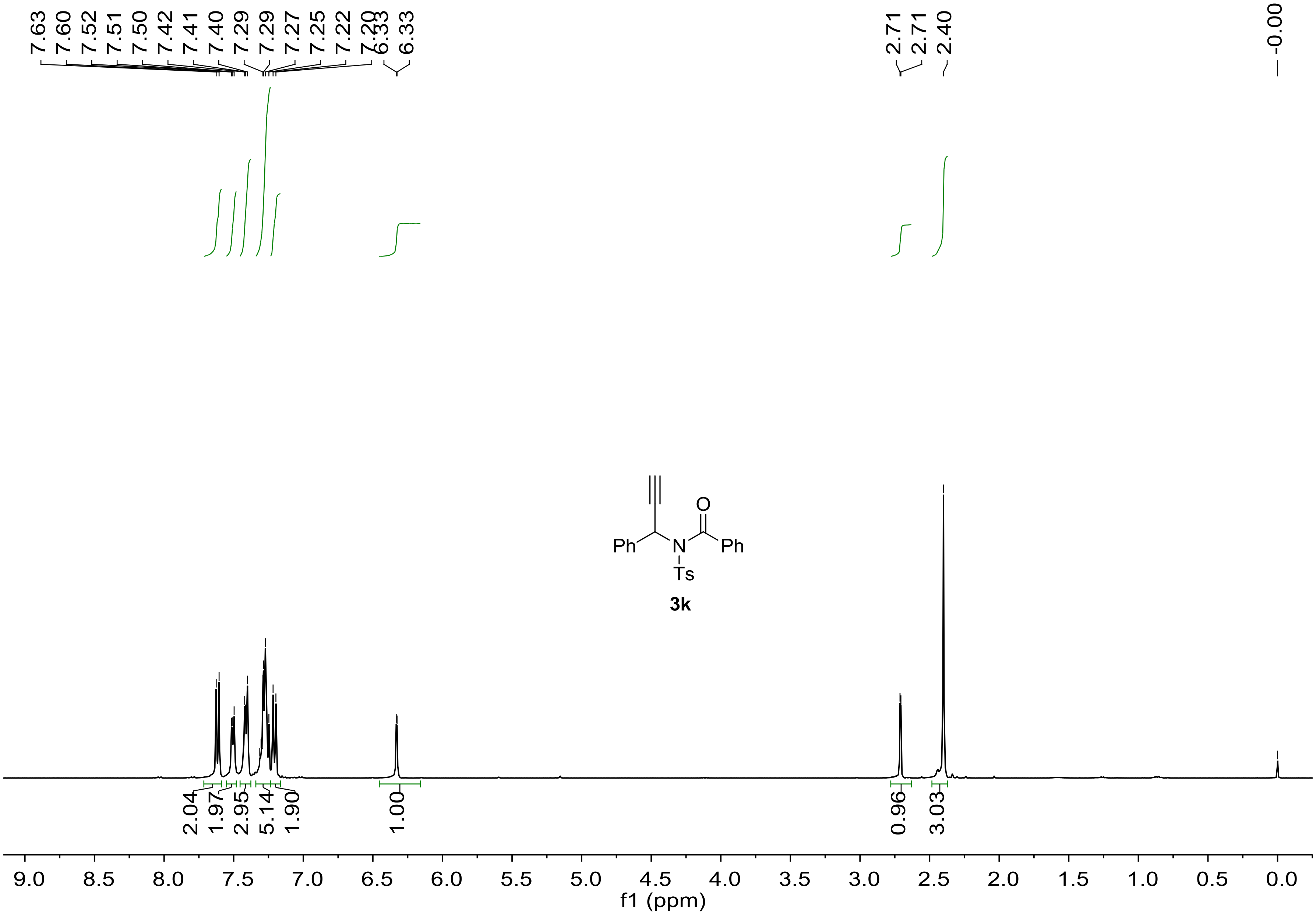
128.01
78.72
77.48
77.16
76.84
72.68
43.98
35.34
30.85
26.19
21.69
O
N
Ts
3j
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


7.63
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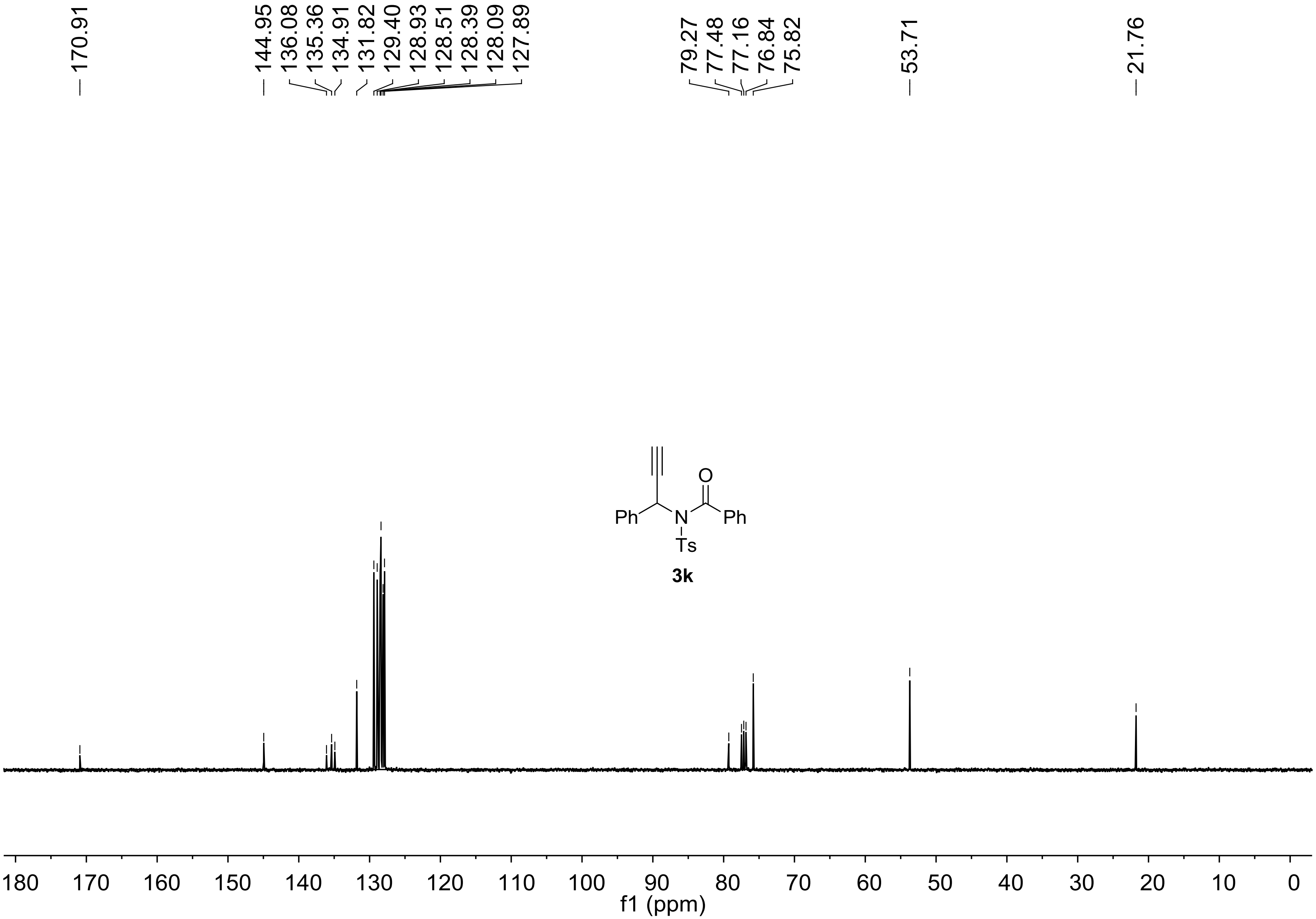
7.51
7.50
7.42
7.41
7.40
7.29
7.29
7.27
7.25
7.22
7.20
6.33
6.33
2.71
2.71
2.40
-0.00
2.04
1.97
2.95
5.14
1.90
1.00
0.96
3.03
O
Ph
N
Ph
Ts
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

3k


170.91
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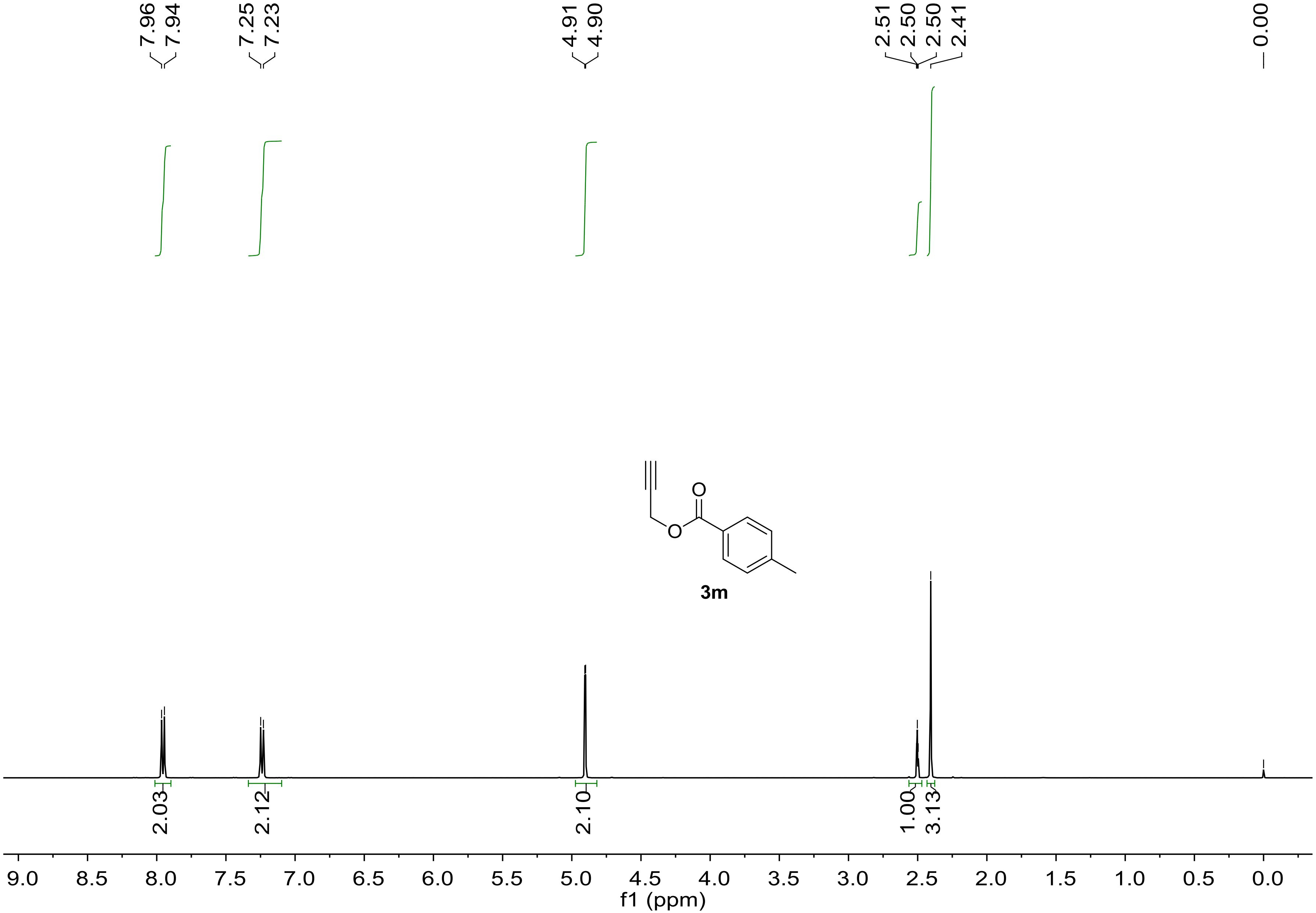
134.91
131.82
129.40
128.93
128.51
128.39
128.09
127.89
79.27
77.48
77.16
76.84
75.82
53.71
21.76
O
Ph
N
Ph
Ts
3k
180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
f1 (ppm)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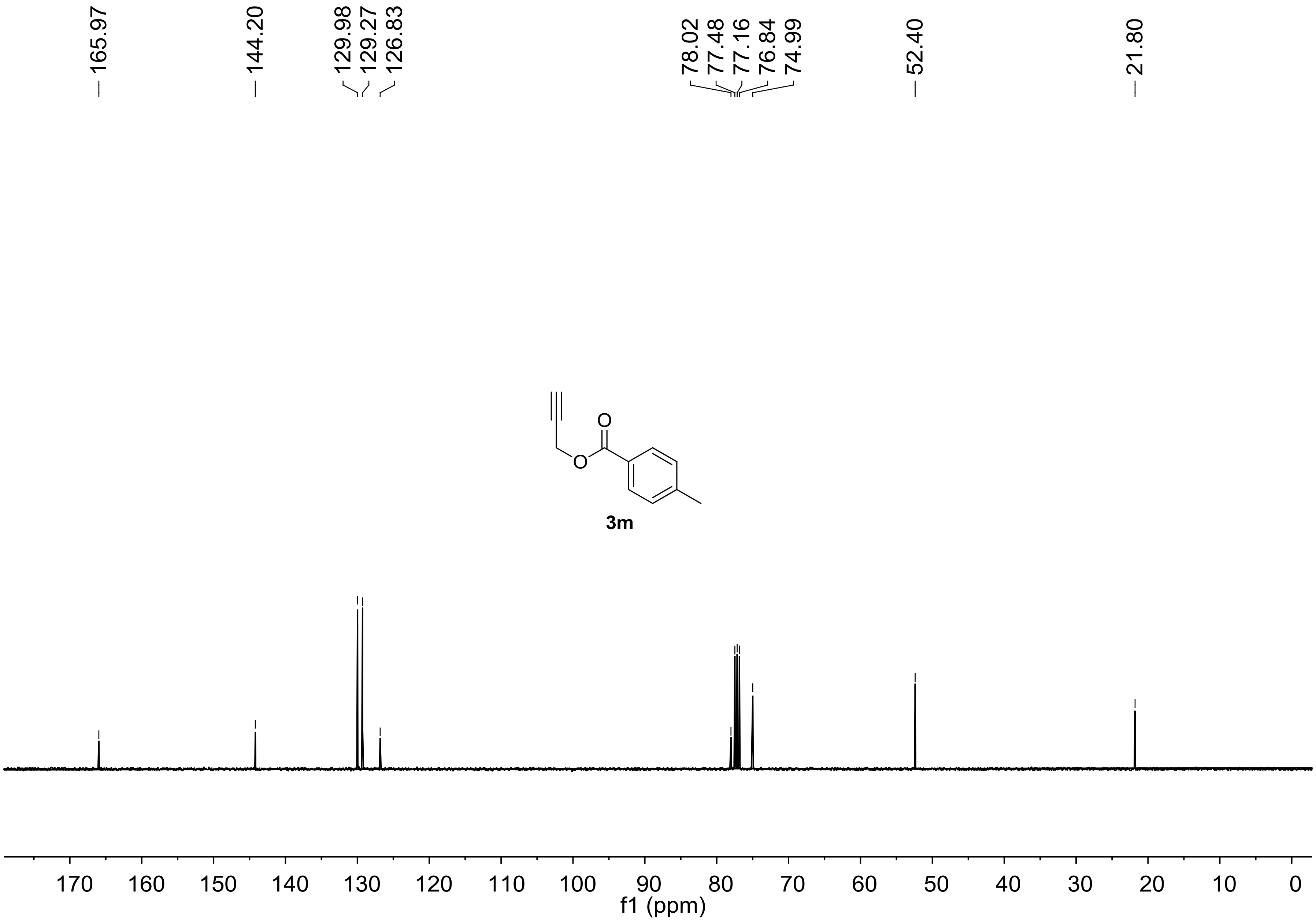
7.94
7.25
7.23
4.91
4.90
2.51
2.50
2.50
2.41
0.00
O
O
3m
2.03
2.12
2.10
1.00
3.13
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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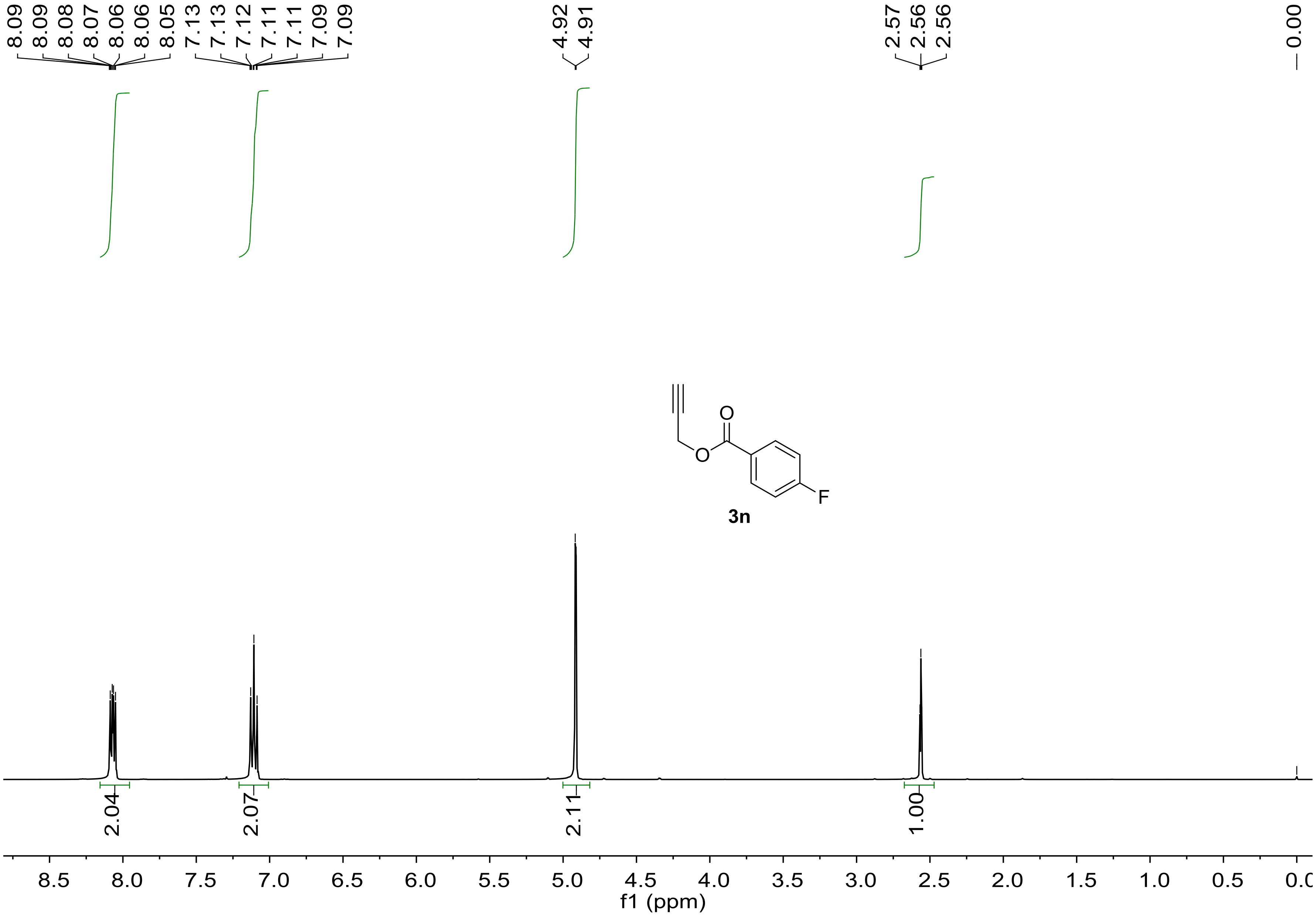
129.27
126.83
78.02
77.48
77.16
76.84
74.99
52.40
21.80
O
O
3m
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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8.09
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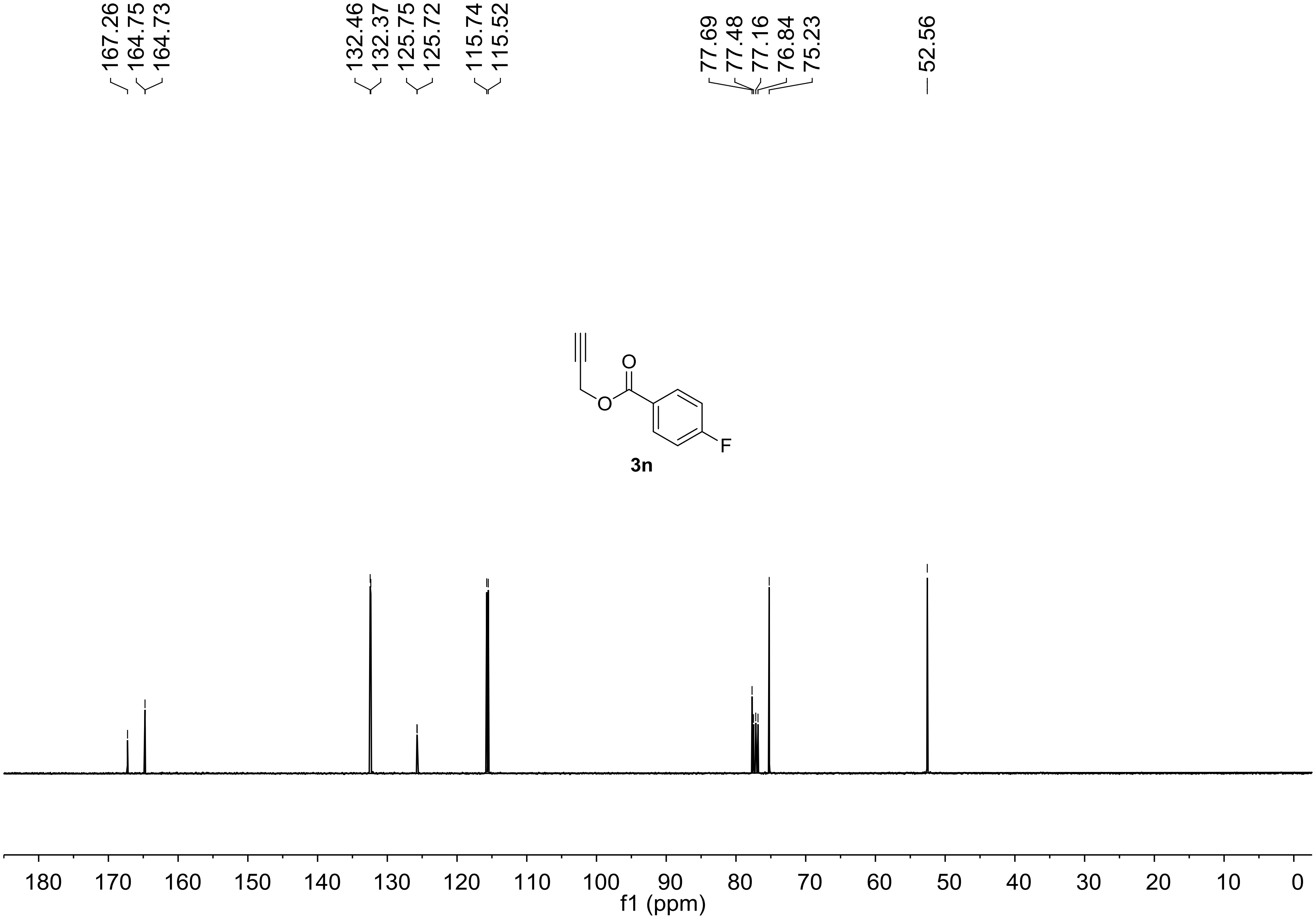
8.07
8.06
8.06
8.05
7.13
7.13
7.12
7.11
7.11
7.09
7.09
4.92
4.91
2.57
2.56
2.56
0.00
O
O
F
3n
2.04
2.07
2.11
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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164.73
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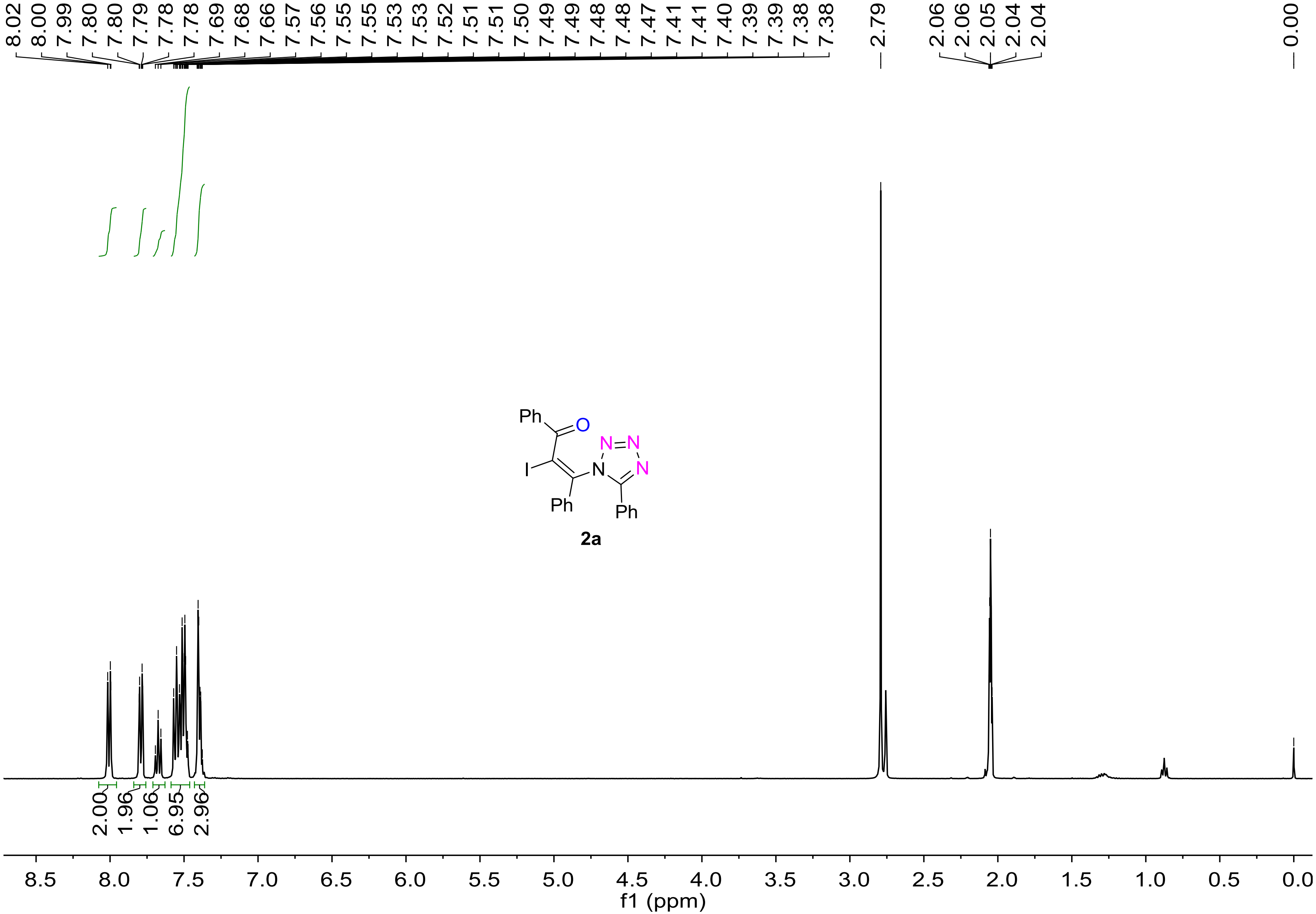
132.37
125.75
125.72
115.74
115.52
77.69
77.48
77.16
76.84
75.23
52.56
O
O
F
3n
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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7.78
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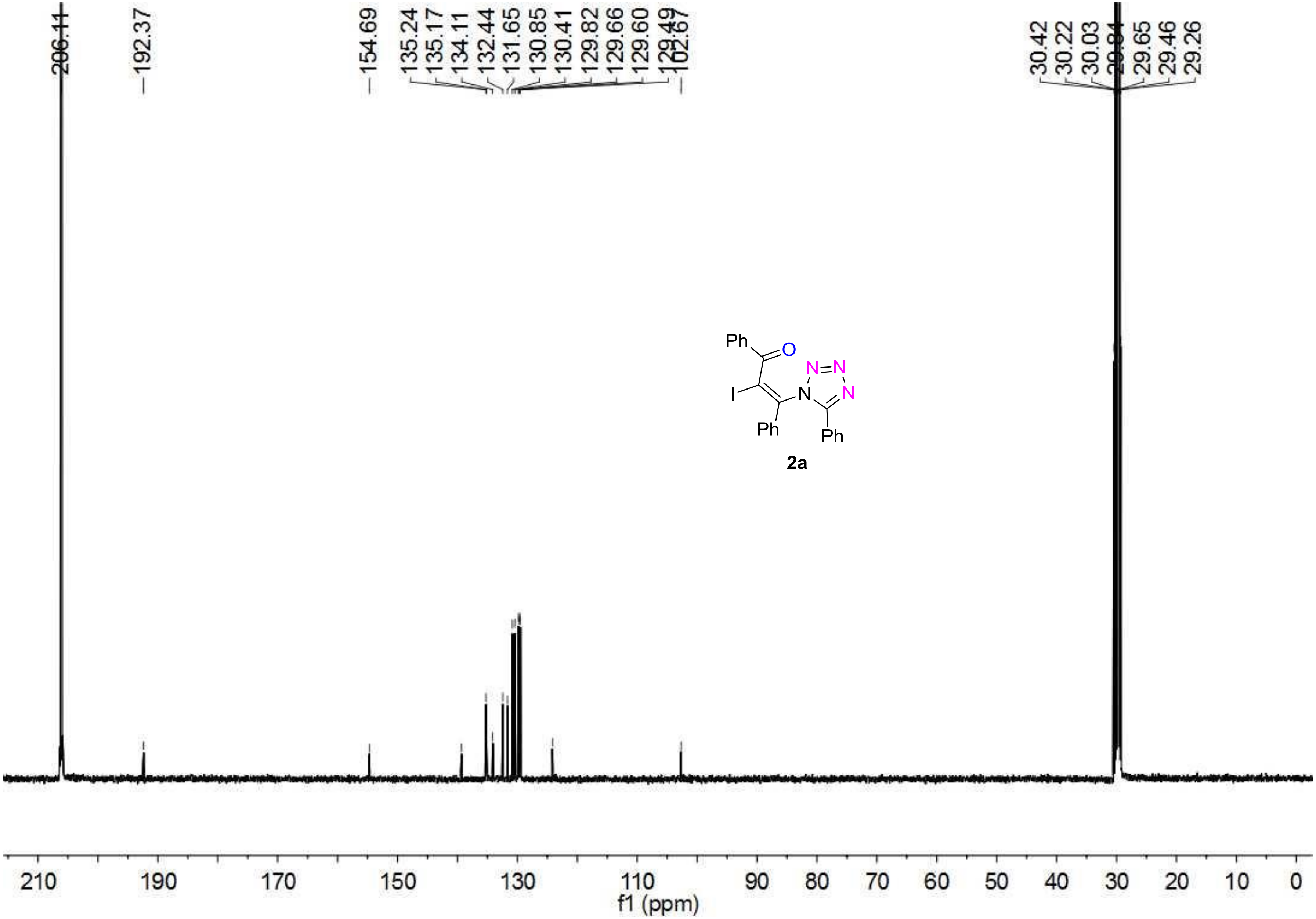
7.56
7.55
7.55
7.53
7.53
7.52
7.51
7.51
7.50
7.49
7.49
7.48
7.48
7.47
7.41
7.41
7.40
7.39
7.39
7.38
7.38
2.79
2.06
2.06
2.05
2.04
2.04
0.00
Ph
O
N
N
N
N
I
Ph
Ph
2a
2.00
1.96
1.06
6.95
2.96
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)


206.11
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135.17
134.11
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131.65
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130.41
129.82
129.66
129.60
129.49
102.67
30.42
30.22
30.03
29.84
29.65
29.46
29.26
Ph
O
N
N=N
N
I
Ph
Ph
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210
190
170
150
130
110
90
80
70
60
50
40
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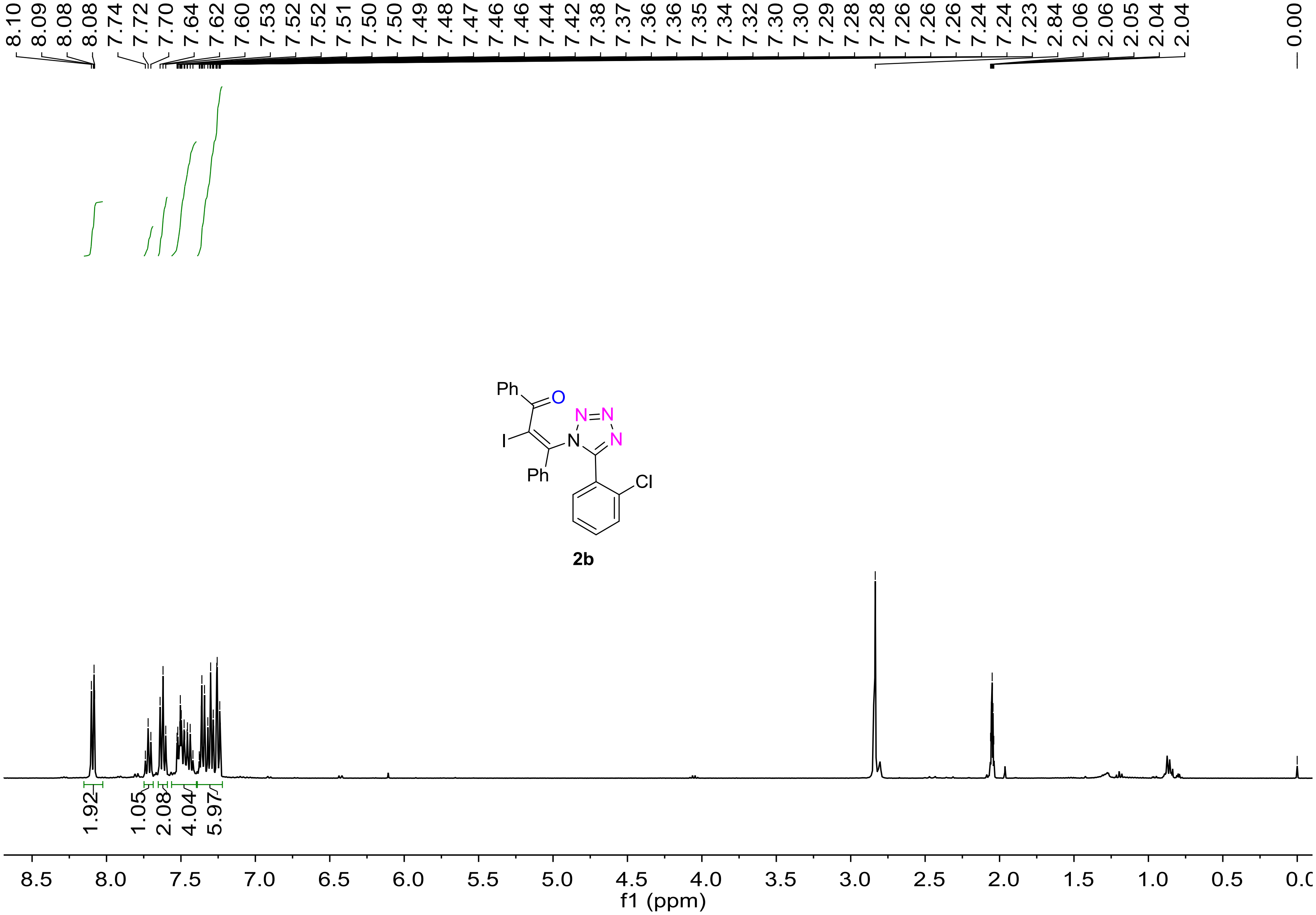
20
10
0
f1 (ppm)


8.10
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7.51
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7.49
7.48
7.47
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7.46
7.44
7.42
7.38
7.37
7.36
7.36
7.35
7.34
7.32
7.30
7.30
7.29
7.28
7.28
7.26
7.26
7.26
7.24
7.24
7.23
2.84
2.06
2.06
2.05
2.04
2.04
0.00
Ph
O
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N
N
I
Ph
Cl
1.92
1.05
2.08
4.04
5.97
8.5
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7.0
6.5
6.0
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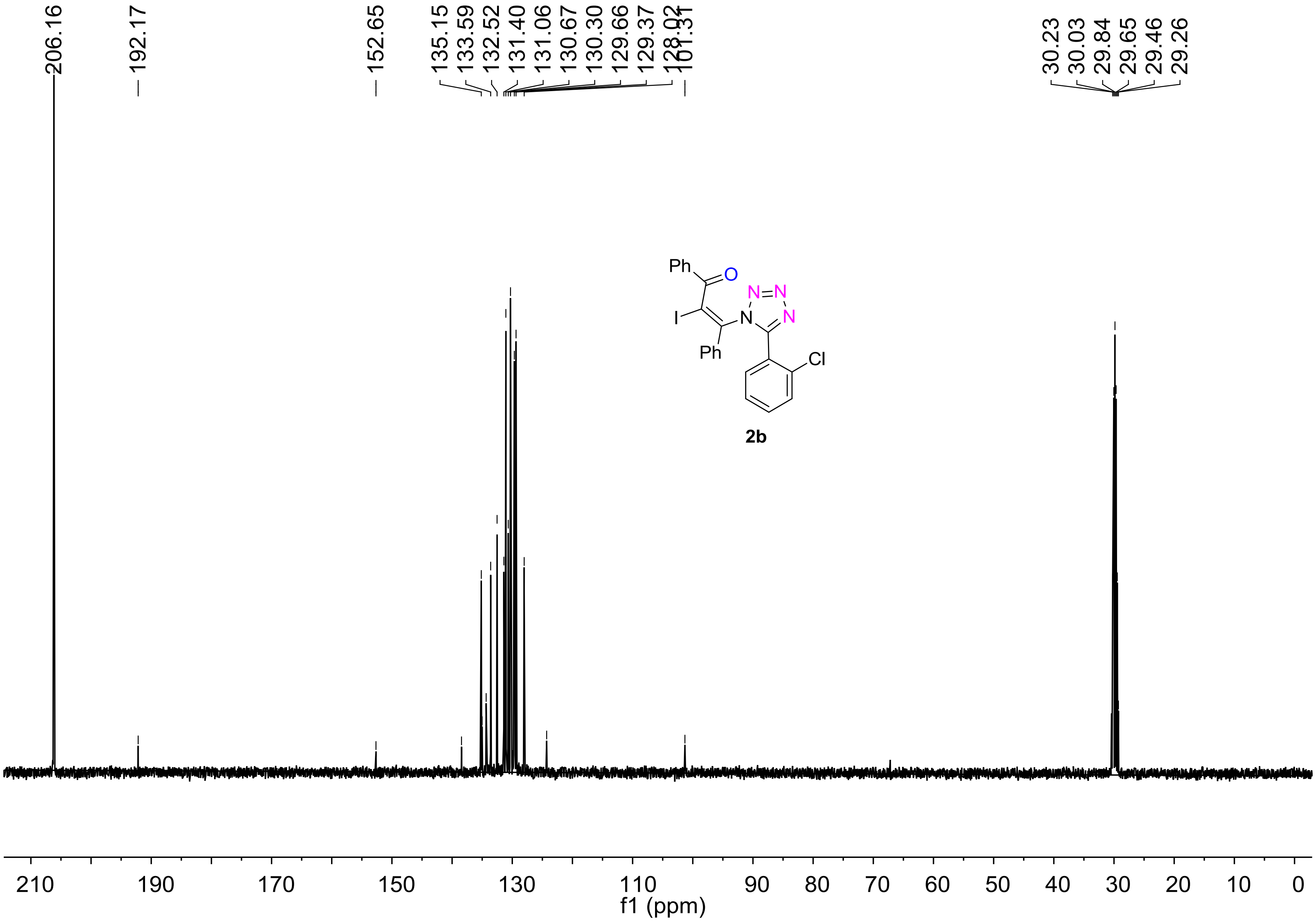
f1 (ppm)

2b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101.31
30.23
30.03
29.84
29.65
29.46
29.26
Ph
O
N
N
N
N
I
Ph
Cl
2b
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130
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90
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70
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50
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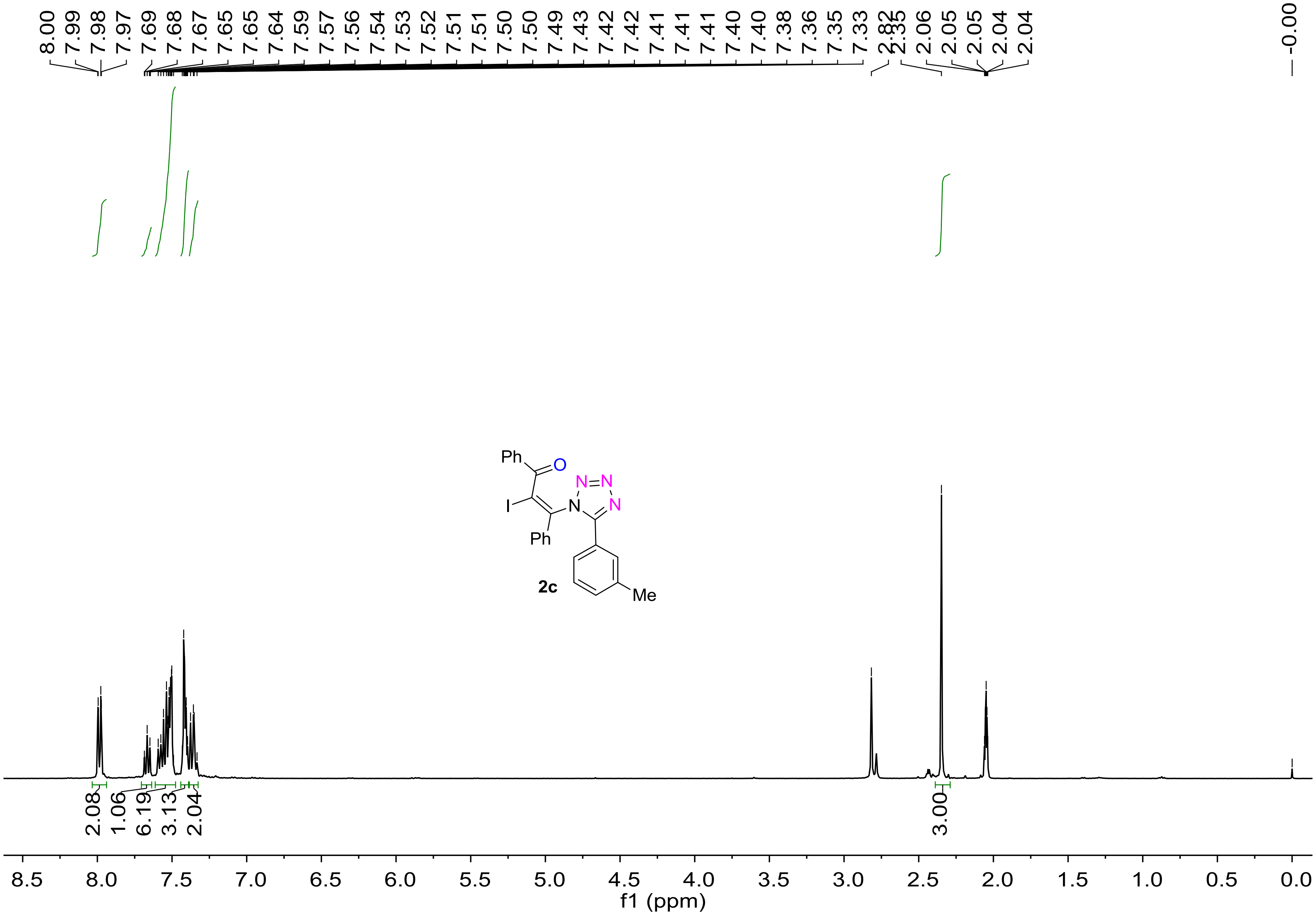
f1 (ppm)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7.54
7.53
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7.51
7.51
7.50
7.50
7.49
7.43
7.42
7.42
7.41
7.41
7.41
7.40
7.40
7.38
7.36
7.35
7.33
2.82
2.35
2.06
2.05
2.05
2.04
2.04
-0.00
Ph
O
N
N
N
N
I
Ph
Me
2c
2.08
1.06
6.19
3.13
2.04
3.00
8.5
8.0
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7.0
6.5
6.0
5.5
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2.5
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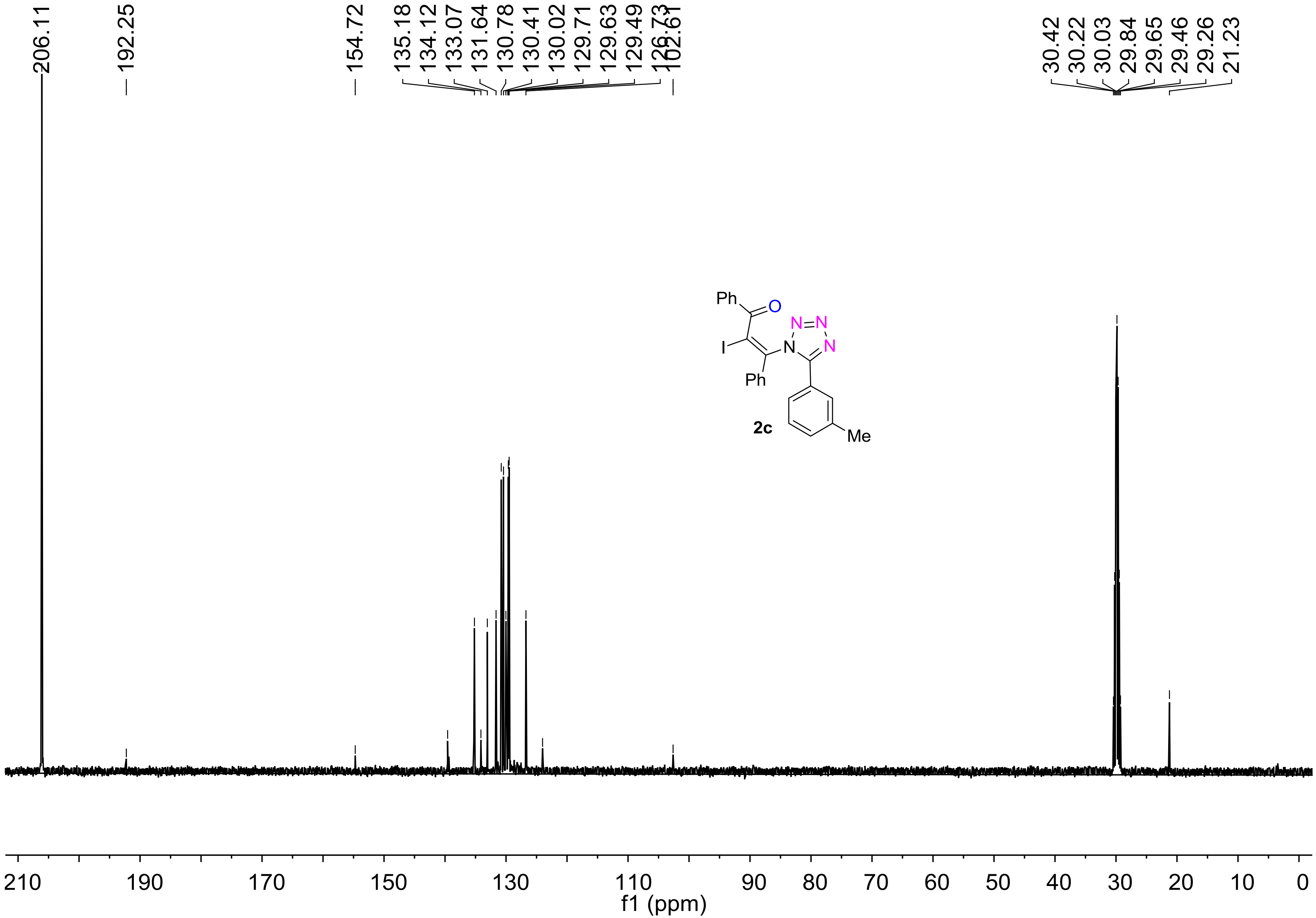
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126.73
102.61
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.23
Ph
O
N
N
N
N
I
Ph
2c
Me
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150
130
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90
80
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50
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20
10
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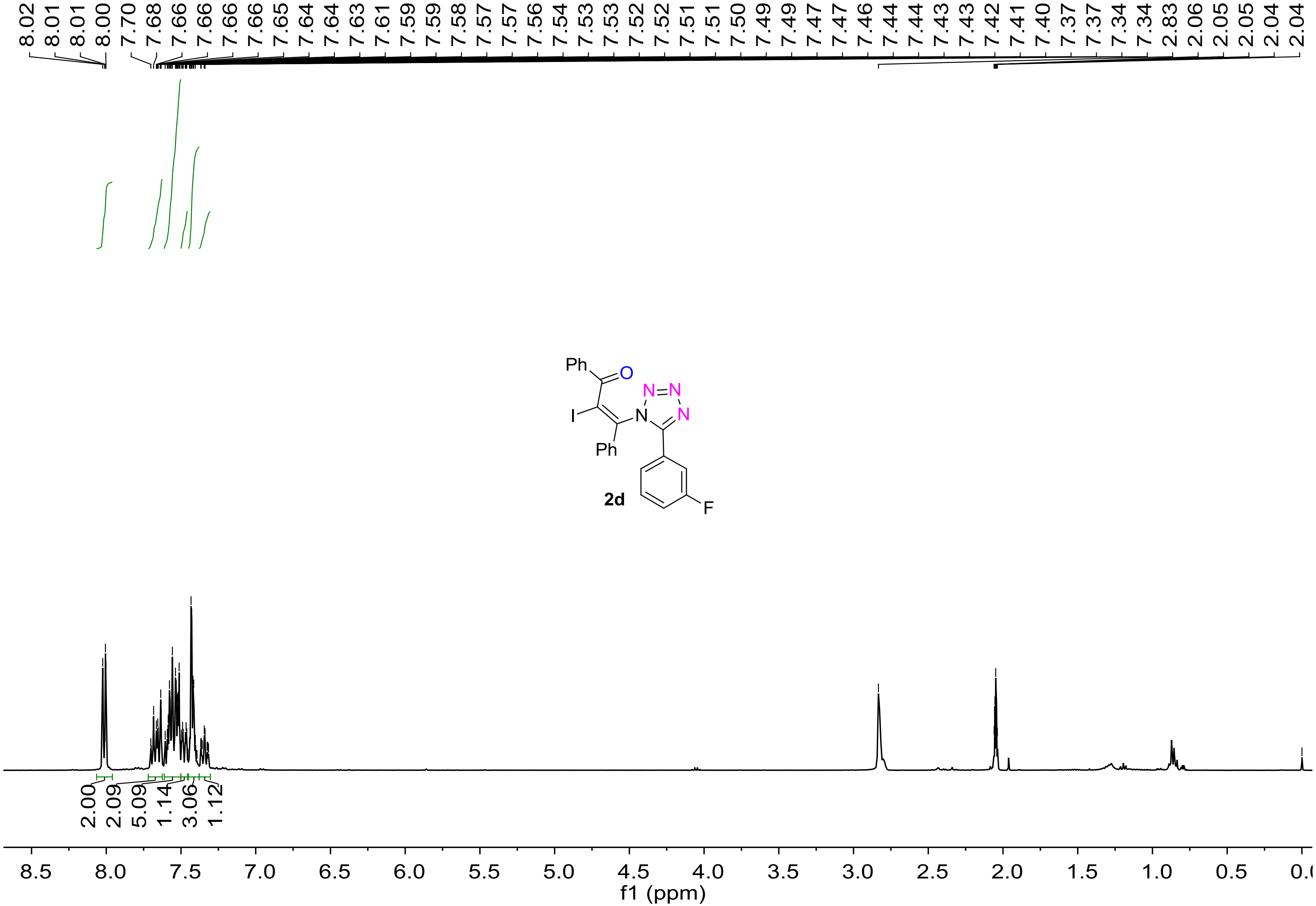
f1 (ppm)



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7.64
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7.57
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7.44
7.43
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7.41
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7.37
7.34
7.34
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2.06
2.05
2.05
2.04
2.04
Ph
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N
N
N
N
I
Ph
F
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3.06
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6.0
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5.0
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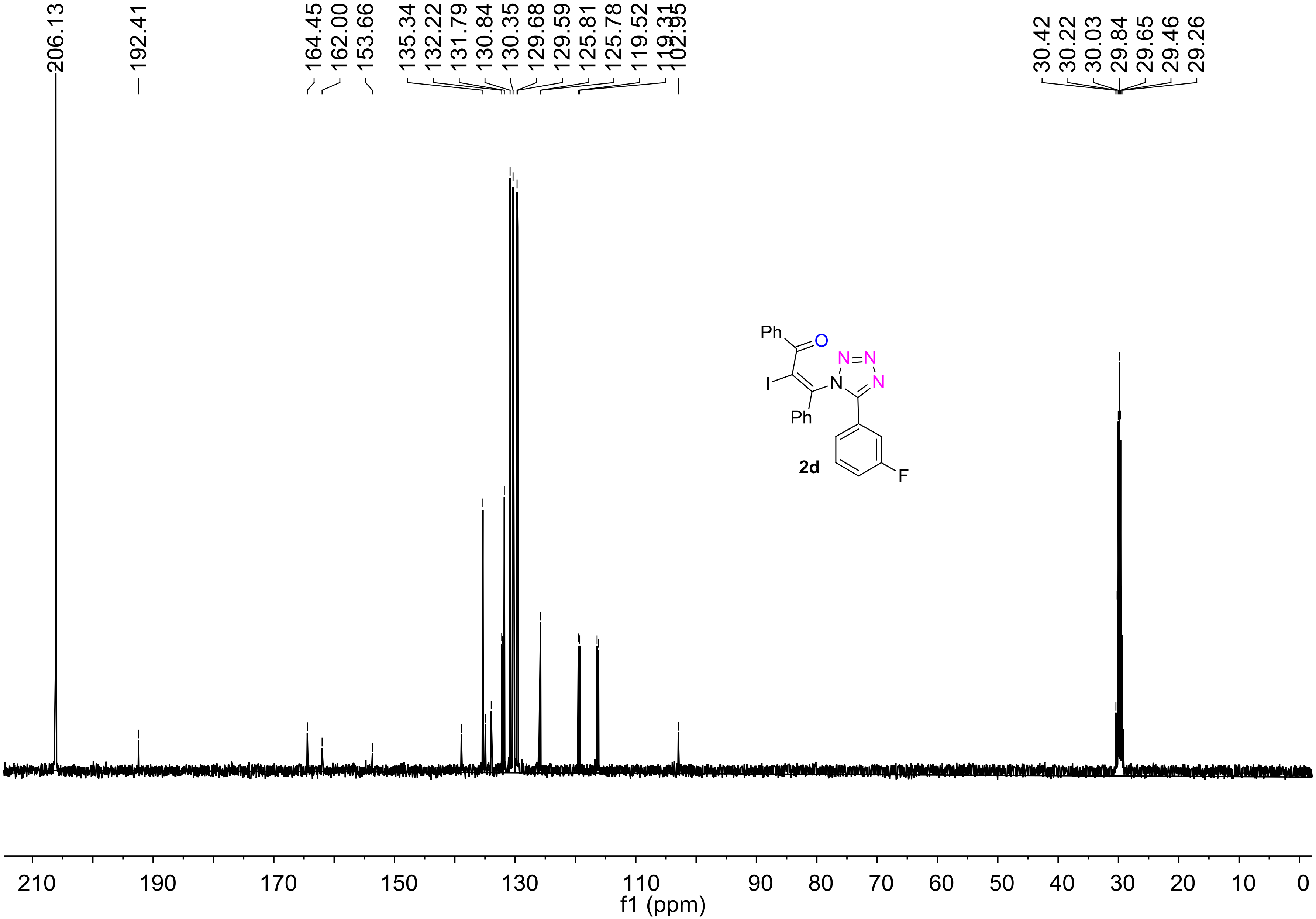
f1 (ppm)

2d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119.31
102.95
30.42
30.22
30.03
29.84
29.65
29.46
29.26
Ph
O
N
N
N
N
I
Ph
F
2d
210
190
170
150
130
110
90
80
70
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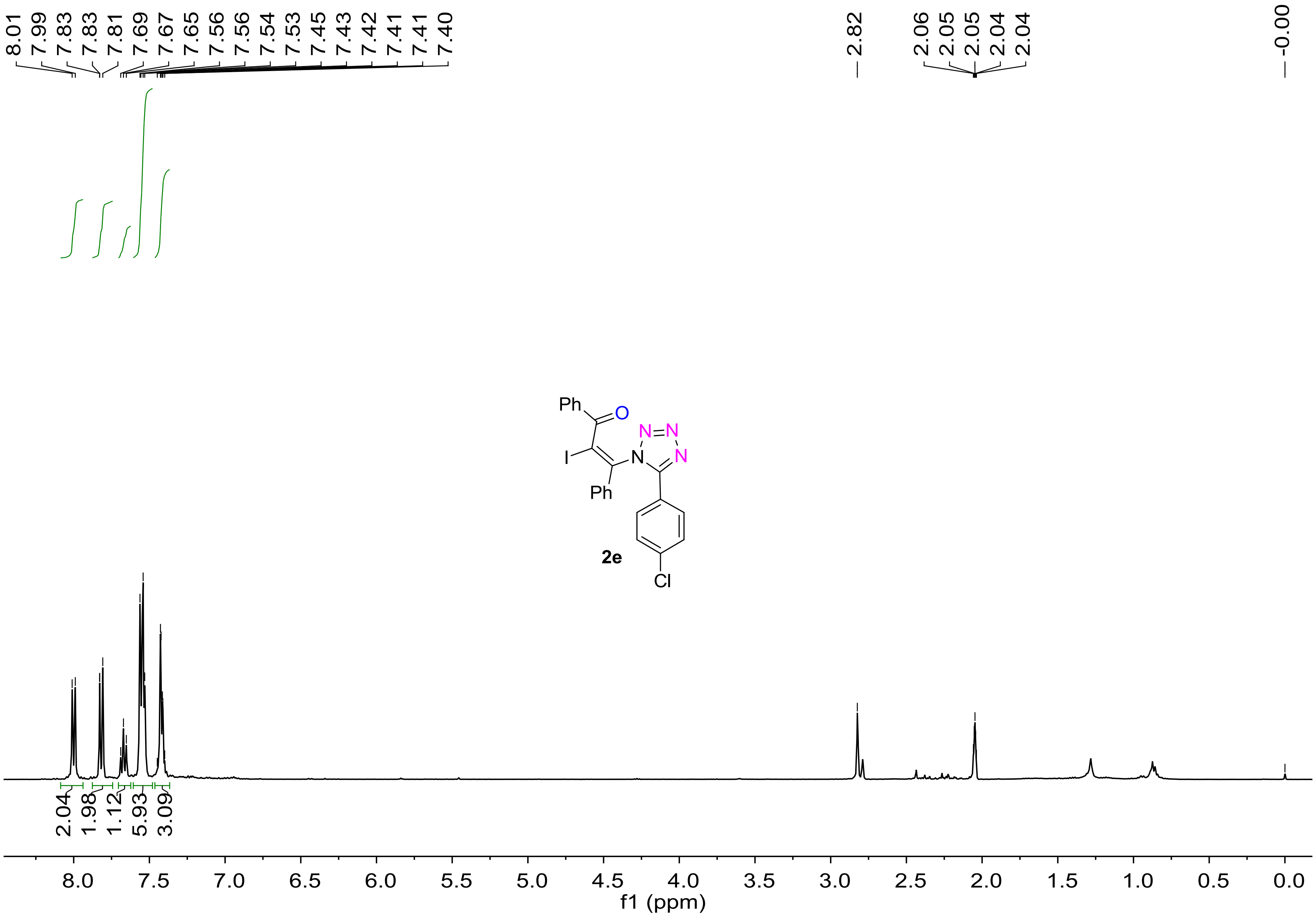
50
40
30
20
10
0
f1 (ppm)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7.45
7.43
7.42
7.41
7.41
7.40
2.82
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2.05
2.05
2.04
2.04
-0.00
Ph
O
N
N
N
N
I
Ph
Cl
2e
2.04
1.98
1.12
5.93
3.09
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
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3.5
3.0
2.5
2.0
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1.0
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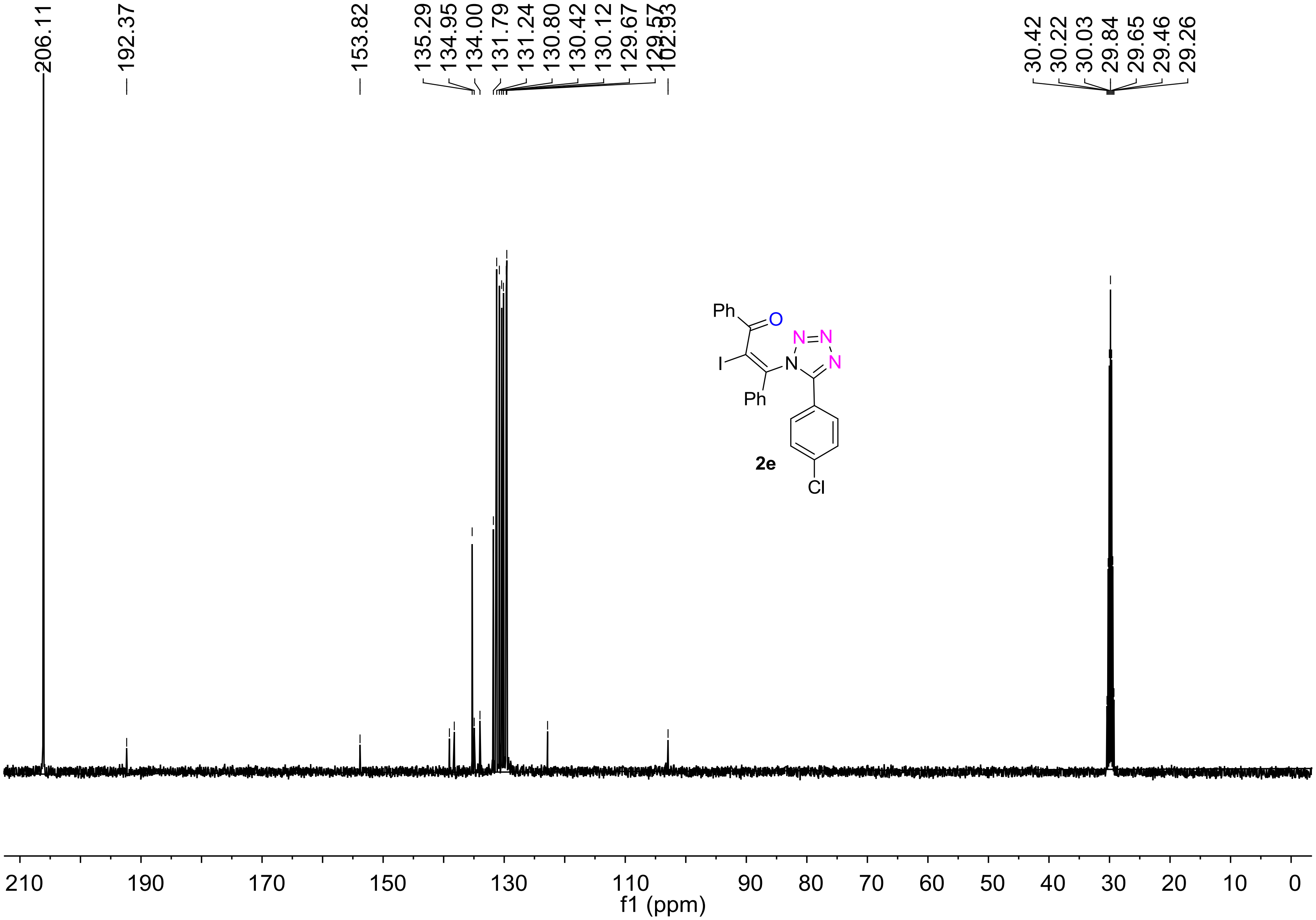
0.0
f1 (ppm)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129.57
102.93
30.42
30.22
30.03
29.84
29.65
29.46
29.26
Ph
O
N
N
N
N
I
Ph
Cl
2e
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170
150
130
110
90
80
70
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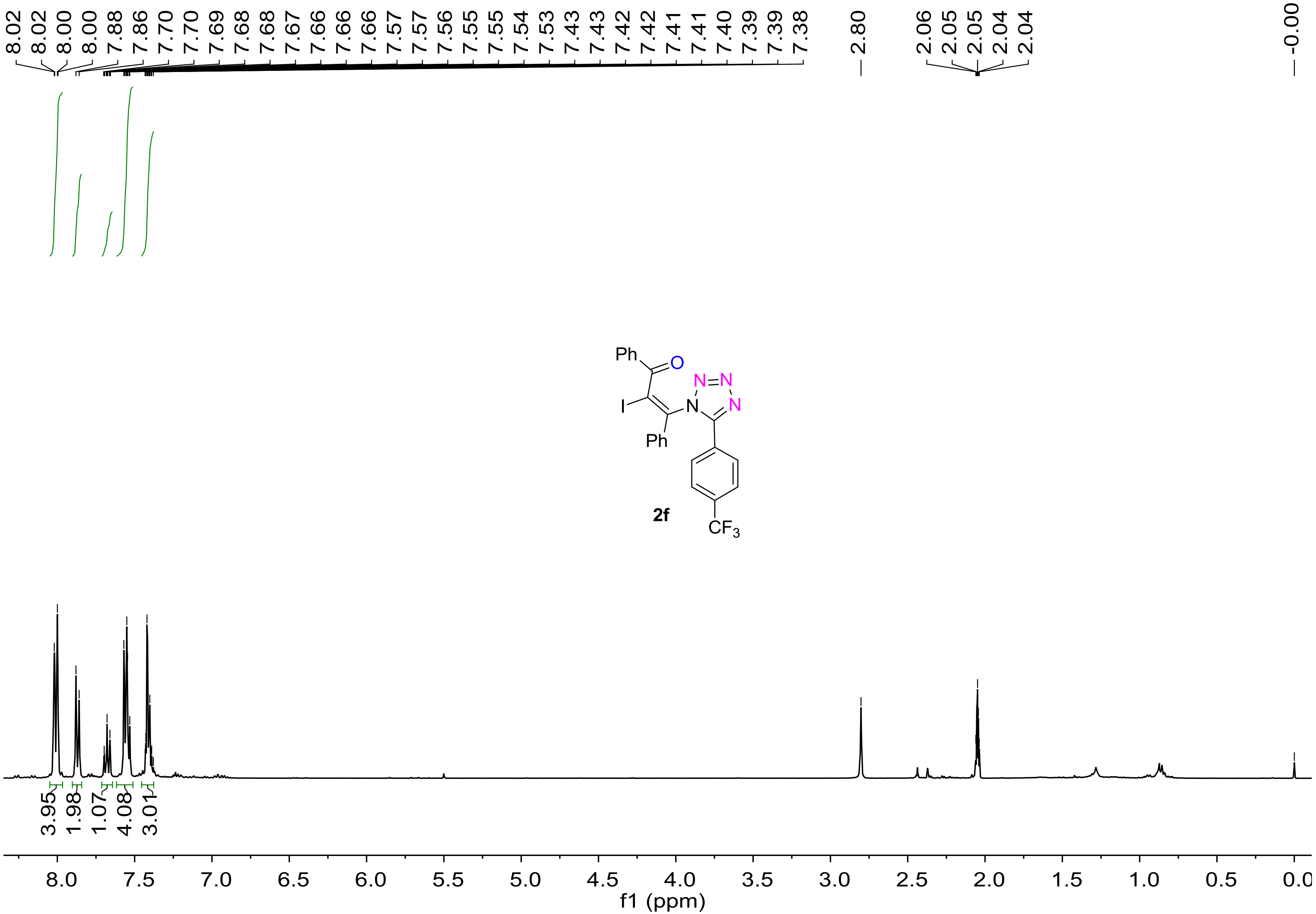
50
40
30
20
10
0
f1 (ppm)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7.66
7.66
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7.57
7.56
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7.55
7.54
7.53
7.43
7.43
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7.42
7.41
7.41
7.40
7.39
7.39
7.38
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2.06
2.05
2.05
2.04
2.04
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N
N
I
Ph
CF3
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1.98
1.07
4.08
3.01
8.0
7.5
7.0
6.5
6.0
5.5
5.0
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4.0
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3.0
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2.0
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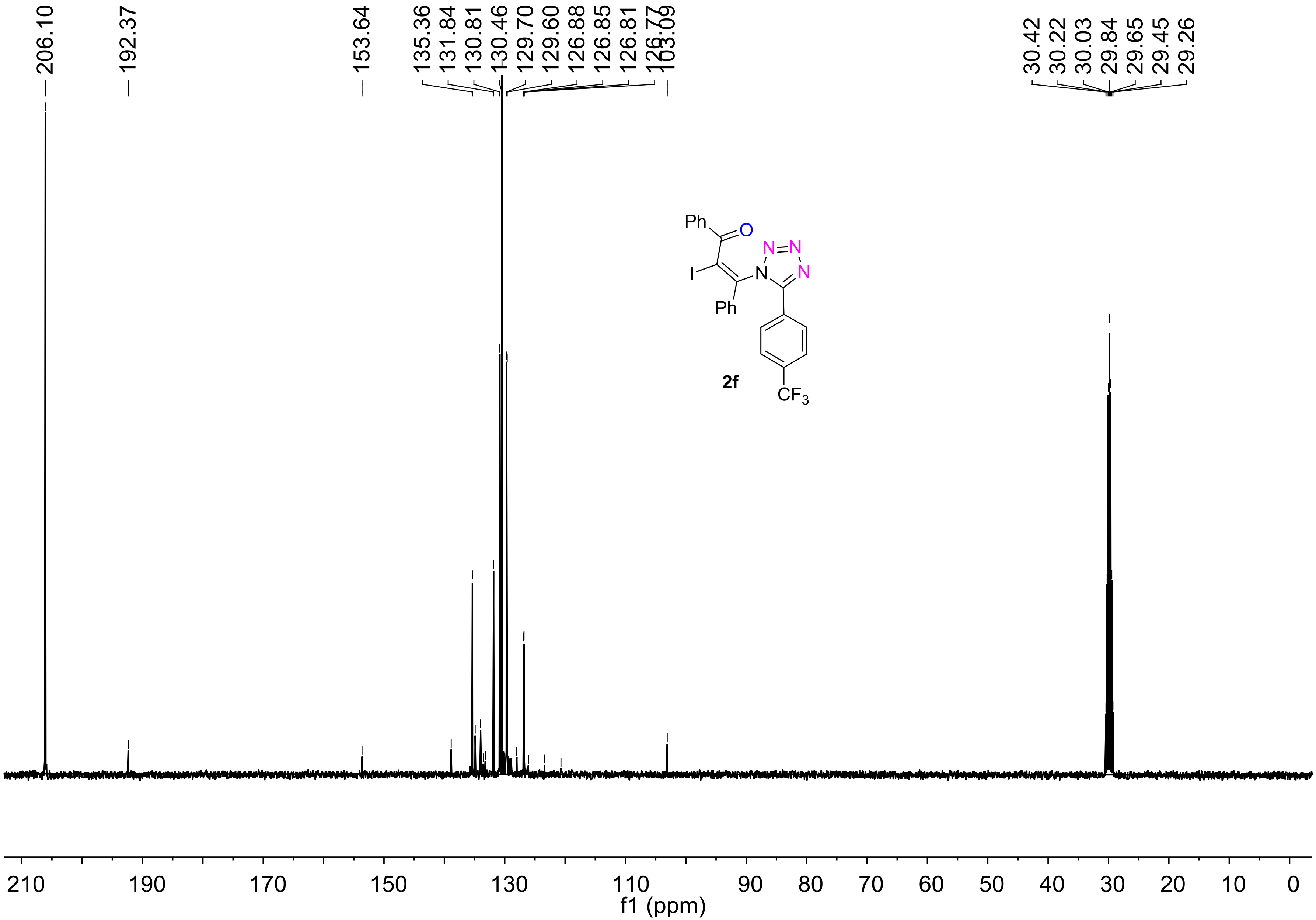
0.0
f1 (ppm)

2f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129.70
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126.88
126.85
126.81
126.77
103.09
30.42
30.22
30.03
29.84
29.65
29.45
29.26
Ph
O
N
N
N
N
I
Ph
CF3
210
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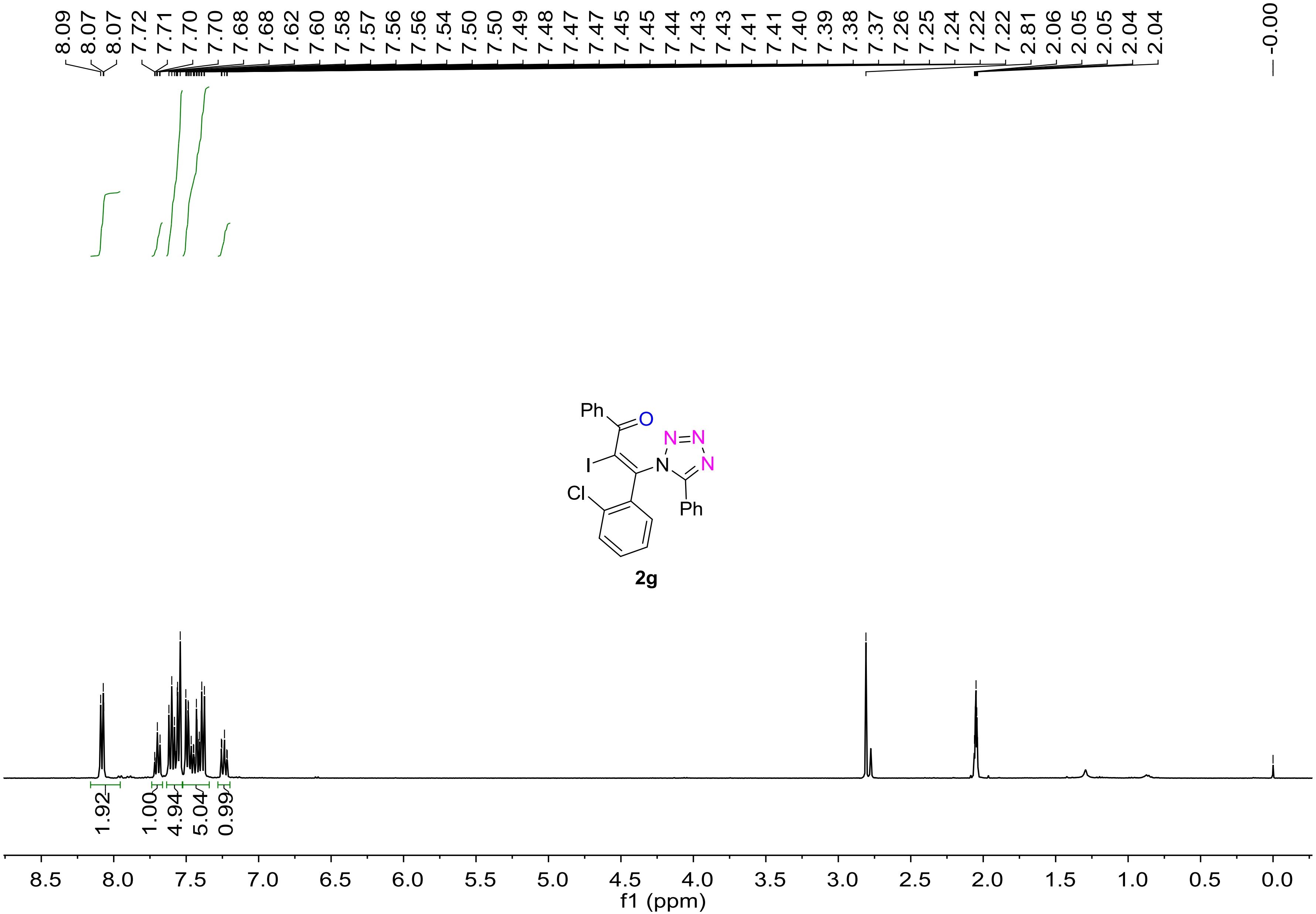
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

2f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7.56
7.54
7.50
7.50
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7.47
7.45
7.45
7.44
7.43
7.43
7.41
7.41
7.40
7.39
7.38
7.37
7.26
7.25
7.24
7.22
7.22
2.81
2.06
2.05
2.05
2.04
2.04
-0.00
Ph
O
N=N
N
N
I
Cl
Ph
2g
1.92
1.00
4.94
5.04
0.99
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
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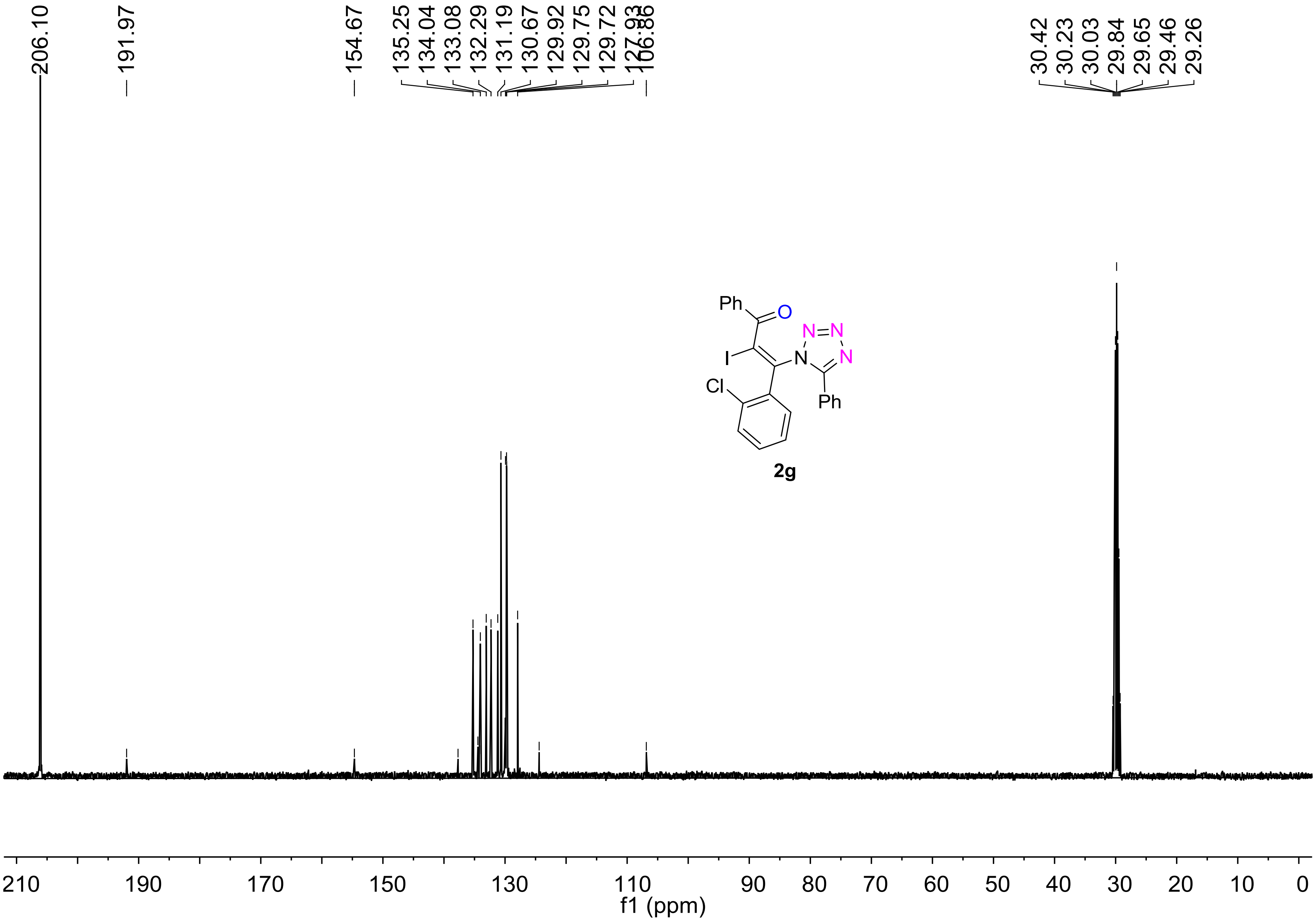
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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129.72
127.93
106.86
30.42
30.23
30.03
29.84
29.65
29.46
29.26
Ph
O
N
N
N
N
I
Cl
Ph
210
190
170
150
130
110
90
80
70
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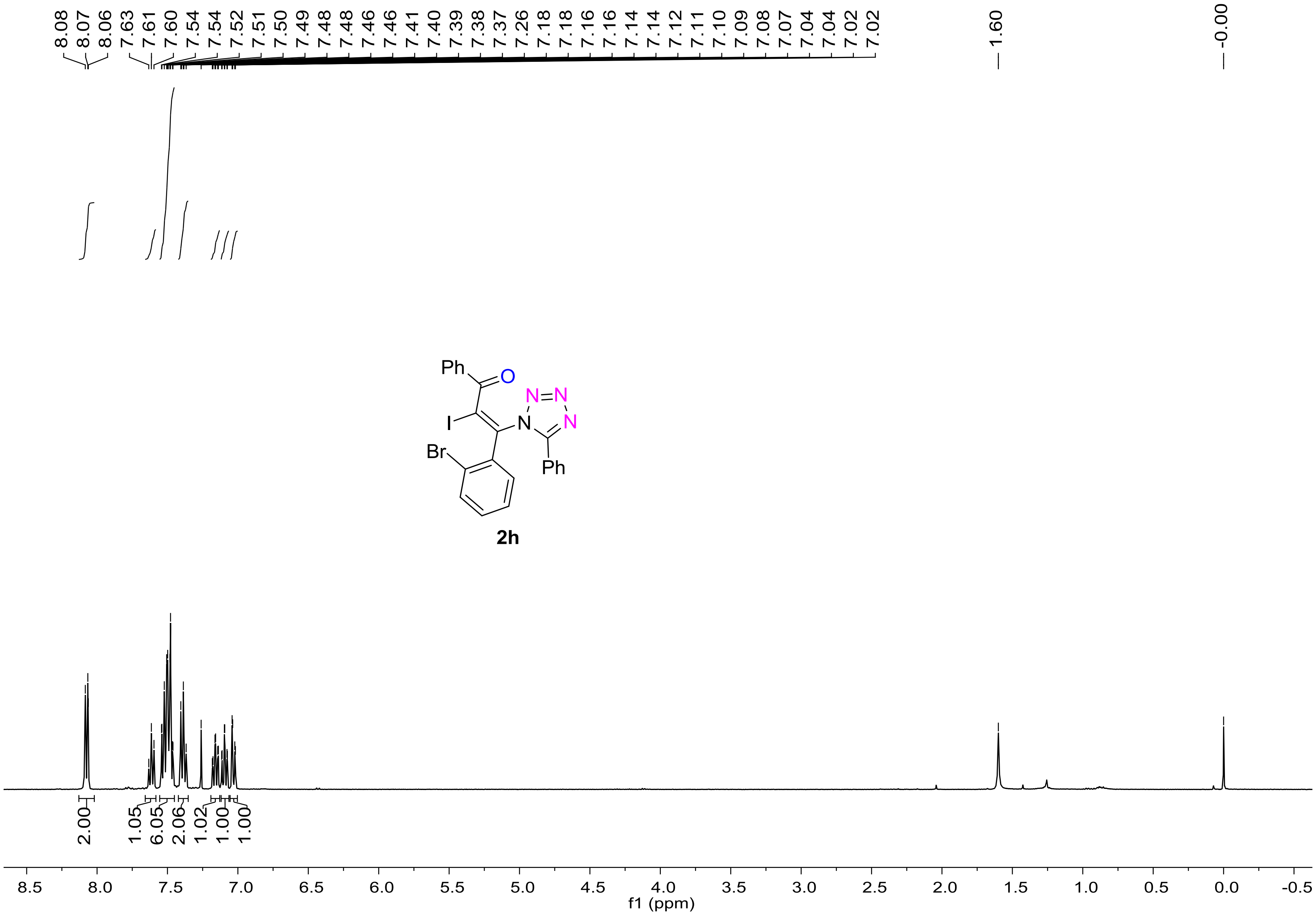
50
40
30
20
10
0
f1 (ppm)

2g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7.48
7.48
7.46
7.46
7.41
7.40
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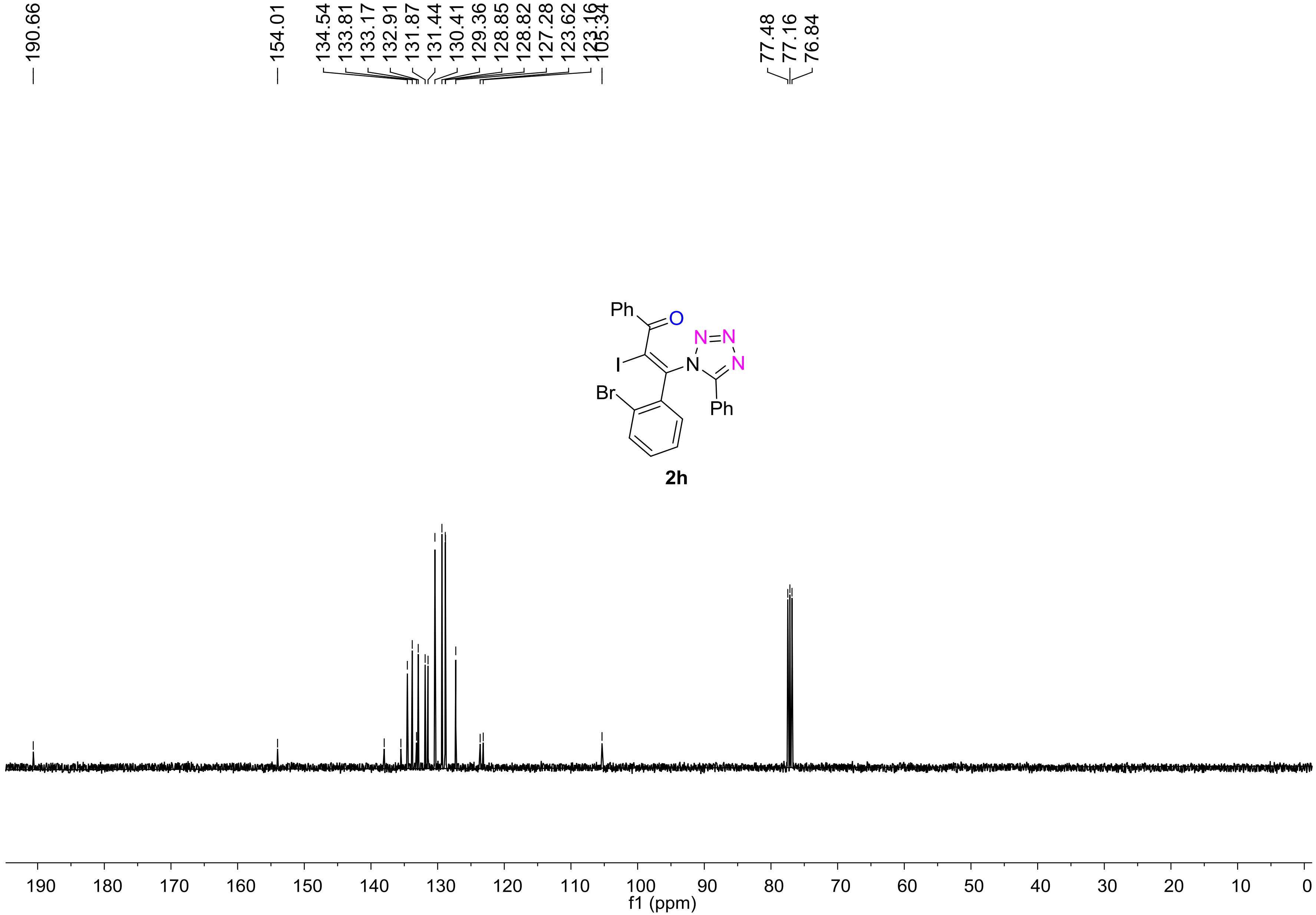
7.38
7.37
7.26
7.18
7.18
7.16
7.16
7.14
7.14
7.12
7.11
7.10
7.09
7.08
7.07
7.04
7.04
7.02
7.02
1.60
-0.00
Ph
O
N
N
N
N
I
Br
Ph
2h
2.00
1.05
6.05
2.06
1.02
1.00
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)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129.36
128.85
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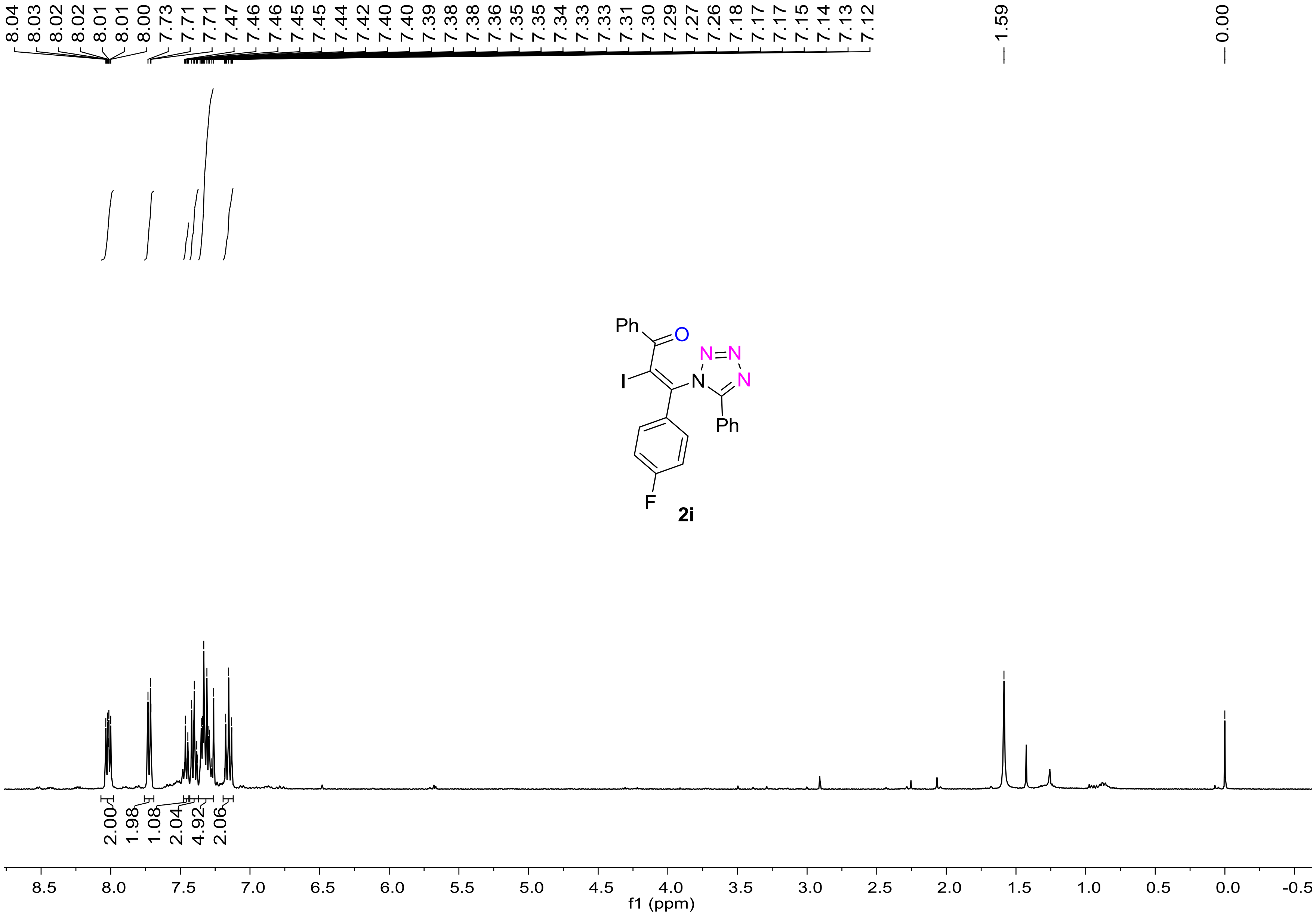
127.28
123.62
123.16
105.34
77.48
77.16
76.84
Ph
O
N=N
N
N
I
Br
Ph
2h
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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7.29
7.27
7.26
7.18
7.18
7.17
7.17
7.15
7.14
7.13
7.12
1.59
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O
N
N
N
N
I
Ph
F
2.00
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1.08
2.04
4.92
2.06
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7.5
7.0
6.5
6.0
5.5
5.0
4.5
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2.5
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0.0
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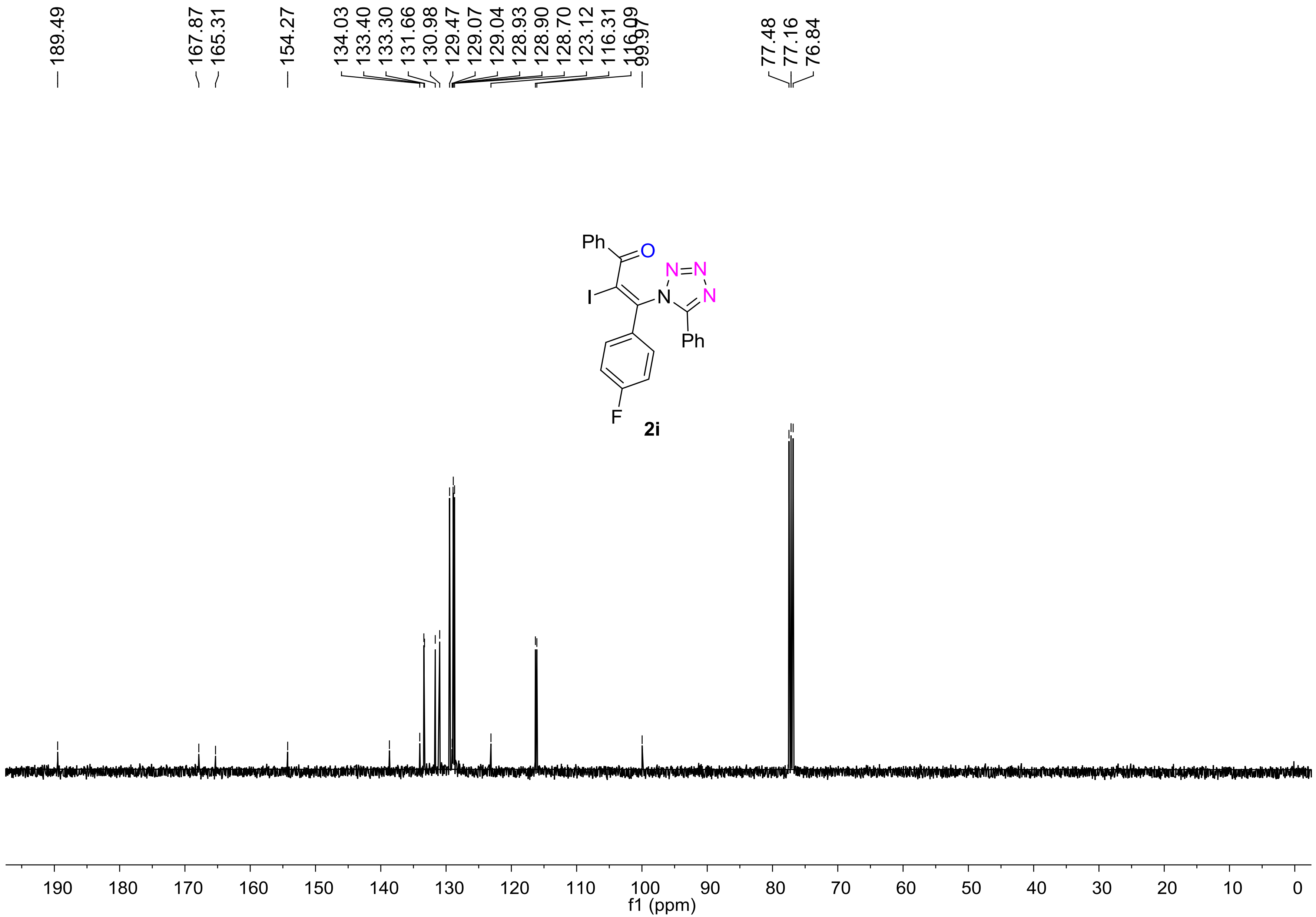
f1 (ppm)

2i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129.47
129.07
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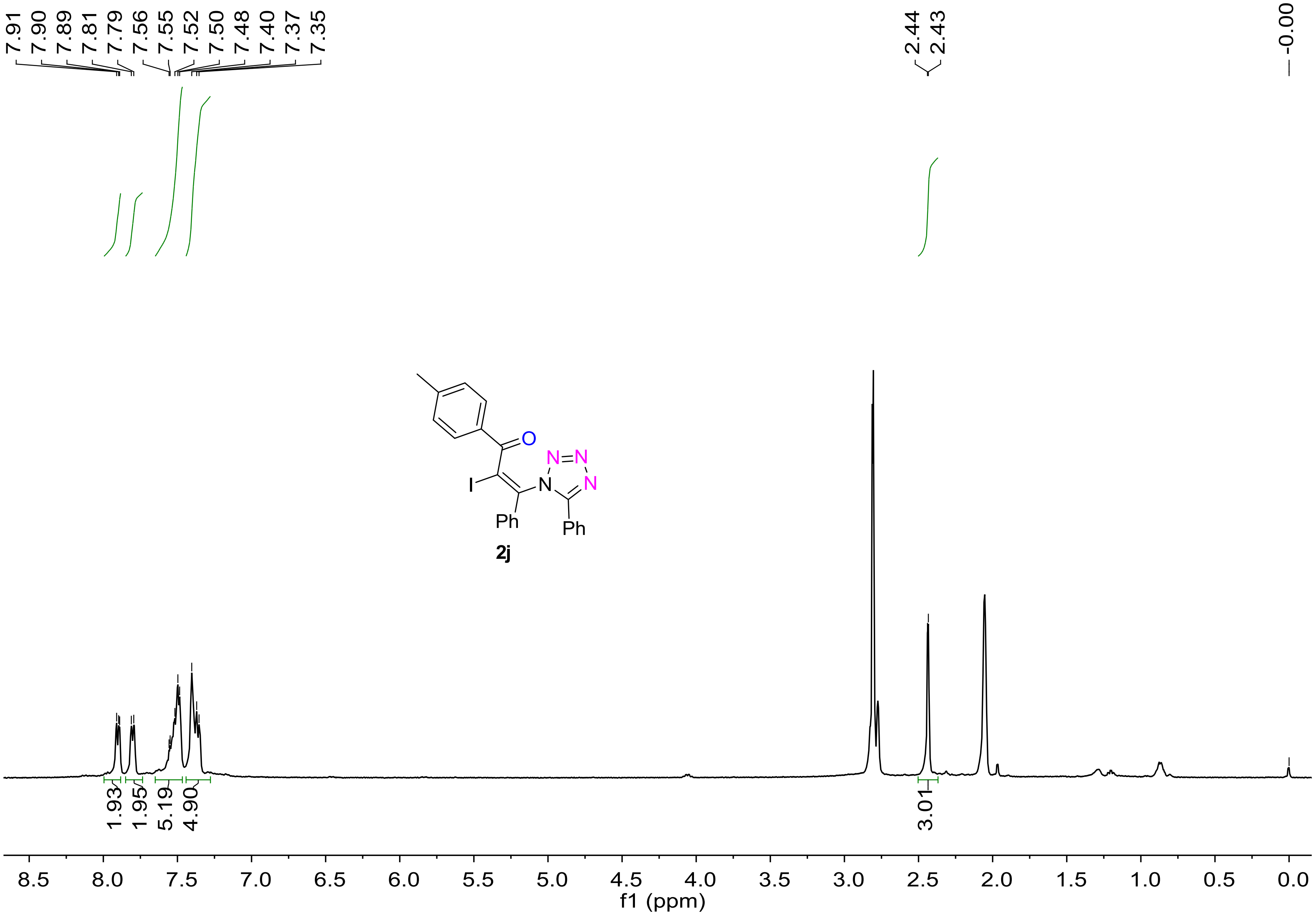
128.90
128.70
123.12
116.31
116.09
99.97
77.48
77.16
76.84
Ph
O
N=N
N
N
I
Ph
F
2i
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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7.35
2.44
2.43
-0.00
O
N=N
N
N
I
Ph
Ph
1.93
1.95
5.19
4.90
3.01
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
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4.0
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3.0
2.5
2.0
1.5
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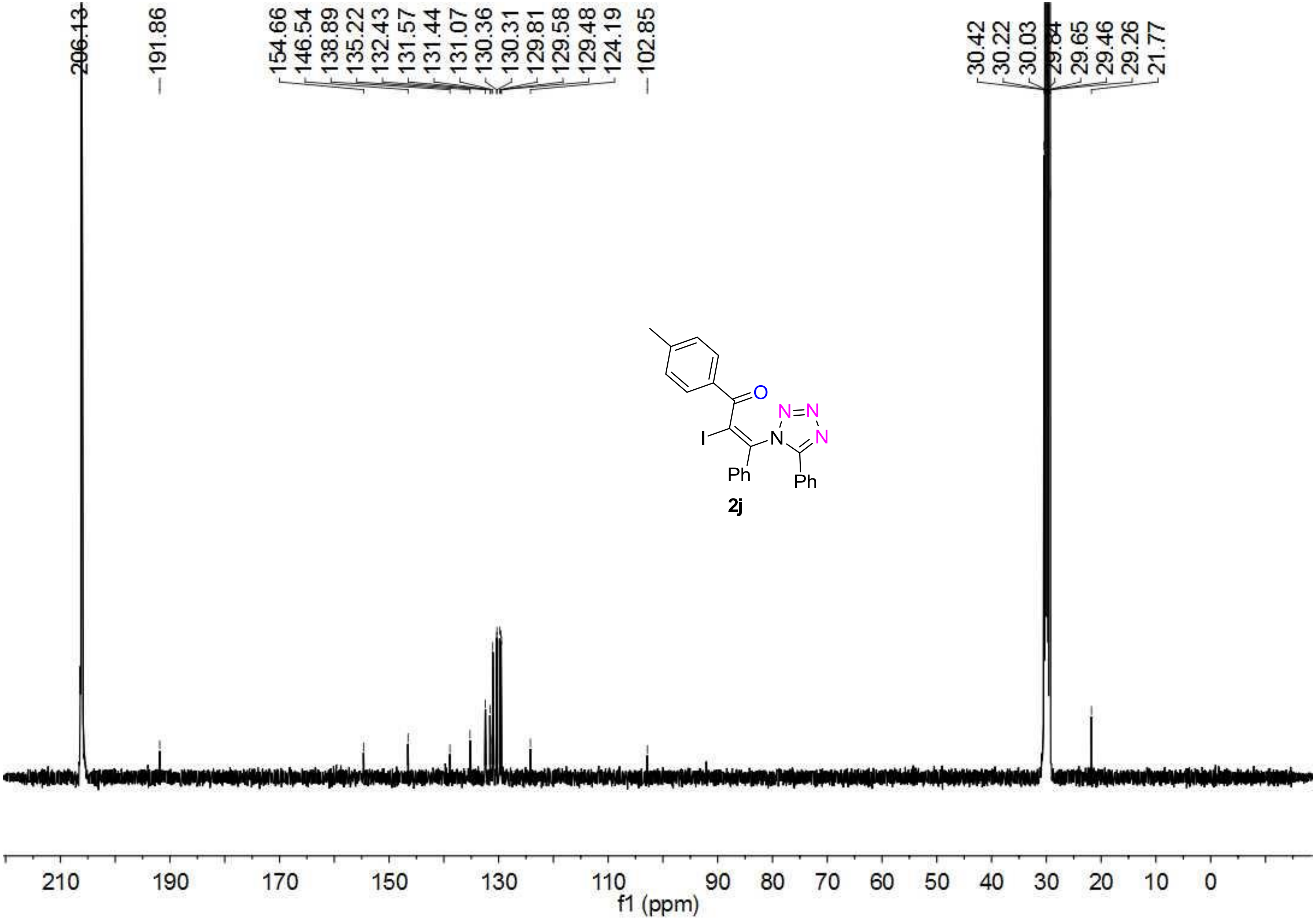
0.0
f1 (ppm)

2j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131.07
130.36
130.31
129.81
129.58
129.48
124.19
102.85
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.77
O
N=N
N
N
I
Ph
Ph
2j
210
190
170
150
130
110
90
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70
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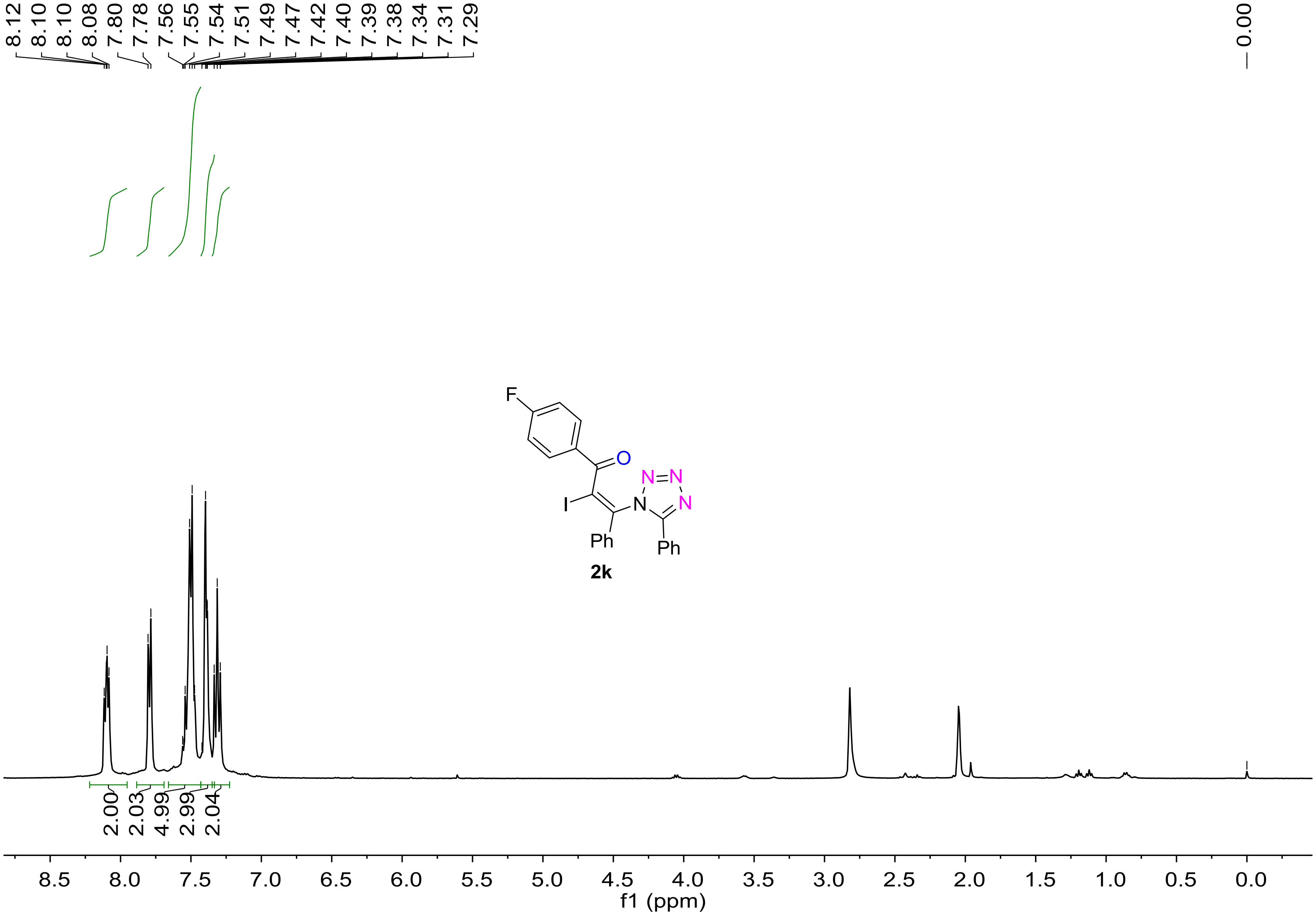
50
40
30
20
10
0
f1 (ppm)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7.42
7.40
7.39
7.38
7.34
7.31
7.29
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2.00
2.03
4.99
2.99
2.04
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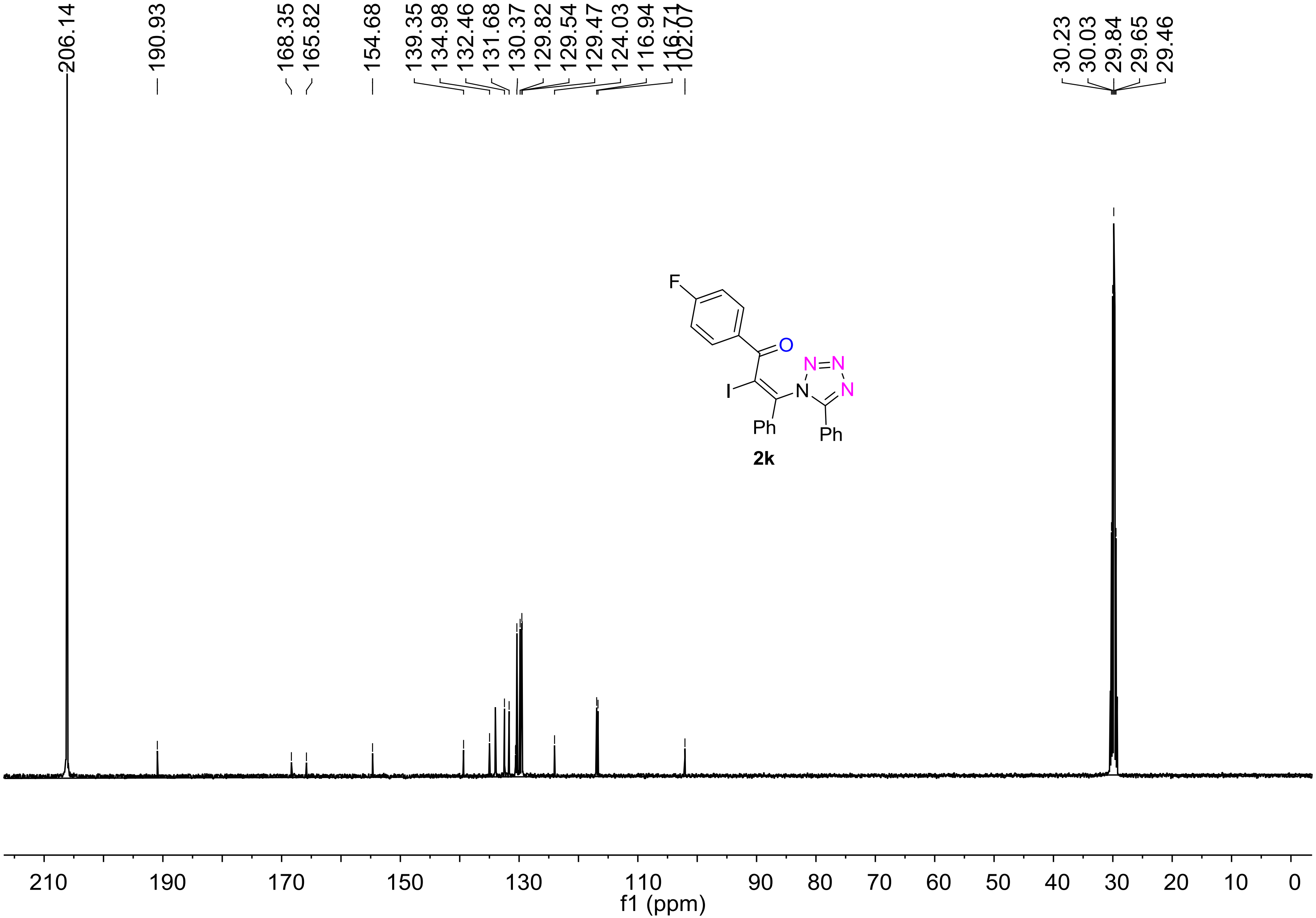
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)
F
O
N=N
N
N
I
Ph
Ph

2k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129.47
124.03
116.94
116.71
102.07
30.23
30.03
29.84
29.65
29.46
F
O
N
N
N
N
I
Ph
Ph
2k
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190
170
150
130
110
90
80
70
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50
40
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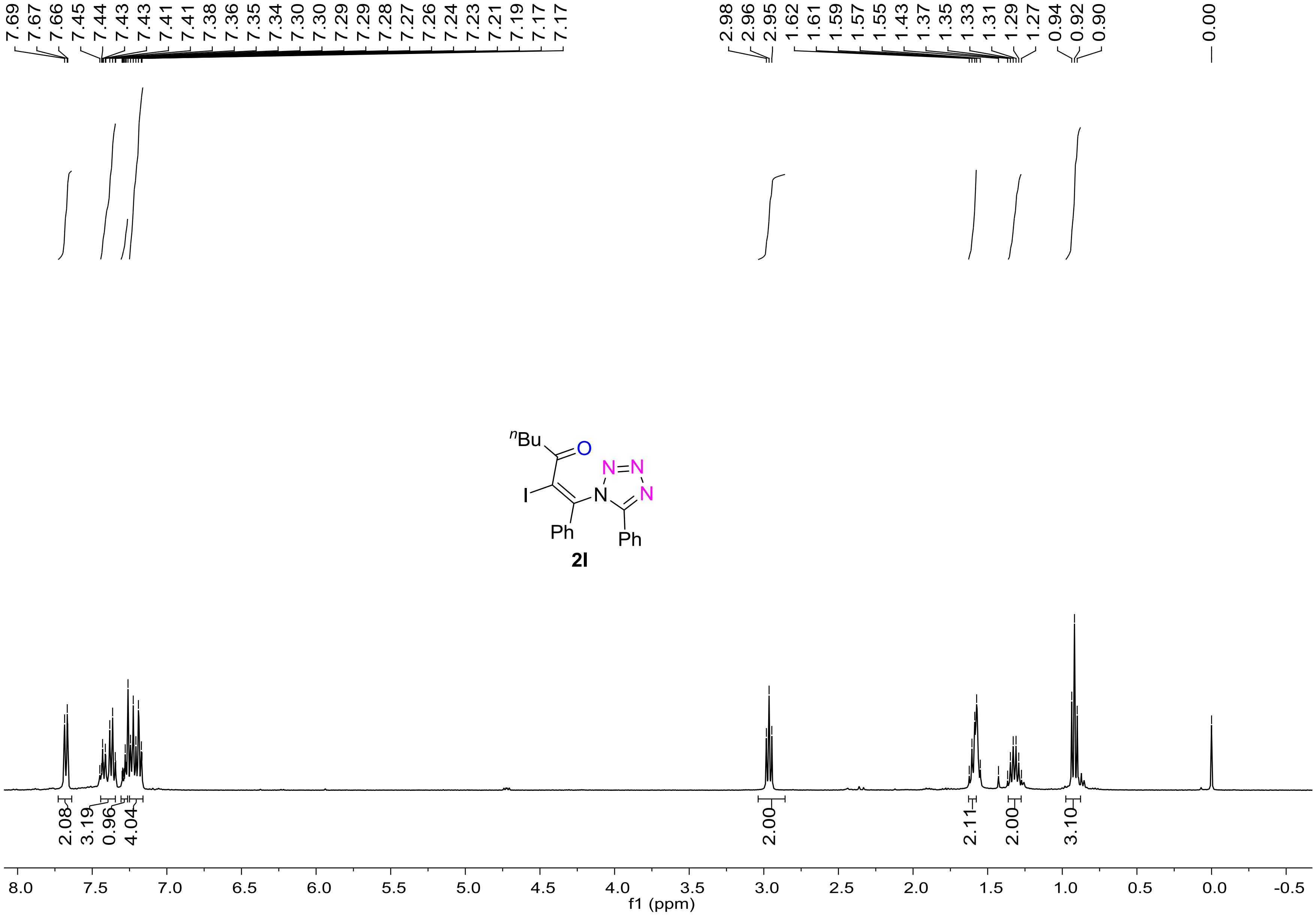
20
10
0
f1 (ppm)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7.30
7.30
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7.28
7.27
7.26
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7.23
7.21
7.19
7.17
7.17
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2.96
2.95
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1.59
1.57
1.55
1.43
1.37
1.35
1.33
1.31
1.29
1.27
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0.92
0.90
0.00
nBu
O
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N
I
Ph
Ph
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2.11
2.00
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7.0
6.5
6.0
5.5
5.0
4.5
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2.5
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1.5
1.0
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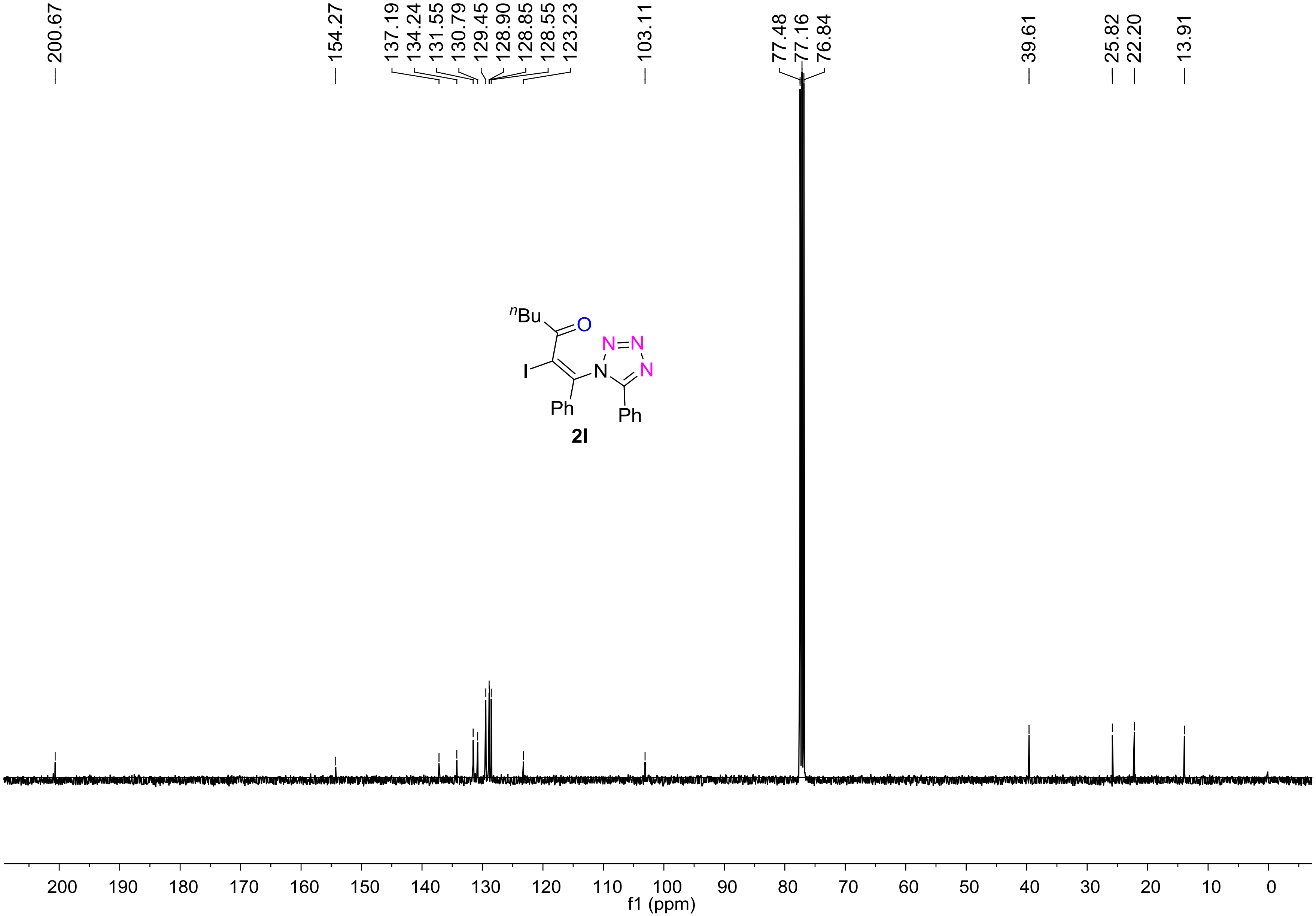
0.0
-0.5
f1 (ppm)

2l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129.45
128.90
128.85
128.55
123.23
103.11
77.48
77.16
76.84
39.61
25.82
22.20
13.91
^{n}Bu
O
N=N
N
N
I
Ph
Ph
2l
200
190
180
170
160
150
140
130
120
110
100
90
80
70
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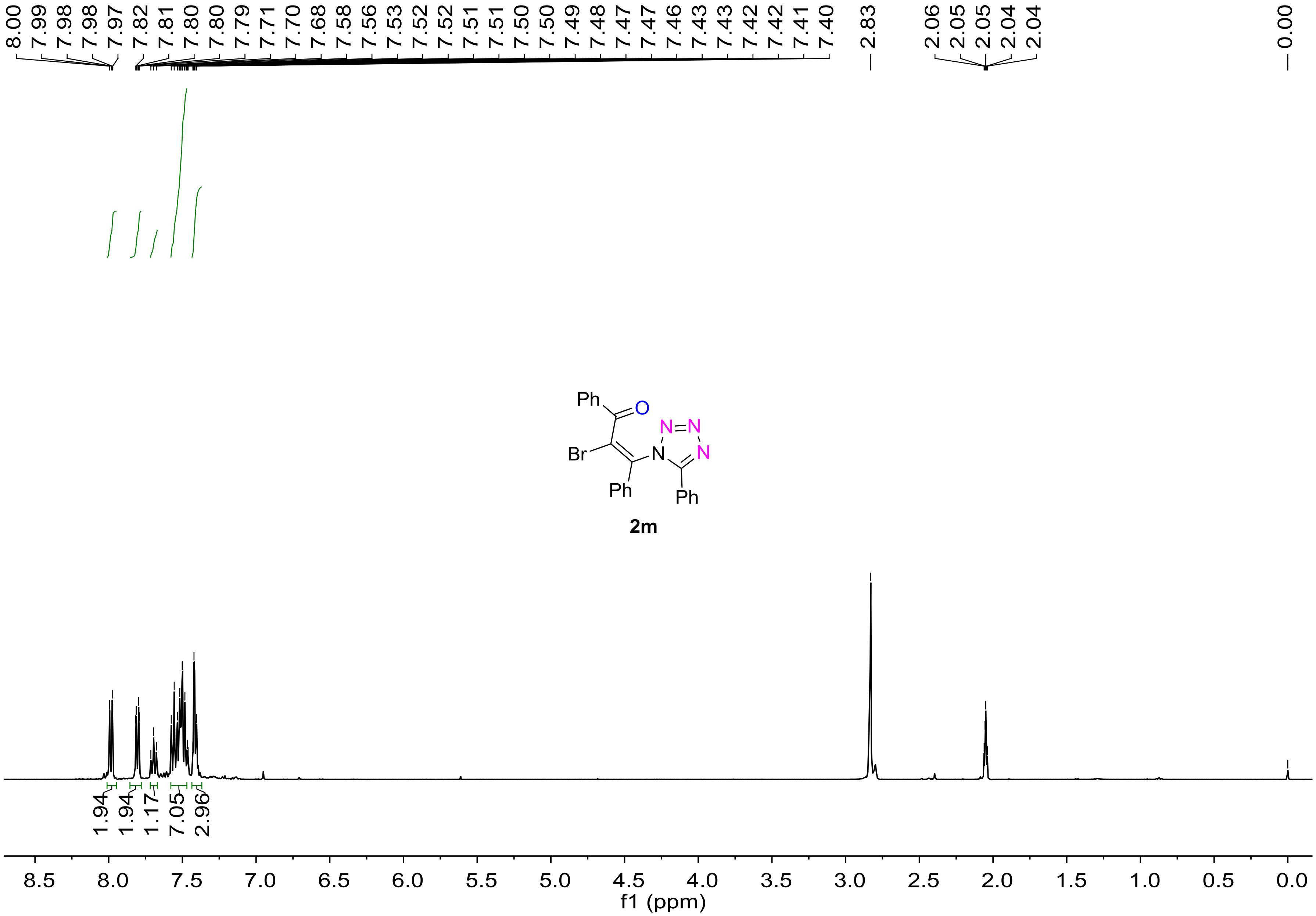
40
30
20
10
0
f1 (ppm)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7.56
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7.52
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7.51
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7.47
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7.43
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7.42
7.41
7.40
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2.05
2.05
2.04
2.04
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Ph
O
N=N
N
N
Br
Ph
Ph
2m
1.94
1.94
1.17
7.05
2.96
8.5
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7.0
6.5
6.0
5.5
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2.5
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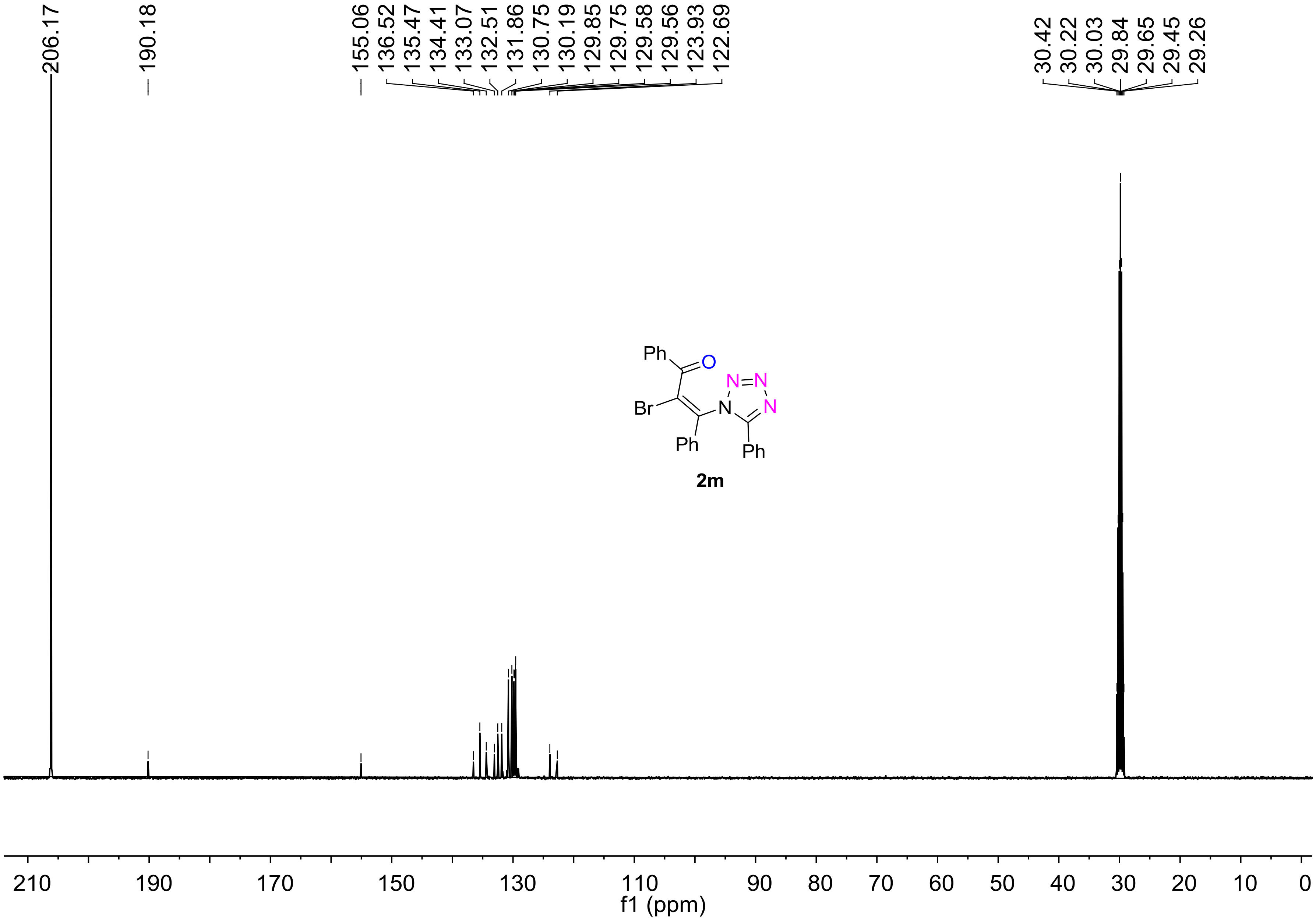
f1 (ppm)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129.56
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122.69
30.42
30.22
30.03
29.84
29.65
29.45
29.26
Ph
O
N=N
N
N
Br
Ph
Ph
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150
130
110
90
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50
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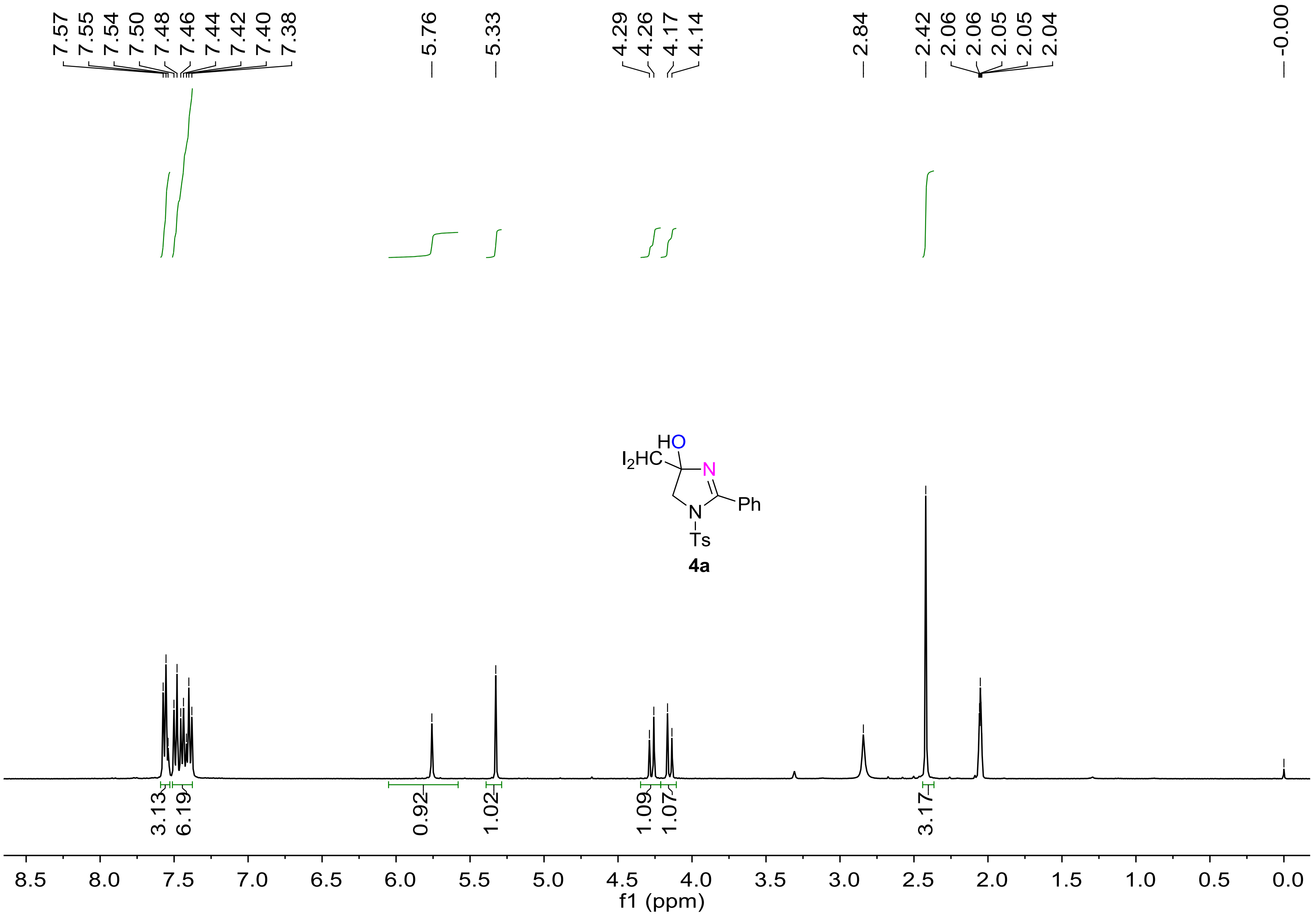
f1 (ppm)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4.17
4.14
2.84
2.42
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2.06
2.05
2.05
2.04
-0.00
HO
I2HC
N
Ph
N
Ts
4a
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1.09
1.07
3.17
8.5
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7.5
7.0
6.5
6.0
5.5
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2.0
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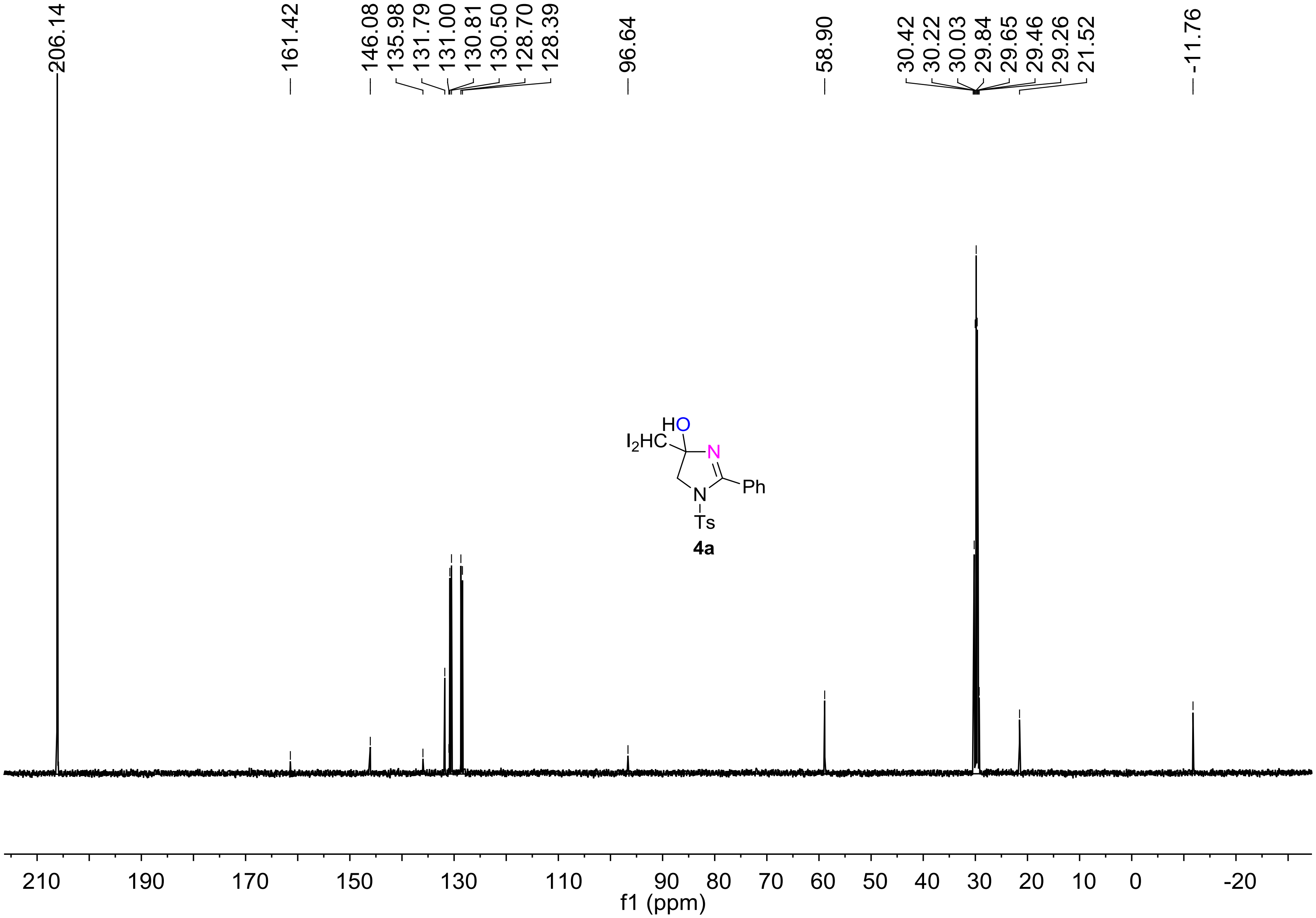
f1 (ppm)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30.03
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29.65
29.46
29.26
21.52
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I2HC
HO
N
N
Ph
Ts
4a
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150
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110
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80
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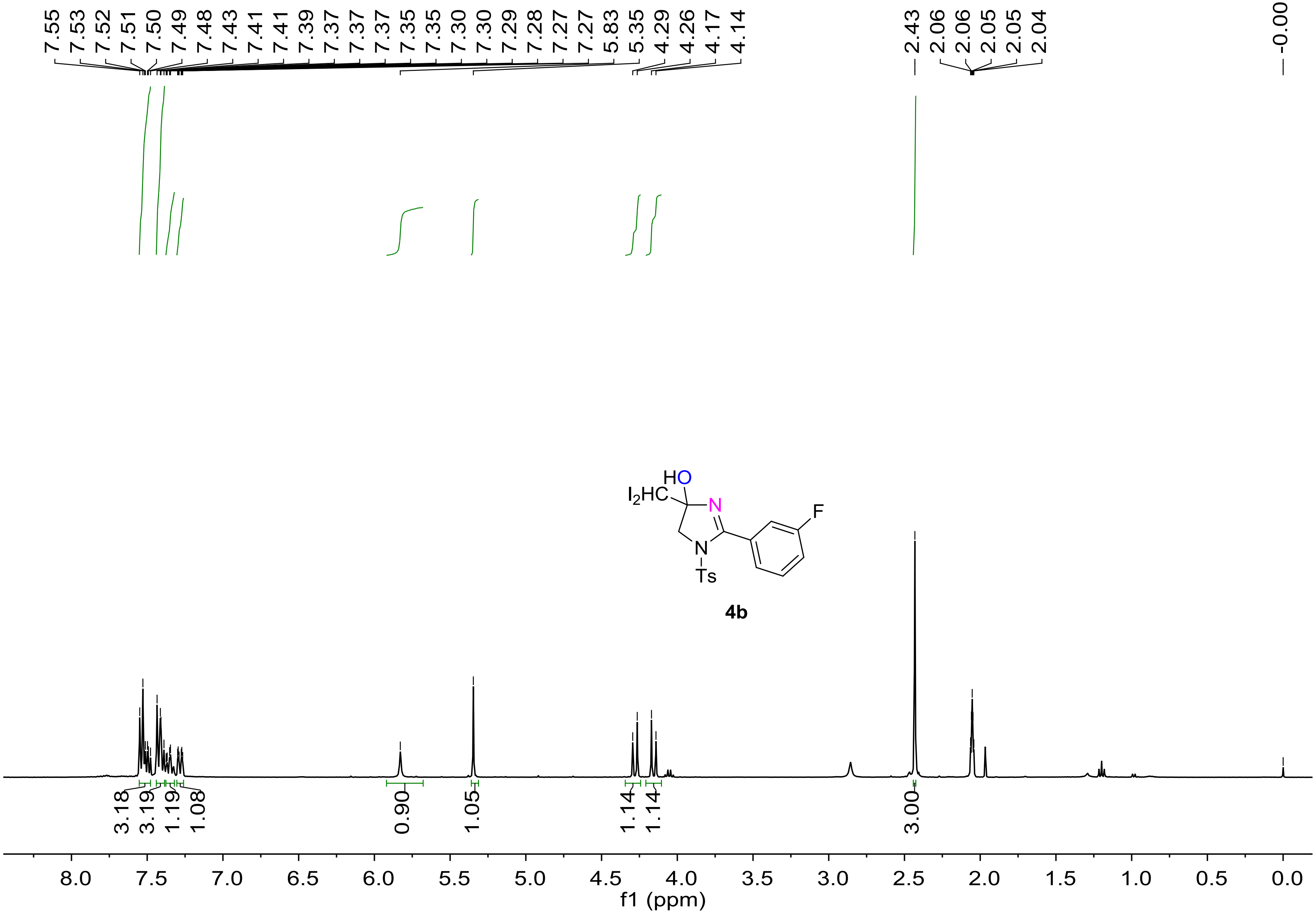
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7.37
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7.35
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7.30
7.29
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7.27
7.27
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5.35
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4.26
4.17
4.14
2.43
2.06
2.06
2.05
2.05
2.04
-0.00
HO
I_2HC
N
N
Ts
F
3.18
3.19
1.19
1.08
0.90
1.05
1.14
1.14
3.00
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7.5
7.0
6.5
6.0
5.5
5.0
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2.0
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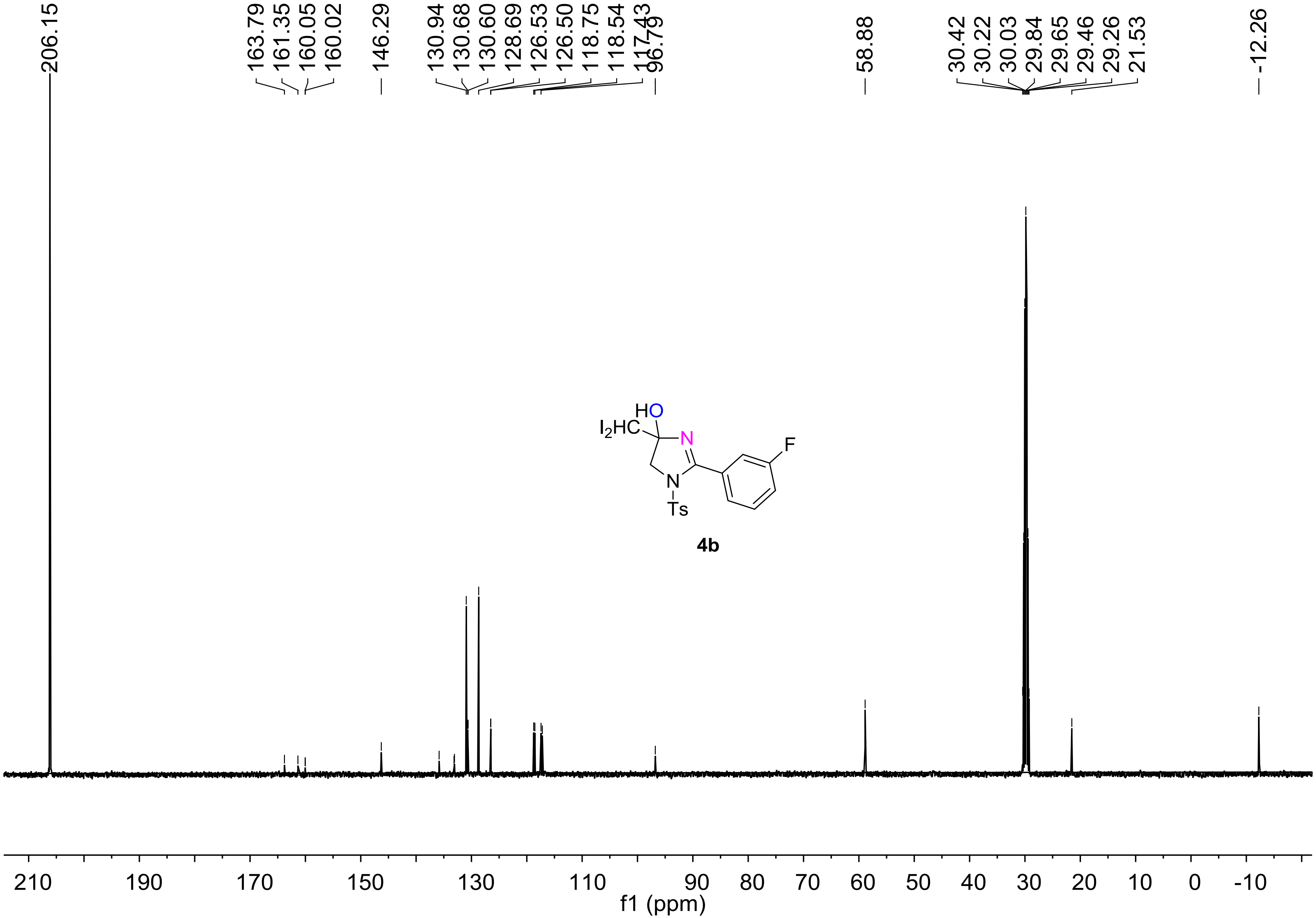
0.0
f1 (ppm)

4b


4b
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126.50
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118.54
117.43
96.79
58.88
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.53
-12.26
HO
I_2HC
N
N
F
Ts
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150
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110
90
80
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30
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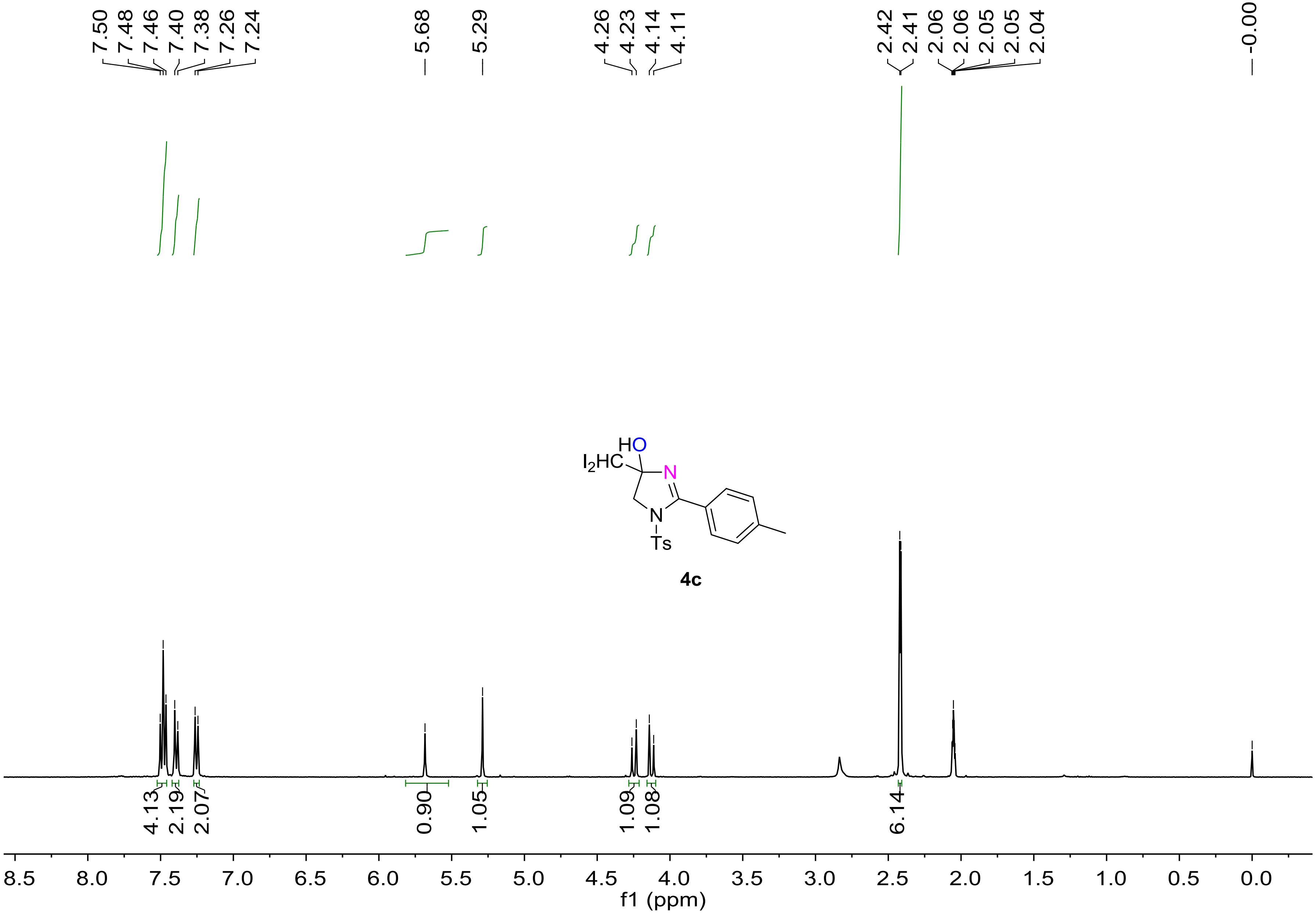
0
-10
f1 (ppm)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4.26
4.23
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4.11
2.42
2.41
2.06
2.06
2.05
2.05
2.04
-0.00
I2HC
HO
N
N
Ts
4.13
2.19
2.07
0.90
1.05
1.09
1.08
6.14
8.5
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7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
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3.0
2.5
2.0
1.5
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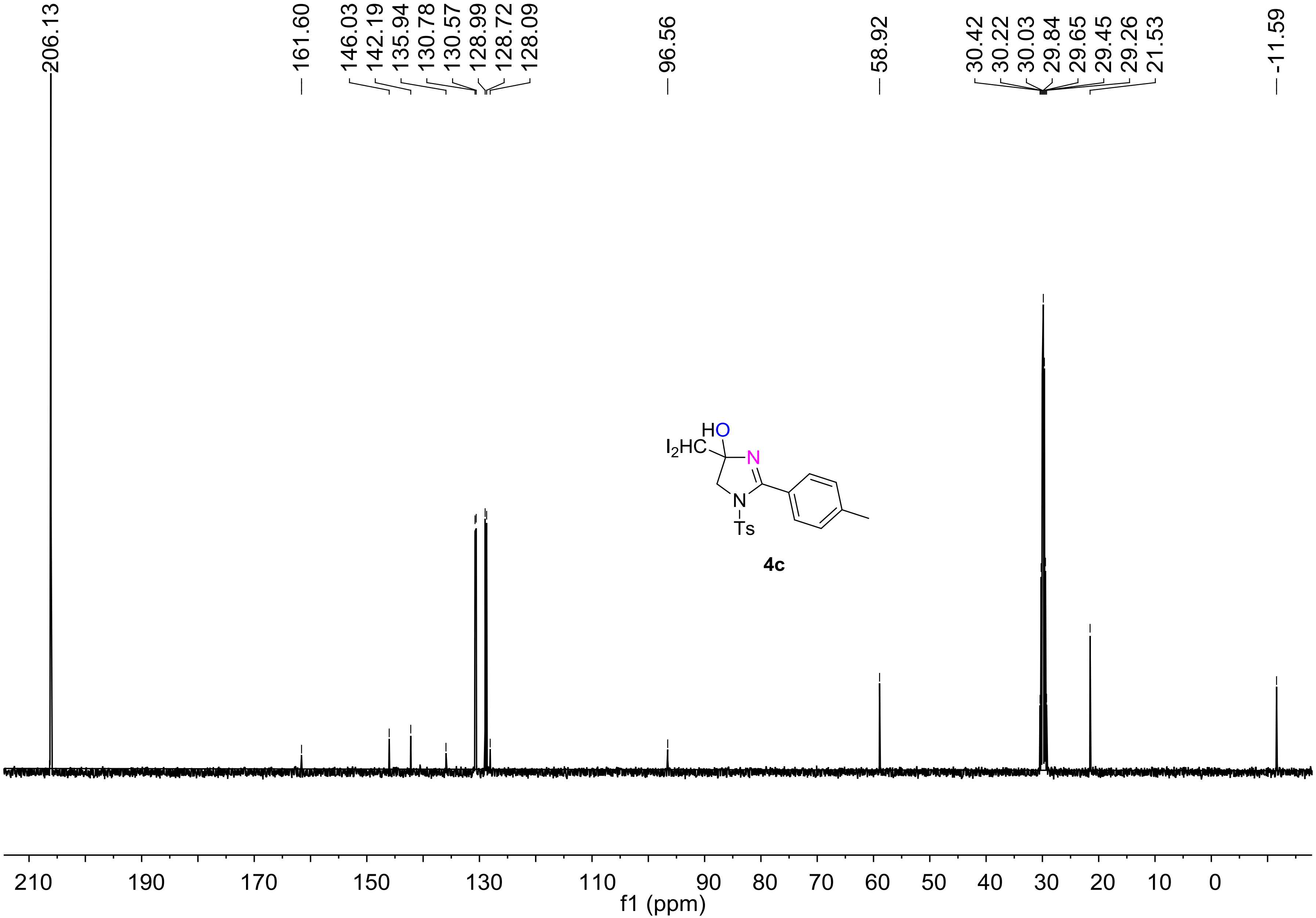
0.5
0.0
f1 (ppm)

4c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128.09
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58.92
30.42
30.22
30.03
29.84
29.65
29.45
29.26
21.53
-11.59
HO
I_2HC
N
N
Ts
4c
210
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170
150
130
110
90
80
70
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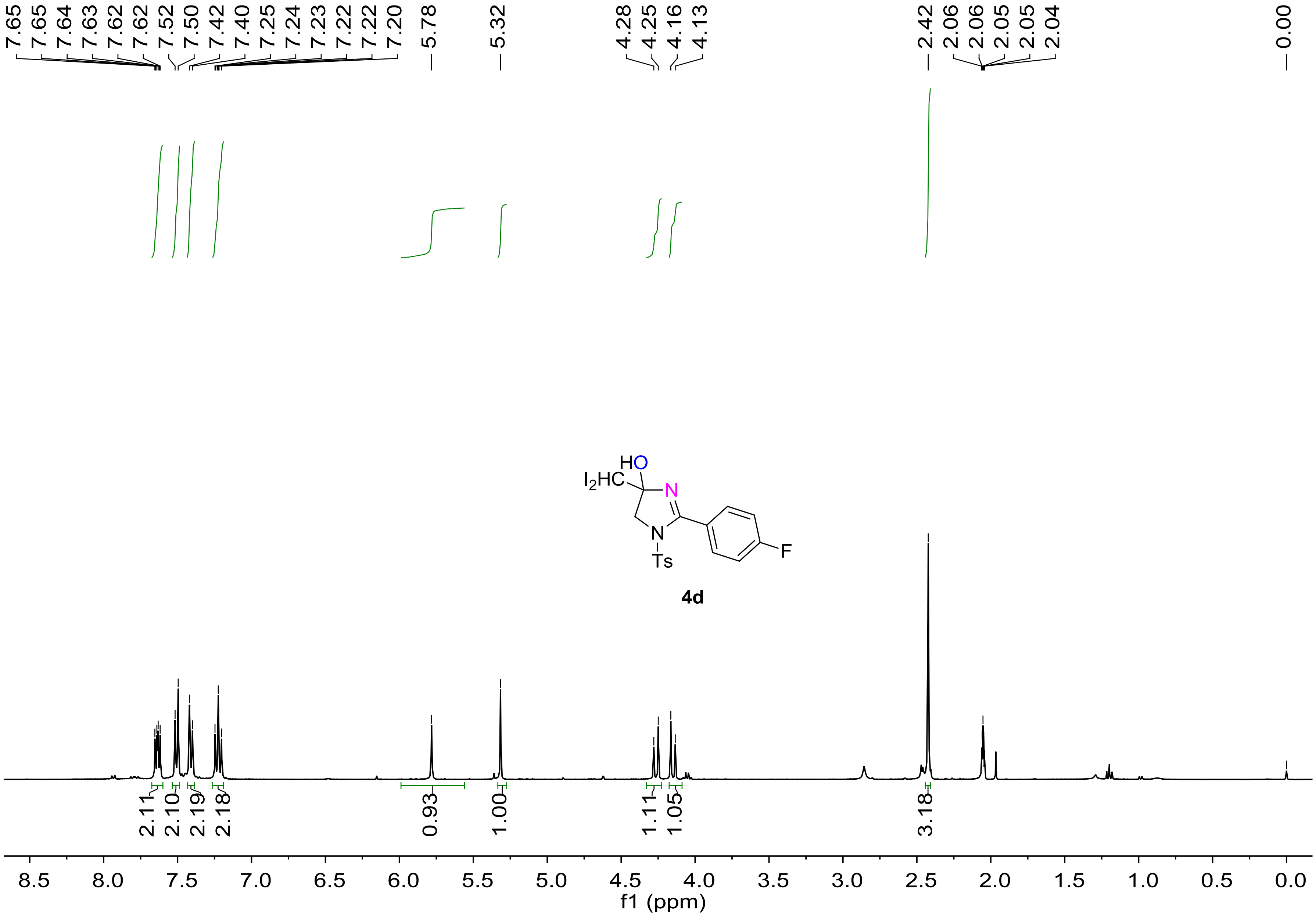
40
30
20
10
0
f1 (ppm)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7.23
7.22
7.22
7.20
5.78
5.32
4.28
4.25
4.16
4.13
2.42
2.06
2.06
2.05
2.05
2.04
0.00
2.11
2.10
2.19
2.18
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1.00
1.11
1.05
3.18
HO
I2HC
N
N
Ts
F
4d
8.5
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7.0
6.5
6.0
5.5
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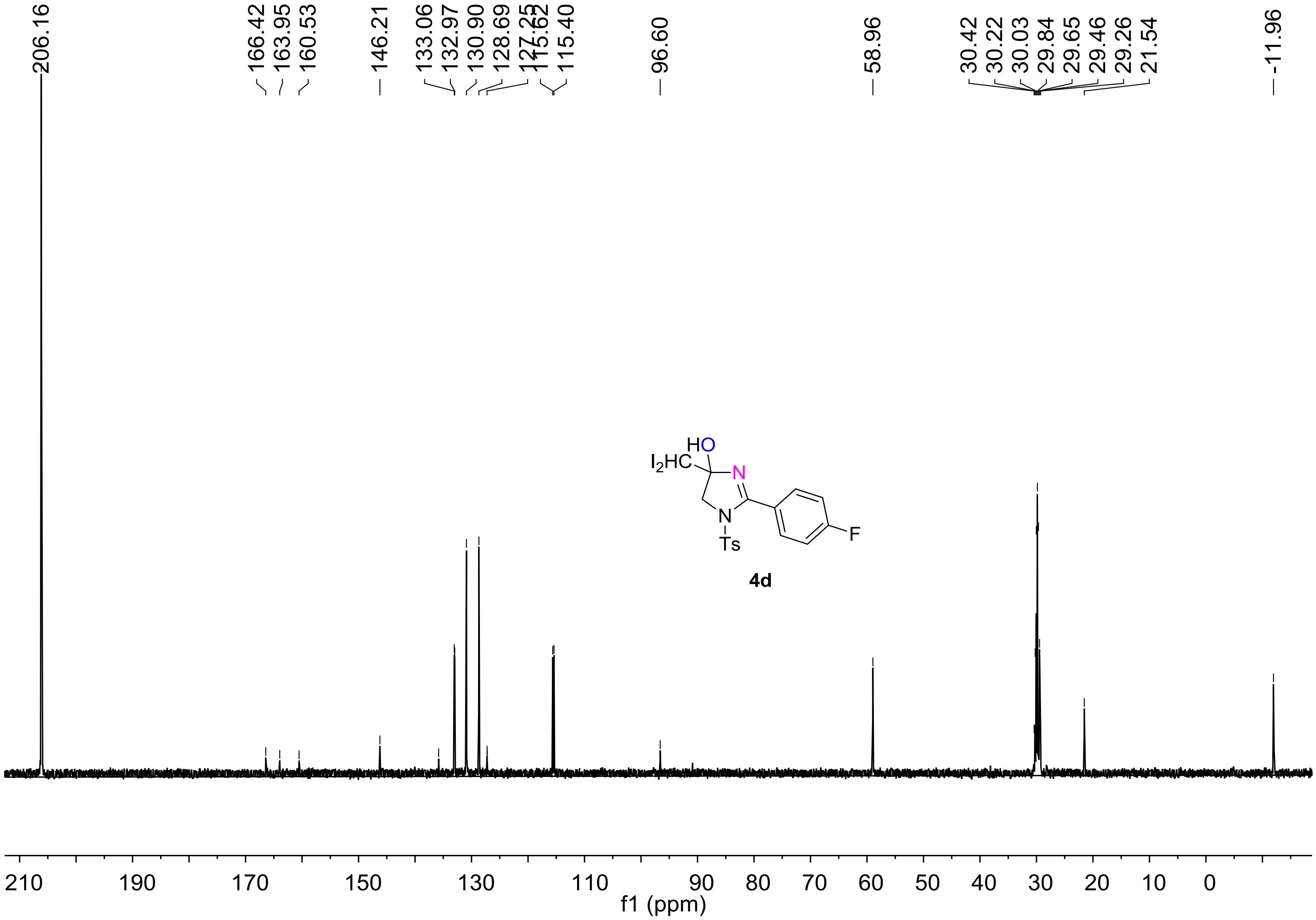
f1 (ppm)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58.96
30.42
30.22
30.03
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29.65
29.46
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HO
I2HC
N
N
Ts
F
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190
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110
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80
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30
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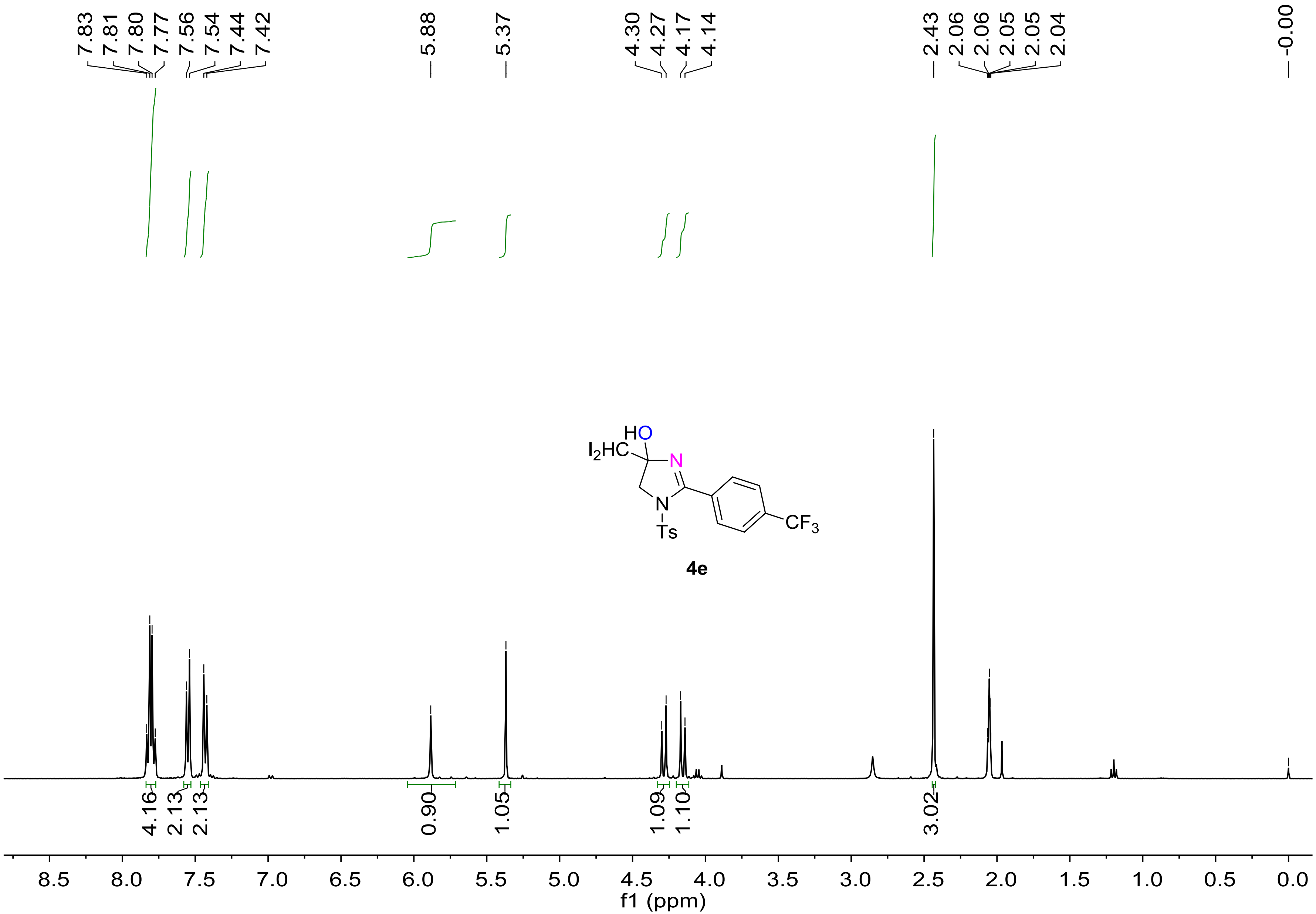
0
f1 (ppm)

4d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4.14
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2.06
2.06
2.05
2.05
2.04
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HO
I2HC
N
N
Ts
CF3
4e
4.16
2.13
2.13
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1.05
1.09
1.10
3.02
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7.5
7.0
6.5
6.0
5.5
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4.5
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2.5
2.0
1.5
1.0
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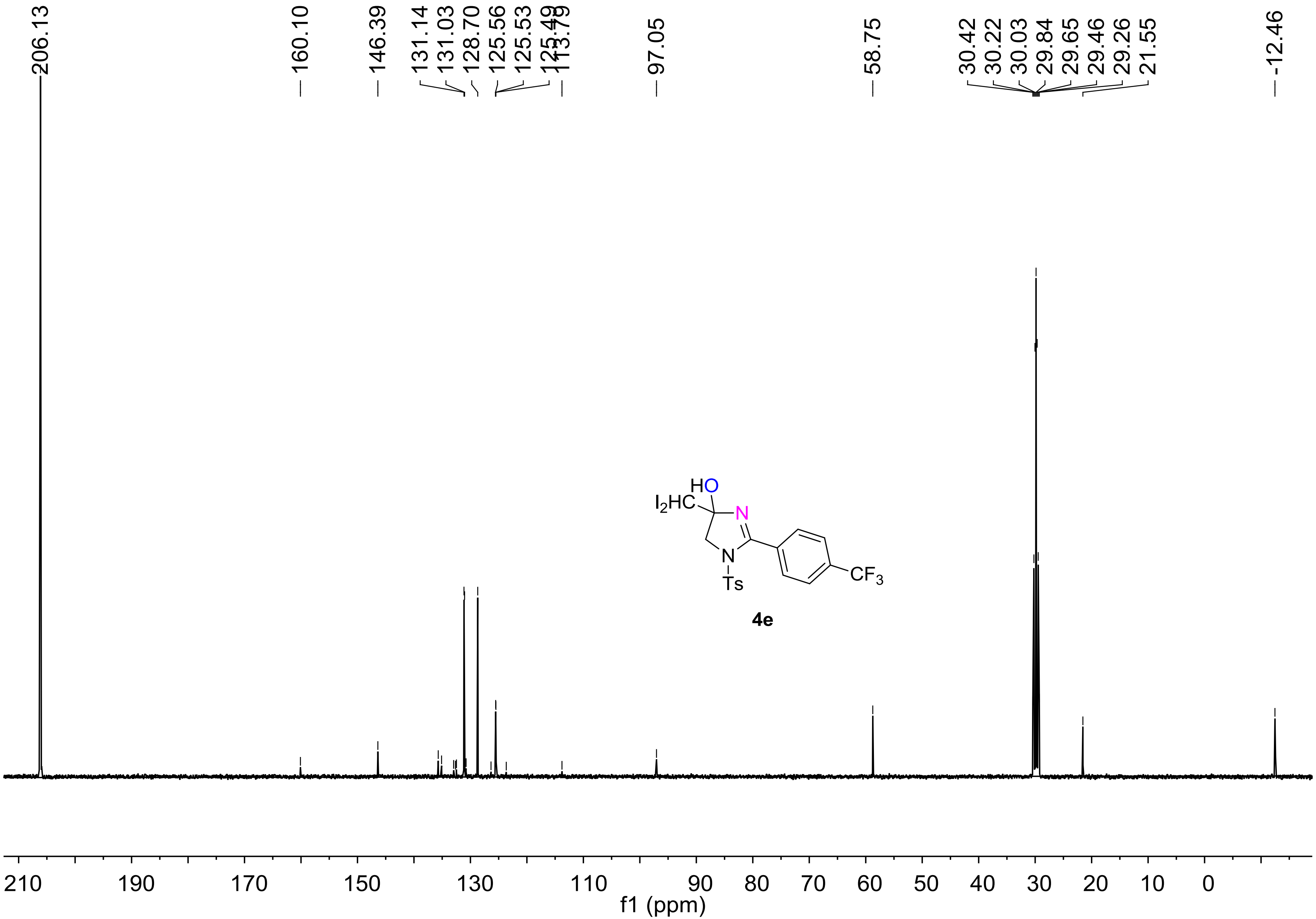
0.0
f1 (ppm)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58.75
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.55
-12.46
HO
I2HC
N
N
Ts
CF3
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190
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130
110
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80
70
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50
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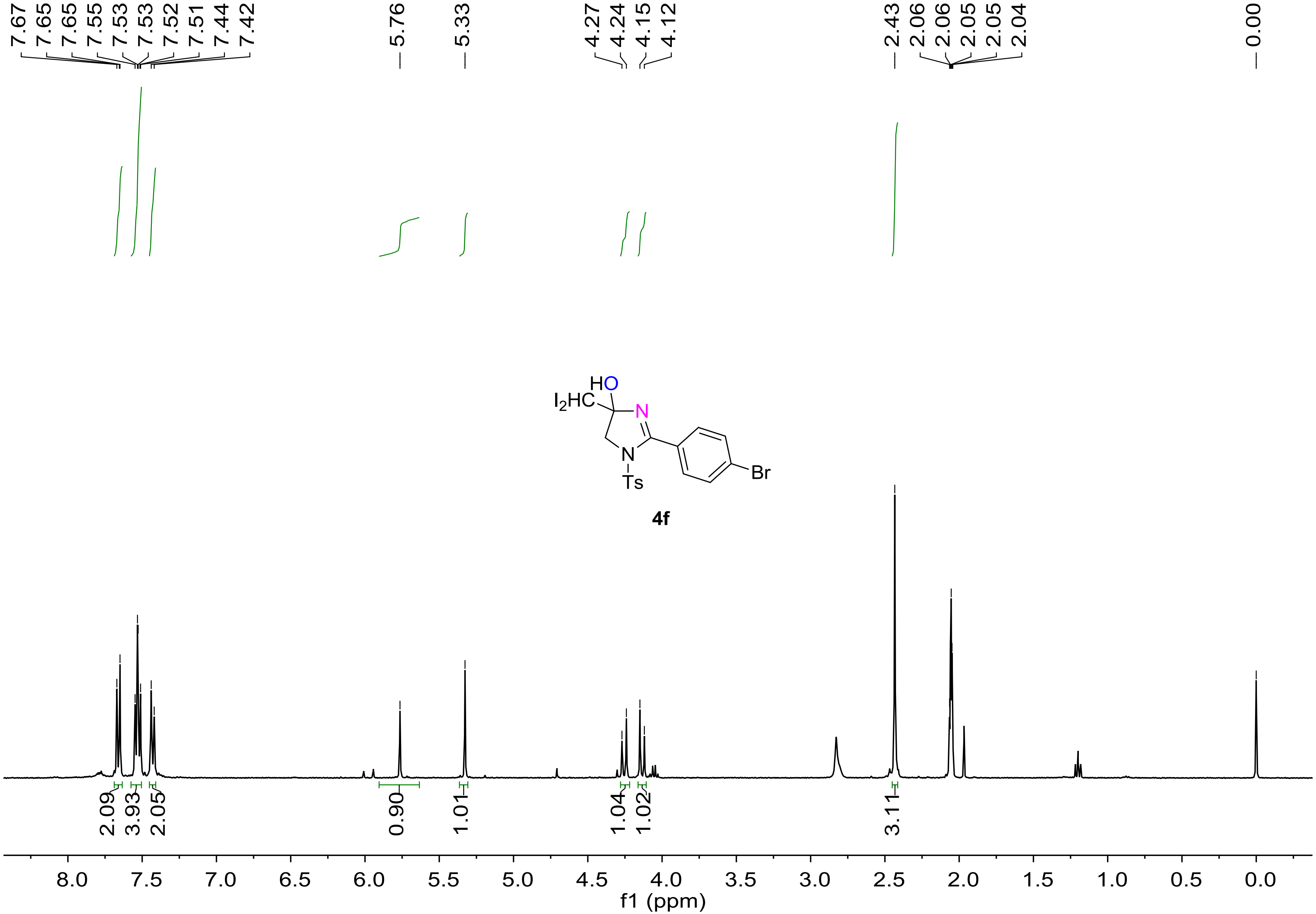
30
20
10
0
f1 (ppm)

4e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4.24
4.15
4.12
2.43
2.06
2.06
2.05
2.05
2.04
0.00
HO
I2HC
N
N
Ts
Br
4f
2.09
3.93
2.05
0.90
1.01
1.04
1.02
3.11
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7.5
7.0
6.5
6.0
5.5
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1.0
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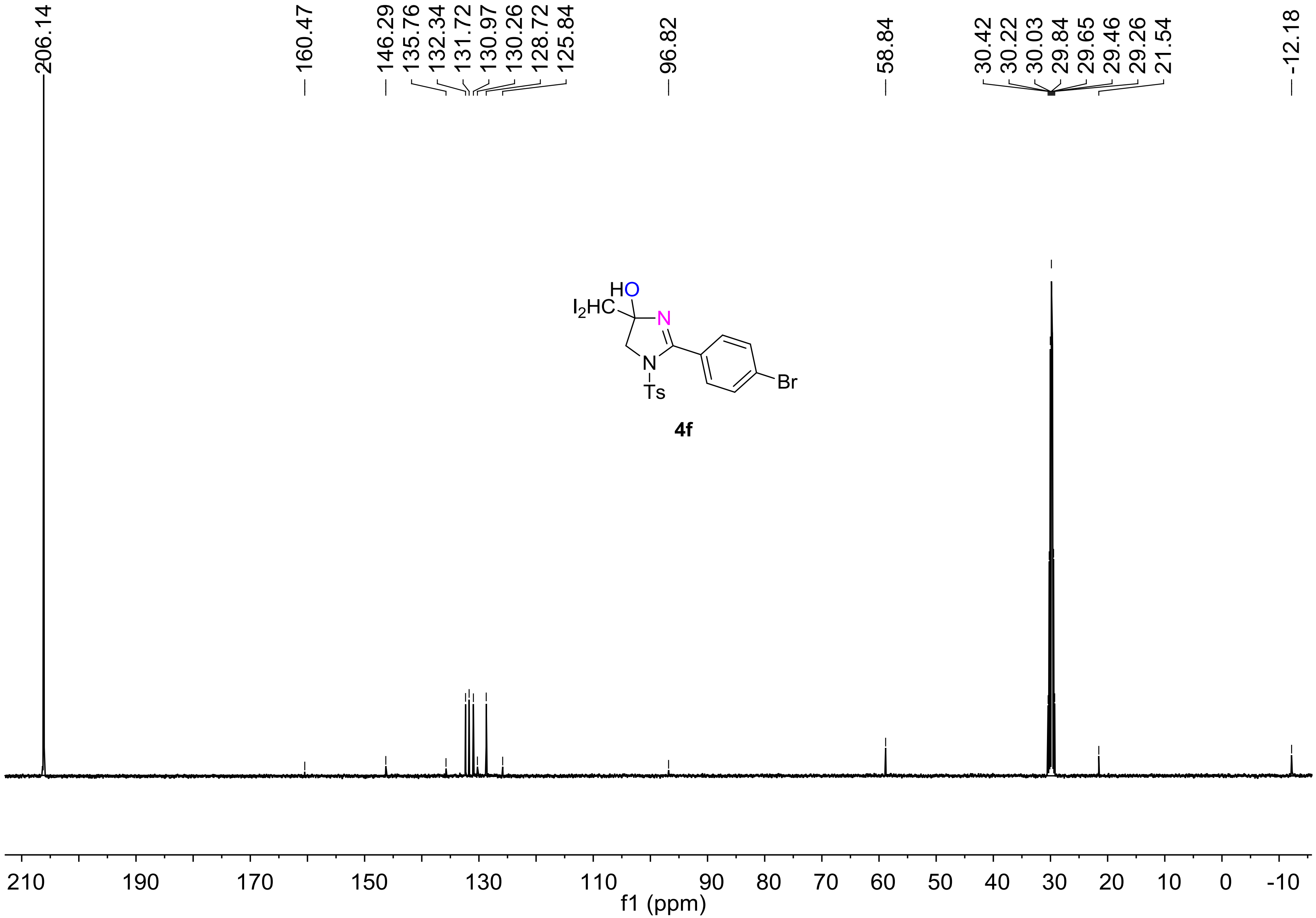
0.0
f1 (ppm)



4f

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30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.54
-12.18
I_2HC
HO
N
N
Ts
Br
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190
170
150
130
110
90
80
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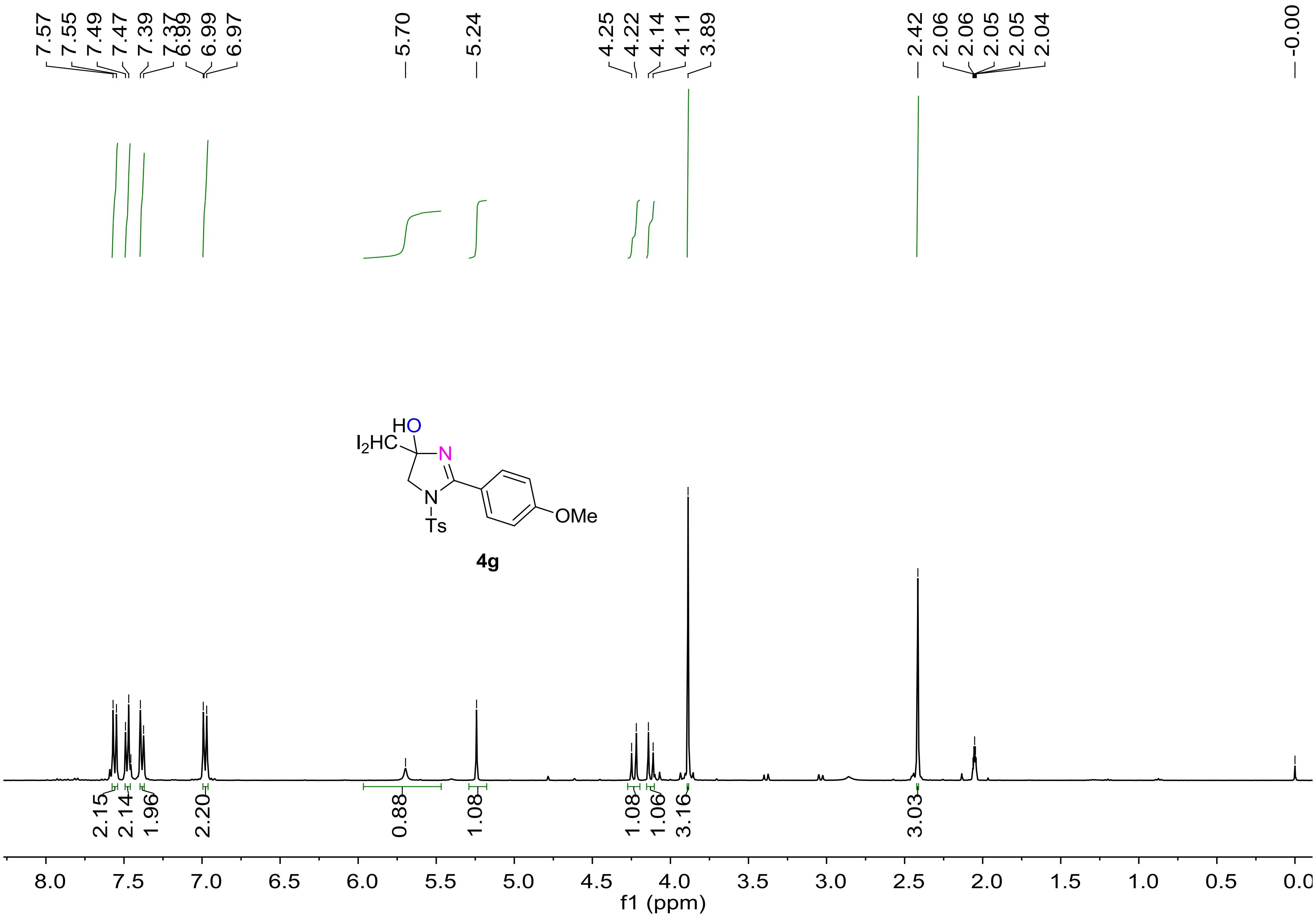
60
50
40
30
20
10
0
-10
f1 (ppm)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4.22
4.14
4.11
3.89
2.42
2.06
2.06
2.05
2.05
2.04
-0.00
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I2HC
N
N
Ts
OMe
4g
2.15
2.14
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0.88
1.08
1.08
1.06
3.16
3.03
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7.5
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6.0
5.5
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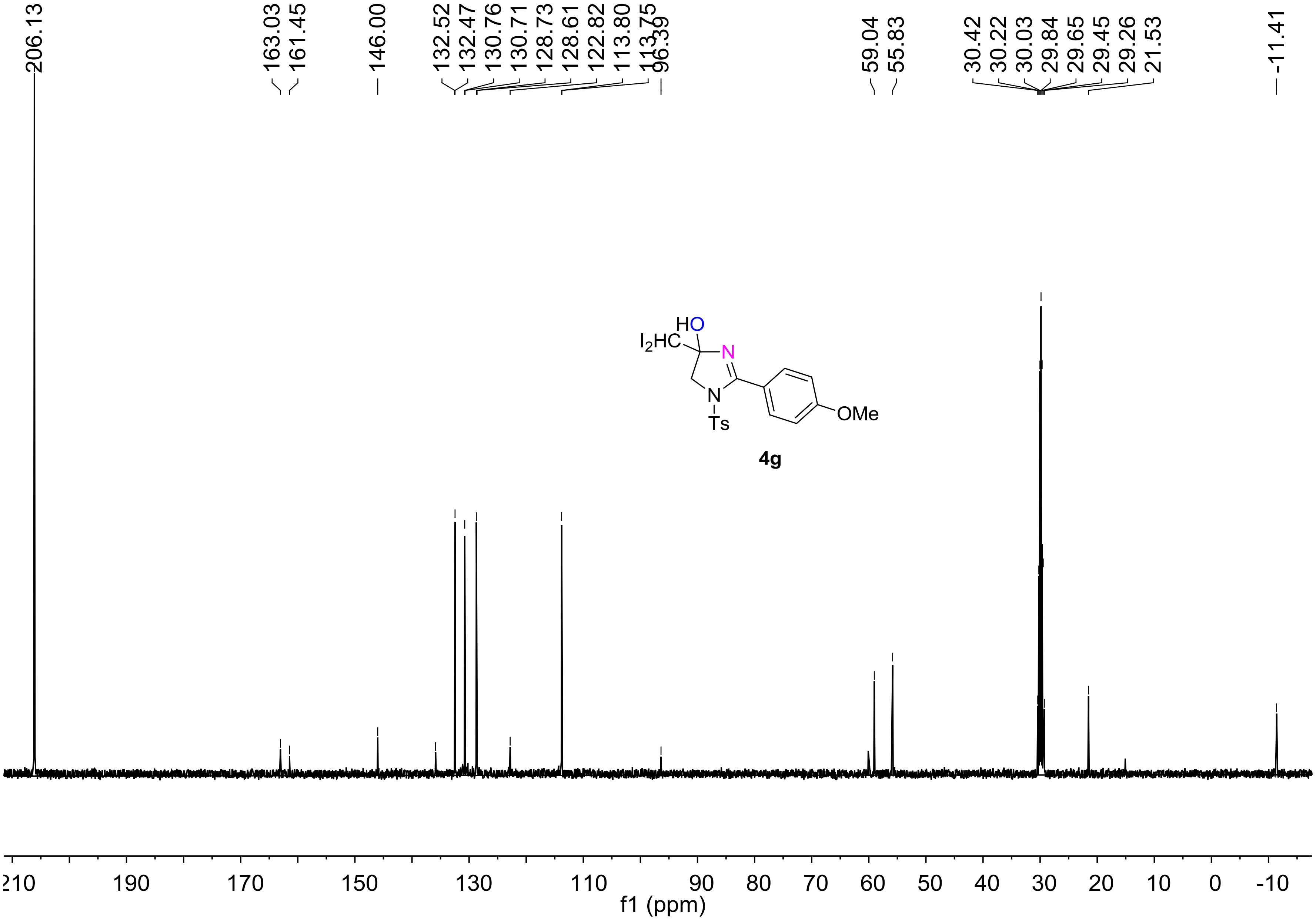
f1 (ppm)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96.39
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30.03
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29.65
29.45
29.26
21.53
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I2HC
HO
N
N
Ts
OMe
4g
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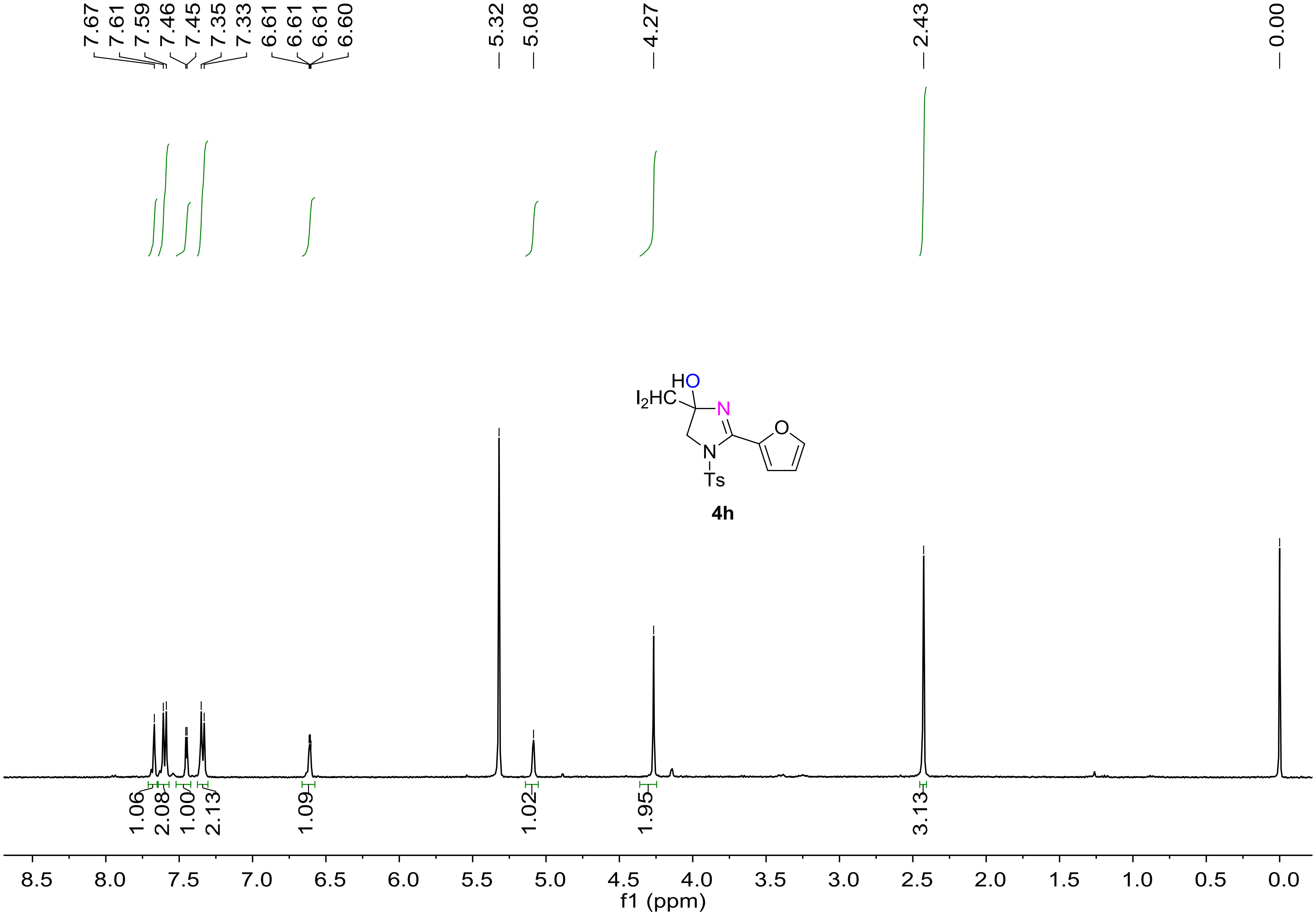
-10
f1 (ppm)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2.08
1.00
2.13
1.09
1.02
1.95
3.13
I2HC
HO
N
O
N
Ts
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7.5
7.0
6.5
6.0
5.5
5.0
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3.0
2.5
2.0
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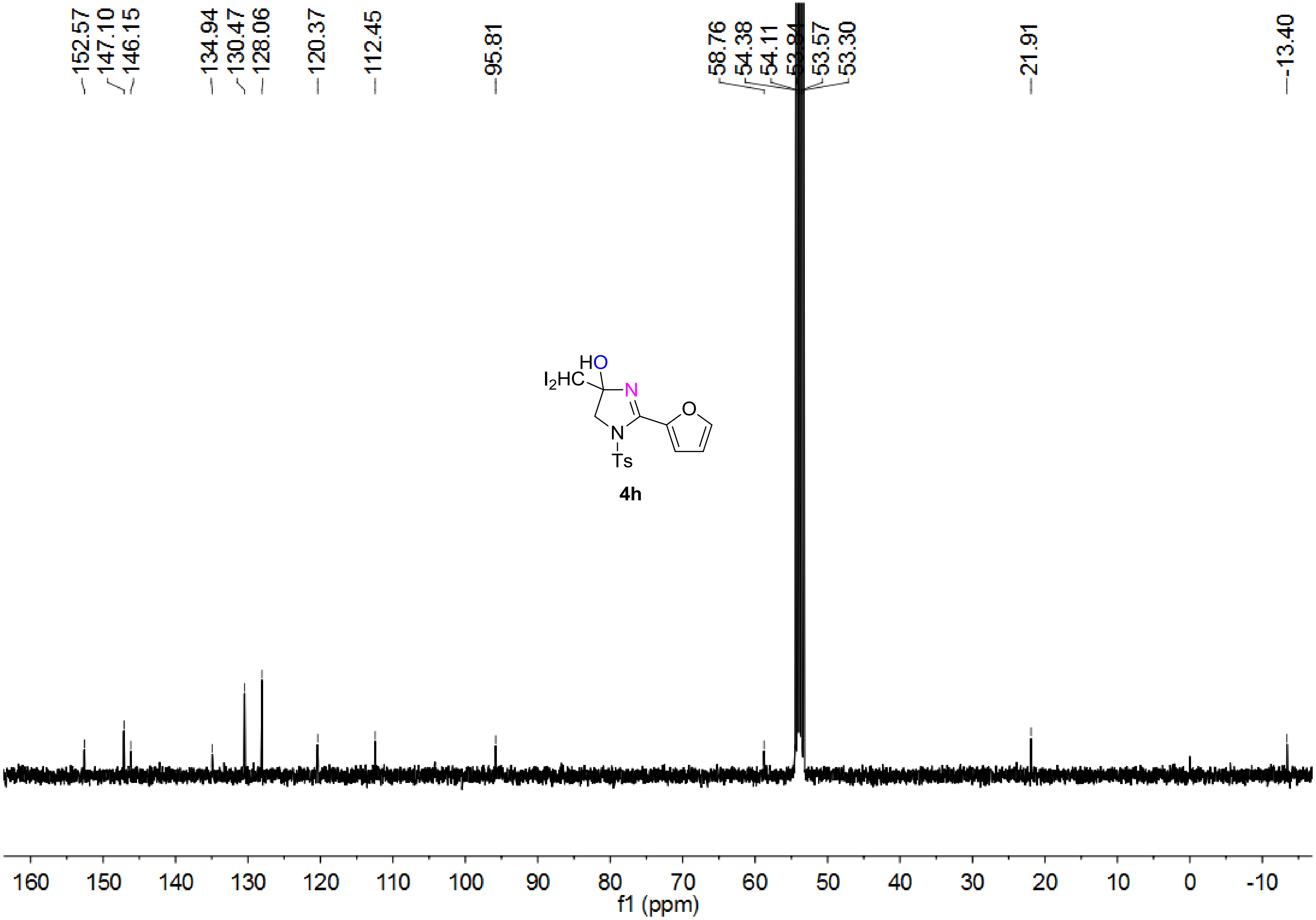
f1 (ppm)

4h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53.57
53.30
21.91
-13.40
HO
I2HC
N
O
N
Ts
4h
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150
140
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120
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100
90
80
70
60
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40
30
20
10
0
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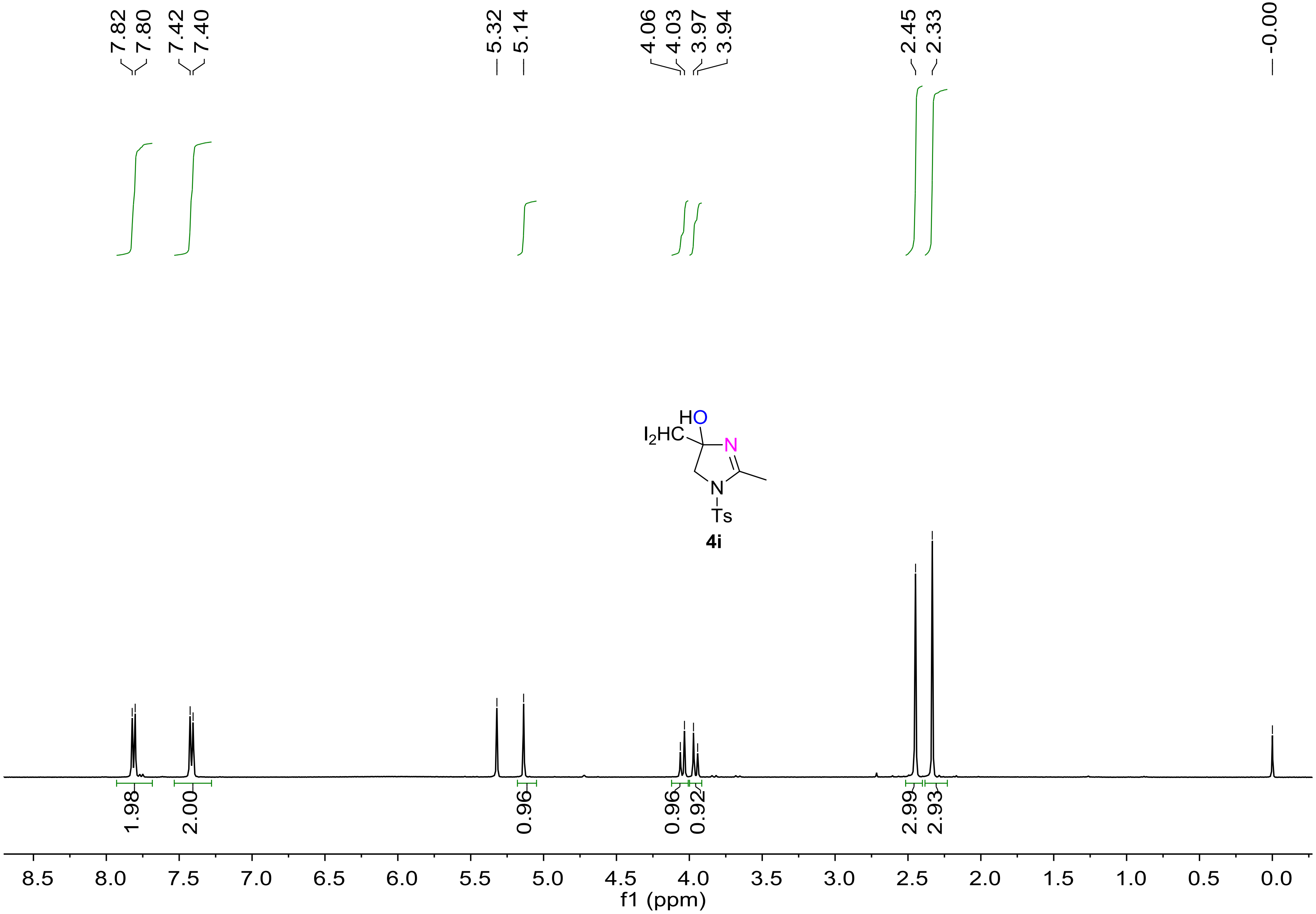
f1 (ppm)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-0.00
HO
I2HC
N
N
Ts
4i
1.98
2.00
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0.96
0.92
2.99
2.93
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6.0
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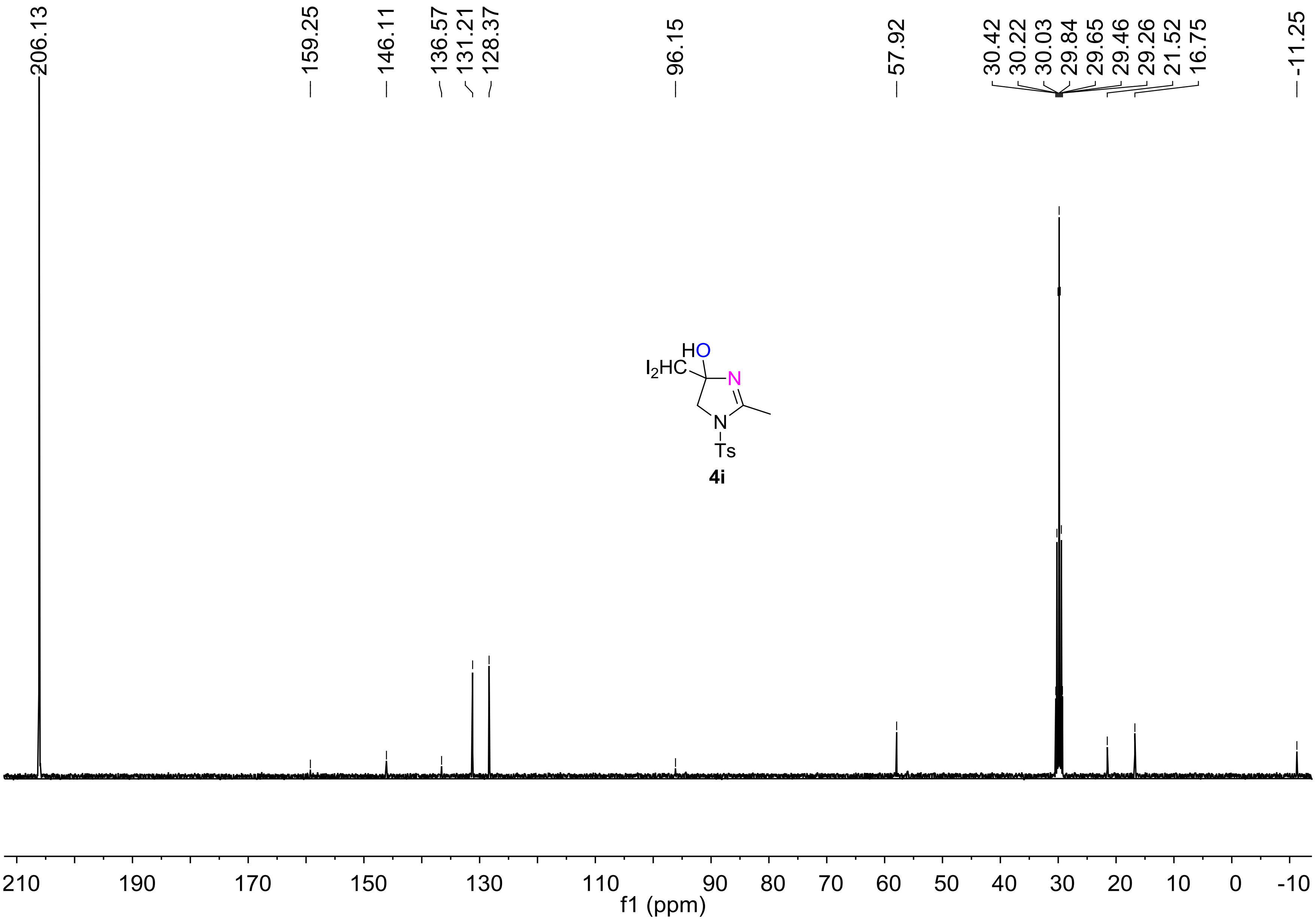
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29.26
21.52
16.75
-11.25
HO
I_2HC
N
N
Ts
4i
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110
90
80
70
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40
30
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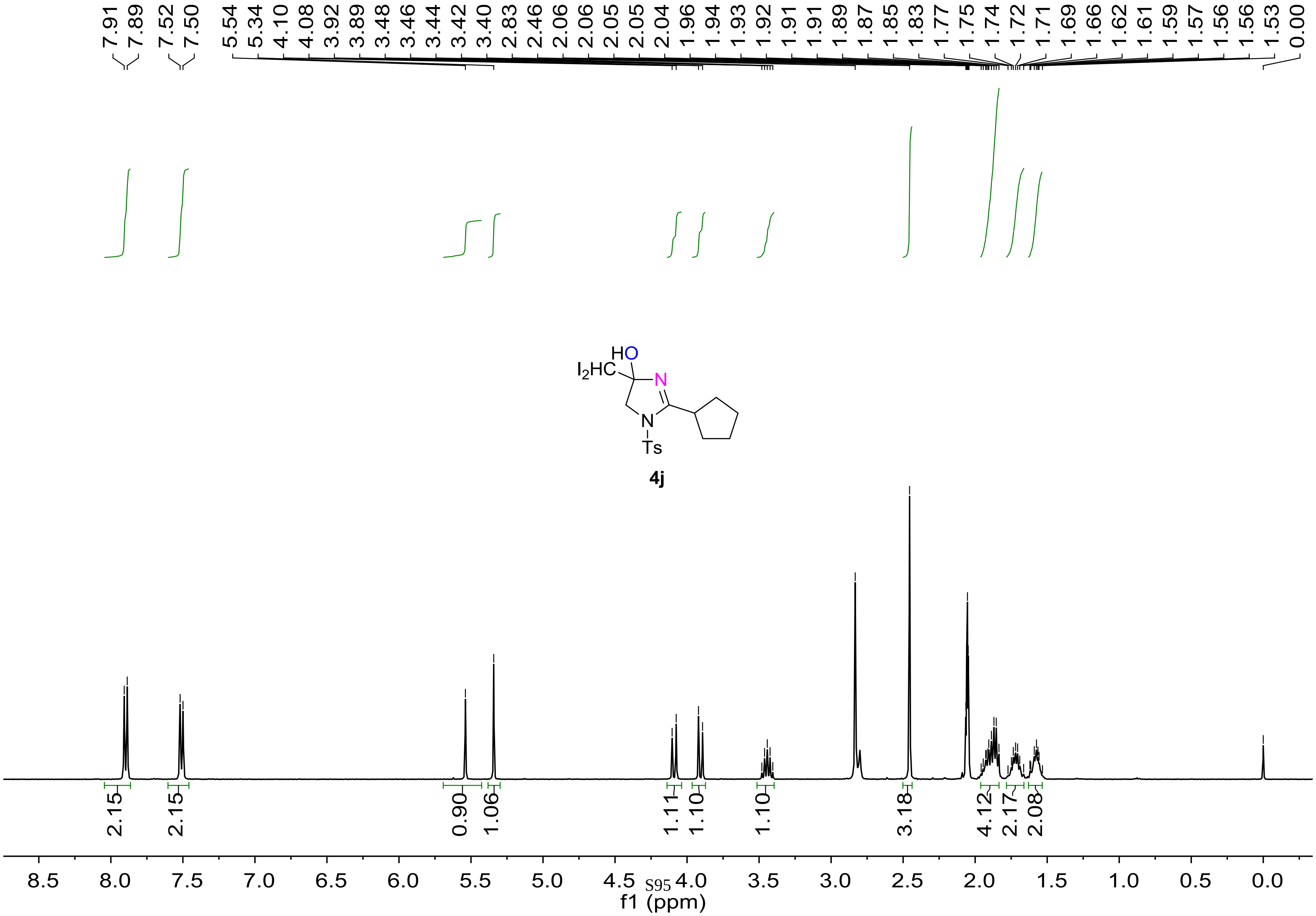
-10
f1 (ppm)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2.46
2.06
2.06
2.05
2.05
2.04
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1.94
1.93
1.92
1.91
1.91
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1.53
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HO
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N
N
Ts
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1.10
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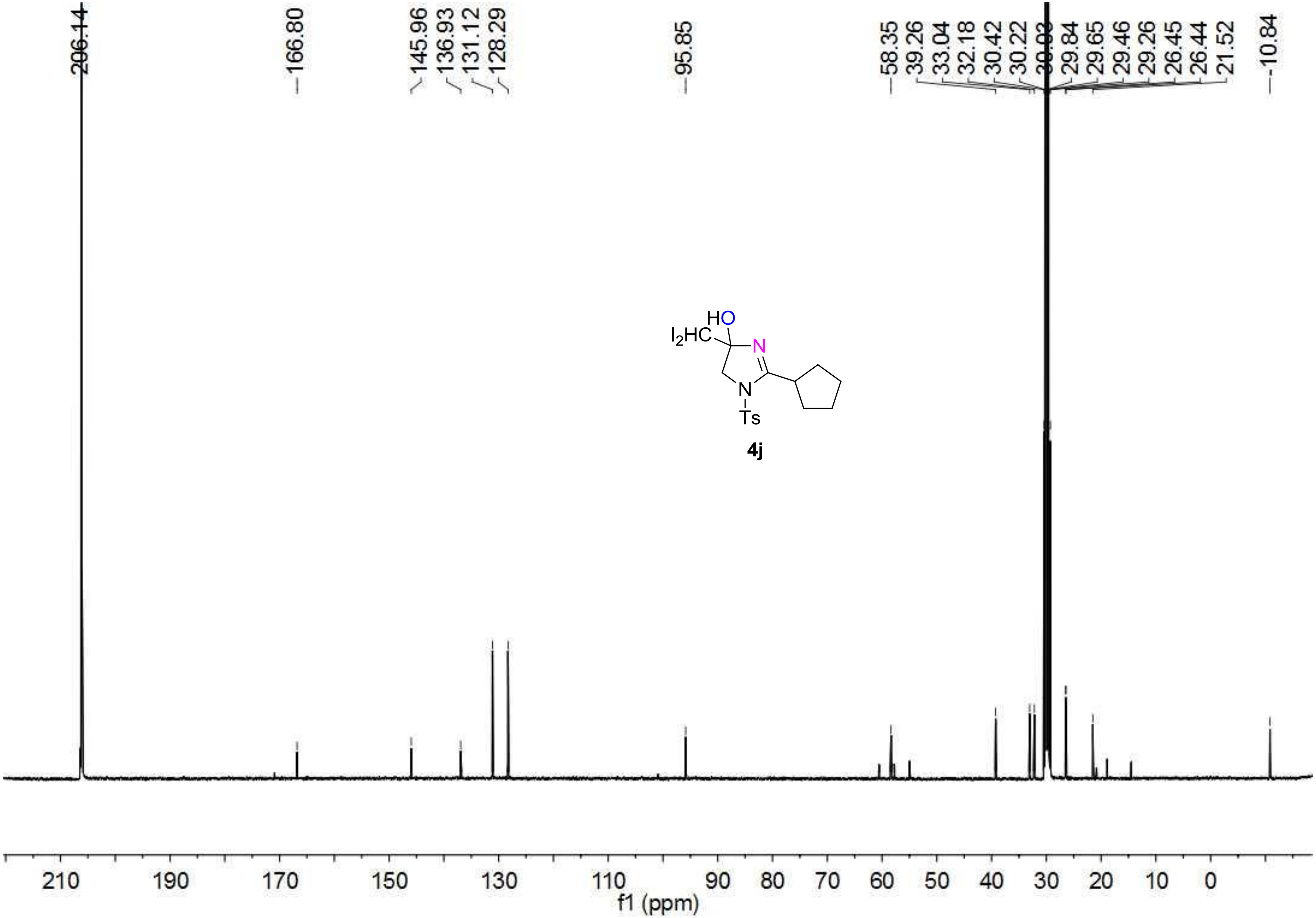
f1 (ppm)

4j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29.26
26.45
26.44
21.52
-10.84
HO
I2HC
N
N
Ts
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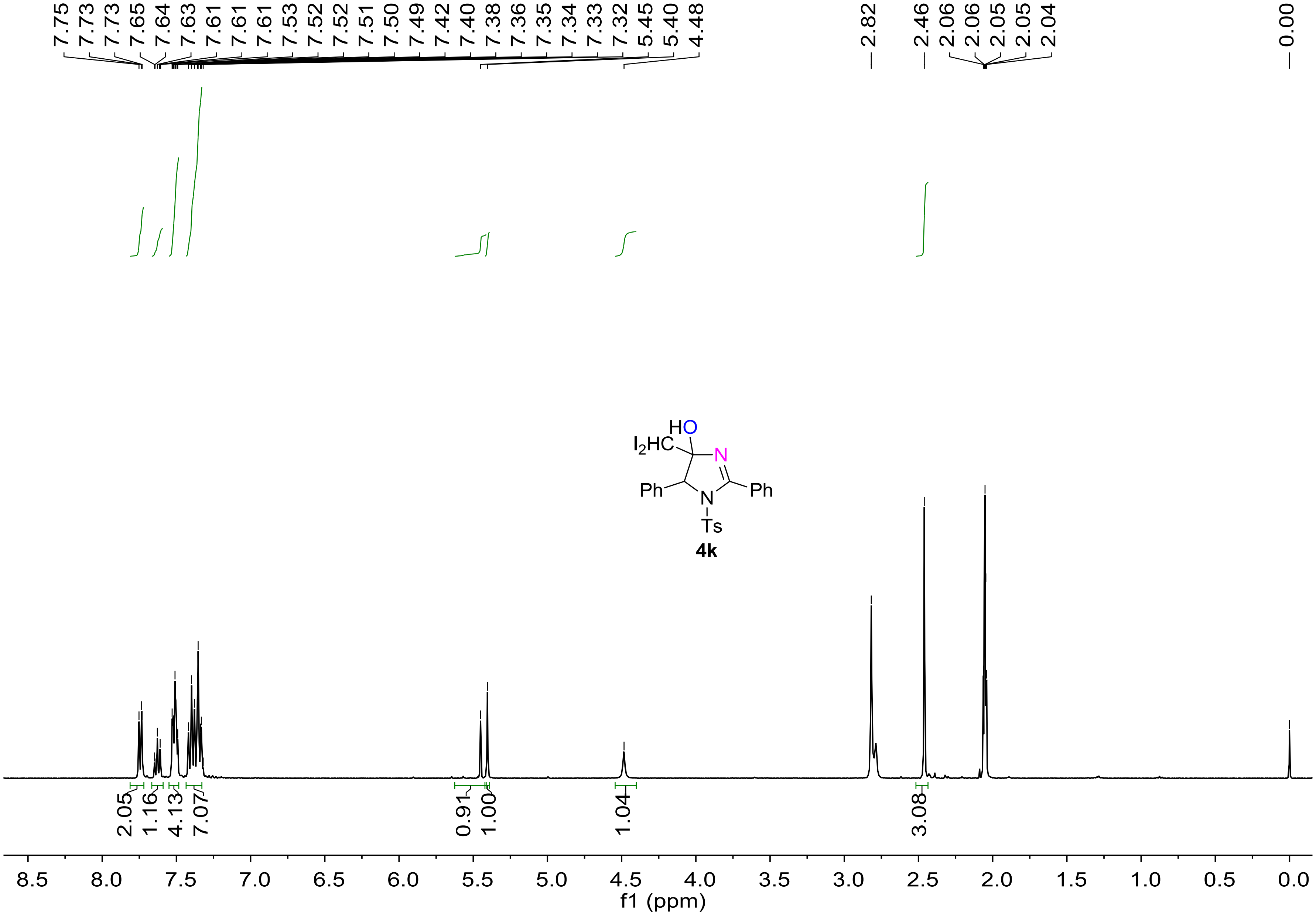
f1 (ppm)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7.33
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2.06
2.05
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2.04
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I2HC
HO
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Ph
N
Ph
Ts
4k
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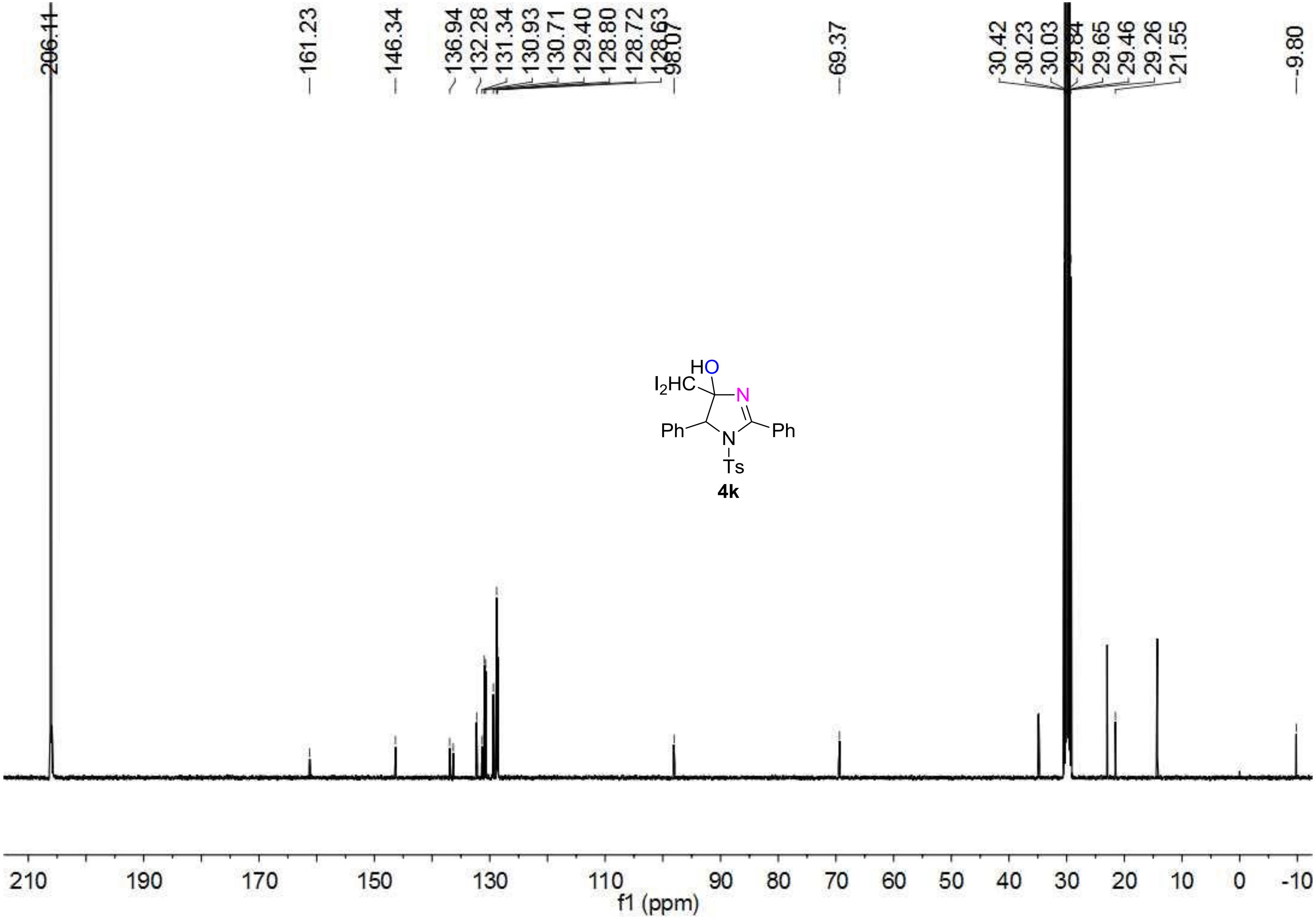
f1 (ppm)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29.26
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I_2HC
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Ph
N
Ph
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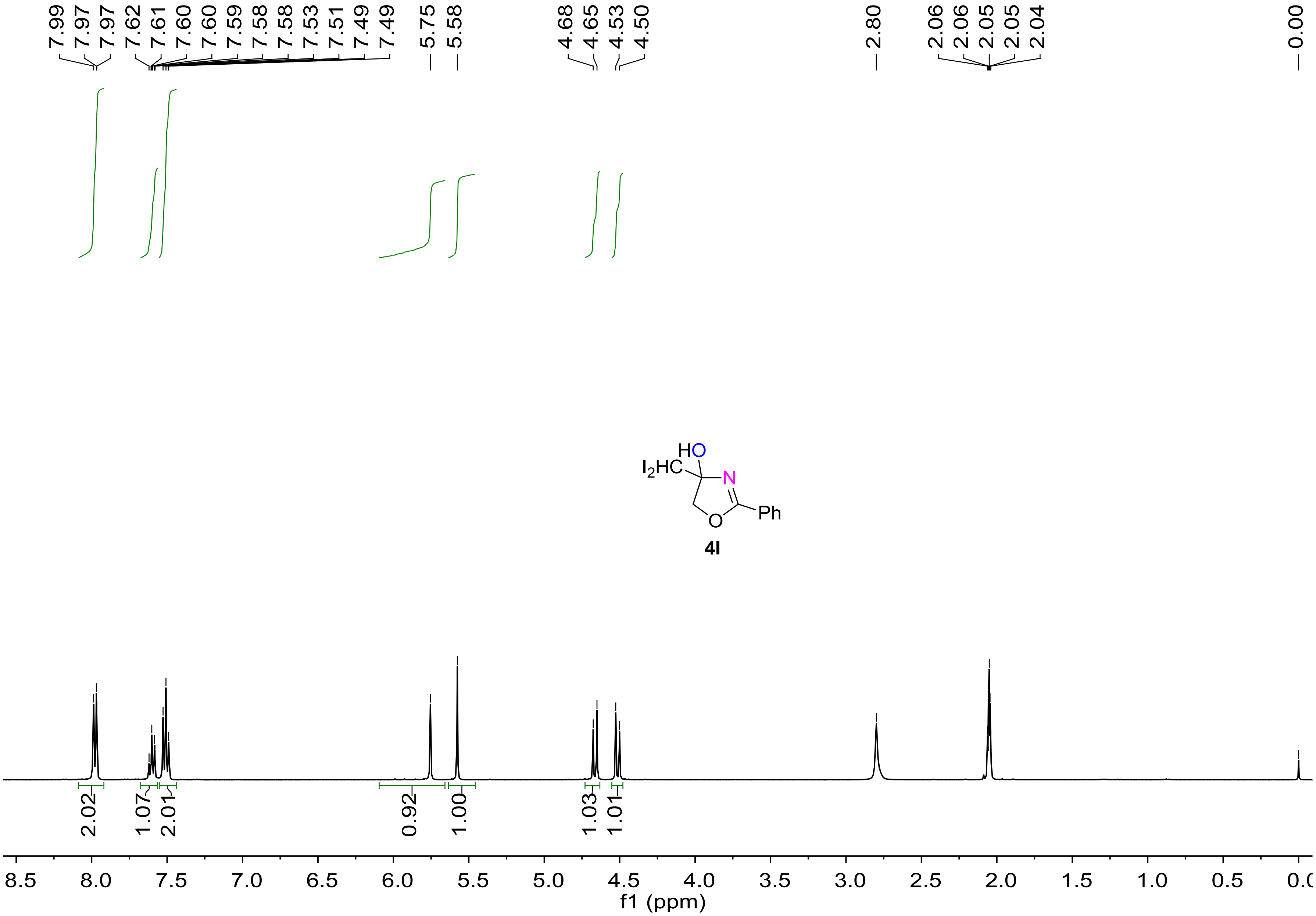
40
30
20
10
0
-10
f1 (ppm)

4k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7.97
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7.61
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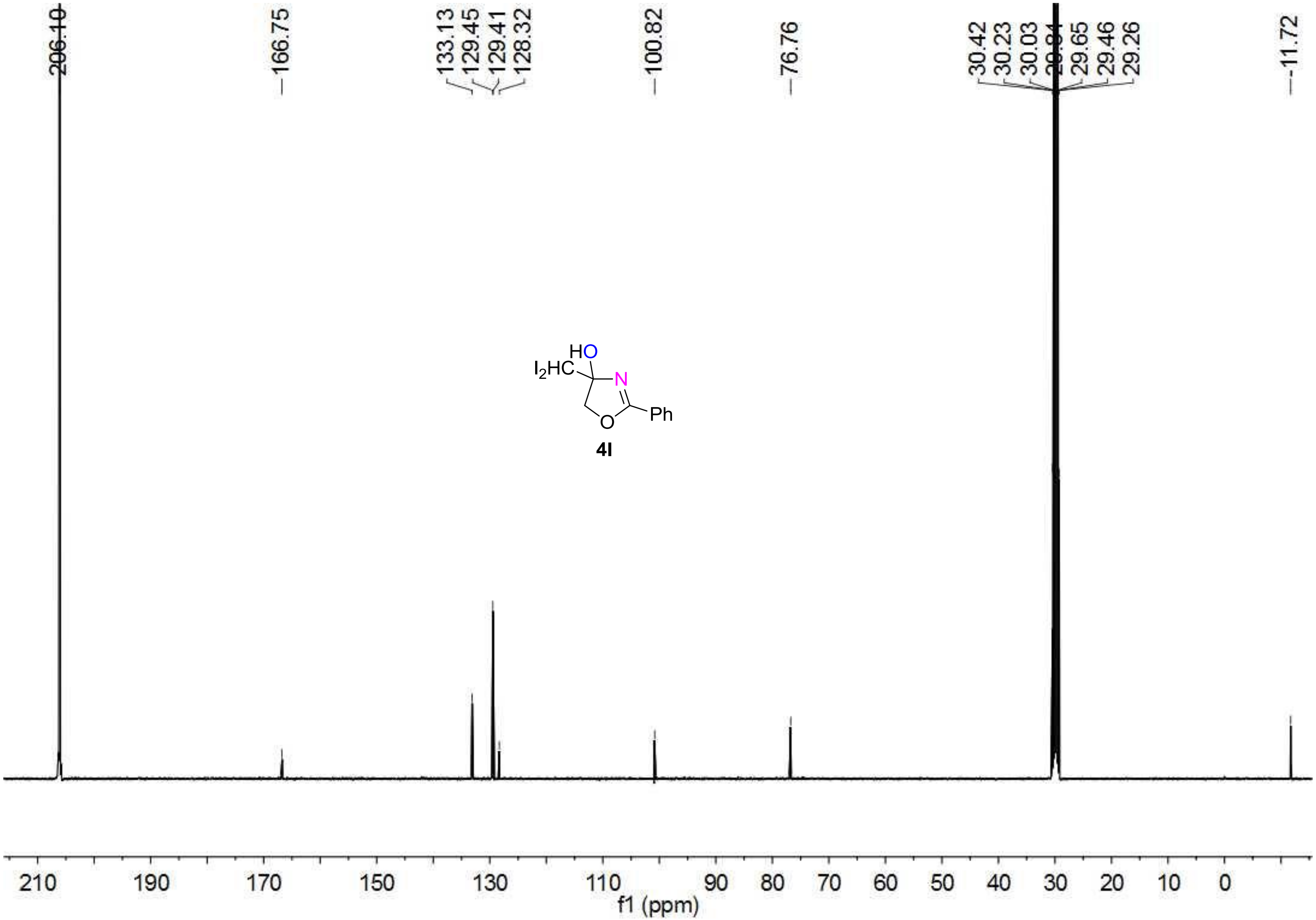
7.60
7.59
7.58
7.58
7.53
7.51
7.49
7.49
5.75
5.58
4.68
4.65
4.53
4.50
2.80
2.06
2.06
2.05
2.05
2.04
0.00
HO
I_2HC
N
O
Ph
4l
2.02
1.07
2.01
0.92
1.00
1.03
1.01
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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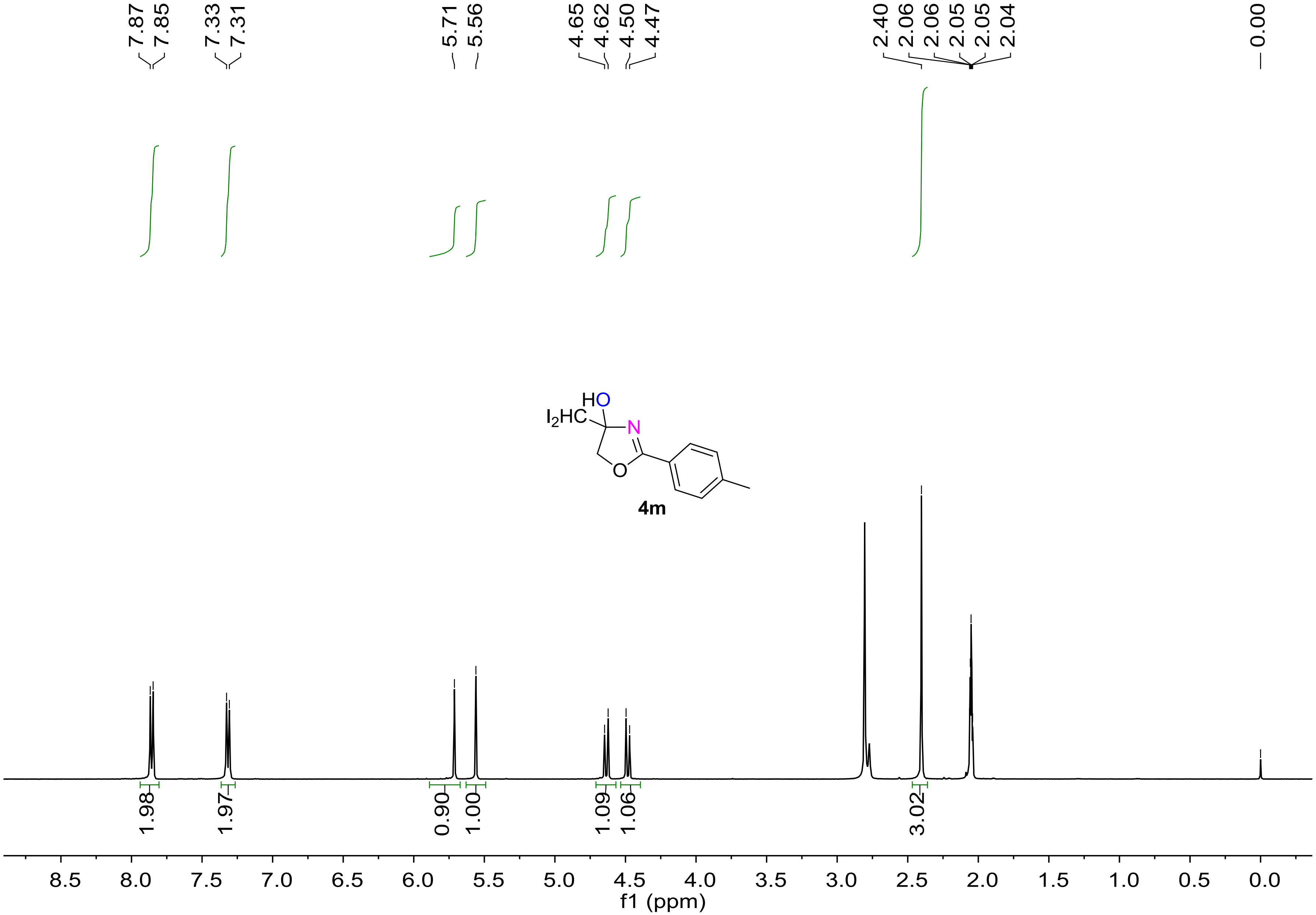
166.75
133.13
129.45
129.41
128.32
100.82
76.76
30.42
30.23
30.03
29.84
29.65
29.46
29.26
-11.72
I$_2$HC
HO
N
O
Ph
4l
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)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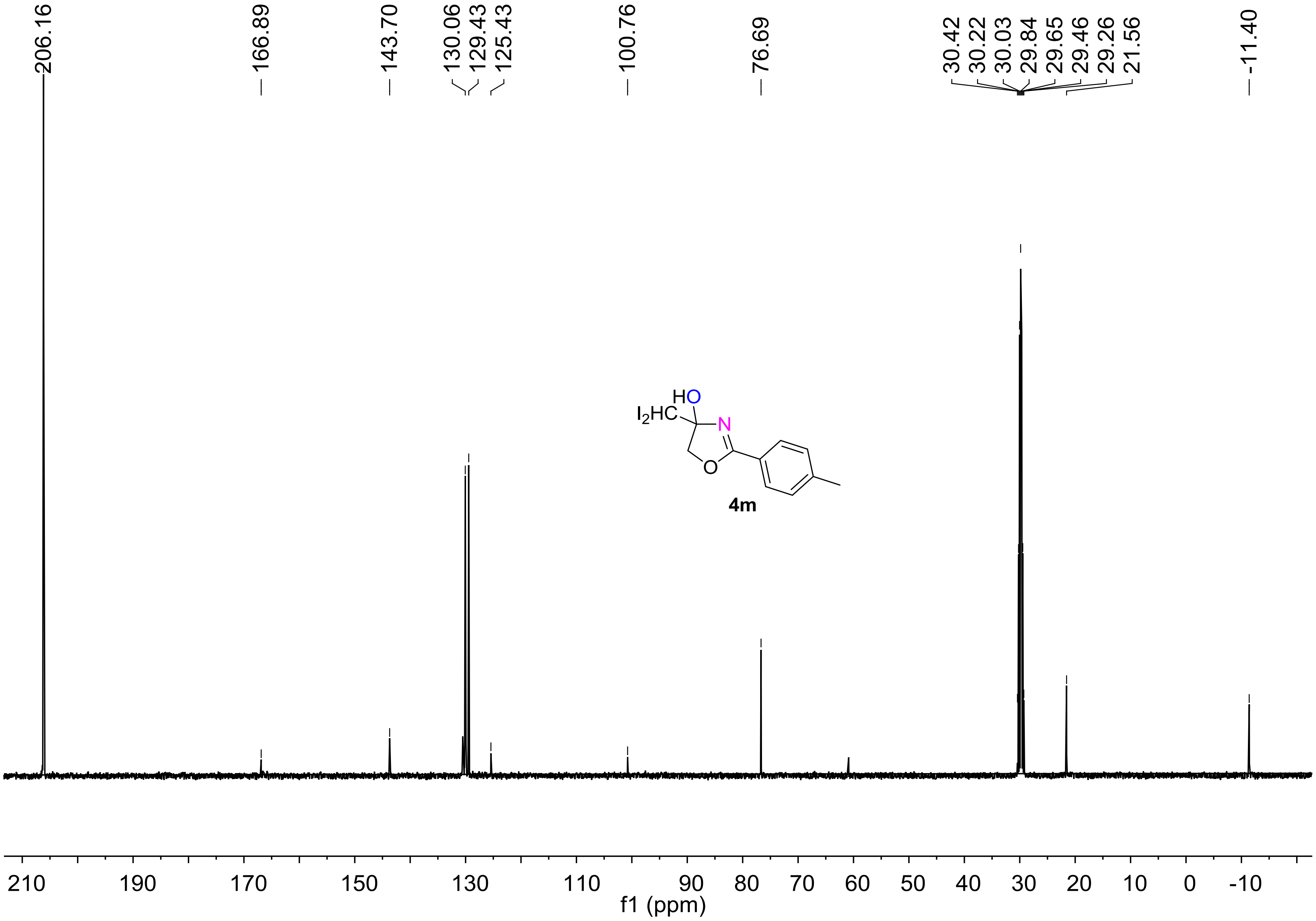
7.85
7.33
7.31
5.71
5.56
4.65
4.62
4.50
4.47
2.40
2.06
2.06
2.05
2.05
2.04
0.00
HO
I2HC
N
O
1.98
1.97
0.90
1.00
1.09
1.06
3.02
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

4m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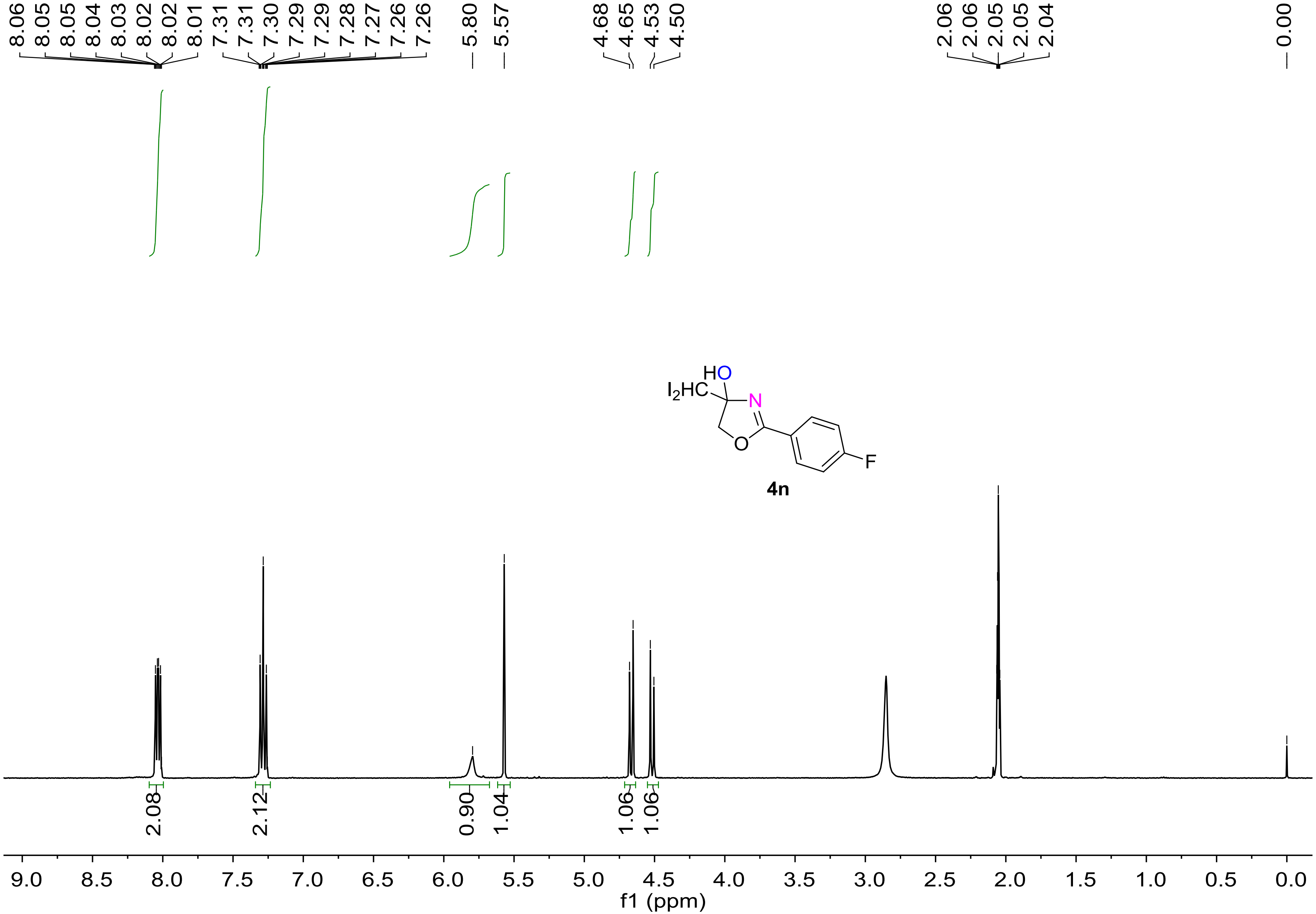
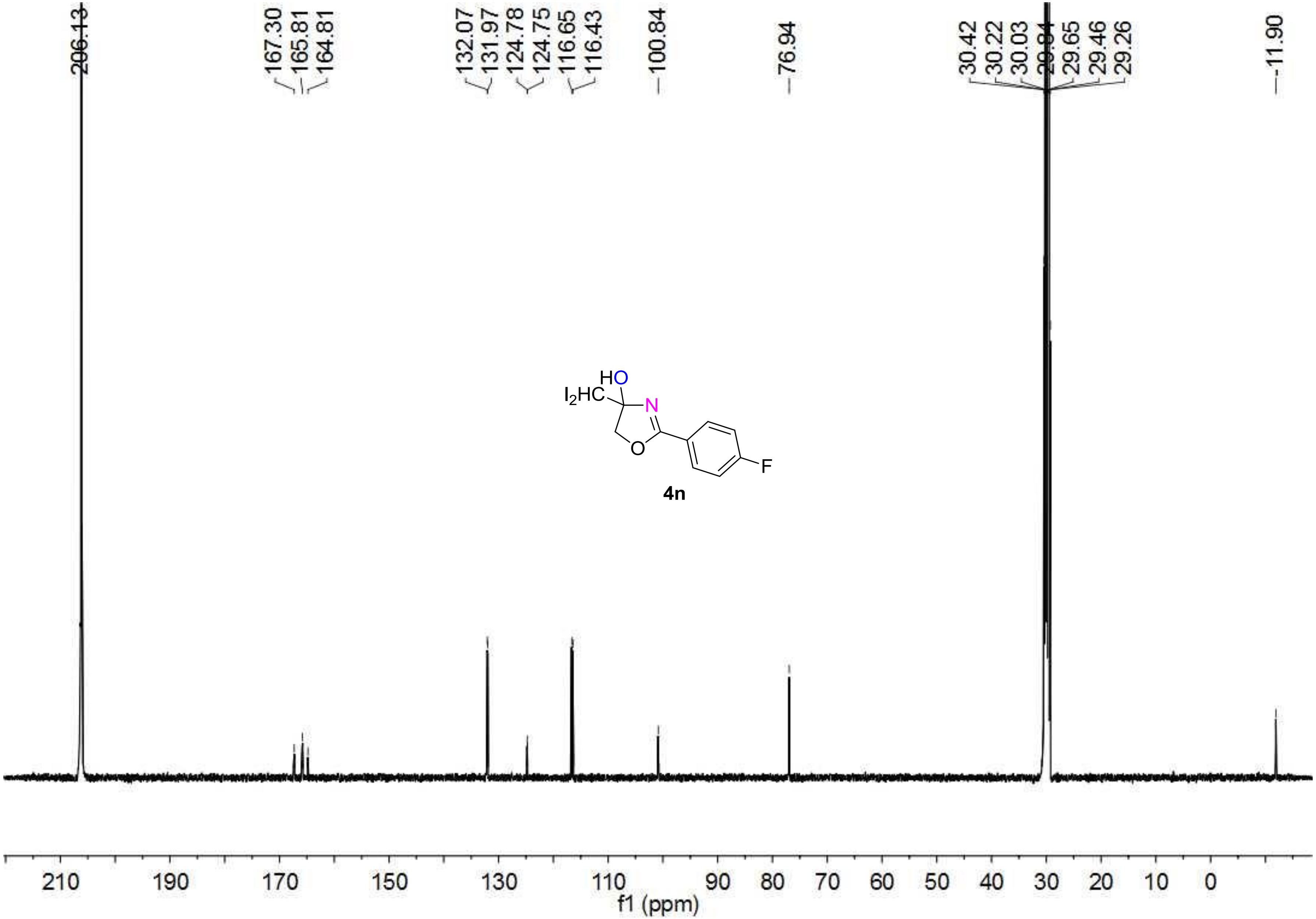
166.89
143.70
130.06
129.43
125.43
100.76
76.69
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.56
-11.40
I2HC
HO
N
O
4m
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)


4n
8.06
8.05
8.05
8.04
8.03
8.02
8.02
8.01
7.31
7.31
7.30
7.29
7.29
7.28
7.27
7.26
7.26
5.80
5.57
4.68
4.65
4.53
4.50
2.06
2.06
2.05
2.05
2.04
0.00
I2HC
HO
N
O
F
2.08
2.12
0.90
1.04
1.06
1.06
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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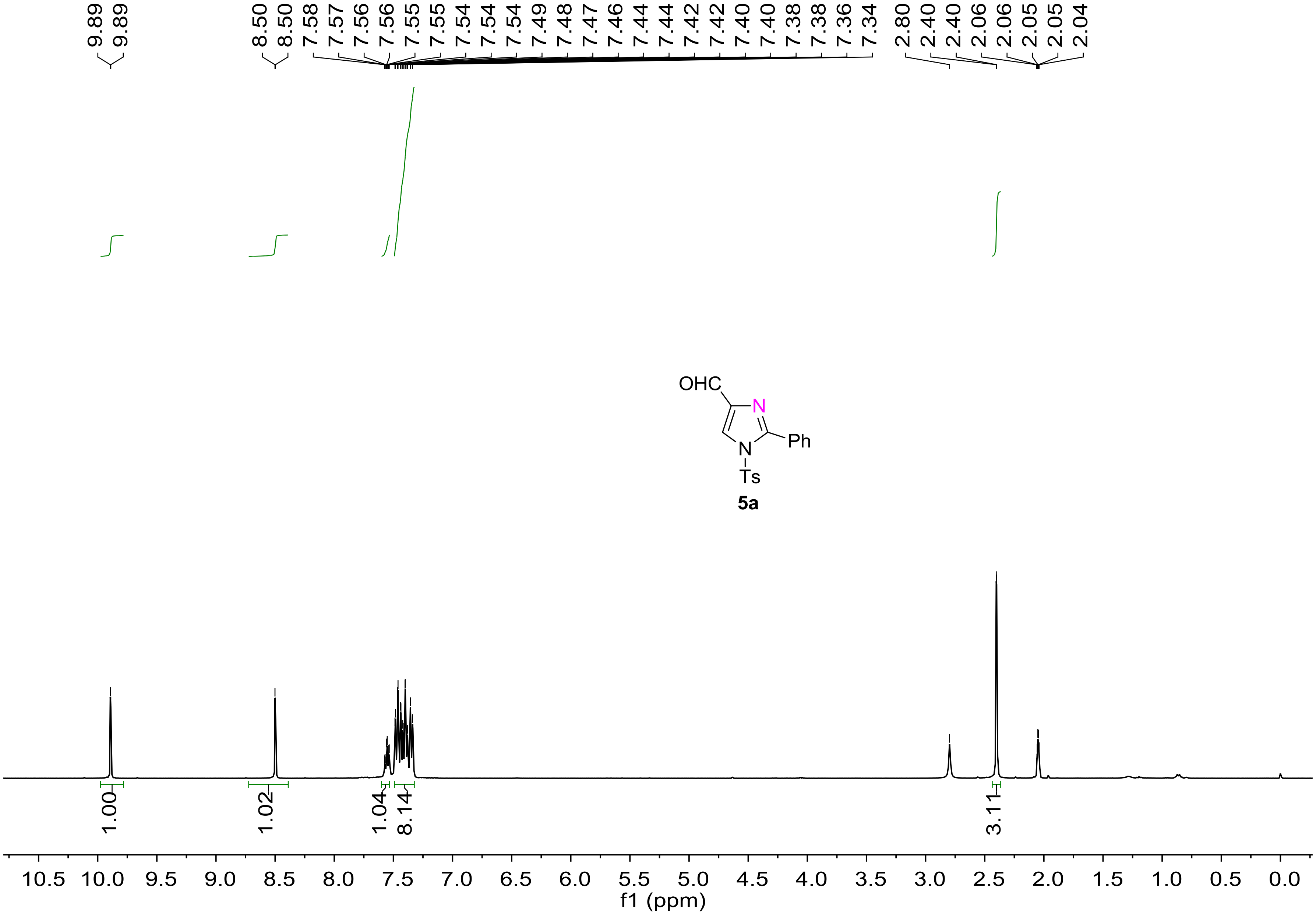
165.81
164.81
132.07
131.97
124.78
124.75
116.65
116.43
100.84
76.94
30.42
30.22
30.03
29.84
29.65
29.46
29.26
11.90
HO
I_2HC
N
O
F
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

4n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9.89
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8.50
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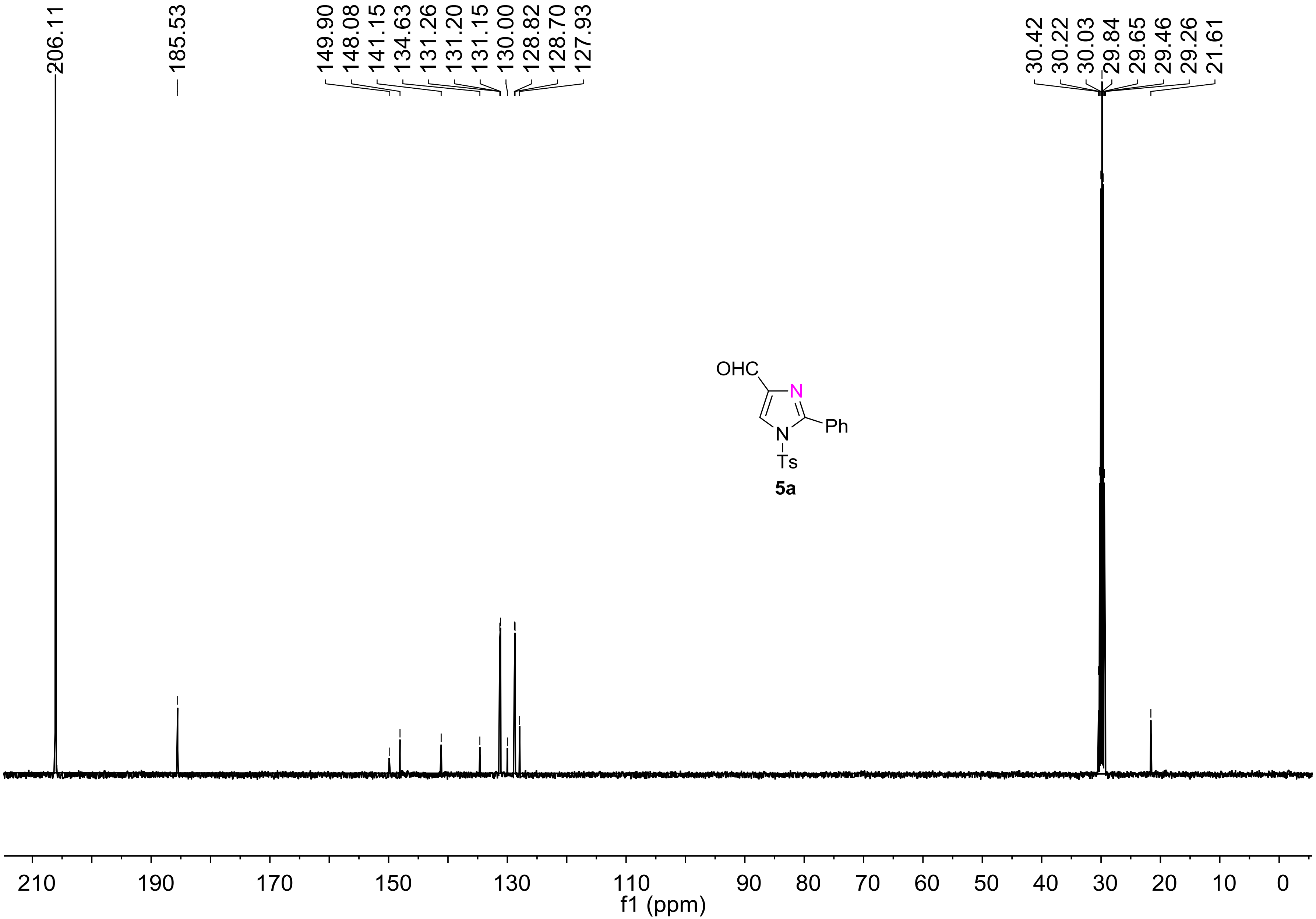
7.57
7.56
7.56
7.55
7.55
7.54
7.54
7.54
7.49
7.48
7.47
7.46
7.44
7.44
7.42
7.42
7.40
7.40
7.38
7.38
7.36
7.34
2.80
2.40
2.40
2.06
2.06
2.05
2.05
2.04
OHC
N
Ph
N
Ts
5a
1.00
1.02
1.04
8.14
3.11
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)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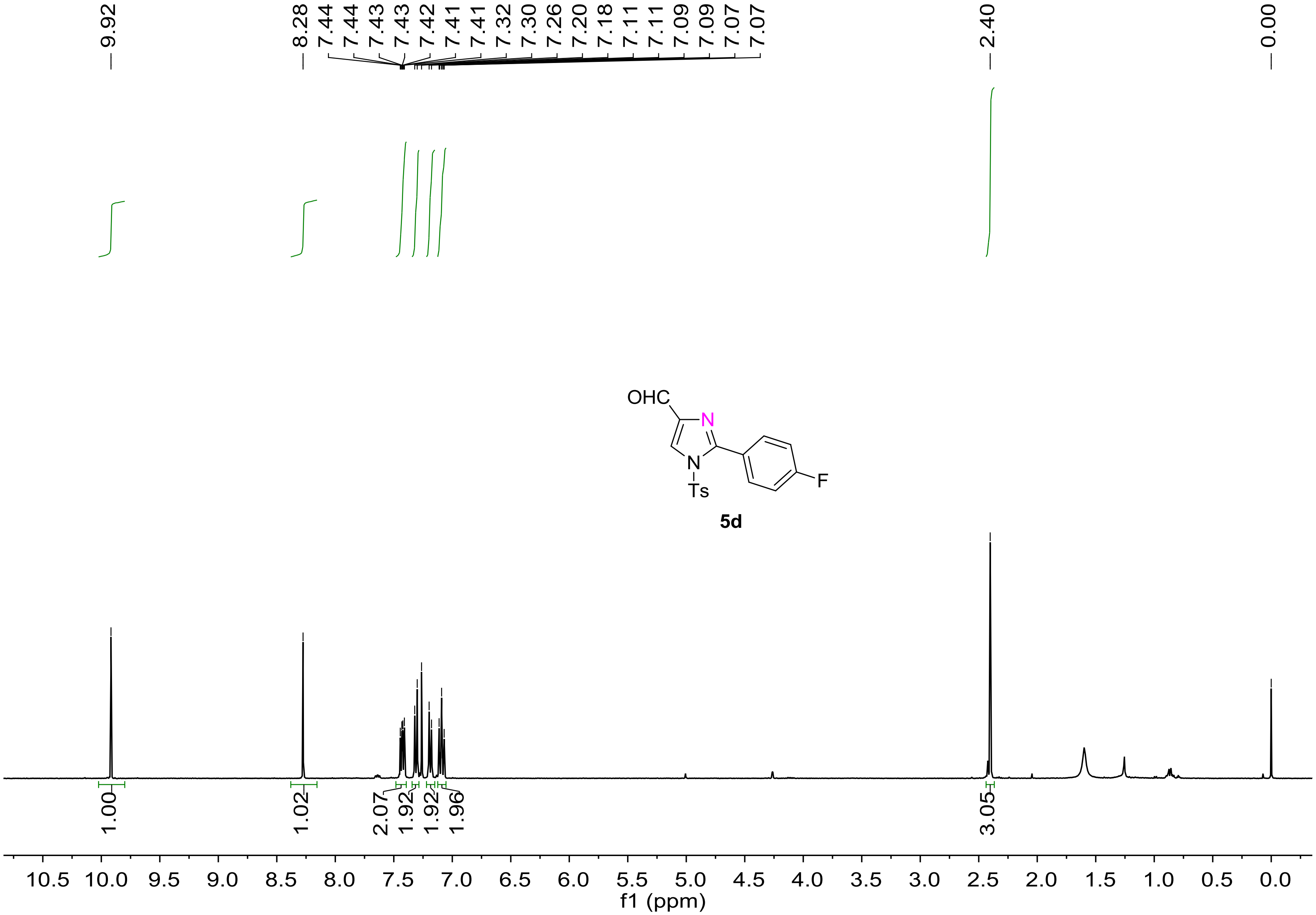
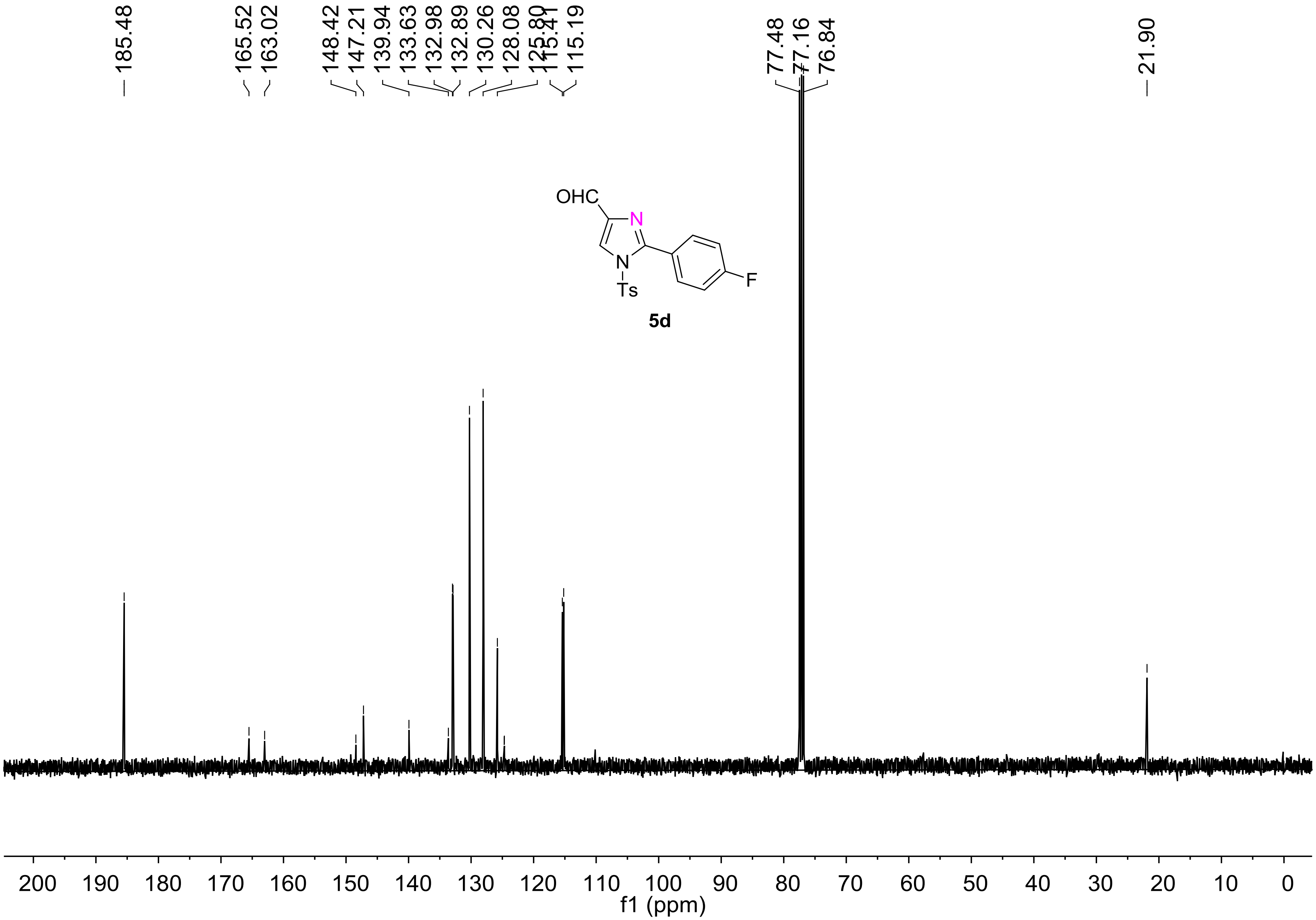
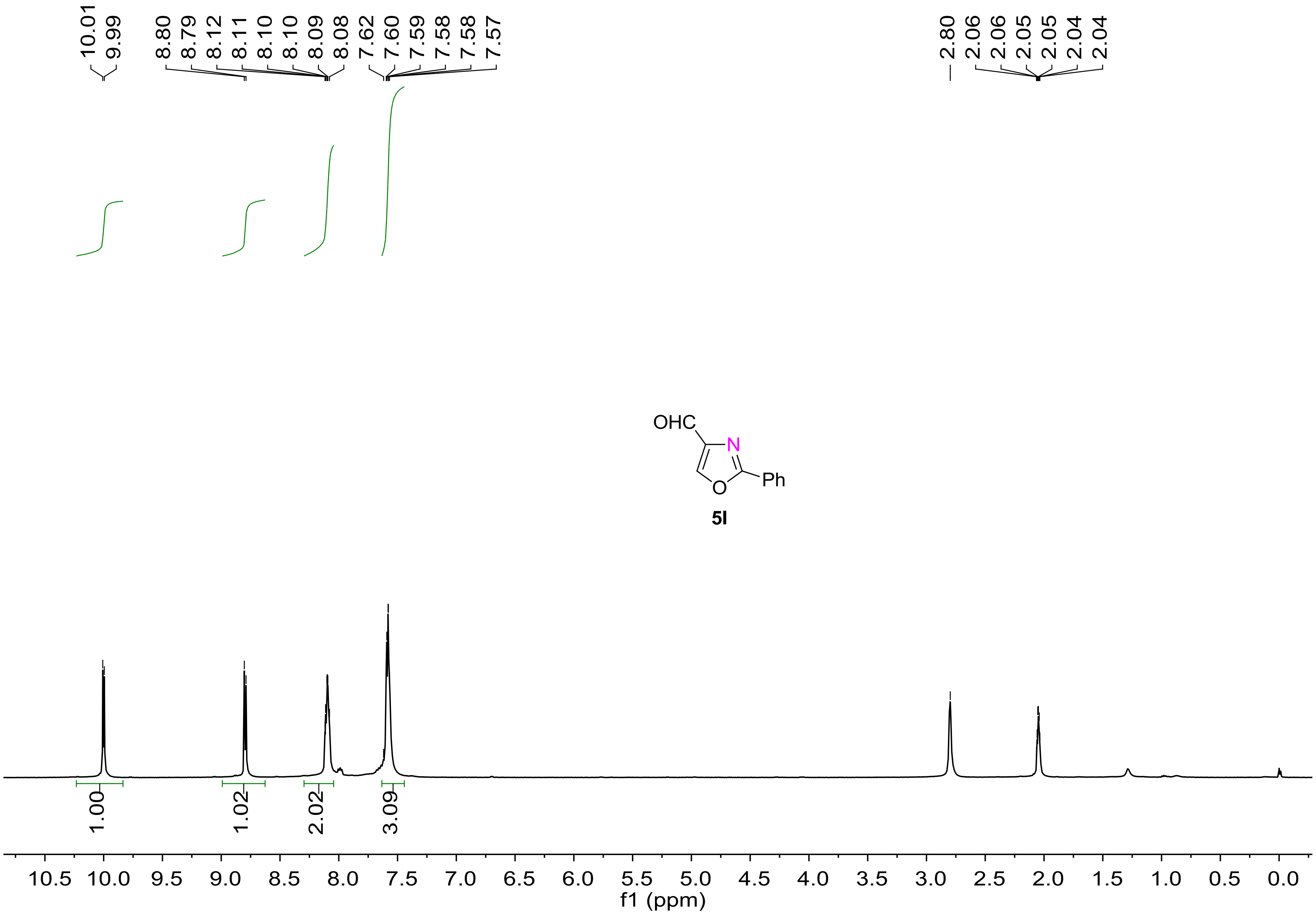
185.53
149.90
148.08
141.15
134.63
131.26
131.20
131.15
130.00
128.82
128.70
127.93
30.42
30.22
30.03
29.84
29.65
29.46
29.26
21.61
OHC
N
N
Ph
Ts
5a
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

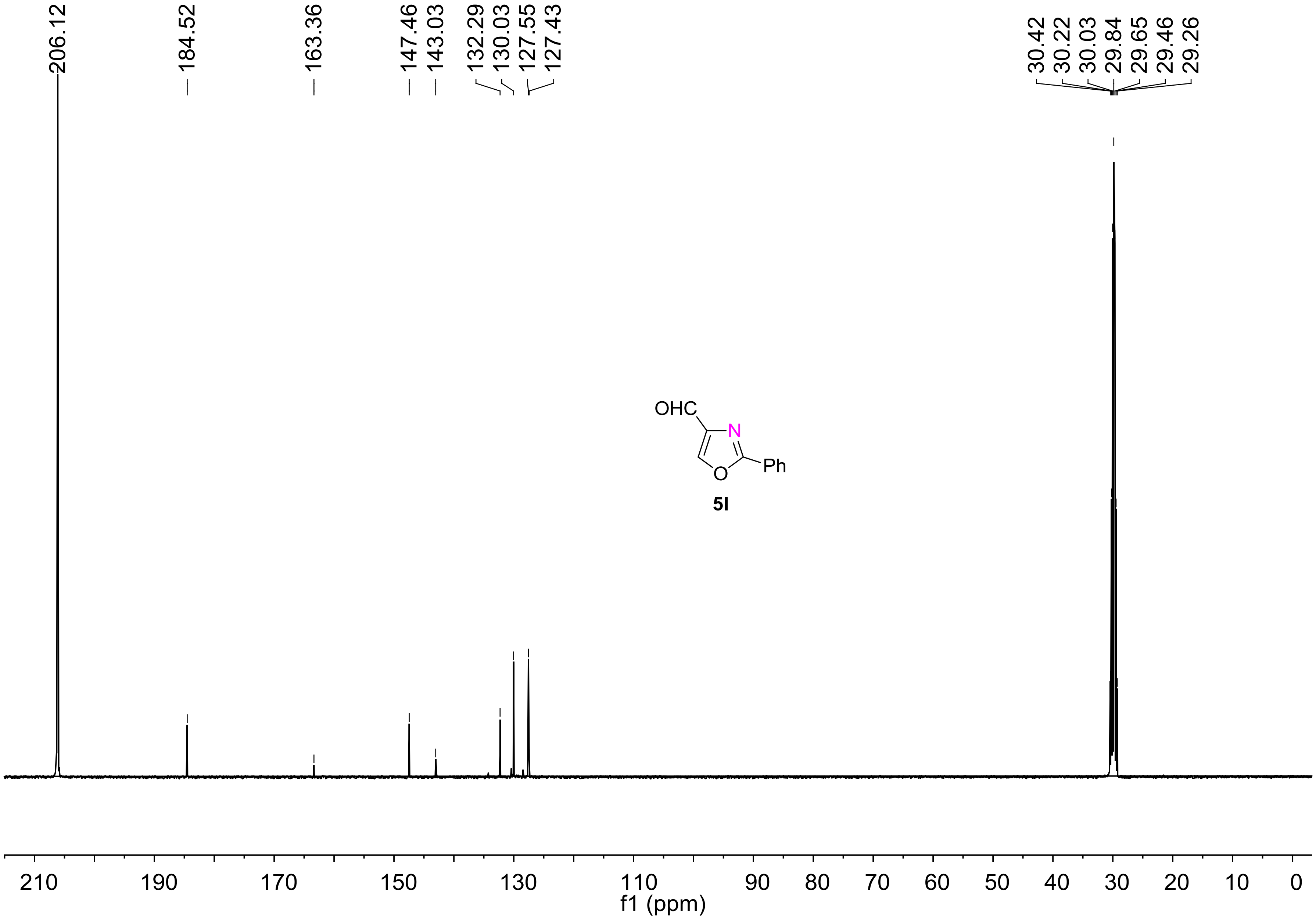

9.92
8.28
7.44
7.44
7.43
7.43
7.42
7.41
7.41
7.32
7.30
7.26
7.20
7.18
7.11
7.11
7.09
7.09
7.07
7.07
2.40
0.00
OHC
N
N
Ts
F
5d
1.00
1.02
2.07
1.92
1.92
1.96
3.05
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)

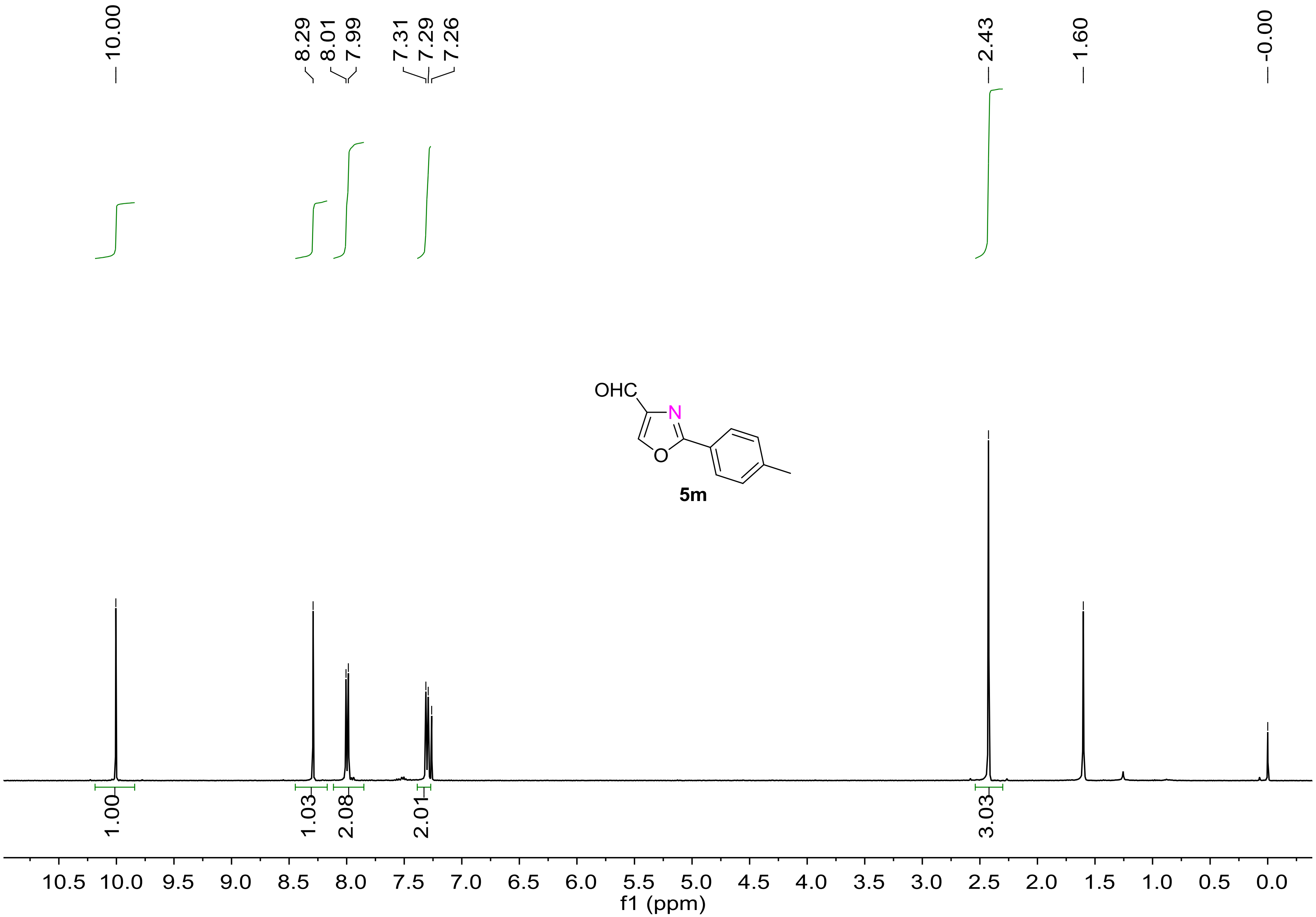


185.48
165.52
163.02
148.42
147.21
139.94
133.63
132.98
132.89
130.26
128.08
125.80
115.41
115.19
77.48
77.16
76.84
21.90
OHC
N
N
Ts
F
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

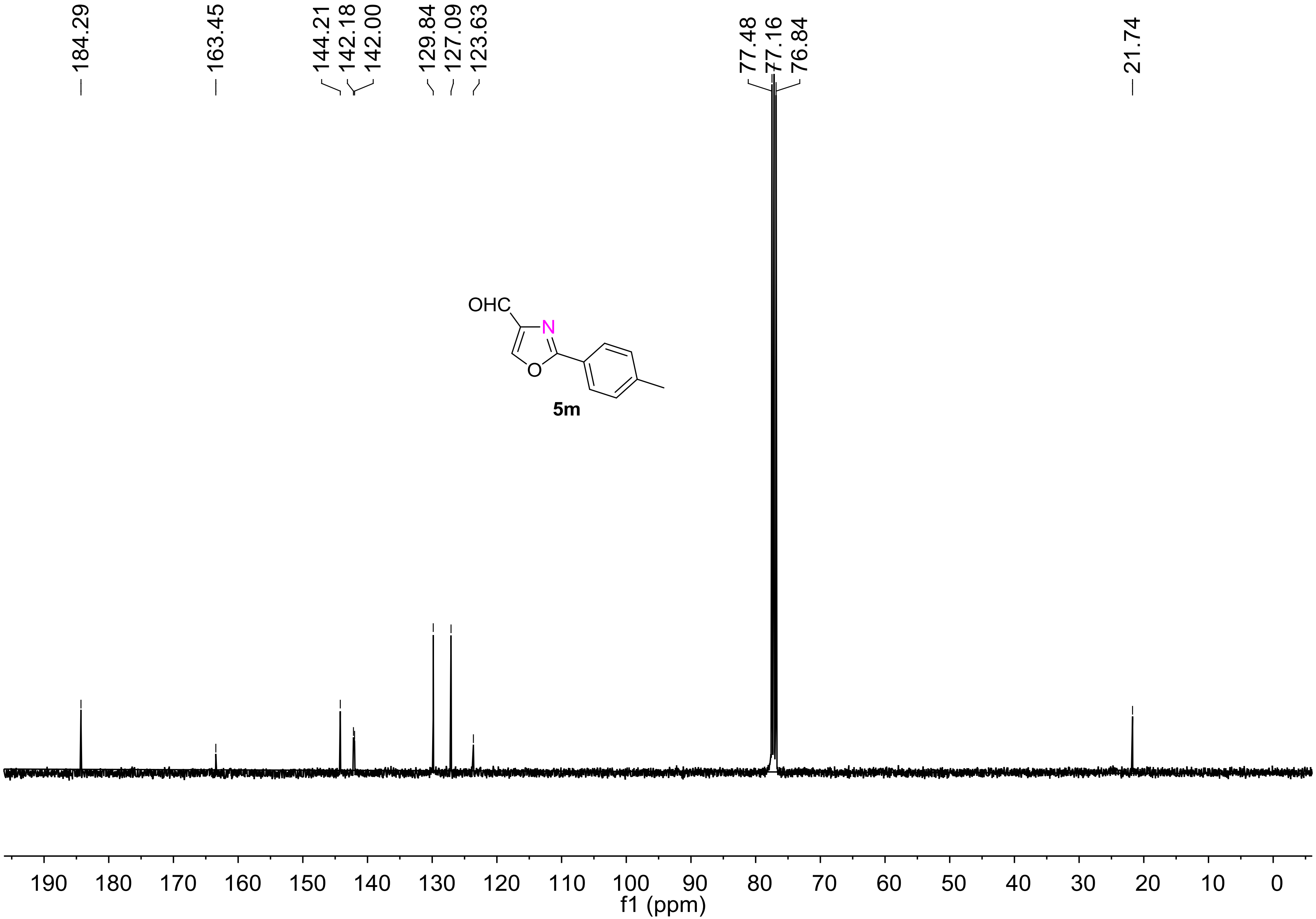
5d


10.01
9.99
8.80
8.79
8.12
8.11
8.10
8.10
8.09
8.08
7.62
7.60
7.59
7.58
7.58
7.57
2.80
2.06
2.06
2.05
2.05
2.04
2.04
OHC
N
O
Ph
5l
1.00
1.02
2.02
3.09
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f1 (ppm)


206.12
184.52
163.36
147.46
143.03
132.29
130.03
127.55
127.43
30.42
30.22
30.03
29.84
29.65
29.46
29.26
OHC
N
O
Ph
5l
210
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)


10.00
8.29
8.01
7.99
7.31
7.29
7.26
2.43
1.60
-0.00
OHC
N
O
1.00
1.03
2.08
2.01
3.03
10.5 10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)

5m


184.29
163.45
144.21
142.18
142.00
129.84
127.09
123.63
77.48
77.16
76.84
21.74
OHC
N
O
5m
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)