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

Cover Page for Supporting Information

Title:

Selective Synthesis of (*Z*)-2-Enynyl-2-Hydroxy-Imidazolidine-4,5-diones via Cu(I)-Mediated Multicomponent Coupling of Terminal Alkynes, Carbodiimides and Oxalyl Chloride

Authors:

Fei Zhao,[†] Yuexing Li,[†] Yang Wang,[†] Wen-Xiong Zhang,*[†, ‡] Zhenfeng Xi[†]

Affiliations:

[†] Beijing National Laboratory for Molecular Sciences, and Key Laboratory of Bioorganic Chemistry and Molecular Engineering of Ministry of Education, College of Chemistry, Peking University, Beijing 100871, China;

[‡] State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin, 300071, China.

E-mail: wx_zhang@pku.edu.cn

Contents:

1) Experimental Details and Characterization Data

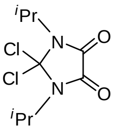
General Method

All the reactions were carried out under nitrogen atmosphere using standard Schlenk technique. All the starting materials were purchased from Acros, Aldrich, TCI and Alfa Aesar without further purification. Solvents were purified by an Mbraun SPS-800 Solvent Purification System and stored under nitrogen. Column chromatography was performed on silica gel 200-300 mesh.

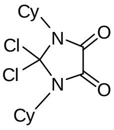
^{1}H NMR and ^{13}C NMR were recorded on a JEOL 300 MHz spectrometer (FT, 300 MHz for ^{1}H; 75 MHz for ^{13}C), or a Bruker AVANCE III 400 spectrometer (FT, 400 MHz for ^{1}H; 100 MHz for ^{13}C) at room temperature with $CDCl_3$, CD_2Cl_2, C_6D_6 or DMSO-d_6 as the solvent and tetramethylsilane (TMS) as the internal standard. Chemical shifts were reported in units (ppm) by assigning TMS resonance in the ^{1}H spectrum as 0.00 ppm and $CDCl_3$ resonance in the ^{13}C spectrum as 77.0 ppm, or CD_2Cl_2 resonance in the ^{13}C spectrum as 53.8 ppm, or C_6D_6 resonance in the ^{13}C spectrum as 128.0 ppm, or DMSO-d_6 resonance in the ^{13}C spectrum as 39.5 ppm. All coupling constants (J values) were reported in Hertz (Hz). Infrared spectra (IR) were recorded on a Thermo Nicolet Avatar 330 FT-IR spectrometer. High-resolution mass spectra (HRMS) were recorded on a Bruker Apex IV FTMS mass spectrometer using ESI (electrospray ionization).

Typical Procedures for Preparation of 2,2-Dichloro-imidazolidindione 1.[1]

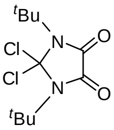
To a 40 mL Et_2O solution of *N,N′*-diisopropylcarbodiimide (1.6 mL, 1.26 g, 10 mmol) was slowly charged with oxalyl chloride (0.94 mL, 1.40 g, 11 mmol) at 0 °C. The reaction was highly exothermic and required keeping cool at 0 °C for several minutes. Then the reaction was allowed to stir at room temperature. After 2 days, the reaction was put into the glovebox. Solvent and excess oxalyl chloride were removed under vacuum. The residue was washed by hexane and dried under vacuum. 2,2-Dichloro-imidazolidindione **1a** was obtained quantitatively as white powder.



1a:[1] Colorless solid, isolated yield 99% (2.53 g); ^{1}H NMR (300 MHz, C_6D_6): δ 1.26 (d, J = 6.9 Hz, 12H, CH_3), 3.64-3.74 (m, 2H, CH); ^{13}C NMR (75 MHz, C_6D_6): δ 18.94 (4 CH_3), 49.25 (2 CH), 103.28 (1 quat. C), 154.29 (2 quat. C).



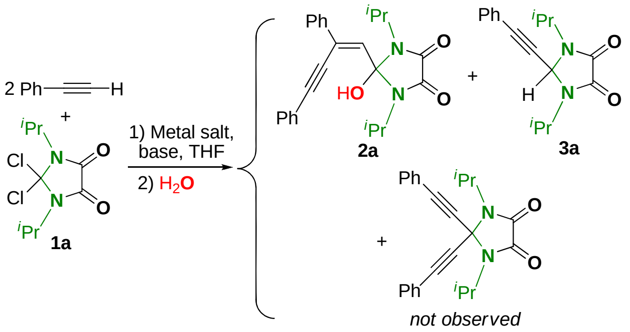
1b: Colorless solid, isolated yield 99% (3.33 g); ^{1}H NMR (400 MHz, C_6D_6, Me_4Si): δ 1.01-1.07 (m, 6H, CH_2), 1.38-1.39 (m, 2H, CH_2), 1.59-1.61 (m, 4H, CH_2), 1.75-1.78 (m, 4H, CH_2), 2.22-2.31 (m, 4H, CH_2), 3.53-3.61 (m, 2H, CH); ^{13}C NMR (100 MHz, C_6D_6, Me_4Si): δ 24.97 (2 CH_2), 25.99 (4 CH_2), 28.85 (4 CH_2), 57.07 (2 CH), 103.87 (1 quat. C), 154.24 (2 quat. C).



1c: Colorless solid, isolated yield 99% (2.81 g); ^{1}H NMR (400 MHz, C_6D_6, Me_4Si): δ 1.55 (s, 18H, CH_3); ^{13}C NMR (100 MHz, C_6D_6, Me_4Si): δ 28.04 (6 CH_3), 61.94 (2 quat. C), 102.37 (1 quat. C), 154.91 (2 quat. C).

Condition Screening for the Formation of 2a by Multicomponent Coupling of Two Phenylethyne and 2-Dichloroimidazoline-4,5-dione Intermediate 1a.

STalbe 1 Condition Screening.$^{a\text{-}c}$



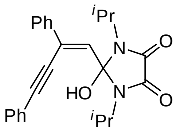
entry	metal salt (equiv)	base (equiv)	temp. (°C)	t (h)	yield **2a**^{a,b}	yield **3a**^{a,b}
1	CuI (1.0)	Et_3N (2.0)	80	6.0	52%	19%
2	CuCl (1.0)	Et_3N (2.0)	25–80	6.0	0%	0%
3	CuBr (1.0)	Et_3N (2.0)	25–80	6.0	0%	0%
4	$PdCl_2$ (0.05)	Et_3N (2.0)	25–80	6.0	0%	0%
5	CuI (0.05)	Et_3N (2.0)	25	6.0	<5%	0%
6	CuI (0.05)	Et_3N (2.0)	80	6.0	12%	<5%
7	NaI (0.05)/CuCl (1.0)	Et_3N (2.0)	80	6.0	70%^{c}	9%
8	**CuI (0.05)/CuCl (1.0)**	**Et_3N (2.0)**	**80**	**6.0**	**70%^{c}**	**9%**
9	CuI (0.05)/CuCl (1.0)	Et_3N (2.0)	50	6.0	53%	8%
10	CuI (0.05)/CuCl (1.0)	Et_3N (2.0)	25	6.0	<5%	0%
11	CuI (0.05)/CuCl (1.0)	DABCO (2.0)	80	6.0	0%	0%
12	CuI (0.05)/CuCl (1.0)	imidazole (2.0)	80	6.0	0%	0%
13	CuI (0.05)/CuCl (1.0)	$^i Pr_2NEt$ (2.0)	80	6.0	61%	8%

[a] Conditions: 0.5 mmol of **1a**, 1.2 mmol of phenylethyne. [b] NMR yield.
[c] Isolated yields.

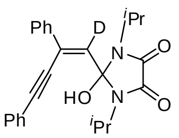
The reaction of **1a** with phenylethyne was established as a model reaction to screen the reaction conditions for the formation of **2a**. The metal salts, such as CuCl, CuBr and $PdCl_2$ instead of CuI gave no product from 25 to 80 °C (STable 1, entries 2–4). In contrast, a combination of NaI and CuCl brought about **2a** in good yield (STable 1, entry 7). This made us realize that iodide anion may play an important role in the reaction. After a series of reaction conditions, such as the amount of CuI, bases, and reaction temperatures, were screened (STable 1, entries 7–13), the optimized reaction condition was established (STable 1, entry 8).

Typical Procedures for Cu(I)-Mediated Synthesis of (*Z*)-2-En-4-yn-1-ols.

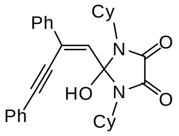
To a sealed tube was charged with **1a** (126 mg, 0.5 mmol), phenylacetalene (122 mg, 1.2 mmol), CuI (4.8 mg, 0.025 mmol), CuCl (50.0 mg, 0.5 mmol) and 5.0 mL of THF in the glovebox. The tube was moved outside the glovebox and charged with Et_3N (101 mg, 1.0 mmol). The reaction mixture was then stirred at 80 °C for 6 h. After the reaction was finished, the mixture was cooled to room temperature and quenched by brine and extracted with ethyl acetate. The organic solution was dried over Na_2SO_4. After filtration, the solution was concentrated under vacuum and the product was purified by flash column chromatography on silica gel. The product **2a** was obtained as colorless oil, and slowly turned to colorless solid at low temperature.



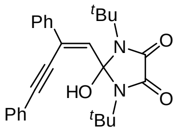
2a: Colorless solid, isolated yield 70% (141 mg); m.p. 172-173 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.35 (d, J = 6.8 Hz, 12H, CH_3), 3.66-3.75 (m, 2H, CH), 6.50 (s, 1H, OH), 6.62 (s, 1H, CH), 7.33-7.45 (m, 6H, CH), 7.59-7.61 (m, 2H, CH), 7.70-7.72 (m, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.94 (2 CH_3), 20.50 (2 CH_3), 46.48 (2 CH), 83.86 (1 quat. C), 94.96 (1 quat. C), 104.30 (1 quat. C), 121.69 (1 quat. C), 126.42 (2 CH), 128.31 (2 CH), 128.71 (2 CH), 129.09 (1 CH), 129.12 (1 CH), 129.28 (1 quat. C), 131.23 (1 CH), 132.32 (2 CH), 137.21 (1 quat. C), 158.25 (2 quat. C); IR (neat): ν 1734 (C=O) cm^{-1}; HRMS calcd for $C_{25}H_{27}N_2O_3$ $[M+H]^+$: 403.2016; found 403.2012. **2a-^{18}O**: HRMS calcd for $C_{25}H_{25}N_2O_2{}^{18}O$ $[M-H]^-$: 403.1902; found 403.1902. It was noted that ESI positive on **2a-^{18}O** would cause the lose of a $H_2{}^{18}O$ molecule. Therefore, ESI negative was applied for **2a-^{18}O**.



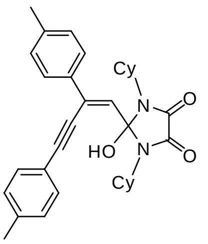
2a-D: Colorless solid, isolated yield 68% (137 mg); ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.38 (d, J = 6.8 Hz, 12H, CH_3), 3.68-3.78 (m, 2H, CH), 6.58 (s, 1H, OH), 7.33-7.44 (m, 6H, CH), 7.58-7.61 (m, 2H, CH), 7.70-7.72 (m, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.95 (2 CH_3), 20.50 (2 CH_3), 46.50 (2 CH), 83.86 (1 quat. C), 94.95 (1 quat. C), 104.29 (1 quat. C), 121.71 (1 quat. C), 126.42 (2 CH), 128.31 (2 CH), 128.71 (2 CH), 129.11 (2 CH), 129.22 (1 quat. C), 131.25 (t, J = 20.4 Hz, 1 CH), 132.31 (2 CH), 137.18 (1 quat. C), 158.28 (2 quat. C); HRMS calcd for $C_{25}H_{26}DN_2O_3$ $[M+H]^+$: 404.2079; found 404.2084.



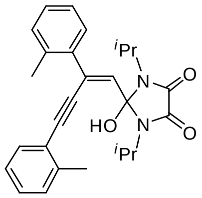
2b: Colorless solid, isolated yield 70% (169 mg); m.p. 191-192 °C; ^{1}H NMR (400 MHz, CD_2Cl_2, Me_4Si): δ 1.14-1.26 (m, 8H, CH_2), 1.77-1.82 (m, 8H, CH_2), 2.09-2.19 (m, 4H, CH_2), 3.35-3.43 (m, 2H, CH), 6.60 (s, 1H, CH), 7.38-7.46 (m, 6H, CH), 7.57-7.59 (m, 2H, CH), 7.71-7.73 (m, 2H, CH); ^{13}C NMR (100 MHz, CD_2Cl_2, Me_4Si): δ 25.55 (4 CH_2), 26.42 (2 CH_2), 26.46 (2 CH_2), 30.93 (2 CH_2), 54.87 (2 CH), 84.34 (1 quat. C), 95.53 (1 quat. C), 122.12 (1 quat. C), 126.93 (2 CH), 128.81 (2 CH), 129.16 (2 CH), 129.69 (2 CH), 129.80 (1 quat. C), 130.80 (1 CH), 132.58 (2 CH), 137.46 (1 quat. C), 158.30 (2 quat. C); IR (neat): ν 1735 (C=O) cm^{-1}; HRMS calcd for $C_{31}H_{35}N_2O_3$ $[M+H]^+$: 483.2642; found 483.2642. It was noted that the NMR spectra was recorded in low concentration because of the poor solubility, and O*H* peak could not be found in ^{1}H NMR spectrum.



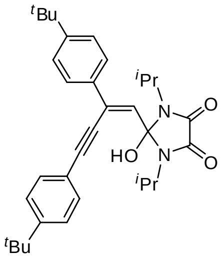
2c: Colorless solid, isolated yield 44% (94.6 mg); m.p. 158-159 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.52 (s, 18H, CH_3), 5.48 (s, 1H, OH), 6.66 (s, 1H CH), 7.34-7.47 (m, 6H, CH), 7.63 (d, J = 6.4 Hz, 2H, CH), 7.71 (d, J = 7.2 Hz, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 28.07 (6 CH_3), 57.25 (2 quat. C), 83.91 (1 quat. C), 96.56 (1 quat. C), 103.77 (1 quat. C), 121.95 (1 quat. C), 124.90 (1 quat. C), 126.20 (2 CH), 128.34 (2 CH), 128.79 (2 CH), 128.86 (1 CH), 128.93 (1 CH), 132.27 (2 CH), 135.38 (1 CH), 137.49 (1 quat. C), 158.52 (2 quat. C); IR (neat): ν 1735 (C=O) cm^{-1}; HRMS calcd for $C_{27}H_{31}N_2O_3$ $[M+H]^+$: 431.2329; found 431.2338.



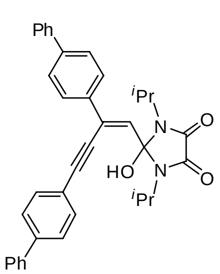
2d: Colorless solid, isolated yield 68% (173 mg); m.p. 186-187 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.13-1.26 (m, 8H, CH_2), 1.68-1.77 (m, 4H, CH_2), 1.83-1.90 (m, 4H, CH_2), 2.10-2.13 (m, 4H, CH_2), 2.34 (s, 3H, CH_3), 2.40 (s, 3H, CH_3), 3.38-3.44 (m, 2H, CH), 6.18 (s, 1H OH), 6.55 (s, 1H, CH), 7.15 (d, J = 8.0 Hz, 2H, CH), 7.24 (d, J = 7.6 Hz, 2H, CH), 7.46 (d, J = 8.0 Hz, 2H, CH), 7.61 (d, J = 8.0 Hz, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 21.13 (2 CH_2), 21.54 (2 CH_2), 25.13 (2 CH_2), 26.05 (1 CH_3), 26.06 (1 CH_3), 28.40 (2 CH_2), 30.15 (2 CH_2), 54.46 (2 CH), 83.59 (1 quat. C), 95.28 (1 quat. C), 104.94 (1 quat. C), 118.73 (1 quat. C), 126.40 (2 CH), 128.79 (1 quat. C), 129.12 (2 CH), 129.34 (2 CH), 129.39 (2 CH), 130.90 (1 quat. C), 132.19 (1 CH), 134.52 (1 quat. C), 139.26 (1 quat. C), 158.14 (2 quat. C); IR (neat): ν 1734 (C=O) cm^{-1}; HRMS calcd for $C_{33}H_{39}N_2O_3$ $[M+H]^+$: 511.2955; found 511.2961.



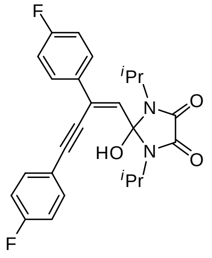
2e: Colorless solid, isolated yield 71% (153 mg); m.p. 156-157 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.49 (d, J = 6.8 Hz, 6H, CH_3), 1.53 (d, J = 7.2 Hz, 6H, CH_3), 2.24 (s, 3H, CH_3), 2.48 (s, 3H, CH_3), 3.77-3.87 (m, 2H, CH), 5.83 (s, 1H, OH), 6.07 (s, 1H, CH), 7.11-7.27 (m, 5H, CH), 7.51-7.54 (m, 2H, CH), 7.70-7.72 (m, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 19.16 (2 CH_3), 20.24 (1 CH_3), 20.55 (1 CH_3), 20.71 (2 CH_3), 46.57 (2 CH), 87.96 (1 quat. C), 95.04 (1 quat. C), 103.33 (1 quat. C), 121.44 (1 quat. C), 125.99 (1 CH), 126.17 (1 CH), 128.50 (1 CH), 128.77 (1 CH), 128.82 (1 CH), 129.24 (1 quat. C), 130.82 (1 CH), 130.91 (1 CH), 132.29 (1 quat. C), 132.87 (1 quat. C), 134.10 (1 CH), 135.12 (1 CH), 138.72 (1 quat. C), 157.95 (2 quat. C); IR (neat): ν 1734 (C=O) cm^{-1}; HRMS calcd for $C_{27}H_{31}N_2O_3$ $[M+H]^+$: 413.2224; found 413.2222.



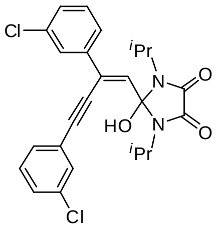
2f: Colorless solid, isolated yield 61% (157 mg); m.p. 157-158 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.26 (s, 9H, CH_3), 1.33-1.35 (m, 21H, CH_3), 3.64-3.71 (m, 2H, CH), 6.52 (s, 1H, OH), 6.60 (s, 1H, CH), 7.38 (d, J = 8.4 Hz, 2H, CH), 7.44 (d, J = 8.4 Hz, 2H, CH), 7.55 (d, J = 8.0 Hz, 2H, CH), 7.65 (d, J = 8.4 Hz, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.95 (2 CH_3), 20.51 (2 CH_3), 31.06 (3 CH_3), 31.22 (3 CH_3), 34.65 (1 quat. C), 34.74 (1 quat. C), 46.43 (2 CH), 83.50 (1 quat. C), 95.07 (1 quat. C), 104.46 (1 quat. C), 118.81 (1 quat. C), 125.32 (2 CH), 125.60 (2 CH), 126.12 (2 CH), 129.12 (1 quat. C), 129.78 (1 CH), 132.18 (2 CH), 134.36 (1 quat. C), 152.26 (1 quat. C), 152.35 (1 quat. C), 158.27 (2 quat. C); IR (neat): ν 1740 (C=O) cm^{-1}; HRMS calcd for $C_{33}H_{43}N_2O_3$ $[M+H]^+$: 515.3268; found 515.3264.



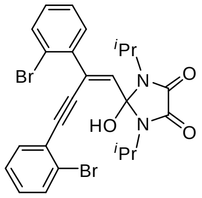
2g: Colorless solid, isolated yield 61% (169 mg); m.p. 151-152 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.22 (d, J = 6.4 Hz, 12H, CH_3), 3.70-3.76 (m, 2H, CH), 6.49 (s, 1H, OH), 6.67 (m, 1H, CH), 7.30-7.76 (m, 18H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.98 (2 CH_3), 20.53 (2 CH_3), 46.51 (2 CH), 84.49 (1 quat. C), 94.98 (1 quat. C), 104.29 (1 quat. C), 120.63 (1 quat. C), 126.81 (2 CH), 126.97 (2 CH), 127.03 (2 CH), 127.08 (2 CH), 127.41 (2 CH), 127.63 (1 CH), 127.67 (1 CH), 128.82 (2 CH), 128.87 (2 CH), 131.11 (1 CH), 132.27 (1 quat. C), 132.83 (2 CH), 136.00 (1 quat. C), 140.24 (1 quat. C), 140.39 (1 quat. C), 141.78 (1 quat. C), 142.02 (1 quat. C), 158.35 (2 quat. C); IR (neat): ν 1735 (C=O) cm^{-1}; HRMS calcd for $C_{37}H_{35}N_2O_3$ [M+H]$^+$: 555.2642; found 555.2638.



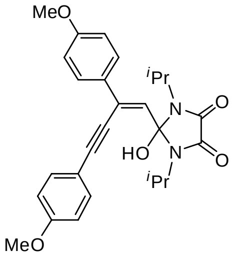
2h: Colorless solid, isolated yield 57% (125 mg); m.p. 169-170 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.36-1.40 (m, 12H, CH_3), 3.70-3.77 (m, 2H, CH), 6.57-6.61 (m, 2H, CH and OH), 6.99-7.14 (m, 4H, CH), 7.40-7.43 (m, 1H, CH), 7.55-7.69 (m, 3H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.87 (2 CH_3), 20.47 (2 CH_3), 46.52 (2 CH), 83.47 (1 quat. C), 94.93 (1 quat. C), 103.40 (1 quat. C), 115.68 (d, J = 22.0 Hz, 2 CH), 115.72 (d, J = 21.8 Hz, 2 CH), 117.65 (d, J = 3.4 Hz, 1 quat. C), 128.17 (d, J = 8.2 Hz, 2 CH), 128.26 (1 quat. C), 130.96 (1 CH), 133.06 (d, J = 3.2 Hz, 1 quat. C), 134.42 (d, J = 8.5 Hz, 2 CH), 158.28 (2 quat. C), 163.13 (d, J = 249.6 Hz, 1 quat. C), 163.38 (d, J = 248.2 Hz, 1 quat. C); IR (neat): ν 1735 (C=O) cm^{-1}; HRMS calcd for $C_{25}H_{25}F_2N_2O_3$ [M+H]$^+$: 439.1828; found 439.1836.



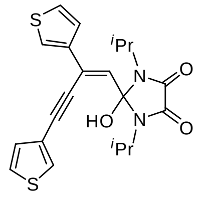
2i: Colorless solid, isolated yield 66% (155 mg); m.p. 182-183 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.36-1.39 (m, 12H, CH_3), 3.69-3.76 (m, 2H, CH), 6.25 (s, 1H, OH), 6.66 (s, 1H, CH), 7.26-7.42 (m, 5H, CH), 7.50-7.56 (m, 2H, CH), 7.64 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.96 (2 CH_3), 20.57 (2 CH_3), 46.57 (2 CH), 84.15 (1 quat. C), 94.71 (1 quat. C), 103.02 (1 quat. C), 123.08 (1 quat. C), 124.54 (1 CH), 126.51 (1 CH), 127.80 (1 quat. C), 129.31 (1 CH), 129.60 (1 CH), 129.63 (1 CH), 129.81 (1 CH), 130.06 (1 CH), 130.75 (1 CH), 131.73 (1 CH), 134.11 (1 quat. C), 134.88 (1 quat. C), 138.62 (1 quat. C), 158.18 (2 quat. C); IR (neat): ν 1740 (C=O) cm^{-1}; HRMS calcd for $C_{25}H_{25}Cl_2N_2O_3$ [M+H]$^+$: 471.1237; found 471.1240.



2j: Colorless solid, isolated yield 68% (190 mg); m.p. 174-175 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.43 (d, J = 6.8 Hz, 6H, CH_3), 1.50 (d, J = 6.8 Hz, 6H, CH_3), 3.77-3.84 (m, 2H, CH), 6.13 (s, 1H, CH), 6.37 (s, 1H, OH), 7.14 (t, J = 7.6 Hz, 1H, CH), 7.20-7.24 (m, 1H, CH), 7.30-7.37 (m, 2H, CH), 7.49 (d, J = 8.0 Hz, 2H, CH), 7.65 (d, J = 7.2 Hz, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 19.32 (2 CH_3), 20.64 (2 CH_3), 46.71 (2 CH), 87.73 (1 quat. C), 94.88 (1 quat. C), 102.18 (1 quat. C), 121.50 (1 CH), 123.72 (1 CH), 125.68 (1 CH), 127.53 (2 CH), 128.50 (1 CH), 129.88 (1 CH), 130.31 (1 quat. C), 130.76 (1 quat. C), 132.02 (1 CH), 133.63 (1 CH), 134.74 (1 quat. C), 137.35 (1 quat. C), 138.61 (1 quat. C) 158.04 (2 quat. C); IR (neat): ν 1742 (C=O) cm^{-1}; HRMS calcd for $C_{25}H_{25}Br_2N_2O_3$ [M+H]$^+$: 559.0226; found 559.0227.



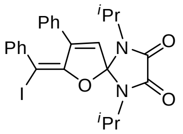
2k: Colorless solid, isolated yield 56% (129 mg); m.p. 103-104 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): δ 1.36-1.40 (m, 12H, CH_3), 3.70-3.78 (m, 5H, CH_3 and CH), 3,84 (s, 3H, CH_3), 6.32 (s, 1H, OH), 6.50 (s, 1H, CH), 6.87 (d, J = 8.8 Hz, 2H, CH), 6.94 (d, J = 8.8 Hz, 2H, CH), 7.55 (d, J = 8.4 Hz, 2H, CH), 7.67 (d, J = 8.8 Hz, 2H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): δ 18.88 (2 CH_3), 20.50 (2 CH_3), 46.37 (2 CH), 55.20 (1 CH_3), 55.36 (1 CH_3), 83.11 (1 quat. C), 95.13 (1 quat. C), 104.39 (1 quat. C), 113.98 (4 CH), 127.66 (2 CH), 128.86 (1 quat. C), 129.68 (1 CH), 130.71 (1 quat. C), 133.30 (1 quat. C), 133.93 (2 CH), 158.21 (2 quat. C), 160.22 (1 quat. C), 160.37 (1 quat. C); IR (neat): *ν* 1735 (C=O) cm^{-1}; HRMS calcd for $C_{27}H_{31}N_2O_5$ [M+H]$^+$: 463.2228; found 463.2227.



2l: Colorless solid, isolated yield 65% (138 mg); m.p. 199-200 °C; ^{1}H NMR (400 MHz, DMSO-d_6, Me_4Si): *δ* 1.26 (d, *J* = 6.8 Hz, 6H, CH_3), 1.39 (d, *J* = 6.8 Hz, 6H, CH_3), 3.58-3.66 (m, 2H, CH), 6.66 (s, 1H, CH), 7.26 (s, 1H, OH), 7.38 (d, *J* = 5.2 Hz, 1H, CH), 7.56 (d, *J* = 4.8 Hz, 1H, CH), 7.62-7.74 (m, 2H, CH), 7.93-7.94 (m, 1H, CH), 7.99-8.00 (m, 1H, CH); ^{13}C NMR (100 MHz, DMSO-d_6, Me_4Si): *δ* 18.58 (2 CH_3), 20.25 (2 CH_3), 45.31 (2 CH), 83.43 (1 quat. C), 94.20 (1 quat. C), 96.88 (1 quat. C), 120.38 (1 quat. C), 122.80 (1 quat. C), 124.95 (1 CH), 125.10 (1 CH), 126.37 (1 CH), 127.55 (1 CH), 129.86 (1 CH), 130.27 (1 CH), 131.66 (1 quat. C), 131.98 (1 CH), 157.47 (2 quat. C); IR (neat): *ν* 1729 (C=O) cm^{-1}; HRMS calcd for $C_{21}H_{23}N_2O_3S_2$ [M+H]$^+$: 415.1145; found 415.1148.

Typical Procedures for Synthesis of Spiro Heterocyclic Compound 5 from (*Z*)-2-En-4-yn-1-ols

To a flask was charged with **2a** (201 mg, 0.5 mmol), iodine (381 mg, 1.5 mmol), $K_3PO_4 \cdot 3H_2O$ (399 mg, 1.5 mmol) and 5.0 mL of THF. The reaction mixture was stirred at room temperature for 3 h. After the reaction was finished, the mixture was quenched by brine, washed with aqueous $Na_2S_2O_3$ and extracted with ethyl acetate. The organic solution was dried over Na_2SO_4. After filtration, the solution was concentrated under vacuum and the product was purified by flash column chromatography on silica gel. The product **5** was obtained as colorless solid.



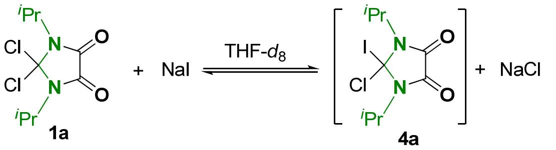
5: Colorless solid, isolated yield 95% (251 mg); m.p. 205-206 °C; ^{1}H NMR (400 MHz, $CDCl_3$, Me_4Si): *δ* 1.39-1.42 (m, 12H, CH_3), 3.58-3.68 (m, 2H, CH), 6.06 (s, 1H, CH), 7.20-7.41 (m, 6H, CH), 7.47-7.53 (m, 4H, CH); ^{13}C NMR (100 MHz, $CDCl_3$, Me_4Si): *δ* 19.90 (2 CH_3), 19.98 (2 CH_3), 45.76 (2 CH), 72.13 (1 quat. C), 104.94 (1 quat. C), 127.91 (2 CH), 128.22 (1 CH), 129.38 (2 CH), 128.66 (1 CH), 128.95 (2 CH), 129.24 (2 CH), 129.29 (1 quat. C), 130.76 (1 CH), 140.99 (1 quat. C), 147.40 (1 quat. C), 150.39 (1 quat. C), 156.64 (2 quat. C); IR (neat): *ν* 1752 (C=O) cm^{-1}; HRMS calcd for $C_{25}H_{26}IN_2O_3$ [M+H]$^+$: 529.0983; found 529.0976.

Reference:

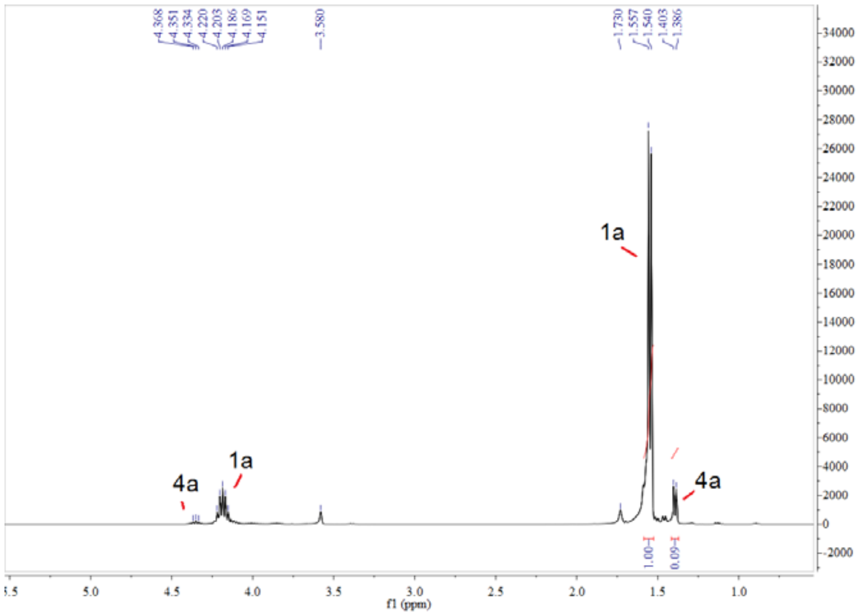
1. F. Zhao, Y. Wang, W.-X. Zhang and Z. Xi, *Org. Biomol. Chem.,* 2012, **10**, 6266.

2) Mechanistic Studies and Discussions

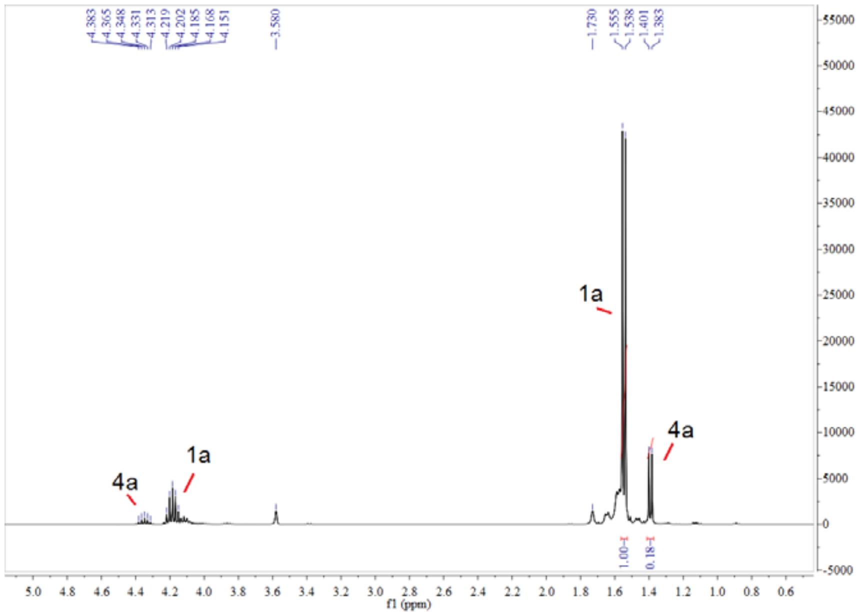
Formation of Iodo-substituted Intermediate. To obtain the evidence of iodo-substituted intermediate, the 1:1 mixture of **1a** and NaI in THF-d_8 was monitored by NMR spectroscopy. ^{1}H and ^{13}C NMR spectra are shown below. A series of new peak was shown in both ^{1}H and ^{13}C NMR spectra, indicating formation of iodo-substituted intermediate **4a**. The ratio of **1a** and **4a** was determined by intergration of doubly splitted methyl hydrogen. The ratio of **1a**:**4a** is 1:0.09 after 1 h, 1:0.18 after 1 day, and 1:0.19 after 7 days. These results clearly show that there was an equilibrium between them (eq 1).



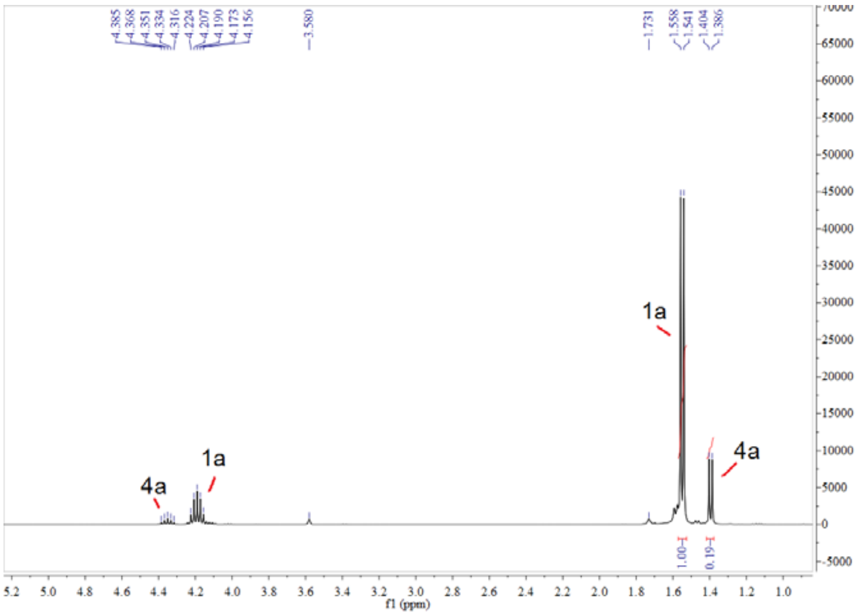
(1)



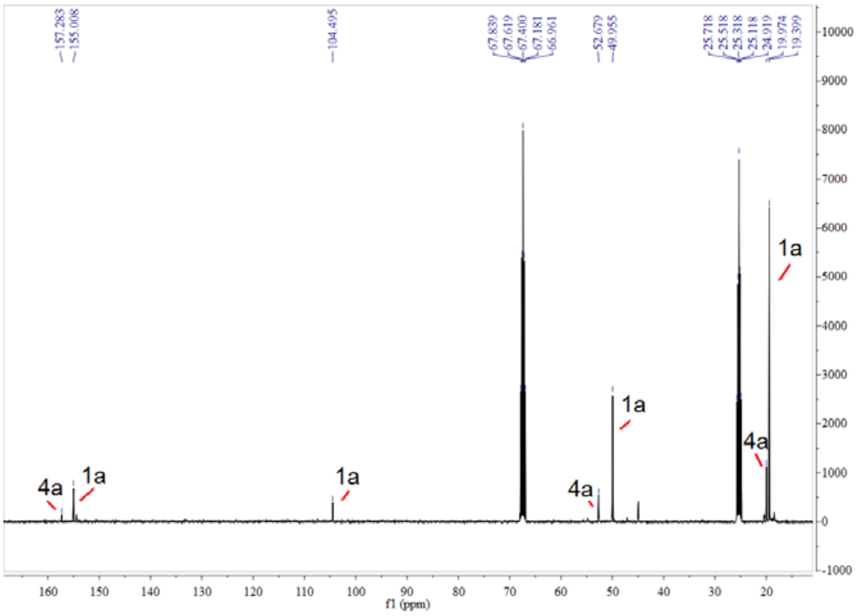
^{1}H NMR Spectrum (1 h)



^{1}H NMR Spectrum (1 day)



^{1}H NMR Spectrum (7 days)

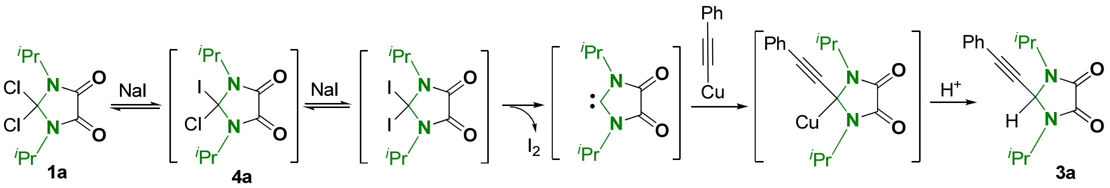


^{13}C NMR Spectrum (7 days)

SFigure 1. In situ NMR spectra of the reaction between **1a** and NaI.

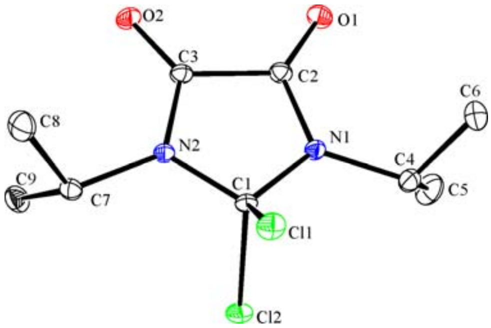
Proposed Mechanism for the Formation of 3a

Byproduct **3a** was proposed to be generated from a carbene intermediate, which probably resulted from iodine elimination of diiodo-substituted intermediate. The carbene intermediate then undergoes an insertion into copper acetylide, followed by hydrogenation to give **3a**.



X-ray Crystallographic Studies for 1a and 2d.

Single crystals of **1a** suitable for X-ray analysis were grown in THF/hexane at room temperature for 1 day. Single crystals of **2d** suitable for X-ray analysis were grown in $CHCl_3$/hexane at room temperature for 1 day. Data collections for **1a** and **2d** was performed at 20 °C on a Rigaku RAXIS RAPID IP diffractometer, using graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). The determination of crystal class and unit cell parameters was carried out by Rapid-AUTO (Rigaku 2000) program package for **1a** and **2d**. The raw frame data was processed using Crystal Structure (Rigaku/MSC 2000) for **1a** and **2d**. The structures of **1a** and **2d** were solved by use of SHELXTL program. Refinement was performed on F^2 anisotropically for all the non-hydrogen atoms by the full-matrix least-squares method. The hydrogen atoms were placed at the calculated positions and were included in the structure calculation without further refinement of the parameters. Crystallographic data (excluding structure factors) have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication nos. CCDC-857965 (**1a**), CCDC-959743 (**2d**·$2CHCl_3$). Copies of these data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.



SFigure 2. ORTEP drawing of **1a** with 30% thermal ellipsoids.

STable 2. Crystal data and structure refinement for **1a**.

Identification code	**1a**	
Empirical formula	$C_9H_{14}Cl_2N_2O_2$	
Formula weight	253.12	
Temperature	293(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2(1)/n	
Unit cell dimensions	a = 5.8444(12) Å	α = 90°
	b = 19.476(4) Å	β = 95.18(3)°
	c = 10.909(2) Å	γ = 90°
Volume	1236.6(4) $Å^3$	
Z	4	
Density (calculated)	1.360 Mg/m^3	
Absorption coefficient	0.509 mm^{-1}	
F(000)	528	
Crystal size	0.30 x 0.30 x 0.20 mm^3	
Theta range for data collection	2.09 to 27.46°.	

Index ranges	-7<=h<=7, -25<=k<=25, -14<=l<=14
Reflections collected	5403
Independent reflections	2809 [R(int) = 0.0418]
Completeness to theta = 27.46°	99.0 %
Absorption correction	Empirical
Max. and min. transmission	0.9051 and 0.8624
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2809 / 0 / 141
Goodness-of-fit on F^2	0.993
Final R indices [I>2sigma(I)]	R1 = 0.0445, wR2 = 0.0943
R indices (all data)	R1 = 0.0692, wR2 = 0.1006
Extinction coefficient	0.130(5)
Largest diff. peak and hole	0.250 and -0.415 e. $Å^{-3}$

STable 3. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for **1a**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
C(1)	588(3)	1429(1)	3866(2)	38(1)
C(2)	2410(4)	1326(1)	2107(2)	45(1)
C(3)	2426(4)	2076(1)	2499(2)	43(1)
C(4)	769(4)	232(1)	2953(2)	55(1)
C(5)	-777(6)	39(2)	1806(3)	86(1)
C(6)	3002(5)	-178(1)	3102(3)	82(1)
C(7)	791(4)	2719(1)	4261(2)	45(1)
C(8)	3018(4)	3046(1)	4814(2)	72(1)
C(9)	-721(5)	3209(1)	3457(2)	64(1)
Cl(1)	1926(1)	1191(1)	5372(1)	55(1)
Cl(2)	-2479(1)	1388(1)	4001(1)	58(1)
N(1)	1272(3)	978(1)	2950(2)	42(1)
N(2)	1291(3)	2095(1)	3537(1)	38(1)
O(1)	3250(3)	1092(1)	1221(1)	63(1)
O(2)	3267(3)	2554(1)	1989(1)	59(1)
H(4)	-77	136	3669	66
H(5A)	-2113	328	1743	129
H(5B)	-1238	-432	1861	129
H(5C)	46	100	1091	129
H(6A)	3843	-107	2396	123
H(6B)	2657	-657	3175	123
H(6C)	3912	-28	3829	123
H(7)	-80	2573	4943	54
H(8A)	3908	2710	5293	108
H(8B)	2670	3423	5332	108

H(8C)	3880	3209	4165	108
H(9A)	118	3376	2801	96
H(9B)	-1163	3588	3945	96
H(9C)	-2070	2970	3117	96

STable 4. Bond lengths [Å] and angles [°] for **1a**.

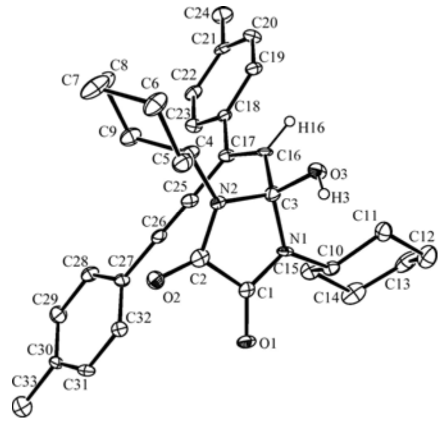
C(1)-N(1)	1.414(3)	Cl(2)-C(1)-Cl(1)	105.29(10)
C(1)-N(2)	1.417(3)	O(1)-C(2)-N(1)	127.5(2)
C(1)-Cl(2)	1.814(2)	O(1)-C(2)-C(3)	126.40(19)
C(1)-Cl(1)	1.815(2)	N(1)-C(2)-C(3)	106.15(17)
C(2)-O(1)	1.212(2)	O(2)-C(3)-N(2)	127.6(2)
C(2)-N(1)	1.363(3)	O(2)-C(3)-C(2)	126.88(19)
C(2)-C(3)	1.522(3)	N(2)-C(3)-C(2)	105.56(17)
C(3)-O(2)	1.210(2)	N(1)-C(4)-C(5)	110.0(2)
C(3)-N(2)	1.364(2)	N(1)-C(4)-C(6)	110.2(2)
C(4)-N(1)	1.483(3)	C(5)-C(4)-C(6)	113.4(2)
C(4)-C(5)	1.523(4)	N(2)-C(7)-C(9)	109.63(17)
C(4)-C(6)	1.526(4)	N(2)-C(7)-C(8)	110.36(18)
C(7)-N(2)	1.493(3)	C(9)-C(7)-C(8)	113.4(2)
C(7)-C(9)	1.523(3)	C(2)-N(1)-C(1)	110.78(17)
C(7)-C(8)	1.523(3)	C(2)-N(1)-C(4)	126.70(18)
N(1)-C(1)-N(2)	106.38(15)	C(1)-N(1)-C(4)	122.51(16)
N(1)-C(1)-Cl(2)	111.98(14)	C(3)-N(2)-C(1)	111.09(17)
N(2)-C(1)-Cl(2)	111.84(14)	C(3)-N(2)-C(7)	126.44(17)
N(1)-C(1)-Cl(1)	110.84(14)	C(1)-N(2)-C(7)	122.47(15)
N(2)-C(1)-Cl(1)	110.59(13)		

Symmetry transformations used to generate equivalent atoms:

STable 5. Anisotropic displacement parameters (Å^{2} x 10$_{3}$) for **1a**. The anisotropic displacement factor exponent takes the form: $-2\pi^{2}[\, h^{2} a^{*2}U^{2} + ... + 2\, h\, k\, a^{*}\, b^{*}\, U^{12} \,]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
C(1)	38(1)	44(1)	32(1)	3(1)	9(1)	-2(1)
C(2)	48(1)	51(1)	37(1)	1(1)	10(1)	1(1)
C(3)	45(1)	48(1)	37(1)	4(1)	11(1)	-2(1)
C(4)	69(2)	44(1)	55(1)	1(1)	20(1)	-6(1)
C(5)	111(3)	72(2)	76(2)	-19(2)	6(2)	-33(2)
C(6)	91(2)	50(2)	110(2)	8(2)	32(2)	16(2)
C(7)	51(1)	46(1)	38(1)	-1(1)	12(1)	1(1)
C(8)	68(2)	72(2)	76(2)	-29(2)	2(1)	-9(1)

C(9)	75(2)	55(2)	63(2)	5(1)	14(1)	18(1)
Cl(1)	65(1)	65(1)	35(1)	12(1)	3(1)	2(1)
Cl(2)	38(1)	69(1)	69(1)	1(1)	15(1)	-5(1)
N(1)	50(1)	39(1)	38(1)	0(1)	13(1)	-4(1)
N(2)	44(1)	40(1)	31(1)	2(1)	12(1)	-1(1)
O(1)	82(1)	66(1)	47(1)	-7(1)	31(1)	1(1)
O(2)	74(1)	55(1)	53(1)	8(1)	30(1)	-11(1)



SFigure 3. ORTEP drawing of **2d** with 30% thermal ellipsoids. Two molecules of $CHCl_3$ are omited for clarity.

STable 6. Crystal data and structure refinement for **2d**·$2CHCl_3$.

Identification code	**2d**·$2CHCl_3$	
Empirical formula	$C_{35}H_{40}Cl_6N_2O_3$	
Formula weight	749.39	
Temperature	123(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2(1)/n	
Unit cell dimensions	a = 10.058(2) Å	α = 90°
	b = 25.771(5) Å	β = 106.01(3)°
	c = 14.912(3) Å	γ = 90°
Volume	3715.5(13) Å^3	
Z	4	
Density (calculated)	1.340 Mg/m^3	
Absorption coefficient	0.499 mm^{-1}	
F(000)	1560	
Crystal size	0.40 x 0.30 x 0.30 mm^3	
Theta range for data collection	2.19 to 27.48°	
Index ranges	-13<=h<=13, -33<=k<=33, -19<=l<=19	
Reflections collected	14812	
Independent reflections	6362 [R(int) = 0.0389]	
Completeness to theta = 27.48°	99.8 %	

Absorption correction	Empirical
Max. and min. transmission	0.8648 and 0.8255
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	8509 / 0 / 420
Goodness-of-fit on F^2	0.992
Final R indices [I>2sigma(I)]	R1 = 0.0749, wR2 = 0.1394
R indices (all data)	R1 = 0.1898, wR2 = 0.1506
Largest diff. peak and hole	1.076 and -0.835 e. Å^{-3}

STable 7. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (Å^2 x 10^3) for **2d**·$2CHCl_3$. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
C(1)	9479(5)	569(2)	4669(3)	21(1)
C(2)	8572(5)	338(2)	3750(4)	26(1)
C(3)	7330(5)	366(2)	4884(3)	24(1)
C(4)	6189(5)	-37(2)	3291(4)	27(1)
C(5)	6584(5)	-573(2)	2979(3)	31(1)
C(6)	5302(5)	-858(2)	2386(4)	39(2)
C(7)	4557(6)	-518(2)	1564(4)	54(2)
C(8)	4197(5)	25(2)	1852(4)	44(2)
C(9)	5448(5)	301(2)	2452(3)	31(1)
C(10)	9291(5)	821(2)	6217(3)	22(1)
C(11)	8661(5)	590(2)	6953(3)	31(1)
C(12)	9432(5)	824(2)	7902(4)	42(2)
C(13)	9375(6)	1407(2)	7916(4)	50(2)
C(14)	9902(6)	1645(2)	7121(4)	45(2)
C(15)	9149(5)	1415(2)	6174(3)	32(1)
C(16)	6160(4)	737(2)	4883(3)	20(1)
C(17)	5929(5)	1193(2)	4445(3)	20(1)
C(18)	4755(5)	1539(2)	4502(3)	20(1)
C(19)	3722(4)	1381(2)	4891(3)	24(1)
C(20)	2693(5)	1710(2)	4975(3)	24(1)
C(21)	2629(5)	2220(2)	4680(3)	27(1)
C(22)	3643(5)	2382(2)	4258(3)	27(1)
C(23)	4676(5)	2044(2)	4174(3)	26(1)
C(24)	1500(5)	2586(2)	4777(4)	39(2)
C(25)	6843(5)	1392(2)	3943(3)	22(1)
C(26)	7568(5)	1580(2)	3529(3)	23(1)
C(27)	8458(5)	1843(2)	3042(3)	22(1)
C(28)	8051(5)	2326(2)	2628(3)	29(1)
C(29)	8907(5)	2598(2)	2208(3)	34(2)
C(30)	10165(5)	2392(2)	2187(3)	27(1)

C(31)	10557(5)	1909(2)	2579(3)	29(1)
C(32)	9713(5)	1632(2)	2997(3)	27(1)
C(33)	11111(5)	2699(2)	1741(4)	55(2)
C(34)	4070(6)	4278(2)	6127(4)	50(2)
C(35)	3029(8)	1641(3)	496(5)	86(2)
Cl(1)	3200(2)	4823(1)	5569(1)	89(1)
Cl(2)	3616(3)	3719(1)	5462(1)	129(1)
Cl(3)	5875(2)	4361(1)	6378(2)	105(1)
Cl(4)	2905(2)	2245(1)	-26(1)	74(1)
Cl(5)	4216(2)	1650(1)	1600(2)	106(1)
Cl(6)	3270(3)	1162(1)	-192(2)	150(1)
N(1)	8717(4)	588(1)	5277(3)	18(1)
N(2)	7365(4)	222(1)	3926(3)	18(1)
O(1)	10701(3)	712(1)	4792(2)	26(1)
O(2)	8917(3)	289(1)	3040(2)	29(1)
O(3)	7106(3)	-78(1)	5374(2)	26(1)

STable 8. Bond lengths [Å] and angles [°] for **2d**·2CHCl$_3$.

C(1)-O(1)	1.247(5)	C(17)-C(25)	1.432(6)
C(1)-N(1)	1.340(5)	C(17)-C(18)	1.502(6)
C(1)-C(2)	1.541(6)	C(18)-C(23)	1.384(6)
C(2)-O(2)	1.208(5)	C(18)-C(19)	1.384(6)
C(2)-N(2)	1.346(5)	C(19)-C(20)	1.369(6)
C(3)-O(3)	1.407(5)	C(20)-C(21)	1.383(6)
C(3)-N(1)	1.472(5)	C(21)-C(22)	1.402(6)
C(3)-N(2)	1.485(5)	C(21)-C(24)	1.513(6)
C(3)-C(16)	1.517(6)	C(22)-C(23)	1.389(6)
C(4)-N(2)	1.457(5)	C(25)-C(26)	1.181(6)
C(4)-C(9)	1.538(6)	C(26)-C(27)	1.465(6)
C(4)-C(5)	1.543(6)	C(27)-C(32)	1.392(6)
C(5)-C(6)	1.535(6)	C(27)-C(28)	1.401(6)
C(6)-C(7)	1.524(7)	C(28)-C(29)	1.386(6)
C(7)-C(8)	1.536(7)	C(29)-C(30)	1.381(6)
C(8)-C(9)	1.506(6)	C(30)-C(31)	1.384(6)
C(10)-N(1)	1.487(5)	C(30)-C(33)	1.525(6)
C(10)-C(11)	1.531(6)	C(31)-C(32)	1.383(6)
C(10)-C(15)	1.536(6)	C(34)-Cl(2)	1.737(6)
C(11)-C(12)	1.537(6)	C(34)-Cl(1)	1.740(6)
C(12)-C(13)	1.505(7)	C(34)-Cl(3)	1.763(5)
C(13)-C(14)	1.551(7)	C(35)-Cl(6)	1.665(7)
C(14)-C(15)	1.527(6)	C(35)-Cl(4)	1.729(7)
C(16)-C(17)	1.332(6)	C(35)-Cl(5)	1.747(7)

O(1)-C(1)-N(1)	127.9(5)	C(23)-C(18)-C(17)	120.5(4)
O(1)-C(1)-C(2)	124.3(4)	C(19)-C(18)-C(17)	122.8(4)
N(1)-C(1)-C(2)	107.9(4)	C(20)-C(19)-C(18)	122.1(5)
O(2)-C(2)-N(2)	129.9(5)	C(19)-C(20)-C(21)	121.9(5)
O(2)-C(2)-C(1)	125.2(5)	C(20)-C(21)-C(22)	116.8(5)
N(2)-C(2)-C(1)	104.9(4)	C(20)-C(21)-C(24)	122.1(5)
O(3)-C(3)-N(1)	112.3(4)	C(22)-C(21)-C(24)	121.0(5)
O(3)-C(3)-N(2)	110.2(4)	C(23)-C(22)-C(21)	120.5(5)
N(1)-C(3)-N(2)	102.0(3)	C(18)-C(23)-C(22)	122.0(5)
O(3)-C(3)-C(16)	106.1(4)	C(26)-C(25)-C(17)	176.6(5)
N(1)-C(3)-C(16)	113.9(4)	C(25)-C(26)-C(27)	176.8(5)
N(2)-C(3)-C(16)	112.4(4)	C(32)-C(27)-C(28)	119.0(4)
N(2)-C(4)-C(9)	113.2(4)	C(32)-C(27)-C(26)	122.0(5)
N(2)-C(4)-C(5)	112.0(4)	C(28)-C(27)-C(26)	119.0(4)
C(9)-C(4)-C(5)	111.6(4)	C(29)-C(28)-C(27)	120.4(5)
C(6)-C(5)-C(4)	110.9(4)	C(30)-C(29)-C(28)	120.2(5)
C(7)-C(6)-C(5)	109.7(5)	C(29)-C(30)-C(31)	119.5(5)
C(6)-C(7)-C(8)	113.6(5)	C(29)-C(30)-C(33)	119.7(5)
C(9)-C(8)-C(7)	111.9(5)	C(31)-C(30)-C(33)	120.8(5)
C(8)-C(9)-C(4)	110.8(4)	C(32)-C(31)-C(30)	121.0(5)
N(1)-C(10)-C(11)	112.9(4)	C(31)-C(32)-C(27)	119.9(5)
N(1)-C(10)-C(15)	110.8(4)	Cl(2)-C(34)-Cl(1)	112.2(3)
C(11)-C(10)-C(15)	111.3(4)	Cl(2)-C(34)-Cl(3)	108.3(3)
C(10)-C(11)-C(12)	107.8(4)	Cl(1)-C(34)-Cl(3)	110.9(3)
C(13)-C(12)-C(11)	113.1(5)	Cl(6)-C(35)-Cl(4)	113.3(4)
C(12)-C(13)-C(14)	111.2(4)	Cl(6)-C(35)-Cl(5)	114.4(4)
C(15)-C(14)-C(13)	111.5(4)	Cl(4)-C(35)-Cl(5)	110.9(4)
C(14)-C(15)-C(10)	109.4(4)	C(1)-N(1)-C(3)	111.9(4)
C(17)-C(16)-C(3)	125.9(4)	C(1)-N(1)-C(10)	120.4(4)
C(16)-C(17)-C(25)	121.4(5)	C(3)-N(1)-C(10)	127.6(4)
C(16)-C(17)-C(18)	122.0(4)	C(2)-N(2)-C(4)	126.1(4)
C(25)-C(17)-C(18)	116.5(4)	C(2)-N(2)-C(3)	113.2(4)
C(23)-C(18)-C(19)	116.6(5)	C(4)-N(2)-C(3)	120.6(4)

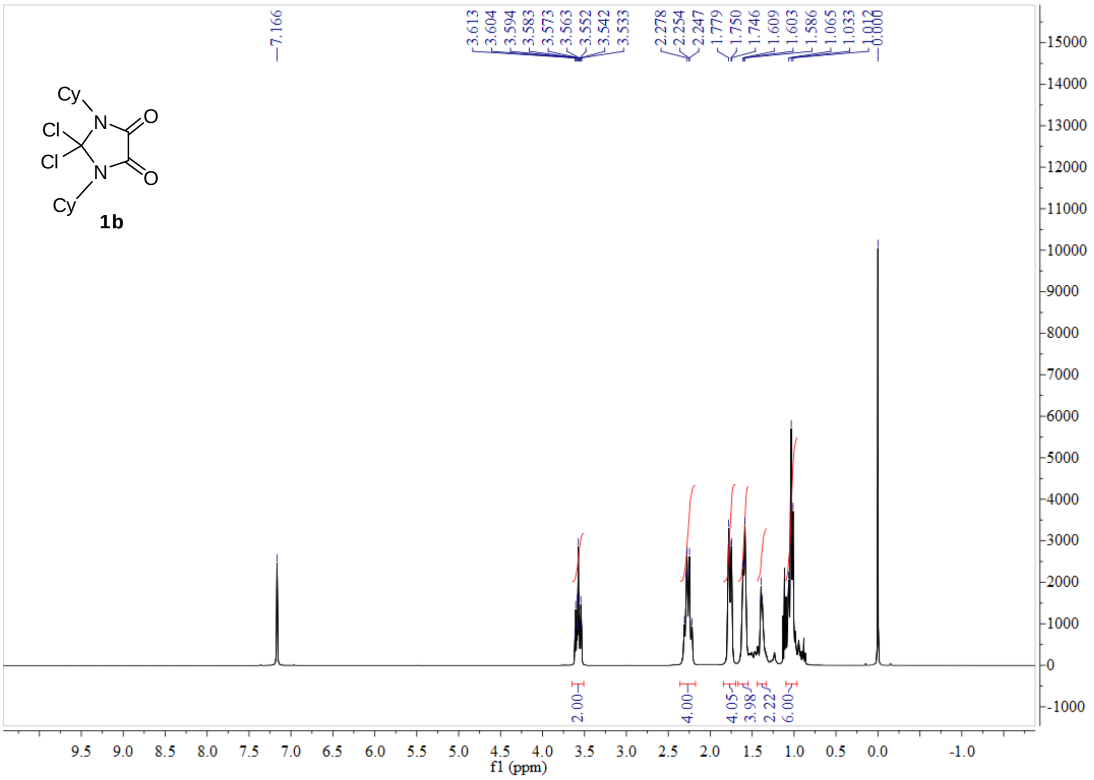
Symmetry transformations used to generate equivalent atoms:

STable 9. Anisotropic displacement parameters ($Å^2$ x 10^3) for **2d**·2CHCl$_3$. The anisotropic displacement factor exponent takes the form: $-2\pi^2 [h^2 a^{*2} U^{11} + ... + 2 h k a^* b^* U^{12}]$

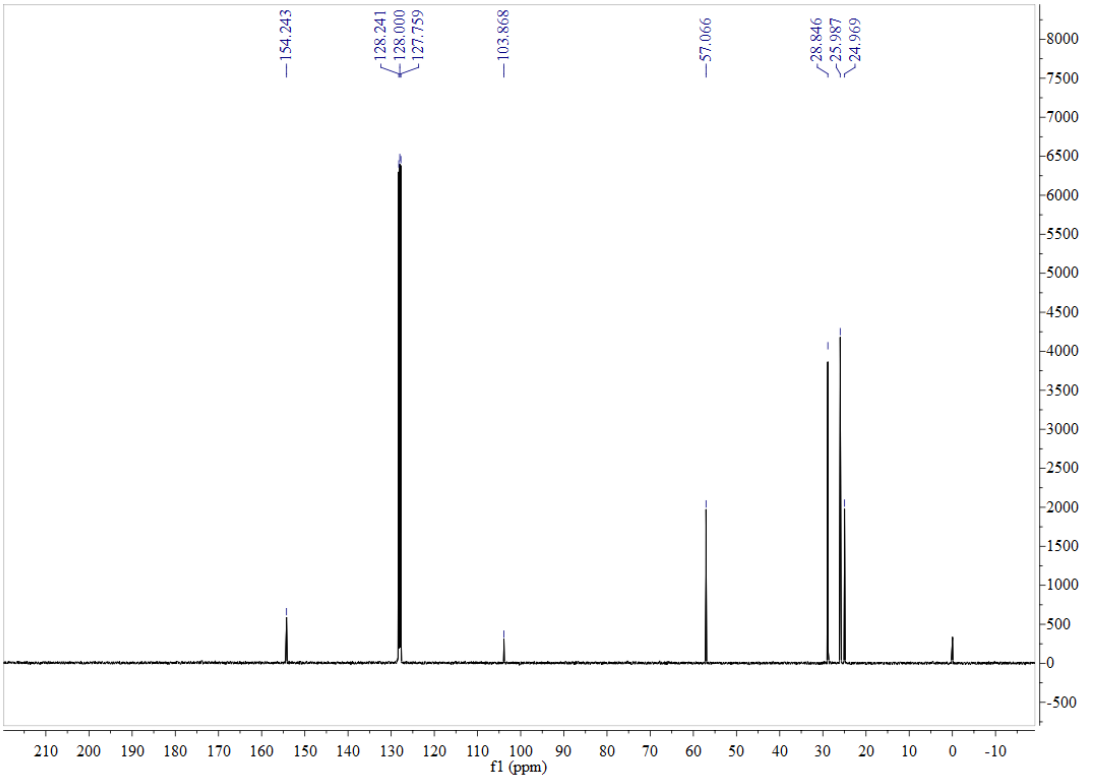
	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
C(1)	21(3)	10(3)	28(3)	8(2)	4(3)	5(2)
C(2)	28(3)	11(3)	35(4)	5(3)	4(3)	1(2)
C(3)	21(3)	24(4)	24(3)	2(3)	2(3)	-6(3)

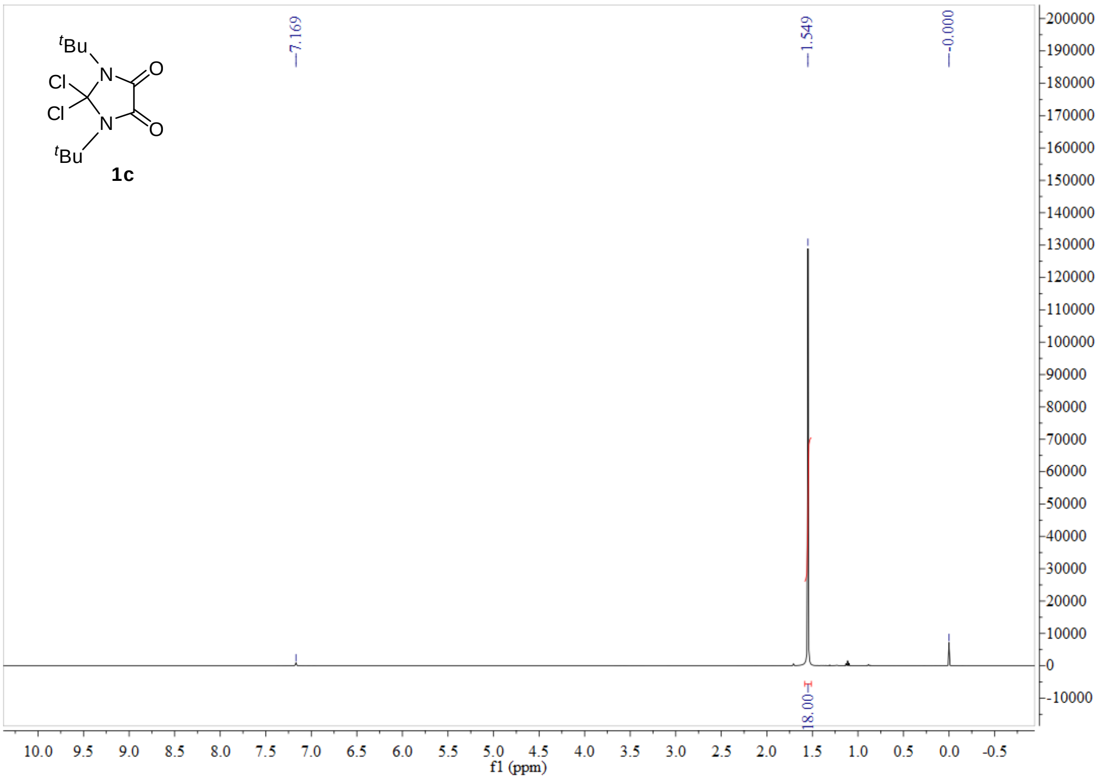
C(4)	19(3)	22(4)	33(3)	-2(3)	-1(3)	-6(2)
C(5)	27(3)	32(4)	33(4)	2(3)	5(3)	1(3)
C(6)	39(4)	30(4)	39(4)	-7(3)	-7(3)	-5(3)
C(7)	38(4)	50(5)	56(5)	-12(4)	-16(3)	-7(3)
C(8)	32(4)	46(5)	43(4)	0(3)	-9(3)	-1(3)
C(9)	24(3)	27(4)	38(4)	2(3)	1(3)	6(3)
C(10)	19(3)	22(4)	23(3)	-7(3)	3(3)	-1(2)
C(11)	35(3)	31(4)	25(3)	-2(3)	9(3)	5(3)
C(12)	48(4)	49(5)	29(4)	-10(3)	9(3)	13(3)
C(13)	36(4)	66(5)	41(4)	-17(4)	-4(3)	24(3)
C(14)	46(4)	21(4)	58(4)	-12(3)	-2(3)	-1(3)
C(15)	34(4)	25(4)	36(4)	-5(3)	7(3)	-4(3)
C(16)	7(3)	32(4)	23(3)	-4(3)	6(2)	-1(2)
C(17)	16(3)	14(3)	30(3)	1(3)	4(3)	-1(2)
C(18)	15(3)	20(3)	22(3)	4(2)	1(2)	-1(2)
C(19)	16(3)	20(3)	33(3)	6(3)	2(3)	-1(2)
C(20)	20(3)	17(3)	39(4)	2(3)	14(3)	1(2)
C(21)	11(3)	36(4)	30(4)	-9(3)	-2(3)	3(3)
C(22)	23(3)	20(3)	33(4)	2(3)	-2(3)	2(3)
C(23)	22(3)	23(4)	33(4)	1(3)	9(3)	0(3)
C(24)	29(4)	39(4)	51(4)	-4(3)	12(3)	10(3)
C(25)	17(3)	14(3)	32(3)	3(3)	4(3)	4(2)
C(26)	16(3)	23(3)	26(3)	8(3)	0(3)	7(2)
C(27)	18(3)	22(3)	24(3)	-3(3)	5(3)	-8(2)
C(28)	21(3)	29(4)	33(4)	2(3)	2(3)	7(3)
C(29)	34(4)	33(4)	34(4)	10(3)	8(3)	-7(3)
C(30)	18(3)	44(4)	20(3)	-2(3)	7(3)	-9(3)
C(31)	15(3)	40(4)	33(4)	4(3)	8(3)	-4(3)
C(32)	23(3)	31(4)	27(3)	2(3)	6(3)	0(3)
C(33)	47(4)	74(5)	43(4)	8(4)	13(3)	-6(4)
C(34)	56(4)	62(5)	27(4)	-1(3)	0(3)	-31(4)
C(35)	113(7)	72(6)	66(6)	3(5)	14(5)	-2(5)
Cl(1)	117(2)	64(2)	59(1)	1(1)	-22(1)	-10(1)
Cl(2)	205(3)	57(2)	74(2)	-2(1)	-45(2)	-33(2)
Cl(3)	77(2)	90(2)	171(2)	-9(2)	75(2)	-13(1)
Cl(4)	64(1)	82(2)	83(2)	30(1)	31(1)	19(1)
Cl(5)	119(2)	81(2)	85(2)	25(1)	-26(1)	1(1)
Cl(6)	271(4)	85(2)	114(2)	-16(2)	86(2)	29(2)
N(1)	9(2)	16(3)	28(3)	3(2)	6(2)	-1(2)
N(2)	14(2)	17(3)	21(3)	0(2)	2(2)	0(2)
O(1)	14(2)	28(2)	35(2)	4(2)	5(2)	1(2)
O(2)	28(2)	36(3)	24(2)	-5(2)	10(2)	4(2)
O(3)	24(2)	20(2)	37(2)	9(2)	12(2)	4(2)

3) ^{1}H NMR and ^{13}C NMR Spectra of All New Compounds

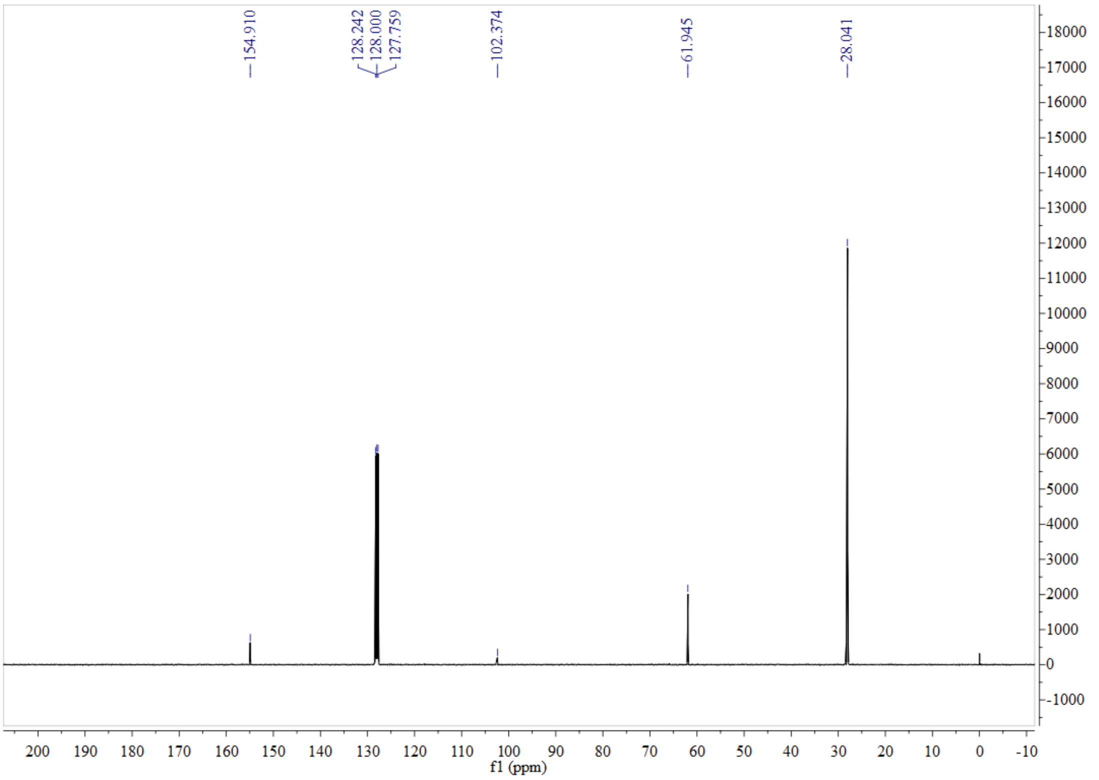


1b

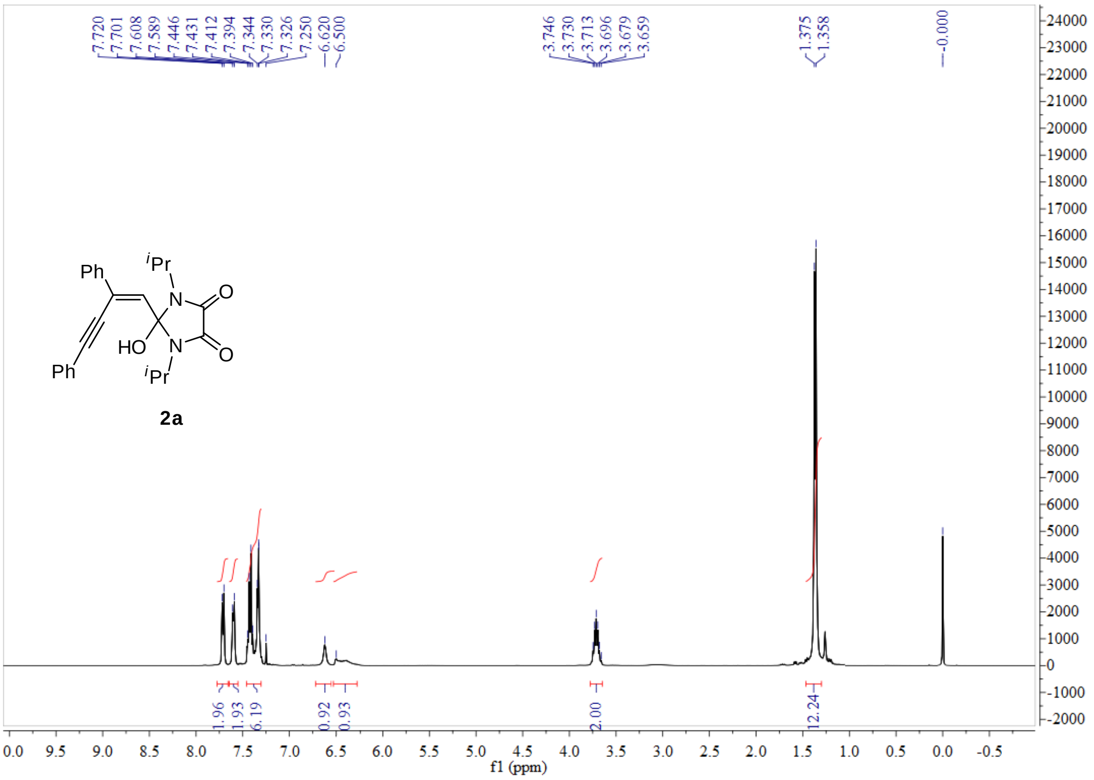


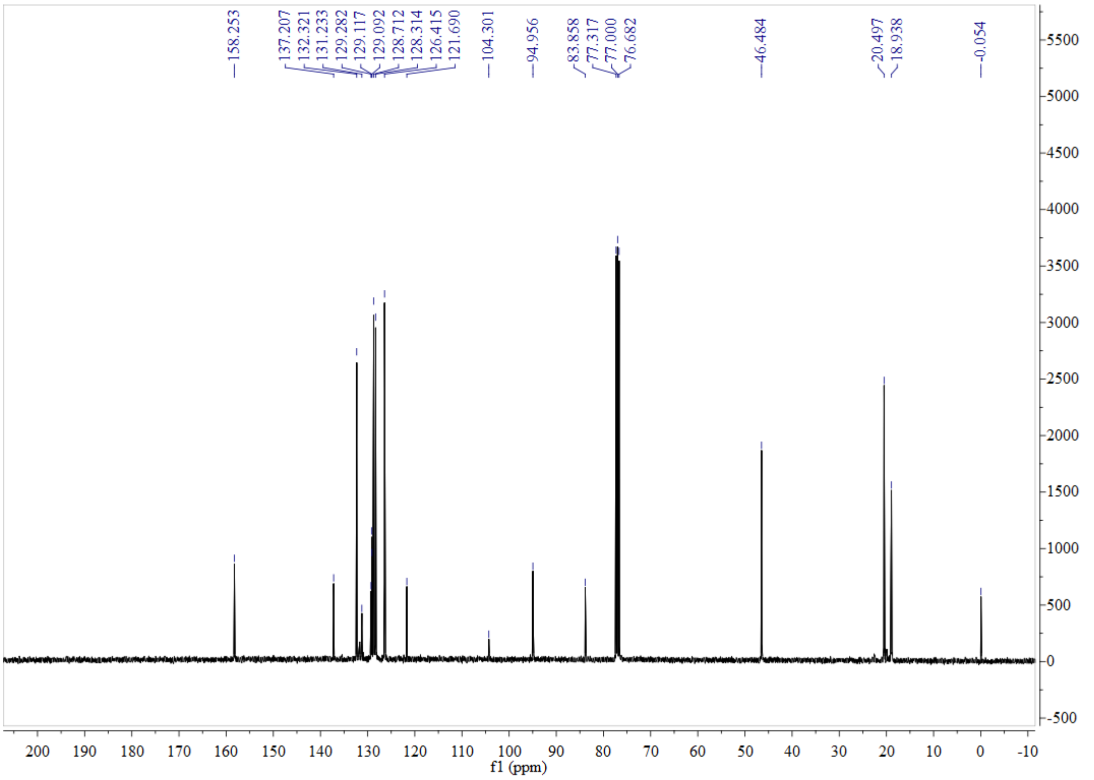


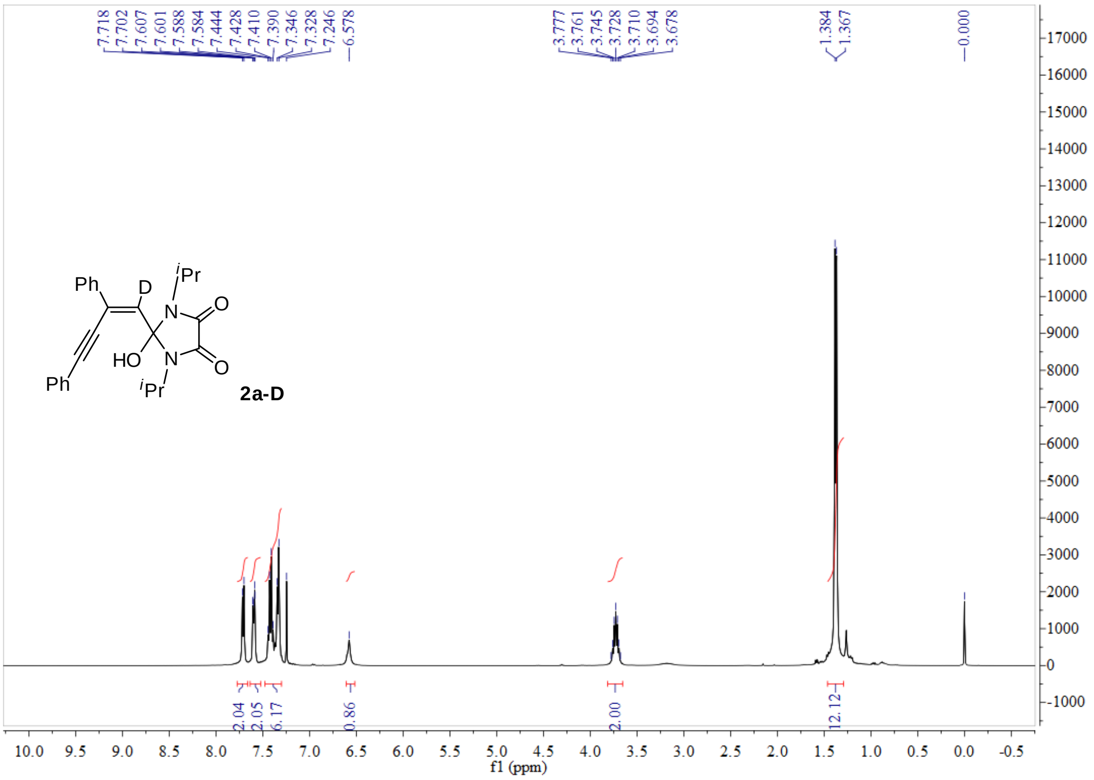
tBu
Cl
Cl
N
N
O
O
tBu
1c
7.169
1.549
0.000
18.00
200000
190000
180000
170000
160000
150000
140000
130000
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
-10000
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)



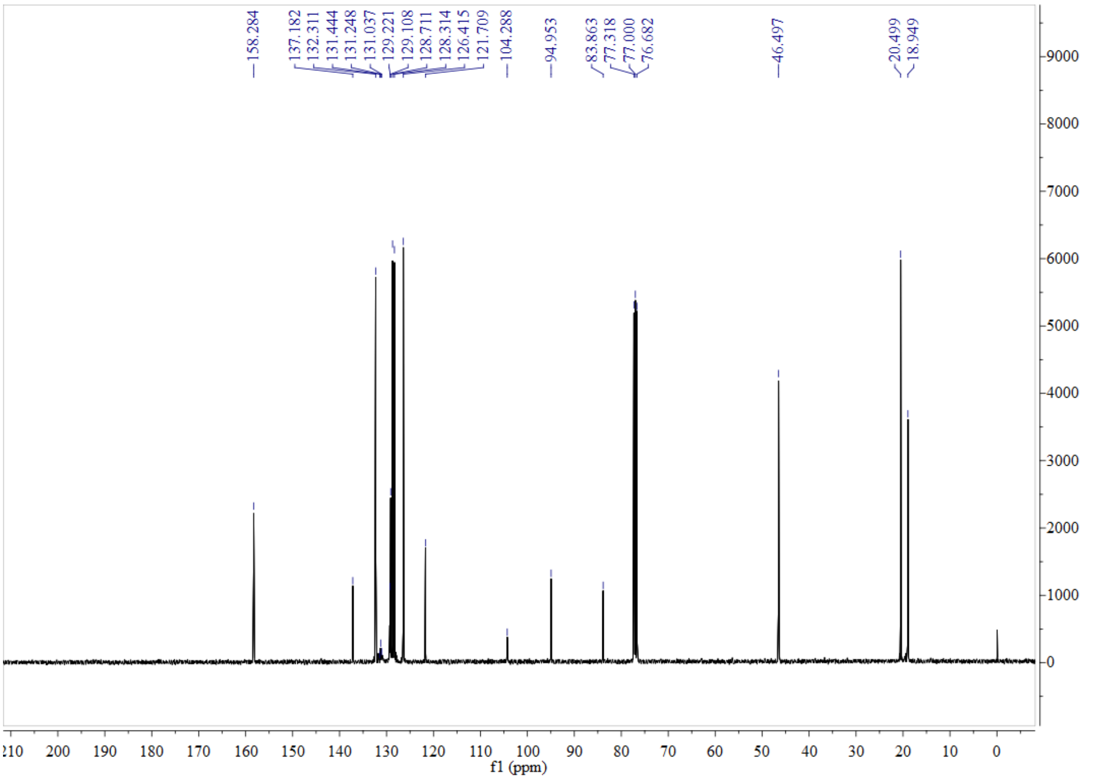
154.910
128.242
128.000
127.759
102.374
61.945
28.041
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

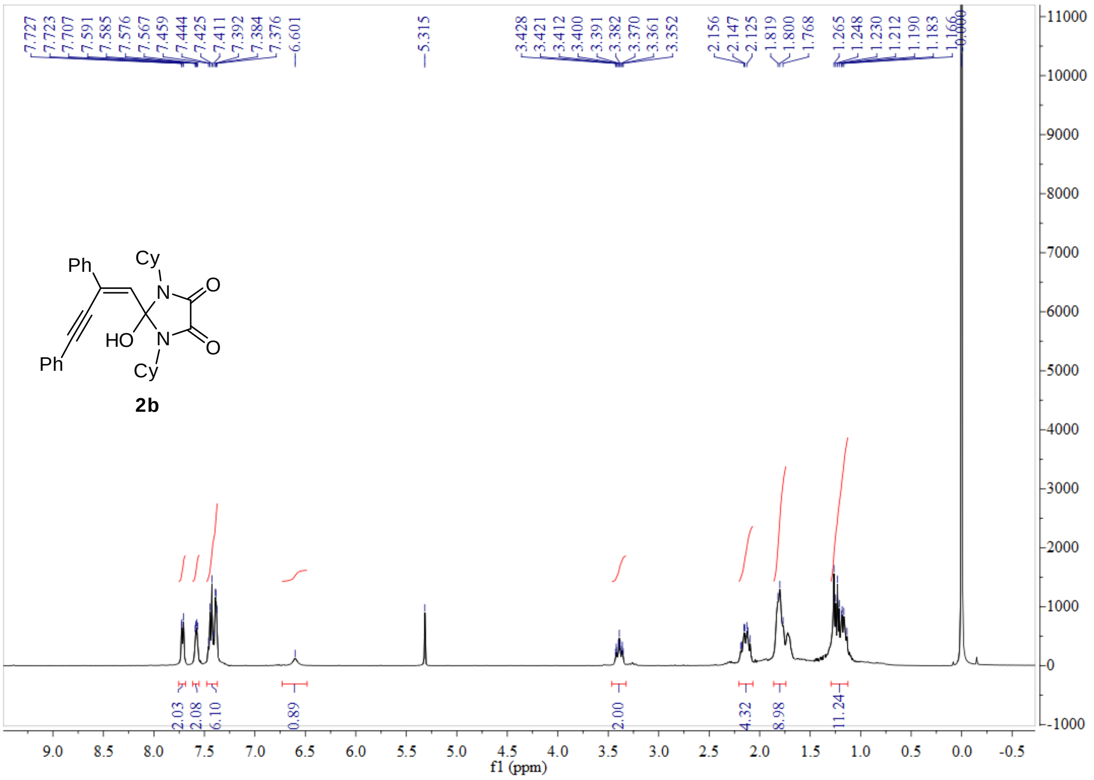

7.720
7.701
7.608
7.589
7.446
7.431
7.412
7.394
7.344
7.330
7.326
7.250
6.620
6.500
3.746
3.730
3.713
3.696
3.679
3.659
1.375
1.358
-0.000
Ph
^{i}Pr
N
O
HO
N
O
^{i}Pr
Ph
2a
1.96
1.93
6.19
0.92
0.93
2.00
12.24
24000
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
0.0
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
-0.5
f1 (ppm)


158.253
137.207
132.321
131.233
129.282
129.117
129.092
128.712
128.314
126.415
121.690
104.301
94.956
83.858
77.317
77.000
76.682
46.484
20.497
18.938
-0.054
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)

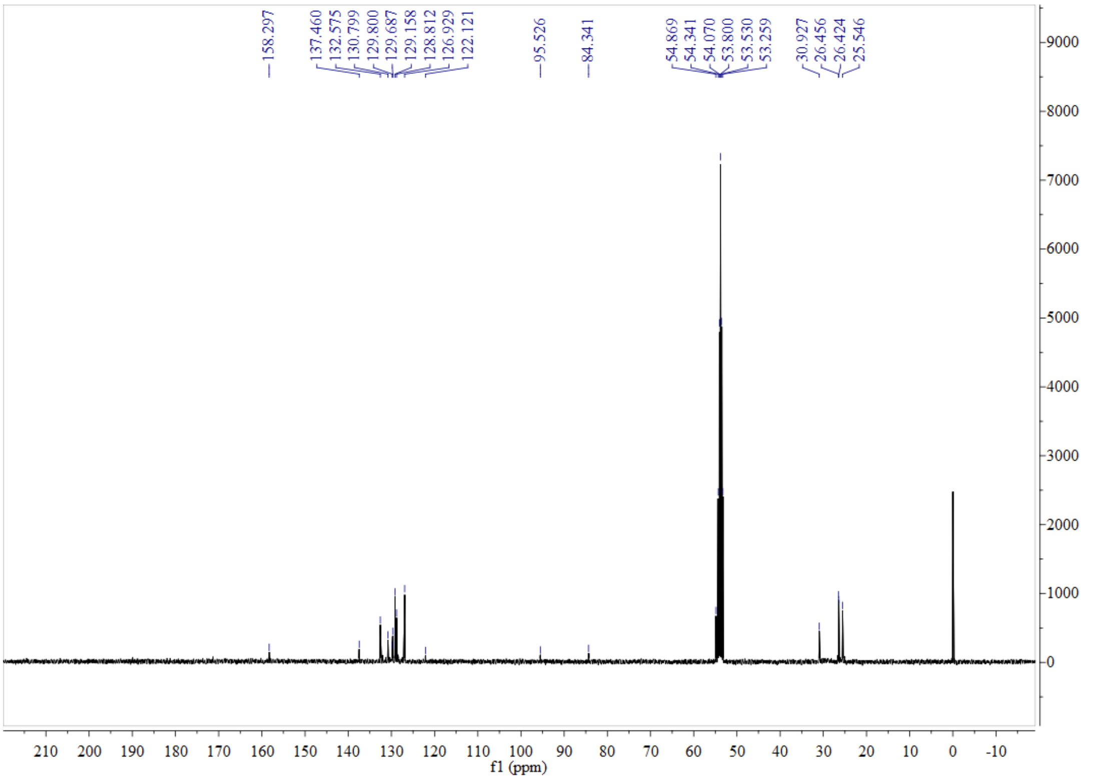

7.718
7.702
7.607
7.601
7.588
7.584
7.444
7.428
7.410
7.390
7.346
7.328
7.246
6.578
3.777
3.761
3.745
3.728
3.710
3.694
3.678
1.384
1.367
0.000
Ph
D
iPr
O
N
HO
N
O
Ph
iPr
2.04
2.05
6.17
0.86
2.00
12.12
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000

2a-D

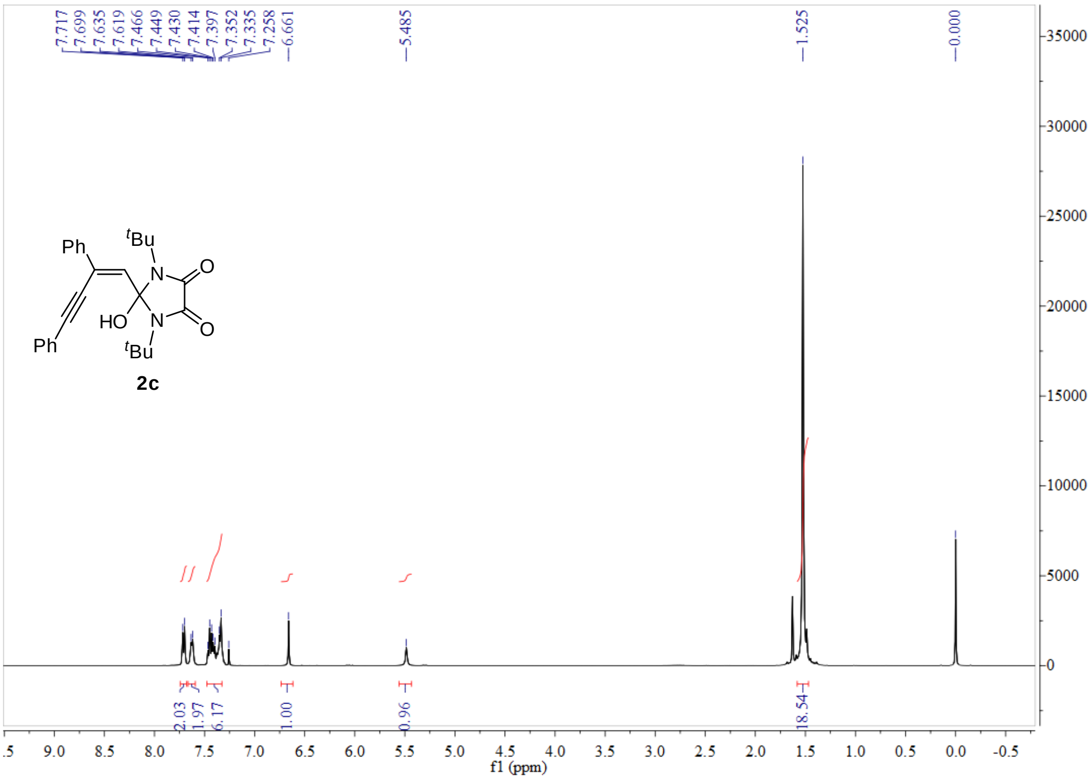

158.284
137.182
132.311
131.444
131.248
131.037
129.221
129.108
128.711
128.314
126.415
121.709
104.288
94.953
83.863
77.318
77.000
76.682
46.497
20.499
18.949
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0

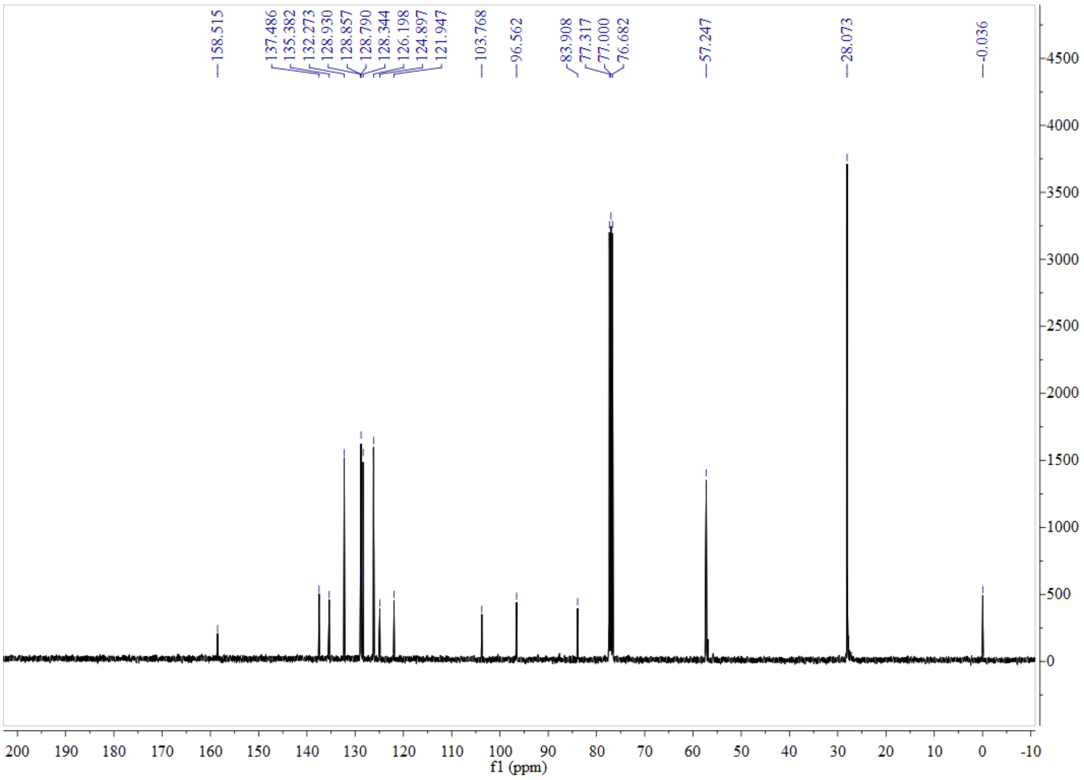

2b

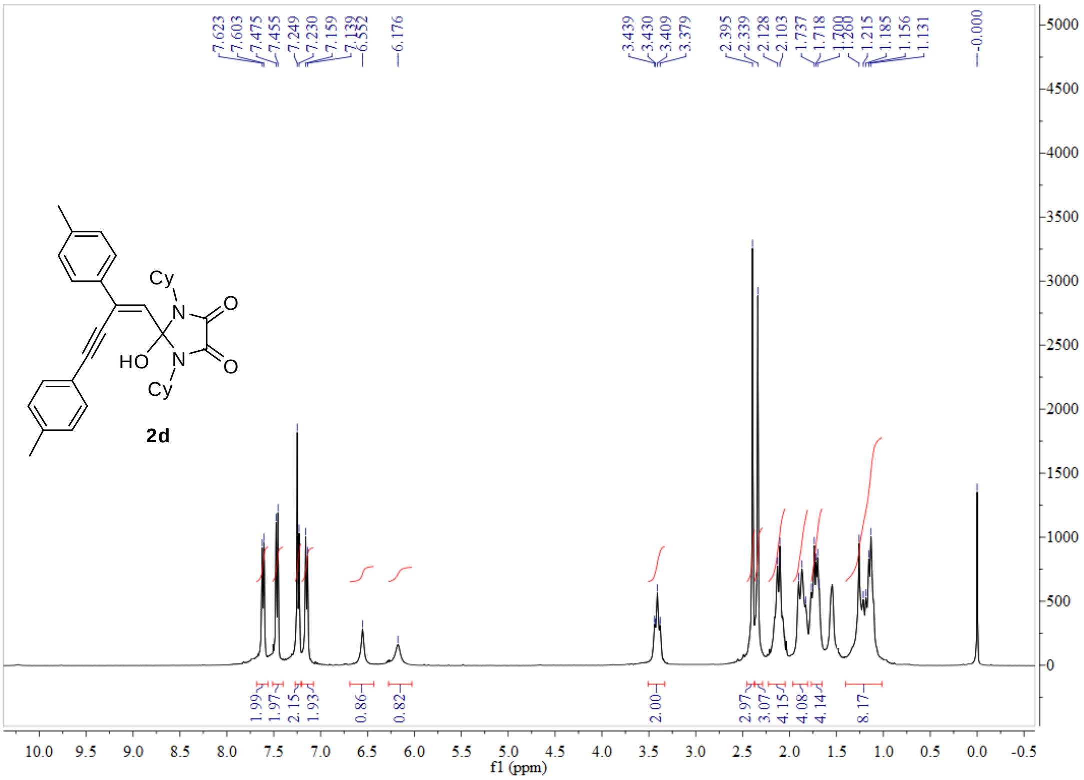
7.727
7.723
7.707
7.591
7.585
7.576
7.567
7.459
7.444
7.425
7.411
7.392
7.384
7.376
6.601
5.315
3.428
3.421
3.412
3.400
3.391
3.382
3.370
3.361
3.352
2.156
2.147
2.125
1.819
1.800
1.768
1.265
1.248
1.230
1.212
1.190
1.183
1.166
0.000
Ph
Cy
N
O
HO
N
O
Cy
Ph
2.03
2.08
6.10
0.89
2.00
4.32
8.98
11.24
9.0 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 -0.5
f1 (ppm)
11000 10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 0 -1000

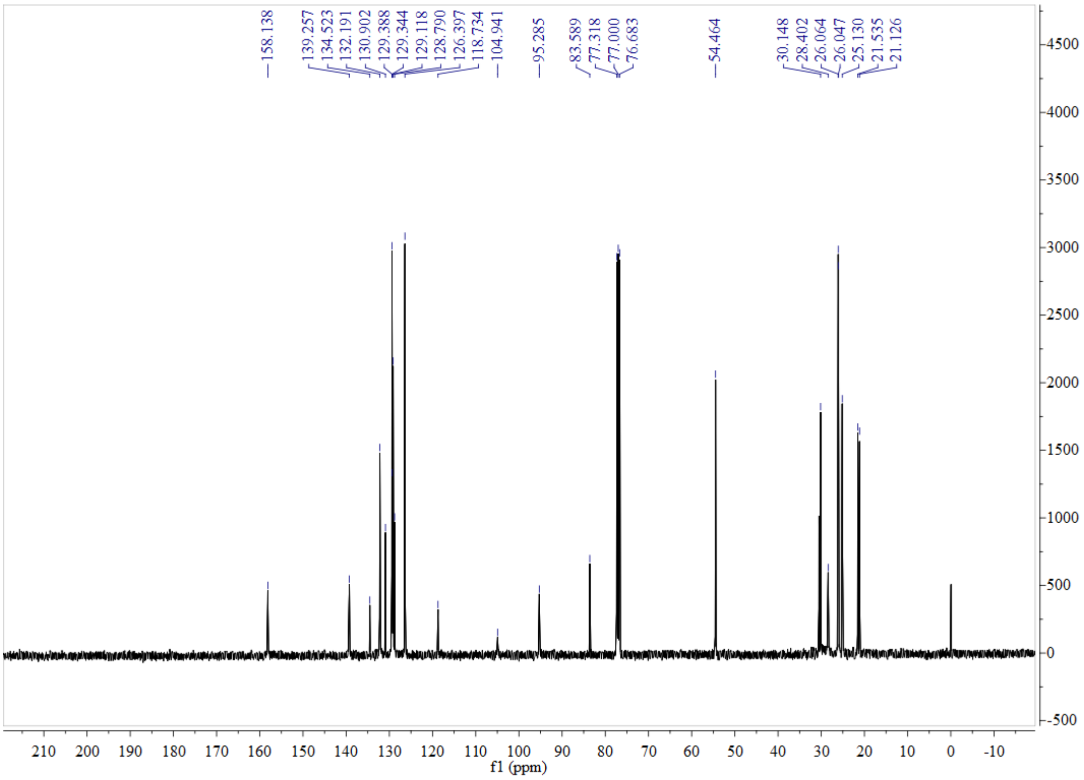


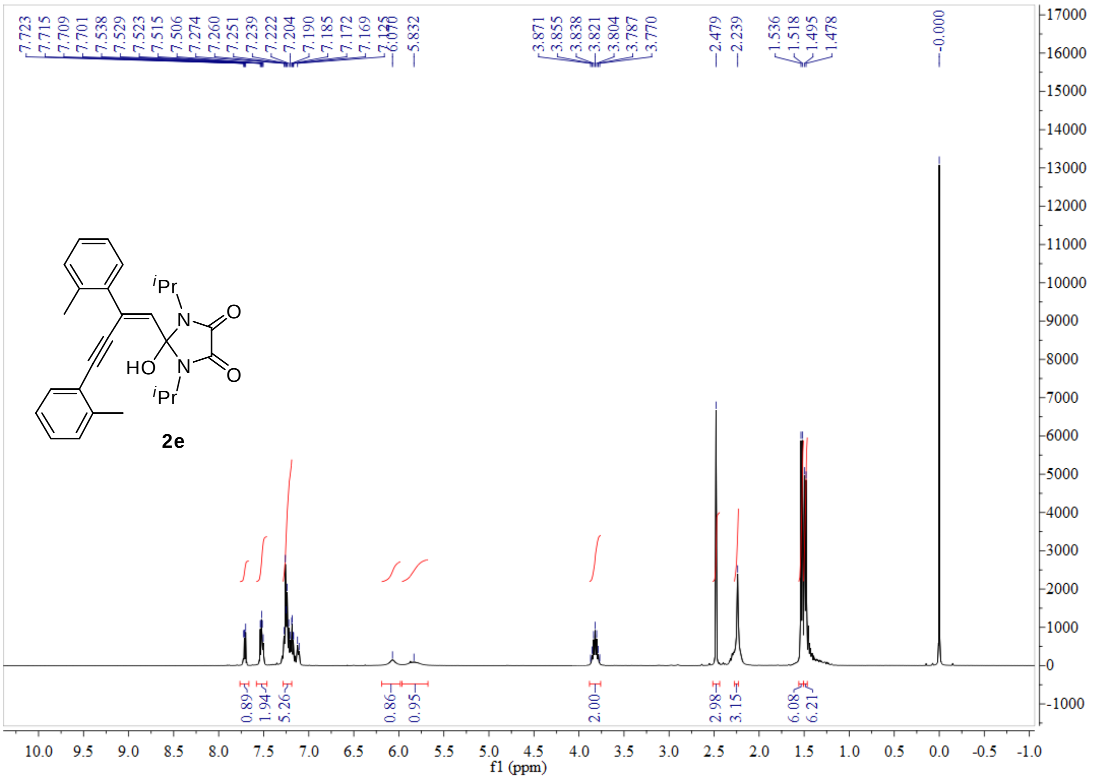
158.297
137.460
132.575
130.799
129.800
129.687
129.158
128.812
126.929
122.121
95.526
84.341
54.869
54.341
54.070
53.800
53.530
53.259
30.927
26.456
26.424
25.546
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)
9000 8000 7000 6000 5000 4000 3000 2000 1000 0

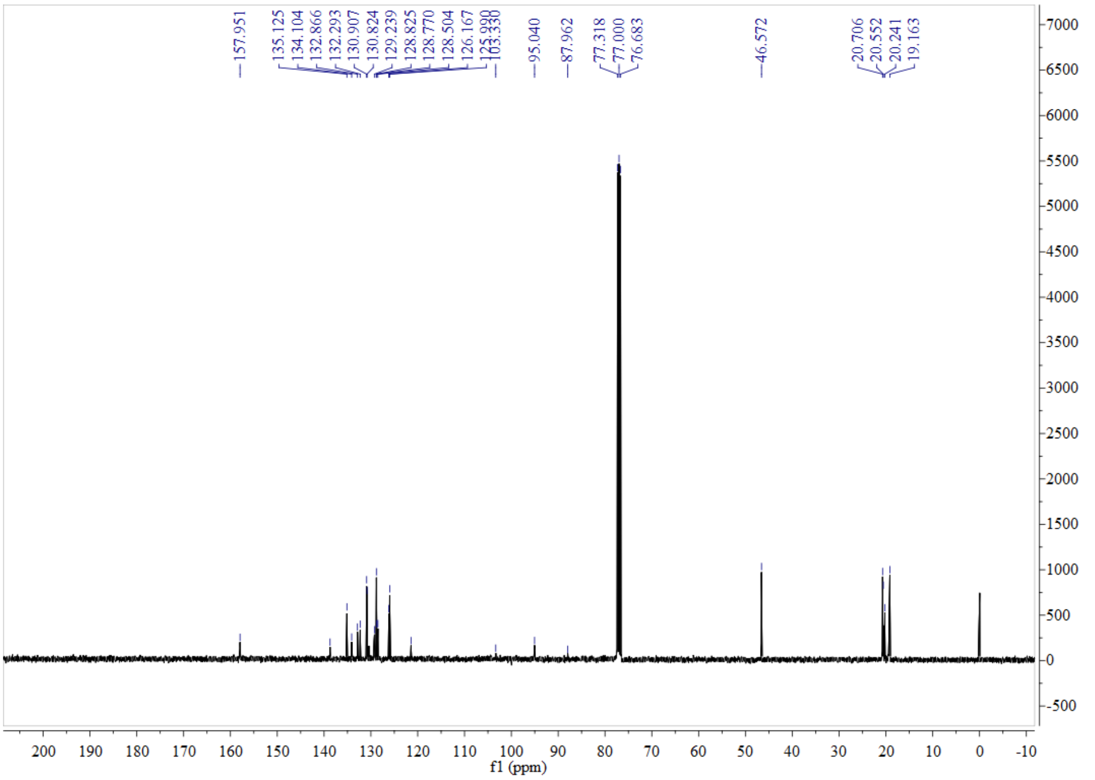

7.717
7.699
7.635
7.619
7.466
7.449
7.430
7.414
7.397
7.352
7.335
7.258
6.661
5.485
1.525
0.000
Ph
^{t}Bu
N
O
HO
N
O
Ph
^{t}Bu
2c
2.03
1.97
6.17
1.00
0.96
18.54
f1 (ppm)

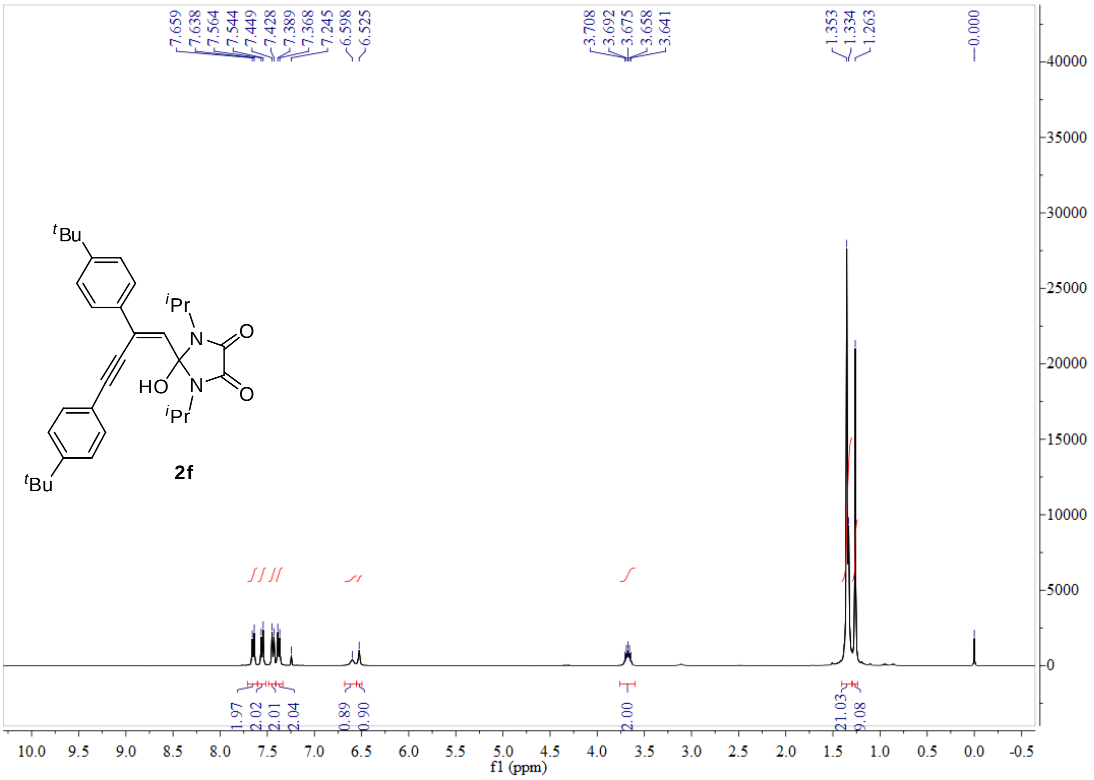

158.515
137.486
135.382
132.273
128.930
128.857
128.790
128.344
126.198
124.897
121.947
103.768
96.562
83.908
77.317
77.000
76.682
57.247
28.073
-0.036
f1 (ppm)


7.623
7.603
7.475
7.455
7.249
7.230
7.159
7.139
6.552
6.176
3.439
3.430
3.409
3.379
2.395
2.339
2.128
2.103
1.737
1.718
1.700
1.260
1.215
1.185
1.156
1.131
-0.000
Cy
N
O
HO
N
O
Cy
2d
1.99
1.97
2.15
1.93
0.86
0.82
2.00
2.97
3.07
4.15
4.08
4.14
8.17
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
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
-0.5
f1 (ppm)

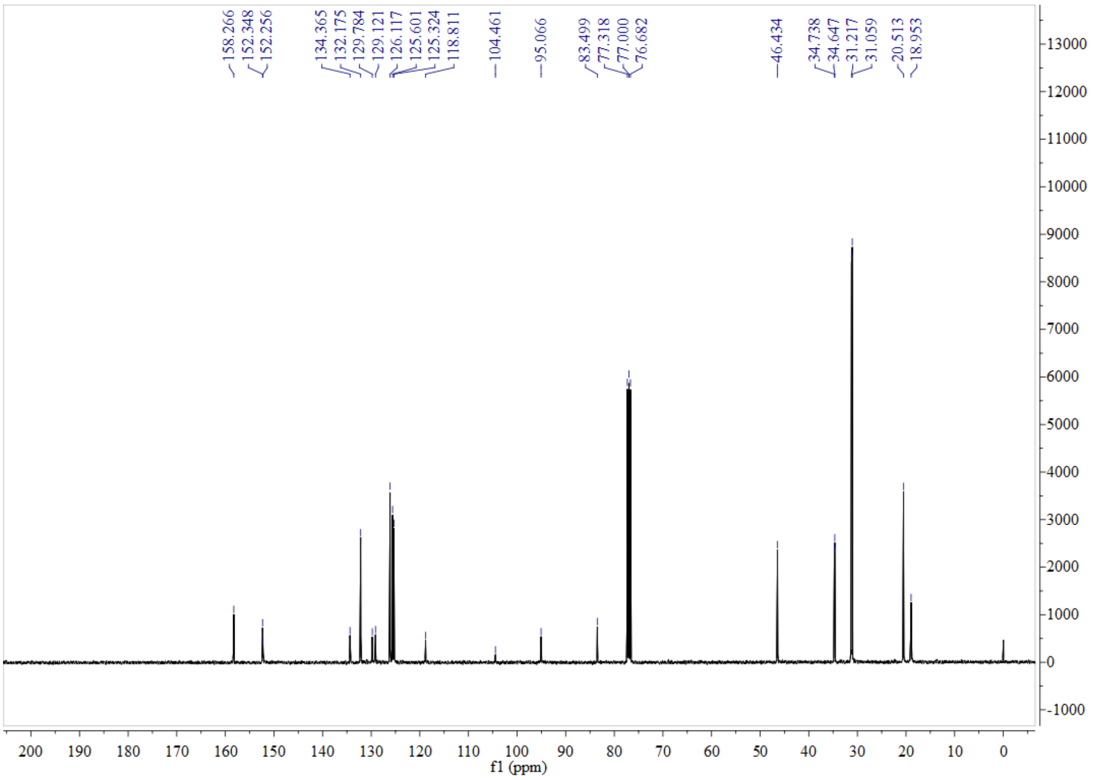

158.138
139.257
134.523
132.191
130.902
129.388
129.344
129.118
128.790
126.397
118.734
104.941
95.285
83.589
77.318
77.000
76.683
54.464
30.148
28.402
26.064
26.047
25.130
21.535
21.126
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)

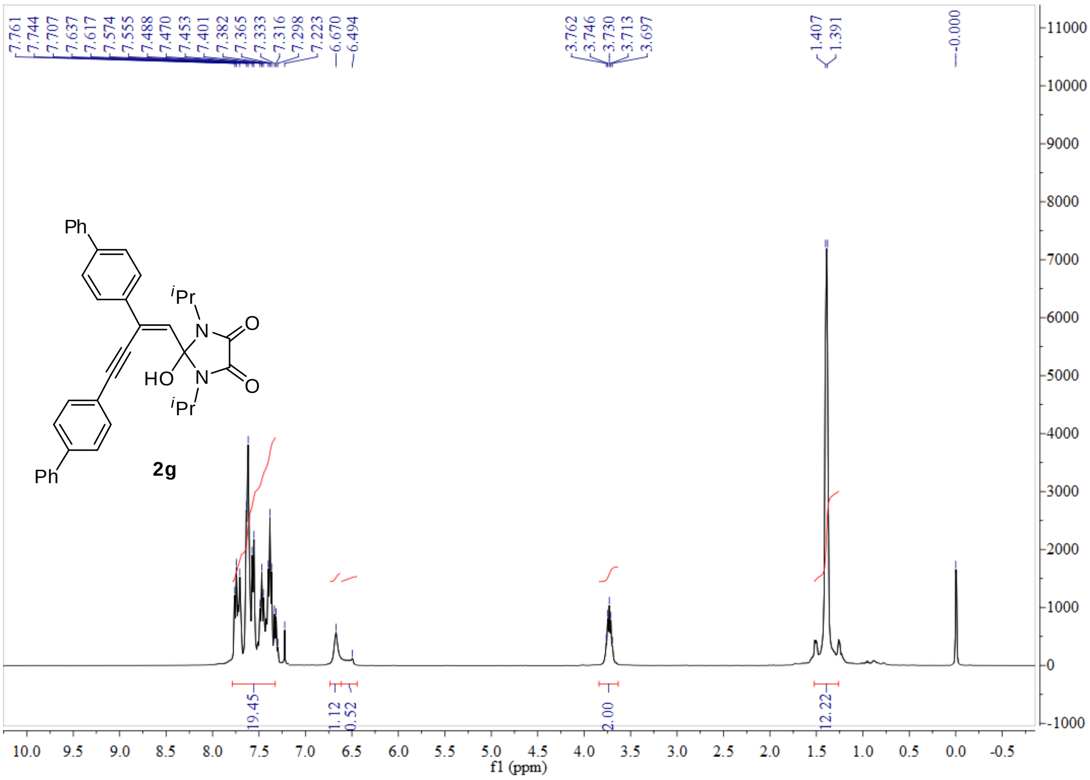

7.723
7.715
7.709
7.701
7.538
7.529
7.523
7.515
7.506
7.274
7.260
7.251
7.239
7.222
7.204
7.190
7.185
7.172
7.169
7.125
6.070
5.832
3.871
3.855
3.838
3.821
3.804
3.787
3.770
2.479
2.239
1.536
1.518
1.495
1.478
-0.000
iPr
N
O
HO
N
O
iPr
2e
0.89
1.94
5.26
0.86
0.95
2.00
2.98
3.15
6.08
6.21
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
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
-0.5
-1.0
f1 (ppm)

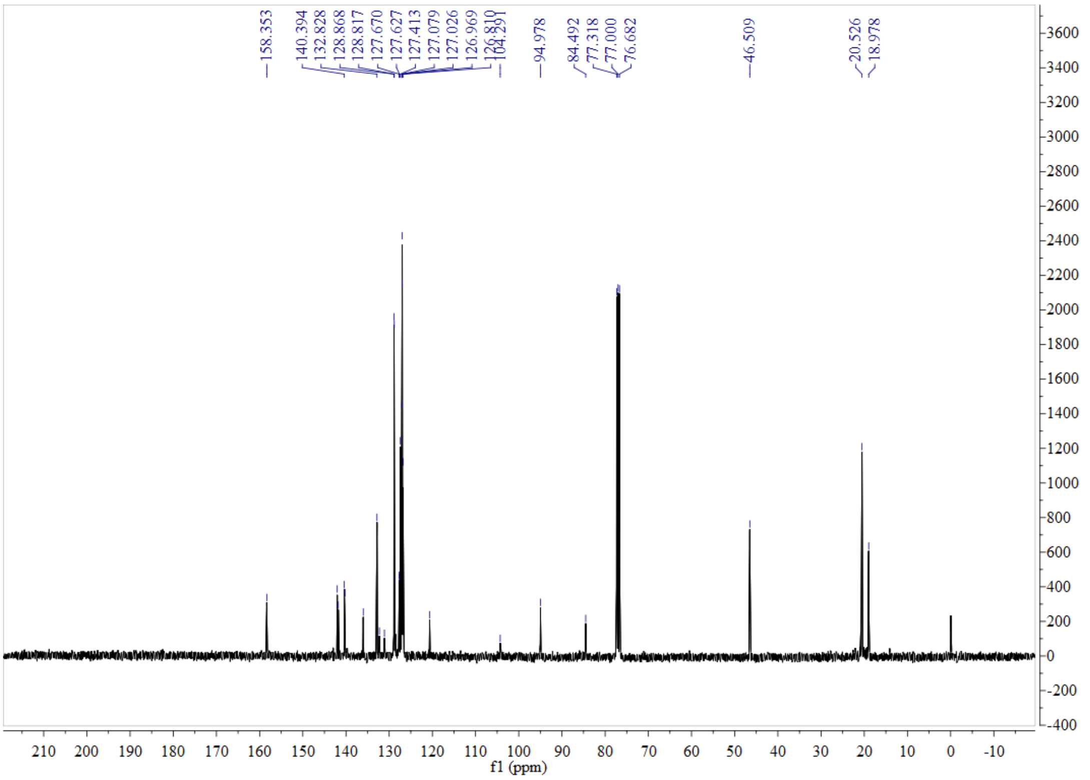

157.951
135.125
134.104
132.866
132.293
130.907
130.824
129.239
128.825
128.770
128.504
126.167
125.990
103.330
95.040
87.962
77.318
77.000
76.683
46.572
20.706
20.552
20.241
19.163
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)

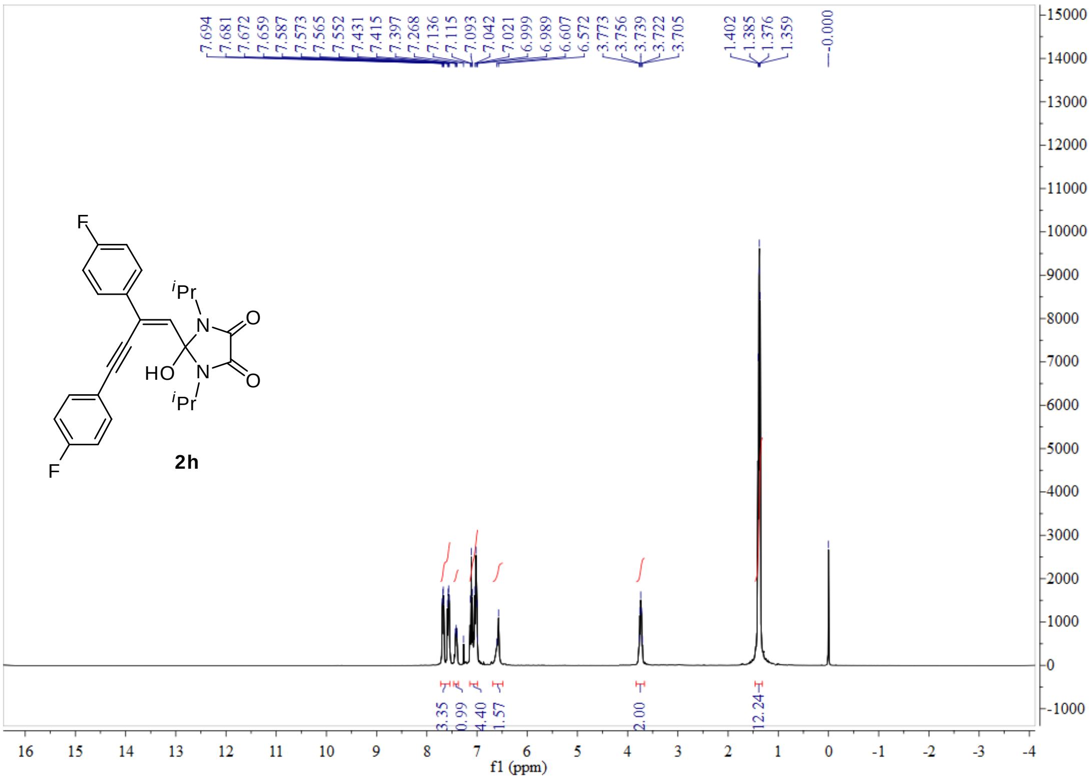

7.659
7.638
7.564
7.544
7.449
7.428
7.389
7.368
7.245
6.598
6.525
3.708
3.692
3.675
3.658
3.641
1.353
1.334
1.263
0.000
1.97
2.02
2.01
2.04
0.89
0.90
2.00
21.03
9.08
40000
35000
30000
25000
20000
15000
10000
5000
0
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)
^{t}Bu
^{i}Pr
N
O
HO
N
O
^{i}Pr
^{t}Bu

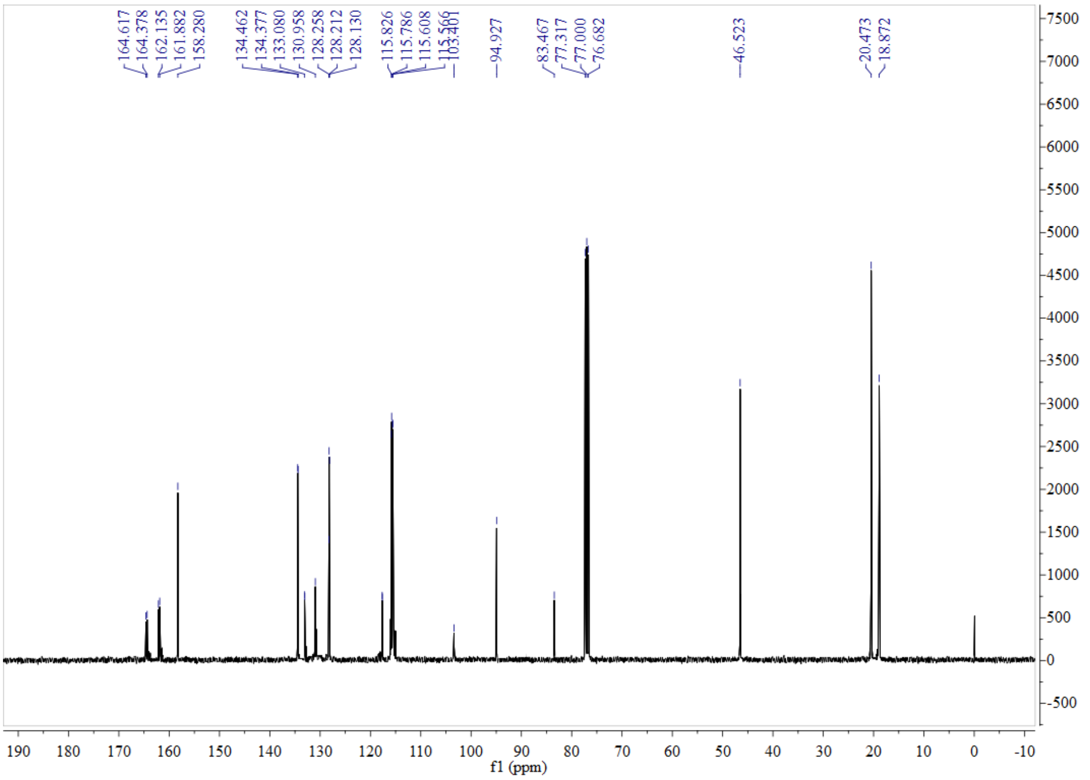
2f

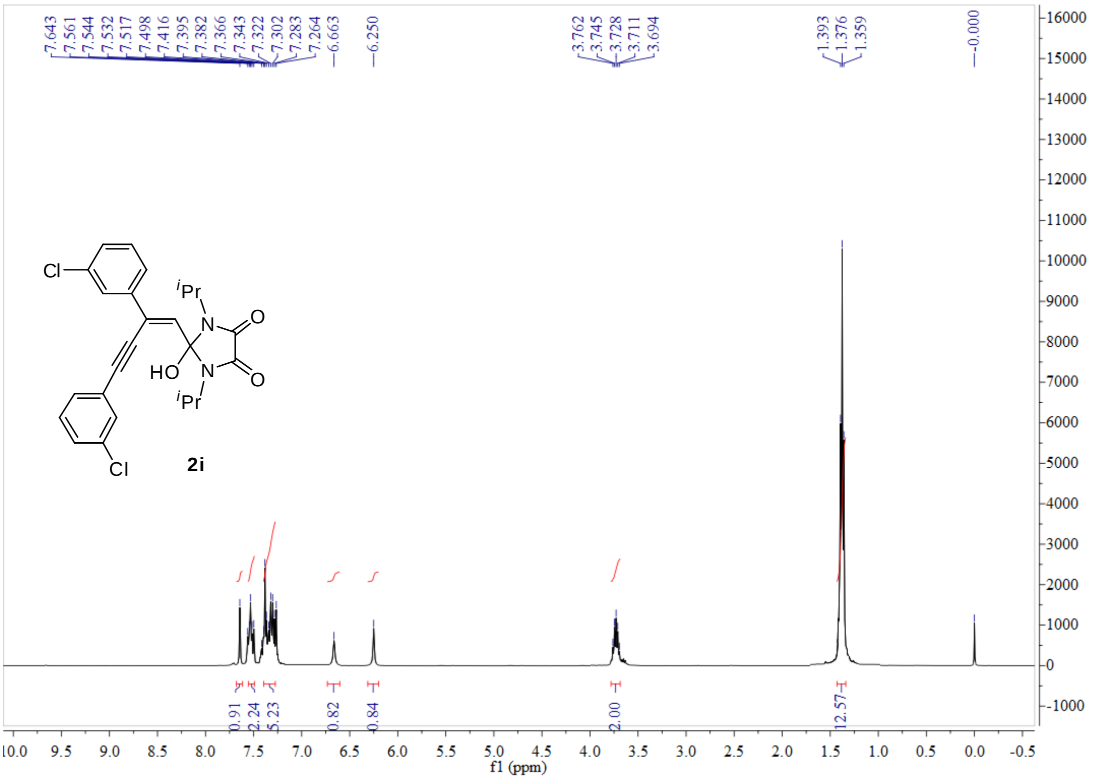

158.266
152.348
152.256
134.365
132.175
129.784
129.121
126.117
125.601
125.324
118.811
104.461
95.066
83.499
77.318
77.000
76.682
46.434
34.738
34.647
31.217
31.059
20.513
18.953
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

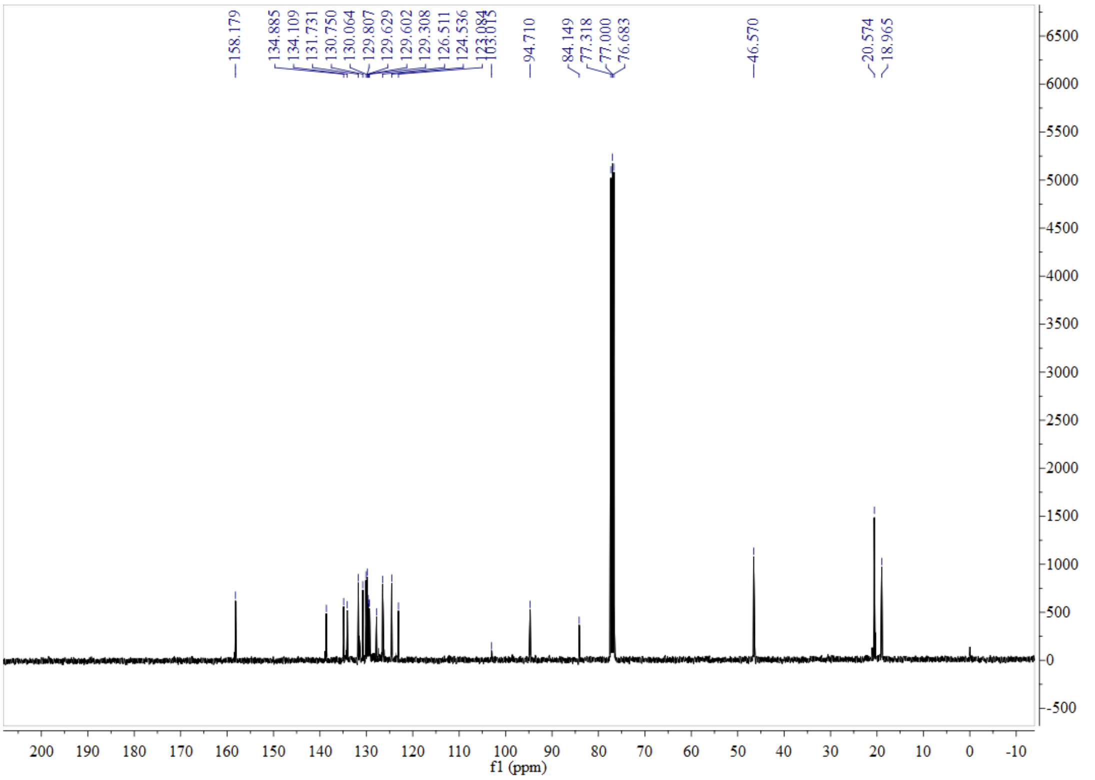

7.761
7.744
7.707
7.637
7.617
7.574
7.555
7.488
7.470
7.453
7.401
7.382
7.365
7.333
7.316
7.298
7.223
6.670
6.494
3.762
3.746
3.730
3.713
3.697
1.407
1.391
-0.000
Ph
^{i}Pr
N
O
HO
N
O
^{i}Pr
Ph
2g
19.45
1.12
0.52
2.00
12.22
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
10.0
9.5
9.0
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
-0.5
f1 (ppm)

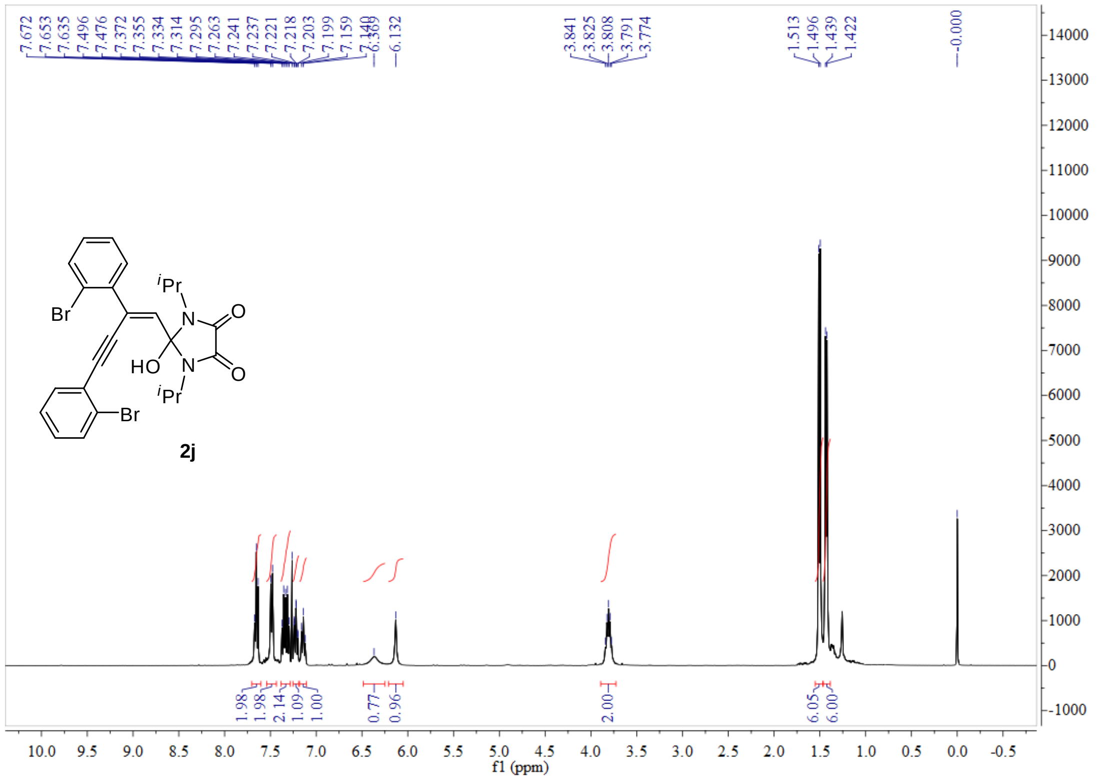

158.353
140.394
132.828
128.868
128.817
127.670
127.627
127.413
127.079
127.026
126.969
126.810
104.291
94.978
84.492
77.318
77.000
76.682
46.509
20.526
18.978
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)


7.694
7.681
7.672
7.659
7.587
7.573
7.565
7.552
7.431
7.415
7.397
7.268
7.136
7.115
7.093
7.042
7.021
6.999
6.989
6.607
6.572
3.773
3.756
3.739
3.722
3.705
1.402
1.385
1.376
1.359
-0.000
3.35
0.99
4.40
1.57
2.00
12.24
F
F
^{i}Pr
^{i}Pr
N
N
O
O
HO
2h
f1 (ppm)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000

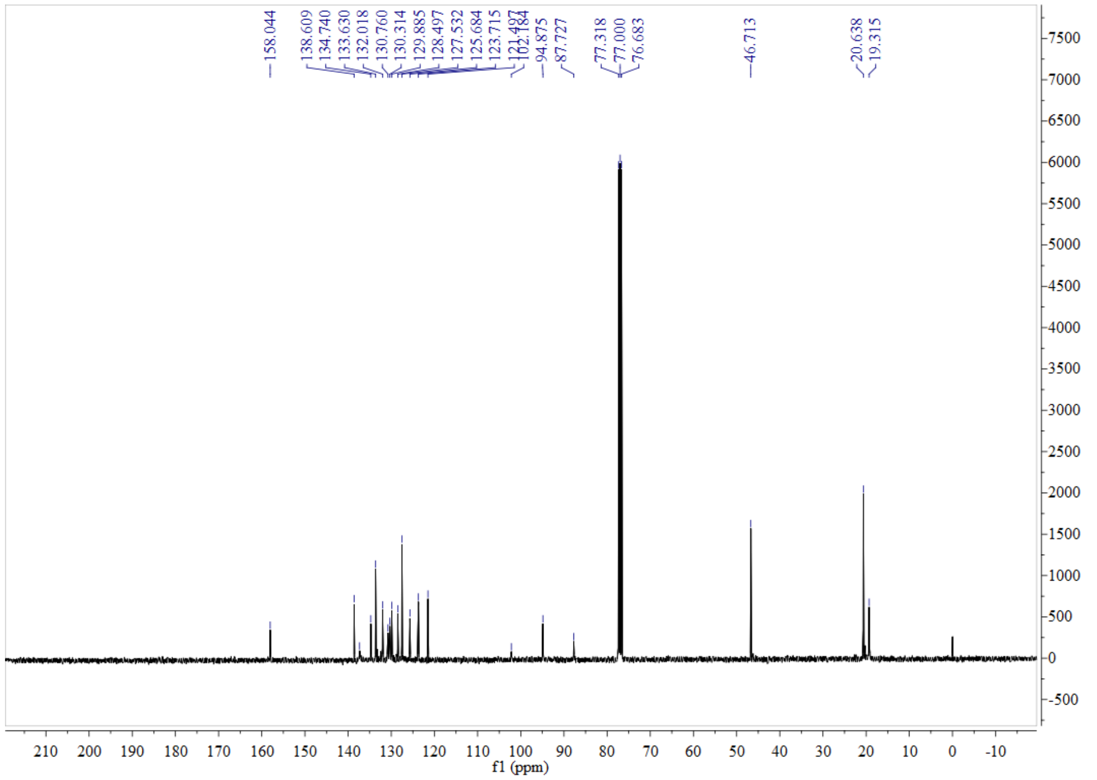

164.617
164.378
162.135
161.882
158.280
134.462
134.377
133.080
130.958
128.258
128.212
128.130
115.826
115.786
115.608
115.566
103.401
94.927
83.467
77.317
77.000
76.682
46.523
20.473
18.872
f1 (ppm)
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500

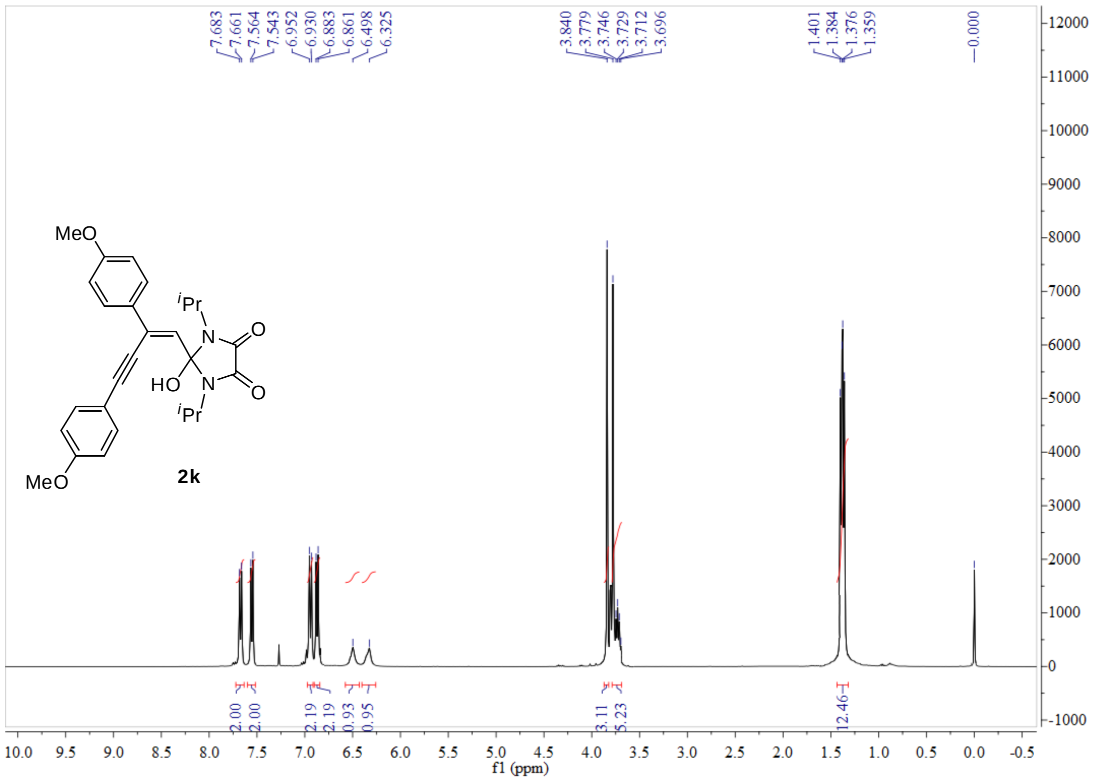

7.643
7.561
7.544
7.532
7.517
7.498
7.416
7.395
7.382
7.366
7.343
7.322
7.302
7.283
7.264
6.663
6.250
3.762
3.745
3.728
3.711
3.694
1.393
1.376
1.359
0.000
Cl
^{i}Pr
N
O
HO
N
O
^{i}Pr
Cl
2i
0.91
2.24
5.23
0.82
0.84
2.00
12.57
f1 (ppm)

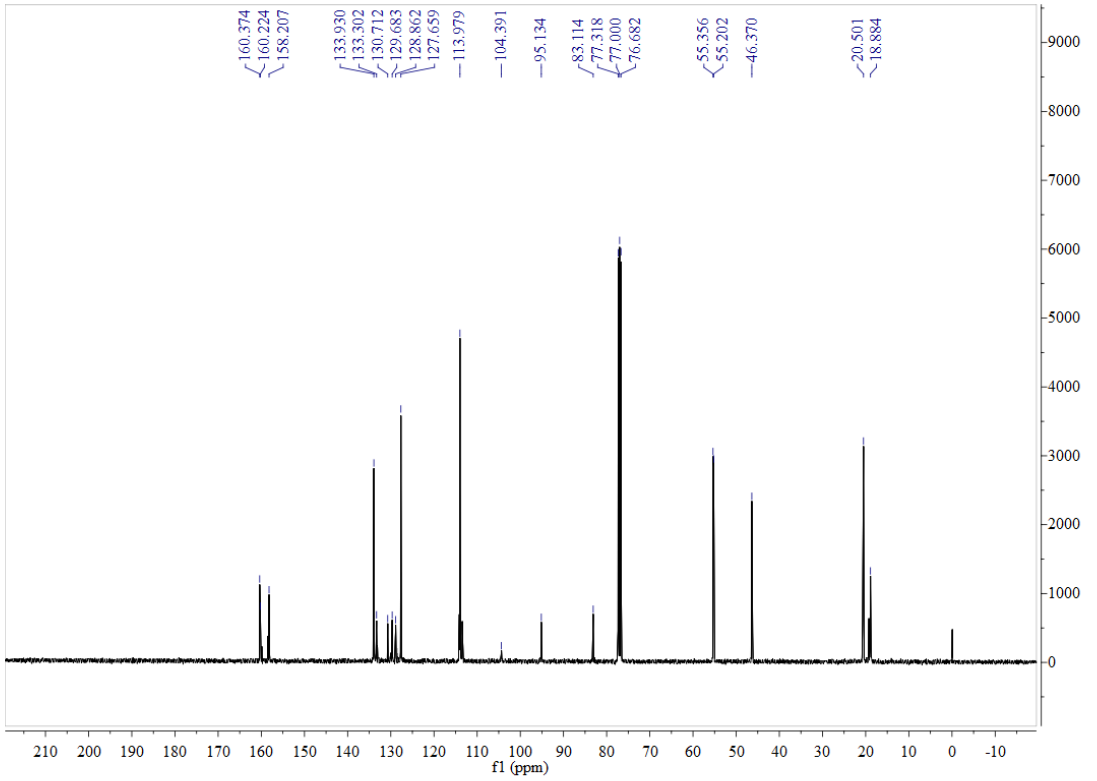

158.179
134.885
134.109
131.731
130.750
130.064
129.807
129.629
129.602
129.308
126.511
124.536
123.084
103.015
94.710
84.149
77.318
77.000
76.683
46.570
20.574
18.965
f1 (ppm)

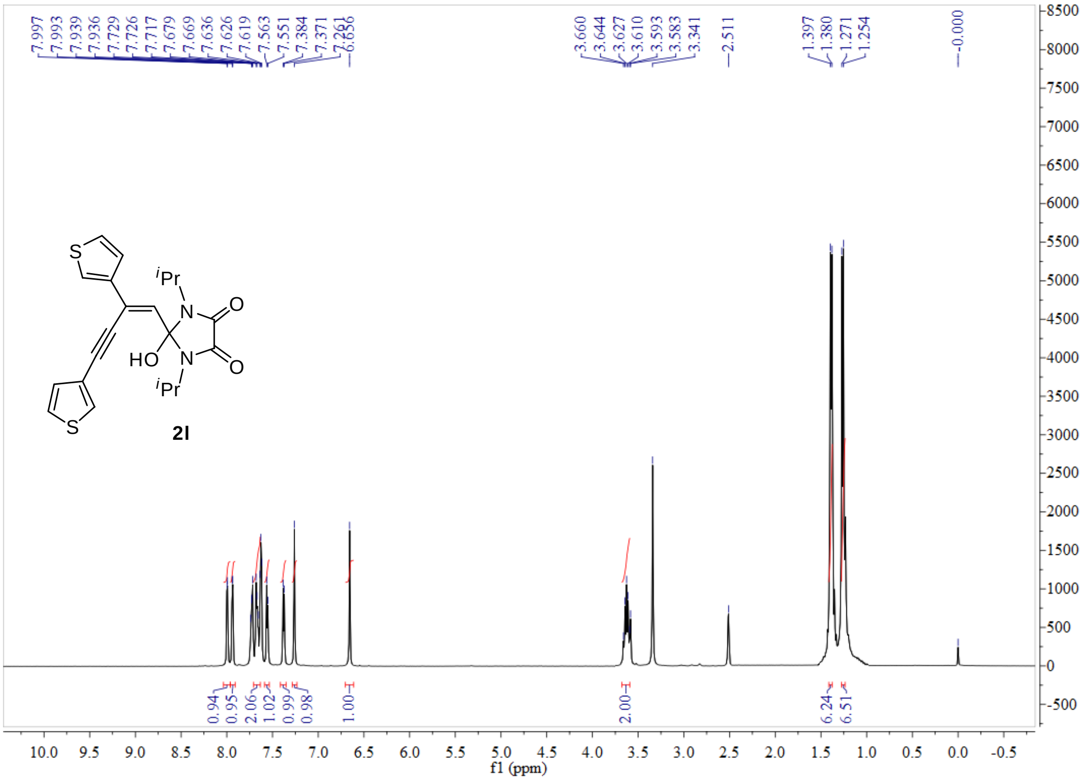

7.672
7.653
7.635
7.496
7.476
7.372
7.355
7.334
7.314
7.295
7.263
7.241
7.237
7.221
7.218
7.203
7.199
7.159
7.140
6.369
6.132
3.841
3.825
3.808
3.791
3.774
1.513
1.496
1.439
1.422
-0.000
Br
iPr
N
O
HO
N
O
iPr
Br
1.98
1.98
2.14
1.09
1.00
0.77
0.96
2.00
6.05
6.00
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000

2j

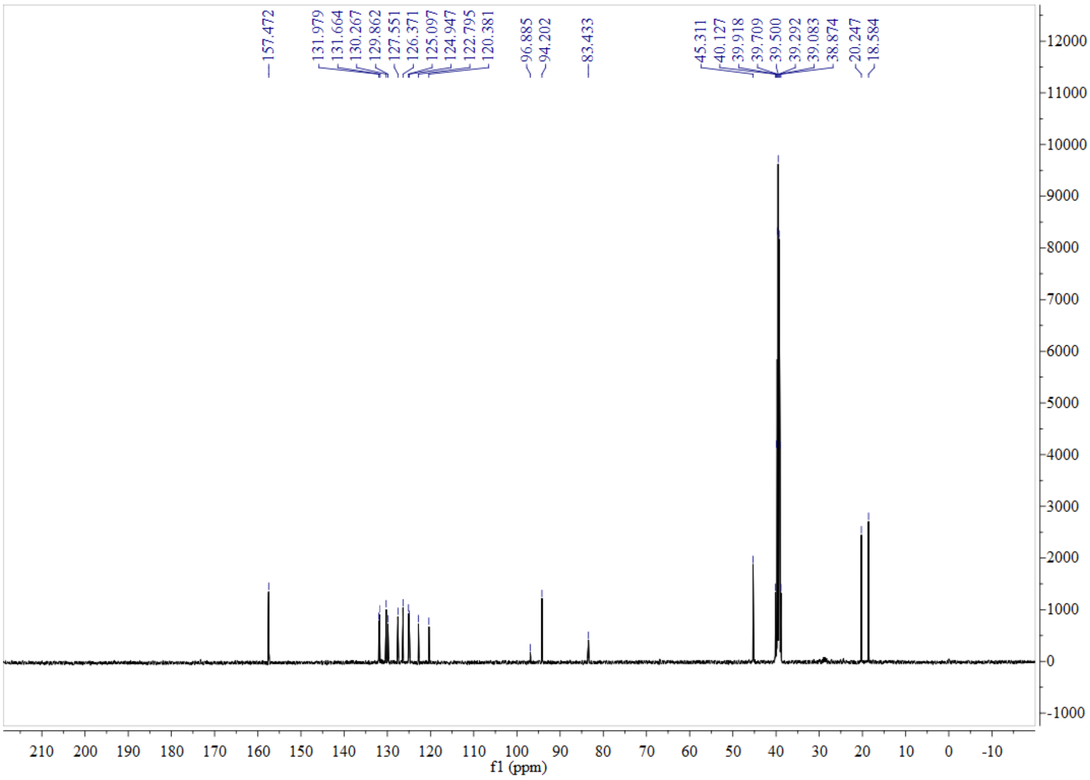

158.044
138.609
134.740
133.630
132.018
130.760
130.314
129.885
128.497
127.532
125.684
123.715
121.497
102.184
94.875
87.727
77.318
77.000
76.683
46.713
20.638
19.315
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500

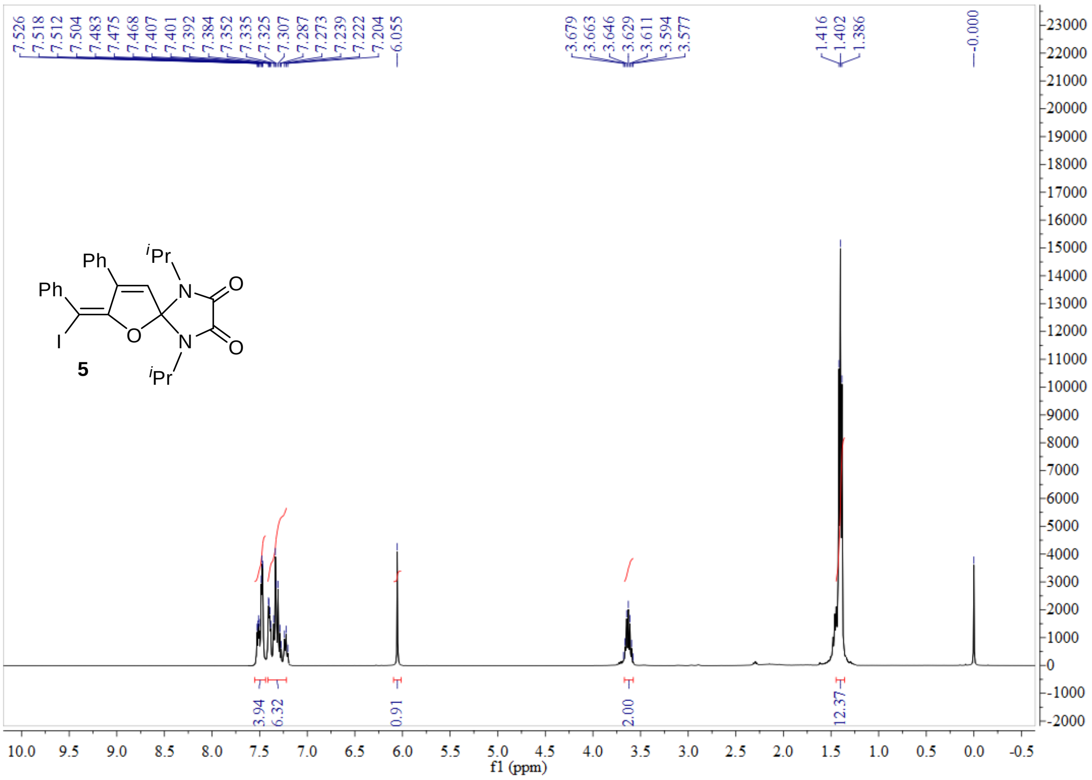

7.683
7.661
7.564
7.543
6.952
6.930
6.883
6.861
6.498
6.325
3.840
3.779
3.746
3.729
3.712
3.696
1.401
1.384
1.376
1.359
0.000
MeO
MeO
^{i}Pr
^{i}Pr
N
N
O
O
HO
2k
2.00
2.00
2.19
2.19
0.93
0.95
3.11
5.23
12.46
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)
12000 11000 10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 0 -1000

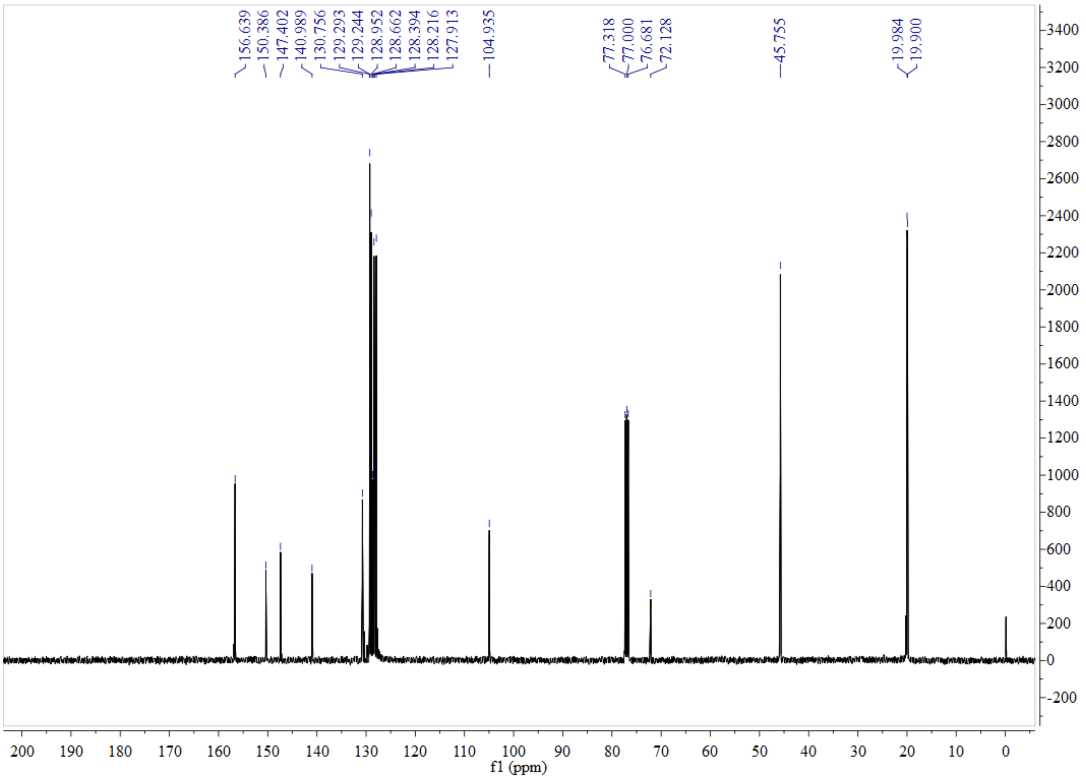

160.374
160.224
158.207
133.930
133.302
130.712
129.683
128.862
127.659
113.979
104.391
95.134
83.114
77.318
77.000
76.682
55.356
55.202
46.370
20.501
18.884
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)
9000 8000 7000 6000 5000 4000 3000 2000 1000 0


7.997
7.993
7.939
7.936
7.729
7.726
7.717
7.679
7.669
7.636
7.626
7.619
7.563
7.551
7.384
7.371
7.261
6.656
3.660
3.644
3.627
3.610
3.593
3.583
3.341
2.511
1.397
1.380
1.271
1.254
0.000
0.94
0.95
2.06
1.02
0.99
0.98
1.00
2.00
6.24
6.51
S
S
iPr
iPr
N
N
O
O
HO
f1 (ppm)
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
-0.5
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500

2l


157.472
131.979
131.664
130.267
129.862
127.551
126.371
125.097
124.947
122.795
120.381
96.885
94.202
83.433
45.311
40.127
39.918
39.709
39.500
39.292
39.083
38.874
20.247
18.584
f1 (ppm)
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000


7.526
7.518
7.512
7.504
7.483
7.475
7.468
7.407
7.401
7.392
7.384
7.352
7.335
7.325
7.307
7.287
7.273
7.239
7.222
7.204
6.055
3.679
3.663
3.646
3.629
3.611
3.594
3.577
1.416
1.402
1.386
-0.000
Ph
Ph
I
O
N
N
O
O
^{i}Pr
^{i}Pr
5
3.94
6.32
0.91
2.00
12.37
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 -0.5
f1 (ppm)
23000 22000 21000 20000 19000 18000 17000 16000 15000 14000 13000 12000 11000 10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 0 -1000 -2000


156.639
150.386
147.402
140.989
130.756
129.293
129.244
128.952
128.662
128.394
128.216
127.913
104.935
77.318
77.000
76.681
72.128
45.755
19.984
19.900
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
f1 (ppm)
3400 3200 3000 2800 2600 2400 2200 2000 1800 1600 1400 1200 1000 800 600 400 200 0 -200