Electrochemically induced oxidative S-O coupling: synthesis of sulfonates from sulfonyl hydrazides and *N*-hydroxyimides or *N*-hydroxybenzotriazoles

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SUPPORTING INFORMATION

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General

NMR spectra were registered on Bruker Avance II 300 MHz instrumental. Chemical shifts were measured relative to residual solvent peaks as an internal standard set to δ 7.25 and δ 77.0 ($CDCl_3$), δ 2.50 and δ 39.51 (DMSO-d_6). High resolution mass spectra (HRMS) were measured on a Bruker maXis instrument equipped with an electrospray ionization (ESI) ion source. [1] The measurements were done in a positive ion mode (interface capillary voltage 4500 V); the mass ratio was from m/z 50 to 3000 Da; external/internal calibration was done with Electrospray Calibrant Solution. A syringe injection was used for solutions in CH_3CN (flow rate 3 μL/min). Nitrogen was applied as a dry gas; interface temperature was set at 180°C. The TLC analyses were carried out on standard silica-gel chromatography plates. The melting points were determined on a Kofler hot-stage apparatus. Chromatography was performed on silica gel (60-200 mesh).

p-Toluenesulfonohydrazide (**1a**), benzenesulfonohydrazide (**1j**), methanesulfonohydrazide (**1m**), *N*-hydroxysuccinimide (**2a**), 2-hydroxyisoindoline-1,3-dione (**2b**), 4,5,6,7-tetrachloro-2-hydroxyisoindoline-1,3-dione (**2c**), 2-hydroxy-3a,4,7,7a-tetrahydro-1*H*-4,7-methanoisoindole-1,3-dione (**2d**), 1*H*-benzo[d][1,2,3]triazol-1-ol (**2e**), 7-chloro-1*H*-benzo[d][1,2,3]triazol-1-ol (**2f**), sodium *p*-toluenesulfinate (**4a**), sodium benzenesulfinate (**4j**), 4-methoxybenzenesulfonyl chloride, 4-fluorobenzenesulfonyl chloride, 4-chlorobenzenesulfonyl chloride, 4-bromobenzenesulfonyl chloride, 4-iodobenzenesulfonyl chloride, 4-acetamidobenzenesulfonyl chloride, naphthalene-2-sulfonyl chloride, 2,4,6-trimethylbenzenesulfonyl chloride, isothiazole-5-sulfonyl chloride, thiophene-2-sulfonyl chloride, tetrabutylammonium perchlorate, NH_4I, NH_4Br, NH_4Cl, KBr, NaBr, $LiClO_4$, Na_2SO_4, Br_2, KOH, THF, MeCN, MeOH, EtOH, $CHCl_3$, petroleum ether (PE, 40/70), ethyl acetate (EA) were purchased from commercial sources and were used as is.

4-Methoxybenzenesulfonohydrazide (**1b**), 4-fluorobenzenesulfonohydrazide (**1c**), 4-chlorobenzenesulfonohydrazide (**1d**), 4-bromobenzenesulfonohydrazide (**1e**), 4-iodobenzenesulfonohydrazide (**1f**), 4-acetamidobenzenesulfonohydrazide (**1g**), naphthalene-2-sulfonohydrazide (**1h**), 2,4,6-trimethylbenzenesulfonohydrazide (**1i**), isothiazole-5-sulfonohydrazide (**1k**), thiophene-2-sulfonohydrazide (**1l**) were synthesized according to the literature through the reaction between corresponding sulfonyl chlorides and hydrazine hydrate.[2] Sodium *p*-chlorobenzene sulfinate (**4d**) was synthesized according to the literature through the reduction of *p*-chlorobenzenesulfonyl chloride.[3]

Voltammetric studies were carried out using potentiostat Elins P-30JM with the scan 100 $mV \cdot s^{-1}$ in a temperature-controlled (25 °C) glass cell (V = 10 mL) under a nitrogen atmosphere. A glassy carbon disk (d = 2.9 mm) was used as the working electrode (polished before each measurement). Software iR compensation using ferrocene (R = 700 Ω) was used in all experiments. A saturated calomel electrode (SCE) separated from the solution being studied by a salt bridge filled with the supporting electrolyte (0.1 M Bu_4NClO_4 in H_2O-THF (1:1)) was used as the reference electrode. A platinum plate (3 cm^2) was used as the counter electrode. All experiments were performed with the concentration of a studied compound of 3 mM in H_2O-THF (1:1).

Electrochemical Study of Redox Properties of the Reagents

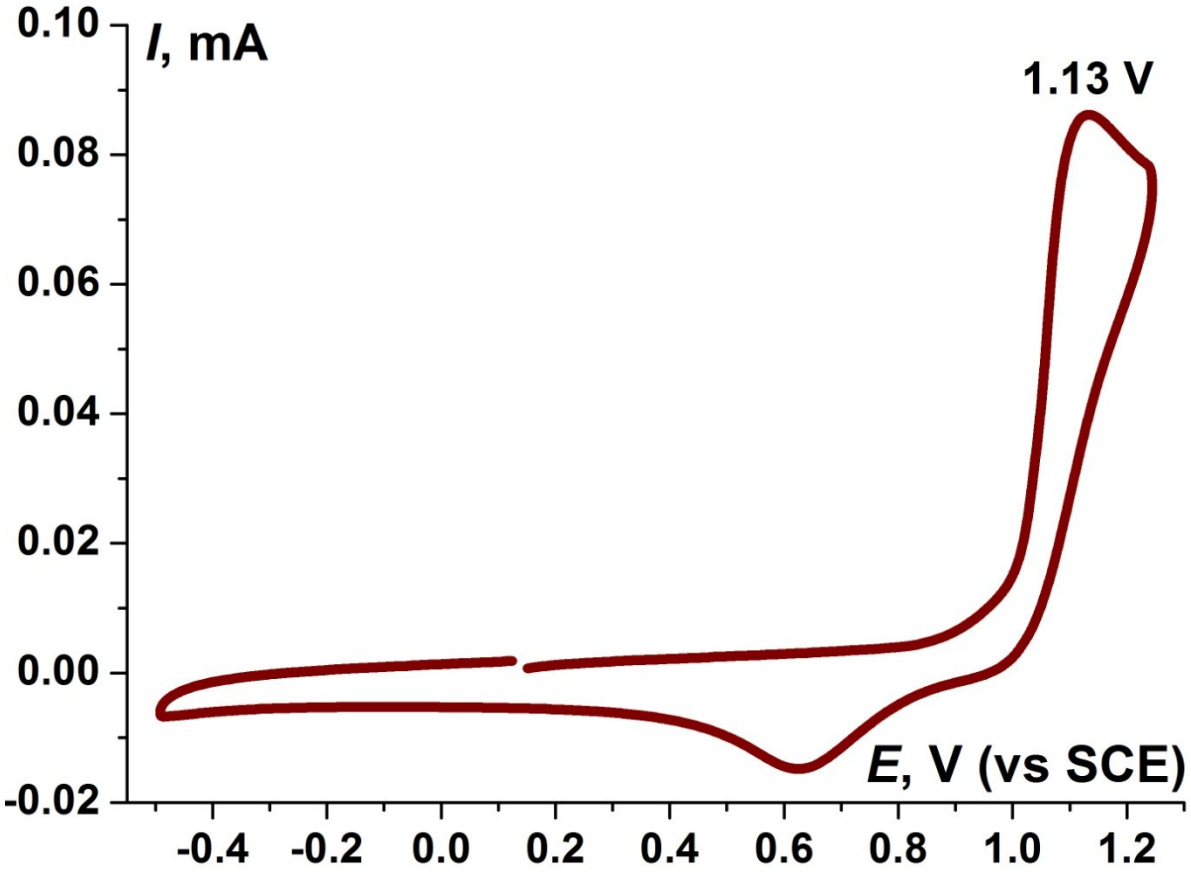


Figure 1a. The CV curve obtained for 3.0 mmol·L^{-1} solution of NH_4Br in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) at a scan rate of 100 mV·s^{-1}.

Table 1a. CV curve parameters in V *vs* SCE for NH_4Br solution in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) under a scan rate of 100 mV·s^{-1}

Substance	E^{onset}	*Scan direction*	$E^{peak}_{forward}$	$E^{peak}_{reverse}$	$E^{1/2}$
Br^-	0.85	+	1.13	0.63	1.05

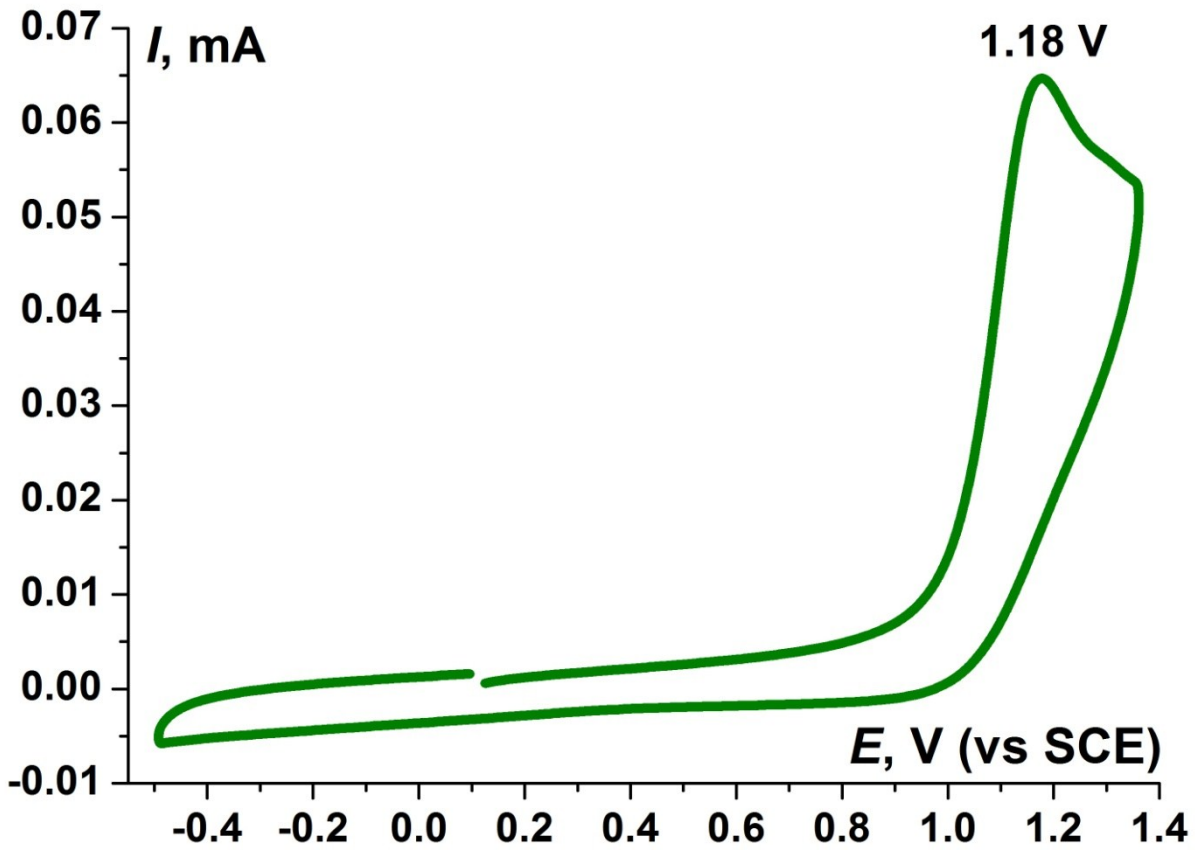


Figure 2a. The CV curve obtained for 3.0 mmol·L^{-1} solution of *p*-toluenesulfonyl hydrazide **1a** in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) at a scan rate of 100 mV·s^{-1}.

Table 2a. CV curve parameters in V *vs* SCE for *p*-toluenesulfonyl hydrazide **1a** solution in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) under a scan rate of 100 mV·s^{-1}

Substance	E^{onset}	*Scan direction*	$E^{peak}_{forward}$	$E^{peak}_{reverse}$	$E^{1/2}$
$TsNHNH_2$	0.92	+	1.18	-	1.08

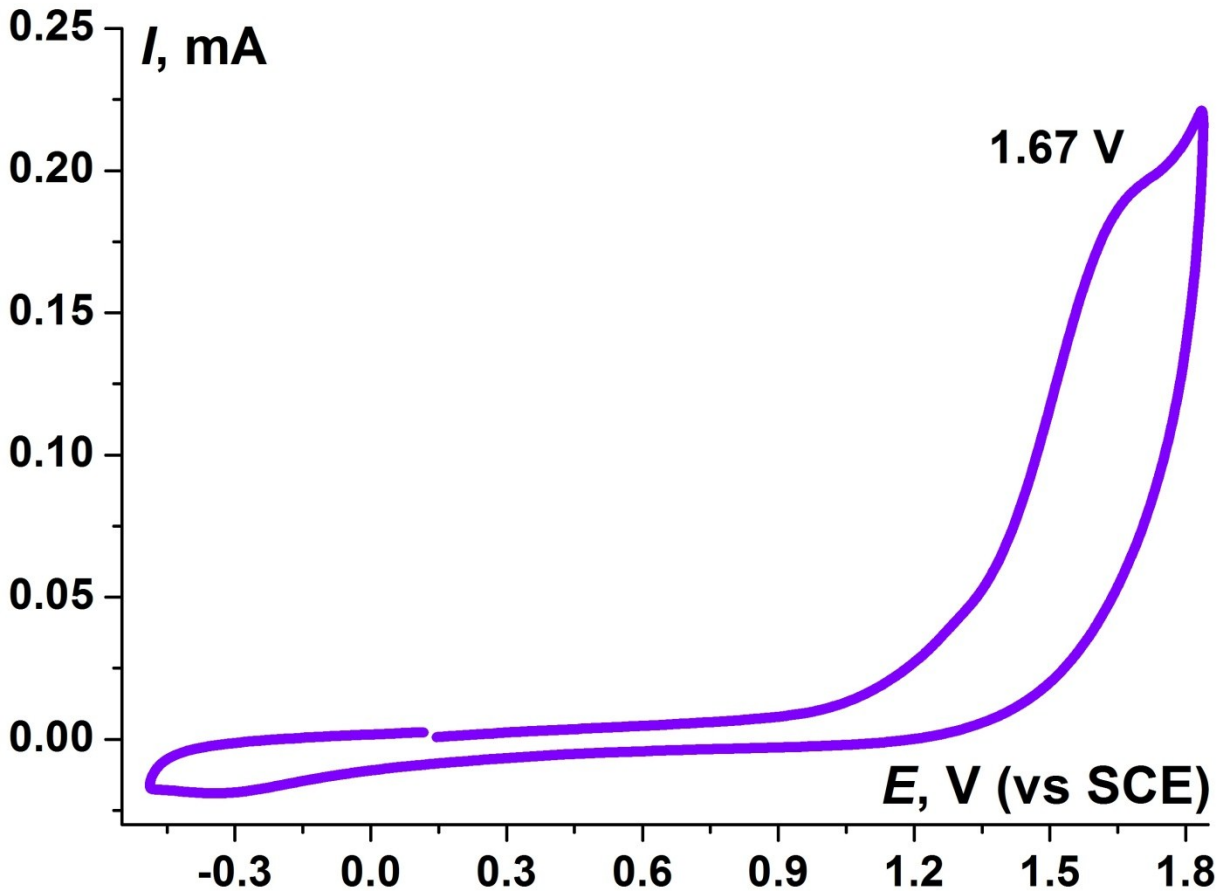


Figure 3a. The CV curve obtained for 3.0 mmol·L^{-1} solution of *N*-hydroxysuccinimide **2a** in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) at a scan rate of 100 mV·s^{-1}.

Table 3a. CV curve parameters in V *vs* SCE for *N*-hydroxysuccinimide **2a** solution in 0.1 M Bu_4NClO_4 in H_2O-THF (1:1) on a working glassy-carbon electrode (d = 2.9 mm) under a scan rate of 100 mV·s^{-1}

Substance	E^{onset}	*Scan direction*	$E^{peak}_{forward}$	$E^{peak}_{reverse}$	$E^{1/2}$
N-hydroxysuccinimide	1.13	+	1.67	-	1.47

Electrochemical reaction of sulfonyl hydrazides with *N*-hydroxy compounds

General procedure 1. Optimization of the reaction conditions for synthesis of 3aa from sulfonyl hydrazide 1a and *N*-hydroxysuccinimide 2a (Table 1): An undivided cell was equipped with a carbon plate anode (5 cm^2) and a stainless steel plate cathode (5 cm^2) and connected to a DC regulated power supply. The solution of of *p*-toluenesulfonyl hydrazide **1a** (1 mmol, 186 mg), *N*-hydroxysuccinimide **2a** (1 mmol, 115 mg) and supporting electrolyte (0.2-3 mmol, 20-435 mg) in H_2O-THF (1:1, 30 mL), H_2O-MeCN (1:1), MeOH-THF (1:1) or MeOH was electrolyzed under constant current conditions (60 mA/cm^2 at 25-60 °C) under magnetic stirring. Electrodes were washed with EA (10 mL), after that reaction mixture was diluted with this EA and organic and water layers were separated. Water layer was extracted with EA (3×10 mL). Combined organic phase was washed with brine (2×8 mL), dried over Na_2SO_4 and concentrated under reduced pressure. The residue was recrystallized from EtOH to give pure desired **3aa** product.

Calculation of the time, which is necessary for passing of exact amount of electricity (representative example Table 1, entry 1).

It is necessary to pass 4 F/mol **1a** of electricity.

$Q = N \cdot F \cdot n_r$
Q — amount of passed electric current, C (Coulomb)
N — number of electrons passed in the cell per 1 molecule of sulfonyl hydrazide **1a**, F/mol
F — Faraday constant, F = 96485 $C \cdot mol^{-1}$
n_r — amount of sulfonyl hydrazide **1a**, mol
$Q = 4 \cdot 96485 \cdot 1 \cdot 10^{-3} = 386$ C

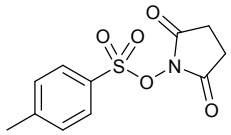
$t = \frac{Q}{I}$
t — time, sec
Q — amount of passed electric current, C (Coulomb)
I — electric current, A
$t = \frac{386}{0.3} = 1286\text{sec} = 21.5\ min$

General procedure 2. Synthesis of products 3aa-3ma, 3ab-3af (Table 2). An undivided cell was equipped with a carbon plate anode (5 cm^2) and a stainless steel plate cathode (5 cm^2) and connected to a DC regulated power supply. The solution of sulfonyl hydrazide **1a-1m** (1 mmol), *N*-hydroxy compound **2a-2f** (1 mmol) and supporting electrolyte NH_4Br (3 mmol) in 30 ml of THF-H_2O (1:1) was electrolyzed using constant current conditions (I = 300 mA, j = 60 mA/cm^2, τ = 1 hour, T = 40 °C) under magnetic stirring. Electrodes were washed with EA (10 mL), after that reaction mixture was diluted with this EA and organic and water layers were separated. Water layer was extracted with EA (3×10 mL). Combined organic phase was washed with brine (2×8 mL), dried over Na_2SO_4 and concentrated under reduced pressure. The desired products **3aa-3ma**, **3ab-3af** were isolated by chromatography on SiO_2 with elution using PE-EA in a gradient of the latter from 10 to 75 vol %.

General procedure 3. Synthesis of products 3aa, 3da, 3ja (Scheme 2) from sodium sulfinates 4a, 4d, 4j and *N*-hydroxysuccinimide 2a (Scheme 2). An undivided cell was equipped with a carbon plate anode (5 cm^2) and a stainless steel plate cathode (5 cm^2) and connected to a DC regulated power supply. The solution of sodium sulfinate **4a, 4d, 4j** (1

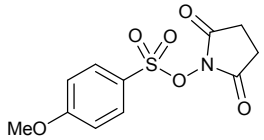
mmol), *N*-hydroxysuccinimide **2a** (1 mmol) and supporting electrolyte NH_4Br (3 mmol) in THF-H_2O (1:1, 30 mL) was electrolyzed using constant current conditions (I = 300 mA, j = 60 mA/cm^2, τ = 1 hour, T = 40 °C) under magnetic stirring. Electrodes were washed with EA (10 mL), after that reaction mixture was diluted with this EA and organic and water layers were separated. Water layer was washed with EA (3×10 mL). Combined organic phase was washed with brine (2×8 mL), dried over Na_2SO_4 and concentrated under reduced pressure. The yields of desired products **3aa, 3da, 3ja** were determined with NMR using 1, 4-dinitrobenzene as internal standard.

*2,5-Dioxopyrrolidin-1-yl 4-methylbenzenesulfonate **(3aa)**.*[4]



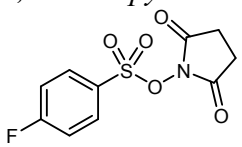
White solid, m.p. = 143-144 °C. Yield 95%. R_f = 0.49 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.45 (s, 3H), 2.78 (s, 4H), 7.37 (d, J = 8.1 Hz, 2H), 7.89 (J = 8.1 Hz, 2H). ^{13}C NMR ($CDCl_3$), δ: 21.8, 25.3, 129.3, 130.0, 131.0, 147.0, 168.6.

*2,5-Dioxopyrrolidin-1-yl 4-methoxybenzenesulfonate **(3ba)**.*



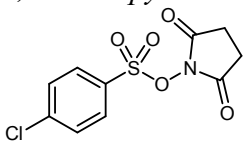
White solid, m.p. = 172-173 °C. Yield 67%. R_f = 0.25 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.70 (s, 4H), 3.89 (s, 3H), 7.18 (d, J = 8.9 Hz, 2H), 7.94 (J = 8.9 Hz, 2H). ^{13}C NMR (DMSO-d_6), δ: 25.4, 56.1, 115.1, 124.1, 131.7, 165.0, 169.7. HRMS (ESI) m/z (M+Na$^+$) calculated for $[C_{11}H_{11}NNaO_6S]^+$: 308.0199. Found: 308.0204.

*2,5-Dioxopyrrolidin-1-yl 4-fluorobenzenesulfonate **(3ca)**.*



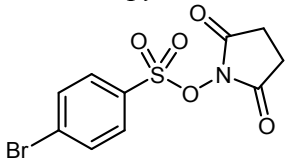
White solid, m.p. = 113-114 °C. Yield 73%. R_f = 0.55 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.69 (s, 4H), 7.51-7.57 (m, 2H), 8.10-8.14 (m, 2H). ^{13}C NMR (DMSO-d_6), δ: 25.4, 117.3 (d, ^{2}J = 11.6 Hz), 129.5 (d, ^{4}J = 1.1 Hz), 132.7 (d, ^{3}J = 5.5 Hz), 166.3 (d, ^{1}J = 128.3 Hz), 169.7. HRMS (ESI) m/z (M+Na$^+$) calculated for $[C_{10}H_8FNNaO_5S]^+$: 295.9999. Found: 296.0005.

*2,5-Dioxopyrrolidin-1-yl 4-chlorobenzenesulfonate **(3da)**.*



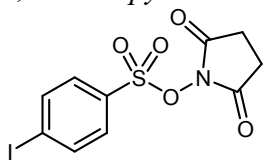
White solid, m.p. = 171-172 °C. Yield 75%. R_f = 0.56 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.70 (s, 4H), 7.77 (d, J = 8.8 Hz, 2H), 8.04 (J = 8.8 Hz, 2H). ^{13}C NMR (DMSO-d_6), δ: 25.5, 130.1, 131.0, 132.2, 141.2, 169.7. HRMS (ESI) m/z (M+Na$^+$) calculated for $[C_{10}H_8ClNNaO_5S]^+$: 311.9704. Found: 311.9713.

*2,5-Dioxopyrrolidin-1-yl 4-bromobenzenesulfonate **(3ea)**.*



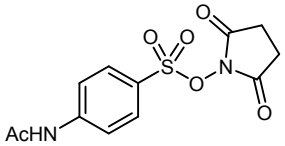
White solid, m.p. = 197-198 °C. Yield 65%. R_f = 0.56 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.70 (s, 4H), 7.90-7.97 (m, 4H). ^{13}C NMR (DMSO-d_6), δ: 25.4, 130.5, 130.9, 132.6, 133.0, 169.6. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{10}H_8BrNNaO_5S]^+$: 357.9178. Found: 357.9187.

2,5-Dioxopyrrolidin-1-yl 4-iodobenzenesulfonate ***(3fa)***.



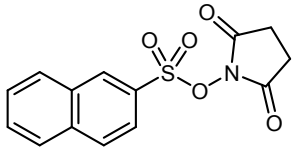
White solid, m.p. = 209-210 °C. Yield 19%. R_f = 0.56 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.70 (s, 4H), 7.75 (d, J = 7.3 Hz, 2H), 8.09 (J = 7.3 Hz, 2H). ^{13}C NMR (DMSO-d_6), δ: 25.4, 105.6, 130.3, 132.9, 138.8, 169.6. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{10}H_8INNaO_5S]^+$: 403.9060. Found: 403.9054.

*2,5-Dioxopyrrolidin-1-yl 4-acetamidobenzenesulfonate (****3ga****).*



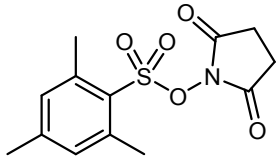
White solid, m.p. = 232-232.5 °C. Yield 45%. R_f = 0.24 (TLC, PE:EA, 1:5). ^{1}H NMR (DMSO-d_6), δ: 2.11 (s, 3H), 2.68 (s, 4H), 7.84 (d, J = 8.8 Hz, 2H), 7.92 (d, J = 8.8 Hz, 2H), 10.54 (s, 1H). ^{13}C NMR (DMSO-d_6), δ: 24.2, 25.4, 118.6, 125.7, 130.7, 145.8, 169.4, 169.6. HRMS (ESI) m/z (M+H^+) calculated for $[C_{12}H_{12}N_2NaO_6S]^+$: 335.0308. Found: 335.0308.

2,5-Dioxopyrrolidin-1-yl naphthalene-2-sulfonate ***(3ha)***.



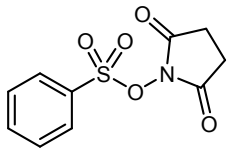
White solid, m.p. = 164-165 °C. Yield 87%. R_f = 0.46 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.69 (s, 4H), 7.73 (dd, J = 8.1, 7.2 Hz, 1H), 7.81 (dd, J = 8.0, 7.2 Hz, 1H), 7.97 (d, J = 9.5 Hz, 1H), 8.12 (d, J = 8.0 Hz, 1H), 8.22 (d, J = 9.5 Hz, 1H), 8.25 (d, J = 8.1 Hz, 1H), 8.79 (s, 1H). ^{13}C NMR (DMSO-d_6), δ: 25.4, 122.9, 128.0, 128.1, 129.8, 129.9, 130.3, 130.4, 131.5, 131.6, 135.6, 169.7. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{14}H_{11}NNaO_5S]^+$: 328.0250. Found: 328.0249.

2,5-Dioxopyrrolidin-1-yl 2,4,6-trimethylbenzenesulfonate ***(3ia)***.*[5]*



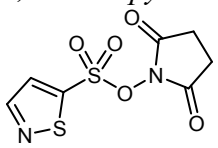
White solid, m.p. = 147-148 °C. Yield 17%. R_f = 0.56 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.32 (s, 3H), 2.65 (s, 6H), 2.76 (s, 4H), 7.00 (s, 2H). ^{13}C NMR ($CDCl_3$), δ: 21.2, 22.9, 26.3, 129.9, 131.9, 141.1, 145.1, 168.6.

*2,5-Dioxopyrrolidin-1-yl benzenesulfonate (****3ja****)*[6]



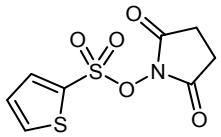
White solid, m.p. = 96-98 °C. Yield 62%. R_f = 0.59 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.79 (s, 4H), 7.59 (t, J = 7.7 Hz, 2H), 7.74 (t, J = 7.7 Hz, 1H), 8.04 (d, J = 7.7Hz, 2H). ^{13}C NMR ($CDCl_3$), δ: 25.4, 129.3, 129.4, 134.2, 135.5, 168.4.

*2,5-Dioxopyrrolidin-1-yl isothiazole-5-sulfonate (**3ka**)*



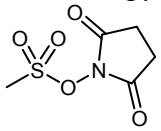
Yellow solid, m.p. = 83-85 °C. Yield 41%. R_f = 0.34 (TLC, PE:EA, 1:1). ^{1}H NMR (DMSO-d_6), δ: 2.74 (s, 4H), 8.36 (d, J = 2.0 Hz, 1H), 8.86 (d, J = 2.0 Hz, 1H). ^{13}C NMR (DMSO-d_6), δ: 25.5, 132.0, 155.5, 159.5, 169.5. HRMS (ESI) m/z ($M+Na^+$) calculated for $[C_7H_6N_2NaO_5S_2]^+$: 284.9610. Found: 284.9613.

*2,5-Dioxopyrrolidin-1-yl thiophene-2-sulfonate (**3la**)*



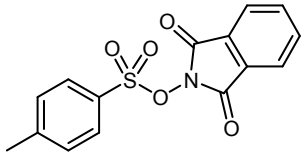
Yellow solid, m.p. = 109-111 °C. Yield 52%. R_f = 0.19 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.80 (s, 4H), 7.19-7.22 (m, 1H), 7.86 (d, J = 4.4 Hz, 1H), 7.90 (d, J = 2.9 Hz, 1H). ^{13}C NMR ($CDCl_3$), δ: 25.4, 128.2, 132.7, 137.1, 137.6, 168.3. HRMS (ESI) m/z ($M+Na^+$) calculated for $[C_8H_7NNaO_5S_2]^+$: 283.9658. Found: 283.9654.

*2,5-Dioxopyrrolidin-1-yl methanesulfonate **(3ma)**.[7]*



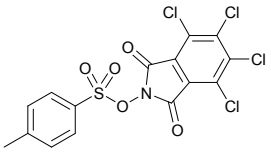
White solid, m.p. = 151-153 °C. Yield 67%. R_f = 0.27 (TLC, PE:EA, 1:5). ^{1}H NMR (DMSO-d_6), δ: 2.76 (s, 4H), 3.55 (s, 3H). ^{13}C NMR (DMSO-d_6), δ: 25.5, 29.5, 170.2.

*1,3-Dioxoisoindolin-2-yl 4-methylbenzenesulfonate **(3ab)**.*



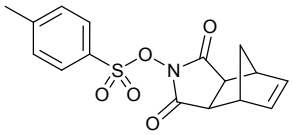
White solid, m.p. = 161-162 °C. Yield 53%. R_f = 0.73 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.48 (s, 3H), 7.39 (d, J = 8.1 Hz, 2H), 7.78-7.86 (m, 4H), 7.93 (d, J = 8.1 Hz, 2H). ^{13}C NMR ($CDCl_3$), δ: 21.9, 124.2, 128.4, 129.5, 130.0, 130.7, 135.1, 147.0, 161.3. HRMS (ESI) m/z ($M+Na^+$) calculated for $[C_{15}H_{11}NNaO_5S]^+$: 340.0250. Found: 340.0246.

*4,5,6,7-Tetrachloro-2-{[(4-methylphenyl)sulfonyl]oxy}-1H-isoindole-1,3(2H)-dione **(3ac)***



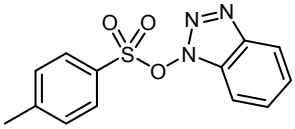
Yellow solid, m.p. = 203.5-205 °C. Yield 38%. R_f = 0.48 (TLC, PE:EA, 5:1). ^{1}H NMR (DMSO-d_6), δ: 2.46 (s, 3H), 7.52 (d, J = 8.1 Hz, 2H), 7.95 (d, J = 8.1 Hz, 2H). ^{13}C NMR (DMSO-d_6), δ: 21.3, 125.5, 128.8, 129.3, 129.5, 130.4, 139.2, 147.4, 157.5. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{15}H_7Cl_4NNaO_5S]^+$: 475.8691. Found: 475.8688.

2-{[(4-Methylphenyl)sulfonyl]oxy}c-3a,4,7,7a-tetrahydro-1H-4,7-methanoisoindole-1,3-dione ***(3ad)***



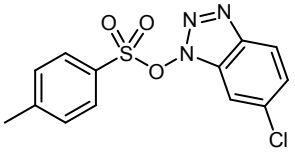
White solid, m.p. = 128.5-130.5 °C. Yield 55%. R_f = 0.32 (TLC, PE:EA, 2:1). ^{1}H NMR ($CDCl_3$), δ: 1.47 (d, J = 9.0 Hz, 1H), 1.74 (d, J = 9.0 Hz, 1H), 2.45 (s, 3H), 3.22-3.26 (m, 2H), 3.40-3.42 (m, 2H), 6.13-6.14 (m, 2H), 7.36 (d, J = 8.1 Hz, 2H), 7.86 (d, J = 8.1 Hz, 2H). ^{13}C NMR ($CDCl_3$), δ: 21.8, 42.8, 44.9, 51.1, 129.3, 129.9, 131.2, 134.8, 146.8, 169.5. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{16}H_{15}NNaO_5S]^+$: 356.0563. Found: 356.0558.

1H-Benzo[d][1,2,3]triazol-1-yl 4-methylbenzenesulfonate ***(3ae)***.



White solid, m.p. = 108-110 °C. Yield 25%. R_f = 0.72 (TLC, PE:EA, 2:1). ^{1}H NMR ($CDCl_3$), δ: 2.42 (s, 3H), 7.33-7.40 (m, 3H), 7.49-7.57 (m, 2H), 7.72 (d, J = 8.3 Hz, 2H), 7.94 (d, J = 8.5 Hz, 1H). ^{13}C NMR ($CDCl_3$), δ: 21.7, 109.2, 120.0, 125.1, 128.5, 128.8, 129.1, 129.6, 130.3, 142.7, 147.9. HRMS (ESI) m/z (M+H^+) calculated for $[C_{13}H_{12}N_3O_3S]^+$: 290.0594. Found: 290.0599.

6-Chloro-1H-benzo[d][1,2,3]triazol-1-yl 4-methylbenzenesulfonate ***(3af)***.



White solid, m.p. = 159-161 °C. Yield 53%. R_f = 0.24 (TLC, PE:EA, 1:1). ^{1}H NMR ($CDCl_3$), δ: 2.49 (s, 3H), 7.37 (dd, J = 8.8, 1.8 Hz, 1H), 7.39 (d, J = 8.5 Hz, 2H), 7.55 (d, J = 1.8 Hz, 1H), 7.76 (d, J = 8.5 Hz, 2H), 7.90 (d, J = 8.8 Hz, 1H). ^{13}C NMR ($CDCl_3$), δ: 22.0, 109.3, 121.2, 126.6, 128.9, 129.3, 129.8, 130.6, 136.0, 141.4, 148.3. HRMS (ESI) m/z (M+Na^+) calculated for $[C_{13}H_{10}ClN_3NaO_3S]^+$: 346.0024. Found: 346.0017.

Control experiment (Scheme 4)

1. Synthesis of *p*-toluenesulfonyl bromide A. *p*-Toluenesulfonyl hydrazide **1a** (2 mmol) was dissolved in $CHCl_3$ (10 ml) and cooled to 0°C. At this temperature molecular bromine (5 mL) dissolved in $CHCl_3$ (5mL) was added while vigorous stirring untill reaction mixture stops to discolor. Then 3 ml of 1M Na_2SO_3 was added to neutralize remaining bromine. The reaction mixture was washed with water (3×5 mL), dried over Na_2SO_4 and concentrated under reduced

pressure. Target *p*-toluenesulfonyl bromide was isolated by chromatography on SiO_2 with elution using PE-EA in a linear gradient of the latter from 0 to 15 vol %. Yield 55%, m.p. = 95-97 °C. R_f = 0.78 (TLC, PE:EA, 10:1). ^{1}H NMR ($CDCl_3$), δ: 2.48 (s, 3H), 7.38 (d, J = 8.2 Hz, 2H), 7.87 (d, J = 8.2 Hz, 2H). ^{13}C NMR ($CDCl_3$), δ: 21.8, 126.5, 130.1, 144.6, 146.7. HRMS (ESI) m/z ($M+H^+$) calculated for $[C_7H_8BrO_2S]^+$: 234.9428. Found: 234.9423.

2. Synthesis of potassium salt of *N*-hydroxysuccinimide C'. Potassium hydroxide (3.5 mmol) was added to the solution of *N*-hydroxysuccinimide **2a** (3.5 mmol) in EtOH (10 mL). Reaction mixture was refluxed for 5 minutes, crystals of target salt precipitated from the solution. After that the reaction mixture was filtered under reduced pressure, precipitate was washed with EtOH (3×5 mL) and dried. Yield 78%. ^{1}H NMR (D_2O), δ: 2.65 (s, 4H). ^{13}C NMR (D_2O), δ: 26.2, 179.9.

3. Synthesis of coupling product 3aa from *p*-toluenesulfonyl bromide A and potassium salt of *N*-hydroxysuccinimide C'. The solution of potassium salt of *N*-hydroxysuccinimide **C'** (1 mmol) in H_2O (1 mL) was added to the solution of *p*-toluenesulfonyl bromide **A** (1 mmol) in THF (5 mL). The reaction mixture was vigorously stirred at 40 °C for an hour. After that it was washed with EA (3×5mL). Combined organic layers were dried over Na_2SO_4, solvent was removed under reduced pressure. The yield of desired product **3aa** was determined by NMR using 1, 4-dinitrobenzene as internal standard.

References

1. A. M. Tsedilin, A. N. Fakhrutdinov, D. B. Eremin, S. S. Zalesskiy, A. O. Chizhov, N. G. Kolotyrkina and V. P. Ananikov, *Mendeleev Commun.,* 2015, **25**, 454.
2. A. O. Terent'ev, O. M. Mulina, D. A. Pirgach, A. I. Ilovaisky, M. A. Syroeshkin, N. I. Kapustina and G. I. Nikishin, *Tetrahedron,* 2017, **73**, 6871.
3. A. U. Meyer, S. Jäger, D. Prasad Hari and B. König, *Adv. Synth. Catal.,* 2015, **357**, 2050.
4. P. Stefanowicz, Ł. Jaremko, M. Jaremko and T. Lis, *New J. Chem.,* 2006, **30**, 258.
5. M. Chanmiya Sheikh, S. Takagi, A. Ogasawara, M. Ohira, R. Miyatake, H. Abe, T. Yoshimura and H. Morita, *Tetrahedron,* 2010, **66**, 2132.
6. M. E. VanVerst, C. L. Bell and L. Bauer, *J. Heterocycl. Chem.,* 1979, **16**, 1329.
7. M. Cal, M. Jaremko, L. Jaremko and P. Stefanowicz, *Amino Acids,* 2013, **44**, 1085.

NMR spectra of synthesized compounds

Acquisition Time (sec)	1.3518	***Date***	19 Jul 2016 10:59:12		
File Name				***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count*** 8124	***Points Count*** 8192
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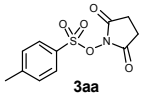

3aa

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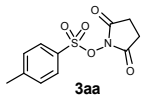
Temperature (degree C)	26.200				



3aa

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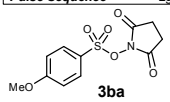

3ba

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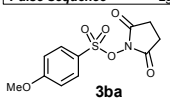

3ba

Acquisition Time (sec)	1.3521	***Date***					
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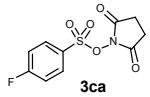
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	24.400



3ca

Acquisition Time (sec)	0.9002	***Date***	29 Mar 2017 11:16:16				
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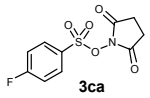
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	23.400



3ca

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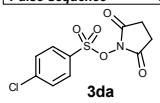

3da

Acquisition Time (sec)	0.9002	***Date***	22 Feb 2017 11:12:00				
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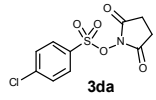
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	25.600



3da

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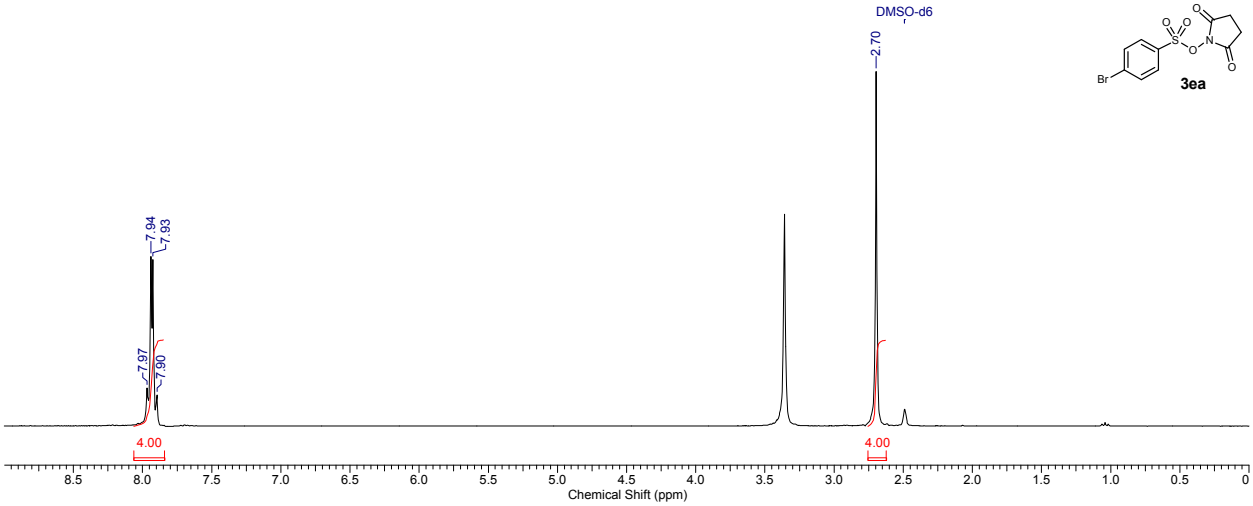
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	24.100



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File Name						***Frequency (MHz)***	75.48
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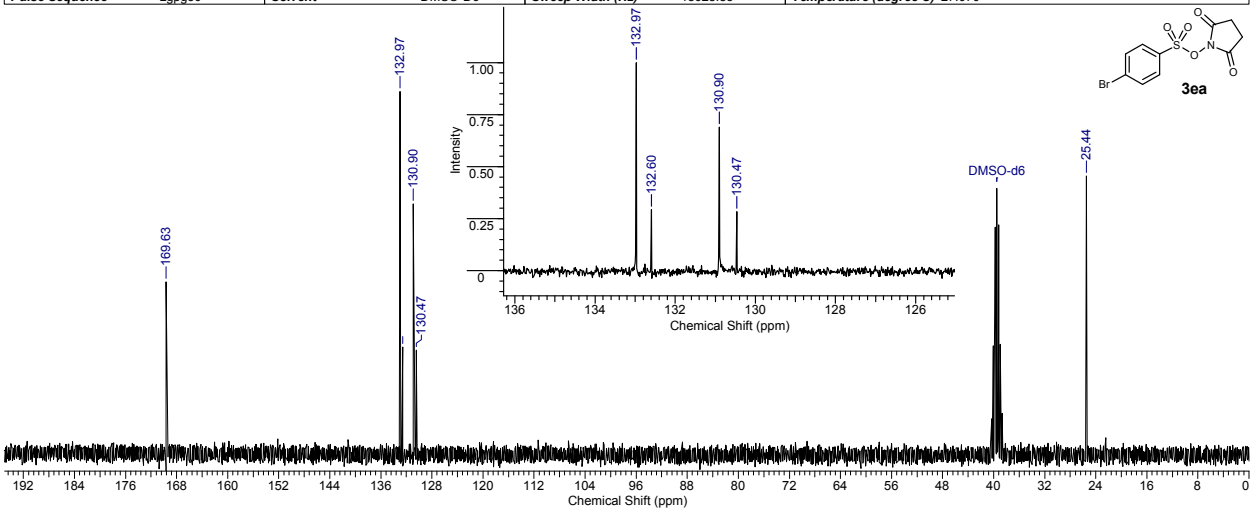
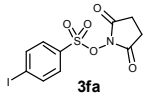


Acquisition Time (sec)	1.3521	***Date***	19 Sep 2018 15:51:28				
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	8116	***Points Count***	8192
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	24.200



3fa

Acquisition Time (sec)	0.9002	***Date***	19 Sep 2018 15:55:44				
File Name						***Frequency (MHz)***	75.48
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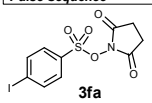
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	24.200



3fa

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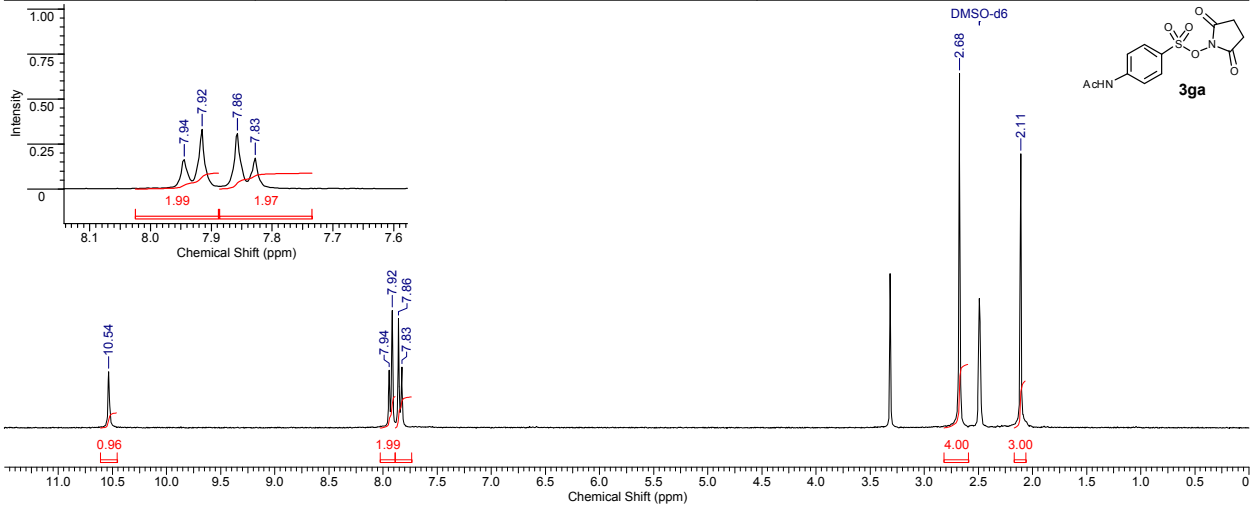
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	25.800



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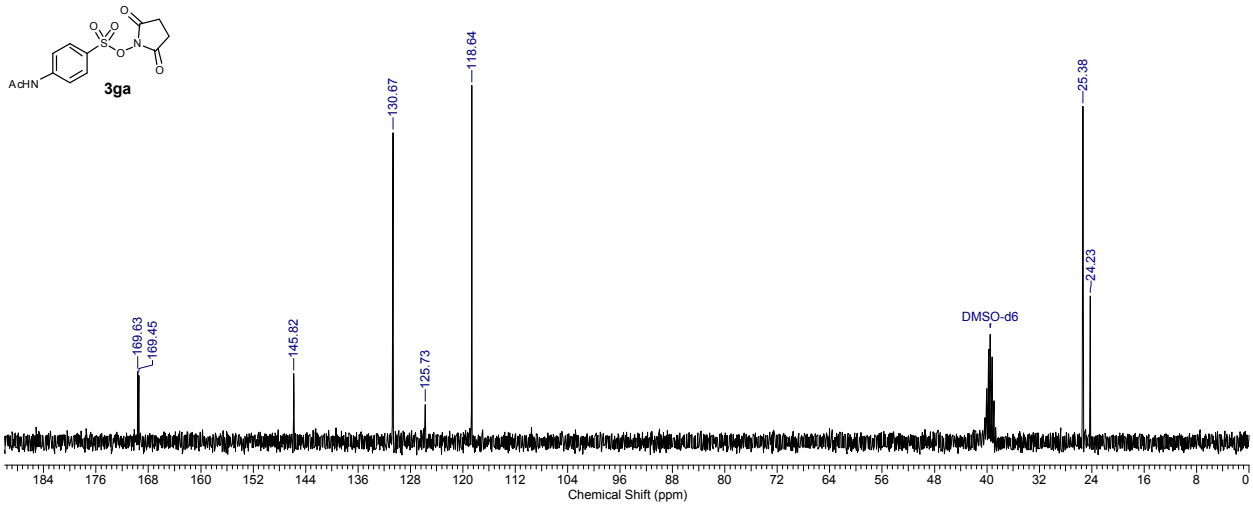

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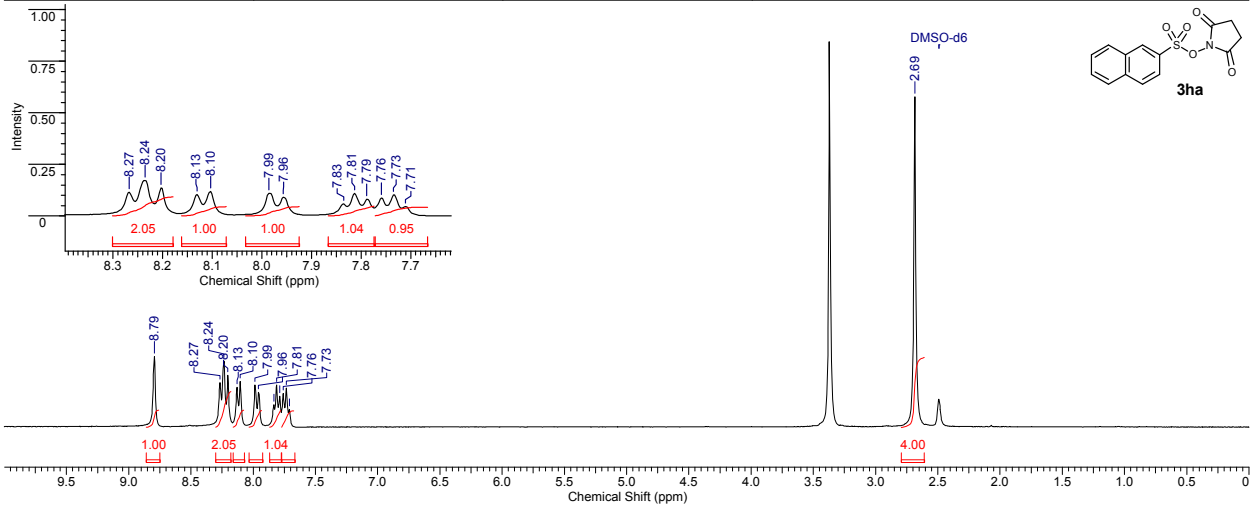

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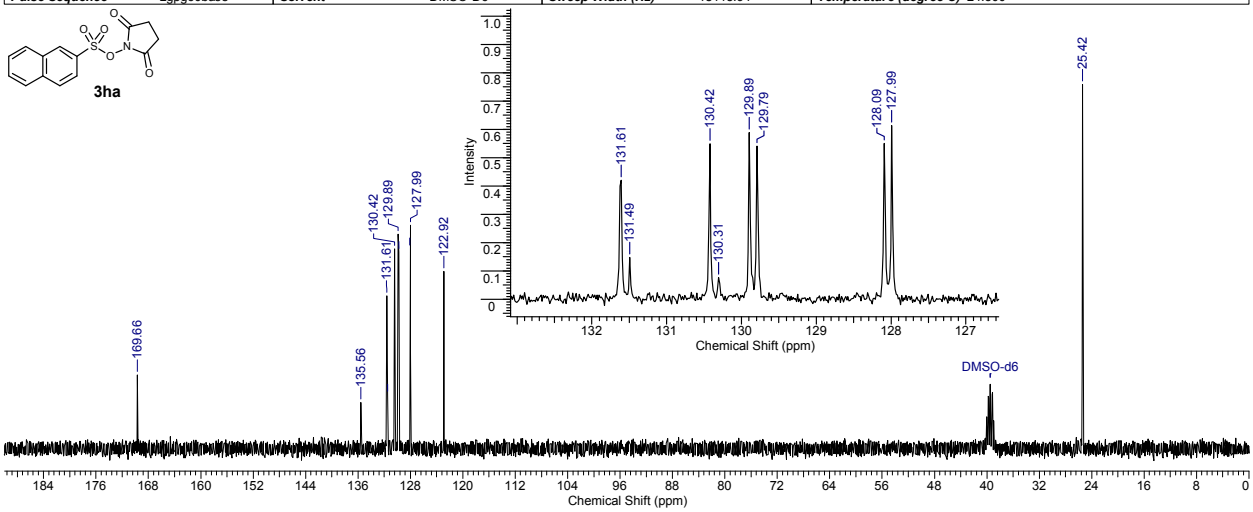
Nucleus	13C	***Number of Transients***	189	***Original Points Count***	16308	***Points Count***	16384
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	24.300



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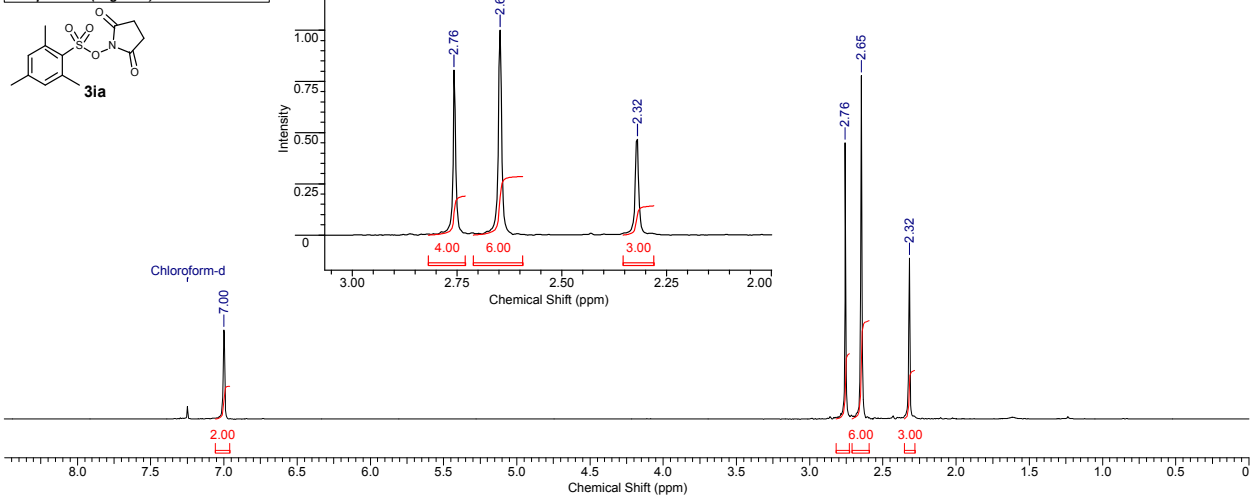
Temperature (degree C)	24.000				



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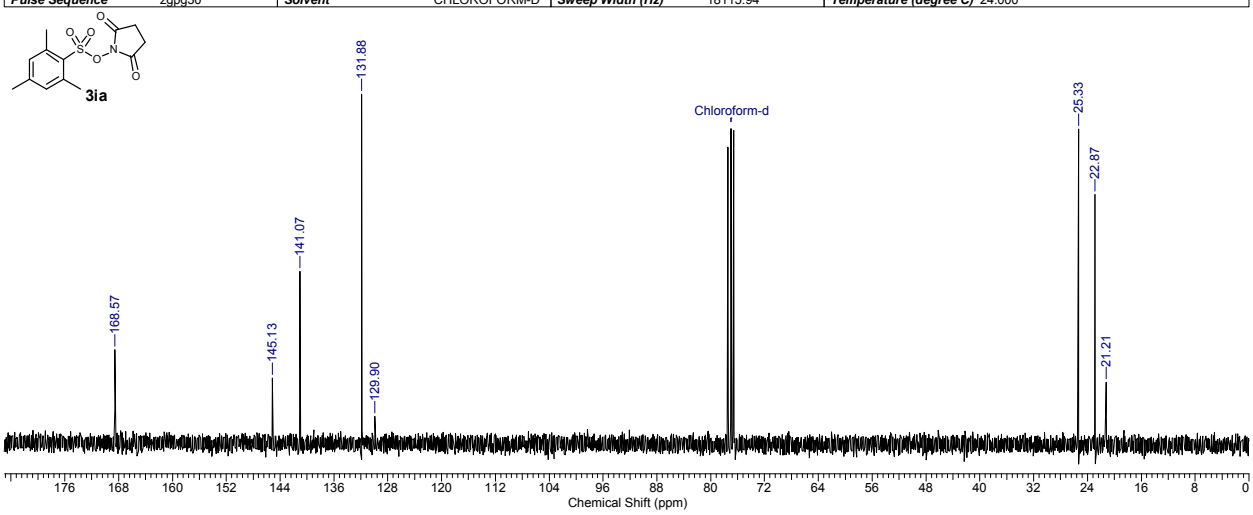
Pulse Sequence	zgpg30	***Solvent***	CHLOROFORM-D	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	24.000



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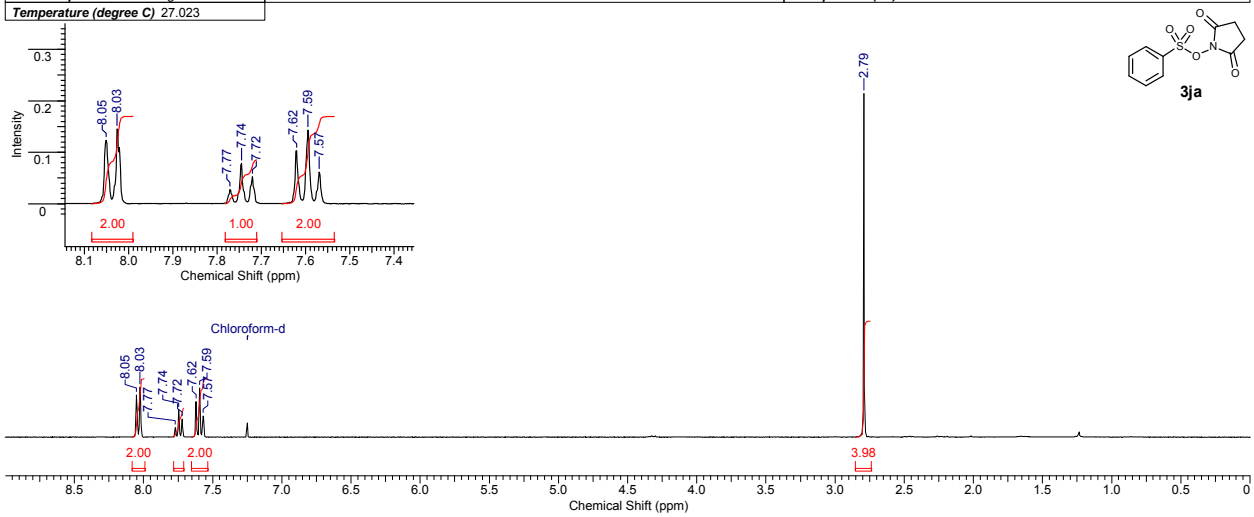
Pulse Sequence	zg	**Solvent**	CHLOROFORM-D			**Sweep Width (Hz)**	6009.62
Temperature (degree C)	27.023						



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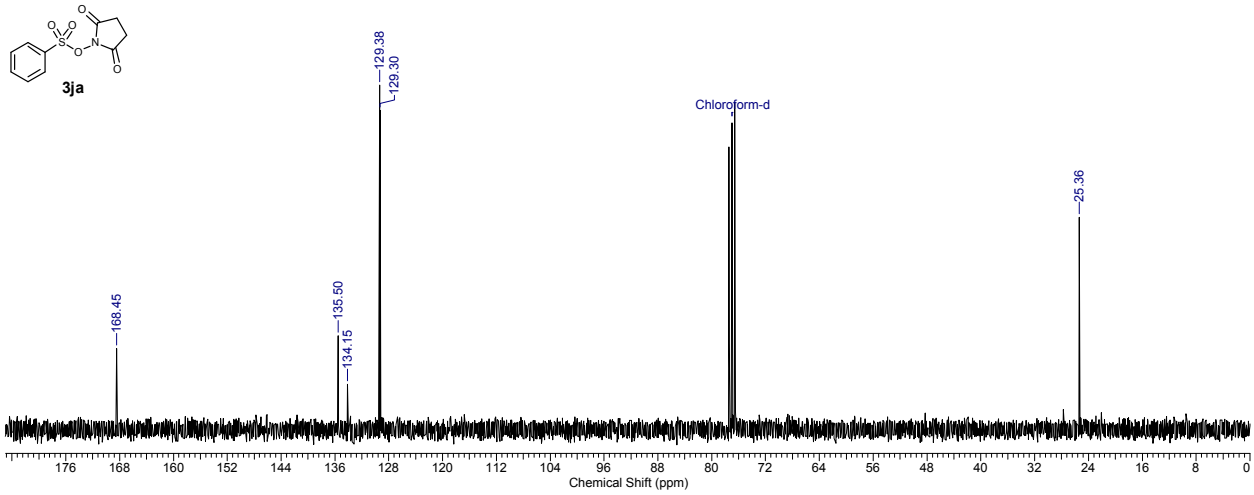
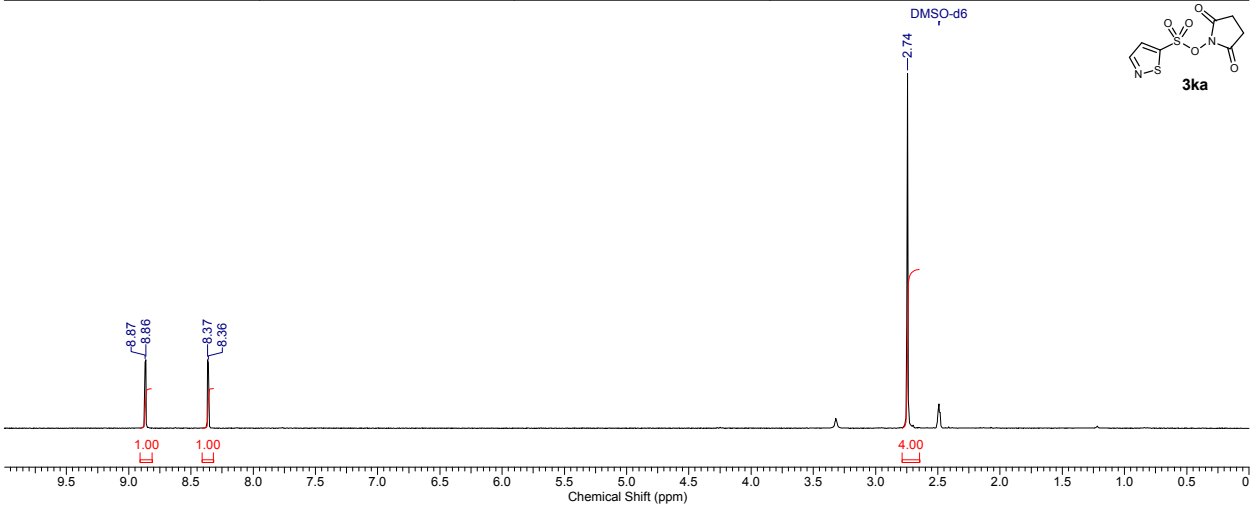
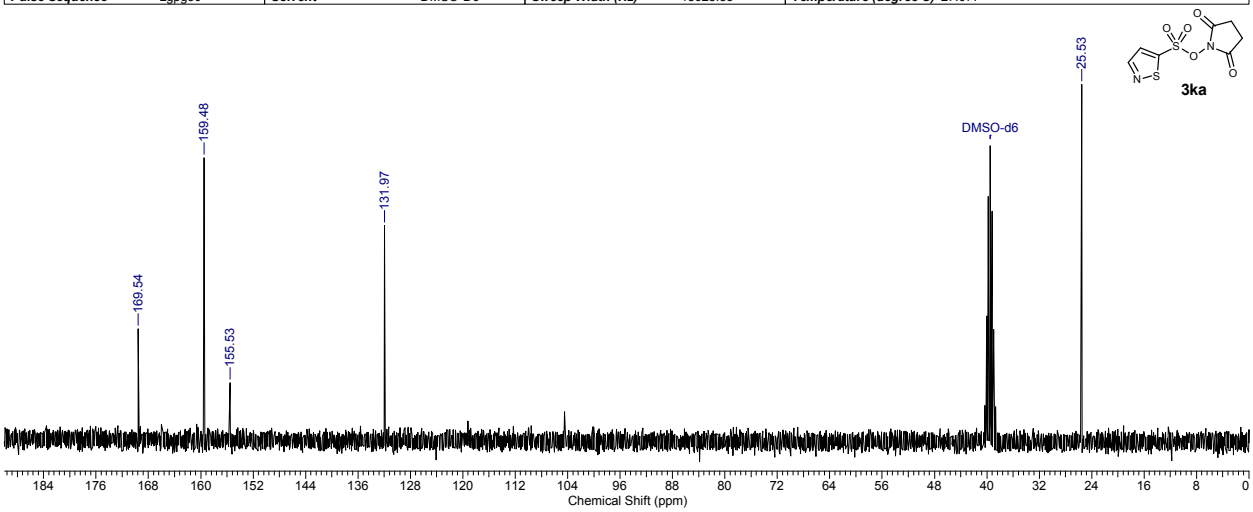
Pulse Sequence	zgpg30	**Solvent**	CHLOROFORM-D			**Sweep Width (Hz)**	18115.94
Temperature (degree C)	26.300						



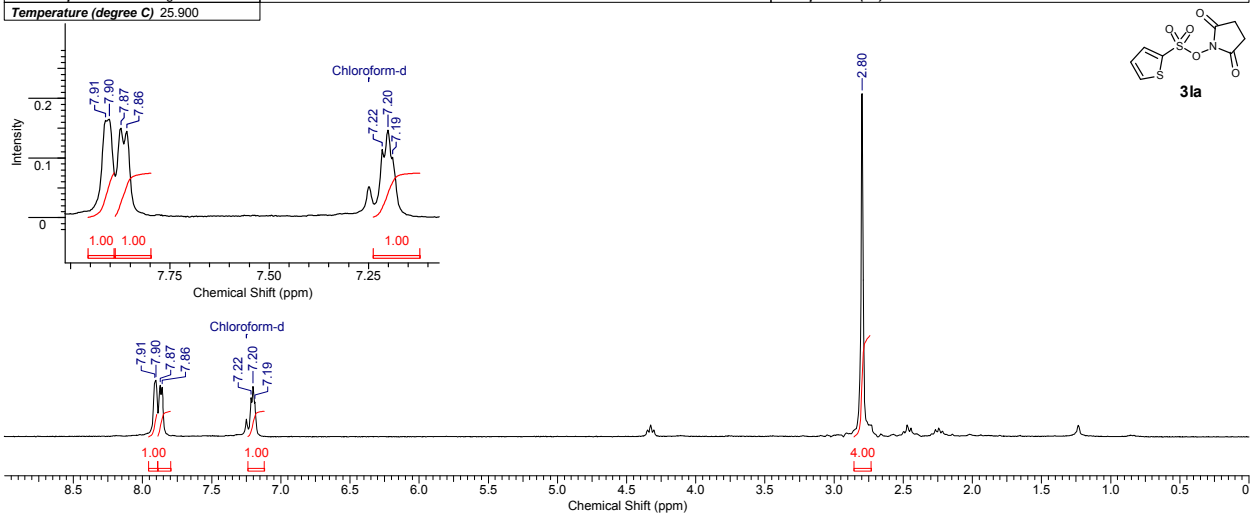
Acquisition Time (sec)	2.7150	***Comment***				***Date***	23 Nov 2018 13:54:08
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	16316	***Points Count***	16384
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6009.62	***Temperature (degree C)***	26.993



Acquisition Time (sec)	0.9050	***Comment***				***Date***	23 Nov 2018 13:56:16
File Name						***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	45	***Original Points Count***	16316	***Points Count***	16384
Pulse Sequence	zgpg30	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18028.85	***Temperature (degree C)***	27.077

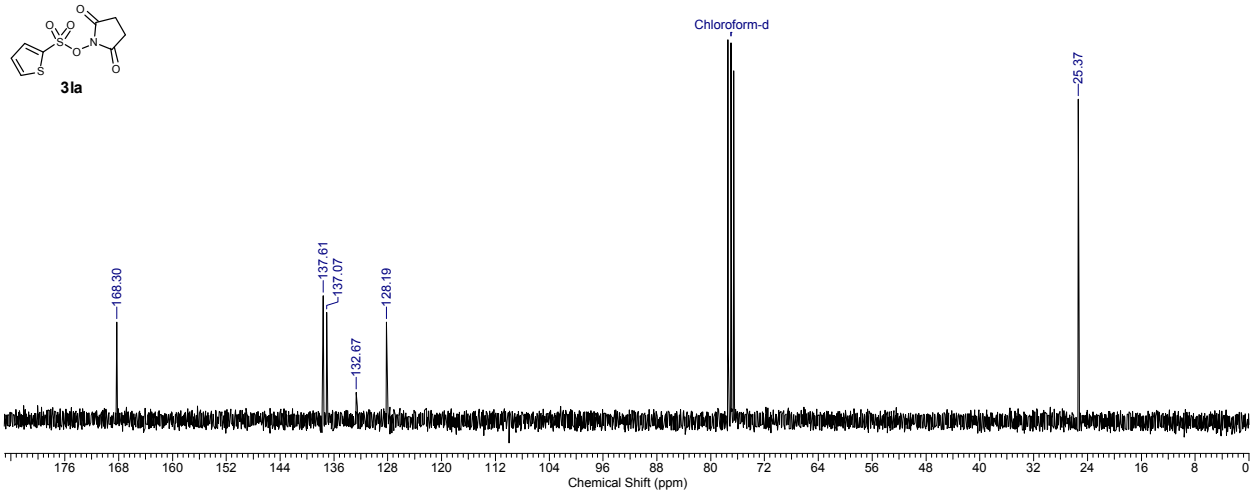


Acquisition Time (sec)	1.3518	***Date***	14 Nov 2018 09:55:12				
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	8124	***Points Count***	8192
Pulse Sequence	zg	***Solvent***	CHLOROFORM-D			***Sweep Width (Hz)***	6009.62
Temperature (degree C)	25.900						



3la

Acquisition Time (sec)	0.9006	***Date***	14 Nov 2018 11:35:28				
File Name						***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	269	***Original Points Count***	16316	***Points Count***	16384
Pulse Sequence	zgpg30	***Solvent***	CHLOROFORM-D			***Sweep Width (Hz)***	18115.94
Temperature (degree C)	25.600						

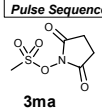


3la

Acquisition Time (sec)	1.3521	***Date***	20 Sep 2017 15:04:32				
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	8116	***Points Count***	8192
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	26.200

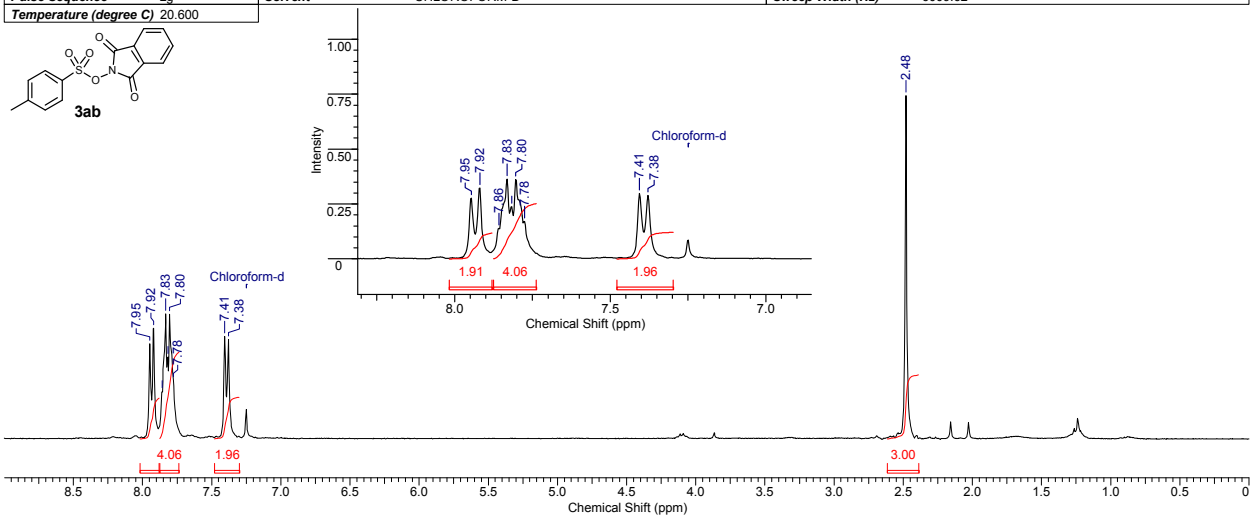
3ma

Acquisition Time (sec)	0.9002	***Date***	21 Sep 2017 10:48:32				
File Name						***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	202	***Original Points Count***	16308	***Points Count***	16384
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	26.000

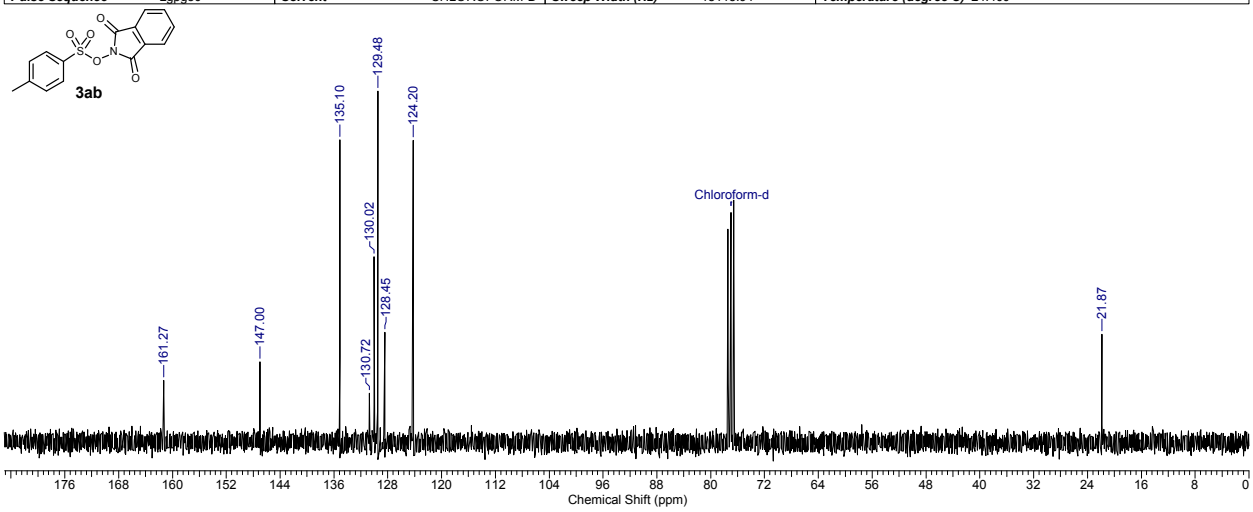


3ma

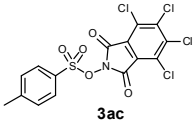
Acquisition Time (sec)	1.3518	***Date***	21 Apr 2016 15:15:12		
File Name				***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count*** 8124	***Points Count*** 8192
Pulse Sequence	zg	***Solvent***	CHLOROFORM-D		***Sweep Width (Hz)*** 6009.62
Temperature (degree C)	20.600				



Acquisition Time (sec)	0.9006	***Date***	20 Mar 2017 15:06:40		
File Name				***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	87	***Original Points Count*** 16316	***Points Count*** 16384
Pulse Sequence	zgpg30	***Solvent***	CHLOROFORM-D	***Sweep Width (Hz)*** 18115.94	***Temperature (degree C)*** 24.400

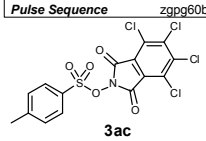


Acquisition Time (sec)	1.3521	***Date***	21 Nov 2018 16:00:00				
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	8116	***Points Count***	8192
Pulse Sequence	zg	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	6002.40	***Temperature (degree C)***	26.400



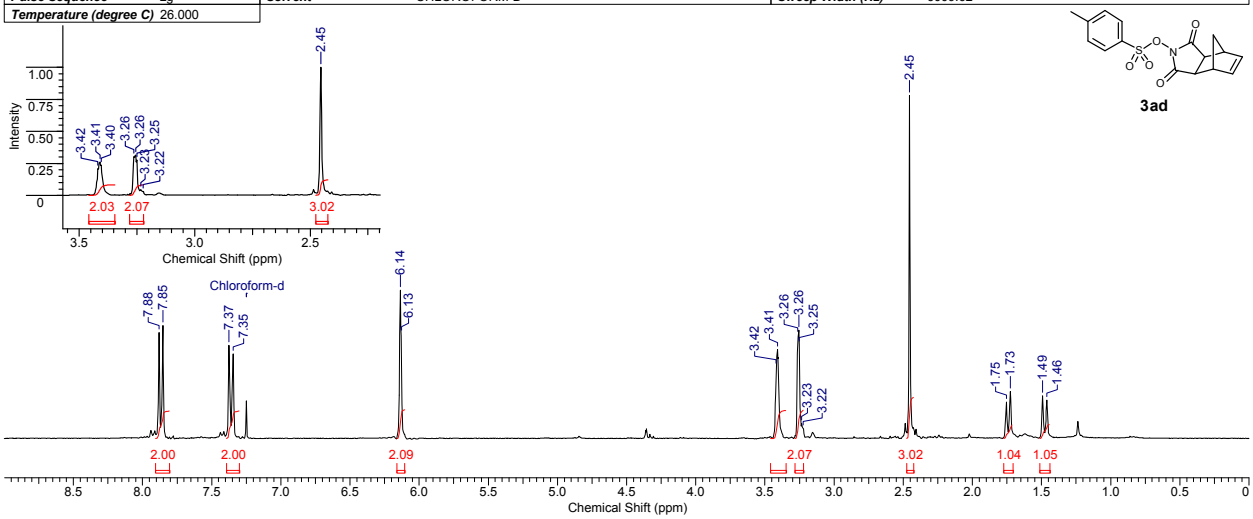
3ac

Acquisition Time (sec)	0.9002	***Date***	21 Nov 2018 16:04:16				
File Name						***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	358	***Original Points Count***	16308	***Points Count***	16384
Pulse Sequence	zgpg60base	***Solvent***	DMSO-D6	***Sweep Width (Hz)***	18115.94	***Temperature (degree C)***	26.400

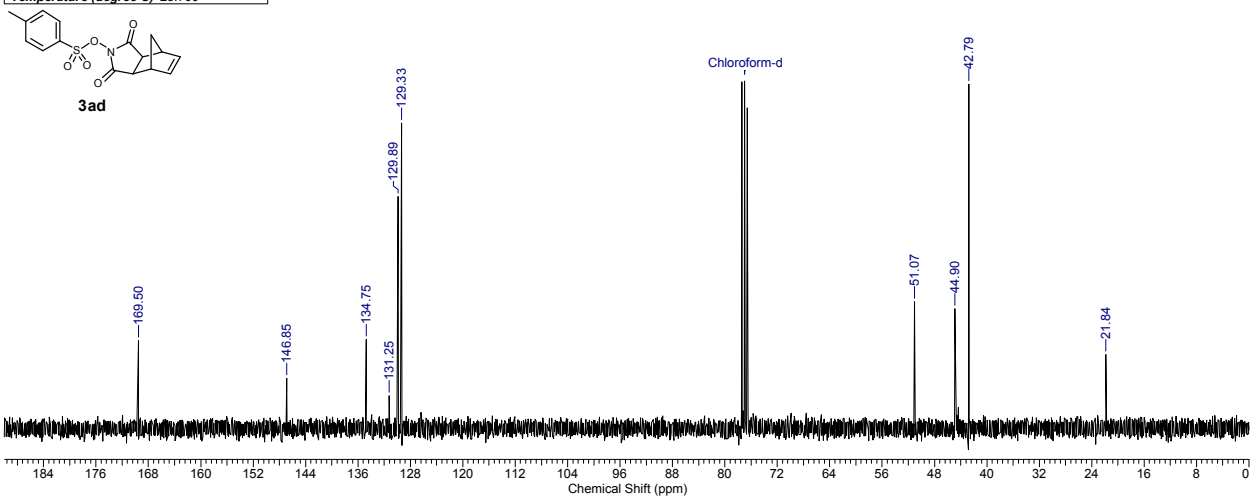


3ac

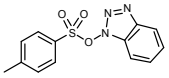
Acquisition Time (sec)	1.3518	**Date**	20 Nov 2018 10:44:16		
File Name				**Frequency (MHz)**	300.13
Nucleus	1H	**Number of Transients**	1	**Original Points Count**	8124
Pulse Sequence	zg	**Solvent**	CHLOROFORM-D	**Sweep Width (Hz)**	6009.62
Temperature (degree C)	26.000				



Acquisition Time (sec)	0.9006	**Date**	20 Nov 2018 14:15:28		
File Name				**Frequency (MHz)**	75.48
Nucleus	13C	**Number of Transients**	148	**Original Points Count**	16316
Pulse Sequence	zgpg30	**Solvent**	CHLOROFORM-D	**Sweep Width (Hz)**	18115.94
Temperature (degree C)	25.700				

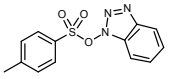


Acquisition Time (sec)	1.3518	**Date**	01 Feb 2017 16:04:16		
File Name				**Frequency (MHz)**	300.13
Nucleus	1H	**Number of Transients**	1	**Original Points Count**	8124	**Points Count**	8192
Pulse Sequence	zg	**Solvent**	CHLOROFORM-D			**Sweep Width (Hz)**	6009.62
Temperature (degree C)	24.800						



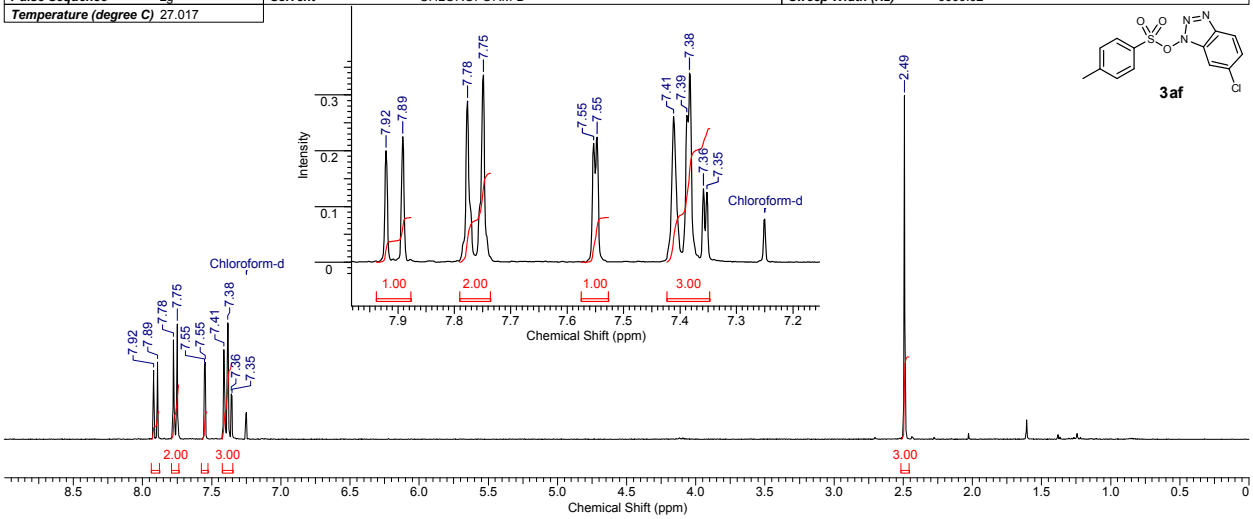
3ae

Acquisition Time (sec)	0.9006	**Date**	02 Feb 2017 11:58:56		
File Name				**Frequency (MHz)**	75.48
Nucleus	13C	**Number of Transients**	97	**Original Points Count**	16316	**Points Count**	16384
Pulse Sequence	zgpg30	**Solvent**	CHLOROFORM-D			**Sweep Width (Hz)**	18115.94
Temperature (degree C)	25.400						

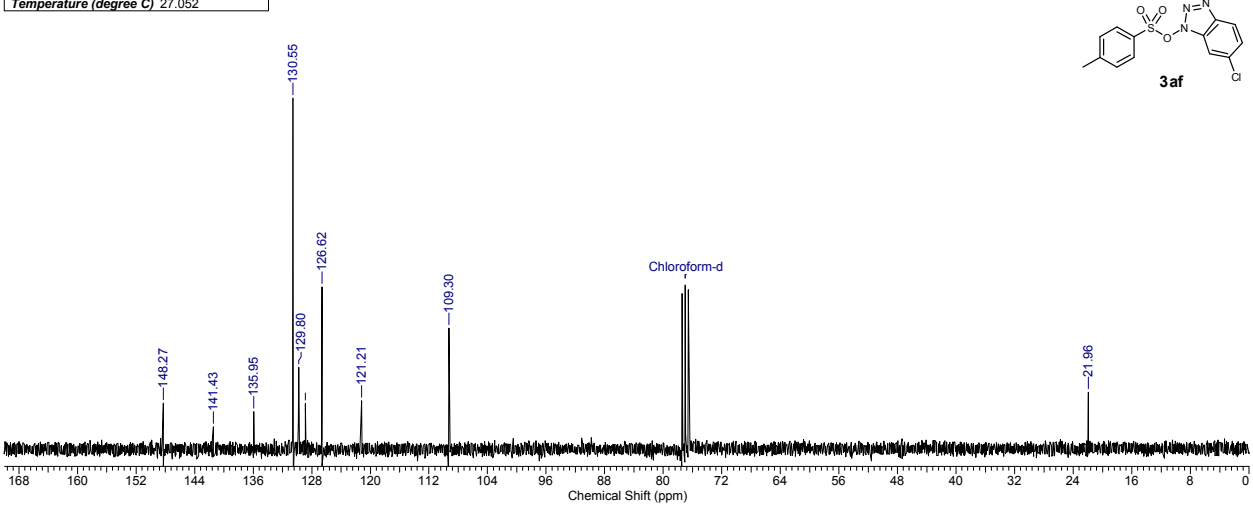


3ae

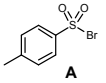
Acquisition Time (sec)	2.7150	***Comment***		***Date***	23 Nov 2018 13:39:12
File Name				***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	16316	***Points Count***	16384
Pulse Sequence	zg	***Solvent***	CHLOROFORM-D			***Sweep Width (Hz)***	6009.62
Temperature (degree C)	27.017						



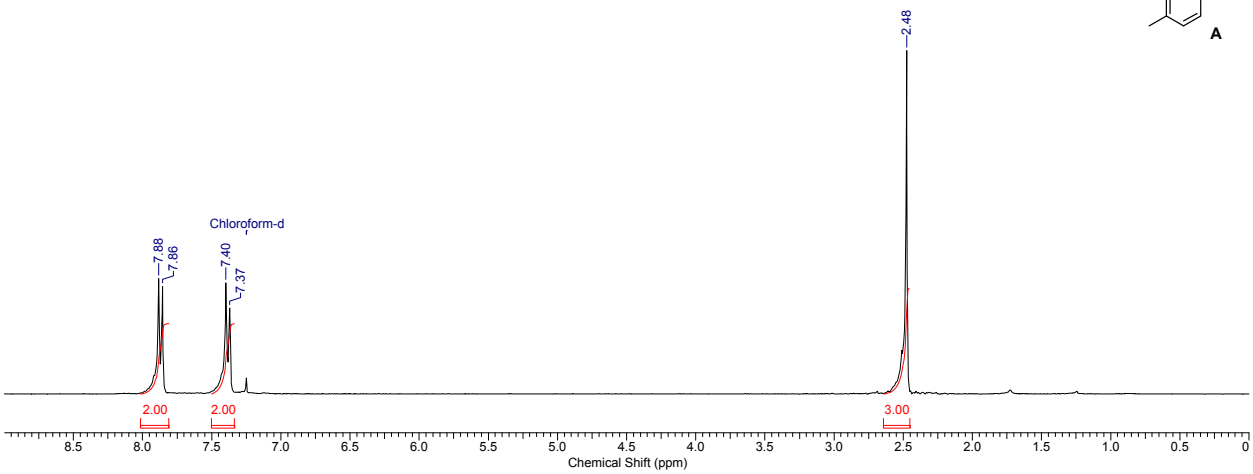
Acquisition Time (sec)	0.9050	***Comment***		***Date***	23 Nov 2018 13:41:20
File Name				***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	58	***Original Points Count***	16316	***Points Count***	16384
Pulse Sequence	zgpg30	***Solvent***	CHLOROFORM-D			***Sweep Width (Hz)***	18028.85
Temperature (degree C)	27.052						



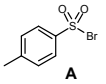
Acquisition Time (sec)	1.3518	***Date***	29 Nov 2018 09:04:00		
File Name				***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count*** 8124	***Points Count*** 8192
Pulse Sequence	zg	***Solvent***	CHLOROFORM-D		***Sweep Width (Hz)*** 6009.62
Temperature (degree C)	27.000				



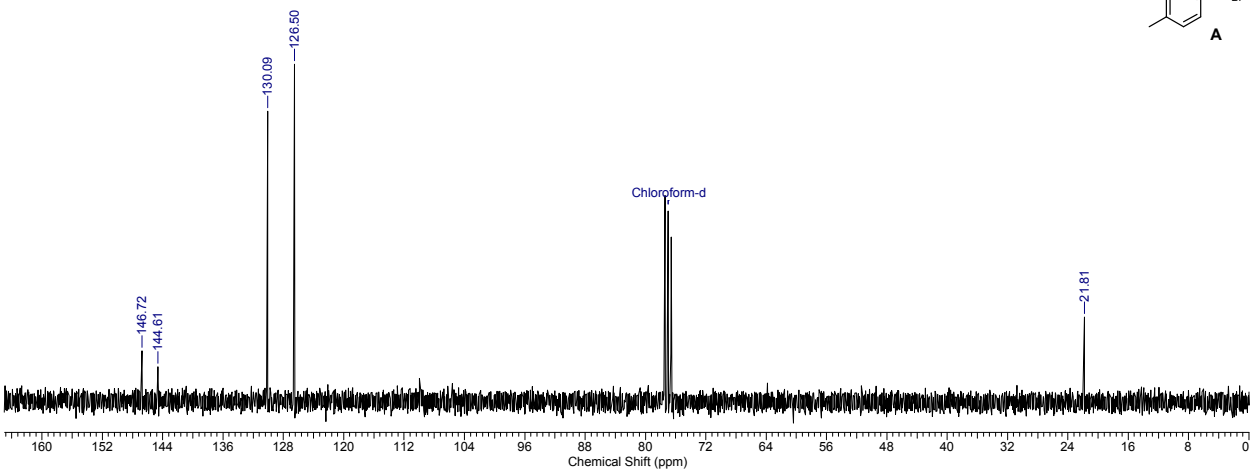
A



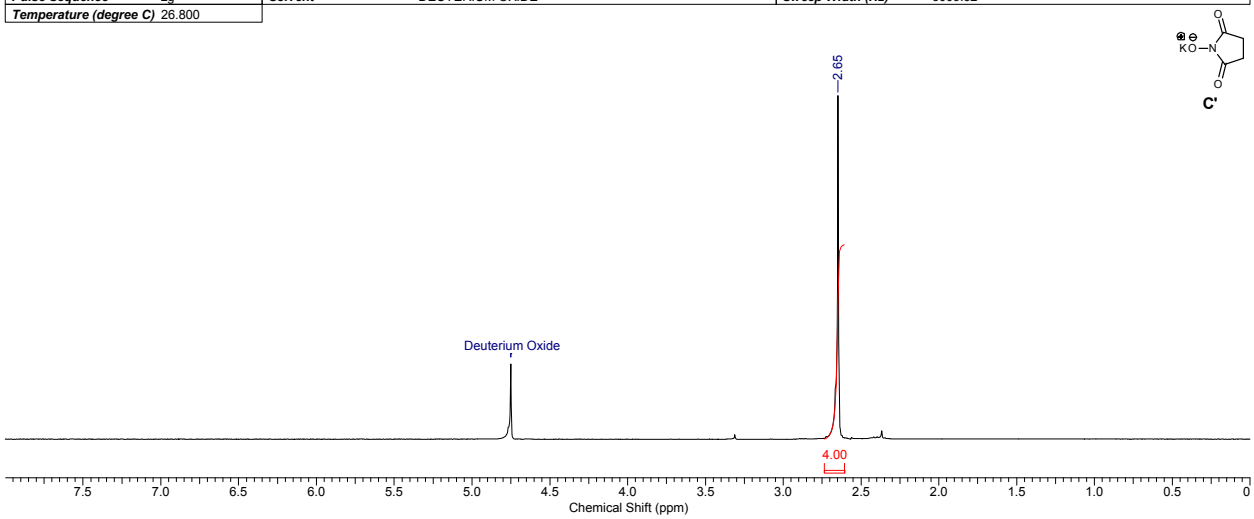
Acquisition Time (sec)	0.9006	***Date***	29 Nov 2018 09:04:00		
File Name				***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	110	***Original Points Count*** 16316	***Points Count*** 16384
Pulse Sequence	zgpg30	***Solvent***	CHLOROFORM-D		***Sweep Width (Hz)*** 18115.94
Temperature (degree C)	27.100				



A



Acquisition Time (sec)	1.3518	***Date***	29 Nov 2018 10:08:00				
File Name						***Frequency (MHz)***	300.13
Nucleus	1H	***Number of Transients***	1	***Original Points Count***	8124	***Points Count***	8192
Pulse Sequence	zg	***Solvent***	DEUTERIUM OXIDE			***Sweep Width (Hz)***	6009.62
Temperature (degree C)	26.800						



Acquisition Time (sec)	0.9002	***Date***	29 Nov 2018 10:10:08				
File Name						***Frequency (MHz)***	75.48
Nucleus	13C	***Number of Transients***	117	***Original Points Count***	16308	***Points Count***	16384
Pulse Sequence	zgpg30base	***Solvent***	DEUTERIUM OXIDE			***Sweep Width (Hz)***	18115.94
Temperature (degree C)	26.900