Supplementary Materials for

Efficient C(sp3)–H carbonylation of light and heavy hydrocarbons with carbon monoxide via HAT photocatalysis in flow

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1. General information

Materials. All reagents and solvents were used as received without further purification. Reagents and solvents were bought from Sigma Aldrich, TCI and Fluorochem. Technical solvents were bought from VWR International and used as received. N-butane gas with 3.5purity was purchased from Praxair, propane gas with 2.5purity was purchased from Benegas, ethane gas with 3.5purity was purchased from Gerling and Holz and Co and methane gas with 4.5purity was purchased from Nippon gases. Carbon monoxide gas (4.8purity) was purchased from Nippon gases, ^{13}CO gas (99.3% purity) was purchased from Eurisotop. The TBADT catalyst was prepared according to reported procedures.[1] Disposable syringes were purchased from Laboratory Glass Specialist. Syringe pumps were purchased from Chemix Inc. model Fusion 200 Touch. All capillary tubing, microfluidic fittings and Back Pressure Regulator (BPR) were purchased from IDEX Health & Science. Product isolation was performed automatically, by a Biotage® Isolation Four, with Biotage® SNAP KP-Sil 4 or 10 g flash chromatography cartridges, or manually, using silica (P60, SILICYCLE). TLC analysis was performed using Silica on aluminum foils TLC plates (F254, SILICYCLE) with visualization under ultraviolet light (254 nm and 365 nm) or appropriate TLC staining (potassium permanganate). Organic solutions were concentrated under reduced pressure on a Büchi rotary evaporator (in vacuo at 40 ºC, ~5 mbar).

NMR spectroscopy. ^{1}H (400 and 300 MHz), ^{13}C (101 and 128 MHz), ^{19}F (282 and 376 MHz) and ^{31}P (121 and 162 MHz) spectra were recorded at ambient temperature using Bruker AV 300-I, AV 400 and AV 500-NEO. 1H NMR spectra are reported in parts per million (ppm) downfield relative to CDCl3 (7.26 ppm) and all 13C NMR spectra are reported in ppm relative to CDCl3 (77.16 ppm) unless stated otherwise. The multiplicities of signals are designated by the following abbreviations: s (singlet), d (doublet), t (triplet), q (quartet), p (pentet), sext (sextet), m (multiplet), dd (doublet of doublets), dt (doublet of triplets), td (triplet of doublets), ddd (doublet of doublet of doublets). Coupling constants (J) are reported in hertz (Hz). NMR data was processed using the MestReNova 14 software package. Known products were characterized by comparing to the corresponding ^{1} NMR, ^{13}C NMR, ^{19}F NMR and ^{31}P NMR with those available in the literature.

Mass spectrometry. High resolution mass spectra (HRMS) were collected on an AccuTOF GC v 4g, JMS-T100GCV Mass spectrometer (JEOL, Japan).

Determination of Regioisomeric and Diastereomeric Ratio. The regioisomeric and diastereomeric ratios were determined by ^{1}H NMR analysis of the crude reaction mixture through integration of diagnostic signals. For cases where the integration of diagnostic signals is not possible, the ratio is calculated after the purification step.

2. Reactor Design

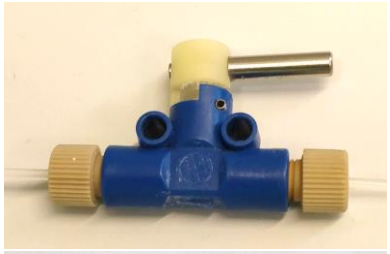
2.1 Flow Equipment

Syringe pump
(Chemyx Fusion 200)

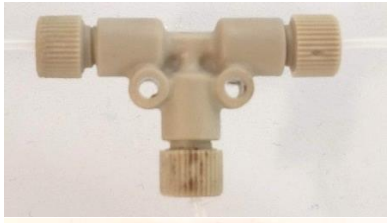
Gastight syringe
(SGE Luer Lock 5 mL)

HPLC pump
(Shimadzu LC-20AD)

Mass Flow Controller
(Bronkhorst EL-FLOW)



Switch Valve
(IDEX P-783)



T-mixer
(IDEX P-712)

BPR holder
(IDEX P-789

BPR cartridge
(IDEX P-789)

Check valve cartridge
(IDEX CV-3000)

Figure S1: Details of flow equipment used for photocatalytic carbonylation reactions.

2.2 Vapourtec Setup

Preliminary experiments were carried out with a Vapourtec UV-150 photochemical reactor setup, equipped with a 60 W 365 nm LED (Figure S2).

Figure S2: Overview of Vapourtec Setup and detail of LEDs and PFA reactor coil (1.3 mm ID, 1.6 mm OD, 10 mL).

2.3 Eagle Reactor

A Signify photochemical reactor is used, consisting of a base assembly with six 365 nm UV-A chip-on-board light modules.[2] Each of these light source modules contain a fan and a heat sink to efficiently dissipate heat generated through the high power LEDs. Also the head cap assembly contains blowers to cool the interior of the reactor system, to reduce undesired thermal side-reactions. The LED modules and chamber cooling blowers are connected to a driver box, allowing to set the current of each of the LED modules individually, as well as the rotation speed of the cooling blowers. The six LED modules (365 nm, max. 144 W combined optical output power) are positioned in an hexagonal form around an aluminum cylinder support (80 mm height, 75 mm diameter), which has the reactor coil wrapped around (FEP capillary tubing: 1.6 mm OD, 0.8 mm ID, 5 mL volume or 0.5 mm ID, 3 mL volume).

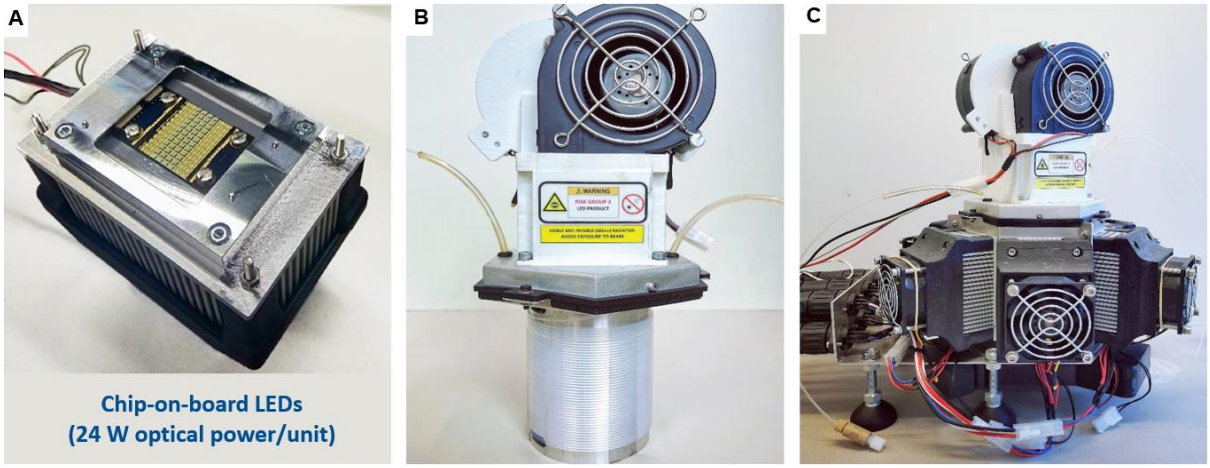


Figure S3: Signify Eagle Reactor with six (A) chip-on-board LED modules, (B) head assembly with reactor coil, and (C) complete assembly with fans, heat sinks and LED modules.

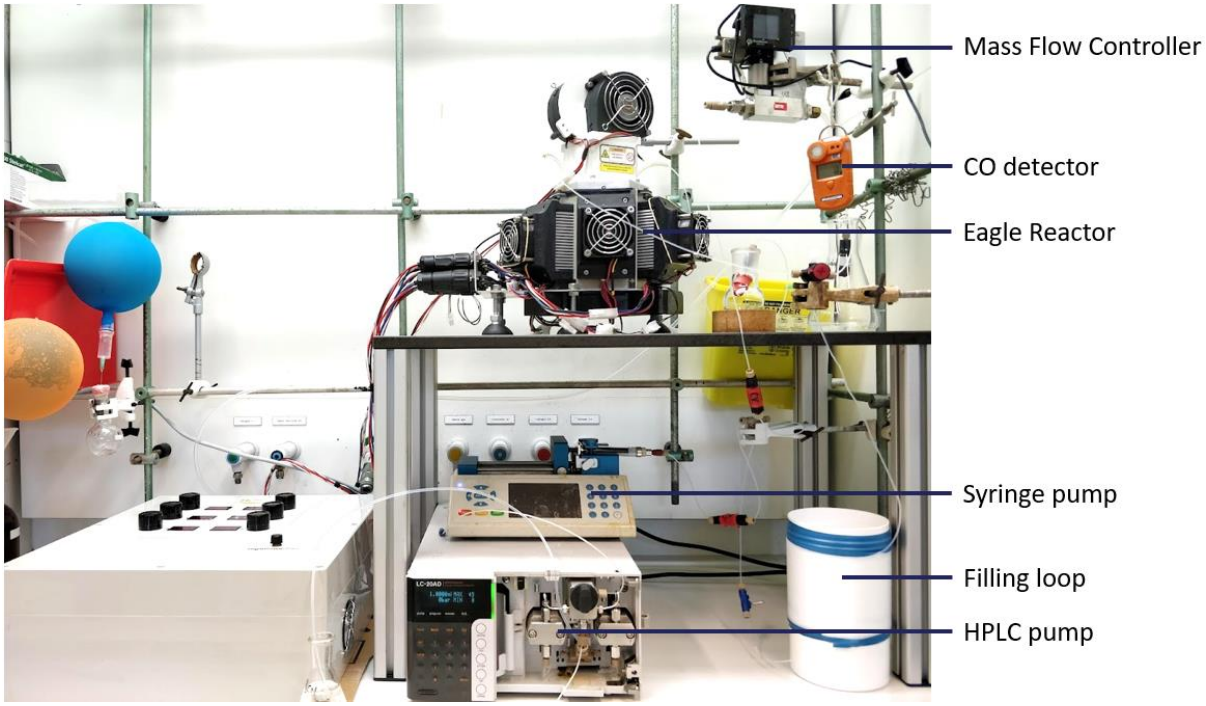


Figure S4: Overview of Setup with Signify Eagle Reactor.

3. General Procedure for Optimization of gas-liquid and gas-gas-liquid Reactions in Flow

An important factor for achieving reproducible results in gas-liquid reactions is a stable gas-liquid flow with a constant distribution of gas-liquid segments. Additionally, small gas- and liquid segments correspond to a high contact area between the gas- and liquid phase and thus a higher chance of reaction between the gaseous and liquid reagents. Below, the procedure for photochemical carbonylations in flow is given for reactions at relatively low pressures (1-7 bar), at higher pressures (17-52 bar) and for gas-gas-liquid reactions with two sequential loop fillings. Specific measures are detailed in these procedures, which contribute to achieving reproducible results.

3.1 Gas-liquid Reactions in Continuous Mode

Reactions can only be performed in continuous mode when the pressure of all input streams are higher than the pressure at the outlet of the reactor. This means that all equipment, which is used for injecting a gas stream (gas cylinder, reducer of gas cylinder and MFC) and for injecting a liquid stream (syringe pump with gastight/disposable syringe, HPLC pump) should be at a higher pressure or should be able to operate at a higher pressure than the design pressure of the BPR and additional pressure drop of the reactor system. Given that the reducer of the CO cylinder in our lab is set to 15 bar, reactions in continuous mode can not exceed this pressure. Additionally, an HPLC pump should be used at pressures higher than 10 bar, rather than a syringe pump and gastight syringe.

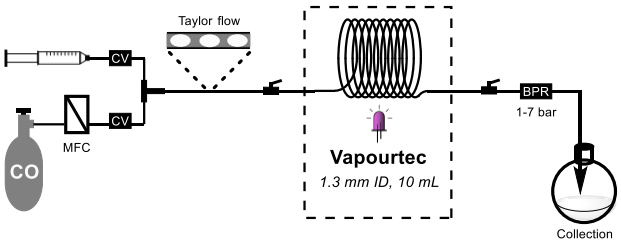


Figure S5: Schematic representation of gas-liquid reactions performed in continuous-mode. MFC: Mass Flow Controller, CV: Check-Valve, BPR: Back-Pressure Regulator.

Before reactions are performed in continuous-mode, measures are taken to maintain a stable pressure and constant gas-liquid flow rate inside the reactor. To pressurize the reactor coil, the coil is first filled with solvent with a back-pressure regulator (BPR) connected at the end. To equilibrate the combined gas-liquid stream, solvent is first mixed with CO gas via a T-mixer and injected into the reactor. Once a stable gas-liquid flow is reached, the syringe pump is stopped and the gas-tight syringe is exchanged for one containing the reaction mixture. When the complete reaction mixture is injected, the syringe is again exchanged for one containing solvent to push out the remaining amount of reaction mixture in the reactor coil under stable flow conditions. Importantly, a check-valve (CV) should be placed after the inlet of gas- and liquid stream, to ensure that flow can only move in one direction.

3.2 Gas-liquid Reactions at Elevated Pressure with Loop Filling Method

For reactions above the maximum pressure of the liquid stream (syringe pump or syringe) or above the maximum pressure of the gas stream (pressure of the gas cylinder or reducer), a different procedure needs to be applied. In these cases, the gas and liquid stream are first combined in a filling loop, then pressurized with a HPLC pump and finally injected into the reactor coil under the desired flow rate with the HPLC pump.

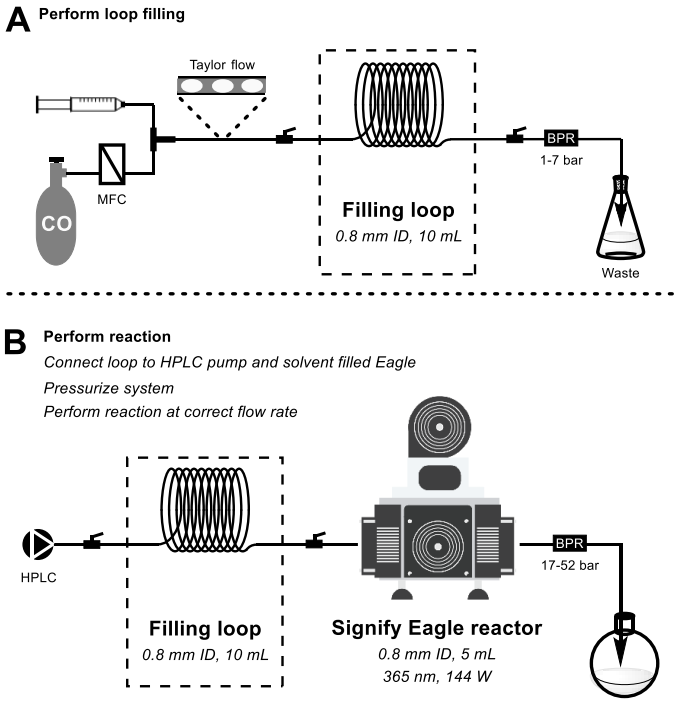


Figure S6: Schematic representation of gas-liquid reactions performed with a loop filling method. (A) Loop filling of gas-liquid mixture, (B) Pressurizing system and reaction under correct flow rate. MFC: Mass Flow Controller, CV: Check-Valve, BPR: Back-Pressure Regulator.

Combination of the gas and liquid stream in the filling loop occurs in the same fashion as the reactions at low pressure. However, after the T-mixer, the gas-liquid stream is injected in a filling loop instead of the photochemical reactor. The filling loop has switch valves connected at either sides, allowing the user to contain the gas-liquid mixture inside the loop after injecting the complete reaction mixture. A large gas slug is usually injected before and after the reaction mixture, to avoid dilution of the reaction mixture with solvent. Once the gas-liquid mixture is contained in the filling loop, the outlet switch valve is connected to the solvent-filled photoreactor with the desired BPR at the outlet, while the inlet switch valve is connected with a HPLC pump. The outlet valve towards the photoreactor can then slowly be opened, with the purpose to preserve the gas-liquid separation in separate slugs as much as possible. Sudden depressurization of the filling loop can cause bypassing of liquid slugs by gas slugs, resulting in lower gas-liquid contact area during the reaction. While flowing solvent towards the filling loop and photoreactor, the capillary tubing between the HPLC pump and BPR are pressurized, the gas segments are compacted and the gas is partially solubilized. However, flow over the BPR only starts when the system has reached the design pressure of the BPR. Once this pressure is reached, the flow rate of the HPLC pump is adjusted to achieve the desired residence time. Reaction is then performed through irradiation of the solution inside the reactor and the reaction mixture is collected at the outlet.

3.3 Gas-gas-liquid Reactions with Two Sequential Loop Fillings

To perform gas-gas-liquid reactions at elevated pressures, two sequential loop fillings are performed. In a first loop filling, the stock solution is combined with a light alkane gas stream in the same fashion as described above, at a relatively low pressure, with a large gas slug before and after injecting the reaction mixture. When the gas-liquid mixture of stock solution and alkane gas is contained in the first filling loop, it can be connected to the HPLC pump at the inlet and pressurized to the design pressure of the second BPR (pressure can be read on HPLC pump).

Before starting the second loop filling, again a large gas slug of CO is pushed into the second loop to avoid dilution of the reaction mixture with solvent. The switch valve from filling loop 1 towards filling loop 2 is slowly opened the mixture of reaction mixture and light alkane gas is pushed with the HPLC pump towards filling loop 2, while being combined with a CO gas stream, both at the appropriate flow rate.

Finally, when all gas-liquid mixture of reaction mixture and light alkane gas is combined with CO gas in filling loop 2, this filling loop can be connected to the HPLC pump at one side and to the solvent-filled photoreactor at the other side with an appropriate BPR at the outlet of the reactor. The mixture of gas, gas and liquid can then be pressurized and pushed over the photoreactor under the desired flow rate.

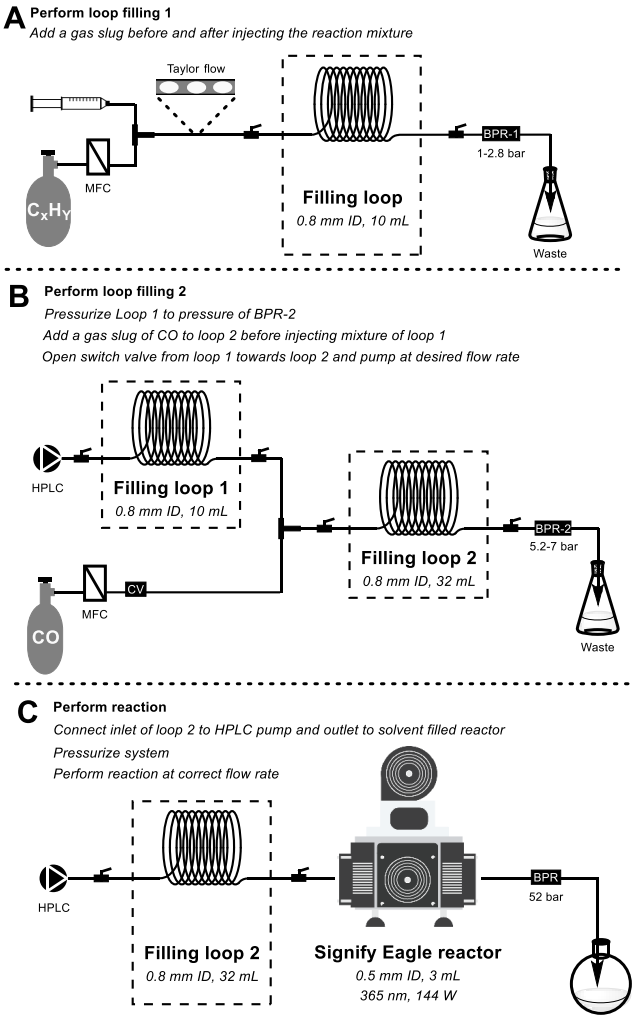


Figure S7: Schematic representation of gas-gas-liquid reactions performed with two sequential loop fillings. (A) Loop filling 1: combining stock solution with light alkane gas. (B) Loop filling 2: combining gas-liquid mixture of stock solution and light alkane gas with CO gas. (C) Gas-gas-liquid reaction over photochemical reactor.

3.4 Calculation of Flow Rates for Desired Stoichiometric Ratio (Gas equivalents)

A tool for calculating gas equivalents was developed by our group to quickly determine the appropriate flow rates for gas-liquid reactions in flow. This tool can be accessed through the following link: https://noel-research-group-streamlit-problem-session-main-esrber.streamlit.app/.

Below the formulas are also deduced and the basic principles are explained, which are used to calculate the required flow rates for a desired stoichiometric ratio of gaseous reagents.

With the loop filling method, the stoichiometric ratio, or gas equivalent, is simply determined by the ratio of the molar flow rates. Pressure (and volumes) are not relevant.

$$Eq_{gas} = \frac{Gas\ molar\ flow\ rate}{Substrate\ molar\ flow\ rate} = \frac{\dot{n}_{gas}}{\dot{n}_{substate}}$$

The molar flow rate of the substrate is:

$$\dot{n}_{substrate} = c_{substrate} \cdot \dot{v}_{liquid}$$

The volumetric flow rate of gas that needs to be applied on the MFC (display gives volumetric flow rate at STP)[1] for a desired stoichiometric ratio can then be calculated as:

$$\dot{v}_{gas} = \frac{\dot{n}_{gas}}{\rho_{molar,gas}} = \frac{MW_{gas}}{\rho_{mass,gas}} \cdot \dot{n}_{gas}$$

For the loop filling method, absolute flow rates are not important. As the gas and liquid streams are mixed inside a filling loop first and not directly fed into the reactor, the absolute gas and liquid flow rates do not determine residence time.

As an example, to calculate the required gas flow rate that should be applied to the MFC to reach 35 equivalents of CO during loop filling, and choosing a substrate concentration of 0.1 M and liquid flow rate of 0.1 mL·min^{-1}, the above formulas can be applied:

$$\dot{v}_{gas} = \frac{MW_{CO}}{\rho_{mass,CO}} \cdot \dot{n}_{CO} = \frac{MW_{CO}}{\rho_{mass,CO}} \cdot Eq_{CO} \cdot c_{substrate} \cdot \dot{v}_{liquid}$$

$$\dot{v}_{gas} = \frac{28.01\ g \cdot mol^{-1}}{1.14\ g \cdot L^{-1}} \cdot 35 \cdot 0.1\ mol \cdot L^{-1} \cdot 0.1\ mL \cdot min^{-1} = 8.6\ mL_{n,CO} \cdot min^{-1}$$

Under the abovementioned reaction conditions, a gas-to-liquid ratio $\dot{v}_{gas}/\dot{v}_{liquid}$ of 86:1 is thus required to achieve 35 equivalents of CO.

[1]For delivering gas to the flow system, a Bronkhorst EL-FLOW is used, a thermal Mass Flow Controller for gasses using the bypass principle.[27] The provider calibrated the instrument using nitrogen and a conversion factor is included internally into the system, to provide flow rates for carbon monoxide at standard temperature and pressure (STP: 0°C, 1.013 bar). Other gasses can also be used, but a conversion factor needs to be applied by the user to account for differences in heat capacity and mass density at normal conditions.[28]

In continuous mode, not only the relative flow rates of gas and liquid are important, but also their absolute volumetric flow rates, as they determine the residence time inside the reactor, together with reactor pressure and reactor volume.

The total volumetric flow rate is the sum of the liquid- and gas volumetric flow rate, with the gas volumetric flow rate being the gas flow rate at STP divided by the reactor pressure (assuming ideal gas behavior).

$$\dot{v}_{total} = \dot{v}_{gas,p} + \dot{v}_{liquid} = \frac{\dot{v}_{gas,STP}}{p} + \dot{v}_{liquid}$$

Together with the formula for calculating the gas-to-liquid ratio for a desired reaction stoichiometry:

$$\frac{\dot{v}_{gas,p}}{\dot{v}_{liquid}} = \frac{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}{\rho_{mass,gas}}$$

One can deduce the required gas flow rate that needs to be applied to the MFC for a desired total volumetric flow rate $\dot{v}_{total}$, reactor pressure p, gas equivalents Eq_{gas}, substrate concentration $c_{substrate}$, mass weight MW_{gas} and mass density $\rho_{mass,gas}$ of the gas, as follows:

$$\dot{v}_{total} = \dot{v}_{gas,p} + \dot{v}_{liquid}$$

$$\dot{v}_{total} = \dot{v}_{gas,p} + \dot{v}_{gas,p} \cdot \frac{\rho_{mass,gas}}{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}$$

$$\dot{v}_{total} = \dot{v}_{gas,p} \cdot \left[1 + \frac{\rho_{mass,gas}}{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}\right]$$

$$\dot{v}_{gas,p} = \frac{\dot{v}_{total}}{\left[1 + \frac{\rho_{mass,gas}}{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}\right]}$$

$$\frac{\dot{v}_{gas,STP}}{p} = \frac{\dot{v}_{total}}{\left[1 + \frac{\rho_{mass,gas}}{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}\right]}$$

$$\dot{v}_{gas,STP} = \frac{p \cdot \dot{v}_{total}}{\left[1 + \frac{p \cdot \rho_{mass,gas}}{Eq_{gas} \cdot c_{substrate} \cdot MW_{gas}}\right]}$$

As an example, when a carbonylation reaction is performed in continuous mode, in a photochemical reactor with an internal volume V_R of 5 mL, and a desired residence time t_R of 10 minutes, the total volumetric flow rate $\dot{v}_{total}$ should be:

$$\dot{v}_{total} = \frac{V_R}{t_R} = \frac{5\ mL}{10\ min} = 0.5\ mL \cdot min^{-1}$$

When the reaction is performed under a reactor pressure p of 7 bar, with 35 equivalents of CO, and a substrate concentration of 0.1 M, the gas flow rate that should be applied to the MFC can be calculated as:

$$\dot{v}_{CO,STP} = \frac{7 \cdot 0.5\ mL \cdot min^{-1}}{\left[1 + \frac{7 \cdot 1.14\ g \cdot L^{-1}}{35 \cdot 0.1\ mol \cdot L^{-1} \cdot 28.01\ g \cdot mol^{-1}}\right]} = 3.24\ mL \cdot min^{-1}$$

The corresponding volumetric flow rate of CO under reaction pressure then becomes:

$$\dot{v}_{CO,7\ bar} = \frac{\dot{v}_{CO,STP}}{p} = \frac{3.24\ mL \cdot min^{-1}}{7} = 0.462\ mL \cdot min^{-1}$$

With a liquid flow rate of:

$$\dot{v}_{liquid} = \frac{\dot{v}_{CO,STP}}{86} = 0.038\ mL \cdot min^{-1}$$

To check, one can calculate the total volumetric flow rate again, based on $\dot{v}_{CO,7\ bar}$ and $\dot{v}_{liquid}$:

$$\dot{v}_{total} = \dot{v}_{CO,7\ bar} + \dot{v}_{liquid} = 0.462 + 0.038 = 0.5\ mL \cdot min^{-1}$$

4. Reaction Optimization: Vapourtec Setup

The three-component reaction between cyclohexane, CO and di-*n*-butyl maleate is chosen as model reaction and an initial screening of reaction parameters is performed in a Vapourtec UV-150 photoreactor (365 nm, 60 W input power) as described above.

4.1 Pressure Screening in Continuous Mode

To begin our investigation, a pressure screening at low pressure is performed in continuous mode. A liquid stream is delivered by a syringe pump and combined with a CO stream via a T-mixer and directly fed into the Vapourtec photoreactor, with a BPR at the outlet. At atmospheric pressure, the Giese adduct is formed as the main product, while selectivity for carbonylation increases with increasing pressure. This can be rationalized with an increased dissolved CO concentration in solution at higher pressure (Henry's law).

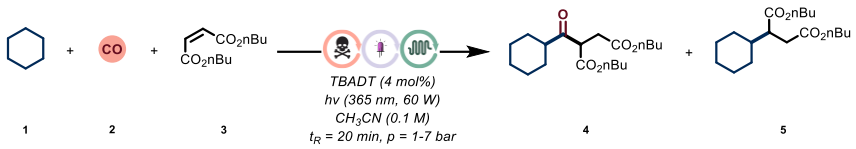


Table S1: Pressure Screening at Low Pressure in a Vapourtec UV-150 Photoreactor.

Entry[a]	p [bar][b]	3[d]	4[d]	5[d]
1	1[c]	7%	36%	57%
2	2.8	4%	52%	44%
3	5.2	5%	74%	21%
4	7	17%	65%	18%

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. At low pressures (1-7 bar), the solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor. A residence time of 20 minutes is maintained. [b] The pressure displayed is the design pressure of the back-pressure regulator. The actual pressure inside the reactor can fluctuate. [c] At atmospheric pressure, lower amount of CO gas was used (5 equiv.). [d] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

4.2 Reaction Temperature

Next the influence of reaction temperature is investigated. A small influence of reactor temperature on selectivity for carbonylation is observed, with lower temperature resulting in higher selectivity. This can be explained by the higher solubility of a gas at lower temperature. However, lower conversion is also observed. For convenience of operation, we further opted for ambient temperatures.

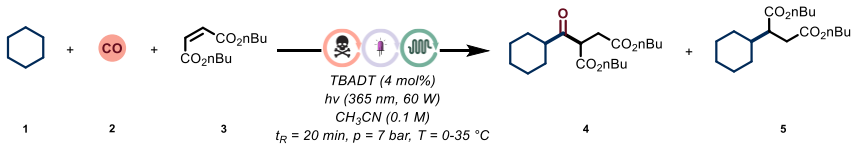


Table S2: Temperature Screening at Low Pressure (7 bar) in a Vapourtec UV-150 Photoreactor.

Entry[a]	T [°C]	3[b]	4[b]	5[b]	Selectivity [%]
1	25	5%	77%	18%	81%
2	35	3%	74%	23%	76%
3	0	12%	75%	13%	85%

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. The solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor, which is maintained at 7 bar. A residence time of 20 minutes is applied. The temperature is read from the temperature sensor of the Vapourtec system. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

4.3 Residence Time at Low Pressure

A residence time screening at low pressure (7 bar) is performed in continuous mode to investigate the influence of residence time on conversion. Conversion increases with increased residence time, with full conversion achieved under these conditions after 40 minutes.

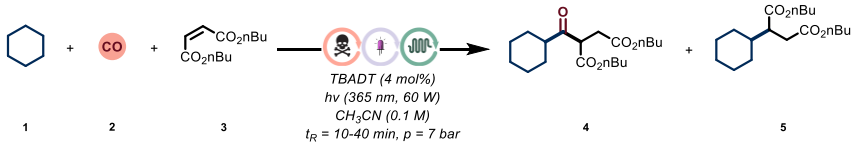


Table S3: Residence Time Screening at Low Pressure (7 bar) in a Vapourtec UV-150 Photoreactor.

Entry[a]	t_R [min]	3[b]	4[b]	5[b]
1	40	0%	76%	24%
2	30	3%	79%	17%
3	20	9%	73%	18%
4	10	22%	62%	16%

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. The solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor, which is maintained at 7 bar. A residence time of 10 to 40 minutes is applied. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

4.4 H-donor equivalents

Next, the influence of H-donor equivalents was investigated. Lower cyclohexane equivalents results in slower reaction kinetics, with no significant effect on selectivity.

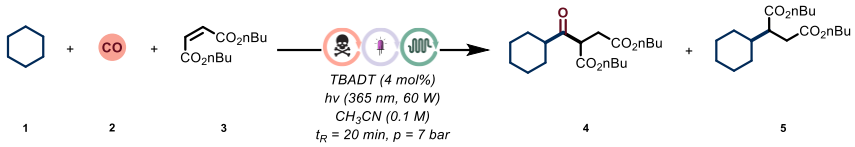


Table S4: Screening H-donor equivalents at Low Pressure (7 bar) in a Vapourtec UV-150 Photoreactor.

Entry[a]	Cy equiv.	3[b]	4[b]	5[b]	Selectivity [%]
1	10	7%	75%	18%	74
2	5	34%	44%	22%	67
3	2	71%	22%	7%	76

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 1 to 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. The solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor, which is maintained at 7 bar. A residence time of 20 minutes is applied. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

4.5 CO equivalents

Also changing the CO equivalents had no significant effect on selectivity for carbonylation over Giese reaction at 7 bar reaction pressure. Given this result, together with the observation that changing CO equivalents mainly influenced the size of the gas slug, we assume that the concentration of CO in solution did not change significantly between the three entry points below.

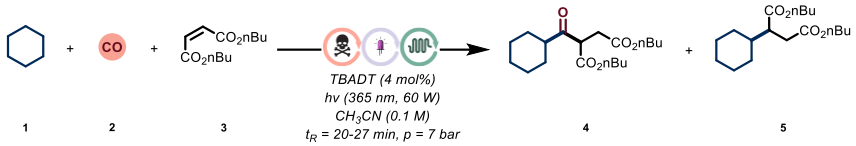


Table S5: Screening H-donor equivalents at Low Pressure (7 bar) in a Vapourtec UV-150 Photoreactor.

Entry[a]	CO equiv.	$t_{R,observed}$ [min]	3[b]	4[b]	5[b]	Selectivity [%]
1	70	27	7%	77%	16%	83
2	35	23	9%	78%	13%	86
3	17	20	15%	73%	12%	86

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. The solution is combined with CO gas (**2**, 17 to 70 equiv.) and directly pushed into the photoreactor, which is maintained at 7 bar. A constant CO flow was maintained, with increasing liquid flow rate, resulting in a somewhat shorter residence time and lower CO equiv. at higher liquid flow rate. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

4.6 Solvent Screening

Apart from acetonitrile, other solvent (mixtures) were screened. Whereas neat acetone did not result in a homogeneous solution, solvent mixtures of CH_3CN:H_2O (4:1) and CH_3CN:CH_2Cl_2 (4:1) did provide a homogeneous mixture, resulting in unchanged reaction performance upon addition of dichloromethane and a somewhat decreased performance upon addition of water.

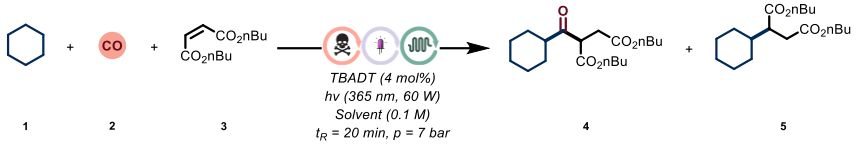


Table S6: Solvent Screening at Low Pressure (7 bar) in a Vapourtec UV-150 Photoreactor.

Entry[a]	Solvent	3[b]	4[b]	5[b]
1	CH_3CN	5%	77%	18%
2	Acetone		Not soluble	
3	CH_3CN:H_2O (4:1)	16%	66%	18%
4	CH_3CN:CH_2Cl_2 (4:1)	3%	79%	18%

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL the appropriate solvent mixture. The solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor, which is maintained at 7 bar. A residence time of 20 minutes is applied. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

5. Reaction optimization: Eagle Reactor

With the initial reaction optimization in the Vapourtec Setup in hand, we sought to exploit the high-intensity irradiation of the Signify Eagle Reactor (365 nm, 144W optical output power) to increase reaction kinetics of the photocatalytic carbonylation.

5.1 Pressure Screening

Given the drastic effect of reaction pressure on the selectivity for carbonylation over Giese reaction (see section 4.1), we investigated the influence of reaction pressure above 7 bar in the Signify Eagle Reactor. When performing reactions above the maximum pressure of the gas cylinder, the reducer of the gas line or the liquid pump, reactions can not be performed in continuous mode. In those cases, a loop filling method is applied, where the gas-liquid mixture is first combined in a filling loop, then pressurized with an HPLC pump and finally pushed over the reactor coil under the desired pressure (See protocol 3.x). Gratifyingly, under 34 bar reaction pressure and higher, selectivity for the desired carbonylated product over the undesired Giese coupling is almost complete.

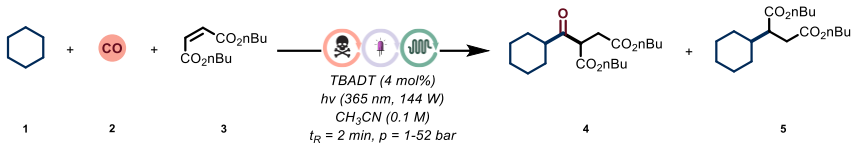


Table S7: Pressure Screening in Signify Eagle Reactor.

Entry[a]	p [bar][b]	3[d]	4[d]	5[d]	Selectivity [%]
1	1[c]	18%	33%	49%	41%
2	7	7%	77%	16%	83%
3	17	15%	79%	6%	93%
4	34	25%	73%	2%	97%
5	52	25%	74%	1%	99%

[a] Reaction conditions: A stock solution is prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL acetonitrile. At low pressures (1-7 bar), the solution is combined with CO gas (**2**, 35 equiv.) and directly pushed into the photoreactor. At high pressures (17-52 bar), the solution is first loop filled with CO gas, after which the loop is pressurized and then the gas-liquid slugs are pumped into the reactor. For both procedures, a residence time of two minutes is maintained. [b] The pressure displayed is the design pressure of the back-pressure regulator. The actual pressure inside the reactor can fluctuate. [c] At atmospheric pressure, lower amount of CO gas was used (5 equiv.). [d] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

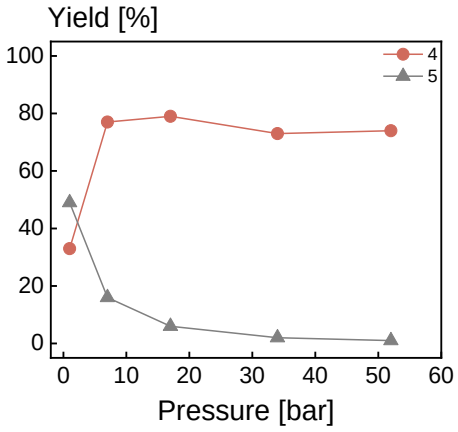


*Figure S8: ^{1}H-NMR yield of dibutyl 2-(cyclohexanecarbonyl)succinate (**4**) and dibutyl 2-cyclohexylsuccinate (**5**) in function of reaction pressure, calculated with an internal standard (trimethoxybenzene).*

5.2 Residence Time Screening

To investigate the residence time required for achieving full conversion, a residence time screening is performed. Already after 30 seconds, a conversion of 72% is observed. However, full conversion is achieved only after 15 minutes residence time.

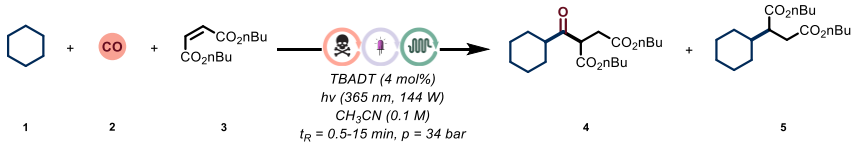


Table S8: Residence Time Screening

Entry[a]	t_R [min]	2[b]	3[b]	4[b]
1	0.5	**28%**	68%	4%
2	1	**12%**	84%	4%
3	2	**9%**	87%	4%
4	5	**10%**	86%	4%
5	15	**3%**	93%	4%

[a] Reaction conditions: A stock solution was prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL of acetonitrile. The solution was loop filled with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

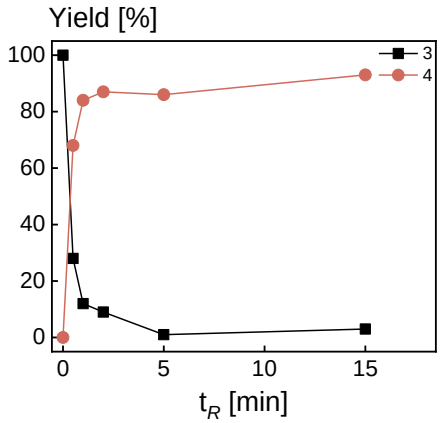


*Figure S9: ^{1}H-NMR yield of di-nbutyl-maleate (**3**) and dibutyl 2-(cyclohexanecarbonyl)succinate (**4**) in function of residence time, calculated with an internal standard (trimethoxybenzene).*

5.3 Catalyst loading

As full conversion of the alkene substrate was observed above 15 minutes residence time, it was evaluated whether a lower catalyst loading could be used. For the model substrate, a catalyst loading as low as 0.25 mol% was sufficient to achieve full conversion after 30 minutes residence time. In the absence of photocatalyst, there was no conversion of di-*n*-butyl-maleate observed.

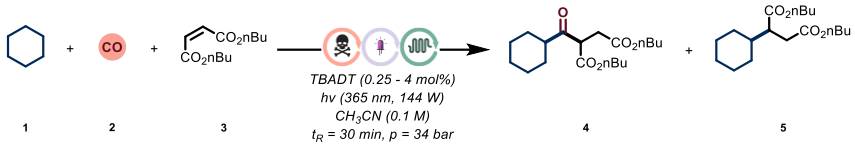


Table S9: Screening Catalyst Loading

Entry[a]	Cat. loading [mol%]	2[b]	3[b]	4[b]
1	0	100%	0%	0%
2	0.25	3%	91%	6%
3	0.5	1%	92%	7%
4	1	1%	98%	1%
5	2	1%	96%	3%
6	4	1%	97%	2%

[a] Reaction conditions: A stock solution was prepared with 0.5 mmol of **3**, 5 mmol of **1** and x mol% of TBADT dissolved in 5 mL of acetonitrile. The solution was loop filled with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

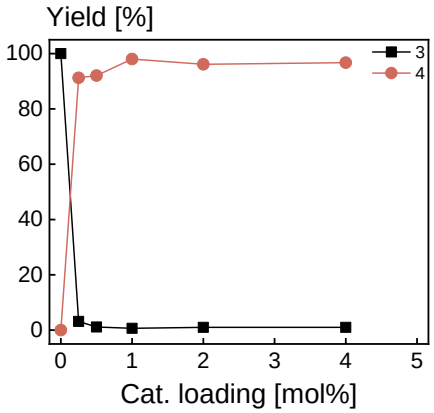


*Figure S10: ^{1}H-NMR yield of di-n-butyl-maleate (**3**) and dibutyl 2-(cyclohexanecarbonyl)succinate (**4**) in function of catalyst loading calculated with an internal standard (trimethoxybenzene).*

5.4 Light Intensity Screening at Low Catalyst Loading

Since a small drop in performance was observed when reducing the catalyst loading to 0.25 mol%, we wanted to investigate would still reach full conversion at lower light intensity. Interestingly, at this low photocatalyst loading (0.25 mol%), the transformation becomes photon limited with decreased light intensity, resulting in only 59% conversion at 24W output power. Additionally, a control experiment confirmed the photocatalytic nature of the transformation, as no reaction occurred in the absence of light.

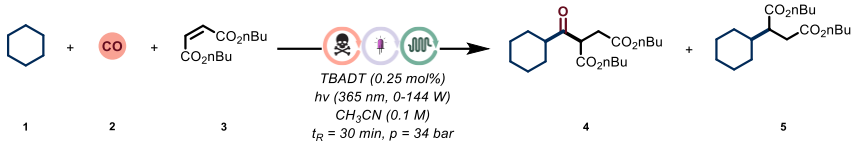


Table S20: Influence of Light Intensity at Low Catalyst Loading.

Entry[a]	Light intensity [W]	3[b]	4[b]	5[b]
1	0	100%	0%	0%
2	24	41%	57%	2%
3	48	27%	70%	2%
4	70	20%	78%	2%
5	91	15%	83%	2%
6	112	5%	89%	6%
7	128	4%	90%	5%
8	144	1%	92%	7%

[a] Reaction conditions: A stock solution was prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL of acetonitrile. The solution was loop filled with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. The optical output power of the Signify Eagle Reactor can be tuned between 24 and 144 W. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

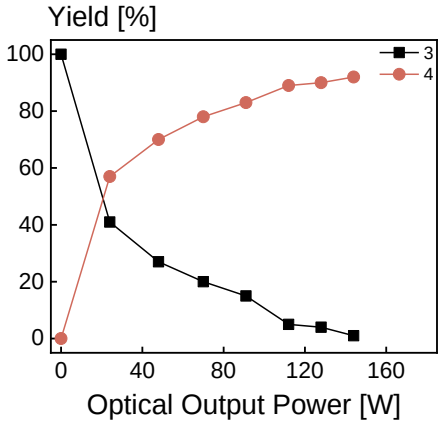


*Figure S11: ^{1}H-NMR yield of di-nbutyl-maleate (**3**) and dibutyl 2-(cyclohexanecarbonyl)succinate (**4**) in function of light intensity, calculated with an internal standard (trimethoxybenzene).*

5.5 Substrate Concentration

With the intention to increase productivity of the flow reaction, we investigated the influence of substrate concentration on reaction outcome. With a slightly diminished reaction performance at 0.2 M, we chose to perform the substrate scope with an alkene concentration of 0.1 M.

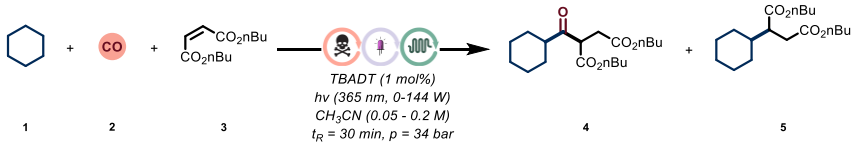


Table S11: Influence of substrate concentration on reaction outcome.

Entry	Substrate concentration [mol/L]	**3**	**4**	**5**
1	0.05	0%	>99%	0%
2	0.1	1%	98%	1%
3	0.2	1%	92%	7%

[a] Reaction conditions: A stock solution was prepared with 0.5 mmol of **3**, 5 mmol of **1** and 4 mol% of TBADT dissolved in 5 mL of acetonitrile. The solution was loop filled with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. [b] ^{1}H-NMR yields are calculated with an internal standard (trimethoxybenzene).

6. Reaction Optimization: Light Alkane Carbonylation

6.1 C2-C4 Light Alkanes

With the aim to maintain reaction conditions as uniform as possible, we decided to apply the same reaction conditions as for the rest of the scope, and push conversion of the alkene substrate by using 4 mol% catalyst loading and by increasing residence time. Additionally, reactions were performed at 52 bar to solubilize the light alkane substrates completely and to ensure maximum selectivity for carbonylation. With dimethyl maleate as alkene substrate, the residence times required for complete conversion, became 2 h, 3 h and 4 h for n-butane, propane and ethane, respectively.

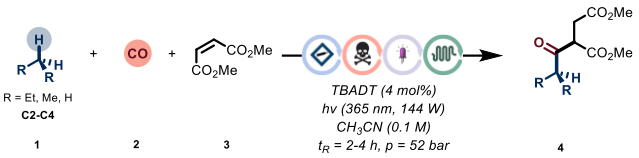


Table S12: Residence time required for C2-C4 light alkanes to achieve full conversion.

Entry	Light Alkane	**t_R [h]**
1	n-butane	2
2	propane	3
3	ethane	4

[a] Reaction conditions: A stock solution was prepared with 0.4 mmol of **3** and 4 mol% of TBADT dissolved in 4 mL of acetonitrile. The solution was first loop filled with alkane gas (**1**, 10 equiv.), then with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. [b] ^{1}H-NMR yields are calculated with an internal standard (biphenyl).

6.2 Methane

When applying the same reaction conditions as for C2-4 light alkanes to methane carbonylation, only messy crude ^{1}H NMR spectra and GCMS chromatograms were obtained, with trace amount of product and also some HAT activation of the reaction solvent CH_3CN. When lowering the substrate concentration and switching to CD_3CN as reaction solvent, conversion of starting material increased, but still only traces of product were observed.

Given recent successes of halogen radical-mediated HAT transformations,[3] we decided to change the HAT photocatalyst to cheap and abundantly available $FeCl_3.6H_2O$, functioning as a source of Cl· which can serve as a powerful H-abstractor. As a first trial, we used a low substrate concentration (0.02 M), high methane equivalents (50 equiv.), high catalyst loading (50 mol%) and a long residence time (8 h), to apply the most forcing conditions possible (entry 4). To our delight, significantly higher product formation was observed using this photocatalyst, with complete conversion of alkene substrate and only trace amounts of solvent activation, even in non-deuterated acetonitrile. Next, we investigated whether the substrate concentration could be increased to synthetically more useful amounts. At a concentration of 0.05 M, the reaction outcome was almost the same as for 0.02 M, but at 0.1 M alkene concentration, more side products were formed. We then tried to lower catalyst loading, methane equivalents and reaction time, still resulting in a similar result. A residence time of 8 h and catalyst loading of 10 mol% was chosen for the substrate scope, because of a slower reaction for other alkene substrates.

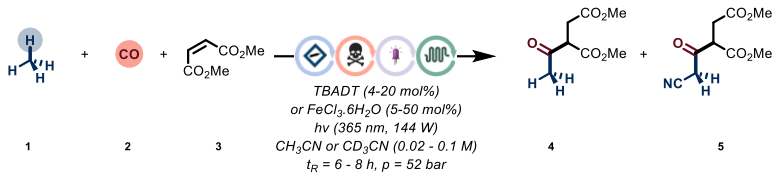


Table S13: Reaction Optimization for Methane Carbonylation.

Entry[a]	Conc. [M]	Catalyst	Solvent	Me equiv.	t_R [h]	3[b]	4[b]	5[b]
1	0.1	TBADT (4 mol%)	CH_3CN	10	6	45%	Traces	Traces
2	0.05	TBADT (8 mol%)	CD_3CN	20	8	18%	Traces	Traces
3	0.02	TBADT (20 mol%)	CD_3CN	50	8	1%	Traces	Traces
4	0.02	$FeCl_3.6H_2O$ (50 mol%)	CH_3CN	50	8	0%	37%	Traces
5	0.05	$FeCl_3.6H_2O$ (20mol%)	CH_3CN	20	8	0%	34%	Traces
6	0.1	$FeCl_3.6H_2O$ (10 mol%)	CH_3CN	10	8	0%	23%	Traces
7	0.05	$FeCl_3.6H_2O$ (5 mol%)	CH_3CN	10	8	0%	31%	Traces
8	0.05	$FeCl_3.6H_2O$ (5 mol%)	CH_3CN	20	8	0%	35%	Traces
9	0.05	$FeCl_3.6H_2O$ (5 mol%)	CH_3CN	20	4	0%	33%	Traces

[a] Reaction conditions: A stock solution was prepared with 0.3 mmol of **3**, and x mol% of TBADT or x mol% of $FeCl_3.6H_2O$ dissolved in 6 mL of appropriate solvent. The solution was first loop filled with methane gas (**1**, 10 to 50 equivalents), then with CO gas (**2**, 35 equiv.), pressurized and the gas-liquid slugs were pumped into the reactor. [b] ^{1}H-NMR yields are calculated with an internal standard (biphenyl). Crude mixtures were also analyzed using GCMS.

7. Scale-up

A scale-up reaction is performed in continuous-flow with cyclohexane as H-donor and dimethyl maleate as alkene substrate. A double reactor coil (PFA: 0.8 mm ID, 15 mL) is used to increase the internal volume, allowing for higher flow rate with the same residence time, and consequently, increased productivity. In 3 hours operation time, a 5.2 mmol stock solution is processed, generating 1.089 g of purified product in 81% yield (productivity of 1.42 mmol·h^{-1}).

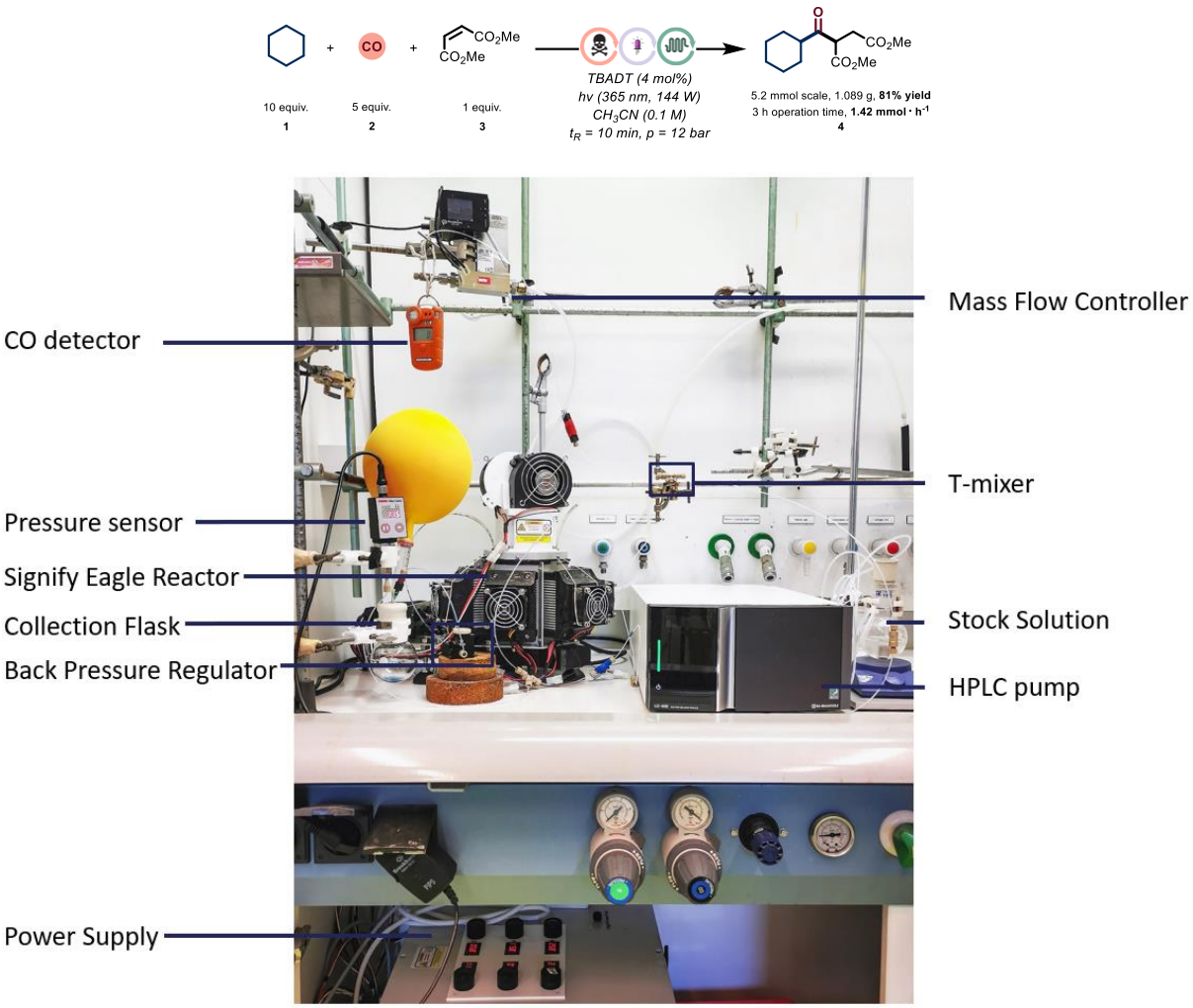


Figure 12: Setup for the scale-up reaction in continuous mode.

8. ^{13}C-labeling

Before applying our photocatalytic carbonylation protocol to isotopic labeling with ^{13}CO, we wanted to investigate whether we could reduce the CO equivalents to provide a more economical procedure. The model reaction with cyclohexane and dimethyl maleate was performed with various CO equivalents and the influence on selectivity for carbonylation was monitored. Elevated pressures (52 bar) were applied, to ensure that most amount of carbon monoxide possible would be pushed into the liquid phase. Interestingly, CO equivalents can be lowered to 5 equivalents without a loss in selectivity. Isotopic labeling experiments were subsequently performed for five representative scope entries, using 5 equivalents of ^{13}CO, under otherwise unchanged conditions.

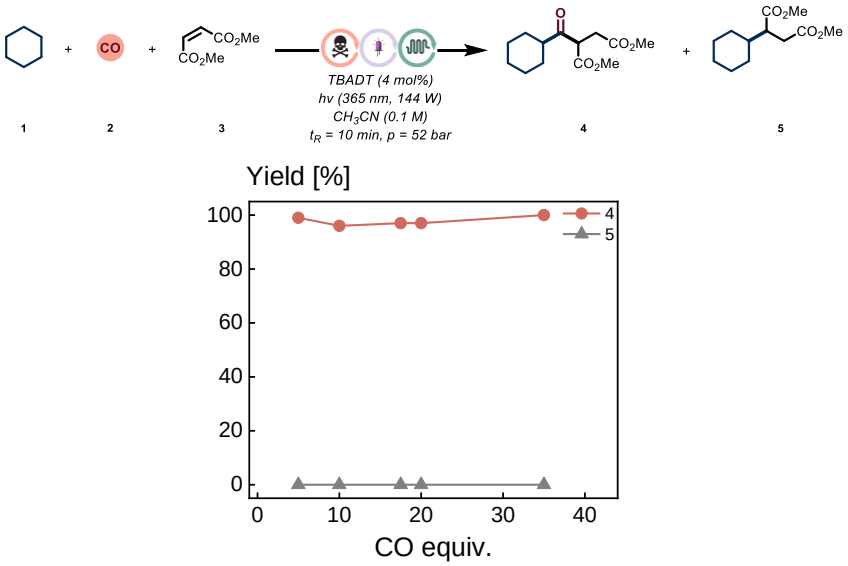


*Figure S13: ^{1}H-NMR yield of dimethyl-maleate (**4**) and dimethyl 2-(cyclohexanecarbonyl)succinate (**5**) in function of CO equivalents, calculated with an internal standard (trimethoxybenzene).*

Figure S14: Setup for isotopic labeling experiment of a light alkane using ^{13}CO. Picture is taken during second loop filling: a gas-liquid mixture of stock solution and light alkane gas (in loop 1) are combined with a gas stream of ^{13}CO (in loop 2). See protocol gas-gas-liquid reaction for a schematic representation.

9. Comparison TBADT and $FeCl_3.6H_2O$

After establishing a successful methane carbonylation protocol using $FeCl_3.6H_2O$ as photocatalyst, we wanted to compare the performance of this catalyst with the performance of TBADT.

9.1 Kinetics

To compare performance of both photocatalysts in terms of reaction kinetics, a residence time screening was performed of the model reaction between cyclohexane, CO and dimethyl maleate. After 10 minutes residence time, a conversion of dimethyl maleate of 97% was observed with 4 mol% TBADT, while only 10% dimethyl maleate was converted with 4 mol% $FeCl_3.6H_2O$.

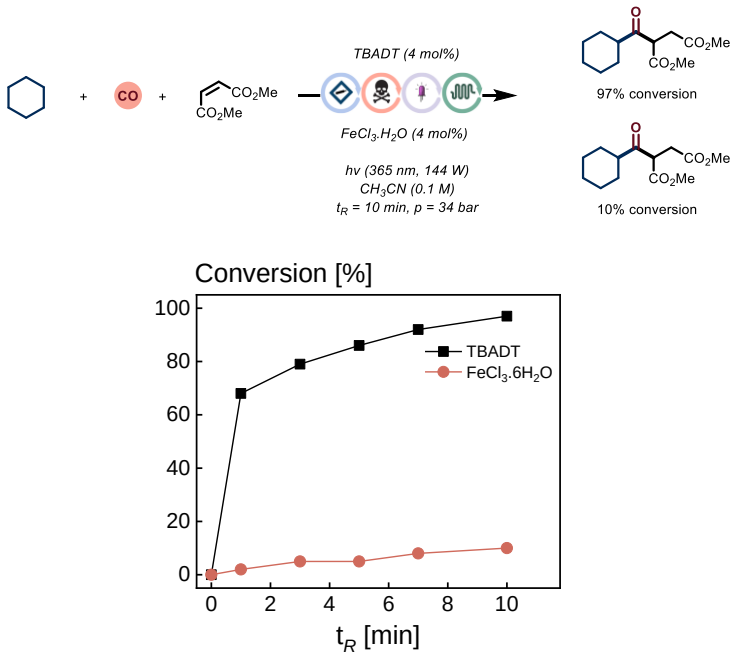
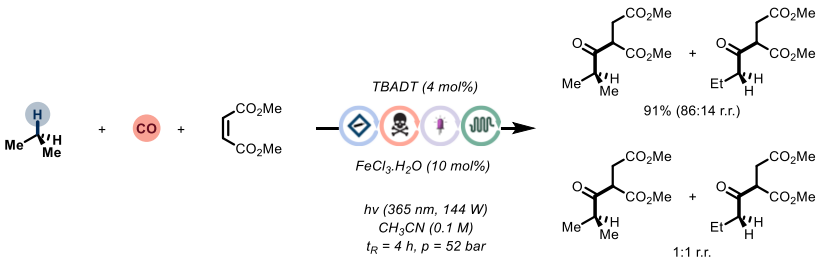


Figure S15:Conversion of dimethyl maleate in function of residence time, calculated from ^{1}H-NMR with an internal standard (trimethoxybenzene).

9.2 Regioselectivity for Light Alkane Scope

Also the difference in regioselectivity for branched or linear product between the two photocatalysts was investigated. The reaction between propane, CO and dimethyl maleate was performed and the regioisomeric ratio of the crude mixture was determined through ^{1}H NMR. For TBADT a regioisomeric ratio of 86:14 for branched to linear product was observed, while no selectivity was observed with $FeCl_3.6H_2O$.



9.3 Reaction Mechanism

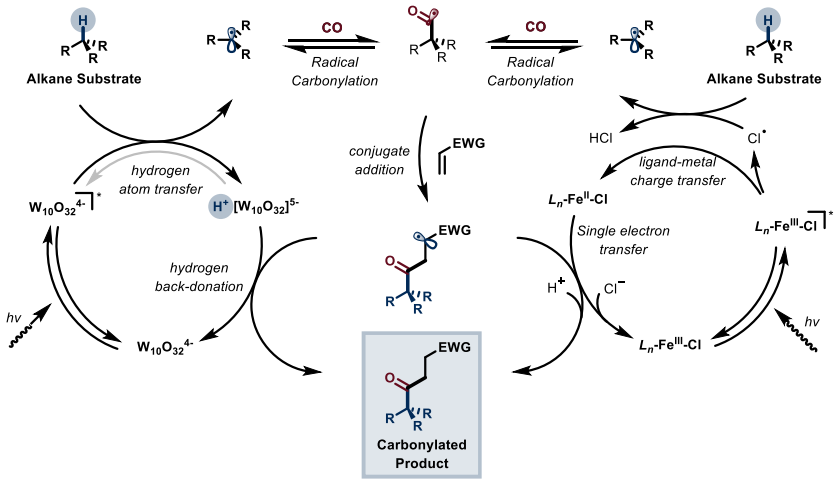


Figure S16:Proposed mechanism for the photocatalytic carbonylation of unactivated alkanes, using TBADT and $FeCl_3.6H_2O$ as HAT photocatalysts.

Based on previous reports,[3,4] we expect the decatungstate and iron trichloride catalyzed reactions to take place under the mechanisms depicted in Scheme 16. For the decatungstate mediated case, reaction starts with activation of the photocatalyst to an excited state ($[W_{10}O_{32}^{4-}]$*), in which the photocatalyst is capable of abstracting a hydrogen atom from the alkane substrate. The resulting alkyl radical is reversibly carbonylated to an acyl radical, which adds to the electron-deficient alkene to generate the coupled radical intermediate. This radical intermediate then interacts with the reduced decatungstate in a second HAT step, forming the product and closing the catalytic cycle. For the $FeCl_3.6H_2O$ catalyzed reactions, a similar mechanism is expected, where the hydrogen atom abstracting species Cl· is generated after irradiating Fe^{III}–Cl to an excited state and subsequent Ligand-Metal Charge Transfer (LMCT). Alkane substrate and Cl· form an alkyl radical and HCl in a irreversible reaction, after which the alkyl radical adds to CO and to the Michael acceptor. The resulting radical intermediate is reduced to its anion by Fe^{II} through a single-electron transfer and protonated to form the product.

It is speculated that methane activation occurs more effectively using $FeCl_3.6H_2O$, mainly because HCl is irreversibly formed through HAT between Cl· and alkane, whereas the reduced decatungstate can easily perform hydrogen back-donation to the highly reactive methyl radical,[5] before it is coupled with CO and/or alkene. However, other contributing factors such as Lewis acid activation or lifetime of hydrogen abstracting species, can not be excluded.[6,7]

10. Limitations of the Scope

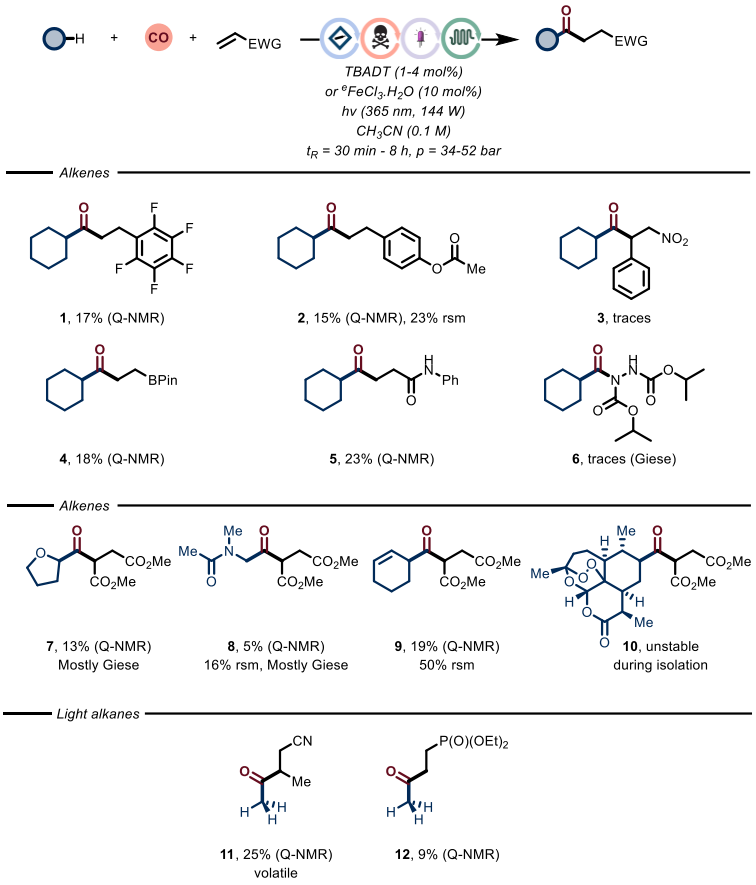


Figure S17:Limitations of the scope.

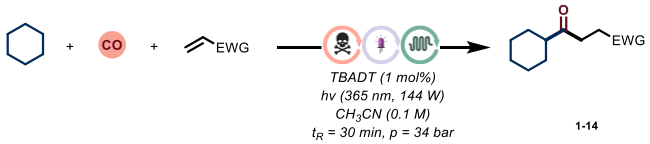
Not all substrates were suitable for the developed protocol. On the alkene side, mildly electron poor and electron rich styrene derivatives gave low yields. Also vinyl boronic acid pinacol ester and *N*-phenyl acrylamide gave low yields. For carbonylation of the highly electrophilic diisopropyl azodicarboxylate, low substrate concentrations are required to avoid direct Giese coupling with the cyclohexyl radical.[8]

On the H-donor side, activated α-heteroatom and allylic alkanes, with corresponding electron rich alkyl radicals, mainly resulted in direct Giese coupling as the major product. For artemisinin, product was observed after reaction, but this decomposed during isolation.

For the methane scope, reaction with crotonitrile resulted in a volatile product, hampering isolation, while low yield was observed for vinyl phosphonate.

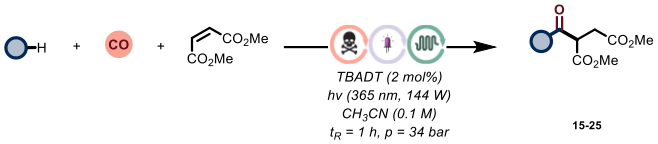
11. Experimental Procedures

11.1 Alkenes



To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with TBADT (13.29 mg, 1 mol%) degassed CH_3CN is added (4 mL, 0.1 M), followed by alkene substrate (0.4 mmol, 1 equiv.) and cyclohexane (432 µL, 4.0 mmol, 10 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a filling loop, with a liquid flow rate of 0.1 mL·min^{-1} and a gas flow rate of 8.61 mL·min^{-1}. A BPR of 5.2 bar is connected at the outlet of the filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 34 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.8 mm ID, 5 mL) at a flow rate of 0.167 mL·min^{-1}, resulting in a residence time of 30 minutes. The solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

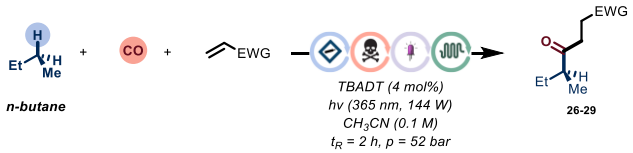
11.2 Liquid Alkanes



To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with TBADT (26.58 mg, 2 mol%) degassed CH_3CN is added (4 mL, 0.1 M), followed by dimethyl maleate (50.16 µL, 0.4 mmol, 1 equiv.) and alkane substrate (4.0 mmol, 10 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a filling loop, with a liquid flow rate of 0.1 mL·min^{-1} and a gas flow rate of 8.61 mL·min^{-1}. A BPR of 5.2 bar is connected at the outlet of the filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 34 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.8 mm ID, 5 mL) at a flow rate of 0.083 mL·min^{-1}, resulting in a residence time of 1 hour. The solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

11.3 Light Alkanes

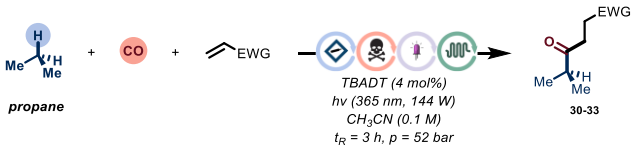
11.3.1 *n*-Butane



To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with TBADT (53.16 mg, 1 mol%) degassed CH_3CN is added (4 mL, 0.1 M), followed by alkene substrate (0.4 mmol, 1 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of n-butane gas (93 mL, 4.0 mmol, 10 equiv.) through a T-mixer into a first filling loop, with a liquid flow rate of 0.2 mL·min^{-1} and a n-butane gas flow rate of 4.65 mL·min^{-1}. Due to the low liquefaction point of n-butane, no BPR is used during the first loop filling. Next, the first filling loop is connected to an HPLC pump and compressed to the pressure of the second filling loop (5.2 bar). Then

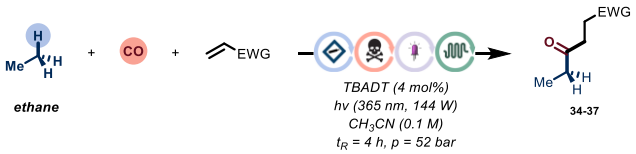
the reaction mixture in the first filling loop is combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a second filling loop, with a liquid flow rate of 0.1 mL·min^{-1} and a gas flow rate of 8.61 mL·min^{-1}. A BPR of 5.2 bar is connected at the outlet of the second filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 52 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.5 mm ID, 3 mL) at a flow rate of 0.025 mL·min^{-1}, resulting in a residence time of 2 h. The solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

11.3.2 Propane



To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with TBADT (53.16 mg, 1 mol%) degassed CH_3CN is added (4 mL, 0.1 M), followed by alkene substrate (0.4 mmol, 1 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of propane gas (98 mL, 4.0 mmol, 10 equiv.) through a T-mixer into a first filling loop, with a liquid flow rate of 0.2 mL·min^{-1} and a propane gas flow rate of 4.9 mL·min^{-1}. A BPR of 2.8 bar is used during the first loop filling. Next, the first filling loop is connected to an HPLC pump and compressed to the pressure of the second filling loop (5.2 bar). Then the reaction mixture in the first filling loop is combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a second filling loop, with a liquid flow rate of 0.1 mL·min^{-1} and a gas flow rate of 8.61 mL·min^{-1}. A BPR of 5.2 bar is connected at the outlet of the second filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 52 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.5 mm ID, 3 mL) at a flow rate of 0.0167 mL·min^{-1}, resulting in a residence time of 3 h. The solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

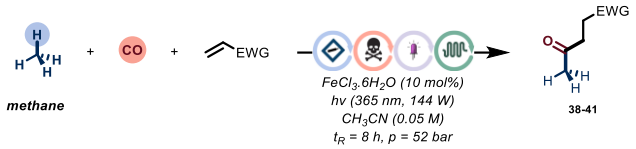
11.3.3 Ethane



To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with TBADT (53.16 mg, 1 mol%) degassed CH_3CN is added (4 mL, 0.1 M), followed by alkene substrate (0.4 mmol, 1 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of ethane gas (94 mL, 4.0 mmol, 10 equiv.) through a T-mixer into a first filling loop, with a liquid flow rate of 0.2 mL·min^{-1} and a ethane gas flow rate of 4.7 mL·min^{-1}. A BPR of 5.2 bar is used during the first loop filling. Next, the first filling loop is connected to an HPLC pump and compressed to the pressure of the second filling loop (5.2 bar). Then the reaction mixture in the first filling loop is combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a second filling loop. A BPR of 7 bar is connected at the outlet of the second filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 52 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.5 mm ID, 3 mL) at a flow rate of 0.0125 mL·min^{-1}, resulting in a residence time of 4 h. The

solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

11.3.4 Methane

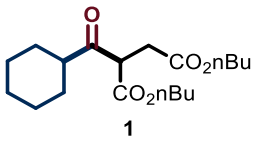


To a nitrogen-purged, screw-capped vial, fitted with a rubber septum and charged with $FeCl_3.6H_2O$ (8.1 mg, 10 mol%) degassed CH_3CN is added (6 mL, 0.05 M), followed by alkene substrate (0.3 mmol, 1 equiv.). The stock solution is charged in a gastight syringe, positioned in a syringe pump and combined with a stream of methane gas (143 mL, 6.0 mmol, 20 equiv.) through a T-mixer into a first filling loop, with a liquid flow rate of 0.2 $mL \cdot min^{-1}$ and a methane gas flow rate of 4.77 $mL \cdot min^{-1}$. A BPR of 5.2 bar is used during the first loop filling. Next, the first filling loop is connected to an HPLC pump and compressed to the pressure of the second filling loop (7 bar). Then the reaction mixture in the first filling loop is combined with a stream of CO gas (344 mL, 14.0 mmol, 35 equiv.) through a T-mixer into a second filling loop. A BPR of 7 bar is connected at the outlet of the second filling loop. After all reaction mixture is injected, the filling loop is connected to the reactor, the system is pressurized to 52 bar and the reaction mixture is pumped over the Eagle reactor (365 nm, 144 W output power, FEP capillary: 0.5 mm ID, 3 mL) at a flow rate of 0.0125 $mL \cdot min^{-1}$, resulting in a residence time of 8 h. The solvent of the resulting reaction mixture is removed under reduced pressure and purification by flash column chromatography on silica gel gave the corresponding products in the stated yield.

12. Characterization Data

12.1 Alkenes

Dibutyl 2-(cyclohexanecarbonyl)succinate (1)

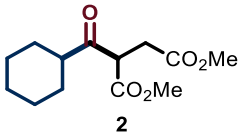


1

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), di-n-butyl maleate (92.4 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **1** (97 mg, 71% yield) as a yellow oil. The spectroscopic data are consistent with those reported previously.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.16 – 4.08 (m, 3H), 4.05 (t, *J* = 6.7 Hz, 2H), 2.92 (dd, *J* = 17.4, 8.1 Hz, 1H), 2.80 (dd, *J* = 17.4, 6.3 Hz, 1H), 2.75 (m, 1H), 2.03 – 1.93 (m, 1H), 1.85 – 1.73 (m, 3H), 1.71 – 1.52 (m, 5H), 1.49 – 1.12 (m, 9H), 0.92 (td, *J* = 7.4, 2.9 Hz, 6H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.1, 171.6, 168.9, 65.7, 65.0, 52.5, 50.7, 32.6, 30.7, 30.6, 29.1, 28.0, 25.9, 25.9, 25.5, 19.2 (2C), 13.8, 13.8.

Dimethyl 2-(cyclohexanecarbonyl)succinate (2)

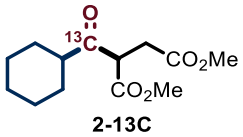


2

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **2** (94 mg, 92% yield) as a yellow oil. The spectroscopic data are consistent with those reported previously.[10]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.15 (dd, J = 8.0, 6.4 Hz, 1H), 3.73 (s, 3H), 3.67 (s, 3H), 3.01 – 2.88 (m, 1H), 2.81 (dd, J = 17.4, 6.4 Hz, 1H), 2.73 – 2.58 (m, 1H), 2.05 – 1.90 (m, 1H), 1.87 – 1.61 (m, 4H), 1.49 – 1.12 (m, 5H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 206.7, 171.6, 168.9, 52.5, 51.9, 51.9, 50.4, 32.1, 28.7, 27.7, 25.6, 25.5, 25.1.
HRMS (FI) *m/z* calcd for $C_{13}H_{20}O_5$: 256.1311; found: 256.1318.

Dimethyl 2-(cyclohexanecarbonyl)succinate (2-^{13}C)

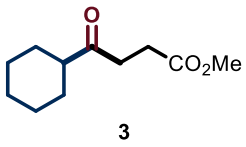


2-13C

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and 13C carbon monoxide (49 mL, 2.0 mmol, 5 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **2-^{13}C** (81 mg, 79% yield) as a yellow oil. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.14 (ddd, *J* = 8.0, 6.4, 5.3 Hz, 1H), 3.73 (s, 2H), 3.66 (s, 3H), 2.94 (ddd, *J* = 17.4, 8.1, 2.8 Hz, 1H), 2.81 (ddd, *J* = 17.5, 6.4, 4.8 Hz, 1H), 2.65 (dqd, *J* = 12.6, 6.2, 2.1 Hz, 1H), 2.02 – 1.92 (m, 1H), 1.85 – 1.73 (m, 3H), 1.71 – 1.63 (m, 1H), 1.49 – 1.34 (m, 1H), 1.34 – 1.12 (m, 4H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.0, 171.9 (d, *J* = 2.2 Hz), 169.3 (d, *J* = 1.8 Hz), 52.8, 52.2 (d, *J* = 35.6 Hz), 52.1, 50.7 (d, *J* = 42.3 Hz), 32.4 (d, *J* = 1.6 Hz), 29.0 (d, *J* = 1.7 Hz), 28.1 (d, *J* = 1.8 Hz), 25.9 (d, *J* = 4.0 Hz), 25.8, 25.5 (d, *J* = 3.7 Hz).
HRMS (FI) *m/z* calcd for $C_{12}{}^{13}C_1H_{20}O_5$: 257.1344; found: 257.1337.

Methyl 4-cyclohexyl-4-oxobutanoate (3)

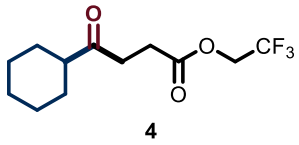


3

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), methyl acrylate (36.2 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **3** (44 mg, 55% yield) as a yellow oil. The spectroscopic data are consistent with those reported previously.[11]

^{1}H NMR (300 MHz, $CDCl_3$) δ 3.66 (s, 3H), 2.75 (t, *J* = 6.7 Hz, 2H), 2.57 (t, *J* = 6.4 Hz, 2H), 2.37 (tt, *J* = 11.2, 3.5 Hz, 1H), 1.93 – 1.82 (m, 2H), 1.82 – 1.72 (m, 2H), 1.71 – 1.62 (m, 1H), 1.45 – 1.10 (m, 5H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 212.2, 173.6, 51.9, 50.8, 35.1, 28.6 (2C), 27.8, 26.0, 25.8 (2C).

2,2,2-trifluoroethyl 4-cyclohexyl-4-oxobutanoate (4)

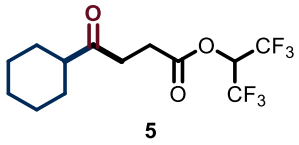


4

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), 2,2,2-trifluoroethyl acrylate (63.4 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **4** (47 mg, 44% yield) as a yellow oil. This compound was previously unreported.

^{1}H NMR (300 MHz, $CDCl_3$) δ 4.45 (q, J = 8.5 Hz, 2H), 2.79 (ddd, J = 7.0, 5.9, 1.1 Hz, 2H), 2.67 (ddd, J = 7.0, 5.9, 1.1 Hz, 2H), 2.37 (td, J = 11.1, 3.5 Hz, 1H), 1.93 – 1.82 (m, 2H), 1.78 (ddd, J = 8.0, 3.6, 1.8 Hz, 1H), 1.72 – 1.61 (m, 1H), 1.45 – 1.14 (m, 6H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 211.6, 171.5, 126.1 (apparent q, *J* = 277.2 Hz), 60.6 (q, *J* = 36.7 Hz), 50.8, 34.9, 28.6 (2C), 27.6, 25.9, 25.7 (2C).
^{19}F NMR (282 MHz, $CDCl_3$) δ -73.8 (t, *J* = 8.6 Hz).
HRMS (FI) *m/z* calcd for $C_{12}H_{17}F_3O_3$: 266.1130; found: 266.1117.

1,1,1,3,3,3-hexafluoropropan-2-yl 4-cyclohexyl-4-oxobutanoate (5)

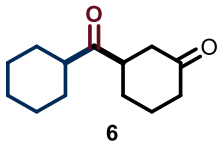


5

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), 1,1,1,3,3,3-hexafluoroisopropyl acrylate (66.8 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **5** (36 mg, 27% yield) as a yellow oil. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (hept, *J* = 6.1 Hz, 1H), 2.83 (ddd, *J* = 6.7, 5.5, 1.3 Hz, 2H), 2.76 (ddd, *J* = 7.1, 5.6, 1.3 Hz, 2H), 2.38 (tt, *J* = 11.2, 3.5 Hz, 1H), 1.92 – 1.83 (m, 2H), 1.79 (dt, *J* = 11.8, 3.1 Hz, 2H), 1.72 – 1.62 (m, 1H), 1.46 – 1.11 (m, 6H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.9, 170.0, 120.5 (2C, apparent d, *J* = 282.4 Hz), 66.7 (apparent p, *J* = 34.8 Hz) , 50.7, 34.7, 28.6 (2C), 27.4, 25.9, 25.7 (2C).
^{19}F NMR (376 MHz, $CDCl_3$) δ -73.3 (t, *J* = 6.3 Hz).
HRMS (FI) *m/z* calcd for $C_{13}H_{16}F_6O_3$: 334.1004; found: 334.1018.

3-(cyclohexanecarbonyl)cyclohexan-1-one (6)



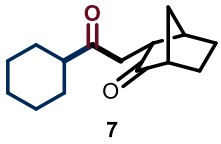
6

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), cyclohexenone (38.45 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5

AcOEt) to afford product **1** (27 mg, 33% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.02 (tt, *J* = 10.9, 4.0 Hz, 1H), 2.57 – 2.42 (m, 2H), 2.40 – 2.26 (m, 3H), 2.15 – 2.05 (m, 1H), 2.04 – 1.95 (m, 1H), 1.87 – 1.55 (m, 8H), 1.39 (dd, *J* = 12.1, 3.2 Hz, 1H), 1.35 – 1.14 (m, 4H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 213.8, 210.6, 49.7, 48.6, 43.1, 41.1, 28.9, 28.3, 27.7, 25.9 (2C), 25.6, 25.3.

(1S,3R,4R)-3-(2-cyclohexyl-2-oxoethyl)bicyclo[2.2.1]heptan-2-one (7)

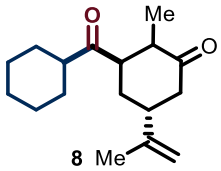


7

Prepared according to the general procedure for alkenes, using cyclohexane (432 μL, 4.0 mmol, 10 equiv.), 3-methylene-2-norbornanone (49.0 μL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **1** (37 mg, 40% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 2.79 (dd, *J* = 17.9, 3.8 Hz, 1H), 2.70 – 2.64 (m, 1H), 2.64 – 2.55 (m, 2H), 2.40 – 2.27 (m, 2H), 1.88 – 1.80 (m, 3H), 1.80 – 1.73 (m, 3H), 1.69 – 1.52 (m, 3H), 1.48 – 1.11 (m, 7H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 219.4, 212.2, 51.1, 50.1, 49.5, 39.1, 37.4, 37.0, 28.7, 28.5, 25.9, 25.8 (2C), 25.7, 21.5.

(5R)-3-(cyclohexanecarbonyl)-2-methyl-5-(prop-1-en-2-yl)cyclohexan-1-one (8)

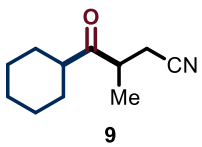


8

Prepared according to the general procedure for alkenes, using cyclohexane (432 μL, 4.0 mmol, 10 equiv.), carvone (62.7 μL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **1** (35 mg, 33% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.79 – 4.66 (m, 2H), 3.48 (td, *J* = 4.9, 3.0 Hz, 1H), 2.54 (ddd, *J* = 14.4, 4.5, 2.0 Hz, 1H), 2.42 (dtt, *J* = 14.5, 11.4, 3.7 Hz, 2H), 2.36 – 2.28 (m, 1H), 2.19 – 2.08 (m, 1H), 2.07 – 1.99 (m, 1H), 1.93 (ddd, *J* = 14.0, 12.1, 4.9 Hz, 1H), 1.87 – 1.73 (m, 2H), 1.73 – 1.61 (m, 6H), 1.49 – 1.35 (m, 1H), 1.34 – 1.11 (m, 4H), 0.97 (d, *J* = 6.7 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 214.7, 209.3, 147.2, 110.2, 52.3, 50.4, 45.4, 45.4, 40.4, 31.8, 28.6, 27.9, 25.9, 25.8, 25.4, 20.7, 12.5.
HRMS (FI) *m/z* calcd for $C_{17}H_{26}O_2$: 262.1932; found: 262.1922.

Dibutyl 2-(cyclohexanecarbonyl)succinate (9)



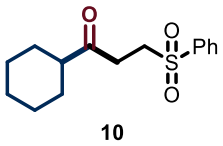
9

Prepared according to the general procedure for alkenes, using cyclohexane (432 μL, 4.0 mmol, 10 equiv.), crotonitrile (32.6 μL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **1** (51 mg, 71% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.04 (apparent sext *J* = 7.2 Hz, 1H), 2.56 (dd, *J* = 16.9, 6.4 Hz, 1H), 2.64 – 2.46 (overlapped m, 1H), 2.40 (dd, *J* = 16.9, 7.7 Hz, 1H), 1.92 – 1.57 (m, 5H), 1.54 – 1.37 (m, 1H), 1.33 – 1.14 (m, 7H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 213.3, 118.7, 49.1, 41.1, 29.1, 28.0, 25.9, 25.8, 25.4, 20.1, 16.9.

1-cyclohexyl-3-(phenylsulfonyl)propan-1-one (10)

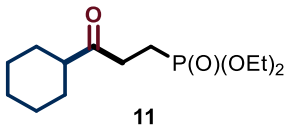


10

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), phenyl vinyl sulfone (67.3 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **10** (56 mg, 50% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[10]

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.96 – 7.86 (m, 2H), 7.71 – 7.63 (m, 1H), 7.62 – 7.52 (m, 2H), 3.37 (dd, *J* = 8.4, 6.7 Hz, 2H), 2.95 (dd, *J* = 8.3, 6.8 Hz, 2H), 2.33 (m, 1H), 1.90 – 1.72 (m, 4H), 1.70 – 1.58 (m, 1H), 1.35 – 1.17 (m, 5H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 209.4, 139.2, 134.0, 129.5 (2C), 128.1 (2C), 50.9, 50.7, 33.0, 28.5 (2C), 25.8, 25.6 (2C).

Diethyl (3-cyclohexyl-3-oxopropyl)phosphonate (11)

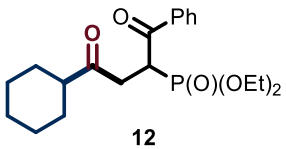


11

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), diethyl vinyl phosphonate (61.5 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **11** (91 mg, 82% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.15 – 3.97 (m, 4H), 2.72 (ddd, *J* = 11.3, 8.4, 7.1 Hz, 2H), 2.39 – 2.28 (m, 1H), 2.04 – 1.91 (m, 2H), 1.88 – 1.70 (m, 4H), 1.69 – 1.59 (m, 1H), 1.38 – 1.11 (overlapping peaks, 5H), 1.30 (t, *J* = 7.1 Hz, 6H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 211.4 (d, *J* = 14.2 Hz), 61.8 (d, *J* = 6.4 Hz, 2C), 50.8, 33.5 (d, *J* = 3.6 Hz), 28.6 (2C), 25.9, 25.7 (2C), 19.4 (d, *J* = 144.2 Hz), 16.5 (d, *J* = 6.0 Hz, 2C) .
^{31}P NMR (162 MHz, $CDCl_3$) δ 32.0.
HRMS (FI) *m/z* calcd for $C_{13}H_{25}O_4P$: 276.1490; found: 276.1466.

diethyl (4-cyclohexyl-1,4-dioxo-1-phenylbutan-2-yl)phosphonate (12)

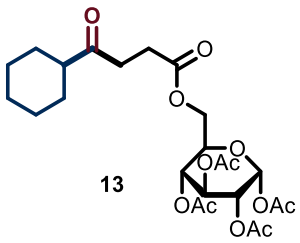


12

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), diethyl (3-oxo-3-phenylprop-1-ene-2-yl)phosphonate (107.3 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **12** (66 mg, 43% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03 (d, J = 6.9 Hz, 2H), 7.56 (t, J = 7.4 Hz, 1H), 7.46 (t, J = 7.6 Hz, 2H), 4.59 (ddd, J = 23.5, 11.0, 2.7 Hz, 1H), 4.12 – 3.93 (m, 4H), 3.69 – 3.56 (m, 1H), 3.04 (ddd, J = 18.4, 9.2, 2.8 Hz, 1H), 2.40 (m, 1H), 2.02 – 1.57 (m, 8H), 1.41 – 1.26 (m, 2H), 1.23 (t, *J* = 7.1 Hz, 3H), 1.13 (t, *J* = 7.0 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.8 (d, *J* = 15.2 Hz), 195.7 (d, *J* = 4.7 Hz), 137.6, 133.3, 129.0 (2C), 128.5 (2C), 63.0 (d, *J* = 6.9 Hz), 62.9 (d, *J* = 6.9 Hz), 50.4, 42.4 (d, *J* = 128.5 Hz), 38.9 (d, *J* = 2.3 Hz), 28.6, 28.5, 25.9, 25.7, 25.7, 16.4 (d, *J* = 5.9 Hz), 16.2 (d, *J* = 6.2 Hz).
^{31}P NMR (162 MHz, $CDCl_3$) δ 22.3.
HRMS (FI) *m/z* calcd for $C_{20}H_{29}O_5P$: 380.1753; found: 380.1742.

(2R,3R,4S,5R,6R)-6-(((4-cyclohexyl-4-oxobutanoyl)oxy)methyl)tetrahydro-2H-pyran-2,3,4,5-tetrayl tetraacetate (13)

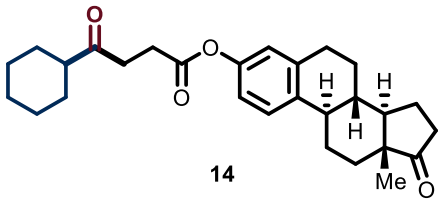


13

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), (2R,3R,4S,5R,6R)-6-((acryloyloxy)methyl) tetrahydro-2H-pyran-2,3,4,5-tetrayl tetraacetate (160.9 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 1:1 AcOEt) to afford product **13** (149 mg, 72% yield) as a colorless oil. This compound was previously unreported.

^{1}H NMR (300 MHz, $CDCl_3$) δ 5.69 (d, *J* = 8.1 Hz, 1H), 5.27 – 5.18 (m, 1H), 5.16 – 5.02 (m, 2H), 4.25 (dd, *J* = 12.5, 4.8 Hz, 1H), 4.16 – 4.03 (m, 1H), 3.82 (ddd, *J* = 9.9, 4.8, 2.3 Hz, 1H), 2.77 – 2.68 (m, 2H), 2.63 – 2.55 (m, 2H), 2.44 – 2.29 (m, 1H), 2.09 (s, 3H), 2.05 – 1.96 (m, 8H), 1.89 – 1.60 (m, 4H), 1.41 – 1.19 (m, 4H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 211.8, 172.6, 170.2, 169.5, 169.3, 169.0, 91.8, 72.9, 72.8, 70.3, 67.9, 61.8, 50.7, 35.0, 28.6 (2C), 27.8, 25.9, 25.7 (2C), 20.9, 20.7 (3C).
MS (FI) *m/z* calcd for $C_{22}H_{30}O_{10}$: [M-HOAc]+ 454.2 ; found: 454.2.

(8R,9S,13S,14S)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6H-cyclopenta[a]phenanthren-3-yl 4-cyclohexyl-4-oxobutanoate (14)



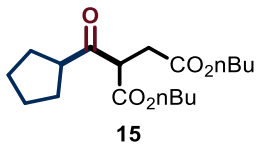
14

Prepared according to the general procedure for alkenes, using cyclohexane (432 µL, 4.0 mmol, 10 equiv.), (8R,9S,13S,14S)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6H-cyclopenta[a]phenanthren-3-yl acrylate (129.8 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **14** (49 mg, 28% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28 (s, 1H), 6.88 – 6.78 (m, 2H), 2.94 – 2.86 (m, 2H), 2.89 – 2.77 (m, 3H), 2.55 – 2.46 (m, 1H), 2.45 – 2.35 (m, 2H), 2.32 – 2.23 (m, 1H), 2.16 – 1.93 (m, 3H), 1.92 – 1.84 (m, 2H), 1.81 – 1.74 (m, 2H), 1.71 – 1.15 (m, 13H), 0.90 (s, 3H), 0.90 – 0.84 (m, 1H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 220.9, 212.0, 172.0, 148.7, 138.1, 137.5, 126.5, 121.7, 118.9, 50.9, 50.6, 48.1, 44.3, 38.1, 36.0, 35.1, 31.7, 29.5, 28.6 (2C), 28.3, 26.5, 26.0, 25.9, 25.8 (2C), 21.7, 14.0.
HRMS (FI) *m/z* calcd for $C_{28}H_{36}O_4$: 436.2614; found: 436.2609.

12.2 Liquid Alkanes

Dibutyl 2-(cyclopentanecarbonyl)succinate (15)



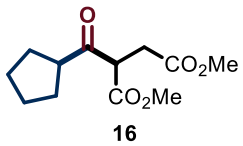
15

Prepared according to the general procedure for liquid alkanes, using cyclopentane (374 µL, 4.0 mmol, 10 equiv.), di-n-butyl maleate (92.4 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (344 mL, 14.0 mmol, 35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **15** (83 mg, 64% yield) as a colorless liquid. This compound was previously unreported.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.13 (t, J = 6.8 Hz, 2H), 4.09 – 3.98 (overlapping peaks, 3H), 3.15 (p, *J* = 7.9 Hz, 1H), 2.94 (dd, *J* = 17.4, 7.9 Hz, 1H), 2.82 (dd, *J* = 17.4, 6.6 Hz, 1H), 1.98 – 1.48 (m, 12H), 1.36 (apparent sext, *J* = 7.4 Hz, 4H), 0.90 (dt, *J* = 8.9, 4.5 Hz, 6H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 206.6, 171.5, 168.8, 65.6, 64.9, 53.8, 51.2, 32.6, 30.7, 30.5, 30.5, 30.1, 28.7, 26.1, 26.0, 19.1, 13.7, 13.7.
HRMS (FI) *m/z* calcd for $C_{18}H_{30}O_5$: 326.2093; found: 326.2087.

Dimethyl 2-(cyclopentanecarbonyl)succinate (16)

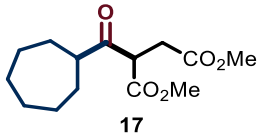


16

Prepared according to the general procedure for liquid alkanes, using cyclopentane (374 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **16** (90 mg, 93% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[10]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.09 (dd, *J* = 7.8, 6.6 Hz, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 3.16 (p, *J* = 8.4 Hz, 1H), 2.94 (dd, *J* = 17.5, 7.9 Hz, 1H), 2.82 (dd, *J* = 17.4, 6.5 Hz, 1H), 2.00 – 1.88 (m, 1H), 1.86 – 1.49 (m, 7H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 206.5, 171.9, 169.3, 53.6, 52.8, 52.1, 51.2, 32.4, 30.1, 28.8, 26.1, 26.1.

Dimethyl 2-(cycloheptanecarbonyl)succinate (17)

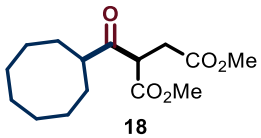


17

Prepared according to the general procedure for liquid alkanes, using cycloheptane (374 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **17** (78 mg, 72% yield) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[9]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.13 (dd, *J* = 7.7, 6.6 Hz, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 2.91 (dd, *J* = 17.4, 7.8 Hz, 1H), 2.87 – 2.77 (overlapping peak, 1H), 2.81 (dd, *J* = 17.4, 6.6 Hz, 1H) 2.00 – 1.87 (m, 1H), 1.86 – 1.36 (m, 11H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.3, 171.9, 169.3, 52.8, 52.8, 52.1, 51.9, 32.3, 30.2, 29.6, 28.4, 28.3, 26.7, 26.5.

Dimethyl 2-(cyclooctanecarbonyl)succinate (18)

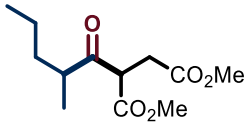


18

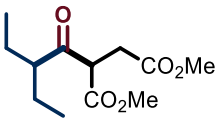
Prepared according to the general procedure for liquid alkanes, using cyclooctane (538 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **2** (65 mg, 57% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.14 (dd, *J* = 7.7, 6.6 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 2.92 (dd, *J* = 17.4, 7.7 Hz, 1H), 2.96 – 2.86 (overlapping peak, 1H), 2.83 (dd, *J* = 17.4, 6.6 Hz, 1H), 1.92 – 1.81 (m, 1H), 1.79 – 1.40 (m, 13H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.4, 172.0, 169.3, 52.9, 52.9, 52.2, 50.3, 32.4, 28.2, 27.8, 26.8, 26.6, 26.4, 25.5, 25.5.
HRMS (FI) *m/z* calcd for $C_{15}H_{24}O_5$: 284.1624; found: 284.1627.

Dimethyl 2-(2-methylpentanoyl)succinate (19)



19a

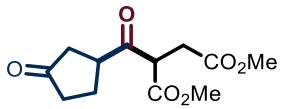


19b

Prepared according to the general procedure for liquid alkanes, using n-pentane (576 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **19a** and **19b** as an inseparable mixture of isomers (88[1:1 d.r.]:12 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (74 mg, 75% yield). This compound was previously unreported.

1H NMR (400 MHz, CDCl3) δ 4.13 (dd, *J* = 17.3, 7.4 Hz, 1H), 3.73 (s, 3H), 3.67 (s, 3H), 3.04 – 2.76 (m, 2H), 1.76 – 1.64 (m, 1H), 1.65 – 1.55 (m, 1H), 1.38 – 1.19 (m, 3H), 1.12 (d, J = 7.1 Hz, 3H), 0.88 (t, J = 7.3 Hz, 3H). Diastereoisomer 19a': 4.13 (dd, *J* = 17.3, 7.4 Hz, 1H), 3.72 (s, 3H), 3.66 (s, 3H), 3.04 – 2.76 (m, 2H), 1.76 – 1.64 (m, 1H), 1.65 – 1.55 (m, 1H), 1.38 – 1.19 (m, 3H), 1.07 (d, J = 6.8 Hz, 3H), 0.89 (t, J = 7.3 Hz, 3H).
Overlapping of peaks avoids the unambiguous ^{1}H characterization of regioisomer **19b**.
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.3, 171.9 (2C), 53.1, 52.9, 52.1, 45.8, 34.6, 32.3, 20.4, 17.0, 14.2. Diastereoisomer 19a': 207.5, 169.3, 169.0, 53.3, 52.8, 52.2, 45.7, 35.3, 32.2, 20.4, 15.9, 14.2. Regioisomer 19b: 206.6, 169.1, 168.9, 54.5, 54.2, 52.7, 42.9, 32.0, 24.3, 23.1, 11.7, 11.5.
HRMS (FI) *m/z* calcd for $C_{12}H_{20}O_5$: 244.1311; found: 244.1311.

Dimethyl 2-(3-oxocyclopentane-1-carbonyl)succinate (20)

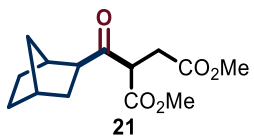


20

Prepared according to the general procedure for liquid alkanes, using cyclopentanone (354 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **20** (87 mg, 85% yield, 54:46 d.r. determined by ^{1}H NMR analysis of the crude reaction mixture) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.21 (dd, *J* = 9.6, 4.9 Hz, 1H), 3.75 (s, 3H), 3.70 – 3.75 (overlapping peak, 1H) 3.68 (s, 3H), 3.11 (dd, *J* = 17.7, 9.6 Hz, 1H), 2.89 (t, *J* = 5.3 Hz, 1H), 2.50 (d, *J* = 8.5 Hz, 2H), 2.44 – 2.31 (m, 2H), 2.29 – 2.13 (m, 2H). Diastereoisomer 20': 4.11 (dd, *J* = 9.0, 5.5 Hz, 1H), 3.76 (s, 3H), 3.67 (s, 3H), 3.70 – 3.75 (overlapping peak, 1H), 3.06 (dd, *J* = 17.6, 9.0 Hz, 1H), 2.83 (t, *J* = 5.3 Hz, 1H), 2.65 – 2.53 (m, 1H), 2.44 – 2.31 (m, 2H), 2.29 – 2.13 (m, 2H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 216.6, 204.5, 171.9, 168.5, 53.1, 52.5, 52.3, 48.0, 40.4, 37.4, 32.1, 26.4. Diastereoisomer 20': 216.2, 205.0, 171.8, 168.6, 53.2, 53.1, 52.3, 48.4, 41.1, 37.7, 32.6, 25.8.
HRMS (FI) *m/z* calcd for $C_{12}H_{16}O_6$: 256.0947; found: 256.0938.

Dimethyl 2-((1S,4R)-bicyclo[2.2.1]heptane-2-carbonyl)succinate (21)



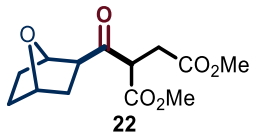
21

Prepared according to the general procedure for liquid alkanes, using norbornane (421 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **2** (84 mg, 78% yield, 60:40 d.r. determined by ^{1}H NMR analysis of the crude reaction mixture) as a colorless liquid. The spectroscopic data are consistent with those reported previously.[12]

1H NMR (300 MHz, CDCl3) δ 4.15 (dd, J = 7.9, 6.5 Hz, 1H), 3.72 (s, 3H), 3.66 (s, 3H), 2.88 (dd, J = 33.5, 7.3 Hz, 1H), 2.81 – 2.66 (m, 2H), 2.54 (d, J = 4.1 Hz, 1H), 2.28 (d, J = 4.3 Hz, 1H), 1.97 – 1.89 (m, 1H), 1.66 – 1.39 (m, 2H), 1.37 – 1.04 (m, 5H). Diastereoisomer 21': 4.03 (t, J = 7.3 Hz, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 2.92 (dd, J = 34.9, 7.7 Hz, 1H), 2.81 – 2.66 (m, 2H), 2.47 (s, 1H), 2.28 (d, J = 4.3 Hz, 1H), 1.84 – 1.76 (m, 1H), 1.66 – 1.39 (m, 2H), 1.37 – 1.04 (m, 5H).

13C NMR (75 MHz, CDCl3) δ 205.0, 171.9, 169.3, 54.0, 53.4, 52.8, 52.1, 40.8, 36.2, 35.9, 32.5, 32.3, 30.1, 28.9. Diastereoisomer 21': 205.2, 171.9, 169.4, 53.7, 53.3, 52.8, 52.1, 39.8, 36.4, 36.2, 33.6, 32.6, 29.6, 28.8.

Dimethyl 2-((1R,4S)-7-oxabicyclo[2.2.1]heptane-2-carbonyl)succinate (22)

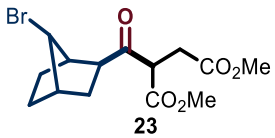


22

Prepared according to the general procedure for liquid alkanes, using 7-oxabicyclo[2.2.1]heptane (507 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **22** (61 mg, 57% yield, 52:48 d.r. determined by ^{1}H NMR analysis of the purified compound) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.83 (s, 1H), 4.66 (s, 1H), 4.06 (t, J = 7.2 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 2.95 – 2.82 (m, 3H), 2.26 – 2.18 (m, 1H), 1.81 – 1.71 (m, 2H), 1.62 – 1.45 (m, 3H).
Diastereoisomer 22': 4.86 (d, *J* = 5.1 Hz, 1H), 4.66 (s, 1H), 4.22 – 4.16 (m, 1H), 3.73 (s, 3H), 3.67 (s, 3H), 3.08 – 2.98 (m, 3H), 2.07 (dtd, *J* = 10.2, 5.3, 2.8 Hz, 1H), 1.81 – 1.71 (m, 2H), 1.62 – 1.45 (m, 3H).
^{13}C NMR (101 MHz, CH_3CN+D_2O) δ 202.8, 171.9, 169.1, 78.1, 55.5, 53.0, 52.2, 34.4, 32.6, 32.4, 30.4, 29.9, 29.6. Diastereoisomer 22': 202.4, 171.9, 169.0, 76.5, 55.2, 53.0, 52.8, 33.1, 32.6, 32.4, 30.4, 29.9, 29.5.
HRMS (FI) *m/z* calcd for $C_{13}H_{30}O_6$: 270.1103; found: 270.1113.

Dimethyl 2-((1R,4S)-7-bromo-bicyclo[2.2.1]heptane-2-carbonyl)succinate (22)

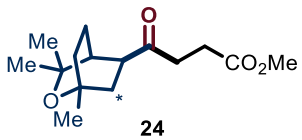


23

Prepared according to the general procedure for liquid alkanes, using 7-bromo-bicyclo[2.2.1]heptane (507 µL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **23** (74 mg, 53% yield, 52:48 d.r. determined by ^{1}H NMR analysis of the purified compound) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.10 (dd, J = 8.3, 6.1 Hz, 1H), 4.04 – 3.98 (m, 2H), 3.72 (s, 3H), 3.68 (s, 3H), 3.05 – 2.89 (m, 3H), 2.84 (dd, J = 5.9, 3.5 Hz, 1H), 2.61 (d, J = 4.4 Hz, 1H), 2.36 (d, J = 4.4 Hz, 1H), 1.70 – 1.60 (m, 1H), 1.49 (dd, J = 12.6, 9.7 Hz, 1H), 1.41 – 1.26 (m, 2H).
Overlapping of peaks avoids the unambiguous ^{1}H characterization of the diastereoisomer **23'**.
^{13}C NMR (101 MHz, $CDCl_3$) δ 204.5, 171.7, 168.8, 55.2, 53.4, 53.0, 52.9, 52.2, 46.3, 42.4, 32.3, 30.8, 27.3, 26.9. Diastereoisomer 23': 204.5, 171.9, 168.9, 55.6, 53.0, 52.9, 52.3, 52.0, 45.5, 42.5, 32.5, 31.4, 27.8, 26.9.
HRMS (FI) *m/z* calcd for $C_{14}H_{19}BrO$: 347.0416; found: 348.0397.

Methyl 4-oxo-4-((1R,4S)-1,3,3-trimethyl-2-oxabicyclo[2.2.2]octan-5-yl)butanoate (24)

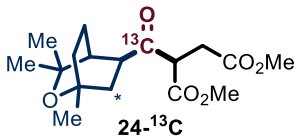


24

Prepared according to the general procedure for liquid alkanes, using eucalyptol (669 µL, 4.0 mmol, 10 equiv.), methyl acrylate (36.2 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **24** (72 mg, 67% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.67 (s, 3H), 3.18 (dt, *J* = 8.4, 2.4 Hz, 1H), 2.86 – 2.76 (m, 1H), 2.71 – 2.66 (m, 1H), 2.65 – 2.54 (m, 2H), 2.12 (dd, *J* = 13.3, 2.8 Hz, 1H), 1.93 – 1.80 (m, 2H), 1.62 – 1.50 (m, 3H), 1.33 (s, 3H), 1.33 – 1.31 (overlapped peak, 1H) 1.30 (s, 3H), 1.09 (s, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.3, 173.5, 73.6, 70.6, 52.0, 46.0, 36.5, 35.3, 31.6, 30.9, 29.1, 28.7, 28.0, 27.3, 17.6.
Overlapping of peaks avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor isomers.
HRMS (FI) *m/z* calcd for $C_{15}H_{24}O_4$: 268.1675; found: 268.1683.

Methyl 4-oxo-4-((1R,4S)-1,3,3-trimethyl-2-oxabicyclo[2.2.2]octan-5-yl)butanoate (24-^{13}C)

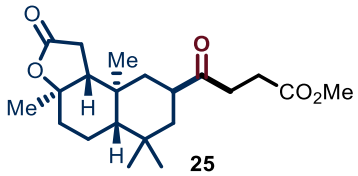


24-^{13}C

Prepared according to the general procedure for liquid alkanes, using eucalyptol (669 µL, 4.0 mmol, 10 equiv.), methyl acrylate (36.2 µL, 0.4 mmol, 1 equiv.) and 13C carbon monoxide (5 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **24-^{13}C** (46 mg, 43% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.67 (s, 3H), 3.21 – 3.14 (m, 1H), 2.86 – 2.76 (m, 1H), 2.70 – 2.65 (m, 1H), 2.64 – 2.55 (m, 2H), 2.18 – 2.07 (m, 1H), 1.90 – 1.80 (m, 2H), 1.56 (ddt, *J* = 15.8, 12.4, 4.3 Hz, 3H), 1.32 (s, 3H), 1.33 – 1.31 (overlapped peak, 1H) 1.30 (s, 3H), 1.08 (s, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.3, 173.5, 73.6, 70.6, 52.0, 46.0 (d, *J* = 40.3 Hz), 36.5, 35.3 (d, *J* = 39.2 Hz), 31.6 (d, *J* = 1.6 Hz), 30.9, 29.1, 28.7, 28.0 (d, *J* = 2.0 Hz), 27.3, 17.6.
Overlapping of peaks avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor isomers.
HRMS (FI) *m/z* calcd for $C_{14}{}^{13}C_1H_{24}O_4$: 269.1708; found: 269.1716.

Methyl 4-oxo-4-((3aR,5aS,9aS,9bR)-3a,6,6,9a-tetramethyl-2-oxododecahydronaphtho[2,1-b]furan-8-yl)butanoate (25)

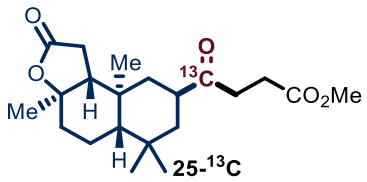


25

Prepared according to the general procedure for liquid alkanes, using sclareolide (500.8 mg, 4.0 mmol, 10 equiv.), methyl acrylate (36.2 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **25** (80 mg, 55% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.67 (s, 3H), 2.84 – 2.73 (m, 3H), 2.56 (dt, *J* = 12.0, 6.3 Hz, 2H), 2.41 (dd, *J* = 16.2, 14.7 Hz, 1H), 2.26 (dd, *J* = 16.0, 6.5 Hz, 1H), 2.08 (dt, *J* = 12.0, 3.3 Hz, 1H), 1.98 (dd, *J* = 14.7, 6.5 Hz, 1H), 1.90 (dt, *J* = 14.2, 3.5 Hz, 1H), 1.74 – 1.62 (m, 2H), 1.59 (dt, *J* = 12.8, 2.7 Hz, 1H), 1.44 – 1.37 (m, 1H), 1.33 (s, 3H), 1.30 – 1.22 (m, 1H), 1.16 (t, *J* = 12.7 Hz, 1H), 1.07 (dd, *J* = 12.6, 2.6 Hz, 1H), 0.94 (s, 6H), 0.89 (s, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 211.3, 176.3, 173.3, 86.0, 58.8, 56.2, 51.8, 43.9, 42.9, 40.9, 38.6, 36.2, 35.5, 33.6, 33.0, 28.6, 27.7, 21.7, 21.3, 20.4, 15.7.
Overlapping of peaks avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor isomers.
HRMS (FI) *m/z* calcd for $C_{21}H_{32}O_5$: 364.2250; found: 364.2260.

Methyl 4-oxo-4-((3aR,5aS,9aS,9bR)-3a,6,6,9a-tetramethyl-2-oxododecahydronaphtho[2,1-b]furan-8-yl)butanoate (25-^{13}C)



25-^{13}C

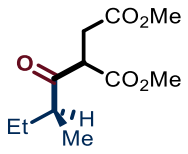
Prepared according to the general procedure for liquid alkanes, using sclareolide (500.8 mg, 4.0 mmol, 10 equiv.), methyl acrylate (36.2 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (5 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **25-^{13}C** (76 mg, 52% yield) as a colorless liquid. This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.67 (s, 3H), 2.86 – 2.70 (m, 3H), 2.59 (td, *J* = 6.5, 4.4 Hz, 2H), 2.41 (dd, *J* = 16.2, 14.7 Hz, 1H), 2.27 (dd, *J* = 16.0, 6.4 Hz, 1H), 2.09 (dt, *J* = 12.0, 3.2 Hz, 1H), 1.99 (dd, *J* = 14.7, 6.5 Hz, 1H), 1.94 – 1.87 (m, 1H), 1.75 – 1.63 (m, 2H), 1.62 – 1.57 (m, 1H), 1.44 – 1.35 (m, 1H), 1.34 (s, 3H), 1.27 (td, *J* = 12.3, 11.0, 2.7 Hz, 1H), 1.16 (t, *J* = 12.7 Hz, 1H), 1.07 (dd, *J* = 12.9, 2.6 Hz, 1H), 0.95 (s, 6H), 0.90 (s, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 211.3, 176.4, 173.3, 86.0, 58.8, 56.1, 51.9, 43.9, 42.9 (d, *J* = 40.6 Hz), 40.9, 38.6, 36.2 (d, *J* = 3.7 Hz), 35.5 (d, *J* = 38.8 Hz), 33.6 (d, *J* = 3.8 Hz), 33.0, 28.6, 27.7, 21.7, 21.3, 20.4, 15.7.
Overlapping of peaks avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor isomers.
HRMS (FI) *m/z* calcd for $C_{20}{}^{13}C_1H_{32}O_5$: 365.2283; found: 365.2275.

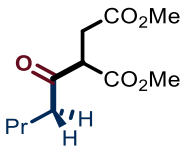
12.3 Light Alkanes

n-Butane

Dimethyl 2-(2-methylbutanoyl)succinate (26a) and dimethyl 2-pentanoylsuccinate (26b)



26a

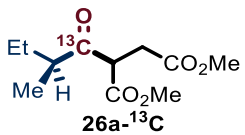


26b

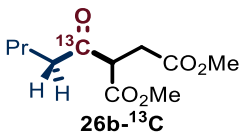
Prepared according to the general procedure for light alkanes, using n-butane (93 mL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **26a** and **26b** as an inseparable mixture of regioisomers (94 [d.r. 1:1]: 6 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (63 mg, 68% yield). The spectroscopic data are consistent with those reported previously.[13]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.12 (t, *J* = 7.1 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 3.01 – 2.72 (m, 3H), 1.82 – 1.67 (m, 1H), 1.45 – 1.32 (m, 1H), 1.13 (d, *J* = 7.0 Hz, 3H), 0.90 (t, *J* = 7.4 Hz, 3H). Diastereoisomer 26a': 4.14 (dd, *J* = 7.8, 6.6 Hz, 1H), 3.73 (s, 3H), 3.67 (s, 3H), 3.01 – 2.72 (m, 3H), 1.82 – 1.67 (m, 1H), 1.45 – 1.32 (m, 1H), 1.08 (d, *J* = 6.8 Hz, 3H), 0.83 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.5, 171.9 (2C), 53.3, 52.9, 52.2, 47.6, 32.3, 25.4, 16.6, 11.7.
Diasteroisomer 26a': 207.3, 169.3, 169.0, 53.1, 52.8, 52.1, 47.4, 32.2, 26.2, 15.4, 11.5.
Overlapping of peaks and low concentration avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor regioisomer **26b**.
HRMS (FI) *m/z* calcd for $C_{11}H_{18}O_5$: 230.1154; found: 230.1157.

Dimethyl 2-(2-methylbutanoyl)succinate (26a-^{13}C) and dimethyl 2-pentanoylsuccinate (26b-^{13}C)



26a-^{13}C

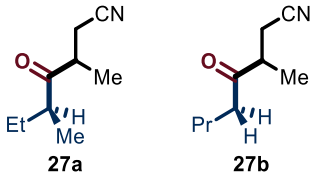


26b-^{13}C

Prepared according to the general procedure for light alkanes, using n-butane (93 mL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **26a-^{13}C** and **26b-^{13}C** as an inseparable mixture of regioisomers (82 [d.r. 1:1]: 18 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (78 mg, 84% yield). These compounds were previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.19 – 4.07 (m, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 3.01 – 2.71 (m, 3H), 1.83 – 1.69 (m, 1H), 1.48 – 1.20 (m, 1H), 1.12 (dd, *J* = 7.1, 4.7 Hz, 3H), 0.89 (t, *J* = 7.4 Hz, 3H).
Diastereoisomer 26b-^{13}C': 4.19 – 4.07 (m, 1H), 3.72 (s, 3H), 3.66 (s, 3H), 3.01 – 2.71 (m, 3H), 1.83 – 1.69 (m, 1H), 1.48 – 1.20 (m, 1H), 1.07 (dd, *J* = 6.8, 4.7 Hz, 3H), 0.83 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.3, 181.0 (2C), 53.11 (d, *J* = 35.2 Hz), 52.2 (2C), 47.6 (d, *J* = 41.1 Hz), 32.2 (d, *J* = 1.5 Hz), 26.1 (d, *J* = 1.6 Hz), 16.6 (d, *J* = 1.9 Hz), 11.7 (d, *J* = 2.2 Hz).
Diastereoisomer 26b-^{13}C': 207.5, 171.9, 171.9, 53.3 (d, *J* = 35.4 Hz), 52.8, 52.7, 47.3 (d, *J* = 41.3 Hz), 32.2 (d, *J* = 1.4 Hz), 25.4 (d, *J* = 1.8 Hz), 15.4 (d, *J* = 1.9 Hz), 11.5 (d, *J* = 2.7 Hz).
Overlapping of peaks and low concentration avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor regioisomer **26b-^{13}C**.
HRMS (FI) *m/z* calcd for $C_{10}{}^{13}C_1H_{18}O_5$: 231.1188; found: 231.1197.

3,5-dimethyl-4-oxoheptanenitrile (27a) and 3-methyl-4-oxooctanenitrile (27b)

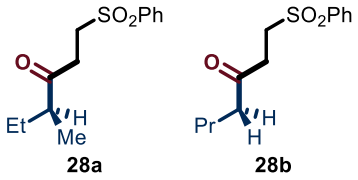


27a **27b**

Prepared according to the general procedure for light alkanes, using n-butane (93 mL, 4.0 mmol, 10 equiv.), crotonitrile (32.6 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **27a** and **27b** as an inseparable mixture of regioisomers (81:19 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (36 mg, 58% yield). These compounds were previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 2.99 (m, 1H), 2.70-2.55 (m, 2H), 2.44-2.38 (m, 1H), 1.77-1.62 (ddq, *J* = 17.5, 14.0, 7.2 Hz, 1H), 1.45-1.34 (ddq, *J* = 17.5, 14.0, 7.2 Hz, 1H), 1.28-1.24 (m, 3H), 1.08 (t, J = 7.3 Hz, 3H), 0.86 (dt, *J* = 15.3, 7.4 Hz, 3H). Diastereoisomer 27a' ^{1}H shifts overlap with 27a.
Minor regioisomer 27b: δ 2.86 (q, *J* = 7.0 Hz, 1H), 2.70-2.55 (m, 3H), 2.44-2.38 (m, 2H), 1.77-1.62 (m, 1H), 1.56 (p, *J* = 7.3 Hz, 2H), 1.28 (m, 3H), 0.89 (t, *J* = 7.3 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 213.8, 118.6, 45.7, 41.4, 26.7, 19.9, 16.8, 15.6, 12.1.
Diastereoisomer 27a': 214.1, 118.6, 46.3, 42.3, 25.4, 20.1, 16.9, 16.6, 11.7.
Minor Regioisomer 27b: 210.3, 118.6, 42.8, 40.5, 25.8, 22.4, 19.9, 16.7, 13.9.
HRMS (FI) *m/z* calcd for $C_9H_{15}NO$: 153.1154; found: 153.1146.

4-methyl-1-(phenylsulfonyl)hexan-3-one (28a) and 1-(phenylsulfonyl)heptan-3-one (28b)

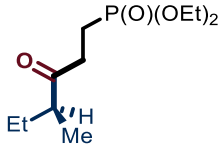


28a **28b**

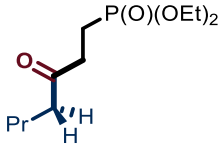
Prepared according to the general procedure for light alkanes, using n-butane (93 mL, 4.0 mmol, 10 equiv.), phenyl vinyl sulfone (67.3 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **28a** and **28b** as an inseparable mixture of regioisomers (74:26 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (53 mg, 52% yield). Compound **28a** was previously unreported. Overlapping of peaks and low concentration avoids the unambiguous 1H and 13C NMR characterization of the minor regioisomer **28b**. the spectroscopic data of compound **28b** are consistent with those reported previously.[14]

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.1 Hz, 2H), 7.67 (t, *J* = 7.4 Hz, 1H), 7.58 (t, *J* = 7.8 Hz, 2H), 3.37 (t, *J* = 7.6 Hz, 2H), 2.95 (td, *J* = 7.4, 4.7 Hz, 2H), 2.45 (m, 1H), 1.64 (m, 1H), 1.38 (m, 1H), 1.05 (d, *J* = 7.0 Hz, 3H), 0.84 (t, *J* = 7.7 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.0, 139.2, 134.0, 129.5 (2C), 128.1 (2C), 50.7, 48.1, 33.4, 25.9, 15.8, 11.7.Regioisomer 28b: 206.3, 139.0, 133.9, 129.4 (2C), 128.0 (2C), 50.6, 42.6, 34.9, 25.8, 22.2, 13.9.
Overlapping of peaks and low concentration avoids the unambiguous ^{1}H NMR characterization of the minor regioisomer **28b**.
HRMS (FI) *m/z* calcd for $C_{13}H_{18}O_3S$: 254.0977; found: 254.0971.

Diethyl (4-methyl-3-oxohexyl)phosphonate (29a) and Diethyl (3-oxoheptyl)phosphonate (29b)



29a



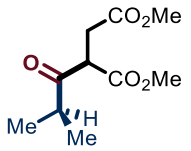
29b

Prepared according to the general procedure for light alkanes, using n-butane (93 mL, 4.0 mmol, 10 equiv.), diethyl vinyl phosphonate (61.5 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **29a** and **29b** as an inseparable mixture of regioisomers (77:23 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (34 mg, 34% yield). Compound **29a** was previously unreported. The spectroscopic data of minor regioisomer **29b** are reported previously.[15]

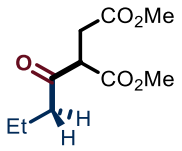
^{1}H NMR (400 MHz, $CDCl_3$) δ 4.09 (dq, *J* = 7.1, 3.4 Hz, 4H), 2.81 – 2.67 (m, 2H), 2.48 (dt, *J* = 13.9, 6.9 Hz, 1H), 2.01 (dt, *J* = 16.4, 7.8 Hz, 2H), 1.68 (dp, *J* = 14.4, 7.3 Hz, 1H), 1.41 (dp, J = 14.0, 7.2 Hz, 1H), 1.31 (t, *J* = 7.0 Hz, 6H), 1.08 (d, *J* = 6.9 Hz, 3H), 0.87 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 212.1 (d, *J* = 14.2 Hz), 61.8 (d, *J* = 6.4 Hz, 2C), 47.9, 34.1 (d, *J* = 3.7 Hz), 26.1, 19.4 (d, *J* = 144.4 Hz), 16.6 (d, *J* = 6.0 Hz, 2C), 16.0, 11.8.
^{31}P NMR (162 MHz, $CDCl_3$) δ 32.0.
Overlapping of peaks and low concentration avoids the unambiguous ^{1}H and ^{13}C NMR characterization of the minor regioisomer **29b**.
HRMS (FI) *m/z* calcd for $C_{11}H_{24}O_4P$: 250.1334; found: 250.1322.

Propane

Dimethyl 2-isobutyrylsuccinate (30a) and dimethyl 2-butyrylsuccinate (30b)



30a

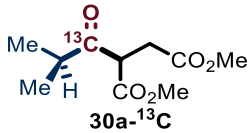


30b

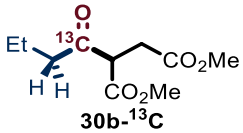
Prepared according to the general procedure for light alkanes, using propane (98 mL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **30a** and **30b** as an inseparable mixture of regioisomers (86:14 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (79 mg, 91% yield). The spectroscopic data are consistent with those reported previously.[16]

^{1}H NMR (300 MHz, $CDCl_3$) δ 4.16 (dd, *J* = 8.0, 6.4 Hz, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 3.01 – 2.90 (m, 2H), 2.82 (dd, *J* = 17.4, 6.4 Hz, 1H), 1.16 (d, *J* = 7.0 Hz, 3H), 1.11 (d, *J* = 6.8 Hz, 3H). Minor regioisomer **30b**: δ 3.98 (dd, *J* = 8.3, 6.3 Hz, 1H), 3.73 (s, 3H), 3.66 (s, 3H), 3.01 – 2.90 (m, 2H), 2.74 – 2.54 (m, 2H), 1.62 (q, *J* = 7.3 Hz, 2H), 0.91 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 207.8, 171.9, 169.2, 52.9, 52.2 (2C), 40.8, 32.4, 18.7, 18.0. Minor regioisomer **30b**: δ 204.0, 172.0, 169.1, 53.9, 52.2, 44.8, 32.3, 18.4, 17.0, 13.6.
HRMS (FI) *m/z* calcd for $C_{10}H_{16}O_5$: 216.0998; found: 216.0997.

Dimethyl 2-isobutyrylsuccinate (30a-^{13}C) and dimethyl 2-butyrylsuccinate (30b-^{13}C)



30a-^{13}C

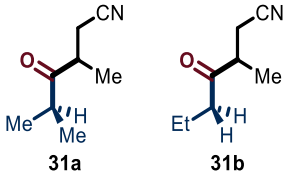


30b-^{13}C

Prepared according to the general procedure for light alkanes, using propane (98 mL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **30a-^{13}C** and **30b-^{13}C** as an inseparable mixture of regioisomers (83:17 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (75 mg, 86% yield). This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.17 (ddd, *J* = 8.1, 6.3, 5.3 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 2.99 – 2.91 (m, 1H), 2.86 (dd, *J* = 6.3, 4.8 Hz, 1H), 2.75 – 2.54 (m, 1H), 1.17 (dd, *J* = 7.0, 4.7 Hz, 3H), 1.12 (dd, *J* = 6.8, 4.6 Hz, 3H).
Regioisomer 30b-^{13}C: 3.99 (dt, *J* = 8.3, 6.0 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 2.99 – 2.91 (m, 3H), 2.81 (dd, *J* = 6.3, 4.8 Hz, 1H), 1.63 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 207.9, 171.9, 169.3, 52.9, 52.2 (d, *J* = 35.6 Hz), 52.2, 40.9 (d, *J* = 41.5 Hz), 32.4, 18.8 (d, *J* = 1.8 Hz), 18.0 (d, *J* = 1.9 Hz).
Regioisomer 30b-^{13}C: 204.0, 181.8, 177.7, 53.9 (d, *J* = 36.1 Hz), 52.2, 44.8 (d, *J* = 41.5 Hz), 41.1, 32.3, 17.0, 13.6.
HRMS (FI) *m/z* calcd for $C_{10}H_{16}O_5$: 217.1031; found: 217.1029.

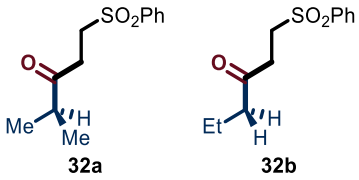
3,5-dimethyl-4-oxohexanenitrile (31a) and 3,5-dimethyl-4-oxohexanenitrile (31b)



Prepared according to the general procedure for light alkanes, using propane (98 mL, 4.0 mmol, 10 equiv.), crotonitrile (36.2 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **31a** and **31b** as an inseparable mixture of regioisomers (75:25 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (26 mg, 47% yield). These compounds were previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 3.06 (td, *J* = 7.5, 6.5 Hz, 1H), 2.81 (hept, *J* = 6.8 Hz, 1H), 2.59 (dd, *J* = 16.9, 6.4 Hz, 1H), 2.42 (dd, *J* = 16.9, 7.6 Hz, 1H), 1.29 (d, *J* = 7.2 Hz, 3H), 1.14 (d, *J* = 7.1 Hz, 3H), 1.11 (d, *J* = 6.7 Hz, 3H). Minor regioisomer **31b**: δ 2.91-2.78 (m 1H), 2.63-2.50 (m, 2H), 2.47-2.39 (m, 2H), 1.63 (q, *J* = 7.3 Hz, 2H), 1.31 (d, *J* = 7.5 Hz, 3H), 0.92 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 214.1, 118.6, 41.0, 39.0, 20.2, 18.9, 17.9, 17.0. Minor regioisomer **31b**: δ 210.2, 118.6, 42.8, 42.7, 19.9, 17.2, 16.7, 13.8.
HRMS (FI) *m/z* calcd for $C_8H_{13}NO$: 139.0997; found: 139.0994.

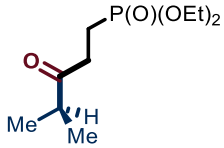
4-methyl-1-(phenylsulfonyl)pentan-3-one (32a) and 1-(phenylsulfonyl)hexan-3-one (32b)



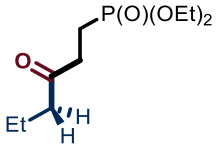
Prepared according to the general procedure for light alkanes, using propane (98 mL, 4.0 mmol, 10 equiv.), phenyl vinyl sulfone (67.3 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **32a** and **32b** as an inseparable mixture of regioisomers (71:29 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (45 mg, 47% yield). The spectroscopic data are consistent with those reported previously.[17,18]

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (dd, *J* = 8.3, 1.4 Hz, 2H), 7.66 (t, *J* = 7.4 Hz, 1H), 7.57 (t, *J* = 7.8 Hz, 2H), 3.37 (dd, *J* = 8.6, 6.6 Hz, 2H), 2.95 (dd, *J* = 8.2, 6.9 Hz, 2H), 2.60 (hept, *J* = 6.9 Hz, 1H), 1.07 (d, *J* = 6.9 Hz, 6H). Minor regioisomer **32b**: δ 7.90 (dd, *J* = 8.3, 1.4 Hz, 2H), 7.66 (t, *J* = 7.4 Hz, 1H), 7.57 (t, *J* = 7.8 Hz, 2H), 3.37 (m, 2H), 2.88 (t, *J* = 7.3, 2H), 2.40 (t, J = 7.3 Hz, 2H), 1.56 (hex, J = 7.4 Hz, 2H), 0.87 (t, J = 7.4 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 210.0, 139.1, 134.0, 129.5 (2C), 128.0 (2C), 50.7, 41.1, 32.7, 18.2 (2C). Minor regioisomer **32b**: δ 206.2, 139.1, 134.0, 129.5 (2C), 128.0 (2C), 50.3, 44.8, 35.0, 17.2, 13.7.

Diethyl (4-methyl-3-oxopentyl)phosphonate (33a) and diethyl (3-oxohexyl)phosphonate (33b)



33a



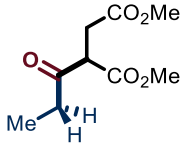
33b

Prepared according to the general procedure for light alkanes, using propane (98 mL, 4.0 mmol, 10 equiv.), diethyl vinyl phosphonate (61.5 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **33a** and **33b** as an inseparable mixture of regioisomers (82:18 ratio determined by ^{1}H NMR analysis of the crude reaction mixture), (36 mg, 38% yield). Compound **33a** was previously unreported. The spectroscopic data of minor regioisomer **33b** are reported previously.[19]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.08 (m, 4H), 2.75 (m, 2H), 2.62 (hept, *J* = 6.9 Hz, 1H), 2.0 (dt, *J* = 17.7, 7.9 Hz, 2H), 1.31 (t, *J* = 7.0 Hz, 6H), 1.11 (d, *J* = 6.9 Hz, 6H). Minor regioisomer **33b**: δ 4.08 (m, 4H), 2.75 (m, 2H), 2.41 (t, *J* = 7.3 Hz, 2H), 2.0 (dt, *J* = 17.7, 7.9 Hz, 2H), 1.61 (q, *J* = 7.4 Hz, 2H), 1.31 (t, *J* = 7.0 Hz, 6H), 0.91 (t, *J* = 7.4 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 212.2 (d, *J* = 14.1 Hz), 61.8 (d, *J* = 6.4 Hz, 2C), 40.9, 33.3 (d, *J* = 3.6 Hz), 20.5 (d, *J* = 144.4 Hz), 18.4 (2C), 16.6 (d, *J* = 6.1 Hz, 2C).
^{31}P NMR (162 MHz, $CDCl_3$) δ 31.9
Overlapping of peaks and low concentration avoids the unambiguous ^{13}C NMR characterization of the minor regioisomer **33b**.
HRMS (FI) *m/z* calcd for $C_{10}H_{21}O_4P$: 236.1177; found: 236.1171.

Ethane

Dimethyl 2-propionylsuccinate (34)

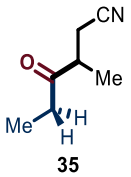


34

Prepared according to the general procedure for light alkanes, using ethane (94 mL, 4.0 mmol, 10 equiv.), di-methyl maleate (50.1 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **34** as a yellow oil, (42 mg, 51% yield). The spectroscopic data are consistent with those reported previously.[10]

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.00 (dd, *J* = 8.3, 6.2 Hz, 1H), 3.74 (s, 3H), 3.67 (s, 3H), 3.00 (dd, *J* = 17.5, 8.3 Hz, 1H), 2.85 (dd, *J* = 17.6, 6.2 Hz, 1H), 2.80 – 2.70 (m, 1H), 2.69 – 2.57 (m, 1H), 1.09 (t, *J* = 7.2 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 204.6, 172.0, 169.2, 53.6, 52.9, 52.2, 36.3, 32.4, 7.7.

3-methyl-4-oxohexanenitrile (35)

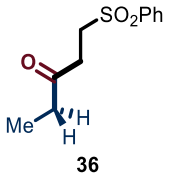


35

Prepared according to the general procedure for light alkanes, using ethane (94 mL, 4.0 mmol, 10 equiv.), crotonitrile (32.6 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **35** as a yellow oil, (18 mg, 36% yield). The spectroscopic data are consistent with those reported previously.[20]

^{1}H NMR (300 MHz, $CDCl_3$) δ 2.96 – 2.81 (m, 1H), 2.69 – 2.53 (m, 2H), 2.53 – 2.35 (m, 2H), 1.31 (dd, *J* = 7.2, 0.8 Hz, 3H), 1.07 (td, *J* = 7.3, 0.9 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 210.7, 118.6, 42.5, 34.0, 19.9, 16.8, 7.7.

1-(phenylsulfonyl)pentan-3-one (36)

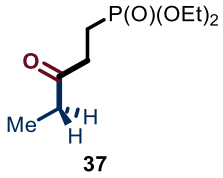


36

Prepared according to the general procedure for light alkanes, using ethane (94 mL, 4.0 mmol, 10 equiv.), phenyl vinyl sulfone (67.3 mg, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **36** as a yellow oil, (45 mg, 49% yield). The spectroscopic data are consistent with those reported previously.[21]

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 7.3 Hz, 2H), 7.67 (t, *J* = 7.4 Hz, 1H), 7.58 (t, *J* = 7.8 Hz, 2H), 2.91 (t, *J* = 7.6 Hz, 2H), 2.91 (t, *J* = 7.6 Hz, 1H), 2.46 (q, *J* = 7.3 Hz, 2H), 1.04 (t, *J* = 7.3 Hz, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 206.8, 139.2, 134.1, 129.6 (2C), 128.1 (2C), 50.8, 36.2, 34.7, 7.8.

Diethyl (3-oxopentyl)phosphonate (37)



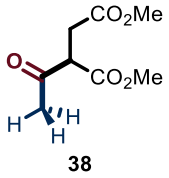
37

Prepared according to the general procedure for light alkanes, using ethane (94 mL, 4.0 mmol, 10 equiv.), diethyl vinyl phosphonate (61.5 µL, 0.4 mmol, 1 equiv.) and carbon monoxide (35 equiv.). The crude mixture was purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **37** as a yellow oil, (37 mg, 42% yield). This compound was previously unreported.

^{1}H NMR (300 MHz, $CDCl_3$) δ 4.17 – 3.94 (m, 4H), 2.67 (ddd, *J* = 11.6, 8.7, 6.8 Hz, 2H), 2.43 (q, *J* = 7.3 Hz, 2H), 2.07 – 1.90 (m, 2H), 1.28 (t, *J* = 7.1 Hz, 6H), 1.04 (t, *J* = 7.3 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 208.8 (d, *J* = 14.5 Hz), 61.8 (d, *J* = 6.3 Hz, 2C), 35.9, 35.1 (d, *J* = 3.8 Hz), 19.5 (d, *J* = 144.4 Hz), 16.5 (d, *J* = 6.1 Hz, 2C), 7.9.
^{31}P NMR (121 MHz, $CDCl_3$) δ 31.7.
HRMS (FI) *m/z* calcd for $C_9H_{19}O_4P$: 222.1021; found: 222.1013.

Methane

Dimethyl 2-acetylsuccinate (38)

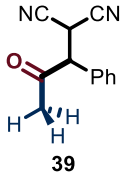


38

Prepared two times according to the general procedure for light alkanes, using methane (143 mL, 6.0 mmol, 20 equiv.), di-methyl maleate (37.6 µL, 0.3 mmol, 1 equiv.) and carbon monoxide (258 mL, 10.5 mmol, 35 equiv.). The combined crude mixtures were purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **38** as a yellow oil, (35 mg, 31% yield). The spectroscopic data are consistent with those reported previously.[22]

^{1}H NMR (300 MHz, $CDCl_3$) δ 4.00 (dd, *J* = 8.1, 6.3 Hz, 1H), 3.76 (s, 3H), 3.68 (s, 3H), 2.99 (dd, *J* = 17.6, 8.1 Hz, 1H), 2.84 (dd, *J* = 17.6, 6.3 Hz, 1H), 2.36 (s, 3H).
^{13}C NMR (75 MHz, $CDCl_3$) δ 201.7, 172.0, 169.0, 54.5, 52.9, 52.2, 32.3, 30.1.

2-(2-oxo-1-phenylpropyl)malononitrile (39)

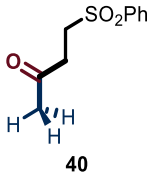


39

Prepared two times according to the general procedure for light alkanes, using methane (143 mL, 6.0 mmol, 20 equiv.), 2-benzylidene malononitrile (46.3 mg, 0.3 mmol, 1 equiv.) and carbon monoxide (258 mL, 10.5 mmol, 35 equiv.). The combined crude mixtures were purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **39** as a yellow oil, (39 mg, 33% yield). The spectroscopic data are consistent with those reported previously.[23]

^{1}H NMR (400 MHz, CD_2Cl_2) δ 7.49 (p, *J* = 3.8 Hz, 3H), 7.29 (dd, *J* = 6.7, 2.9 Hz, 2H), 4.39 (d, *J* = 8.1 Hz, 1H), 4.30 (d, *J* = 8.1 Hz, 1H), 2.15 (s, 3H).
^{13}C NMR (101 MHz, CD_2Cl_2) δ 201.6, 131.2, 130.3, 130.2 (2C), 128.8 (2C), 112.1, 111.5, 59.1, 28.6, 25.9.

4-(phenylsulfonyl)butan-2-one (40)

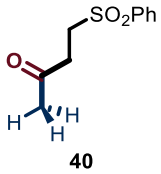


40

Prepared two times according to the general procedure for light alkanes, using methane (143 mL, 6.0 mmol, 20 equiv.), phenyl vinyl sulfone (50.5 mg, 0.3 mmol, 1 equiv.) and carbon monoxide (258 mL, 10.5 mmol, 35 equiv.). The combined crude mixtures were purified by flash column chromatography (100% n-pentane to n-pentane 95:5 AcOEt) to afford product **40** as a yellow oil, (22 mg, 17% yield). The spectroscopic data are consistent with those reported previously.[24]

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 7.0 Hz, 2H), 7.68 (t, *J* = 7.4 Hz, 1H), 7.59 (t, *J* = 7.7 Hz, 2H), 3.38 (dd, *J* = 8.2, 6.8 Hz, 2H), 2.94 (dd, *J* = 8.2, 6.9 Hz, 2H), 2.19 (s, 3H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 203.8, 139.1, 134.1, 129.6 (2C), 128.1 (2C), 50.7, 35.9, 30.0.

(2R,3R,4S,5R,6R)-6-(((4-oxopentanoyl)oxy)methyl)tetrahydro-2H-pyran-2,3,4,5-tetrayl tetraacetate (41)



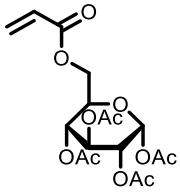
40

Prepared two times according to the general procedure for light alkanes, using methane (143 mL, 6.0 mmol, 20 equiv.), di-methyl maleate (120.7 mg, 0.3 mmol, 1 equiv.) and carbon monoxide (258 mL, 10.5 mmol, 35 equiv.). The combined crude mixtures were purified by flash column chromatography (n-pentane 90:10 Et_2O (10%MeOH) to n-pentane 70:30 Et_2O (10%MeOH)) to afford product **41** as a white solid, (37 mg, 14% yield). This compound was previously unreported.

^{1}H NMR (400 MHz, $CDCl_3$) δ 5.70 (d, *J* = 8.2 Hz, 1H), 5.24 (t, *J* = 9.4 Hz, 1H), 5.17 – 5.04 (m, 2H), 4.26 (dd, *J* = 12.4, 4.8 Hz, 1H), 4.14 (dd, *J* = 12.5, 2.2 Hz, 1H), 3.83 (ddd, *J* = 10.1, 4.8, 2.2 Hz, 1H), 2.75 (td, *J* = 6.4, 4.6 Hz, 2H), 2.65 – 2.50 (m, 2H), 2.19 (s, 3H), 2.11 (s, 3H), 2.02 (d, *J* = 8.6 Hz, 9H).
^{13}C NMR (101 MHz, $CDCl_3$) δ 206.5, 172.5, 170.2, 169.6, 169.4, 169.1, 91.8, 72.9, 72.8, 70.4, 67.9, 61.9, 38.0, 29.9, 28.0, 21.0, 20.7 (3C).
MS (FD) *m/z* calcd for $C_{19}H_{26}O_{12}$: [M+H]+ 447.2 ; found: 447.0

12.4 Starting Materials

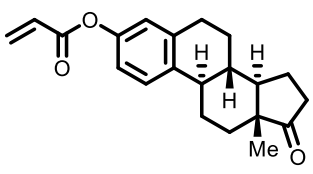
(2S,3R,4S,5R,6R)-6-((acryloyloxy)methyl)tetrahydro-2Hpyran-2,3,4,5-tetrayl tetraacetate.



Prepared by following a procedure reported in the literature.[25]

^{1}H NMR (300 MHz, $CDCl_3$) δ 6.44 (dd, *J* = 17.3, 1.4 Hz, 1H), 6.14 (dd, *J* = 17.3, 10.4 Hz, 1H), 5.88 (dd, *J* = 10.4, 1.4 Hz, 1H), 5.72 (d, *J* = 8.0 Hz, 1H), 5.32 – 5.20 (m, 1H), 5.20 – 5.07 (m, 2H), 4.36 – 4.20 (m, 2H), 3.88 (m, 1H), 2.11 (s, 3H), 2.03 (s, 6H), 2.01 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.2, 169.5, 169.4, 169.1, 165.7, 132.0, 127.8, 91.8, 72.9, 72.8, 70.4, 68.1, 61.9, 21.0, 20.7 (3C).

(8R,9S,13S,14S)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6H-cyclopenta[a]phenanthrene-3-yl acrylate



Prepared by following a procedure reported in the literature.[26]

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, *J* = 8.5 Hz, 1H), 6.95 – 6.83 (m, 2H), 6.59 (dd, *J* = 17.3, 1.3 Hz, 1H), 6.31 (dd, *J* = 17.3, 10.4 Hz, 1H), 5.99 (dd, *J* = 10.5, 1.3 Hz, 1H), 2.91 (dd, *J* = 8.5, 3.7 Hz, 2H), 2.56 – 2.45 (m, 1H), 2.45 – 2.37 (m, 1H), 2.29 (td, *J* = 10.9, 4.1 Hz, 1H), 2.21 – 1.90 (m, 4H), 1.70 – 1.38 (m, 6H), 0.91 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 220.9, 165.0, 148.6, 138.1, 137.5, 132.5, 128.1, 126.5, 121.6, 118.8, 50.5, 48.0, 44.3, 38.1, 36.0, 31.7, 29.5, 26.4, 25.9, 21.7, 13.9.

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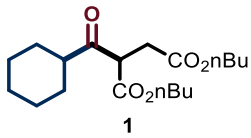
14. NMR Spectra

^{1}H NMR (400 MHz, $CDCl_3$)



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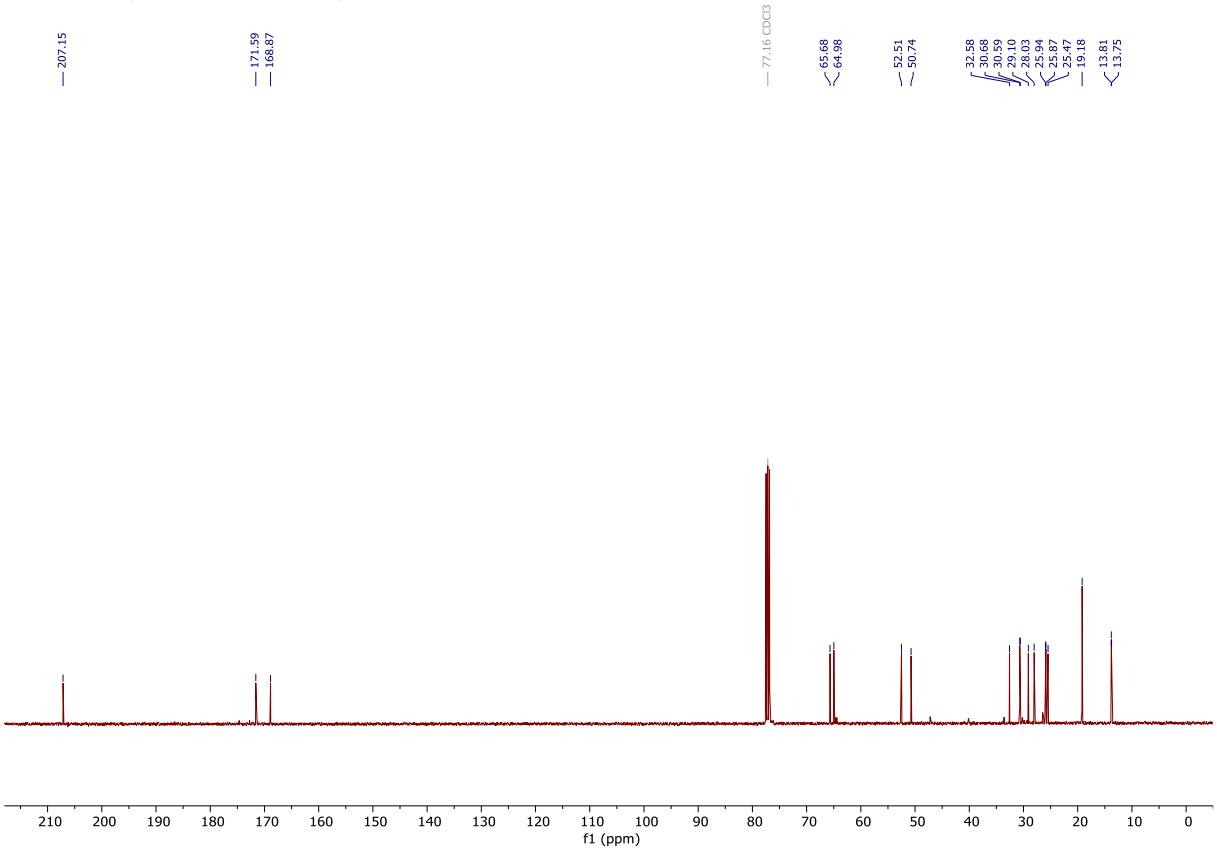
^{13}C NMR (101 MHz, $CDCl_3$)



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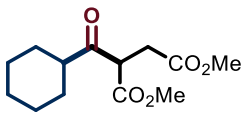

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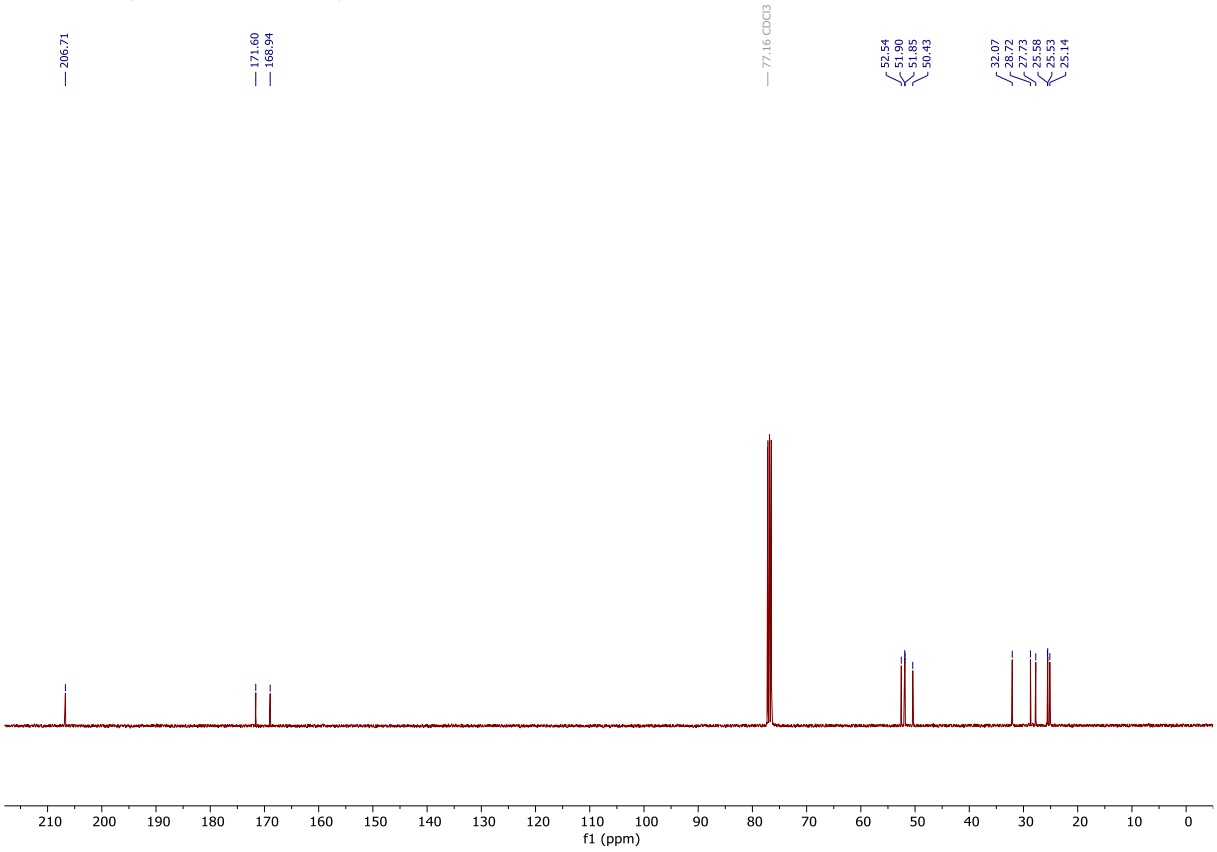

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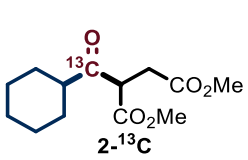
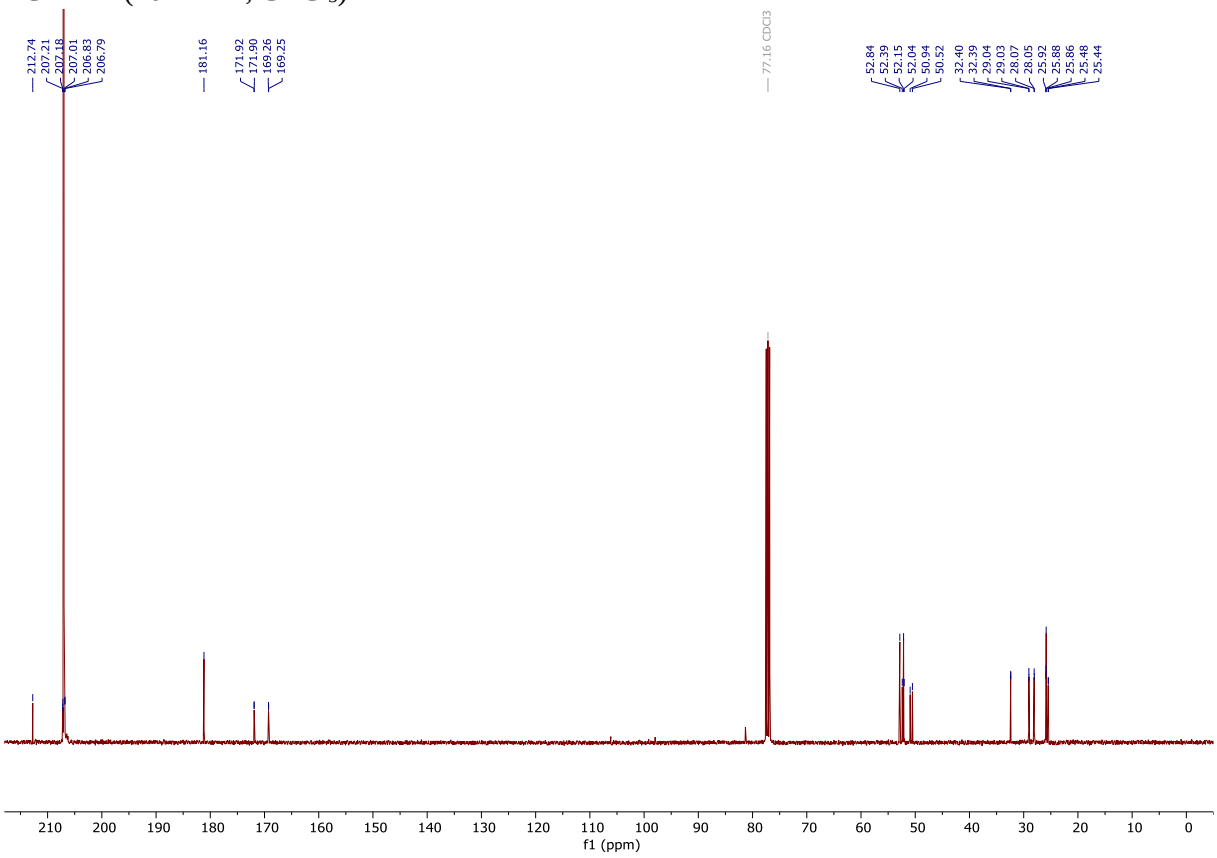


2-^{13}C

^{13}C NMR (101 MHz, $CDCl_3$)



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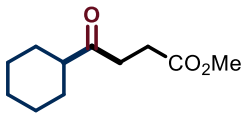

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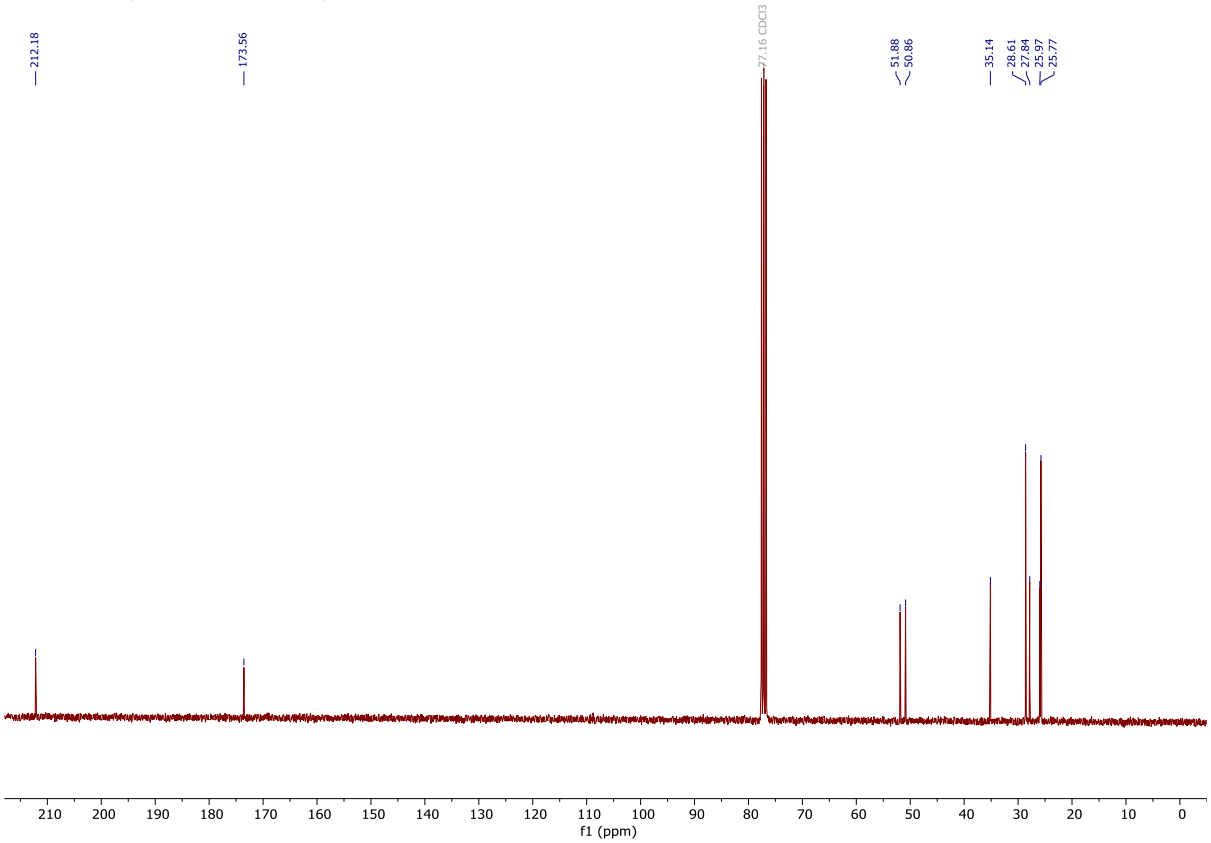
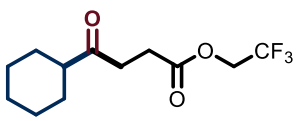
^{13}C NMR (75 MHz, $CDCl_3$)



^{1}H NMR (300 MHz, $CDCl_3$)



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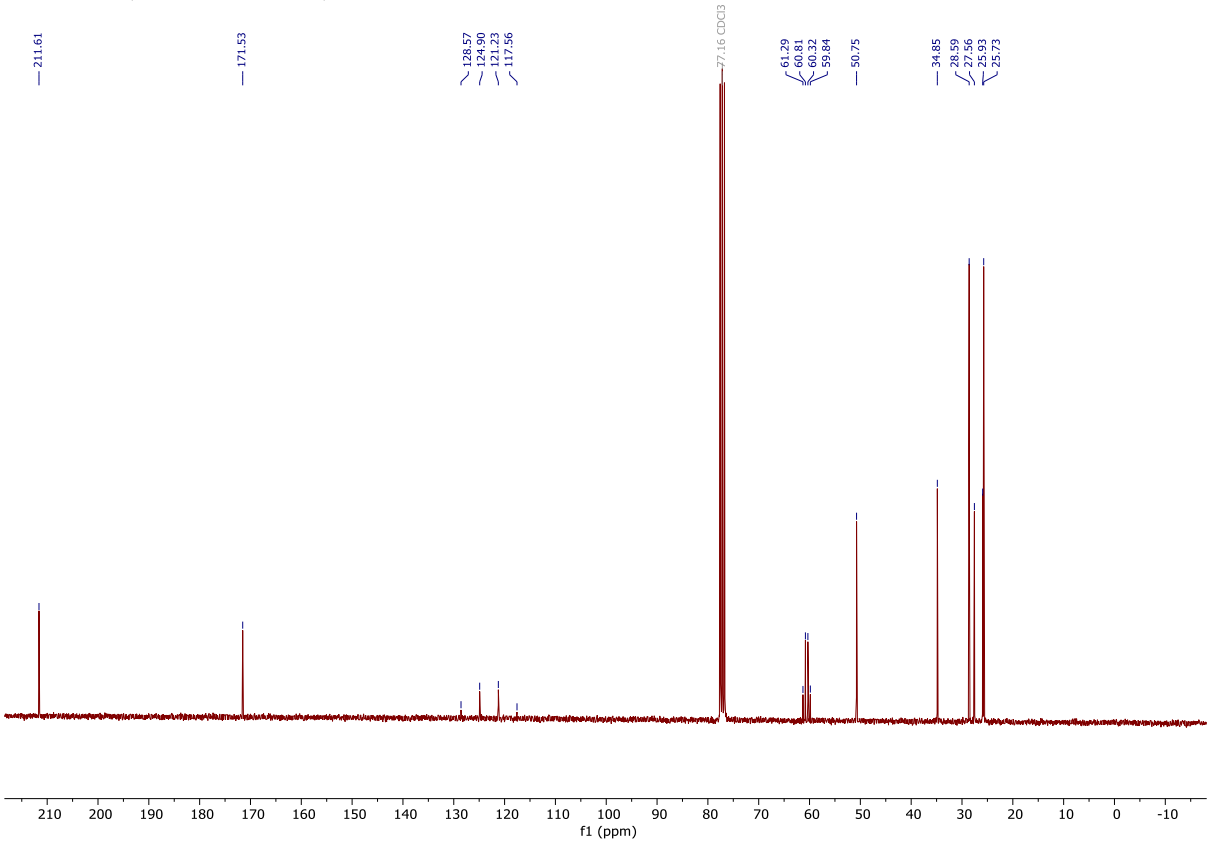
^{13}C NMR (75 MHz, $CDCl_3$)



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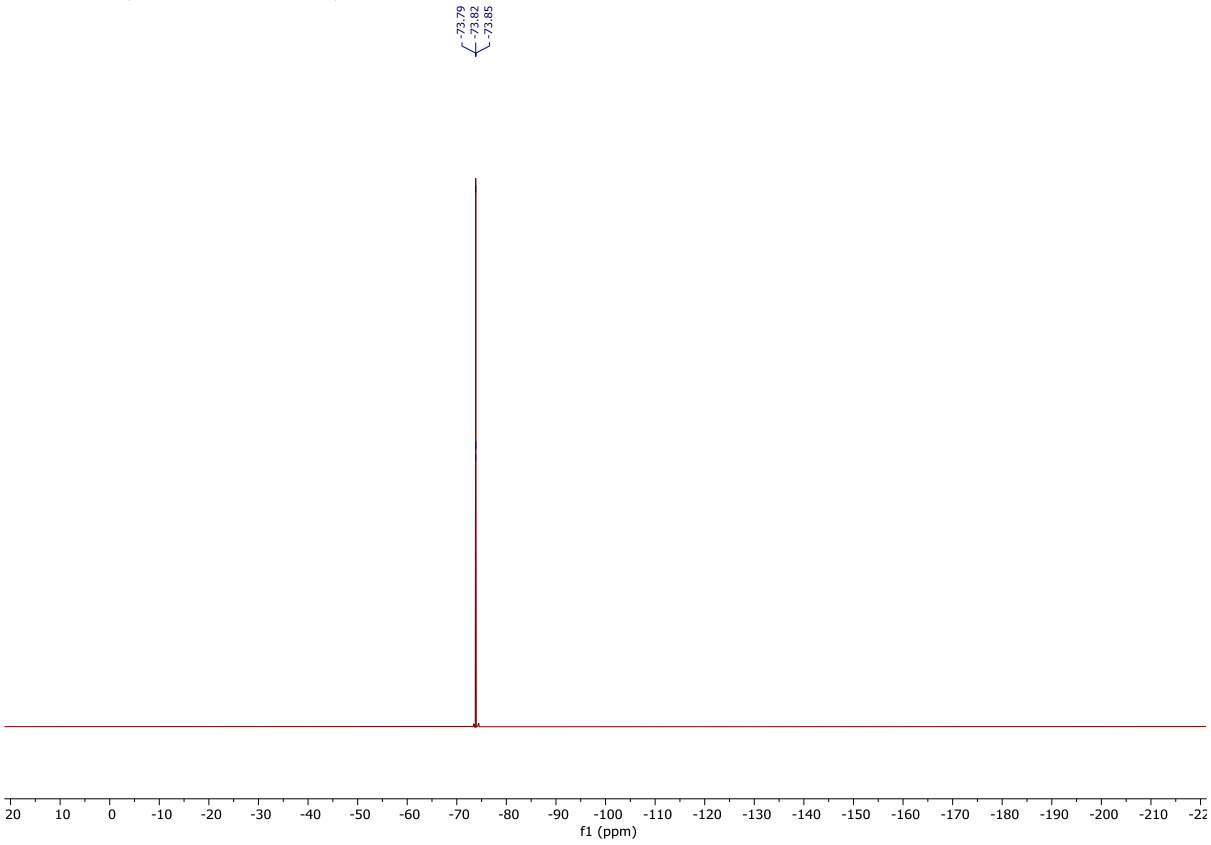
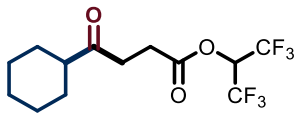


^{1}H NMR (400 MHz, $CDCl_3$)



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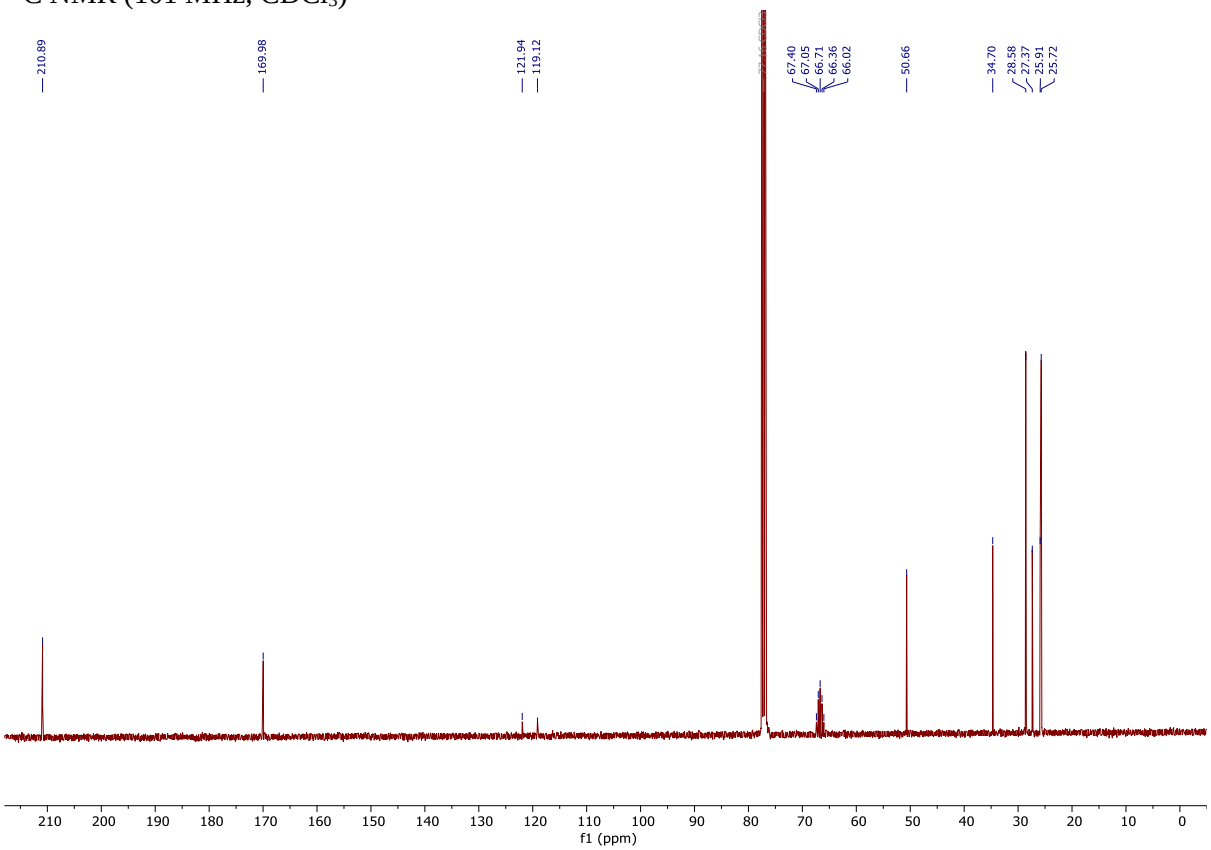
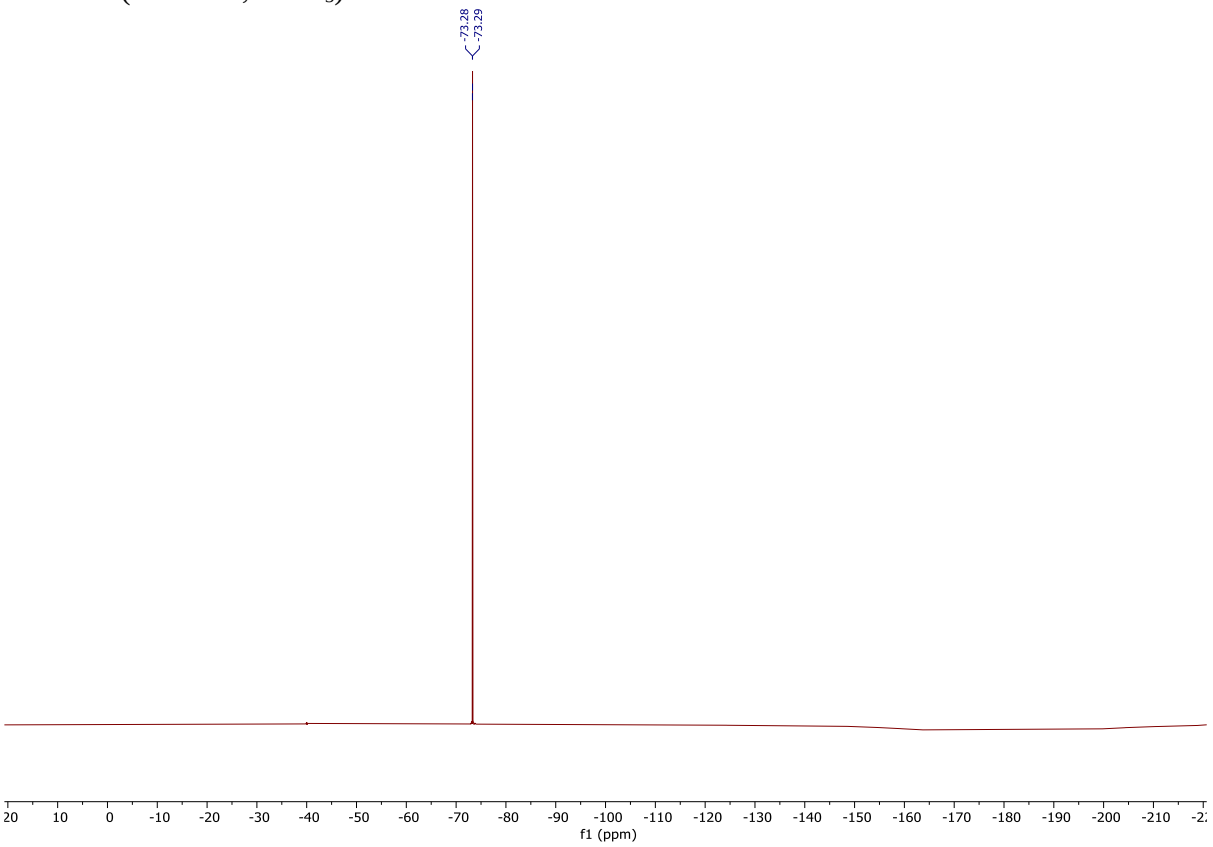


^{19}F NMR (376 MHz, $CDCl_3$)



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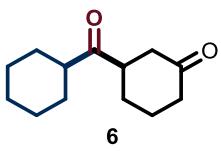

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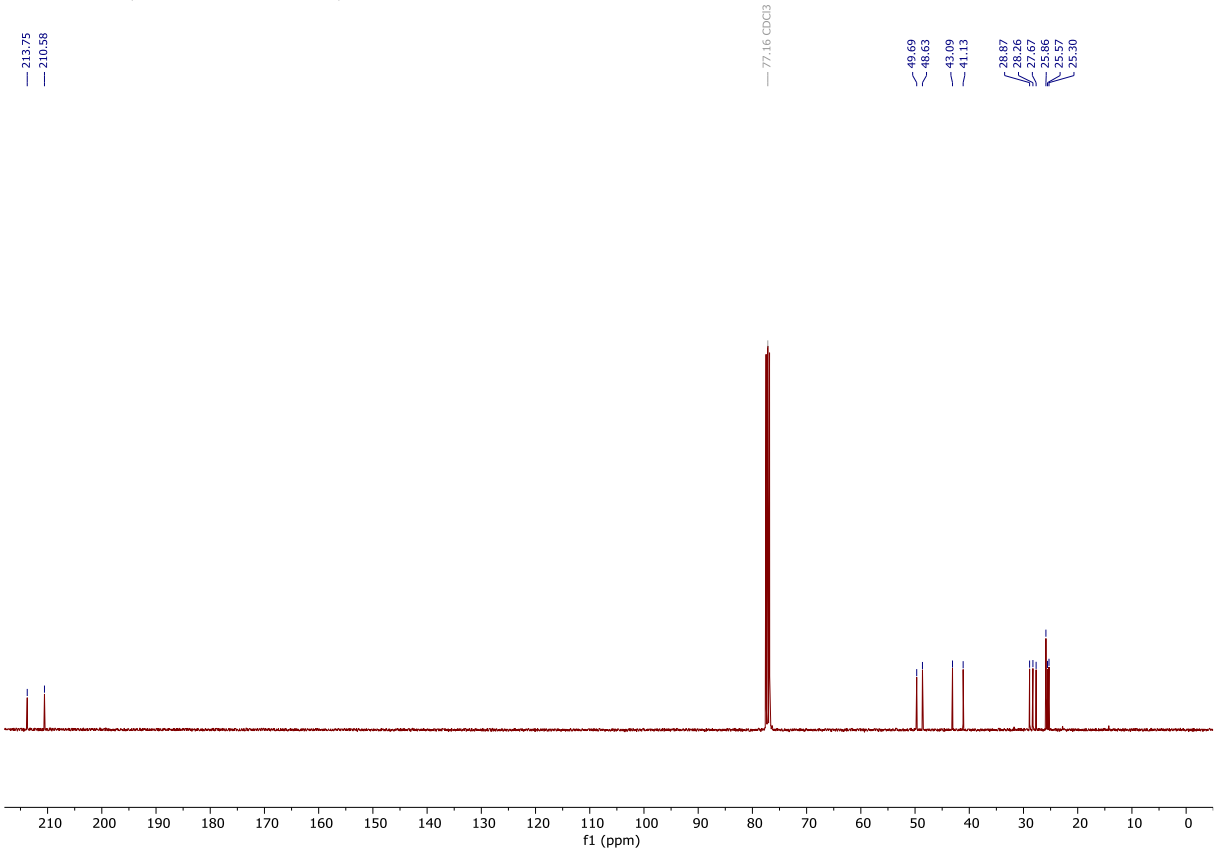
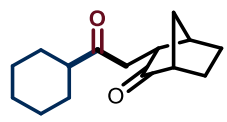
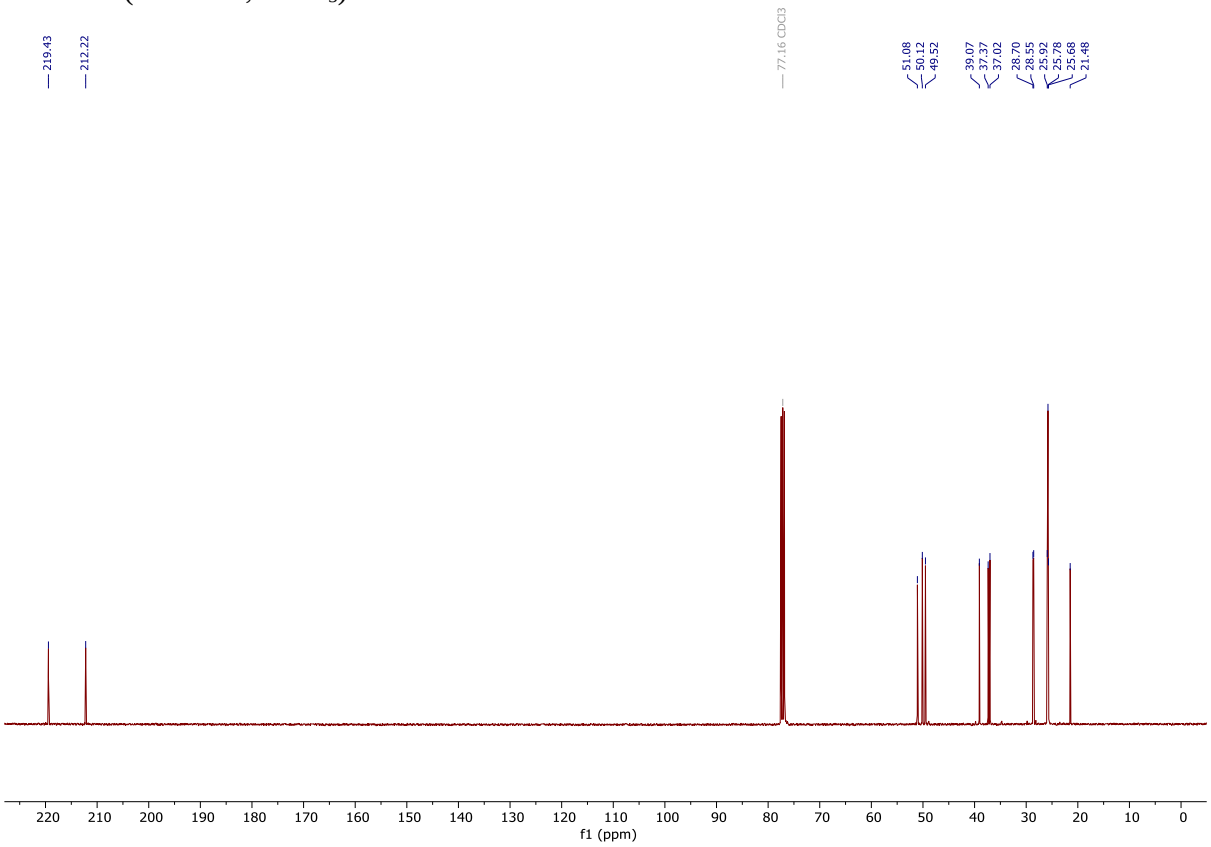


^{1}H NMR (400 MHz, $CDCl_3$)

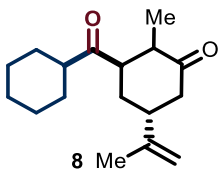


7

^{13}C NMR (101 MHz, $CDCl_3$)



^{1}H NMR (400 MHz, $CDCl_3$)



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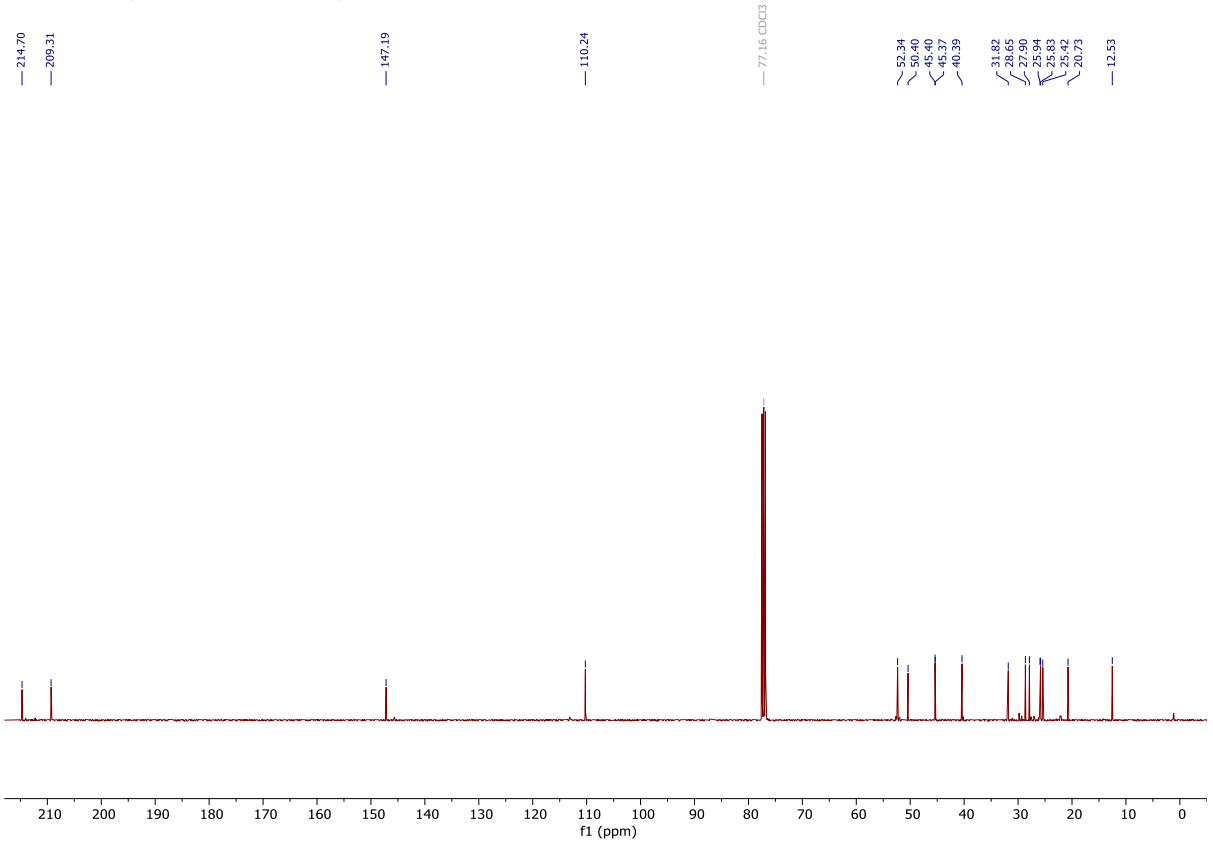

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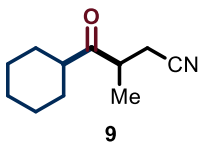
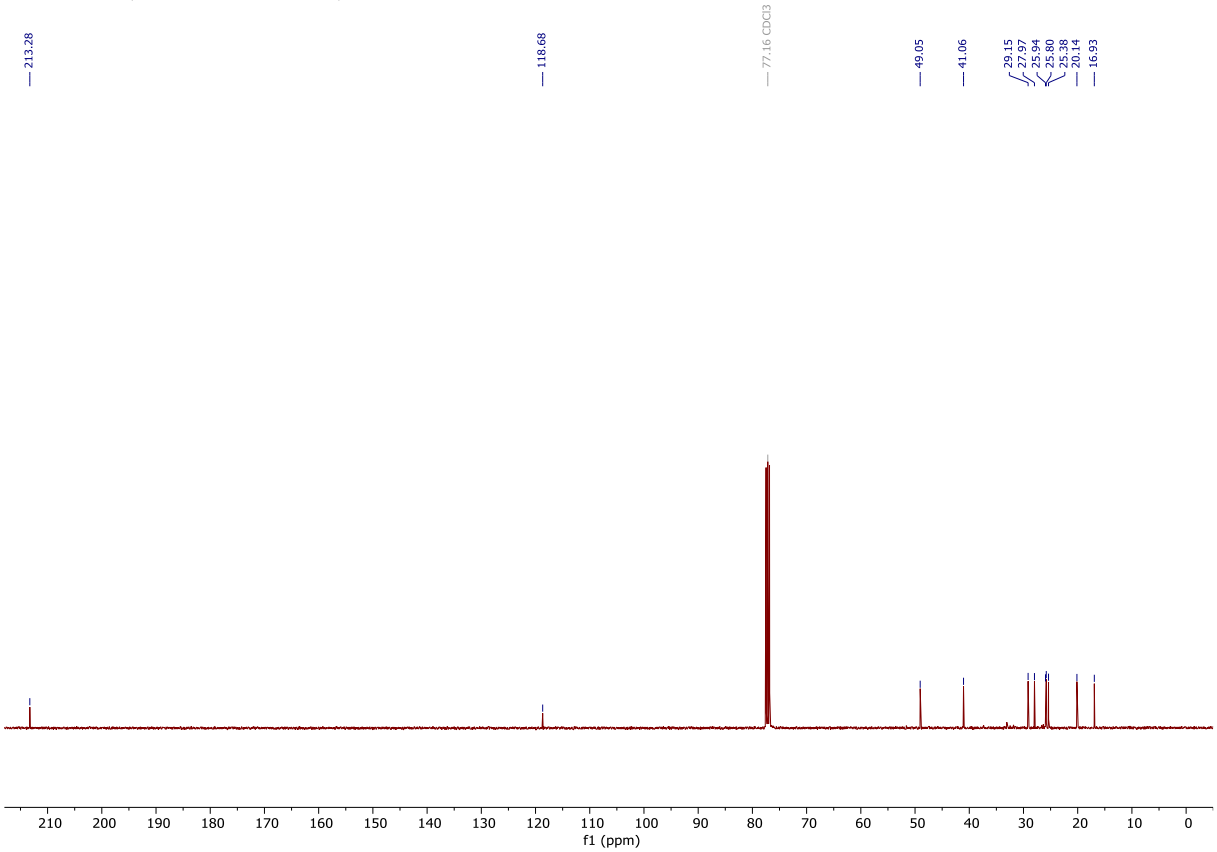
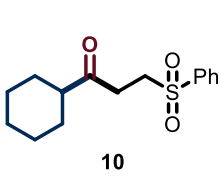


9

^{13}C NMR (101 MHz, $CDCl_3$)



^{1}H NMR (300 MHz, $CDCl_3$)



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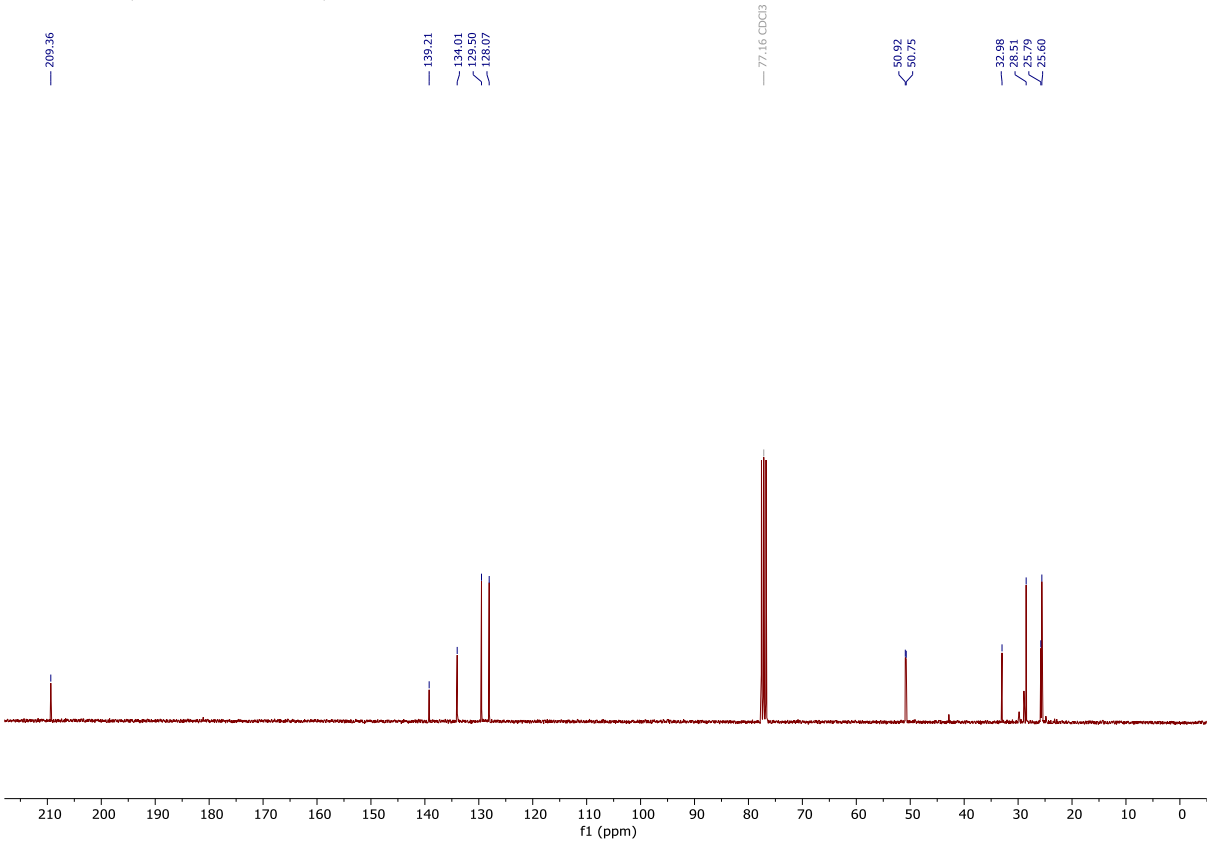
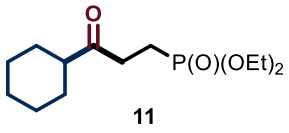
^{13}C NMR (75 MHz, $CDCl_3$)

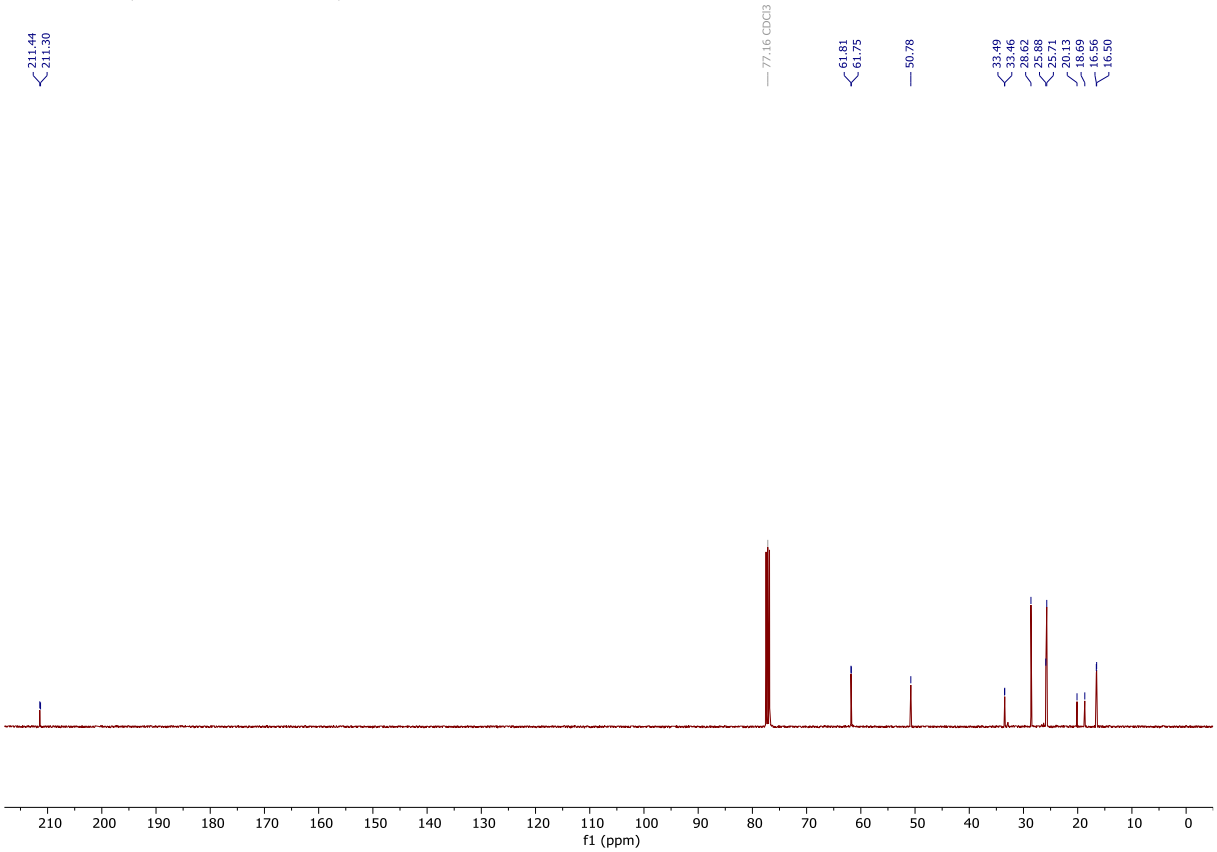


^{1}H NMR (400 MHz, $CDCl_3$)

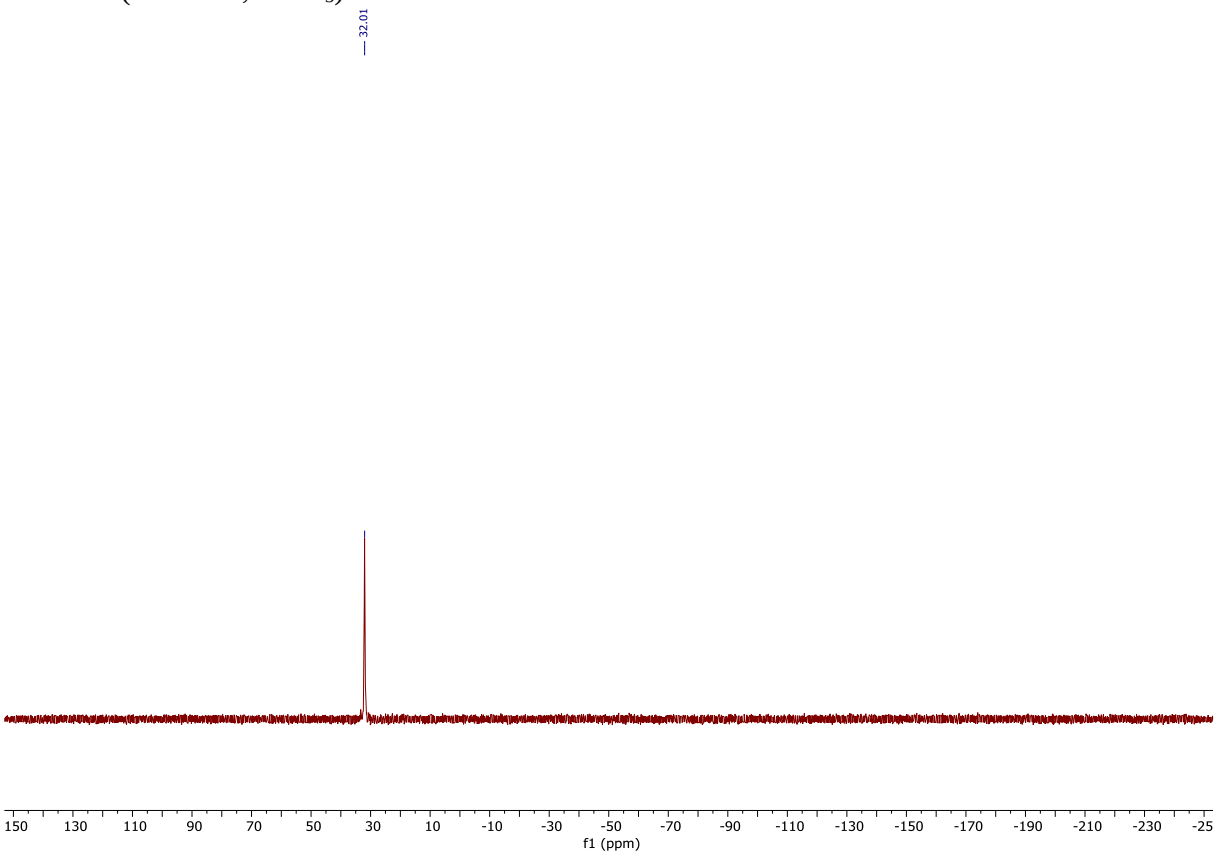


11

^{13}C NMR (101 MHz, $CDCl_3$)



^{31}P NMR (162 MHz, $CDCl_3$)



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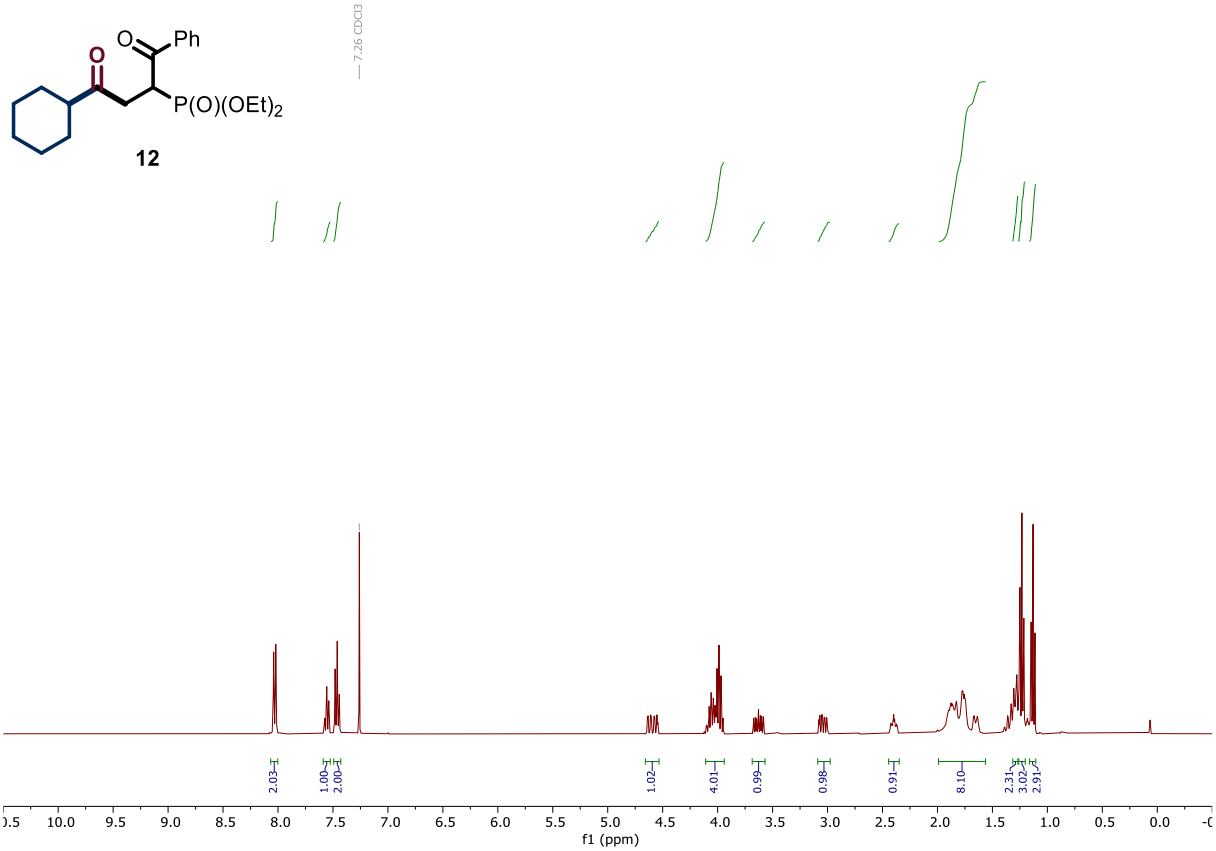

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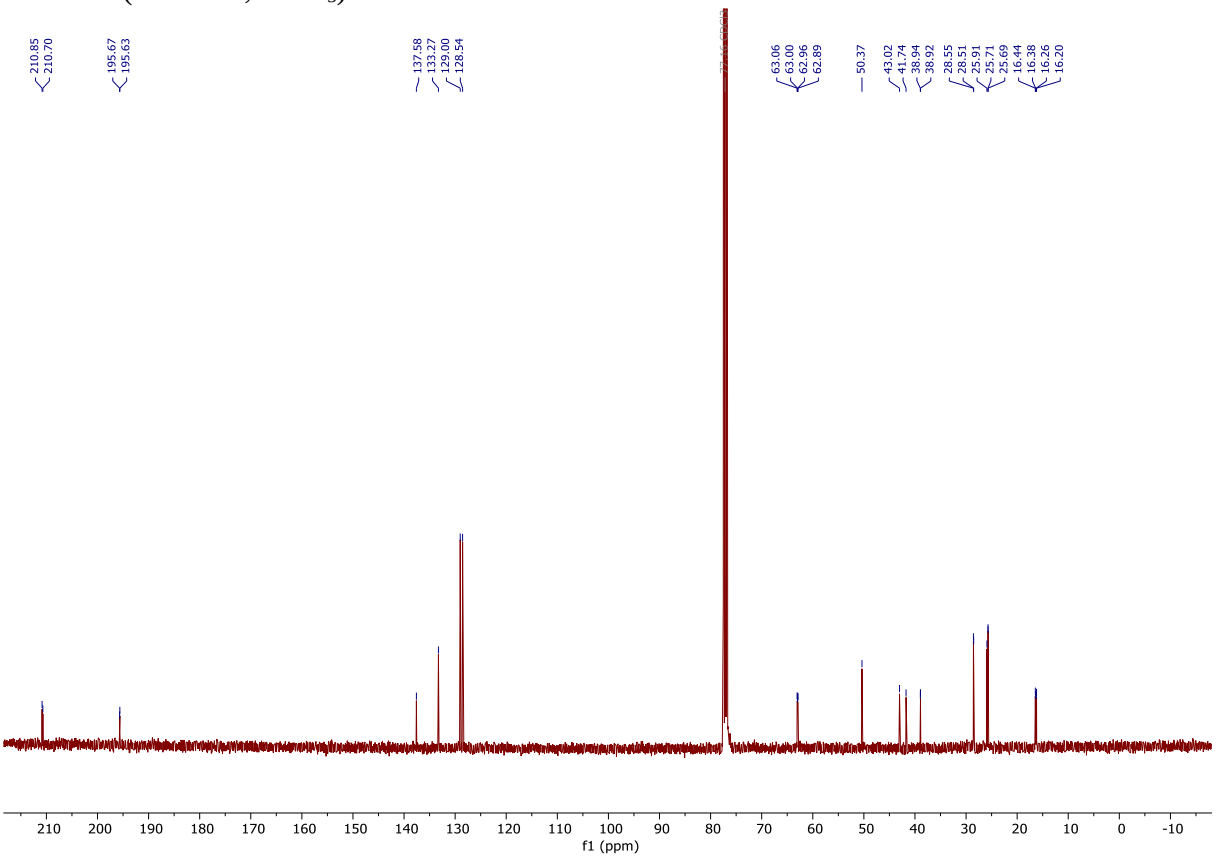
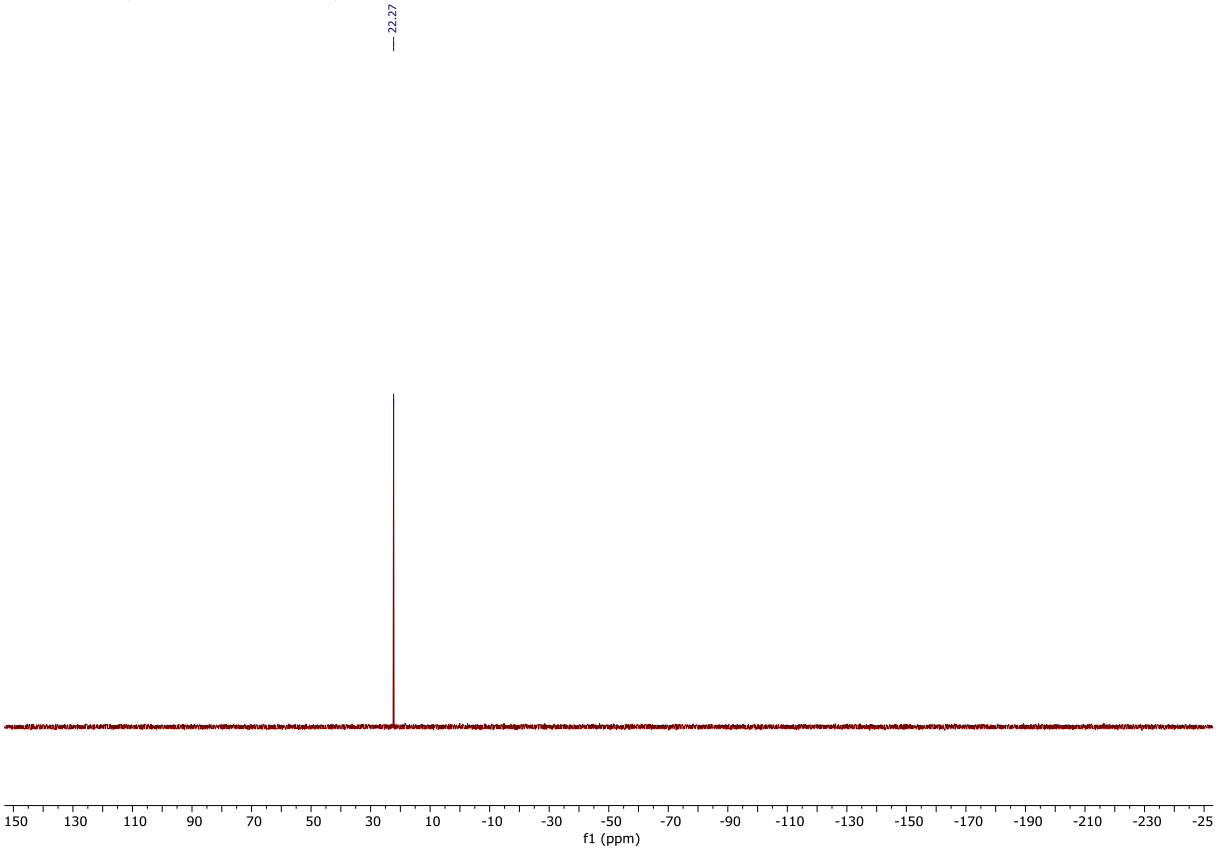
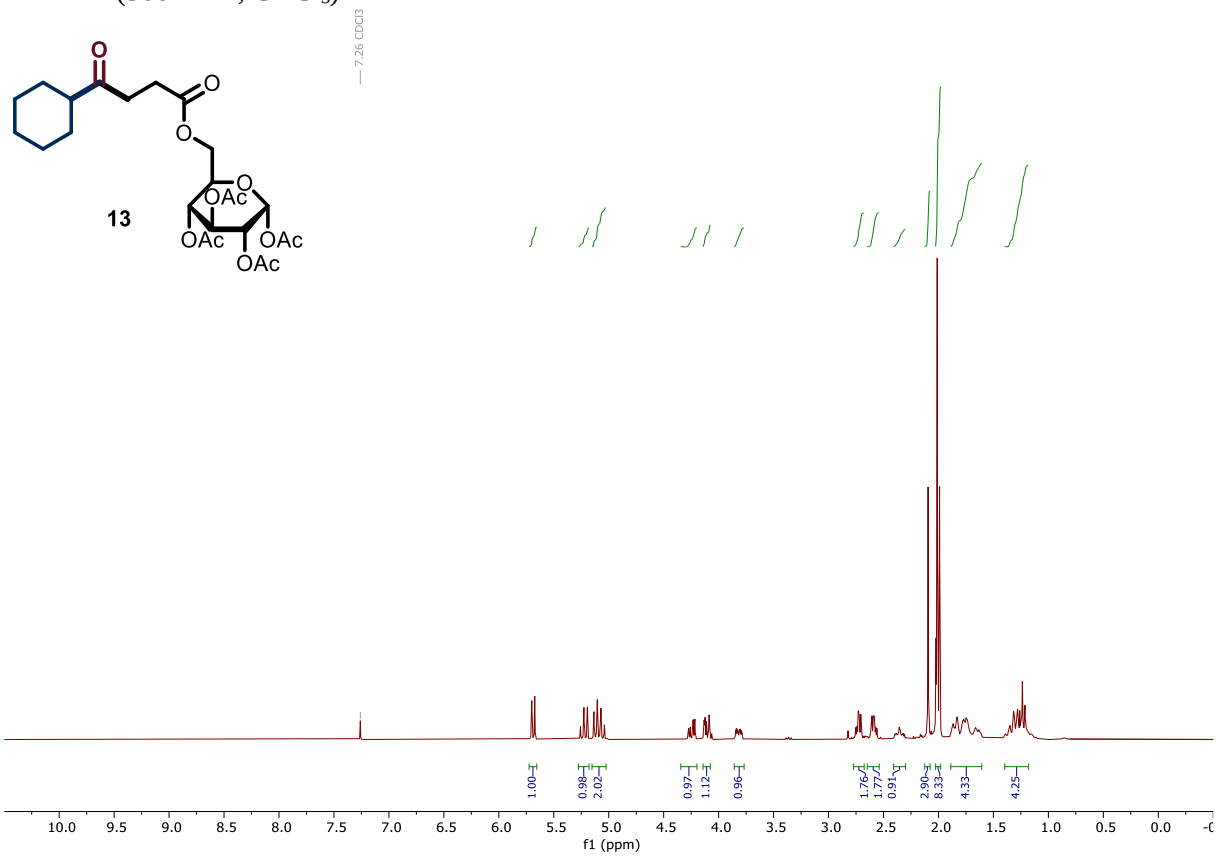


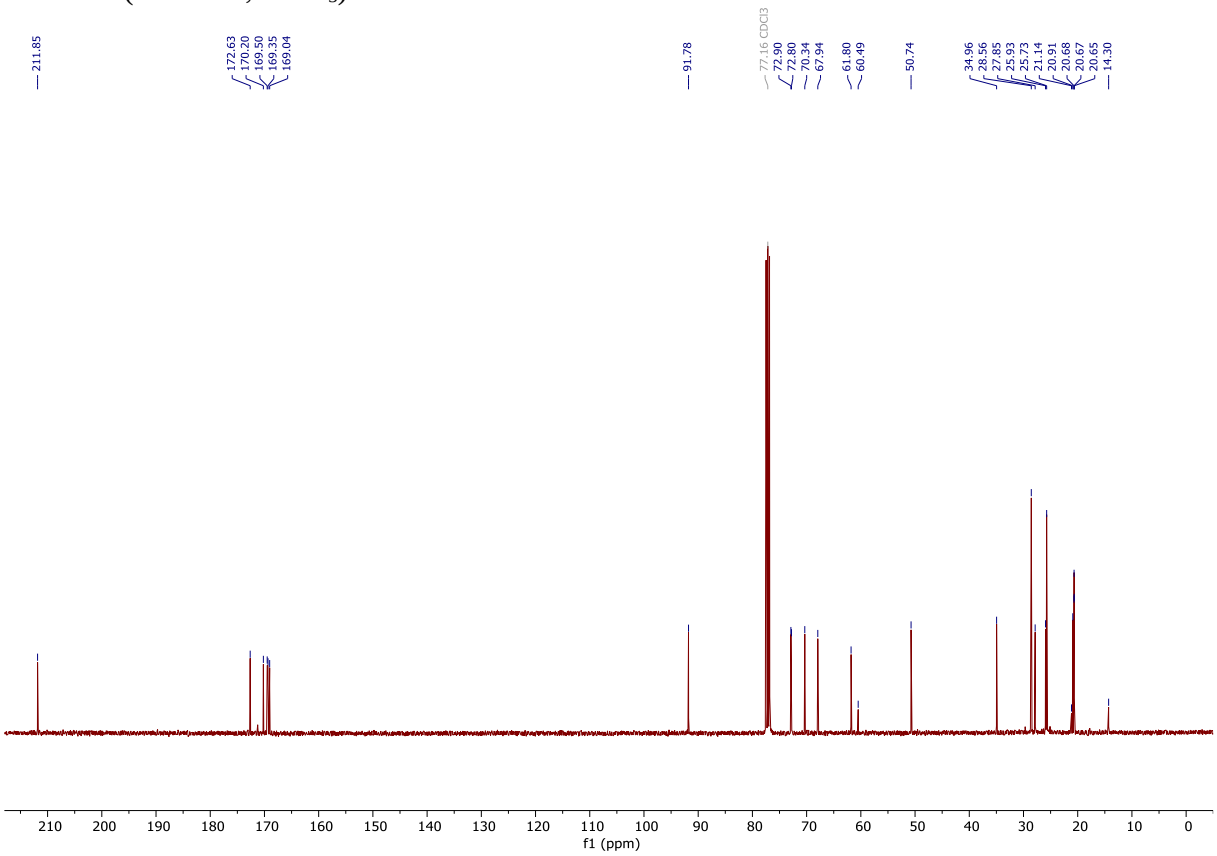
^{31}P NMR (162 MHz, $CDCl_3$)



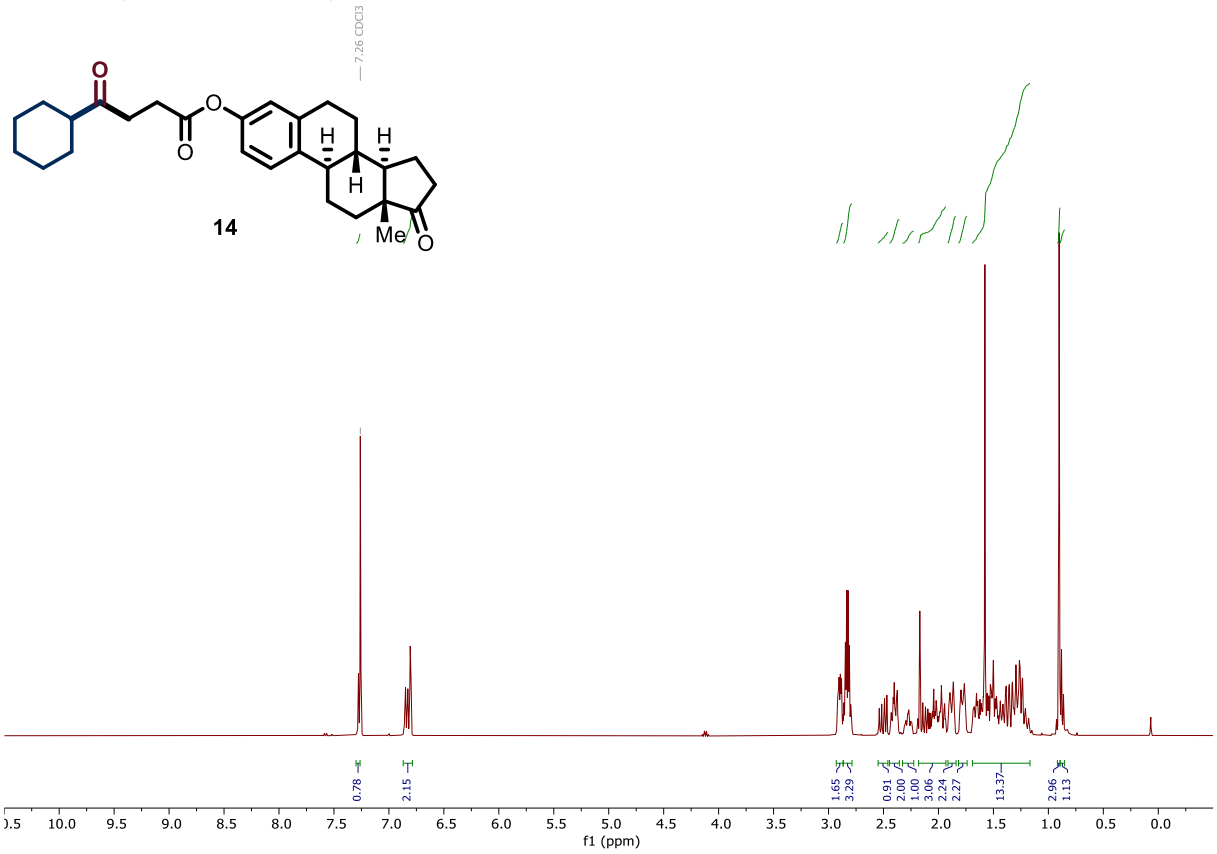
^{1}H NMR (300 MHz, $CDCl_3$)



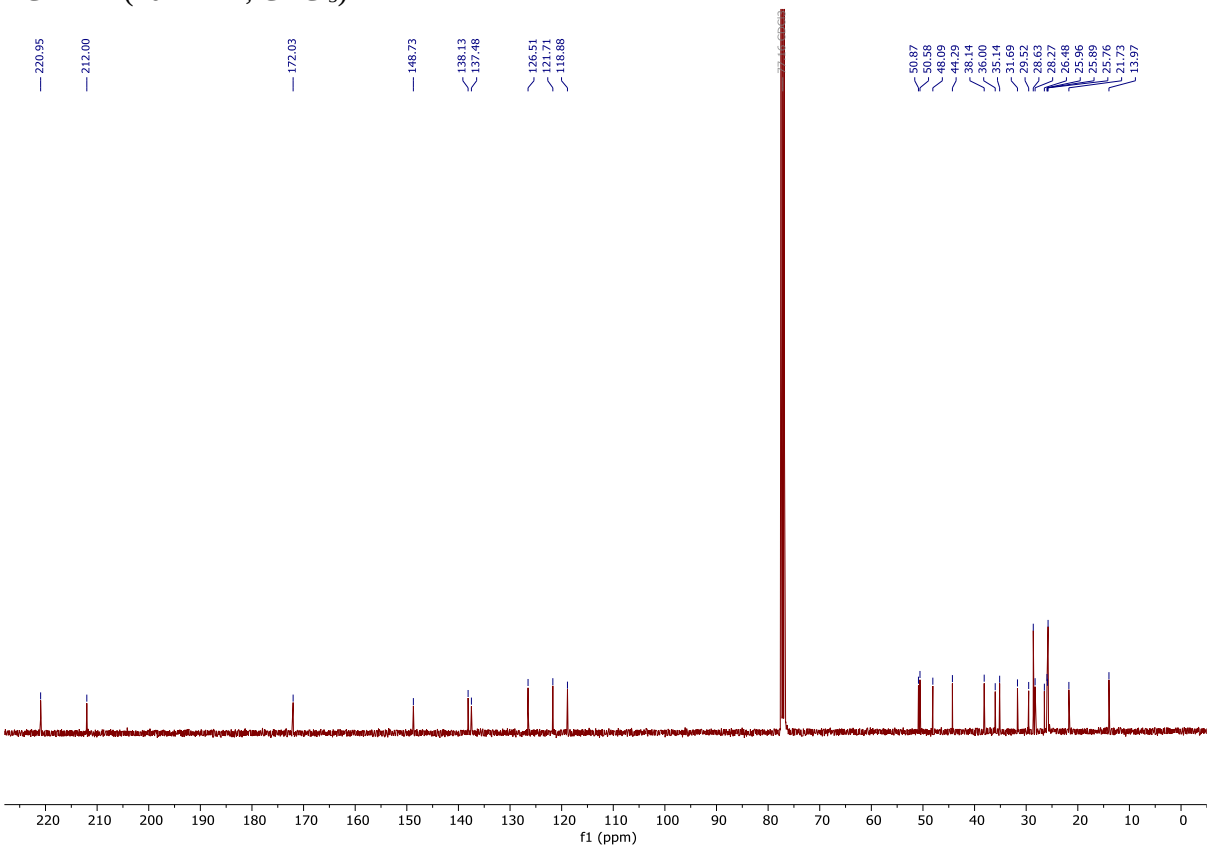
^{13}C NMR (101 MHz, $CDCl_3$)



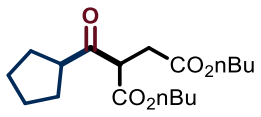
^{1}H NMR (400 MHz, $CDCl_3$)



^{13}C NMR (101 MHz, $CDCl_3$)

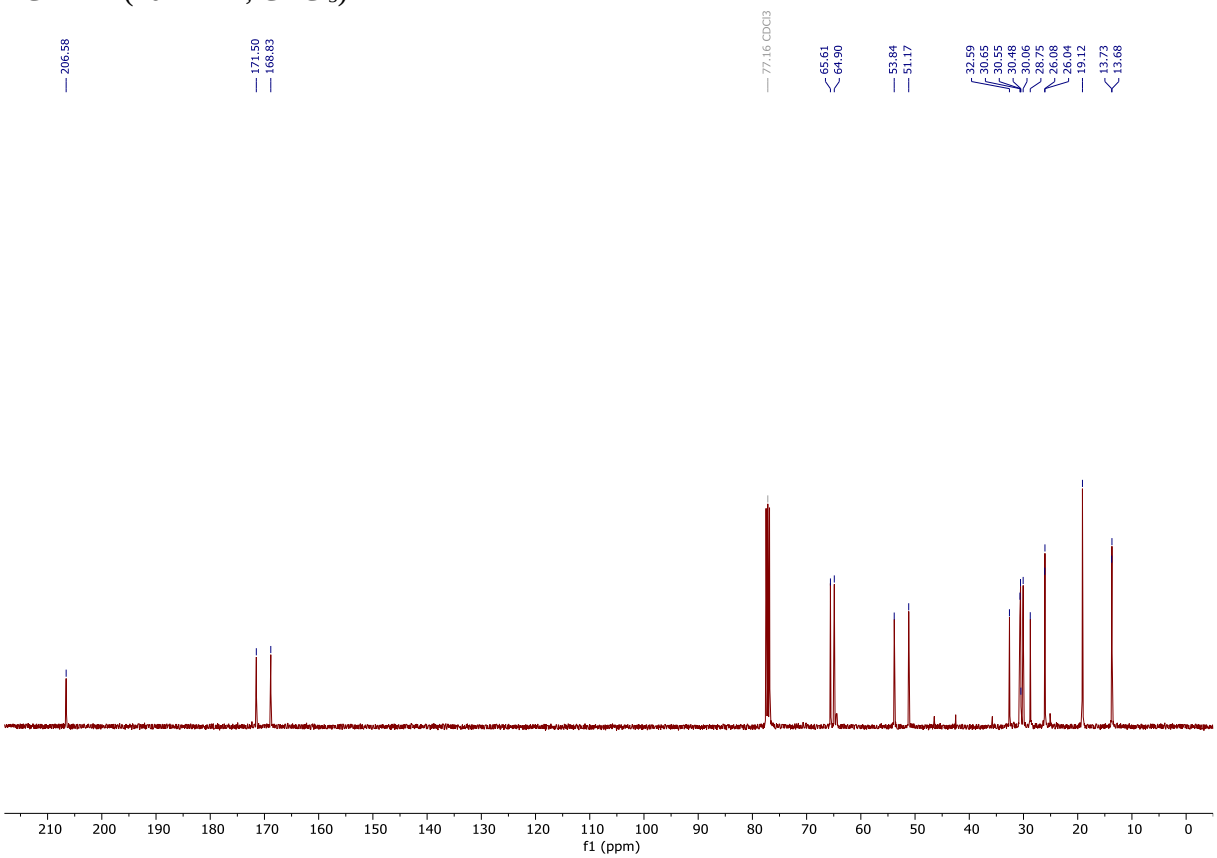


^{1}H NMR (400 MHz, $CDCl_3$)

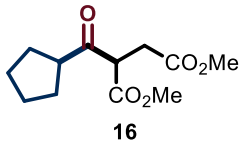


15

^{13}C NMR (101 MHz, $CDCl_3$)

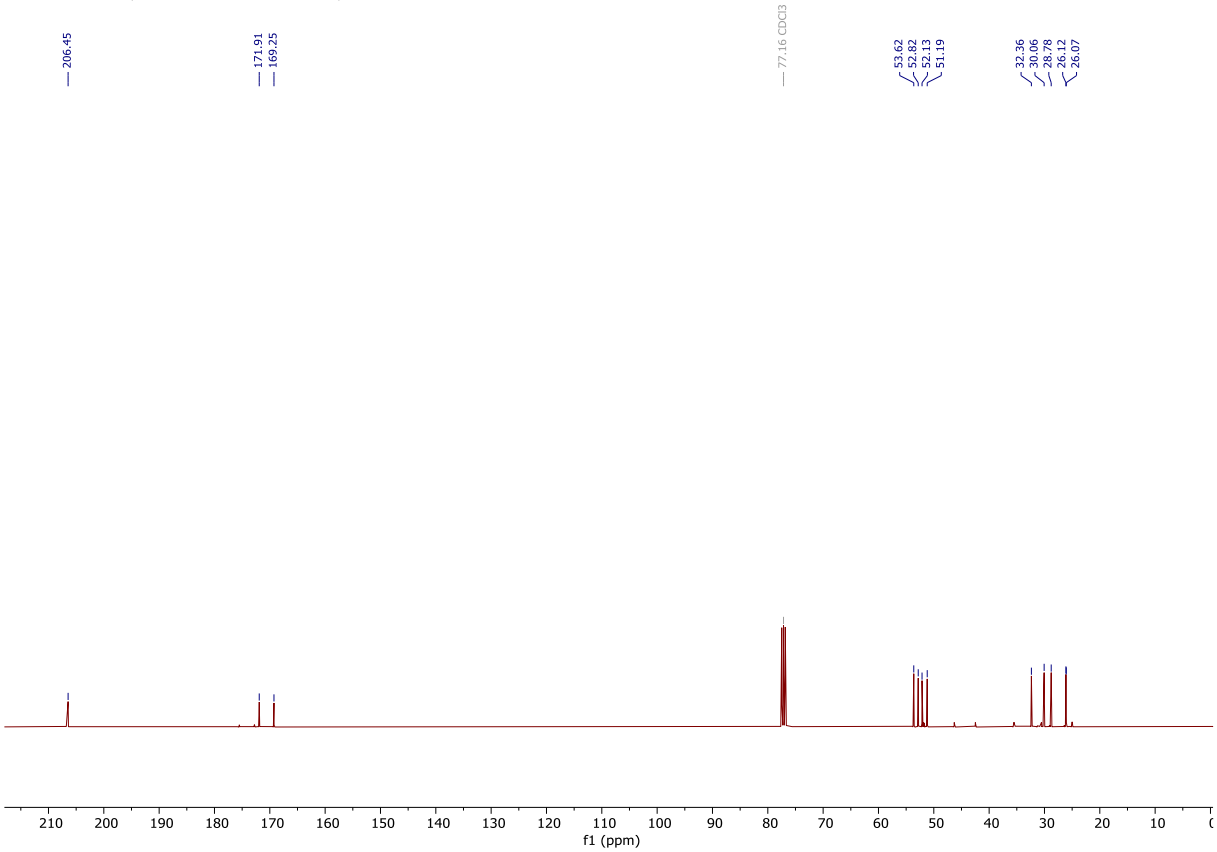


^{1}H NMR (400 MHz, $CDCl_3$)

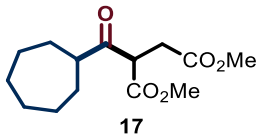


16

^{13}C NMR (101 MHz, $CDCl_3$)

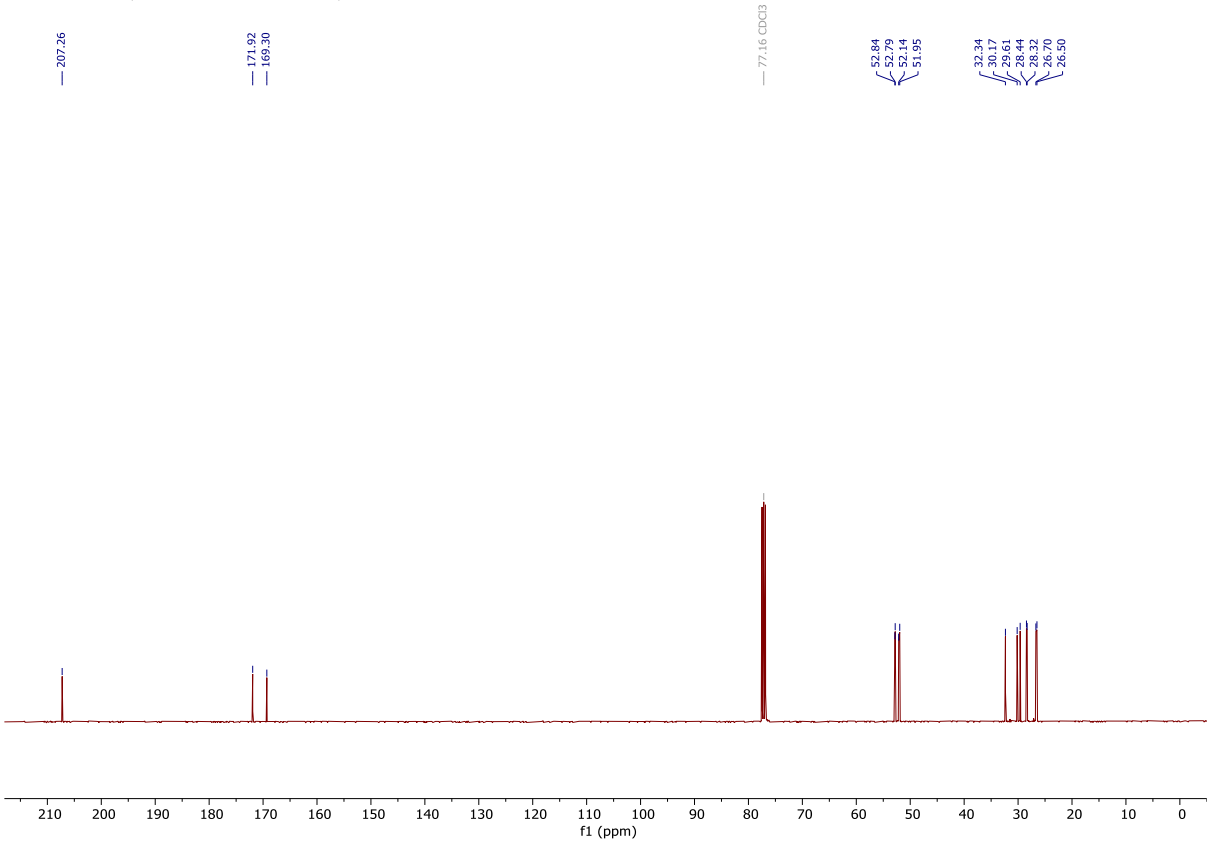


^{1}H NMR (400 MHz, $CDCl_3$)

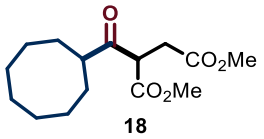


17

^{13}C NMR (101 MHz, $CDCl_3$)

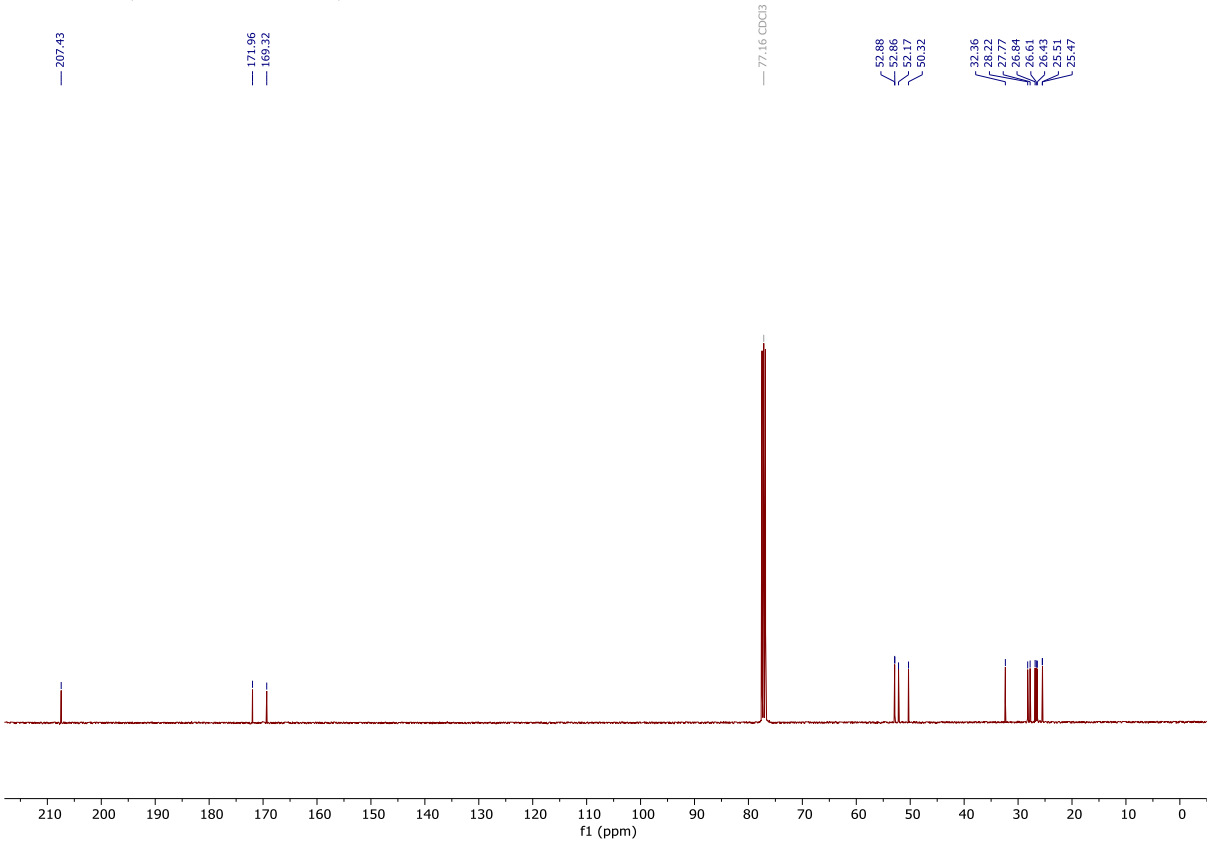


^{1}H NMR (400 MHz, $CDCl_3$)

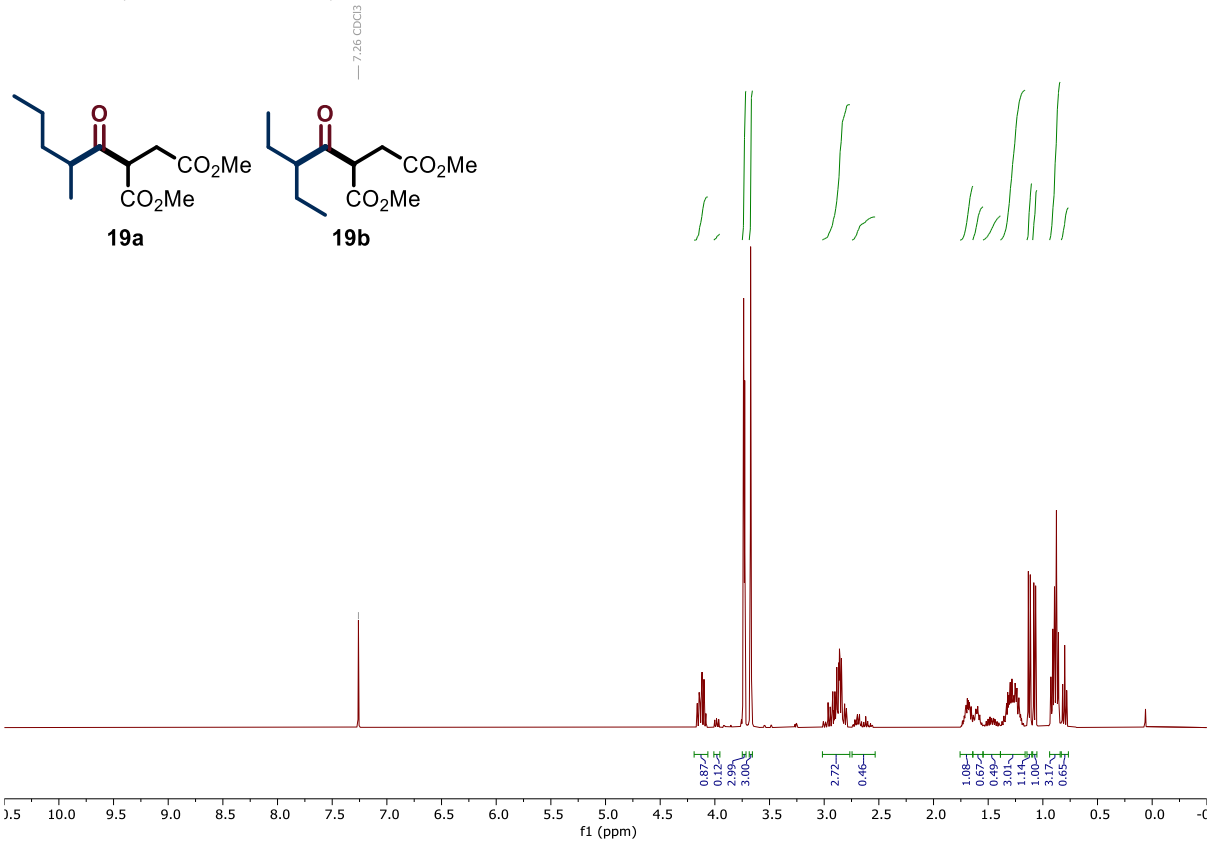


18

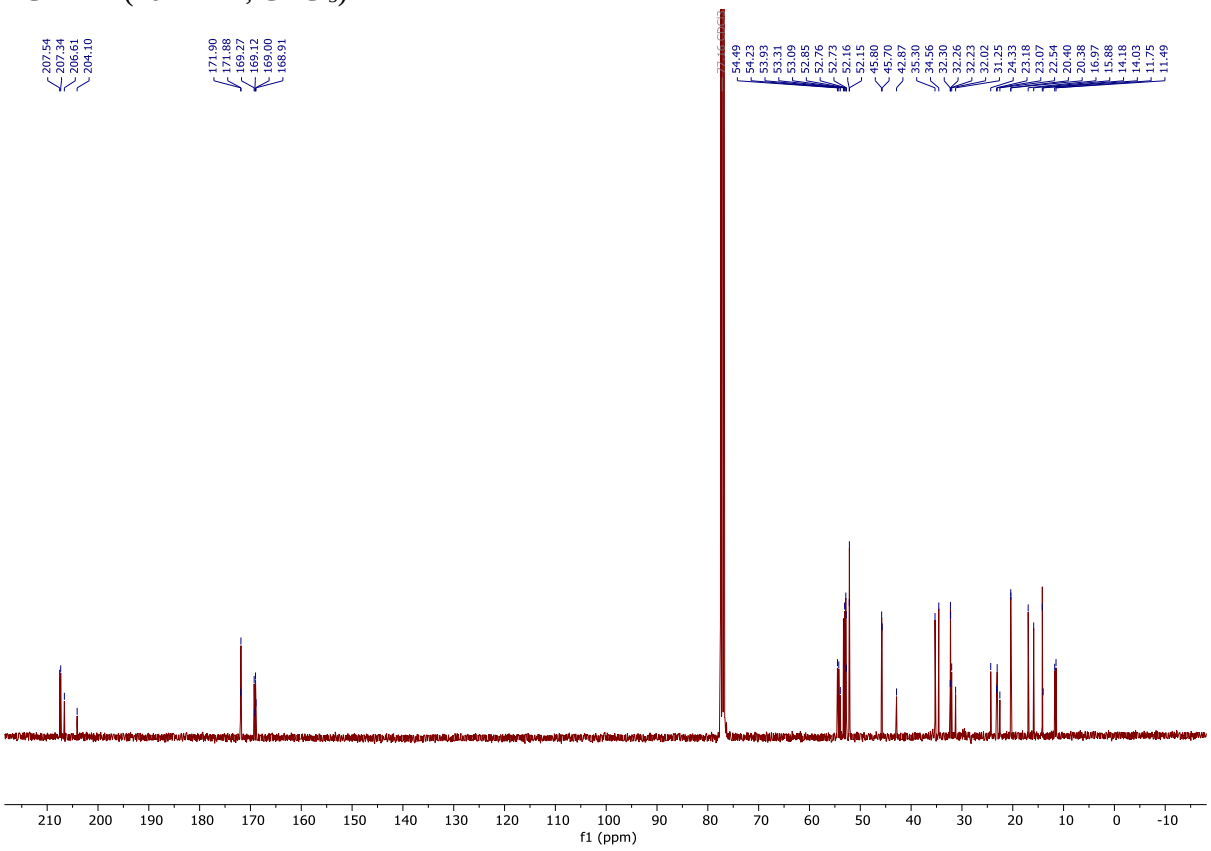
^{13}C NMR (101 MHz, $CDCl_3$)



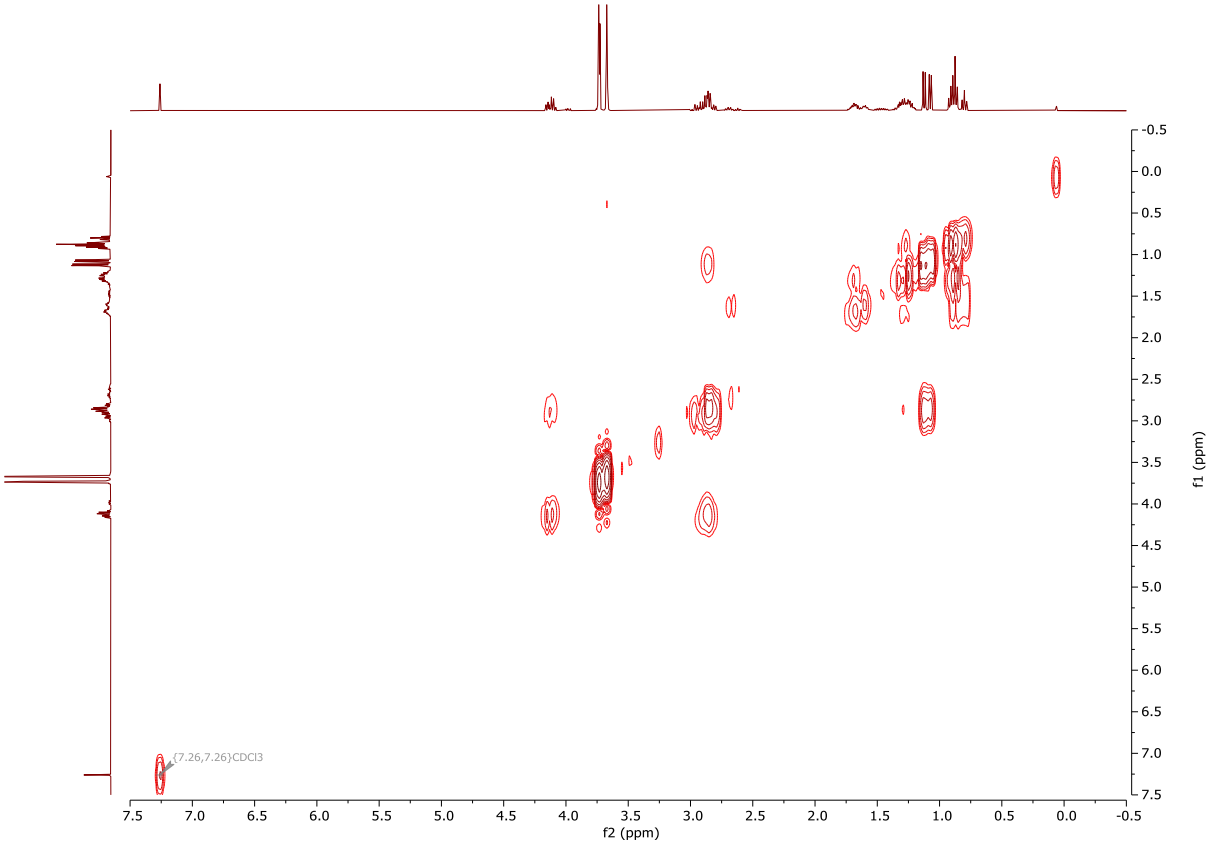
^{1}H NMR (400 MHz, $CDCl_3$)



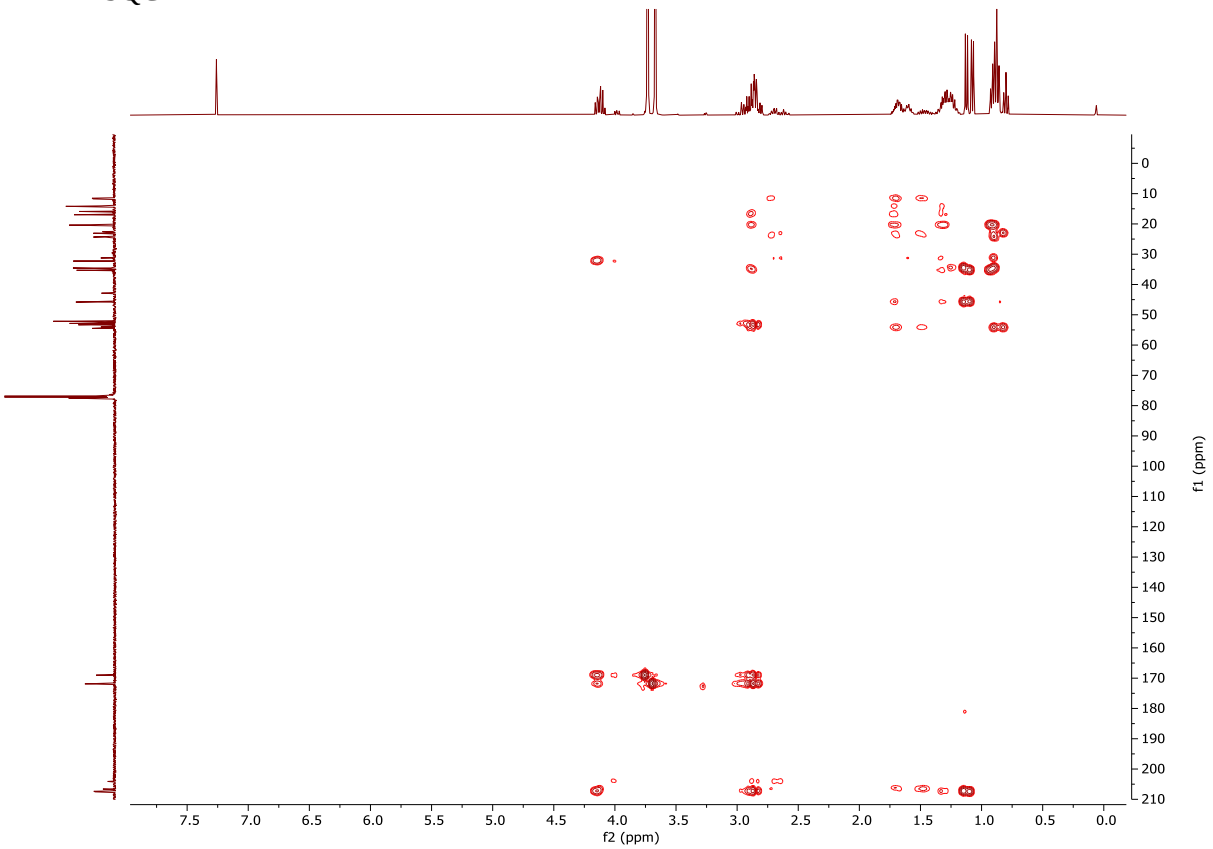
^{13}C NMR (101 MHz, $CDCl_3$)



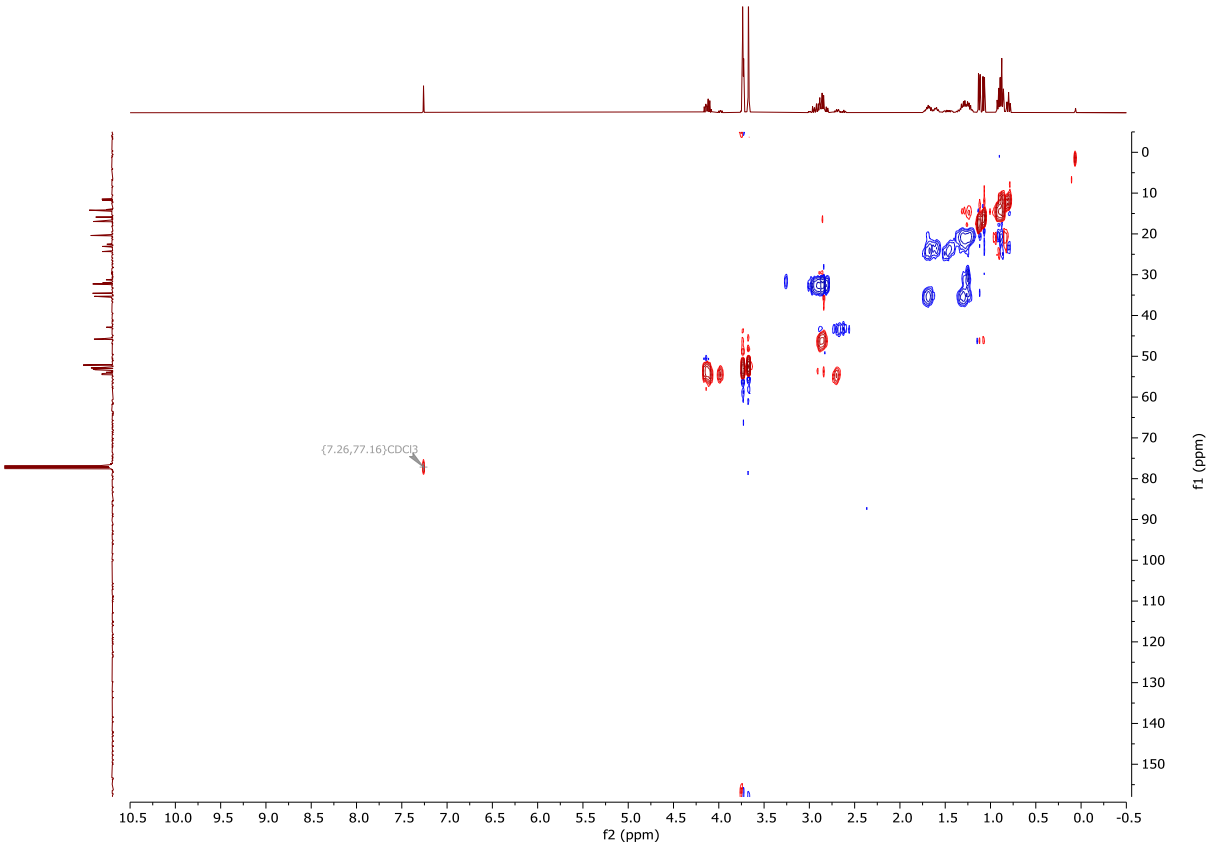
^{1}H-^{1}H COSY



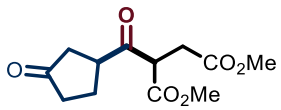
^{1}H-^{1}H HSQC



^{1}H-^{13}C HMBC

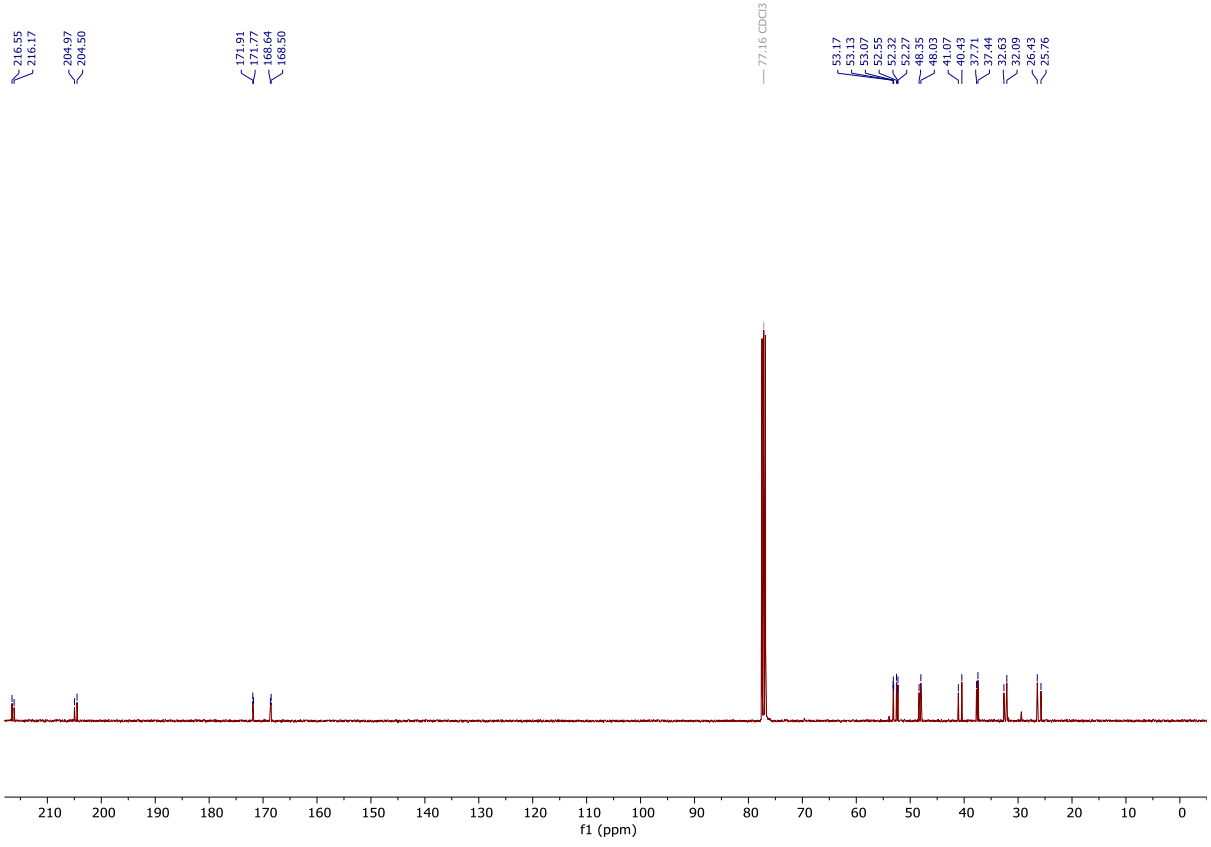


^{1}H NMR (400 MHz, $CDCl_3$)

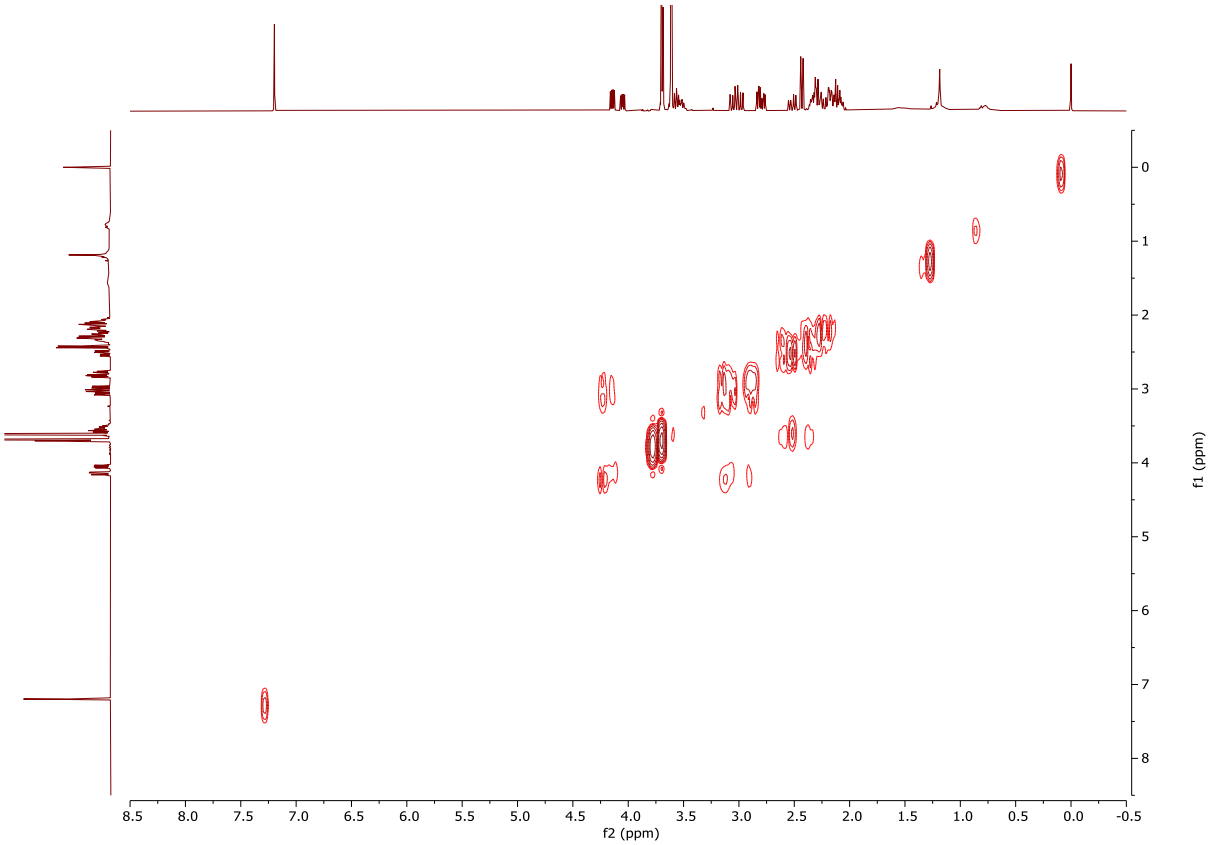


20

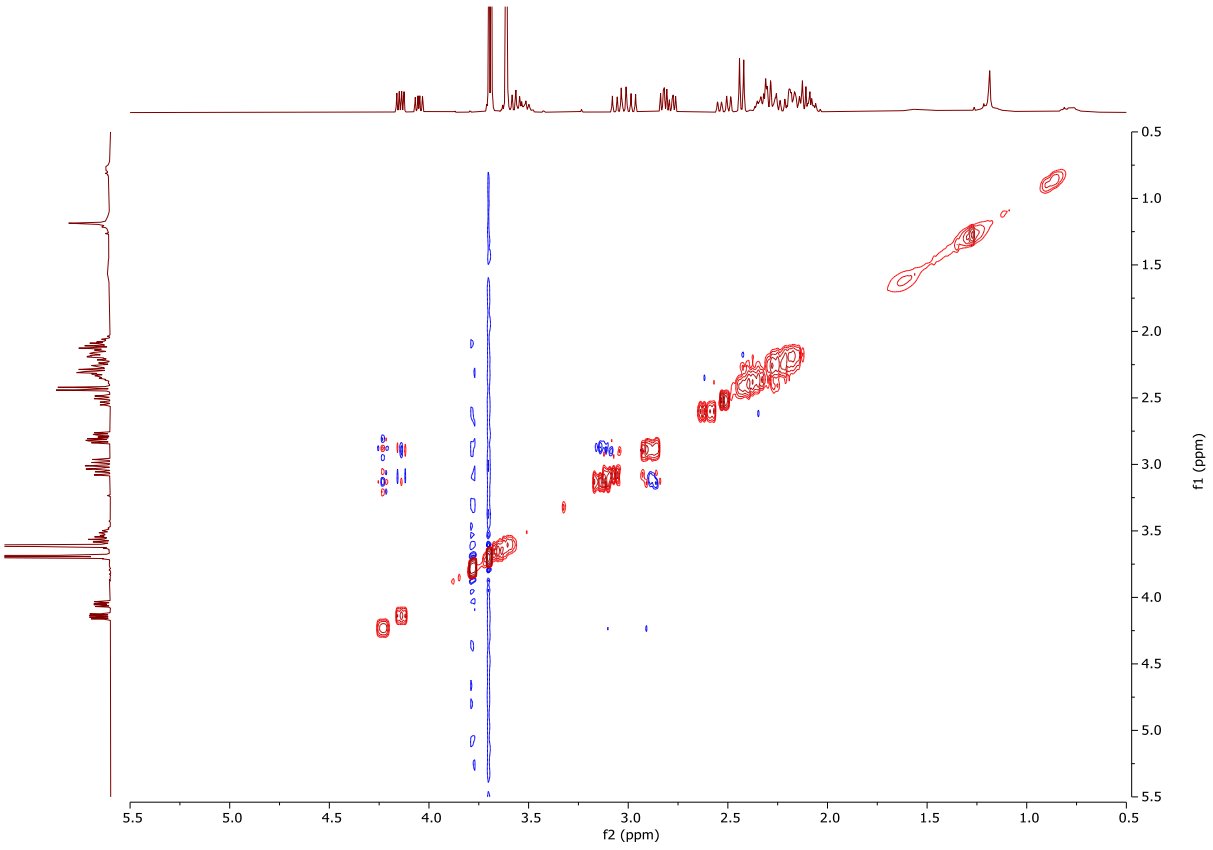
^{13}C NMR (101 MHz, $CDCl_3$)



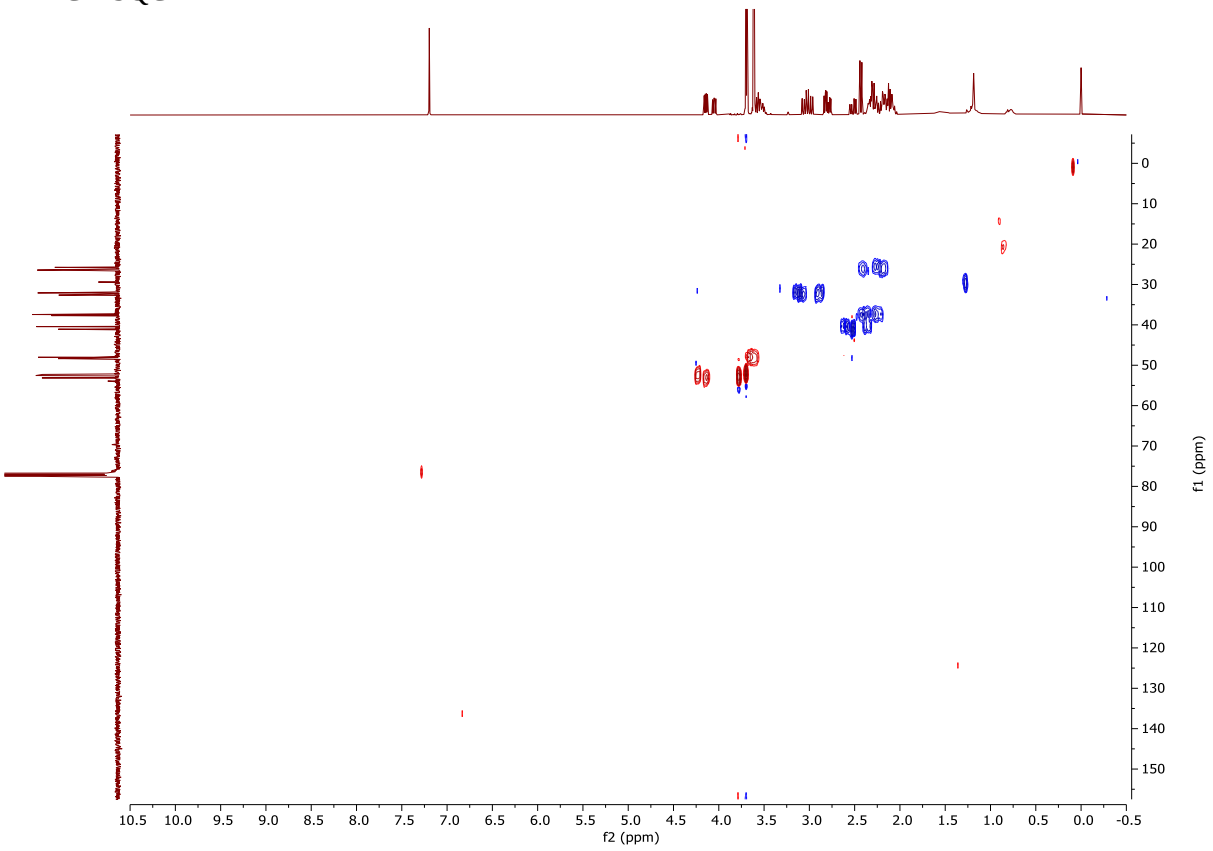
^{1}H-^{1}H COSY



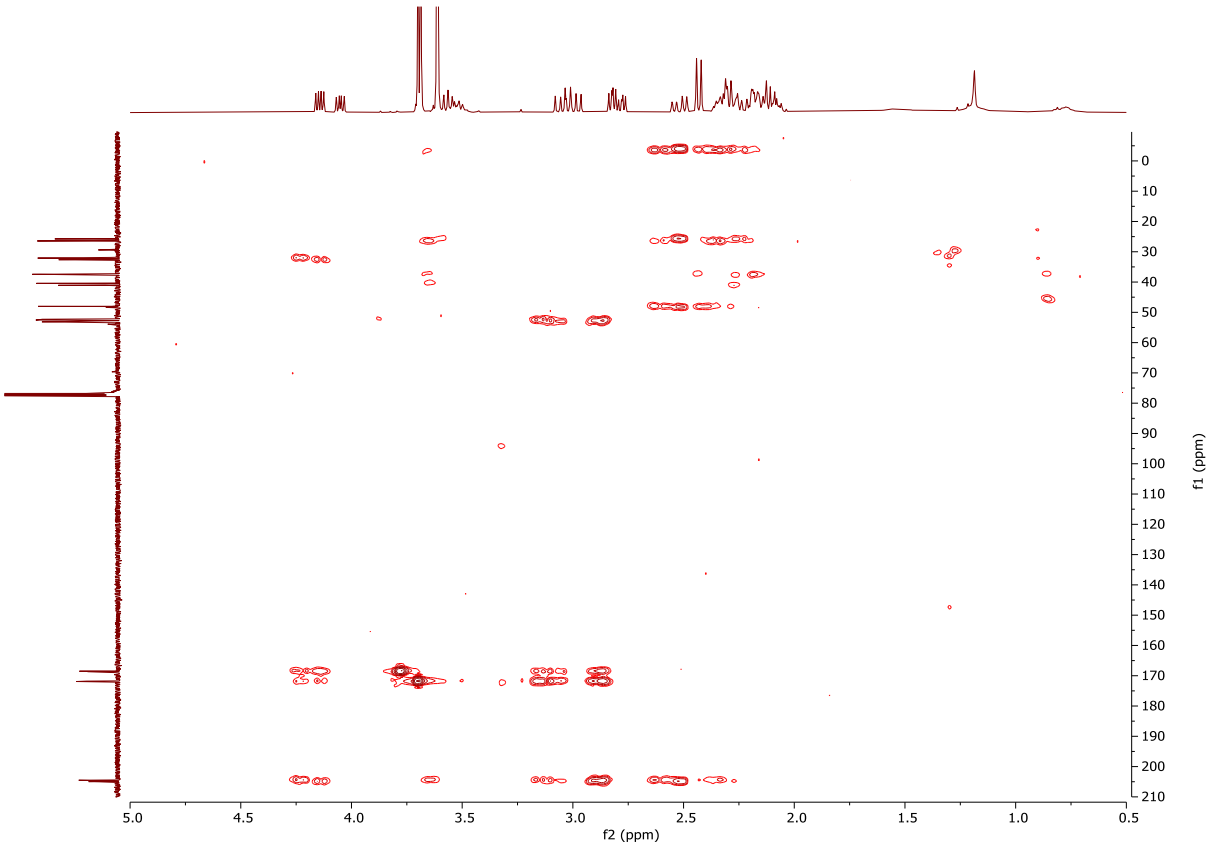
^{1}H-^{1}H NOESY



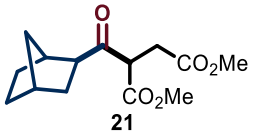
^{1}H-^{13}C HSQC



^{1}H-^{13}C HMBC

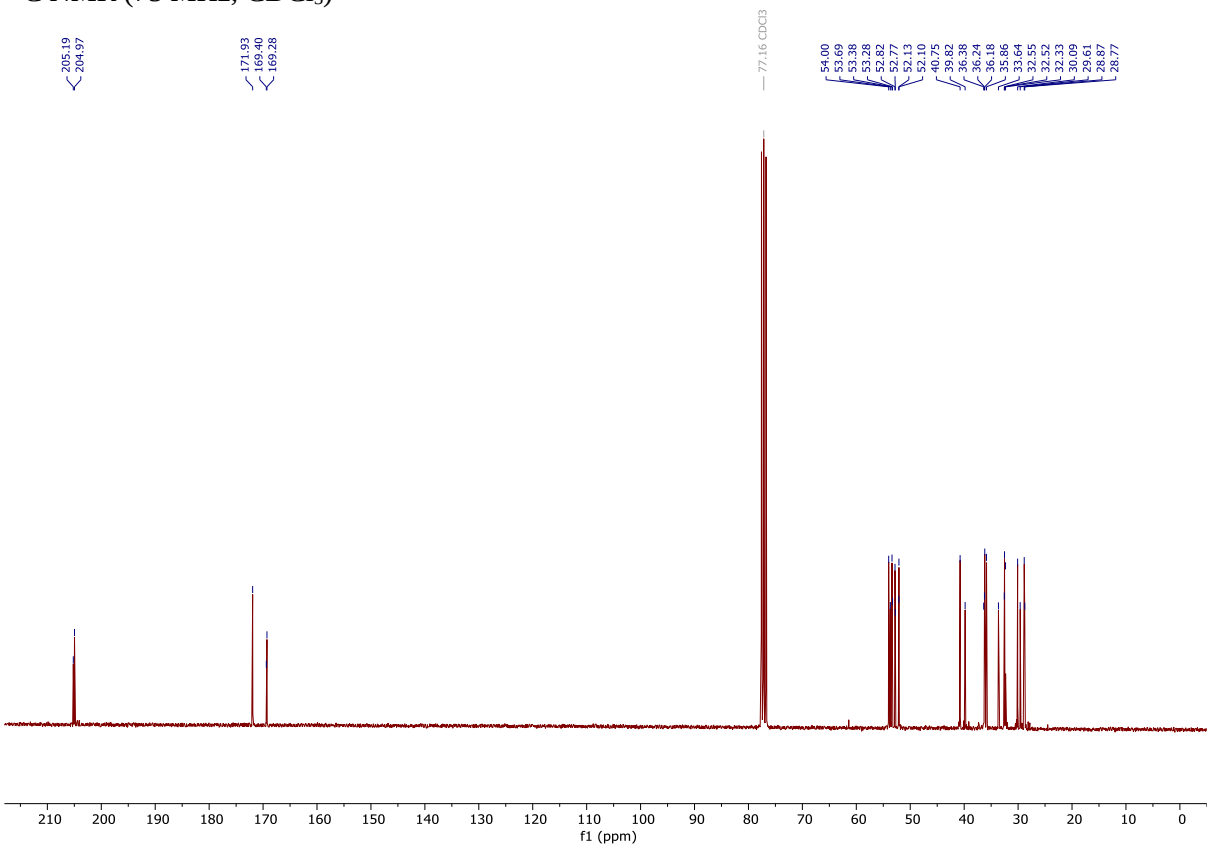


^{1}H NMR (400 MHz, $CDCl_3$)

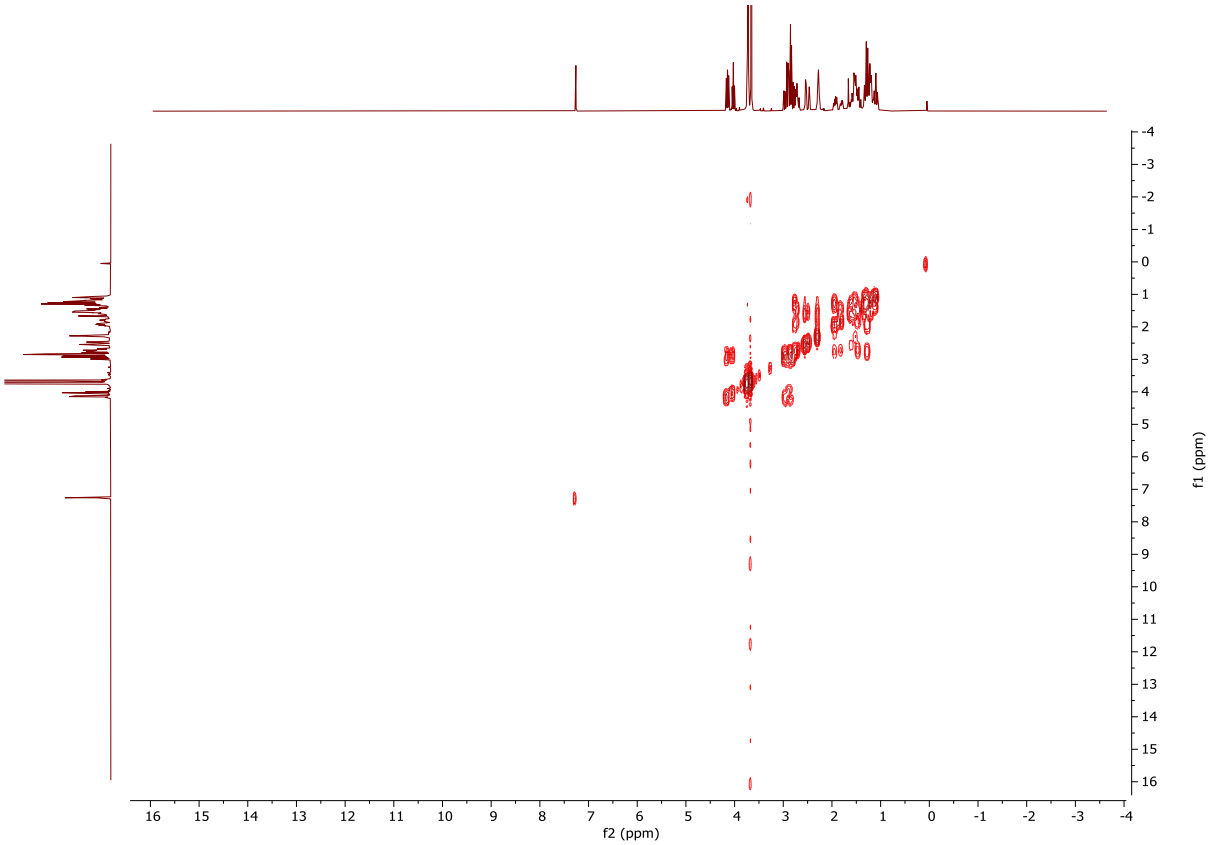


21

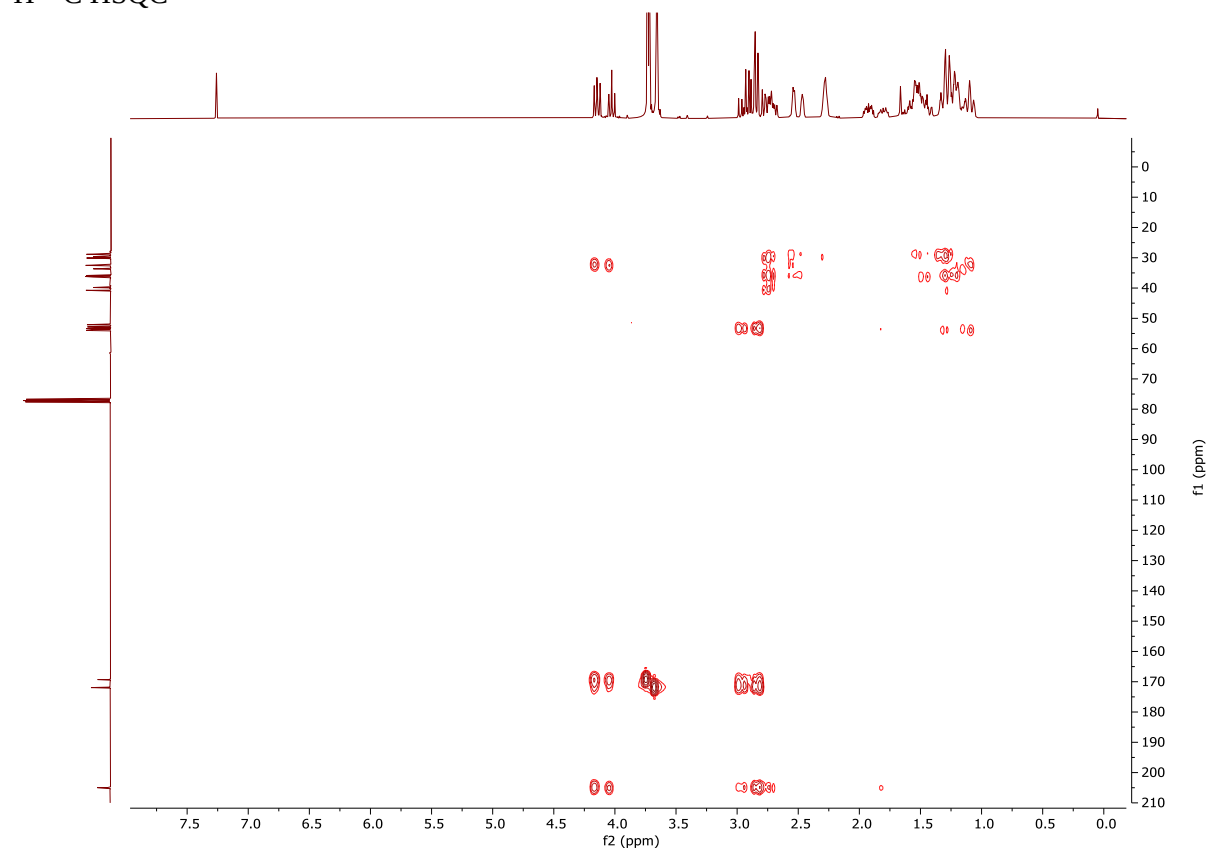
^{13}C NMR (75 MHz, $CDCl_3$)



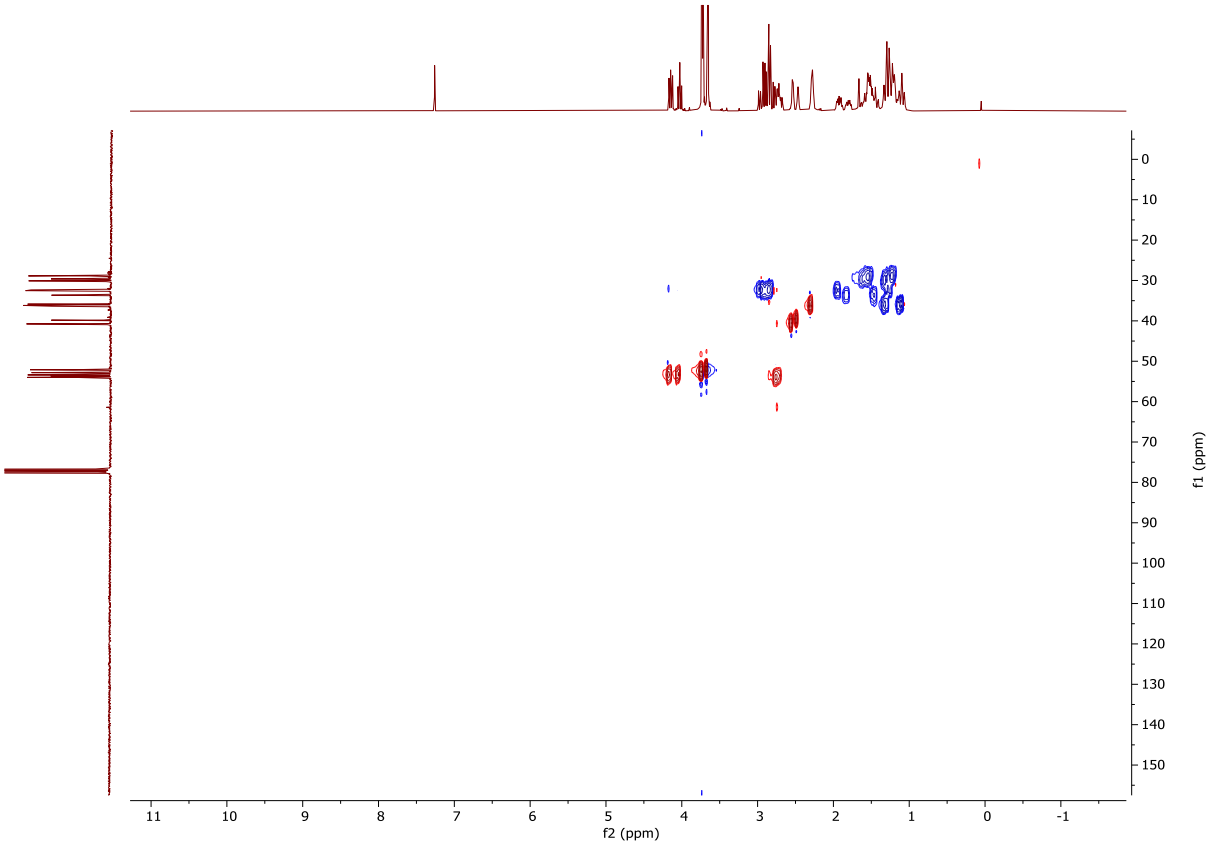
^{1}H-^{1}H COSY



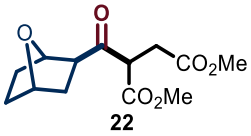
^{1}H-^{13}C HSQC



^{1}H-^{13}C HMBC

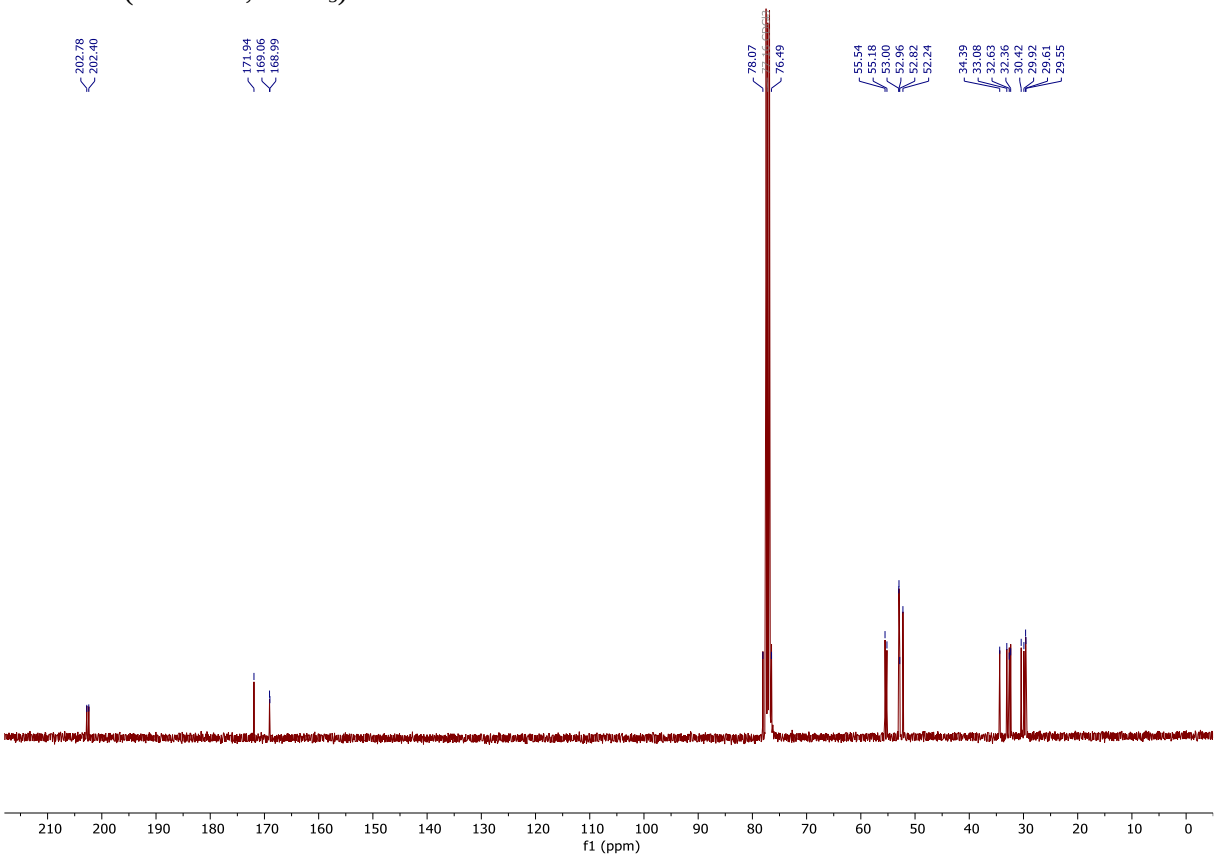


^{1}H NMR (400 MHz, $CDCl_3$)

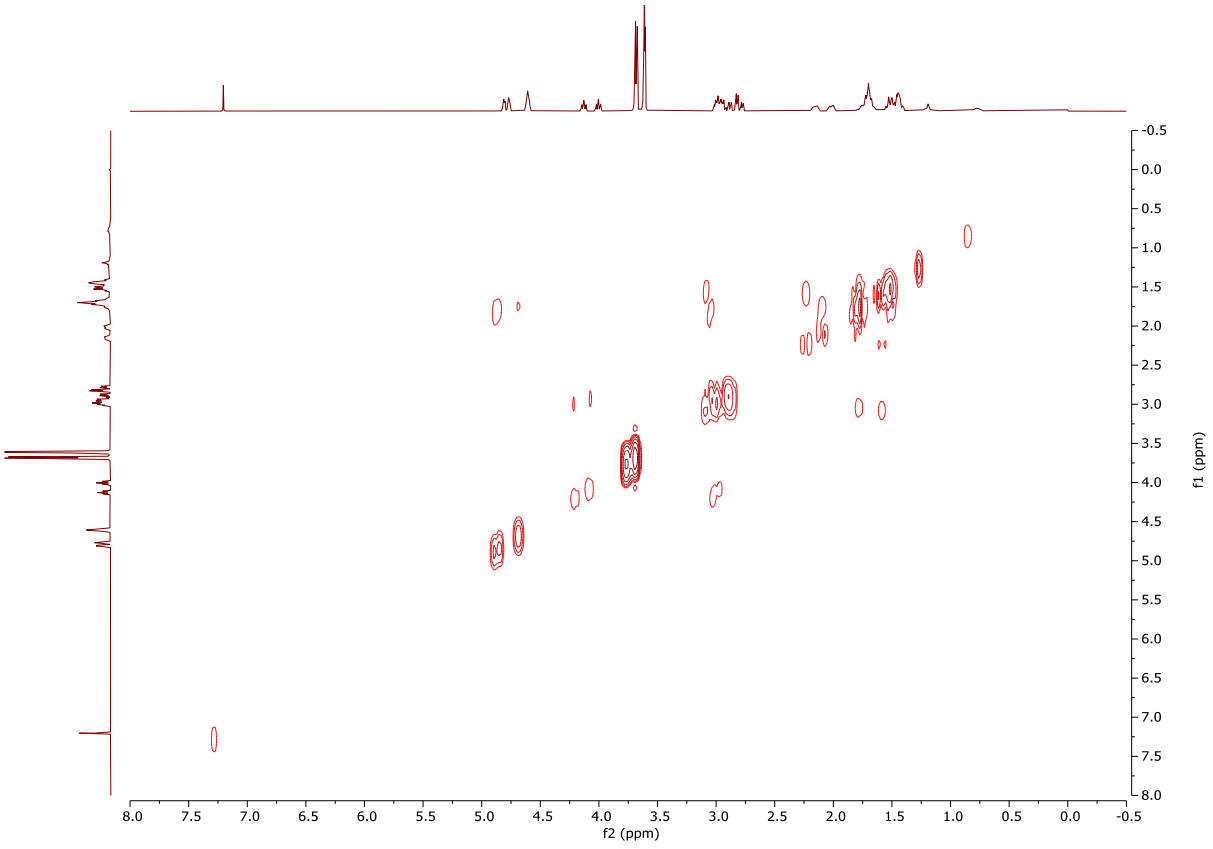


22

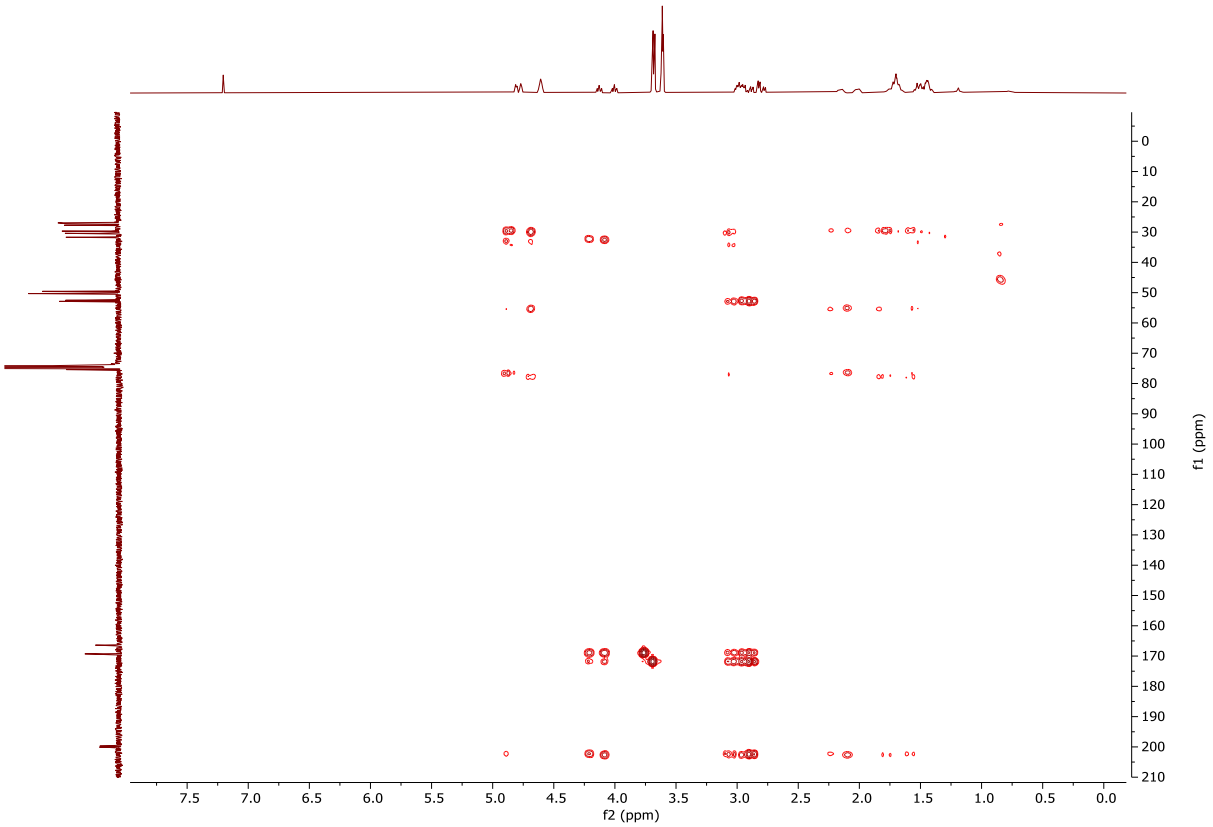
^{13}C NMR (101 MHz, $CDCl_3$)



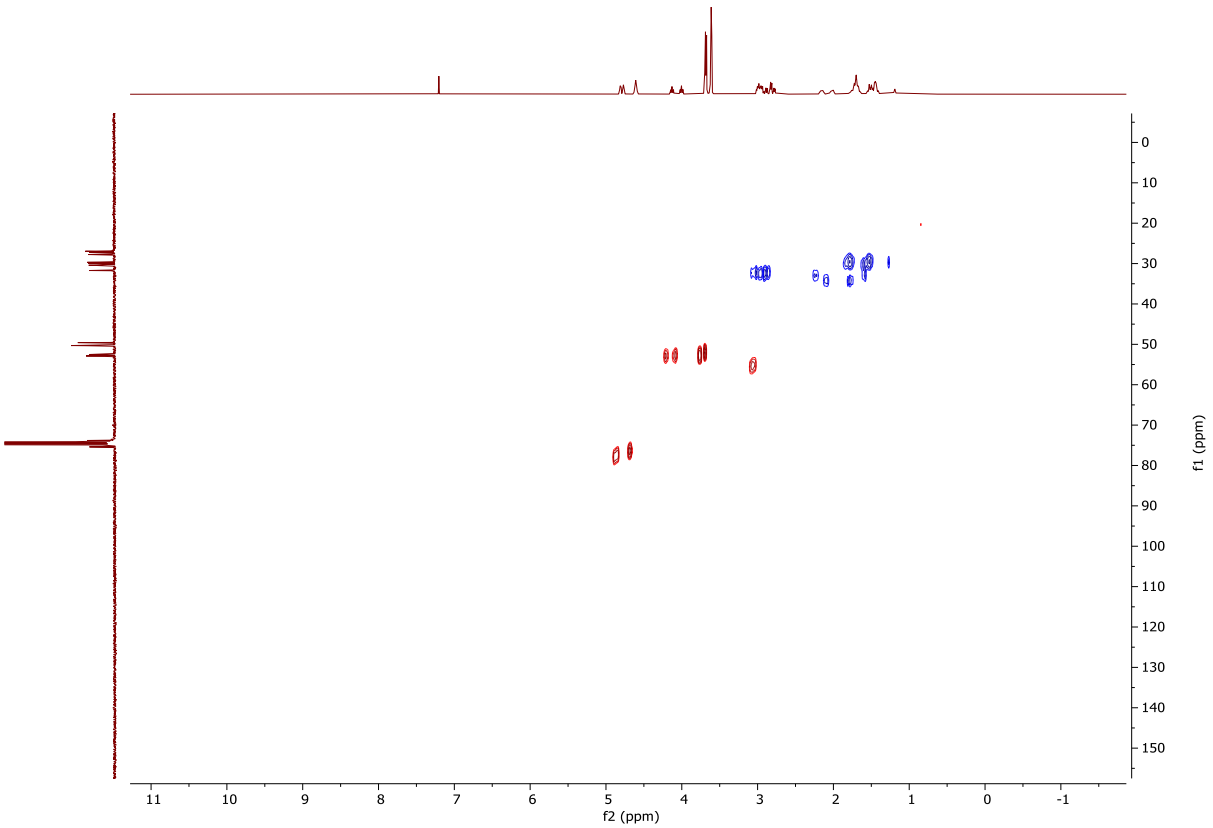
^{1}H-^{1}H COSY



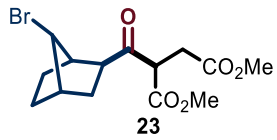
^{1}H-^{13}C HSQC



^{1}H-^{13}C HMBC

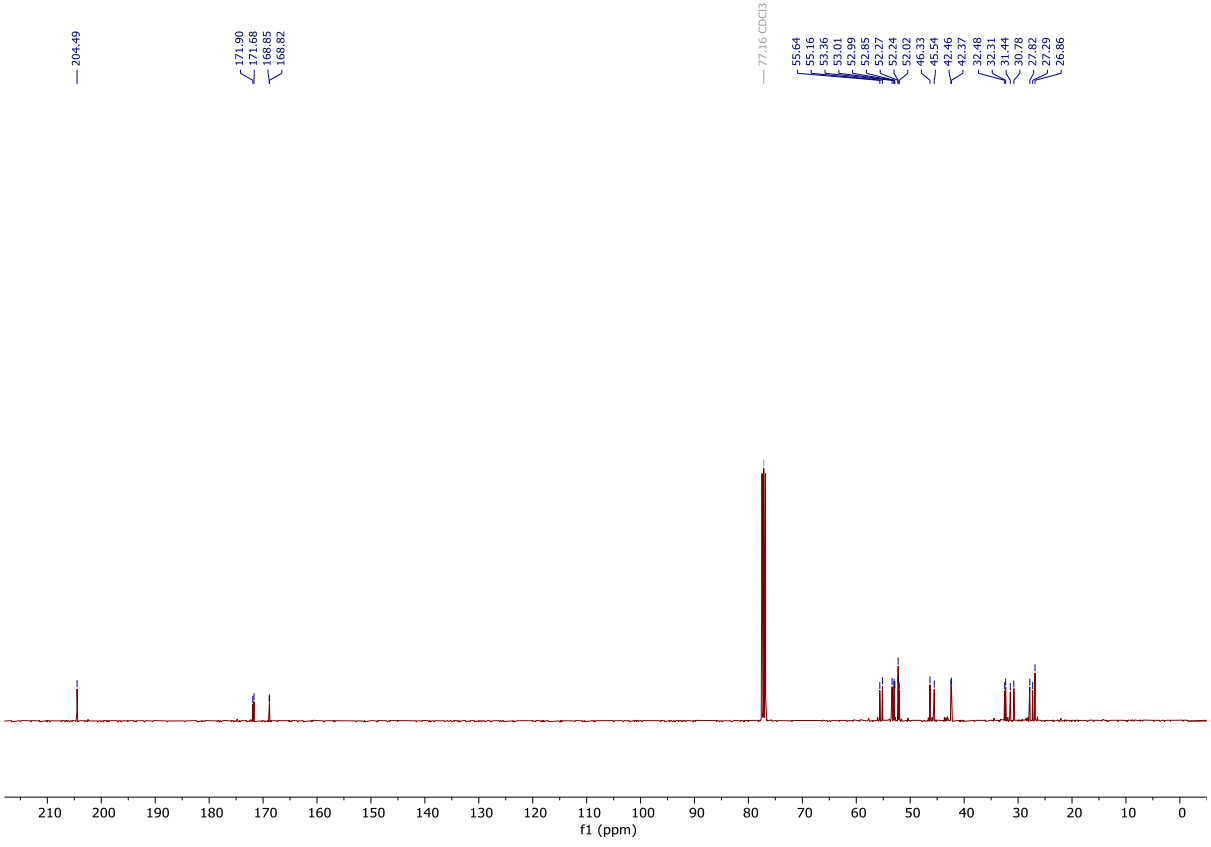


^{1}H NMR (400 MHz, $CDCl_3$)

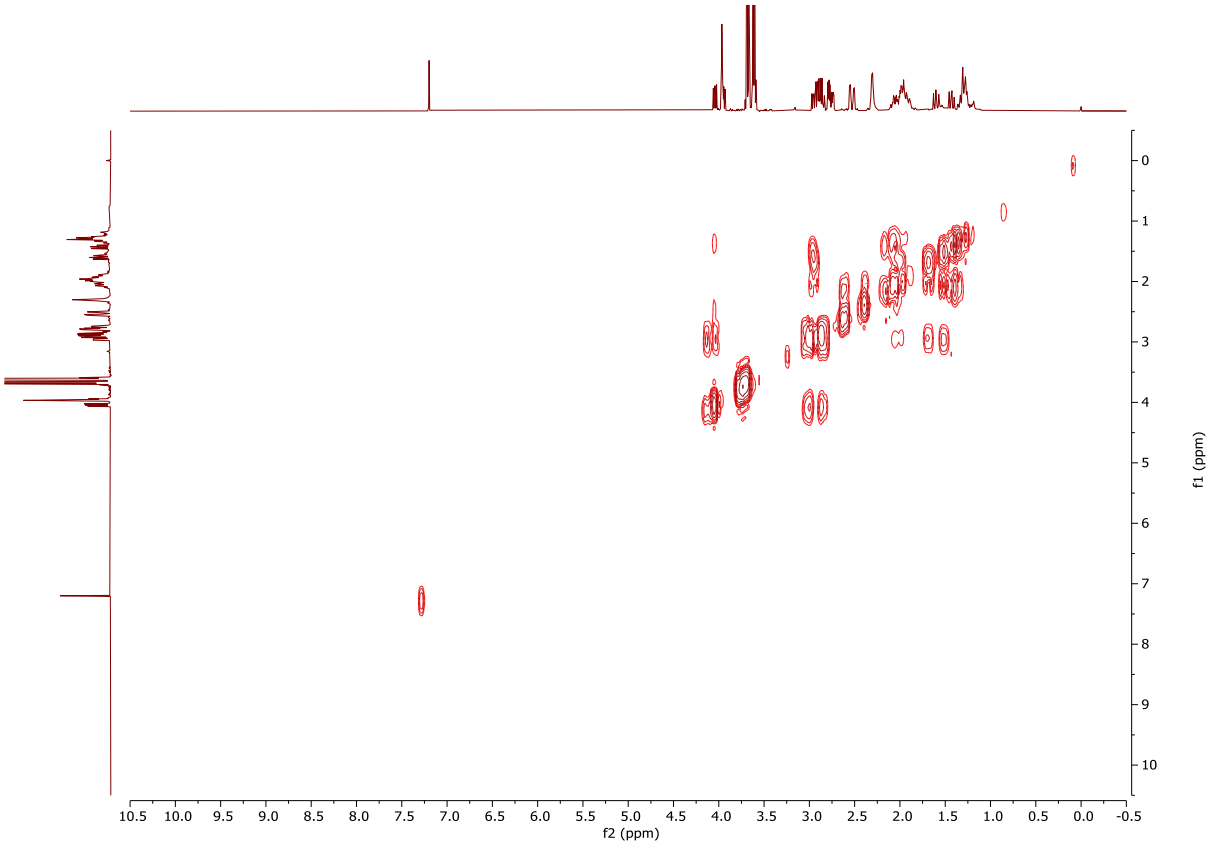


23

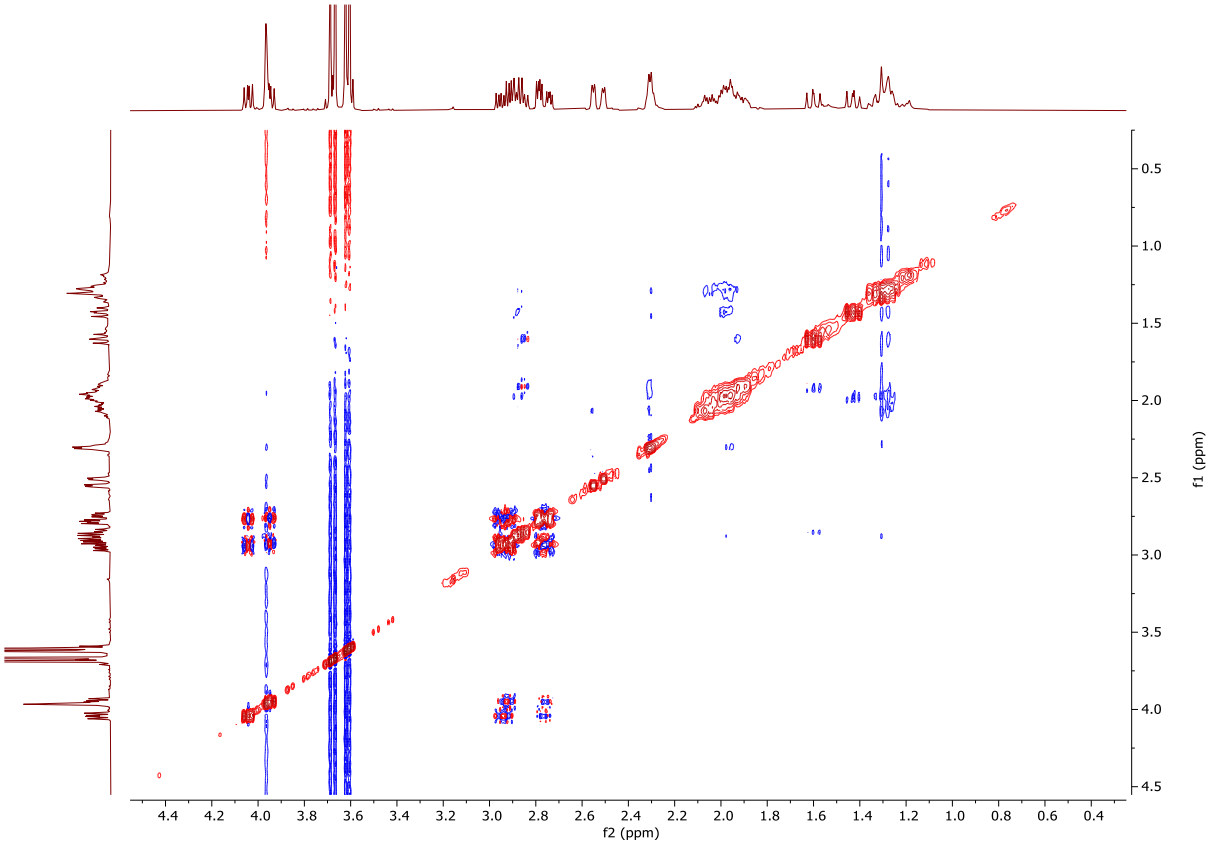
^{13}C NMR (101 MHz, $CDCl_3$)



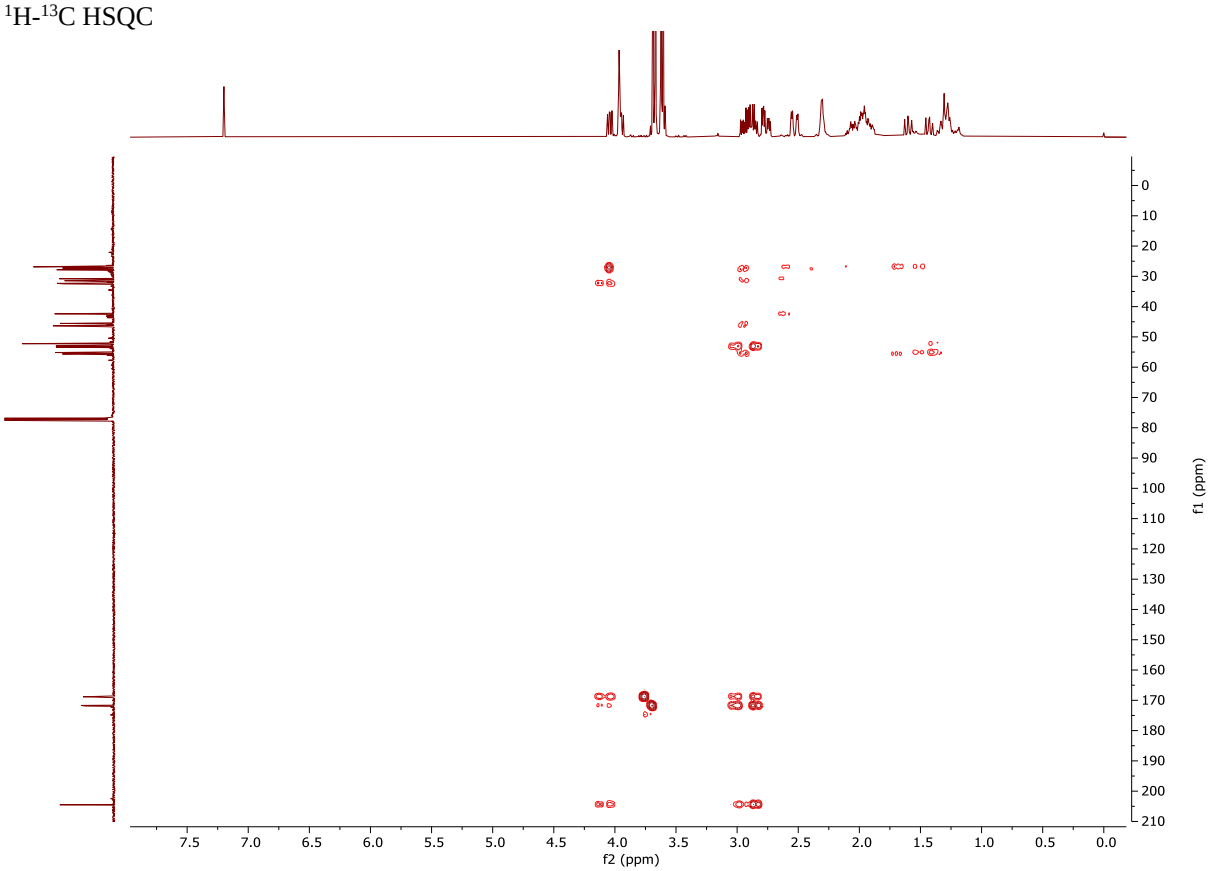
^{1}H-^{1}H COSY



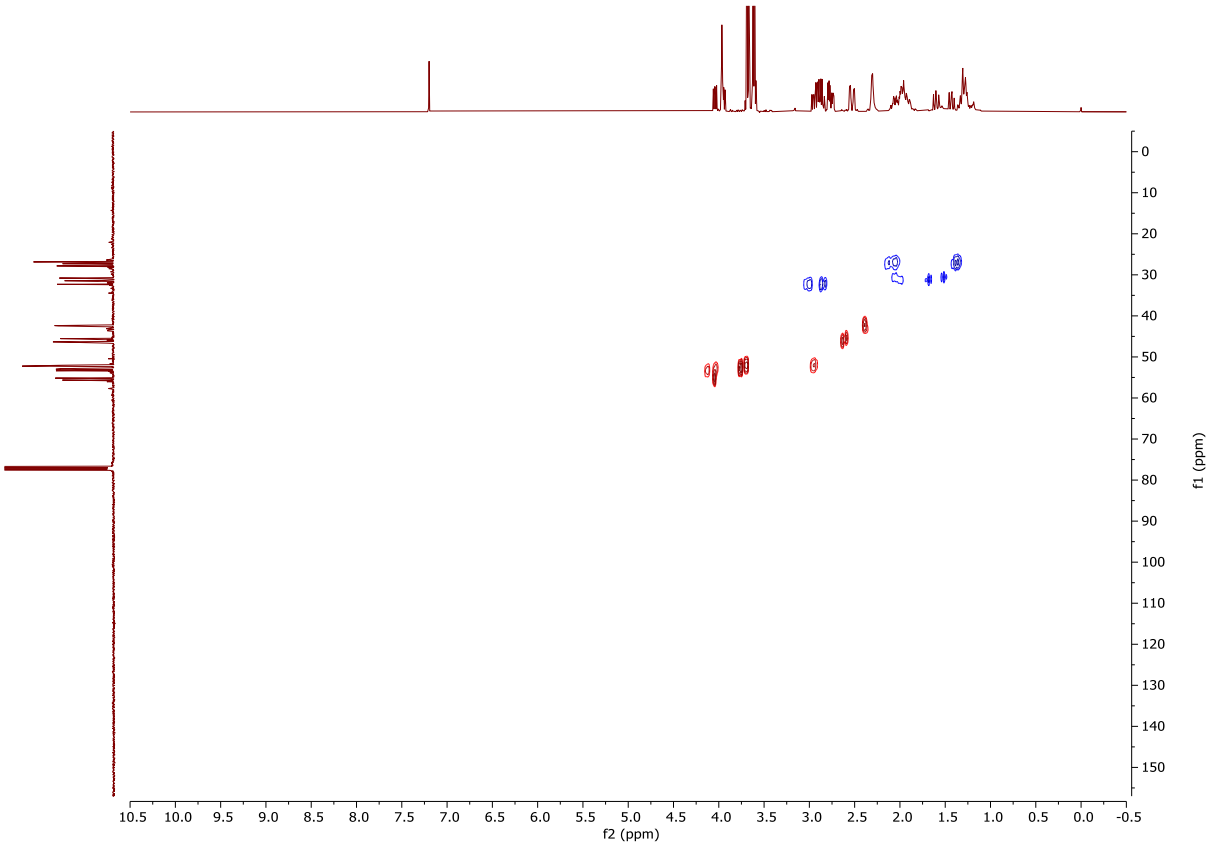
^{1}H-^{1}H NOESY



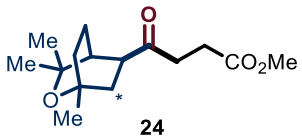
^{1}H-^{13}C HSQC



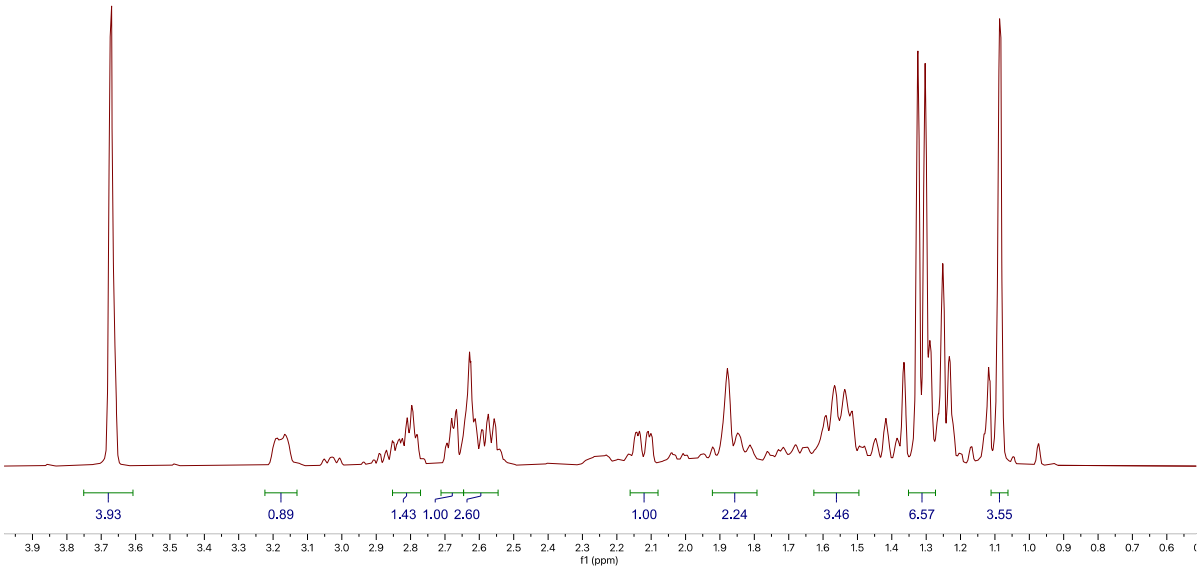
^{1}H-^{13}C HMBC



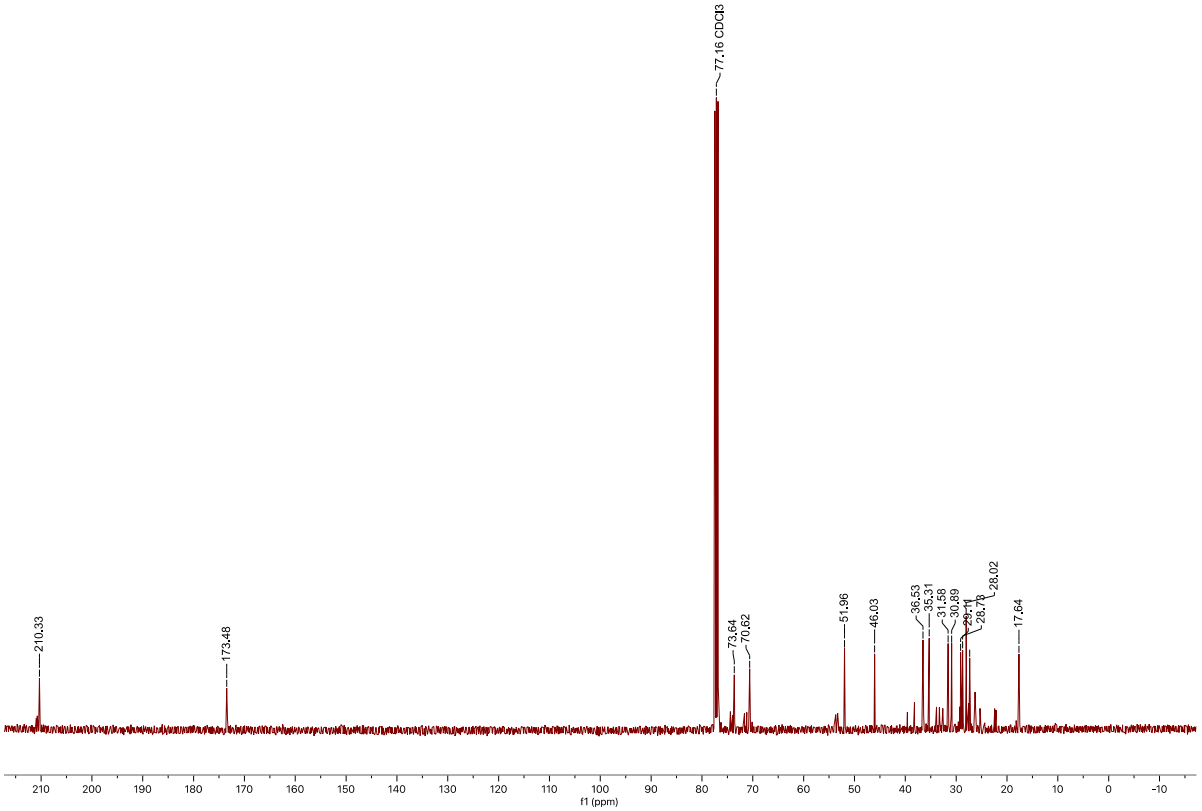
^{1}H NMR (400 MHz, $CDCl_3$)



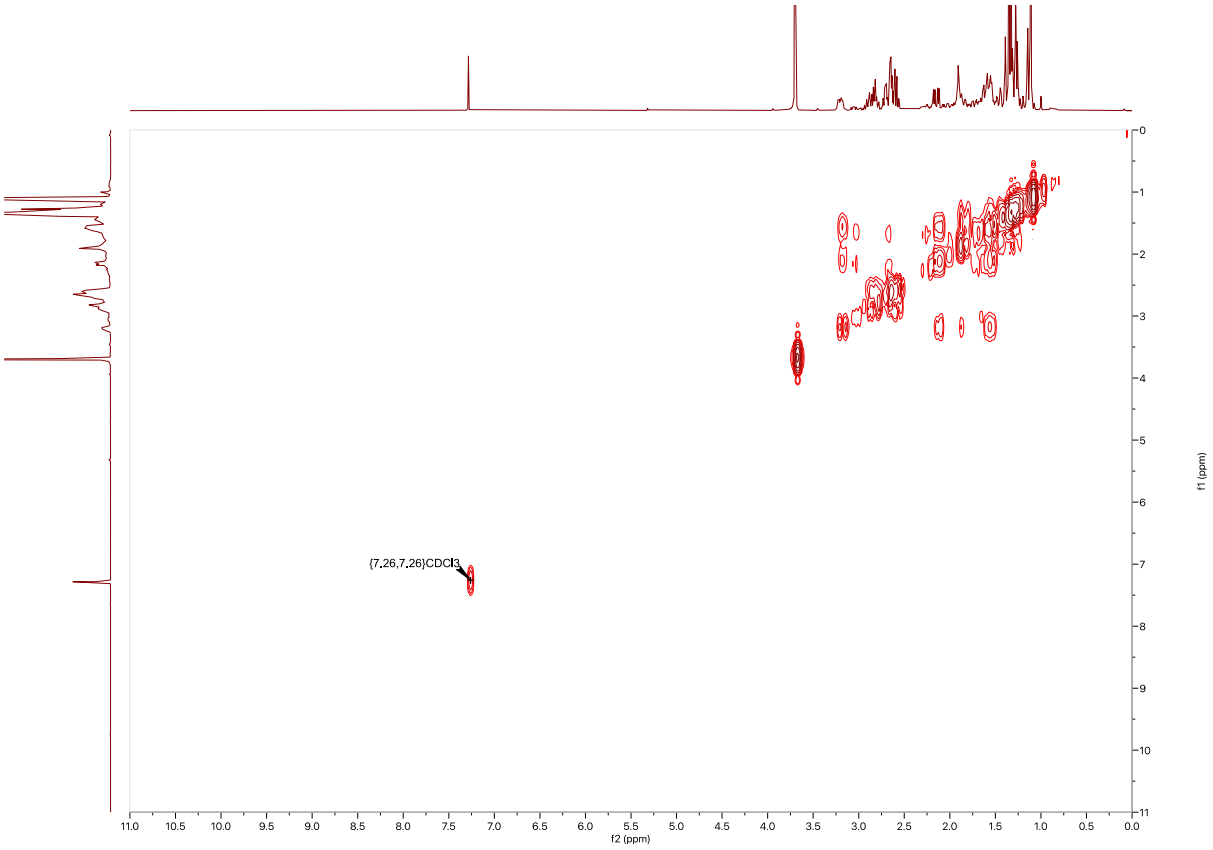
24



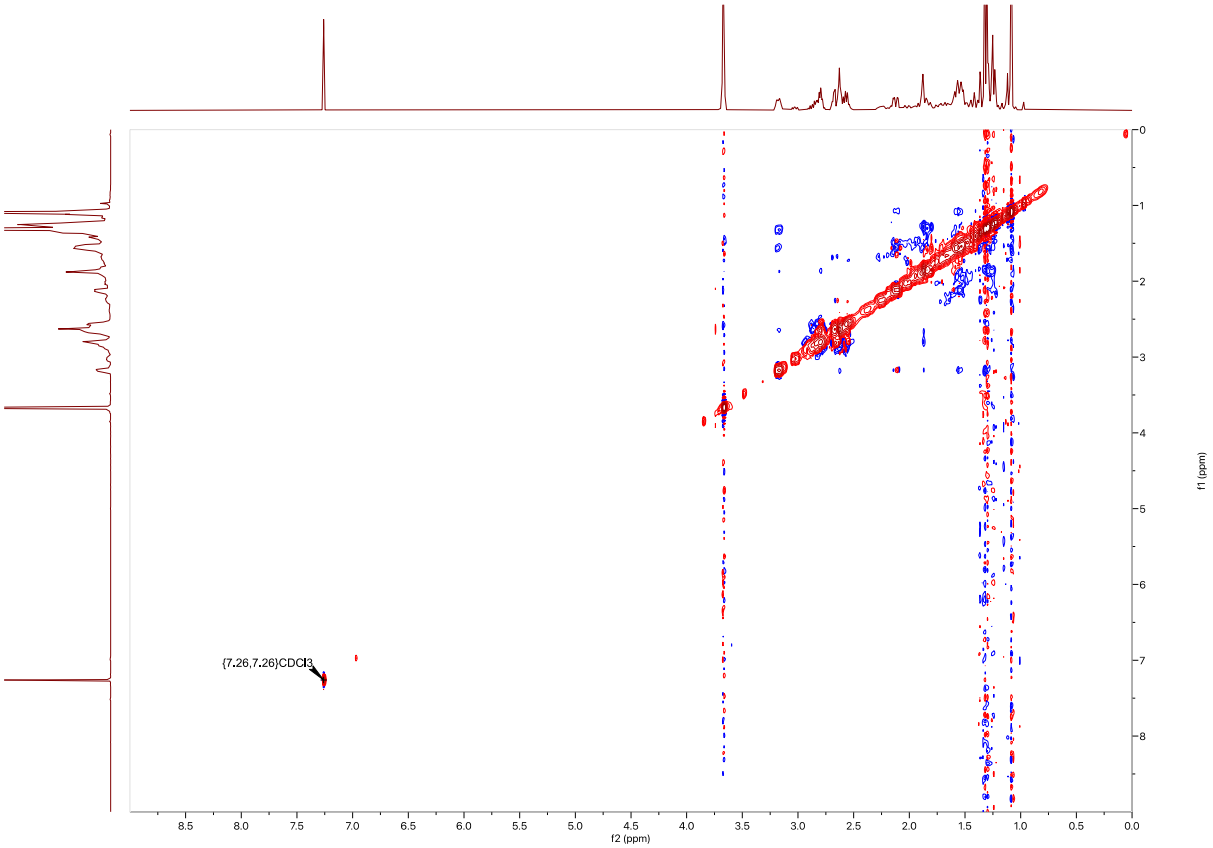
^{13}C NMR (101 MHz, $CDCl_3$)



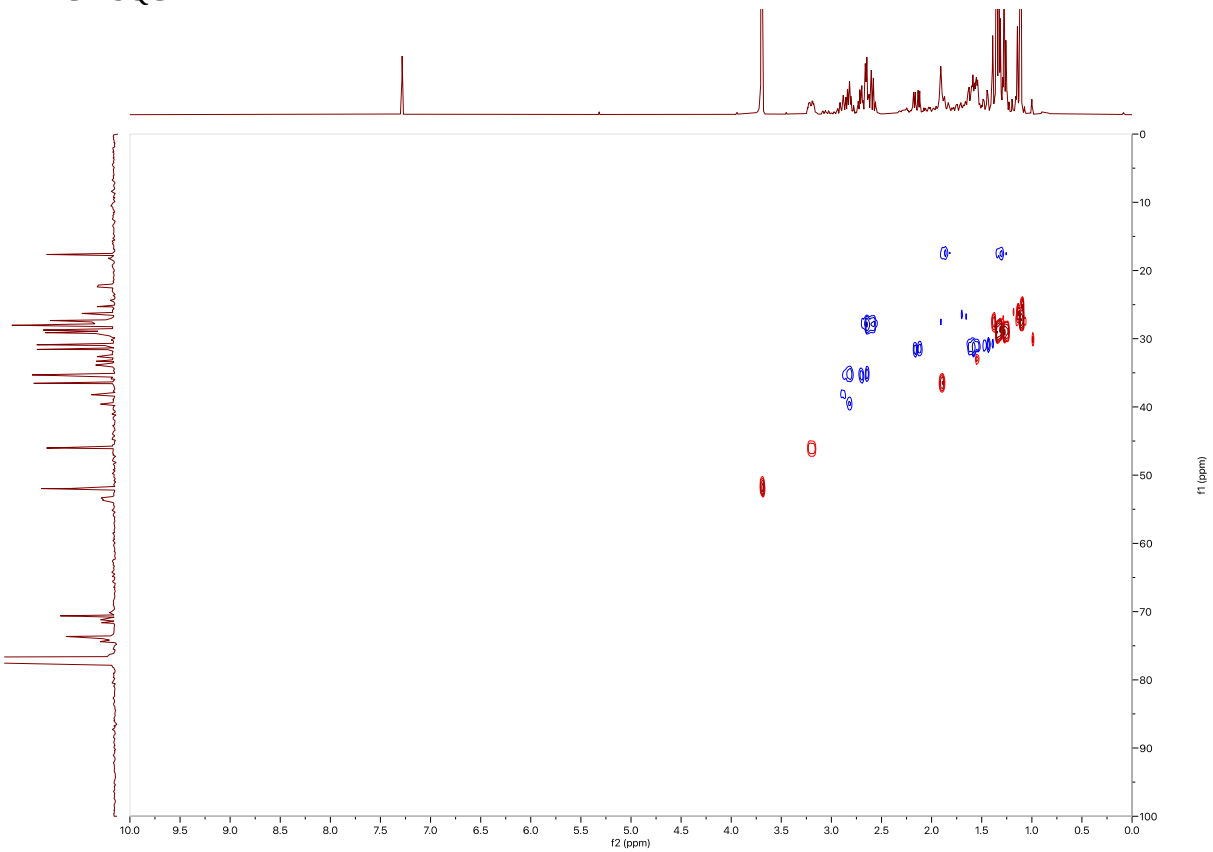
^{1}H-^{1}H COSY



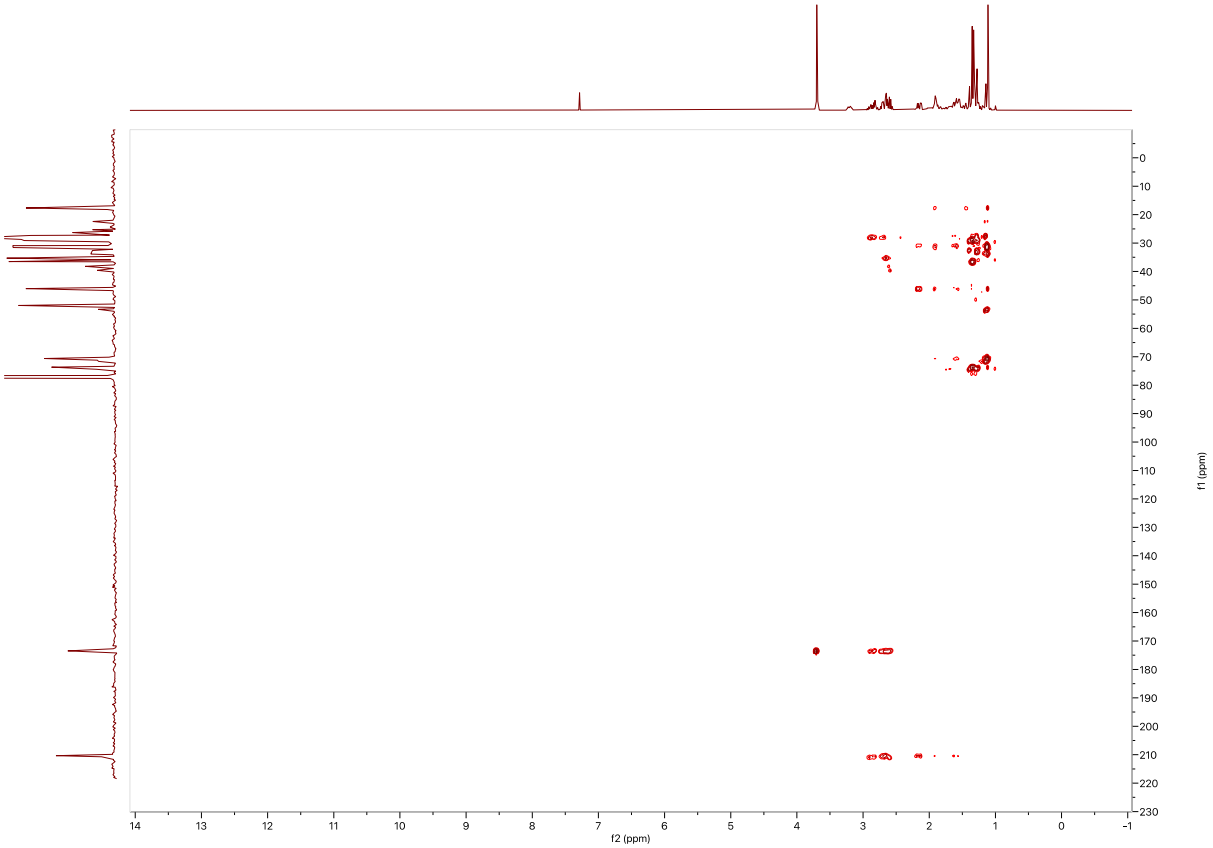
^{1}H-^{1}H NOESY



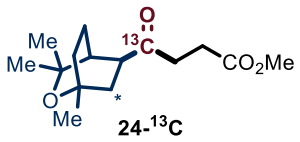
^{1}H-^{13}C HSQC



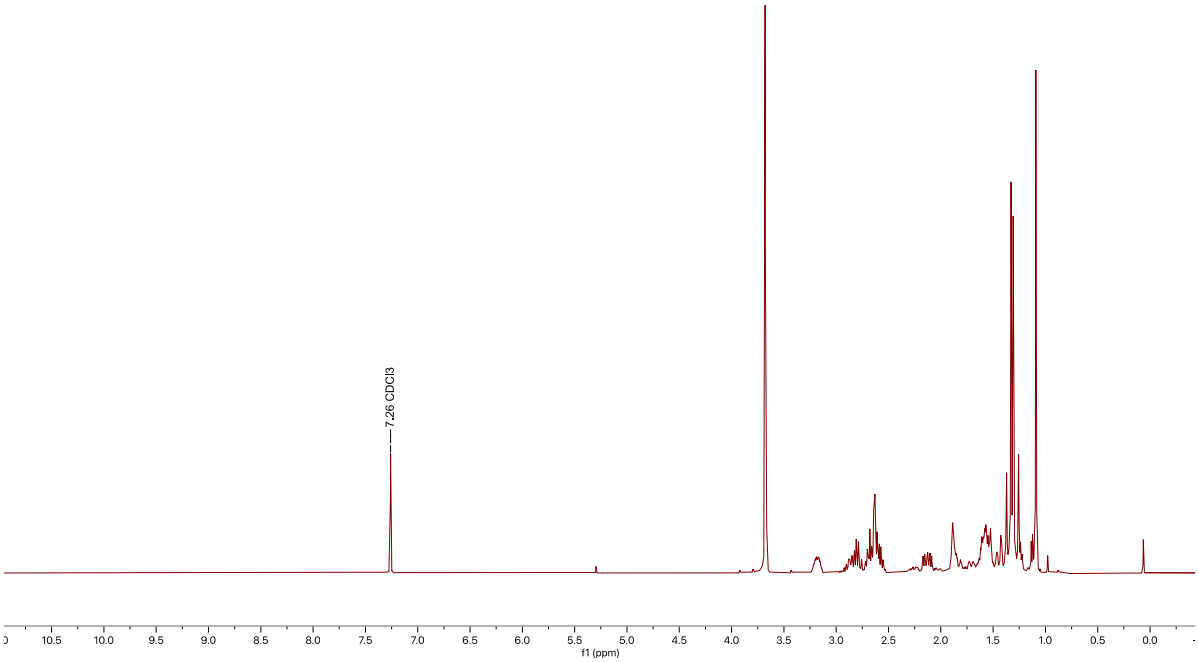
^{1}H-^{13}C HMBC

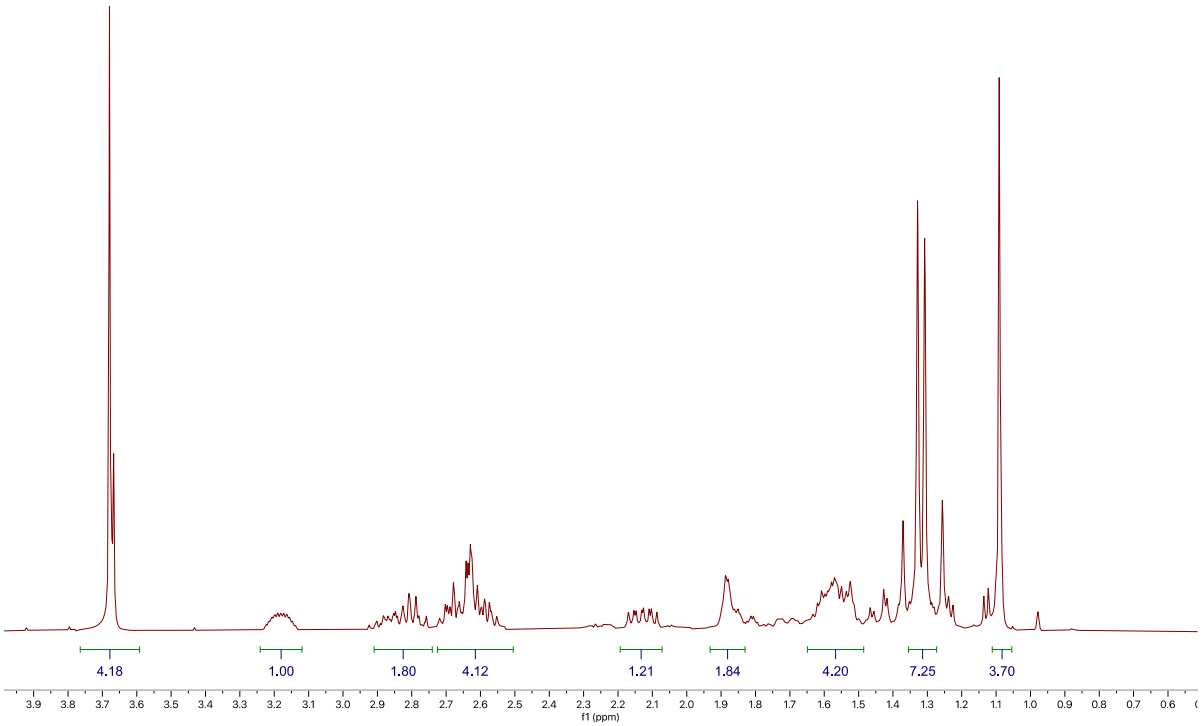


^{1}H NMR (400 MHz, $CDCl_3$)

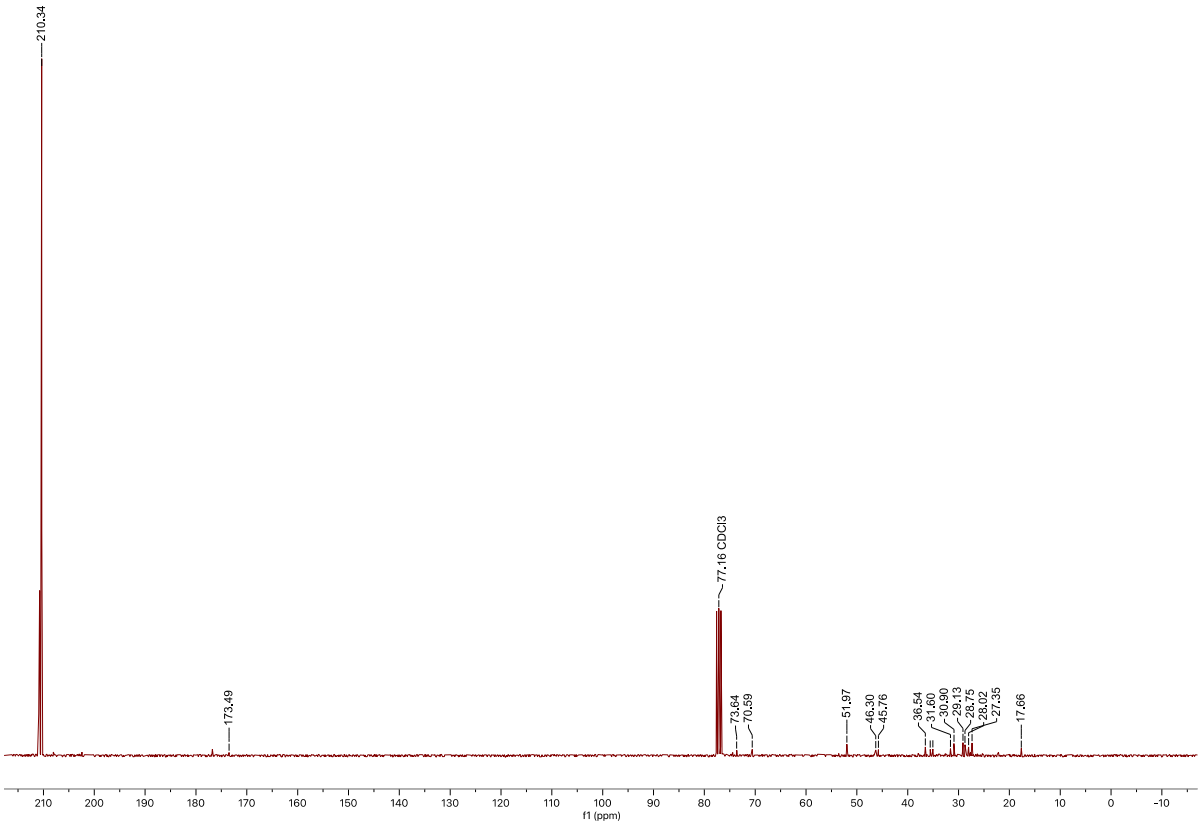


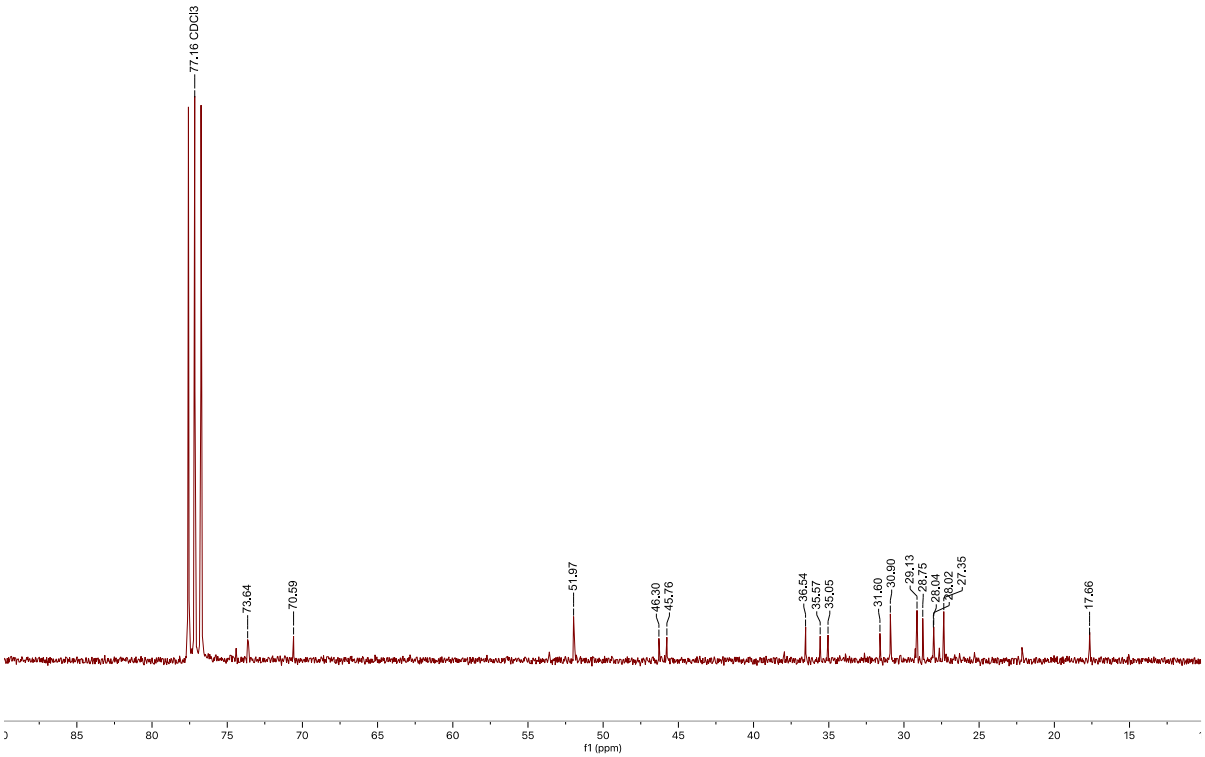
24-^{13}C



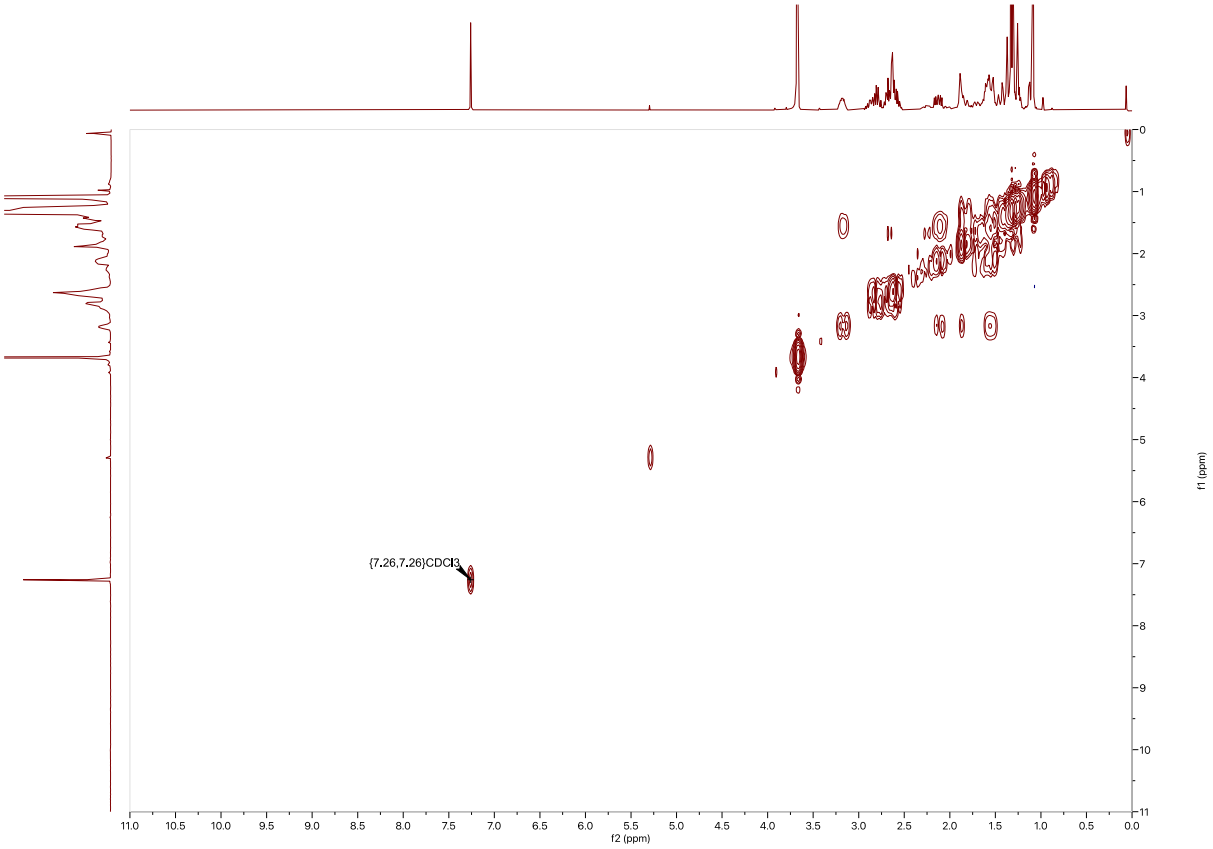


^{13}C NMR (101 MHz, $CDCl_3$)

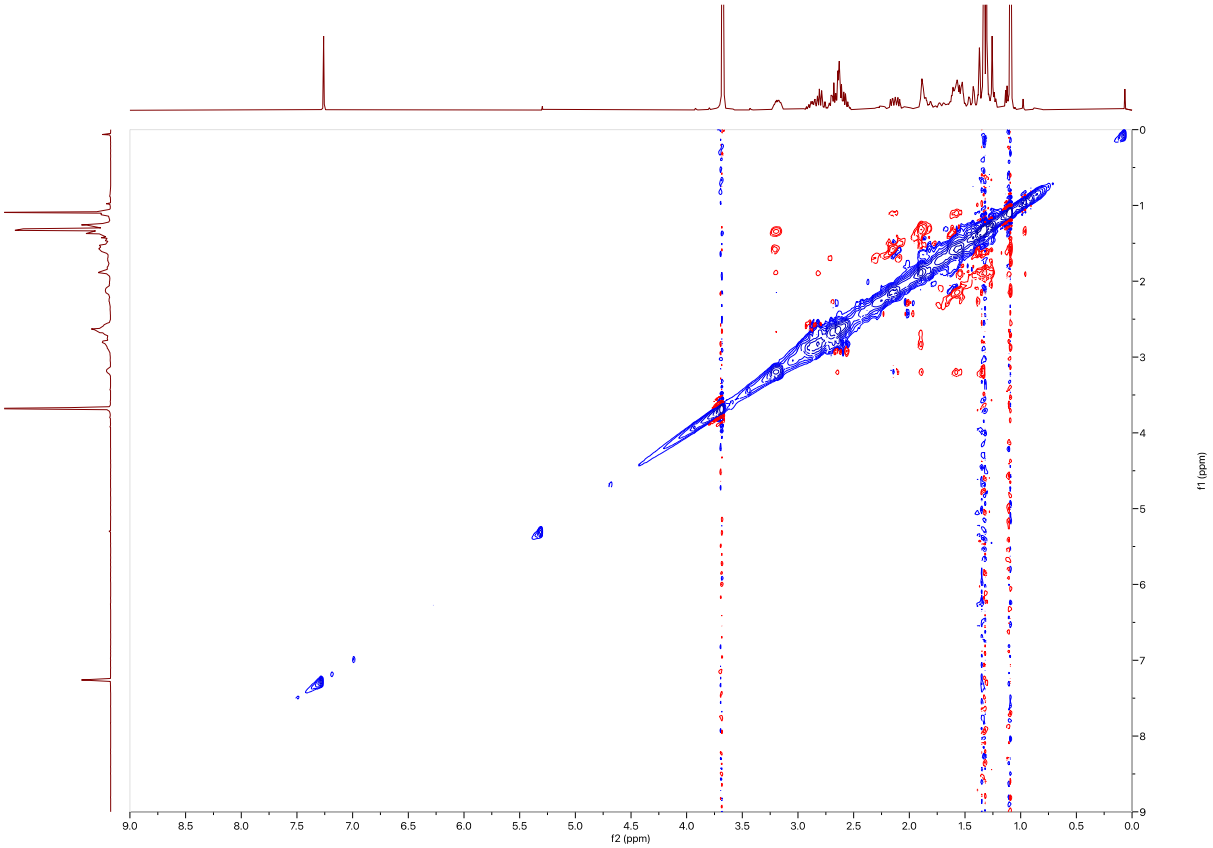



77.16 CDCl3
73.64
70.59
51.97
46.30
45.76
36.54
35.57
35.05
31.60
30.90
29.13
28.75
28.04
26.02
27.35
17.66
f1 (ppm)

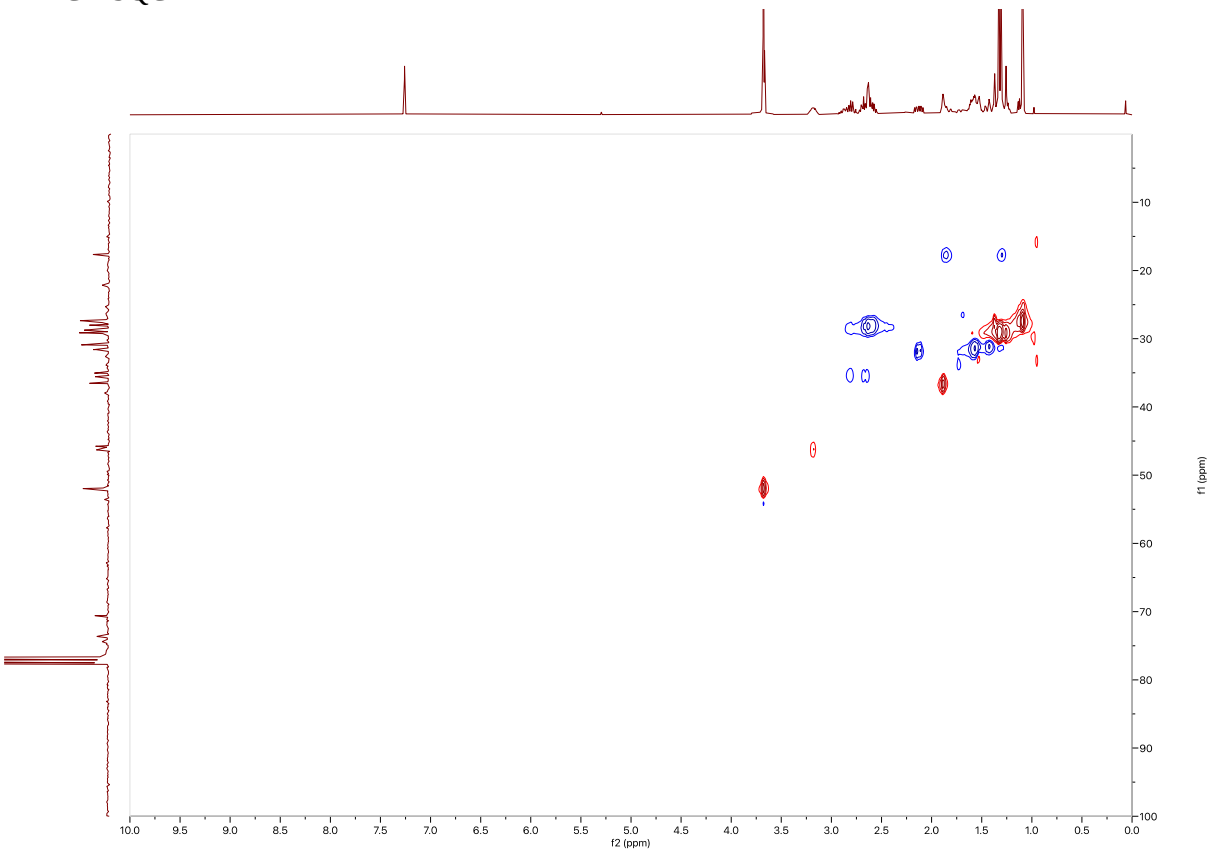
^{1}H-^{1}H COSY


{7.26,7.26}CDCl3
f2 (ppm)
f1 (ppm)

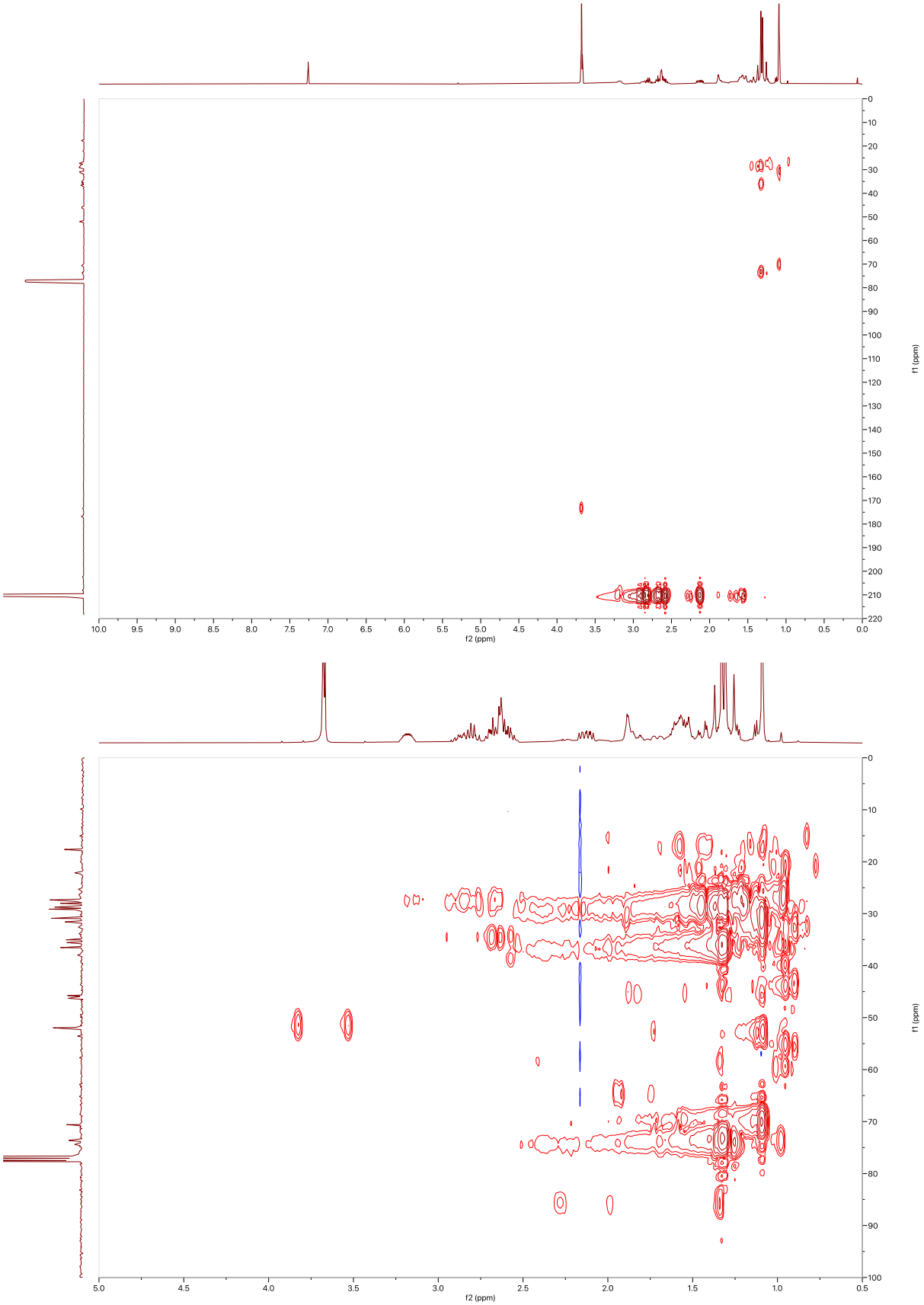
^{1}H-^{1}H NOESY



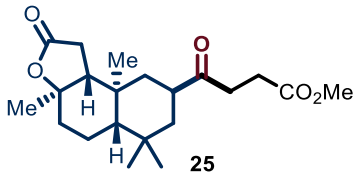
^{1}H-^{13}C HSQC



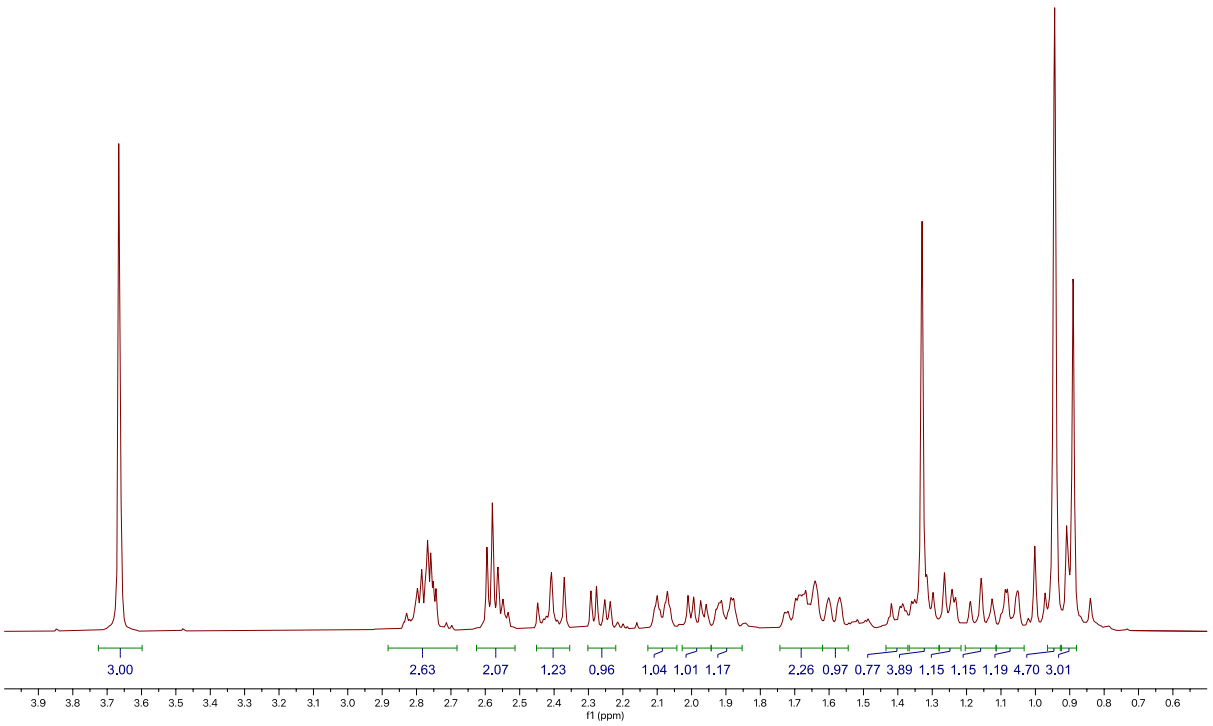
^{1}H-^{13}C HMBC



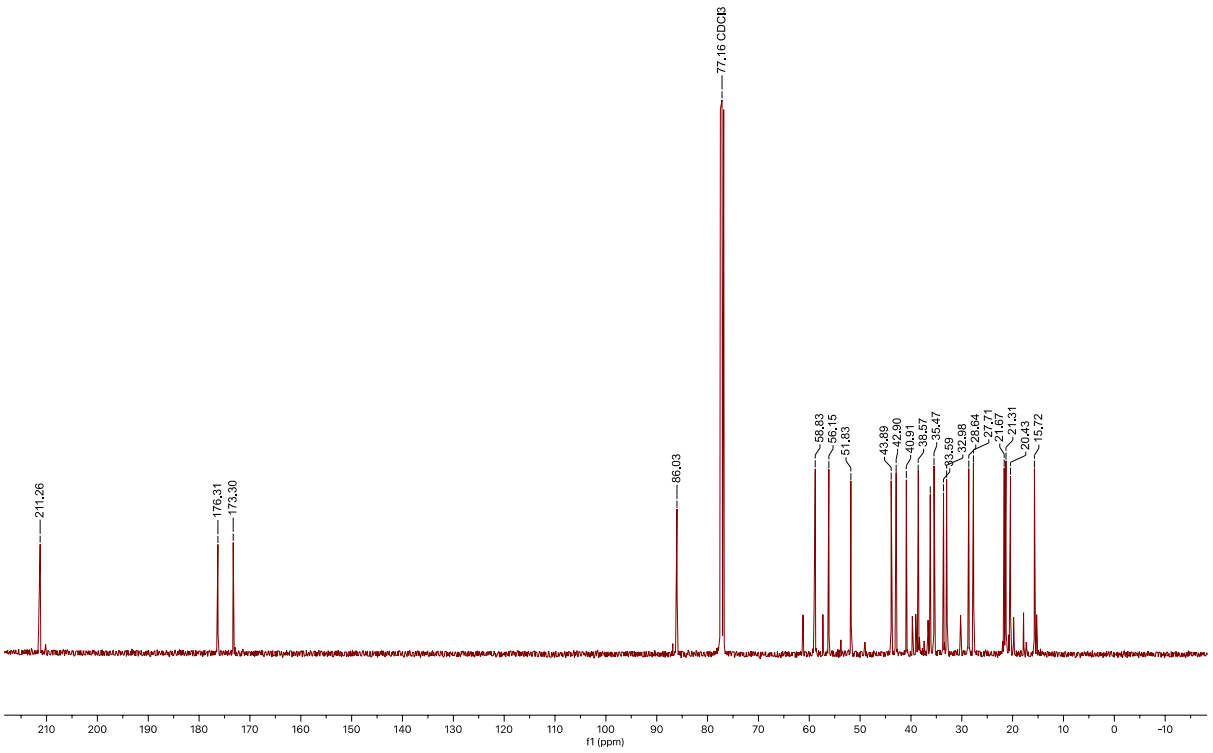
^{1}H NMR (400 MHz, $CDCl_3$)



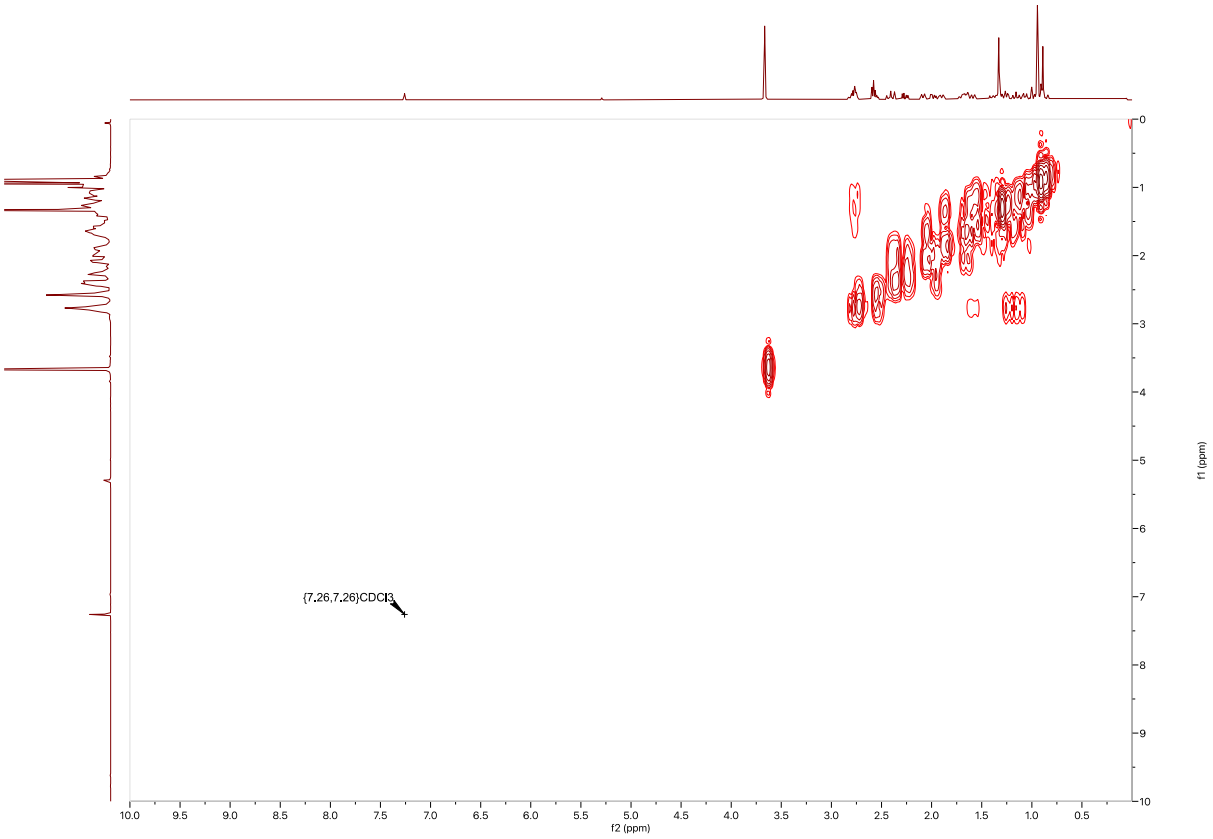
25



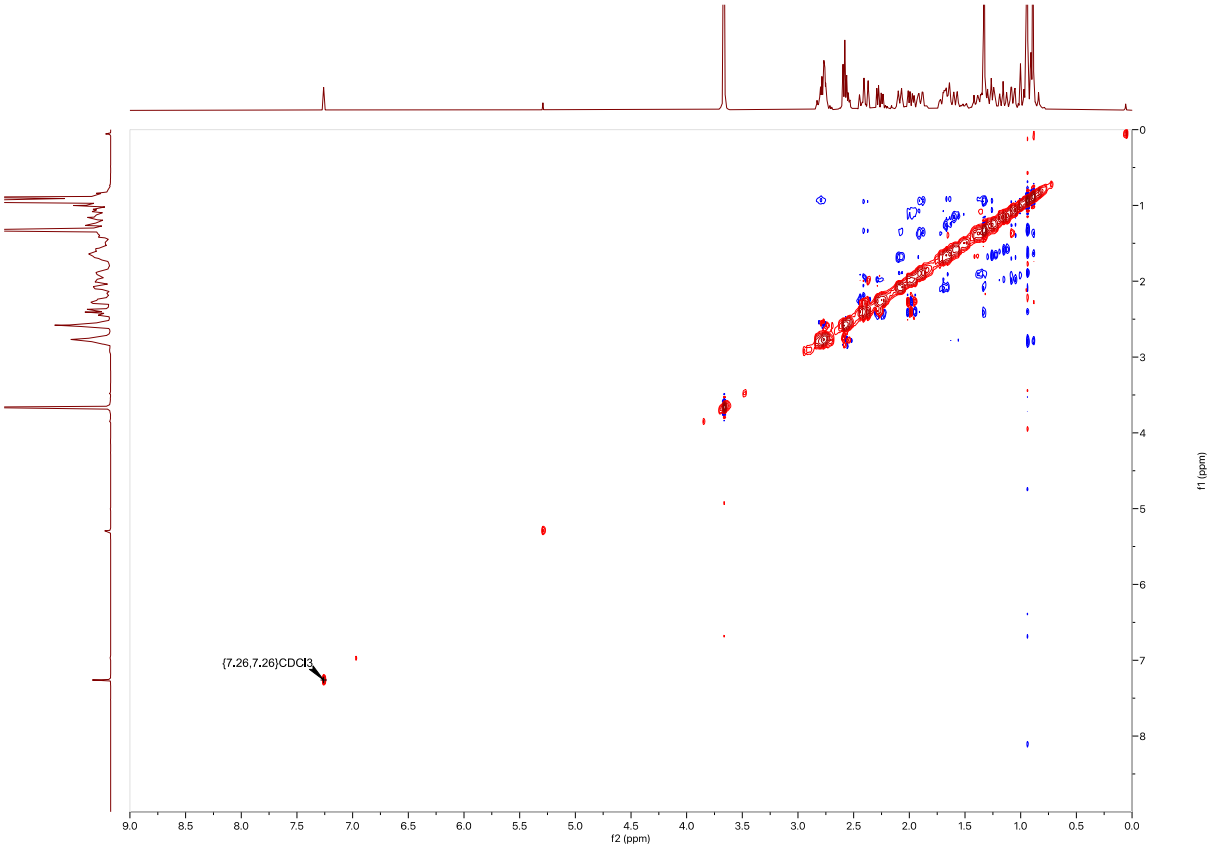
^{13}C NMR (101 MHz, $CDCl_3$)



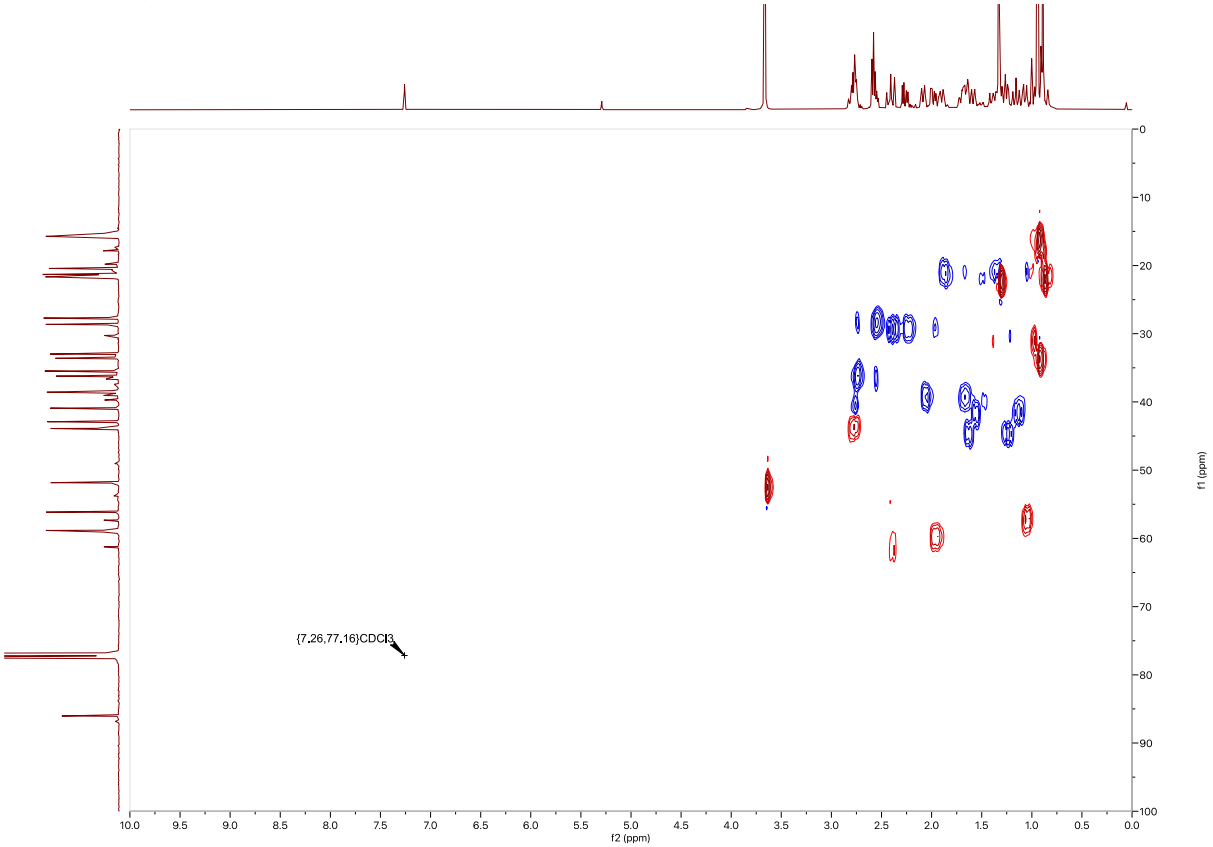
^{1}H-^{1}H COSY



^{1}H-^{1}H NOESY

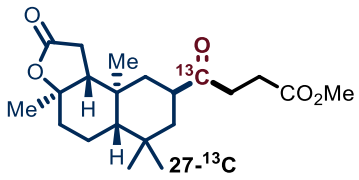


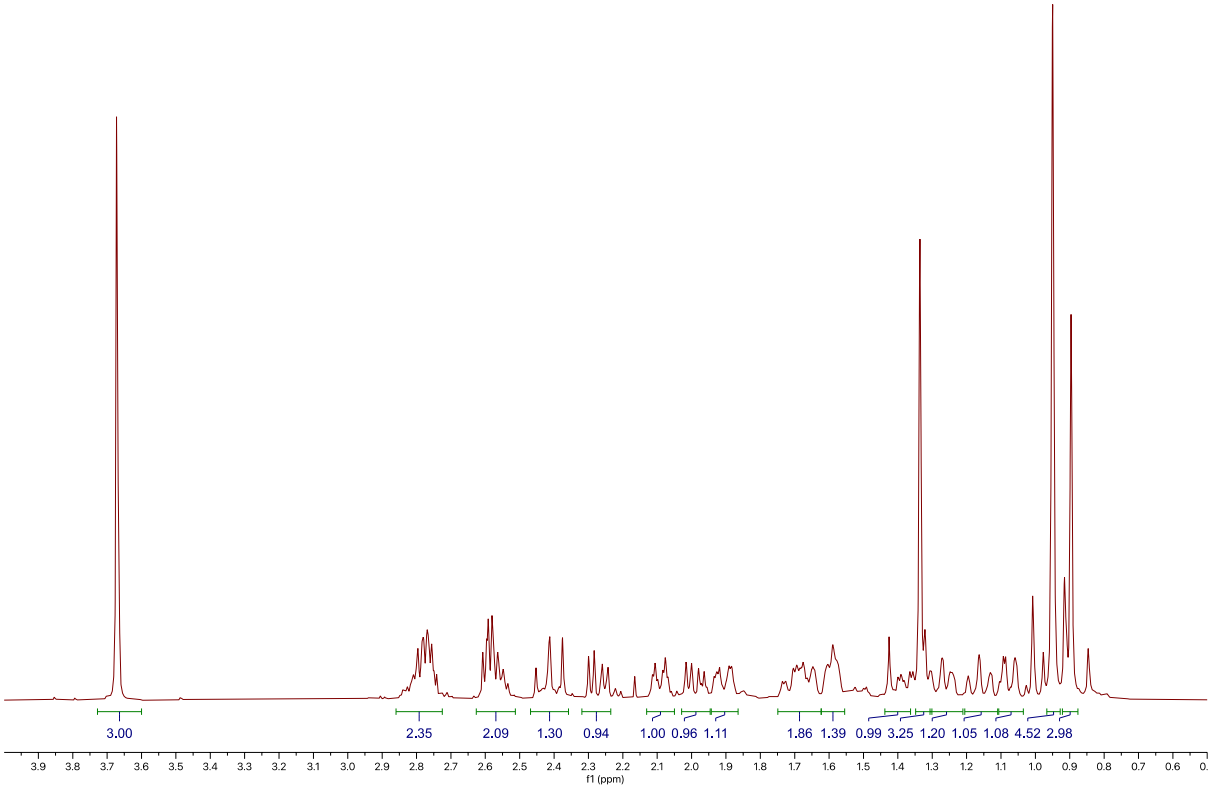
^{1}H-^{13}C HSQC



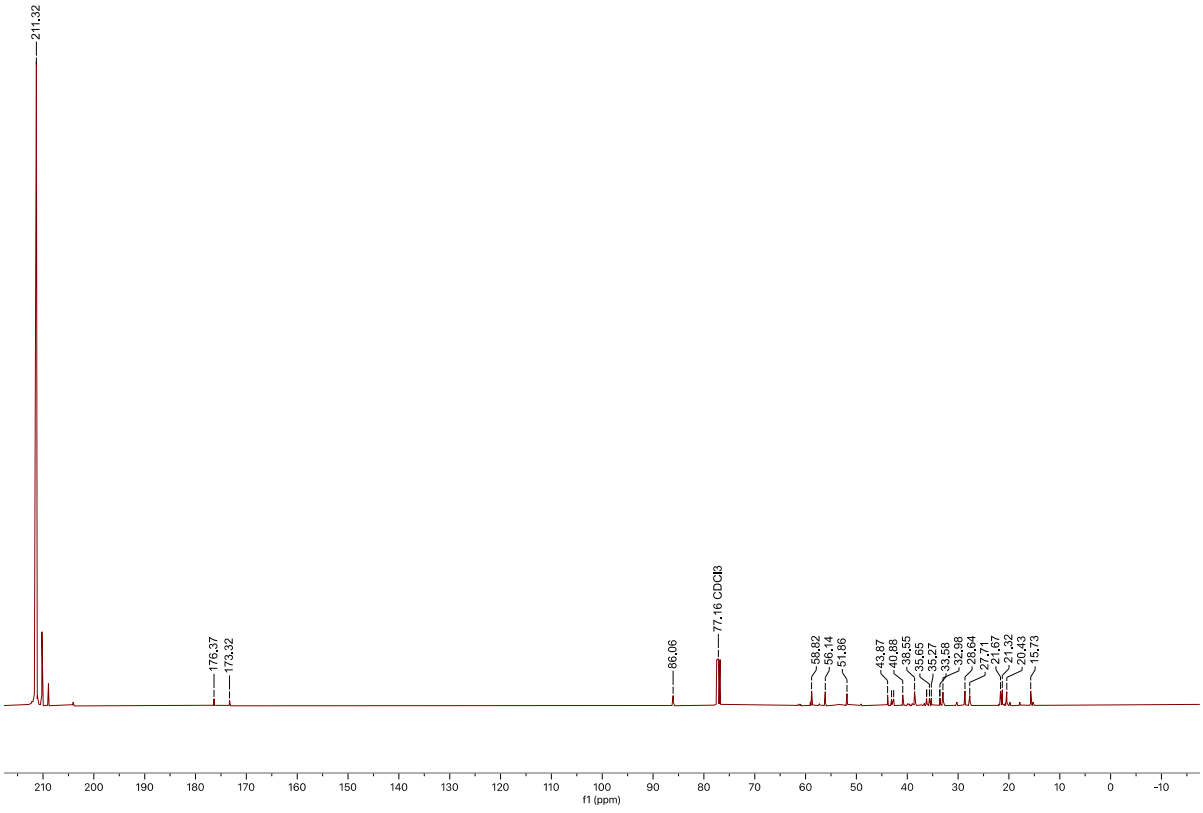
^{1}H-^{13}C HMBC

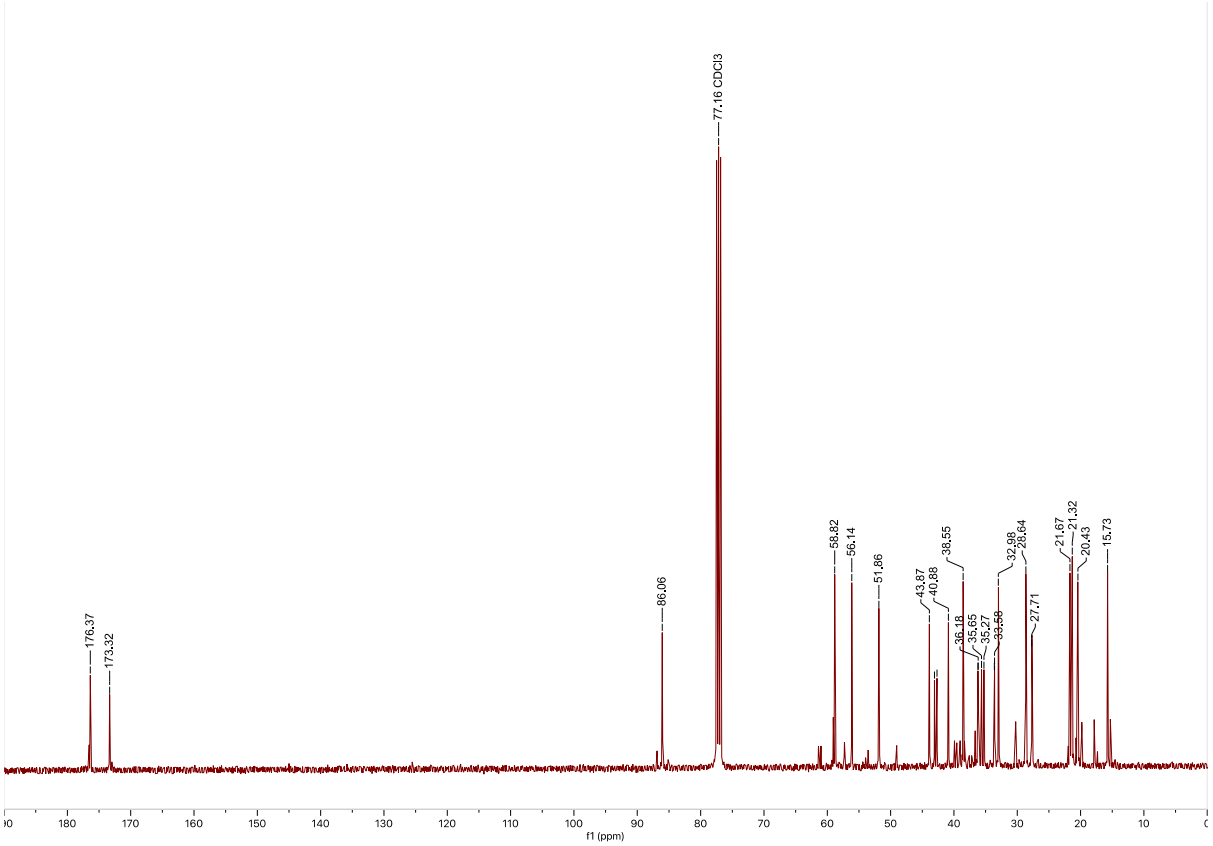
^{1}H NMR (400 MHz, $CDCl_3$)



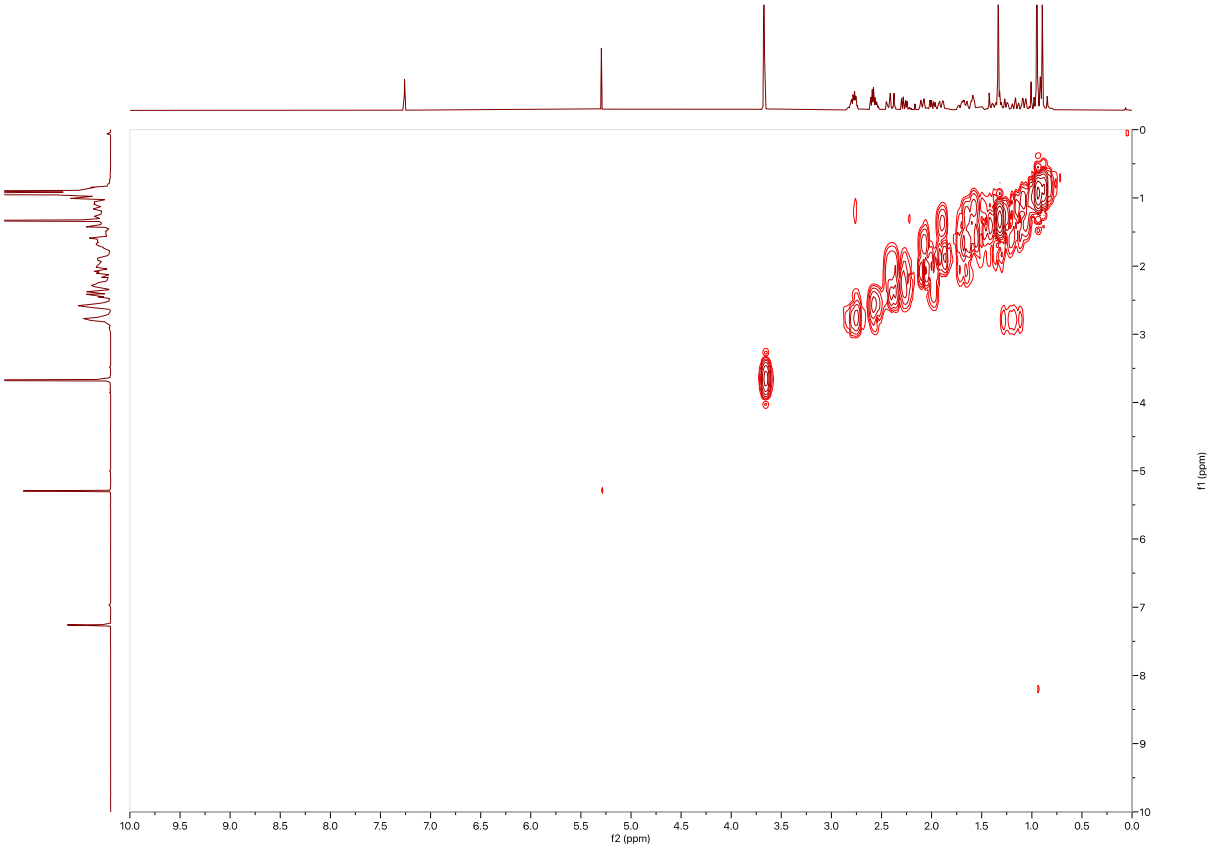


^{13}C NMR (101 MHz, $CDCl_3$)

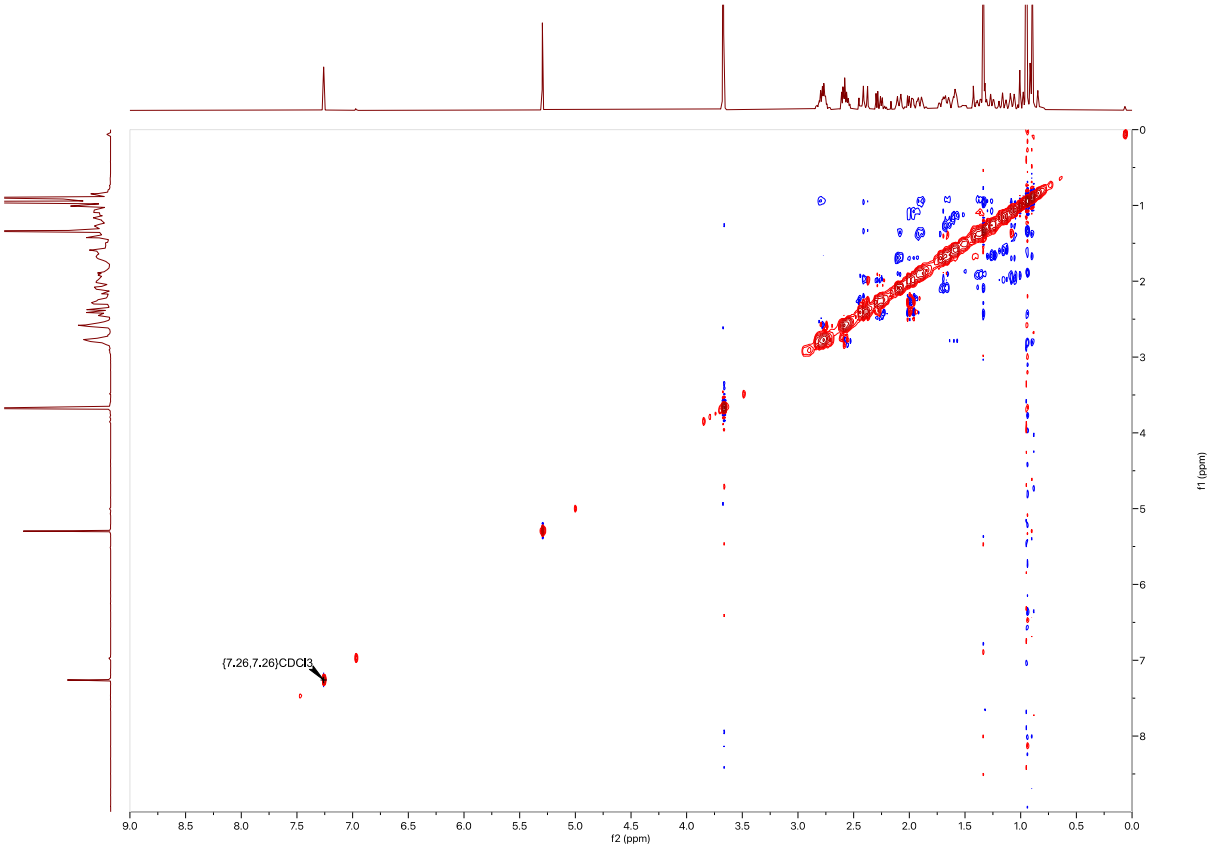



77.16 CDCl3
176.37
173.32
86.06
58.82
56.14
51.86
43.87
40.88
38.55
36.18
35.65
35.27
32.98
28.64
27.71
21.67
21.32
20.43
15.73
f1 (ppm)

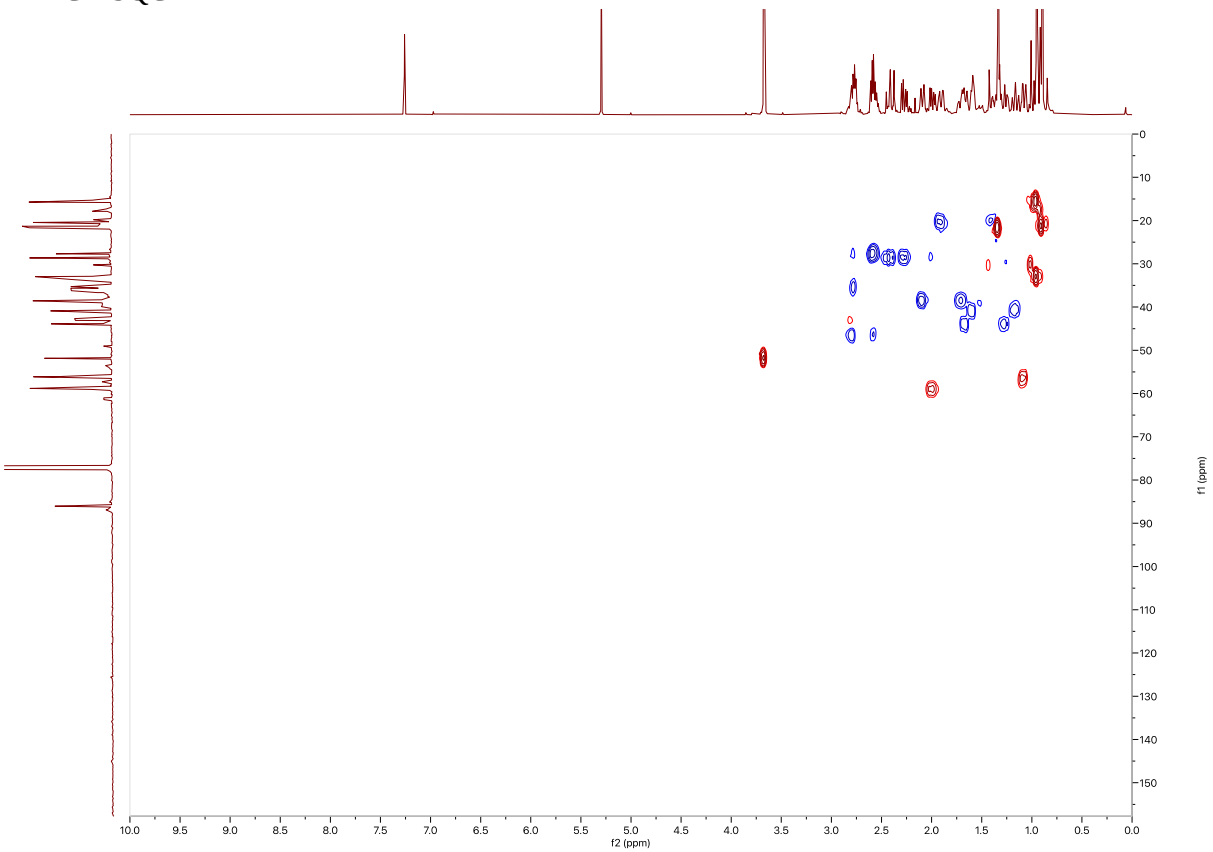
^{1}H-^{1}H COSY


f2 (ppm)
f1 (ppm)

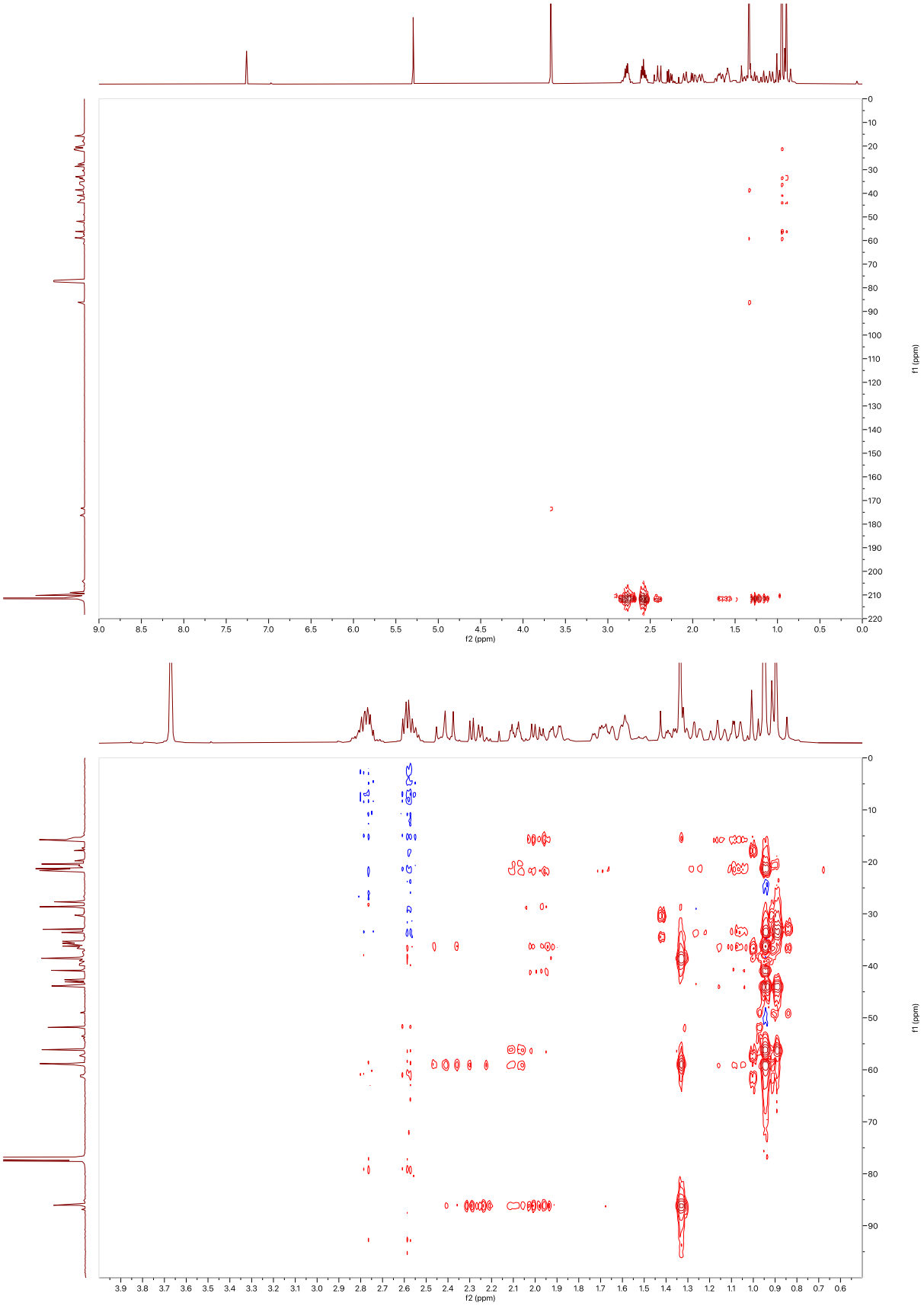
^{1}H-^{1}H NOESY



^{1}H-^{13}C HSQC

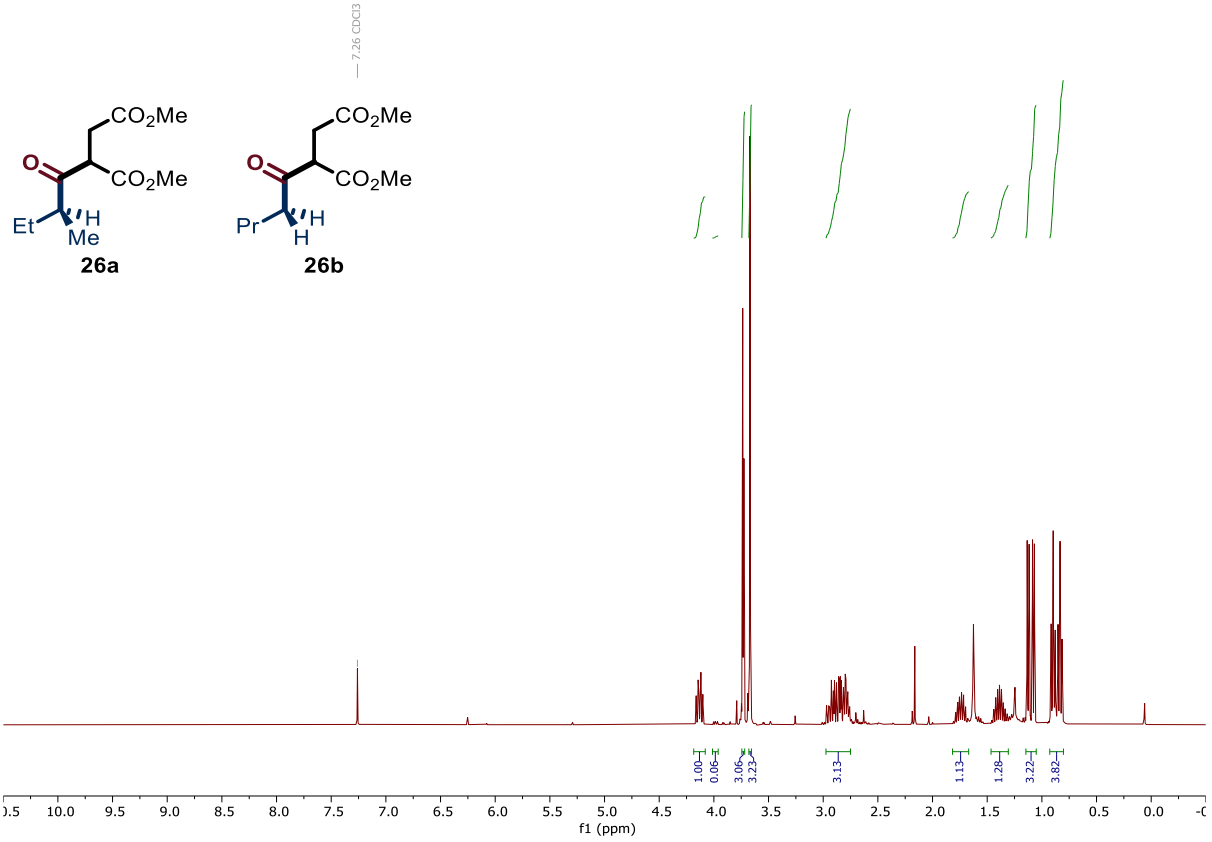


^{1}H-^{13}C HMBC

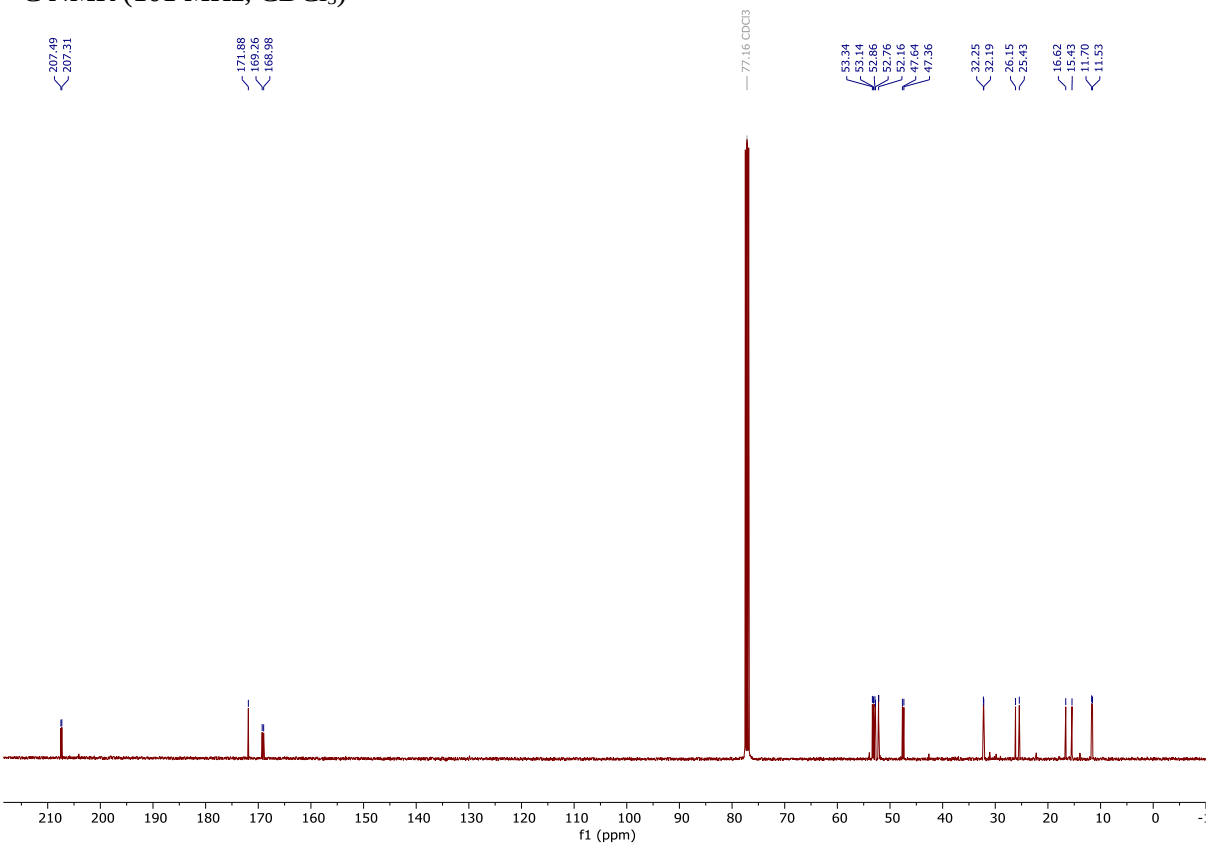


LIGHT ALKANES

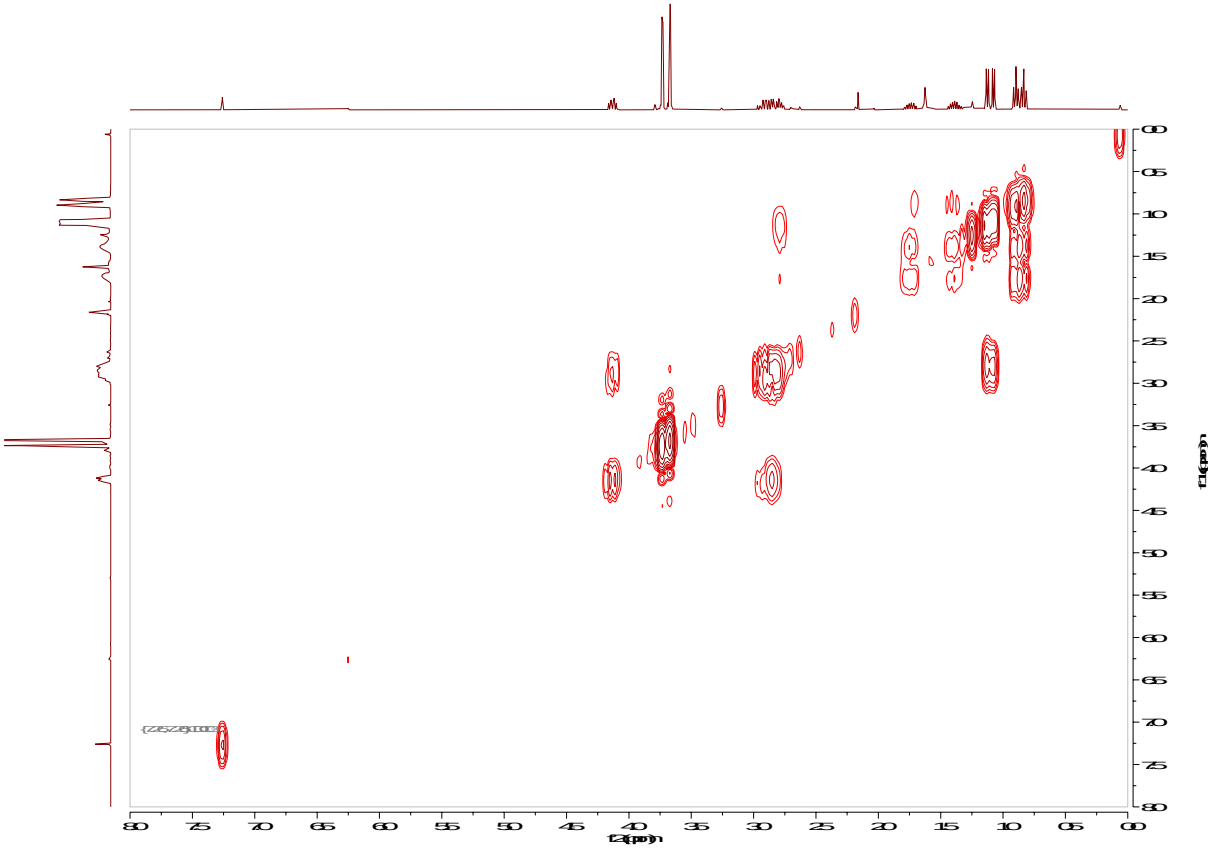
^{1}H NMR (400 MHz, $CDCl_3$)



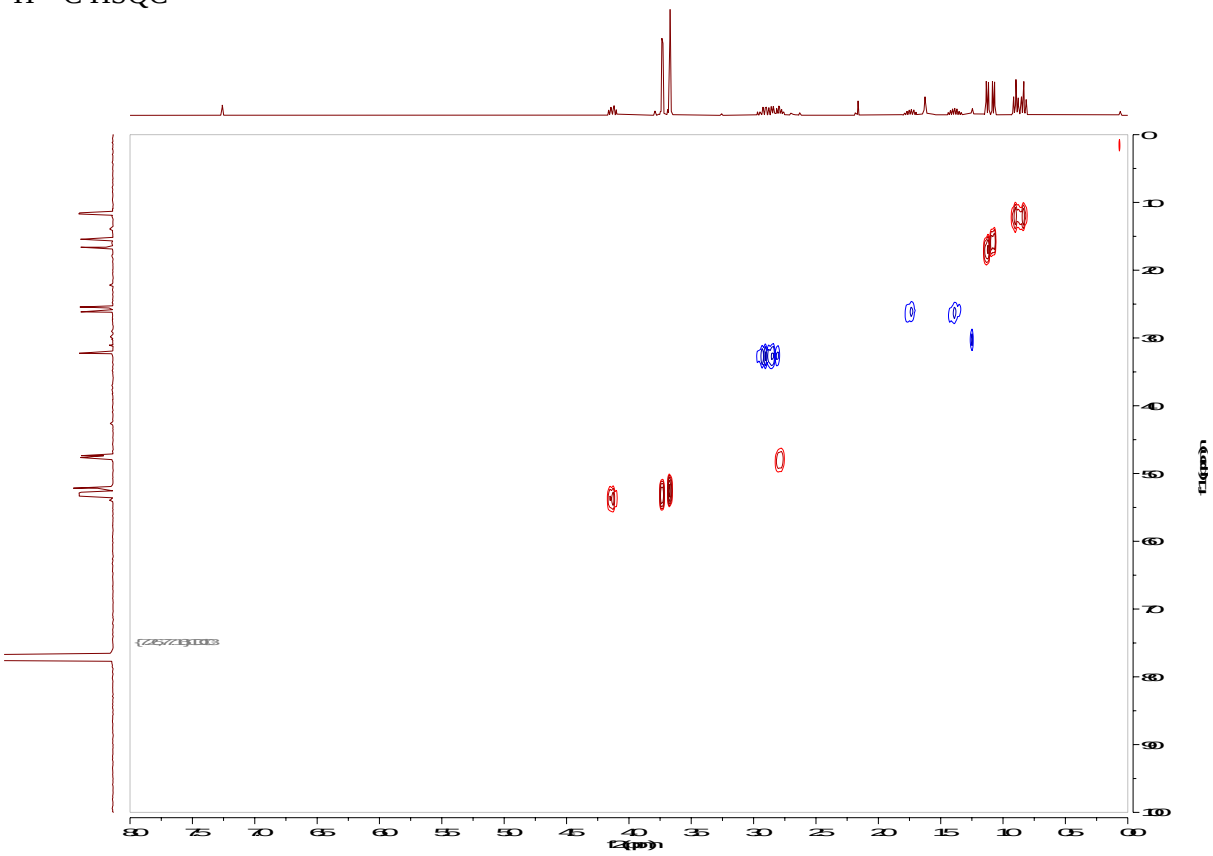
^{13}C NMR (101 MHz, $CDCl_3$)



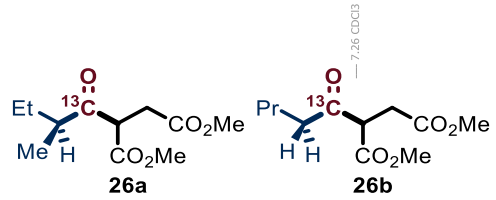
^{1}H-^{1}H COSY



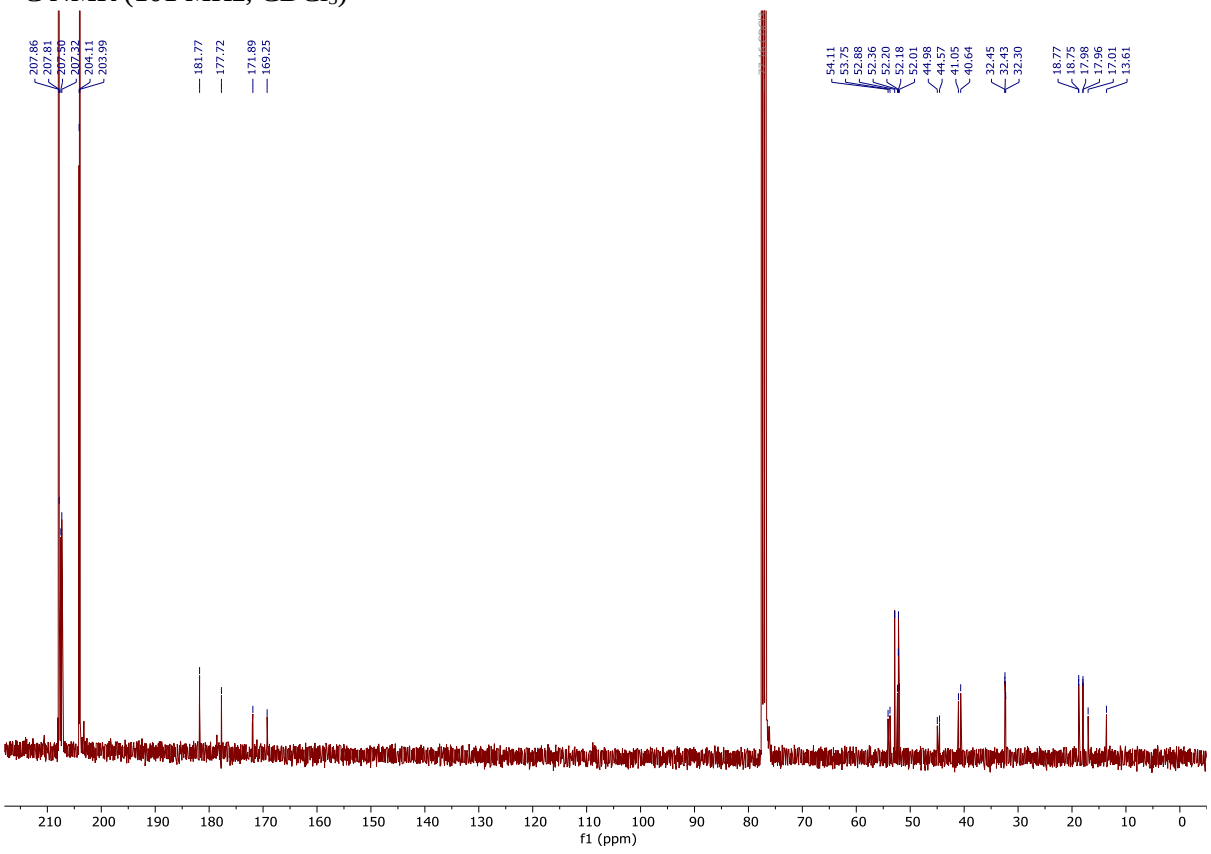
^{1}H-^{13}C HSQC



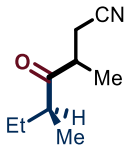
^{1}H NMR (400 MHz, $CDCl_3$)



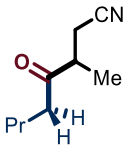
^{13}C NMR (101 MHz, $CDCl_3$)



^{1}H NMR (400 MHz, $CDCl_3$)

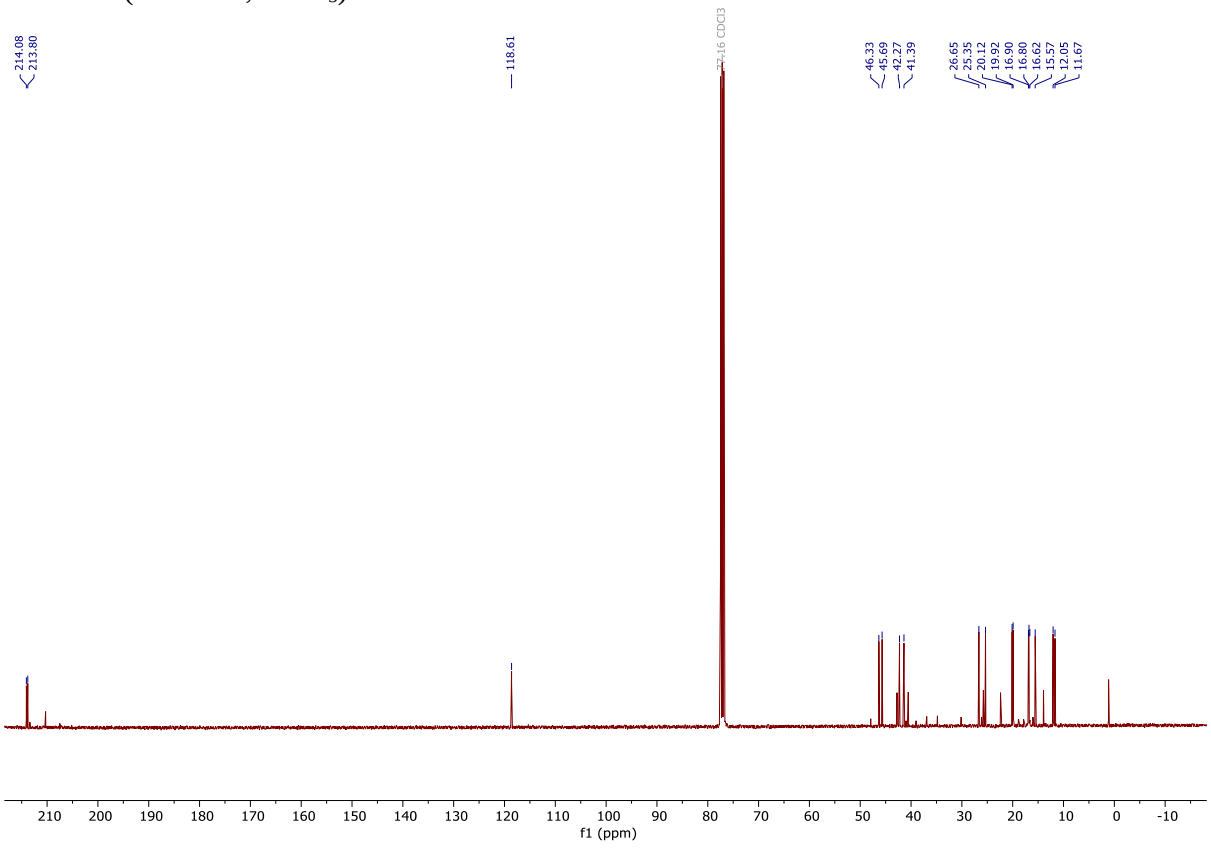


27a

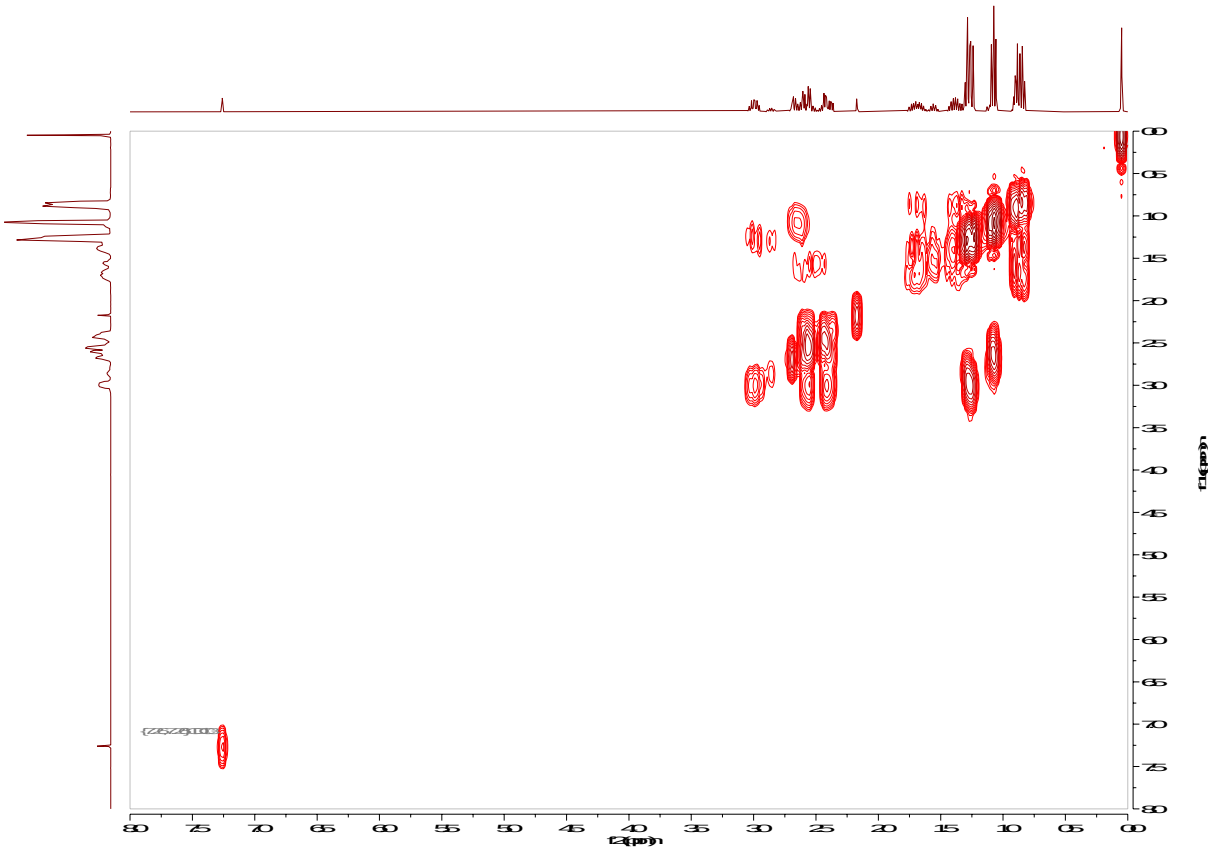


27b

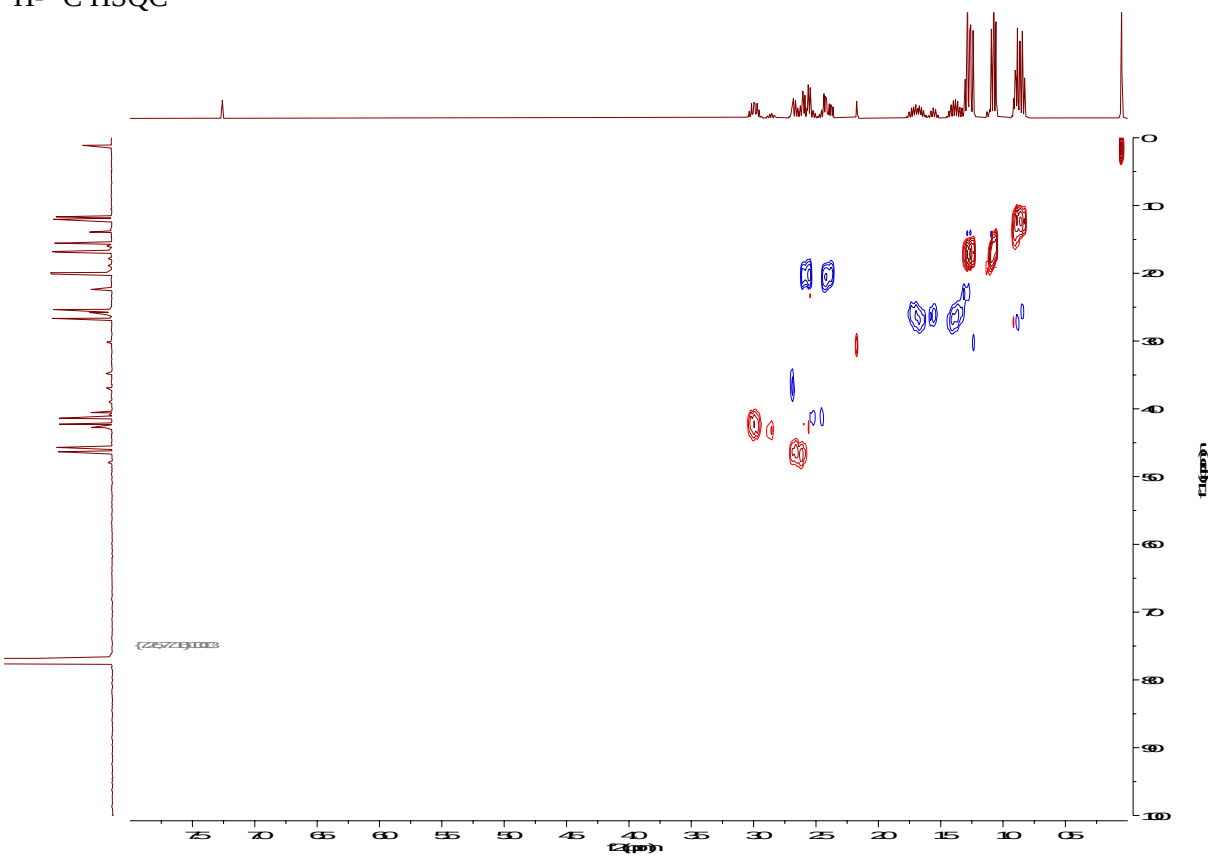
^{13}C NMR (101 MHz, $CDCl_3$)



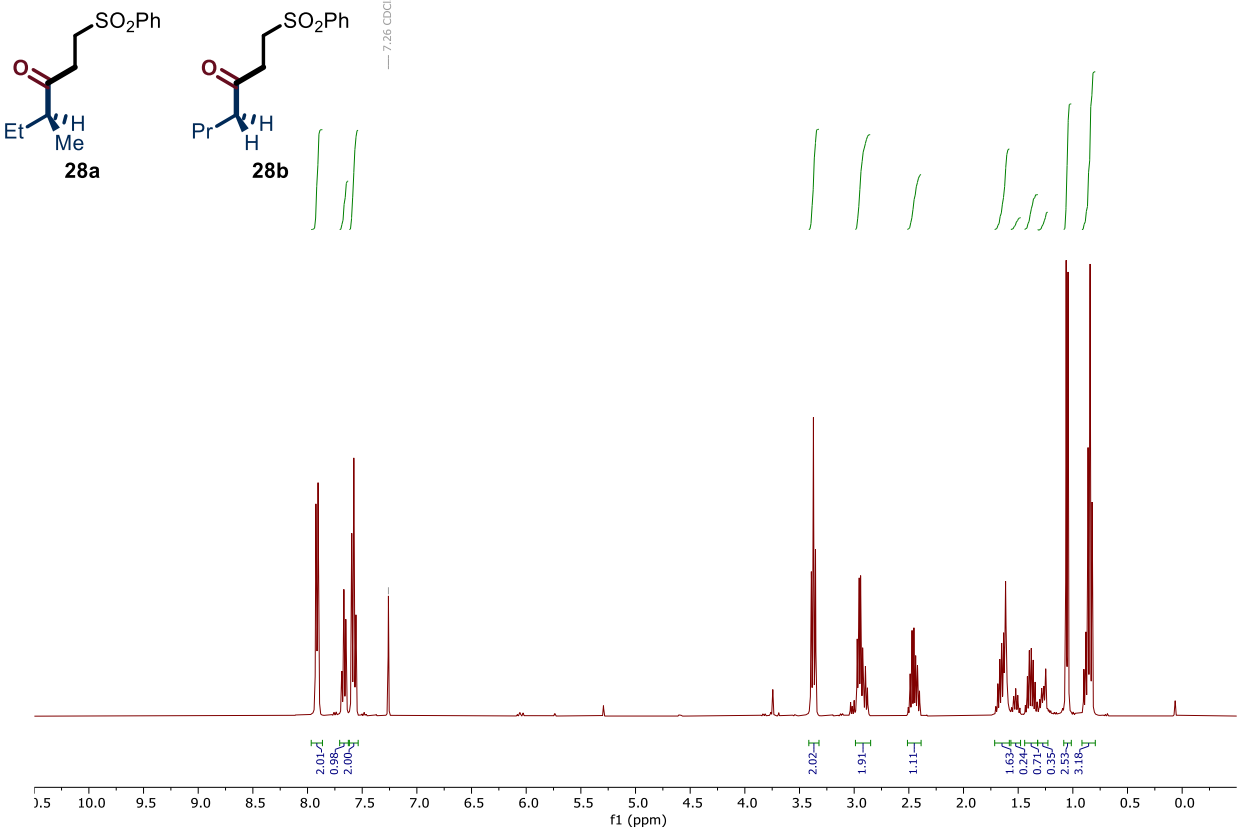
^{1}H-^{1}H COSY



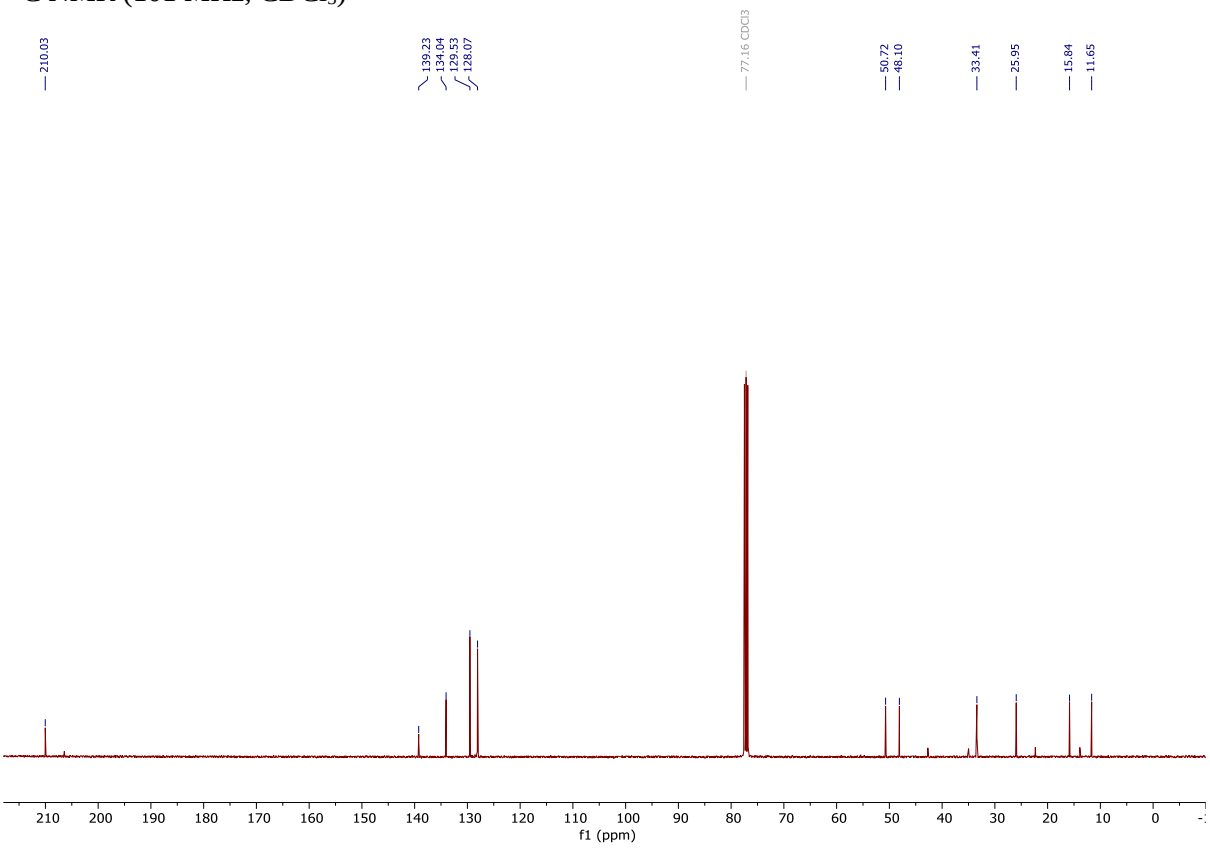
^{1}H-^{13}C HSQC



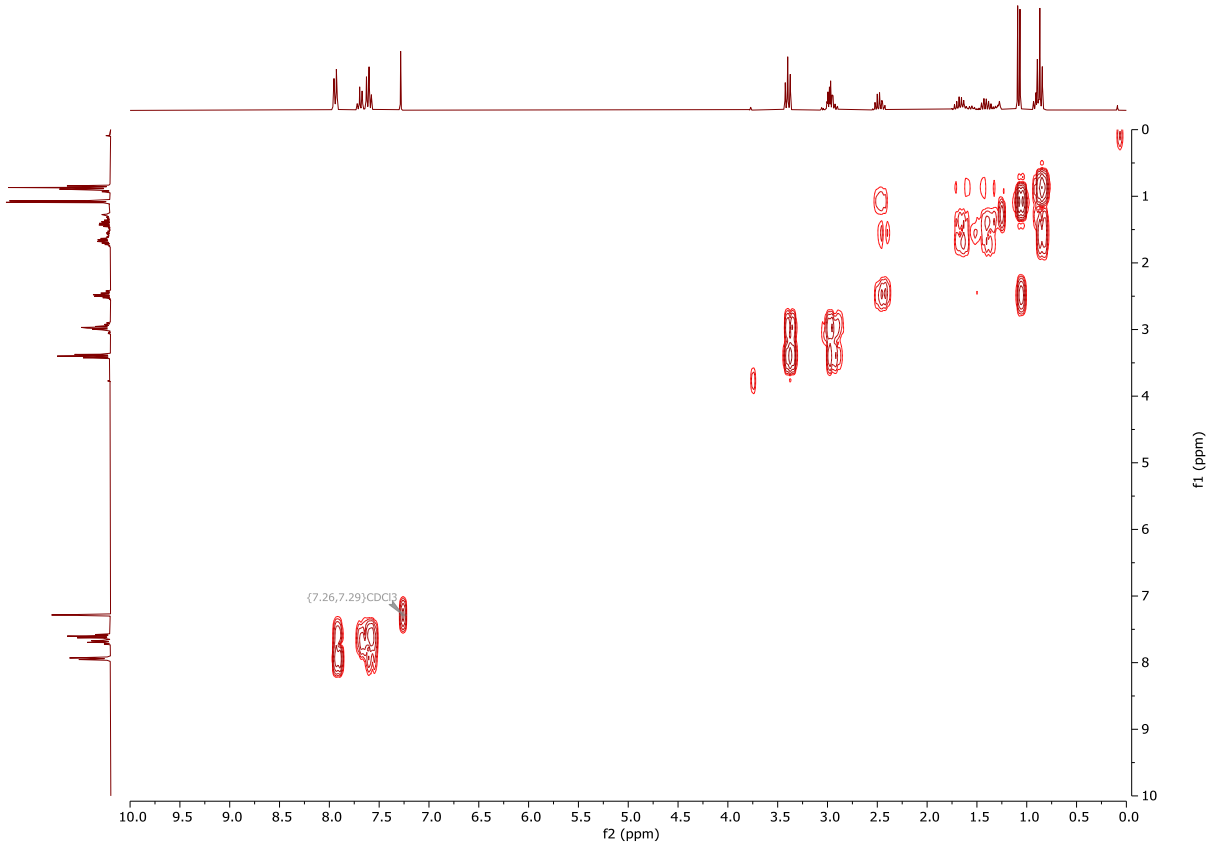
^{1}H NMR (400 MHz, $CDCl_3$)



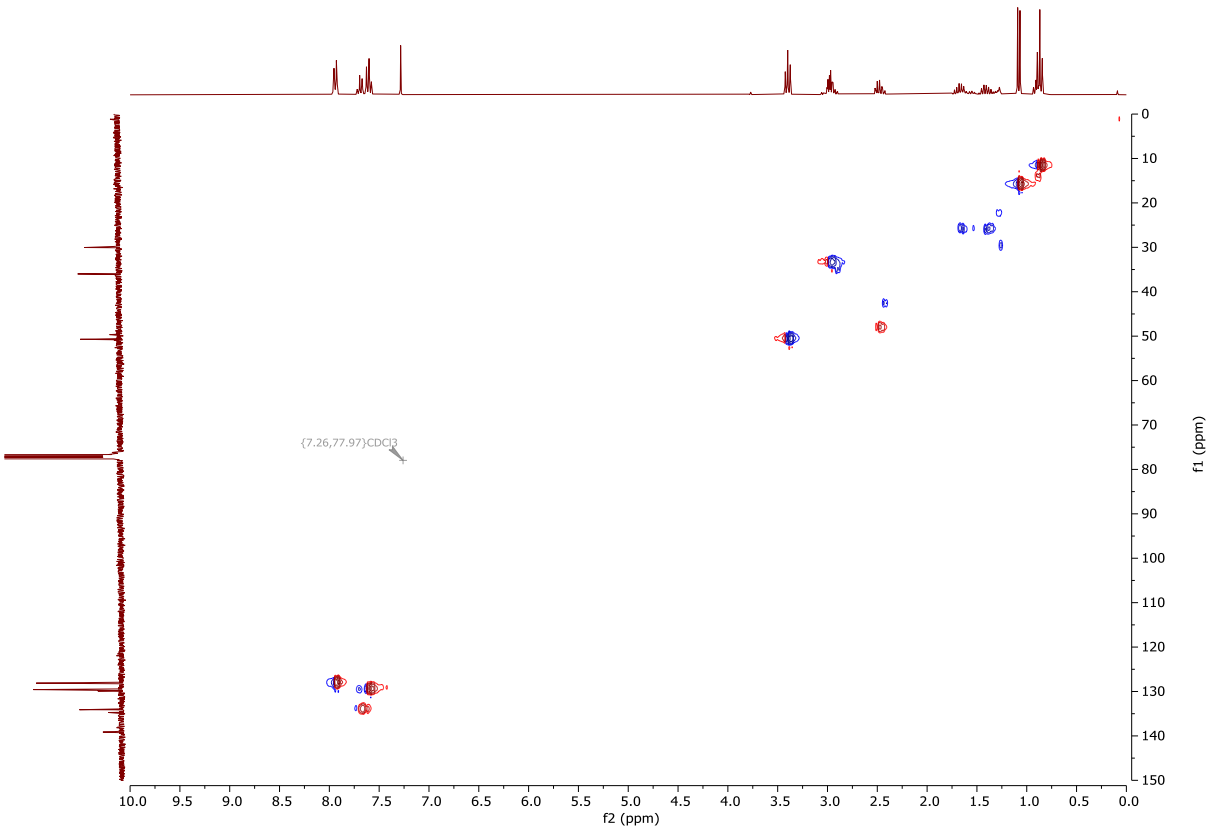
^{13}C NMR (101 MHz, $CDCl_3$)



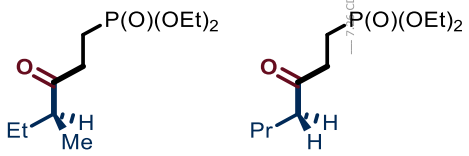
^{1}H-^{1}H COSY



^{1}H-^{13}C HSQC



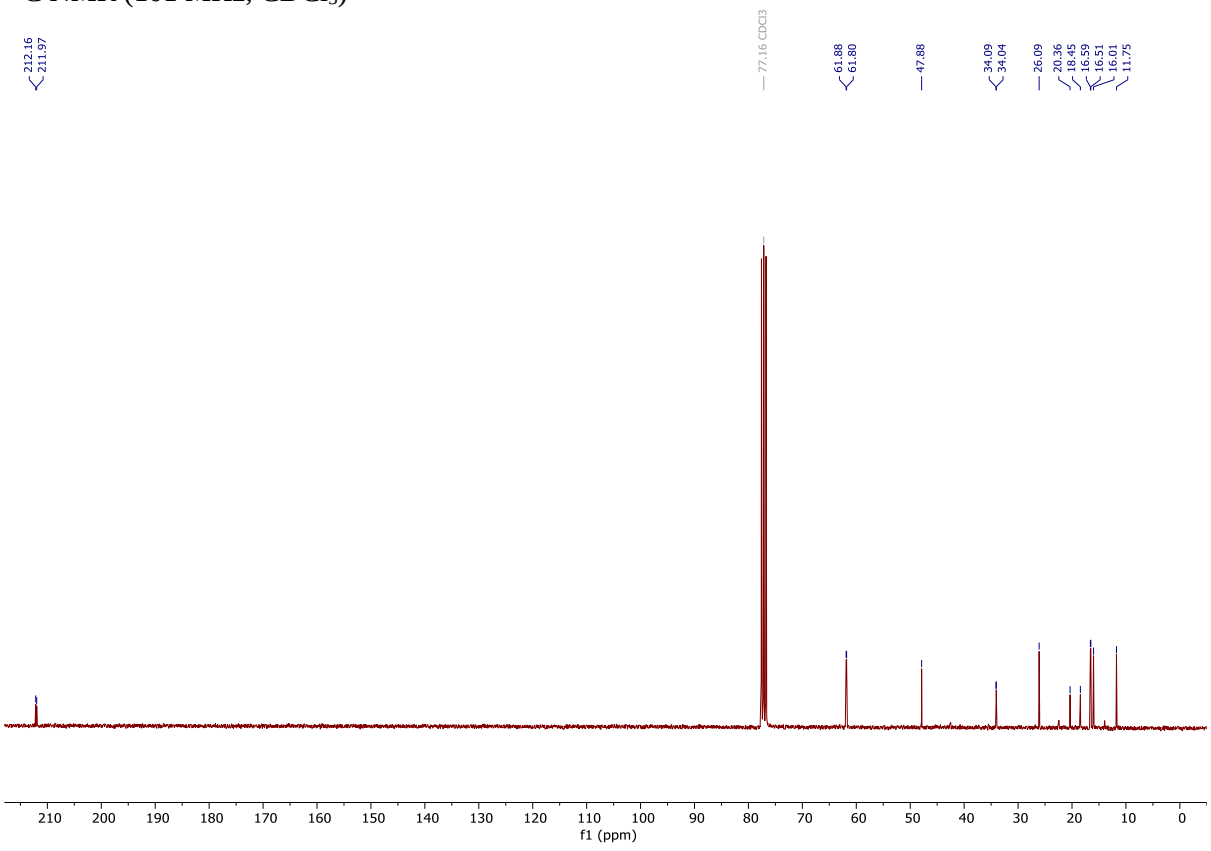
^{1}H NMR (400 MHz, $CDCl_3$)



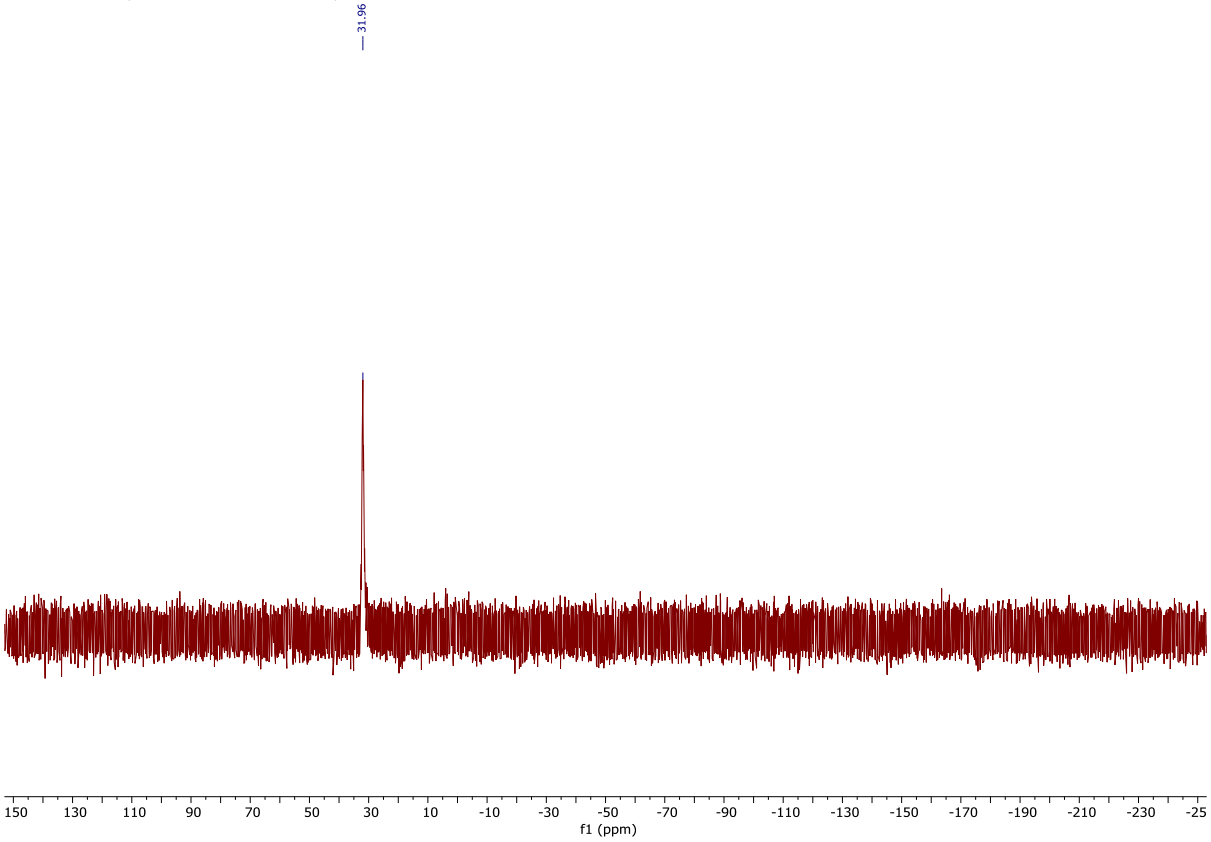
29a

29b

^{13}C NMR (101 MHz, $CDCl_3$)

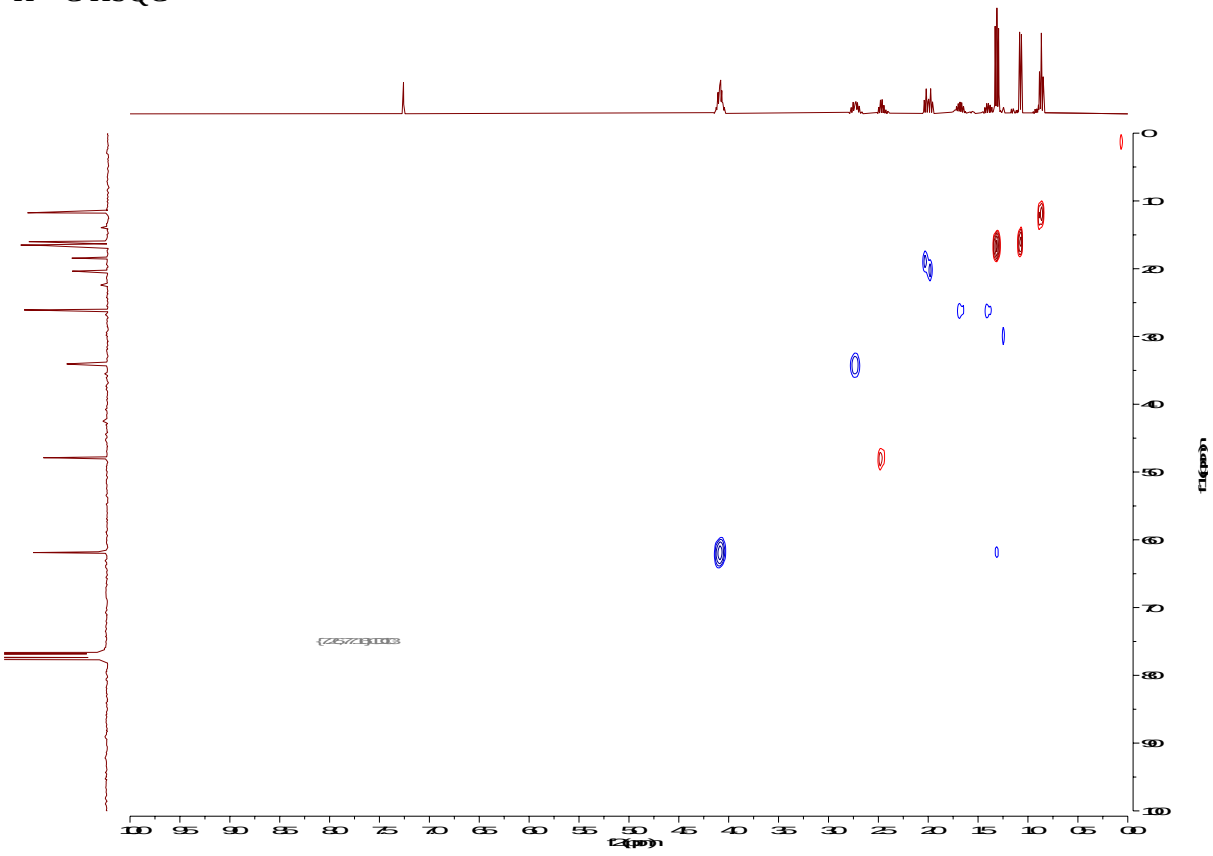


^{31}P NMR (162 MHz, $CDCl_3$)



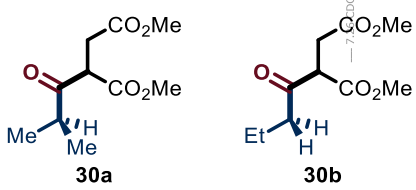
^{1}H-^{1}H COSY

^{1}H-^{13}C HSQC

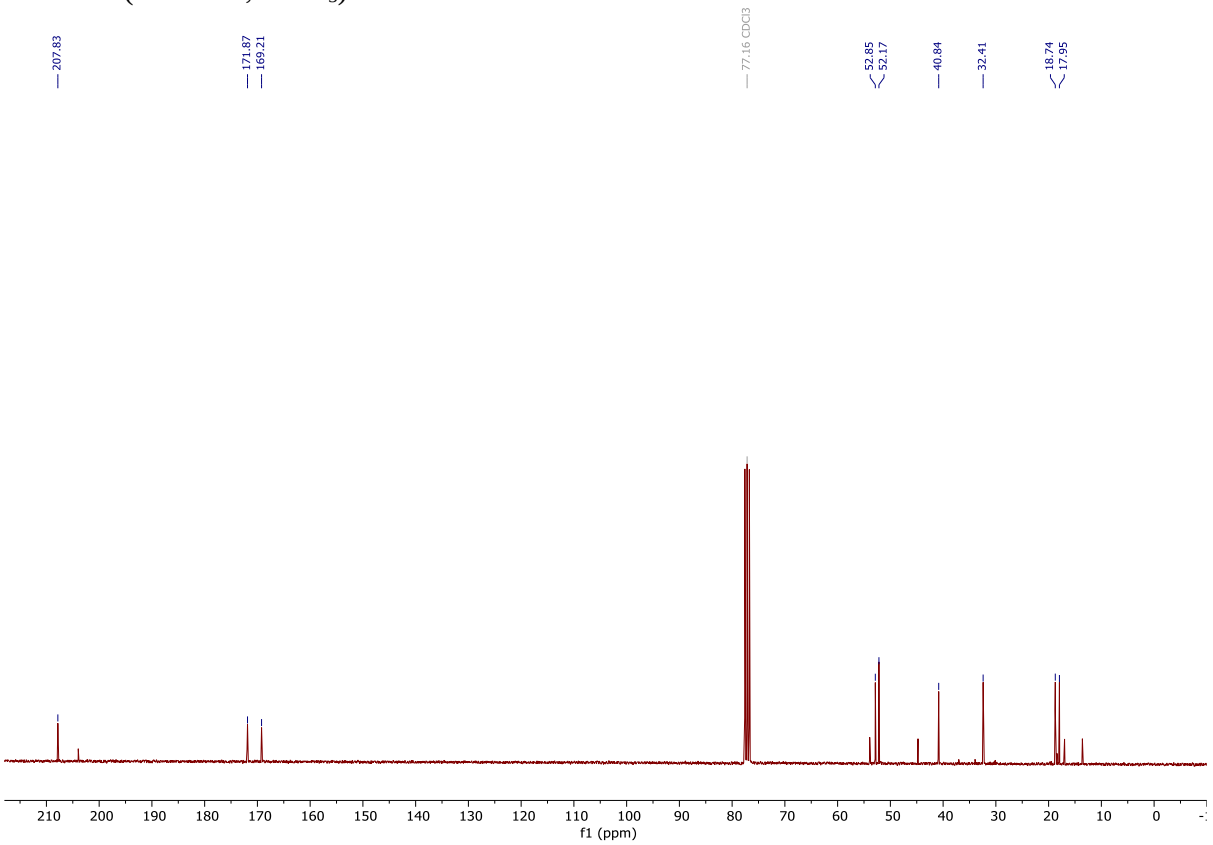


PROPANE

^{1}H NMR (400 MHz, $CDCl_3$)

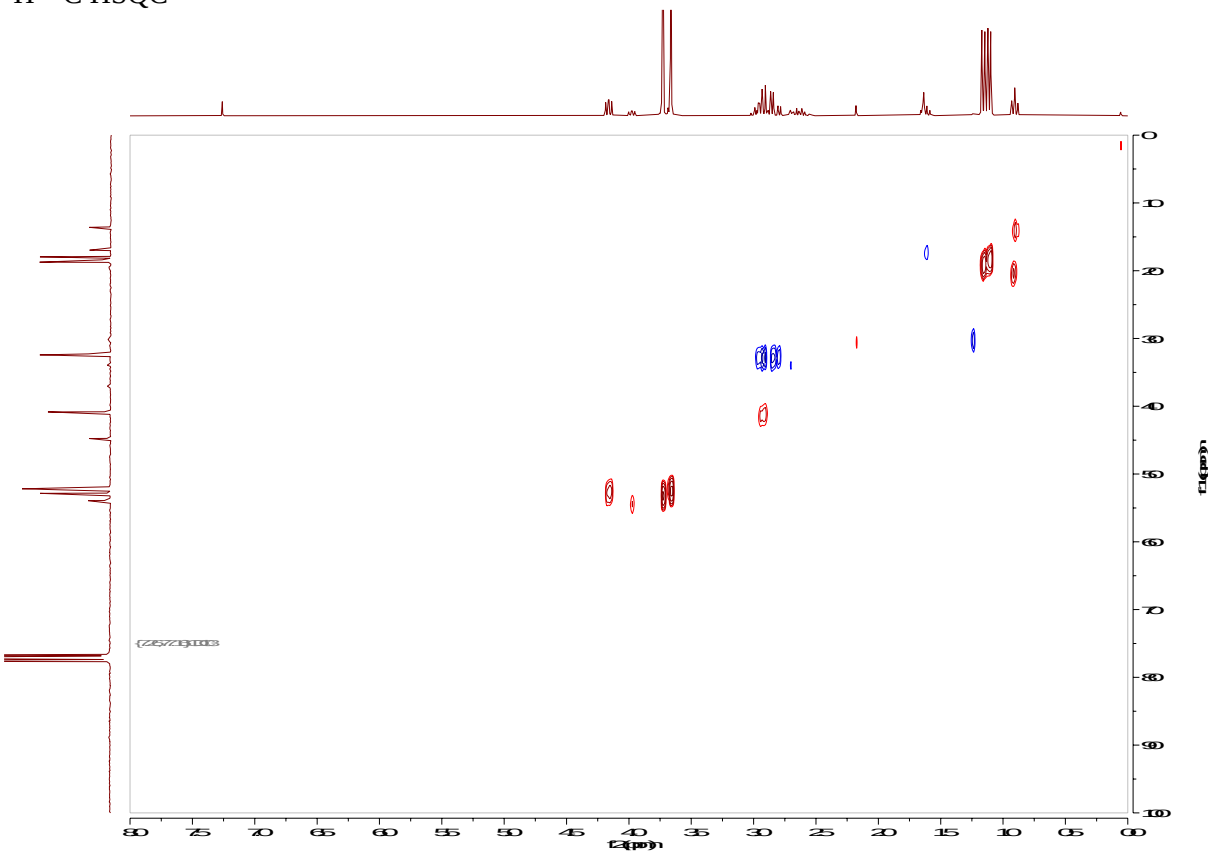


^{13}C NMR (101 MHz, $CDCl_3$)

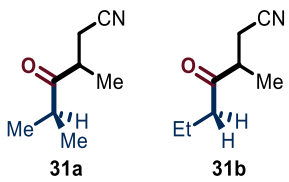


^{1}H-^{1}H COSY

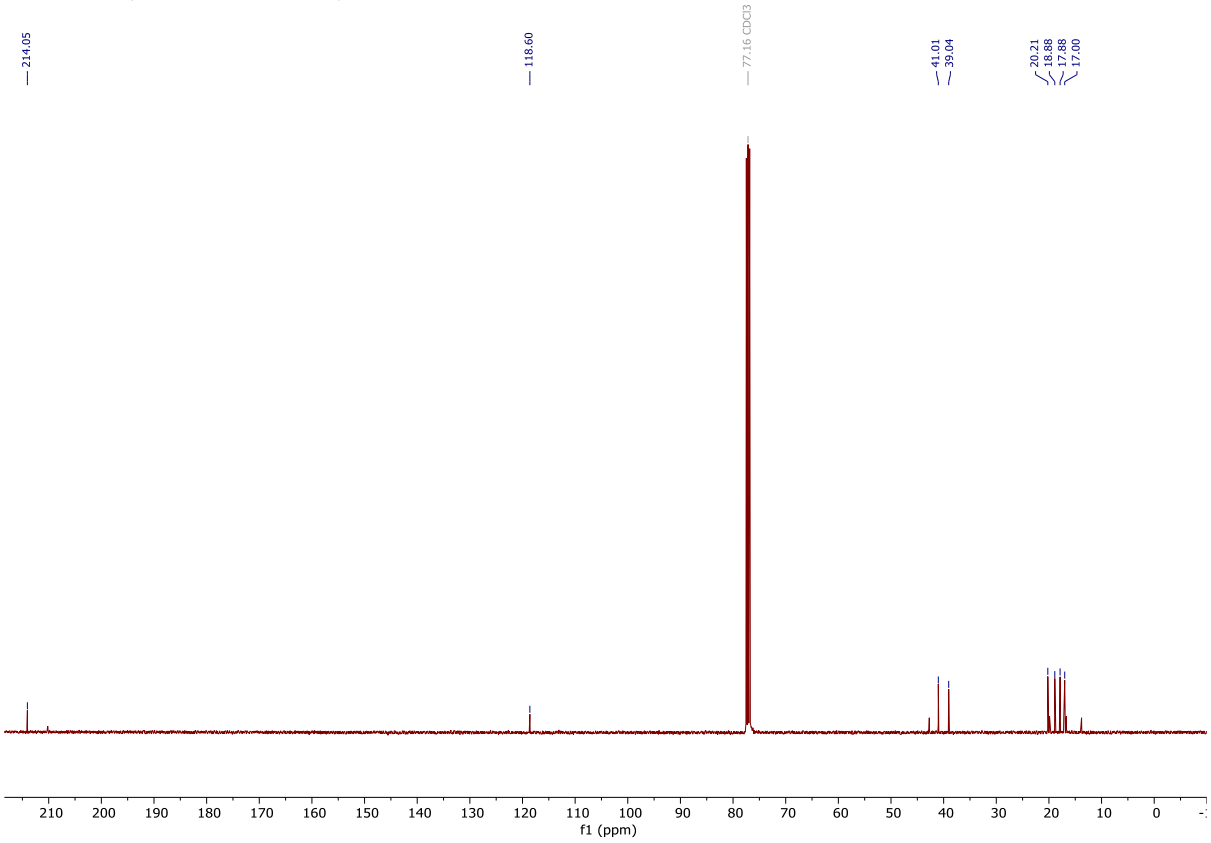
^{1}H-^{13}C HSQC



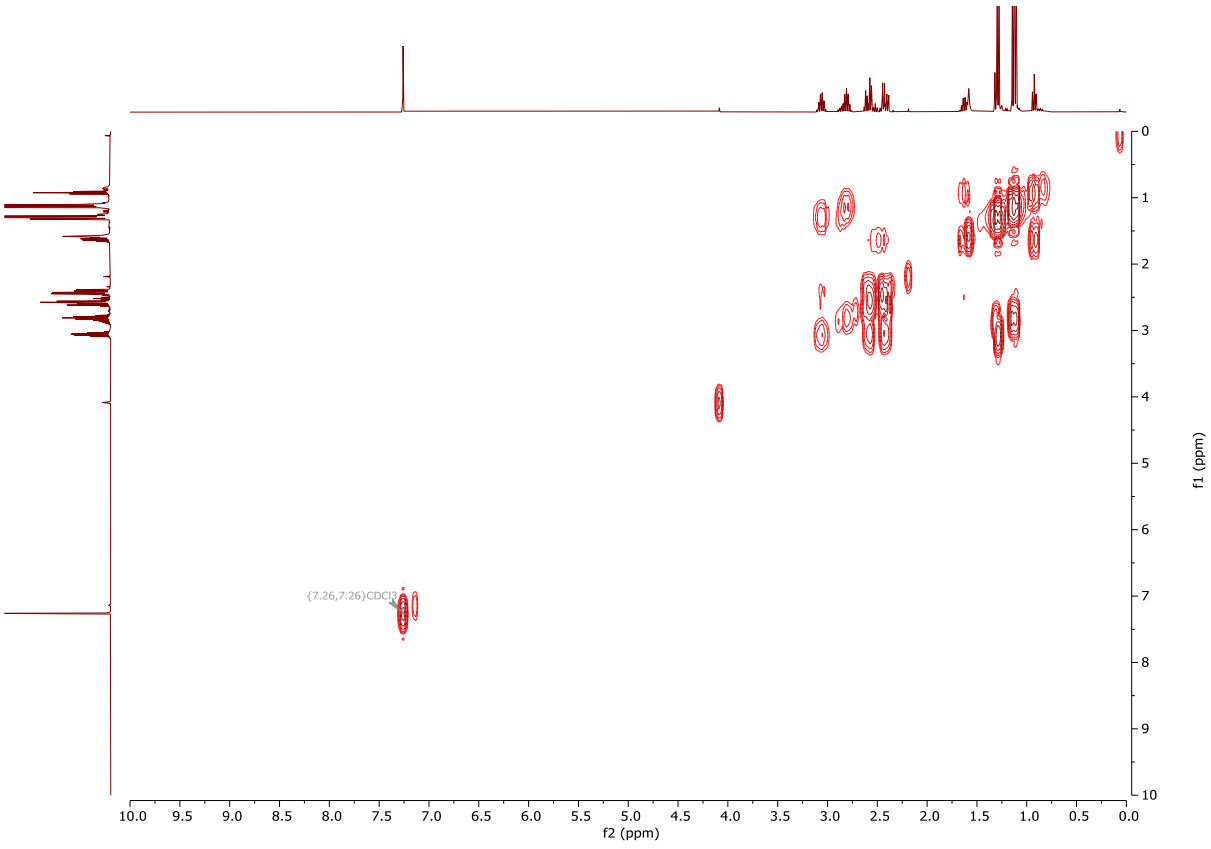
^{1}H NMR (400 MHz, $CDCl_3$)



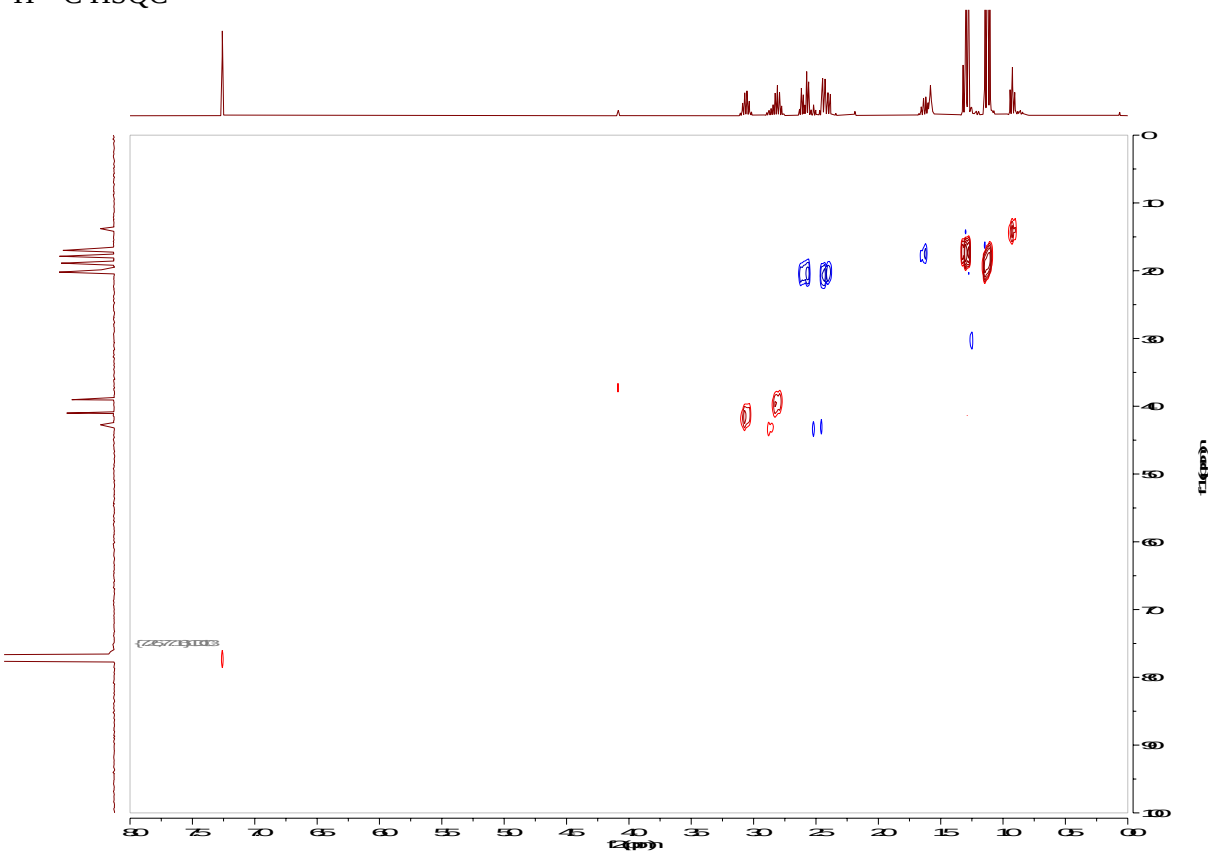
^{13}C NMR (101 MHz, $CDCl_3$)



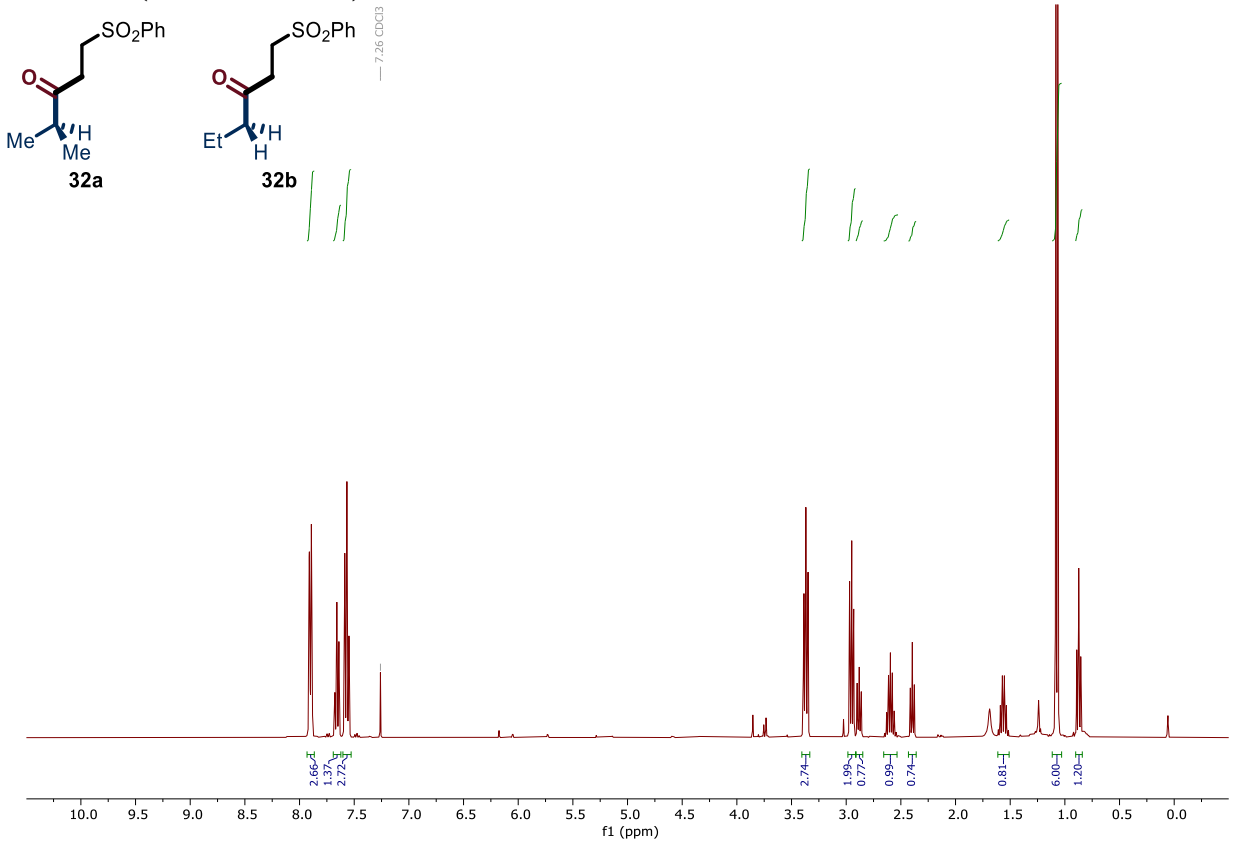
^{1}H-^{1}H COSY



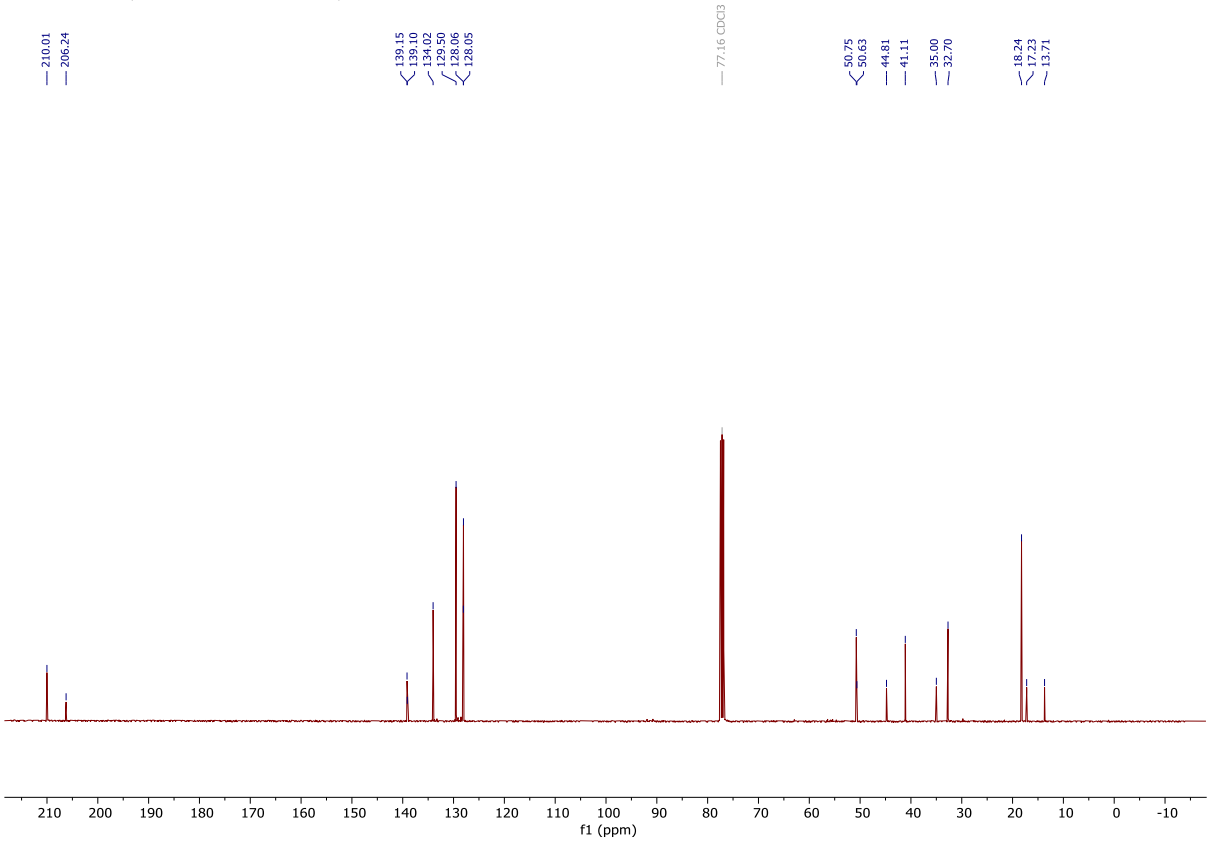
^{1}H-^{13}C HSQC



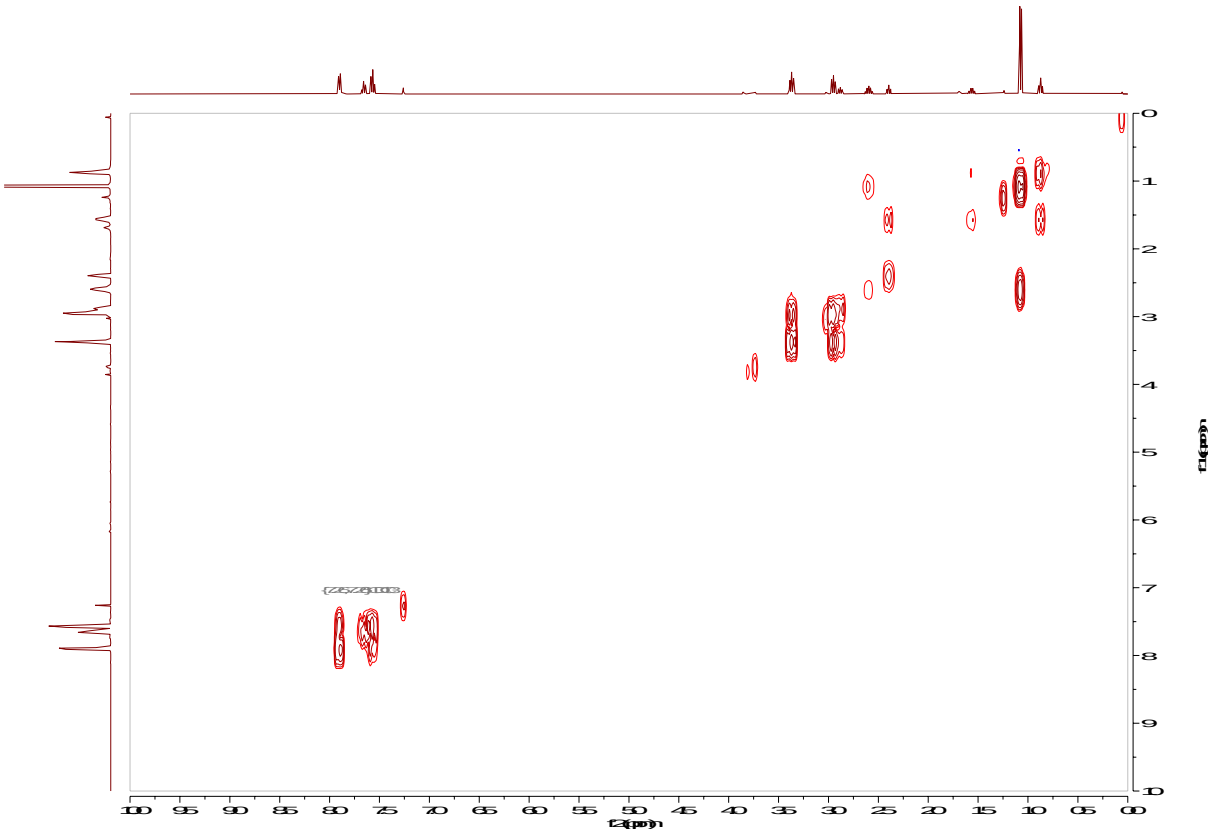
^{1}H NMR (400 MHz, $CDCl_3$)



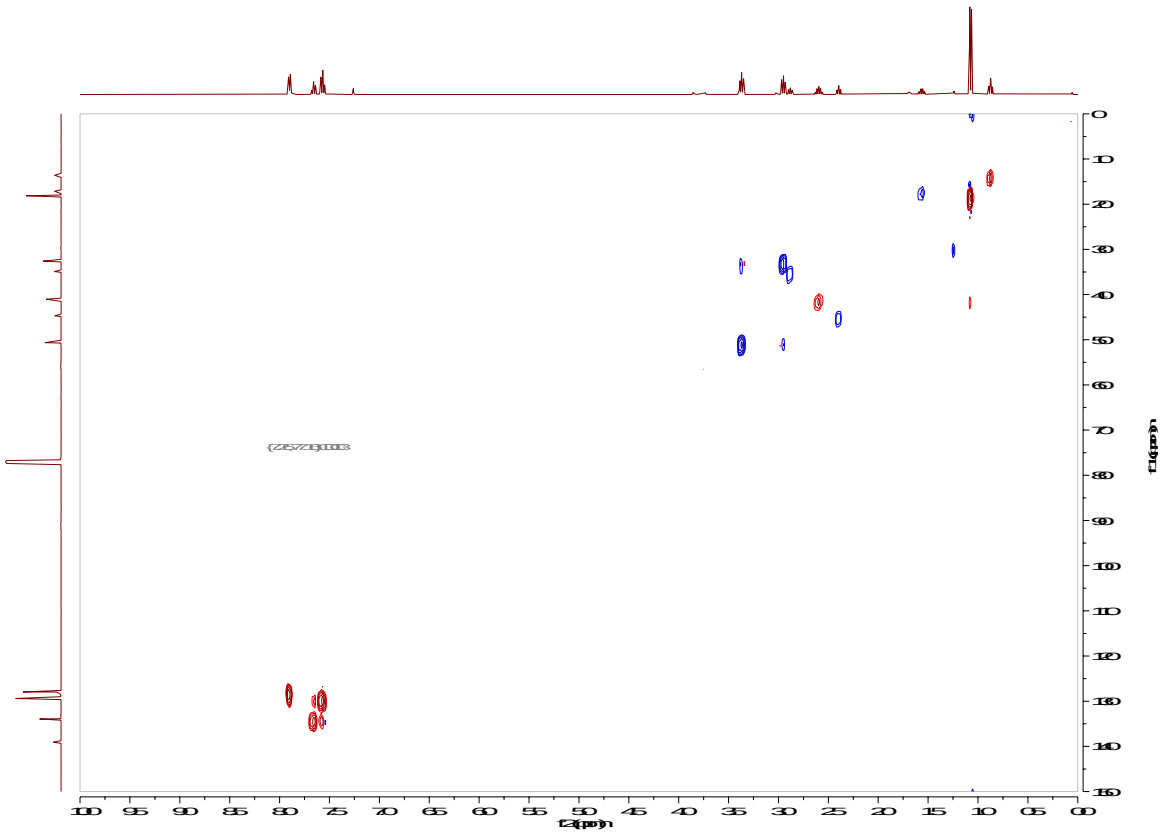
^{13}C NMR (101 MHz, $CDCl_3$)



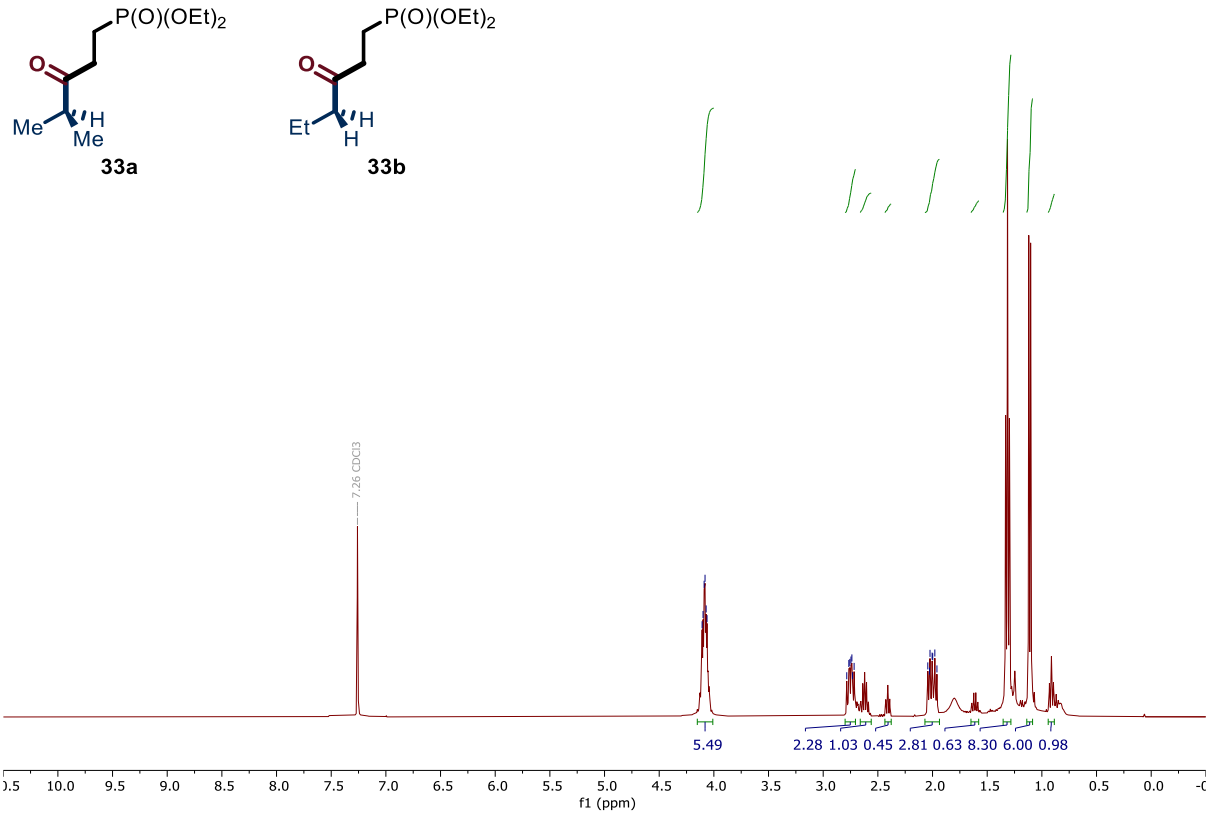
^{1}H-^{1}H COSY



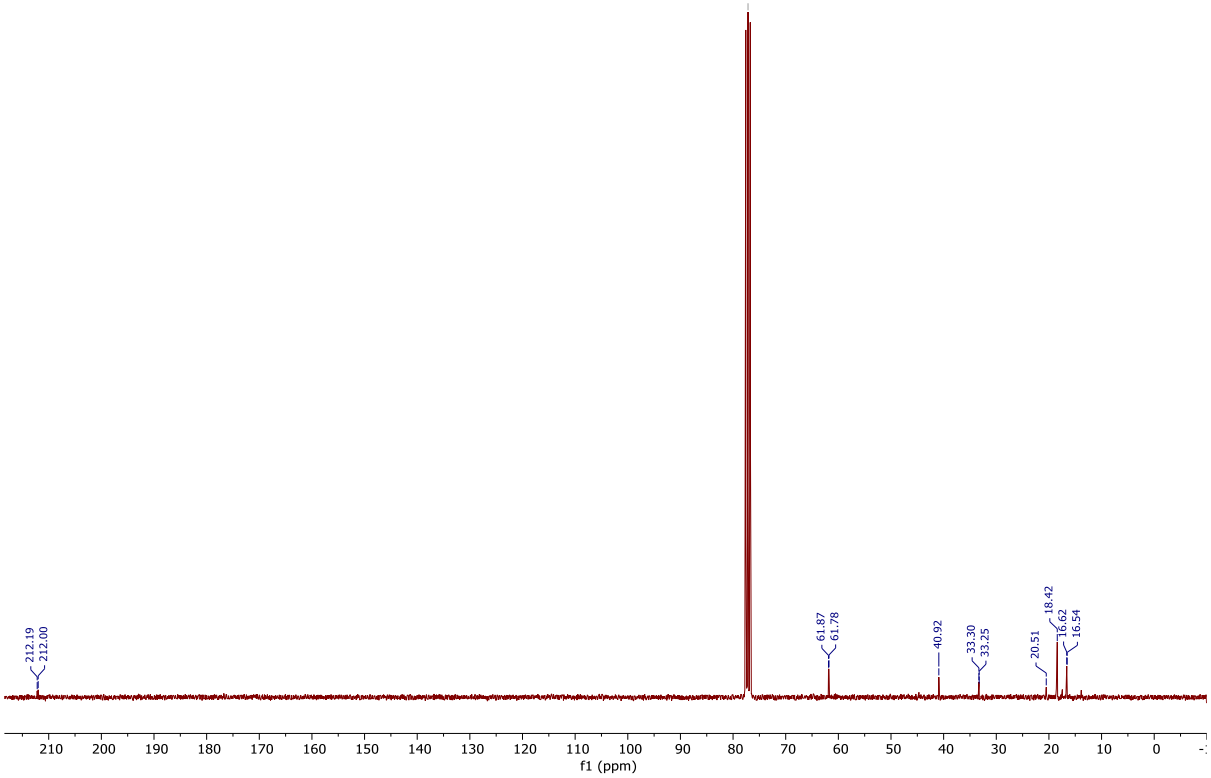
^{1}H-^{13}C HSQC



^{1}H NMR (400 MHz, $CDCl_3$)

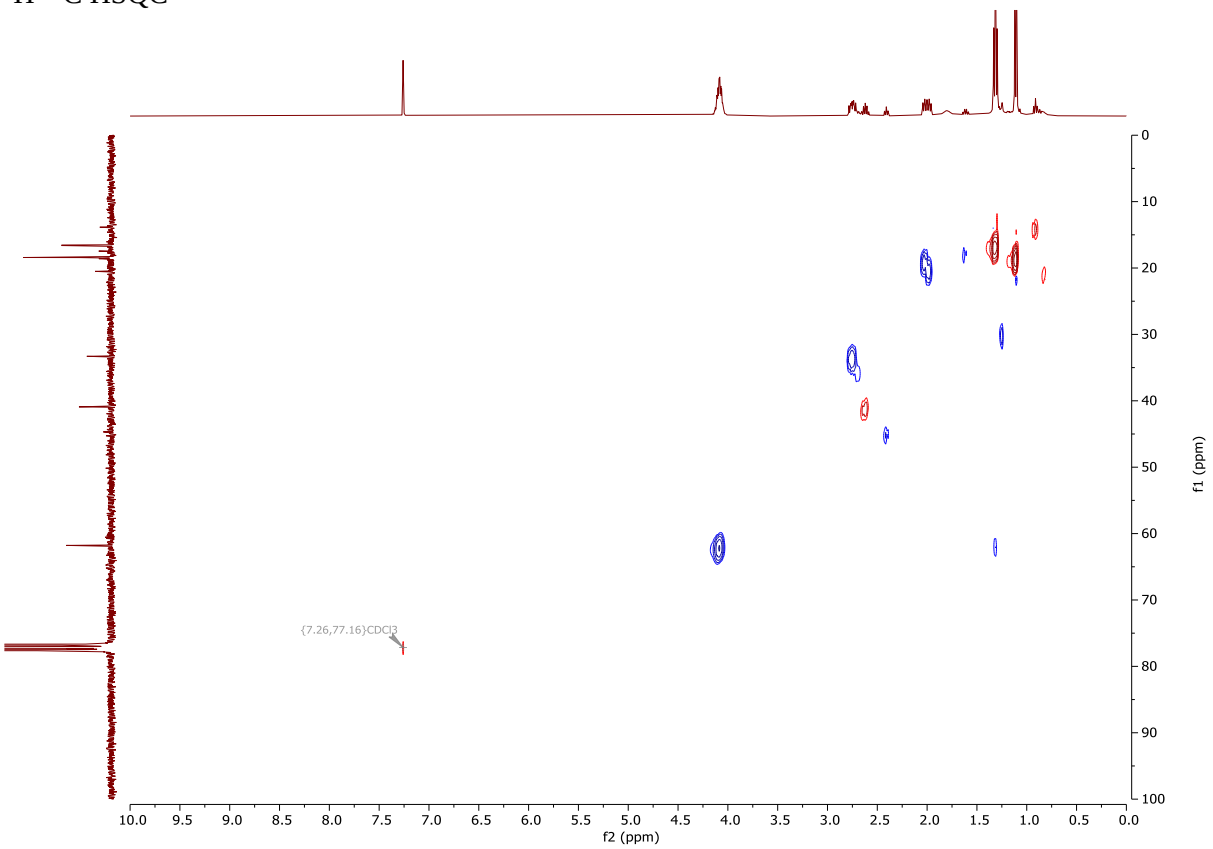


^{13}C NMR (101 MHz, $CDCl_3$)

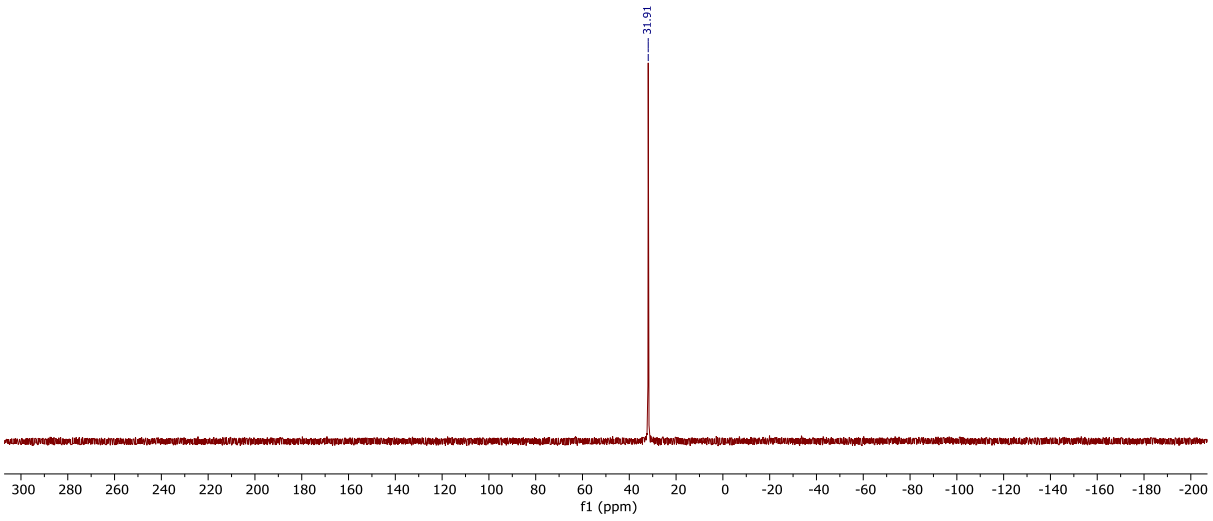


^{1}H-^{1}H COSY

^{1}H-^{13}C HSQC

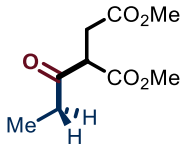


^{31}P NMR (162 MHz, $CDCl_3$)



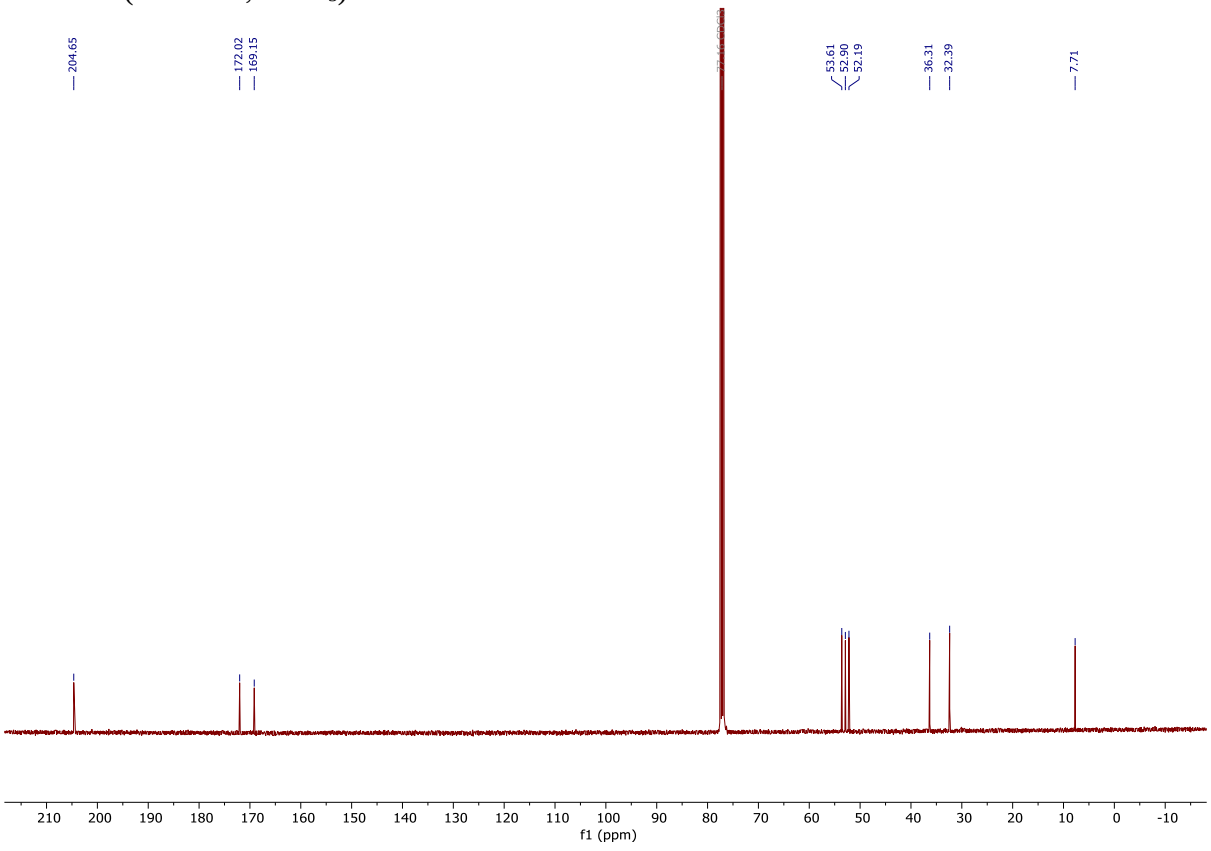
ETHANE

^{1}H NMR (400 MHz, $CDCl_3$)

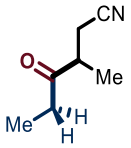


34

^{13}C NMR (101 MHz, $CDCl_3$)

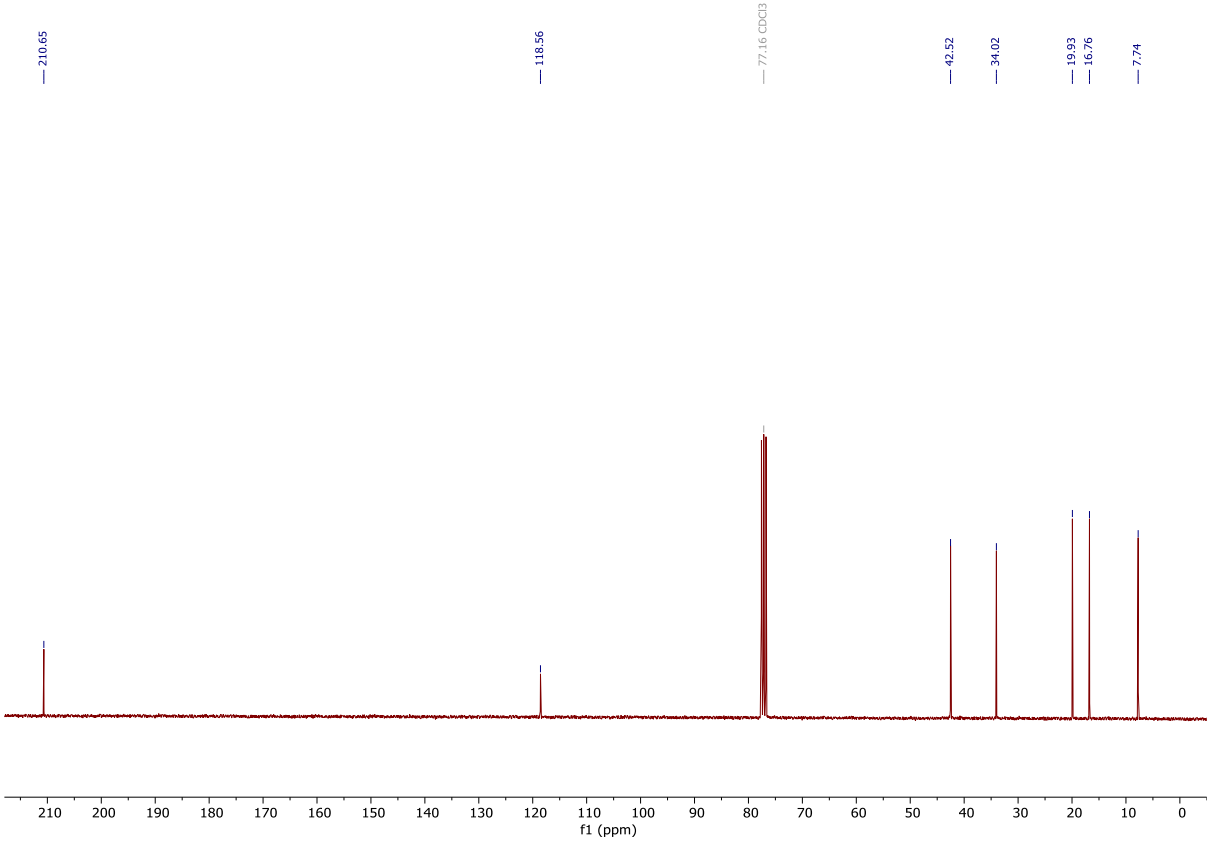


^{1}H NMR (300 MHz, $CDCl_3$)

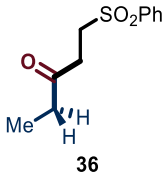


35

^{13}C NMR (75 MHz, $CDCl_3$)

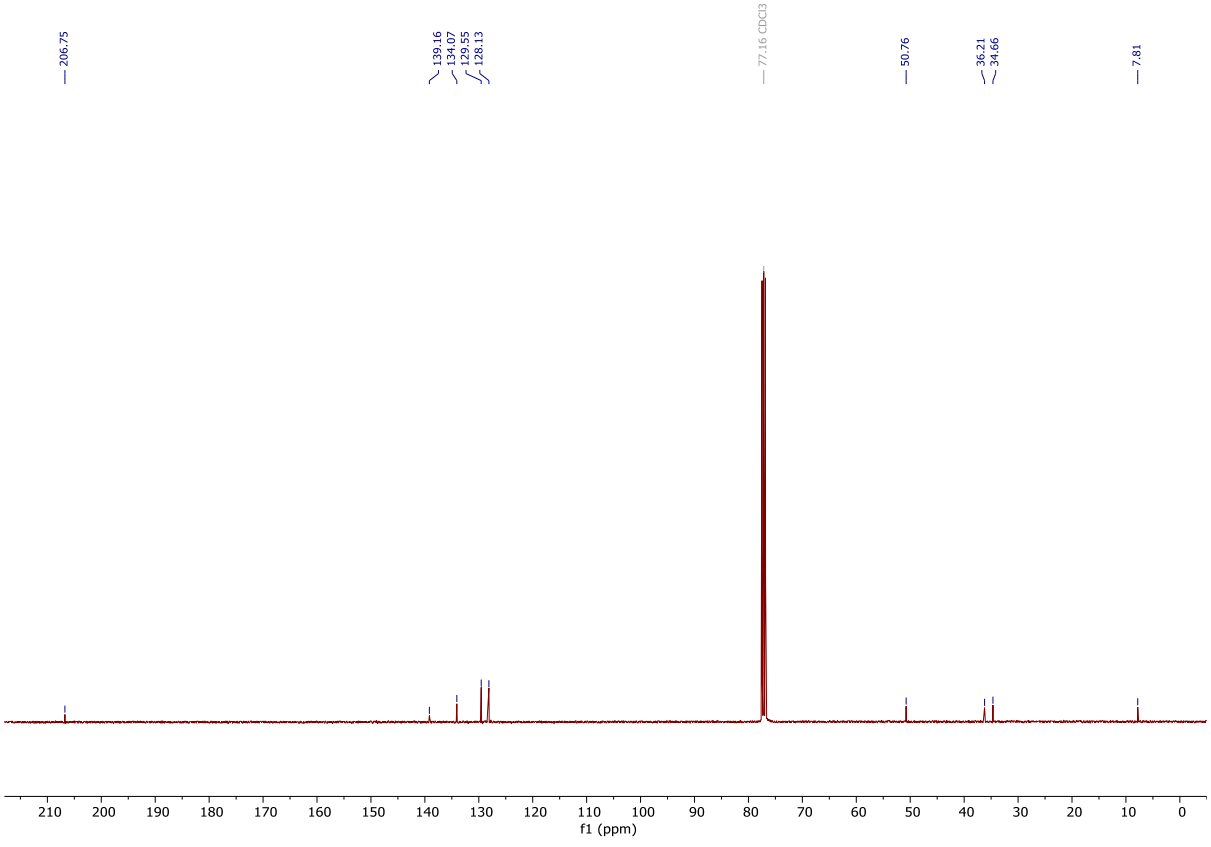


^{1}H NMR (400 MHz, $CDCl_3$)

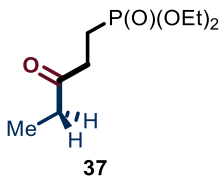


36

^{13}C NMR (101 MHz, $CDCl_3$)

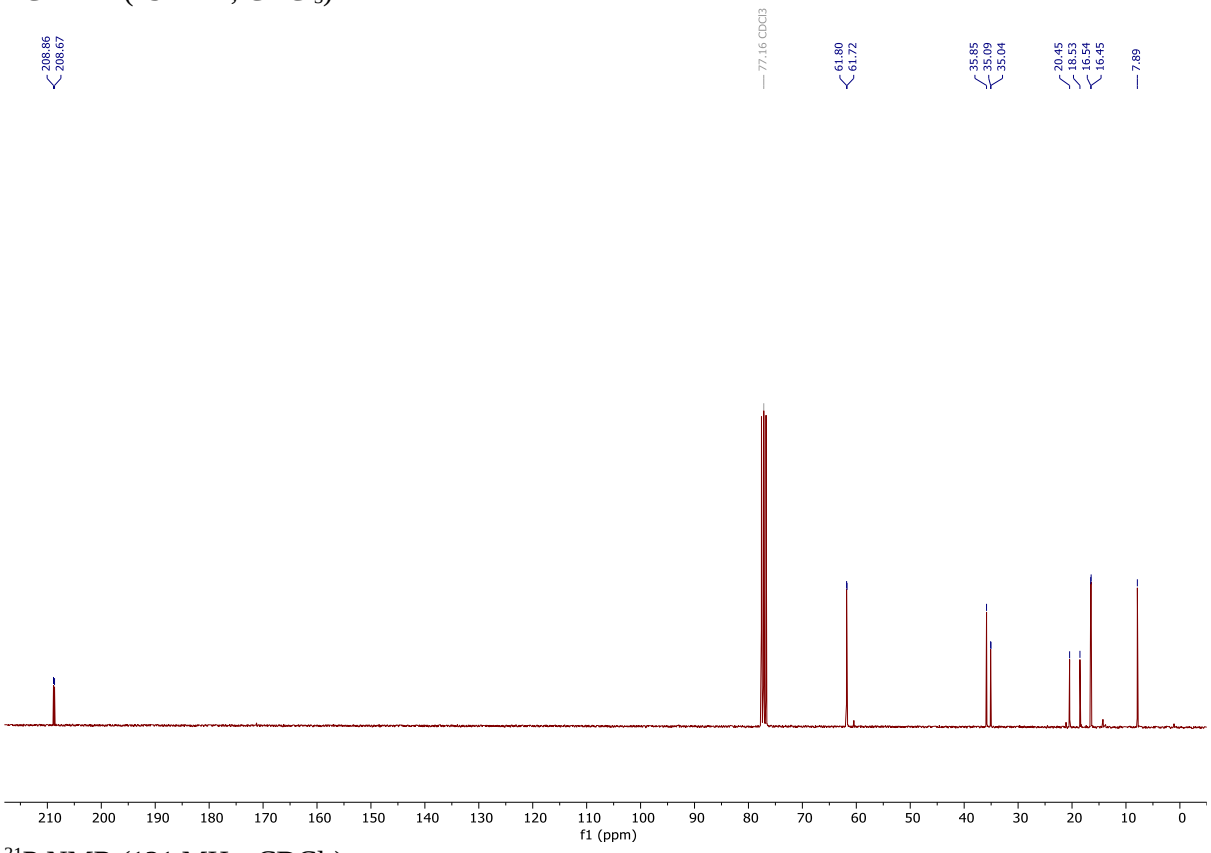


^{1}H NMR (300 MHz, $CDCl_3$)

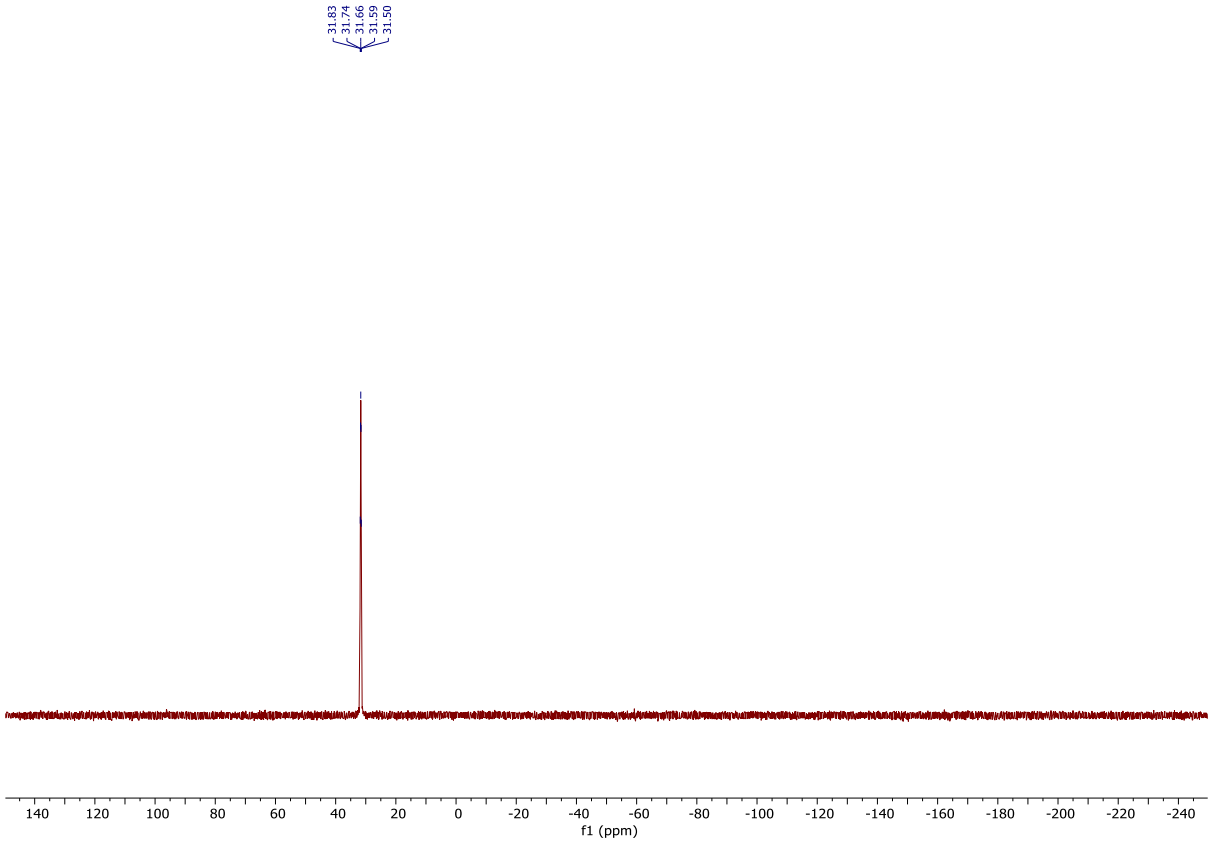


37

^{13}C NMR (75 MHz, $CDCl_3$)

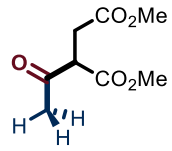


^{31}P NMR (121 MHz, $CDCl_3$)


31.83
31.74
31.66
31.59
31.50
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
f1 (ppm)

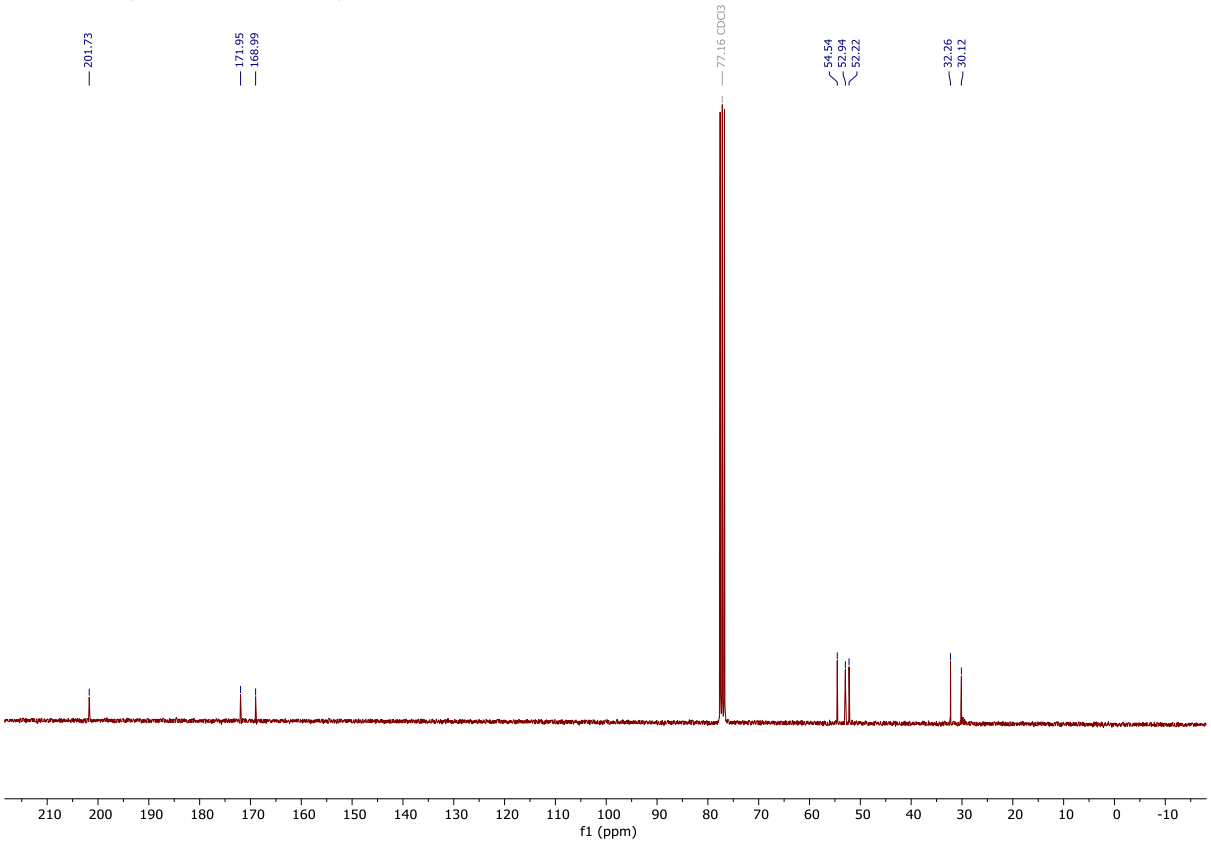
METHANE

^{1}H NMR (300 MHz, $CDCl_3$)

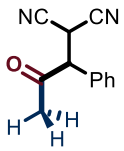


38

^{13}C NMR (101 MHz, $CDCl_3$)

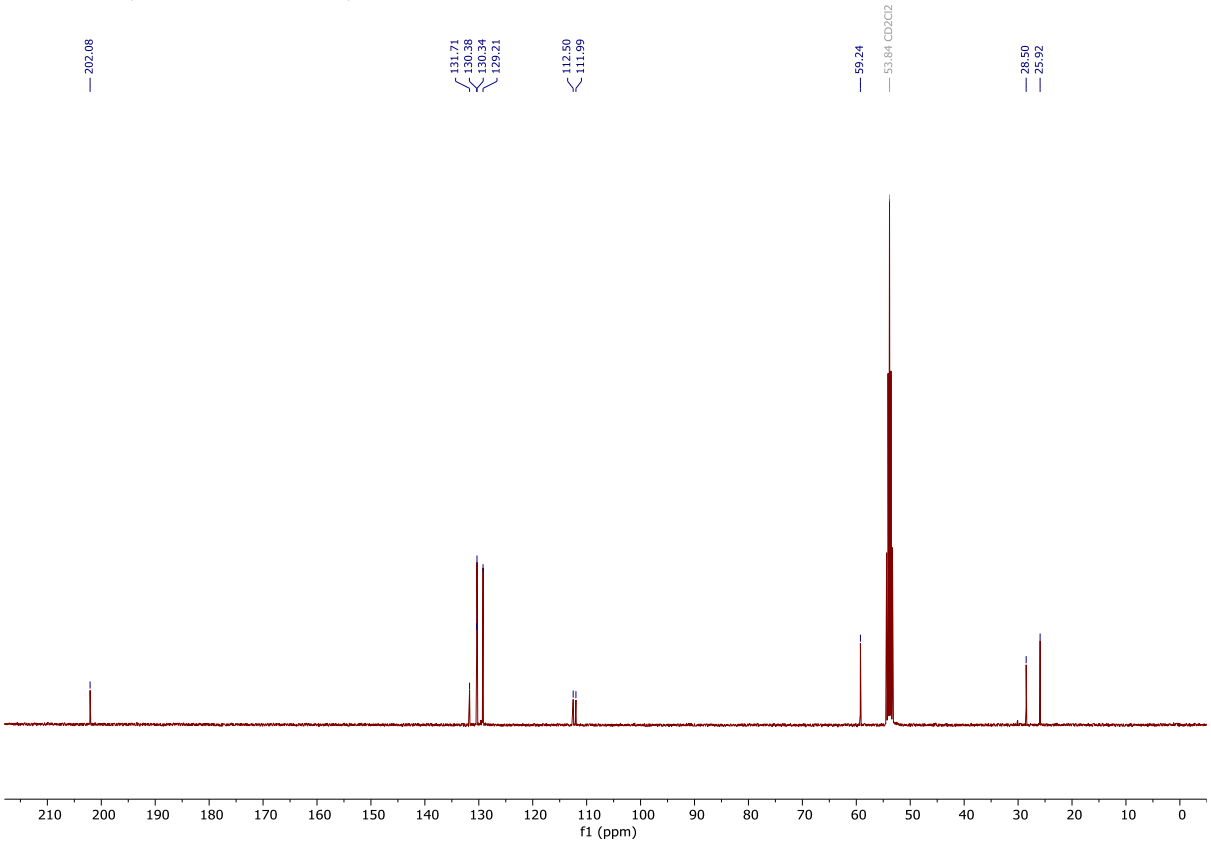


^{1}H NMR (400 MHz, CD_2Cl_2)

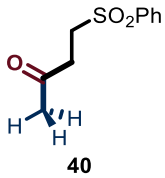


39

^{13}C NMR (101 MHz, CD_2Cl_2)

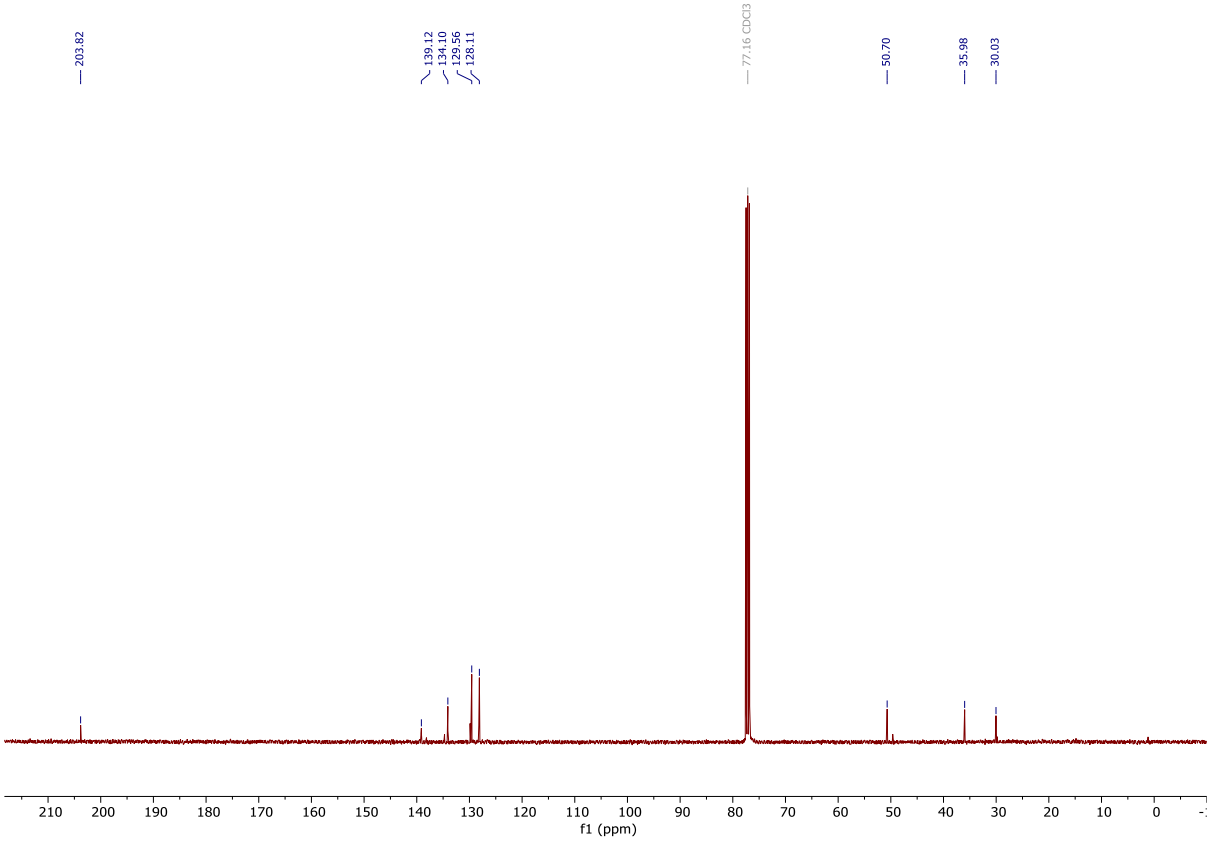


^{1}H NMR (400 MHz, $CDCl_3$)

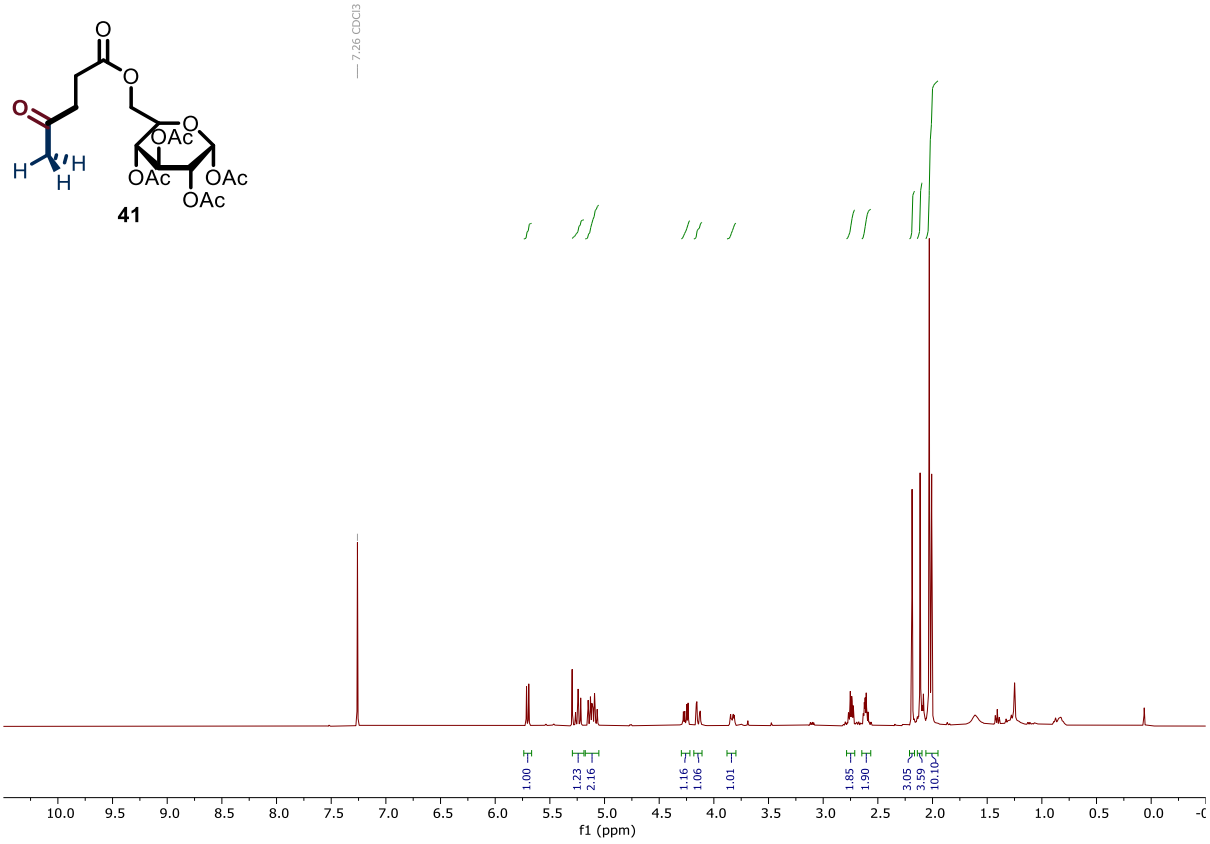


40

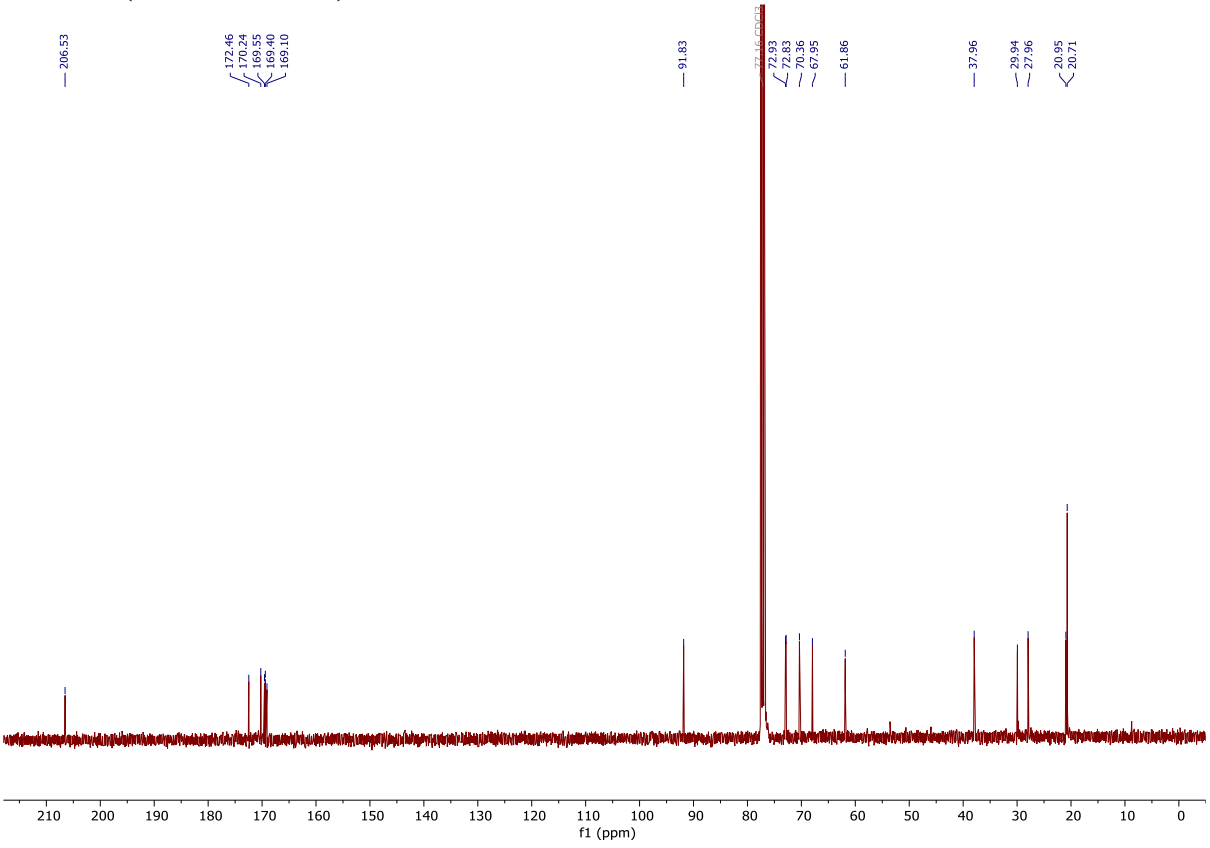
^{13}C NMR (101 MHz, $CDCl_3$)



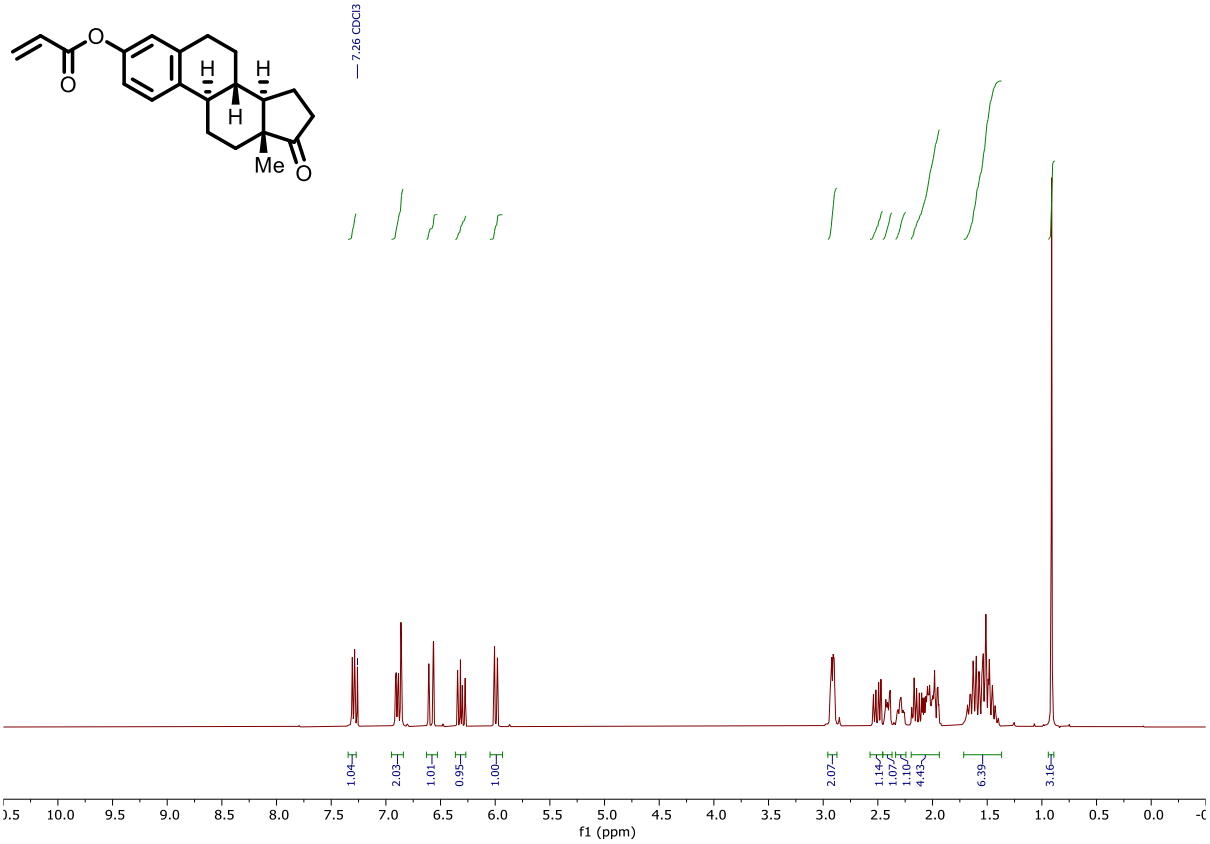
^{1}H NMR (400 MHz, $CDCl_3$)

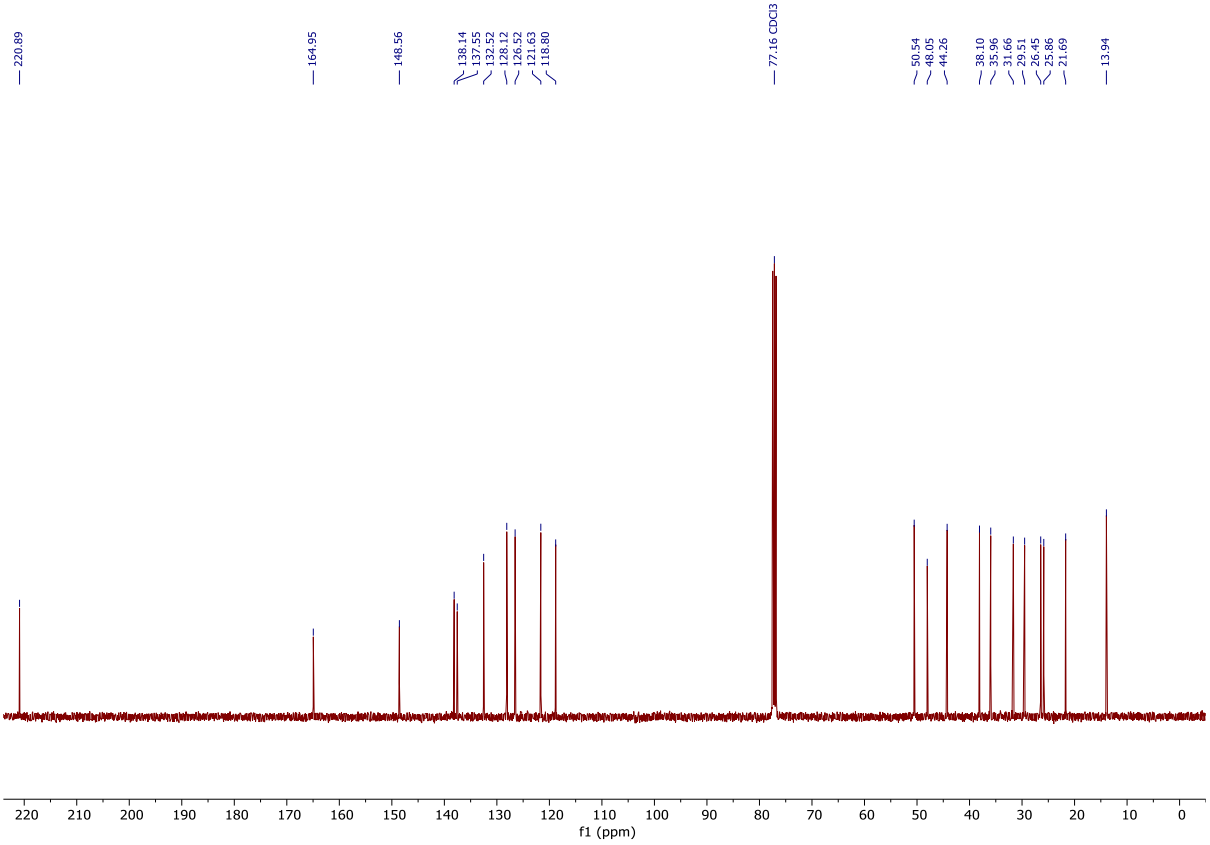


^{13}C NMR (101 MHz, $CDCl_3$)

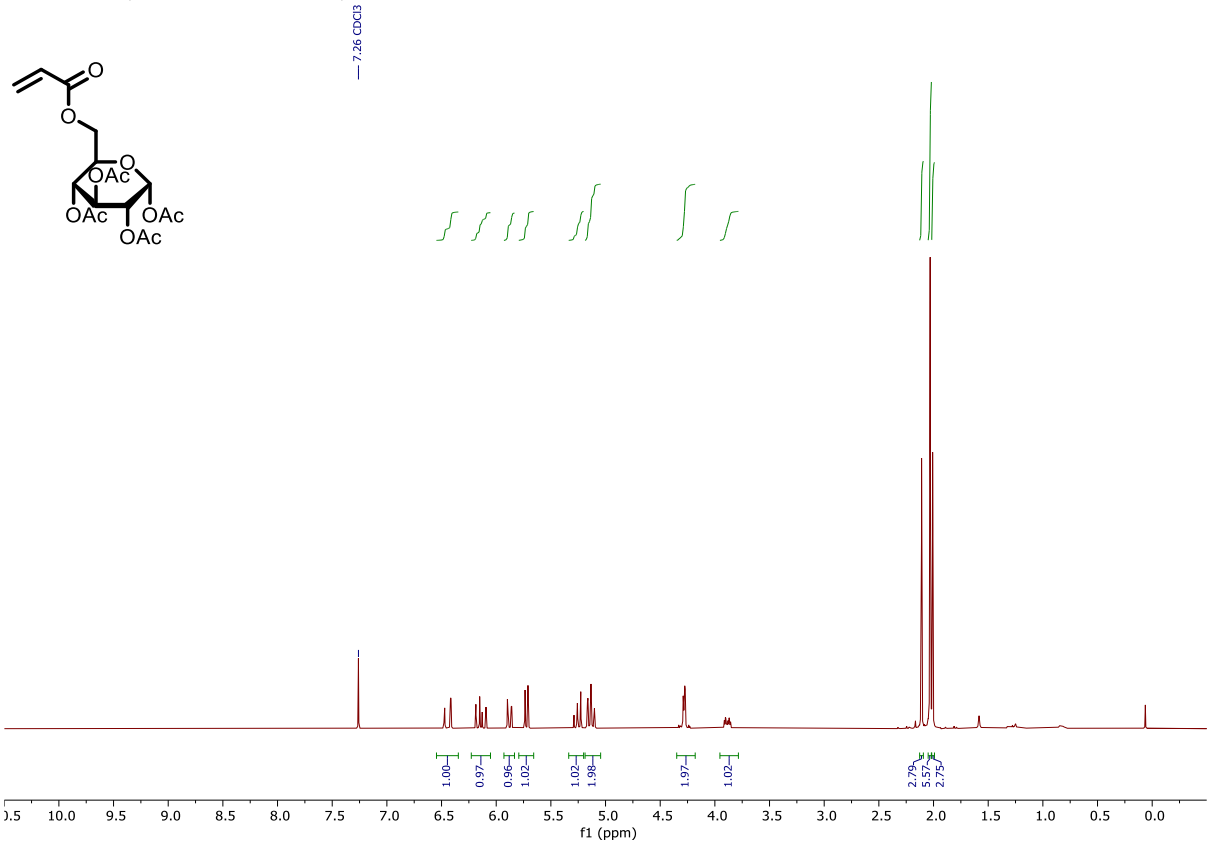


STARTING MATERIALS





1H NMR (300 MHz, CDCl3)



13C NMR (75 MHz, CDCl3)