

Synthesis and reactivity of octa(methoxycarbonyl)cycloheptatriene

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General information

¹H NMR and ¹³C NMR spectra were recorded on a Bruker AVANCE II 300 spectrometer at 300 MHz and 75 MHz, respectively, in CDCl₃ with tetramethylsilane as an internal reference standard, and DMSO-*d*₆. ¹³C NMR spectra for the compounds **6** were recorded on a Q. One AS600 spectrometer at 150 MHz in CDCl₃.

HRMS spectra were obtained with a Bruker microTOF II instrument (ESI, positive or negative ion modes, capillary voltage 4500 V). Melting points were determined on a melting point apparatus Stuart SMP10.

All other reagents and solvents are commercially available and were used without additional purification.

Quantum chemical calculations were carried out using ORCA 5.0.4 software package.^{S1-S3} Combination of CREST and CENSO level 2 software packages were used to find the most stable conformations of ground states.^{S4,S5} Geometry of the corresponding triplet state was found by optimization of the ground state geometry.

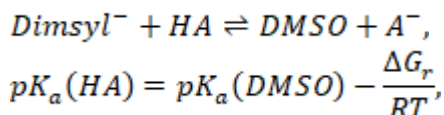
Geometry optimization and frequency calculations were performed using the method r²SCAN-3c, while the electron energy was obtained at revDSD-PBEP86(D4)/aug-cc-pVTZ/CPCM(DMSO) level of theory.^{S6-S9}

Optimized structures were verified by frequency computations as minima (zero imaginary frequencies) or transition structures (a single imaginary frequency).^{S10} In case of calculations of planarized molecules corresponding restrictions on the geometry of the seven-membered rings were imposed during the optimization process.

In all cases where energetic parameters were considered, the following expression for Gibbs free energy of formation was used:

$$\Delta G_f(X) = \Delta G_f(r^2\text{SCAN-3c}) - E_{SPE}(r^2\text{SCAN-3c}) \\ + E_{SPE}(\text{revDSD-PBEP86(D4)/aug-cc-pVTZ/CPCM(DMSO)}).$$

Determination of pK_a values was based on a calculation of ΔG_r value for the deprotonation of acids with dimsyl-anion, which can be further combined with known pK_a value for DMSO:



where HA corresponds to the octa(methoxycarbonyl)cycloheptadiene.^{S11}

Fukui functions were calculated in the Multiwfn 3.8 program package.^{S12} Visualization was performed with IboView and IQmol program package.

Synthetic procedures

Heptamethyl cyclohepta-2,4,6-trien-1,2,3,4,5,6,7-heptacarboxylate HMCH

A flask equipped with a stirring bar was charged with octa(methoxycarbonyl)cycloheptadiene (1.000 g, 1.79 mmol), DMSO (1.5 ml), pyridine (1.44 ml, 17.9 mmol), and catalyst (see Table S1 below), and the mixture was stirred without a lid for 72 hours. The resulting mixture was diluted with 5 ml of CH₂Cl₂, filtered through silica gel layer, washed with aq. NH₄Cl (3×5 ml), dried over Na₂SO₄ and concentrated under reduced pressure. The mixture then was recrystallized from methanol to give the product in the form of colorless powder.

Table S1. List of catalysts

Entry	Catalyst	Mol. %	Yield, %
1	CuBr ₂	30	32
2	CuCl ₂ ·2H ₂ O	30	47
3	CuCl	30	30
4	Cu(acac) ₂	5	45
5	FeCl ₃ ·6H ₂ O	30	40
6	CuSO ₄ ·5H ₂ O	3	80
7	Cu(NCMe) ₄ PF ₆	30	50

¹H NMR (CDCl₃, 300 MHz, ppm): δ 5.18 (s, 1H), 3.81 (s, 6H), 3.80 (s, 6H), 3.63 (s, 3H).

The NMR spectrum corresponds to the previously reported.^{S13}

Octamethyl cyclohepta-2,4,6-trien-1,1,2,3,4,5,6,7-octacarboxylate E8

A flask equipped with a stirring bar was charged with octa(methoxycarbonyl)cycloheptadiene (1.000 g, 1.79 mmol), DMF (1.5 ml), pyridine (1.44 ml, 17.9 mmol), and CuBr (0.078 g, 0.54 mmol), and the mixture was stirred without a lid. After 72 hours it was purified by flash column chromatography (CH₂Cl₂), washed with aqueous NH₄Cl (3×20 ml), dried over Na₂SO₄ and evaporated under reduced pressure. The residue was recrystallized from methanol to give **E8** in the form of white powder, 0.567 g, 57% yield. Decomp. over 147 °C.

¹H NMR (DMSO-*d*₆, 300 MHz, ppm): δ 3.74 (s, 12H), 3.70 (s, 9H), 3.60 (s, 3H).

¹³C NMR (DMSO-*d*₆, 75 MHz, ppm): δ 166.3, 164.7, 164.4, 164.3, 164.2, 136.3, 136.2, 131.2, 61.6, 54.8, 54.6, 54.1, 54.0, 53.8.

HRMS (ESI) *m/z*: calcd for C₂₃H₂₄O₁₆NH₄⁺ 574.1403 [M+NH₄]⁺; found: 574.1399.

Tetramethyl (*E*)-3-(4,5,6-tris(methoxycarbonyl)-1-methyl-2-oxo-1,2-dihydropyridin-3-yl)prop-2-ene-1,1,2,3-tetracarboxylate 6a

A vial equipped with a stirring bar was charged with **E8** (0.400 g, 0.72 mmol), methanol (4 ml) and 40% aqueous solution of methylamine (0.086 ml), and the mixture was stirred at room temperature 72 hours and

then concentrated under reduced pressure. The residue was recrystallized from methanol to give product **6a** as a fine white powder, 0.315 g, 79% yield. m.p. 153–154°C.

¹H NMR (CDCl₃, 300 MHz, ppm): δ 4.19 (s, 1H), 4.03 (s, 3H), 3.82 (s, 3H), 3.81 (s, 3H), 3.79 (s, 6H), 3.75 (s, 6H), 3.52 (s, 3H).

¹³C NMR (151 MHz, CDCl₃, ppm): δ 166.5, 166.2, 165.9, 164.9, 164.8, 162.8, 162.1, 158.9, 147.0, 142.8, 137.8, 133.6, 123.3, 104.8, 54.7, 53.9, 53.3, 53.2, 53.1, 53.0, 52.8, 34.0.

HRMS (ESI) *m/z*: calcd for C₂₃H₂₅NO₁₅Na⁺ 578.1116 [M+Na]⁺; found: 578.1119.

Tetramethyl (*E*)-3-(1-benzyl-4,5,6-tris(methoxycarbonyl)-2-oxo-1,2-dihydropyridin-3-yl)prop-2-ene-1,1,2,3-tetracarboxylate **6b**

A vial equipped with a stirring bar was charged with **E8** (0.400 g, 0.72 mmol), methanol (4 ml) and benzylamine (1.4 eq., 0.109 ml, 1.00 mmol), and the mixture was stirred at room temperature 72 hours and then concentrated under reduced pressure. The residue was recrystallized from methanol to give the product **6b** as a white powder, 0.159 g, 35%. m.p. 181–183°C.

¹H NMR (CDCl₃, 300 MHz, ppm): δ 7.37 – 7.27 (m, 3H), 7.23 – 7.15 (m, 2H), 5.38 (d, *J* = 15.1 Hz, 1H), 5.14 (d, *J* = 15.1 Hz, 1H), 4.21 (s, 1H), 3.82 (s, 6H), 3.80 (s, 3H), 3.77 (s, 3H), 3.76 (s, 3H), 3.73 (s, 3H), 3.57 (s, 3H).

¹³C NMR (151 MHz, CDCl₃, ppm): δ 166.5, 166.2, 165.9, 164.9, 164.7, 162.9, 162.0, 159.0, 146.4, 142.7, 137.9, 134.7, 133.5, 128.7, 128.2, 127.6, 124.3, 105.9, 54.7, 53.5, 53.2, 53.2, 53.1, 53.0, 53.0, 52.8, 50.0.

HRMS (ESI) *m/z*: calcd for C₂₉H₂₉NO₁₅K⁺ 670.1169 [M+K]⁺; found: 670.1165.

Hexamethyl benzene-1,2,3,4,5,6-hexacarboxylate **7**

A vial equipped with a stirring bar was charged with a solution of **E8** (0.056 g, 0.10 mmol) in the mixture of acetonitrile/water 19:1 (1.5 mL), then sodium borohydride (0.006 g, 0.15 mmol) was added. The resulting mixture was stirred at room temperature, and the colour gradually turned yellow. After 1 hour, the solvent was evaporated under reduced pressure. The residue was purified by column chromatography (toluene/acetone 9:1) to give the product **7** in the form of white powder, 0.027 g, 62%. m.p. 188°C.^{S14}

¹H NMR (CDCl₃, 300 MHz, ppm): δ 3.88 (s, 18H).

Methylpyridinium formation in the synthesis of HMCH

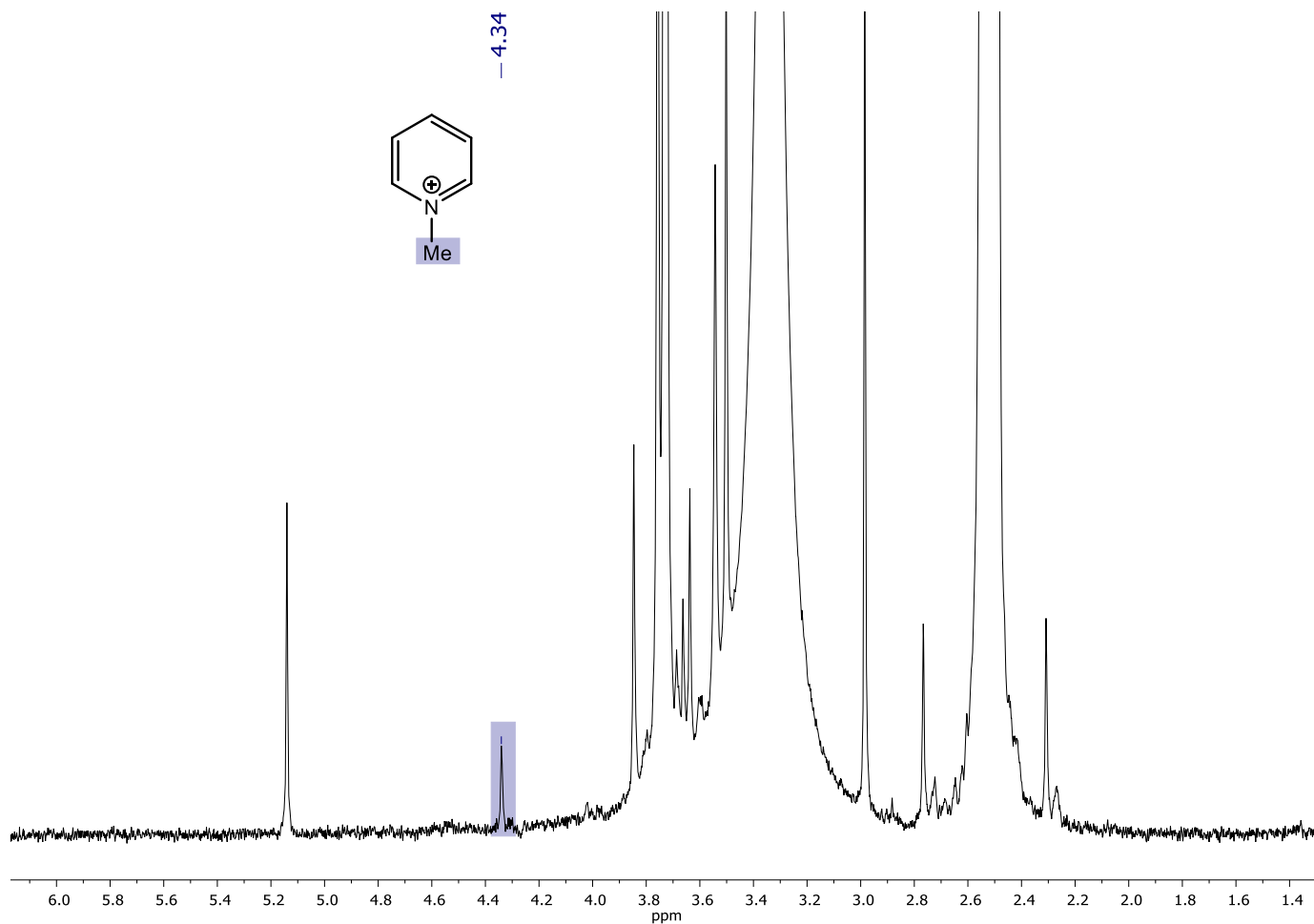


Figure S1. Typical NMR ^1H (300 MHz, $\text{DMSO}-d_6$) spectrum of the reaction mixture in the synthesis of **HMCH** through the Cu-catalyzed oxidation of octa(methoxycarbonyl)cycloheptadiene. The signal of methylpyridinium ($\delta = 4.34$ ppm, s, for the methyl group of methylpyridinium) is observed.

Degradation of octa(methoxycarbonyl)cycloheptadiene in reaction with TEA

Octa(methoxycarbonyl)cycloheptatriene (0.018 mmol, 0.010 g), DMSO- d_6 and TEA (5 eq., 0.090 mmol, 12 μ l) were added to an NMR tube, and the mixture was kept for 3 hours at room temperature. Then an ^1H NMR spectrum of the mixture was recorded, the signals of penta(methoxycarbonyl)cyclopentadienide and 1,1,2-tricarbomethoxyethylene were observed ($\delta = 3.52$ ppm, s, for the methyl groups of penta(methoxycarbonyl)cyclopentadienide, and $\delta = 3.76, 3.75, 3.70$ ppm, all s, for the methyl groups of 1,1,2-tricarbomethoxyethylene).

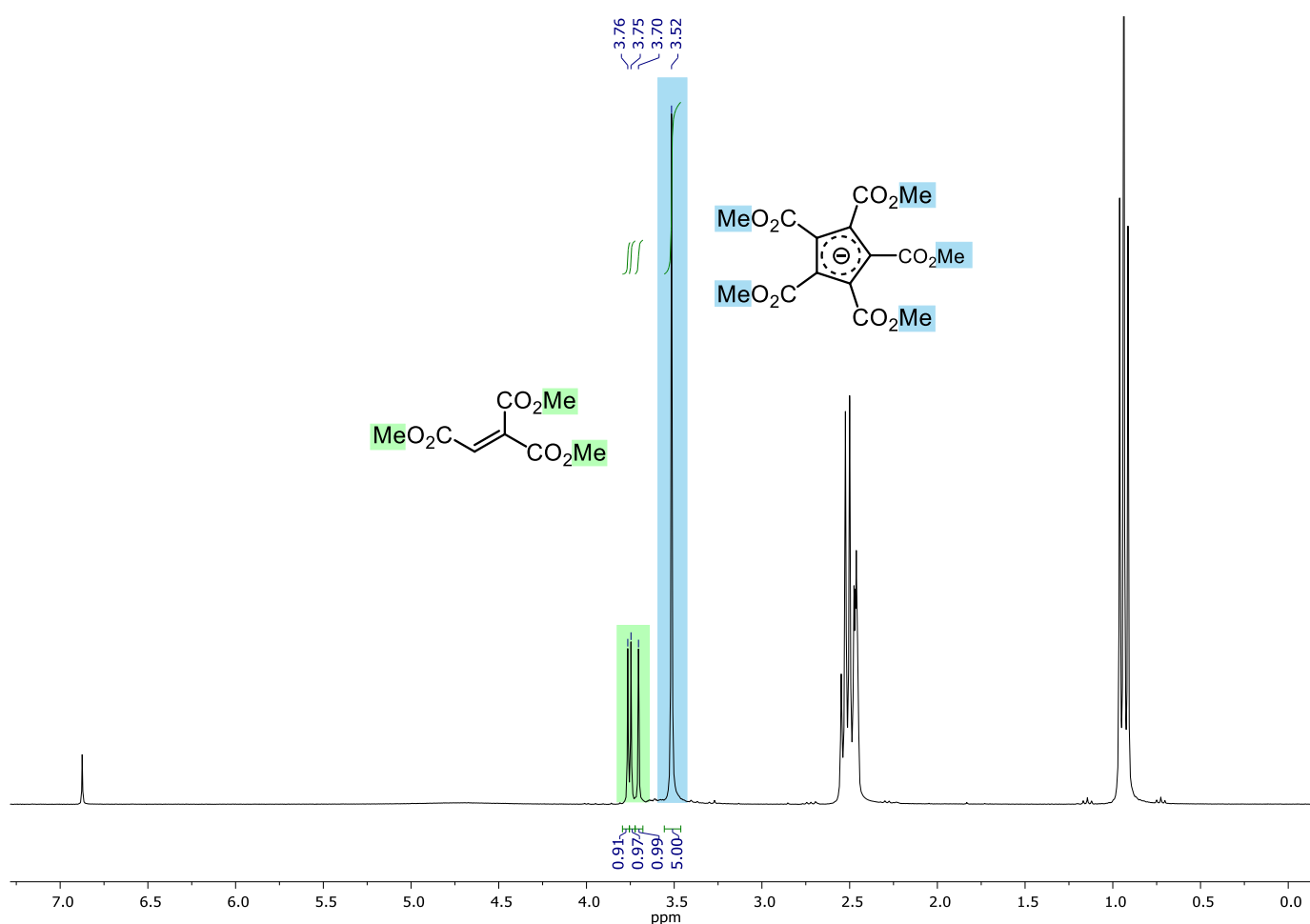


Figure S2. NMR ^1H spectrum of penta(methoxycarbonyl)cyclopentadienide and 1,1,2-tricarbomethoxyethylene in DMSO- d_6 (300 MHz).

DFT studies of the reactions mechanisms

The reactions energy profiles were calculated at revDSD-PBEP86(D4)/aug-cc-pVTZ//r2SCAN-3c level of theory.

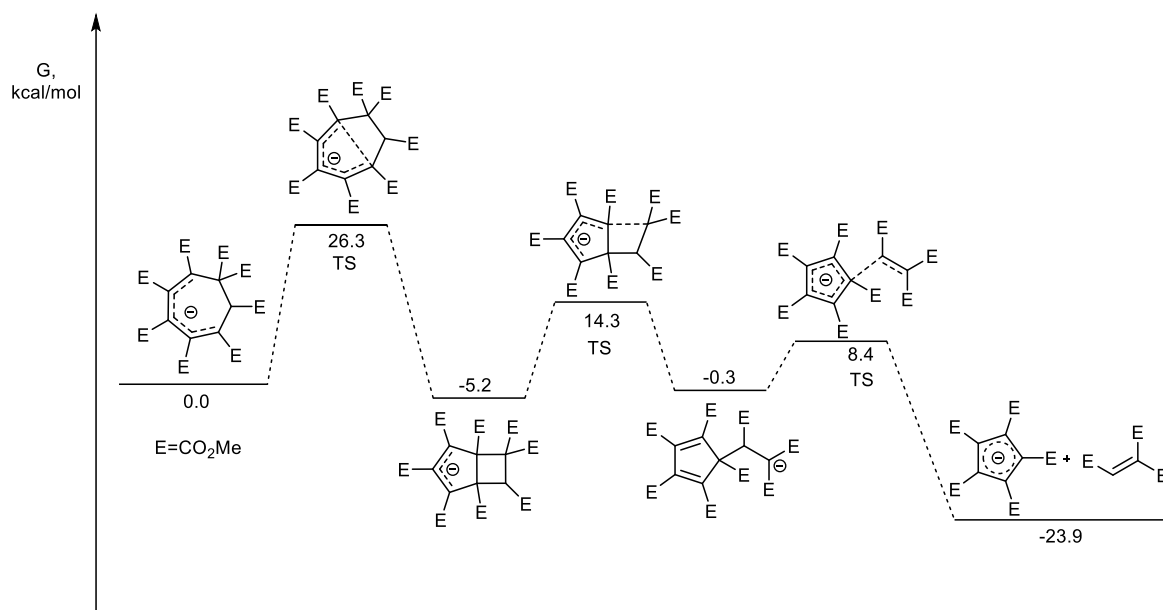


Figure S3. DFT study of reaction of octa(methoxycarbonyl)cycloheptadiene **1** with sodium borohydride.

Fukui function of norcaradiene 8

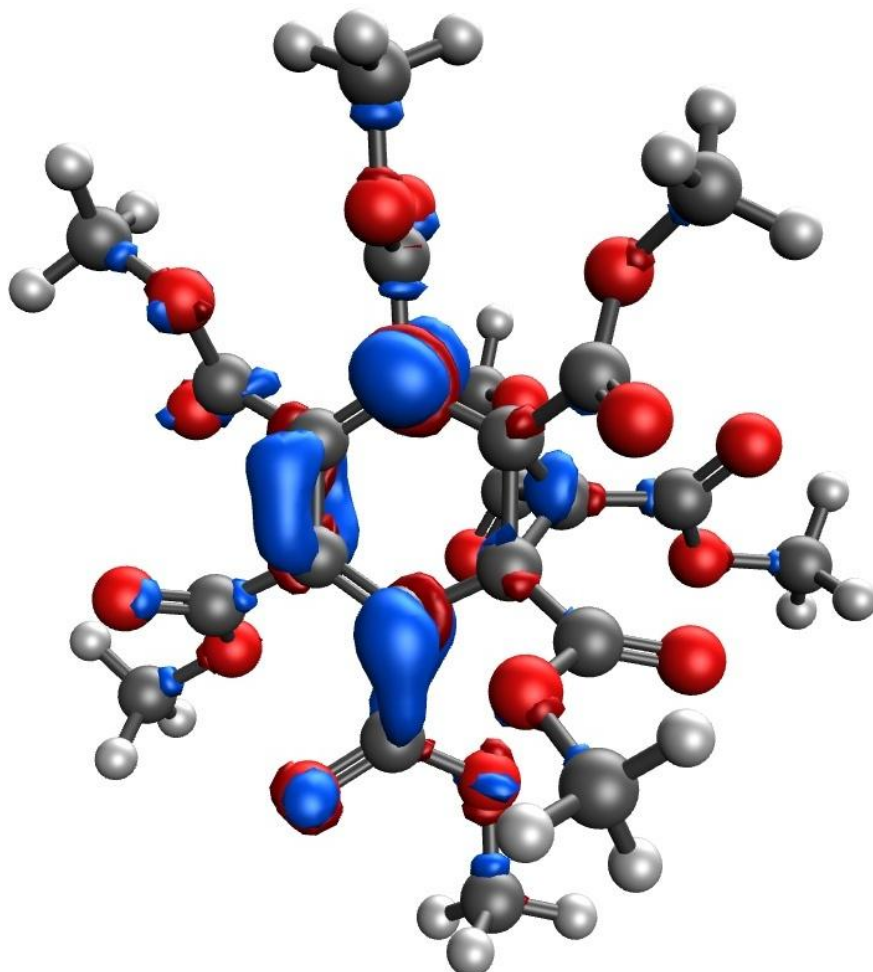
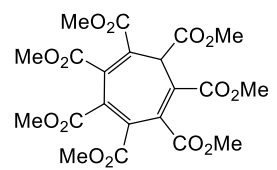


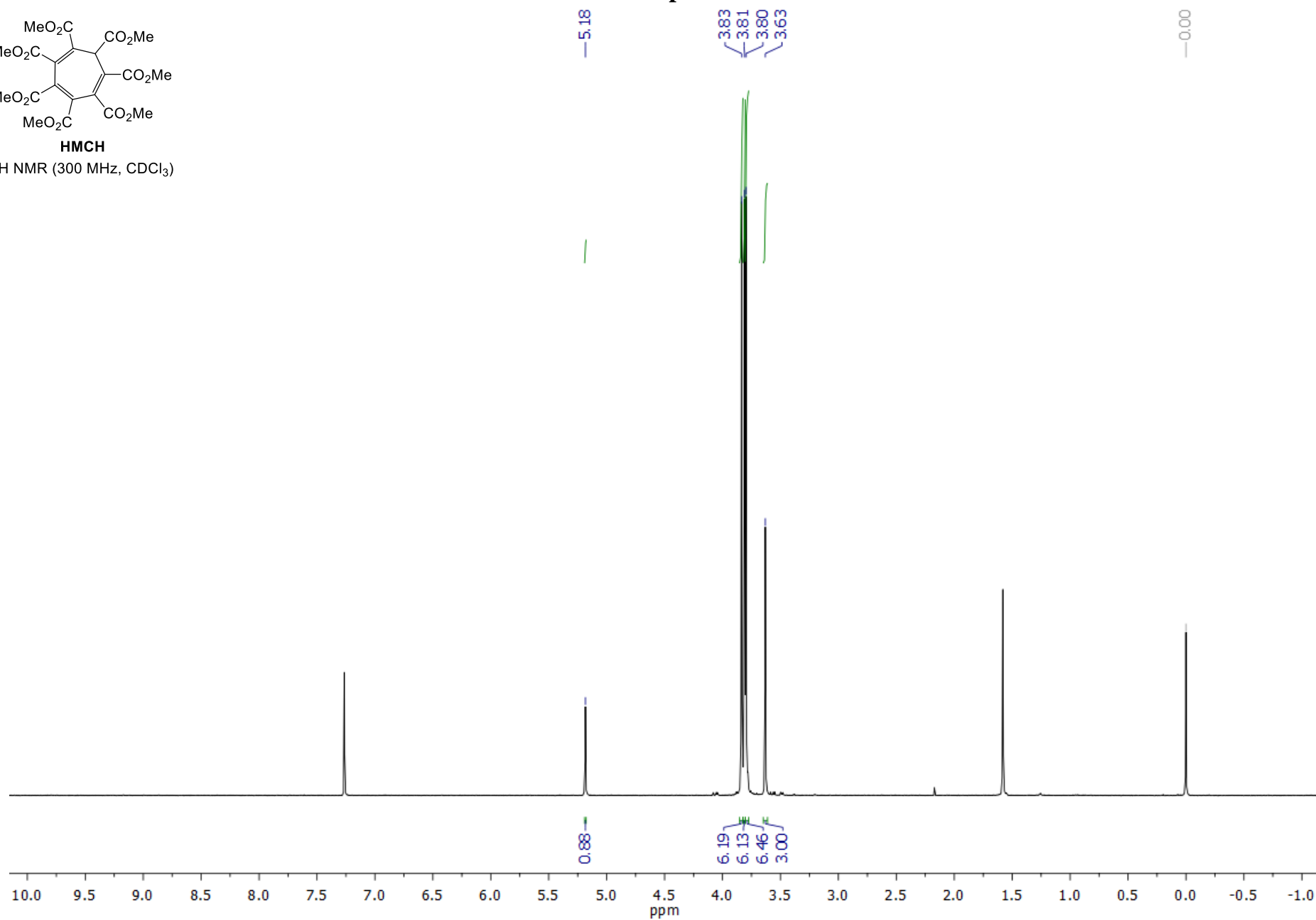
Figure S4. Fukui function representation of norcaradiene **8**.

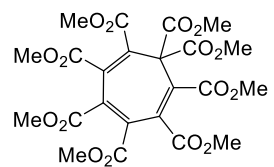


HMCH

^1H NMR (300 MHz, CDCl_3)

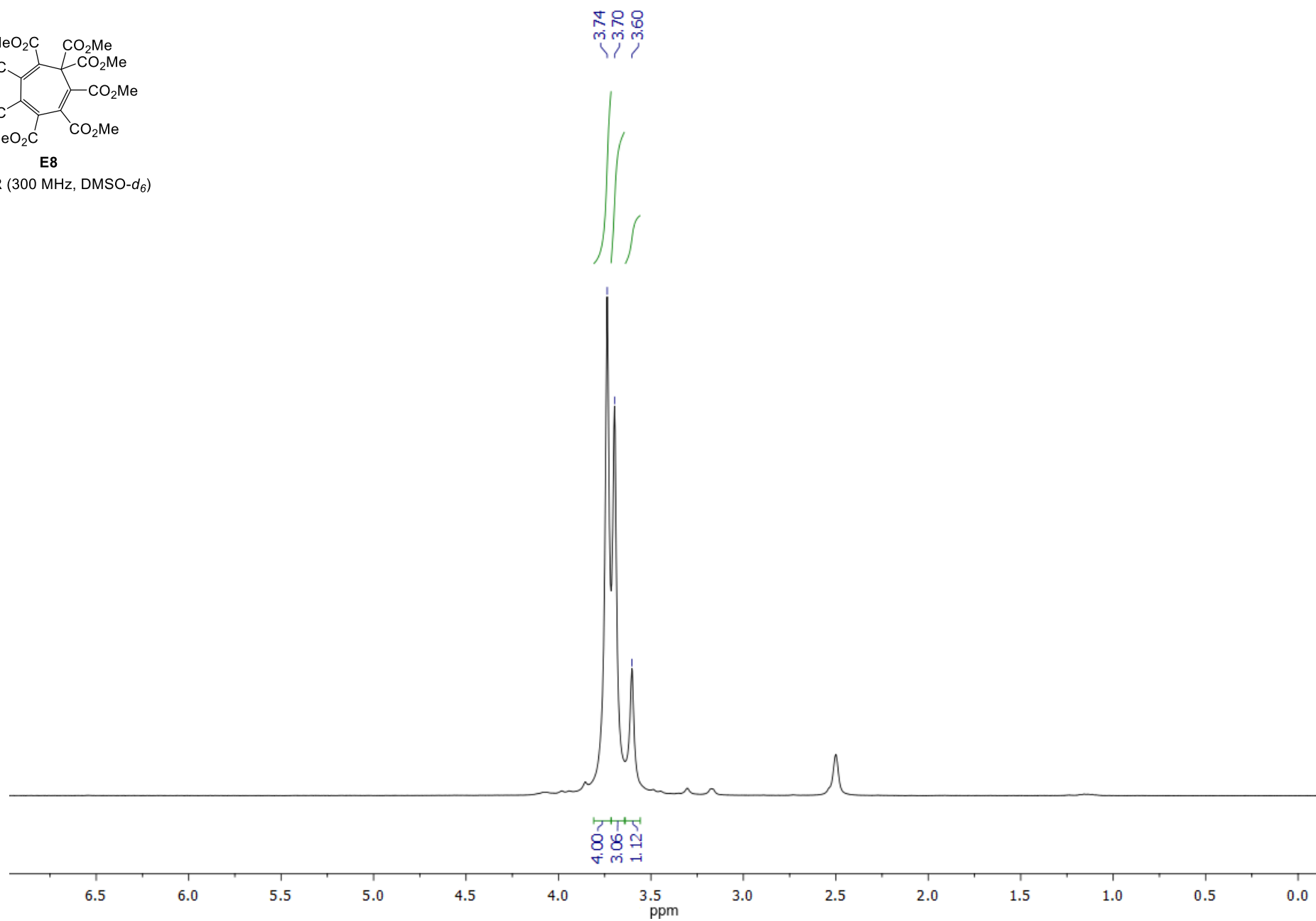
NMR spectra

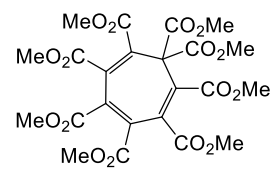




E8

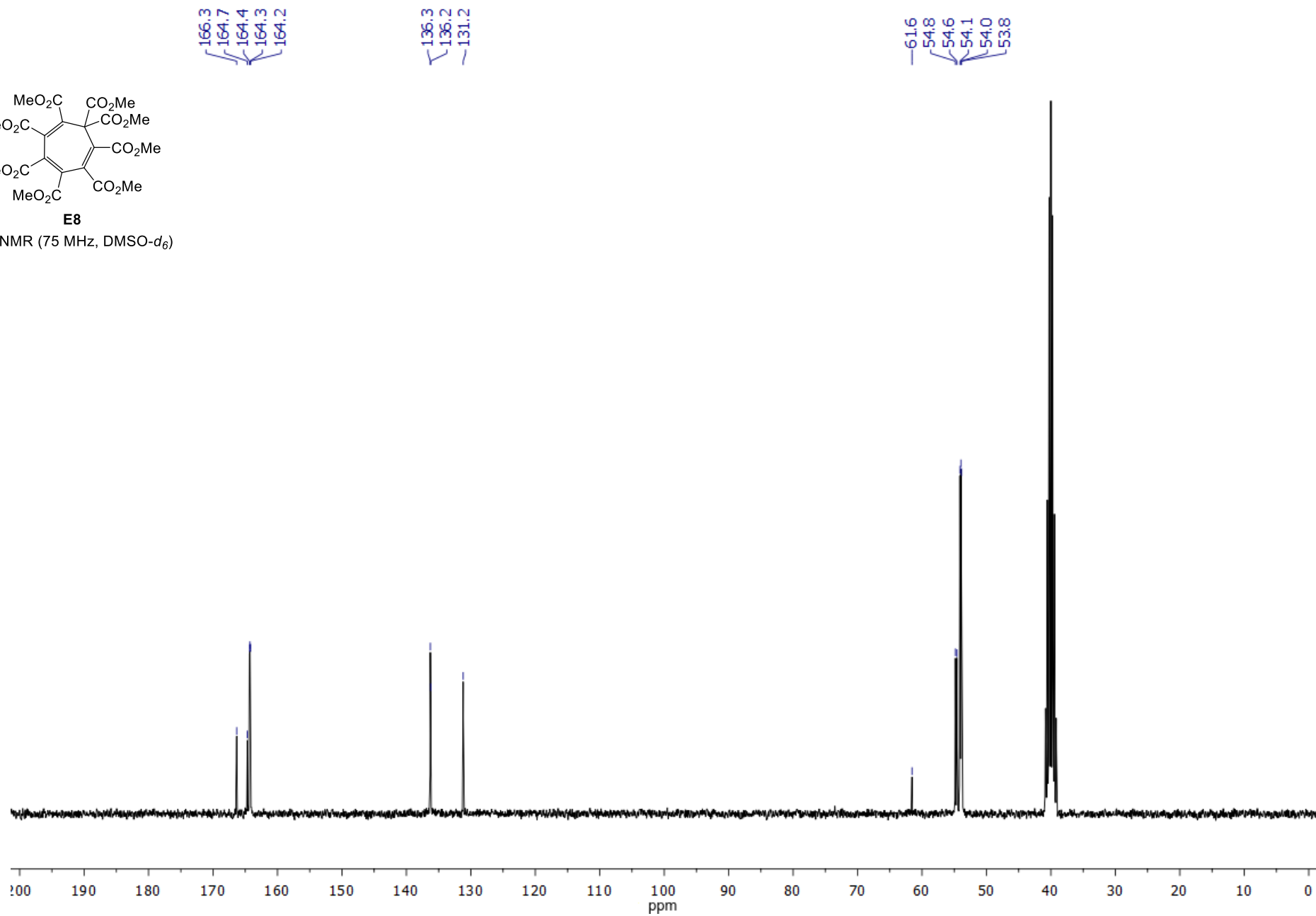
^1H NMR (300 MHz, $\text{DMSO}-d_6$)

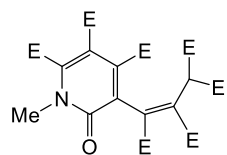




E8

¹³C NMR (75 MHz, DMSO-*d*₆)

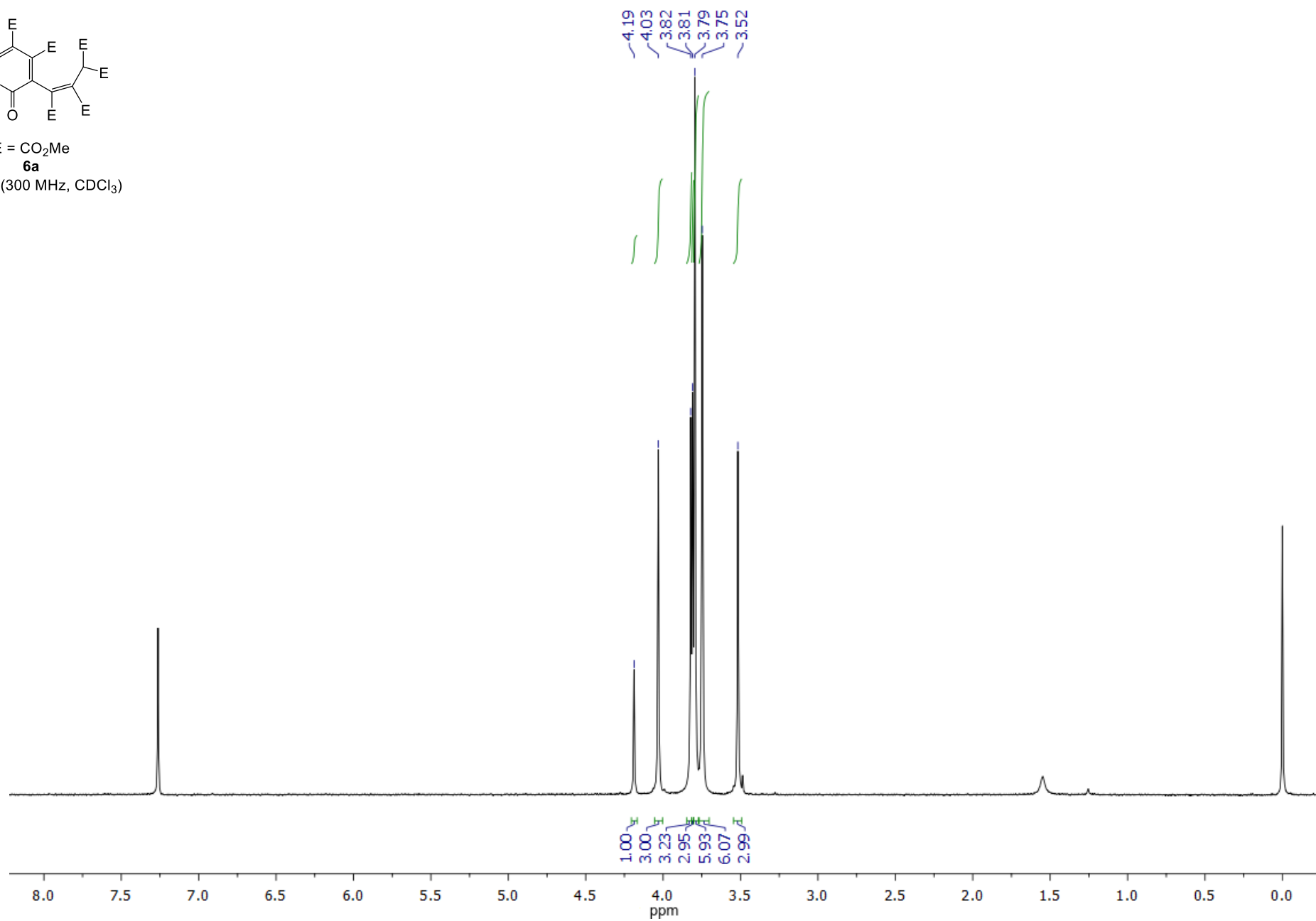


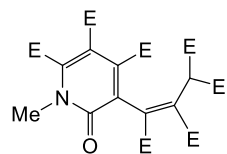


E = CO₂Me

6a

¹H NMR (300 MHz, CDCl₃)

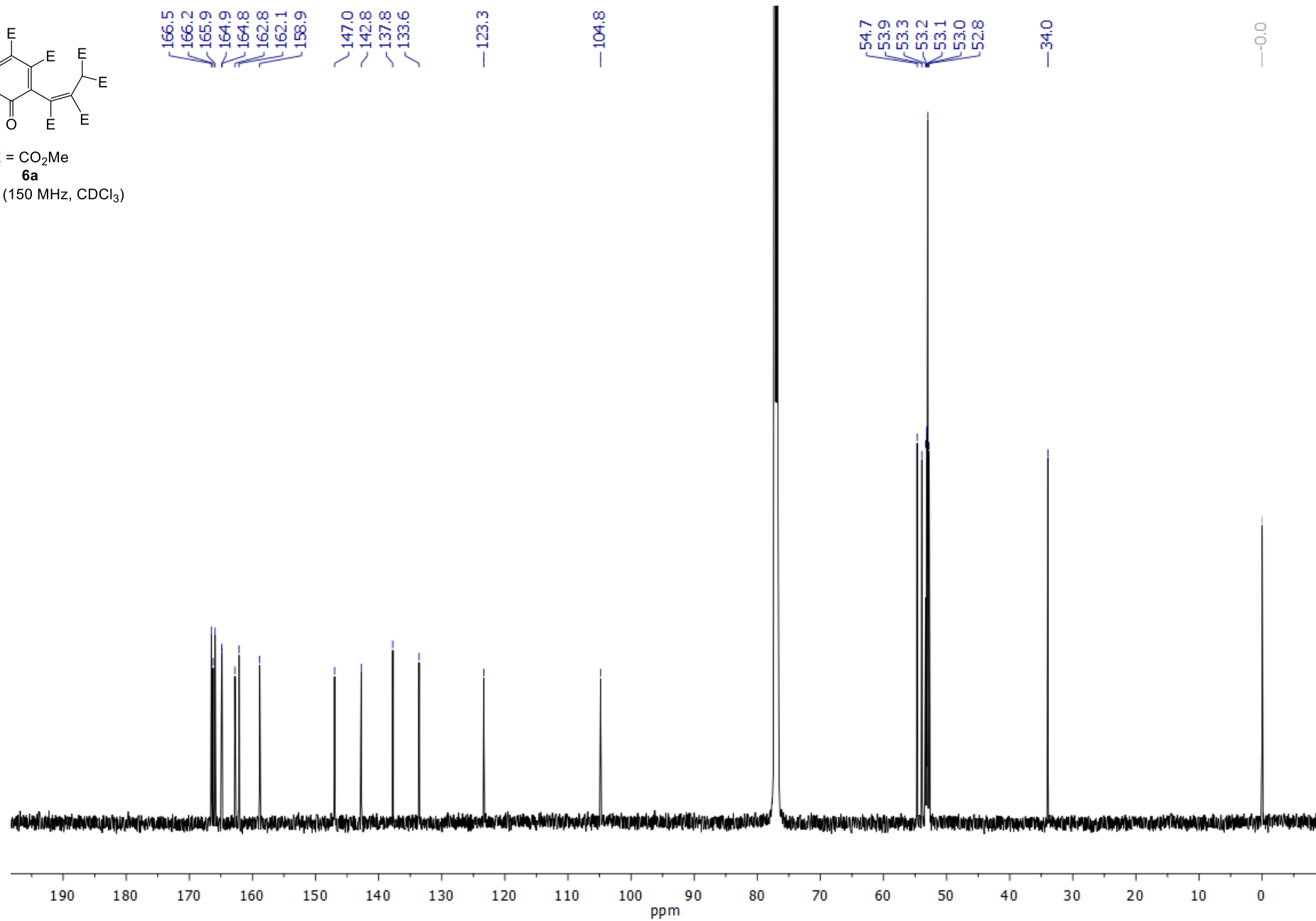


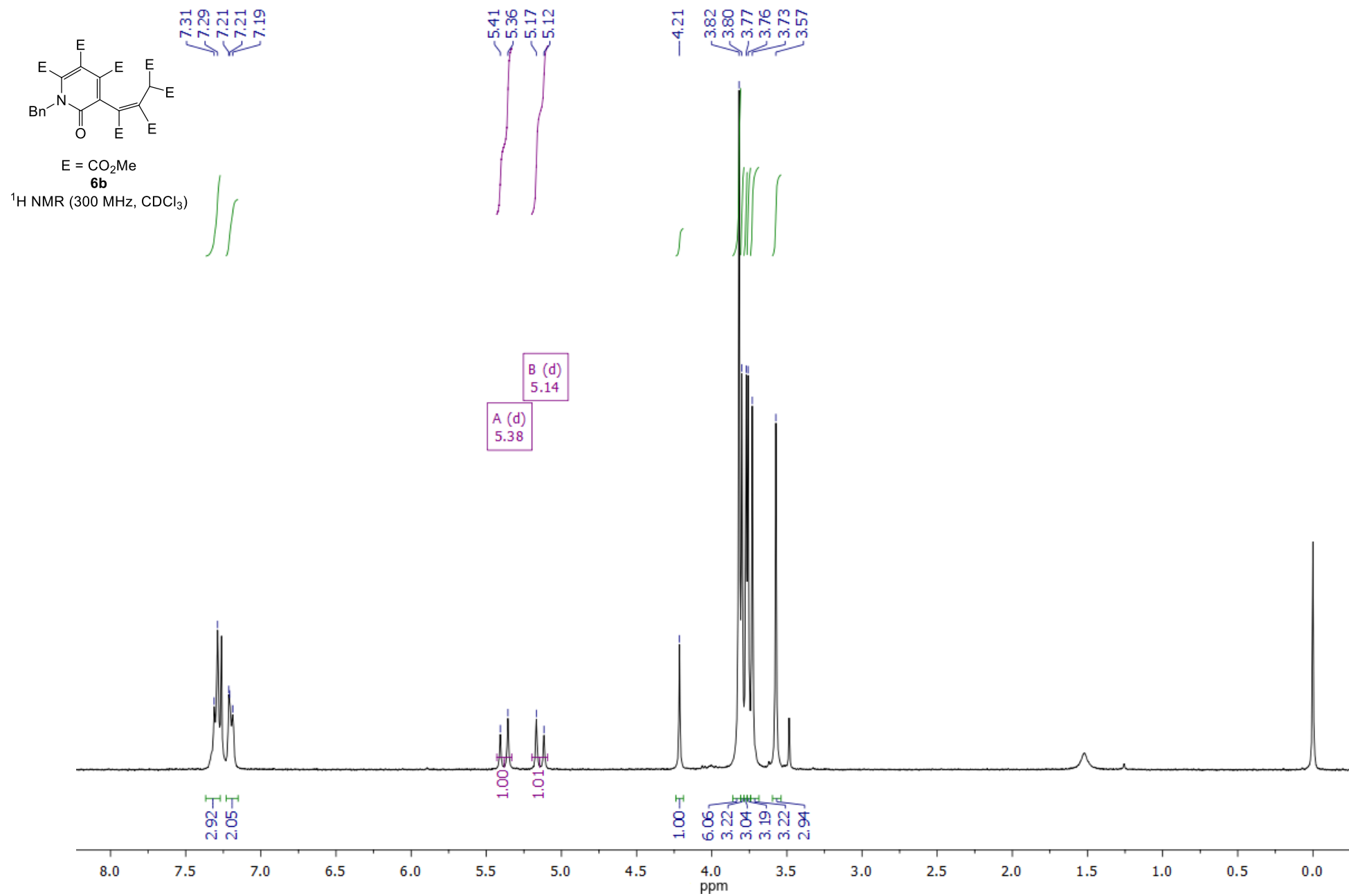


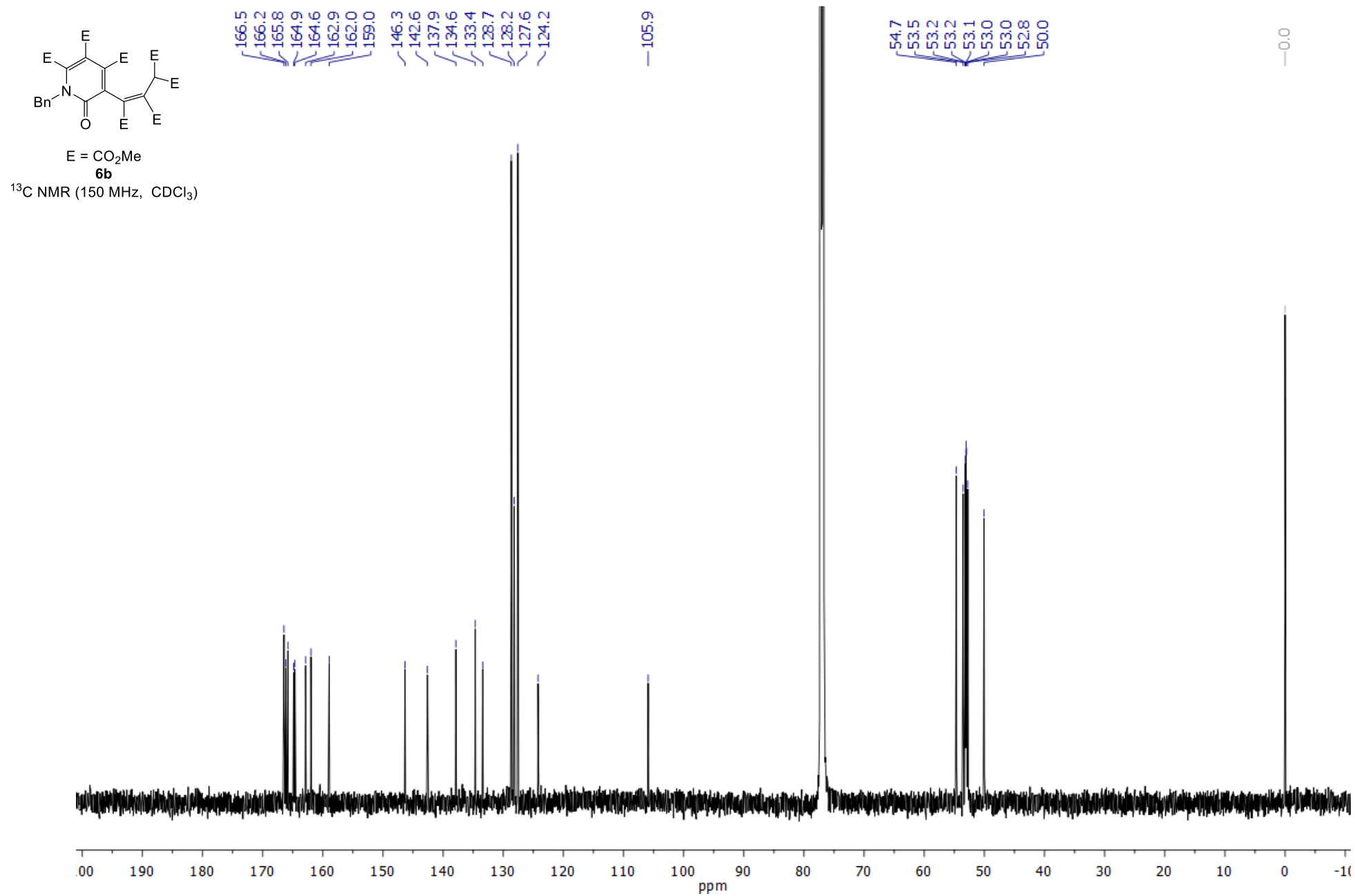
E = CO₂Me

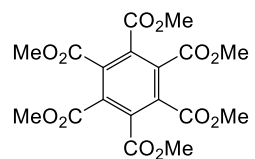
6a

¹³C NMR (150 MHz, CDCl₃)



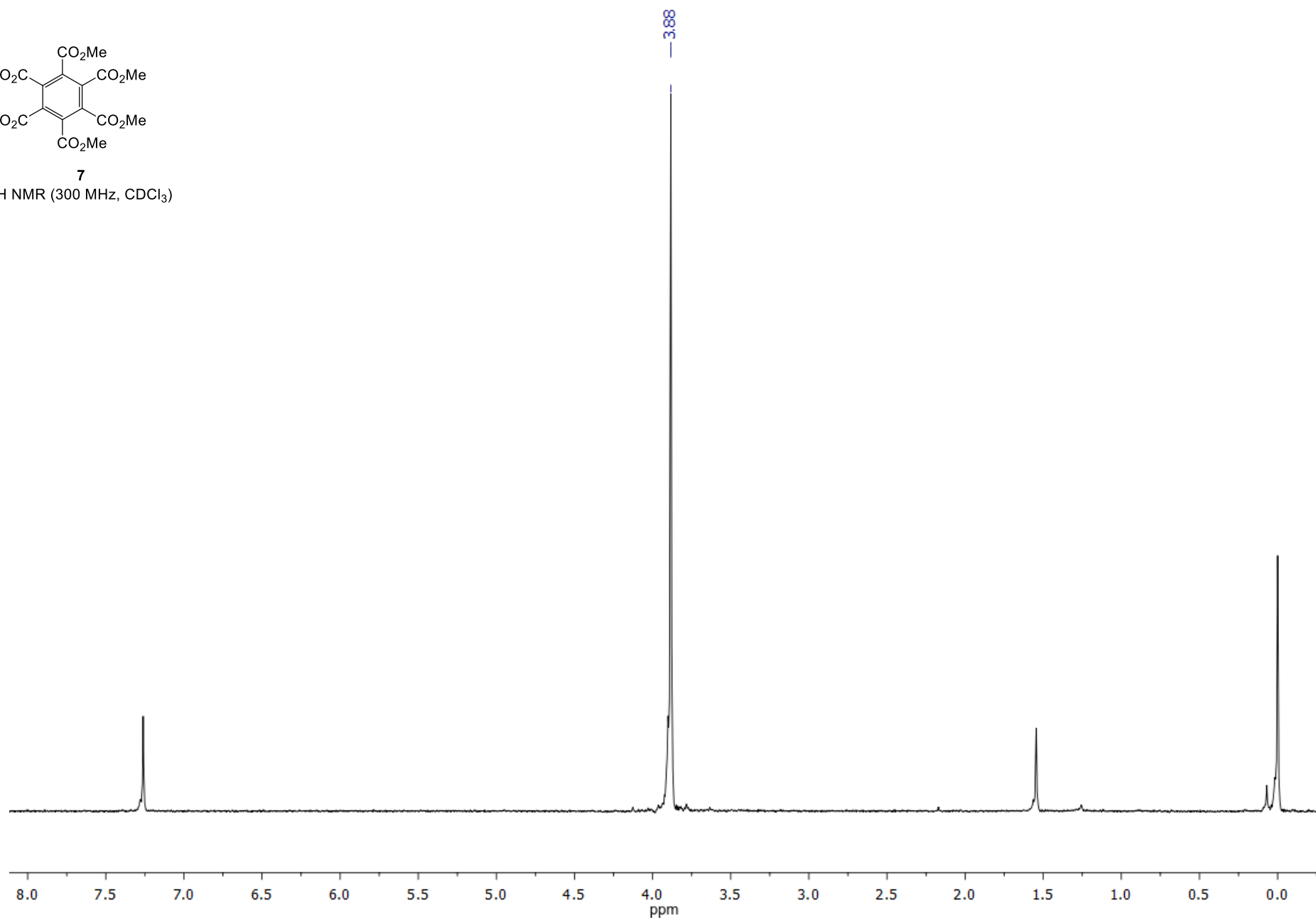






7

^1H NMR (300 MHz, CDCl_3)



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