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Protic additives in aprotic solvent: a tool to improve sodium borohydride reductions of C–C bonds

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General Information

^{1}H NMR and ^{13}C NMR spectra were recorded on a «Bruker AVANCE II 300» spectrometer at 300 and 75 MHz, respectively, in $CDCl_3$ with tetramethylsilane as an internal reference standard and DMSO-d_6. 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.

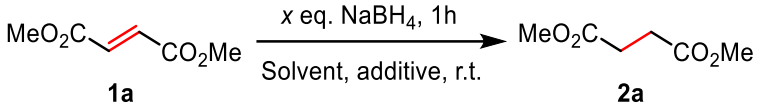
Substrates **1a-c** were commercially available reagents. Substrates **1d**,[S1] **1g**,[S2] **1j**,[S3] **1k**,[S4] **1l**,[S5] **3a**,[S6] **3b**,[S7] **8b**,[S8] were obtained according to the respective literature procedures. Substrates **1e**,[S9] **1f**,[S10] **1h**,[S11] **1i**,[S12] and **8a** were provided by our colleagues Dr. Denis D. Borisov, Dr. Irina A. Borisova and Dr. Mikhail O. Zubkov.

Quantum chemical calculations were carried out using ORCA 5.0.4 software package.2–4 CREST software package was used to find the most stable conformations.[S13,S14] The calculation of ring-opening stages were performed in the following manner. Geometry optimization and frequency calculations were performed using the method r^{2}SCAN-3c, while the electron energy was obtained at revDSD-PBEP86(D4)/aug-cc-pVTZ/CPCM(methanol) level of theory.[S15–S18] The calculations of the general mechanism was performed on PBE0-D3(BJ)/def2-TZVP/CPCM(methanol) theory level.[S19] The Grimme's dispersion corrections with Becke-Johnson damping were utilized.[S20,S21] All ground stated had no imaginary frequencies, all transition states had one imaginary frequency and the direction of the vibration corresponded to the reaction coordinate. The results of modelling are presented in supplementary file as Cartesian coordinates. The energy values are given in kcal/mol. The NICS(0), NICS(1), NICS(1)$_{zz}$ values were obtained using PBE0(D4)/pcsSeg-2//r2SCAN-3 level of theory.

Optimization of reduction conditions

The optimization of reaction conditions for the reduction of activated esters and nitriles was carried out on dimethyl fumarate **1a** as model substrate. The conversions and yields were determined *via* GC with cetane as internal standard. It was discovered in advance that the reduction reaction rate was sufficient to carry out the reaction at ambient temperature. Moreover, the addition of small amounts of protic solvents to the reaction mixtures was efficient to prevent olygomerization processes. Water and trifluoroethanol gave most attractive results, however water was chosen as attractive for industrial scale.

Table S1. Optimization of reduction of dimethyl fumarate 1a to dimethyl succinate 2a.



1a **2a**

Entry	Reagent	Solvent	Additive	Conversion, %[a]	NMR yield, %[b]
1	3 eq. $NaBH_4$	MeOH	—	100[c]	9
2	3 eq. $NaBH_4$	MeCN	—	33[d]	22
3	3 eq. $NaBH_4$	MeCN	5% MeOH	75[e]	69
4	3 eq. $NaBH_4$	MeCN	5% AcOH	<5%[f]	<5%
5	3 eq. $NaBH_4$	MeCN	5% F_3CCH_2OH	100	93
6	2 eq. $NaBH_4$	MeCN	5% F_3CCH_2OH	99	93
7	3 eq. $NaBH_4$	MeCN	5% H_2O	100	96
8	2 eq. $NaBH_4$	MeCN	5% H_2O	98	90
9	1.5 eq. $NaBH_4$	MeCN	5% H_2O	93	87
10	1 eq. $NaBH_4$	MeCN	5% H_2O	93	85

[a] – Determined as the ratio of integral intensity of all ester groups to that of the starting material's ester groups; [b] – determined as the ratio of integral intensity of the product's ester groups to that of all ester groups; [c] – contaminated with products of one ester group's reduction; [d] – contaminated with oligomerization products; [e] – contaminated with products of the addition of methanol to **1a**; [f] – little or no reduction reaction was detected.

Synthetic Procedures

The reduction of activated alkenes at room temperature

To a solution of activated alkene **1** (1 mmol) in 15 ml of 5% water in acetonitrile (v/v) *x* eq. of sodium borohydride were added. The reaction mixture was stirred at r.t. for *y* h, then diluted with water and extracted with ethyl acetate 3 times. The combined organic fractions were dried over sodium sulfate and evaporated.

Dimethyl succinate, **2a**

As the substrate, the corresponding fumarate was used. The reaction time was 1 h, sodium borohydride amount was 2.0 eq. No additional purification procedures needed, the final product (85% yield) was obtained as a colorless oil. ^{1}H NMR (300.13 MHz, $CDCl_3$) δ 3.67 (s, 6H, OCH_3), 2.61 (s, 4H, CH_2). The NMR spectrum corresponds to previously reported.[S22]

Diethyl succinate, **2b**

As the substrate, the corresponding fumarate was used. The reaction time was 2.5 h, sodium borohydride amount was 2.5 eq. No additional purification procedures needed, the final product (93% yield) was obtained as a colorless oil. ^{1}H NMR (300.13 MHz, $CDCl_3$) δ 4.15 (q, J = 7.2 Hz, 4H, OCH_2), 2.62 (s, 4H, CH_2–CH_2), 1.26 (t, J = 7.1 Hz, 6H, CH_3). The NMR spectrum corresponds to previously reported.[S23]

Diisopropyl succinate, **2c**

As the substrate, the corresponding fumarate was used. The reaction time was 3 h, sodium borohydride amount was 3.5 eq. The crude product was purified with column chromatography $CHCl_3$/EtOAc 4:1 (v/v) on silica-gel, the final product (87% yield) was obtained as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.02 (hept, J = 6.3 Hz, 2H, CH), 2.58 (s, 4H, CH_2), 1.23 (d, J = 6.3 Hz, 12H, CH_3). The NMR spectrum corresponds to previously reported.[S24]

Trimethyl propane-1,2,3-tricarboxylate, **2d**

The reaction time was 3 h, sodium borohydride amount was 5.0 eq. The crude product was purified with column chromatography $CHCl_3$/AcOH 200:1 (v/v) on silica-gel, the final product (39% yield) was obtained as a colorless oil. ^{1}H NMR (300.13 MHz, $CDCl_3$) δ 3.72 (s, 3H, $CHCO_2C\mathit{H}_3$), 3.69 (s, 6H, $CH_2CO_2C\mathit{H}_3$), 3.28 (p, J = 6.7 Hz, 1H, CH), 2.79 (dd, J = 16.7, 6.8 Hz, 2H, CH_2), 2.61 (dd, J = 16.7, 6.5 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S25]

Dimethyl 2-(cyclohexylmethyl)malonate, **2e**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$/EtOAc 4:1 (v/v) on silica-gel, the final product (58% yield) was obtained as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.73 (s, 6H, OCH_3), 3.49 (t, J = 7.7 Hz, 1H, CH(CO_2Me)$_2$), 1.81 (t, J = 7.3 Hz, 2H, CH–CH_2–CH), 1.76 – 1.59 (m, 5H, cyclohexyl), 1.29 – 1.05 (m, 4H, cyclohexyl), 0.90 (q, J = 10.8, 10.1 Hz, 2H, cyclohexyl). The NMR spectrum corresponds to previously reported.[S26]

Dimethyl 2-benzylmalonate, **2f**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$ on silica-gel, the final product (72% yield) was obtained as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35 – 7.15 (m, 5H, Ar), 3.70 (s, 6H, OCH_3), 3.68 (t, J = 7.8 Hz, 1H, CH_2–CH), 3.22 (d, J = 7.8 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S27]

Dimethyl 2-(4-methoxybenzyl)malonate, **2g**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$ on silica-gel, the final product (73% yield) was obtained as white crystals. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.11 (d, J = 8.6 Hz, 2H, Ar), 6.81 (d, J = 8.6 Hz, 2H, Ar), 3.78 (s, 3H, ArOCH_3), 3.70 (s, 6H, CO_2CH_3), 3.63 (t, J = 7.8 Hz, 1H, CH_2–CH), 3.16 (d, J = 7.8 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S28]

Dimethyl 2-(4-cyanobenzyl)malonate, **2h**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$ on silica-gel, the final product (90% yield) was obtained as white crystals. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.58 (d, *J* = 8.1 Hz, 2H, Ar), 7.32 (d, *J* = 8.2 Hz, 2H, Ar), 3.71 (s, 6H, OCH_3), 3.67 (t, *J* = 7.8 Hz, 1H, CH_2–C*H*), 3.28 (d, *J* = 7.7 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S29]

Dimethyl 2-(2,6-dichlorobenzyl)malonate, **2i**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$ on silica-gel, the final product (78% yield) was obtained as white powder, m.p. 97–99°C. ^{1}H NMR (300.13 MHz, $CDCl_3$) δ 7.29 (d, *J* = 8.3 Hz, 2H, Ar), 7.12 (dd, *J* = 8.7, 7.4 Hz, 1H, Ar), 3.83 (dd, *J* = 8.1, 7.3 Hz, 1H, CH_2–C*H*), 3.72 (s, 6H, OCH_3), 3.57 (d, *J* = 7.7 Hz, 2H, CH_2), ^{13}C NMR (75.5 MHz, $CDCl_3$) δ: 196.0 (*C*O_2CH_3), 136.9 (C–Cl), 133.9 (Ar), 128.8 (Ar), 128.5 (Ar), 52.8 (OCH_3), 50.0 (CH_2–*C*H), 30.2 (CH_2). HRMS Calc. for [$C_{12}H_{12}O_4Cl_2$+H] 291.0185, found 291.0179.

2-Benzylmalononitrile, **2j**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The crude product was purified with column chromatography $CHCl_3$/AcOH 100:1 (v/v) on silica-gel, the final product (73% yield) was obtained as white crystals. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.46 – 7.29 (m, 5H, Ar), 3.91 (t, *J* = 6.9 Hz, 1H, CH_2–C*H*), 3.29 (d, *J* = 6.9 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S30]

2-(4-Nitrobenzyl)malononitrile, **2k**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The final product was crystallized in toluene (60% yield) as grey powder, ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.30 (d, *J* = 8.7 Hz, 2H, Ar), 7.55 (d, *J* = 8.5 Hz, 2H, Ar), 4.03 (t, *J* = 6.6 Hz, 1H, CH_2–C*H*), 3.41 (d, *J* = 6.6 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S31]

5-Benzyl-1,3-dimethylpyrimidine-2,4,6(1H,3H,5H)-trione, **2l**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. When extracted, sulfuric acid 1M solution in water phase is needed. No additional purification procedures needed, the final product (99% yield) was obtained as white powder. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.24 (dt, *J* = 6.7, 4.2 Hz, 3H, Ar), 7.03 (dd, *J* = 6.7, 2.9 Hz, 2H, Ar), 3.78 (t, *J* = 4.8 Hz, 1H, CH_2–C*H*), 3.47 (d, *J* = 4.8 Hz, 2H, CH_2), 3.13 (s, 6H, N–CH_3). The NMR spectrum corresponds to previously reported.[S32]

Heptamethyl bicyclo[3.2.0]hept-2-ene-1,2,3,4,5,6,7-heptacarboxylate, **4**

The reaction time was 1 h, sodium borohydride amount was 1.5 eq. The final product was crystallized in methanol (54% yield) as yellow crystals, mp = 136-137°C. ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.88 (s, 1H, =C–CH), 4.35 (d, *J* = 10.7 Hz, 1H, ^{cbut}CH), 4.08 (d, *J* = 10.7 Hz, 1H, ^{cbut}CH), 3.75 (s, 3H, O–CH_3), 3.67 (s, 3H, O–CH_3), 3.66 (s, 3H, O–CH_3), 3.65 (s, 3H, O–CH_3), 3.63 (s, 3H, O–CH_3), 3.62 (s, 3H, O–CH_3), 3.58 (s, 3H, O–CH_3). The NMR spectrum corresponds to previously reported.[S6]

The reduction of cycloheptatriene derivatives into cyclopentadienyl anion 5

To a solution of either **3a** or **3b** (1 mmol) in 15 ml acetonitrile, 76 mg (2 mmol, 2 eq.) of sodium borohydride were added. The reaction mixture was refluxed for 5 h, then diluted with water and extracted with ethyl acetate 3 times. The combined organic fractions were dried over sodium sulfate and evaporated. The product was isolated by crystallization from methanol.

Sodium pentakis(methoxycarbonyl)cyclopentadienide, **5**

Yellow powder, ^{1}H NMR (300 MHz, [D_6]-DMSO) δ 3.55 (s, 15H, O–CH_3). The NMR spectrum corresponds to previously reported.[S33]

The reduction of diarylcyclopropenones

To a suspension of 1,3-diarylcyclopropenone **8a** or **9a** (1 mmol) in 5 ml absoluted methanol sodium borohydride (5 eq.) was gradually added while stirring. Then, the reaction mixture, gradually becoming orange, was stirred at r.t. for 1 h, then diluted with water and extracted to dichloromethane 3 times. The combined organic fractions were dried over sodium sulfate and evaporated.

1,3-Diphenylpropan-2-ol, **9a**

Yellow oil, difficult to separate from its isomer, **10a**. ^{1}H NMR (300 MHz, $CHCl_3$) δ 7.38-7.30 (m, 10H, Ar), 4.08 (ddd, *J* = 8.1, 4.8, 3.4 Hz, 1H, C*H*(OH)), 2.88 (dd, *J* = 13.7, 4.8 Hz, 2H, CH_2), 2.77 (dd, *J* = 13.7, 8.1 Hz, 2H, CH_2). The NMR spectrum corresponds to previously reported.[S34]

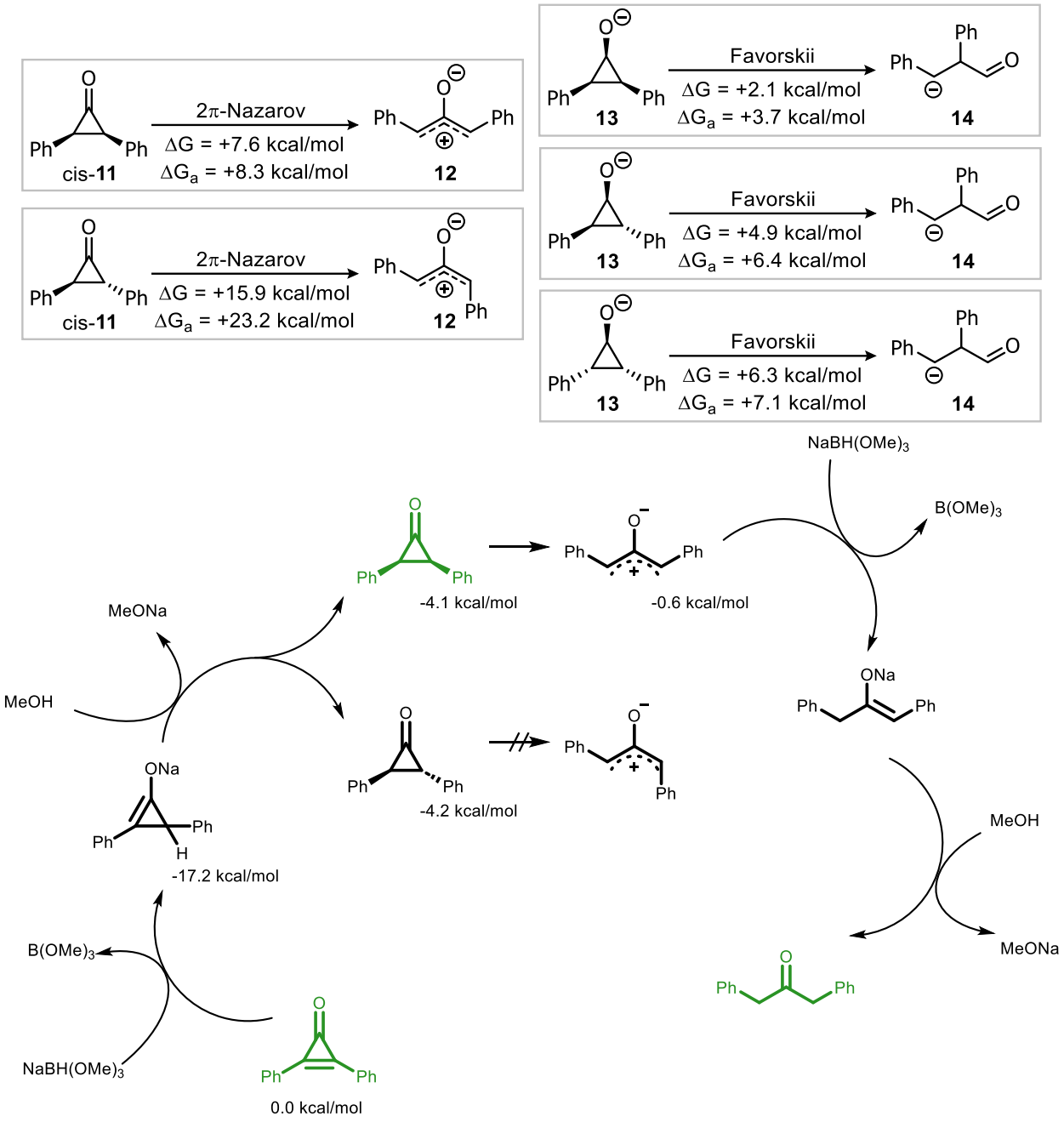
2,3-Diphenylpropan-1-ol, **10a**

Yellow oil, difficult to separate from its isomer, **9a**. ^{1}H NMR (300 MHz, $CHCl_3$) δ 7.24-7.05 (m, 10H, Ar), 3.77 (d, *J* = 5.6 Hz, 2H, C*H*$_2$(OH)), 3.13–3.03 (m, 2H, Ph–CH_2), 2.96 (dd, *J* = 24.4, 6.9 Hz, 1H). The NMR spectrum corresponds to previously reported.[S35]

1,3-Bis(2,5-dimethylthiophen-3-yl)propan-2-ol, **9b**

The crude product was purified with column chromatography $CHCl_3$/EtOAc 4:1. The final product (78% yield) was obtained as yellow oil. ^{1}H NMR ($CDCl_3$, 300 MHz, δ, м.д.): 6.49 (с, 2H, Ar), 3.93 (м, 1H, CH), 2.65–2.59 (м, 4H, CH_2), 2.38 (с, 6H, Me), 2.29 (с, 6H, Me). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 135.8 (Ar), 133.7 (Ar), 132.3 (Ar), 127.3 (Ar), 72.6 (–CH_2–*C*HOH), 35.9 (–*C*H_2–CHOH), 15.2 (–*C*H_3), 13.1 (–*C*H_3). HRMS: Calc. for [$C_{15}H_{20}OS_2$+Na] 303.0853; found 303.0848.

Molecular modelling



NICS values

2,3-Diphenylcyclopropen-1-one
NICS(0) = –19

NICS(1) = –8

NICS(1)$_{zz}$ = –9

Transition state for cis*-2,3-diphenylcyclopropan-1-one cleavage*
NICS(0) = –14

NICS(1) = –3; –5

NICS(1)$_{zz}$ = –6;–10

Cartesian coordinates

$NaBH(OMe)_3$

O	0.849940000000	0.657433000000	0.836041000000
B	0.107646000000	1.471293000000	-0.145719000000
H	-0.622492000000	0.805706000000	-0.884725000000
O	-0.603706000000	2.417607000000	0.725516000000
O	1.072497000000	2.280854000000	-0.937717000000
C	-1.476716000000	3.299624000000	0.073325000000
H	-1.917014000000	3.977015000000	0.809632000000
H	-0.959702000000	3.901852000000	-0.684497000000
H	-2.290266000000	2.757212000000	-0.426679000000
C	1.630737000000	-0.380814000000	0.309927000000
H	1.036068000000	-1.041517000000	-0.335068000000
H	2.474465000000	-0.006072000000	-0.284319000000
H	2.034390000000	-0.977060000000	1.132606000000
C	1.348876000000	1.944197000000	-2.266485000000
H	0.429326000000	1.862908000000	-2.859587000000
H	1.972639000000	2.725070000000	-2.710642000000
H	1.887511000000	0.991554000000	-2.354675000000
Na	1.642203000000	2.822194000000	1.206807000000

Trimethyl borate

O	0.605113000000	0.532782000000	0.797168000000
B	0.318894000000	1.744602000000	0.229459000000
O	-0.704792000000	2.411135000000	0.839952000000
O	1.061108000000	2.136265000000	-0.845024000000
C	-1.444547000000	3.472902000000	0.267559000000
H	-2.407898000000	3.512054000000	0.777095000000
H	-0.937781000000	4.430230000000	0.407541000000
H	-1.622756000000	3.313879000000	-0.798134000000
C	1.721342000000	-0.217735000000	0.358705000000
H	1.584828000000	-0.566090000000	-0.668374000000
H	2.641091000000	0.370669000000	0.407922000000
H	1.816278000000	-1.082067000000	1.016322000000
C	1.156175000000	3.450239000000	-1.363482000000
H	2.092460000000	3.514191000000	-1.918682000000
H	0.330339000000	3.667011000000	-2.043979000000
H	1.171866000000	4.196819000000	-0.567227000000

2,3-Diphenylcyclopropen-1-one (GS1)

C	-2.559061000000	-0.401807000000	0.725234000000
C	-1.940930000000	-1.151949000000	-0.306613000000
C	-2.845695000000	-0.184270000000	-0.621756000000
O	-2.716829000000	-0.143749000000	1.908188000000
C	-3.639951000000	0.639504000000	-1.470218000000
C	-3.685103000000	0.589810000000	-2.857270000000
C	-4.420770000000	1.562847000000	-0.789371000000
C	-4.506813000000	1.456013000000	-3.556140000000
C	-5.244312000000	2.433613000000	-1.483558000000
C	-5.288232000000	2.379785000000	-2.870773000000
H	-3.075101000000	-0.128696000000	-3.392316000000
H	-4.379468000000	1.596899000000	0.292847000000
H	-4.539696000000	1.412319000000	-4.638378000000
H	-5.850954000000	3.152720000000	-0.945832000000
H	-5.931274000000	3.057533000000	-3.420604000000
C	-1.035630000000	-2.164510000000	-0.774294000000
C	-0.266340000000	-2.871543000000	0.154504000000
C	-0.910515000000	-2.450212000000	-2.137077000000
C	0.618083000000	-3.845523000000	-0.275519000000
C	-0.026298000000	-3.426323000000	-2.560756000000
C	0.738631000000	-4.123161000000	-1.631814000000
H	-0.369059000000	-2.645933000000	1.209672000000
H	-1.510136000000	-1.905597000000	-2.856483000000
H	1.215102000000	-4.390620000000	0.446122000000
H	0.069232000000	-3.647339000000	-3.617392000000
H	1.431121000000	-4.886777000000	-1.967201000000

Trans-*2,3-diphenylcyclopropan-1-one*

C	-0.535275000000	-0.075916000000	-0.395326000000
C	-1.256935000000	-1.207244000000	-0.971770000000
C	-1.805851000000	0.287210000000	-1.010431000000
O	0.433935000000	0.290752000000	0.202731000000
H	-2.608785000000	0.450371000000	-0.292571000000
C	-1.948707000000	0.995409000000	-2.300589000000
C	-0.846689000000	1.280881000000	-3.105929000000
C	-3.218364000000	1.368050000000	-2.739156000000
C	-1.014091000000	1.915305000000	-4.327792000000
C	-3.383953000000	2.006520000000	-3.958937000000
C	-2.282440000000	2.280640000000	-4.758870000000
H	0.151828000000	1.014033000000	-2.775000000000
H	-4.080482000000	1.152461000000	-2.116869000000
H	-0.147521000000	2.132629000000	-4.942074000000
H	-4.377998000000	2.290275000000	-4.286006000000
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C	-1.940900000000	-2.252973000000	-0.182668000000
C	-2.299423000000	-2.050167000000	1.150683000000
C	-2.250941000000	-3.471357000000	-0.783946000000
C	-2.962040000000	-3.040461000000	1.858842000000
C	-2.910384000000	-4.463341000000	-0.072630000000
C	-3.269864000000	-4.251177000000	1.251008000000
H	-2.057974000000	-1.114570000000	1.645158000000
H	-1.973329000000	-3.638672000000	-1.819123000000
H	-3.233822000000	-2.867547000000	2.894101000000
H	-3.144753000000	-5.405017000000	-0.556277000000
H	-3.784465000000	-5.025487000000	1.808197000000
H	-0.870562000000	-1.526229000000	-1.938349000000

Cis-*2,3-diphenylcyclopropan-1-one*

C	-1.252153000000	0.396156000000	-0.153948000000
C	-0.907659000000	-0.734610000000	-0.998995000000
C	-2.166066000000	0.211865000000	-1.279430000000
O	-1.046159000000	0.979739000000	0.871594000000
H	-1.989887000000	0.844938000000	-2.144557000000
C	-3.556119000000	-0.266412000000	-1.121182000000
C	-4.396648000000	-0.280877000000	-2.233502000000
C	-4.045957000000	-0.740467000000	0.095884000000
C	-5.692821000000	-0.764130000000	-2.135790000000
C	-5.339873000000	-1.230178000000	0.191536000000
C	-6.168021000000	-1.244565000000	-0.922938000000
H	-4.024665000000	0.087779000000	-3.183696000000
H	-3.417083000000	-0.726776000000	0.978947000000
H	-6.332721000000	-0.766869000000	-3.011085000000
H	-5.704389000000	-1.597789000000	1.144164000000
H	-7.180513000000	-1.623842000000	-0.845193000000
C	-1.096011000000	-2.133200000000	-0.534656000000
C	-0.872690000000	-2.497340000000	0.789127000000
C	-1.529570000000	-3.098760000000	-1.441772000000
C	-1.078624000000	-3.807861000000	1.201349000000
C	-1.733580000000	-4.406203000000	-1.030998000000
C	-1.509482000000	-4.763959000000	0.293467000000
H	-0.537751000000	-1.751389000000	1.501324000000
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H	-2.071814000000	-5.148761000000	-1.744971000000
H	-1.671647000000	-5.786401000000	0.615279000000
H	-0.132012000000	-0.574140000000	-1.744038000000

*Zwitterion **12***

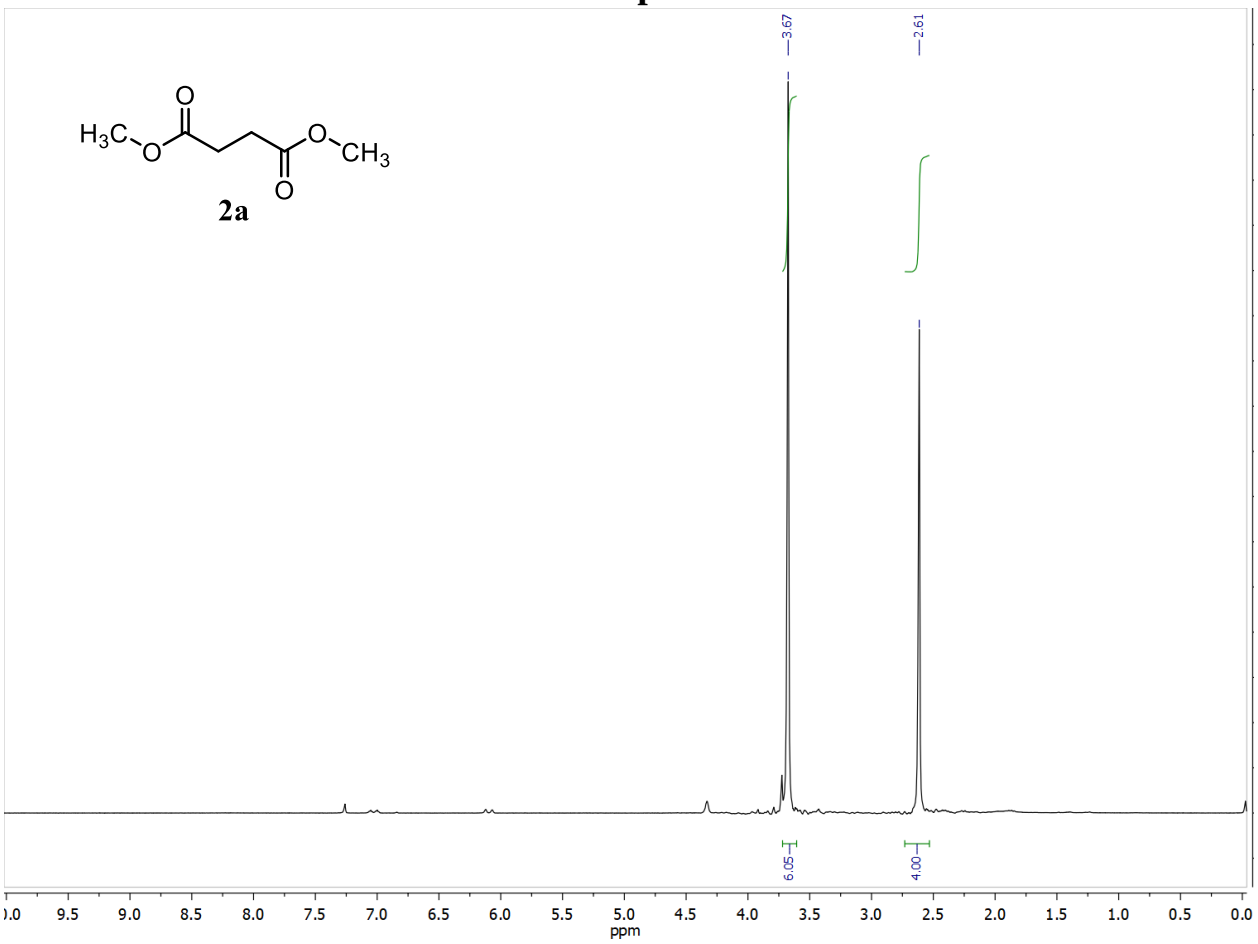
C	-0.625048000000	-0.842071000000	1.220186000000

C	0.420884000000	-0.965243000000	0.255302000000
C	-1.810106000000	-0.376644000000	0.572932000000
O	-0.528950000000	-1.134832000000	2.443439000000
H	0.193375000000	-0.635051000000	-0.751864000000
H	-1.722066000000	-0.122025000000	-0.477076000000
C	-3.101960000000	-0.214866000000	1.137090000000
C	-4.138028000000	0.266121000000	0.307370000000
C	-3.399736000000	-0.514659000000	2.483755000000
C	-5.412941000000	0.442629000000	0.799913000000
C	-4.681902000000	-0.337983000000	2.965640000000
C	-5.688125000000	0.140516000000	2.131821000000
H	-3.914362000000	0.495771000000	-0.729027000000
H	-2.600724000000	-0.882731000000	3.112341000000
H	-6.199681000000	0.814069000000	0.153892000000
H	-4.905690000000	-0.571698000000	4.000145000000
H	-6.691105000000	0.278749000000	2.519648000000
C	1.726594000000	-1.486304000000	0.449142000000
C	2.597252000000	-1.538101000000	-0.660942000000
C	2.193385000000	-1.956466000000	1.695214000000
C	3.875469000000	-2.037379000000	-0.533475000000
C	3.475676000000	-2.456064000000	1.811363000000
C	4.318141000000	-2.498327000000	0.704555000000
H	2.242710000000	-1.177990000000	-1.620882000000
H	1.521194000000	-1.910914000000	2.540719000000
H	4.534541000000	-2.071799000000	-1.392999000000
H	3.828866000000	-2.816441000000	2.770682000000
H	5.323846000000	-2.890547000000	0.805421000000

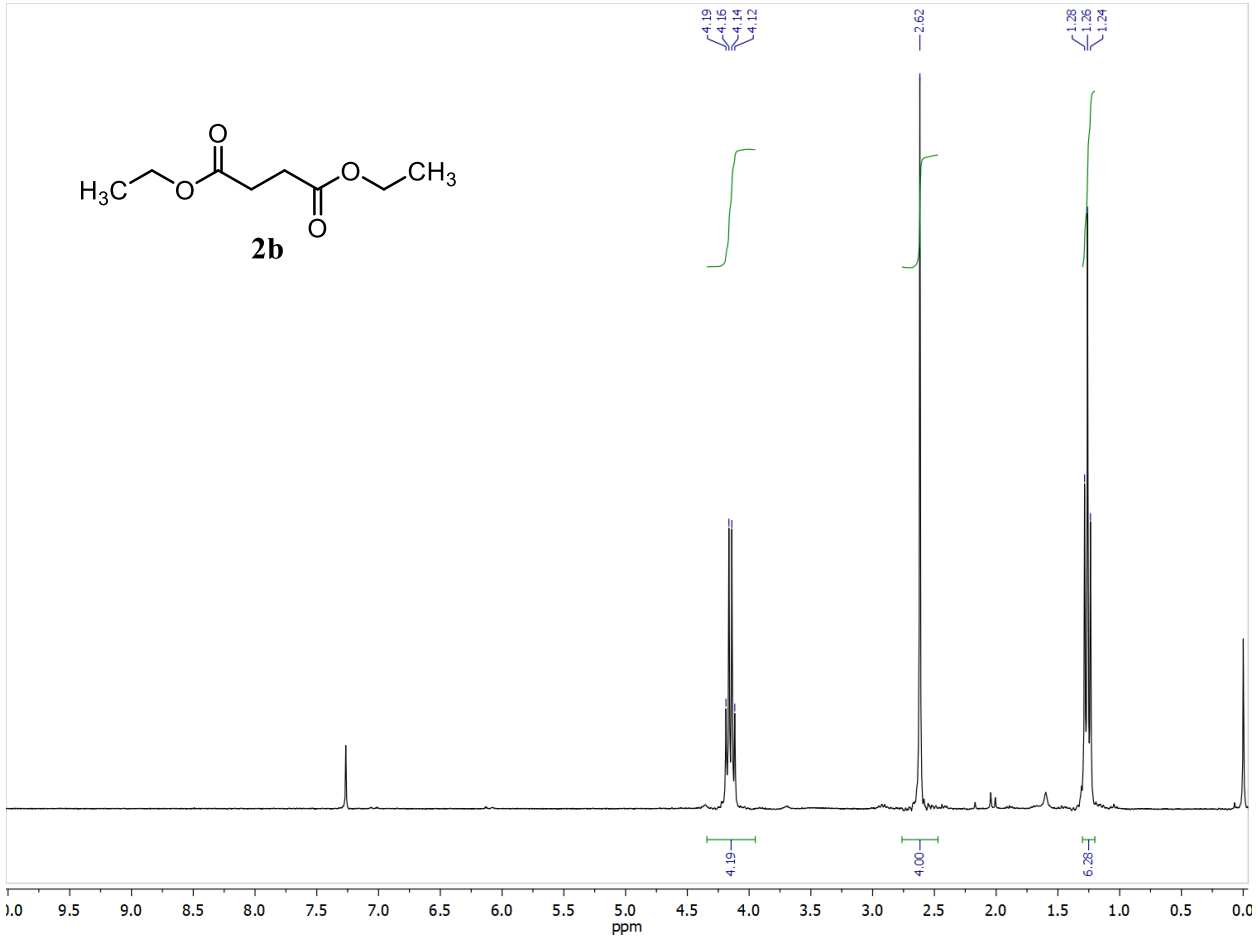
Transition state for cis*-2,3-diphenylcyclopropan-1-one cleavage*

C	-0.749543000000	-1.767283000000	0.236411000000
C	0.479797000000	-1.752271000000	-0.494777000000
C	-1.416889000000	-0.980291000000	-0.754226000000
O	-0.980487000000	-1.933013000000	1.434488000000
H	0.466243000000	-2.084080000000	-1.524883000000
H	-1.400020000000	-1.328079000000	-1.778912000000
C	-2.097256000000	0.265073000000	-0.505275000000
C	-2.606285000000	0.981765000000	-1.599357000000
C	-2.265700000000	0.793473000000	0.783958000000
C	-3.268406000000	2.180705000000	-1.412319000000
C	-2.919379000000	1.999194000000	0.962908000000
C	-3.425082000000	2.694595000000	-0.129957000000
H	-2.473235000000	0.581203000000	-2.598728000000
H	-1.887431000000	0.241987000000	1.634721000000
H	-3.661052000000	2.720254000000	-2.266479000000
H	-3.043496000000	2.399331000000	1.962712000000
H	-3.942867000000	3.635485000000	0.017754000000
C	1.745773000000	-1.298969000000	0.022304000000
C	1.929971000000	-0.936838000000	1.365742000000
C	2.836748000000	-1.210376000000	-0.856120000000
C	3.165339000000	-0.495856000000	1.804963000000
C	4.070664000000	-0.777003000000	-0.408416000000
C	4.238125000000	-0.415764000000	0.923893000000
H	1.097569000000	-1.016443000000	2.052722000000
H	2.698717000000	-1.485879000000	-1.896279000000
H	3.297778000000	-0.218373000000	2.844462000000
H	4.905287000000	-0.717415000000	-1.097430000000
H	5.205118000000	-0.075134000000	1.276116000000

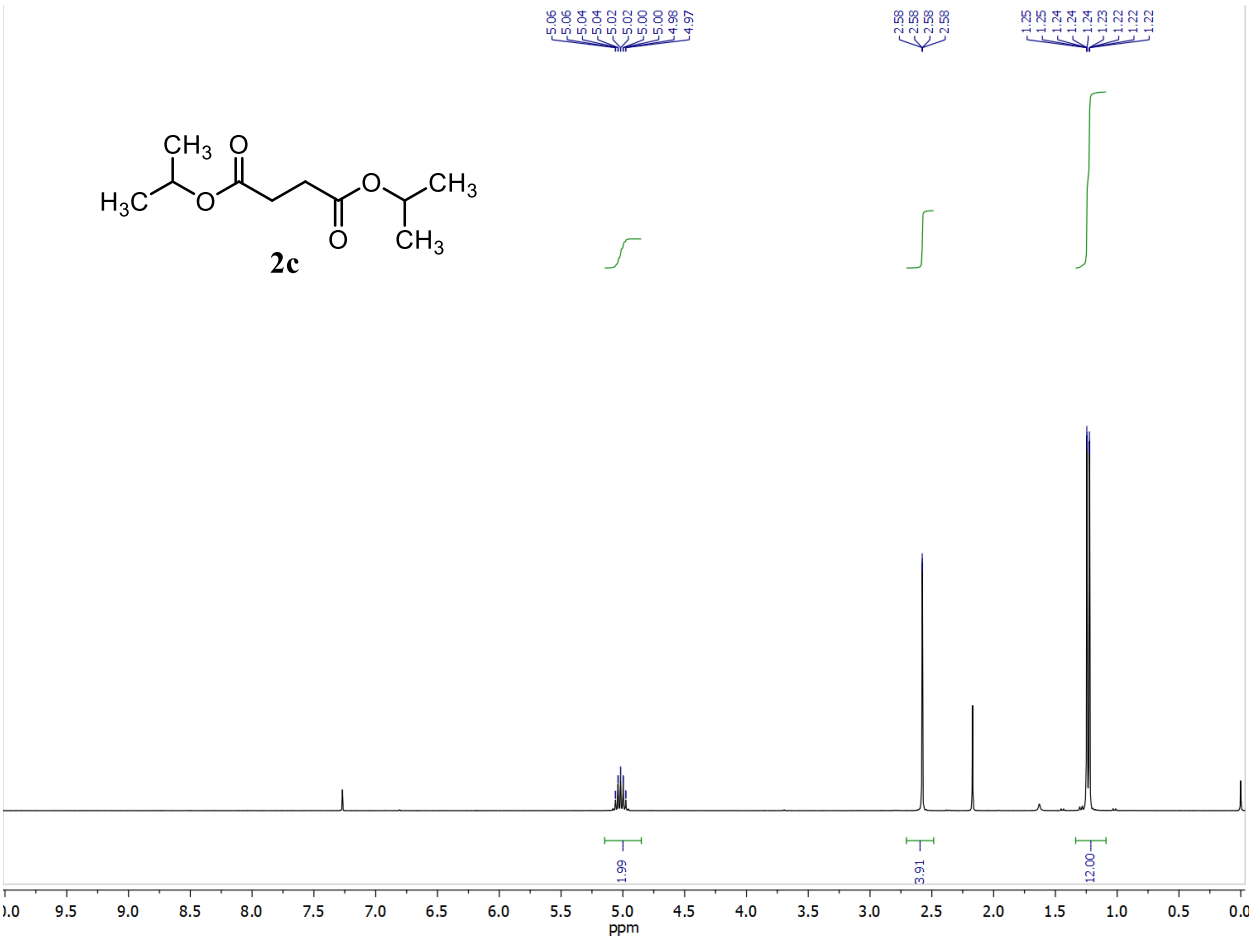
NMR Spectra

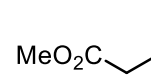


2a



2b


5.06
5.06
5.04
5.04
5.02
5.02
5.00
5.00
4.98
4.97
2.58
2.58
2.58
2.58
1.25
1.25
1.24
1.24
1.24
1.23
1.22
1.22
1.22
1.99
3.91
12.00
ppm

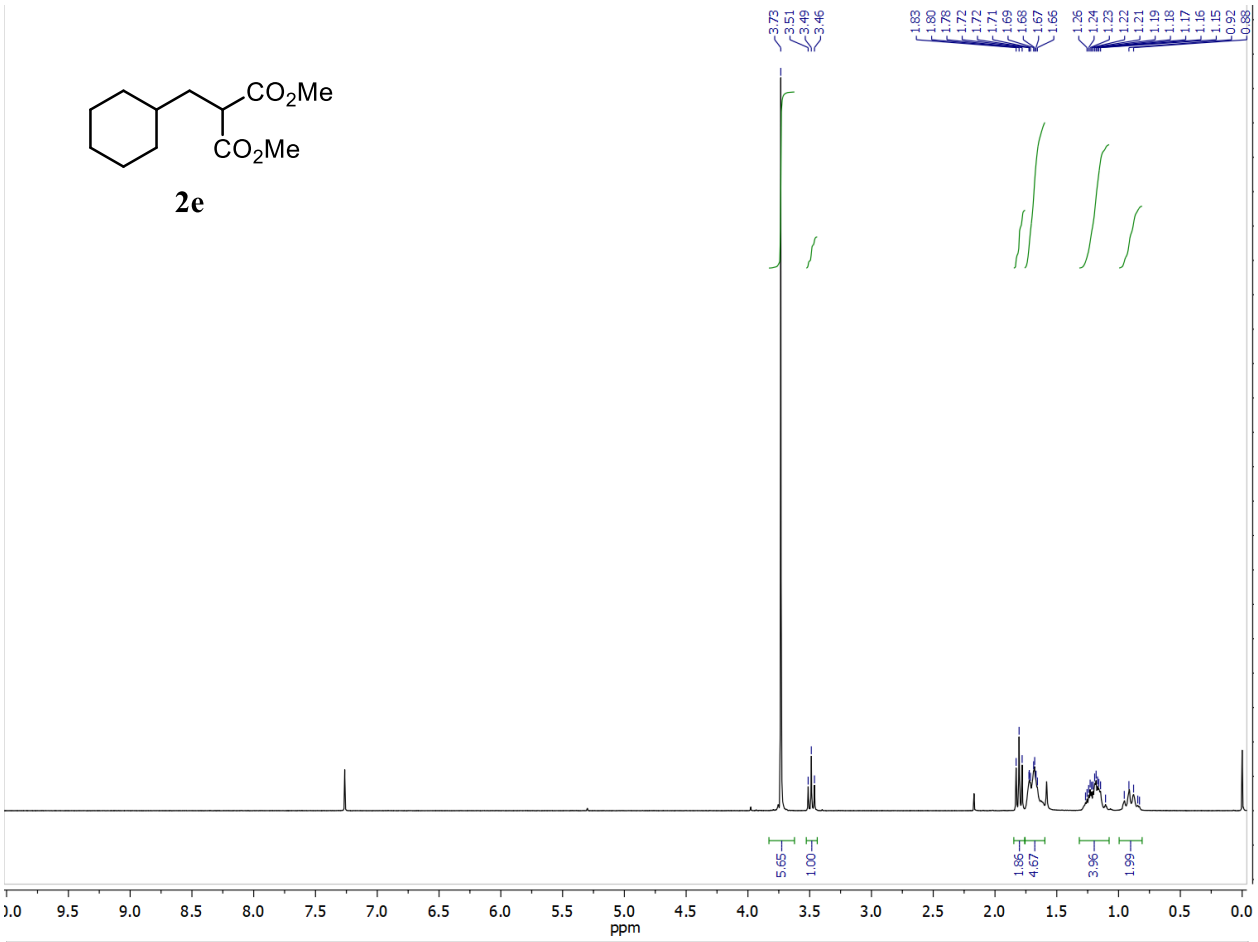

CH3
O
H3C
O
O
CH3
O
CH3

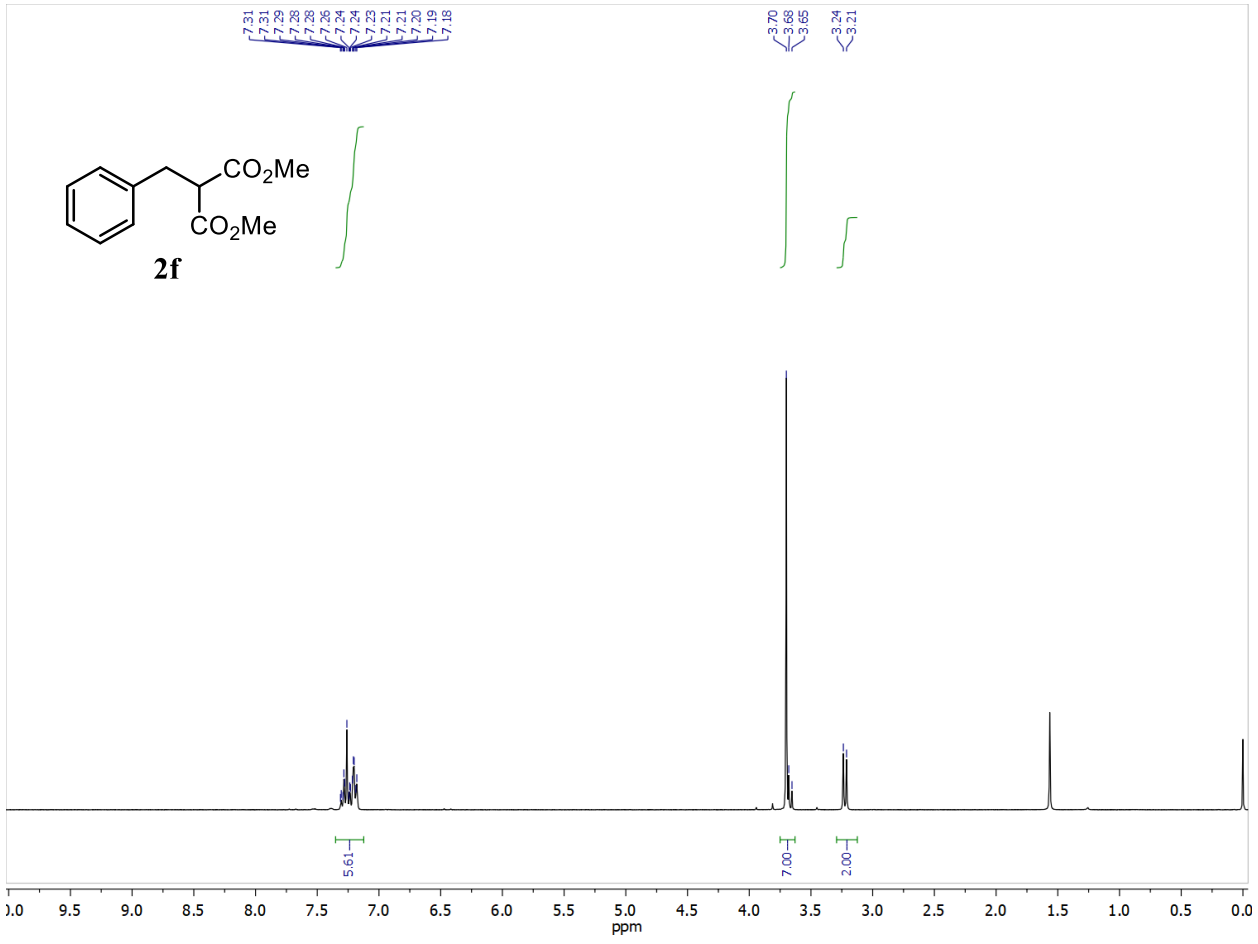
2c

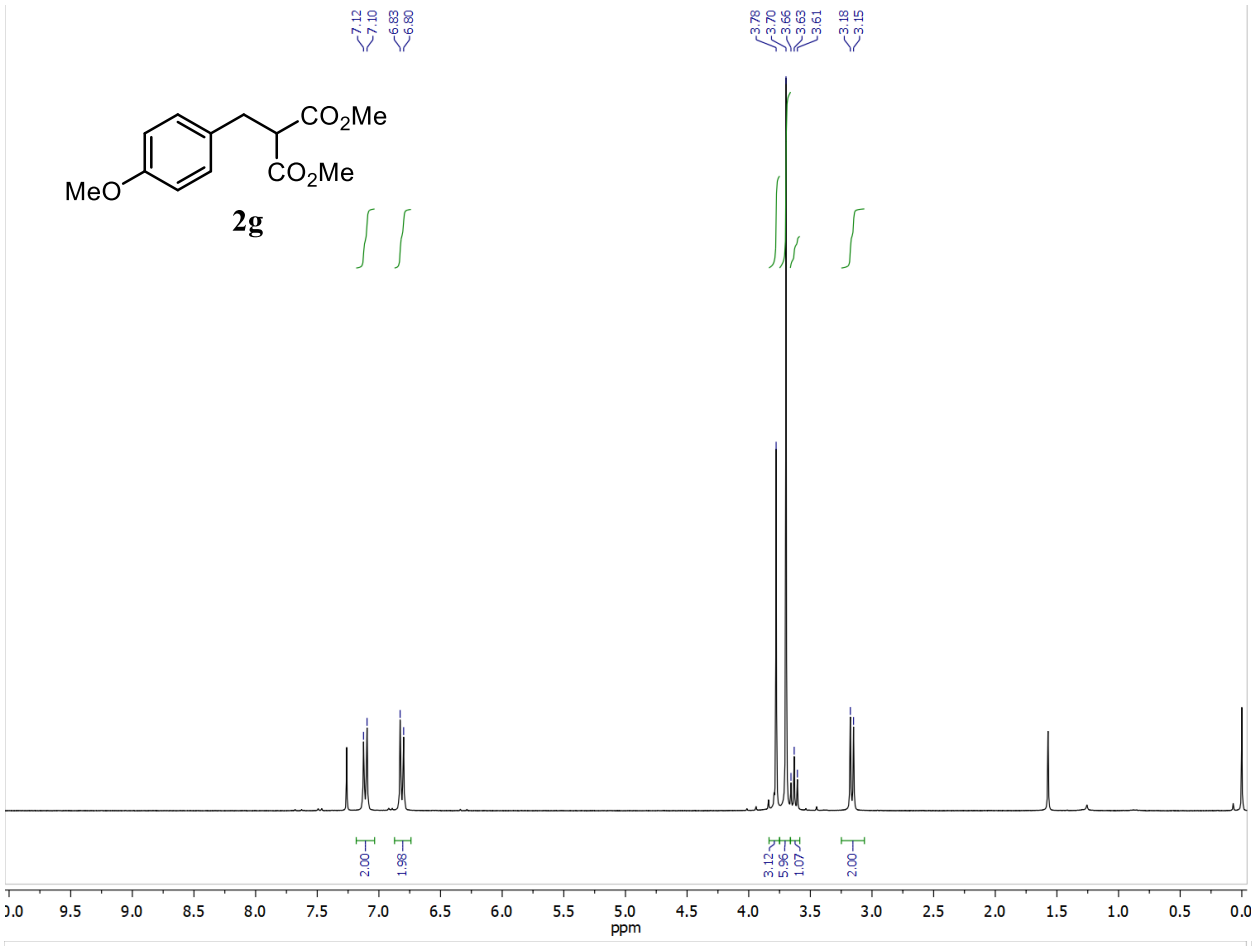
CO2Me
MeO2C
CO2Me

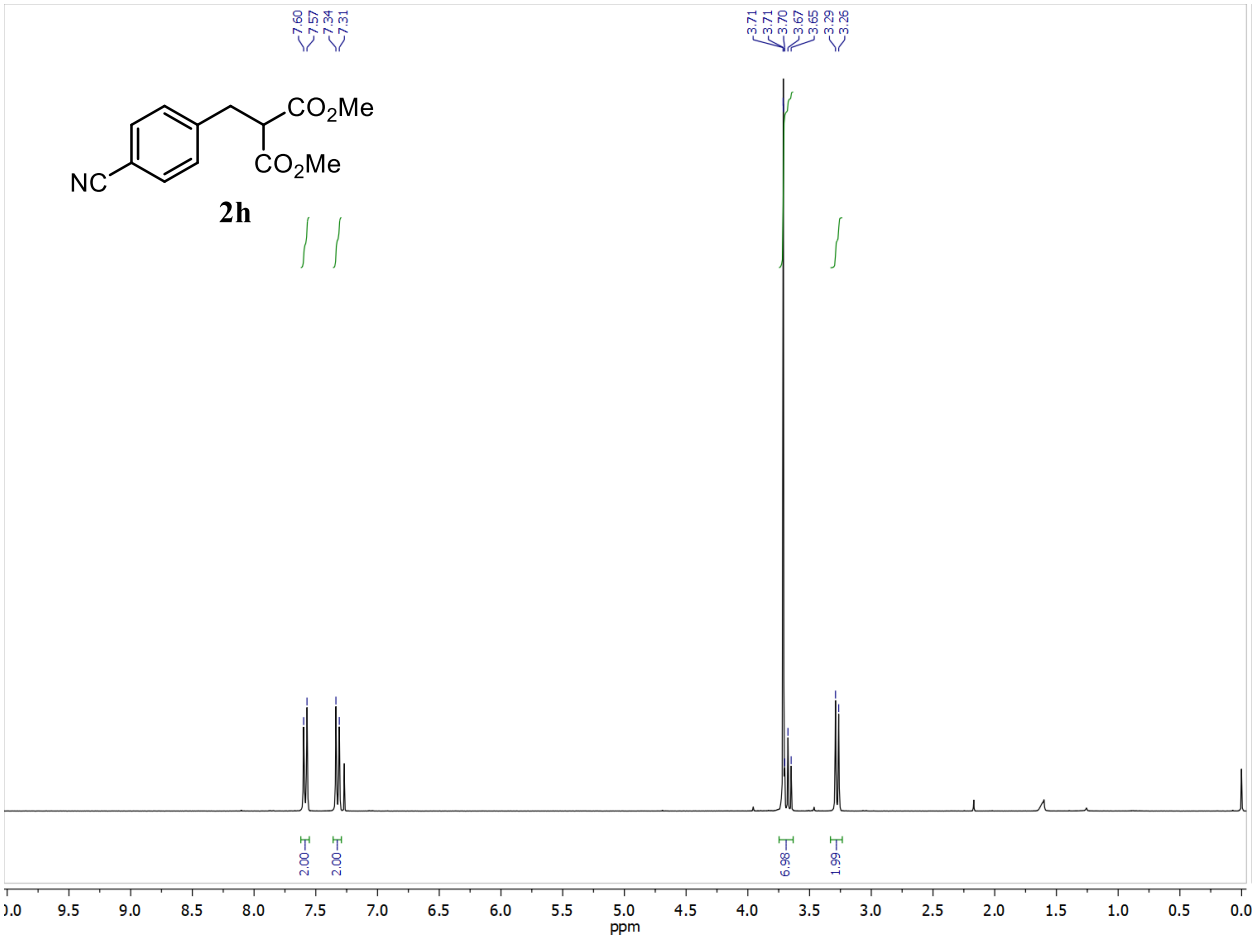
2d

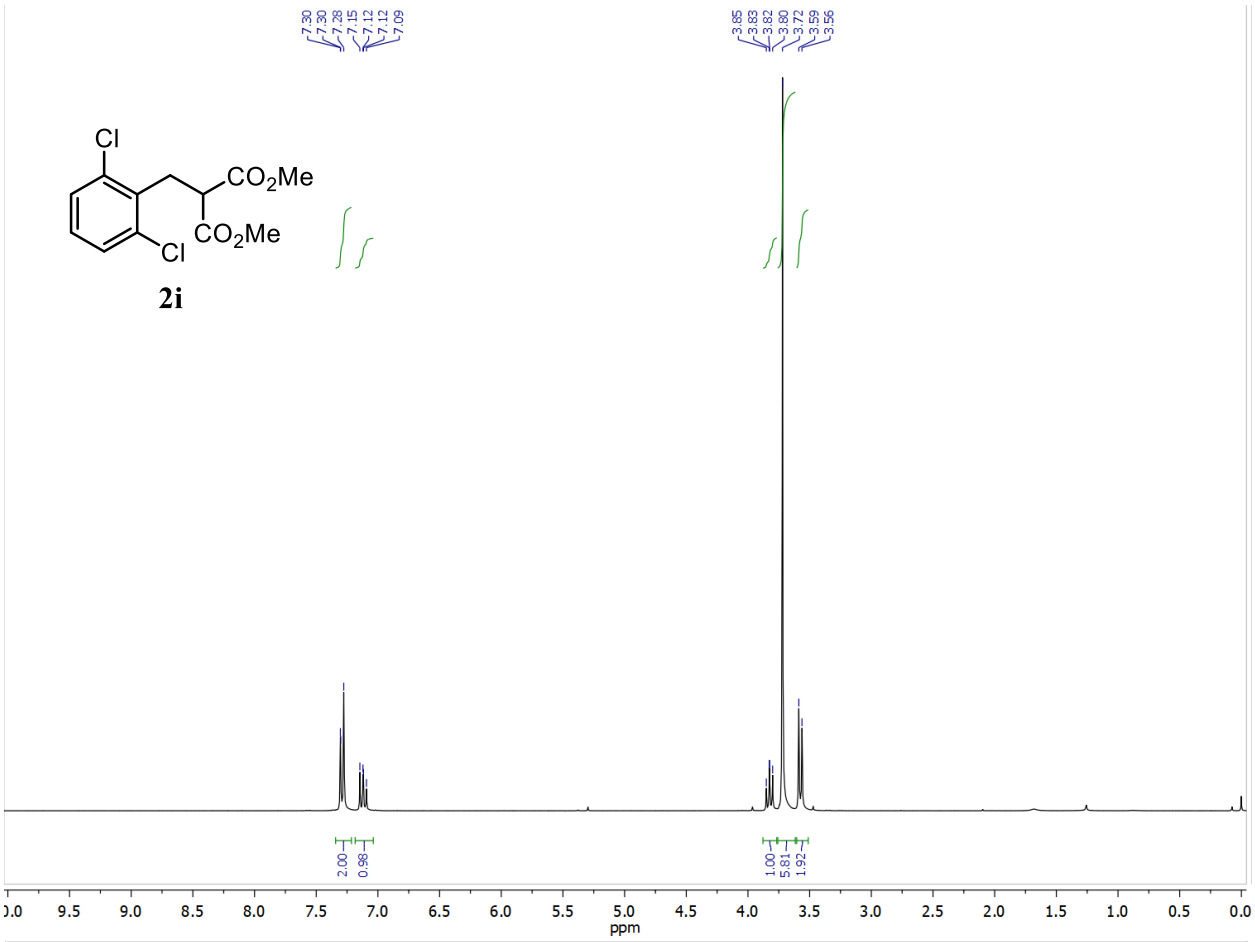
3.72
3.69
3.32
3.30
3.28
3.25
3.23
2.82
2.80
2.77
2.75
2.65
2.63
2.60
2.57
9.22
1.00
1.95
2.00
ppm

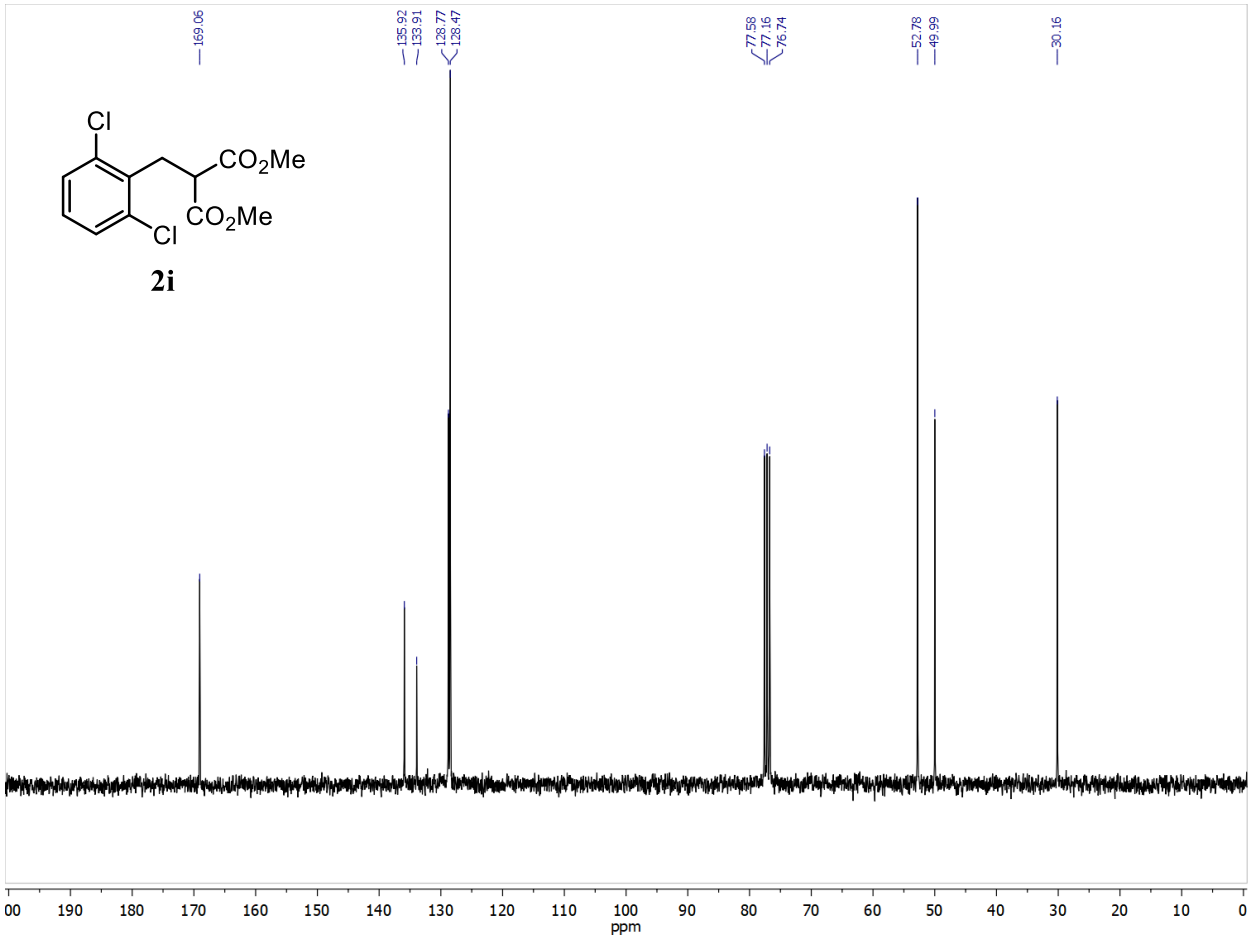

CO2Me
CO2Me
2e
3.73
3.51
3.49
3.46
1.83
1.80
1.78
1.72
1.72
1.71
1.69
1.68
1.67
1.66
1.26
1.24
1.23
1.22
1.21
1.19
1.18
1.17
1.16
1.15
0.92
0.88
5.65
1.00
1.86
4.67
3.96
1.99
ppm

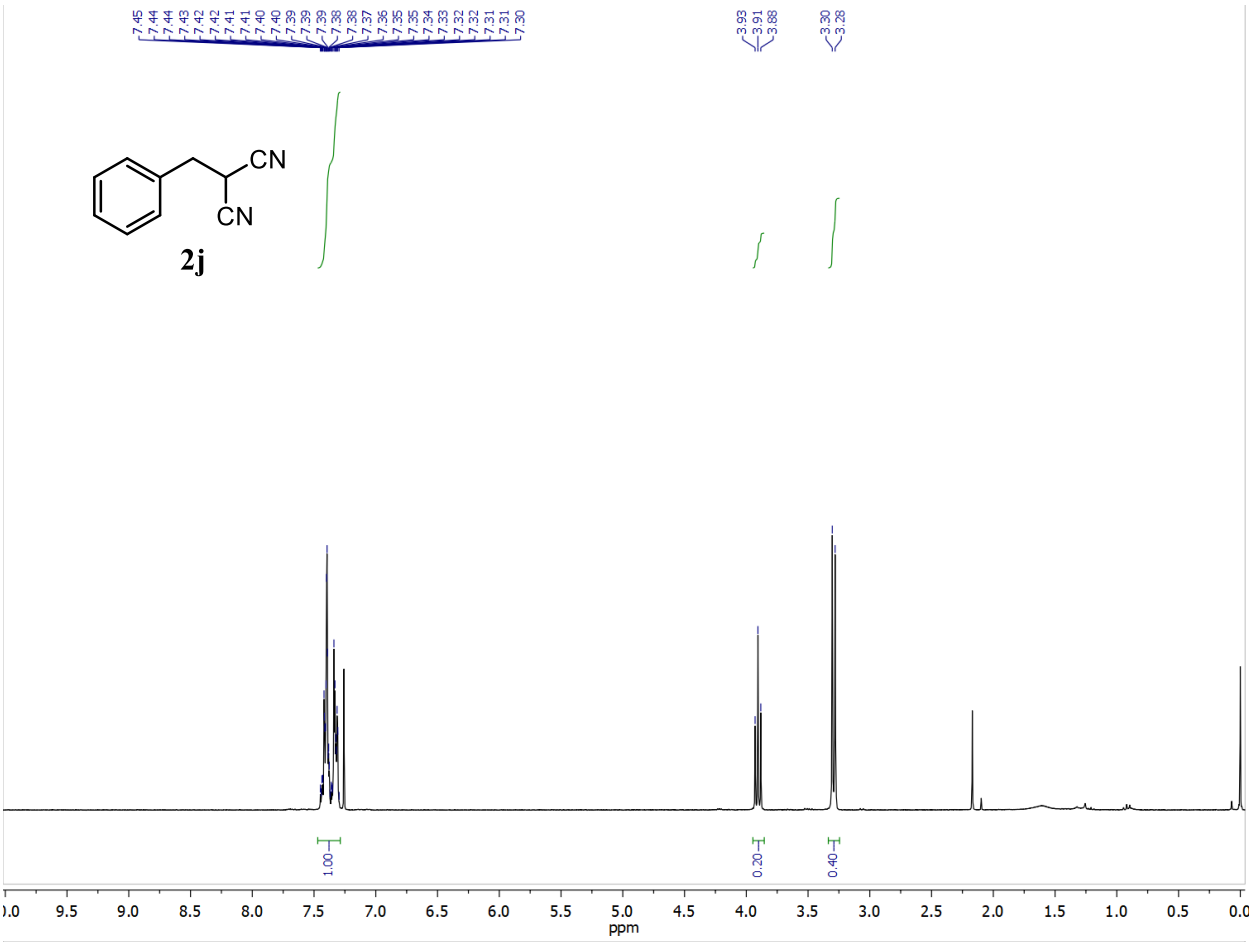

CO2Me
CO2Me
2f
7.31
7.31
7.29
7.28
7.28
7.26
7.24
7.24
7.23
7.21
7.21
7.20
7.19
7.18
3.70
3.68
3.65
3.24
3.21
5.61
7.00
2.00
ppm

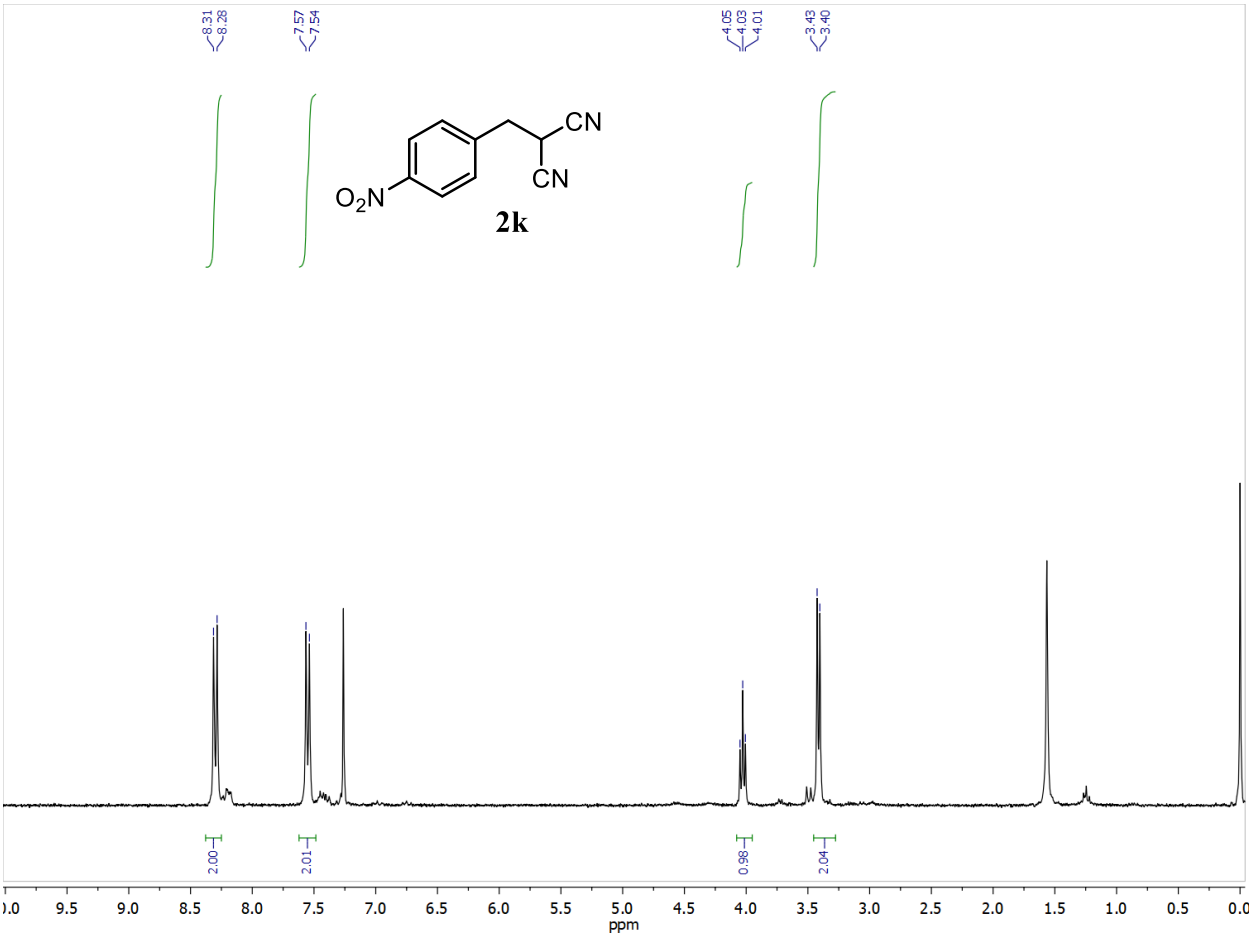

7.12
7.10
6.83
6.80
3.78
3.70
3.66
3.63
3.61
3.18
3.15
CO2Me
CO2Me
MeO
2g
2.00
1.98
3.12
5.96
1.07
2.00
ppm

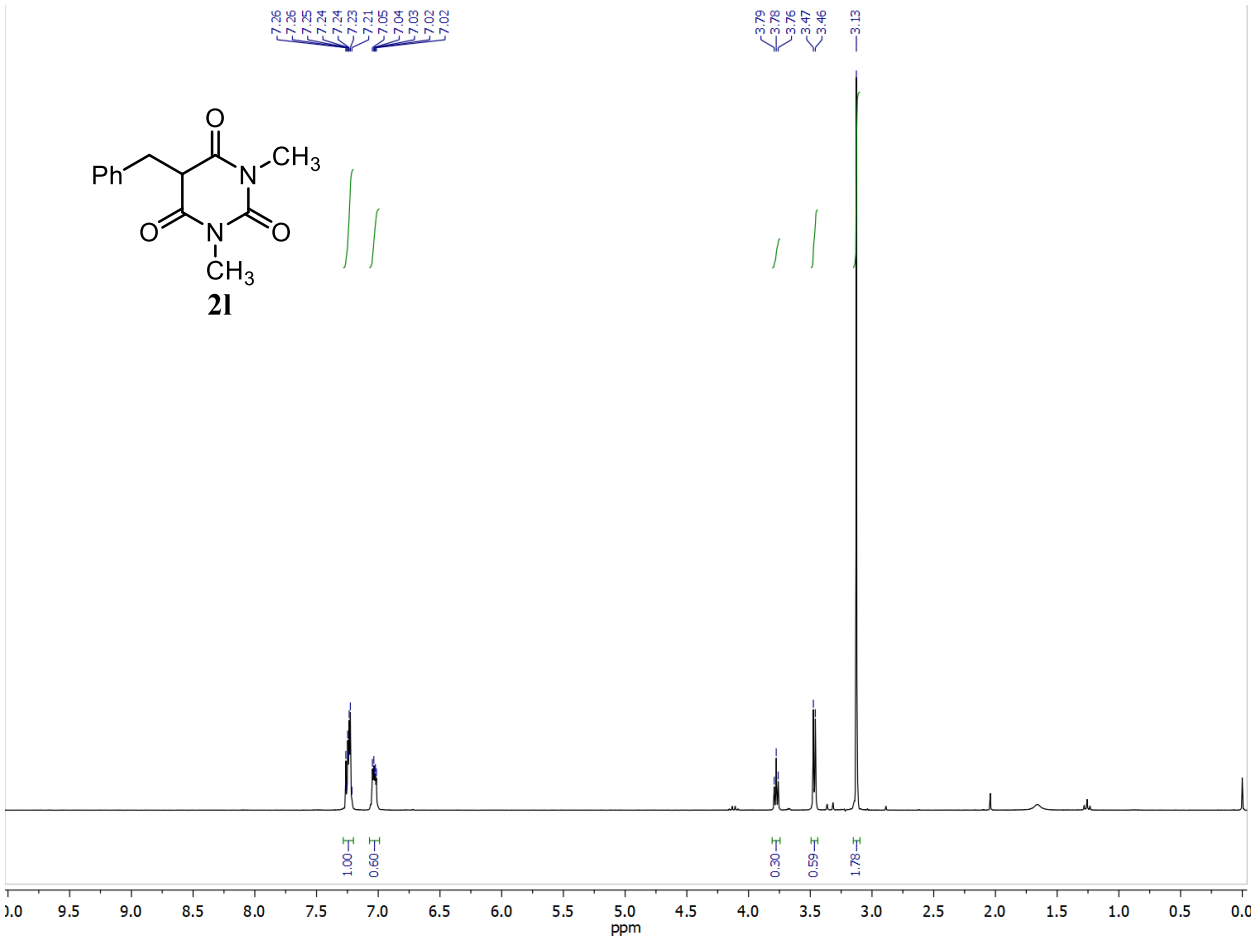

7.60
7.57
7.34
7.31
3.71
3.71
3.70
3.67
3.65
3.29
3.26
CO2Me
CO2Me
NC
2h
2.00
2.00
6.98
1.99
ppm


7.30
7.30
7.28
7.15
7.12
7.12
7.09
3.85
3.83
3.82
3.80
3.72
3.59
3.56
Cl
CO2Me
CO2Me
Cl
2i
2.00
0.98
1.00
5.81
1.92
ppm

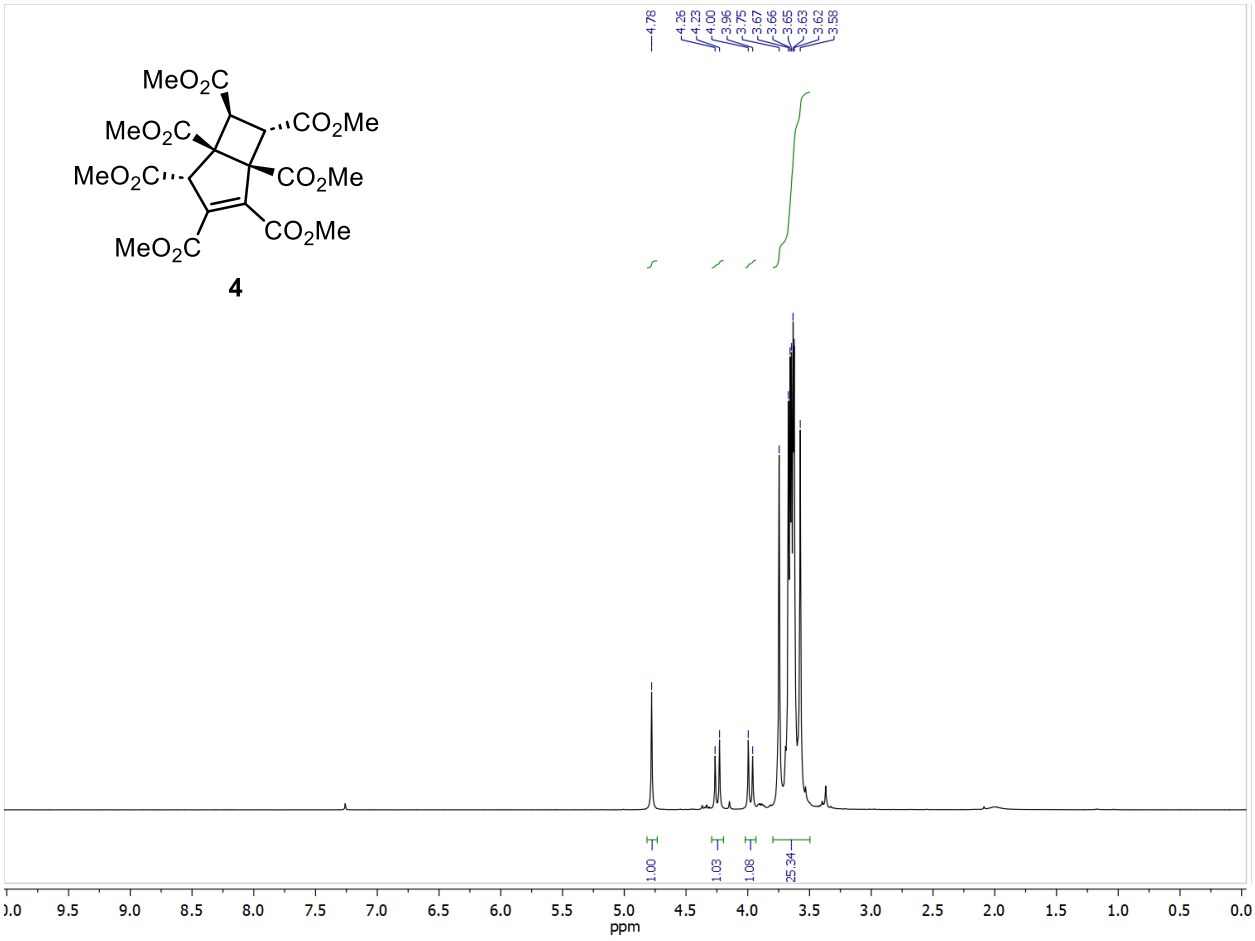

169.06
135.92
133.91
128.77
128.47
77.58
77.16
76.74
52.78
49.99
30.16
Cl
CO2Me
CO2Me
Cl
2i
ppm


7.45
7.44
7.44
7.43
7.42
7.42
7.41
7.41
7.40
7.40
7.39
7.39
7.39
7.38
7.38
7.37
7.36
7.35
7.35
7.34
7.33
7.32
7.32
7.31
7.31
7.30
3.93
3.91
3.88
3.30
3.28
CN
CN
2j
1.00
0.20
0.40
ppm

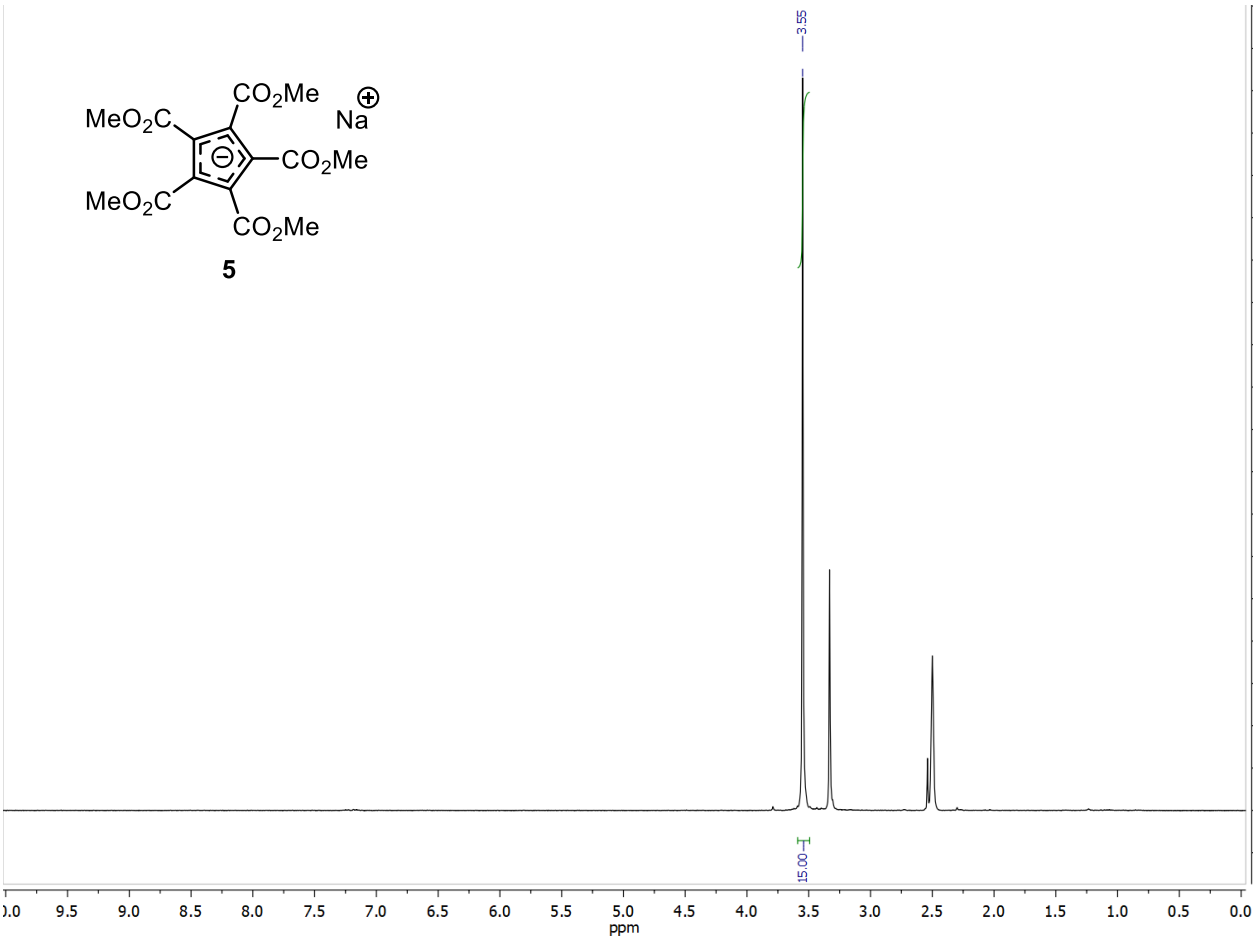

8.31
8.28
7.57
7.54
4.05
4.03
4.01
3.43
3.40
CN
CN
O2N
2k
2.00
2.01
0.98
2.04
ppm

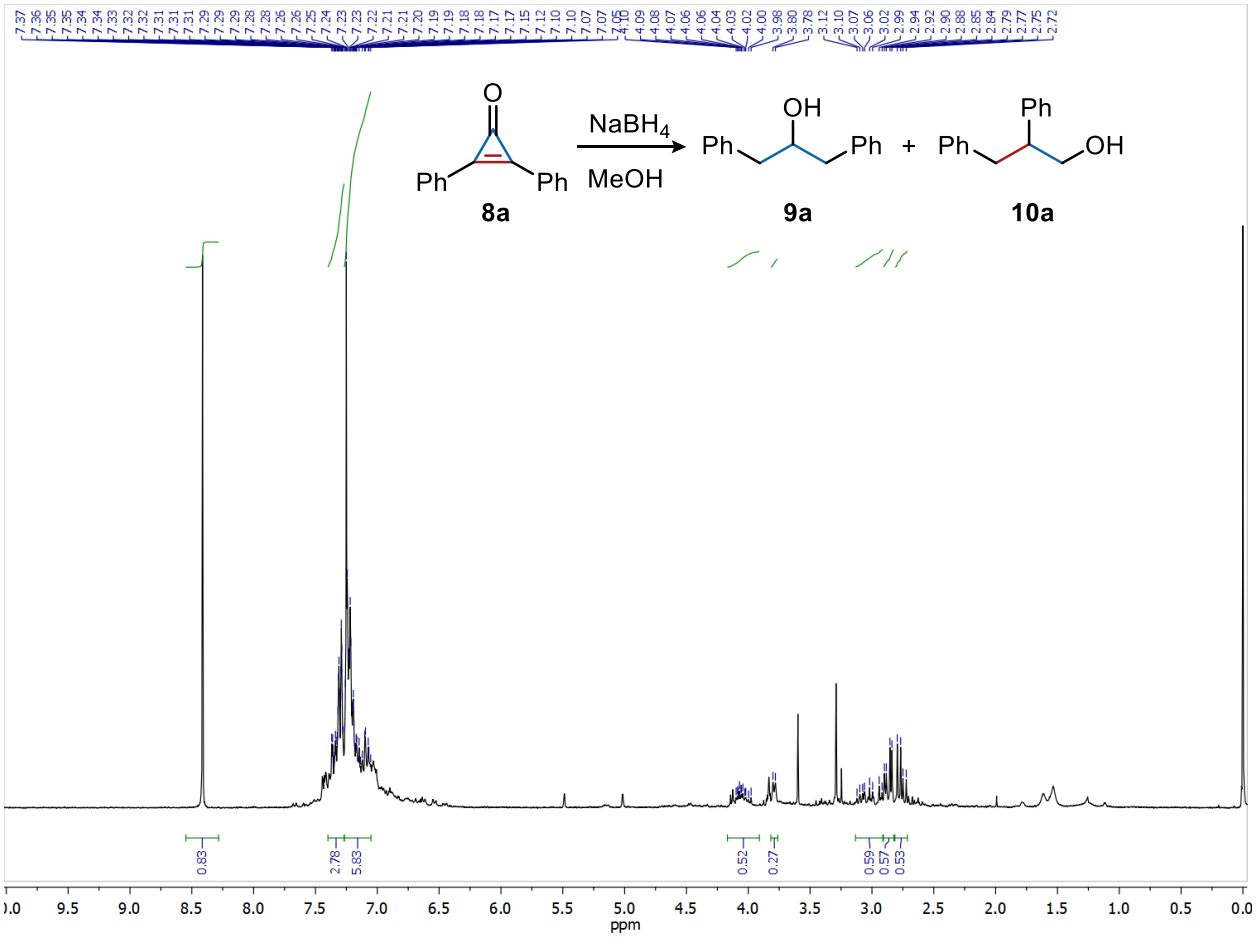

7.26
7.26
7.25
7.24
7.24
7.23
7.21
7.05
7.04
7.03
7.02
7.02
7.02
3.79
3.78
3.76
3.47
3.46
3.13
Ph
N
CH3
O
O
O
N
CH3
1.00
0.60
0.30
0.59
1.78
ppm

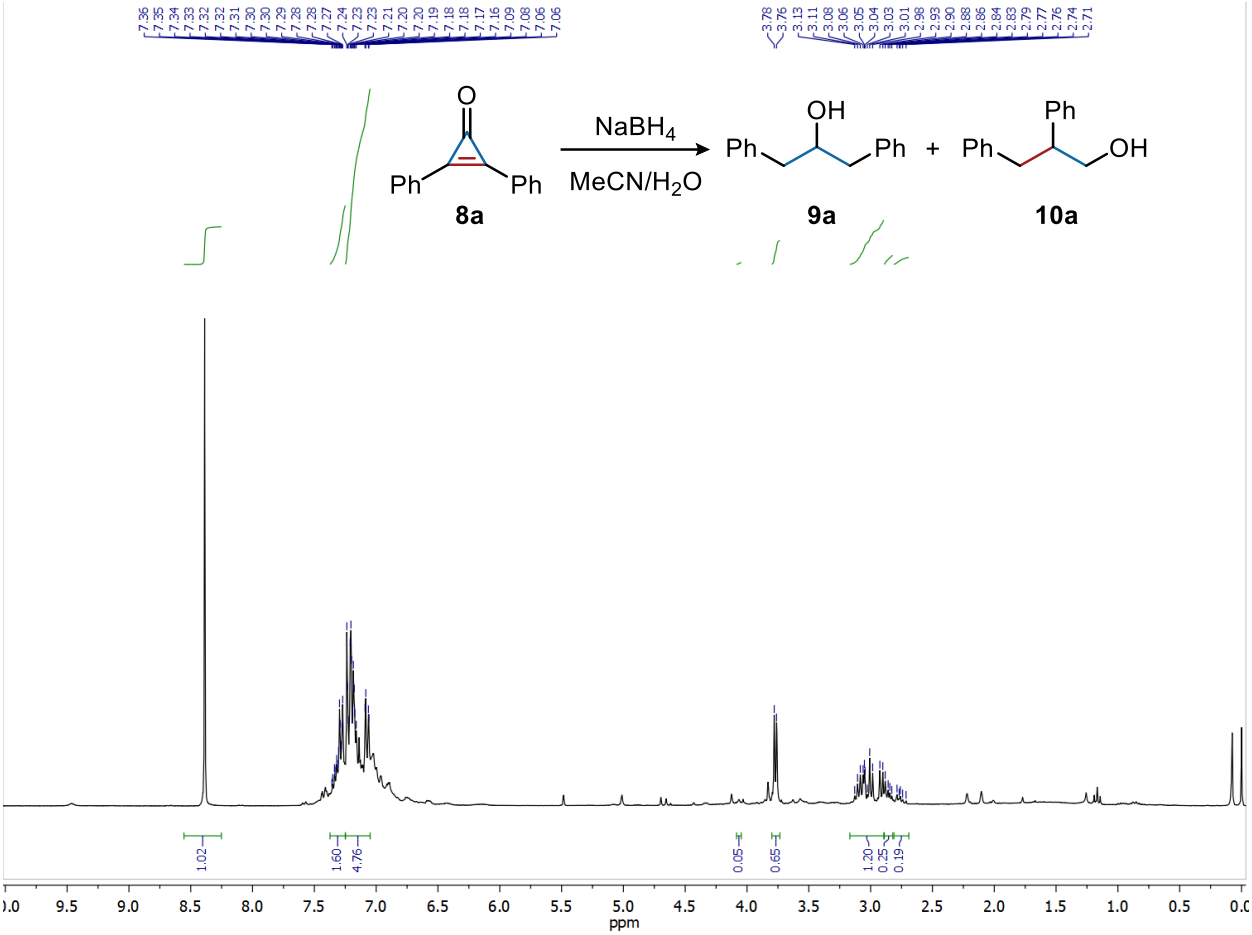
21

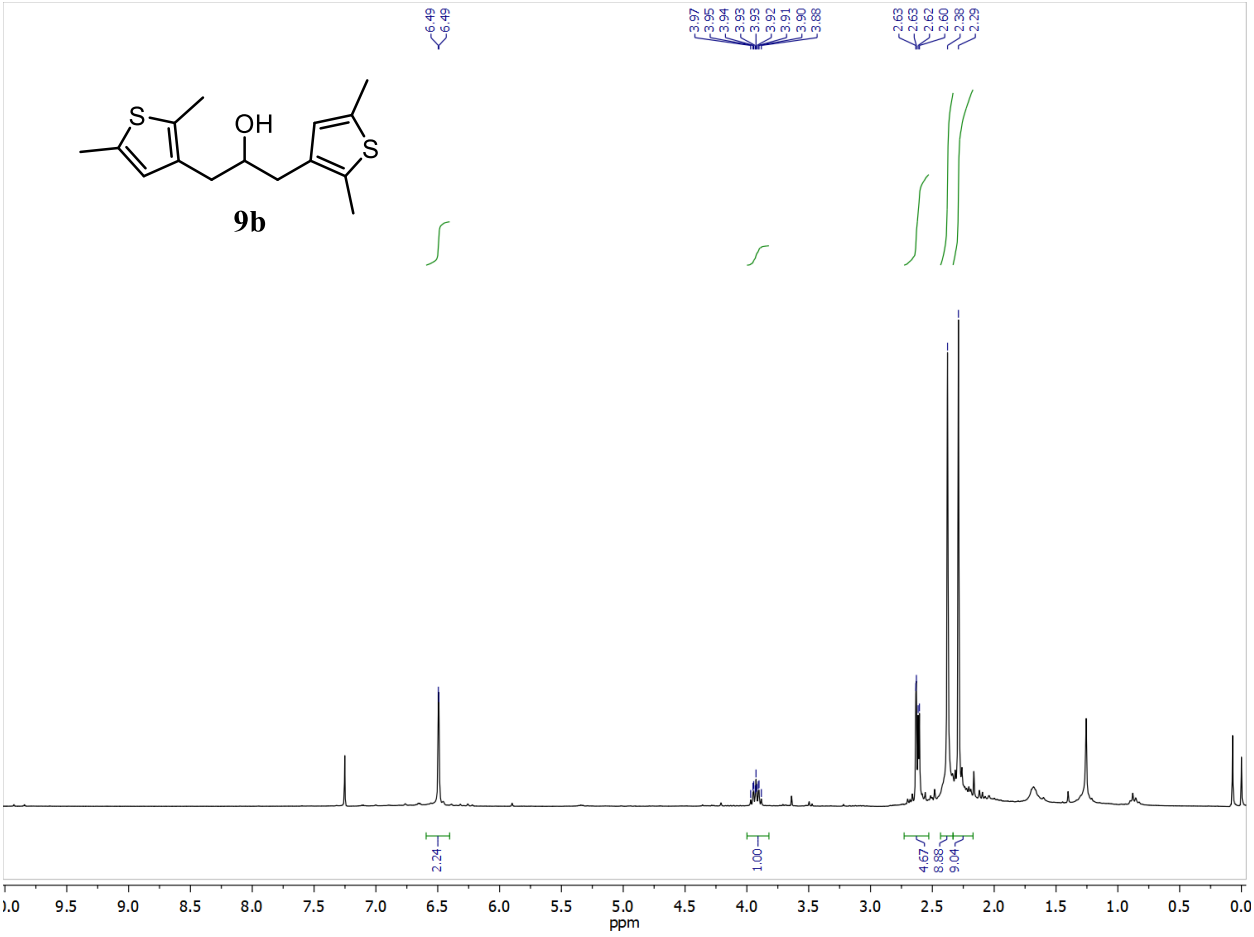

4.78
4.26
4.23
4.00
3.96
3.75
3.67
3.66
3.65
3.63
3.62
3.58
MeO2C
MeO2C
MeO2C
MeO2C
CO2Me
CO2Me
CO2Me
1.00
1.03
1.08
25.34
ppm

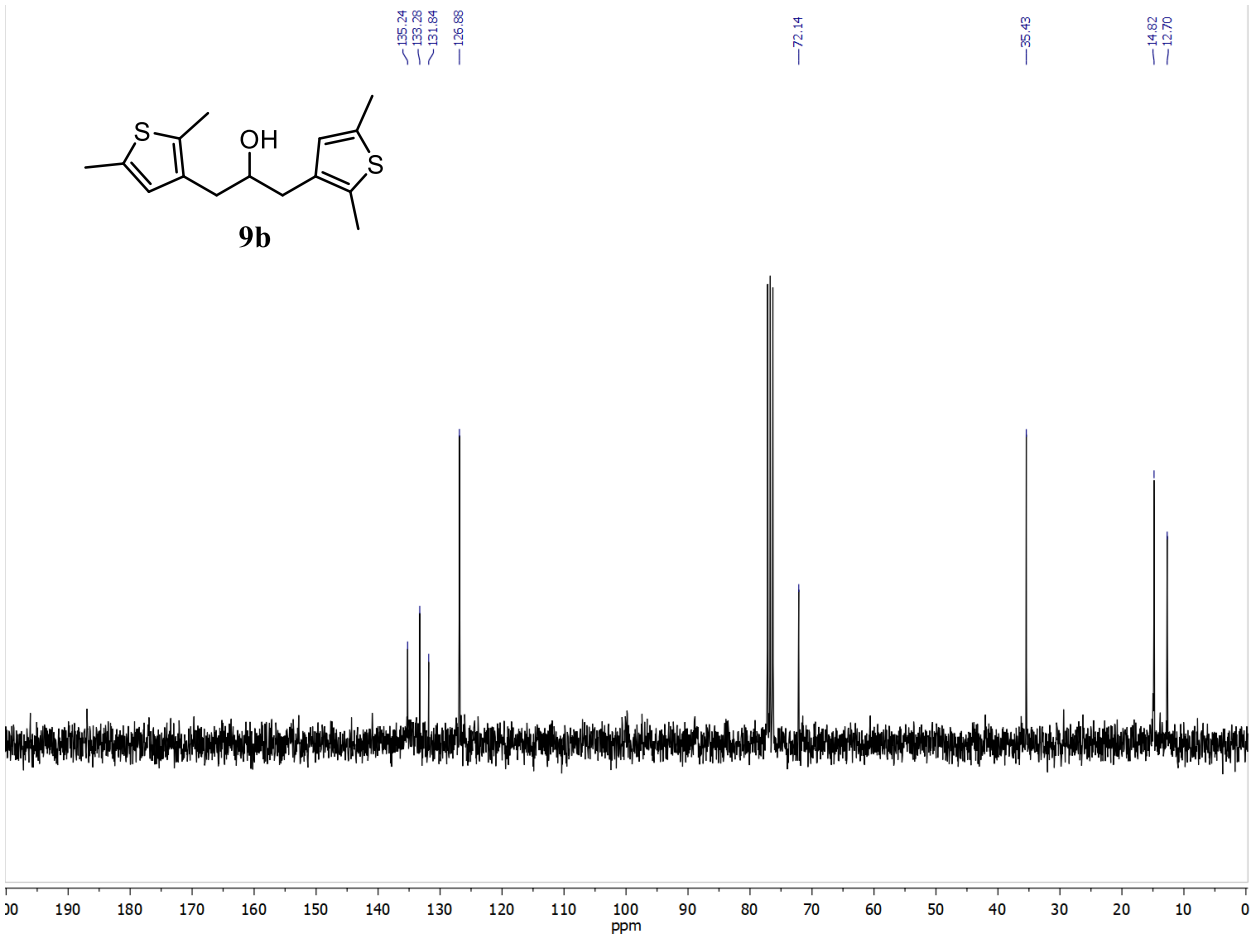
4

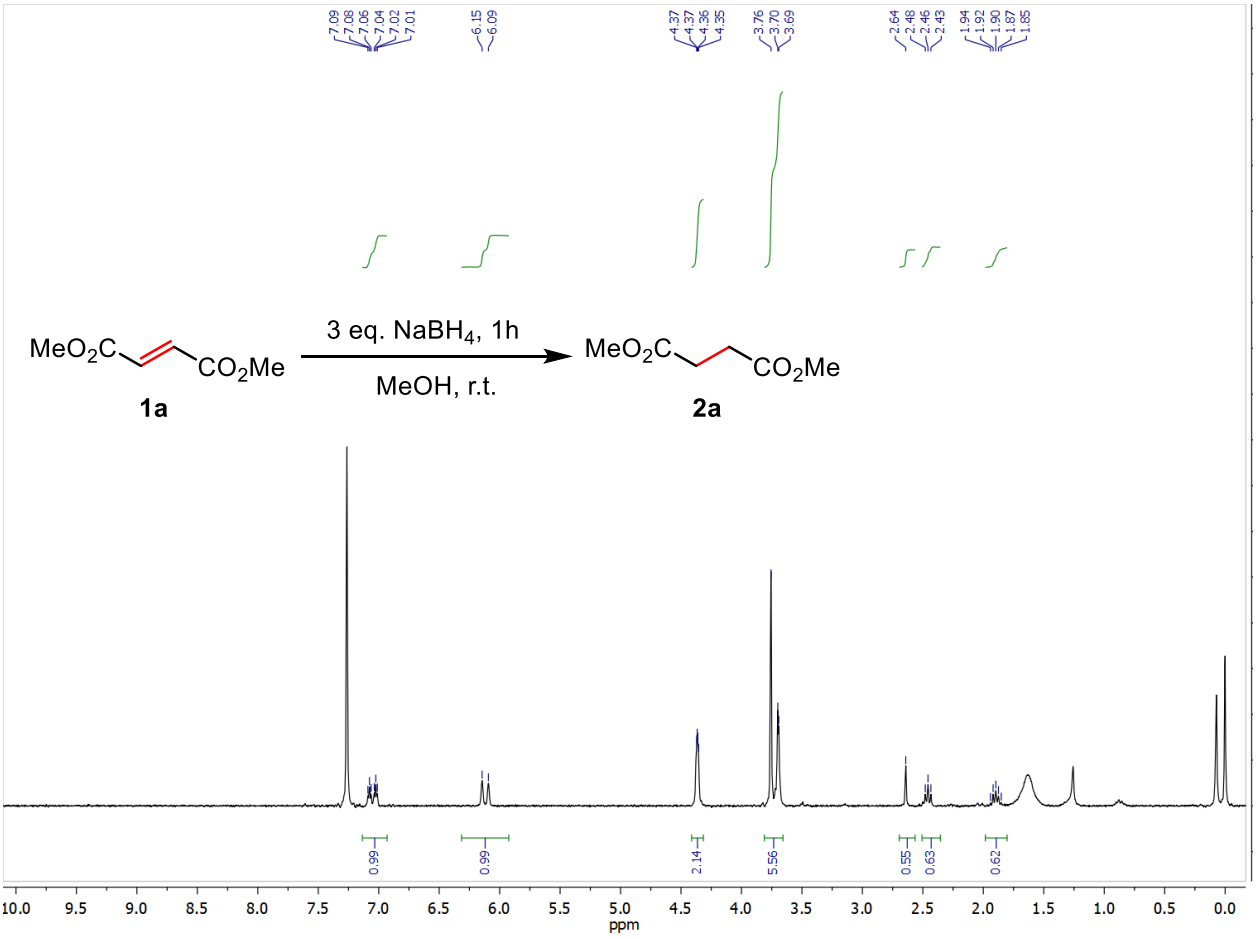

MeO2C
CO2Me
Na
CO2Me
MeO2C
CO2Me
5
3.55
15.00
ppm

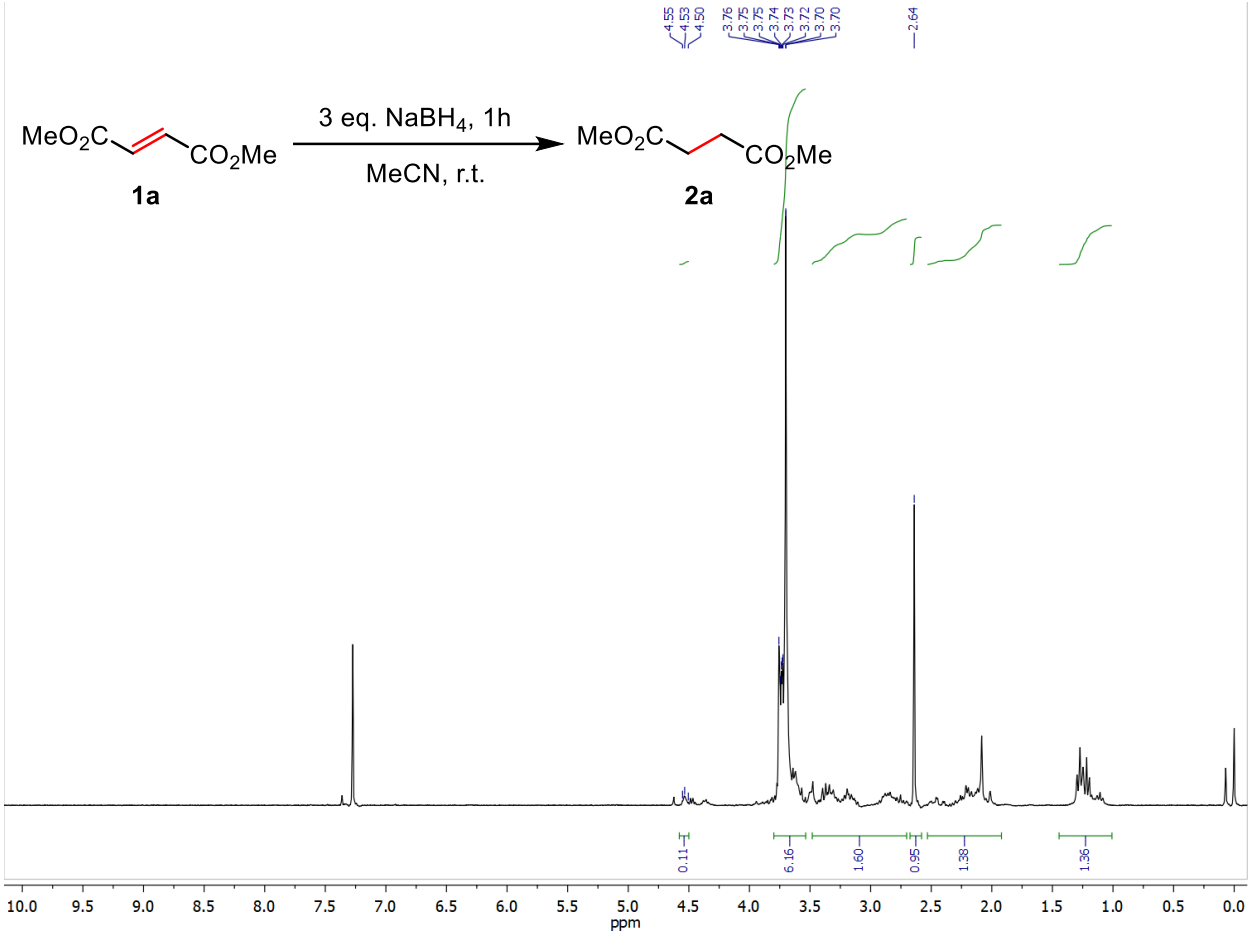

O
Ph
Ph
8a
NaBH4
MeOH
OH
Ph
Ph
9a
+
Ph
Ph
OH
10a
0.83
2.78
5.83
0.52
0.27
0.59
0.57
0.53
ppm

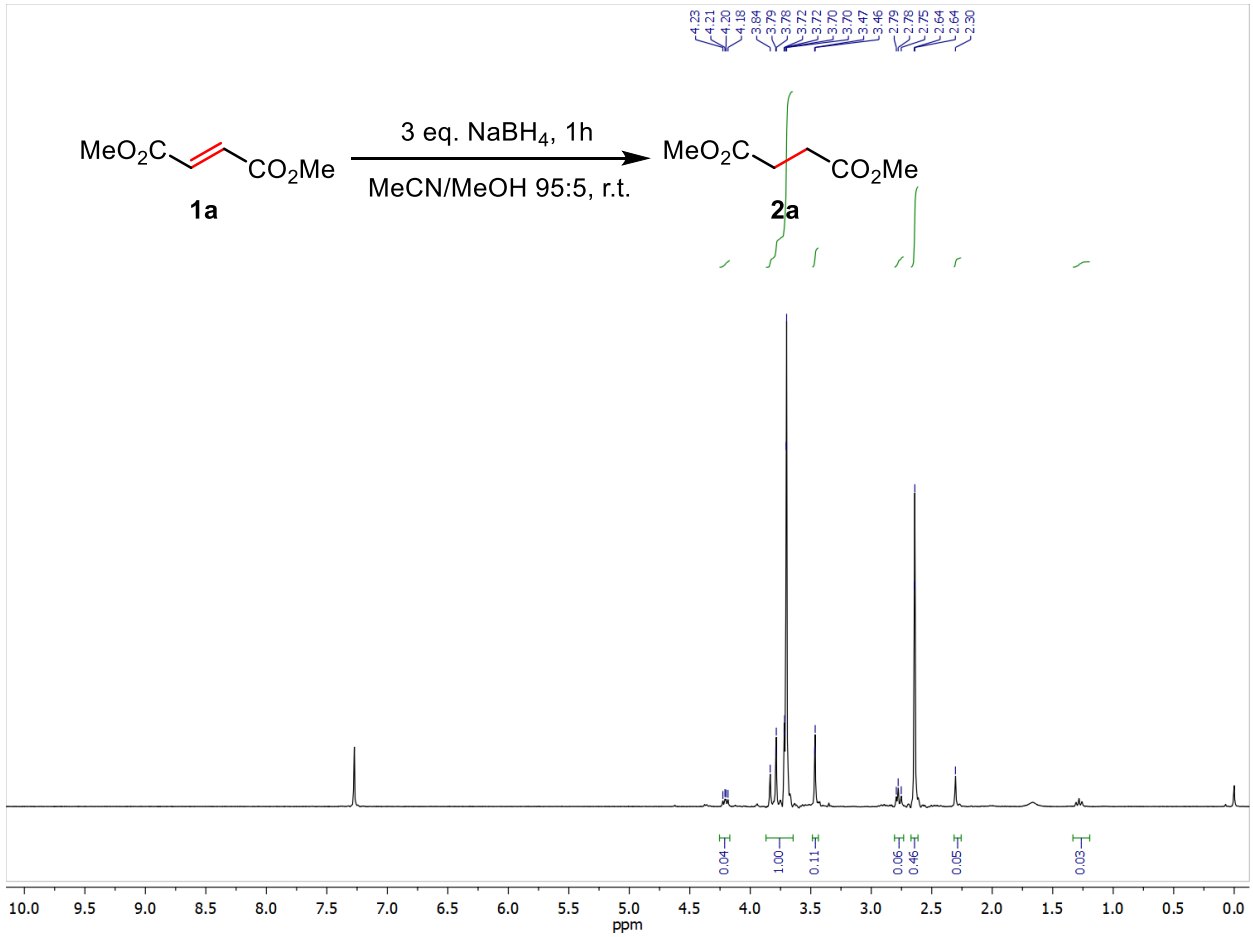

NaBH4
MeCN/H2O
Ph
Ph
O
8a
OH
Ph
Ph
9a
Ph
Ph
OH
10a
ppm

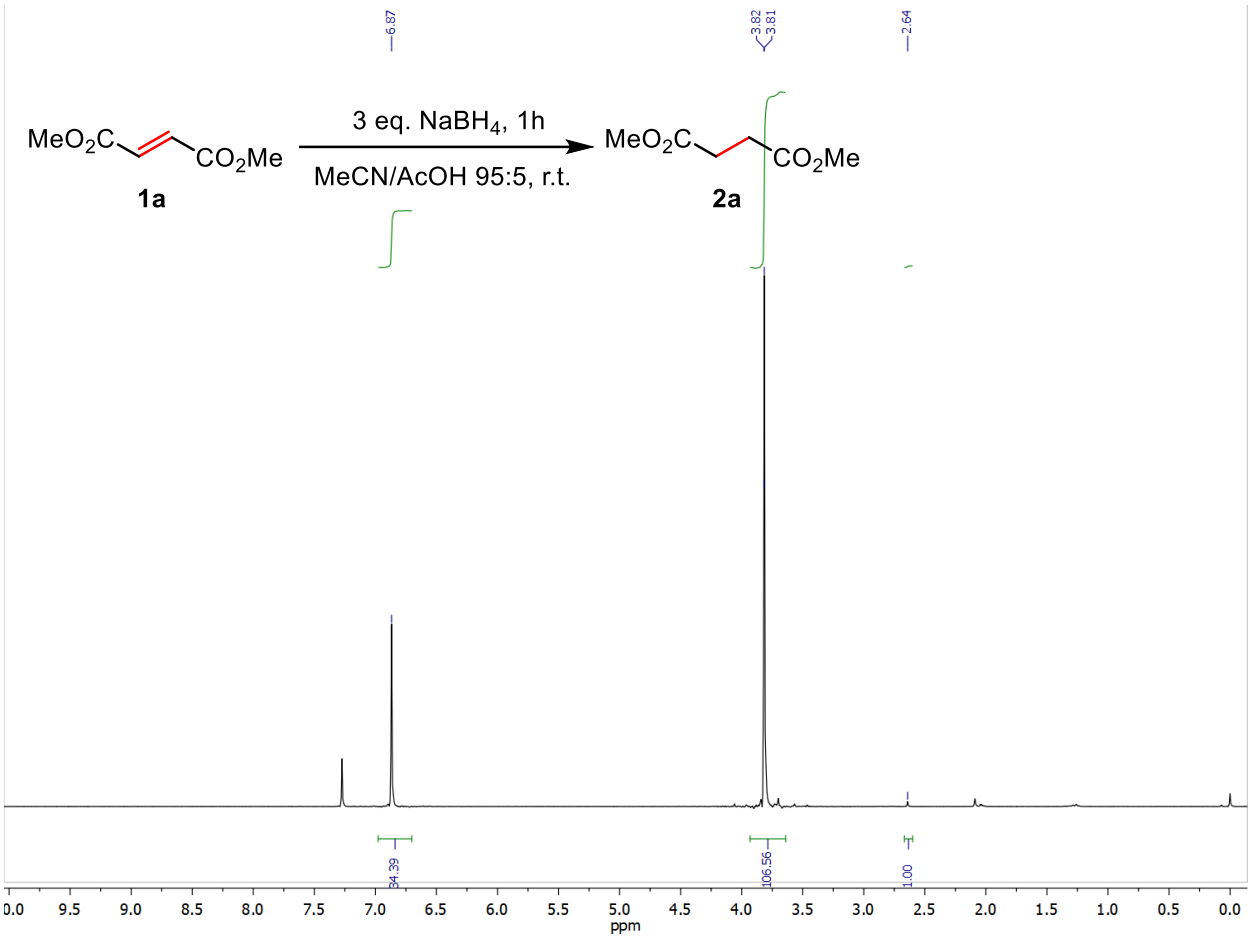

S
OH
S
9b
ppm

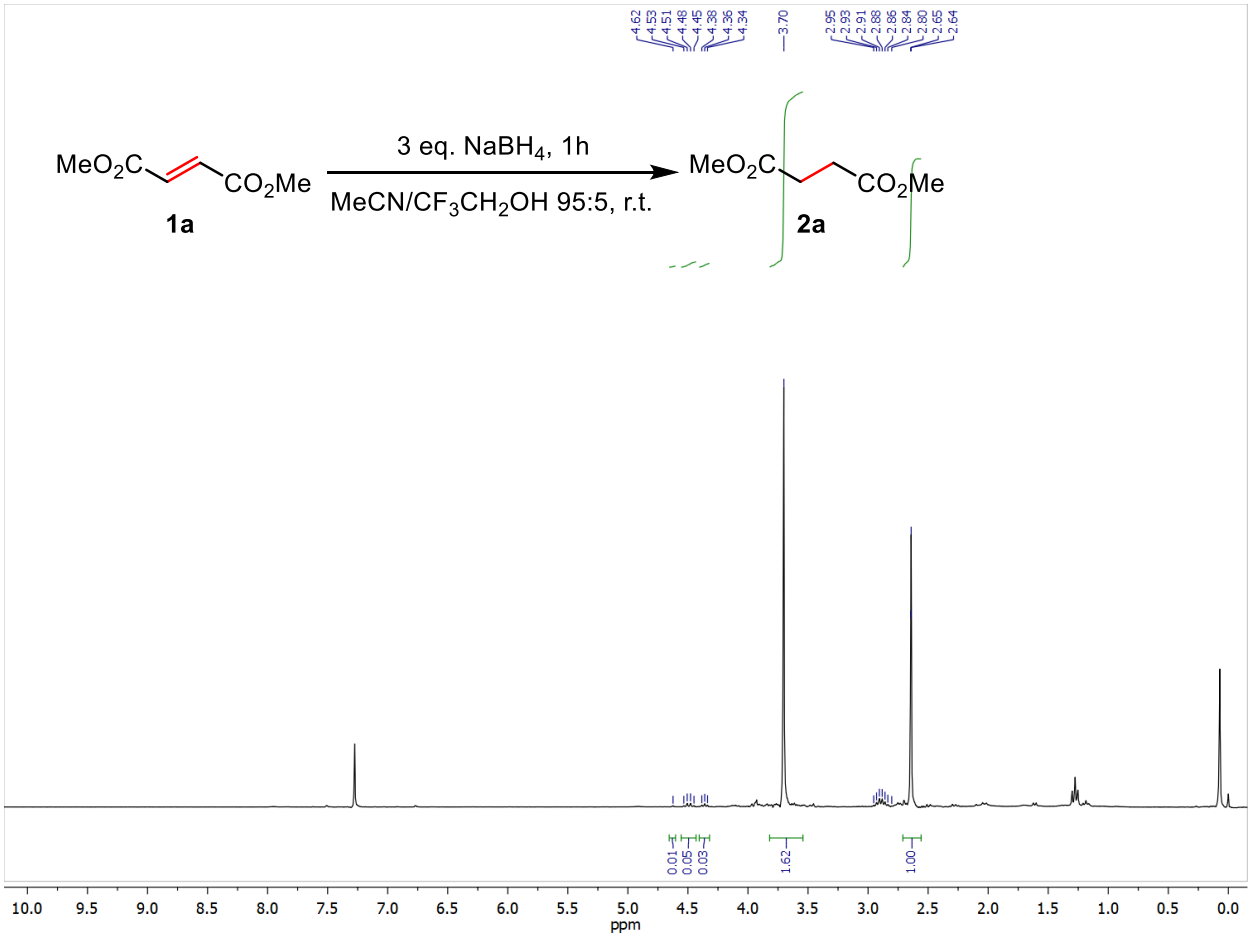

135.24
133.28
131.84
126.88
72.14
35.43
14.82
12.70
S
OH
S
9b
ppm

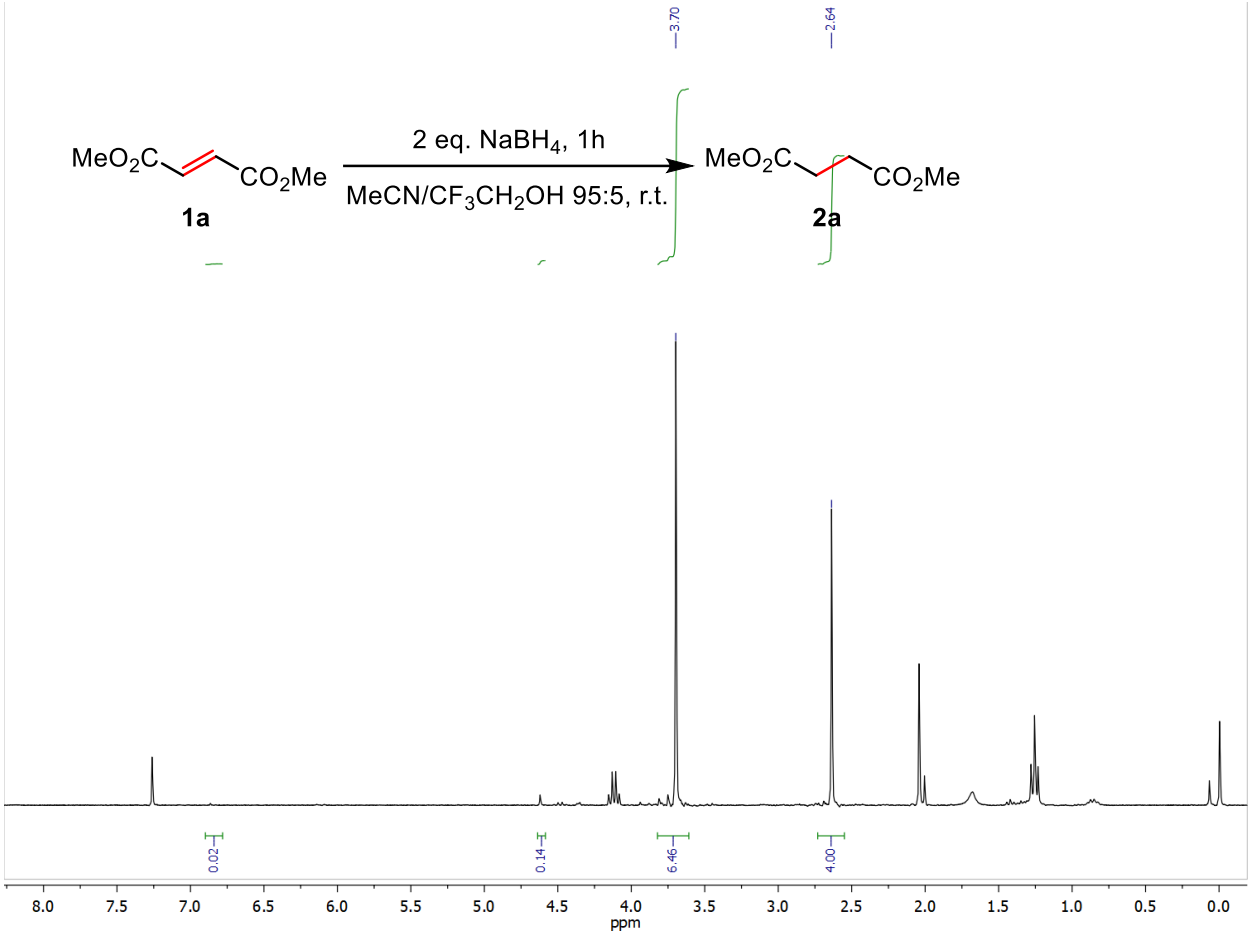

7.09
7.08
7.06
7.04
7.02
7.01
6.15
6.09
4.37
4.37
4.36
4.35
3.76
3.70
3.69
2.64
2.48
2.46
2.43
1.94
1.92
1.90
1.87
1.85
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeOH, r.t.
MeO2C
CO2Me
2a
0.99
0.99
2.14
5.56
0.55
0.63
0.62
ppm

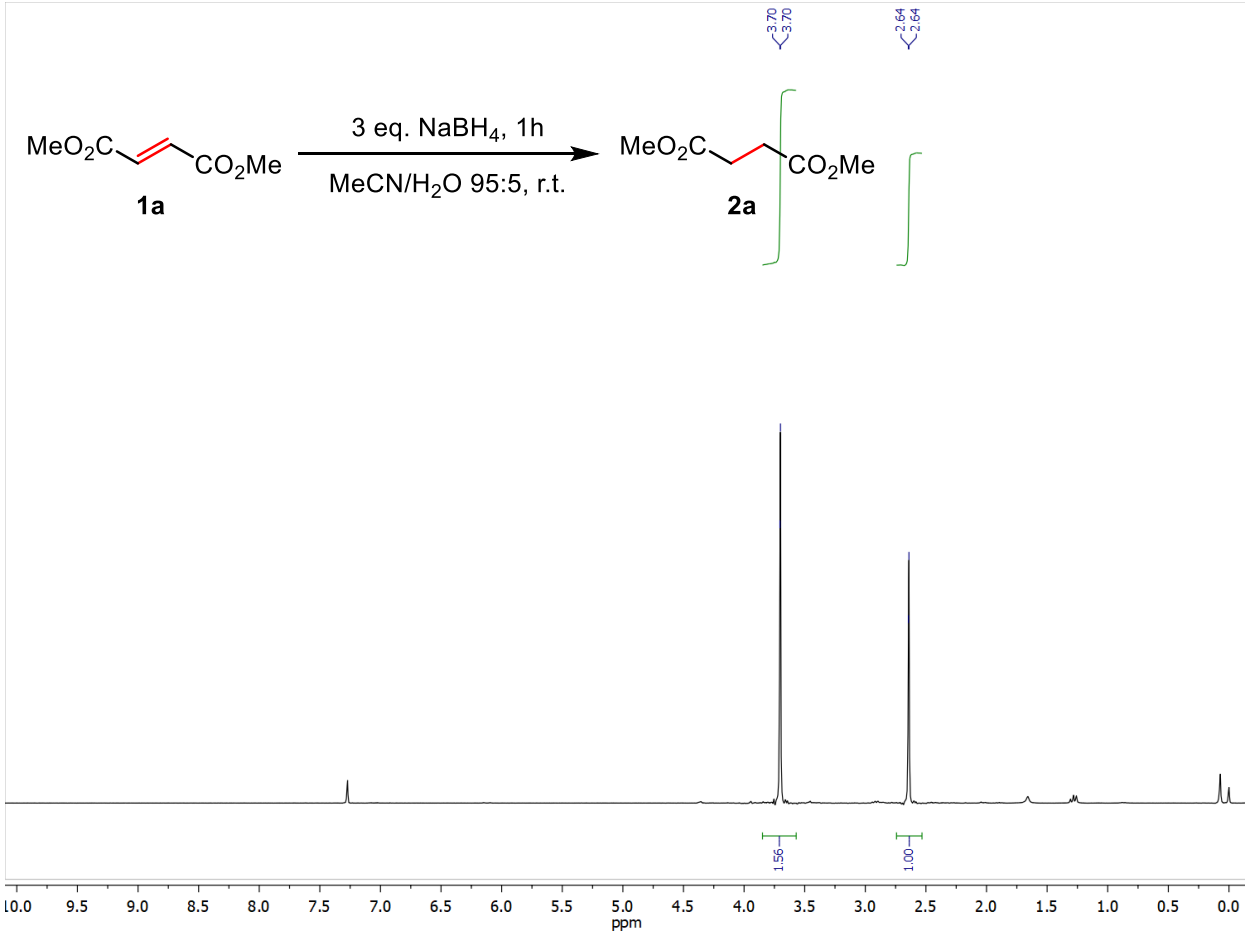

4.55
4.53
4.50
3.76
3.75
3.75
3.74
3.73
3.72
3.70
3.70
2.64
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeCN, r.t.
MeO2C
CO2Me
2a
0.11
6.16
1.60
0.95
1.38
1.36
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm

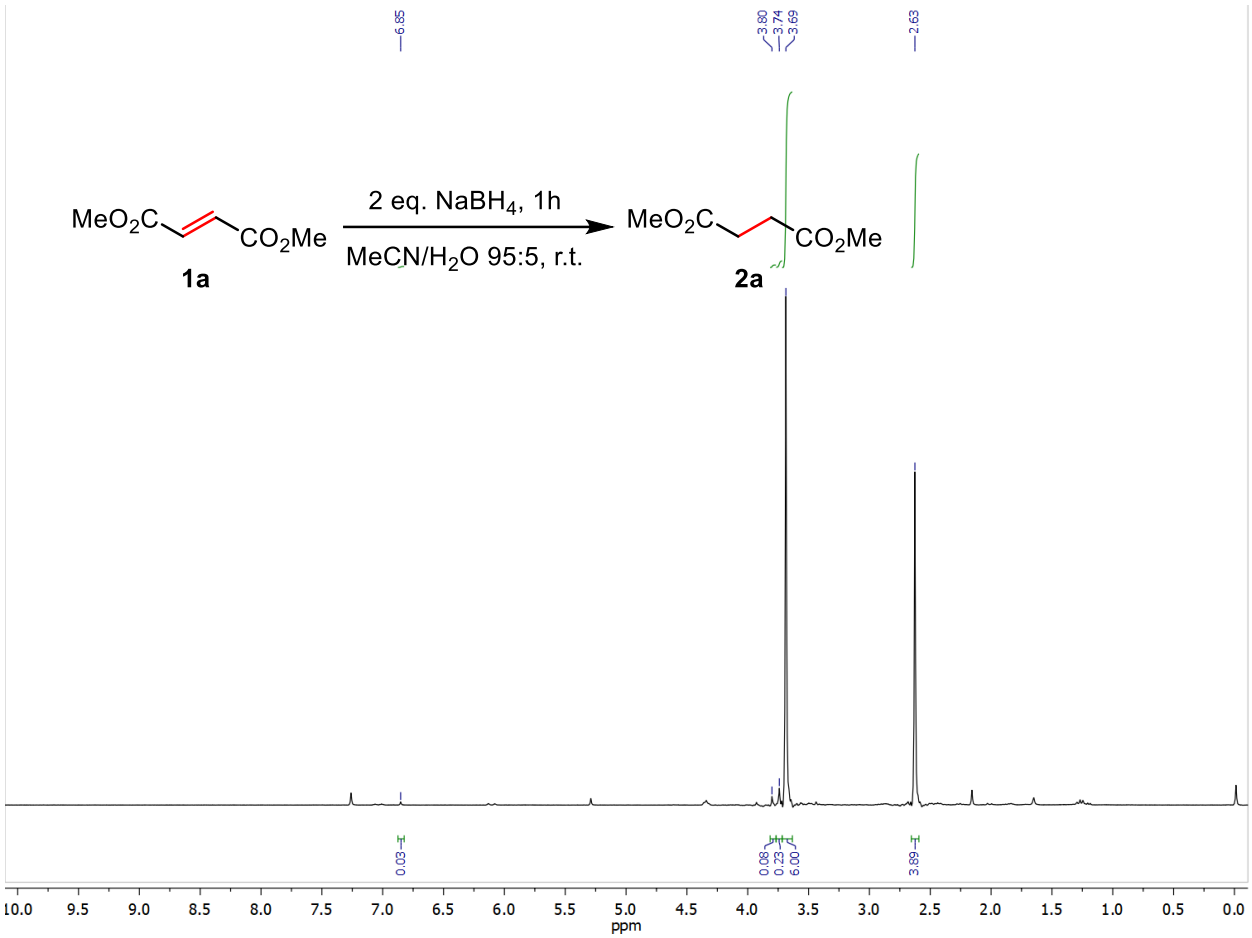

4.23
4.21
4.20
4.18
3.84
3.79
3.78
3.72
3.70
3.70
3.47
3.46
2.79
2.78
2.75
2.64
2.64
2.30
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeCN/MeOH 95:5, r.t.
MeO2C
CO2Me
2a
0.04
1.00
0.11
0.06
0.46
0.05
0.03
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm

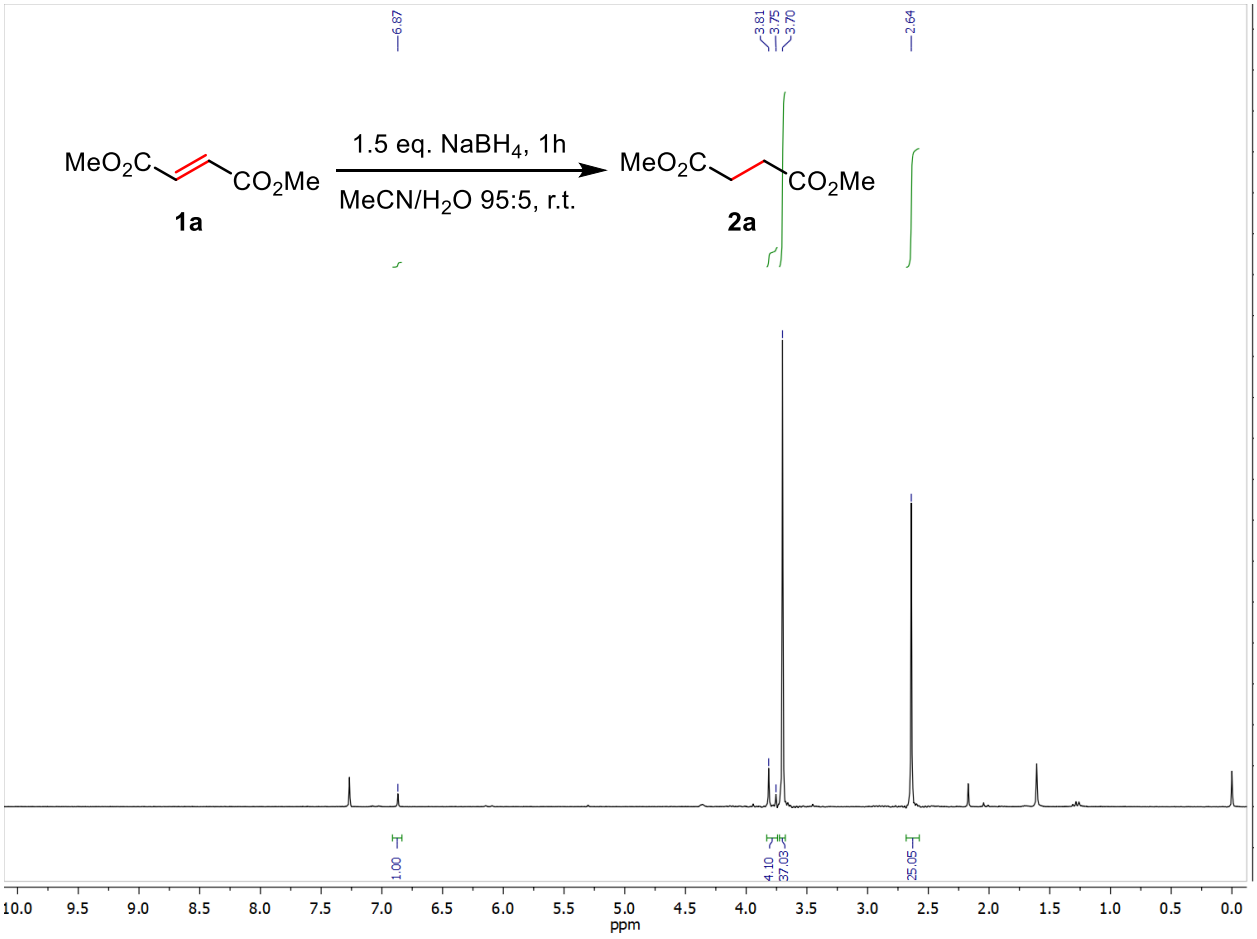

6.87
3.82
3.81
2.64
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeCN/AcOH 95:5, r.t.
MeO2C
CO2Me
2a
84.39
105.56
1.00
ppm

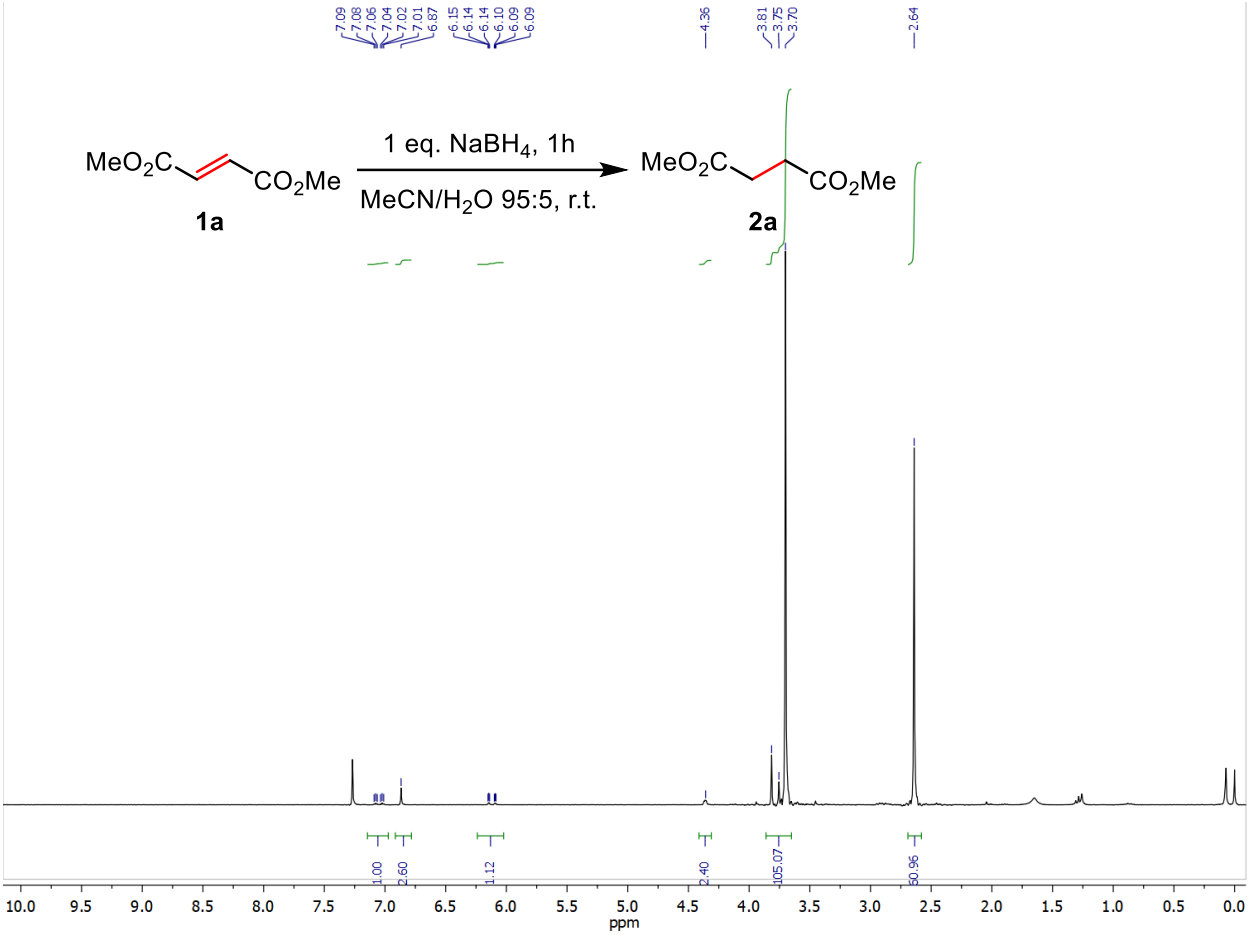

4.62
4.53
4.51
4.48
4.45
4.38
4.36
4.34
3.70
2.95
2.93
2.91
2.88
2.86
2.84
2.80
2.65
2.64
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeCN/CF3CH2OH 95:5, r.t.
MeO2C
CO2Me
2a
0.01
0.05
0.03
1.62
1.00
ppm


3.70
2.64
MeO2C
CO2Me
1a
2 eq. NaBH4, 1h
MeCN/CF3CH2OH 95:5, r.t.
MeO2C
CO2Me
2a
0.02
0.14
6.46
4.00
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm


3.70
3.70
2.64
2.64
MeO2C
CO2Me
1a
3 eq. NaBH4, 1h
MeCN/H2O 95:5, r.t.
MeO2C
CO2Me
2a
1.56
1.00
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm


6.85
3.80
3.74
3.69
2.63
MeO2C
CO2Me
1a
2 eq. NaBH4, 1h
MeCN/H2O 95:5, r.t.
MeO2C
CO2Me
2a
0.03
0.08
0.23
6.00
3.89
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm


6.87
3.81
3.75
3.70
2.64
MeO2C
CO2Me
1a
1.5 eq. NaBH4, 1h
MeCN/H2O 95:5, r.t.
MeO2C
CO2Me
2a
1.00
4.10
37.03
25.05
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
ppm



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