Electronic Supplementary Material (ESI) for Catalysis Science & Technology.

Stabilization and activation of unstable propynal in the zeolite nanospace and its application to addition reactions

Daijiro Hayashi, Yuta Igura, Yoichi Masui, Makoto Onaka*
Department of Chemistry, Graduate School of Arts and Sciences, The University of Tokyo
E-mail: conaka@mail.ecc.u-tokyo.ac.jp

Table of contents

I. Materials and analytical methods

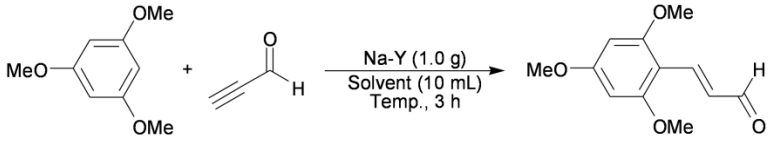
Propynal was synthesized by the oxidation of 2-propyn-1-ol using chromium (VI) oxide as previously reported. Cyclohexane, 3,4-dihydro-2*H*-pyran, 2,3-dihydrofuran, butyl vinyl ether, anisole, 1,3-dimethoxybenzene, and 1,3,5-trimethoxybenzene were purchased from Tokyo Chemical Industry Co., Ltd. (Tokyo, Japan). Ethyl diazoacetate was purchased from Sigma-Aldrich Co. LLC. (St. Louis, USA). α-Diazoacetophenone and 1-diazo-3,3-dimethyl-2-butanone were synthesized from benzoyl chloride or pivaloyl chloride as previously reported.[1]

Gas chromatography (GC) was performed using an Agilent 6850 series II Network GC equipped with a flame ionization detector and an Agilent HP-1 capillary column (30 m × 0.32 mm × 0.25 μm). Quantitative analysis of products was conducted using an internal standard of decane, tetradecane or triphenylmethane. GC/mass spectrometry (MS) was performed using a Shimadzu GCMS-QP2010 Plus operated in the electron ionization mode and equipped with an Agilent HP-1 capillary column (30 m × 0.32 mm × 0.25 μm).

Liquid ^{1}H and ^{13}C NMR spectra were recorded using a Bruker AVANCE III/500 spectrometer. Proton chemical shifts were referenced to the internal tetramethylsilane at 0.00 ppm. Carbon chemical shifts were referenced to $CDCl_3$ at 77.16 ppm or DMSO-d_6 at 39.52 ppm. Solid-state ^{13}C nuclear magnetic resonance spectroscopy (^{13}C-DD or CP/MAS-NMR) was performed on a Bruker AVANCE III/400 spectrometer operating at a resonance frequency of 100.6 MHz using a 4-mm WVT probe tube, 5.0 s recycle delay time, 10 kHz spinning rate. Chemical shifts were referenced to the carbonyl carbon signal of external glycine at 176.03 ppm. Analytical thin layer chromatography (TLC) was performed using Merk silica gel 60 F254.

II. Tables S1, Table S2, and Scheme S1

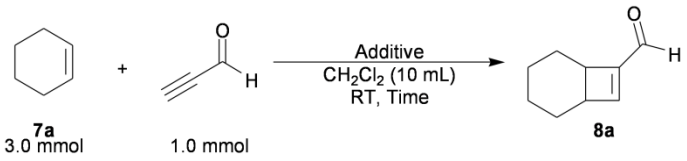
Table S1 1,4-Addition of 1,3,5-trimethoxybenzene to pyopynal[a]



Entry	**4c**	Solvent	Temp. (°C)	Yield[c] (%)
1	10 g	—	100	43
2[b]	10 mmol	chlorobenzene	100	24
3	10 mmol	bromobenzene	140	16
4	10 mmol	ethyl acetate	60	trace

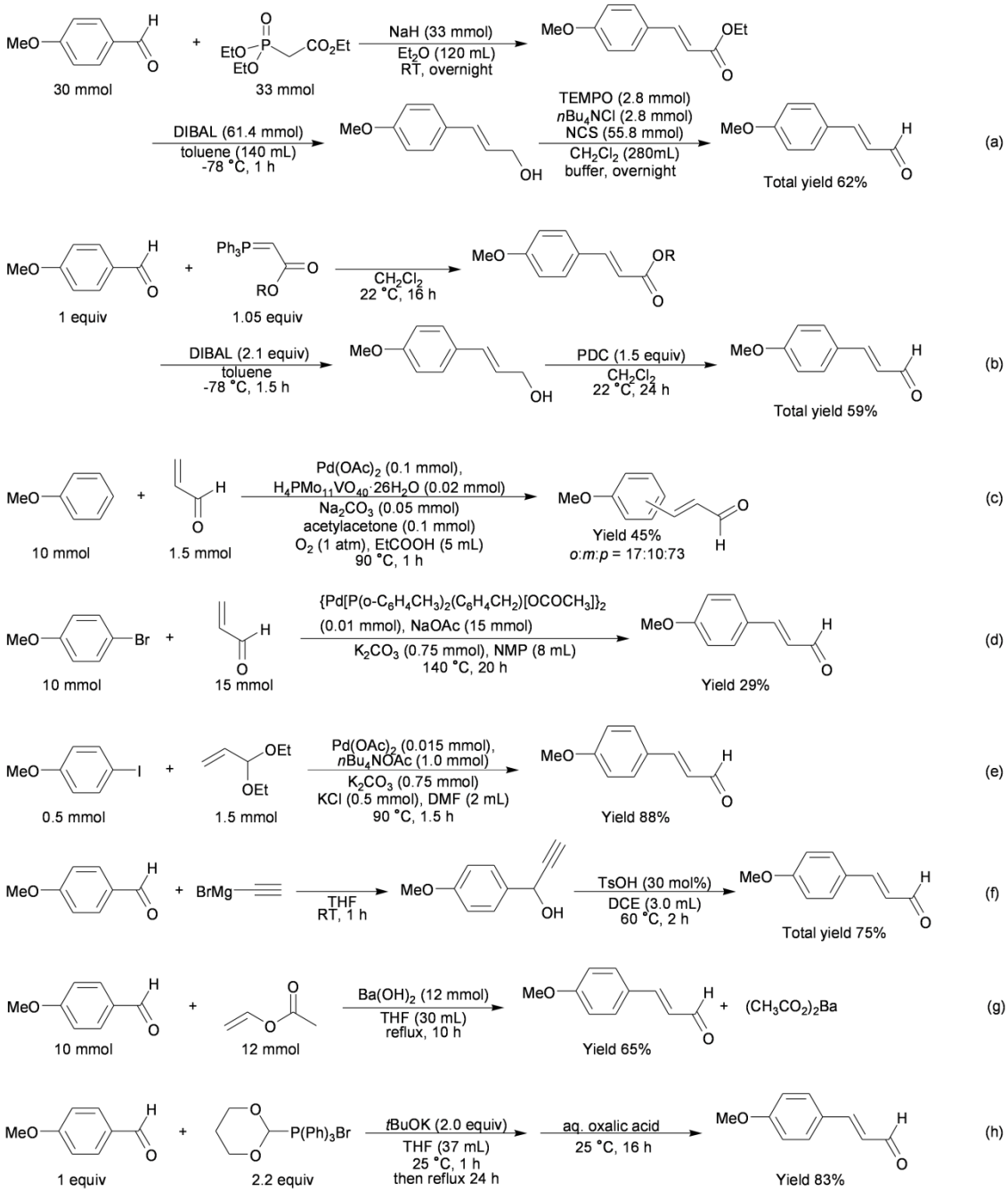
[a] Reaction conditions: **4c** (10 mL), pyopynal (1.0 mmol), Na-Y (1.0 g), solvent (10 mL), 3 h. [b] Pyopynal was added using a syringe pump over 1 h. [c] Yield was determined by GC analysis.

Table S2 [2 + 2] Cycloaddition of cyclohexene to propynal



Entry	Additive	Amount	Time (h)	Yield[a] (%)
1	Na-Y	1.0 g	36	13
2	Na-Y	1.0 g	72	23
3	Na-Y	1.0 g	216	10
4[b]	Na-Y	1.0 g	72	13
5[c]	Na-Y	1.0 g	72	0
6[d]	Na-Y	1.0 g	72	0
7[e]	Na-Y	1.0 g	72	9
8[e]	Na-Y	1.0 g	168	19
9[e]	—	—	209	0
10	SiO_2[f]	1.37 g	72	< 1
11	SiO_2-Al_2O_3[g]	1.25 g	1	10
12	SiO_2-Al_2O_3[g]	1.25 g	8	trace
13	H-Y	0.1 g	1	4
14	H-Y	0.1 g	24	5
15	$AlCl_3$	1.0 equiv.	1	0
16	$AlCl_3$	1.0 equiv.	8	0
17	$EtAlCl_2$	0.5 equiv.	8	0
18	$EtAlCl_2$	0.5 equiv.	72	0

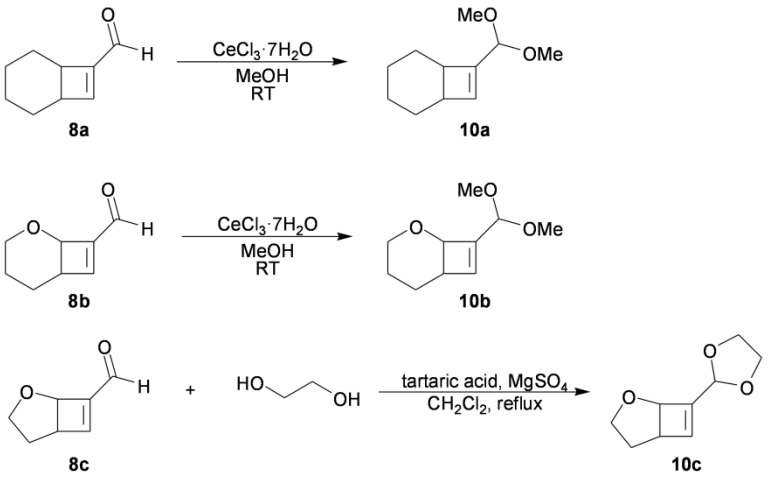
[a] Yield was determined by ^{1}H NMR of the crude mixture. [b] 30 °C. [c] Solvent: AcOEt. [d] Solvent: CH_3CN. [e] 10 mL of **7a** instead of CH_2Cl_2 was used. [f] Merck Silica Gel 60. [g] JRC-SAL-2, Si/Al = 5.3.



Scheme S1 Synthesis of *p*-methoxy cinnamaldehyde. (a) the Horner-Emmons reaction,[2] (b) the Wittig reaction,[3] (c) the direct Heck reaction,[4] (d) the Heck reaction,[5] (e) the Heck reaction,[6] (f) the Grignard reaction and the Meyer-Schuster rearrangement,[7] (g) cross aldol reaction,[8] and (h) the Wittig reaction.[9]

III. Structure determination of the [2 + 2] cycloadducts

The [2 + 2] cycloadducts were hard to be isolated because of their lability and contamination with some reaction byproducts. To confirm the cycloadducts, acetalization of **8a** and **8b** with methanol was performed by $CeCl_3 \cdot 7H_2O$, and **8c** with ethylene glycol by tartaric acid (Scheme S2).[10] In the "V. Compound Data" section described below, only the NMR data were shown for the cycloadducts, and the NMR, IR, and HRMS data were shown for the acetals.



Scheme S2 Acetalization of **8**.

The structure of **8b** and **8c** were confirmed by the HMBC technique to distinguish them from constitutional isomers, **9b** and **9c** (Fig. S1).

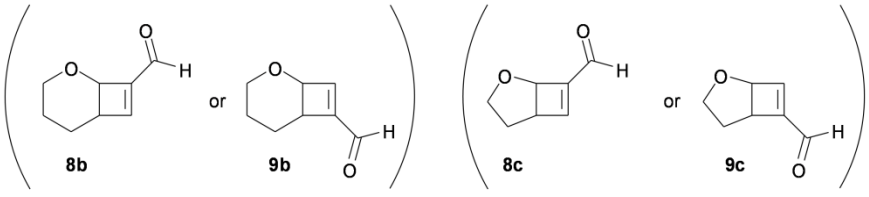


Fig. S1 Constitutional isomers of **8** and **9**.

The HMBC spectrum of **8b** showed that three observed correlations, one H^a–C^a (red) and two H^b–C^b (blue), corresponded to three-bond correlations for **8b** (Fig. S2 and Fig**. S3**). The four-bond correlation is not reasonable for the HMBC technique, then the [2 + 2] cycloadduct was not **9b**.

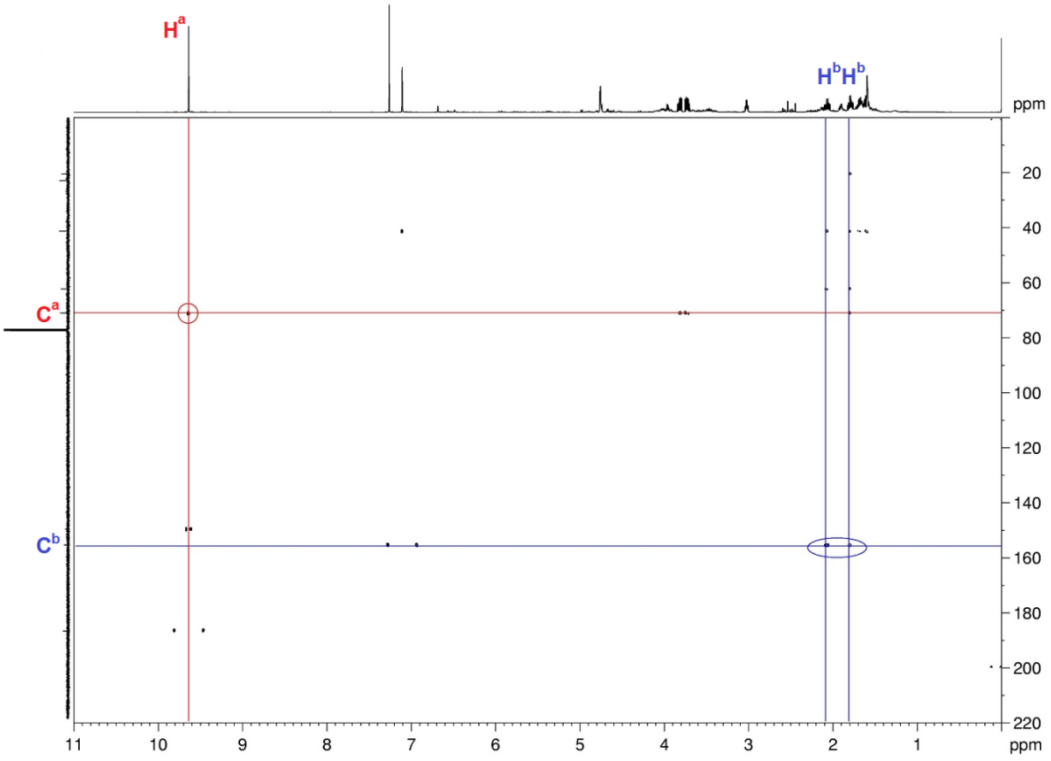


Fig. S2 The HMBC spectrum of **8b**.

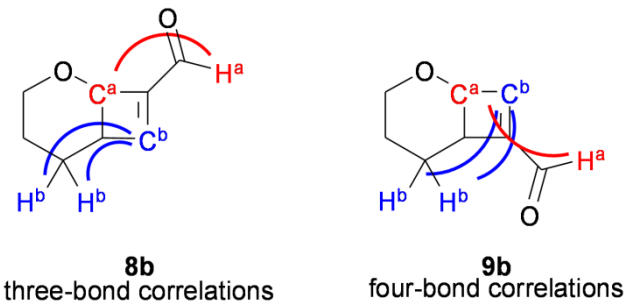


Fig. S3 The HMBC correlations of one H^a–C^a (red) and two H^b–C^b (blue).

The same conclusion was also obtained using the HMBC technique for **8c** (Fig. S4Fig. S5). The HMBC spectrum of **8c** showed that three observed correlations, one H^a–C^a (red) and two H^b–C^b (blue), corresponded to three-bond correlations for **8c**.

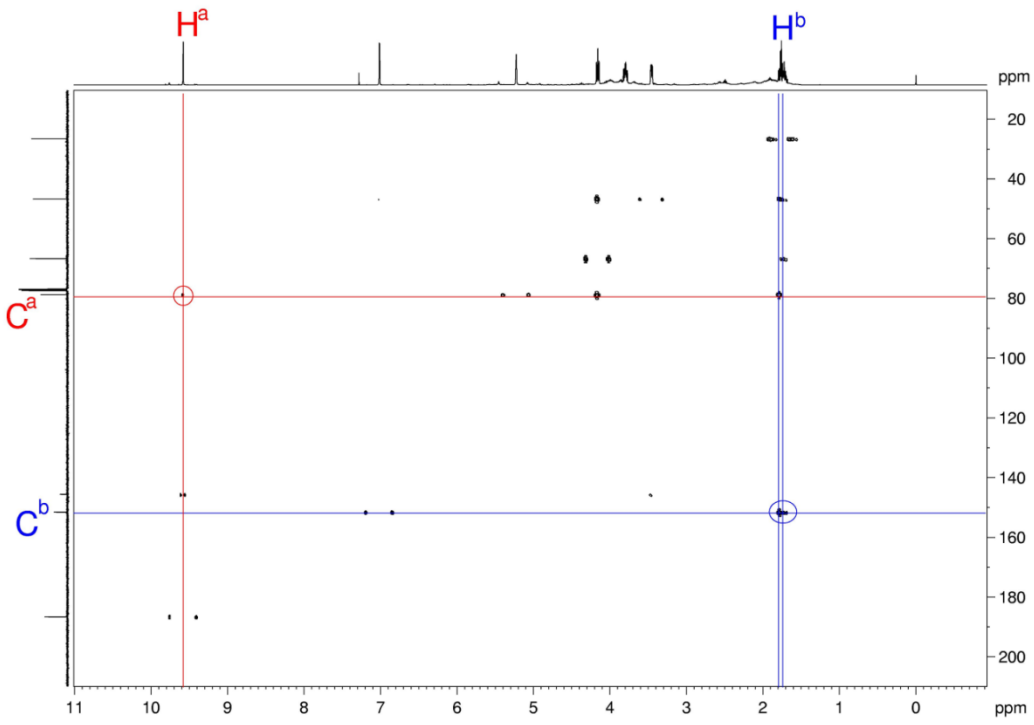


Fig. S4 The HMBC spectrum of **8c**.

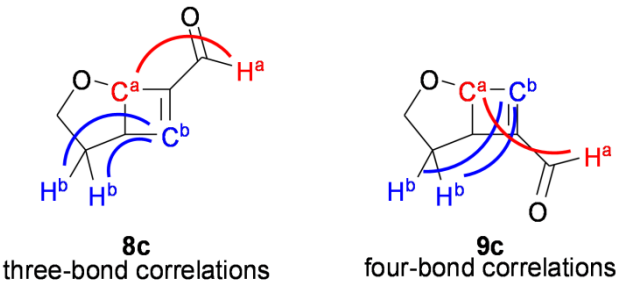


Fig. S5 The HMBC correlations of one H^a–C^a (red) and two H^b–C^b (blue).

IV. The quantum chemical calculation on the reaction mechanism of the [2 + 2] cycloaddition

The calculations were performed with Gaussian 09 using B3LYP density functional and the 6-311+G basis set.[11]

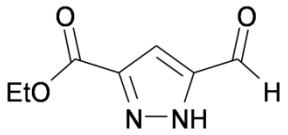
Table S3 Optimized Gibbs free energies (ΔG, kcal mol^{-1}) as a function of the length of two bonds (C^1–C^8 and C^6–C^7) created by the [2 + 2] cycloaddition of **7b** to propynal.

Bond C^1–C^8 (Å) \ Bond C^6 – C^7 (Å)	1.53	1.58	1.63	1.68	1.73	1.78	1.83	1.88	1.93	1.98	2.03
1.54	**0.0**	7.1	14.0	24.1	36.6	50.6	65.8	81.7	97.9	114.2	130.5
1.59	6.9	9.7	16.8	27.1	39.8	54.0	69.4	85.5	101.9	118.4	134.9
1.64	13.3	16.3	23.6	34.1	46.9	61.4	77.0	93.3	109.9	126.6	143.2
1.69	22.5	25.7	33.2	43.9	57.0	71.7	87.5	103.9	120.8	137.7	154.5
1.74	33.7	37.1	44.8	55.8	69.0	83.9	99.9	116.6	133.7	150.8	167.8
1.79	46.3	49.9	57.8	69.0	82.5	97.6	113.8	130.7	147.9	165.3	182.5
1.84	59.6	63.5	71.6	83.0	96.7	112.0	128.5	145.6	163.0	180.6	198.0
1.89	73.4	77.5	85.8	97.4	111.3	126.9	143.5	160.9	178.6	196.3	214.0
1.94	87.4	91.6	100.1	111.9	126.1	141.8	158.7	176.3	194.2	212.2	230.1
1.99	101.2	105.7	114.4	126.4	140.7	156.7	173.8	191.5	209.7	227.9	246.0
2.04	114.8	119.5	128.4	140.6	155.2	171.3	188.6	206.6	224.9	243.3	261.6
2.09	127.8	132.7	141.8	154.2	169.0	185.4	202.8	221.0	239.5	258.1	276.6
2.14	140.2	145.2	154.6	167.2	182.1	198.7	216.4	234.8	253.5	272.3	290.9
2.19	147.6	152.6	162.1	174.8	190.0	206.9	224.9	243.5	262.5	281.5	300.4

Bond C^1–C^8 (Å)											
2.24	156.2	161.4	171.0	183.8	199.1	216.0	234.0	252.7	271.7	290.6	309.3
2.29	164.4	169.7	179.3	192.3	207.6	224.6	242.6	261.2	280.1	298.9	317.4
2.34	172.2	177.5	187.3	200.3	215.6	232.6	250.5	269.1	287.8	306.3	324.2
2.39	179.6	185.0	194.7	207.8	223.1	240.0	257.9	276.3	294.7	312.6	260.0
2.44	186.7	192.1	201.9	214.8	230.1	246.9	264.7	282.8	300.6	252.8	247.5
2.49	193.6	198.9	208.7	221.6	236.7	253.4	270.9	288.5	245.5	241.5	236.4
2.54	200.3	205.6	215.2	228.0	243.0	259.4	276.5	238.5	235.7	231.7	226.6
2.59	206.8	212.0	221.5	234.2	249.0	265.1	281.5	230.0	227.1	223.2	218.2
2.64	213.1	218.3	227.7	240.2	254.7	270.3	224.8	222.8	219.9	215.9	210.9
2.69	219.3	224.4	233.7	246.0	260.2	220.2	218.8	216.7	213.7	209.8	204.9
2.74	225.4	230.4	239.5	251.7	265.4	215.4	214.0	211.8	208.7	204.7	199.8
2.79	231.4	236.3	245.3	257.1	212.7	211.6	210.2	207.7	204.6	200.6	195.8
2.84	237.6	242.2	**250.9**	211.0	209.7	208.5	206.9	204.5	201.4	197.4	192.6
2.89	243.8	248.1	256.5	208.9	207.4	206.2	204.5	202.1	198.8	194.8	190.0
2.94	250.0	254.1	209.2	207.1	205.7	204.3	202.6	200.1	196.8	192.7	187.9
2.99	256.1	260.0	207.6	205.4	204.0	202.8	201.1	198.6	195.3	191.2	186.3

V. Compound data

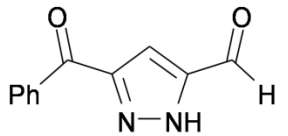
5-Formyl-1*H*-pyrazole-3-carboxylic acid ethyl ester (**2a**)[12]



2a

^{1}H NMR (500 MHz, DMSO-d_6, 60 °C): δ ppm 1.32 (t, J = 7.1 Hz, 3H, OCH_2CH_3), 4.34 (q, J = 7.1 Hz, 2H, OCH_2CH_3), 7.27 (s, 1H, N*H*), 9.93 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, DMSO-d_6, 60 °C): δ ppm 13.8, 60.7, 109.4, 138.3, 148.1, 159.2, 184.4; Anal. Calcd for $C_7H_8N_2O_3$: C, 50.00; H, 4.80; N, 16.66. Found: C, 49.94; H, 4.88; N, 16.48.

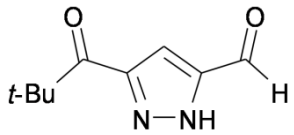
5-Benzoyl-2*H*-pyrazole-3-carbaldehyde (**2b**)[13]



2b

^{1}H NMR (500 MHz, DMSO-d_6, 22 °C): δ ppm 7.26 (s, 1H, N*H*), 7.51-7.54 (m, 2H, Ar*H* *meta* to CO), 7.62 (t, J = 7.4 Hz, 1H, Ar*H* para to CO), 8.02-8.04 (m, 2H, Ar*H* *ortho* to CO), 9.94 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, DMSO-d_6, 23 °C): δ ppm 110.6, 128.1, 130.3, 132.1, 138.3, 150.0, 151.0, 186.2, 186.8; Anal. Calcd for $C_{11}H_8N_2O_2$: C, 66.00; H, 4.03; N, 13.99. Found: C, 65.95; H, 4.21; N, 13.91.

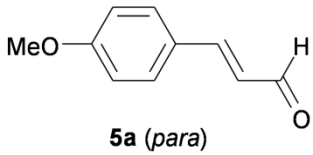
5-(2,2-Dimethyl-propionyl)-2*H*-pyrazole-3-carbaldehyde (**2c**)



2c

^{1}H NMR (500 MHz, DMSO-d_6, 22 °C): δ ppm 1.32 (s, 9H, CH_3), 7.46 (s, 1H, N*H*), 9.93 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, DMSO-d_6, 24 °C): δ ppm 26.9, 43.3, 110.4, 144.5, 147.4, 184.8, 198.1; Anal. Calcd for $C_9H_{12}N_2O_2$: C, 59.99; H, 6.71; N, 15.55. Found: C, 59.82; H, 6.82; N, 15.31.

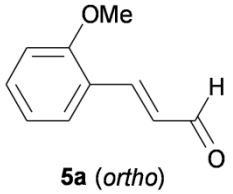
(*E*)-3-(4'-Methoxyphenyl)propanal (**5a**, *para*-adduct)[14]



5a (*para*)

^{1}H NMR (500 MHz, $CDCl_3$, 23 °C): δ ppm 3.86 (s, 3H, OCH_3), 6.61 (dd, *J* = 7.8, 15.9 Hz, 1H, C*H*CHO), 6.95 (d, *J* = 8.8 Hz, 2H, Ar*H ortho* to OCH_3), 7.42 (d, *J* = 15.9 Hz, 1H, ArC*H*), 7.52 (d, *J* = 8.8 Hz, 2H, Ar*H meta* to OCH_3), 9.85 (d, *J* = 7.8 Hz, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 23 °C): δ ppm 55.6, 114.7, 126.6, 126.9, 130.4, 152.8, 162.3, 193.8.

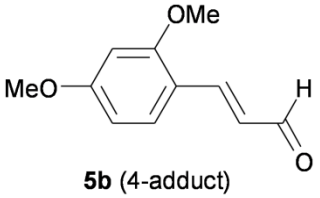
(*E*)-3-(2'-Methoxyphenyl)propanal (**5a**, *ortho*-adduct)[15]



5a (*ortho*)

^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ ppm 3.92 (s, 3H, OC*H*$_3$), 6.79 (dd, *J* = 7.8, 16.0 Hz, 1H, C*H*CHO), 6.95 (d, *J* = 8.3 Hz, 1H, Ar*H ortho* to OCH_3), 7.00 (t, *J* = 7.5 Hz, 1H, Ar*H para* to OCH_3), 7.41 (ddd, *J* = 1.7, 7.5, 8.2 Hz, 1H, Ar*H para* to CH), 7.56 (d, *J* = 1.5, 7.8 Hz, 1H, Ar*H ortho* to CH), 7.84 (d, *J* = 16.0 Hz, 1H, ArC*H*), 9.69 (d, *J* = 7.9 Hz, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 25 °C): δ ppm 55.7, 111.4, 121.0, 123.1, 129.0, 129.3, 132.8, 148.3, 158.4, 194.7.

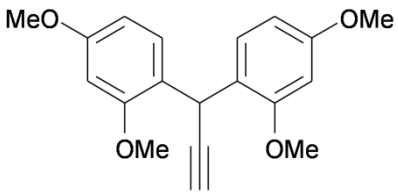
(*E*)-3-(2',4'-Dimethoxyphenyl)propanal (**5b**, 4-adduct)[16]



5b (4-adduct)

^{1}H NMR (500 MHz, $CDCl_3$, 26 °C): δ ppm 3.85 (s, 3H, OC*H*$_3$ *para* to ArCH), 3.88 (s, 3H, OC*H*$_3$ *ortho* to ArCH), 6.46 (d, *J* = 2.4 Hz, 1H, Ar*H ortho* to two OCH_3), 6.54 (dd, *J* = 2.4, 8.7 Hz, 1H, Ar*H para* to OCH_3), 6.70 (dd, *J* = 7.9, 16.0 Hz, 1H, C*H*CHO), 7.48 (d, *J* = 8.6 Hz, 1H, Ar*H ortho* to CH), 7.52 (d, *J* = 8.8 Hz, 2H, Ar*H meta* to OCH_3), 7.73 (d, *J* = 16.0 Hz, 1H, ArC*H*), 9.62 (d, *J* = 7.9 Hz, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 55.6, 55.7, 98.5, 105.8, 116.3, 126.9, 130.6, 148.5, 160.0, 163.9, 194.7.

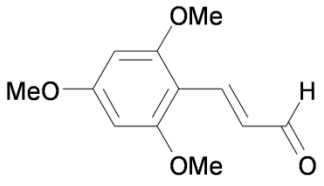
3,3-Bis(2',4'-dimethoxyphenyl)-1-propyne (**6b**)



6b

^{1}H NMR (500 MHz, $CDCl_3$, 22 °C): δ ppm 2.26 (d, *J* = 2.6 Hz, 1H, C≡C*H*), 3.76 (s, 6H, OCH_3), 3.78 (s, 6H, OCH_3), 5.55 (d, *J* = 2.5 Hz, 1H, Ar_2C*H*), 6.43–6.45 (4H, Ar*H*), 7.26 (d, *J* = 8.0 Hz, 2H, Ar*H ortho* to two OCH_3); ^{13}C NMR (126 MHz, $CDCl_3$, 22 °C): δ ppm 29.3, 55.4, 55.9, 70.1, 85.9, 98.9, 104.1, 122.1, 129.4, 157.6, 159.9; IR (CCl_4): 3303, 3288, 3075, 3003, 2957, 2939, 2837, 2113, 1674, 1609, 1589, 1503, 1465, 1439, 1416, 1292, 1262, 1208, 1176, 1157, 1117, 1039, 935, 924, 834, 791, 762, 636; HRMS calcd for $C_{19}H_{20}O_4$: 312.1362, found: 312.1367.

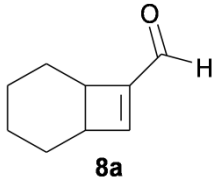
(*E*)-3-(2',4'6'-Trimethoxyphenyl)propanal (**5c**)[17]



5c

^{1}H NMR (500 MHz, $CDCl_3$, 26 °C): δ ppm 3.87 (s, 3H, OCH_3 *para* to ArCH), 3.89 (s, 6H, OCH_3 *ortho* to ArCH), 6.13 (s, 1H, Ar*H*), 7.06 (dd, *J* = 8.1, 16.0 Hz, 1H, C*H*CHO), 7.85 (d, *J* = 16.0 Hz, 1H, ArC*H*), 9.58 (d, *J* = 8.1 Hz, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 55.6, 55.9, 90.6, 106.1, 129.3, 144.9, 161.6, 164.1, 196.7.

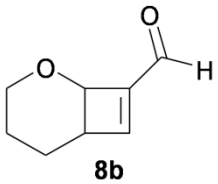
Bicyclo[4.2.0]oct-7-ene-7-carbaldehyde (**8a**)



8a

^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ ppm 1.43-1.57 (m, 2H), 1.60-1.66 (dt, *J* = 5.7, 13.8 Hz, 2H), 1.70-1.76 (dt, *J* = 5.7, 13.9 Hz, 2H), 1.79-1.86 (m, 2H), 2.92 (q, *J* = 5.5 Hz, 1H, C^{1}*H*), 3.14 (q, *J* = 5.4 Hz, 1H, C^{6}*H*), 7.05 (d, *J* = 1.1 Hz, 1H, C^{8}*H*), 9.57 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 18.6, 19.2, 23.6, 24.0, 39.1, 39.8, 150.8, 155.7, 187.6.

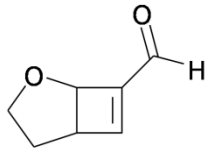
2-Oxa-bicyclo[4.2.0]oct-7-ene-8-carbaldehyde (**8b**)



8b

^{1}H NMR (500 MHz, $CDCl_3$, 29 °C): δ ppm 1.58-1.62 (m, 1H, C^{4}*H*), 1.67-1.70 (m, 1H, C^{4}*H*), 1.76-1.83 (ddt, *J* = 5.4, 8.1, 13.6 Hz, 1H, C^{5}*H*), 2.03-2.11 (dddd, *J* = 5.4, 7.0, 8.2, 13.5 Hz, 1H, C^{5}*H*), 3.00-3.05 (m, 1H, C^{6}*H*), 3.70-3.76 (ddd, *J* = 6.3, 8.0, 11.4 Hz, 1H, C^{3}*H*HO), 3.79-3.85 (ddd , *J* = 6.2, 7.7, 11.4 Hz, 1H, C^{3}H*H*O), 4.76 (dd, *J* = 1.7, 4.1 Hz, 1H, C^{1}*H*), 7.11 (t, *J* = 1.4 Hz, 1H, C^{7}*H*), 9.64 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 29 °C): δ ppm 20.4, 22.8, 41.2, 62.3, 70.9, 149.5, 155.3, 186.6.

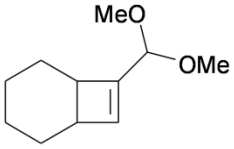
2-Oxa-bicyclo[3.2.0]hept-6-ene-7-carbaldehyde (**8c**)



8c

^{1}H NMR (500 MHz, $CDCl_3$, 26 °C): δ ppm 1.70–1.80 (m, 2H, C$^{4}H_2$), 3.46 (dd, *J* = 2.3, 8.0 Hz, 1H, C^{5}H), 3.77–3.83 (m, 1H, C$^{3}H_2$), 4.16 (t, *J* = 8.6 Hz, 1H, C$^{3}H_2$), 5.23 (s, 1H, C^{1}H), 7.02 (d, *J* = 2.7 Hz, 1H, C^{6}H), 9.58 (s, 1H, C*H*O); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 26.6, 46.7, 66.7, 78.7, 145.6, 151.6, 186.6.

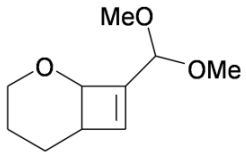
7-Dimethoxymethyl-bicyclo[4.2.0]oct-7-ene (**10a**)



10a

^{1}H NMR (500 MHz, $CDCl_3$, 26 °C): δ ppm 1.34-1.44 (m, 2H), 1.46-1.53 (m, 1H), 1.55-1.65 (m, 3H), 1.67-1.76 (m, 2H), 2.73 (q, *J* = 5.4 Hz, 1H, C^{1}H), 2.86 (q, *J* = 5.3 Hz, 1H, C^{6}H), 3.31 (s, 3H, OCH_3), 3.37 (s, 3H, OCH_3), 4.79 (s, 1H, OC*H*O), 6.13 (s, 1H, C^{8}H); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 18.8, 19.0, 24.0, 24.5, 37.9, 40.4, 52.2, 53.5, 99.7, 136.5, 148.2; IR (neat): 3041, 2988, 2934, 2865, 2827, 1681, 1463, 1449, 1366, 1343, 1277, 1206, 1193, 1113, 1078, 1053, 974, 908, 822.

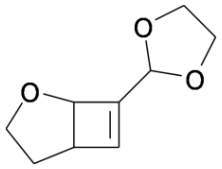
8-Dimethoxymethyl-2-oxa-bicyclo[4.2.0]oct-7-ene (**10b**)



10b

^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): δ ppm 1.52-1.56 (m, 1H), 1.64-1.75 (m, 2H), 1.92-1.97 (m, *J* = 6.5, 7.7, 13.1 Hz, 1H), 3.35 (s, 3H, OC*H*$_3$), 3.39 (s, 3H, OC*H*$_3$), 3.64-3.70 (ddd, *J* = 6.2, 8.2, 11.3 Hz, 1H, C^{3}*H*HO), 3.87-3.92 (ddd, *J* = 5.9, 7.9, 11.3 Hz, 1H, C^{3}H*H*O), 4.50 (dd, *J* = 1.4, 3.9 Hz, 1H, OC^{1}*H*), 4.89 (s, 1H, OC*H*O), 6.29 (s, 1H, C^{7}*H*); ^{13}C NMR (126 MHz, $CDCl_3$, 25 °C): δ ppm 20.4, 23.5, 39.5, 52.8, 53.5, 62.3, 72.4, 99.0, 139.2, 148.0; IR (CCl_4): 3263, 3049, 2942, 2865, 1727, 1631, 1609, 1446, 1354, 1262, 1198, 1113, 1072, 967, 911, 893, 862, 773, 726; HRMS calcd for $C_{10}H_{16}O_3$: 184.1099, found: 184.1095.

7-[1,3]Dioxolan-2-yl-2-oxa-bicyclo[3.2.0]hept-6-ene (**10c**)



10c

^{1}H NMR (500 MHz, $CDCl_3$, 26 °C): δ ppm 1.56-1.62 (tdd, *J* = 7.7, 11.4, 12.7 Hz, 1H, C^{4}*H*H), 1.63-1.68 (dd, *J* = 5.4, 12.7 Hz 1H, C^{4}H*H*), 3.28 (dd, *J* = 3.0, 7.8 Hz, 1H, C^{5}*H*), 3.88-3.95 (m, 3H), 4.01-4.04 (m, 2H, OC*H*$_2$CH_2O), 4.10 (t, *J* = 8.3 Hz, 1H, C^{3}*H*HO), 5.04 (t, *J* = 2.8 Hz, 1H, C^{1}*H*O), 5.32 (s, 1H, OC*H*O), 6.22 (d, *J* = 2.6 Hz,1H, C^{6}*H*); ^{13}C NMR (126 MHz, $CDCl_3$, 26 °C): δ ppm 27.0, 45.5, 65.0, 65.2, 66.6, 79.7, 98.4, 135.8, 144.7; IR (neat): 3047, 2958, 2880, 1688, 1639, 1476, 1360, 1323, 1298, 1209, 1126, 1098, 1064, 1025, 940, 907, 874, 830.

VI. Additional references

1 T. Aoyama and T. Shioiri, *Tetrahedron Lett.*, 1980, **21**, 4461–4462.

2 O. Chuzel and O. Piva, *Synth. Commun.*, 2003, **33**, 393–402.

3 T. D. Avery, D. Caiazza, J. A. Culbert, D. K. Taylor and E. R. T. Tiekink, *J. Org. Chem.*, 2005, **70**, 8344–8351.

4 T. Yamada, S. Sakaguchi and Y. Ishii, *J. Org. Chem.*, 2005, **70**, 5471–5474.

5 A. Nejjar, C. Pinel and L. Djakovitch, *Adv. Synth. Catal.*, 2003, **345**, 612–619.

6 G. Battistuzzi, S. Cacchi and G. Fabrizi, *Org. Lett.*, 2003, **5**, 777–780.

7 J. Park, J. Yun, J. Kim, D.-J. Jang, C. H. Park and K. Lee, *Synth. Commun.*, 2014, **44**, 1924–1929.

8 P. K. Mahata, O. Barun, H. Ila and H. Junjappa, *Synlett*, 2000, 1345–1347.

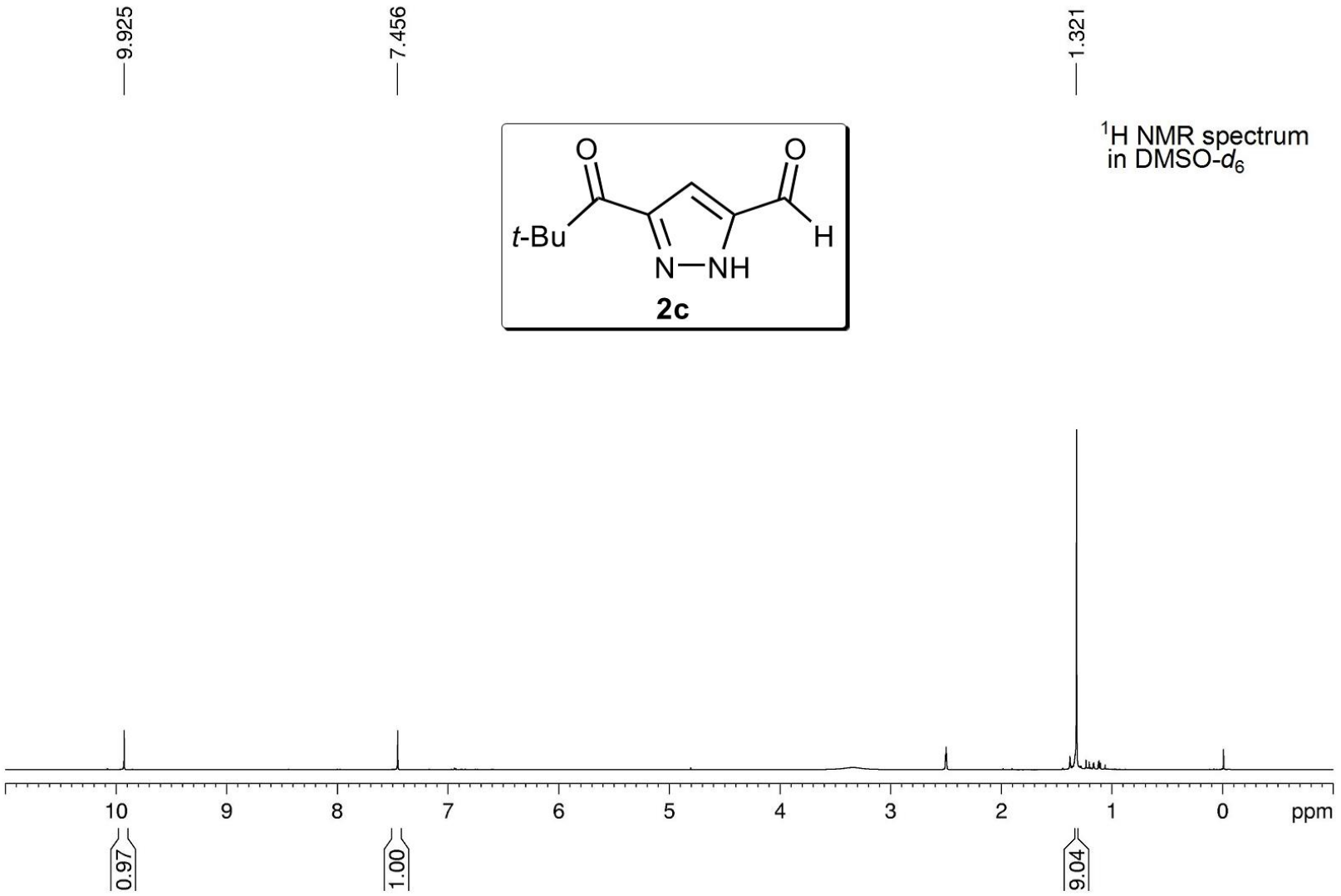
9 T. Pecchioli, M. K. Muthyala, R. Haag and M. Christmann, *Beilstein J. Org. Chem.*, 2015, **11**, 730–738.

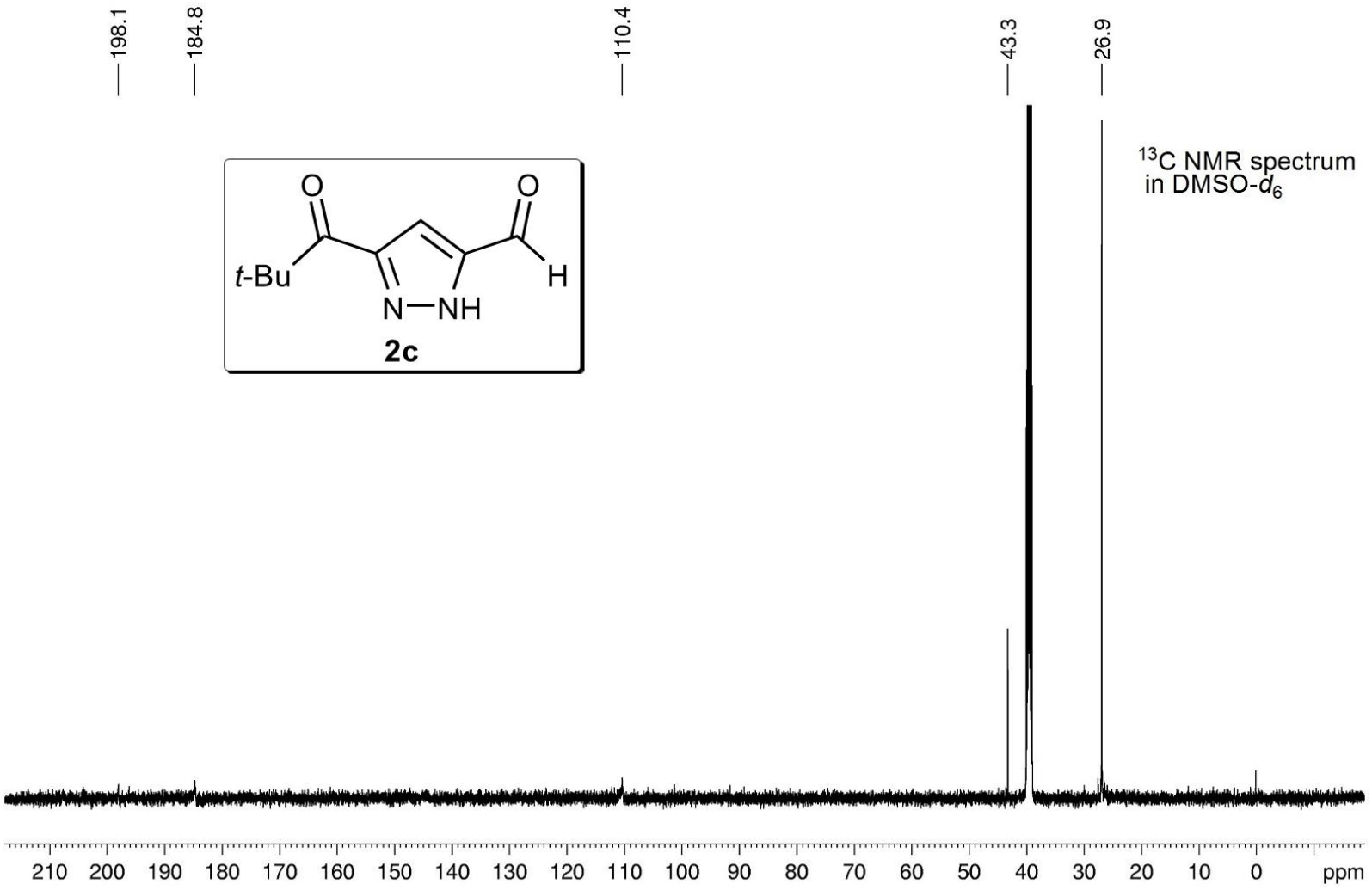
10 T.-J. Lu, J.-F. Yang and L.-J. Sheu, *J. Org. Chem.*, 1995, **60**, 2931–2934.

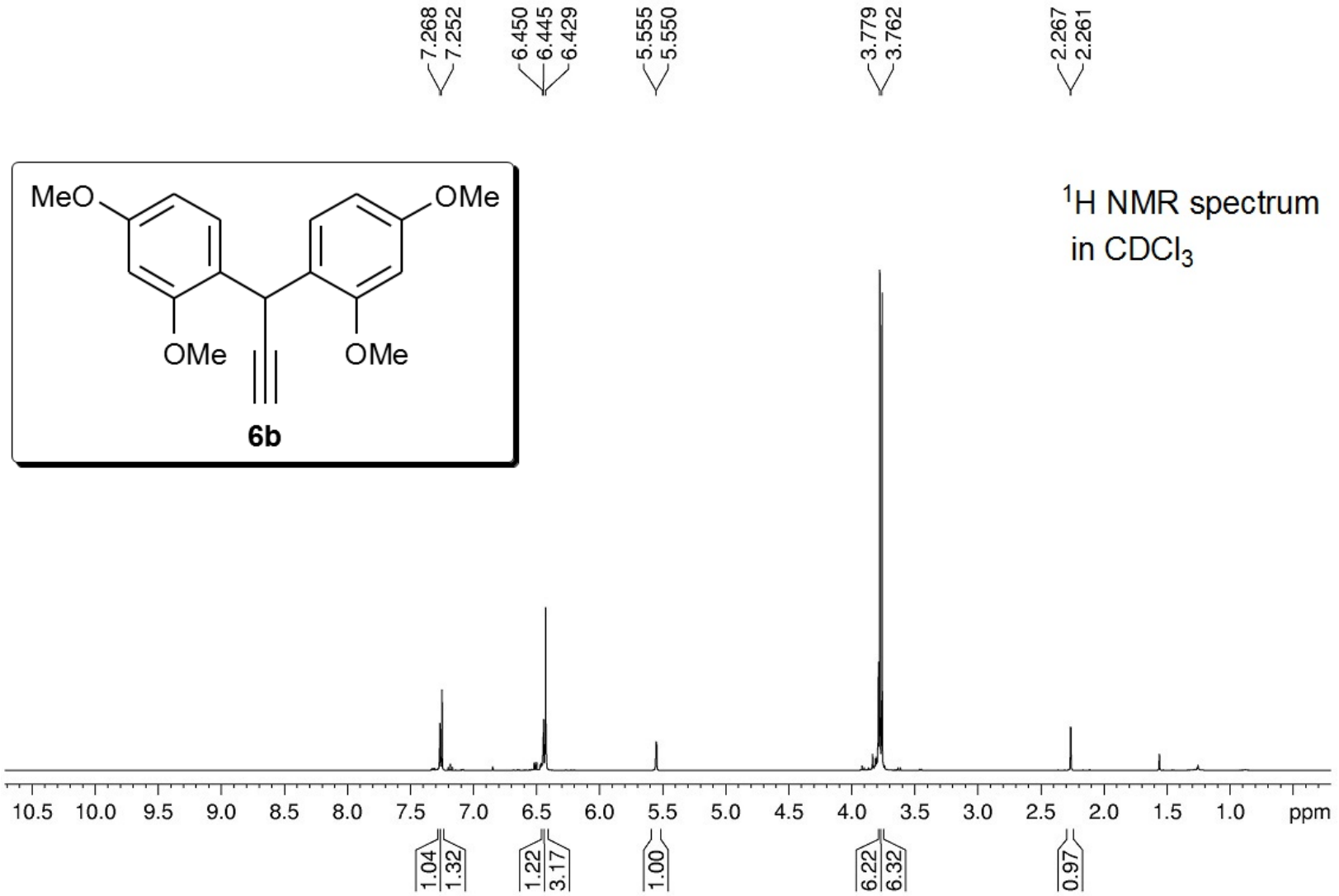
11 Gaussian 09, Revision D.01, Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A., Jr.; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, M. J.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, Ö.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. Gaussian, Inc., Wallingford CT, 2009.

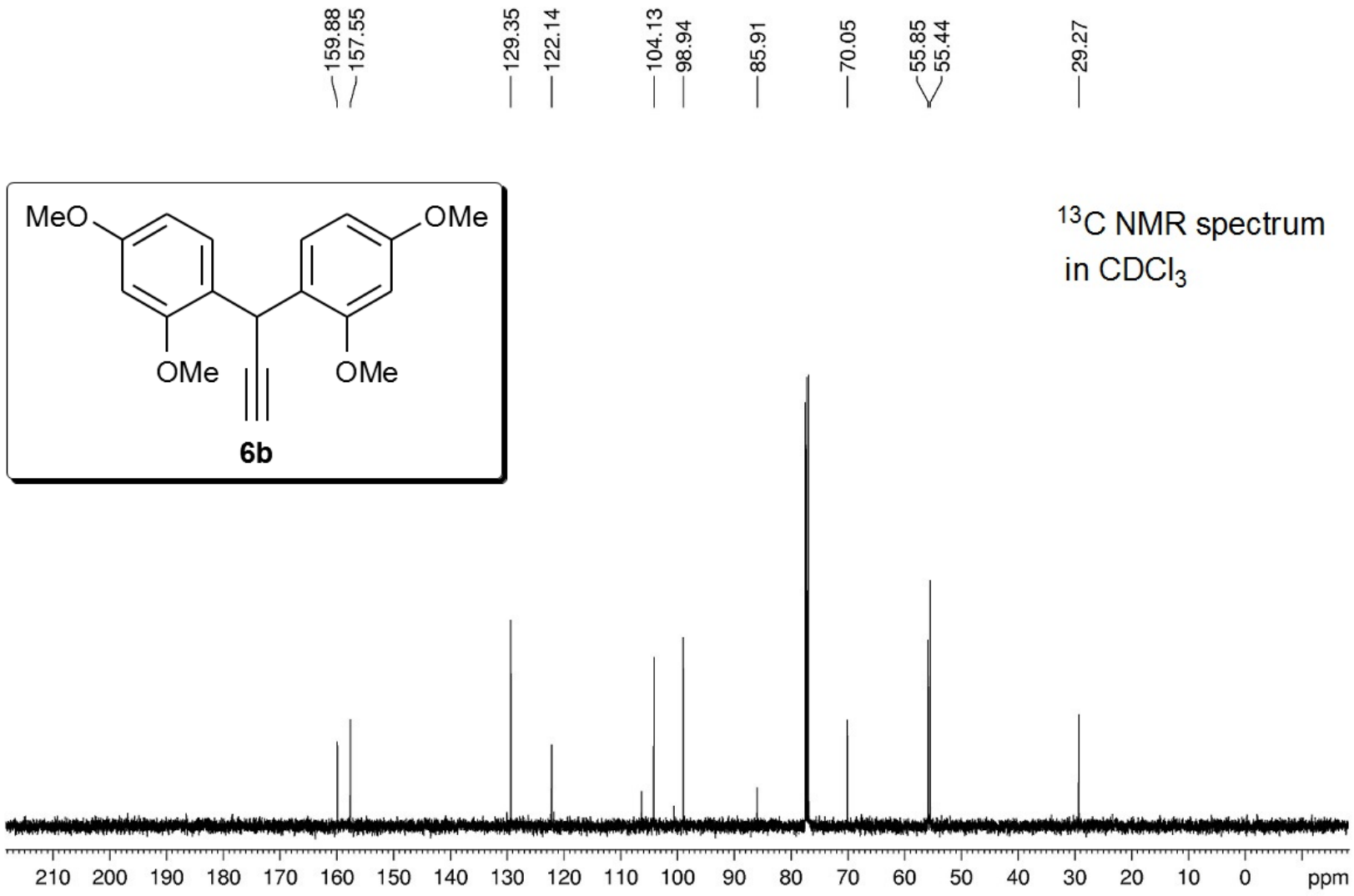
12 E. V Tretyakov, S. E. Tolstikov, G. V Romanenko, Y. G. Shvedenkov, R. Z. Sagdeev and V. I. Ovcharenko, *Russ. Chem. Bull.*, 2005, **54**, 2169–2181.

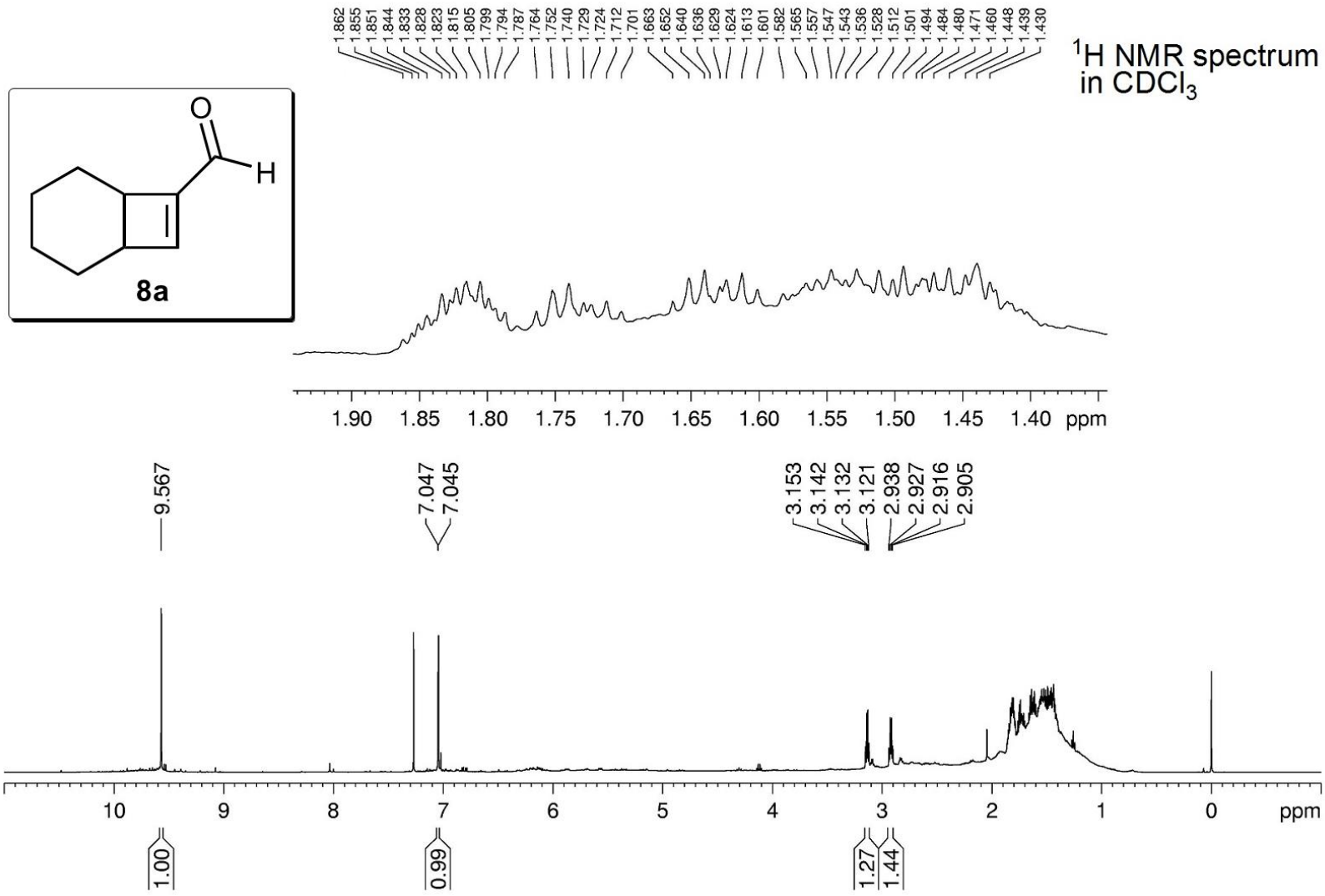
13 H. Abdallah, R. Grée and R. Carrié, *Bull. Soc. Chim. Fr.*, 1985, 794–802.
14 H. Miyamura, G. C. Y. Choo, T. Yasukawa, W.-J. Yoo and S. Kobayashi, *Chem. Commun.*, 2013, **49**, 9917–9919.
15 P. W. Moore, P. M. Mirzayans and C. M. Williams, *Chem. – A Eur. J.*, 2015, **21**, 3567–3571.
16 R. C. Barcelos, J. C. Pastre, V. Caixeta, D. B. Vendramini-Costa, J. E. de Carvalho and R. A. Pilli, *Bioorg. Med. Chem.*, 2012, **20**, 3635–3651.
17 H. Irngartinger, P. W. Fettel, T. Escher, P. Tinnefeld, S. Nord and M. Sauer, *Eur. J. Org. Chem.*, 2000, 455–465.

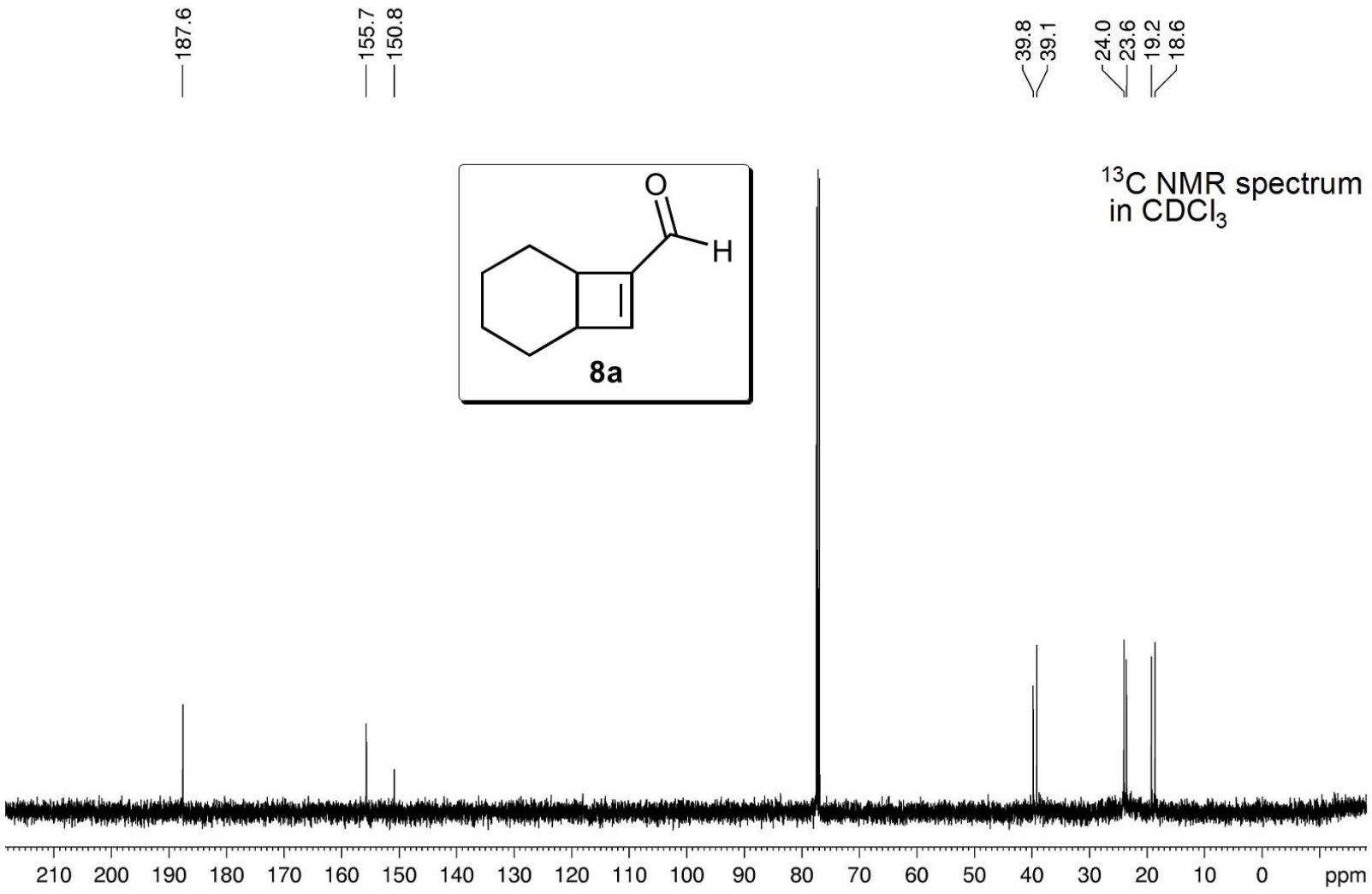

9.925
7.456
1.321
O
O
t-Bu
H
N—NH
2c
^{1}H NMR spectrum
in DMSO-d_6
10
9
8
7
6
5
4
3
2
1
0
ppm
0.97
1.00
9.04

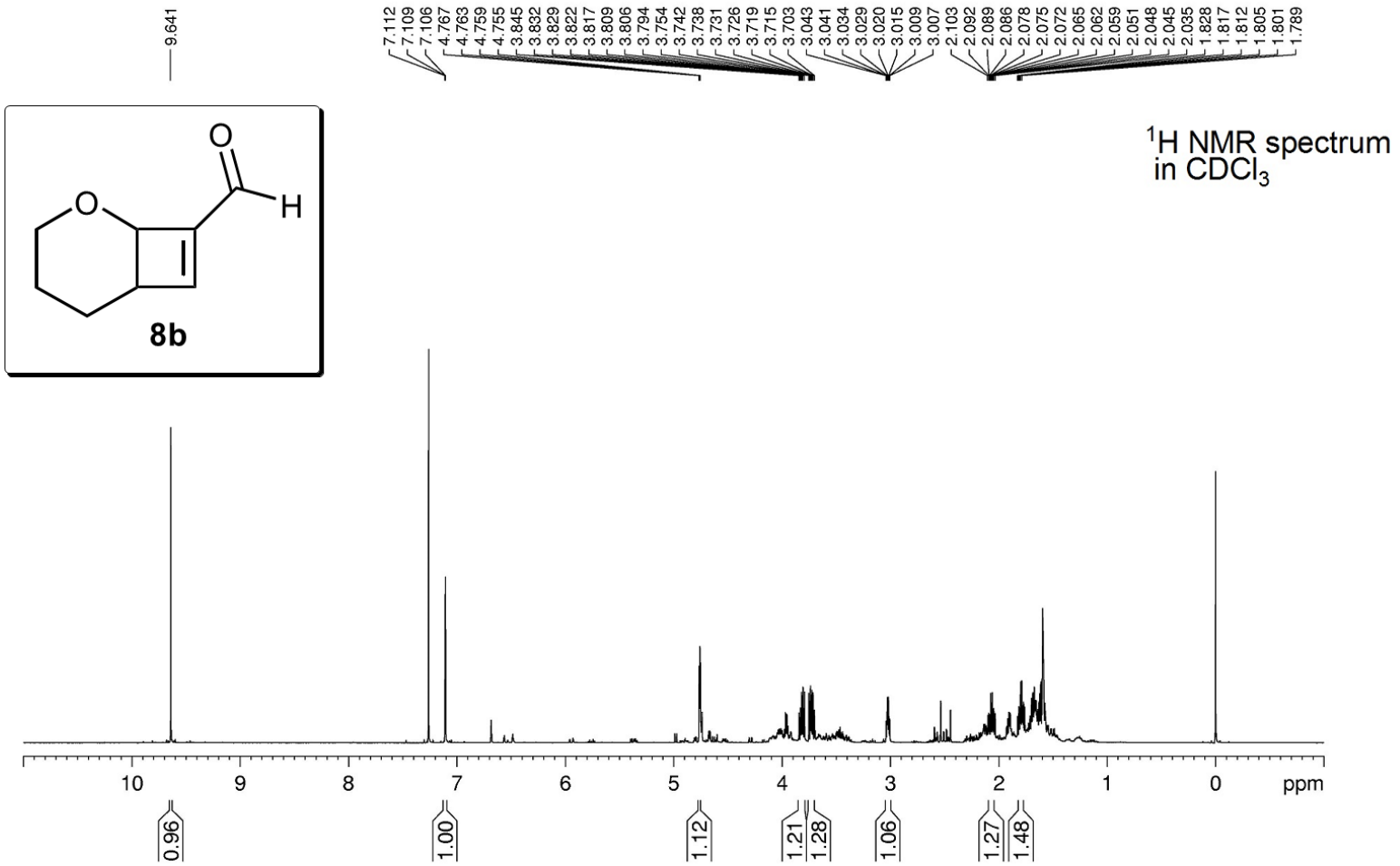

198.1
184.8
110.4
43.3
26.9
O
O
t-Bu
H
N—NH
2c
^{13}C NMR spectrum
in DMSO-d_6
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

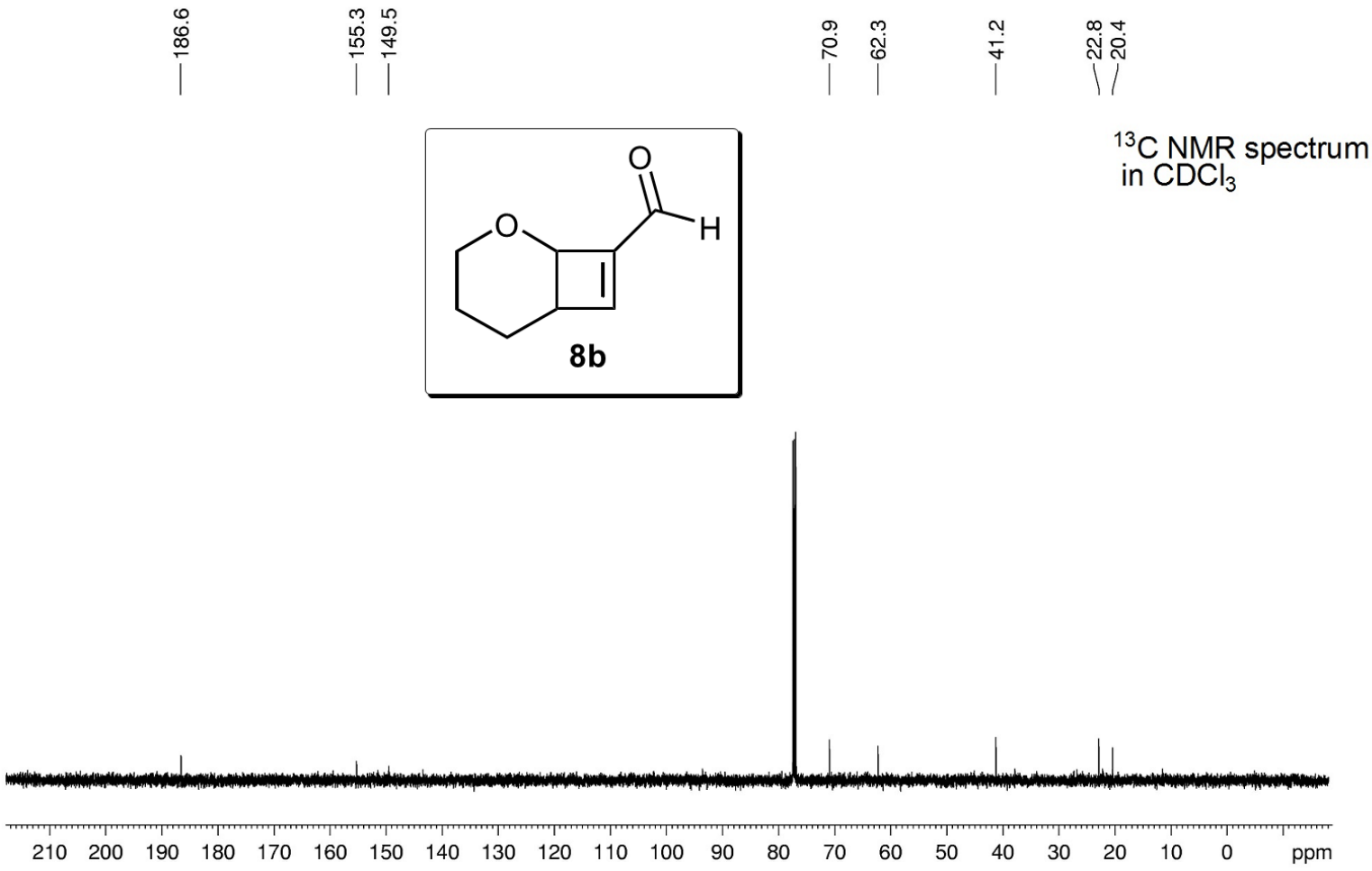

7.268
7.252
6.450
6.445
6.429
5.555
5.550
3.779
3.762
2.267
2.261
MeO
OMe
OMe
OMe
6b
^{1}H NMR spectrum
in $CDCl_3$
10.5 10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 ppm
1.04
1.32
1.22
3.17
1.00
6.22
6.32
0.97

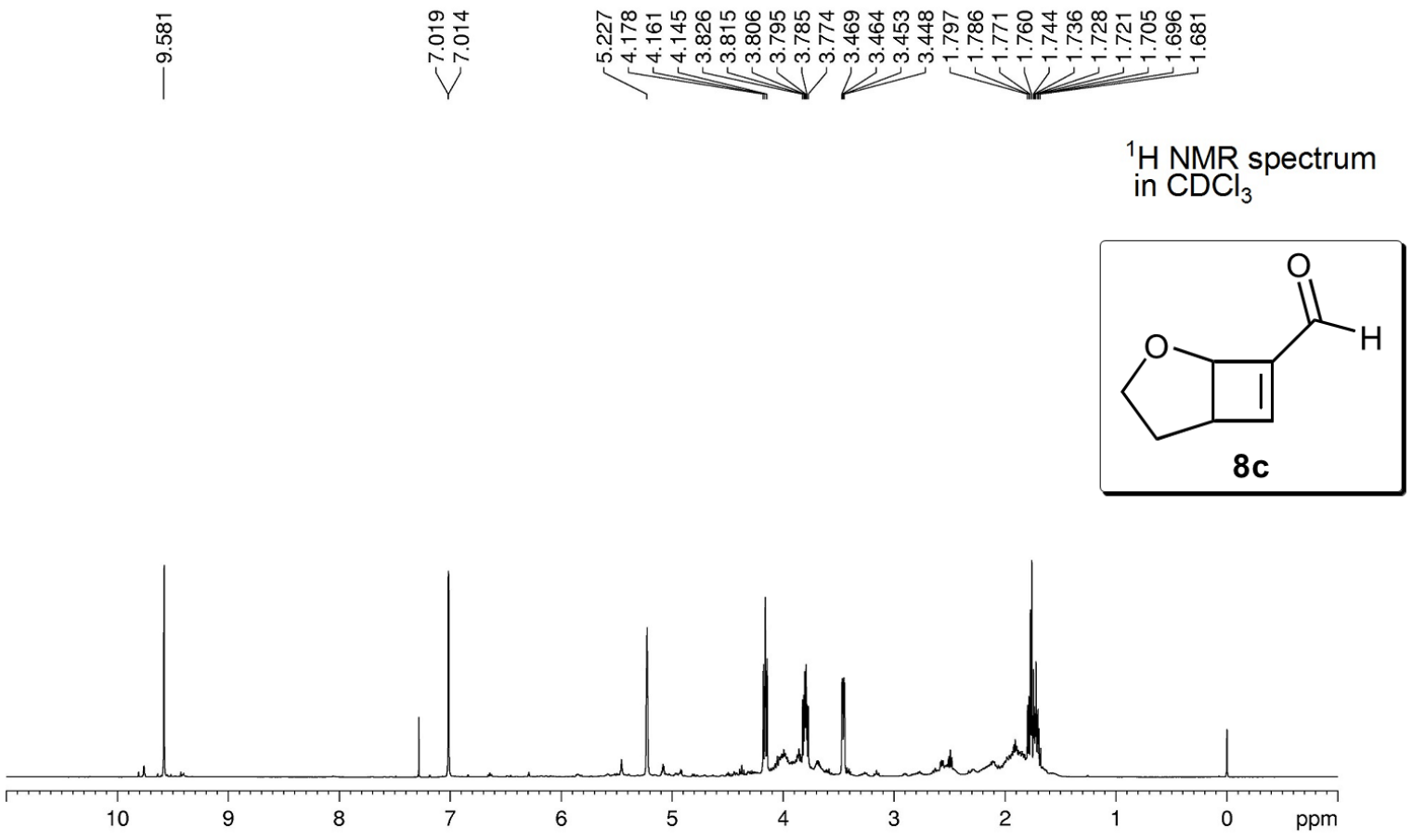

159.88
157.55
129.35
122.14
104.13
98.94
85.91
70.05
55.85
55.44
29.27
MeO
OMe
OMe
OMe
6b
13C NMR spectrum
in CDCl3
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

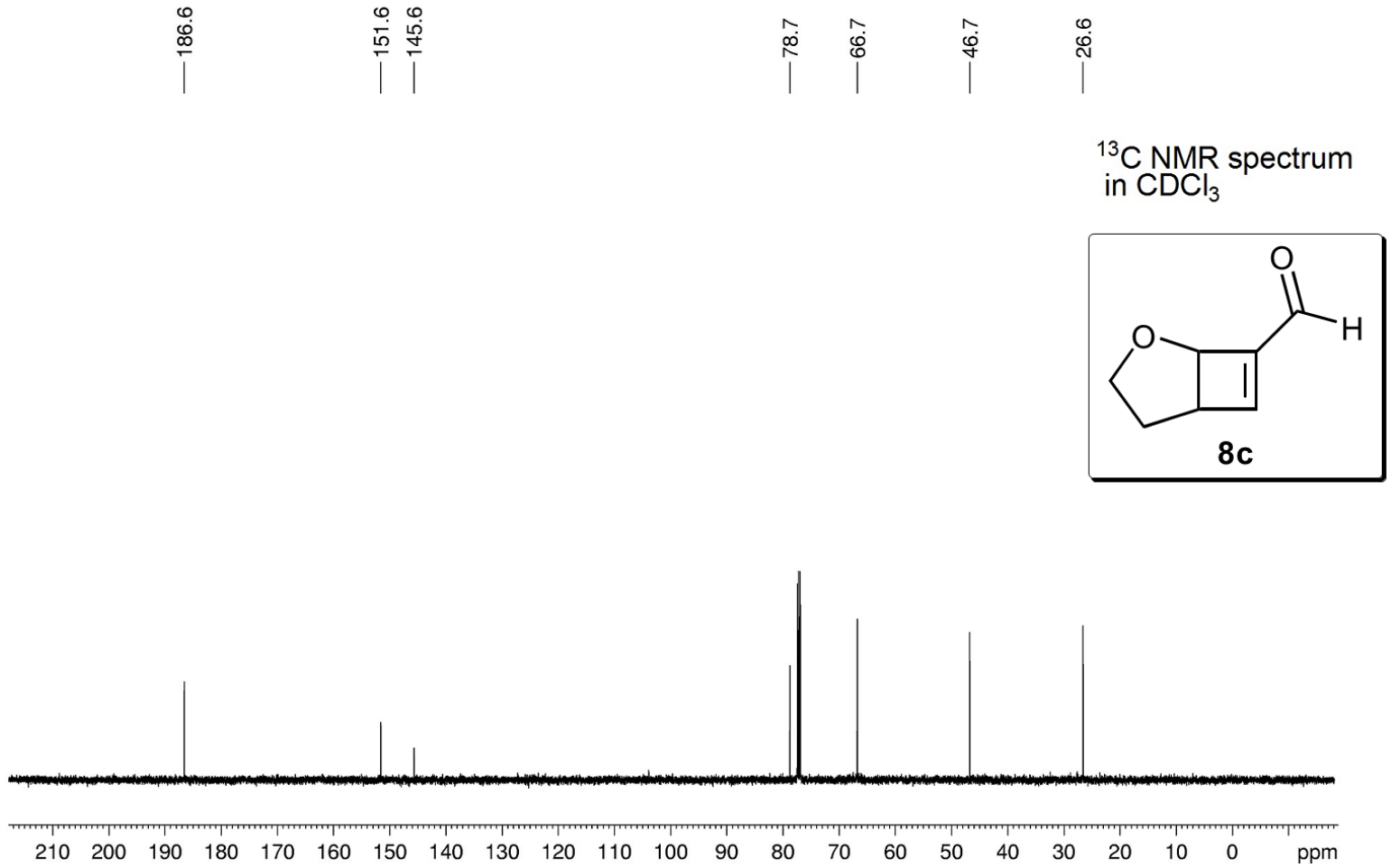

1.862
1.855
1.851
1.844
1.833
1.828
1.823
1.815
1.805
1.799
1.794
1.787
1.764
1.752
1.740
1.729
1.724
1.712
1.701
1.663
1.652
1.640
1.636
1.629
1.624
1.613
1.601
1.582
1.565
1.557
1.547
1.543
1.536
1.528
1.512
1.501
1.494
1.484
1.480
1.471
1.460
1.448
1.439
1.430
^{1}H NMR spectrum in $CDCl_3$
O
H
8a
1.90 1.85 1.80 1.75 1.70 1.65 1.60 1.55 1.50 1.45 1.40 ppm
9.567
7.047
7.045
3.153
3.142
3.132
3.121
2.938
2.927
2.916
2.905
10 9 8 7 6 5 4 3 2 1 0 ppm
1.00
0.99
1.27
1.44

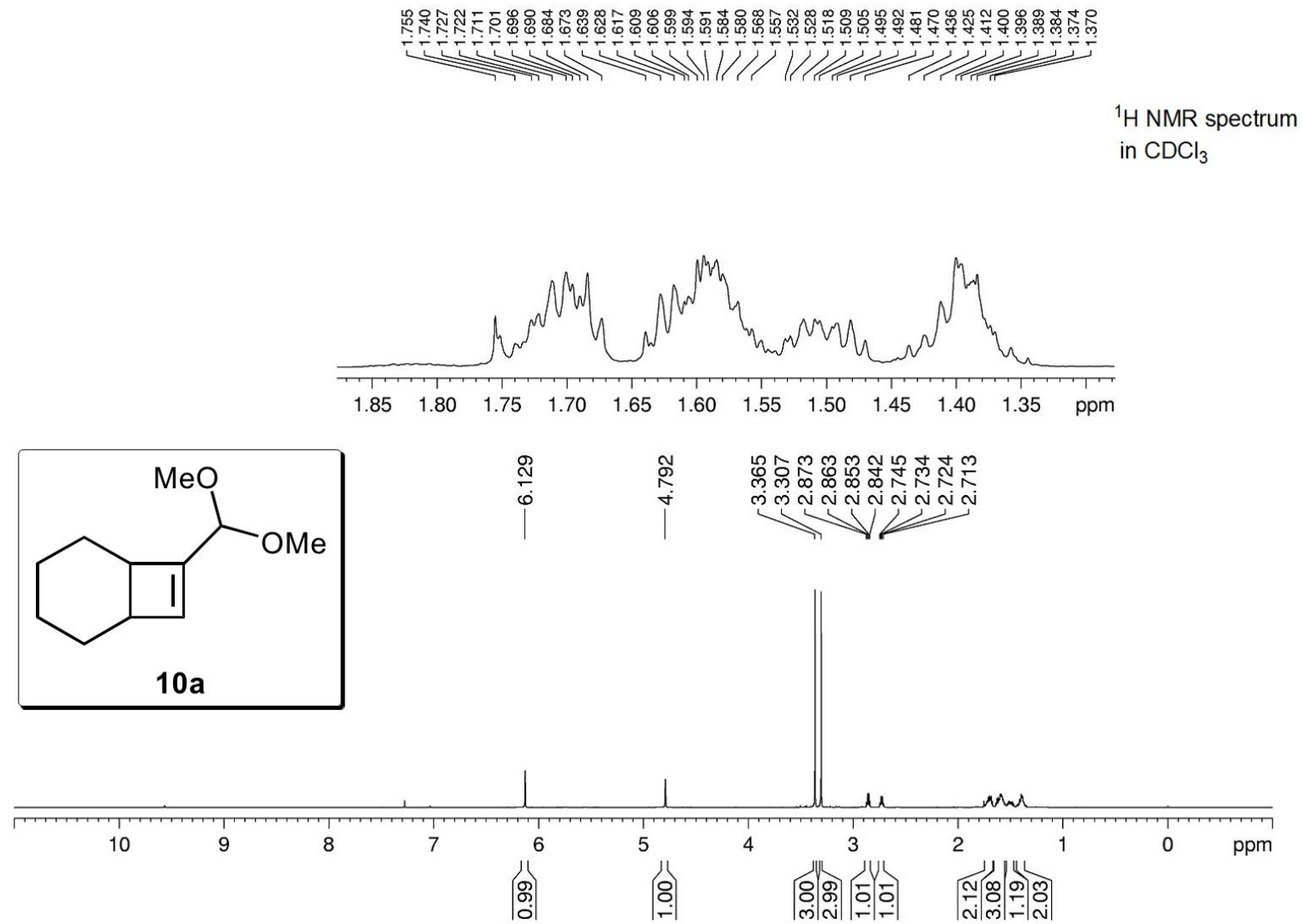

187.6
155.7
150.8
39.8
39.1
24.0
23.6
19.2
18.6
O
H
8a
^{13}C NMR spectrum
in $CDCl_3$
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

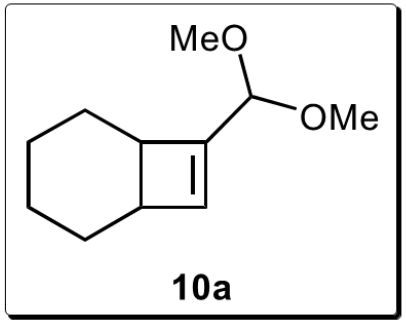

9.641
7.112
7.109
7.106
4.767
4.763
4.759
4.755
3.845
3.832
3.829
3.822
3.817
3.809
3.806
3.794
3.754
3.742
3.738
3.731
3.726
3.719
3.715
3.703
3.043
3.041
3.034
3.029
3.020
3.015
3.009
3.007
2.103
2.092
2.089
2.086
2.078
2.075
2.072
2.065
2.062
2.059
2.051
2.048
2.045
2.035
1.828
1.817
1.812
1.805
1.801
1.789
O
O
H
8b
^{1}H NMR spectrum
in $CDCl_3$
10
9
8
7
6
5
4
3
2
1
0
ppm
0.96
1.00
1.12
1.21
1.28
1.06
1.27
1.48


186.6
155.3
149.5
70.9
62.3
41.2
22.8
20.4
O
O
H
8b
^{13}C NMR spectrum
in $CDCl_3$
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm


9.581
7.019
7.014
5.227
4.178
4.161
4.145
3.826
3.815
3.806
3.795
3.785
3.774
3.469
3.464
3.453
3.448
1.797
1.786
1.771
1.760
1.744
1.736
1.728
1.721
1.705
1.696
1.681
^{1}H NMR spectrum
in $CDCl_3$
O
O
H
8c
10
9
8
7
6
5
4
3
2
1
0
ppm


186.6
151.6
145.6
78.7
66.7
46.7
26.6
13C NMR spectrum
in CDCl3
O
O
H
8c
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

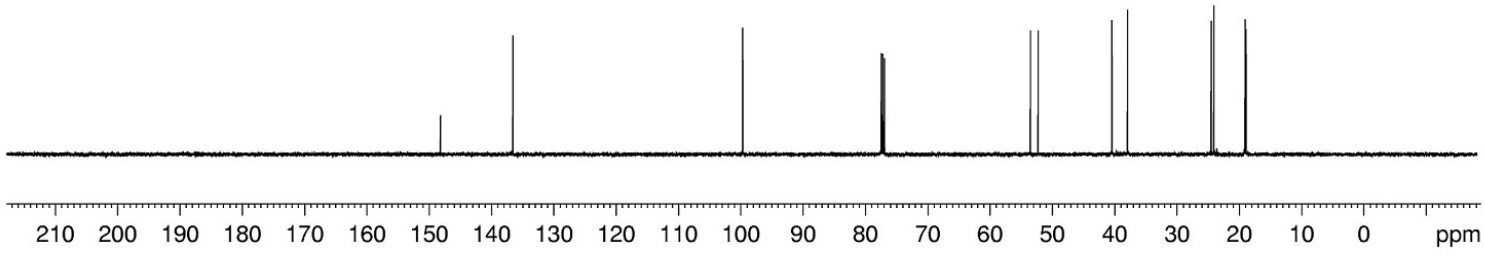

1.755
1.740
1.727
1.722
1.711
1.701
1.696
1.690
1.684
1.673
1.639
1.628
1.617
1.609
1.606
1.599
1.594
1.591
1.584
1.580
1.568
1.557
1.532
1.528
1.518
1.509
1.505
1.495
1.492
1.481
1.470
1.436
1.425
1.412
1.400
1.396
1.389
1.384
1.374
1.370
1H NMR spectrum
in CDCl3
1.85 1.80 1.75 1.70 1.65 1.60 1.55 1.50 1.45 1.40 1.35 ppm
MeO
OMe
10a
6.129
4.792
3.365
3.307
2.873
2.863
2.853
2.842
2.745
2.734
2.724
2.713
10 9 8 7 6 5 4 3 2 1 0 ppm
0.99
1.00
3.00
2.99
1.01
1.01
2.12
3.08
1.19
2.03

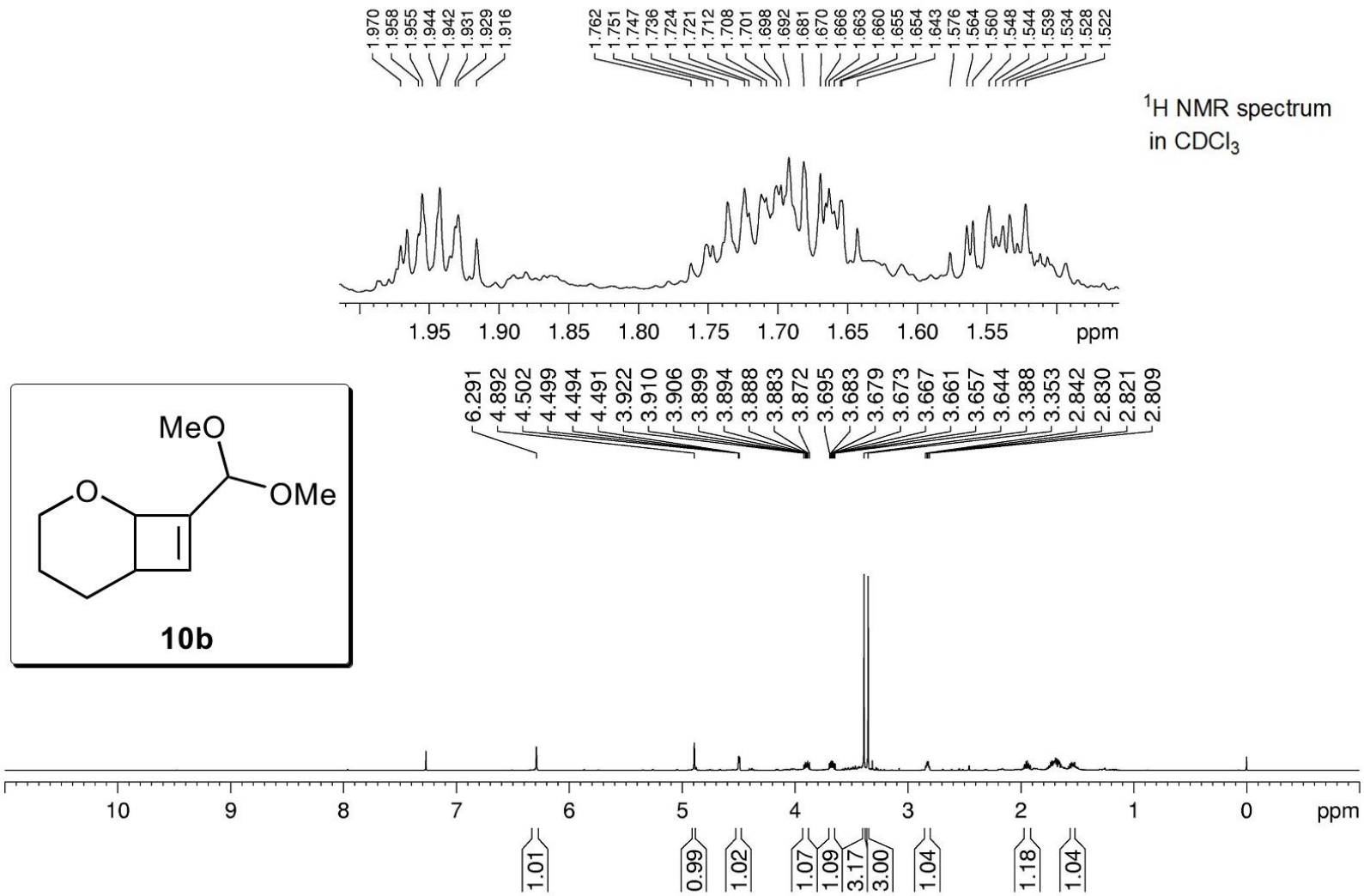


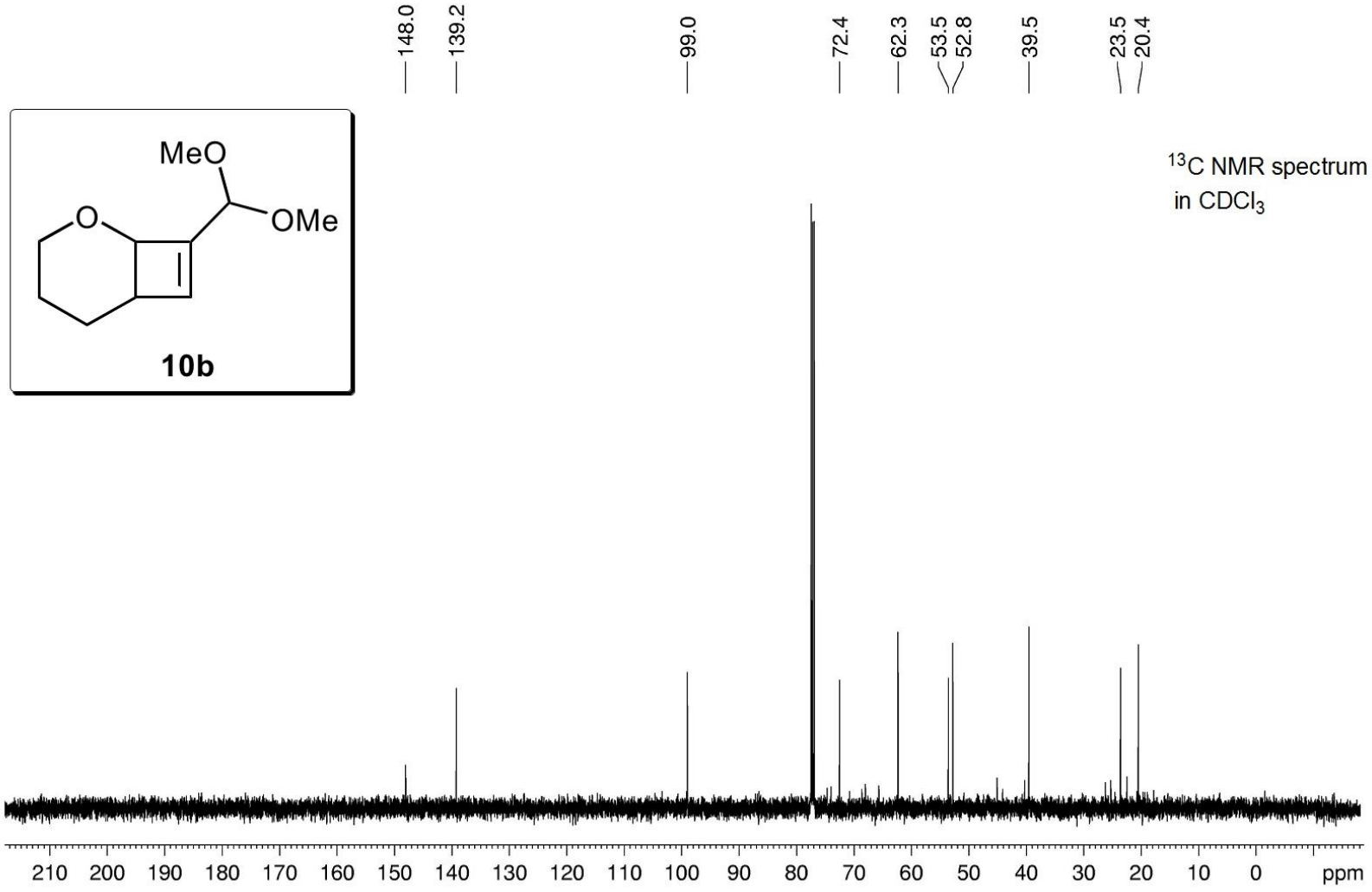
10a

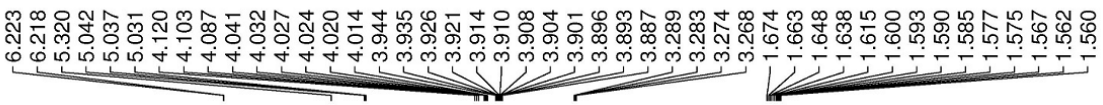
148.2
136.5
99.7
53.5
52.2
40.4
37.9
24.5
24.0
19.0
18.8

^{13}C NMR spectrum
in $CDCl_3$

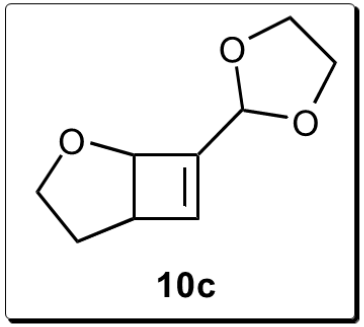



1.970
1.958
1.955
1.944
1.942
1.931
1.929
1.916
1.762
1.751
1.747
1.736
1.724
1.721
1.712
1.708
1.701
1.698
1.692
1.681
1.670
1.666
1.663
1.660
1.655
1.654
1.643
1.576
1.564
1.560
1.548
1.544
1.539
1.534
1.528
1.522
1H NMR spectrum
in CDCl3
1.95
1.90
1.85
1.80
1.75
1.70
1.65
1.60
1.55
ppm
6.291
4.892
4.502
4.499
4.494
4.491
3.922
3.910
3.906
3.899
3.894
3.888
3.883
3.872
3.695
3.683
3.679
3.673
3.667
3.661
3.657
3.644
3.388
3.353
2.842
2.830
2.821
2.809
MeO
OMe
O
10b
10
9
8
7
6
5
4
3
2
1
0
ppm
1.01
0.99
1.02
1.07
1.09
3.17
3.00
1.04
1.18
1.04

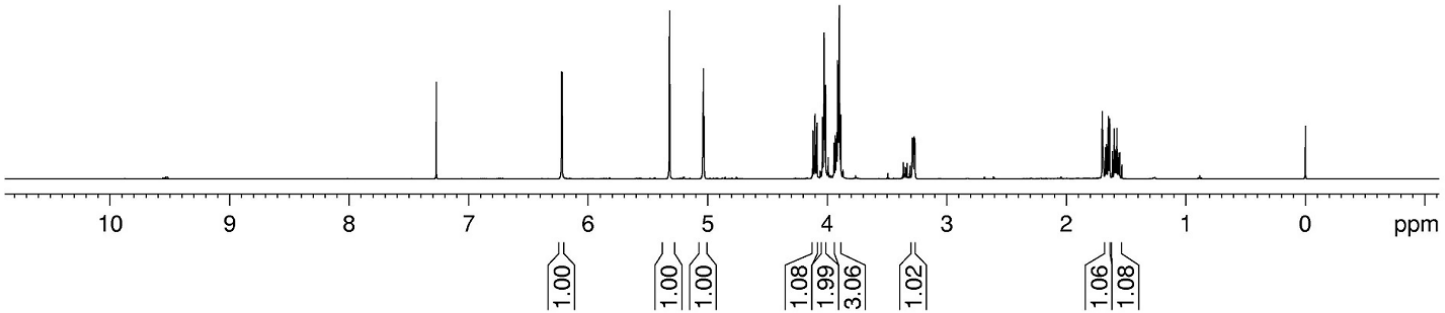

148.0
139.2
99.0
72.4
62.3
53.5
52.8
39.5
23.5
20.4
MeO
OMe
O
10b
^{13}C NMR spectrum
in $CDCl_3$
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

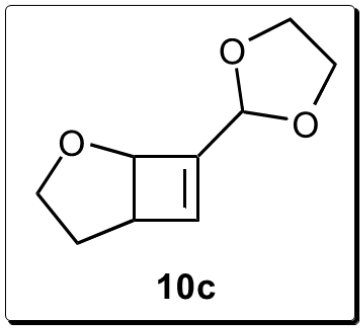


^{1}H NMR spectrum
in $CDCl_3$



10c





10c

^{13}C NMR spectrum in $CDCl_3$