Supplementary Material (ESI) for Chemical Communications

Supporting information

The Synthesis of Chiral *N*-Heterocyclic Carbene-Borane and –Diorganoborane Complexes and their use in the Asymmetric Reduction of Ketones

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1. General remarks

Starting materials sourced from commercial suppliers were used as received unless otherwise stated. Dry solvents, where necessary, were obtained by distillation using standard procedures or by passage through a column of anhydrous alumina using equipment from Anhydrous Engineering based on the Grubbs design.[1]

Petrol refers to the fraction of petroleum ether boiling in the range of 40-60 ℃.

Reactions requiring anhydrous conditions were run under an atmosphere of dry nitrogen passed though two sequential drying columns – one packed with calcium chloride and one packed with phosphorous pentoxide; glassware and needles were either flame dried immediately prior to use or placed in an oven (160 ℃) for at least 16 h and allowed to cool under an atmosphere of dry nitrogen; liquid reagents, solutions or solvents were added *via* syringe through rubber septa. The removal of solvents *in vacuo* was achieved using either a Büchi rotary evaporator (bath temperatures up to 40 ℃) at a pressure of either 15 mm Hg (diaphragm pump) or 0.1 mm Hg (oil pump), as appropriate, or a high vacuum line at room temperature.

Commercially available Merck Kieselgel 60F_{254} aluminium-backed plates and Macherey-Nagel Polygram Sil G/UV_{254} plastic-backed plates were used for TLC analysis. Visualisation was achieved by UV fluorescence, basic $KMnO_4$ solution and heat, ninhydrin stain and heat, ammonium molybdate solution and heat, dinitrophenylhydrazine and heat, anisaldehyde stain and heat or iodine vapour. Flash column chromatography was performed using Fluorochem 60 silica: 230-400 mesh (40-63 μm). The crude material was applied to the column as a solution or by pre-adsorption onto silica, as appropriate.

Melting points were determined using a Reichert melting point table and temperature controller and are uncorrected. Infra-red spectra were recorded in the range 4000-600 cm^{-1} on a Perkin Elmer Spectrum either as neat films or solids compressed onto a diamond window. Abbreviations used are: w (weak), m (medium), s (strong) and br (broad).

NMR spectra were recorded on a JEOL GX270, JEOL GX400, JEOL Lambda 300, JEOL Eclipse 400, JEOL Eclipse 300, Varian 400 or Varian 500 spectrometer. Chemical shifts are quoted in parts per million (ppm); ^{1}H NMR spectra are referenced to TMS or residual protons of the deuterated solvent as an internal standard; ^{13}C NMR are referenced to TMS or the deuterated solvent as an internal standard; ^{19}F NMR spectra are referenced to CCl_3F as an external standard; ^{11}B NMR spectra are referenced to BF_3 as an external standard. Coupling constants (*J*) are quoted to the nearest 0.1 Hz. Unless otherwise noted, all coupling constants relate to $^{3}J_{H\text{-}H}$ couplings. Other abbreviations used are: s (singlet), d (doublet), t

(triplet), q (quartet), m (multiplet), br (broad) and app. (apparent). Assignments of ^{1}H NMR and ^{13}C NMR signals were made, where possible, using COSY, DEPT, HMQC and HMBC experiments.

Mass spectra were determined by the University of Bristol mass spectrometry service by either electron impact (EI+) or chemical ionisation (CI+) using a Fisons VG Analytical Autospec spectrometer, or by electrospray ionisation (ESI+) using a Brüker Daltonics Apex IV spectrometer or by nanospray ionisation using an Applied Biosystems QStar XL (Quadrupole-Quadrupole Time-of-flight) instrument with an Advion Biosciences Nanomate HD 'chip-based' nanospray source. Chiral HPLC was performed on an Agilent 1100 LC system equipped with a quaternary pump, diode array detector and column thermostat under the conditions specified in each case. Chiral GC was run on an Agilent 6890N network GC system with an FID detector under the conditions specified in each case. GCMS was run on an Agilent 6890 series GC system equipped with an Agilent 5973 network mass selective detector. Optical rotations were measured using a Bellingham & Stanley ADP220 Polarimeter.

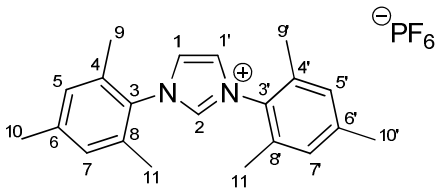
Imidazolium salts **3**·HCl,[2] **4**·HOTf,[3] **5**·HOTf[3] and **6**·HOTf[4] were prepared according to known literature procedures.

2. Experimental details

2.1 Synthesis of imidazolium salts

1,3-Bis(2,4,6-trimethylphenyl)imidazolium hexafluorophosphate (3·HPF$_6$)

To a saturated aqueous solution of IMes hydrochloride[2] (**3**·HCl) (26.7 g, 78.4 mmol, 1.0 eq) was added a saturated aqueous solution of ammonium hexafluorophosphate (12.8 g, 78.4 mmol, 1.0 eq). The resulting pale yellow suspension was stirred for 30 minutes then filtered and recrystallised (DCM/hexane) to yield **3**·HPF$_6$ as a white crystalline solid (33.9 g, 96 %).



3·HPF$_6$

^{1}H NMR (270 MHz, $CDCl_3$): δ 2.09 (s, 12H, C-9, C-9', C-11 & C-11' C$\underline{H}_3$), 2,35 (s, 6H, C-10 & C-10' C$\underline{H}_3$), 7.03 (s, 4H, C-5, C-5', C-7 & C-7' C$\underline{H}$), 7.54 (d, *J* = 1.7 Hz, 2H, C-1 & C-1' C$\underline{H}$), 8.57 (s, 1H, C-2 C$\underline{H}$).

^{13}C NMR (68 MHz, $CDCl_3$): δ 17.1 (C-9, C-9', C-11 & C-11'), 21.1 (C-10 & C-10'), 125.2 (C-1 & C-1'), 129.9 (C-5, C-5', C-7 & C-7'), 130.2 (C-4, C-4', C-8 & C-8'), 133.9 (C-6 & C-6'), 136.4 (C-3 & C-3'), 141.6 (C-2).

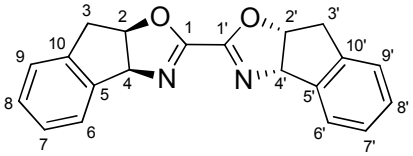
IR (υ_{max} cm^{-1}, film): 2925 (w), 1624 (m), 1532 (m) 1479 (m), 1226 (s), 1075 (s), 1004 (s).

MS (EI+) *m/z* (%): 305 (100) [M].$^+$

m.p. >300 ℃ (DCM/hexane).

(3a*S*,3'a*S*,8a*R*,8'a*R*)-8,8a,8',8'a-Tetrahydro-3a*H*,3'a*H*-2,2'-biindeno[1,2-*d*]oxazole (9)

To a solution of (1*S*,2*R*)-(−)-*cis*-1-amino-2-indanol (5.00 g, 33.5 mmol, 2.0 eq) in MeOH (54 mL) was added drop-wise a solution of dimethyl oxalimidate[5] (1.95 g, 16.8 mmol, 1.0 eq) in MeOH (40 mL). The reaction was stirred at ambient temperature and monitored by GC-MS. After 5 days the reaction reached >97 % conversion, then the solvent was removed *in vacuo*. Purification by column chromatography (70 % EtOAc/Pet. Ether) yielded **11** as a white solid (4.34 g, 82 %).



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^{1}H NMR (500 MHz, $CDCl_3$): δ 3.32 (d, J^2 = 18.0 Hz, 2H, C-3 & C-3' C$\underline{H}_2$), 3.40 (dd, J^2 = 18.0, J = 6.7 Hz, 2H, C-3 & C-3' C$\underline{H}_2$), 5.44 (ddd, J = 8.0, 6.7, 1.6 Hz, 2H, C-2 & C-2' C$\underline{H}$), 5.69 (d, J = 8.0 Hz, 2H, C-4 & C-4' C$\underline{H}$), 7.18 – 7.24 (m, 6H, C-7, C-7', C-8, C-8', C-9', & C-9' C$\underline{H}$), 7.47 – 7.49 (m, 2H, C-6 & C-6' C$\underline{H}$).

^{13}C NMR (125 MHz, $CDCl_3$): δ 39.1 (C-3 & C-3'), 76.9 (C-4 & C-4'), 84.2 (C-2 & C-2'), 125.1 (Ar$\underline{C}$H), 125.5 (C-6 & C-6'), 127.3 (Ar$\underline{C}$H), 128.6 (Ar$\underline{C}$H), 139.3 (C-5 & C-5' / C-10 & C-10'), 140.1 (C-5 & C-5' / C-10 & C-10'), 154.9 (C-1 & C-1').

IR (u_{max} cm^{-1}, film): 2971 (w), 2244 (m), 1616 (s), 1480 (w), 1429 (w), 1235 (w), 1130 (s), 983 (m).

MS (EI) *m/z* (%): 316 (90) [M],$^{+}$ 104 (100).

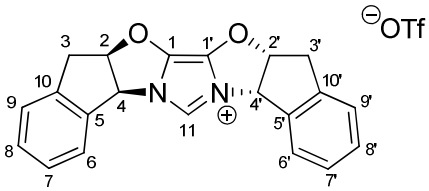
HRMS (EI): calc. for $C_{20}H_{16}N_2O_2$ 316.1212, found 316.1222.

$[\alpha]^{20}_{D}$ = -373 (*c* = 1.0, DCM).

m.p. 207 – 210 ℃.

2,3,10,14,21,22-Hexahydroimidazo[4,3-*b*:5,1-*b*'] bis(3*aS*,8*aR*)-8,8*a*-dihydro-3*aH*-ideno[1,3]oxazol-11-ium trifluoromethanesulfonate (6·HOTf)

Following the procedure of Glorius and co-workers,[3c] to a flame-dried sealed tube was added, *in a glove box and in the dark,* silver triflate (2.97 g, 11.6 mmol, 1.47 eq.). The tube was then evacuated and back-filled with N_2 before anhydrous DCM (40 mL) was added. To this solution was added chloromethyl pivalate (1.68 mL, 11.6 mmol, 1.47 eq.), and the solution stirred at 18 ℃ in the dark for 45 minutes. After this time, the reaction mixture was filtered and transferred, *via* a cannula equipped with a filter paper, to a second flame-dried sealed tube containing (3*aS*,3'*aS*,8*aR*,8'*aR*)-8,8*a*,8',8'*a*-tetrahydro-3*aH*,3'*aH*-2,2'-biindeno[1,2-*d*]oxazole (**9**) (2.50 g, 7.90 mmol, 1.00 eq.) under an atmosphere of N_2. The solution was stirred in the dark at 40 °C for 15 h then cooled to room temperature and the solvent removed *in vacuo*. The resulting solid was purified by column chromatography (2 % MeOH/DCM, 4 % MeOH/DCM), followed by recrystallisation (DCM/Et_2O) to yield **6**·HOTf as a white crystalline solid (2.20 g, 58 %).



6·HOTf

^{1}H NMR (500 MHz, $CDCl_3$): δ 3.43 (d, J^2 = 18.3 Hz, 2H, C-3 & C-3' C$\underline{H}_2$), 3.50 (dd, J^2 = 18.3, J = 6.0 Hz, 2H, C-3 & C-3' C$\underline{H}_2$), 6.07 (app. td, J = 6.2, 1.4 Hz, 2H, C-2 & C-2' C$\underline{H}$), 6.28 (d, J = 6.5 Hz, 2H, C-4 & C-4' C$\underline{H}$), 7.23 – 7.35 (m, 6H, C-7, C-7', C-8, C-8', C-9', & C-9' C$\underline{H}$), 7.76 (d, J = 7.7 Hz, 2H, C-6 & C-6' C$\underline{H}$), 9.32 (s, 1H, C-11 C$\underline{H}$).

^{13}C NMR (125 MHz, $CDCl_3$): δ 38.2 (C-3 & C-3'), 66.8 (C-4 & C-4'), 95.1 (C-2 & C-2'), 113.9 (C-11), 120.6 (q, J = 320 Hz, $\underline{C}F_3$), 124.8 (C-1 & C-1'), 125.2 (Ar$\underline{C}$H), 125.8 (C-6 & C-6'), 128.7 (Ar$\underline{C}$H), 130.6 (C-7 & C-7'), 134.8 (C-10 & C-10'), 139.7 (C-5 & C-5').

^{19}F NMR (470 MHz, $CDCl_3$): δ -78.4 (s, 3F, $OSO_2C\underline{F}_3$).

IR (υ_{max} cm^{-1}, film): 3127 (w), 1716 (m), 1533 (s), 1446 (m), 1270 (s), 1249 (s), 1165 (s), 1027 (s), 970 (m).

MS (ESI) *m/z*: 329 $[M]^+$

HRMS (ESI): calc. for $C_{21}H_{17}N_2O_2^+$ 329.1285, found 329.1284.

$[\alpha]^{23}_D$ = +182 (*c* = 0.9, DCM).

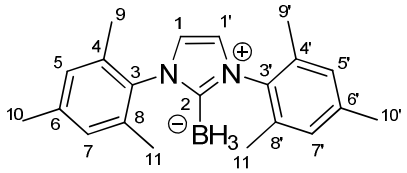
m.p. 197 – 199 ℃ (DCM/Et_2O).

The spectroscopic properties of this compound were consistent with those reported in the literature.[4]

2.2 Synthesis of NHC-borane complexes

1,3-Bis(2,4,6-trimethylphenyl)imidazol-2-ylidene-borane (3·BH_3)

To a solution of 1,3-bis(2,4,6-trimethylphenyl)imidazolium hexafluorophosphate (**3**·HPF_6) (4.11 g, 9.13 mmol, 1.0 eq) in THF (135 mL) at 0 ℃ (which was dried under high vacuum at 130 ℃ for 16 h), was added drop-wise a solution of KHMDS (0.5 M in PhMe, 18.5 mL, 9.22 mmol, 1.01 eq). After 30 minutes, a solution of BH_3•SMe_2 (2.0 M in THF, 4.6 mL, 9.22 mmol, 1.01 eq) was added drop-wise. The reaction mixture was stirred at 0 ℃ for 30 minutes then warmed to ambient temperature. After 2 h the solvent was removed *in vacuo* to yield an off-white solid which was triturated with small volumes of DCM and filtered. The filtrate was concentrated *in vacuo* and passed through a short plug of silica, eluting with DCM. The combined fractions were concentrated *in vacuo* and dried under high vacuum to yield **3**·BH_3 as a white solid (2.56 g, 88 %).



3·BH_3

^{1}H NMR (300 MHz, $CDCl_3$): δ 0.53 (br q, *J* = 83.5 Hz, 3H, B<u>H</u>$_3$), 2.08 (s, 12H, C-9, C-9', C-11 & C-11' C<u>H</u>$_3$), 2.35 (s, 6H, C-10 & C-10' C<u>H</u>$_3$), 6.99 (s, 2H, C-1 & C-1 C<u>H</u>), 7.01 (s, 4H, C-5, C-5', C-7 & C-7' C<u>H</u>).

^{13}C NMR (75 MHz, $CDCl_3$): δ 17.6 (C-9, C-9', C-11 & C-11'), 21.1 (C-10 & C-10'), 120.4 (C-1 & C-1'), 129.0 (C-5, C-5', C-7 & C-7'), 134.4 (C-4, C-4', C-8 & C-8'), 134.8 (C-6 & C-6'), 139.0 (C-3 & C-3'). No C-2 carbon signal observed.

^{11}B NMR (128 MHz, $CDCl_3$): δ -38.3 (q, *J* = 87.9 Hz, <u>B</u>H_3).

IR (u_{max} cm^{-1}, film): 2920 (m, CH), 2326 (w, BH_3), 1486 (m, C=C), 1413 (m), 1419 (m), 1233 (m), 1112 (m), 854 (s).

MS (ESI) *m/z*: 341 $[M+Na]^+$.

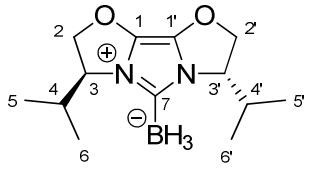
HRMS (ESI): calc. for $C_{21}H_{27}BN_2Na^+$ 341.2160, found 341.2171.

m.p. > 140 ℃ (dec).

The spectroscopic properties of this compound were consistent with those reported in the literature.**Error! Bookmark not defined.**[d]

(3*S*,7*S*)-3,7-Di-*iso*-propyl-2,3,7,8-tetrahydroimidazo[4,3-*b*:5,1-*b*'] bis[1,3]oxazol-4-ylidene-borane (4·BH_3)

To a THF (17 mL) solution of (3*S*,7*S*)-3,7-di-*iso*-propyl-2,3,7,8 tetrahydroimidazo[4,3-*b*:5,1-*b*']bis[1,3]oxazol-4-ium triflate (**4**·HOTf) (506 mg, 1.31 mmol, 1.0 eq, which was dried under high vacuum at 90 ℃ for 16 h) at -78 ℃, was added drop-wise a solution of *n*-BuLi (2.56 M in hexanes, 520 µL, 1.32 mmol, 1.01 eq). After 30 minutes at -78 ℃, a solution of BH_3•SMe_2 (1.95 M in THF, 0.68 mL, 1.32 mmol, 1.01 eq) was added dropwise. The reaction mixture was stirred at -78 ℃ for 30 minutes then warmed to ambient temperature. After 3 h the solvent was removed *in vacuo* to yield an off-white solid which was triturated with small volumes of DCM and filtered. The filtrate was concentrated *in vacuo* and passed through a short plug of silica eluting with DCM. The combined fractions were concentrated *in vacuo* and dried under high vacuum to yield **4**·BH_3 as a white solid (314 mg, 96 %).



4·BH_3

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.73 (d, *J* = 6.8 Hz, 6H, C-6 & C-6' C$\underline{H}_3$), 0.90 (br q, *J* = 86.2 Hz, 3H, B$\underline{H}_3$), 0.91 (d, *J* = 7.0 Hz, 6H, C-5 & C-5' C$\underline{H}_3$), 2.72 (d sep, *J* = 7.0, 3.7 Hz, 2H, C-4 & C-4' C$\underline{H}$), 4.39 - 4.44 (m, 2H, C-2 & C-2' C$\underline{H}_2$), 4.65 - 4.74 (m, 4H, C-2 & C-2' C$\underline{H}_2$ & C-3 & C-3' C$\underline{H}$).

^{13}C NMR (100 MHz, $CDCl_3$): δ 14.6 (C-6 & C-6'), 18.9 (C-5 & C-5'), 29.0 (C-4 & C-4') 61.1 (C-3 & C-3'), 76.3 (C-2 & C-2'), 123.4 (C-1 & C-1'). No C-7 carbon signal observed.

^{11}B NMR (96 MHz, $CDCl_3$) δ -37.9 (q, *J* = 87.0 Hz, $\underline{B}H_3$).

IR (υ_{max} cm^{-1}, film): 2962 (m, CH), 2280 (m, BH3), 2273 (m, BH3), 1748 (m, OC=CO), 1437 (s, C-C), 1259 (s), 1210 (s), 1115 (s), 937 (s), 881 (m), 826 (m).

MS (CI) *m/z* (%): 249 (100) $[M-H]^+$.

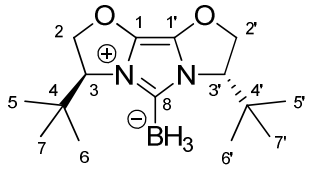
HRMS (CI): calc. for $C_{13}H_{22}BN_2O_2^+$ 249.1774, found 249.1769.

$[\alpha]_D^{24}$ = +112° (*c* = 1.0, DCM).

m.p. > 195 ℃ (dec).

(3*S*,7*S*)-3,7-Di-*tert*-butyl-2,3,7,8-tetrahydroimidazo[4,3-*b*:5,1-*b*'] bis[1,3]oxazol-4-ylidene-borane (5·BH_3)

To a THF (26 mL) solution of (3*S*,7*S*)-3,7-di-*tert*-butyl-2,3,7,8 tetrahydroimidazo[4,3- *b*:5,1-*b*']bis[1,3]oxazol-4-ium triflate (**5**·HOTf) (817 mg, 1.97 mmol, 1.0 eq, which was dried under high vacuum at 90 ℃ for 16 h) at -78 ℃, was added drop-wise a solution of *n*-BuLi (2.56 M in hexanes, 0.78 mL, 1.99 mmol, 1.01 eq). After 30 minutes at -78 ℃, a solution of BH_3•SMe_2 (1.95 M in THF, 1.00 mL, 1.99 mmol, 1.01 eq) was added dropwise. The reaction mixture was stirred at -78 ℃ for 30 minutes then warmed to ambient temperature. After 3 h the solvent was removed *in vacuo* to yield an off white solid which was triturated with small volumes of DCM and filtered. The filtrate was concentrated *in vacuo* and passed through a short plug of silica eluting with DCM. The combined fractions were concentrated *in vacuo* and dried under high vacuum to yield **5**·BH_3 as a white solid (518 mg, 95 %).



5·BH_3

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.11 (s, 18H, C-5, C-5', C-6, C-6', C-7 & C-7' C$\underline{H}_3$), 1.11 (broad q, *J* = 85.3 Hz, 3H, B$\underline{H}_3$), 4.29 (dd, *J* = 6.4, 1.2 Hz, 2H, C-3 & C-3' C$\underline{H}$), 4.72 (dd, J^2 = 9.0, *J* = 6.4 Hz, 2H, C-2 & C-2' C$\underline{H}_2$), 4.82 (dd, J^2 = 9.0, *J* = 1.2 Hz, 2H, C-2 & C-2' C$\underline{H}_2$).

^{13}C NMR (100 MHz, $CDCl_3$): δ 27.5 (C-5, C-5', C-6, C-6', C-7 & C-7'), 36.2 (C-4 & C-4'), 66.4 (C-3 & C-3'), 79.0 (C-2 & C-2'), 123.8 (C-1 & C-1'). No C-8 carbon signal observed.

^{11}B NMR (128 MHz, $CDCl_3$) δ -35.2 (q, *J* = 87.9 Hz, $\underline{B}H_3$).

IR (υ_{max} cm^{-1}, film): 2962 (m, CH), 2338 (w, BH_3), 1732 (m, OC=CO), 1470 (m, C-C), 1419 (m), 1375 (s), 1257 (s), 1152 (s), 1029 (m), 900 (m).

MS (CI) *m/z* (%): 265 (100) [M-BH_3].$^{+}$

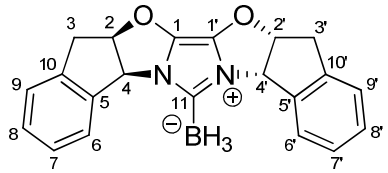
HRMS (CI): calc. for $C_{15}H_{25}N_2O_2^{+}$ 265.1911, found 265.1916.

$[\alpha]_D^{23}$ = +180°(*c* = 1.0, DCM).

m.p. > 213 ℃ (dec).

2,3,10,14,21,22-Hexahydroimidazo[4,3-*b*:5,1-*b*'] bis(3*aS*,8*aR*)-8,8*a*-dihydro-3*aH*-ideno[1,3]oxazol-11-ylidene borane (6·BH_3)

To a THF (3 mL) solution of 2,3,10,14,21,22-hexahydroimidazo[4,3-*b*:5,1-*b*'] bis(3*aS*,8*aR*)-8,8*a*-dihydro-3*aH*-ideno[1,3]oxazol-11-ium triflate (**6**·HOTf) (100 mg, 0.209 mmol, 1.0 eq, which was dried under high vacuum at 90 ℃ for 16 h) at -78 ℃, was added drop-wise a solution of *n*-BuLi (2.5 M in hexanes, 84 µL, 0.209 mmol, 1.0 eq). After 30 minutes of stirring at -78 ℃, a solution of BH_3•SMe_2 (2 M in THF, 105 µL, 0.209 mmol, 1.0 eq) was added drop-wise. The reaction mixture was stirred at -78 ℃ for 30 minutes then warmed to ambient temperature. After 3 h the solvent was removed *in vacuo* to yield an off-white solid, which was passed through a short plug of silica eluting with 70 % DCM/hexane. The combined fractions were concentrated *in vacuo* and dried under high vacuum to yield **6**·BH_3 as a white solid (33 mg, 46 %).



6·BH_3

^{1}H NMR (500 MHz, $CDCl_3$): δ 1.54 (br q, *J* = 87.0 Hz, 3H, B<u>H</u>$_3$), 3.37 (dd, J^2 = 18.0, *J* = 5.2 Hz, 2H, C-3 & C-3' C<u>H</u>$_2$), 3.44 (d, *J* = 18.0 Hz, 2H, C-3 & C-3' C<u>H</u>$_2$), 5.82 (ddd. *J* = 5.9, 5.2, 1.0 Hz, 2H, C-2 & C-2' C<u>H</u>), 5.93 (d, *J* = 5.9 Hz, 2H, C-4 & C-4' C<u>H</u>), 7.29 – 7.38 (m, 6H, C-7, C-7', C-8, C-8', C-9 & C-9' C<u>H</u>), 8.21 (d, *J* = 6.7 Hz, 2H, C-6 & C-6' C<u>H</u>).

^{13}C NMR (125 MHz, $CDCl_3$): δ 37.7 (C-3 & C-3'), 64.9 (C-4 & C-4'), 94.1 (C-2 & C-2'), 122.9 (C-1 & C-1'), 125.1 (Ar-H), 127.6 (C-6 & C-6'), 128.1 (Ar-H), 129.8 (Ar-H), 137.5 (C-10 & C-10'), 139.9 (C-5 & C-5'). No C-11 carbon signal observed.

^{11}B NMR (96 MHz, $CDCl_3$): δ -35.3 (br q, *J* = 87.0 Hz, <u>B</u>H$_3$).

IR (u_{max} cm^{-1}, film): 2971 (w), 2355 (s, BH_3), 1735 (s), 1428 (s), 1320 (m), 1175 (s), 1037 (m), 984 (s).

MS (CI) *m/z* (%): 342 (30) [M],$^+$ 341 (100).

HRMS (CI): calc. for $C_{21}H_{18}BN_2O_2^+$ 341.1461, found 341.1466.

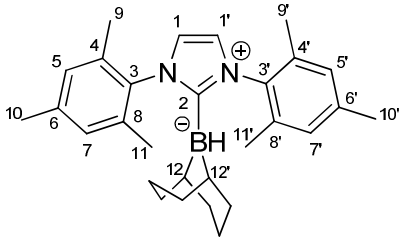
$[\alpha]_D^{26}$ = + 461° (*c* = 0.18, DCM).

m.p. > 195 ℃ (dec).

2.3 Synthesis of NHC-9-BBN complexes

1,3-Bis(2,4,6-trimethylphenyl)imidazol-2-ylidene-9-borabicyclo[3.3.1]nonane (3·9-BBN)

To a THF (32 mL) solution of 1,3-bis(2,4,6-trimethylphenyl)imidazolium hexafluorophosphate (**3**·HPF_6) (1.00 g, 2.22 mmol, 1.0 eq, which was dried under high vacuum at 130 ℃ for 16 h) at 0 ℃, was added drop-wise a solution of KHMDS (0 .5 M in PhMe, 4.5 mL, 2.24 mmol, 1.01 eq). After 30 minutes at 0 ℃, a solution of 9-BBN (0.5 M in THF, 4.50 mL, 2.24 mmol, 1.01 eq) was added drop-wise. The reaction mixture was stirred at 0 ℃ for 30 minutes then warmed to ambient temperature. After 2 h the solvent was removed *in vacuo* to yield an off white solid which was passed through a short plug of silica, eluting with DCM. The combined fractions were concentrated *in vacuo* and dried under high vacuum to yield **3**·9-BBN as a white solid (824 mg, 87 %).



3·9-BBN

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.25 (br s, 2H, C-12 & C-12' C<u>H</u>), 1.13 - 165 (m, 12H, 9-BBN C<u>H</u>$_2$), 2.16 (s, 12H, C-9, C-9', C-11 & C-11' C<u>H</u>$_3$), 2.33 (s, 6H, C-10 & C-10' C<u>H</u>$_3$), 6.80 (s, 2H, C-1 & C- 1 C<u>H</u>), 6.93 (s, 4H, C-5, C-5', C-7 & C-7' C<u>H</u>). No BH proton signal observed.

^{13}C NMR (100 MHz, $CDCl_3$): δ 17.1 (C-9, C-9', C-11 & C-11'), 19.9 (br, C-12 & C-12'), 20.1 (C-10 & C-10'), 22.9 (9-BBN <u>C</u>H$_2$), 24.7 (9-BBN <u>C</u>H$_2$), 30.9 (9-BBN <u>C</u>H$_2$), 36.0 (9-BBN <u>C</u>H$_2$), 120.7 (C-1 & C-1'), 127.7 (C-5, C-5', C-7 & C-7'), 134.2 (C-4, C-4', C-8 & C-8'), 134.4 (C-6 & C-6'), 137.8 (C-3 & C-3'). No C-2 carbon signal observed.

^{11}B NMR (96 MHz, $CDCl_3$): δ -16.6 (d, *J* = 59.6 Hz, <u>B</u>H).

IR (u_{max} cm^{-1}, film): 2897 (m), 2818 (m), 2206 (w, B–H), 1484 (m), 1406 (m), 1272 (m), 1212 (m), 1082 (m), 1018 (m), 851 (s).

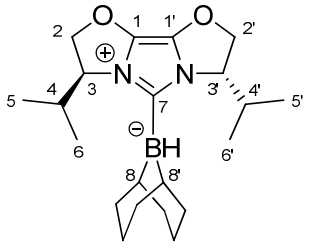
MS (ESI) *m/*z: 425 $[M\text{-}H]^+$.

HRMS (ESI): calc. for $C_{29}H_{38}N_2B^+$ 425.3123, found 425.3123.

m.p. > 198 ℃ (dec).

(3*S*,7*S*)-3,7-Di-*iso*-propyl-2,3,7,8-tetrahydroimidazo[4,3-*b*:5,1-*b*'] bis[1,3]oxazol-4-ylidene-9-borobicyclo[3.3.1]nonane (4·9-BBN)

To a THF (3.5 mL) solution of (3*S*,7*S*)-3,7-di-*iso*-propyl-2,3,7,8 tetrahydroimidazo[4,3-*b*:5,1-*b*']bis[1,3]oxazol-4-ium triflate (**4**·HOTf) (100 mg, 0.259 mmol, 1.0 eq, which was dried under high vacuum at 90 ℃ for 16 h) at -78 ℃, was added drop-wise a solution of *n*-BuLi (2.56 M hexanes, 0.10 mL, 0.262 mmol, 1.01 eq). After 30 minutes at -78 ℃, a solution of 9-BBN (0.5 M THF, 0.52 mL, 0.262 mmol, 1.01 eq) was added drop-wise. The reaction mixture was stirred at -78 ℃ for 30 minutes and then warmed to ambient temperature. After 3 h the solvent was removed *in vacuo* to yield **4**·9-BBN as a white solid which was dissolved in deuterated THF and transferred to a Young's NMR tube.



4·9-BBN

^{1}H NMR (400 MHz ^{11}B decoupled, THF-d_8): δ 0.73 (d, *J* = 7.1 Hz, 6H, C-6 & C-6' C$\underline{H}_3$), 0.93 (d, *J* = 7.1 Hz, 6H, C-5 & C-5' C$\underline{H}_3$), 0.98 (broad s, 1H, B$\underline{H}$), 1.30 - 1.90 (m, 14H, 9-BBN C$\underline{H}$ & C$\underline{H}_2$), 2.53 (dsep, *J* = 7.1, 3.4 Hz, 2H, C-4 & C-4' C$\underline{H}$), 4.46 - 4.49 (m, 2H, C-3 & C-3' C$\underline{H}$), 4.69 (dd, *J* = 9.0, 6.8 Hz, 2H, C-2 & C-2' C$\underline{H}_2$), 4.79 (dd, *J* = 9.0, 1.0 Hz, 2H, C-2 & C-2' C$\underline{H}_2$).

^{13}C NMR (100 MHz, THF-d_8) δ 15.0 (C-6 & C-6'), 19.0 (C-5 & C-5'), 26.4 (C-4 & C-4'), 33.2, 33.6, 36.7, 37.2 (9-BBN $\underline{C}$H$_2$), 63.1 (C-3 & C-3'), 77.0 (C-2 & C-2'), 124.7 (C-1 & C-1'). No C-7, C-8 and C-8' carbon signals observed.

^{11}B NMR (96 MHz, THF-d_8): δ -19.1 (d, *J* = 78. 5 Hz, $\underline{B}$H).

MS (ESI+) *m/z*: 357 $[M-H]^+$

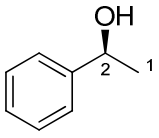
HRMS (ESI): calc. for $C_{21}H_{34}BN_2O_2^+$ 357.3208, found 357.3208.

NB: This complex, and the corresponding *t*-Bu·THIBO-9-BBN complex, **5**·9-BBN, was found to decompose upon exposure to air, so was generated and used *in situ* in the ketone reductions.

2.4 Ketone reductions using NHC-borane complexes

(*S*)-1-Phenylethanol 8a

To a THF (10.0 mL) solution of (3*S*,7*S*)-3,7-di-*tert*-butyl-2,3,7,8-tetrahydroimidazo[4,3-*b*:5,1-*b'*] bis[1,3]oxazol-4-ium trifluoromethanesulfonate (**6**·HOTf) (300 mg, 0.73 mmol, 1.0 eq) at -78 ℃, which was dried under high vacuum at 90 ℃ f or 16 h, was added drop-wise a solution of *n*-BuLi (2.5 M in hexanes, 0.29 mL, 0.725 mmol, 1.0 eq). After 30 minutes at -78 ℃ a solution of 9-BBN (0.5 M in THF, 1.45 mL, 0.73 mmol, 1.00 eq) was added drop-wise. The reaction mixture was stirred at -78 ℃ for 30 minutes then warmed to ambient temperature. After 2 h the solvent was removed *in vacuo* to yield an off white solid which was triturated with PhMe (25.0 mL). The supernatant was transferred to another Schlenk flask *via* a cannula equipped with a filter paper. The solvent was removed *in vacuo* to yield a white solid which was dissolved in DCM (4.5 mL) and cooled to -90 ℃. The solution was then treated with freshly distilled BF_3•OEt_2 (0.92 mL, 0.73 mmol, 1.0 eq) and acetophenone **7a** (87 mg, 0.73 mmol, 1.0 eq). After stirring at -90 ℃ for 16 h the reaction was quenched by the addition of aqueous NaOH (2 M, 5.0 mL) and extracted with DCM (3 x 5 mL). The combined organic fractions were concentrated *in vacuo* and purified by column chromatography (8:2 DCM/hexane) to yield (*S*)-1-phenylethanol (71 mg, 80 %, 84 % *ee*) as a colourless oil.



8a

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.49 (d, *J* = 6.4 Hz, 3H, C-1 C$\underline{H}_3$), 2.28 (s, 1H, O$\underline{H}$), 4.87 (q, *J* = 6.4 Hz, 1H, C-2 C$\underline{H}$), 7.26 – 7.39 (m, 5H, Ar-$\underline{H}$).

^{13}C NMR (75 MHz, $CDCl_3$): δ 25.1 (C-1), 70.2 (C-2), 125.3 (Ar$\underline{C}$H), 127.3 (Ar$\underline{C}$H), 128.4 (Ar$\underline{C}$H), 145.8 (Ar-C).

MS (EI) *m/*z (%): 122 (33) [M],$^+$ 107 (100).

GC SUPELCO Beta Dex™ 30 m x 0.25 nm, 0.25 µm film. He carrier gas (2 mL/min). Inj T = 220 ℃, Det T = 300 ℃, Oven T = 80 ℃ for 2 minutes, then ramp at 1.5 ℃/min to 160 ℃, then ramp at 25 ℃/min to 220 ℃ and hold for 10 minutes. *R*-Rt = 26.5 minutes, *S*-Rt = 27.4 minutes, 84 % *ee (S)*.

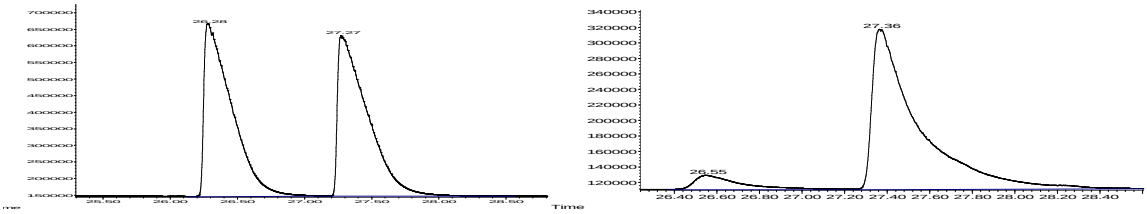
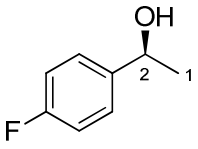


Figure 1: GC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[6]

(*S*)-4-Fluoro-*α*-methylbenzyl alcohol 8b



8b

Reaction conducted using 100 mg of 4-fluoroacetophenone **7b** using the above procedure to afford (*S*)-4-fluoro-α-methylbenzyl alcohol (77 mg, 76 %, 85 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.46 (d, *J* = 6.6 Hz, 3H, C-1 C<u>H</u>$_3$), 2.34 (s, 1H, O<u>H</u>), 4.85 (q, *J* = 6.6 Hz, 1H, C-2 C<u>H</u>), 6.99 – 7.05 (m, 2H, Ar<u>H</u>), 7.29 – 7.34 (m, 2H, Ar<u>H</u>).

^{13}C NMR (75 MHz, $CDCl_3$): δ 25.1 (C-1), 69.6 (C-2), 115.0 (Ar<u>C</u>H), 115.3 (Ar<u>C</u>H), 126.9 (Ar<u>C</u>H), 127.0 (Ar<u>C</u>H), 141.5 (Ar-C), 161.2 (d, *J* = 244.6 Hz, Ar-F).

MS (EI) *m/*z (%): 140 (18) [M],$^{+}$ 125 (100).

GC SUPELCO Beta Dex™ 30 m x 0.25 nm, 0.25 µm film. He carrier gas (2 mL/min). Inj T = 220 ℃, Det T = 300 ℃, Oven T = 80 ℃ for 2 minutes, then ramp at 1.5 ℃/min to 160 ℃, then ramp at 25 ℃/min to 220 ℃ and hold for 10 minutes. *R*-Rt = 24.7 minutes, *S*-Rt = 25.5 minutes, 85 % *ee* (*S)*.

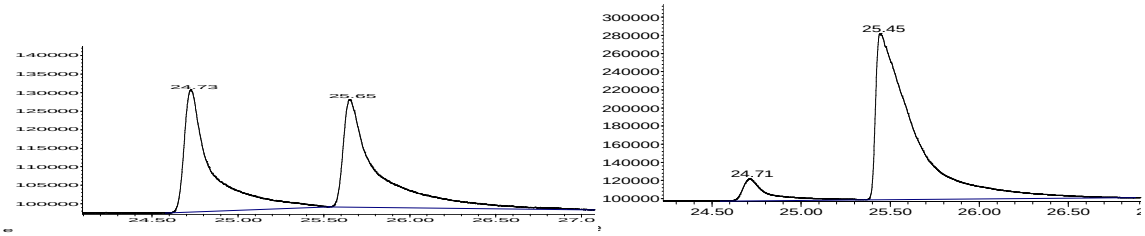
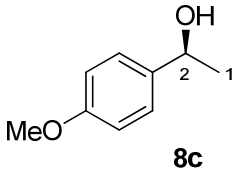


Figure 2: GC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[7]

(*S*)-4-Methoxy-α-methylbenzyl alcohol 8c



8c

Reaction conducted using 109 mg of 4-methoxyacetophenone **7c** dissolved in DCM (0.3 mL) using the above procedure to afford (*S*)-4-methoxy-α-methylbenzyl alcohol (82 mg, 74 %, 59 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.48 (d, *J* = 6.6 Hz, 3H, C-1 C$\underline{H}_3$), 2.01 (d, *J* = 3.4 Hz, 1H, O$\underline{H}$), 3.81 (s, 3H, C-3 C$\underline{H}_3$), 4.85 (dq, *J* = 3.4, 6. 6 Hz, 1H, C-2 C$\underline{H}$), 6.87 – 6.91 (m, 2H, Ar-$\underline{H}$), 7.28 – 7.32 (m, 2H, Ar-$\underline{H}$).

^{13}C NMR (75 MHz, $CDCl_3$): δ 24.9 (C-1), 55.2 (C-3), 69.8 (C-2), 113.7 (Ar$\underline{C}$H), 126.6 (Ar$\underline{C}$H), 138.0 (Ar-C), 158.8 (Ar-O$\underline{C}H_3$).

MS (EI) *m/z* (%): 152 (30) [M],$^{+}$ 137 (100).

Chiralcel OD at λ 230 nm, Isocratic 2 % IPA/Hexane 1.00 mL/min, 20 °C, *R*-Rt = 28.6 minutes, *S*-Rt = 33.7 minutes, 59 % *ee (S)*.

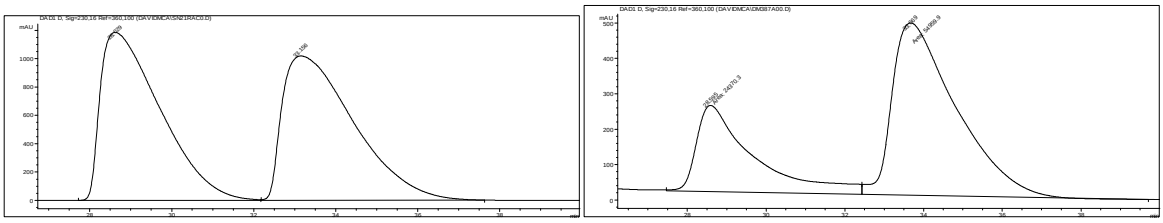
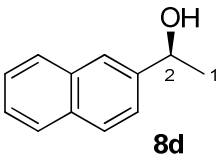


Figure 31: HPLC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[8]

(*S*)-1-(Naphthalen-2-yl)ethanol 8d



8d

Reaction conducted using 123 mg of 2-acetonaphthone **7d** dissolved in DCM (0.3 mL) using the above procedure to afford (*S*)-1-(naphthalen2-yl)ethanol (109 mg, 87 %, 71 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.60 (d, *J* = 6.6 Hz, 3H, C-1 C$\underline{H}_3$), 2.10 (br s, 1H, O$\underline{H}$), 5.07 (q, *J* = 6.6 Hz, 1H, C-2 C$\underline{H}$), 7.46 – 7.53 (m, 3H, Ar-$\underline{H}$), 7.81 – 7.86 (m, 4H, Ar-$\underline{H}$).

^{13}C NMR (75 MHz, $CDCl_3$): δ 25.1 (C-1), 70.5 (C-2), 123.8 (ArCH), 125.8 (ArCH), 126.1 (ArCH), 127.6 (ArCH), 127.9 (ArCH), 128.3 (ArCH), 132.9 (Ar-C), 133.3 (Ar-C), 143.1 (Ar-C).

MS (EI) *m/*z (%): 172 (42) [M],$^+$ 129 (100).

Chiralcel OJ at λ 230 nm, Isocratic 5 % IPA/Hexane 0.50 mL/min, 0 ℃ , *S*-Rt = 46.4 minutes, *R*-Rt = 51.3 minutes, 71 % *ee (S)*.

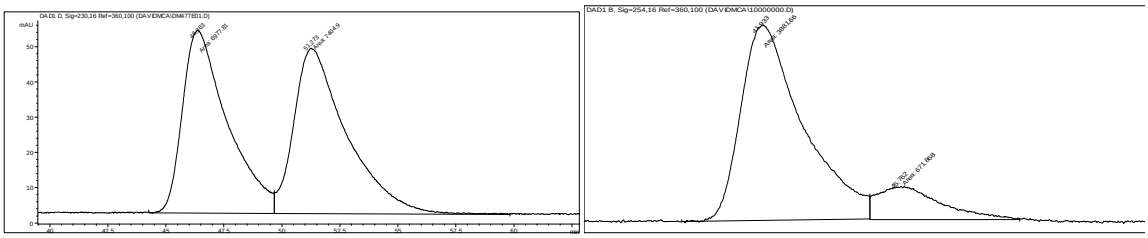
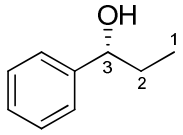


Figure 42: HPLC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[9]

(*R*)-1-Phenylpropanol 8e



8e

Reaction conducted using 97 mg of propiophenone **7e** using the above procedure to afford (*R*)-1-phenylpropanol (81 mg, 82 %, 63 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (t, *J* = 7.6 Hz, 3H, C-1, CH_3), 1.70 – 1.88 (m, 2H, C-2 CH_2), 1.98 (s, 1H, OH), 4.59 (t, *J* = 6.6 Hz, 1H, C-3 CH), 7.25 – 7.36 (m, 5H, Ar-H).

^{13}C NMR (75 MHz, $CDCl_3$): δ 10.1 (C-1), 31.9 (C-2), 76.0 (C-3), 125.9 (ArCH), 127.5 (ArCH), 128.4 (ArCH), 144.6 (Ar-C).

MS (EI) *m/*z (%): 136 (14) [M],$^+$ 107 (100).

GC SUPELCO Beta Dex™ 30 m x 0.25 nm, 0.25 µm film. He carrier gas (2 mL/min). Inj T = 220 ℃, Det T = 300 ℃, Oven T = 80 ℃ for 2 minutes, then ramp at 1.5 ℃/min to 160 ℃, then ramp at 25 ℃/min to 220 ℃ and hold for 10 minutes. *S*-Rt = 28.8 minutes, *R*-Rt = 29.2 minutes, 63 % *ee (R)*.

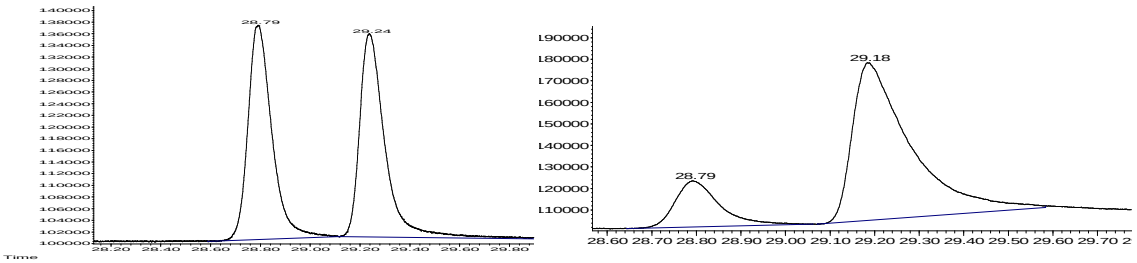
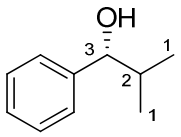


Figure 5: GC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[10]

(*R*)-2-Methyl-1-phenylpropan-1-ol 8f



8f

Reaction conducted using 107 mg of isobutyrophenone **7f** using the above procedure to afford (*R*)-2-methyl-1-phenylpropan-1-ol (71 mg, 65 %, 24 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.73 (d, *J* = 6.9 Hz, 3H, C-1 C$\underline{H}_3$), 0.93 (d, *J* = 6.9 Hz, 3H, C-1 C$\underline{H}_3$), 1.80 (br s, 1H, O$\underline{H}$), 1.89 (octet, *J* = 6.9 Hz, 1H, C-2 C$\underline{H}$), 4.29 (d, *J* = 6.9 Hz, 1H, C-3 C$\underline{H}$), 7.17 – 7.29 (m, 5H, Ar-$\underline{H}$).

^{13}C NMR (75 MHz, $CDCl_3$): δ 18.2 (C-1), 19.0 (C-1), 35.2 (C-2), 80.0 (C-3), 126.5 (Ar$\underline{C}$H), 127.4 (Ar$\underline{C}$H), 128.2 (Ar$\underline{C}$H), 143.6 (Ar-C).

MS (EI) *m/*z (%): 150 (6) [M],$^{+}$ 107 (100).

Chiralcel OD-H at λ 210 nm, Isocratic 3 % IPA/Hexane 0.50 mL/min, 0 ℃, *S*-Rt = 15.0 minutes, *R*-Rt = 16.3 minutes, 24 % *ee (R)*.

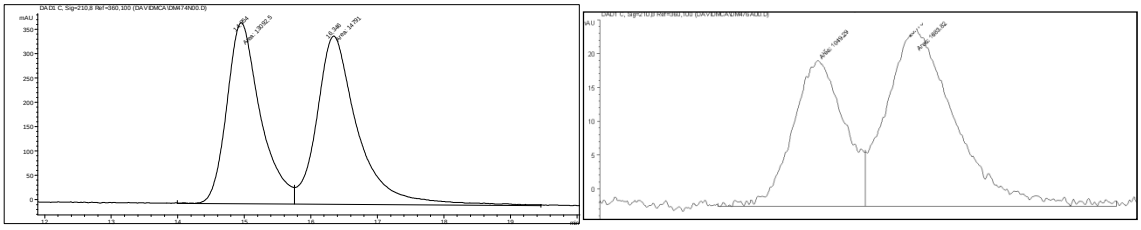
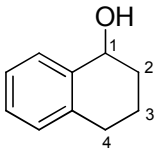


Figure 6: HPLC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[11]

1,2,3,4-Tetrahydro-1-naphthol 8g



8g

Reaction conducted using 106 mg of α-tetralone **7g** using the above procedure to afford 1,2,3,4-tetrahydro-1-naphthol (73 mg, 68 %, 0 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.73 – 2.08 (m, 5H), 2.69 – 2.87 (m, 2H), 4.77 (m, 1H, C-1 C<u>H</u>), 7.10 – 7.44 (m, 4H, Ar-<u>H</u>).

^{13}C NMR (75 MHz, $CDCl_3$): δ 18.7 (C-3), 29.2 (C-4), 32.2 (C-2), 68.0 (C-1), 126.1 (Ar<u>C</u>H), 127.5 (Ar<u>C</u>H), 128.6 (Ar<u>C</u>H), 128.9 (Ar<u>C</u>H), 137.0 (Ar-C), 138.7 (Ar-C).

MS (EI) *m/z* (%): 148 (18) [M],$^{+}$ 130 (100).

GC SUPELCO Beta Dex™ 30 m x 0.25 nm, 0.25 µm film. He carrier gas (2.2 mL/min). Inj T = 220 ℃, Det T = 300 ℃, Oven T = 80 ℃ for 3 minutes, then ramp at 0.5 ℃/min to 140 ℃ and hold for 5 minutes, then ramp at 25 ℃/min to 200 ℃ and hold for 5 minutes. *S*-Rt = 98.5 minutes, *R*-Rt = 100.0 minutes, 0 % *ee*.

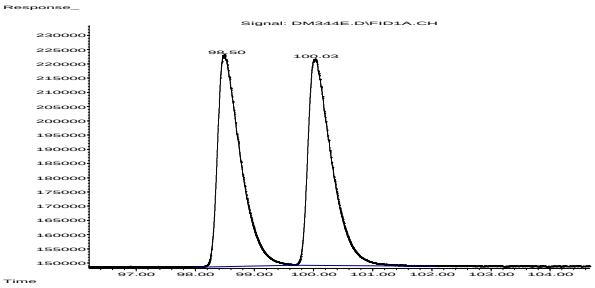
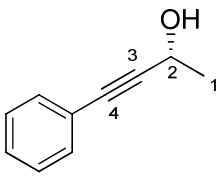


Figure 7: GC trace of the racemate

The spectroscopic properties of this compound were consistent with those reported in the literature.[12]

(*R*)-4-Phenyl-3-butyn-2-ol 8h



8h

Reaction conducted using 105 mg of 4-phenyl-3-butyn-2-one **7h** using the above procedure to afford (*R*)-4-phenyl-3-butyn-2-ol (93 mg, 88 %, 70 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.56 (d, *J* = 6.6 Hz, 3H, C-1 C$\underline{H}_3$), 2.19 (s, 1H, O$\underline{H}$), 4.76 (q, *J* = 6.6 Hz, 1H, C-2 C$\underline{H}$), 7.28 – 7.44 (m, 5H, Ar-$\underline{H}$).

^{13}C NMR (100 MHz, $CDCl_3$): δ 24.3 (C-1), 58.8 (C-2), 84.0 (C-4), 90.9 (C-3), 122.5 (Ar-C), 128.2 (Ar$\underline{C}$H), 131.6 (Ar$\underline{C}$H).

MS (EI) *m/*z (%): 146 (32) [M],$^{+}$ 131 (100).

Chiralcel OD at λ 230 nm, Isocratic 15 % IPA/Hexane 1.00 mL/min, 20 ℃, *R*-Rt = 5.3 minutes, *S*-Rt = 10.5 minutes, 70 % *ee (R)*.

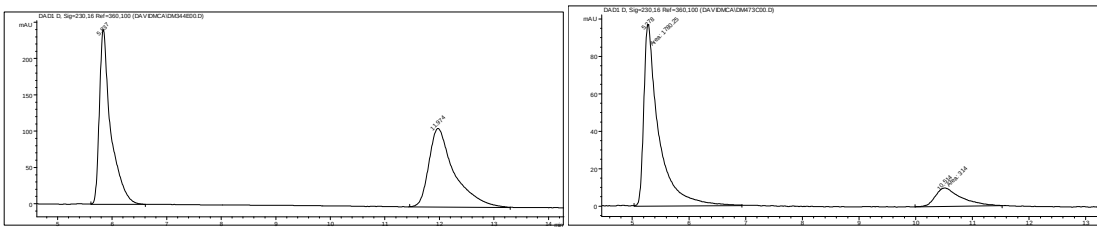
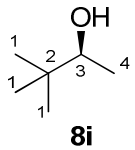


Figure 8: HPLC traces of the racemate (left) and the enantioselective reaction (right).

The spectroscopic properties of this compound were consistent with those reported in the literature.[13]

(*S*)-3,3-Dimethyl-2-butanol 8i



8i

Reaction conducted using 73 mg of 3,3-dimethylbutan-2-one **7i** using the above procedure to afford (*S*)-3,3-dimethyl-2-butanol (67 mg, 90 %, 62 % *ee*).

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.89 (s, 9H, C-1 C$\underline{H}_3$), 1.11 (d, *J* = 6.4 Hz, 3H, C-4 C$\underline{H}_3$), 4.47 (d, *J* = 4.7 Hz, 1H, O$\underline{H}$), 3.46 (dq, *J* = 4.7, 6.4 Hz, 1H, C-3 C$\underline{H}$).

^{13}C NMR (75 MHz, $CDCl_3$): δ 17.8 (C-4), 25.4 (C-1), 34.8 (C-2), 75.6 (C-3).

MS (EI) *m/*z (%): 102 (10) [M],$^{+}$ 57 (100).

GC SUPELCO Beta Dex™ 30 m x 0.25 nm, 0.25 μm film. He carrier gas (1.3 mL/min). Inj T = 250 ℃, Det T = 250 ℃, Oven T = 70 ℃ for 30 minutes, then ramp at 25 ℃/min to 200 ℃ and hold for 5 minutes. *R*-Rt = 5.1 minutes, *S*-Rt = 5.4 minutes, 62 % *ee (S)*.

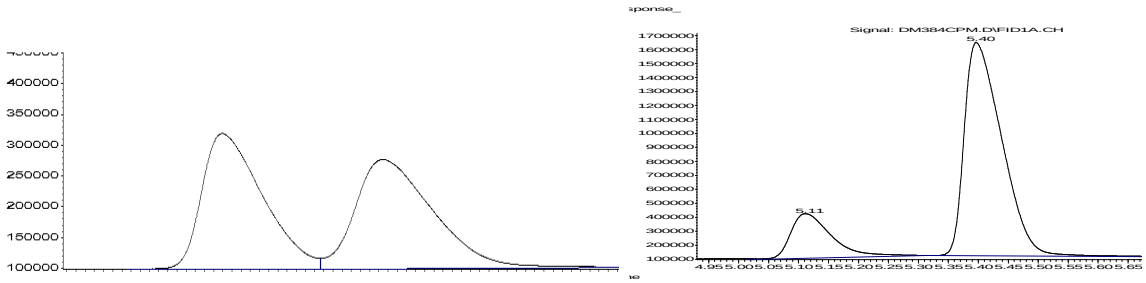
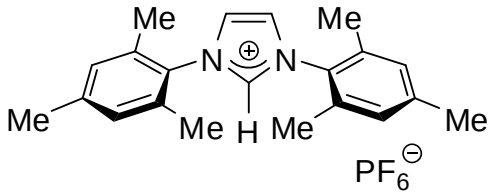


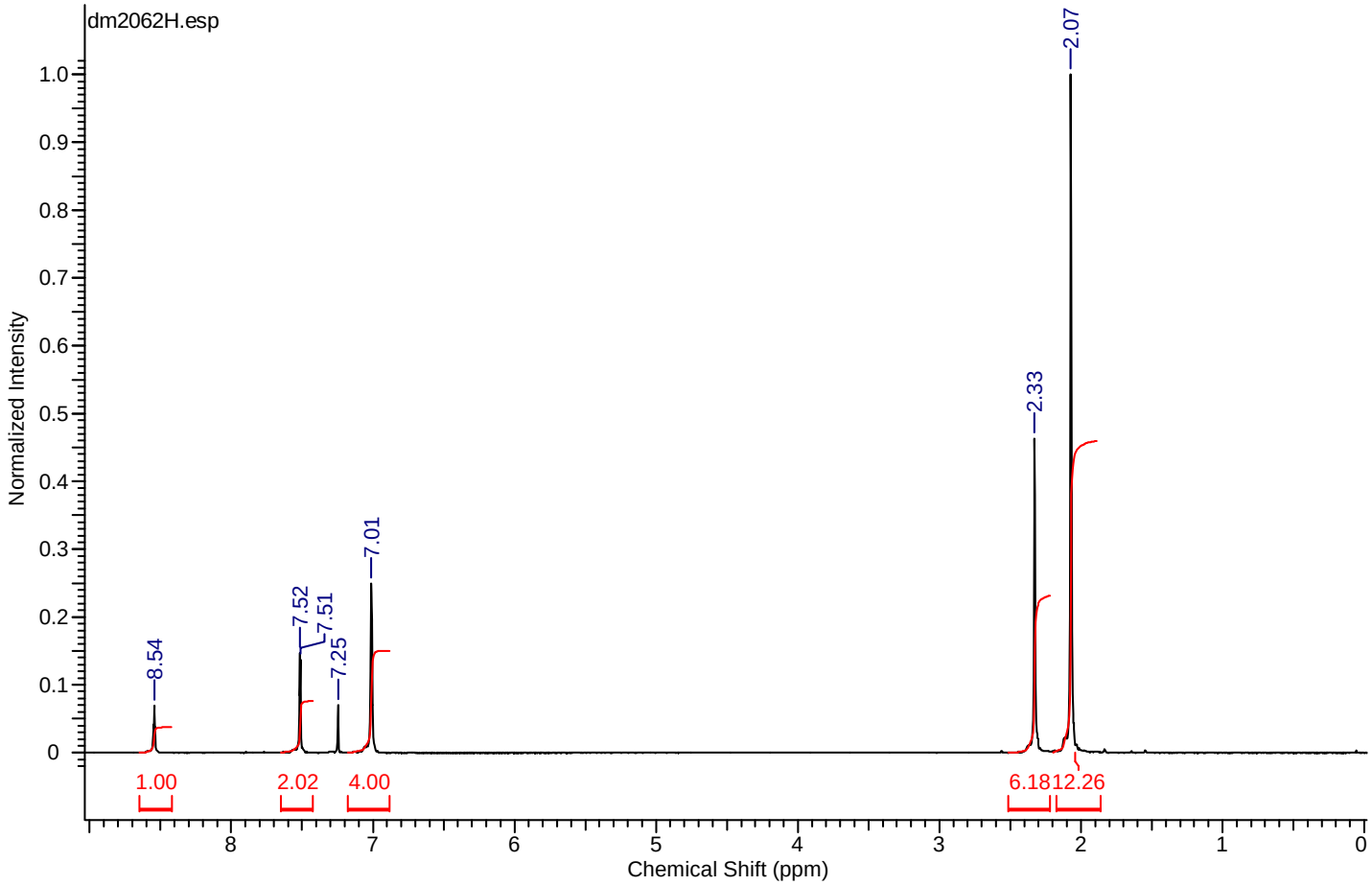
Figure 9: GC traces of the racemate (left) and the enantioselective reaction (right).

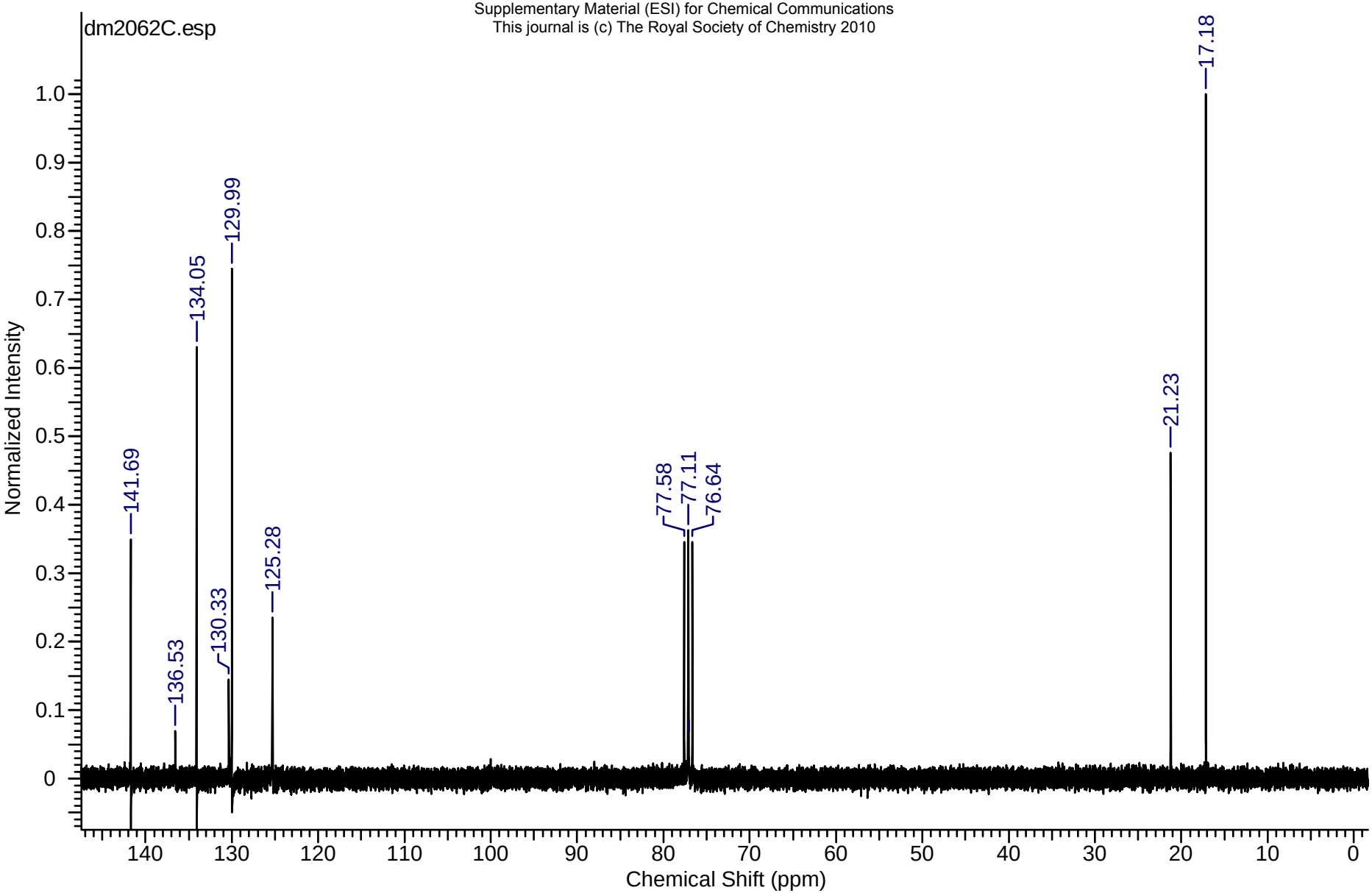
The spectroscopic properties of this compound were consistent with those reported in the literature.[14]

3. Spectra



3·HPF_6

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Normalized Intensity
Chemical Shift (ppm)
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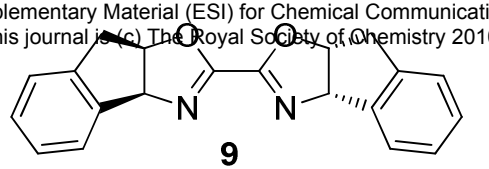
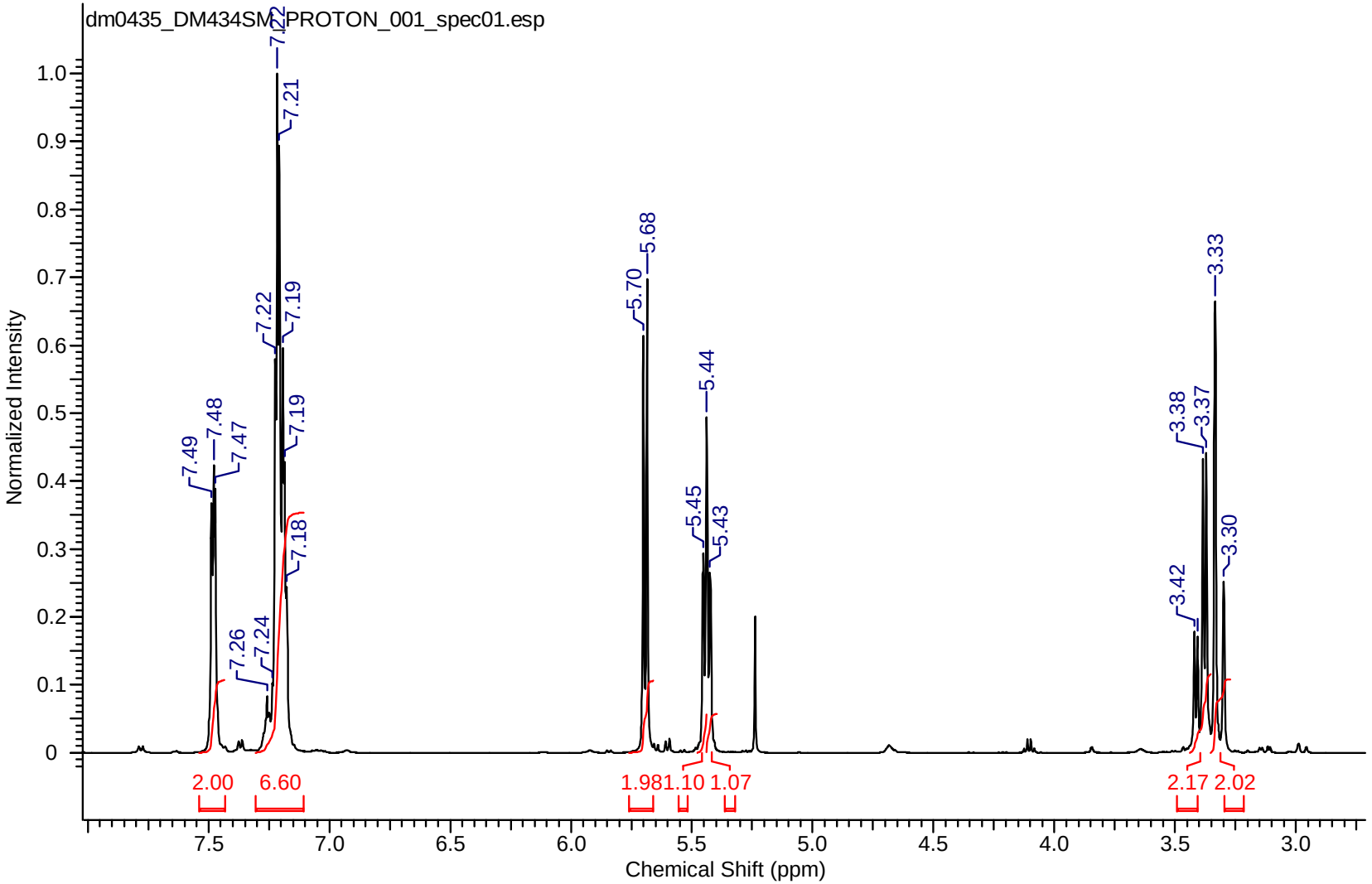
134.05
130.33
129.99
125.28
77.58
77.11
76.64
21.23
17.18


O
O
N
N

9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Normalized Intensity
Chemical Shift (ppm)
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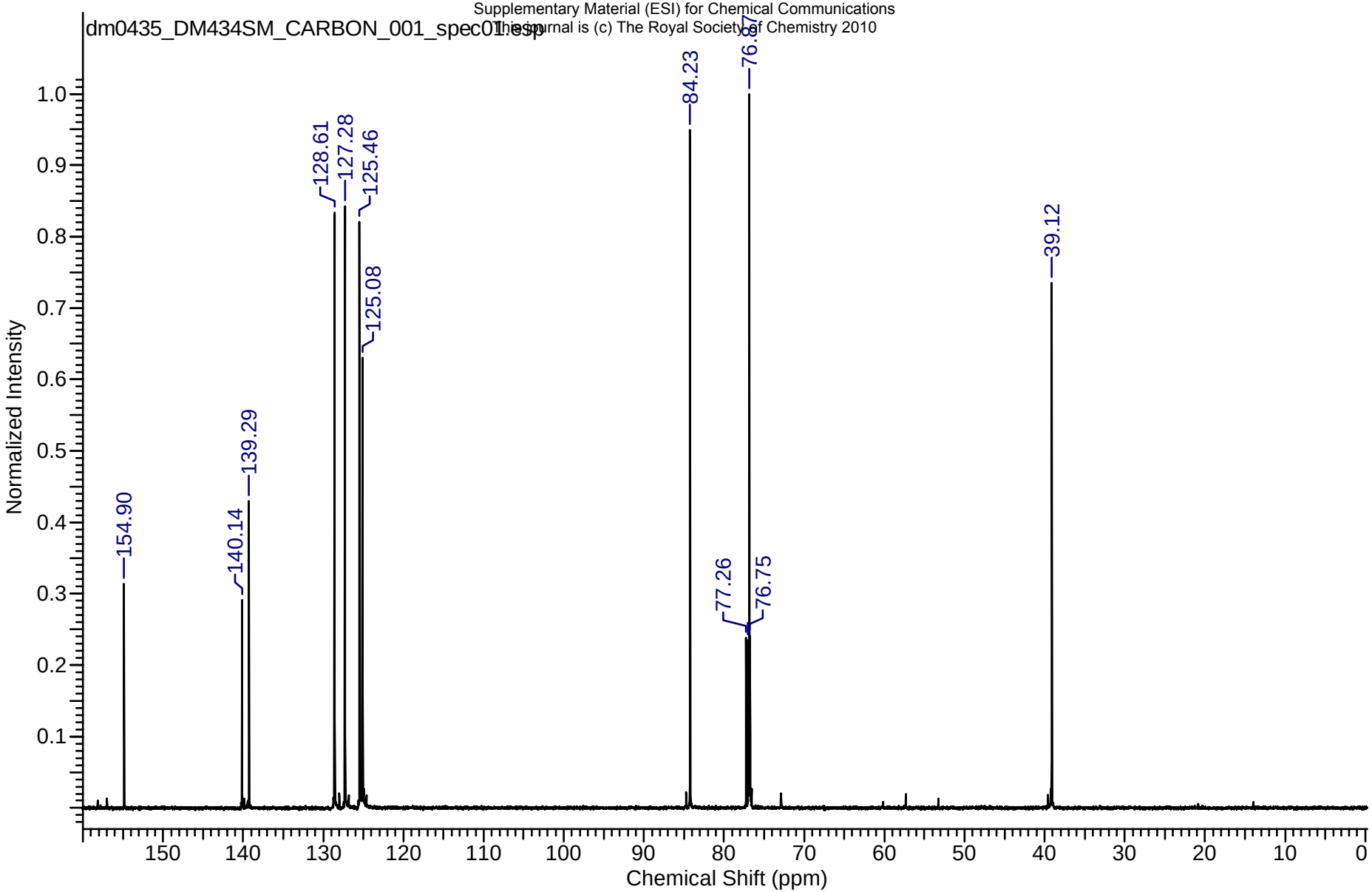
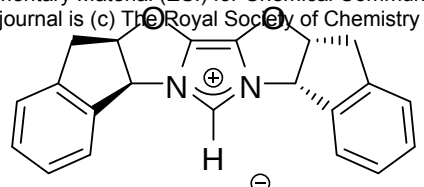
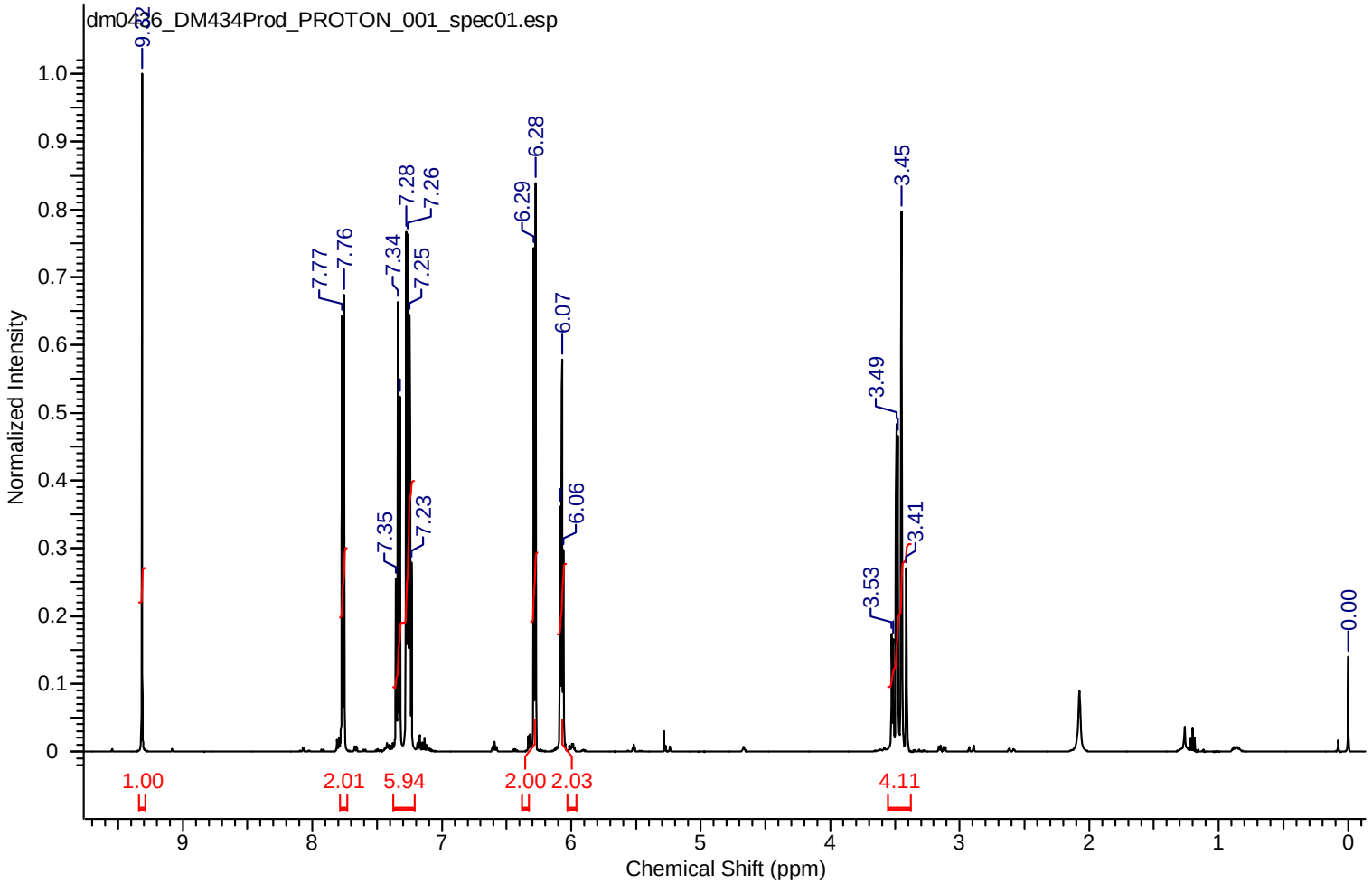
7.48
7.47
7.26
7.24
7.22
7.21
7.19
7.19
7.18
5.70
5.68
5.45
5.44
5.43
3.42
3.38
3.37
3.33
3.30
2.00
6.60
1.98
1.10
1.07
2.17
2.02




N
N
H
OTf

6·HOTf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Normalized Intensity
Chemical Shift (ppm)
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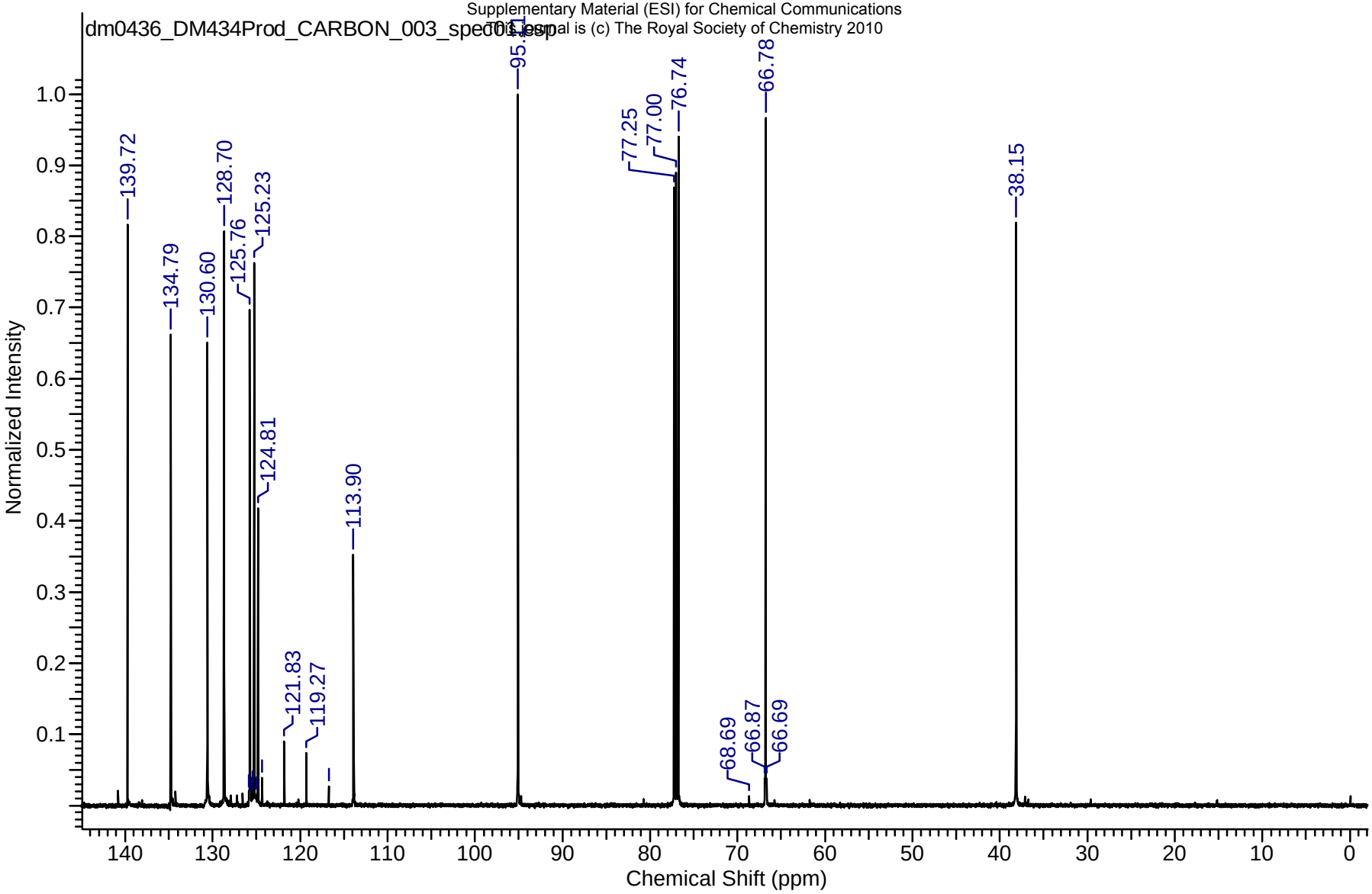
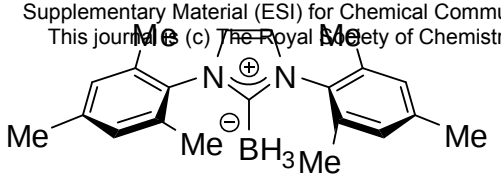
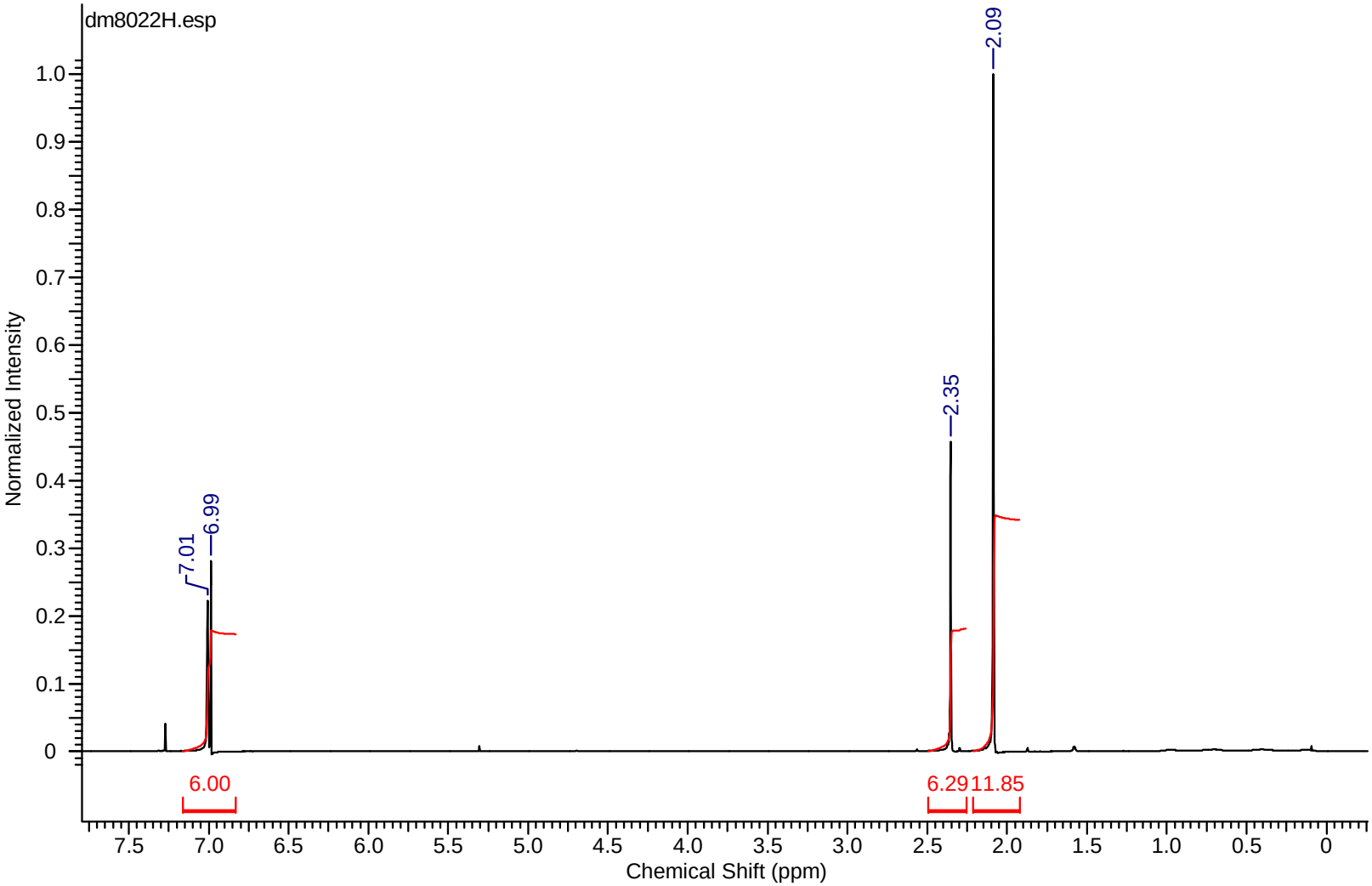
7.77
7.76
7.34
7.28
7.26
7.25
7.35
7.23
6.29
6.28
6.07
6.06
3.49
3.45
3.53
3.41
0.00
1.00
2.01
5.94
2.00
2.03
4.11




Me
Me
N
N
Me
Me
BH3
Me
Me

3·BH_3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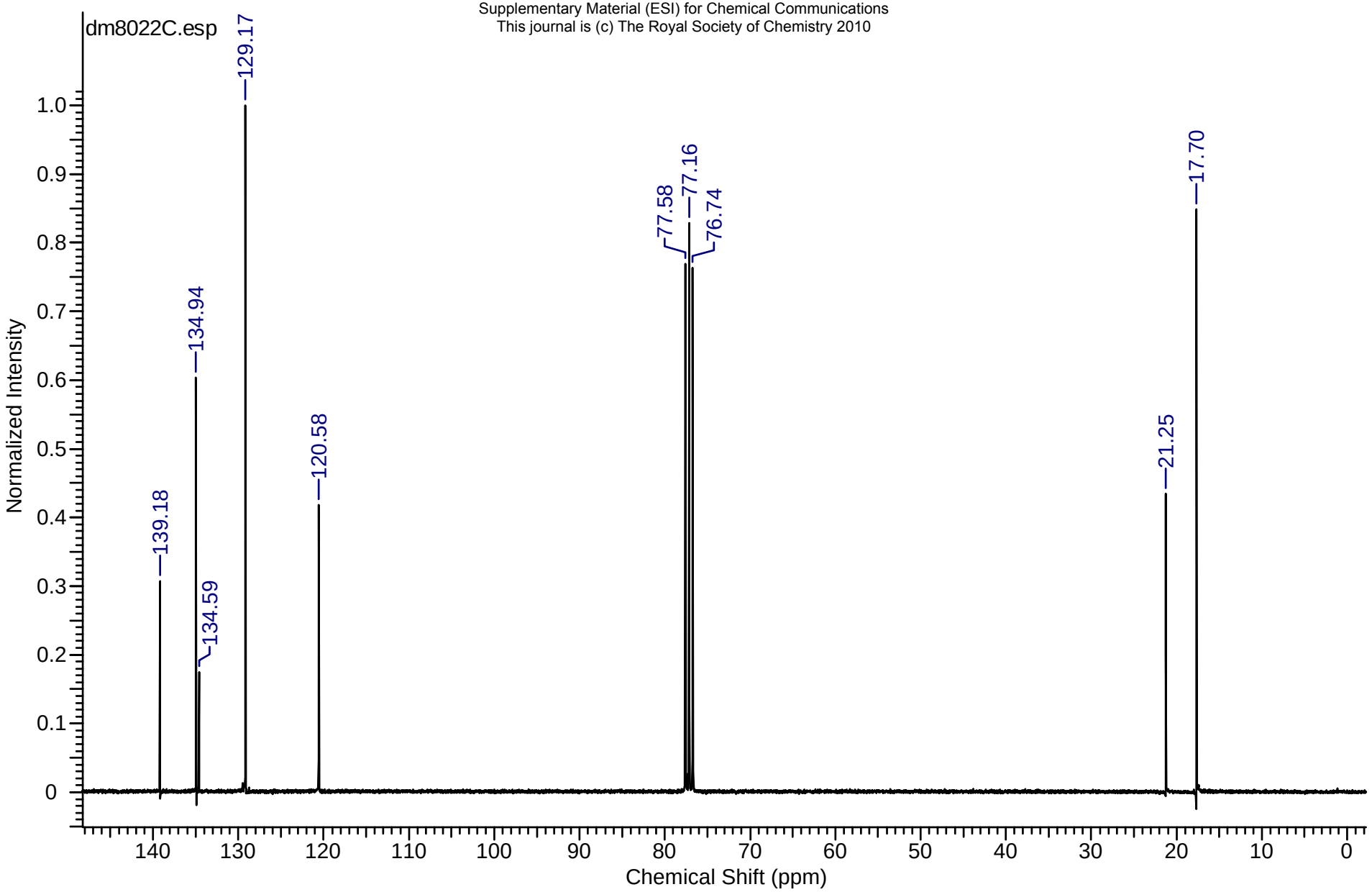
2.09
6.00
6.29
11.85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Chemical Shift (ppm)
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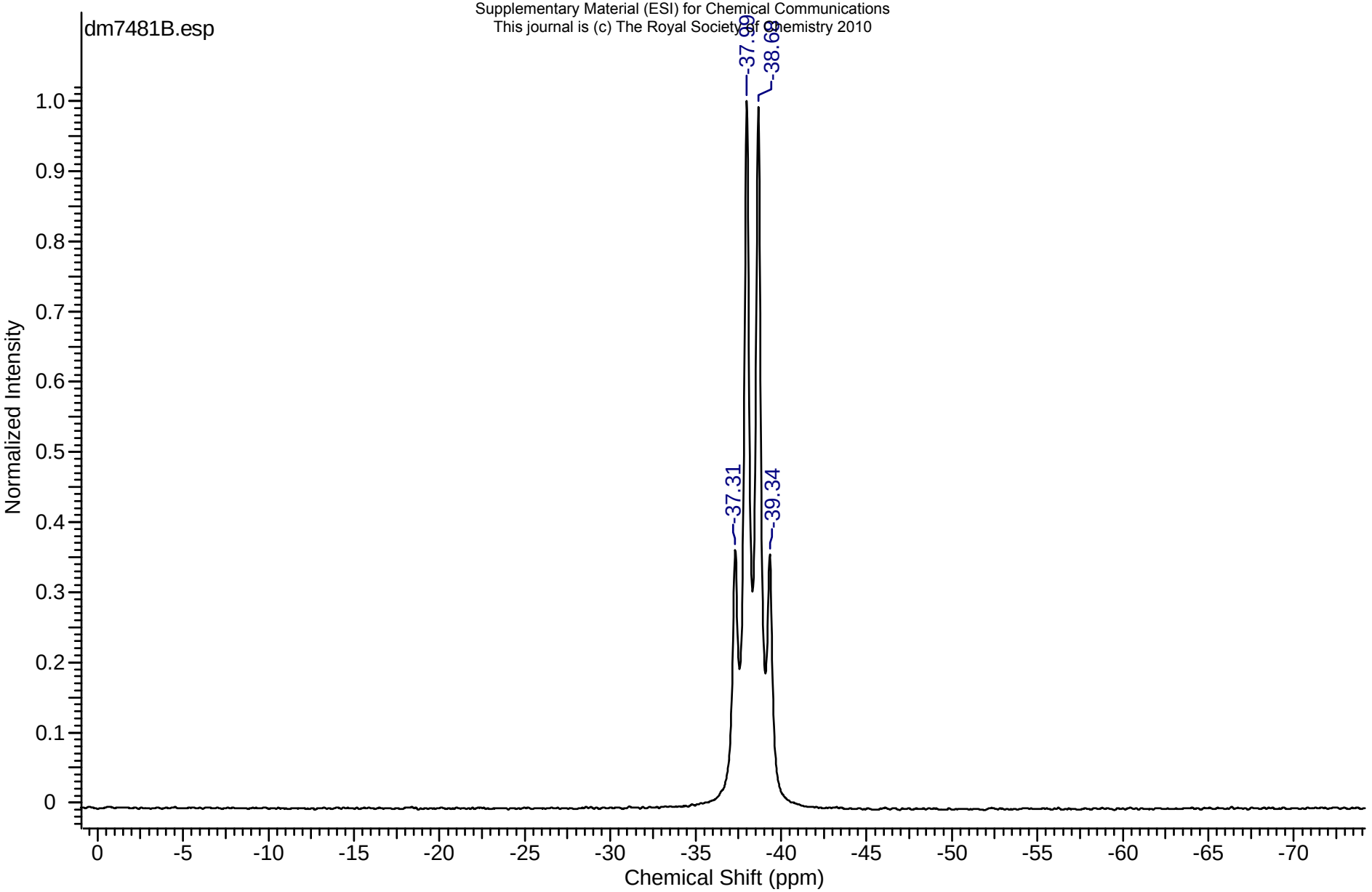
134.94
134.59
129.17
120.58
77.58
77.16
76.74
21.25
17.70


dm7481B.esp
-37.29
-38.69
-37.31
-39.34
Normalized Intensity
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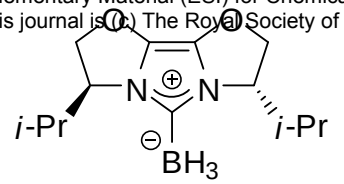
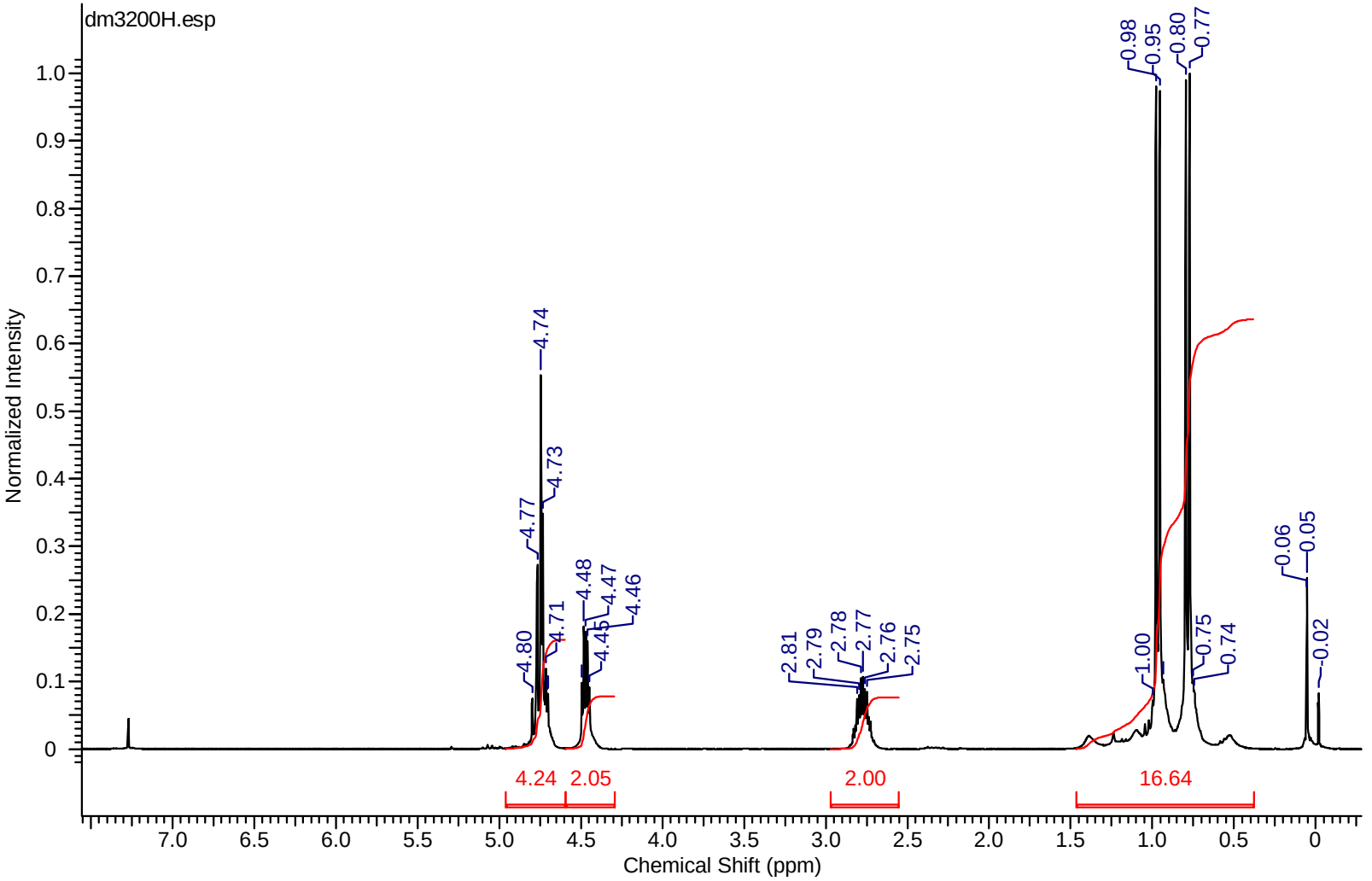
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
Chemical Shift (ppm)


i-Pr
N
N
i-Pr
BH3

4·BH_3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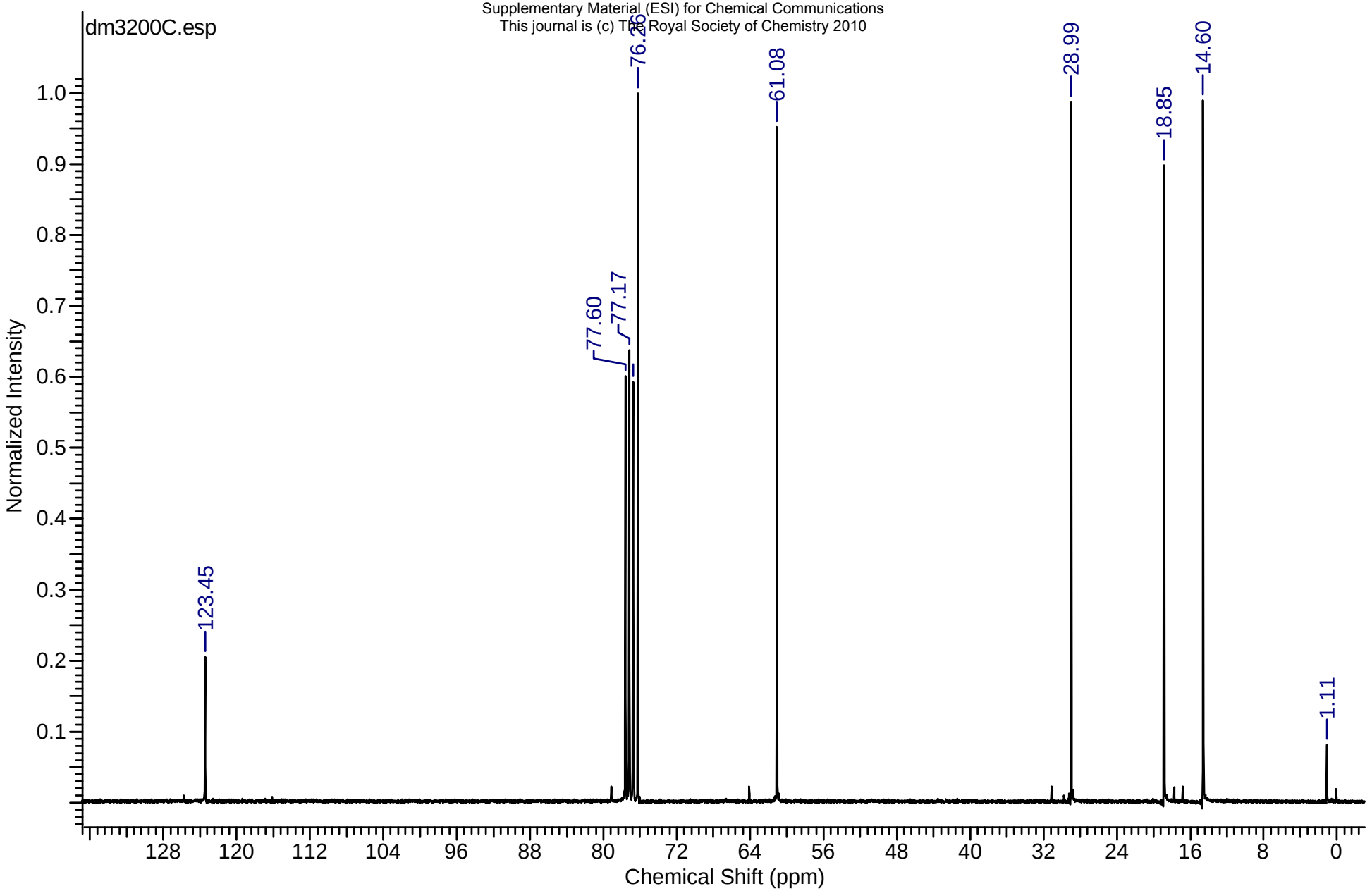
4.48
4.47
4.46
4.71
4.80
4.45
2.81
2.79
2.78
2.77
2.76
2.75
0.98
0.95
0.80
0.77
1.00
0.75
0.74
0.06
0.05
0.02
4.24
2.05
2.00
16.64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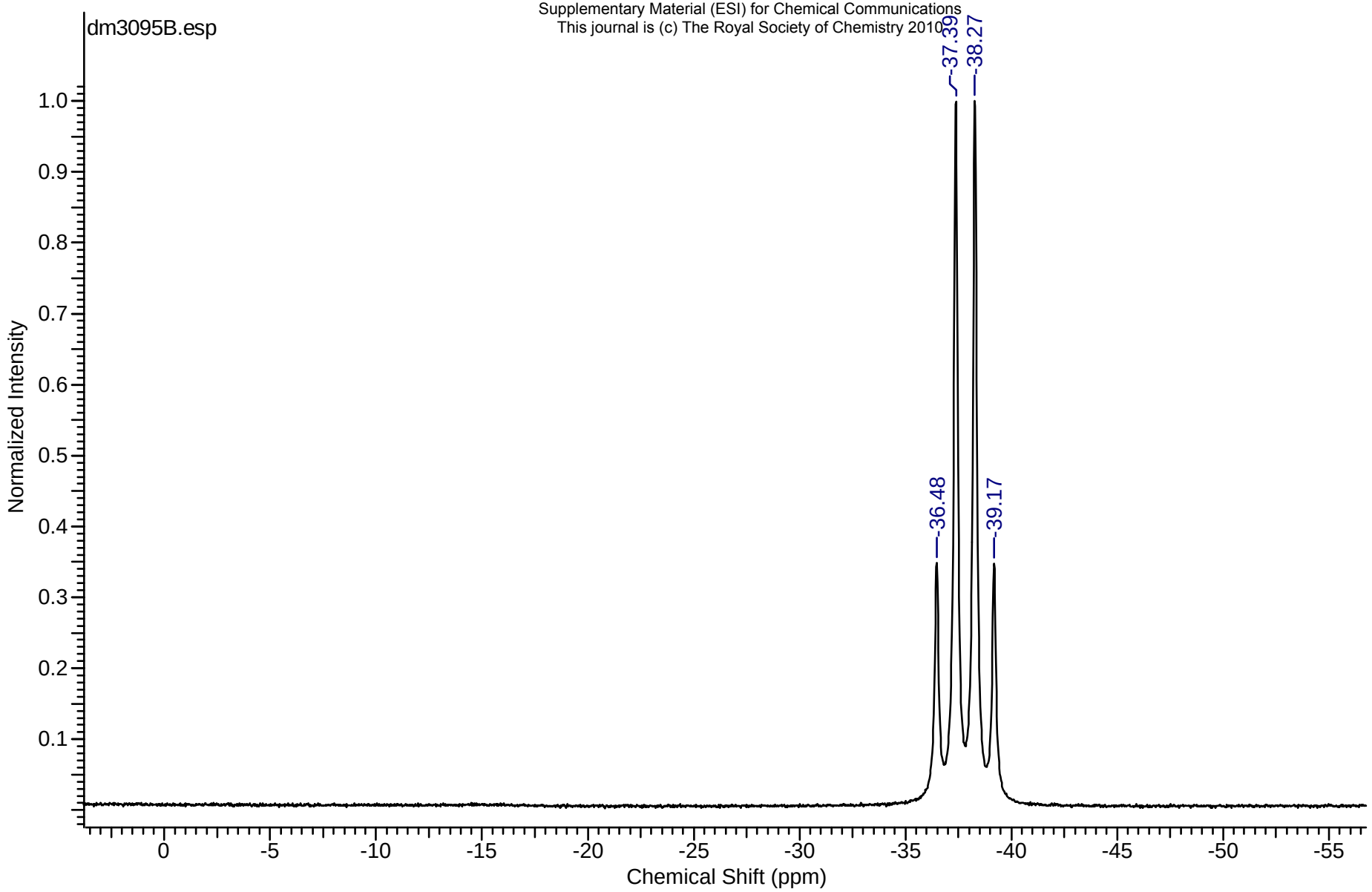
0.6
0.5
0.4
0.3
0.2
0.1
123.45
77.60
77.17
76.29
61.08
28.99
18.85
14.60
1.11
128
120
112
104
96
88
80
72
64
56
48
40
32
24
16
8
0
Chemical Shift (ppm)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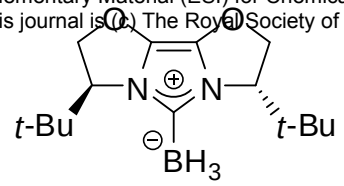
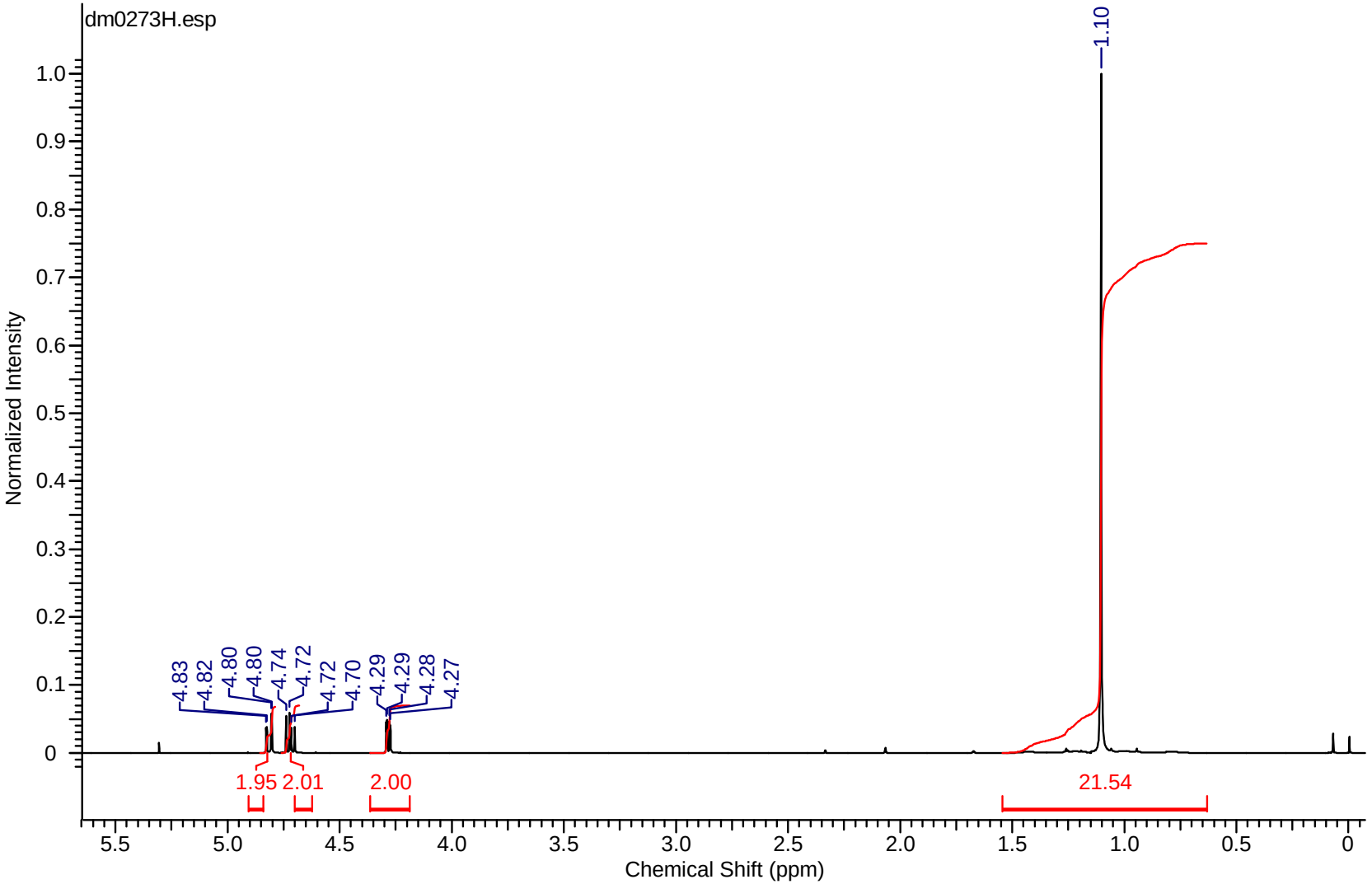
0.5
0.4
0.3
0.2
0.1
-37.39
-38.27
-36.48
-39.17
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
Chemical Shift (ppm)


t-Bu
N
N
t-Bu
BH3

5·BH_3


dm0273H.esp
Normalized Intensity
Chemical Shift (ppm)
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4.82
4.80
4.80
4.74
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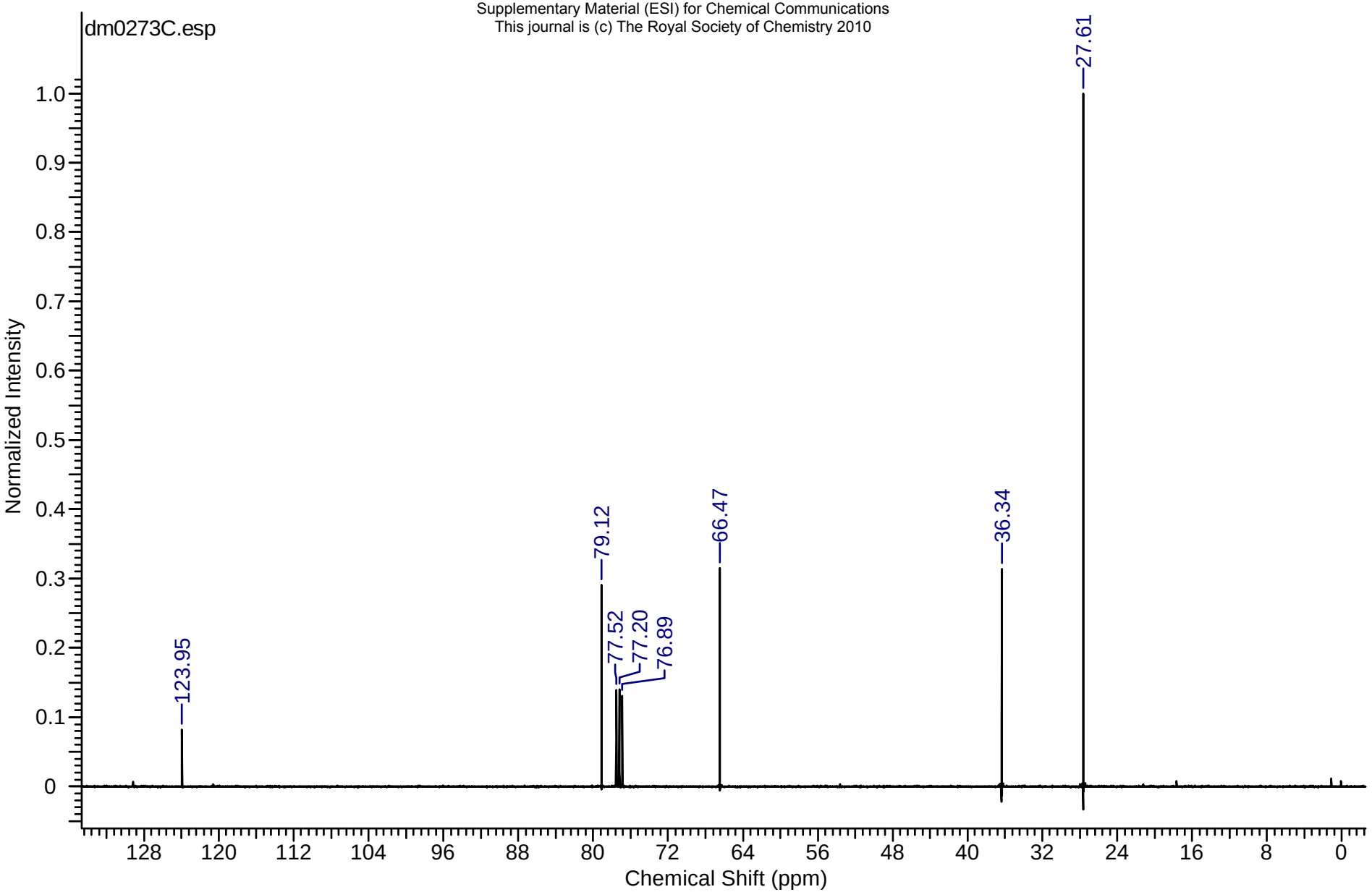
4.72
4.70
4.29
4.29
4.28
4.27
1.95
2.01
2.00
21.54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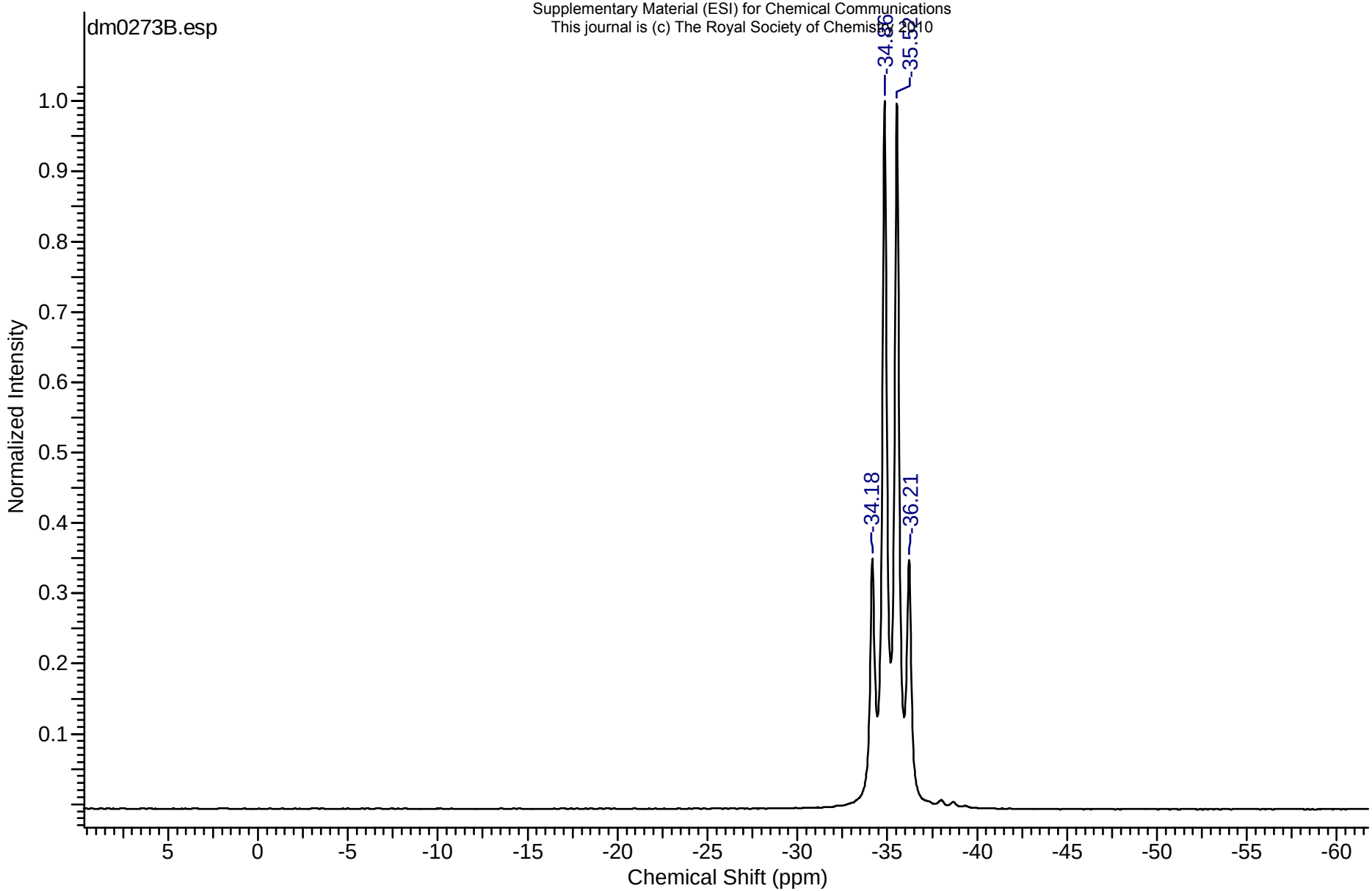
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
27.61
79.12
66.47
36.34
123.95
77.52
77.20
76.89
128
120
112
104
96
88
80
72
64
56
48
40
32
24
16
8
0
Chemical Shift (ppm)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Normalized Intensity
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0.7
0.6
0.5
0.4
0.3
0.2
0.1
34.18
34.86
35.52
36.21
5
0
-5
-10
-15
-20
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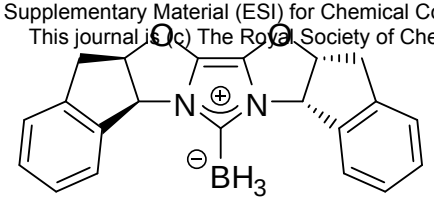
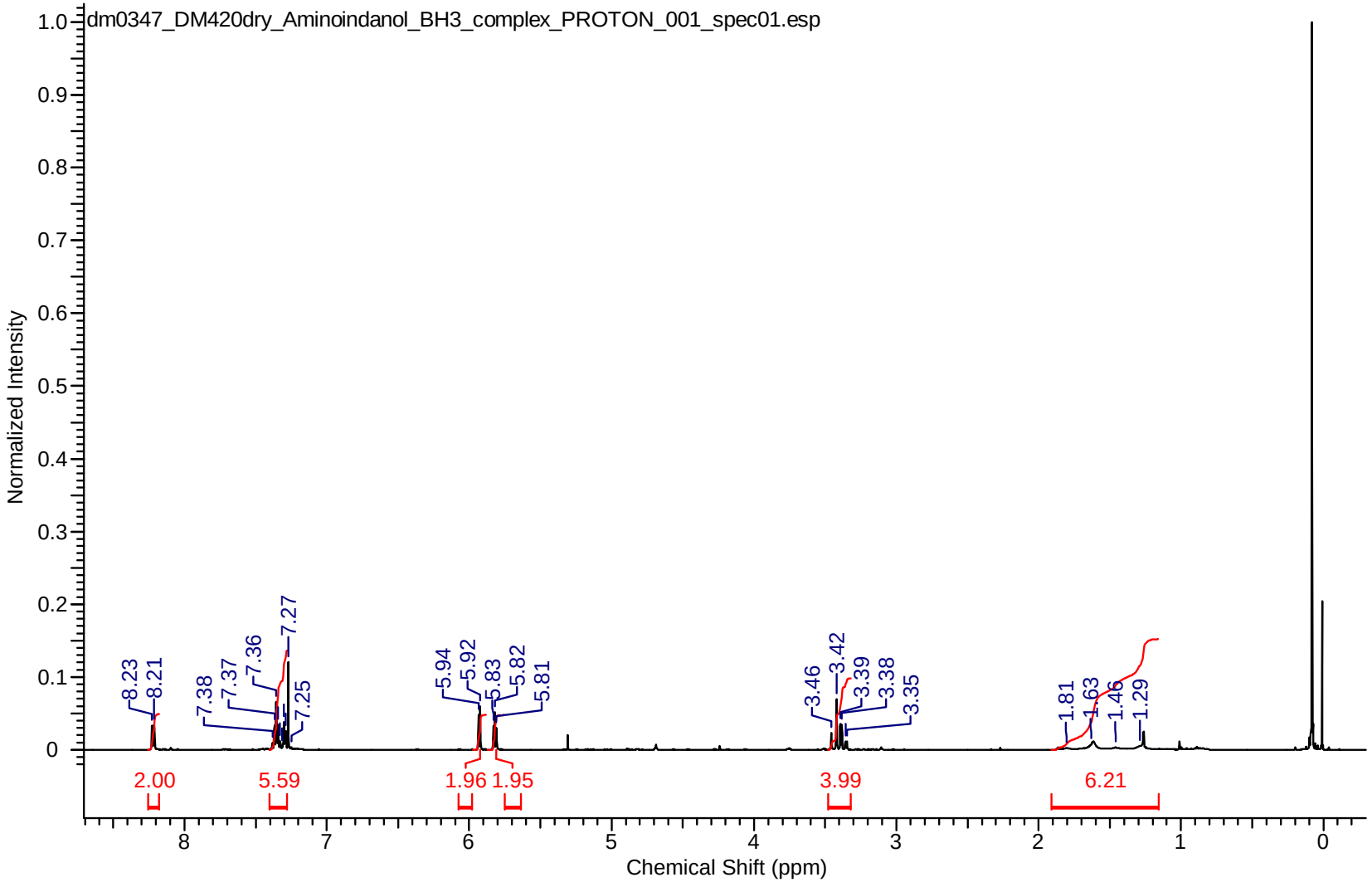
-40
-45
-50
-55
-60
Chemical Shift (ppm)


O
O
N
N
BH3

6·BH_3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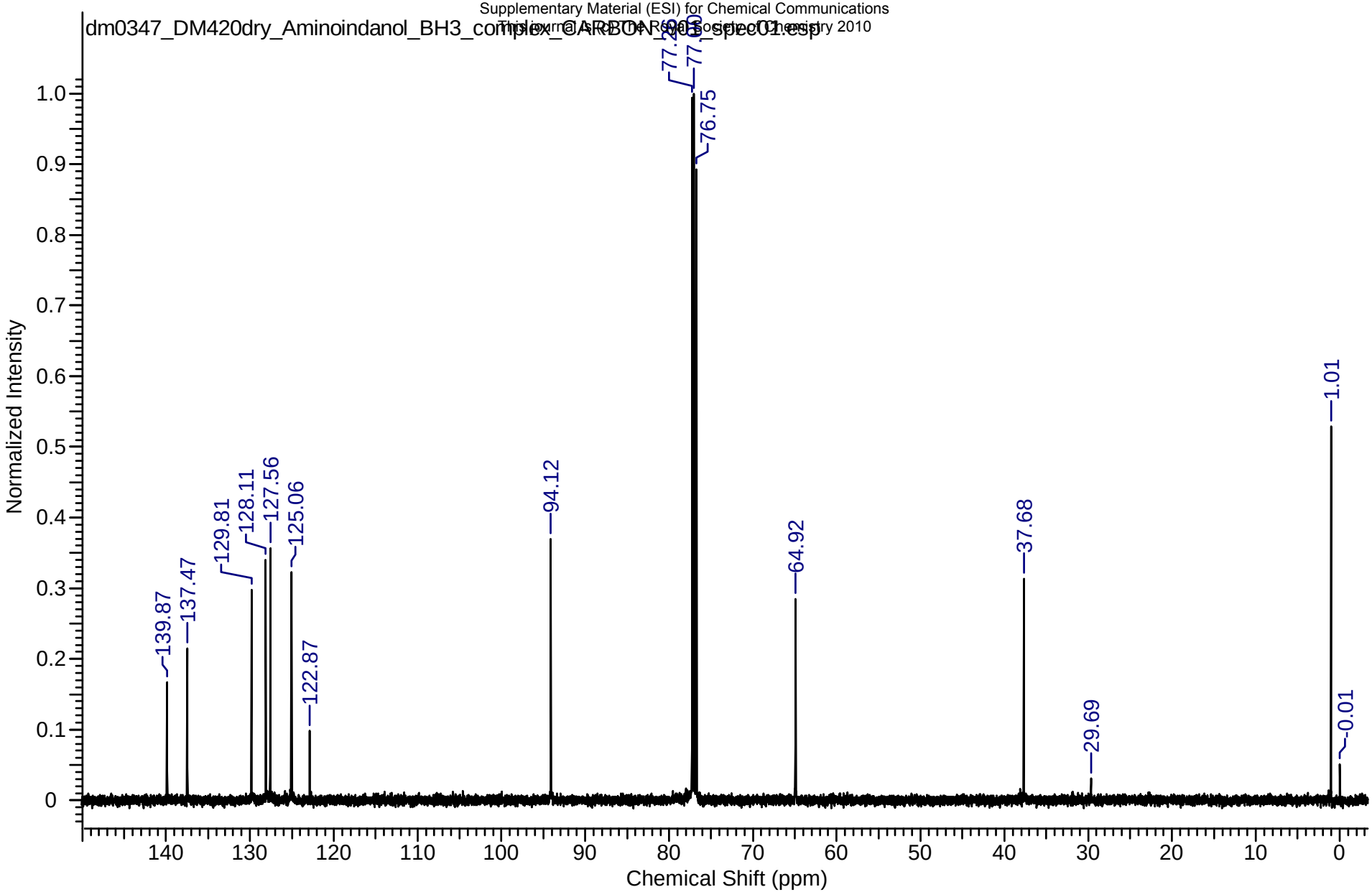
Normalized Intensity
Chemical Shift (ppm)
8.23
8.21
7.38
7.37
7.36
7.27
7.25
5.94
5.92
5.83
5.82
5.81
3.46
3.42
3.39
3.38
3.35
1.81
1.63
1.46
1.29
2.00
5.59
1.96
1.95
3.99
6.21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Normalized Intensity
Chemical Shift (ppm)
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77.00
76.75
139.87
137.47
129.81
128.11
127.56
125.06
122.87
94.12
64.92
37.68
29.69
1.01
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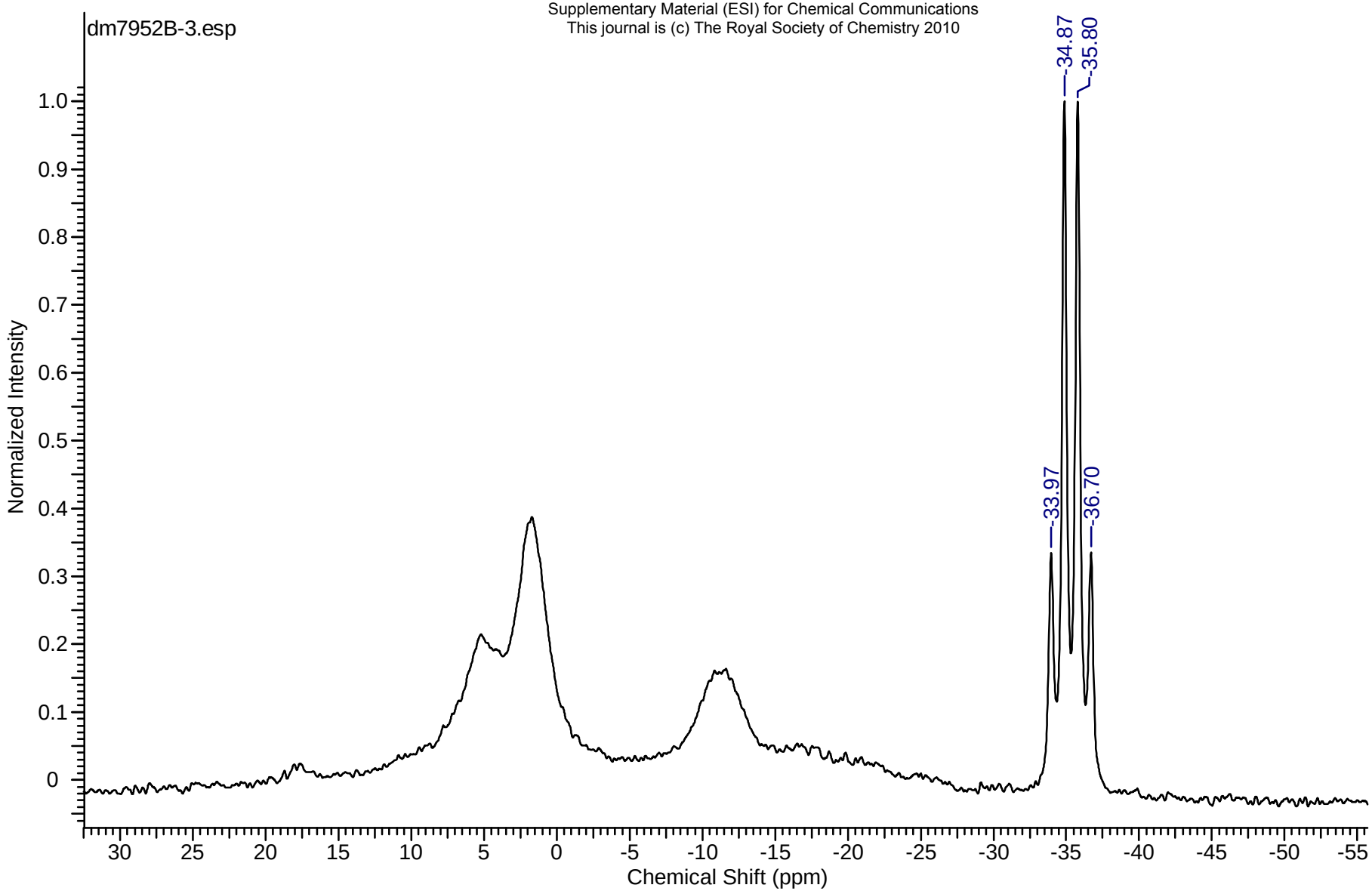
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0.6
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0.4
0.3
0.2
0.1
0
-34.87
-35.80
-33.97
-36.70
30
25
20
15
10
5
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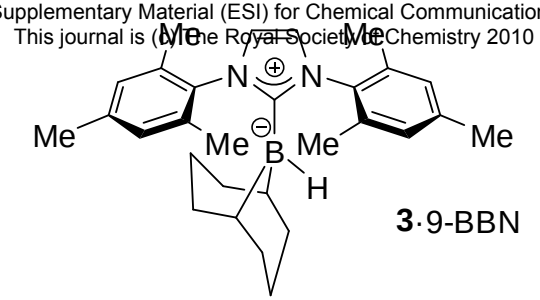
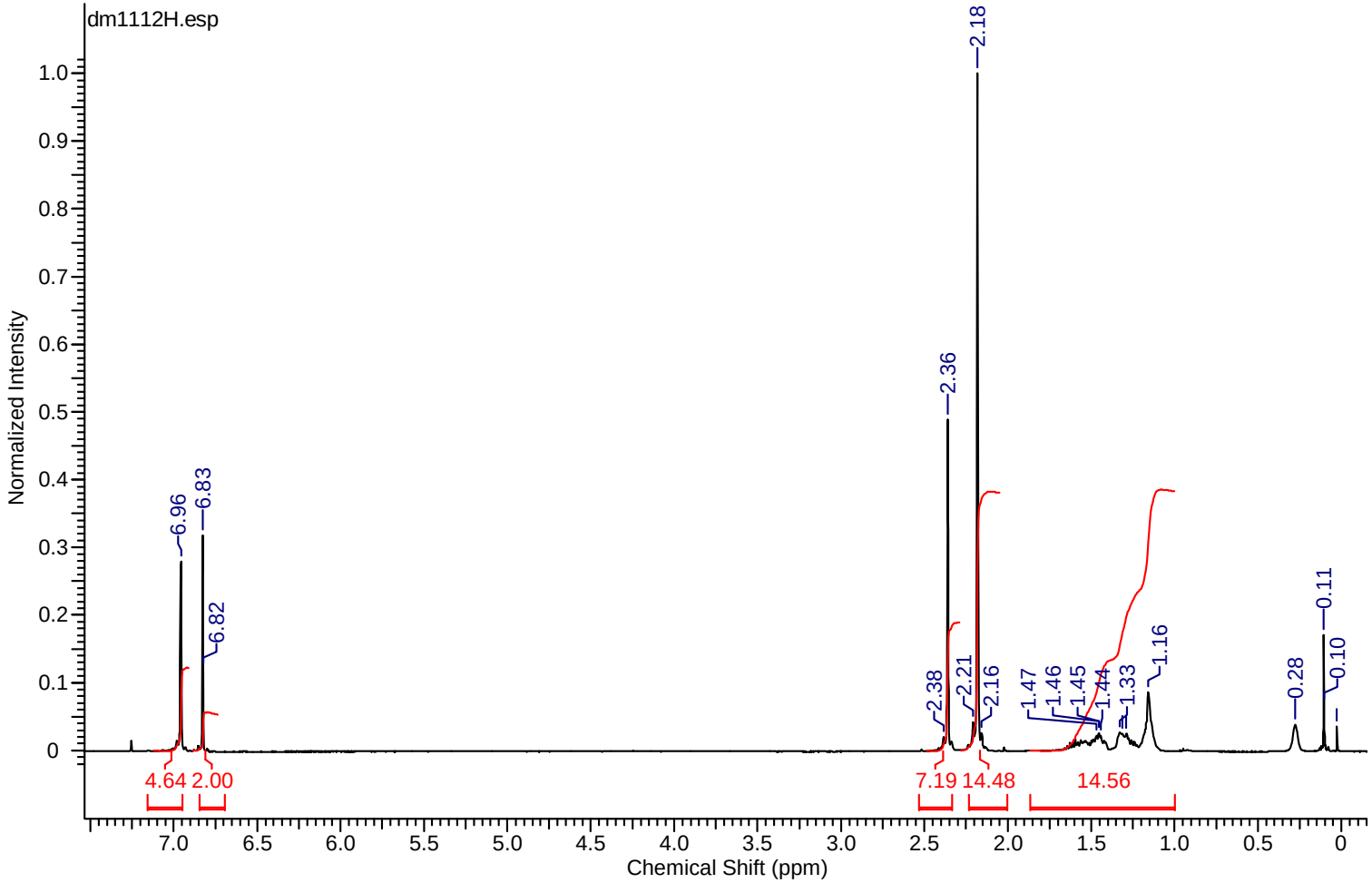
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
Chemical Shift (ppm)


Me
Me
N
N
Me
Me
Me
B
Me
H

3·9-BBN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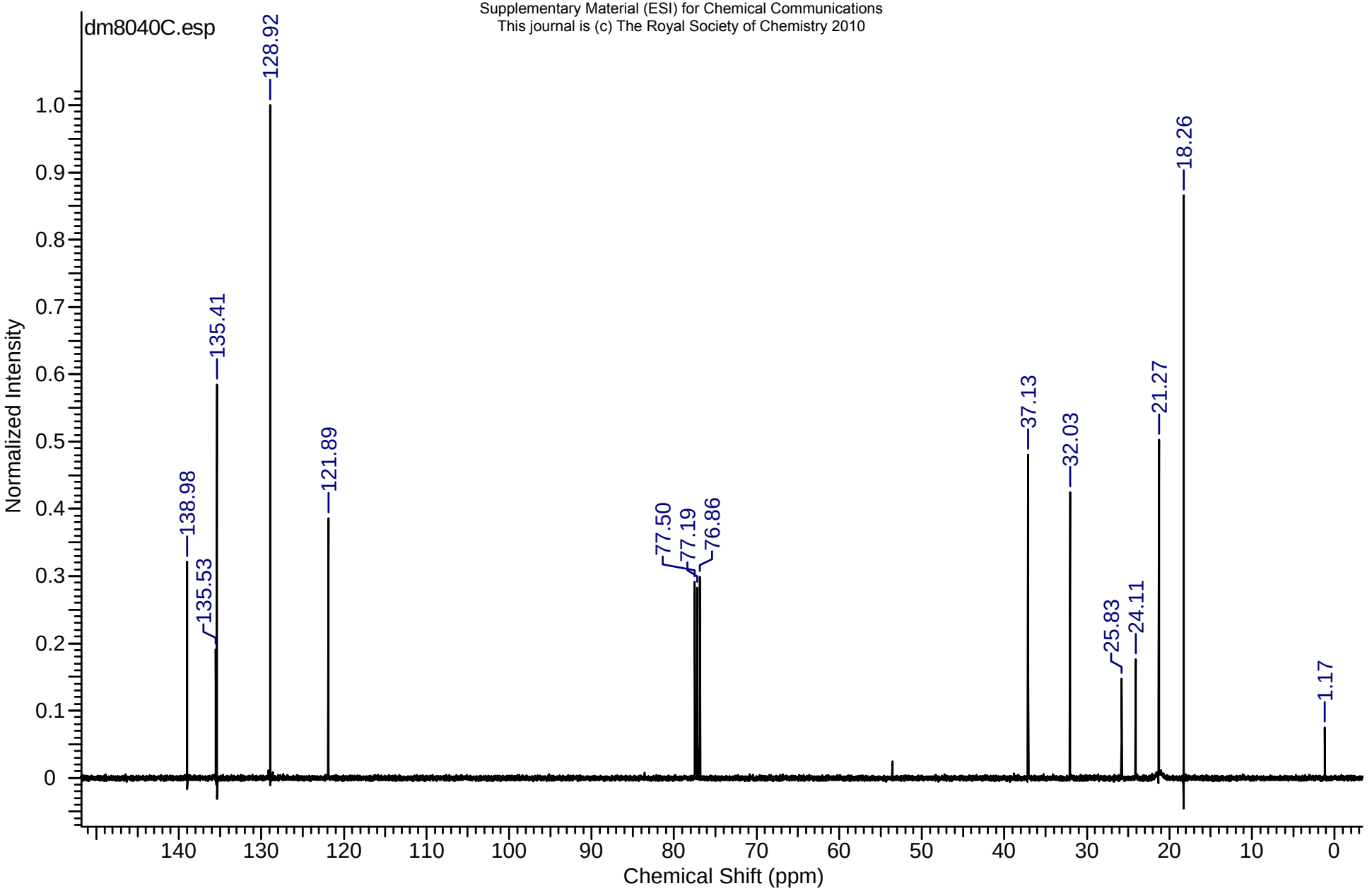
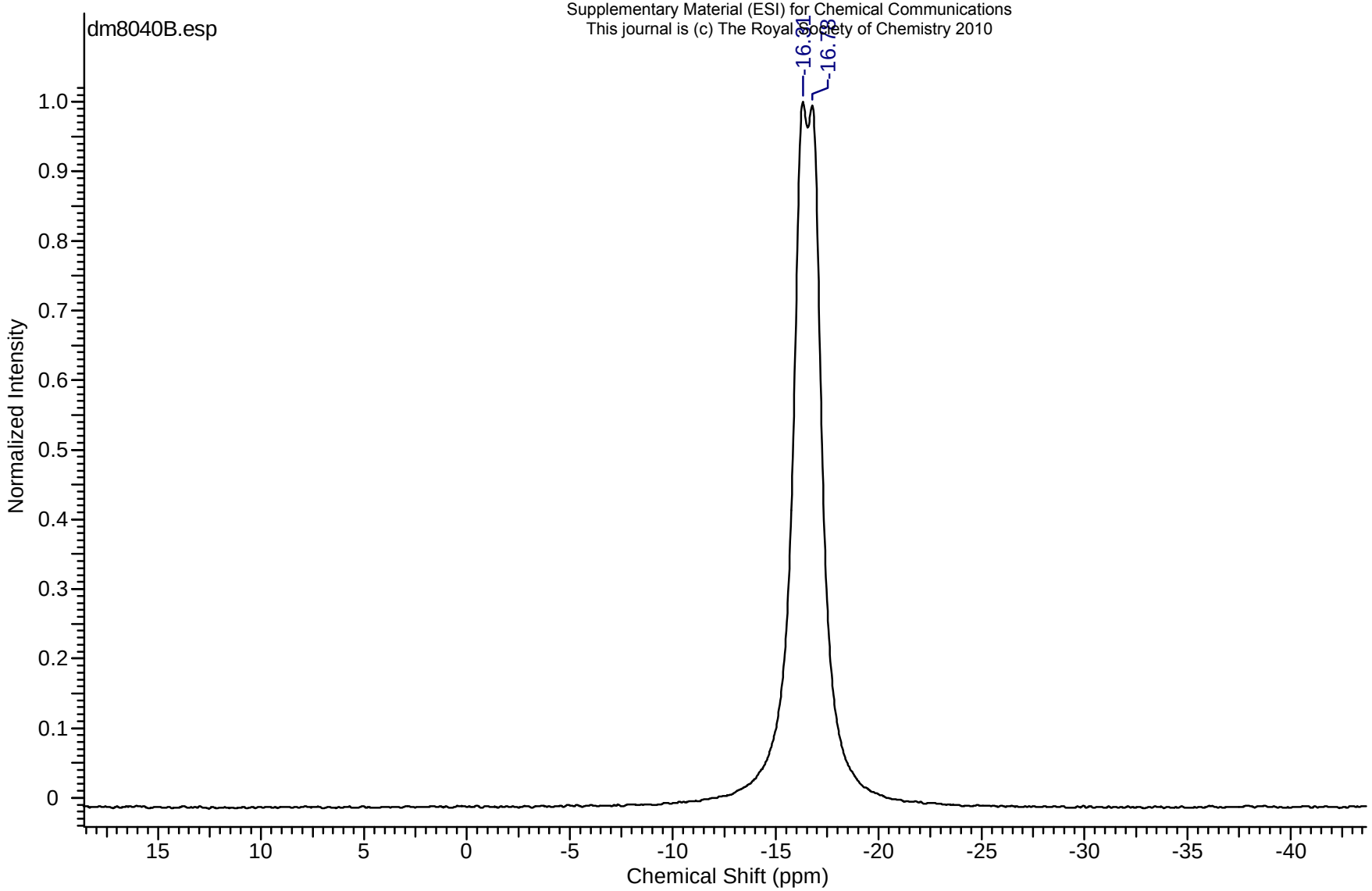
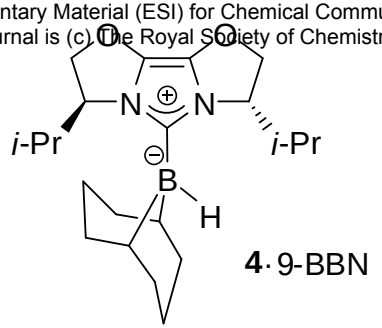
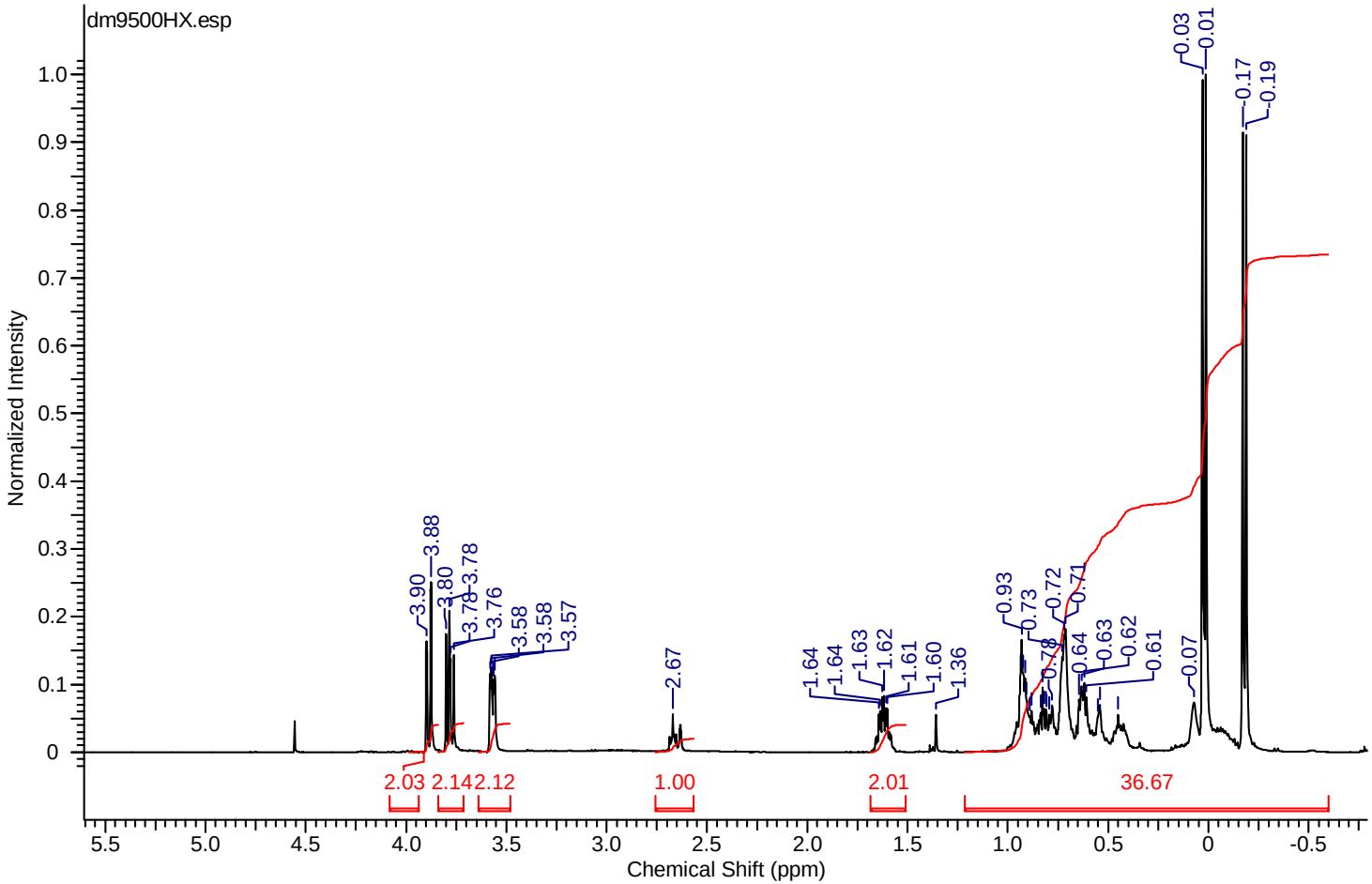
Normalized Intensity
Chemical Shift (ppm)
6.96
6.83
6.82
2.36
2.18
2.38
2.21
2.16
1.47
1.46
1.45
1.44
1.33
1.16
0.28
0.11
0.10
4.64
2.00
7.19
14.48
14.56


dm8040C.esp
128.92
135.41
138.98
135.53
121.89
77.50
77.19
76.86
37.13
32.03
25.83
24.11
21.27
18.26
1.17
Normalized Intensity
Chemical Shift (ppm)


dm8040B.esp
-16.791
Normalized Intensity
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
Chemical Shift (ppm)


O
O
N
N
i-Pr
i-Pr
B
H

4·9-BBN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Normalized Intensity
Chemical Shift (ppm)
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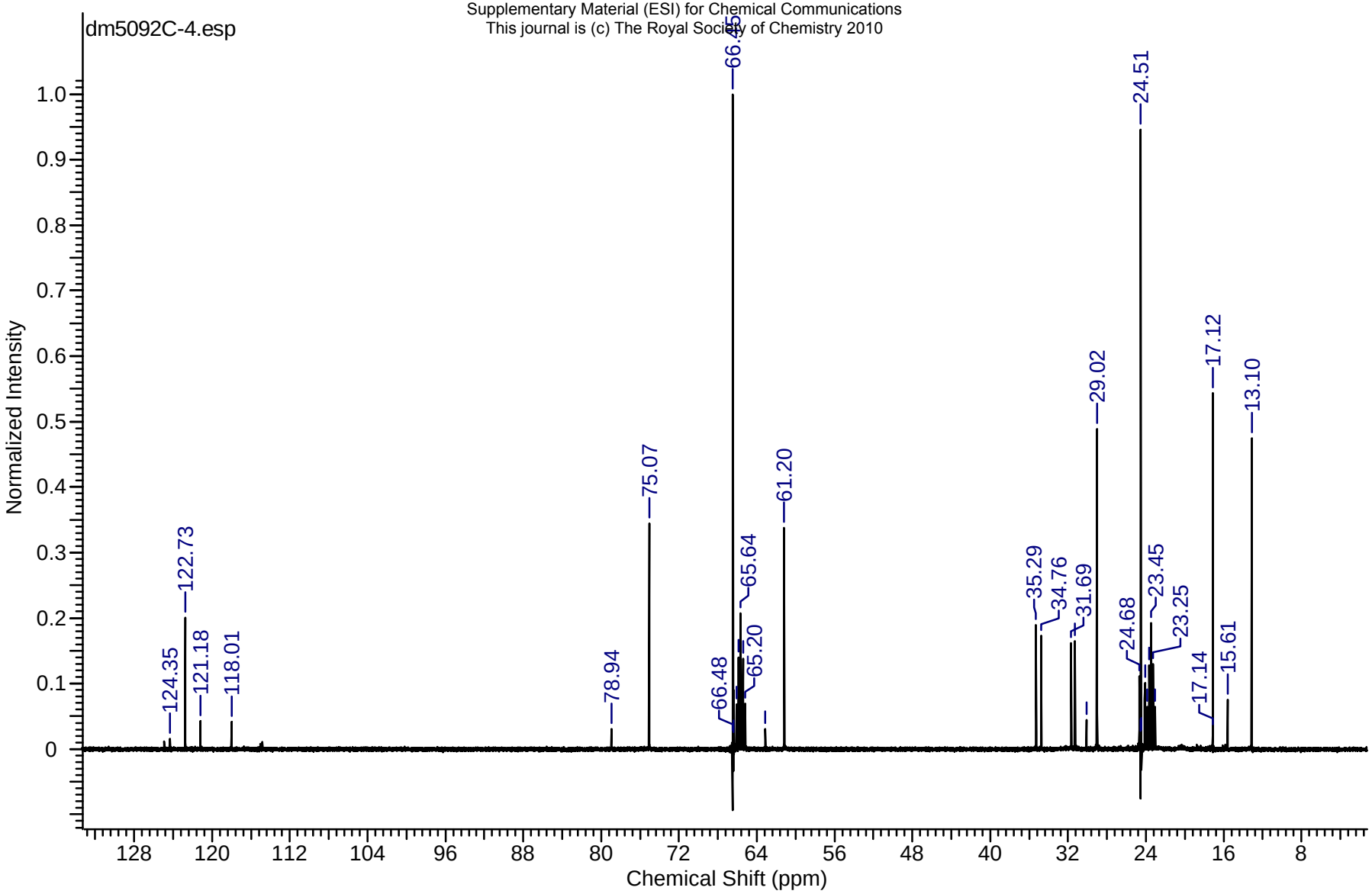
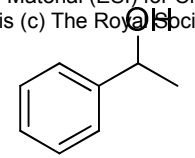
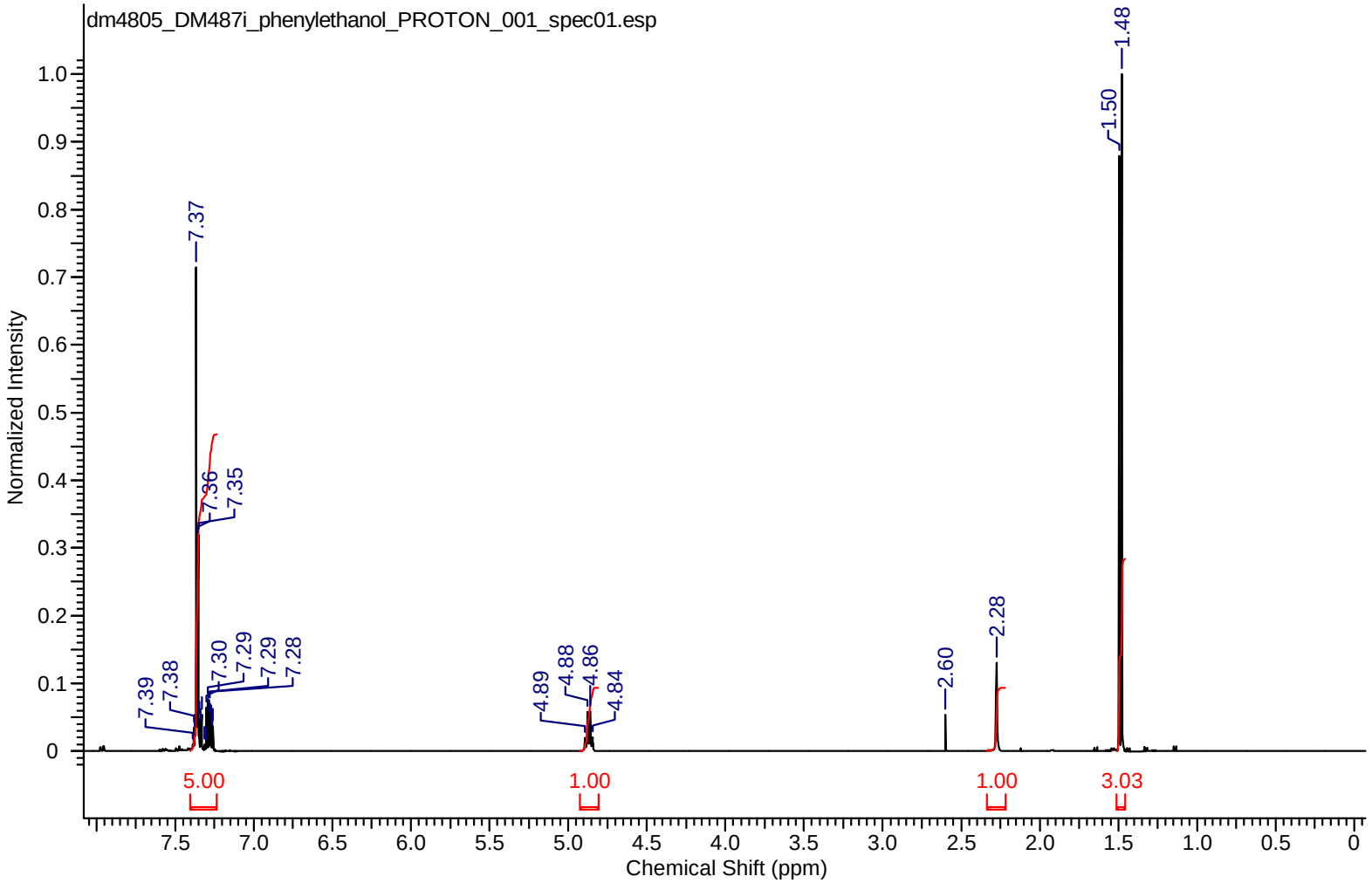
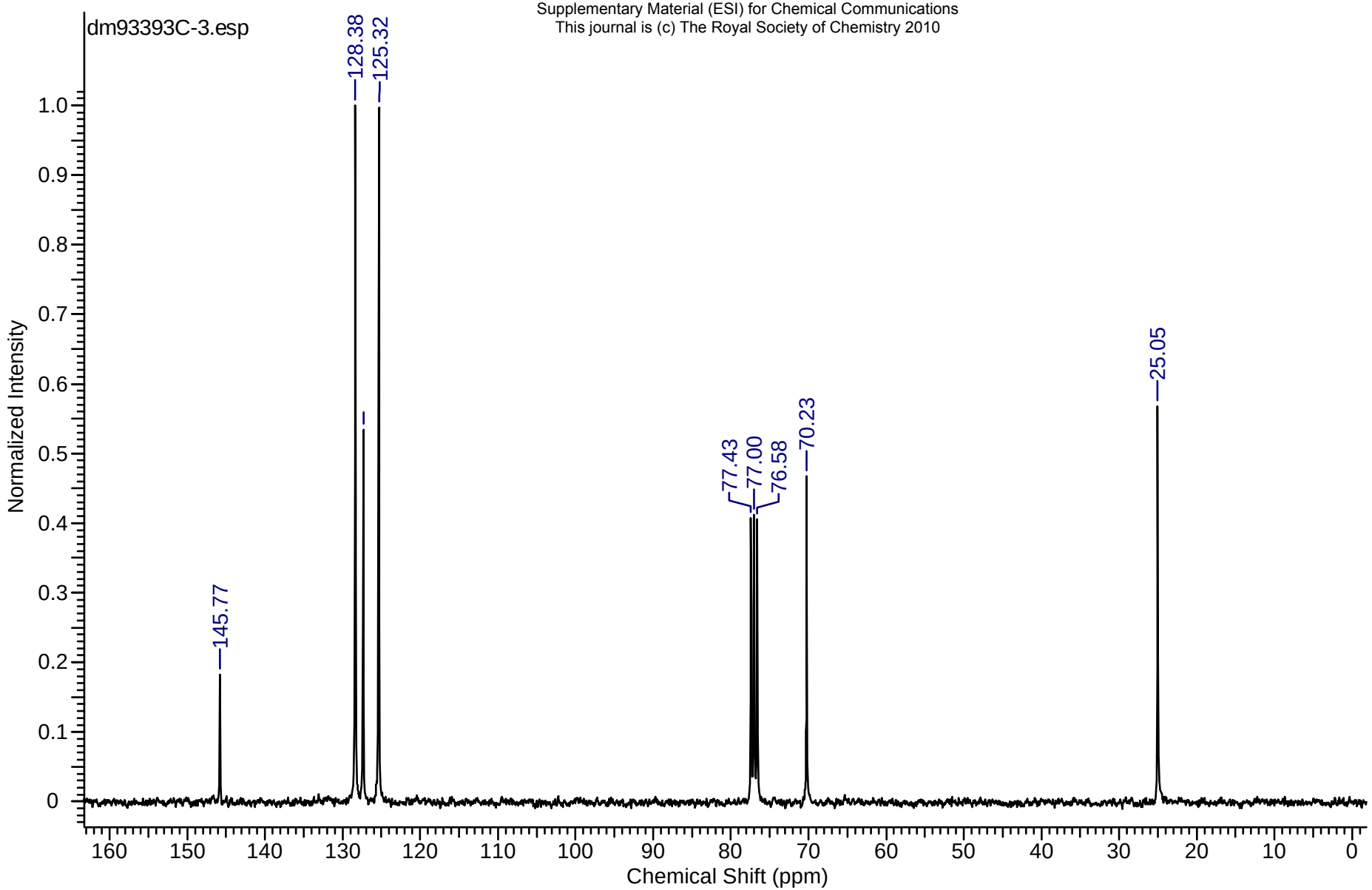
3.88
3.80
3.78
3.78
3.76
3.58
3.58
3.57
2.67
1.64
1.64
1.63
1.62
1.61
1.60
1.36
0.93
0.73
0.72
0.71
0.78
0.64
0.63
0.62
0.61
0.07
0.03
0.01
0.17
0.19
2.03
2.14
2.12
1.00
2.01
36.67

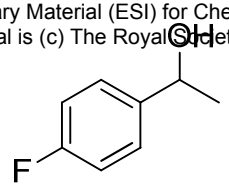

dm5092C-4.esp
Normalized Intensity
Chemical Shift (ppm)
66.49
24.51
75.07
61.20
29.02
17.12
13.10
122.73
124.35
121.18
118.01
78.94
66.48
65.64
65.20
35.29
34.76
31.69
24.68
23.45
23.25
17.14
15.61


OH

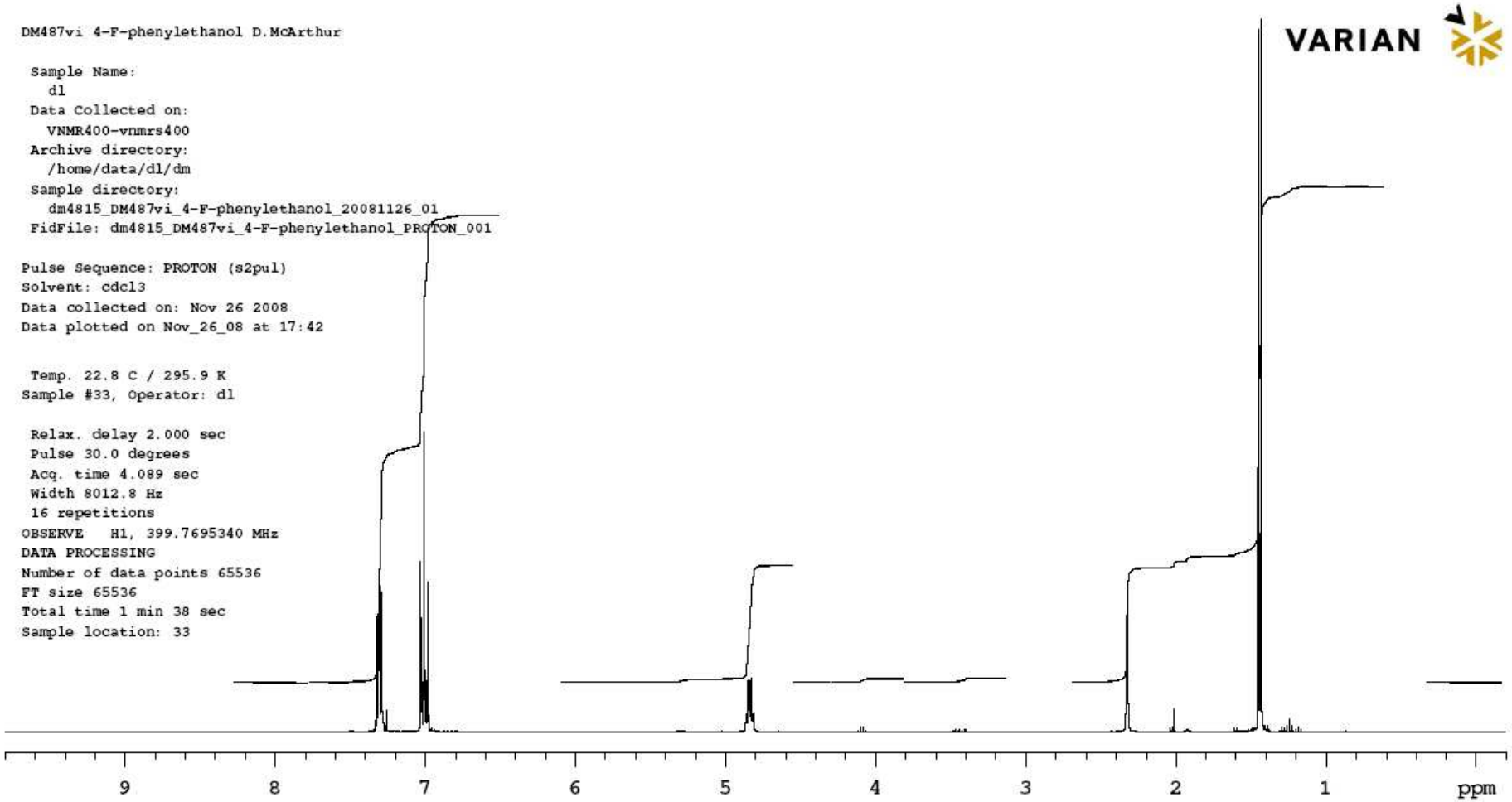
8a

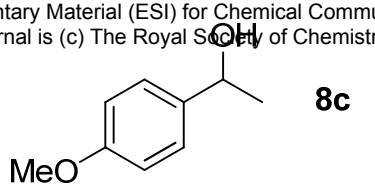

dm4805_DM487i_phenylethanol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.39
7.38
7.37
7.36
7.35
7.30
7.29
7.29
7.28
4.89
4.88
4.86
4.84
2.60
2.28
1.50
1.48
5.00
1.00
1.00
3.03


dm93393C-3.esp
128.38
125.32
145.77
77.43
77.00
76.58
70.23
25.05
Normalized Intensity
Chemical Shift (ppm)

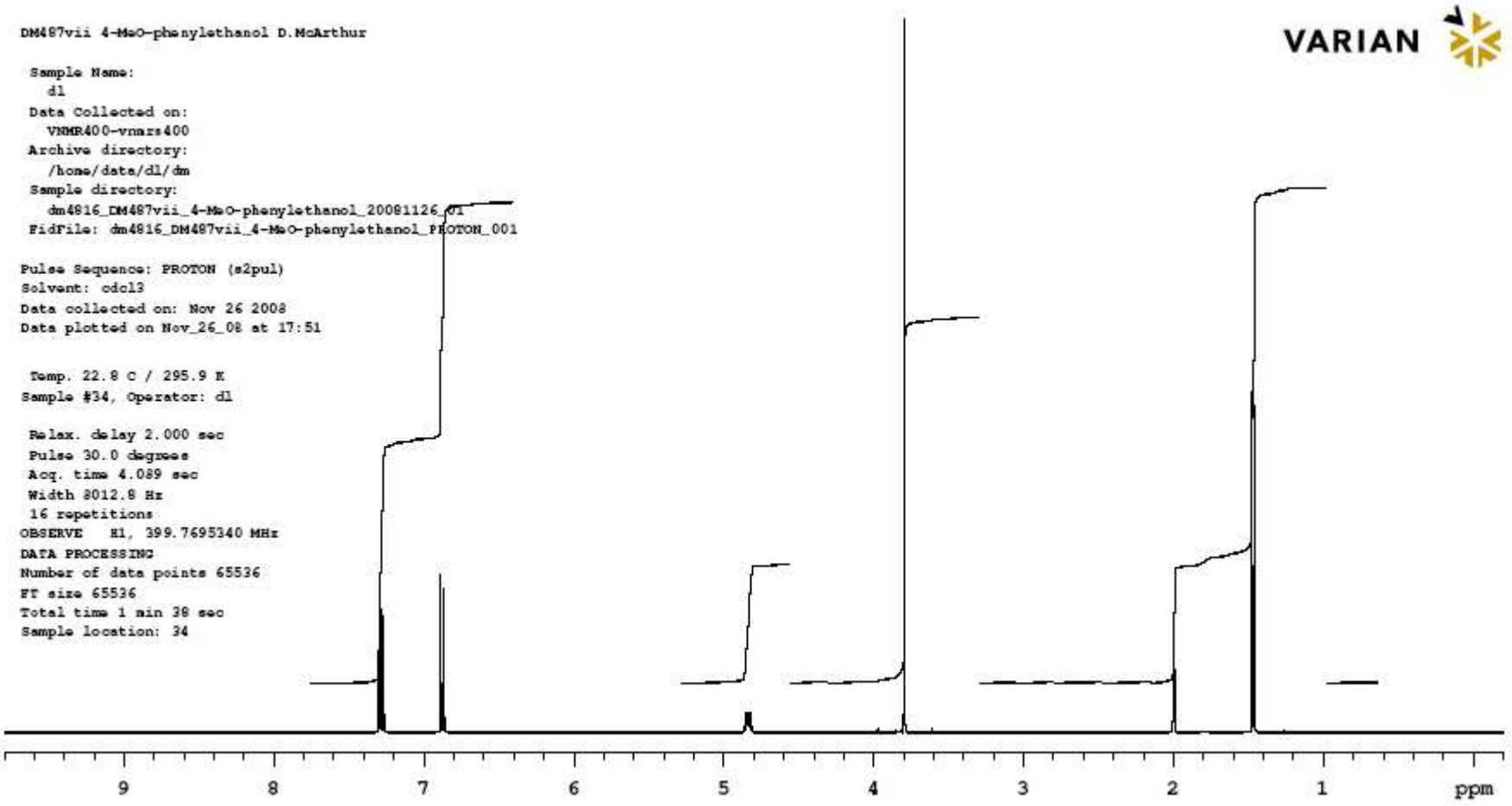

OH
F

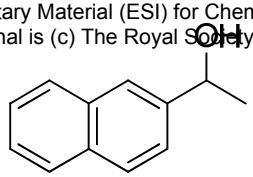
8b


DM487vi 4-F-phenylethanol D.McArthur
Sample Name:
dl
Data Collected on:
VNMR400-vnmrs400
Archive directory:
/home/data/dl/dm
Sample directory:
dm4815_DM487vi_4-F-phenylethanol_20081126_01
FidFile: dm4815_DM487vi_4-F-phenylethanol_PROTON_001
Pulse Sequence: PROTON (s2pul)
Solvent: cdcl3
Data collected on: Nov 26 2008
Data plotted on Nov_26_08 at 17:42
Temp. 22.8 C / 295.9 K
Sample #33, Operator: dl
Relax. delay 2.000 sec
Pulse 30.0 degrees
Acq. time 4.089 sec
Width 8012.8 Hz
16 repetitions
OBSERVE H1, 399.7695340 MHz
DATA PROCESSING
Number of data points 65536
FT size 65536
Total time 1 min 38 sec
Sample location: 33
VARIAN
9
8
7
6
5
4
3
2
1
ppm

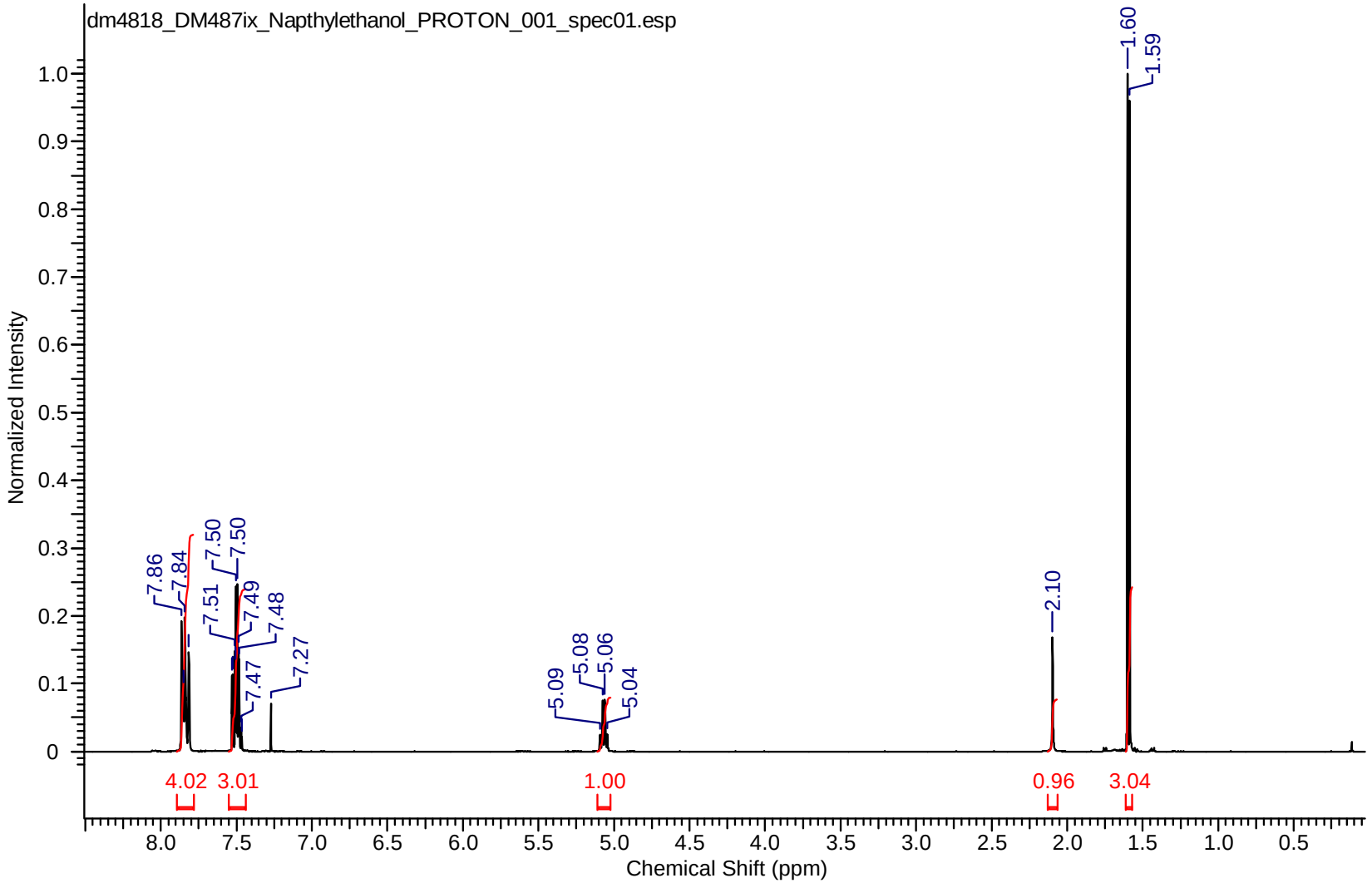

OH
MeO

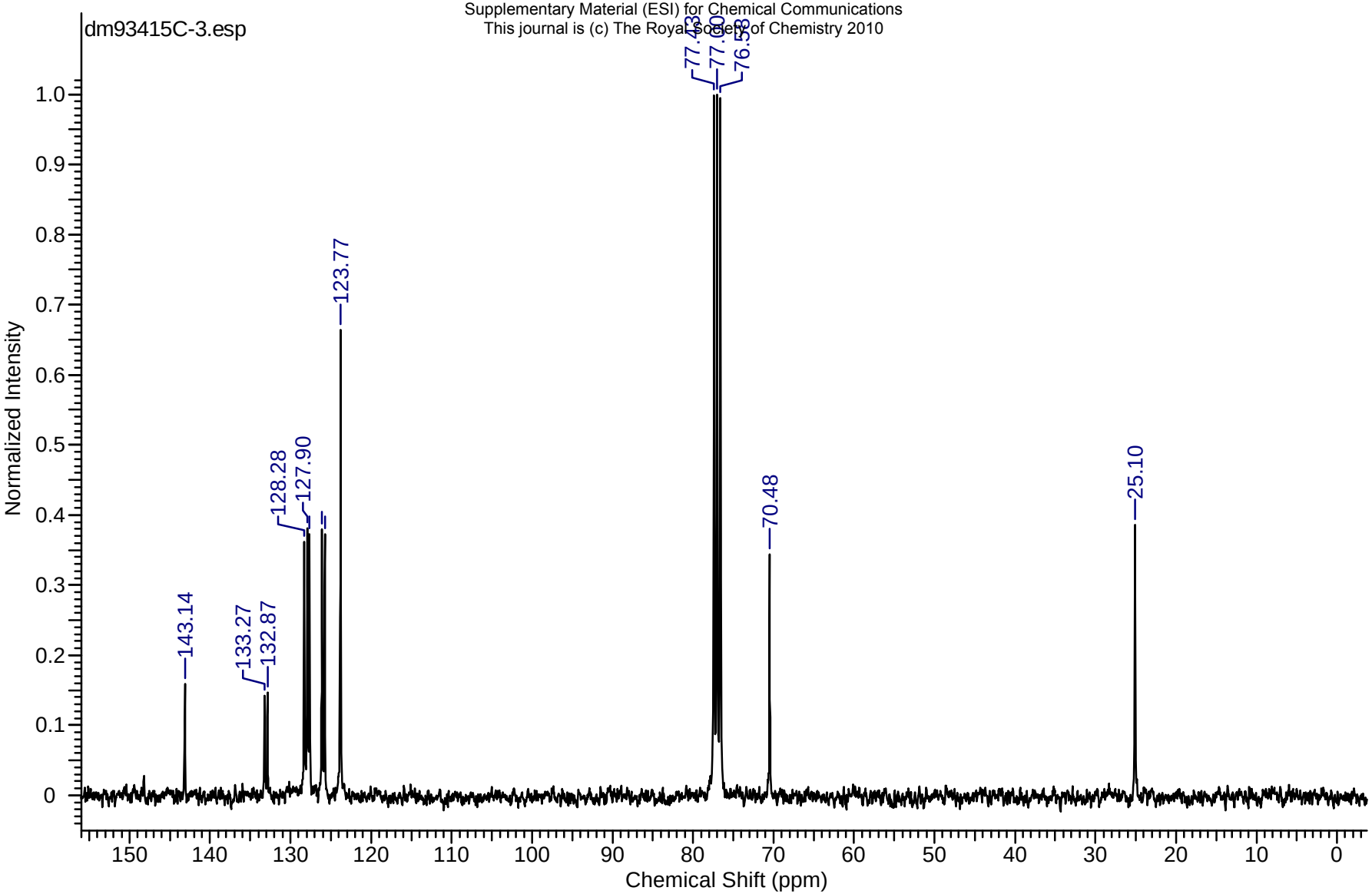
8c

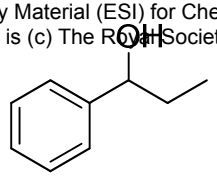

DM487vii 4-MeO-phenylethanol D.McArthur
Sample Name:
dl
Data Collected on:
VNMR400-vnmrs400
Archive directory:
/home/data/dl/dm
Sample directory:
dm4816_DM487vii_4-MeO-phenylethanol_20081126_01
FidFile: dm4816_DM487vii_4-MeO-phenylethanol_PROTON_001
Pulse Sequence: PROTON (s2pul)
Solvent: cdcl3
Data collected on: Nov 26 2008
Data plotted on Nov_26_08 at 17:51
Temp. 22.8 C / 295.9 K
Sample #34, Operator: dl
Relax. delay 2.000 sec
Pulse 30.0 degrees
Acq. time 4.089 sec
Width 8012.8 Hz
16 repetitions
OBSERVE H1, 399.7695340 MHz
DATA PROCESSING
Number of data points 65536
FT size 65536
Total time 1 min 38 sec
Sample location: 34
VARIAN
9
8
7
6
5
4
3
2
1
ppm


OH

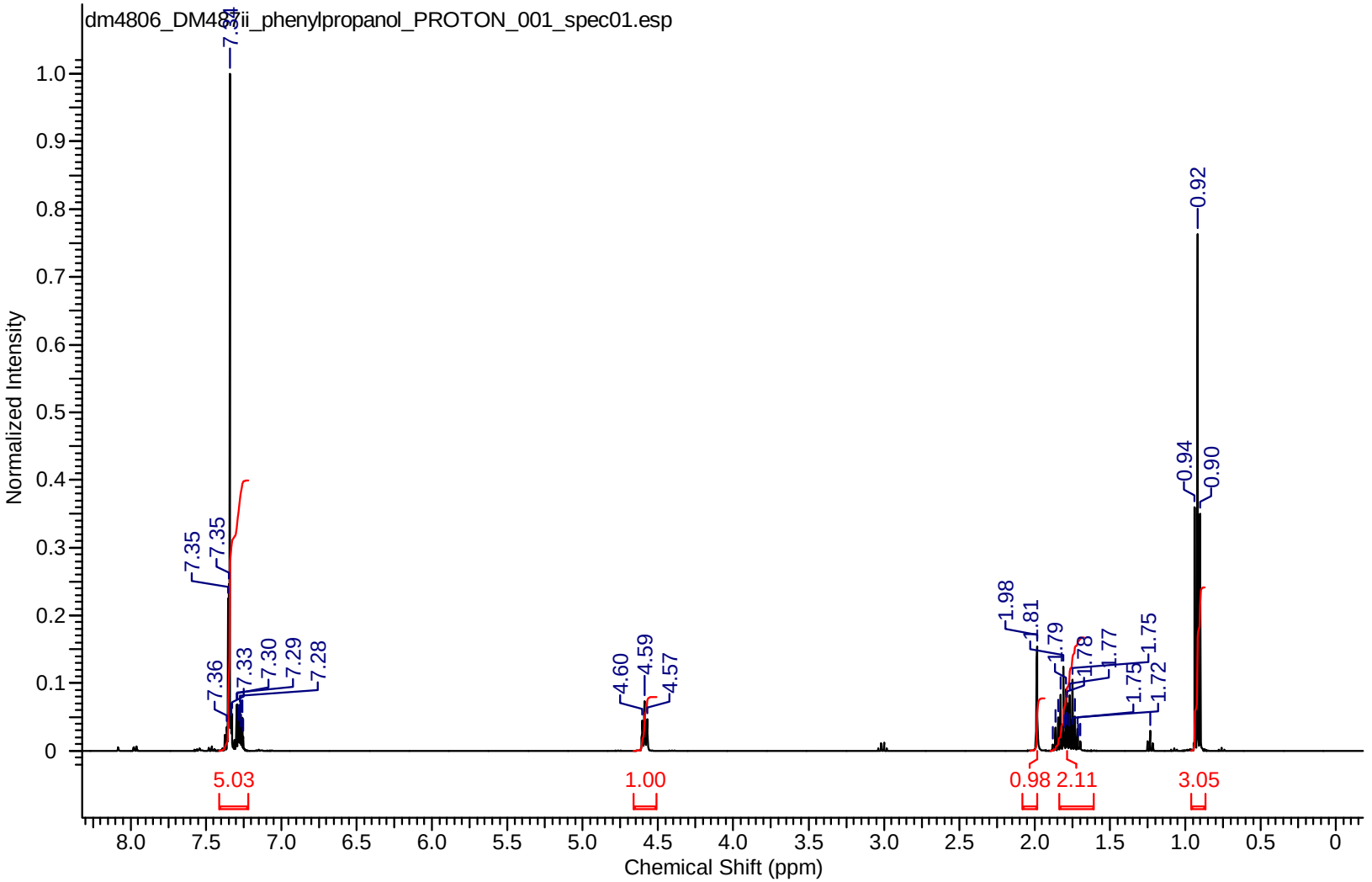
8d

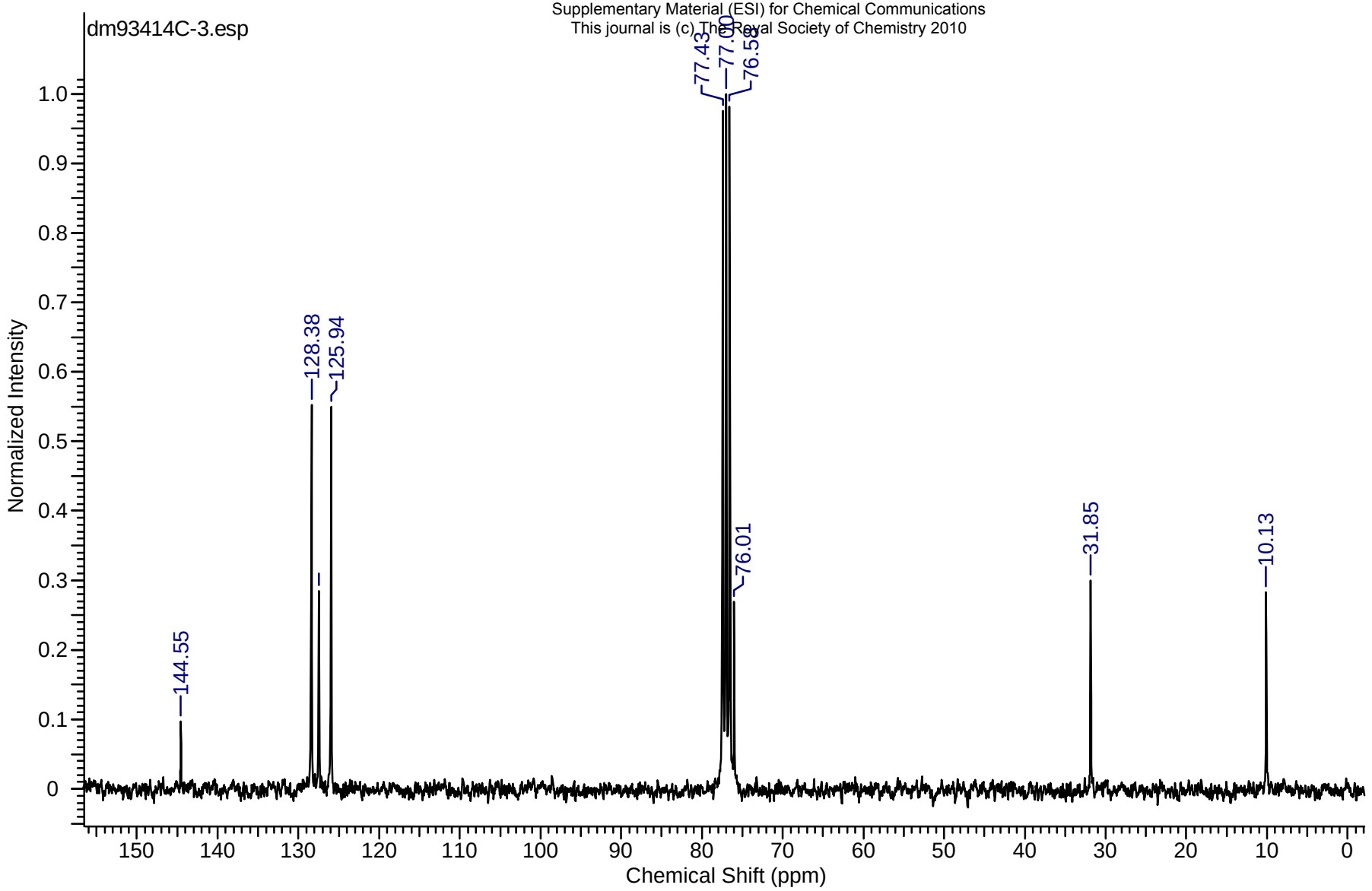

dm4818_DM487ix_Napthylethanol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.86
7.84
7.51
7.50
7.50
7.49
7.48
7.47
7.27
5.09
5.08
5.06
5.04
2.10
1.60
1.59
4.02
3.01
1.00
0.96
3.04

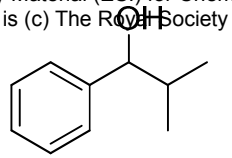

dm93415C-3.esp
Normalized Intensity
Chemical Shift (ppm)
143.14
133.27
132.87
128.28
127.90
123.77
77.48
77.00
76.58
70.48
25.10



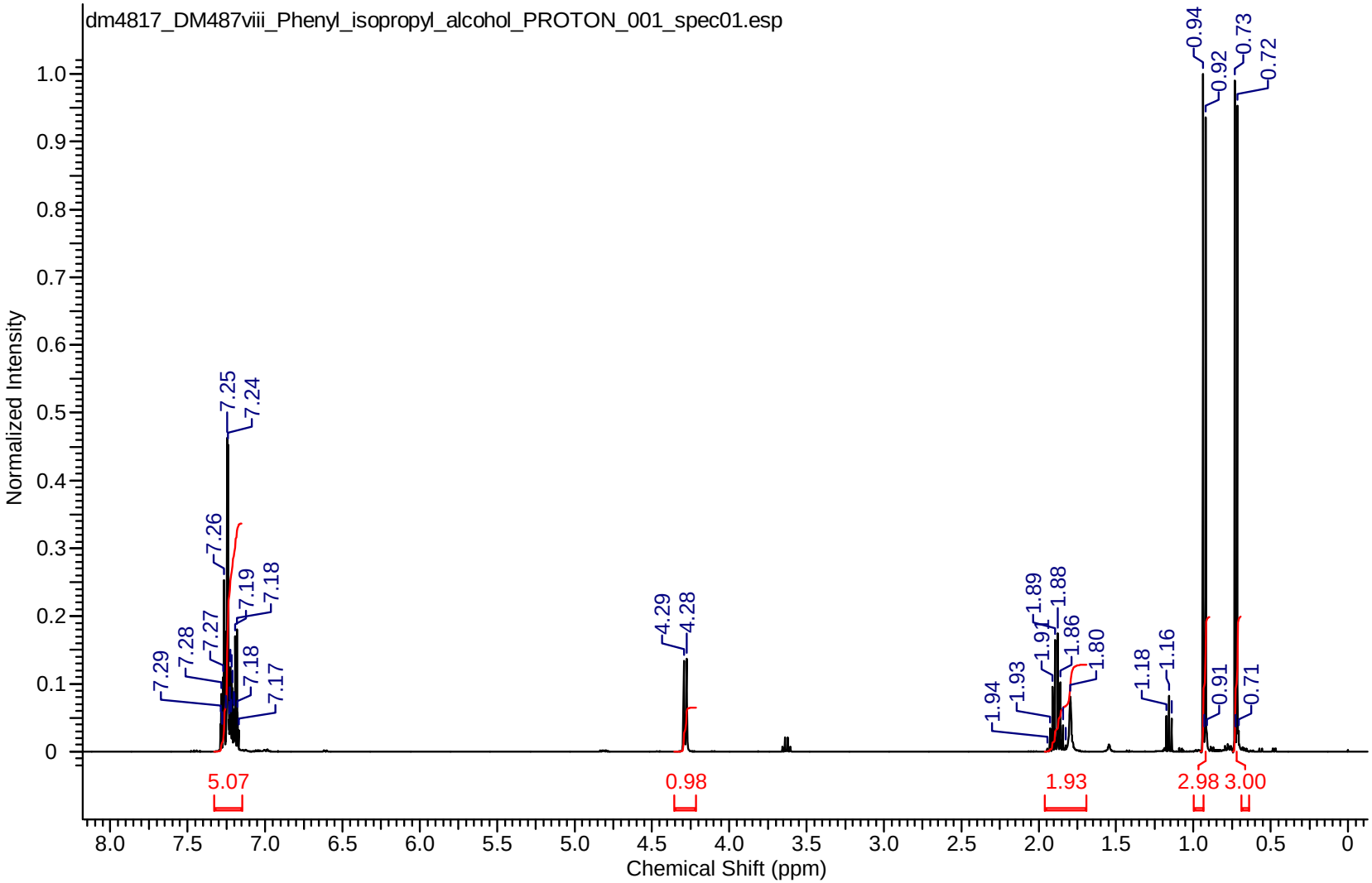
8e

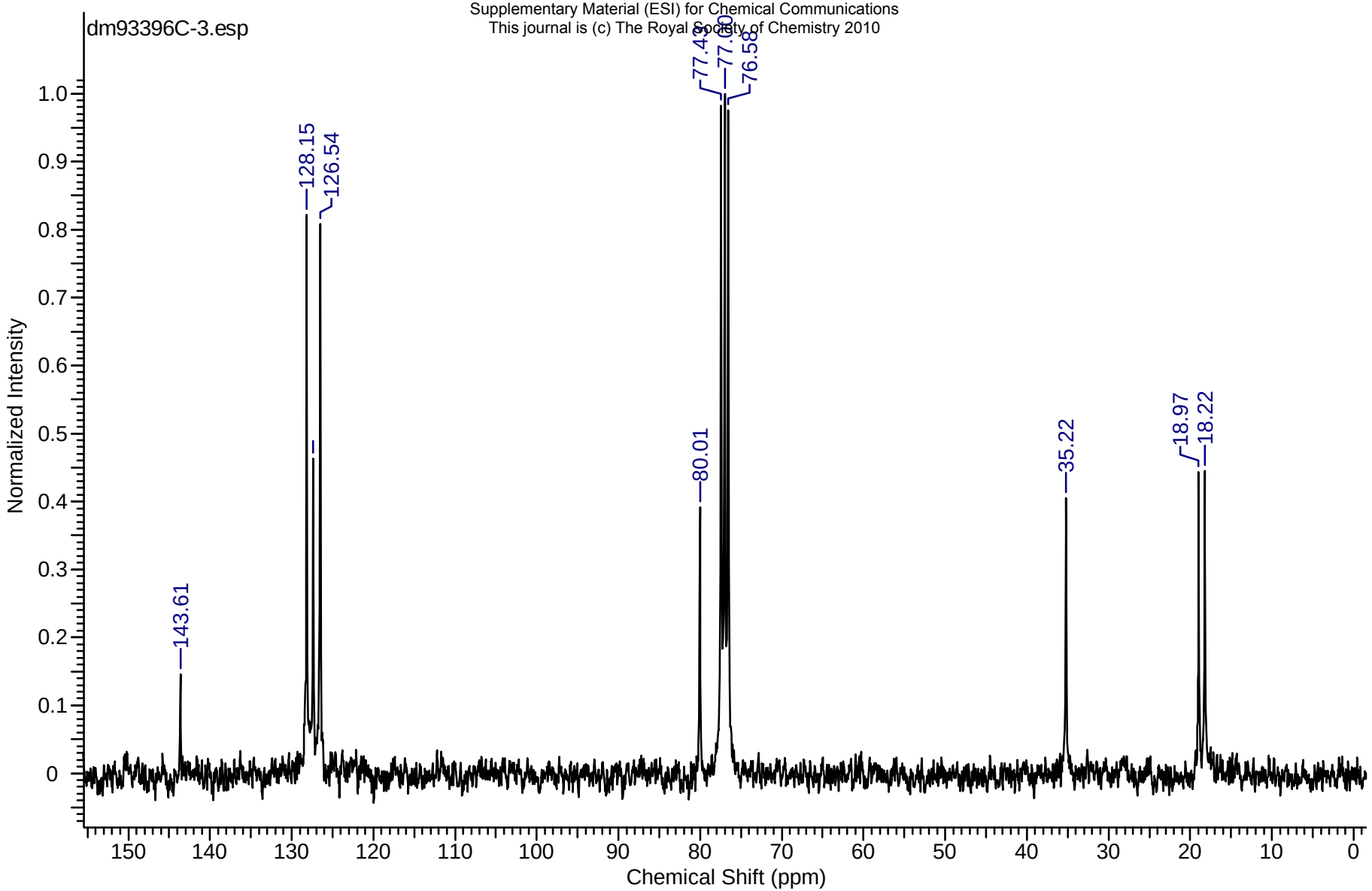

dm4806_DM483ii_phenylpropanol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.34
7.35
7.35
7.36
7.33
7.30
7.29
7.28
4.60
4.59
4.57
1.98
1.81
1.79
1.78
1.77
1.75
1.75
1.72
0.94
0.92
0.90
5.03
1.00
0.98
2.11
3.05

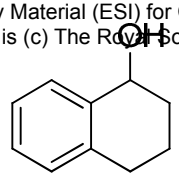

dm93414C-3.esp
Normalized Intensity
Chemical Shift (ppm)
144.55
128.38
125.94
77.43
77.00
76.58
76.01
31.85
10.13



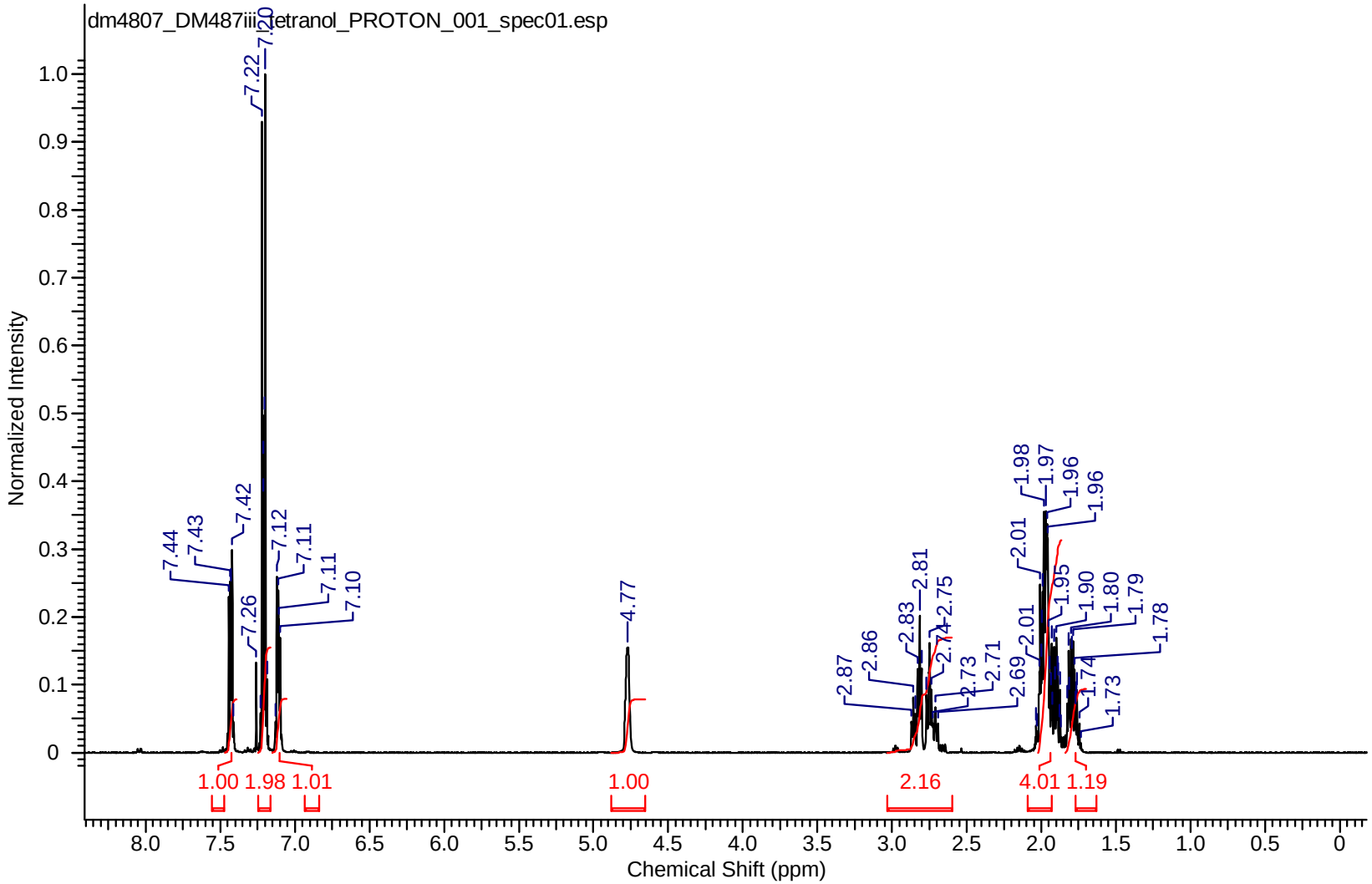
8f

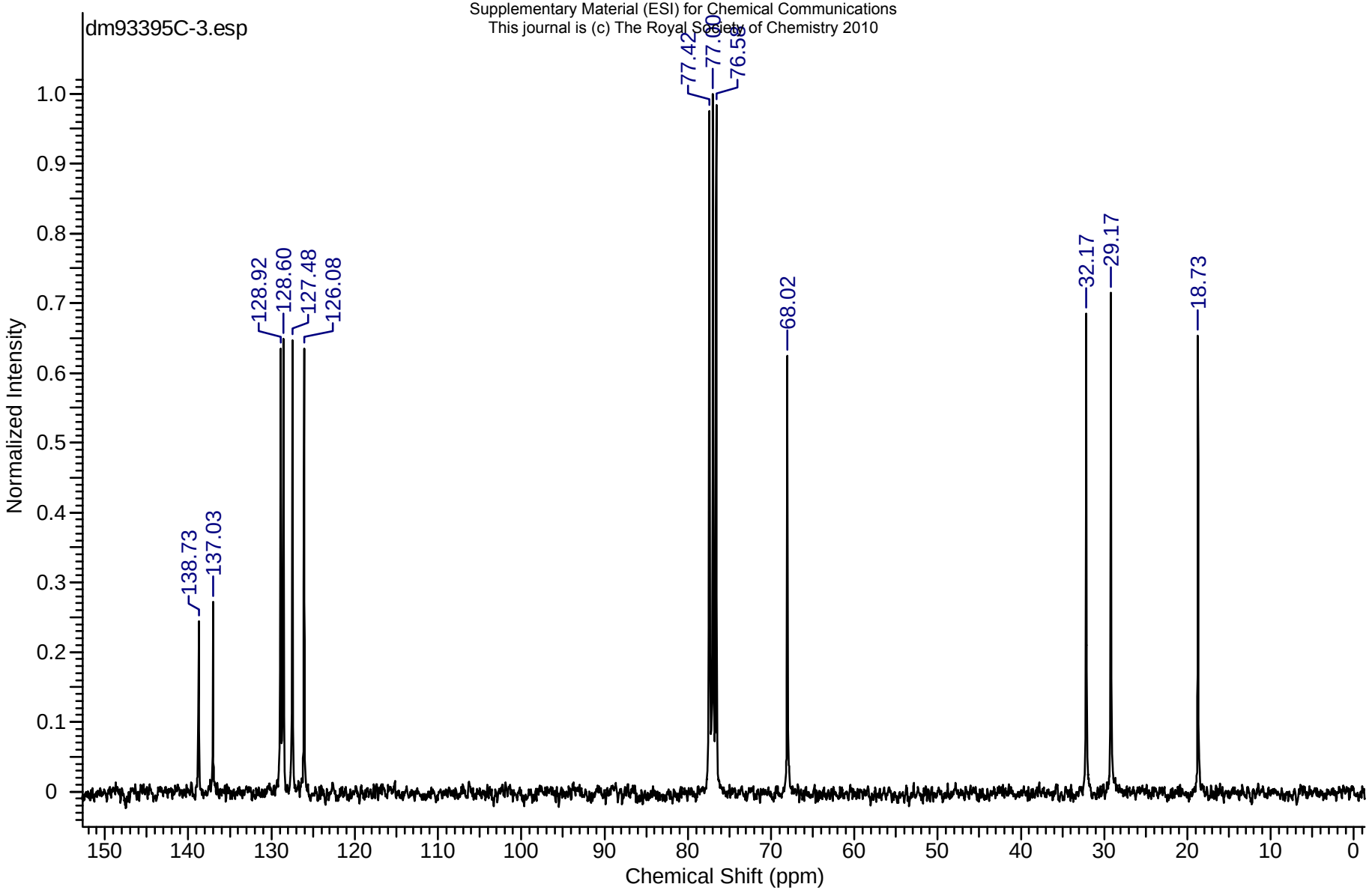

dm4817_DM487viii_Phenyl_isopropyl_alcohol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.29
7.28
7.27
7.26
7.25
7.24
7.19
7.18
7.18
7.17
4.29
4.28
1.94
1.93
1.91
1.89
1.88
1.86
1.80
1.18
1.16
0.94
0.92
0.91
0.73
0.72
0.71
5.07
0.98
1.93
2.98
3.00

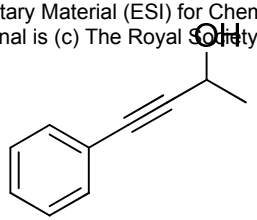

dm93396C-3.esp
Normalized Intensity
Chemical Shift (ppm)
143.61
128.15
126.54
80.01
77.41
77.00
76.58
35.22
18.97
18.22



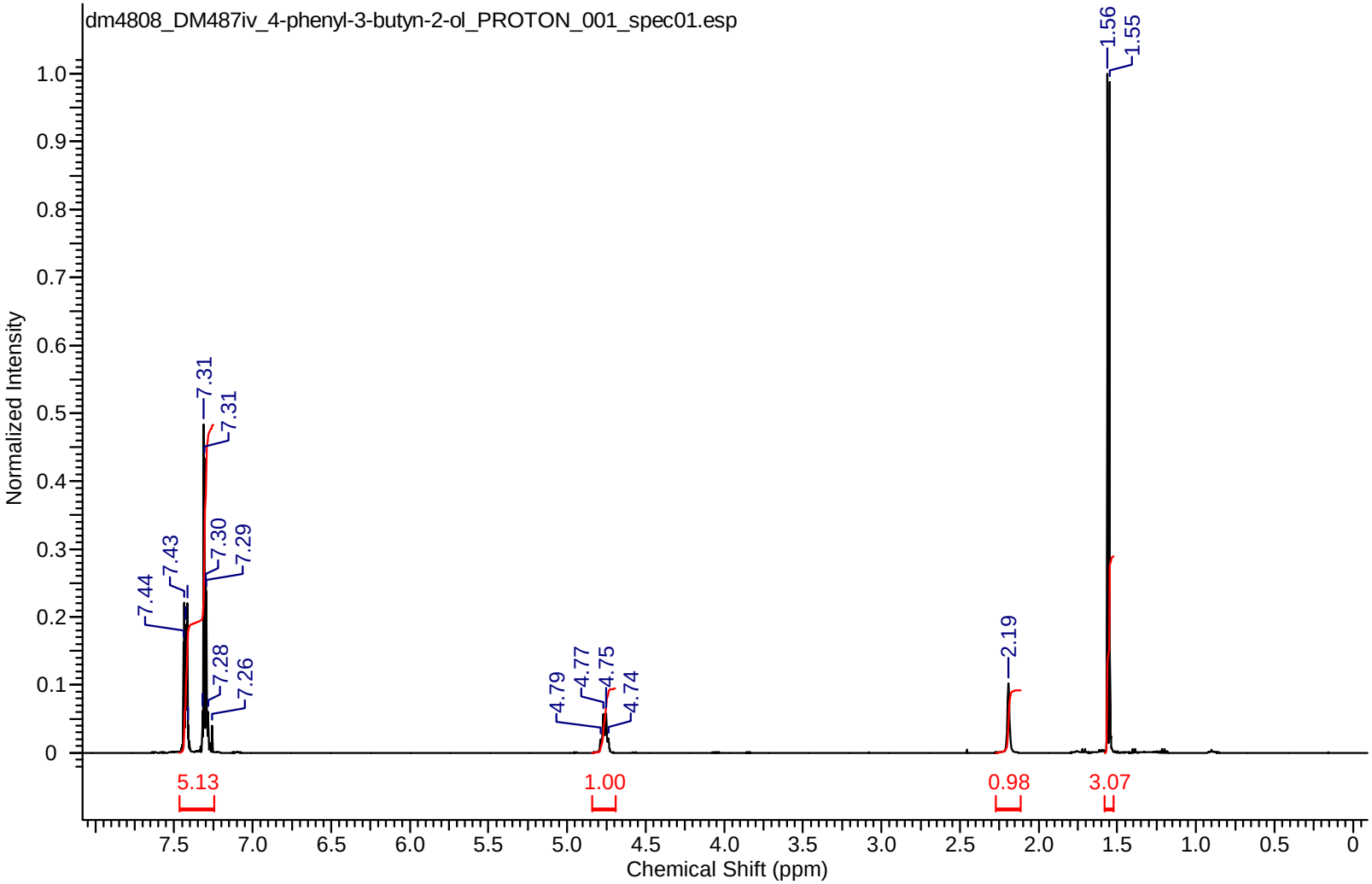
8g

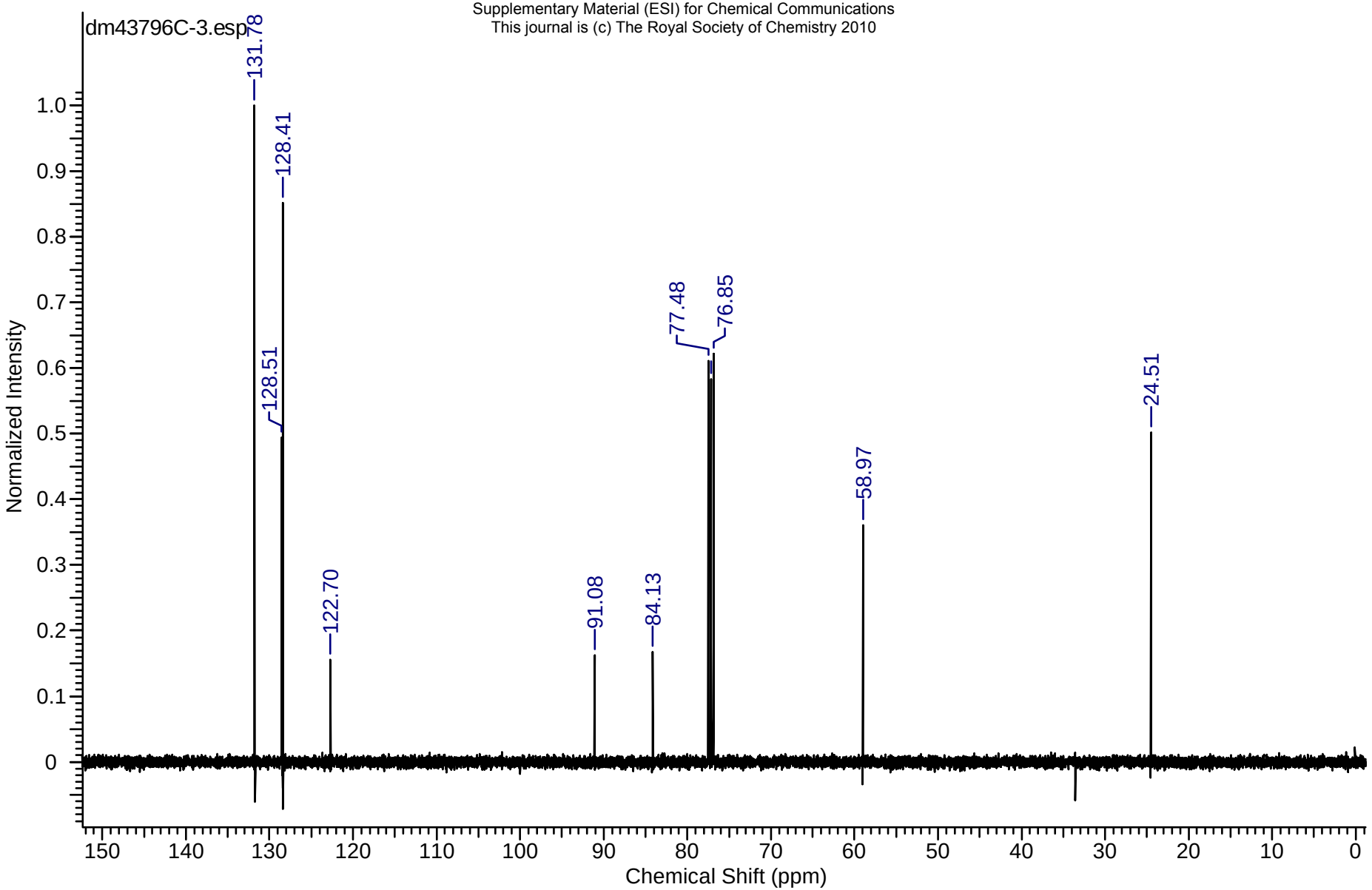

dm4807_DM487iii_tetranol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.44
7.43
7.42
7.26
7.22
7.20
7.12
7.11
7.11
7.10
4.77
2.87
2.86
2.83
2.81
2.75
2.74
2.73
2.71
2.69
2.01
2.01
1.98
1.97
1.96
1.96
1.95
1.90
1.80
1.79
1.78
1.74
1.73
1.00
1.98
1.01
1.00
2.16
4.01
1.19

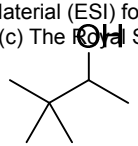

dm93395C-3.esp
Normalized Intensity
Chemical Shift (ppm)
138.73
137.03
128.92
128.60
127.48
126.08
77.42
77.00
76.58
68.02
32.17
29.17
18.73



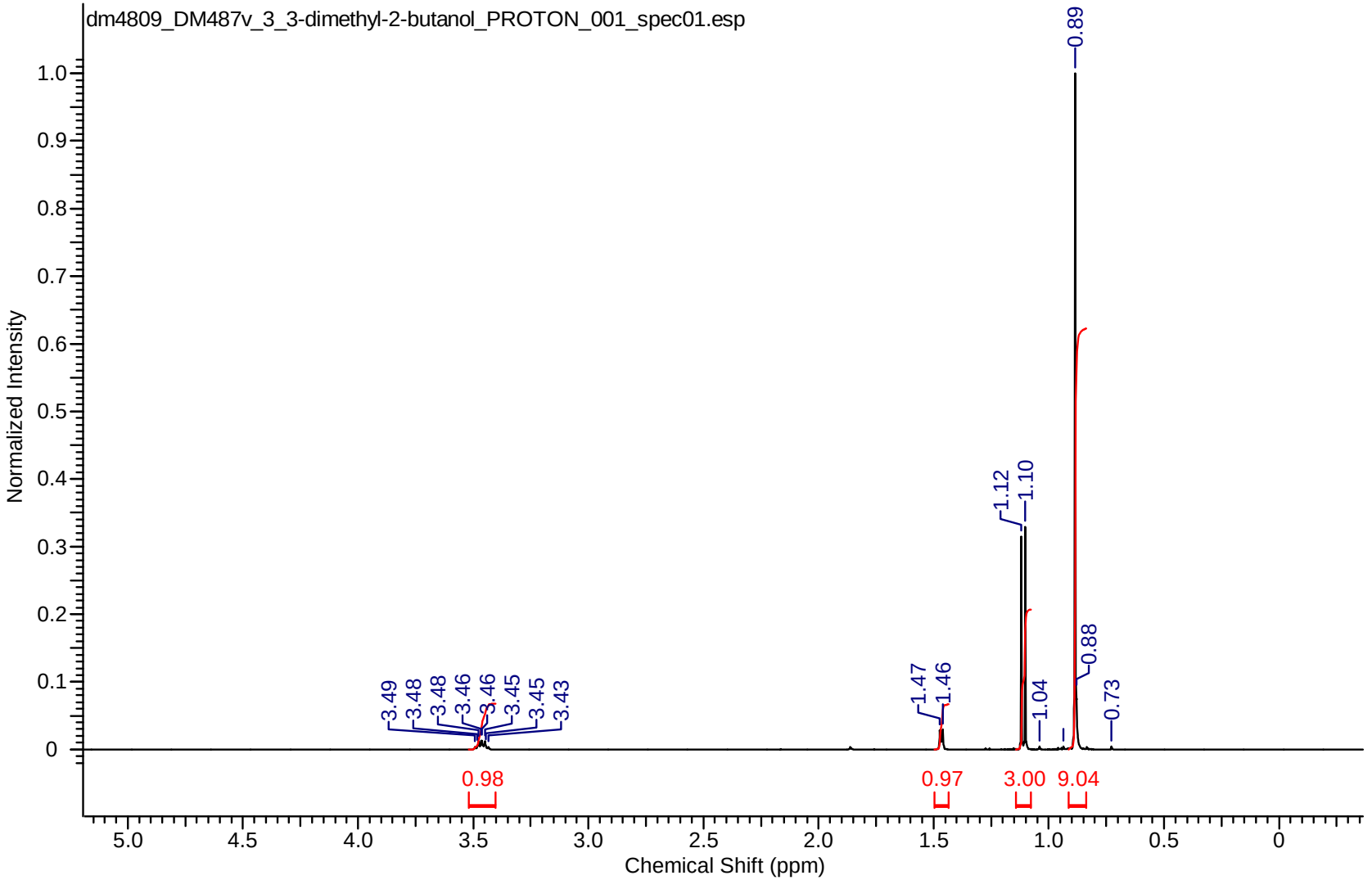
8h

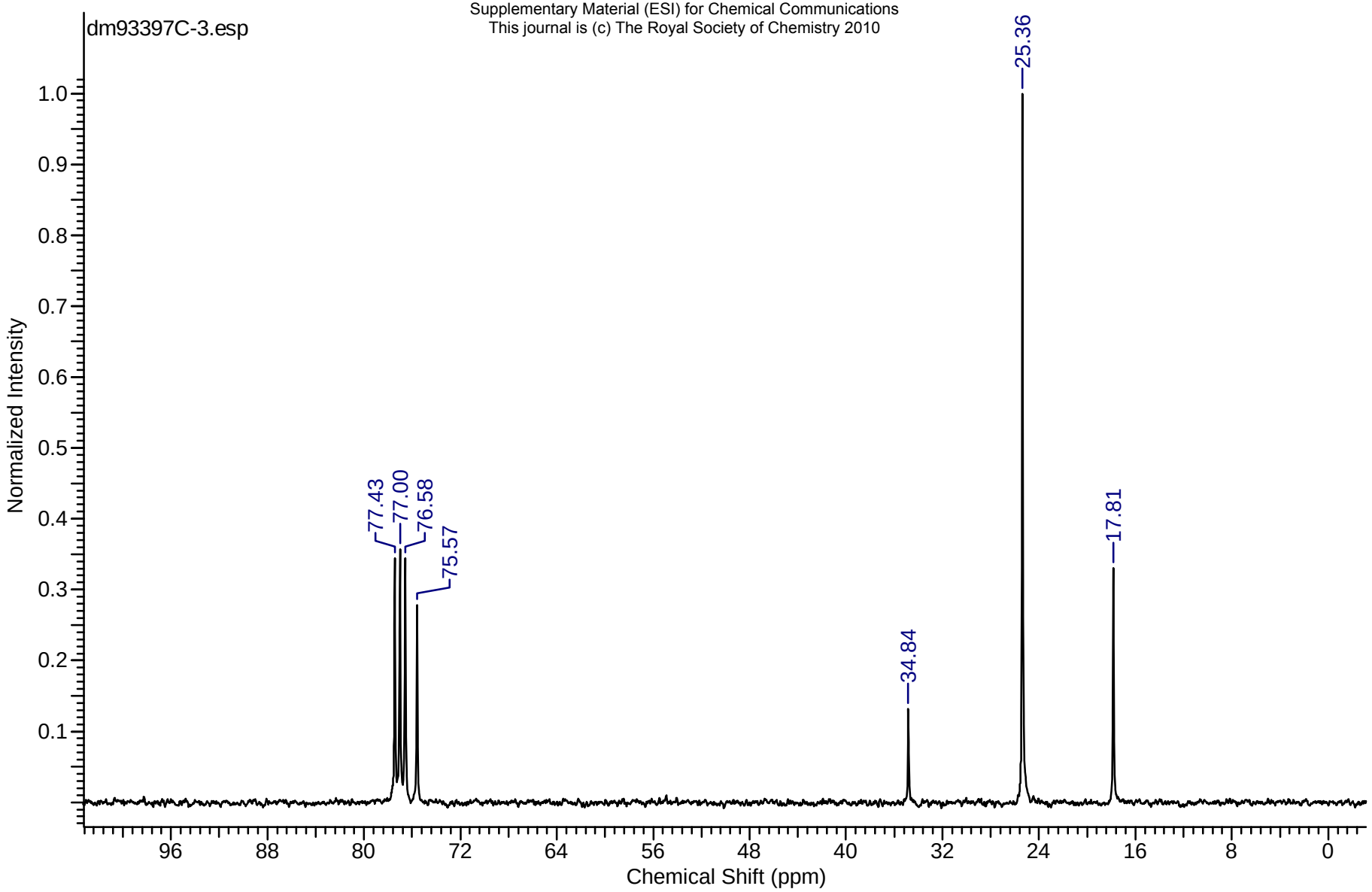

dm4808_DM487iv_4-phenyl-3-butyn-2-ol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
7.44
7.43
7.31
7.31
7.30
7.29
7.28
7.26
4.79
4.77
4.75
4.74
2.19
1.56
1.55
5.13
1.00
0.98
3.07


dm43796C-3.esp
131.78
128.41
128.51
122.70
91.08
84.13
77.48
76.85
58.97
24.51
Normalized Intensity
Chemical Shift (ppm)



8i


dm4809_DM487v_3_3-dimethyl-2-butanol_PROTON_001_spec01.esp
Normalized Intensity
Chemical Shift (ppm)
3.49
3.48
3.48
3.46
3.46
3.45
3.45
3.43
1.47
1.46
1.12
1.10
1.04
0.89
0.88
0.73
0.98
0.97
3.00
9.04


dm93397C-3.esp
Normalized Intensity
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
77.43
77.00
76.58
75.57
34.84
25.36
17.81
96
88
80
72
64
56
48
40
32
24
16
8
0
Chemical Shift (ppm)

4. References

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