Relationship between the conformational degree of freedom of template-containing threads and slippage in the formation of [2]rotaxane building-blocks

B. Riss-Yaw, C. Clavel, Ph. Laurent and F. Coutrot*

Supramolecular **M**achines and **AR**chitectures **T**eam, Institut des Biomolécules Max Mousseron (IBMM) UMR 5247 CNRS, Université Montpellier, ENSCM, case courrier 1706, Bâtiment Chimie (17), 3ème étage, Faculté des Sciences, Place Eugène Bataillon 34095 Montpellier cedex 5, France.

Tél : (+) 33 4 67 14 38 43 - Fax: (+) 33 4 67 63 10 46

E-mail: frederic.coutrot@univ-montp2.fr, homepage: www.glycorotaxane.fr

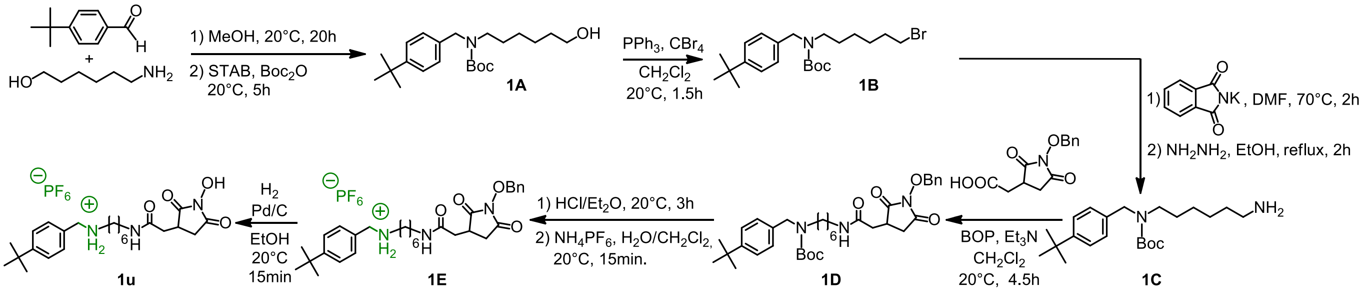
Table of contents

1. General methods

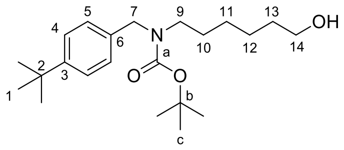
All reactions were carried out under an atmosphere of argon unless otherwise indicated. All reagents were used as received without further purification. Dichloromethane was distilled over P_2O_5 and was degassed by bubbling Ar for 20 min. Analytical thin-layer chromatography (TLC) was performed on silica gel 60 F254 plates. Compounds were visualized by dipping the plates in an ethanolic solution of 10% sulphuric acid, ninhydrine or an aqueous solution of $KMnO_4$, followed by heating. ^{1}H NMR and ^{13}C NMR spectra were obtained on a spectrometer (respectively at 600.27, 500.17 or 400.13 MHz and 150.94, 125.77 or 100.62 MHz). Chemical shifts of ^{1}H NMR and ^{13}C NMR are given by using $CHCl_3$, CH_2Cl_2 and CH_3CN as references (7.27 ppm, 5.32 ppm, and 1.94 ppm respectively for ^{1}H spectrum, and 77.0 ppm, 54.0 ppm, and 118.26 ppm respectively for ^{13}C spectrum). ^{1}H assignments were deduced from 2D ^{1}H-^{1}H NMR COSY experiments. ^{13}C assignments were deduced from 2D ^{13}C-^{1}H NMR HSQC experiments. Coupling constants (J) are reported in hertz (Hz). Standard abbreviations indicating multiplicity were used as follows: s (singlet), br (broad), d (doublet), t (triplet), q (quartet), quint (quintuplet), m (multiplet). Mass spectra (MS) and high-resolution mass spectra (HRMS) were recorded respectively on a ZQ Micromass apparatus and a Q-TOF Micro apparatus.

2. Synthesis of the semi rotaxane 1

2.1. General synthetic pathway of molecular axle 1u



2.2. Synthesis of the *N*-carbamoylated alcohol 1A



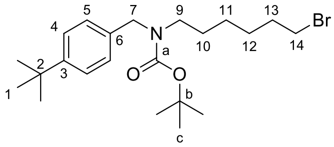
1A

A solution of 4-*tert*-butylbenzaldehyde (4.18 mL, 25 mmol, 1 equiv.) and 6-aminohexanol (3.42 g, 30 mmol, 1.2 equiv.) in MeOH (105 mL) was stirred for 20h at room temperature. Boc_2O (11.78 g, 54 mmol, 2.16 equiv.) and sodium triacetoxyborohydride “STAB” (5.75 g, 27 mmol, 1.1 equiv.) were then added and the reaction mixture was stirred for a further 5h at room temperature. MeOH was evaporated under *vacuum* and the obtained crude was purified by chromatography on a silicagel column (PE/AcOEt 90:10 to 70:30) to give pure **1A** (6.13 g, 67% over 3 steps) as a light yellow oil.

R$_f$: 0.52 (PE/AcOEt 6/4).

^{1}H NMR (400 MHz, CDCl$_3$, 298K): δ ppm = 7.34 (d, 2H, $^{3}J_{H4\text{-}H5}$ = 7.9Hz, H$_4$), 7.19-7.12 (m, 2H, H$_5$), 4.44-4.34 (m, 2H, H$_7$), 3.60 (t, 2H, $^{3}J_{H8'\text{-}H9'}$ = 6.4Hz, H$_{14}$), 3.24-3.06 (m, 2H, H$_9$), 2.09 (br s, 1H, OH), 1.58-1.41 (m, 13H, H$_c$ H$_{10}$ H$_{13}$), 1.40-1.21 (m, 4H, H$_{11}$ H$_{12}$), 1.31 (s, 9H, H$_1$).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 155.7 (C$_a$), 149.9 (C$_3$), 135.4 (C$_6$), 127.3 & 126.9 (C$_5$), 125.2 (C$_4$), 79.5 (C$_b$), 62.6 & 62.4 (C$_{14}$), 49.7 & 49.2 (C$_7$), 46.1 & 45.8 (C$_9$), 34.4 (C$_2$), 31.3 (C$_1$), 28.4 (C$_c$), 32.5 & 28.0 & 27.5 & 26.6 & 26.2 & 25.4 & 25.1 (C$_{10}$ C$_{11}$ C$_{12}$ C$_{13}$).
HRMS (ESI): [M+Na]$^+$ calcd for $C_{22}H_{37}NO_3Na^+$: 386.2671, found: 386.2679.

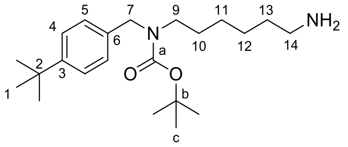
2.3. Synthesis of the *N*-carbamoylated bromo compound 1B



1B

To a solution of the alcohol **1A** (11.03 g, 29.6 mmol, 1 equiv.) in CH$_2$Cl$_2$ (150 mL) was added successively PPh$_3$ (15.5 g, 59 mmol, 2 equiv.) and CBr$_4$ (19.6 g, 59 mmol, 2 equiv.). The light brown solution was stirred for 1h30 at room temperature before being concentrated and added by a solution of PE/AcOEt 95:5. The precipitate was filtered off and the filtrate concentrated. The obtained residue was purified by chromatography using a silicagel column (PE/AcOEt 100:0 to 75:35) to give the pure brominated compound **1B** (11.56 g, 89%) as a pale yellow oil.
R$_f$: 0.70 (PE/AcOEt 6/4).
^{1}H NMR (400 MHz, CDCl$_3$, 298K): δ ppm = 7.35 (d, 2H, $^{3}J_{H4\text{-}H5}$= 7.9Hz, H$_4$), 7.21-7.14 (m, 2H, H$_5$), 4.45-4.36 (m, 2H, H$_7$), 3.39 (t, 2H, $^{3}J_{H8'\text{-}H9'}$ = 6.6Hz, H$_{14}$), 3.24-3.08 (m, 2H, H$_9$), 1.88-1.78 (m, 2H, H$_{13}$), 1.56-1.37 (m, 13H, H$_c$ H$_{10}$ H$_{12}$), 1.33 (s, 9H, H$_1$), 1.33-1.23 (m, 2H, H$_{11}$).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 155.6 (C$_a$), 149.9 (C$_3$), 135.3 (C$_6$), 127.3 & 126.9 (C$_5$), 125.3 (C$_4$), 79.4 (C$_b$), 49.9 & 49.3 (C$_7$), 46.1 (C$_9$), 34.4 (C$_2$), 33.7 (C$_{14}$), 32.6 (C$_{13}$), 31.3 (C$_1$), 28.4 (C$_c$), 27.8 & 27.5 & 25.9 (C$_{10}$ C$_{11}$ C$_{12}$).
HRMS (ESI): [M+Na]$^+$ calcd for $C_{22}H_{36}NO_2BrNa^+$: 448.1827, found: 448.1824.

2.4. Synthesis of the primary amino compound 1C

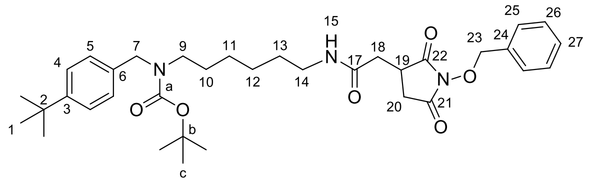


1C

To a solution of the brominated compound **1B** (6.11 g, 14 mmol, 1 equiv.) in dry DMF (78 mL) was added potassium phthalimide (3.91 g, 21 mmol, 1.5 equiv.). The solution was stirred for 2h at 70°C, then cooled to room temperature, and partially concentrated. The resulting mixture was filtered through a celite pad. After abundant washing of the celite pad with CH$_2$Cl$_2$, the filtrate was concentrated to a pale orange oil, which was used for the next step without further purification.
The obtained oil was diluted in EtOH (140 mL) and added by hydrazine (2.47 g, 49 mmol, 3.5 equiv.). The reaction mixture was vigorously stirred for 2h at reflux. At the end of the reaction, an aqueous solution of KOH 1M (140 mL) was added and EtOH was evaporated. The aqueous layer was then

extracted three times with CH_2Cl_2 (3x70 mL). The combined organic layers were dried over $MgSO_4$ and concentrated to give **1C** (5.097 g, 99%) as a pale yellow oil.
R_f: 0.11 (PE/AcOEt 2/8)
^{1}H NMR (400 MHz, $CDCl_3$, 298K): δ ppm = 7.34 (d, 2H, $^3J_{H4\text{-}H5}$ = 7.5Hz, H_4), 7.19-7.11 (m, 2H, H_5), 4.44-4.32 (m, 2H, H_7), 3.22-3.05 (m, 2H, H_9), 2.68 (t, 2H, $^3J_{H14\text{-}H13}$ = 6.7Hz, H_{14}), 1.74 (br s, NH_2), 1.54-1.35 (m, 13H, H_c H_{13} H_{10}), 1.34-1.21 (m, 4H, H_{11} H_{12}), 1.30 (s, 9H, H_1).
^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 155.9 (C_b), 149.9 (C_3), 135.4 (C_6), 127.3 & 126.9 (C_5), 125.2 (C_4), 79.3 (C_b), 49.8 & 49.2 (C_7), 46.1 (C_9), 42.0 (C_{14}), 34.4 (C_2), 31.3 (C_1), 28.4 (C_c), 33.6 & 28.0 & 27.6 & 26.6 & 26.5 (C_9 C_{10} C_{11} C_{12}).
HRMS (ESI): $[M+H]^+$ calcd for $C_{22}H_{39}N_2O_2^+$: 363.3012, found: 363.3011.

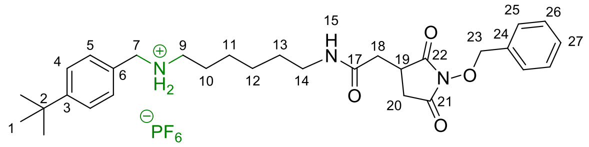
2.5. Synthesis of compound 1D



1D

The primary amine **1C** (1.124g, 3.1 mmol, 1 equiv.) and the *O*-benzyl-*N*-hydroxysuccinimide derivative (818 mg, 3.1 mmol, 1 equiv.) were dissolved in CH_2Cl_2 (57 mL). To this solution was added successively BOP (1.790 g, 4.0 mmol, 1.3 equiv.) and Et_3N (960 µL, 6.8 mmol, 2.2 equiv.). After checking the basicity of the solution, the mixture was stirred for 4h30 at RT. Then, an aqueous solution of HCl 1M was added until pH 1. The aqueous layer was extracted three times with CH_2Cl_2 (3x30 mL). The resulting organic layers were washed twice with a saturated aqueous $NaHCO_3$ solution (2x50 mL), then with brine (50 mL), dried over $MgSO_4$ and concentrated. The obtained crude was purified by chromatography on a silicagel column (PE/AcOEt 60:40 to 40:60) to give the pure compound **1D** (1.647 g, 87%) as a white solid.
R_f: 0.46 (PE/AcOEt 2/8)
^{1}H NMR (400 MHz, CD_3Cl, 298K): δ ppm = 7.53-7.47 (m, 2H, H_{26}), 7.39-7.35 (m, 3H, H_{25} H_{27}), 7.34 (d, 2H, $^3J_{H4\text{-}H5}$ = 7.9 Hz, H_4), 7.15 (d, 2H, $^3J_{H5\text{-}H4}$ = 7.9 Hz, H_5), 6.29 & 5.77 (2 br s, 1H, H_{15}), 5.13 (s, 2H, H_{23}), 4.42-4.34 (m, 2H, H_7), 3.24-3.06 (m, 4H, H_9 H_{14}), 3.05-2.96 (m, 1H, H_{19}), 2.84 (dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.9 Hz, $^3J_{H20b\text{-}H19}$ = 9.1 Hz, H_{20b}), 2.69-2.59 (m, 2H, H_{18}), 2.50 (dd, 1H, $^2J_{H20a\text{-}H20b}$ = 17.9Hz, $^3J_{H20a\text{-}H19}$ = 4.6Hz, H_{20a}), 1.55-1.39 (m, 4H, H_{13} H_{10}), 1.45 (sl, 9H, H_c), 1.35-1.20 (m, 4H, H_{11} H_{12}), 1.31 (s, 9H, H_1).
^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 173.8 (C_{17}), 170.7 & 169.1 (C_{21} C_{22}), 156.0 & 155.8 (C_a), 150.0 (C_3), 135.2 (C_{24}), 133.4 (C_6), 129.8 & 129.2 & 128.4 ($C_{25\text{-}27}$), 127.1 & 126.9 (C_5), 125.3 (C_4), 79.6 (C_b), 78.5 (C_{23}), 49.6 & 49.1 (C_7), 46.1 & 45.2 (C_9), 39.5 & 38.8 (C_{14}), 35.4 (C_{18}), 34.4 (C_2), 33.6 (C_{19}), 31.7 (C_{20}), 31.3 (C_1), 28.4 (C_c), 28.8 & 27.2 & 25.6 & 25.4 (C_9 C_{10} C_{11} C_{12}).
HRMS (ESI): $[M+Na]^+$ calcd for $C_{35}H_{49}N_3O_6Na^+$: 630.3519, found: 630.3523.

2.6. Synthesis of compound 1E



1E

To the *N*-carbamoylated compound **1D** (1.752 g, 2.88 mmol, 1 equiv.) was added a 1.8M solution of HCl in Et_2O (40 mL, 72 mmol, 25 equiv.). After stirring for 3h at 0°C, the mixture was concentrated before being dissolved in a small volume of Et_2O and concentrated three times. The resulting crude was diluted in CH_2Cl_2 (20 mL), milli-Q water (20 mL) and NH_4PF_6 (1.400 g, 8.6 mmol, 3 equiv.) were added. The biphasic mixture was vigorously stirred at room temperature for 15 min. The aqueous layer was extracted three times with CH_2Cl_2 (3x15mL). The combined organic layers were dried over $MgSO_4$ and concentrated. The resulting white solid was purified by chromatography on a silicagel column (CH_2Cl_2 /MeOH 98:2 to 94:6) to give the pure ammonium-containing product **1E** (1.628 g, 86%) as a white solid.

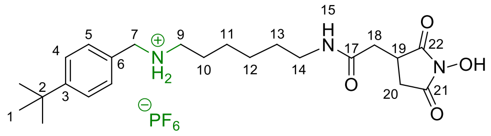
R_f: 0.53 (CH_2Cl_2/MeOH 9/1)

^{1}H NMR (400 MHz, CD_3CN, 298K): δ ppm = 7.52-7.46 (m, 2H, H_{26}), 7.50 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.4 Hz, H_4), 7.42-7.36 (m, 3H, H_{25} H_{27}), 7.37 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.4 Hz, H_5), 7.06-6.46 (br s, 2H, H_8), 6.52 (br t, 1H, H_{15}), 5.02 (s, 2H, H_{23}), 4.10 (s, 2H, H_7), 3.11 (q, 2H, $^3J_{H14\text{-}13}$ = $^3J_{14\text{-}15}$ = 6.6 Hz, H_{14}), 3.03-2.95 (m, 3H, H_{19} H_9), 2.77 (dd, 1H, $^2J_{H20a\text{-}H20b}$ = 17.8Hz, $^3J_{H20a\text{-}H19}$ = 9.2 Hz, H_{20a}), 2.66 (dd, 1H, $^2J_{H18a\text{-}H18b}$ = 16.3Hz, $^3J_{H18a\text{-}H19}$ = 5.9 Hz, H_{18a}), 2.57 (dd, 1H, $^2J_{H18b\text{-}H18a}$ = 16.3Hz, $^3J_{H18b\text{-}H19}$ = 4.6 Hz, H_{18b}), 2.34 (dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.8Hz, $^3J_{H20b\text{-}H19}$ = 4.4 Hz, H_{20b}), 1.63 (quint, 2H, $^3J_{H10\text{-}H11}$ = $^3J_{H10\text{-}H9}$ = 7.5 Hz, H_{10}), 1.43 (quint, 2H, $^3J_{13\text{-}14}$ = $^3J_{13\text{-}12}$ = 6.9 Hz, 2H, H_{13}), 1.38-1.25 (m, 4H, H_{11} H_{12}), 1.31 (s, 9H, H_1).

^{13}C NMR (100 MHz, CD_3CN, 298K): δ ppm = 175.3 & 172.3 & 170.9 (C_{17} C_{21} C_{22}), 153.7 (C_3), 135.2 (C_{24}), 130.7 (C_5), 130.6 & 130.0 & 129.4 ($C_{25\text{-}27}$), 128.6 (C_6), 126.9 (C_4), 79.0 (C_{23}), 52.0 (C_7), 48.5 (C_9), 39.4 (C_{14}), 35.8 (C_{18}), 35.2 (C_2), 34.4 (C_{19}), 32.3 (C_{20}), 31.3 (C_1), 29.7 (C_{13}), 26.3 & 26.2 & 26.1 (C_{10} C_{11} C_{12}).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{30}H_{42}N_3O_4^+$: 508.3175, found: 508.3179.

2.7. Synthesis of the molecular axle 1u



1u

To a solution of **1E** (351 mg, 0.54 mmol, 1 equiv.) in EtOH (15 mL) was added 10%-Pd/C (300 mg). The solution was stirred 15 min under a hydrogen atmosphere before filtration through a celite pad. After abundant washing of the celite pad, the filtrate was concentrated to give the pure **1u** (297 mg, 98%) without any further purification.

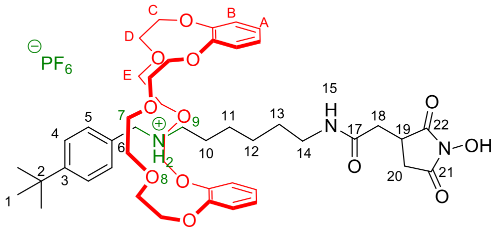
R_f: 0.23 (CH_2Cl_2/MeOH 9/1)

^{1}H NMR (400 MHz, CD_3CN, 298K): δ ppm = 7.50 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.4 Hz, H_4), 7.39 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.4 Hz, H_5), 6.57 (br t, 1H, H_{15}), 4.13 (s, 2H, H_7), 3.11 (q, 2H, $^3J_{H14\text{-}H13}$ = $^3J_{H14\text{-}H15}$ = 6.6 Hz, H_{14}), 3.06-2.95 (m, 3H, H_{19} H_9), 2.75 (dd, 1H, $^2J_{H20a\text{-}H20b}$ = 17.8 Hz, $^3J_{H20a\text{-}H19}$ = 9.0 Hz, H_{20a}), 2.63 (dd, 1H, $^2J_{H18a\text{-}H18b}$ = 16.2 Hz, $^3J_{H18a\text{-}H19}$ = 6.0 Hz, H_{18a}), 2.57 (dd, 1H, $^2J_{H18b\text{-}H18a}$ = 16.2 Hz, $^3J_{H18b\text{-}H19}$ = 4.9 Hz, H_{18b}), 2.34 (dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.8 Hz, $^3J_{H20b\text{-}H19}$ = 4.4 Hz, H_{20b}), 1.64 (quint, 2H, $^3J_{H10\text{-}H11}$ = $^3J_{H10\text{-}H9}$ = 7.5 Hz, H_{10}), 1.43 (quint, 2H, $^3J_{H13\text{-}H14}$ = $^3J_{H13\text{-}12}$ = 6.9 Hz, 2H, H_{13}), 1.38-1.23 (m, 4H, H_{11} H_{12}), 1.31 (s, 9H, H_1).

^{13}C NMR (100 MHz, CD_3CN, 298K): δ ppm = 175.7 & 172.8 & 171.3 (C_{17} C_{21} C_{22}), 153.6 (C_3), 130.6 (C_5), 128.6 (C_6), 126.8 (C_4), 52.0 (C_7), 48.5 (C_9), 39.5 (C_{14}), 35.7 (C_{18}), 35.2 (C_2), 34.4 (C_{19}), 32.1 (C_{20}), 31.3 (C_1), 29.5 (C_{13}), 26.3 & 26.2 & 26.0 (C_{10} C_{11} C_{12}).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{23}H_{36}N_3O_4^+$: 418.2706, found: 418.2694.

2.8. Preparation of semi rotaxane 1



1

A 0.12 M solution of the transporter thread **1u** (53.5 mg, 0.095 mmol, 1 equiv.) and DB24C8 (128.2 mg, 0.286 mmol, 3 equiv.) in dry CH_2Cl_2 (2.6 mL) was stirred 12h at rt before being concentrated. The resulting solid was purified by chromatography on lipophilic sephadex LH20 (CH_2Cl_2) to afford pure **1** (86.5 mg, 90%) as a white powder.

R_f: 0.69 (CH_2Cl_2/MeOH 9/1)

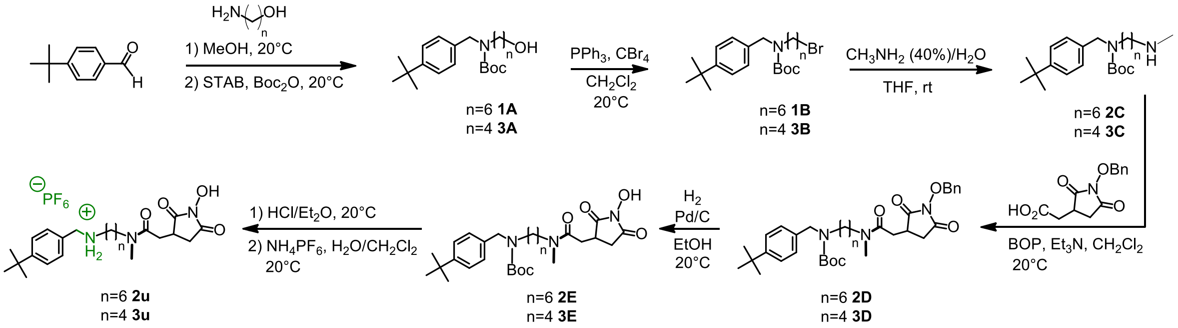
^{1}H NMR (400 MHz, CD_3CN, 298K): δ ppm = 7.29 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.4Hz, H_5), 7.22 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.4Hz, H_4), 7.18-7.03 (br s, 2H, H_8), 6.91 (s, 8H, H_A H_B), 6.37 (br t, 1H, H_{15}), 4.57-4.51 (m, 2H, H_7), 4.20-4.13 & 4.10-4.02 (2m, 2x4H, H_C $H_{C'}$), 3.85-3.75 (m, 8H, H_D $H_{D'}$), 3.68-3.59 & 3.56-3.47 (2m, 2x4H, H_E $H_{E'}$), 3.31-3.21 (m, 2H, H_9), 3.03-2.92 (m, 3H, H_{19} H_{14}), 2.75 (dd, 1H, $^2J_{H20a\text{-}H20b}$ = 17.4Hz, $^3J_{H20a\text{-}H19}$ = 8.9Hz, H_{20a}), 2.65-2.52 (m, 2H, H_{18}), 2.34 (dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.9Hz, $^3J_{H20b\text{-}H19}$ = 4.1Hz, H_{20b}), 1.49-1.39 (m, 2H, H_{10}), 1.23 (s, 9H, H_1), 1.20-1.13 (m, 2H, H_{13}), 1.07-0.98 (m, 4H, H_{11} H_{12}).

^{13}C NMR (101 MHz, CD_3CN, 298K): δ ppm = 175.4 & 172.5 (C_{21} C_{22}), 170.5 (C_{17}), 153.0 (C_3), 148.5 ($C_{IV\ arom\ DB24C8}$), 130.5 (C_6 C_5), 126.3 (C_4), 122.4 & 113.6 (C_A C_B), 71.6 (C_E $C_{E'}$), 71.1 (C_D $C_{D'}$), 69.0 (C_C $C_{C'}$), 52.8 (C_7), 48.6 (C_9), 39.6 (C_{14}), 35.8 (C_{20}), 35.1 (C_2), 34.5 (C_{19}), 32.4 (C_{18}), 31.4 (C_1), 29.7 (C_{13}), 27.1 (C_{10}), 26.7 & 26.5 (C_{11} C_{12}).

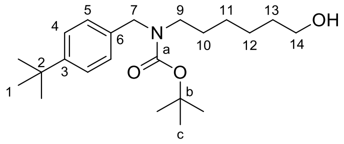
HRMS (ESI): $[M-PF_6]^+$ calcd for $C_{47}H_{68}N_3O_{12}^+$: 866.4803, found: 866.4799.

3. Synthesis of the semi rotaxanes 2 and 3

3.1. General synthetic pathway for molecular axles 2u and 3u

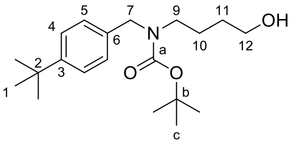


3.2. Synthesis of the N-carbamoylated alcohols 1A and 3A



1A

Synthesis of **1A** has already been described in paragraph 2.2

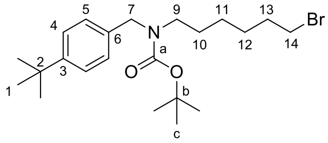


3A

A solution of 4-*tert*-butylbenzaldehyde (1.92 mL, 25 mmol, 1 equiv.) and 4-aminobutanol (1.02 g, 11.5 mmol, 1 equiv.) in MeOH (30 mL) was stirred for 19h at room temperature. Boc$_2$O (3.01 g, 13.8 mmol, 1.2 equiv.) and sodium triacetoxyborohydride “STAB” (4.87 g, 23 mmol, 2 equiv.) were then added and the reaction mixture was stirred for a further 4h30 at room temperature. MeOH was evaporated under *vacuum* and the obtained crude was purified by chromatography on a silicagel column (PE/AcOEt 85:15 to 70:30) to give pure **3A** (2.33 g, 61% over 3 steps) as a colorless oil.

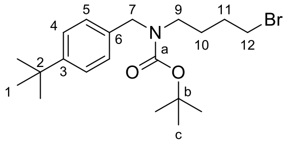
R_f: 0.42 (PE/EtOAc 6/4)
^{1}H NMR (400 MHz, CDCl$_3$, 298k): δ ppm = 7.34 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.3 Hz, H_4), 7.16 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.3 Hz, H_5), 4.40 (br s, 2H, H_7), 3.62 (t, 2H, $^3J_{H12\text{-}H11}$ = 5.9 Hz, H_{12}), 3.28-3.12 (m, 2H, H_9), 1.64-1.50 (m, 2H, H_{10}), 1.57-1.48 (m, 2H, H_{11}), 1.47 (s, 9H, H_c), 1.32 (s, 9H, H_1).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 155.9 (C_a), 150.0 (C_3), 135.3 (C_6), 127.0 (C_5), 125.3 (C_4), 79.6 (C_b), 62.4 (C_{12}), 49.9 & 49.3 (C_7), 45.9 (C_9), 34.4 (C_2), 31.3 (C_1), 29.6 (C_{11}), 28.4 (C_c), 24.2 (C_{10}).
MS (ESI): $[M+H]^+$ calcd for $C_{20}H_{34}NO_3^+$: 336.25, found: 336.21.

3.3. Synthesis of the N-carbamoylated bromo compounds 1B and 3B



1B

Synthesis of **1B** has already been described in paragraph 2.3



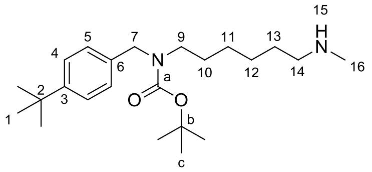
3B

To a solution of the alcohol **3A** (413 mg, 1.23 mmol, 1 equiv.) in CH$_2$Cl$_2$ (12 mL) was added successively PPh$_3$ (645 mg, 2.46 mmol, 2 equiv.) and CBr$_4$ (836 mg, 2.46 mmol, 2 equiv.). The light brown solution was stirred for 30 min at room temperature before being concentrated. The obtained residue was purified by chromatography using a silicagel column (PE/AcOEt 90:10) to give the pure brominated compound **3B** (460 mg, 94%) as a yellow oil.
R_f: 0.43 (PE/EtOAc 9/1)
^{1}H NMR (400 MHz, CDCl$_3$, 298k): δ ppm = 7.35 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.3 Hz, H_4), 7.17 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.3 Hz, H_5), 4.41 (br s, 2H, H_7), 3.39 (t, 2H, $^3J_{H12\text{-}H11}$ = 6.1 Hz, H_{12}), 3.28-3.12 (m, 2H, H_9), 1.89-1.75 (m, 2H, H_{11}), 1.72-1.59 (m, 2H, H_{10}), 1.49 (s, 9H, H_c), 1.33 (s, 9H, H_1).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 155.8 (C_a), 150.1 (C_3), 135.2 (C_6), 127.4 & 127.1 (C_5), 125.4 (C_4), 79.7 (C_b), 49.9 & 49.3 (C_7), 45.2 (C_9), 34.4 (C_2), 33.3 (C_{12}), 31.3 (C_1), 30.0 (C_{11}), 28.4 (C_c), 26.4 (C_{10}).
MS (ESI): $[M+H]^+$ calcd for $C_{20}H_{33}BrNO_2^+$: 398.17, found: 398.12.

3.4. Synthesis of the N-methyl amines 2C and 3C

General procedure:

To a 40% solution of methylamine in water (35 equiv) in THF (5 mL) was added dropwise a solution of bromide **2-3B** (1 equiv) in THF (10 mL). The mixture was stirred overnight before addition of dichloromethane (30 mL) and NaOH 1M (30 mL). The two layers were partitioned and the aqueous layer was further extracted with dichloromethane (4 x 30 mL). The organic layers were combined, dried over $MgSO_4$ and concentrated to give the amines **2-3C** as a colourless oil without any further purification.



2C

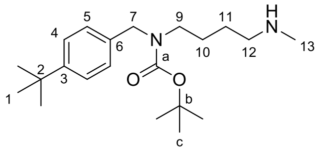
Methyl amine **2C** (1.17 g, quantitative) was obtained as a colorless oil from bromide **1B** (2.33g, 3.12 mmol).

R$_f$: 0.17 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (400 MHz, $CDCl_3$, 298k): δ ppm = 7.33 (d, 2H, $^3J_{H4-H5}$ = 8.2 Hz, H_4), 7.15 (br d, 2H, H_5), 6.95 (br s, 1H, H_{15}), 4.38 (br s, 2H, H_7), 3.21-2.95 (m, 2H, H_9), 2.85 & 2.41 (2br t, 2H, H_{14}), 2.62 & 2.27 (2s, 3H, H_{16}), 1.83-1.73 & 1.56-1.29 (2m, 4H, H_{10} H_{13}), 1.46 (s, 9H, H_c), 1.31 (s, 9H, H_1), 1.32-1.20 (m, 4H, H_{11} H_{12}).

^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 156.0 & 155.6 (C_a), 149.9 (C_3), 135.4 (C_6), 127.3 & 126.9 (C_5), 125.3 (C_4), 80.7 & 79.4 (C_b), 55.3 & 49.8 & 49.5 & 49.3 (C_7 C_{14}), 46.2 & 46.1 & 46.0 (C_9), 40.4 ($C_{16\text{-}cis}$), 34.4 (C_2), 33.1 ($C_{16\text{-}trans}$), 31.3 (C_1), 28.4 (C_c), 28.0 & 27.7 & 27.5 & 27.1 & 26.7 & 26.4 & 26.2 (C_{10} C_{11} C_{12} C_{13}).

MS (ESI): $[M+H]^+$ calcd for $C_{23}H_{41}N_2O_2^+$: 377.32, found: 377.30.



3C

Methyl amine **3C** (376 mg, 94%) was obtained as a colorless oil from bromide **3B** (440 mg, 1.15 mmol).

R$_f$: 0.15 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (400 MHz, $CDCl_3$, 298k): δ ppm = 7.34 (d, 2H, $^3J_{H4-H5}$ = 8.3 Hz, H_4), 7.16 (br d, 2H, H_5), 4.40 (br s, 2H, H_7), 3.27-3.10 (m, 2H, H_9), 2.55 (t, 2H, $^3J_{H12-H11}$ = 6.9 Hz, H_{13}), 2.41 (s, 3H, H_{12}), 1.58-1.38 (m, 4H, H_{10} H_{11}), 1.47 (s, 9H, H_c), 1.32 (s, 9H, H_1).

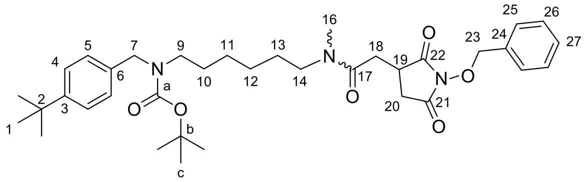
^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 155.8 & 155.4 (C_a), 149.8 (C_3), 135.3 (C_6), 127.2 & 126.8 (C_5), 125.1 (C_4), 79.2 (C_b), 51.5 (C_{12}), 49.8 & 49.2 (C_7), 46.0 (C_9), 36.1(C_{13}), 34.2 (C_2), 31.2 (C_1), 28.3 (C_c), 26.8 (C_{11}), 25.7 & 25.4 (C_{10}).

MS (ESI): $[M+H]^+$ calcd for $C_{21}H_{37}N_2O_2^+$: 349.28, found: 349.25.

3.5. Synthesis of compounds 2D and 3D

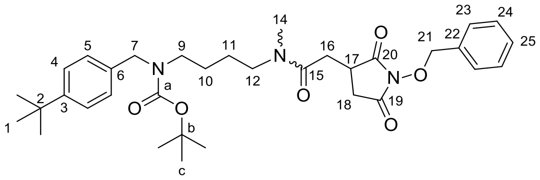
General procedure:

The primary amine **2-3C** (1 equiv.) and the *O*-benzyl-*N*-hydroxysuccinimide derivative (1 equiv.) were dissolved in CH_2Cl_2 (20 mL for 1.15 mmol of amine). To this solution was added successively BOP (1.3 equiv.) and Et_3N (2.2 equiv.). After checking the basicity of the solution, the mixture was stirred for 4h30 at room temperature. Then, an 1M aqueous solution of HCl was added until the pH reached 1. The aqueous layer was extracted three times with dichloromethane (3 x 30 mL) and the resulting organic layers were washed with a saturated $NaHCO_3$ aqueous solution (3 x 30 mL). The aqueous layer was then extracted with dichloromethane (3 x 30 mL) and the combined organic layers were dried over $MgSO_4$ and concentrated. The crude was purified by chromatography on a silica gel column (PE/AcOEt 1/1) to give compound **2-3D**.



2D

Compound **2D** (1.54 g, 79%) was obtained as a white solid from methyl amine **2C** (1.17 g, 3.12 mmol).
R$_f$: 0.77 (CH_2Cl_2/CH_3OH 9/1)
^{1}H NMR (500 MHz, $CDCl_3$, 298k): δ ppm = 7,55-7.50 (m, 2H, H_{25}), 7.40-7.31 (m, 5H, H_4 H_{26} H_{27}), 7.19-7.12 (m, 2H, H_5), 5.19-5.11 (m, 2H, H_{23}), 4.45-4.33 (m, 2H, H_7), 3.40-3.32 & 3.28-3.05 (2m, 4H, H_9 H_{14}), 3.04-2.97 (m, 1H, H_{19}), 2.93 & 2.88 (2s, 3H, $H_{16\text{-trans}}$ $H_{16\text{-cis}}$), 2.92-2.81 (m, 1H, H_{20a}), 2.82-2.70 (m, 2H, H_{18}), 2.48 (dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.8 Hz, $^3J_{H20b\text{-}H19}$ = 4.7 Hz, H_{20b}), 1.58-1.39 (m, 13H, H_c H_{10} H_{13}), 1.32 & 1.31 (2s, 9H, H_1), 1.32-1.21 (m, 4H, H_{11} H_{12}).
^{13}C NMR (125 MHz, $CDCl_3$, 298K): δ ppm = 174.1 (C_{17}), 171.0 & 170.9 & 168.7 & 168.7 (C_{21} C_{22}), 156.0 & 155.6 (C_a), 150.0 & 149.9 (C_3), 135.4 (C_6), 133.7 & 133.7 (C_{24}), 129.9 & 129.8 (C_{25}), 129.1 & 129.1 (C_{27}), 128.4 (C_{26}), 127.3 & 126.9 (C_5), 125.3 (C_4), 79.4 & 78.6 (C_b), 78.4 (C_{23}), 49.9 & 49.7 & 49.2 & 47.7 (C_7 C_{14}), 46.1 & 46.0 (C_9), 35.0 ($C_{16\text{-trans}}$), 34.4 (C_2), 33.8 (C_{19}), 33.3 & 33.2 ($C_{16\text{-cis}}$ C_{18}), 32.4 & 32.4 (C_{20}), 31.3 (C_1), 28.4 (C_c), 28.2 & 28.0 & 27.6 & 27.1 & 26.5 (C_{10} C_{11} C_{12} C_{13}).
MS (ESI): $[M+H]^+$ calcd for $C_{36}H_{52}N_3O_6^+$: 622.39, found: 622.37.



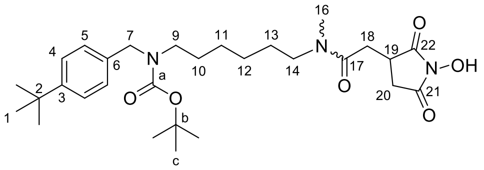
3D

Compound **3D** (602 mg, 88%) was obtained as a yellow oil from methyl amine **3C** (404 mg, 1.15 mmol).
R$_f$: 0.51 (PE/AcOEt 2/8)
^{1}H NMR (500 MHz, $CDCl_3$, 298K): δ ppm = 7,55-7.50 (m, 2H, H_{23}), 7.40-7.31 (m, 5H, H_4 H_{24} H_{25}), 7.19-7.12 (m, 2H, H_5), 5.18-5.11 (m, 2H, H_{21}), 4.44-4.33 (m, 2H, H_7), 3.43-3.32 & 3.28-3.09 (2m, 4H, H_9 H_{12}), 3.04-2.97 (m, 1H, H_{17}), 2.91 & 2.85 (2s, 3H, $H_{14\text{-trans}}$ $H_{14\text{-cis}}$), 2.91-2.80 (m, 1H, H_{18a}), 2.85-2.70 (m, 2H, H_{16}), 2.51-2.44 (m, 1H, H_{18b}), 1.54-1.40 (m, 13H, H_c H_{10} H_{11}), 1.32 & 1.31 (2s, 9H, H_1).
^{13}C NMR (125 MHz, $CDCl_3$, 298K): δ ppm = 174.1 (C_{15}), 171.0 & 168.8 (C_{19} C_{20}), 155.8 (C_a), 150.3 & 150.0 (C_3), 135.4 & 135.2 (C_6), 133.7 & 133.7 (C_{22}), 129.9 & 129.9 (C_{23}), 129.1 & 129.1 (C_{25}), 128.4

(C_{24}), 127.4 & 127.0 (C_5), 125.4 & 125.3 (C_4), 79.9 & 79.6 (C_b), 78.4 (C_{21}), 50.0 & 49.8 & 49.3 & 47.4 (C_7 C_{12}), 45.8 & 45.7 & 45.4 (C_9), 35.0 ($C_{14\text{-trans}}$), 34.5 & 34.4 (C_2), 33.8 & 33.8 (C_{16} C_{17}), 33.2 ($C_{14\text{-cis}}$), 32.4 & 32.4 (C_{18}), 31.3 (C_1), 28.4 (C_c), 25.4 & 25.1 & 24.9 & 24.4 (C_{10} C_{11}).
MS (ESI): $[M+H]^+$ calcd for $C_{34}H_{48}N_3O_6^+$: 594.35, found: 594.33.

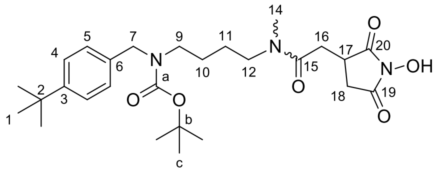
3.6. Synthesis of compounds 2E and 3E

General procedure:
To a solution of *O*-benzylsuccinimide **2-3D** in EtOH (60 mL for 2,25 mmol of D) was added 10%-Pd/C (40% in mass). The solution was stirred 10 min under a hydrogen atmosphere before filtration through a celite pad. After abundant washing of the celite pad, the filtrate was concentrated to give **2-3E**.



2E

Compound **2E** (969 mg, 79%) was obtained as a white solid after purification by chromatography using a silicagel column (CH_2Cl_2/MeOH 100:0 to 96:4) from compound **2D** (1.40 g, 2.25 mmol).
R$_f$: 0.53 (CH_2Cl_2/CH_3OH 9/1)
^{1}H NMR (400 MHz, CDCl$_3$, 298k): δ ppm = 7.36-7.31 (m, 2H, H_4), 7.15 (br d, 2H, H_5), 4.38 (br s, 2H, H_7), 3.39-3.09 (2m, 4H, H_9 H_{14}), 3.09-3.02 (m, 1H, H_{19}), 2.95 & 2.88 (2s, 3H, $H_{16\text{-trans}}$ $H_{16\text{-cis}}$), 2.92-2.77 (m, 3H, H_{20a} H_{18}), 2.50 (br dd, 1H, H_{20b}), 1.59-1.39 (m, 13H, H_c H_{10} H_{13}), 1.31 (s, 9H, H_1), 1.33-1.21 (m, 4H, H_{11} H_{12}).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 174.9 & 174.8 (C_{17}), 171.9 & 169.6 & 169.4 (C_{21} C_{22}), 155.7 (C_a), 150.0 & 149.9 (C_3), 135.3 (C_6), 127.3 & 126.9 (C_5), 125.3 (C_4), 79.6 (C_b), 50.0 & 49.2 & 47.9 (C_7 C_{14}), 46.2 & 46.0 (C_9), 35.2 ($C_{16\text{-trans}}$), 34.4 (C_2), 33.7 & 33.4 (C_{19} $C_{16\text{-cis}}$), 32.8 (C_{18}), 32.1 & 32.0 (C_{20}), 31.3 (C_1), 28.4 (C_c), 28.0 & 27.5 & 27.0 (C_{10} C_{13}), 26.4 (C_{11} C_{12}).
MS (ESI): $[M\text{-Boc}+2H]^+$ calcd for $C_{24}H_{38}N_3O_4^+$: 432.29, found: 432.27.



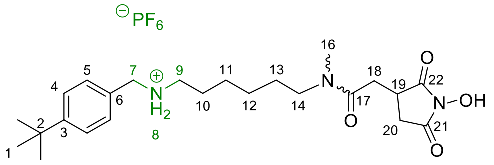
3E

Compound **3E** (598 mg, 94%) was obtained as a white oil without any purification from compound **3D** (745 mg, 2.25 mmol).
R$_f$: 0.77 (CH_2Cl_2/CH_3OH 9/1)
^{1}H NMR (400 MHz, CDCl$_3$, 298k): δ ppm = 7.37-7.31 (m, 2H, H_4), 7.15 (br d, 2H, H_5), 4.31 (br s, 2H, H_7), 3.36-3.11 (m, 4H, H_9 H_{12}), 3.10-3.01 (m, 1H, H_{17}), 2.93 & 2.86 (2s, 3H, $H_{14\text{-trans}}$ $H_{14\text{-cis}}$), 2.94-2.80 (m, 1H, H_{18a}), 2.87-2.74 (m, 2H, H_{16}), 2.54-2.43 (m, 1H, H_{18b}), 1.54-1.41 (m, 13H, H_c H_{10} H_{11}), 1.31 & 1.31 (2s, 9H, H_1).
^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 175.0 & 174.9 (C_{15}), 171.9 & 169.5 (C_{19} C_{20}), 155.9 (C_a), 150.2 & 150.0 (C_3), 135.3 & 135.1 (C_6), 127.3 & 127.0 (C_5), 125.4 & 125.3 (C_4), 80.1 & 79.8 (C_b), 50.0 &

49.8 & 49.6 & 47.7 (C_7 C_{12}), 45.8 & 45.5 (C_9), 35.2 ($C_{14\text{-trans}}$), 34.4 & 34.4 (C_2), 33.8 & 33.6 & 33.5 & 32.9 ($C_{14\text{-cis}}$ C_{16} C_{17}), 32.1 & 32.1 (C_{18}), 31.3 (C_1), 28.4 (C_c), 25.4 & 25.1 & 24.8 & 24.4 (C_{10} C_{11}).
MS (ESI): $[M+H]^+$ calcd for $C_{27}H_{42}N_3O_6^+$: 504.31, found: 504.29.

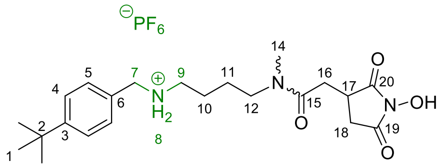
3.7. Synthesis of the molecular axles 2u and 3u

General procedure:
To the *N*-carbamoylated compound **2-3D** (1 equiv.) was added a 1.8M solution of HCl in Et_2O (25 equiv.). After stirring for 2h at 0°C, the mixture was concentrated before being dissolved in a small volume of Et_2O and concentrated three times. The resulting crude was diluted in CH_2Cl_2 (20 mL), milli-Q water (20 mL) and NH_4PF_6 (3 equiv.) were added. The biphasic mixture was vigorously stirred at room temperature for 30 min. The aqueous layer was extracted three times with CH_2Cl_2 (3x15mL). The combined organic layers were dried over $MgSO_4$ and concentrated to give the pure ammonium-containing product **2u-3u**.



2u

Compound **2u** (907 mg, 89%) was obtained as a white solid without any purification from compound **2D** (869 mg, 1.60 mmol).
R_f: 0.43 (CH_2Cl_2/CH_3OH 9/1)
^{1}H NMR (500 MHz, CD_3CN, 298k): δ ppm = 7.53-7.48 (m, 2H, H_4), 7.39 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.3 Hz, H_5), 6.91 (br s, 2H, H_8), 4.14 & 4.13 (2s, 2H, $H_{7\text{-trans}}$ $H_{7\text{-cis}}$), 3.29 (t, 0.65x2H, $^3J_{H14\text{-}H13}$ = 7.2 Hz, $H_{14\text{-trans}}$) & 3.24 (td, 0.35x2H, $^3J_{H14\text{-}H13}$ = 7.2 Hz, $^4J_{H14\text{-}H12}$ = 3.6 Hz, $H_{14\text{-cis}}$), 3.05-2.96 (m, 2H, H_9), 3.01-2.95 (m, 1H, H_{19}), 2.91 & 2.79 (2s, 3H, $H_{16\text{-trans}}$ $H_{16\text{-cis}}$), 2.89-2.78 (m, 2H, H_{18}), 2.79 & 2.75 (2dd, 1H, $^2J_{H20a\text{-}H20b}$ = 17.6 Hz, $^3J_{H20a\text{-}H19}$ = 9 Hz, $H_{20a\text{-cis}}$ $H_{20a\text{-trans}}$), 2.33 & 2.35 (2dd, 1H, $^2J_{H20b\text{-}H20a}$ = 17.6 Hz, $^3J_{H20b\text{-}H19}$ = 4.5 Hz, $H_{20b\text{-cis}}$ $H_{20b\text{-trans}}$), 1.70-1.60 (m, 2H, H_{10}), 1.55 & 1.47 (2quint., 2H, $^3J_{H13\text{-}H12}$ = $^3J_{H13\text{-}H14}$ = 7.2 Hz, $H_{13\text{-cis}}$ $H_{13\text{-trans}}$), 1.40-1.32 (m, 2H, H_{11}), 1.32 (s, 9H, H_1), 1.35-1.25 (m, 2H, $H_{12\text{-cis}}$), 1.28-1.17 (m, 2H, $H_{12\text{-trans}}$).
^{13}C NMR (125 MHz, CD_3CN, 298K): δ ppm = 176.1 & 175.9 (C_{17}), 173.0 & 172.9 & 171.0 & 170.5 (C_{21} C_{22}), 153.8 (C_3), 130.7 (C_5), 128.7 & 128.6 (C_6), 126.9 (C_4), 52.1 & 52.0 (C_7), 50.0 & 47.3 (C_{14}), 48.7 & 48.5 (C_9), 35.3 ($C_{16\text{-trans}}$), 34.6 (C_2), 34.4 (C_{19}), 34.0 (C_{18}), 33.5 & 33.3 ($C_{16\text{-cis}}$), 32.7 & 32.6 (C_{20}), 31.4 (C_1), 28.3 ($C_{13\text{-cis}}$), 27.2 ($C_{13\text{-trans}}$), 26.6 & 26.5 & 26.3 & 26.1 & 26.0 (C_{10} C_{11} C_{12}).
HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{24}H_{38}N_3O_4^+$: 432.2861, found: 432.2862.



3u

Compound **3u** (629 mg, 99%) was obtained as a white solid without any purification from compound **3D** (584 mg, 1.16 mmol).
R_f: 0.52 (CH_2Cl_2/CH_3OH 9/1)
^{1}H NMR (500 MHz, CD_3CN, 298k): δ ppm = 7.53-7.47 (m, 2H, H_4), 7.40 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.3 Hz, H_5), 4.14-4.08 (m, 2H, H_7), 3.38-3.31 & 3.30-3.21 (2m, 2H, H_{12}) 3.09-2.98 (m, 3H, H_9 H_{17}), 2.93 & 2.79 (2s, 3H, $H_{14\text{-trans}}$ $H_{14\text{-cis}}$), 2.89-2.78 (m, 2H, H_{16}), 2.79-2.71 (m, 1H, H_{18a}), 2.37 & 2.34 (2dd, 1H, $^2J_{H18b\text{-}H18a}$ =

17.7 Hz, $^{3}J_{H18b\text{-}H17}$ = 4.5 Hz, H_{18b}), 1.78-1.70 & 1.68-1.49 (2m, 2H, H_{10} H_{11}), 1.32 & 1.31 (2s, 9H, $H_{1\text{-}cis}$ $H_{1\text{-}trans}$).

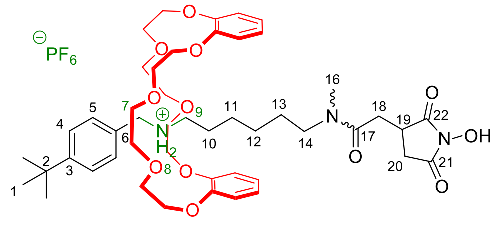
^{13}C NMR (125 MHz, CD_3CN, 298K): δ ppm = 176.2 & 176.0 (C_{15}), 173.0 & 171.9 & 170.6 (C_{19} C_{20}), 153.9 & 153.7 (C_3), 130.7 (C_5), 128.8 (C_6), 126.9 (C_4), 52.1 & 52.1 (C_7), 49.4 & 46.5 (C_{12}), 48.1 (C_9), 35.5 & 35.3 ($C_{14\text{-}trans}$), 34.5 & 34.5 (C_2 C_{17}), 33.9 (C_{16}), 33.5 & 33.3 ($C_{14\text{-}cis}$), 32.7 (C_{18}), 31.4 (C_1), 25.6 & 24.5 & 23.7 & 22.9 (C_{10} C_{11}).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{22}H_{34}N_3O_4^+$: 404.2553, found: 404.2549.

3.8. Synthesis of the semi rotaxanes 2 and 3

General procedure:

To a 0.12M solution of molecular axle **2u/3u** (1 equiv) in amylene-stabilized dichloromethane was added dibenzo-24-crown-8 (3 equiv). The reaction mixture was stirred at room temperature before being concentrated. The crude residue was extensively triturated with toluene (20 x 10 mL) in order to remove most of the DB24C8 excess before being purified by chromatography on a lipophilic sephadex LH20 (CH_2Cl_2) to give pure semi rotaxane **2/3** as a white solid.



2

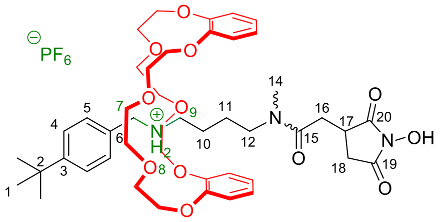
Semi rotaxane **2** (807 mg, 64%) was obtained after 209h of stirring from compound **2u** (707 mg, 1.22 mmol).

R_f: 0.67 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (500 MHz, CD_3CN, 298k): δ ppm = 7.32-7.27 (m, 2H, H_5), 7.25-7.20 (m, 2H, H_4), 7.13 (br s, 2H, H_8), 6.94-6.88 (m, 8H, H_A H_B), 4.57-4.51 (m, 2H, H_7), 4.21-4.13 & 4.10-4.02 (2m, 8H, H_C $H_{C'}$), 3.86-3.75 (m, 8H, H_D $H_{D'}$), 3.69-3.60 & 3.57-3.48 (2m, 8H, H_E $H_{E'}$), 3.34-3.23 (2m, 2H, H_9), 3.17-3.03 (m, 2H, H_{14}), 3.01-2.94 (m, 1H, H_{19}), 2.86 & 2.75 (2s, 3H, $H_{16\text{-}trans}$ $H_{16\text{-}cis}$), 2.85-2.69 (m, 3H, H_{18} H_{20a}), 2.31 (dd, 1H, $^{2}J_{H20b\text{-}H20a}$ = 17.6 Hz, $^{3}J_{H20b\text{-}H19}$ = 4.3 Hz, H_{20b}), 1.49-1.39 (m, 2H, H_{10}), 1.30-1.15 (m, 2H, H_{13}), 1.23 & 1.24 (2s, 9H, $H_{1\text{-}cis}$ $H_{1\text{-}trans}$), 1.08-1.00 (m, 2H, H_{11}), 1.02-0.92 (m, 2H, H_{12}).

^{13}C NMR (125 MHz, CD_3CN, 298K): δ ppm = 175.9 (C_{17}), 173.0 & 170.5 & 170.3 (C_{21} C_{22}), 153.1 & 153.0 (C_3), 148.5 ($C_{IV\ DB24C8}$), 130.4 (C_5 C_6), 126.4 & 126.3 (C_4), 122.4 & 122.3 & 113.6 (C_A C_B), 71.5 (C_E $C_{E'}$), 71.1 (C_D $C_{D'}$), 69.0 (C_C $C_{C'}$), 52.7 (C_7), 50.0 ($C_{14\text{-}cis}$), 49.6 (C_9), 47.8 ($C_{14\text{-}trans}$), 35.4 & 35.1 ($C_{16\text{-}trans}$), 34.6 & 34.5 (C_2 C_{19}), 34.0 (C_{18}), 33.5 & 33.3 ($C_{16\text{-}cis}$), 32.8 & 32.7 (C_{20}), 31.4 (C_1), 28.4 ($C_{13\text{-}cis}$), 27.3 & 27.2 & 27.1 (C_{10} $C_{13\text{-}trans}$), 26.8 & 26.6 & 26.6 (C_{11} C_{12}).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{48}H_{70}N_3O_{12}^+$: 880.4967, found: 880.4959.



3

Semi rotaxane **3** (694 mg, 60%) was obtained after 136h of stirring from compound **3u** (629 mg, 1.15 mmol).

R$_f$: 0.63 (CH_2Cl_2/CH_3OH 9/1)

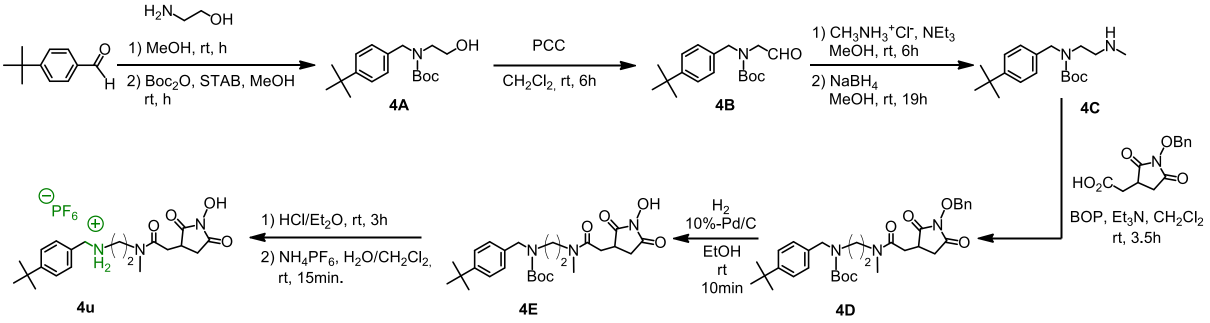
^{1}H NMR (500 MHz, CD_3CN, 298k): δ ppm = 7.32-7.24 (m, 2H, H_5), 7.21 (br d, 2H, H_4), 7.15 (br s, 2H, H_8), 6.96-6.88 (m, 8H, H_A H_B), 4.55-4.48 (m, 2H, H_7), 4.22-4.13 & 4.11-4.02 (2m, 8H, H_C $H_{C'}$), 3.85-3.75 (m, 8H, H_D $H_{D'}$), 3.68-3.61 & 3.56-3.48 (2m, 8H, H_E $H_{E'}$), 3.37-3.25 (2m, 2H, H_9), 3.13-2.90 (3m, 3H, H_{12} H_{17}), 2.70 & 2.58 (2s, 3H, $H_{14\text{-trans}}$ $H_{14\text{-cis}}$), 2.80-2.52 (m, 3H, H_{16} H_{18a}), 2.30-2.22 (m, 1H, H_{18b}), 1.45-1.35 (m, 2H, H_{10}), 1.25 & 1.23 (2s, 9H, $H_{1\text{-cis}}$ $H_{1\text{-trans}}$), 1.30-1.16 (m, 2H, H_{11}).

^{13}C NMR (125 MHz, CD_3CN, 298K): δ ppm = 175.7 & 175.7 (C_{15}), 172.7 & 170.6 & 170.2 (C_{19} C_{20}), 153.2 & 153.0 (C_3), 148.5 ($C_{IV\ DB24C8}$), 130.5 & 130.5 & 130.6 (C_5 C_6), 126.4 & 126.3 (C_4), 122.5 & 122.4 & 113.7 & 113.6 (C_A C_B), 71.5 (C_E $C_{E'}$), 71.1 (C_D $C_{D'}$), 69.1 & 69.1 (C_C $C_{C'}$), 52.8 & 52.8 (C_7), 49.4 & 49.4 & 49.2 (C_9 $C_{12\text{-cis}}$), 47.4 ($C_{12\text{-trans}}$), 35.2 & 35.1 ($C_{14\text{-trans}}$), 34.5 & 34.3 (C_2 C_{19}), 33.9 (C_{16}), 33.4 & 33.2 ($C_{14\text{-cis}}$), 32.7 & 32.6 (C_{18}), 31.4 (C_1), 25.6 & 24.9 & 24.9 & 24.6 (C_{11} C_{12}).

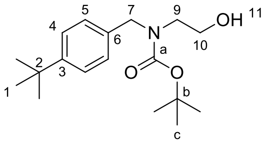
HRMS (ESI): $[M-PF_6]^+$ calcd for $C_{46}H_{66}N_3O_{12}^+$: 852.4651, found: 852.4646.

4. Synthesis of the semi rotaxane 4

4.1. General synthetic pathway of molecular axle 4u



4.2. Synthesis of the N-carbamoylated alcohol 4A



4A

A solution of 4-*tert*-butylbenzaldehyde (2.70 mL, 16.2 mmol, 1.01 equiv.) and 2-aminoethanol (0.98 g, 16 mmol, 1 equiv.) in MeOH (27 mL) was stirred for 7h at room temperature. Boc_2O (3.49 g, 16 mmol, 1 equiv.) and sodium triacetoxyborohydride "STAB" (3.39 g, 16 mmol, 1 equiv.) were then added and the reaction mixture was stirred for a further 12h at room temperature. MeOH was evaporated under *vacuum* and the obtained crude was purified by chromatography on a silicagel column (PE/AcOEt 85/15) to give pure **4A** (6.13 g, 64% over 3 steps) as a colorless oil which solidified at low temperature.

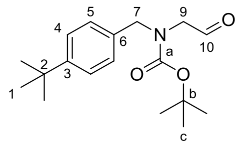
R_f: 0.68 (PE/EtOAc 7/3)

^{1}H NMR (500 MHz, $CDCl_3$, 298k): δ ppm = 7.36 (d, 2H, $^3J_{H4-H5}$ = 8.2 Hz, H_4), 7.18 (d, 2H, $^3J_{H5-H4}$ = 8.2 Hz, H_5), 4.45 (br s, 2H, H_7), 3.70 (br t, 2H, H_{10}), 3.39 (br s, 2H, H_9), 3.11 (br s, 1H, H_{11}), 1.49 (s, 9H, H_c), 1.32 (s, 9H, H_1).

^{13}C NMR (125 MHz, $CDCl_3$, 298K): δ ppm = 157.4 (C_a), 150.3 (C_3), 135.0 (C_6), 127.1 (C_5), 125.4 (C_4), 80.5 (C_b), 62.1 & 61.2 (C_{10}), 51.6 & 50.6 (C_7), 49.6 & 49.0 (C_9), 34.4 (C_2), 31.3 (C_1), 28.4 (C_c).

MS (ESI): $[M+Na]^+$ calcd for $C_{18}H_{29}NNaO_3^+$: 330.20, found: 330.20.

4.3. Synthesis of the N-carbamoylated aldehyde 4B



4B

To a solution of alcohol **4A** (3.14 g, 10.2 mmol, 1 equiv.) in dichloromethane (100 mL) was added pyridinium chlorochromate “PCC” (8.70 g, 40.4 mmol, 4 equiv.). The orange solution was stirred for 5h at room temperature before being concentrated. The crude was purified by chromatography on a silica gel column (PE/EtOAc 15/85) to give pure aldehyde **4B** (1.14 g, 37%) as a colorless oil.

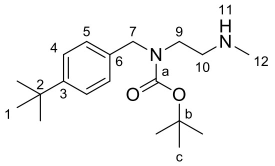
R_f: 0.79 (PE/EtOAc 3/7)

^{1}H NMR (400 MHz, $CDCl_3$, 298k): δ ppm = 9.50 & 9.44 (2br s, 1H, H_{10}), 7.40-7.30 (m, 2H, H_4), 7.24-7.11 (2br d, 2H, H_5), 4.53 & 4.48 (2br s, 2H, H_7), 3.92 & 3.79 (2br s, 2H, H_9), 1.52 & 1.48 (2br s, 9H, H_c), 1.32 (s, 9H, H_1).

^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 199.1 & 199.0 (C_{10}), 155.9 & 155.4 (C_a), 150.7 (C_3), 134.1 & 134.0 (C_6), 127.9 & 127.4 (C_5), 125.6 (C_4), 80.9 (C_b), 56.3 & 56.2 (C_9), 51.6 & 51.1 (C_7), 34.5 (C_2), 31.3 (C_1), 28.3 & 28.2 (C_c).

MS (ESI): $[M-Boc+2H]^+$ calcd for $C_{13}H_{20}NO^+$: 206.15, found: 206.15.

4.4. Synthesis of the *N*-methyl amine 4C



4C

To a solution of aldehyde **4B** (0.99 g, 3.3 mmol, 1 equiv.) and methylamine hydrochloride (1.10 g, 16.3 mmol, 5 equiv.) in MeOH (12 mL) was added triethylamine (4.5 mL, 29.6 mmol, 9.3 equiv.) and the mixture was stirred for 6h at room temperature. The solution was then cooled with an ice bath before addition of sodium borohydride (0.13 g, 3.3 mmol, 1 equiv.). The reaction mixture was allowed to warm up until room temperature and stirred for 19h before being concentrated. The crude was then purified by chromatography on a silica gel column (CH_2Cl_2/CH_3OH 95/5) to give pure *N*-methylamine **4C** (0.59 g, 56 %) as a yellow viscous oil.

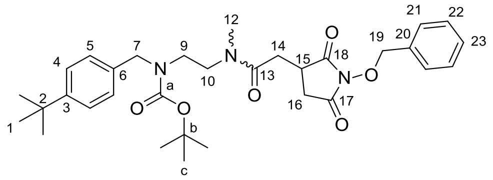
R_f: 0.54 (CH_2Cl_2/CH_3OH 96/4)

^{1}H NMR (400 MHz, CDCl$_3$, 298k): δ ppm = 7.32 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.2 Hz, H$_4$), 7.18 (br d, 2H, H$_5$), 4.43 (br s, 2H, H$_7$), 3.57 (br t, 2H, $^3J_{H10\text{-}H9}$ = 6.5 Hz, H$_{10}$), 3.14-2.90 (m, 2H, H$_9$), 2.64 (br s, 3H, H$_{12}$), 1.47 (s, 9H, H$_c$), 1.29 (s, 9H, H$_1$).

^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 156.4 (C$_a$), 150.5 (C$_3$), 134.3 (C$_6$), 127.3 (C$_5$), 125.6 (C$_4$), 81.1 (C$_b$), 51.4 & 50.4 (C$_7$), 47.7 & 47.1 (C$_9$), 43.1(C$_{10}$), 34.4 (C$_2$), 32.9 (C$_{12}$), 31.3 (C$_1$), 28.3 (C$_c$).

MS (ESI): [M+H]$^+$ calcd for $C_{19}H_{33}N_2O_2^+$: 321.25, found: 321.25.

4.5. Synthesis of compounds 4D



4D

A solution of *N*-methylamine **4C** (0.30 g, 0.9 mmol, 1 equiv) and *O*-benzyl-NHS acid derivative (0.24 g, 0.9 mmol, 1 equiv) in dichloromethane (16 mL) was cooled with an ice bath before successive addition of BOP (0.53 g, 1.2 mmol, 1.3 equiv) and Et$_3$N (0.20 g, 1.9 mmol, 2.1 equiv). After checking the basicity of the solution, the reaction mixture was stirred for 16h30 at room temperature. Then, an 1M aqueous solution of HCl was added until the pH reached 1. The aqueous layer was extracted three times with dichloromethane (3 x 10 mL) and the resulting organic layers were washed with a saturated NaHCO$_3$ aqueous solution (2 x 10 mL). The aqueous layer was then extracted with a dichloromethane (3 x 10 mL) and the combined organic layers were dried over MgSO$_4$ and concentrated. The crude was purified by chromatography on a silica gel column (PE/AcOEt 1/1) to give compound **4D** (0.41 g, 79 %) as a slightly orange solid.

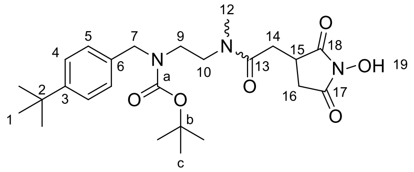
R$_f$: 0.53 (PE/AcOEt 8/2)

^{1}H NMR (500 MHz, CDCl$_3$, 298k): δ ppm = 7,56-7.50 (m, 2H, H$_{21}$), 7.40-7.29 (m, 5H, H$_4$ H$_{22}$ H$_{23}$), 7.22-7.10 (m, 2H, H$_5$), 5.16 (br s, 2H, H$_{17}$), 4.37 (br s, 2H, H$_7$), 3.63-3.18 (m, 4H, H$_9$ H$_{10}$), 3.04-2.69 (m, 7H, H$_{12}$ H$_{14}$ H$_{15}$ H$_{16a}$), 2.53-2.40 (m, 1H, H$_{16b}$), 1.50 & 1.47 (2br s, 9H, H$_c$), 1.32 & 1.30 (2s, 9H, H$_1$).

^{13}C NMR (100 MHz, CDCl$_3$, 298K): δ ppm = 174.1 (C$_{13}$), 171.0 & 169.3 (C$_{17}$ C$_{18}$), 155.7 (C$_a$), 150.8 & 150.2 (C$_3$), 135.0 (C$_6$), 133.7 (C$_{20}$), 129.9 & 129.8 (C$_{21}$), 129.2 & 129.1 (C$_{23}$), 128.4 (C$_{22}$), 127.2 (C$_5$), 125.6 & 125.4 (C$_4$), 80.6 & 80.0 (C$_b$), 78.4 & 78.3 (C$_{19}$), 51.8 & 50.7 & 50.1 (C$_7$), 48.1 & 47.5 (C$_9$), 44.8 & 44.1 & 43.8 & 43.1 (C$_{10}$), 35.8 (C$_{15}$), 34.5 & 34.4 (C$_2$), 33.8 & 33.7 & 33.6 (C$_{12}$), 32.7 (C$_{14}$), 32.3 & 32.2 (C$_{16}$), 31.3 (C$_1$), 28.4 (C$_c$).

MS (ESI): [M+H]$^+$ calcd for $C_{32}H_{44}N_3O_6^+$: 566.32, found: 566.32.

4.6. Synthesis of compound 4E



4E

To a solution of compound **4D** (0.76 g, 1.4 mmol) in EtOH (36 mL) was added 10%-Pd-C (550 mg). The solution was stirred 10 min under a hydrogen atmosphere before filtration through a celite pad. The resulting filtrate was concentrated to give pure compound **4E** (0.64 g, quantitative) as white solid without any further purification.

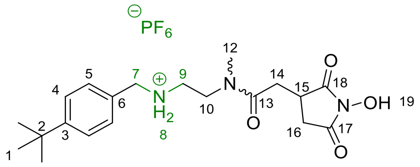
R_f: 0.55 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (400 MHz, $CDCl_3$, 298k): δ ppm = 7.38-7.31 (m, 2H, H_4), 7.22-7.10 (m, 2H, H_5), 4.37 (br s, 2H, H_7), 3.71-3.11 (m, 4H, H_9 H_{10}), 3.10-2.68 (m, 7H, H_{12} H_{14} H_{15} H_{16a}), 2.55-2.38 (m, 1H, H_{16b}), 1.50 & 1.47 & 1.44 (3s, 9H, H_c), 1.30 (2s, 9H, H_1).

^{13}C NMR (100 MHz, $CDCl_3$, 298K): δ ppm = 175.0 & 174.8 (C_{13}), 172.0 & 171.9 & 170.1 (C_{17} C_{18}), 155.8 & 155.6 (C_a), 150.8 & 150.3 (C_3), 135.0 & 134.5 (C_6), 127.8 & 127.6 & 127.2 (C_5), 125.6 & 125.4 (C_4), 80.7 & 80.2 (C_b), 51.8 & 50.6 & 50.3 (C_7), 48.3 & 47.7 (C_9), 44.7 & 44.2 & 43.9 & 43.3 (C_{10}), 34.5 & 34.4 (C_2), 36.0 & 34.0 & 33.6 & 33.4 & 32.4 & 32.0 & 31.8 (C_{12}, C_{14}, C_{15}, C_{16}), 31.3 (C_1), 28.4 (C_c).

MS (ESI): $[M+H]^+$ calcd for $C_{25}H_{38}N_3O_6^+$: 476.28, found: 476.28.

4.7. Synthesis of the molecular axle 4u



4u

To compound **4E** (0.29 g, 0.62 mmol, 1 equiv.) was added a 2.5 M solution chloride acid in Et_2O (6.9 mL, 28 equiv.) and the mixture was stirred at room temperature until TLC analysis revealed no trace of the starting material (1h30). The mixture was evaporated to dryness and the residue was partitioned between dichloromethane (3.3 mL) and MilliQ H_2O (3.3 mL). NH_4PF_6 (0.30 g, 1.8 mmol, 3 equiv.) was added and the biphasic mixture was vigorously stirred for 30 minutes. The aqueous layer was extracted with dichloromethane (12 x 10 mL) and the combined organic layers were dried over $MgSO_4$ before being concentrated to afford the molecular axle **4u** (0.30 g, 92%) as white solid without further purification.

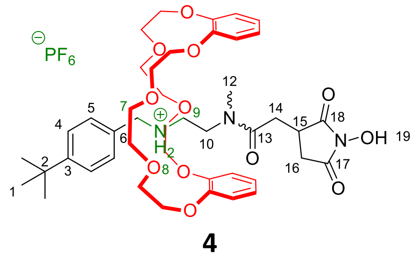
R_f: 0.24 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (400 MHz, CD_3CN, 298k): δ ppm = 7.51 (d, 2H, $^3J_{H4\text{-}H5}$ = 8.3 Hz, H_4), 7.35 (d, 2H, $^3J_{H5\text{-}H4}$ = 8.3 Hz, H_5), 4.15 (br s, 2H, H_7), 3.73-3.63 & 3.51-3.41 (2m, 2H, H_{10}), 3.22-3.16 (m, 2H, H_9), 3.09-3.02 (m, 1H, H_{15}), 2.95 (s, 3H, H_{12}), 2.87-2.82 (m, 2H, H_{14}), 2.79 (dd, 1H, $^2J_{H16a\text{-}H16b}$ = 17.8 Hz, $^3J_{H16a\text{-}H15}$ = 8.9 Hz, H_{16a}), 2.41 (dd, 1H, $^2J_{H16b\text{-}H16a}$ = 17.8 Hz, $^3J_{H16b\text{-}H15}$ = 4.5 Hz, H_{16b}), 1.32 (2s, 9H, H_1).

^{13}C NMR (100 MHz, CD_3CN, 298K): δ ppm = 175.6 (C_{13}), 174.7 & 172.7 (C_{17} C_{18}), 153.7 (C_3), 130.6 (C_4), 128.7 (C_6), 127.1 (C_5), 51.9 (C_7), 48.0 (C_9), 46.2 (C_{10}), 36.8 (C_{12}), 35.2 (C_2), 34.3 & 34.1 (C_{14}, C_{15}), 32.4 (C_{16}), 31.3 (C_1).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{20}H_{30}N_3O_4^+$: 376.2234, found: 376.2236.

4.8. Synthesis of the semi rotaxane 4



4

To a 0.12M solution of molecular axle **4u** (0.18 g, 0.3 mmol, 1 equiv) in amylene-stabilized dichloromethane (2.9 mL) was added dibenzo-24-crown-8 (0.46 g, 1.0 mmol, 3 equiv). The reaction mixture was stirred for 28 h at room temperature before being concentrated. The crude residue was extensively triturated with toluene (20 x 10 mL) in order to remove most of the DB24C8 excess before being purified by chromatography on a lipophilic sephadex LH20 (CH_2Cl_2) to give pure semi rotaxane **4** (0.22 g, 66%) as a white solid.

R_f: 0.58 (CH_2Cl_2/CH_3OH 9/1)

^{1}H NMR (500 MHz, CD_3CN, 298k): δ ppm = 7.22 (br d, 2H, H_5), 7.18 (br d, 2H, H_4), 6.93-6.89 (m, 8H, H_A H_B), 4.54-4.49 & 4.49-4.43 (2m, 2H, $H_{7\text{-cis}}$ $H_{7\text{-trans}}$), 4.23-4.13 & 4.13-4.03 (2m, 8H, H_C $H_{C'}$), 3.92-3.73 (m, 8H, H_D $H_{D'}$), 3.74-3.55 (2m, 8H, H_E $H_{E'}$), 3.67-3.49 & 3.31-3.23 (2m, 2H, H_{10}), 3.57-3.43 (m, 2H, H_9), 2.95-2.88 & 2.86-2.80 (2m, 1H, $H_{15\text{-trans}}$ $H_{15\text{-cis}}$), 2.72 & 2.68 (2s, 3H, $H_{12\text{-trans}}$ $H_{12\text{-cis}}$), 2.73-2.65 (m, 1H, H_{16a}), 2.68-2.54 (m, 2H, H_{14}), 2.27 & 2.16 (2dd, 1H, $^2J_{H16b\text{-}H16a}$ = 17.6 Hz, $^3J_{H16b\text{-}H15}$ = 4.5 Hz, $H_{16b\text{-trans}}$ $H_{16b\text{-cis}}$), 1.23 & 1.22 (2s, 9H, $H_{1\text{-cis}}$ $H_{1\text{-trans}}$).

^{13}C NMR (125 MHz, CD_3CN, 298K): δ ppm = 175.4 (C_{13}), 172.7 & 171.6 (C_{17} C_{18}), 153.2 (C_3), 148.5 & 148.4 ($C_{IV\ DB24C8}$), 130.7 & 130.4 (C_5), 129.6 (C_6), 126.5 & 126.3 (C_4), 122.5 &122.4 & 122.3 & 113.8 & 113.6 (C_A C_B), 71.6 (C_E $C_{E'}$), 71.3 & 71.1 (C_D $C_{D'}$), 69.0 (C_C $C_{C'}$), 53.1 (C_7), 46.6 & 46.2 (C_9), 45.1 (C_{10}), 37.5 (C_{12}), 35.2 (C_2), 34.3 (C_{15}), 33.7 (C_{14}), 32.5 (C_{16}), 31.3 (C_1).

HRMS (ESI): $[M\text{-}PF_6]^+$ calcd for $C_{44}H_{62}N_3O_{12}^+$: 824.4340, found: 824.4333.

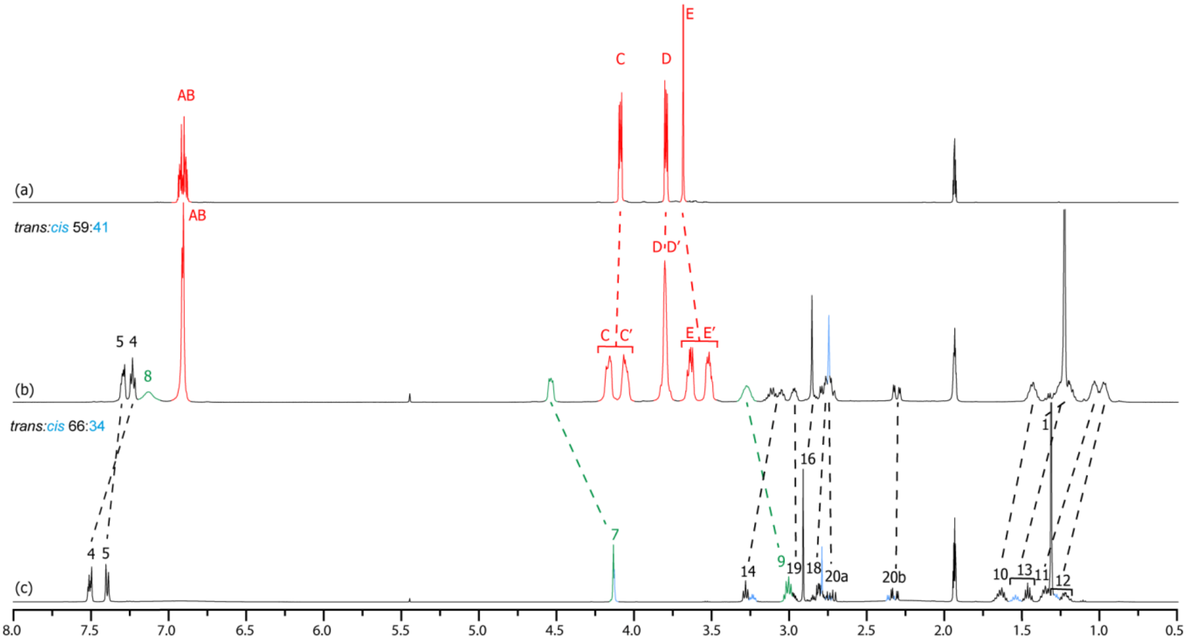
5. ^{1}H NMR characterization for rotaxanes 1-4

The interlocked structures of these compounds were unambiguously demonstrated by comparison between ^{1}H NMR spectra of free DB24C8, uncomplexed threads **2u-4u** and rotaxanes **2-4**. The following tables list the influence of DB24C8 on the 1H NMR chemical shifts of the encircle threads in the rotaxanes **2-4**.

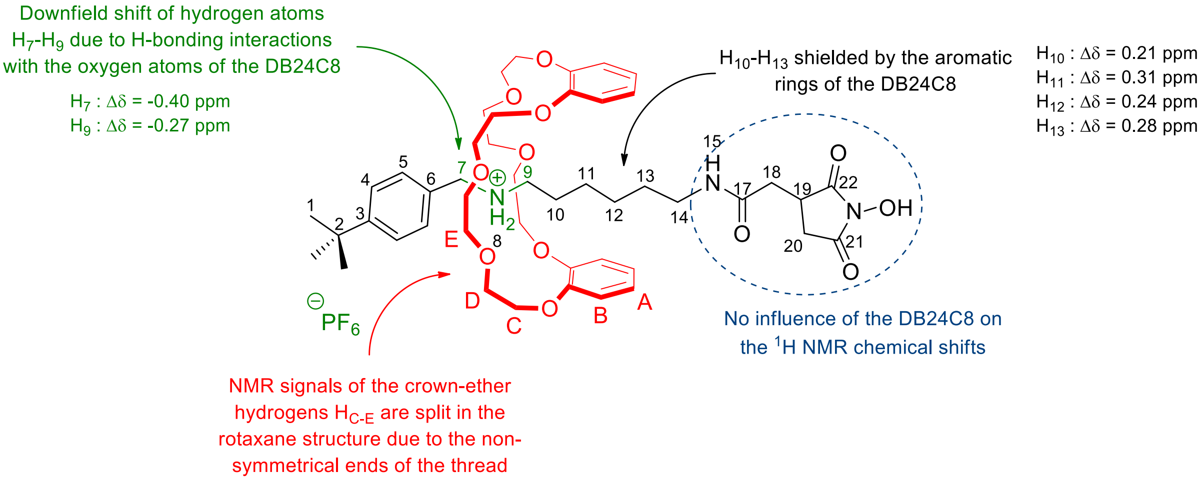
5.1. ^{1}H NMR characterization for rotaxane 1

Characterization of rotaxane **1** has already been described in a previous article[1].

5.2. ^{1}H NMR characterization for rotaxane 2



^{1}H NMR spectra (500 MHz, CD_3CN, 298K) of: (a) DB24C8, (b) the rotaxane **2** and (c) the uncomplexed thread **2u**.



Downfield shift of hydrogen atoms H_7-H_9 due to H-bonding interactions with the oxygen atoms of the DB24C8

H_7 : $\Delta\delta$ = -0.40 ppm
H_9 : $\Delta\delta$ = -0.27 ppm

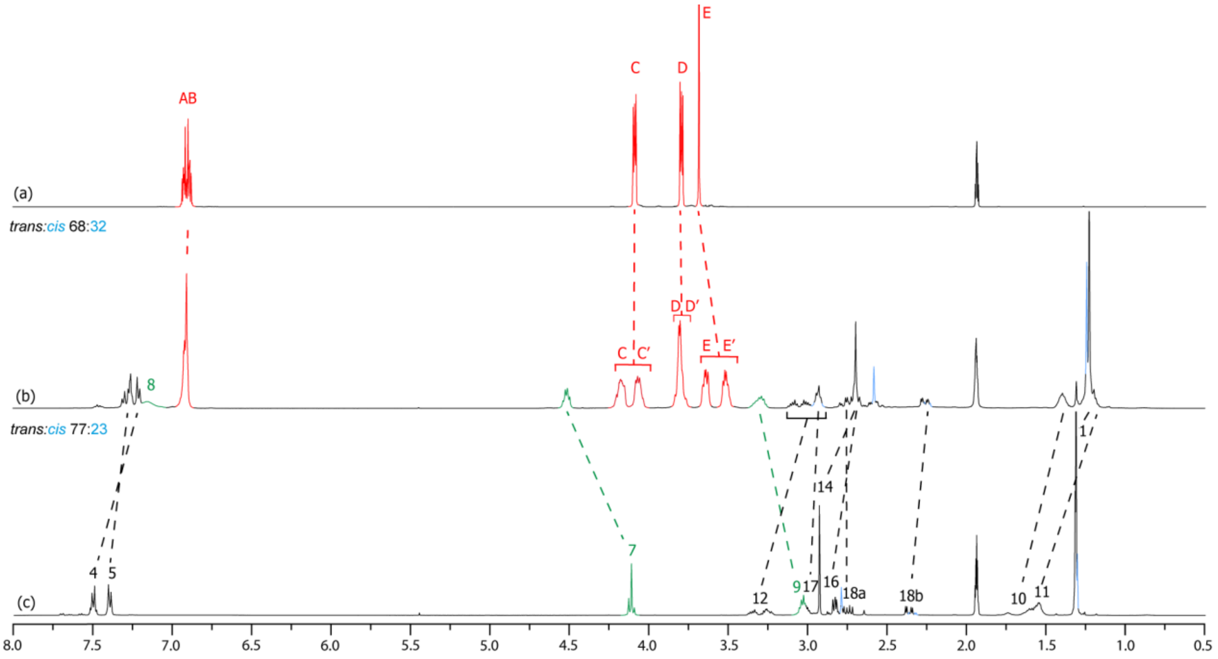
H_{10}-H_{13} shielded by the aromatic rings of the DB24C8

H_{10} : $\Delta\delta$ = 0.21 ppm
H_{11} : $\Delta\delta$ = 0.31 ppm
H_{12} : $\Delta\delta$ = 0.24 ppm
H_{13} : $\Delta\delta$ = 0.28 ppm

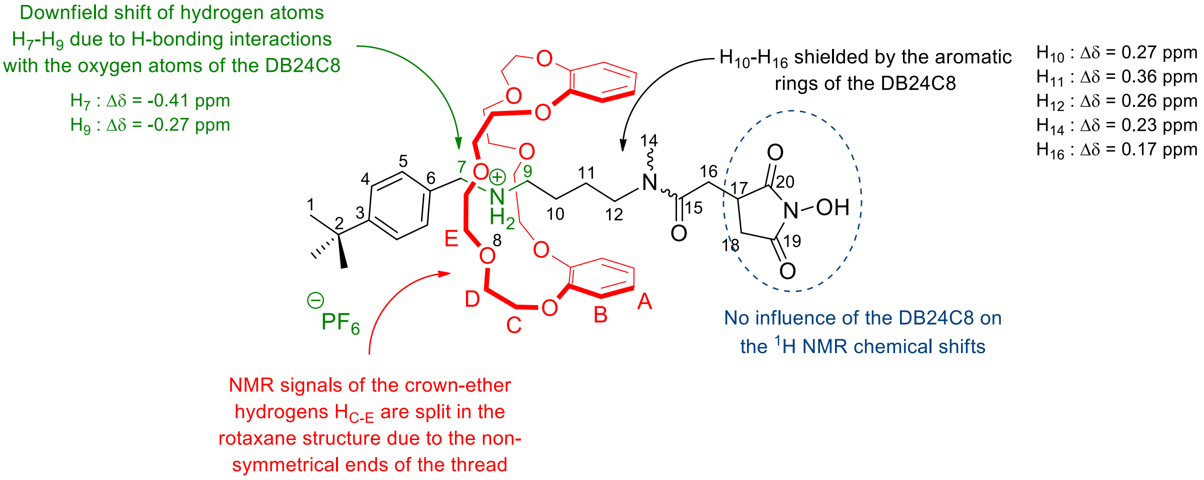
No influence of the DB24C8 on the ^1H NMR chemical shifts

NMR signals of the crown-ether hydrogens H_{C-E} are split in the rotaxane structure due to the non-symmetrical ends of the thread

5.3. ¹H NMR characterization for rotaxane 3



^1H NMR spectra (500 MHz, CD_3CN, 298K) of: (a) DB24C8, (b) the rotaxane **3** and (c) the uncomplexed thread **3u**.



Downfield shift of hydrogen atoms H_7-H_9 due to H-bonding interactions with the oxygen atoms of the DB24C8

H_7 : $\Delta\delta$ = -0.41 ppm
H_9 : $\Delta\delta$ = -0.27 ppm

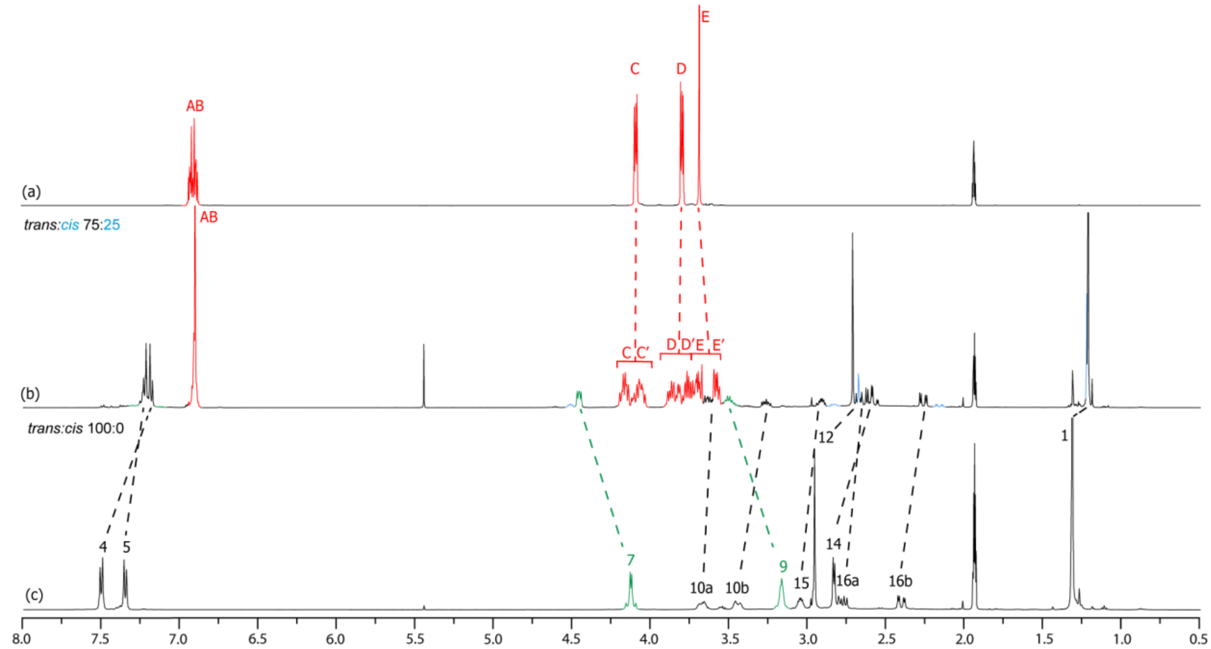
H_{10}-H_{16} shielded by the aromatic rings of the DB24C8

H_{10} : $\Delta\delta$ = 0.27 ppm
H_{11} : $\Delta\delta$ = 0.36 ppm
H_{12} : $\Delta\delta$ = 0.26 ppm
H_{14} : $\Delta\delta$ = 0.23 ppm
H_{16} : $\Delta\delta$ = 0.17 ppm

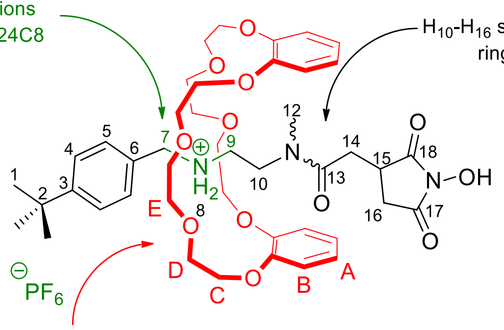
No influence of the DB24C8 on the ^1H NMR chemical shifts

NMR signals of the crown-ether hydrogens H_{C-E} are split in the rotaxane structure due to the non-symmetrical ends of the thread

5.4. ^{1}H NMR characterization for rotaxane 4



^{1}H NMR spectra (500 MHz, CD_3CN, 298K) of: (a) DB24C8, (b) the rotaxane **4** and (c) the uncomplexed thread **4u**.



Downfield shift of hydrogen atoms H_7-H_9 due to H-bonding interactions with the oxygen atoms of the DB24C8

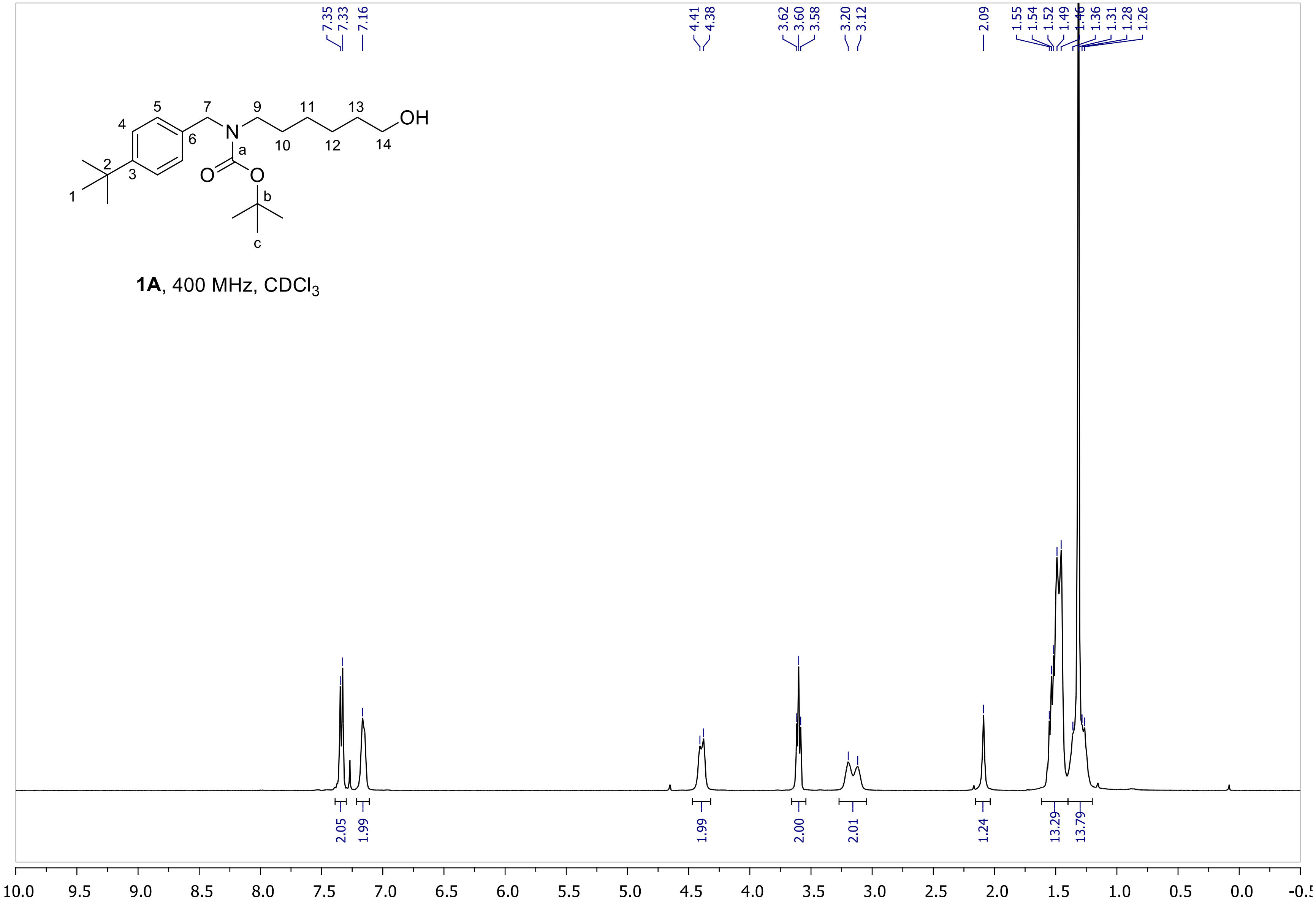
H_7 : Δδ = -0.31 ppm
H_9 : Δδ = -0.31 ppm

H_{10}-H_{16} shielded by the aromatic rings of the DB24C8

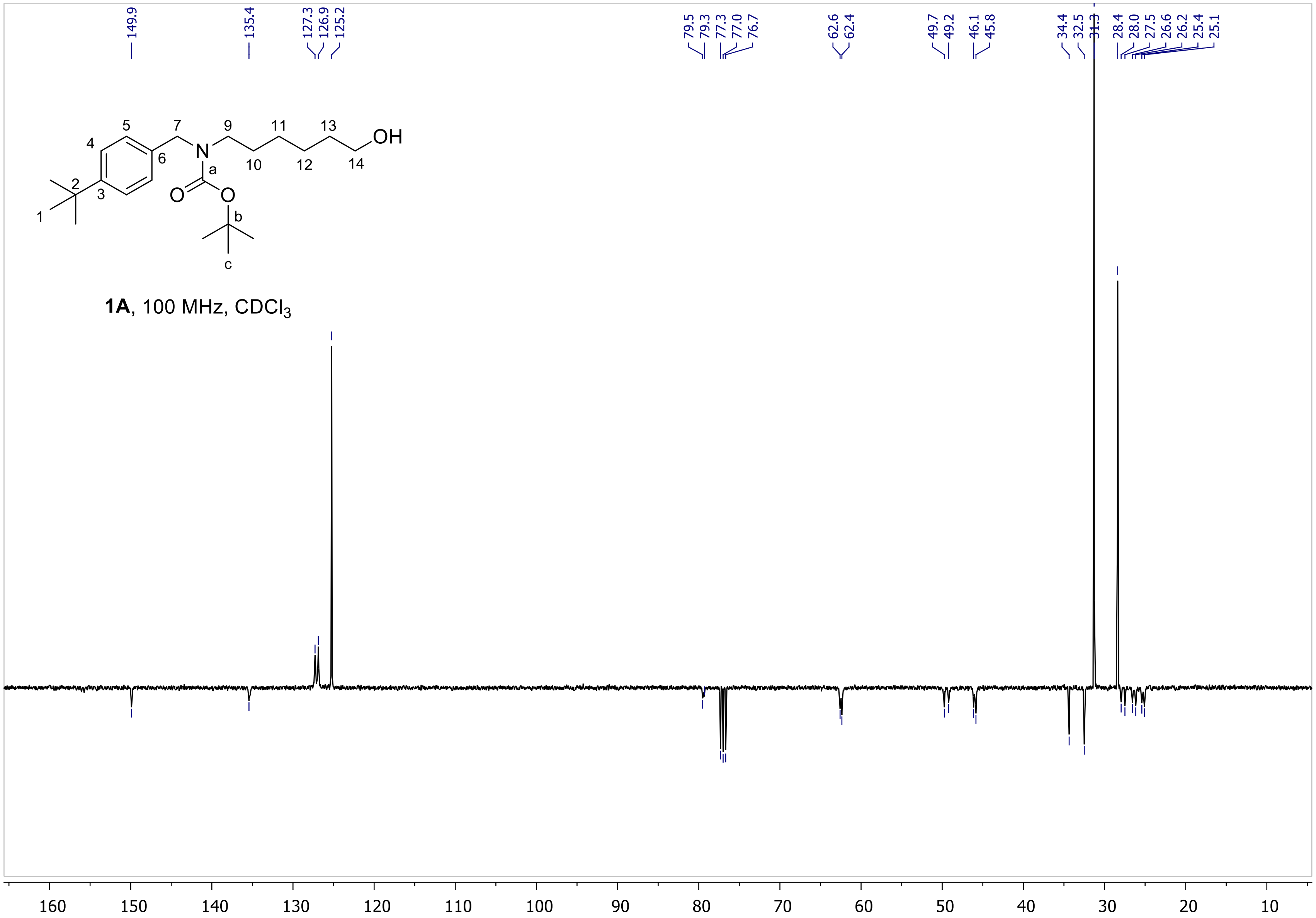
H_{10} : Δδ = 0.14 ppm
H_{12} : Δδ = 0.23 ppm
H_{14} : Δδ = 0.24 ppm
H_{15} : Δδ = 0.14 ppm
H_{16a} : Δδ = 0.10 ppm
H_{16b} : Δδ = 0.14 ppm

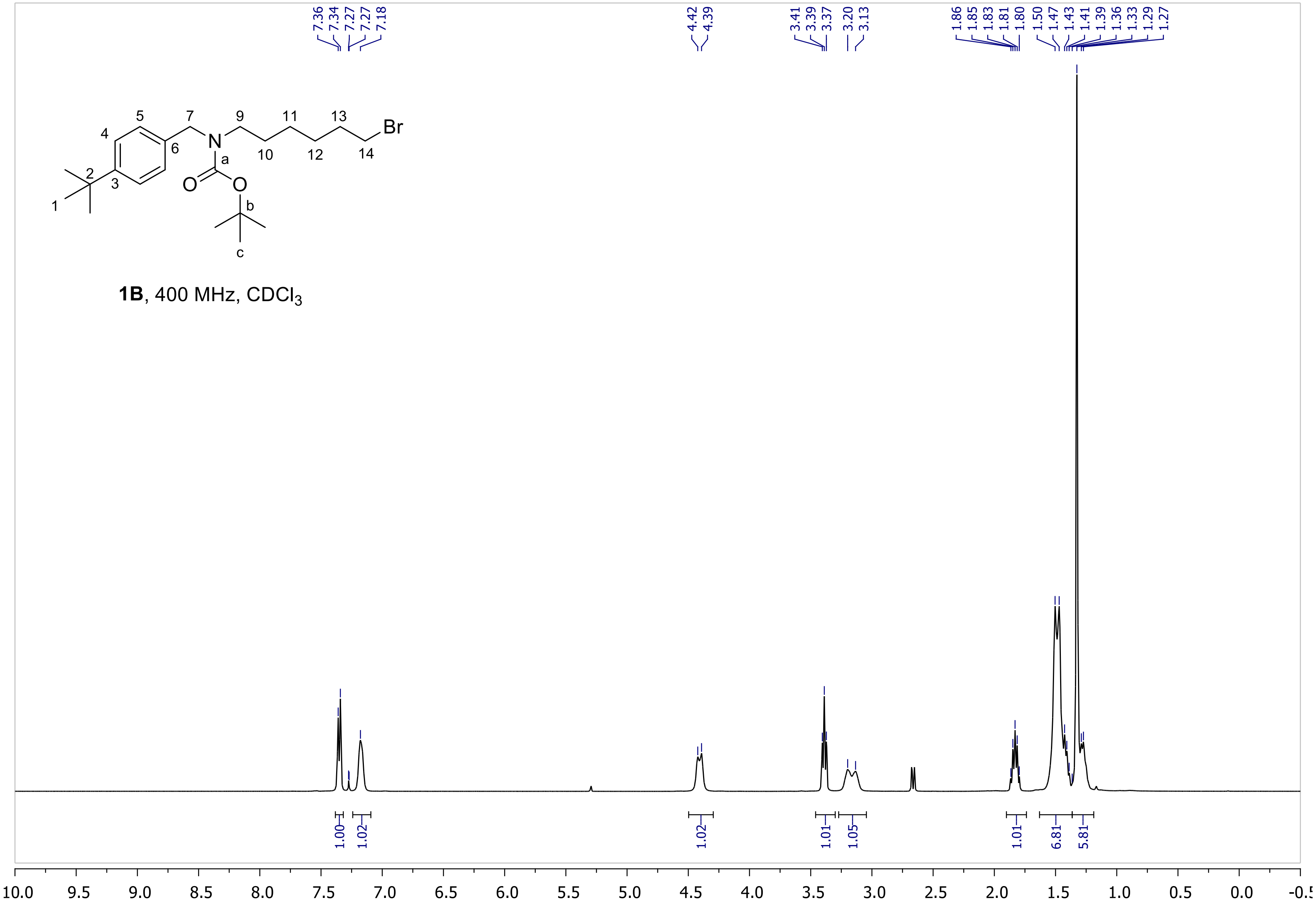
NMR signals of the crown-ether hydrogens H_{C-E} are split in the rotaxane structure due to the non-symmetrical ends of the thread

NMR SPECTRA

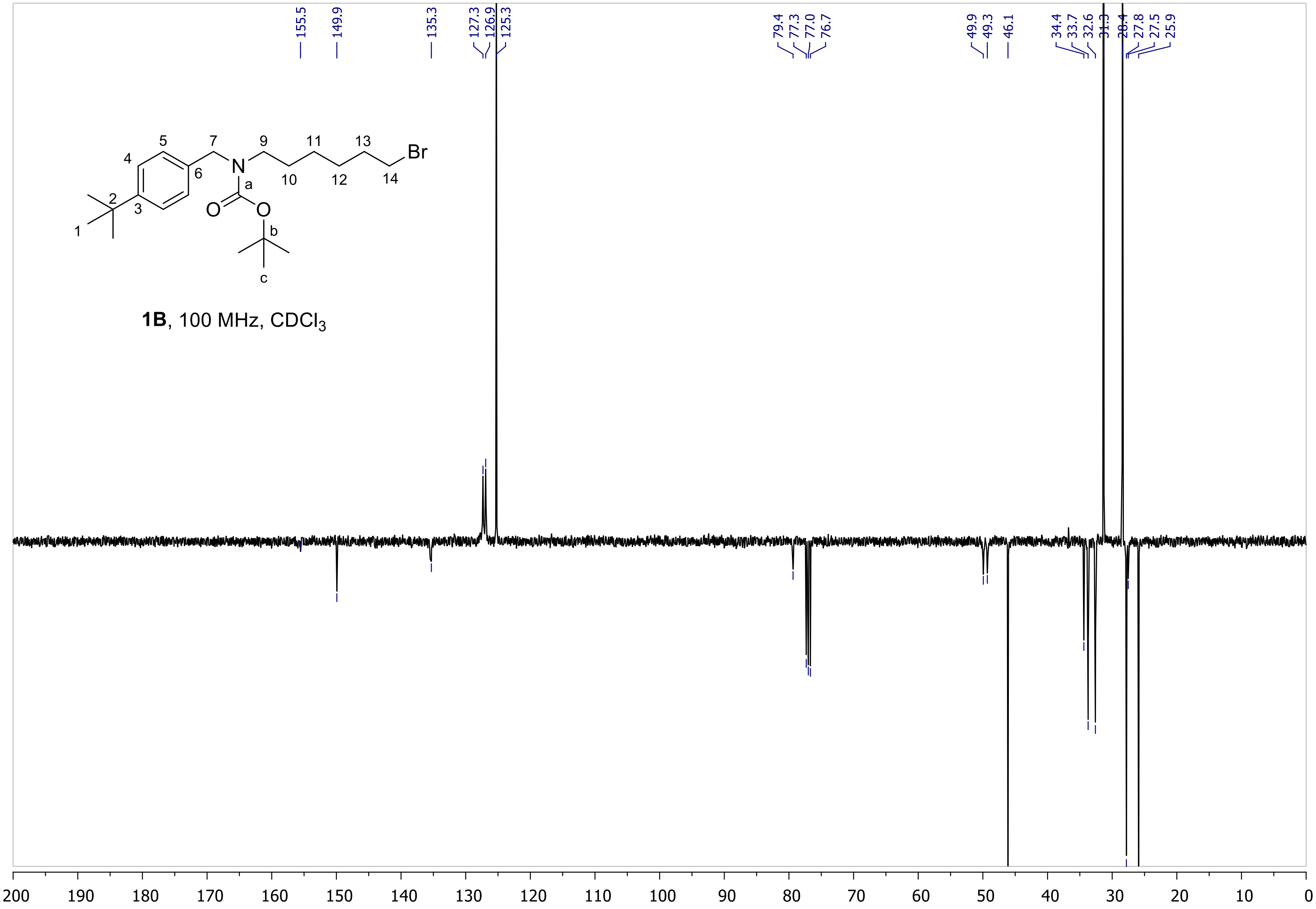


1A, 400 MHz, $CDCl_3$

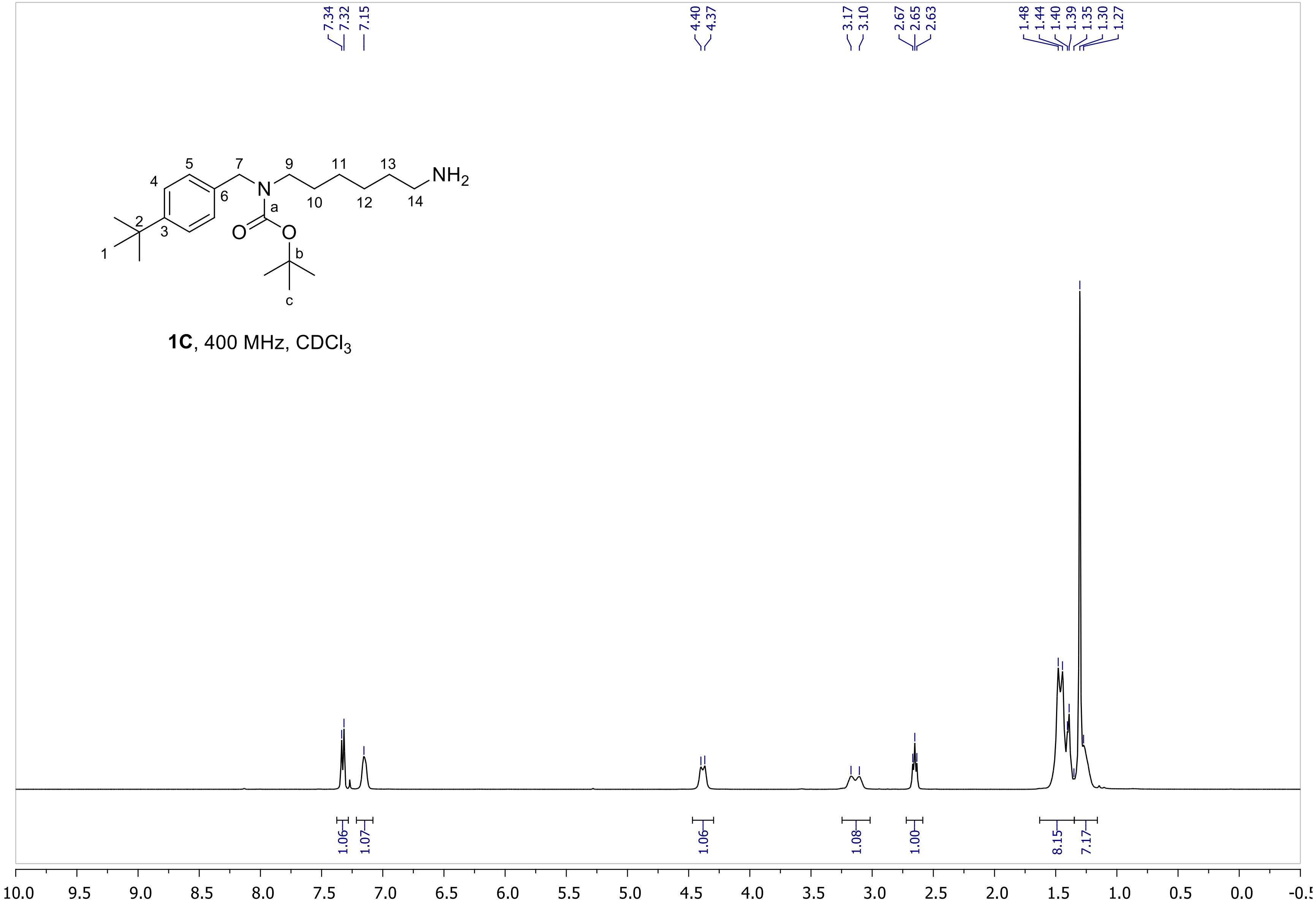

1A, 100 MHz, $CDCl_3$

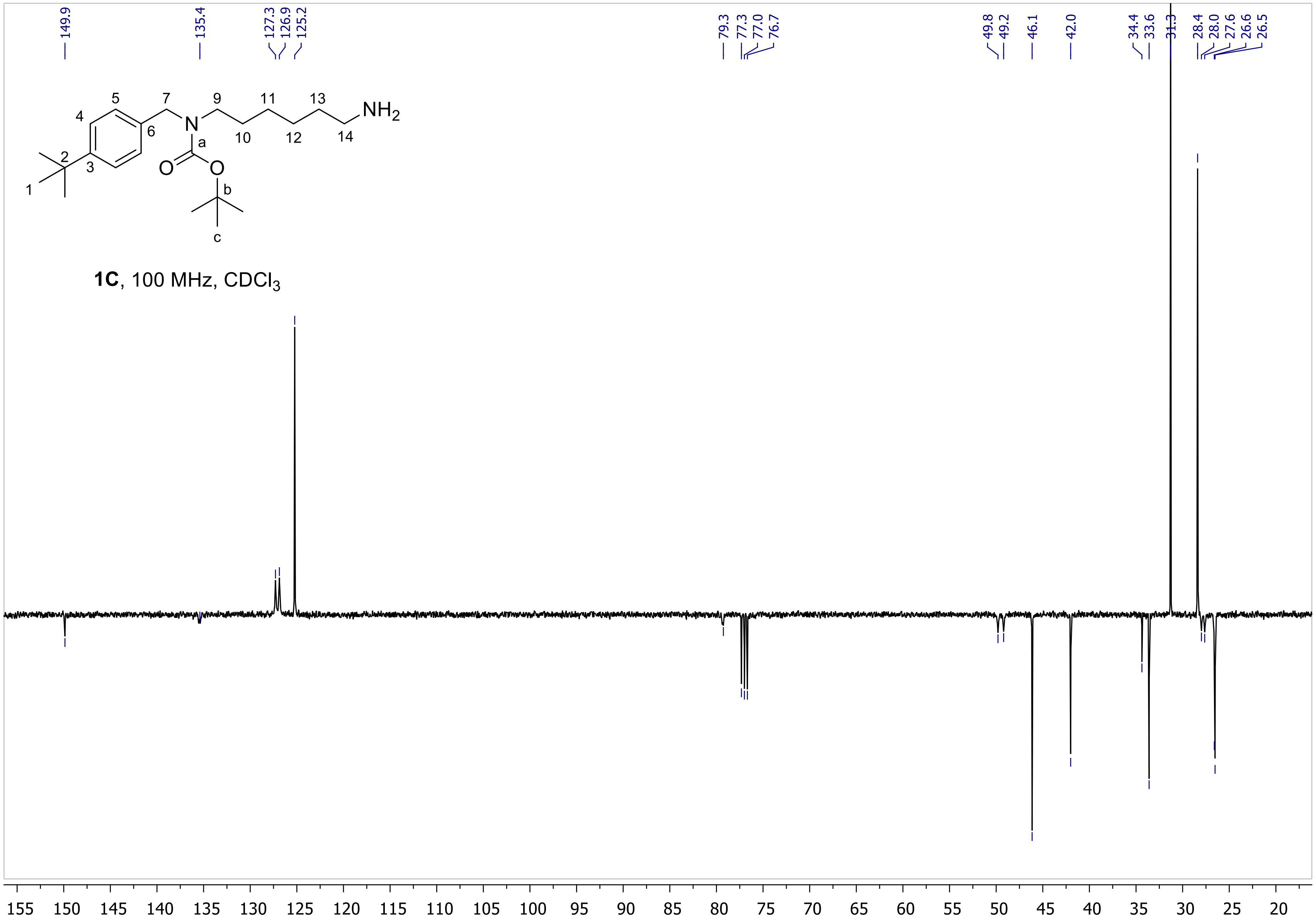


1B, 400 MHz, CDCl$_3$

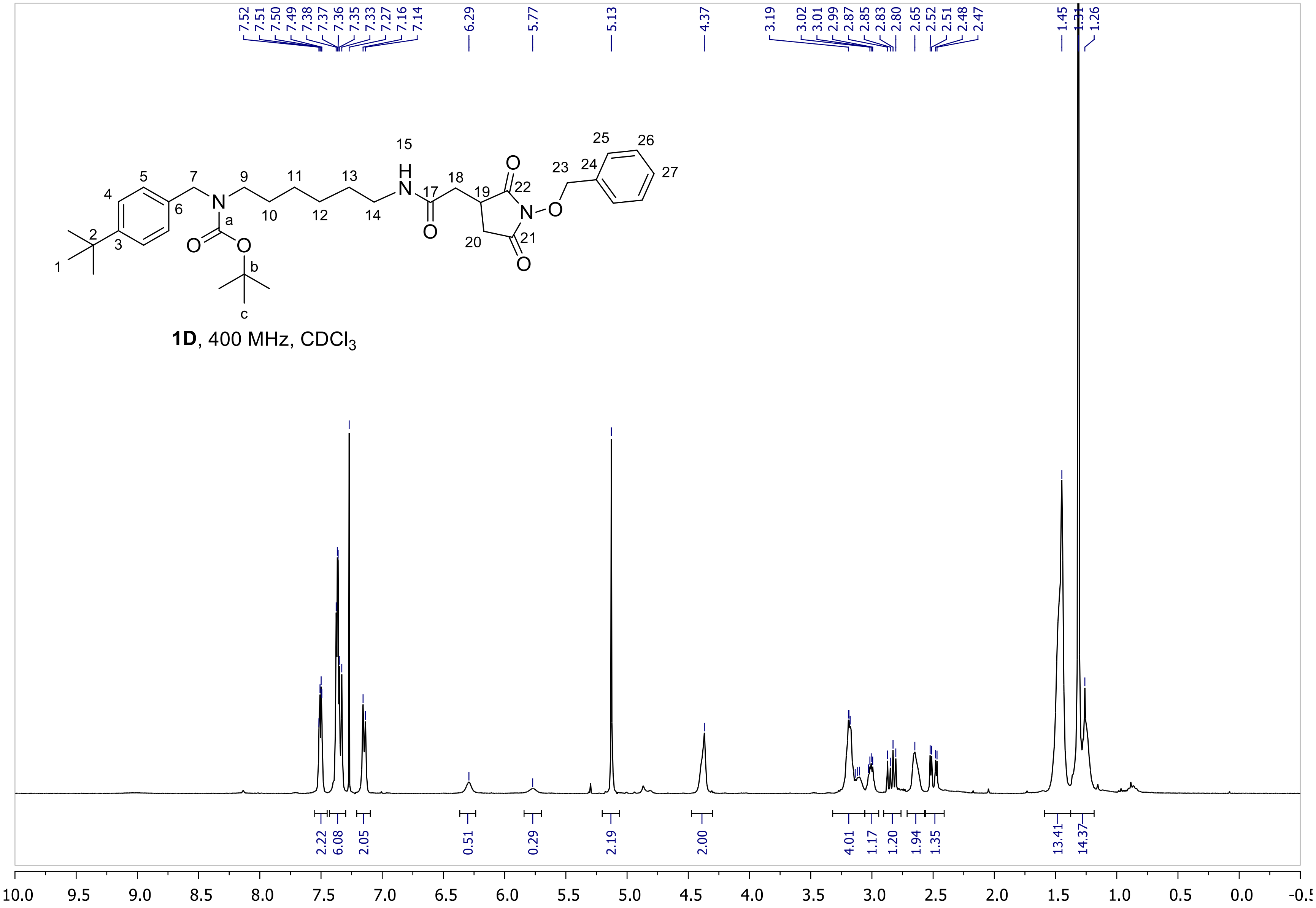


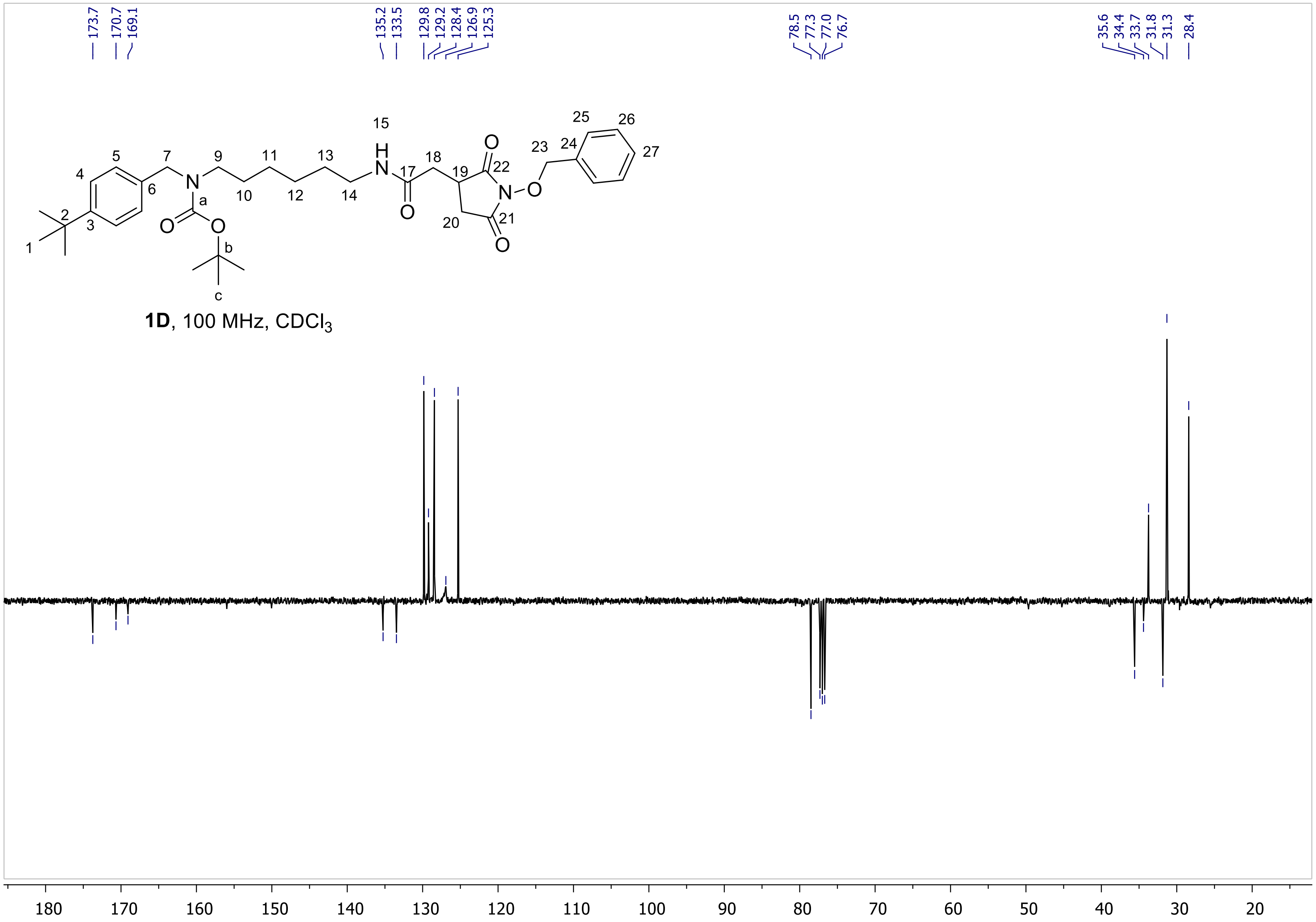
1B, 100 MHz, CDCl$_3$

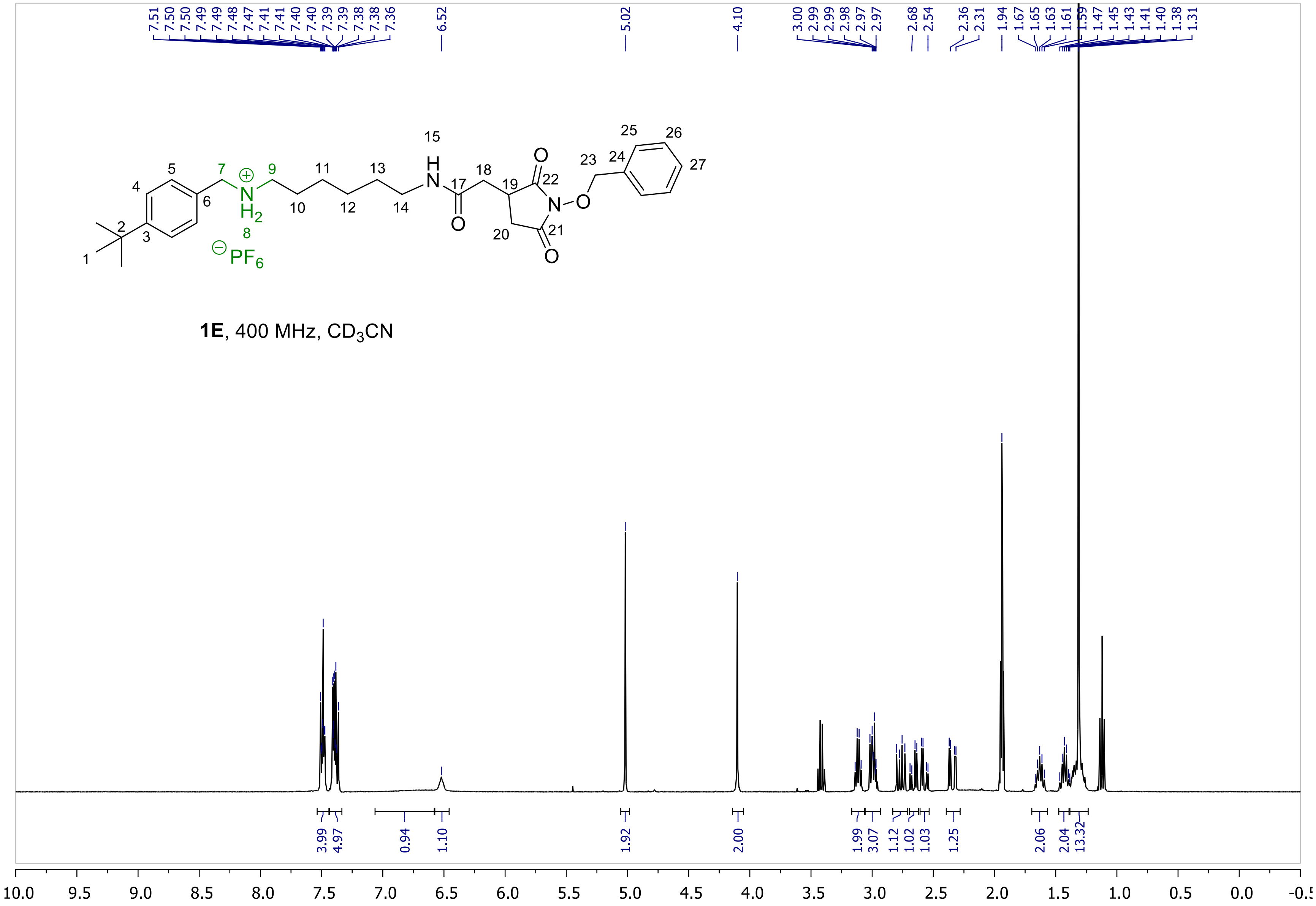

7.34
7.32
7.15
4.40
4.37
3.17
3.10
2.67
2.65
2.63
1.48
1.44
1.40
1.39
1.35
1.30
1.27
1
2
3
4
5
6
7
9
10
11
12
13
14
a
b
c
N
O
O
NH2
1C, 400 MHz, CDCl3
1.06
1.07
1.06
1.08
1.00
8.15
7.17
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5



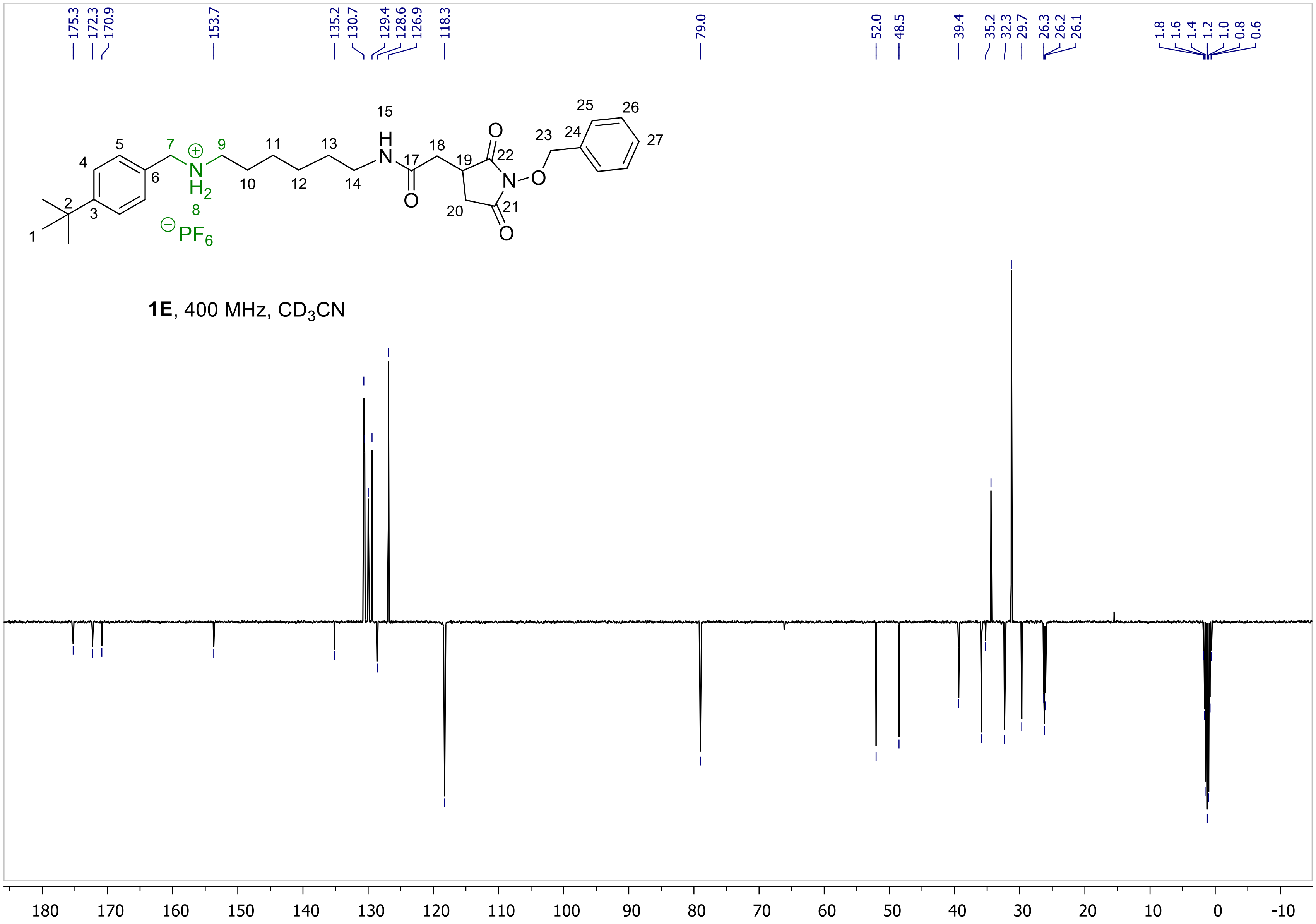
1C, 100 MHz, CDCl$_3$

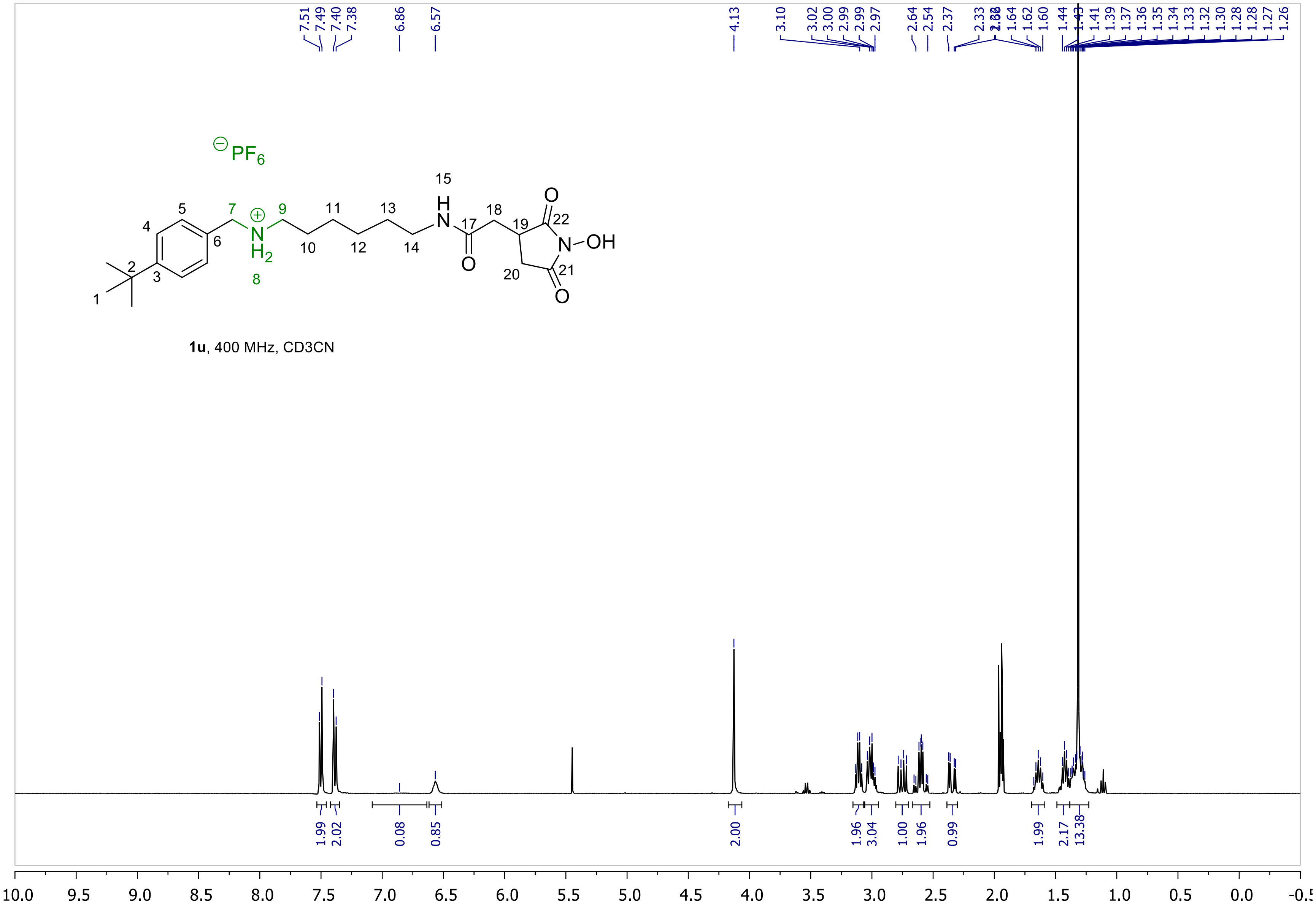

7.52
7.51
7.50
7.49
7.38
7.37
7.36
7.35
7.33
7.27
7.16
7.14
6.29
5.77
5.13
4.37
3.19
3.02
3.01
2.99
2.87
2.85
2.83
2.80
2.65
2.52
2.51
2.48
2.47
1.45
1.31
1.26
1
2
3
4
5
6
7
a
b
c
9
10
11
12
13
14
15
17
18
19
20
21
22
23
24
25
26
27
N
H
O
1D, 400 MHz, CDCl3
2.22
6.08
2.05
0.51
0.29
2.19
2.00
4.01
1.17
1.20
1.94
1.35
13.41
14.37
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5

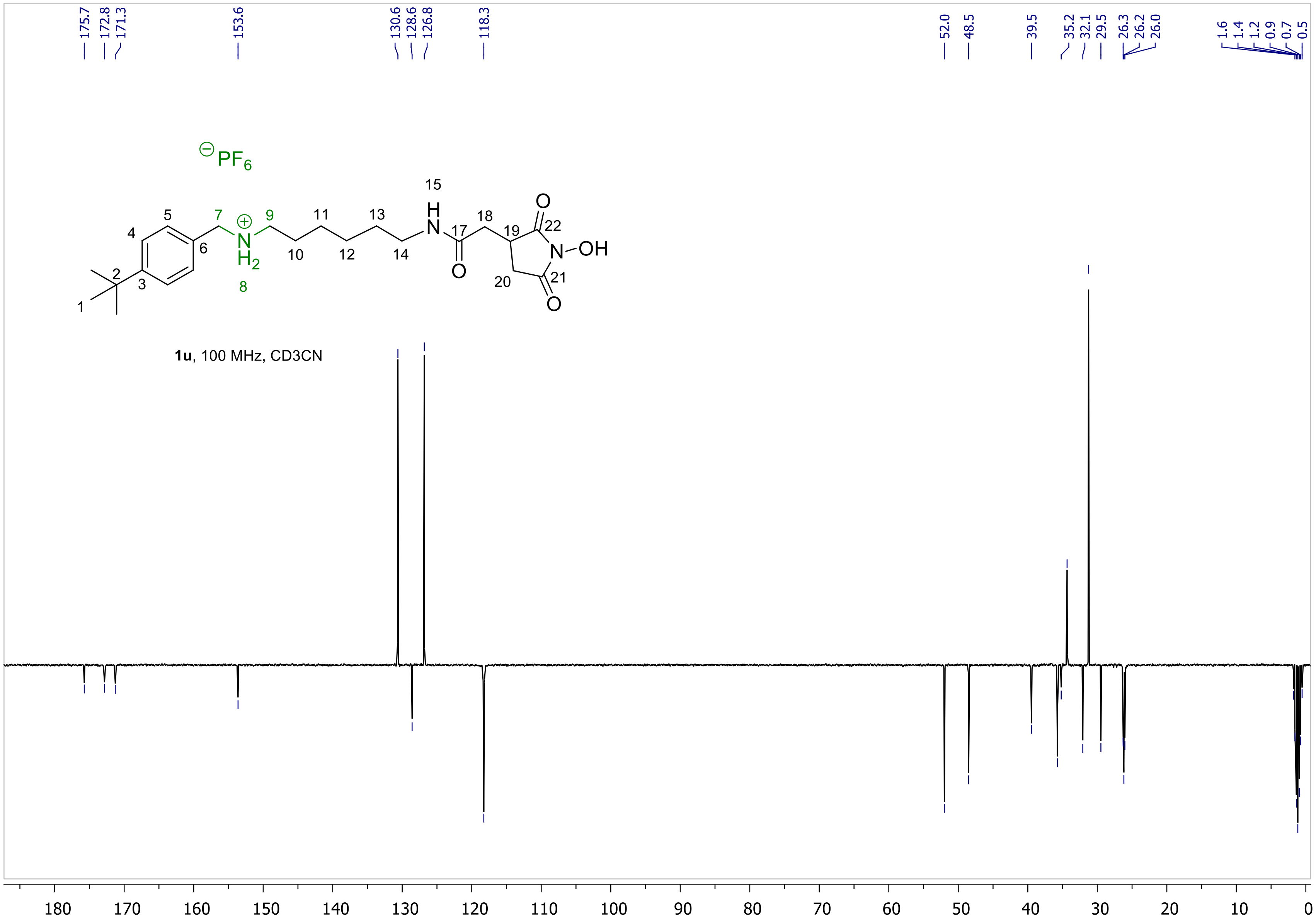

1D, 100 MHz, $CDCl_3$

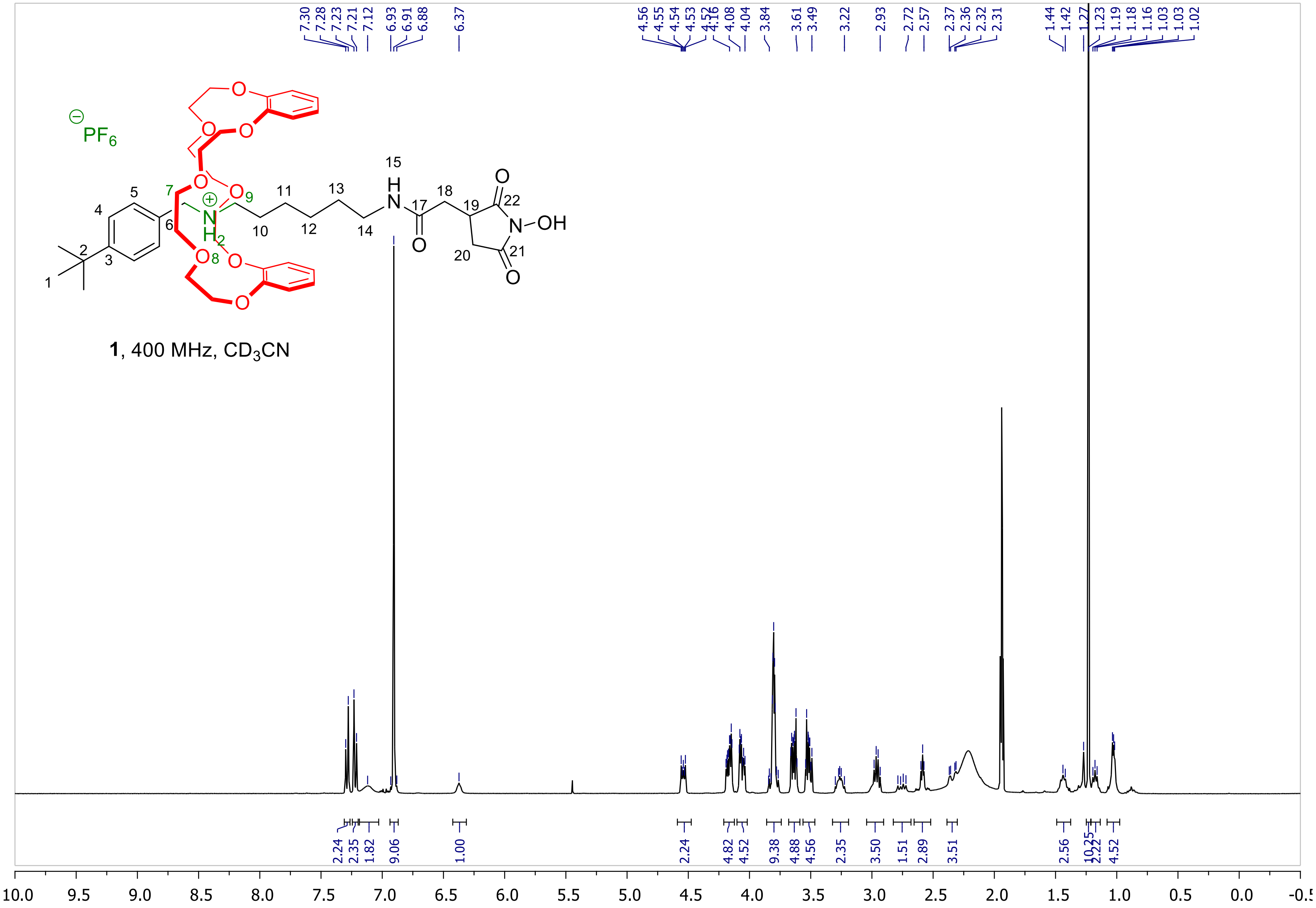


1E, 400 MHz, CD_3CN

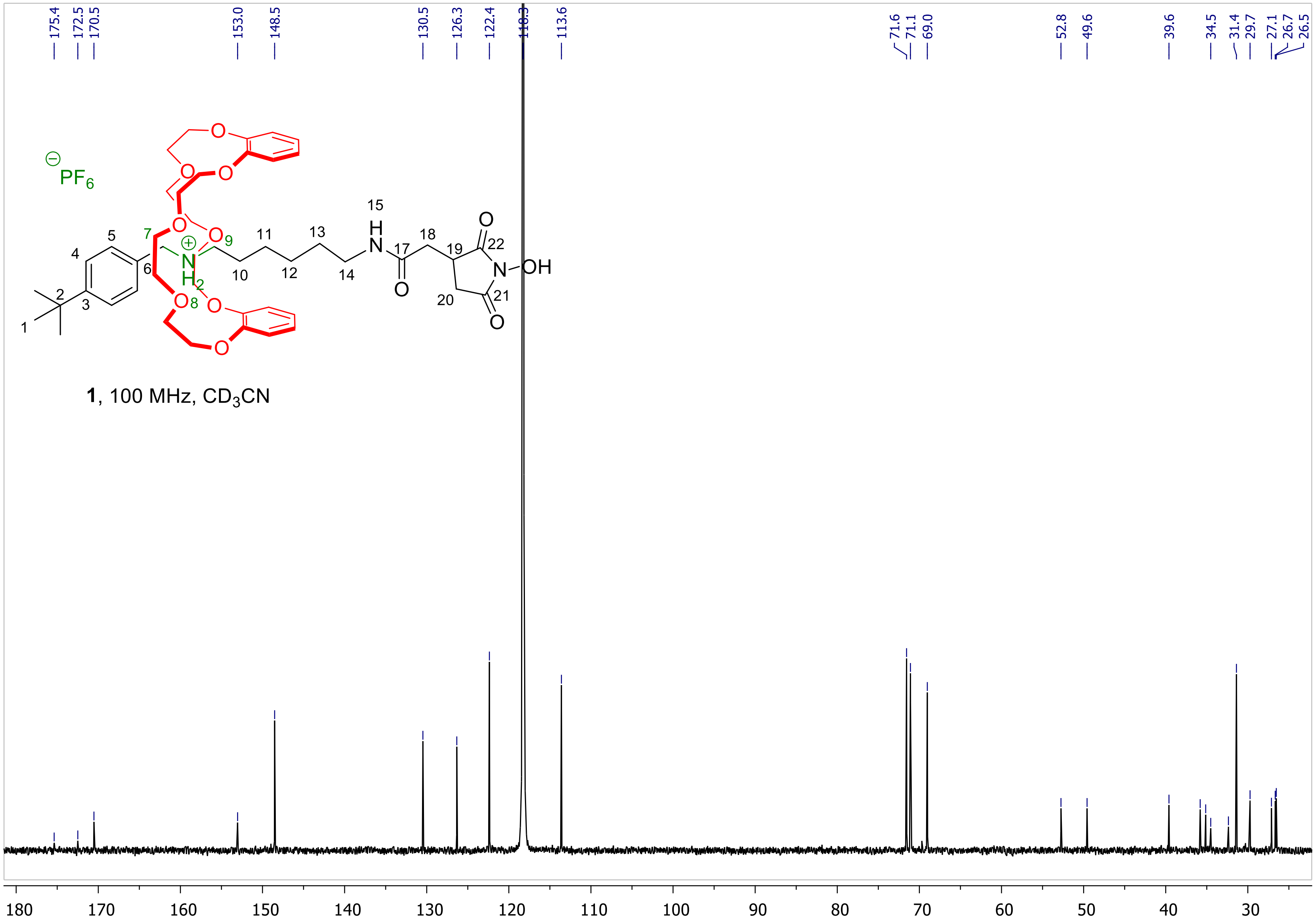

175.3
172.3
170.9
153.7
135.2
130.7
129.4
128.6
126.9
118.3
79.0
52.0
48.5
39.4
35.2
32.3
29.7
26.3
26.2
26.1
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
18
19
20
21
22
23
24
25
26
27
$\oplus$ N H$_2$
$\ominus$PF$_6$
H N
O
N–O
1E, 400 MHz, CD$_3$CN
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

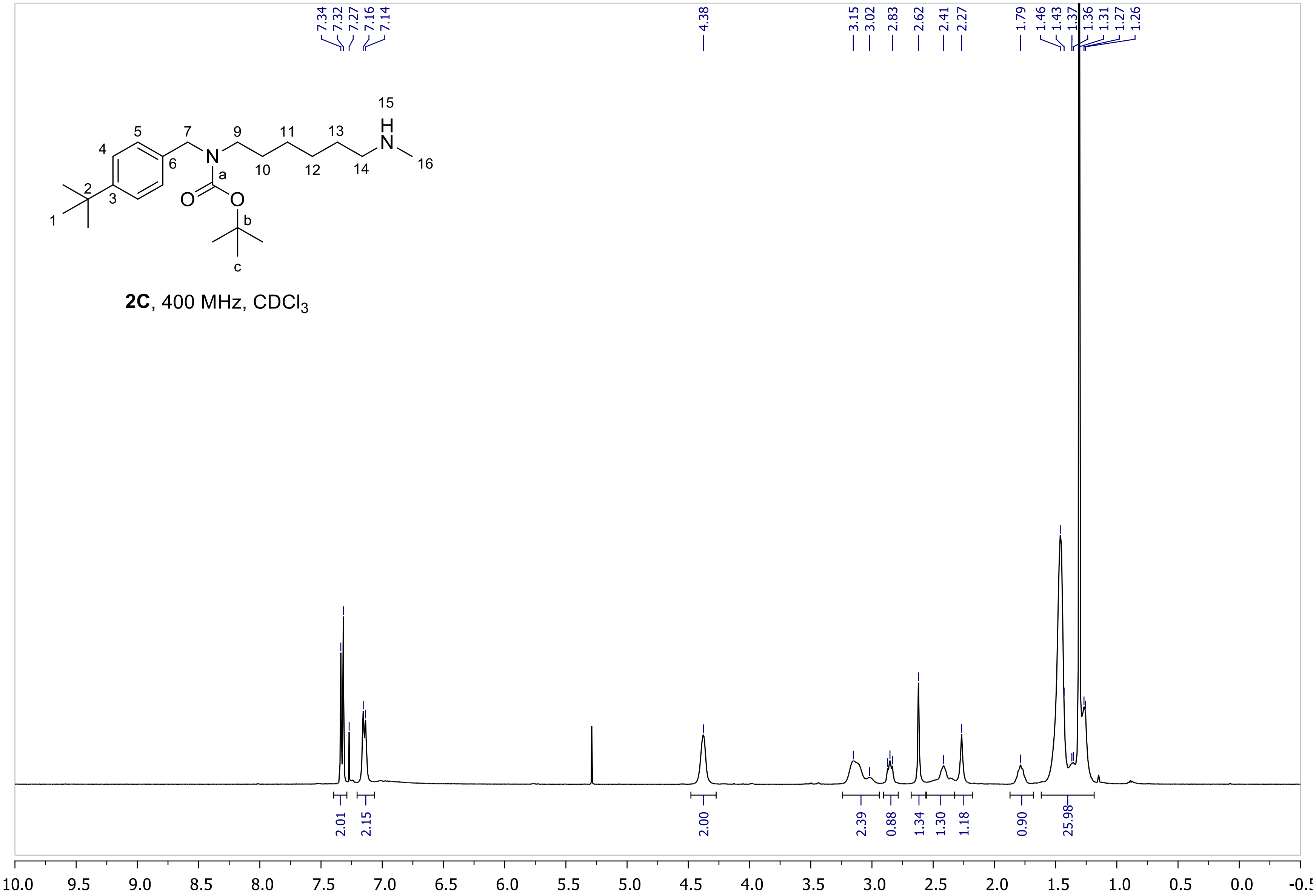
7.51
7.49
7.40
7.38
6.86
6.57
4.13
3.10
3.02
3.00
2.99
2.99
2.97
2.64
2.54
2.37
2.33
1.64
1.62
1.60
1.44
1.43
1.41
1.39
1.37
1.36
1.35
1.34
1.33
1.32
1.30
1.28
1.27
1.26
⊖PF6
15
H
N
O
OH
1
2
3
4
5
6
7
8
H2
9
10
11
12
13
14
17
18
19
20
21
22
1u, 400 MHz, CD3CN
1.99
2.02
0.08
0.85
2.00
1.96
3.04
1.00
1.96
0.99
1.99
2.17
13.38
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5

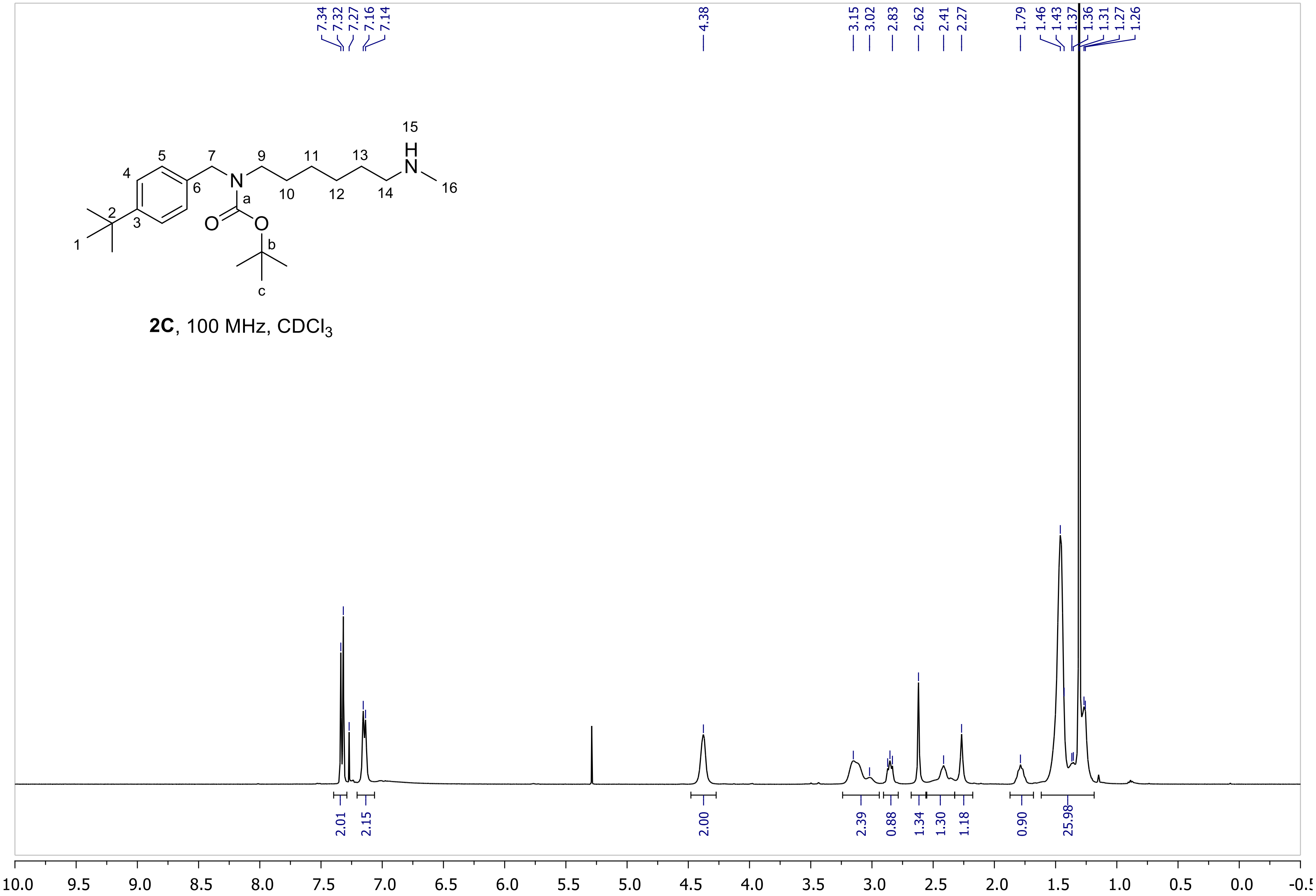

175.7
172.8
171.3
153.6
130.6
128.6
126.8
118.3
52.0
48.5
39.5
35.2
32.1
29.5
26.3
26.2
26.0
1.6
1.4
1.2
0.9
0.7
0.5
⊖PF6
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
18
19
20
21
22
N
H2
H
N
O
N-OH
O
O
1u, 100 MHz, CD3CN
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0



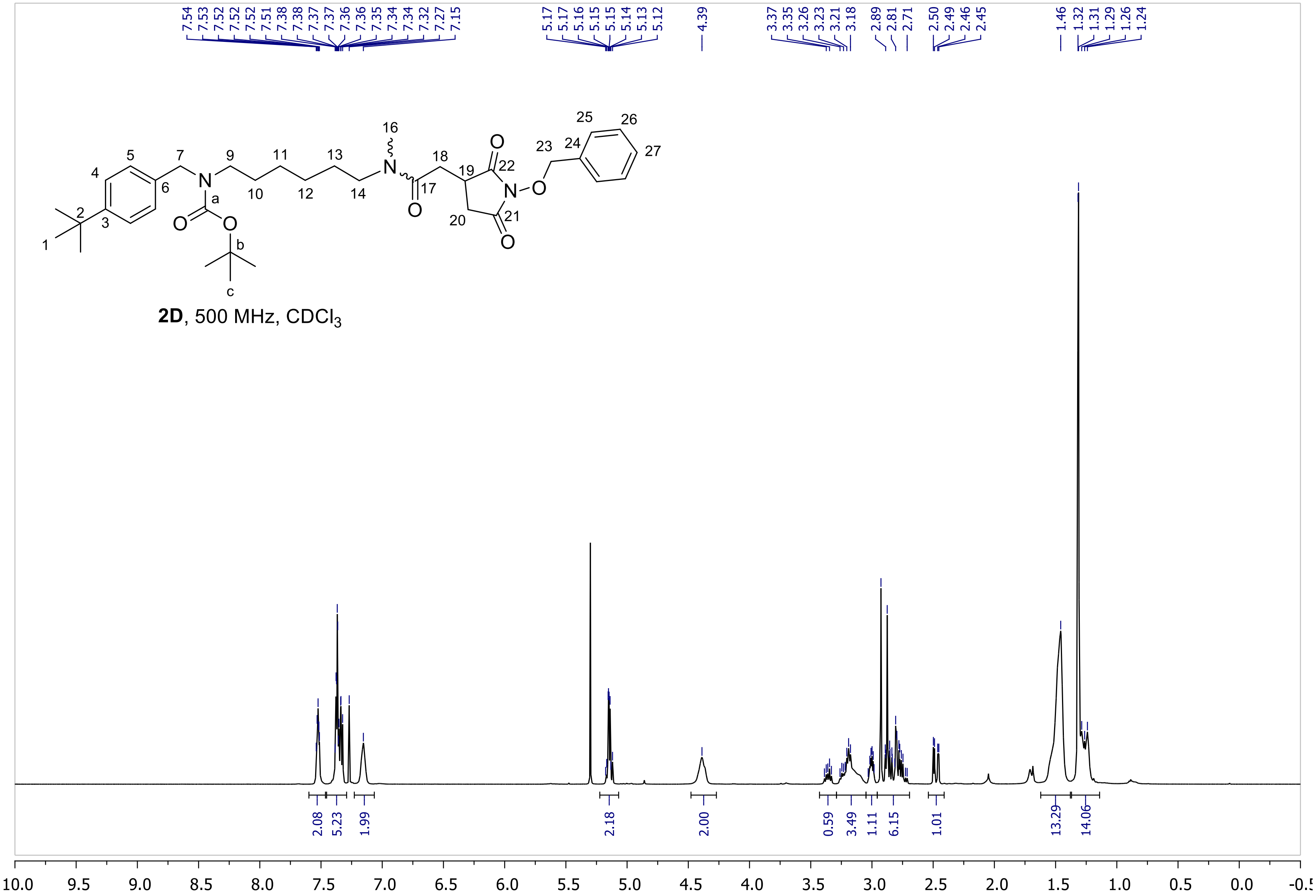
1, 400 MHz, CD_3CN


175.4
172.5
170.5
153.0
148.5
130.5
126.3
122.4
118.3
113.6
71.6
71.1
69.0
52.8
49.6
39.6
34.5
31.4
29.7
27.1
26.7
26.5
PF6
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
18
19
20
21
22
N
H
OH
O
1, 100 MHz, CD3CN
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30

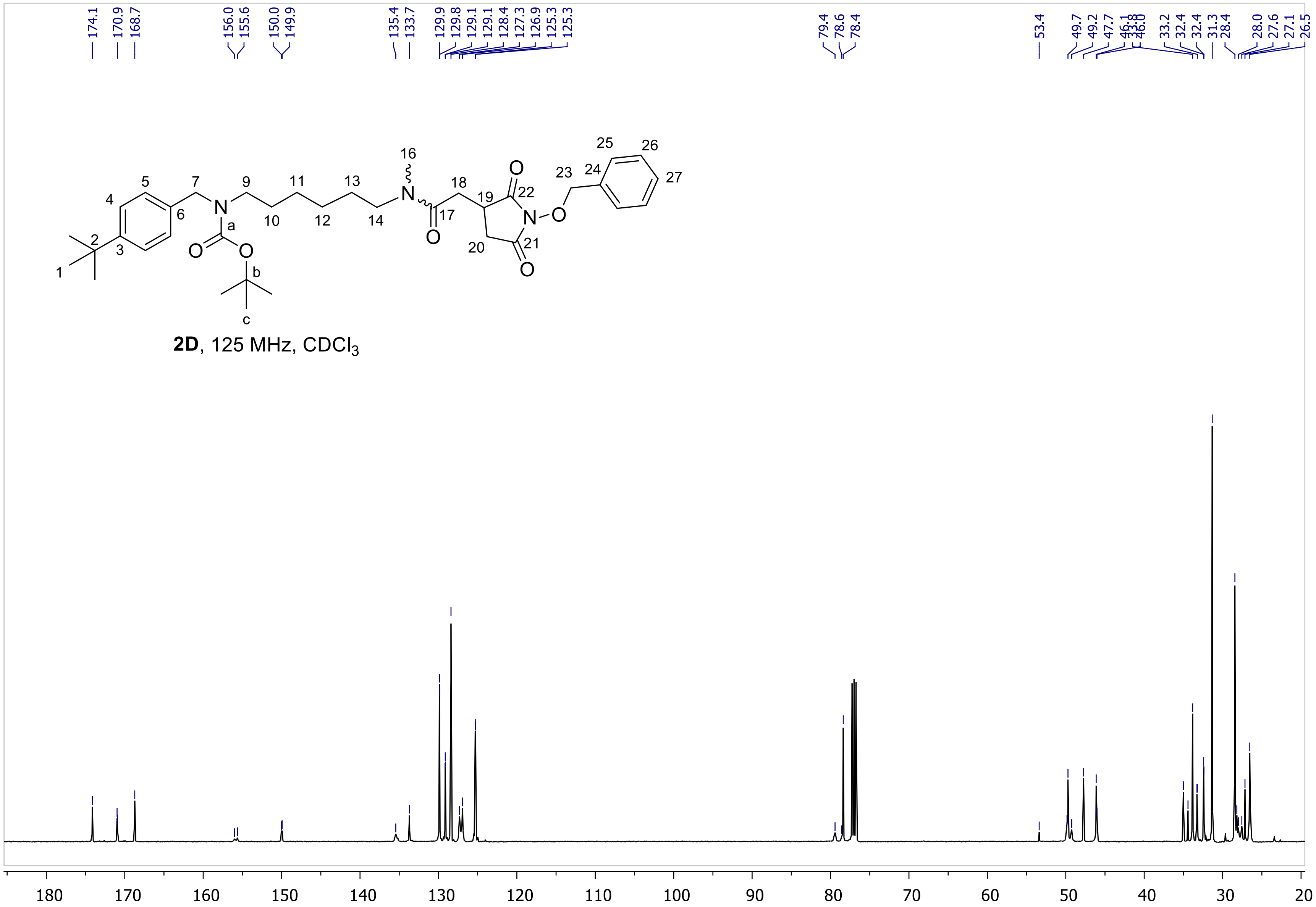

2C, 400 MHz, $CDCl_3$



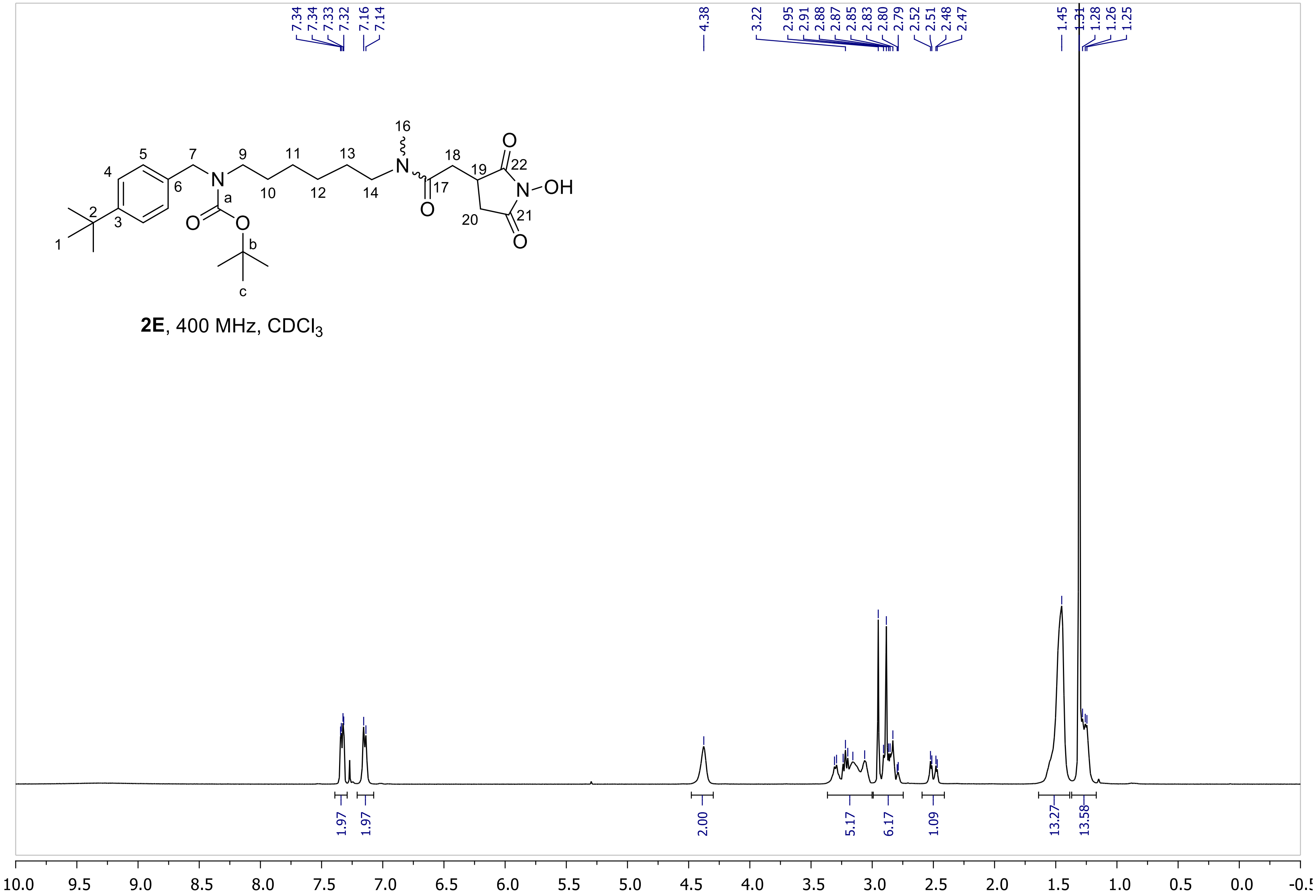
2C, 100 MHz, $CDCl_3$



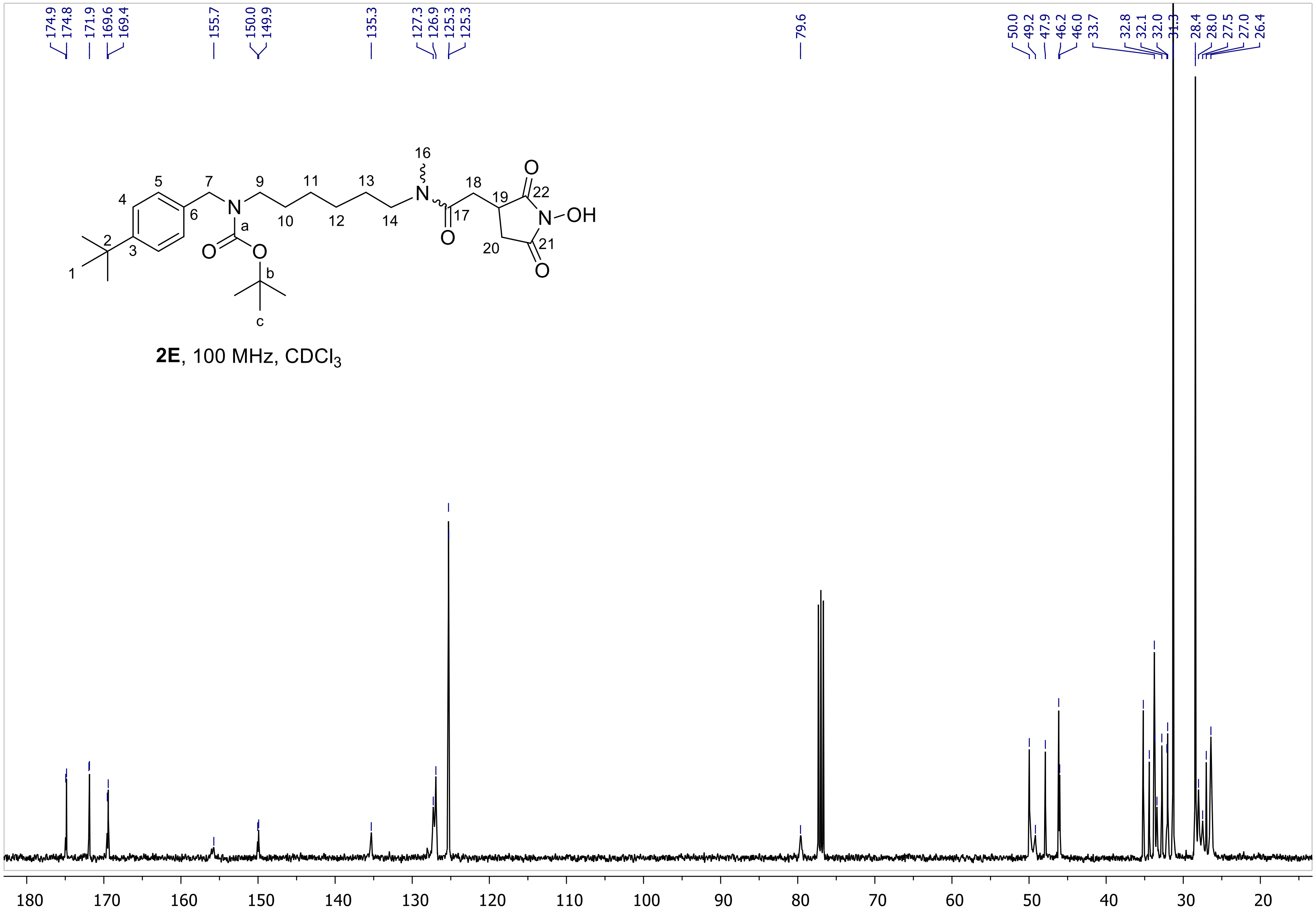
2D, 500 MHz, $CDCl_3$



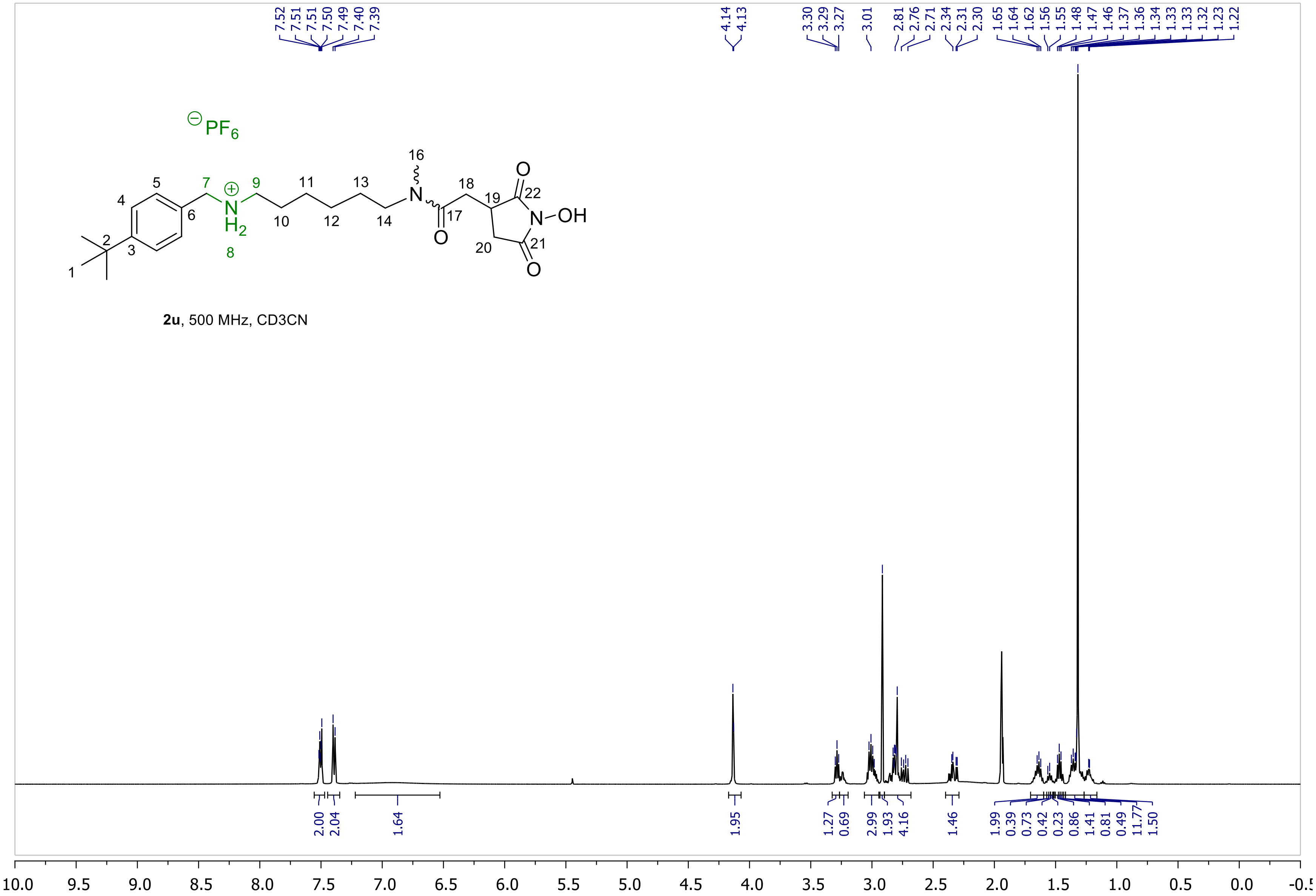
2D, 125 MHz, $CDCl_3$



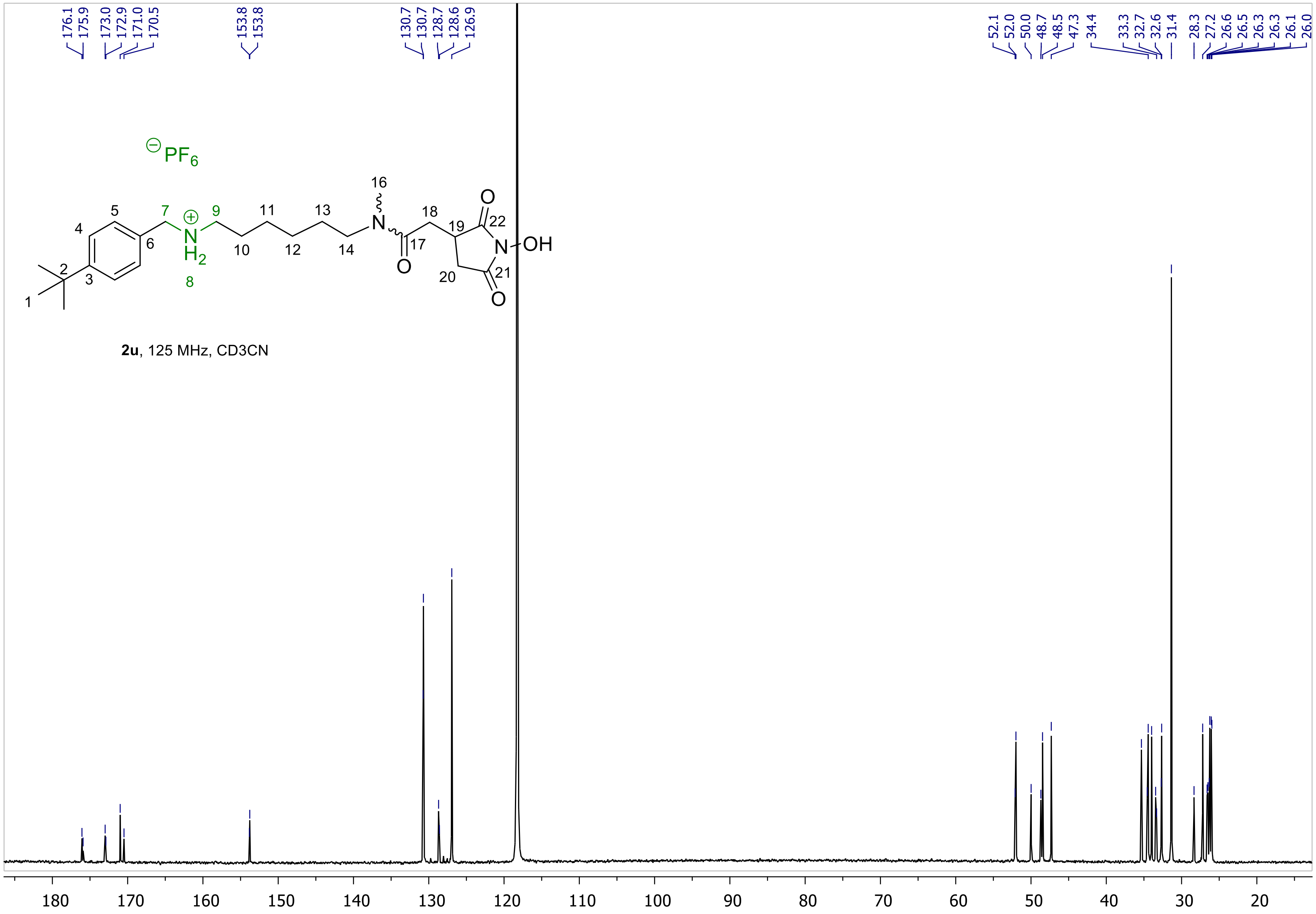
2E, 400 MHz, $CDCl_3$

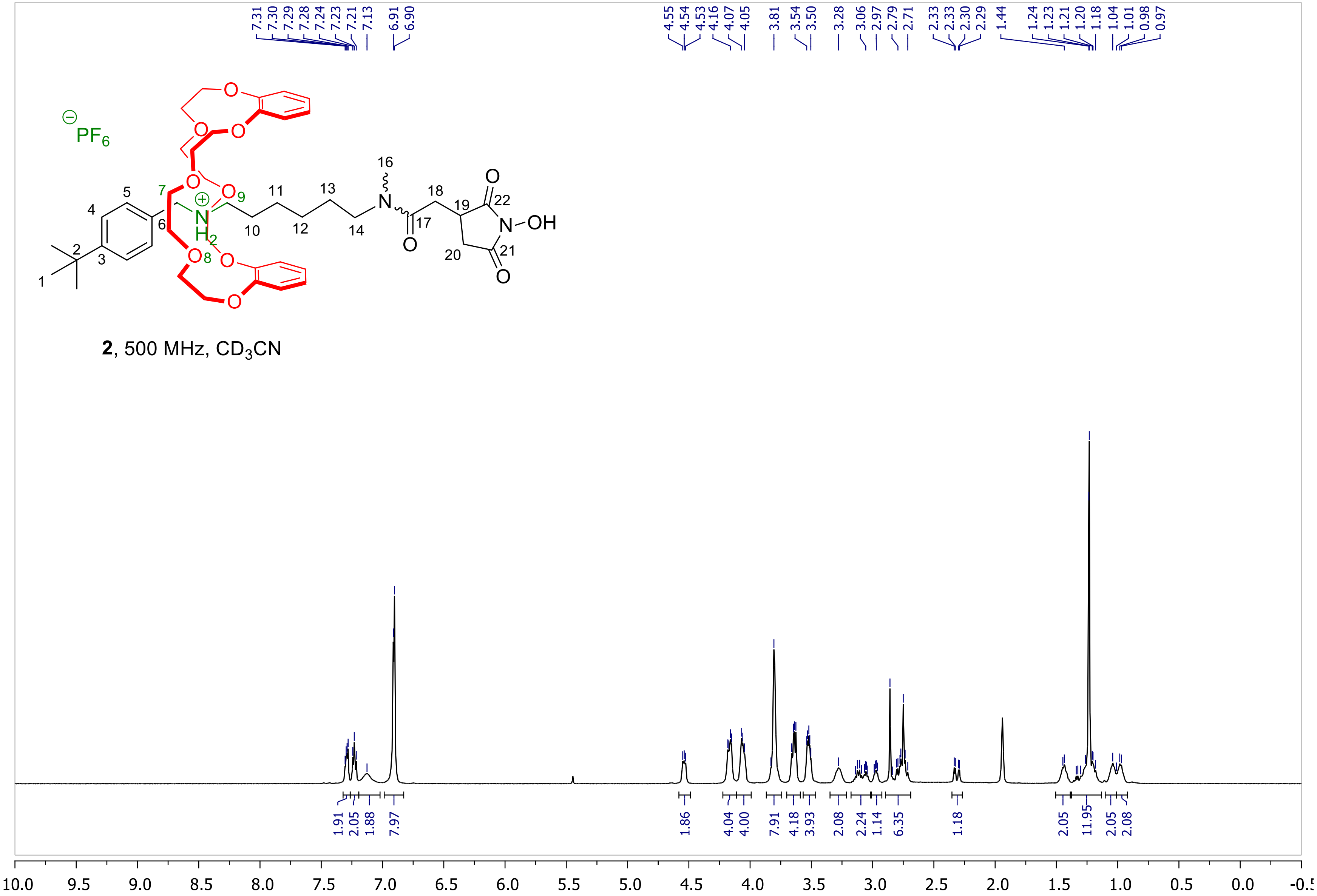


2E, 100 MHz, $CDCl_3$

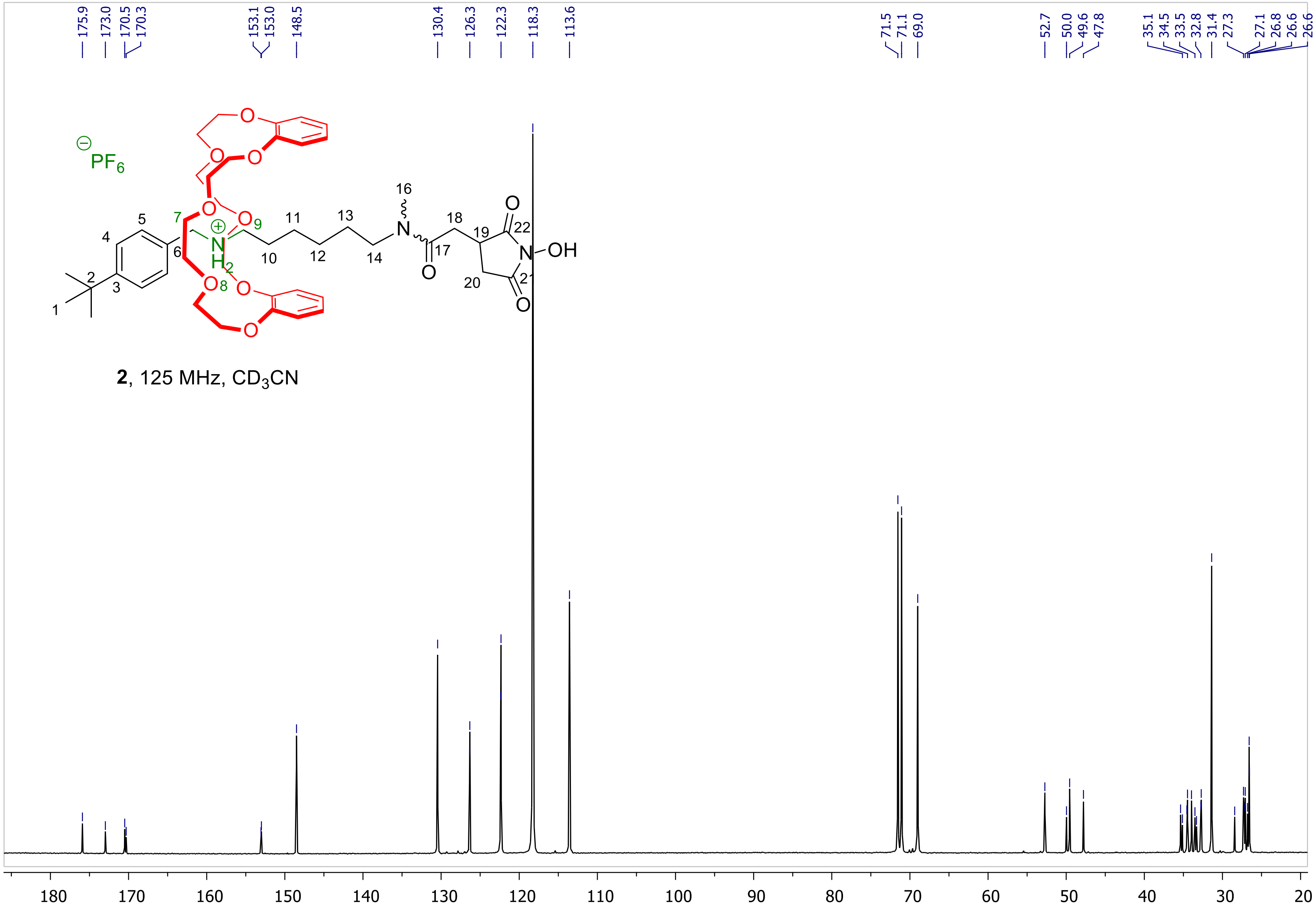


2u, 500 MHz, CD3CN

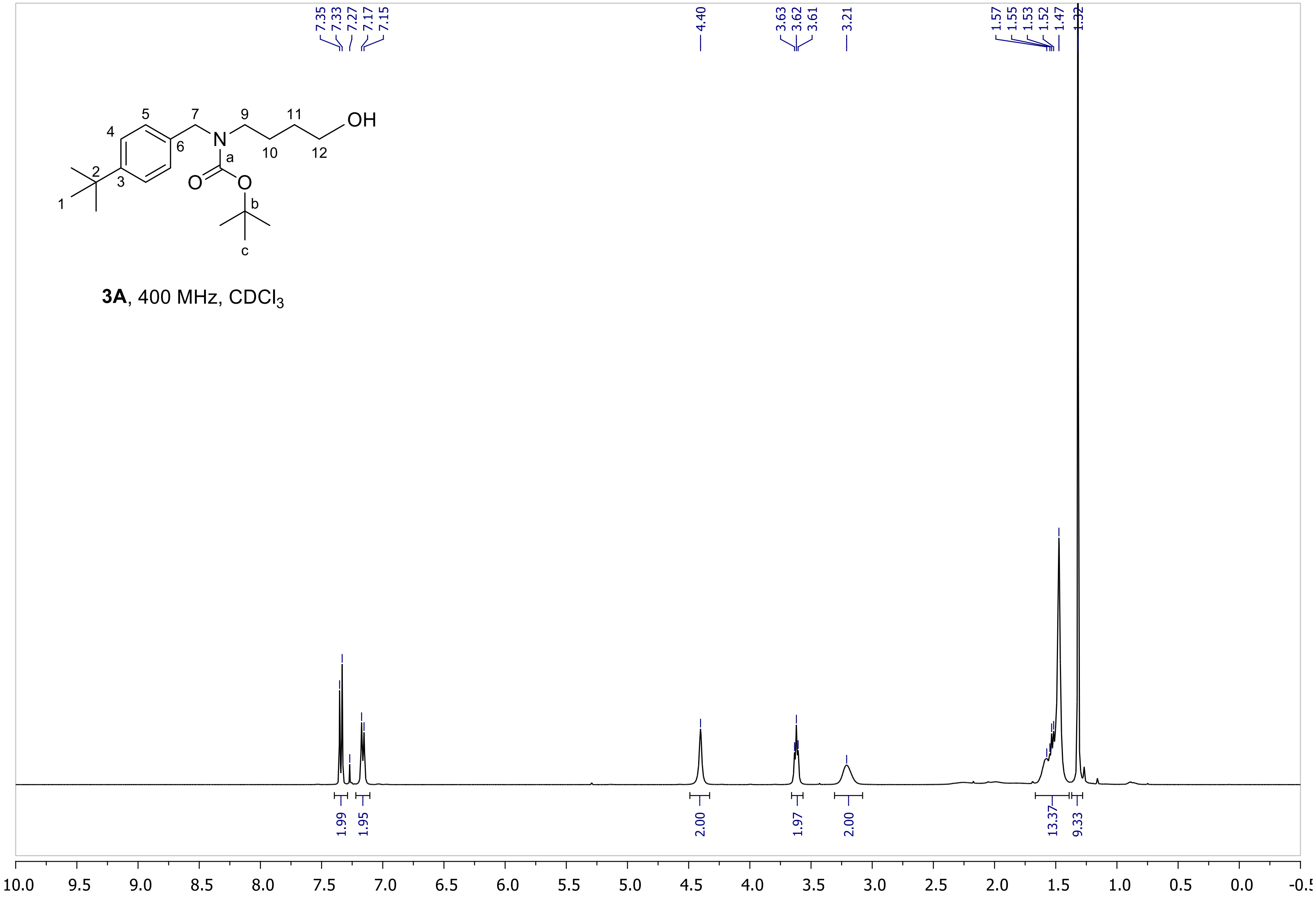

2u, 125 MHz, CD3CN



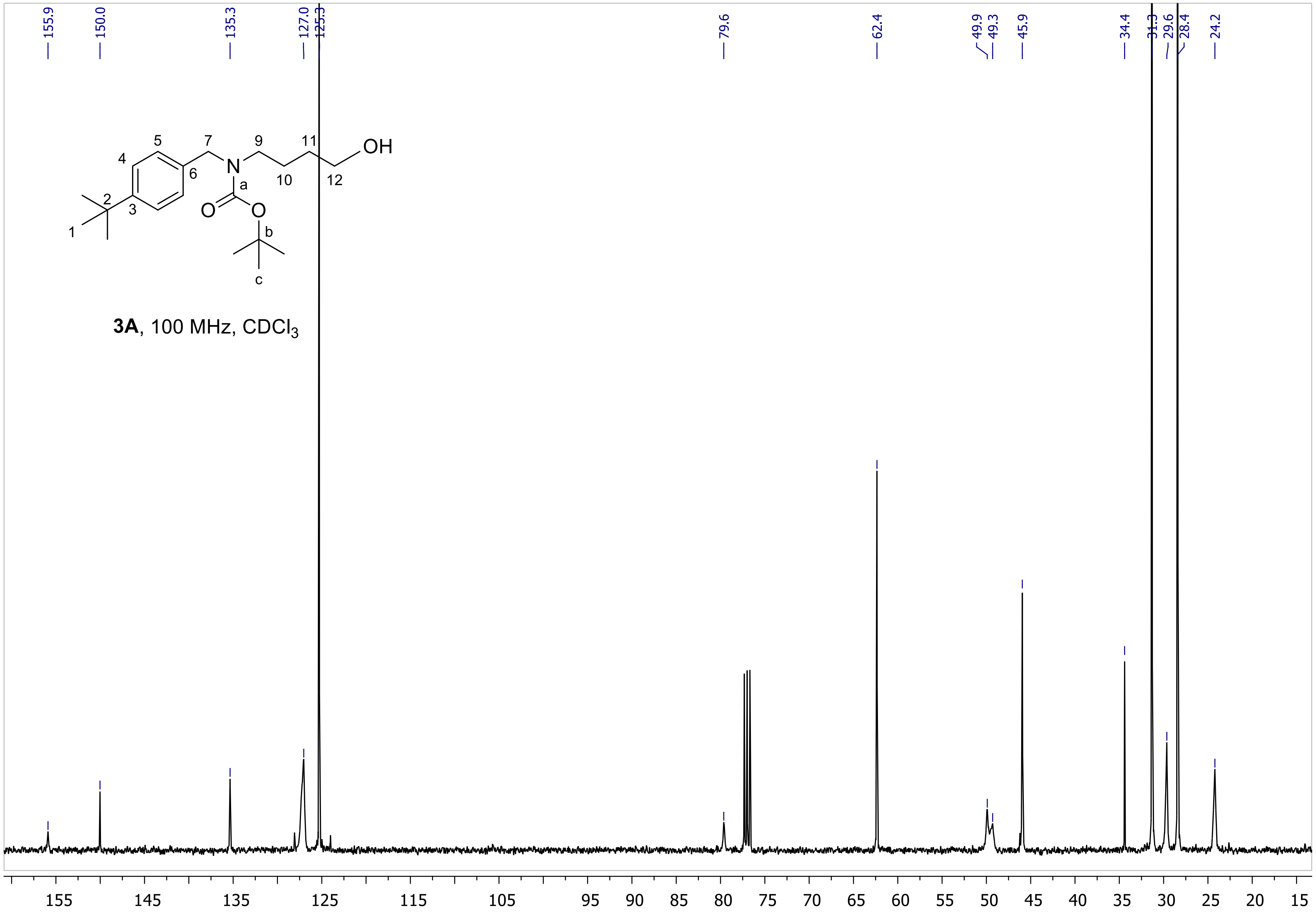
2, 500 MHz, CD_3CN



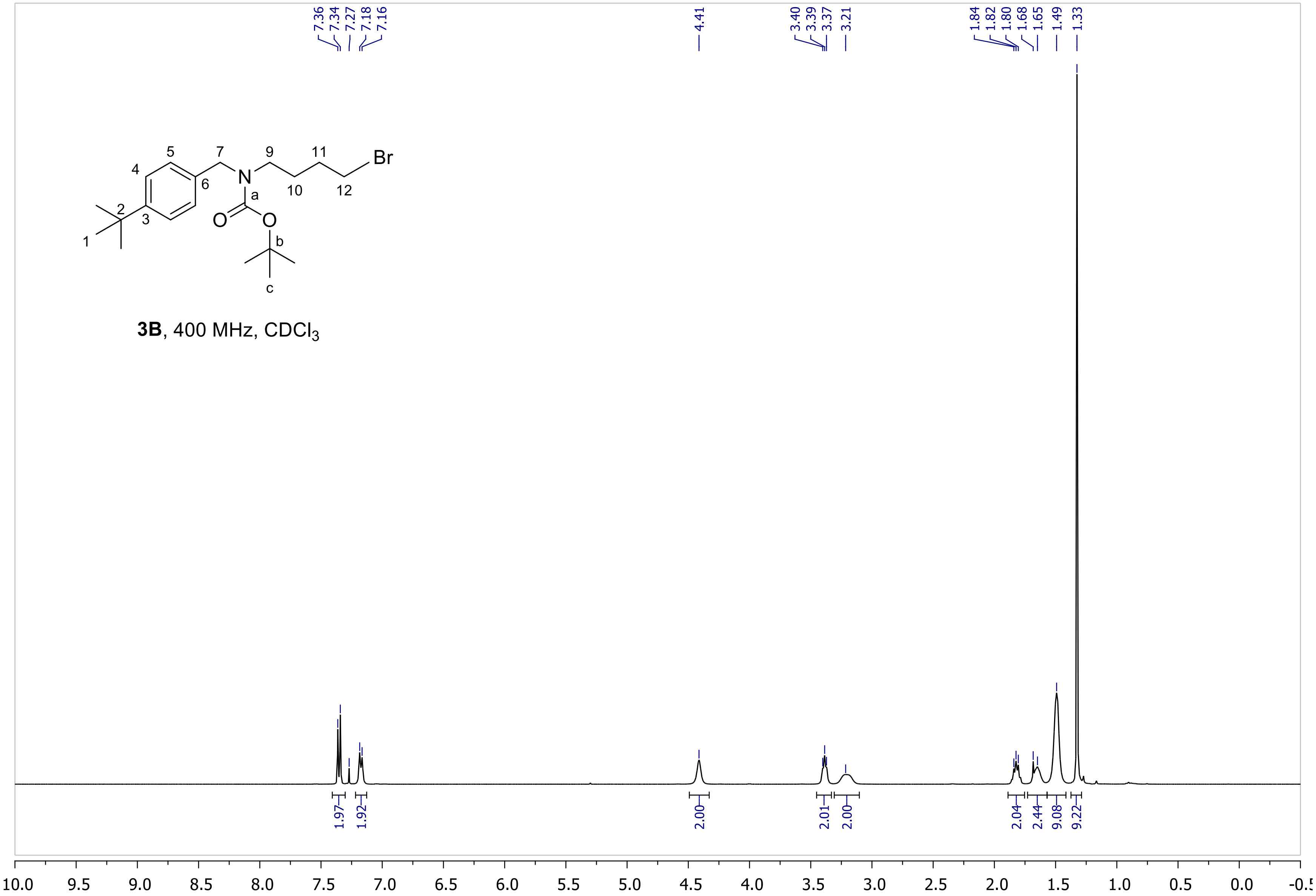
2, 125 MHz, CD_3CN



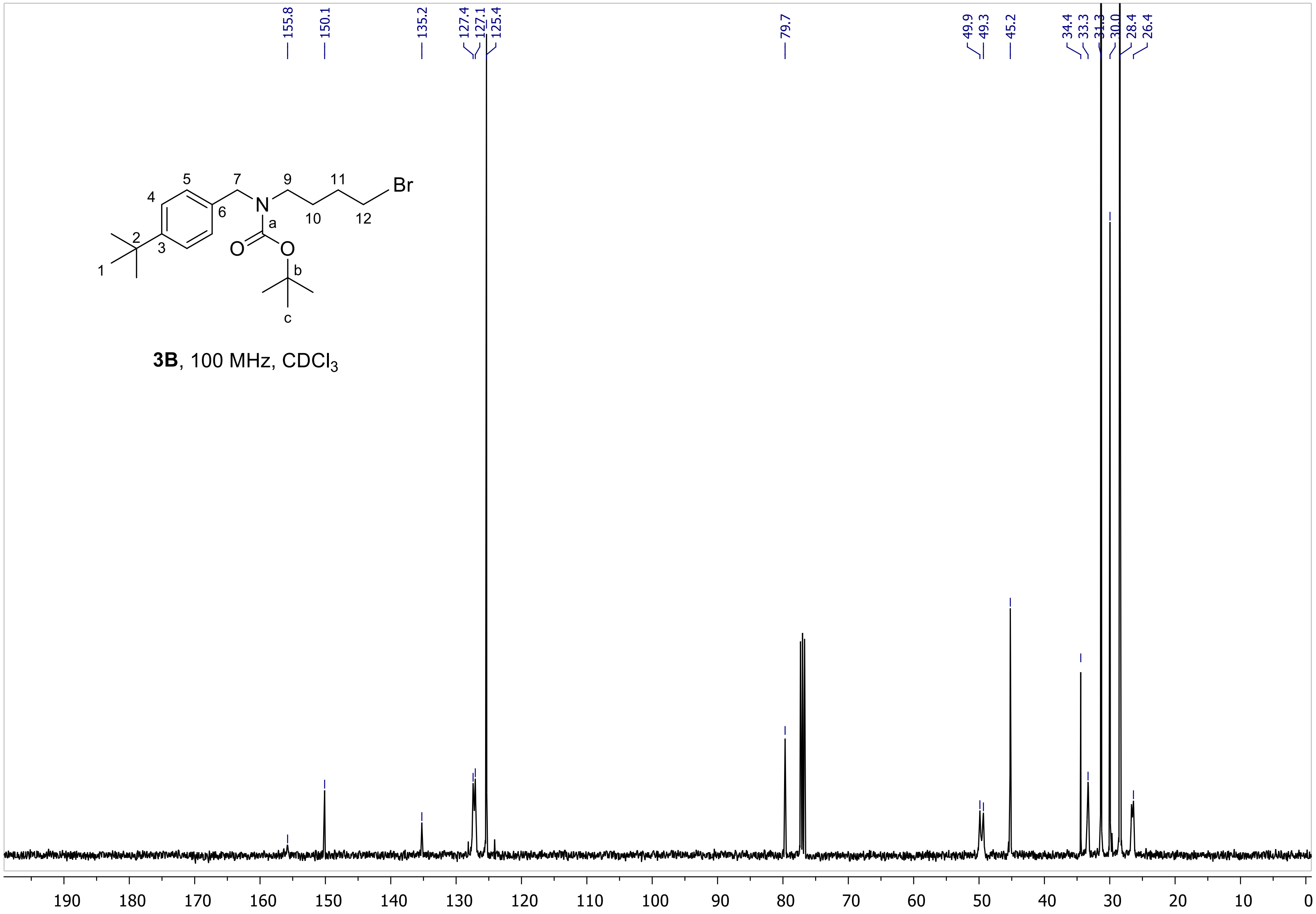
3A, 400 MHz, $CDCl_3$



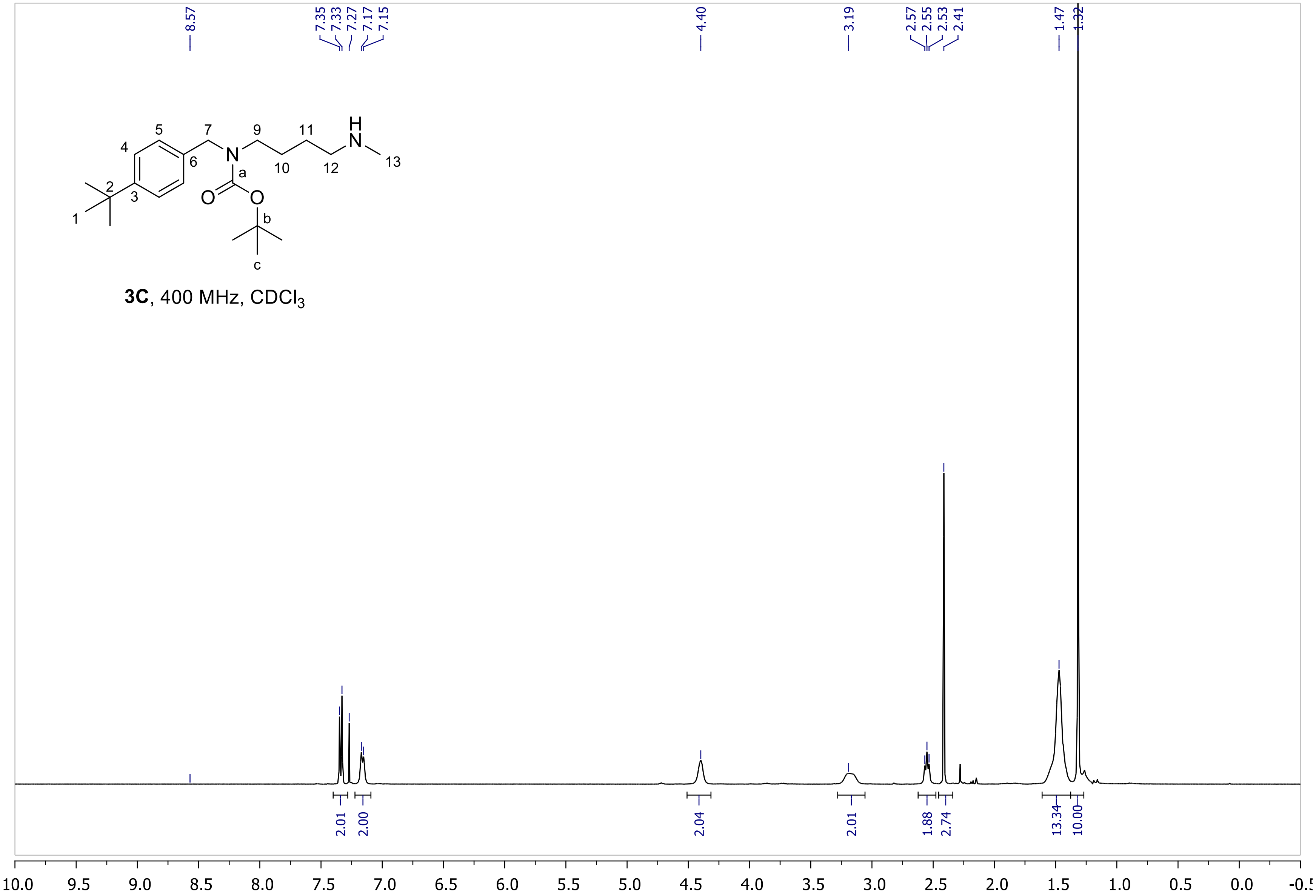
3A, 100 MHz, $CDCl_3$

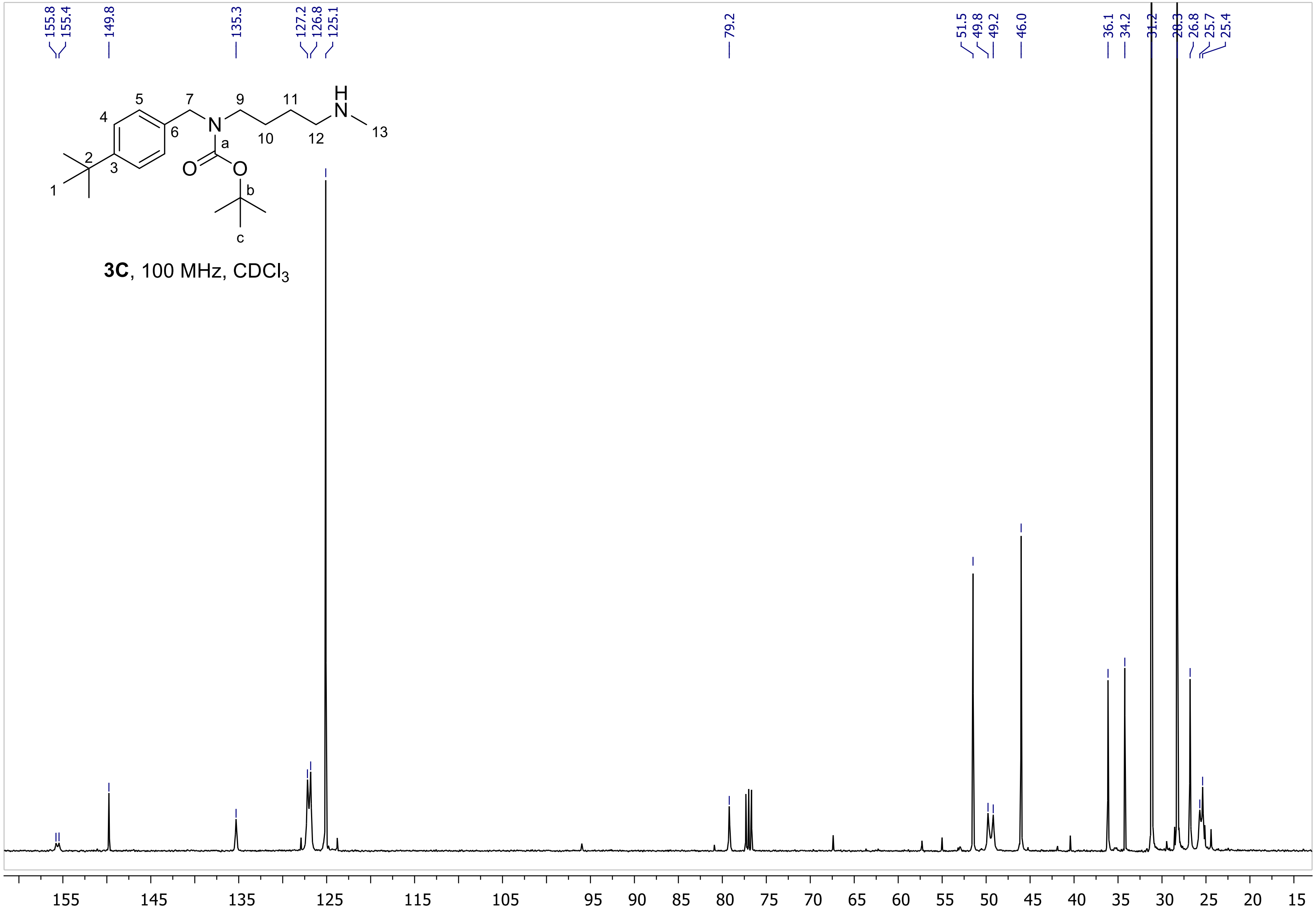


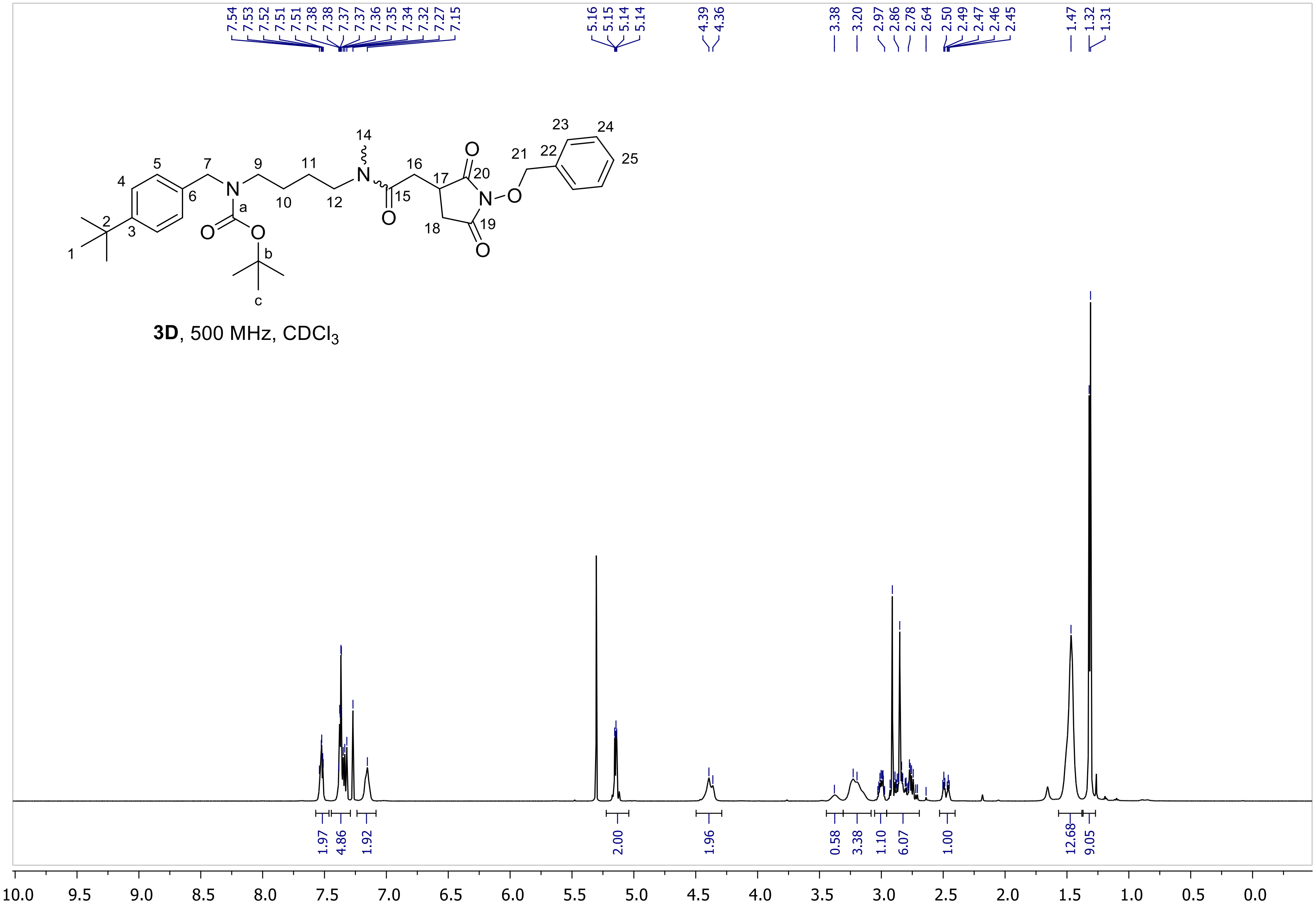
3B, 400 MHz, CDCl$_3$

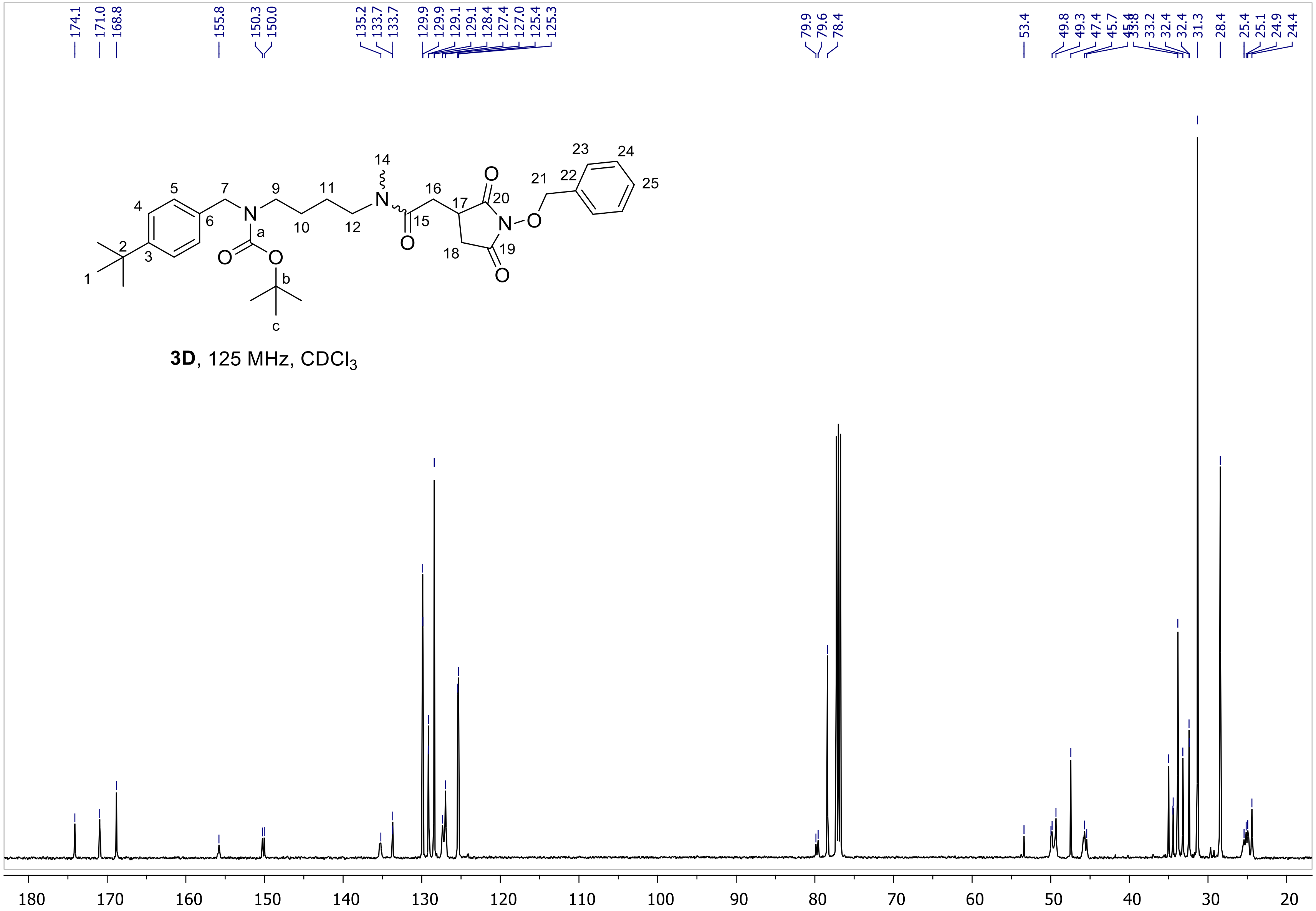


3B, 100 MHz, $CDCl_3$

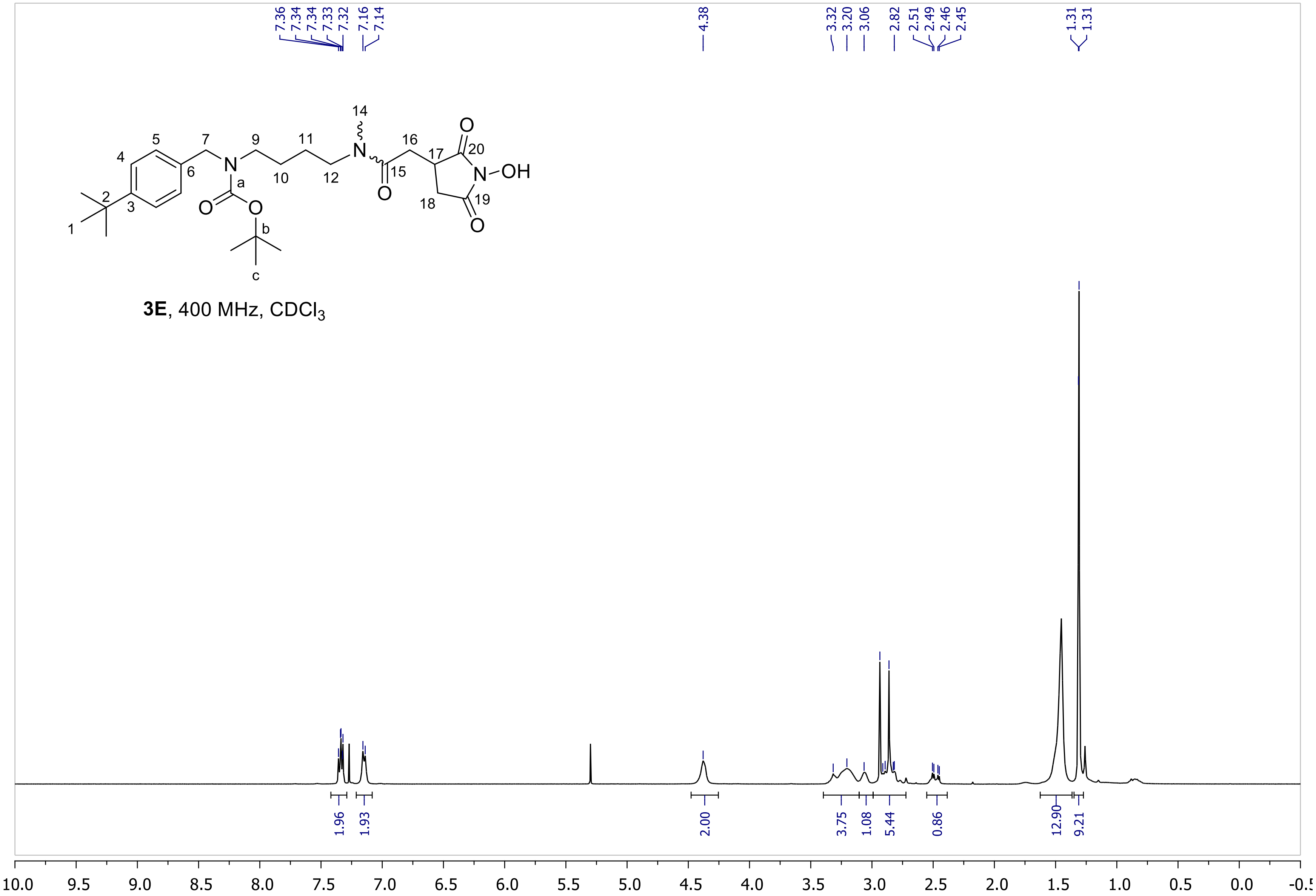

3C, 400 MHz, $CDCl_3$

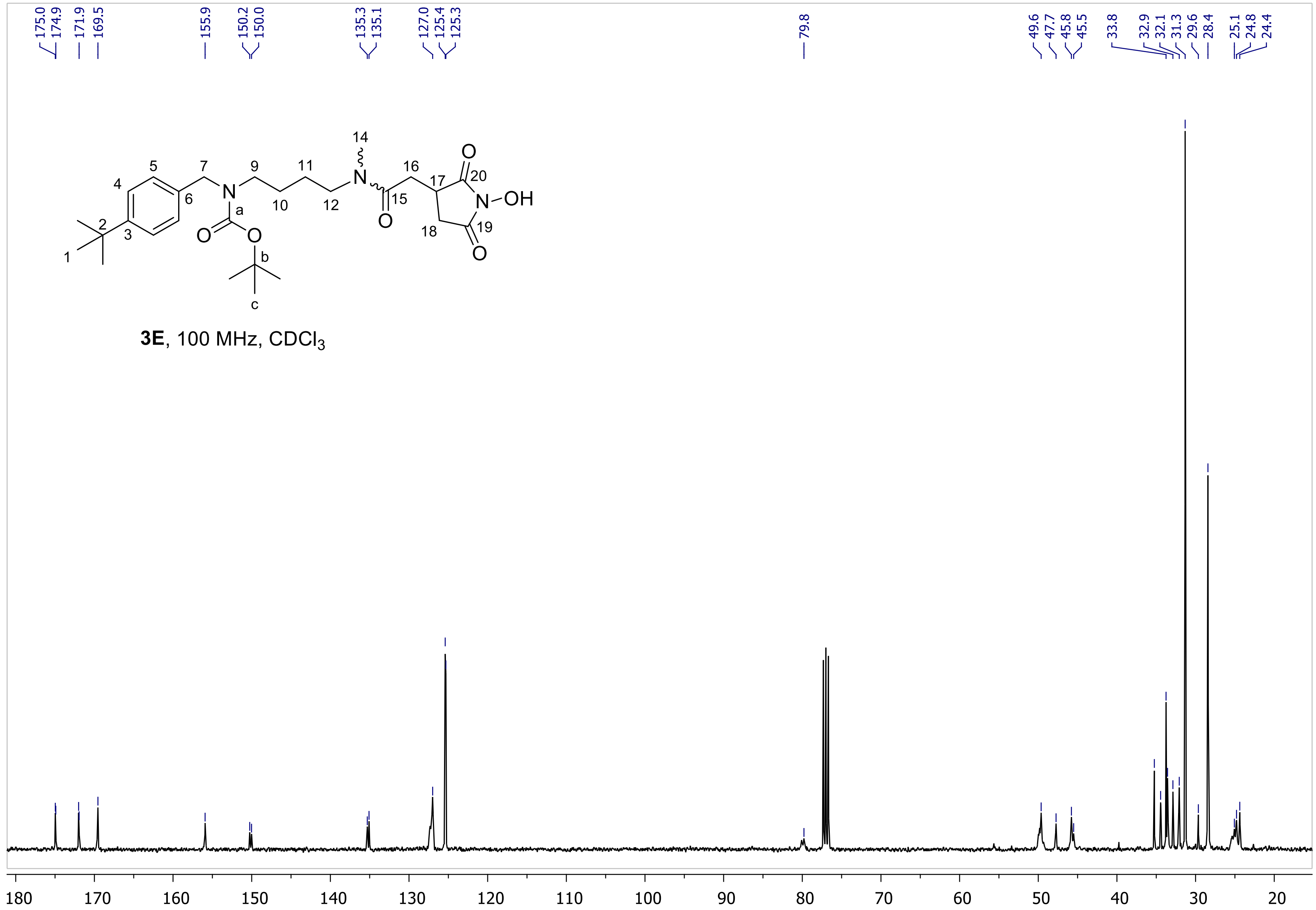

3C, 100 MHz, $CDCl_3$


3D, 500 MHz, $CDCl_3$

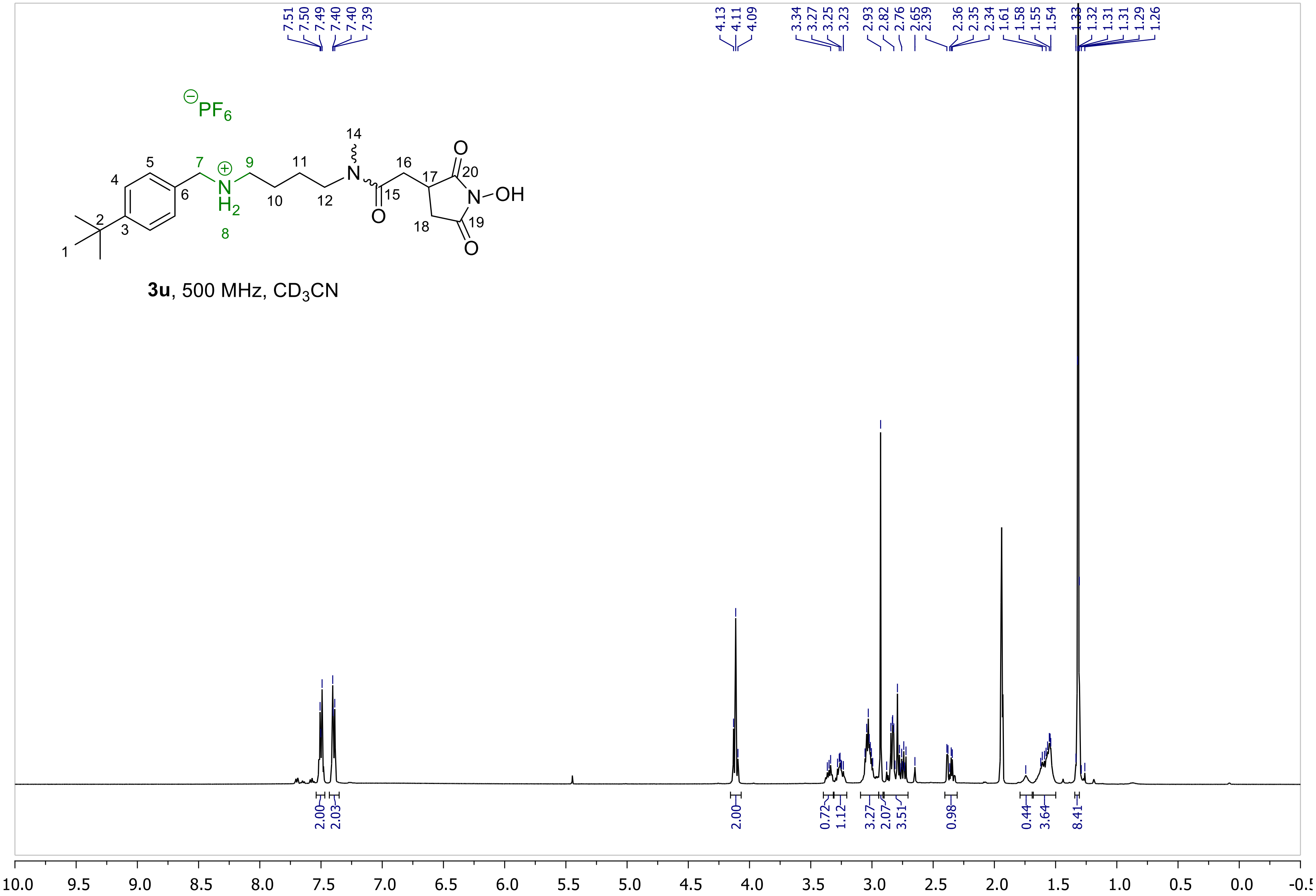


3D, 125 MHz, $CDCl_3$

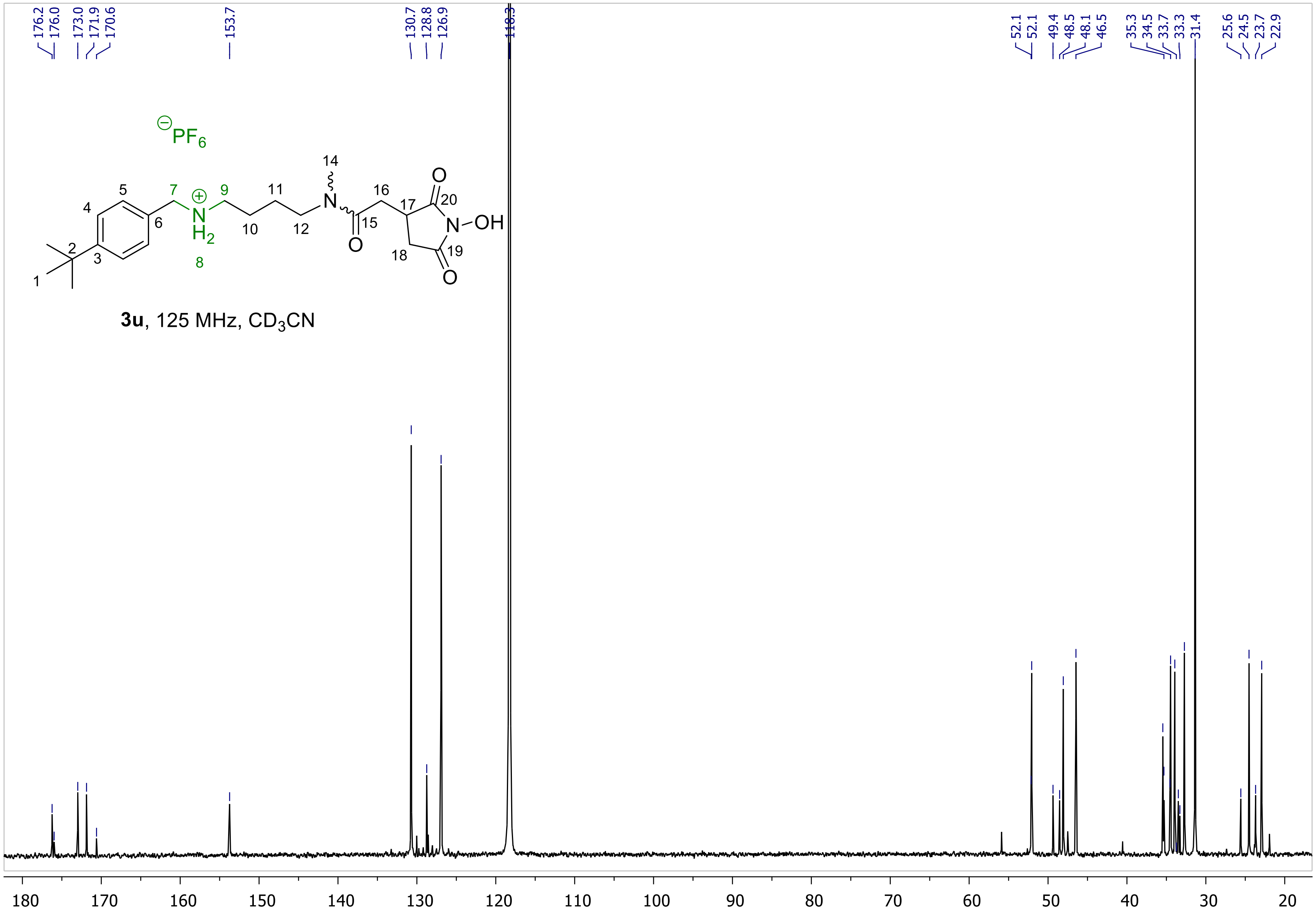

3E, 400 MHz, $CDCl_3$



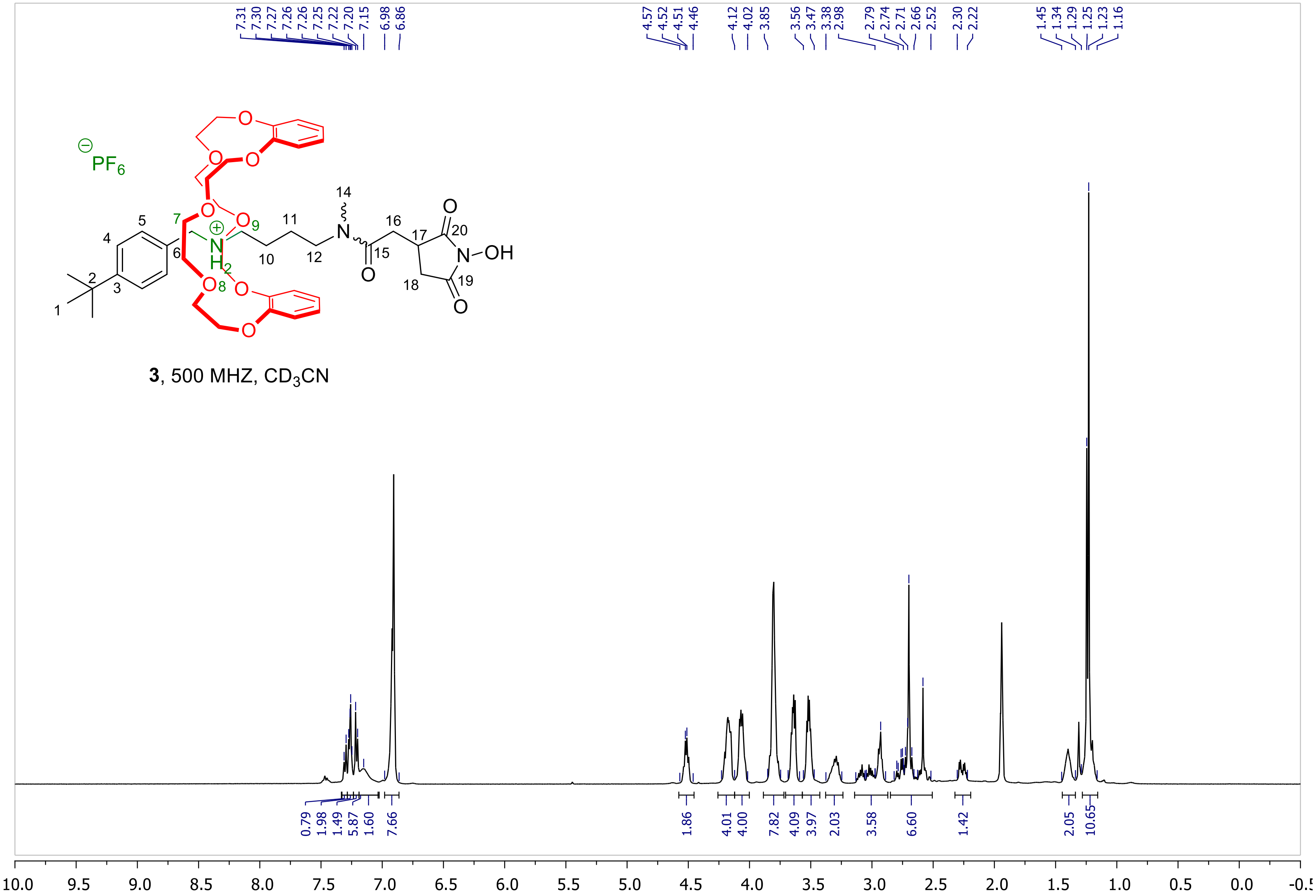
3E, 100 MHz, $CDCl_3$

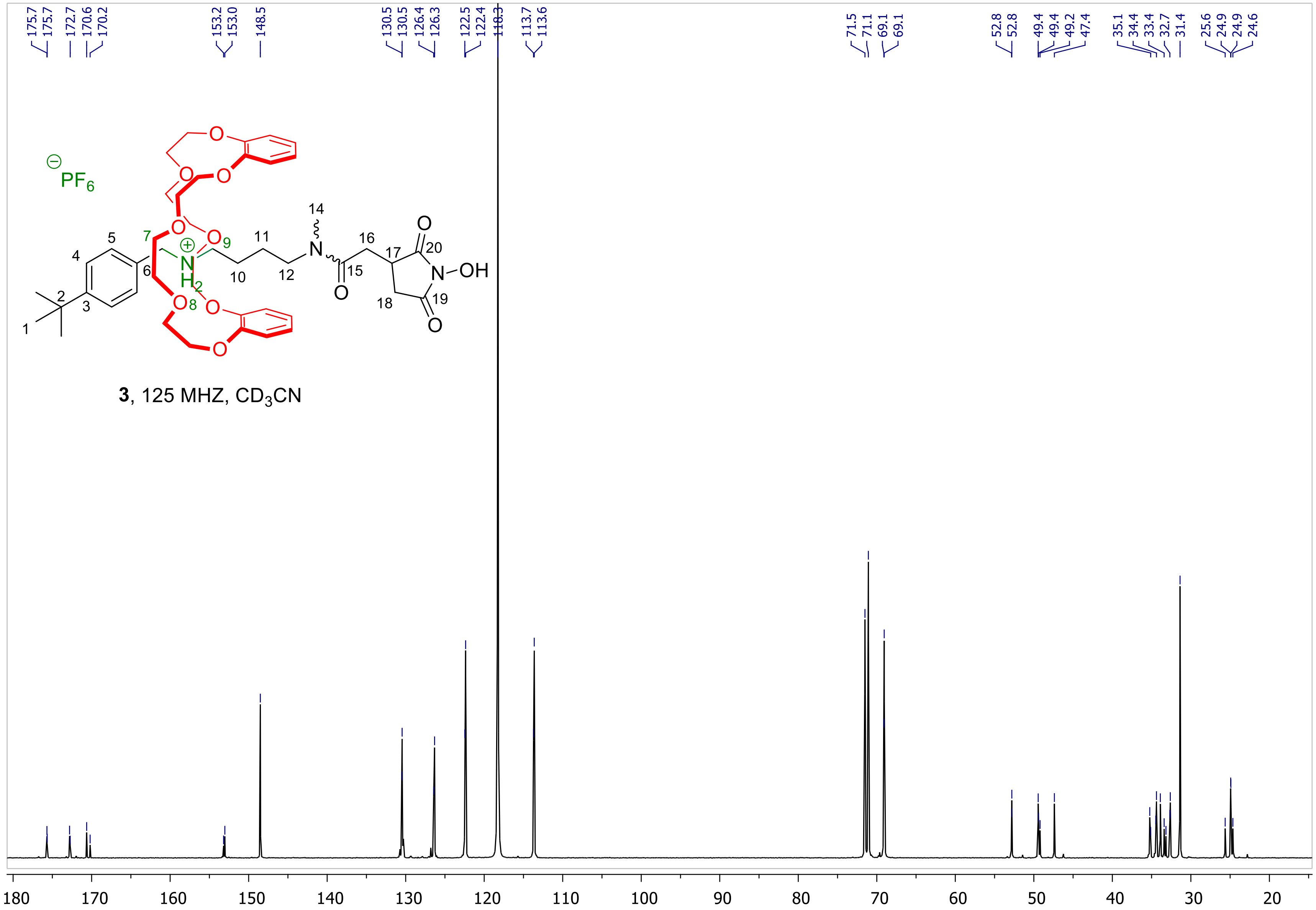


3u, 500 MHz, CD_3CN

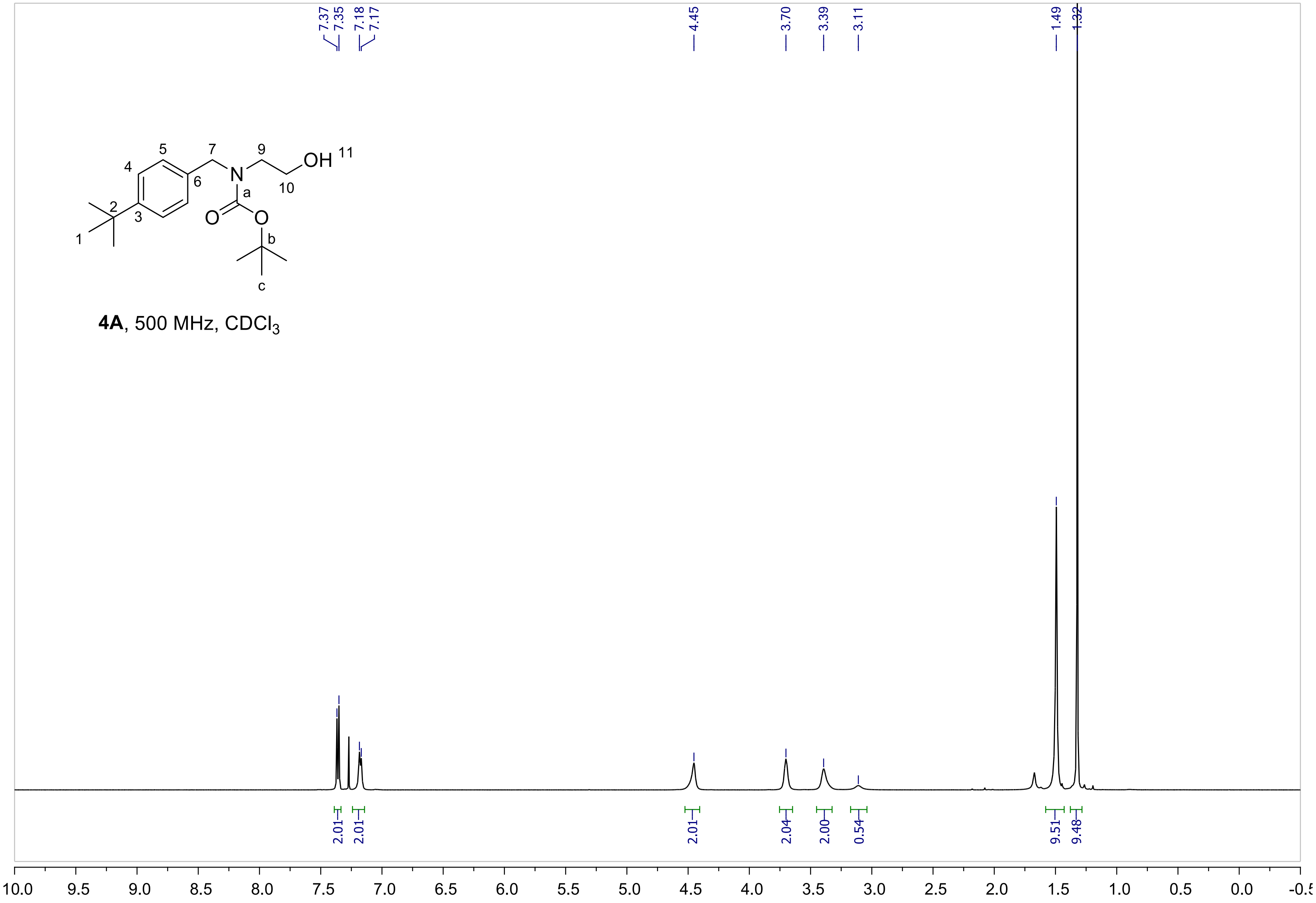


3u, 125 MHz, CD_3CN

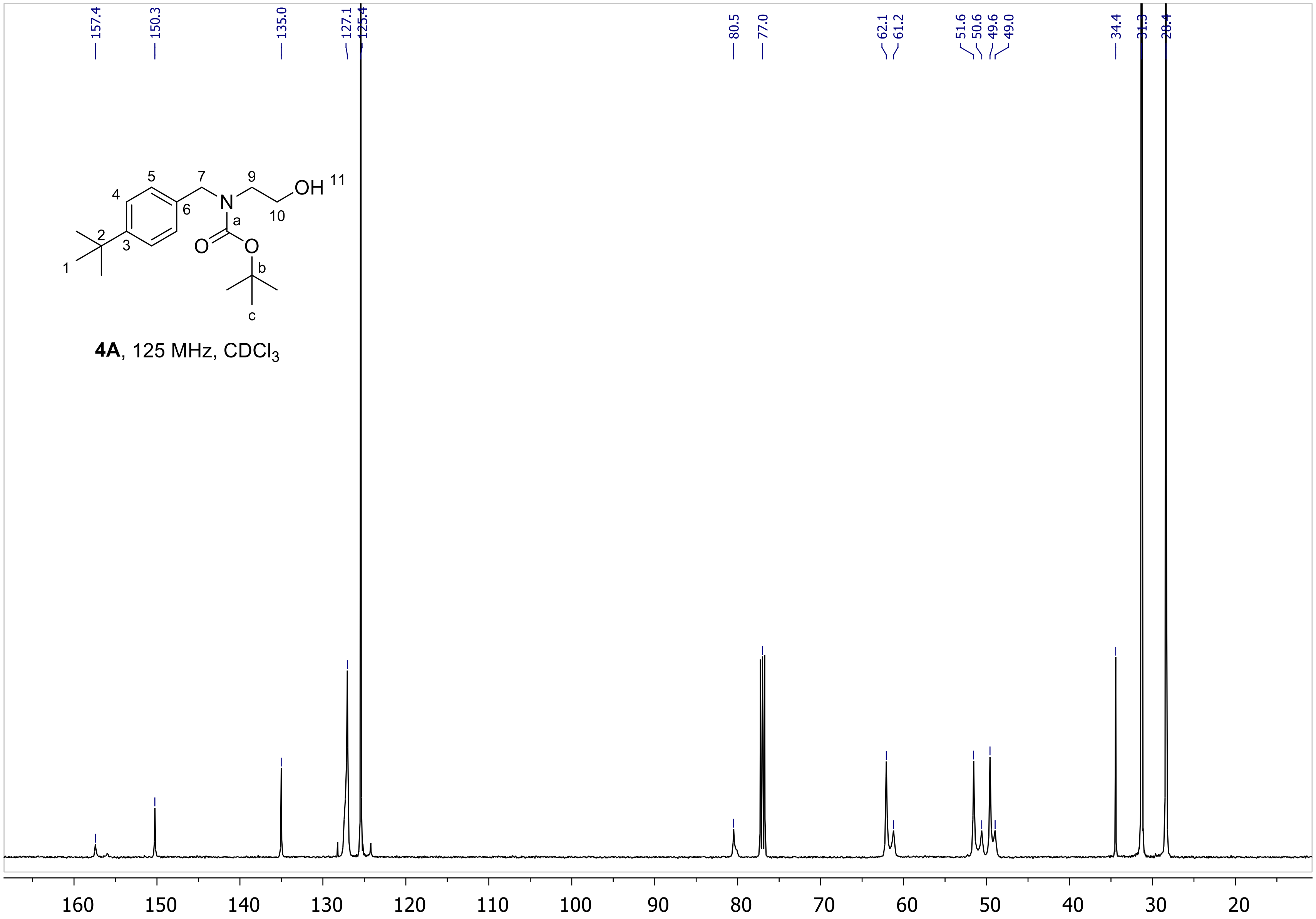

3, 500 MHZ, CD_3CN



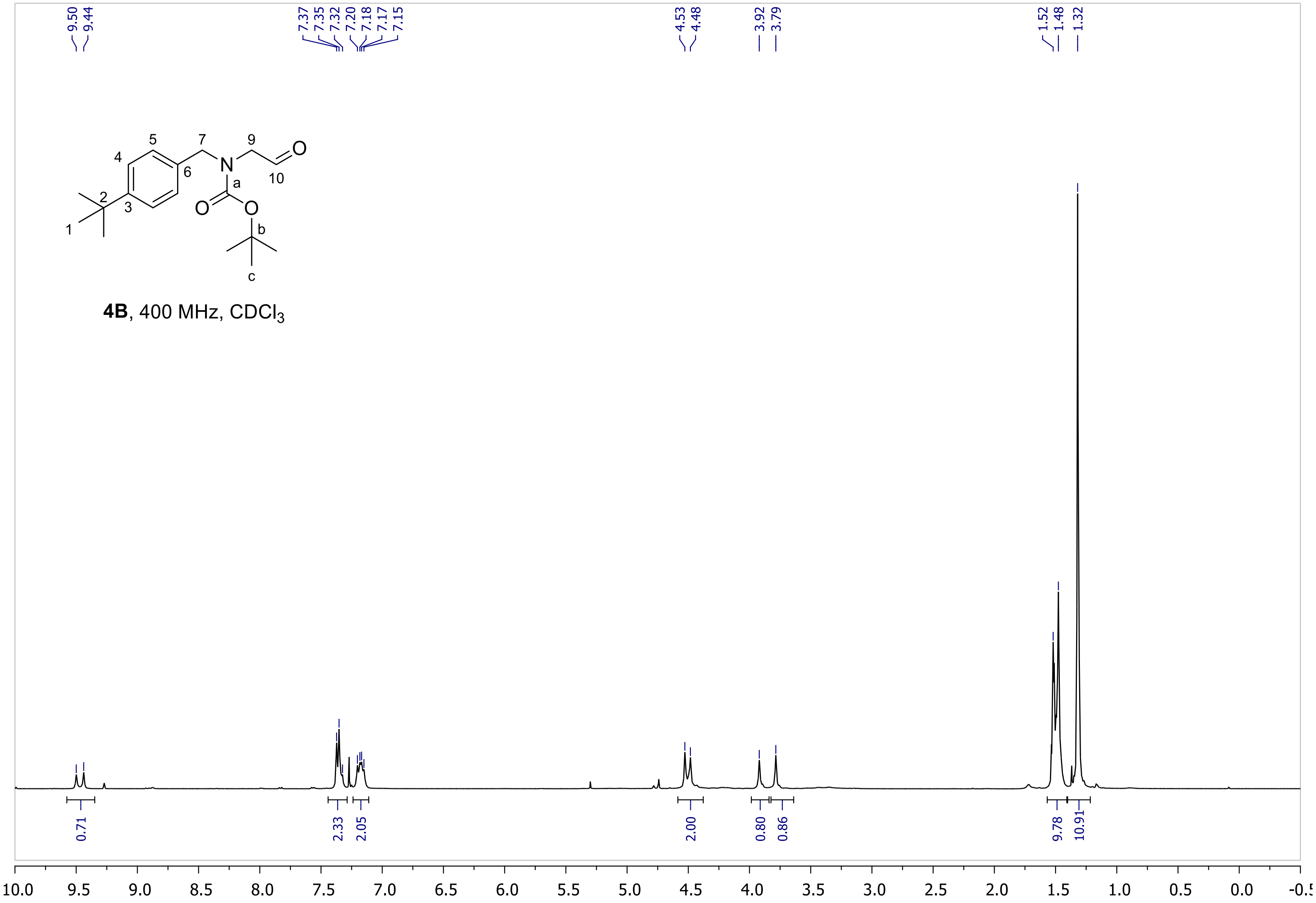
3, 125 MHZ, CD_3CN

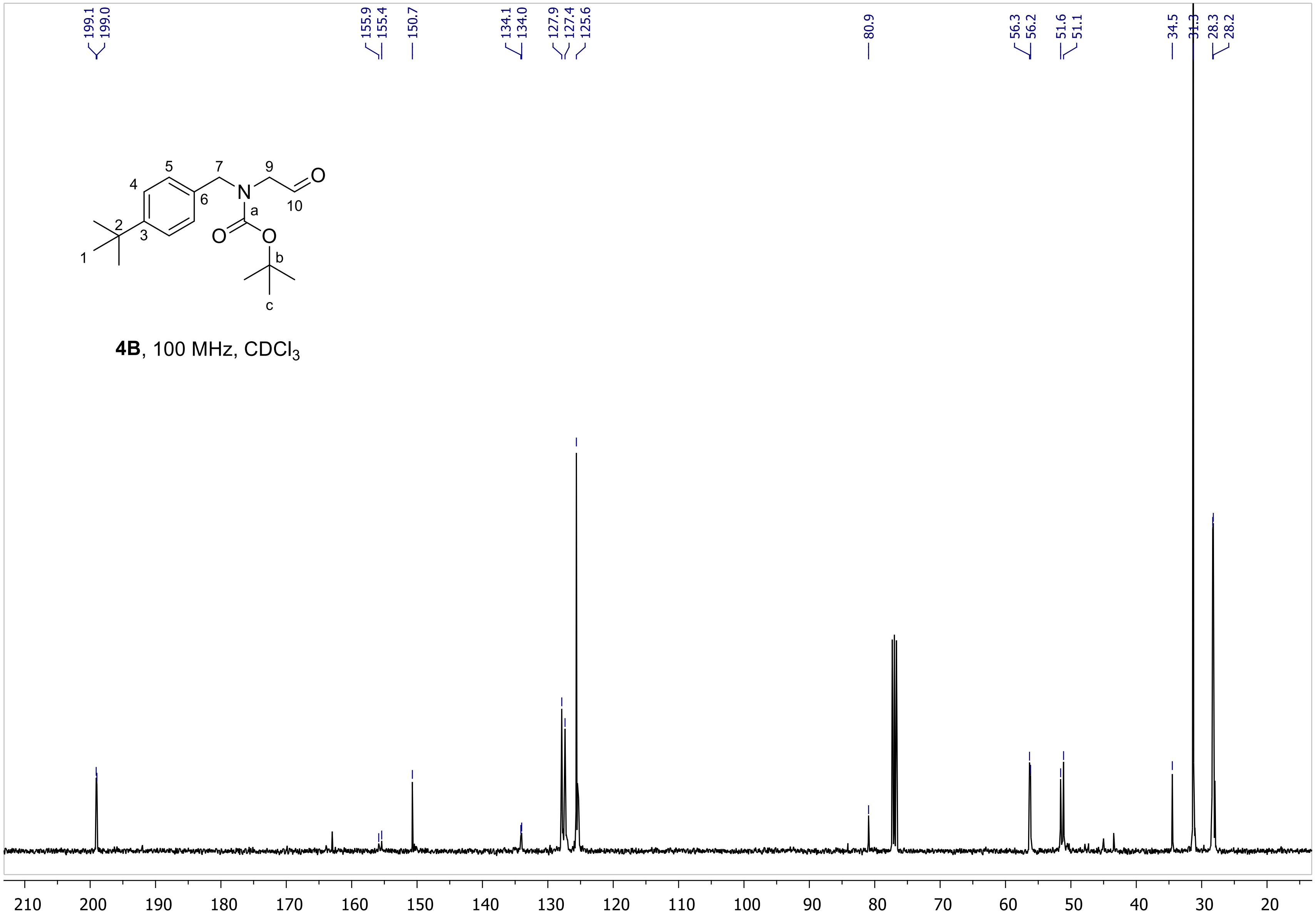


4A, 500 MHz, $CDCl_3$

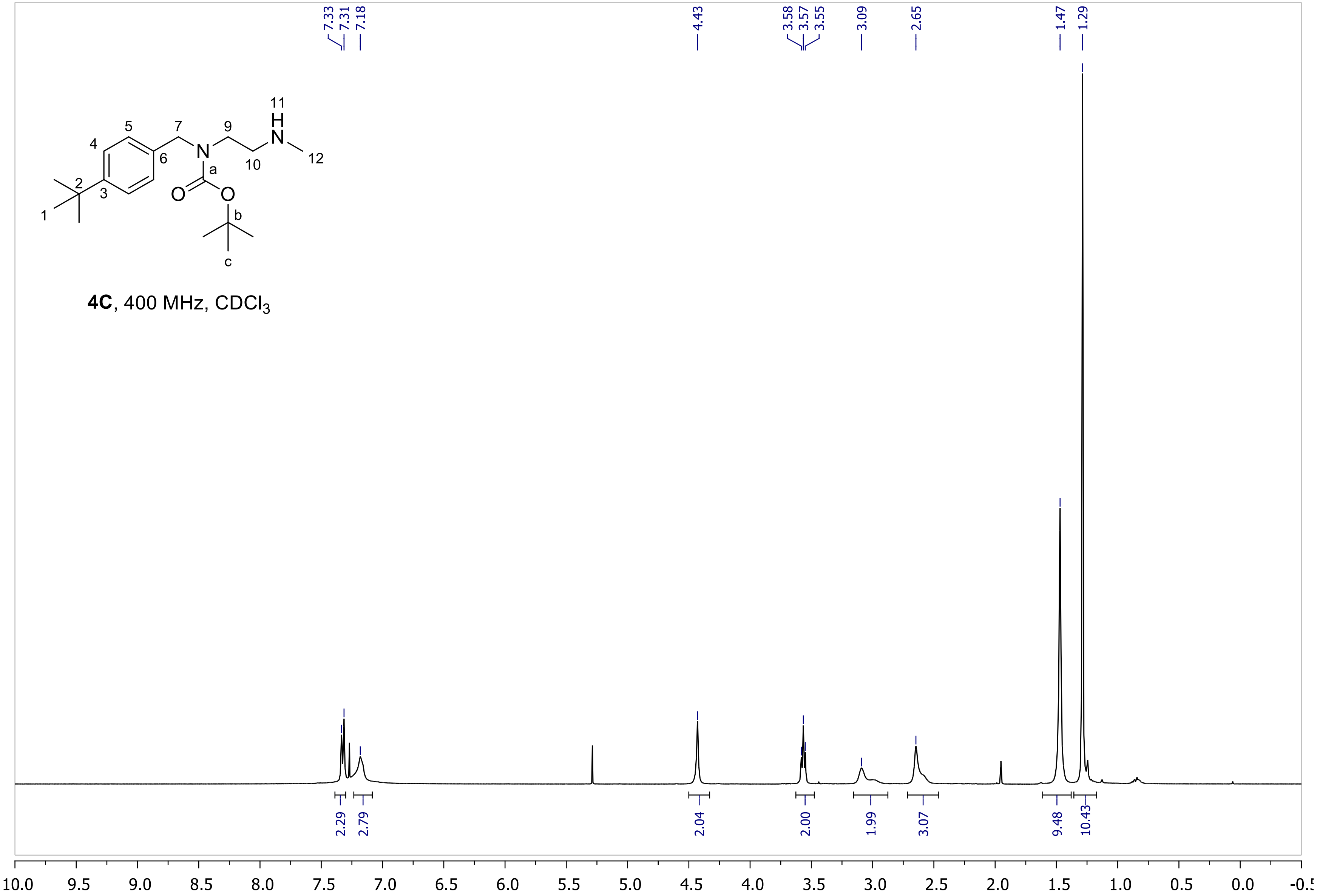


4A, 125 MHz, $CDCl_3$

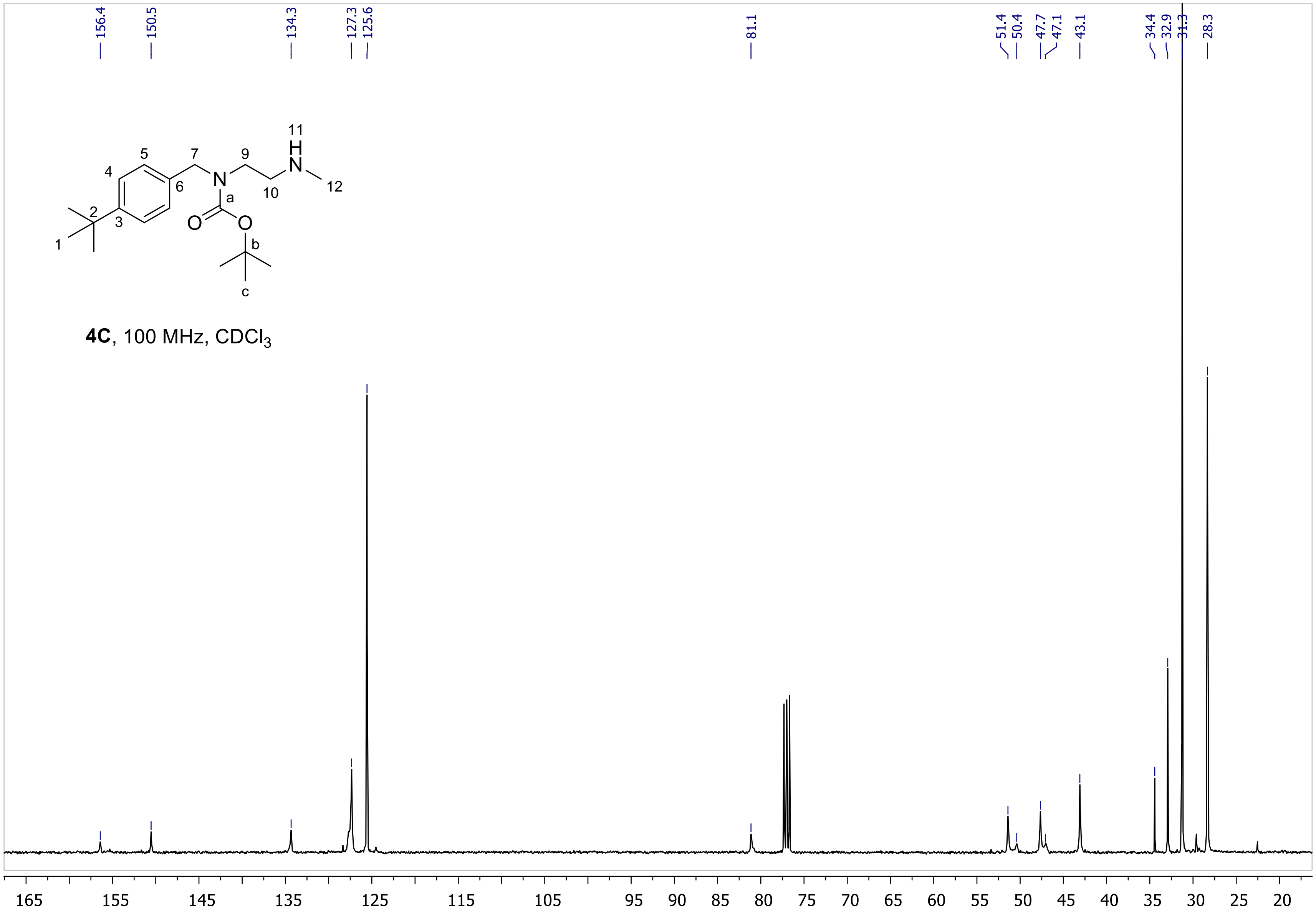

9.50
9.44
7.37
7.35
7.32
7.20
7.18
7.17
7.15
4.53
4.48
3.92
3.79
1.52
1.48
1.32
5
7
9
4
N
O
6
10
2
a
3
O
O
1
b
c
4B, 400 MHz, CDCl3
0.71
2.33
2.05
2.00
0.80
0.86
9.78
10.91
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.



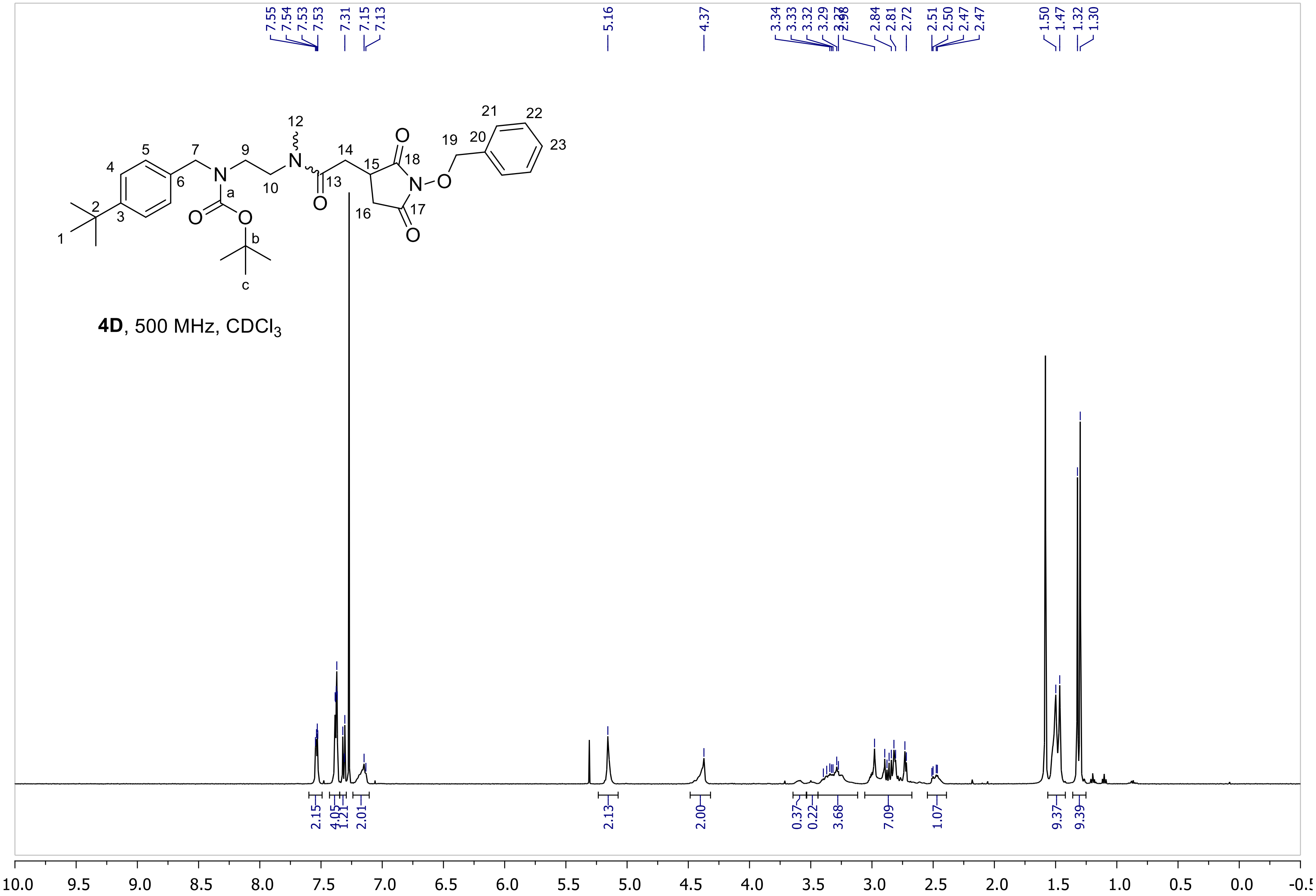
4B, 100 MHz, $CDCl_3$



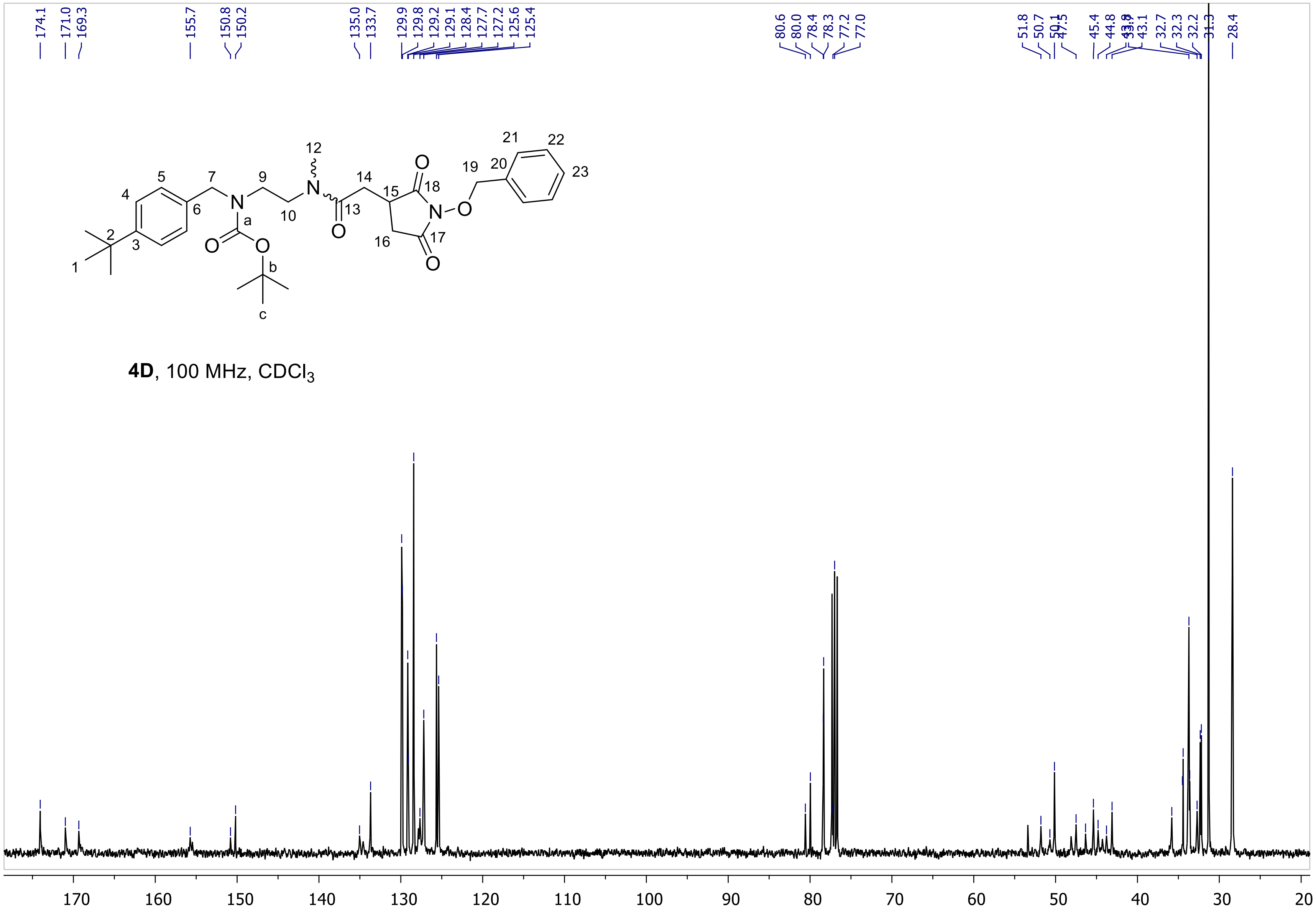
4C, 400 MHz, $CDCl_3$



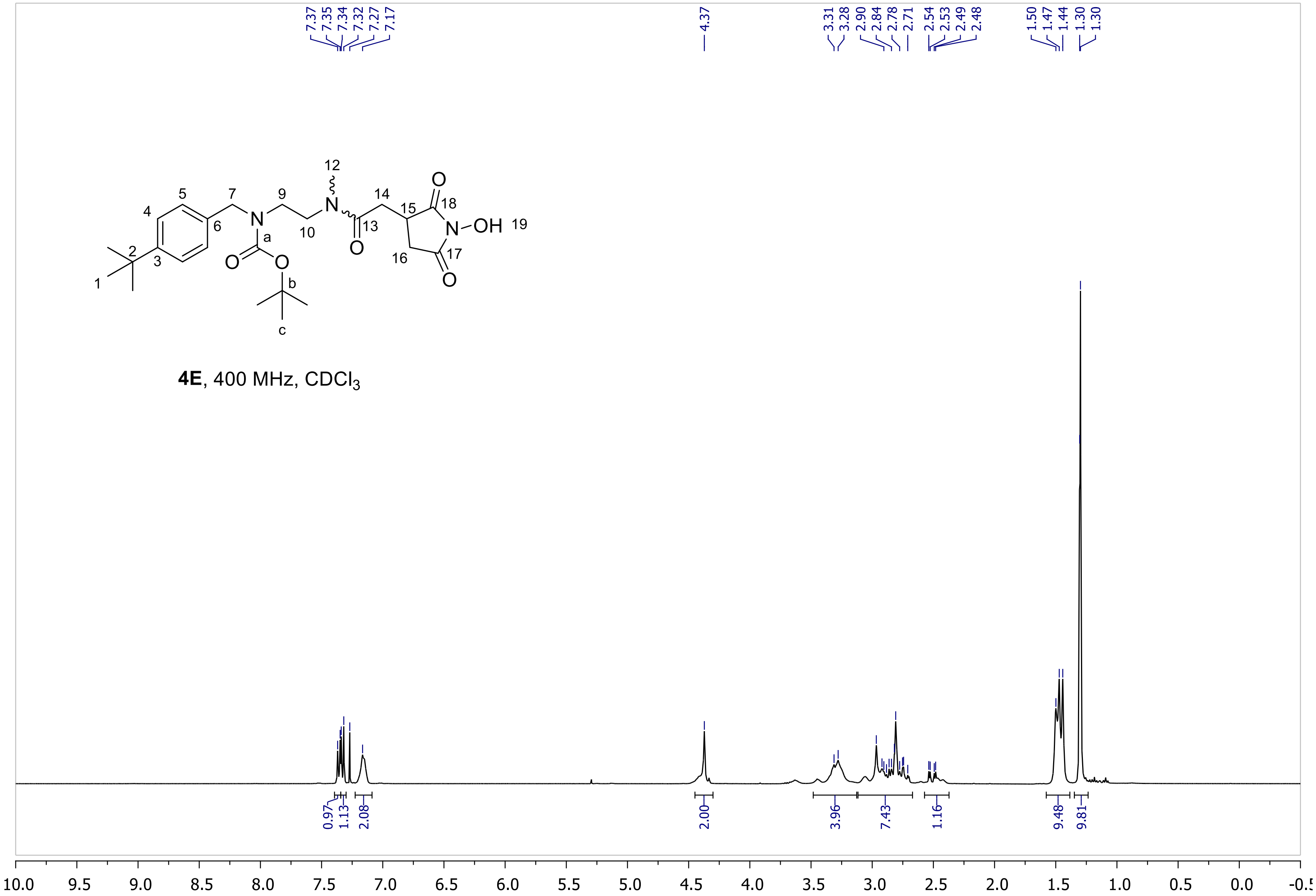
4C, 100 MHz, $CDCl_3$



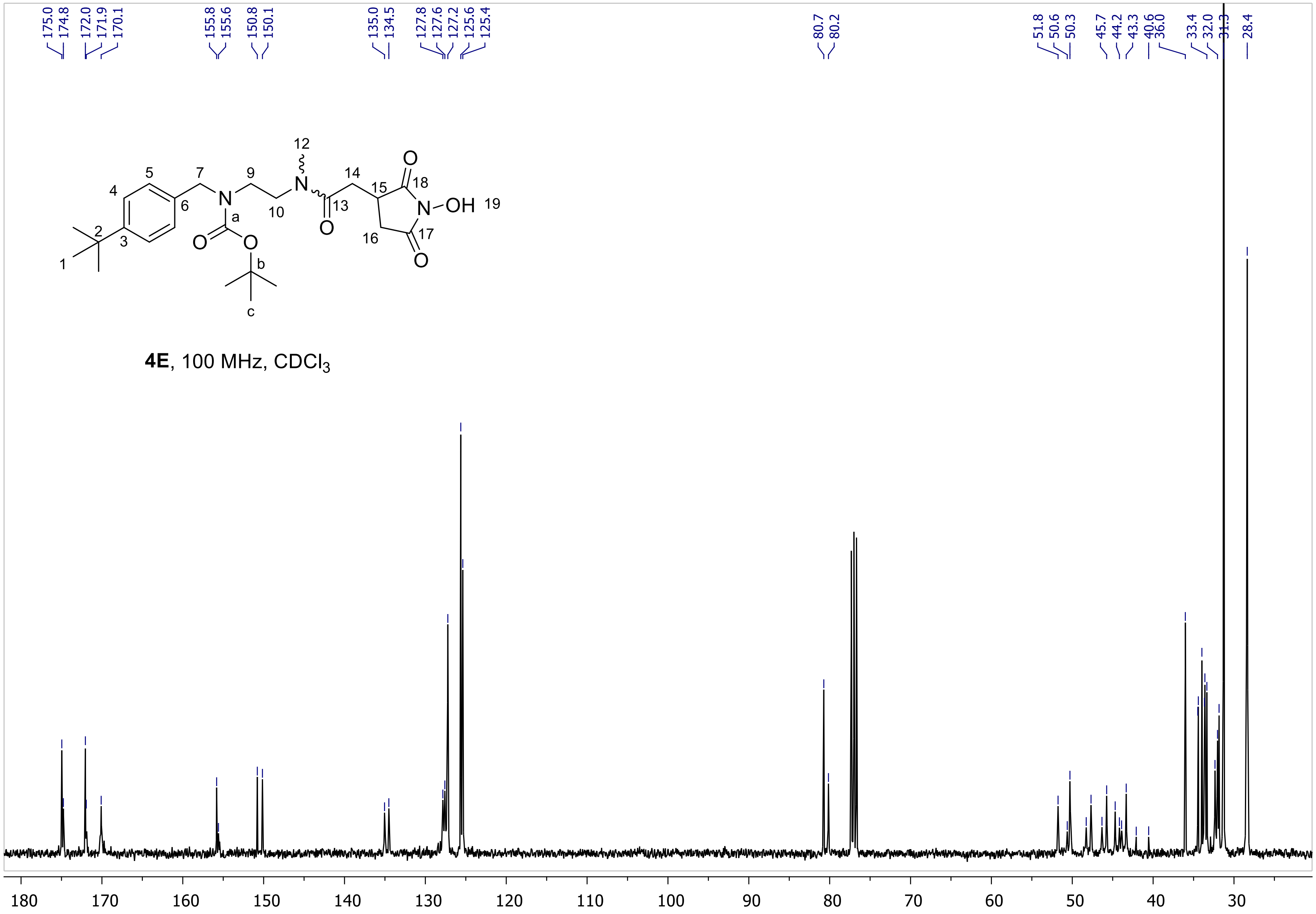
4D, 500 MHz, $CDCl_3$



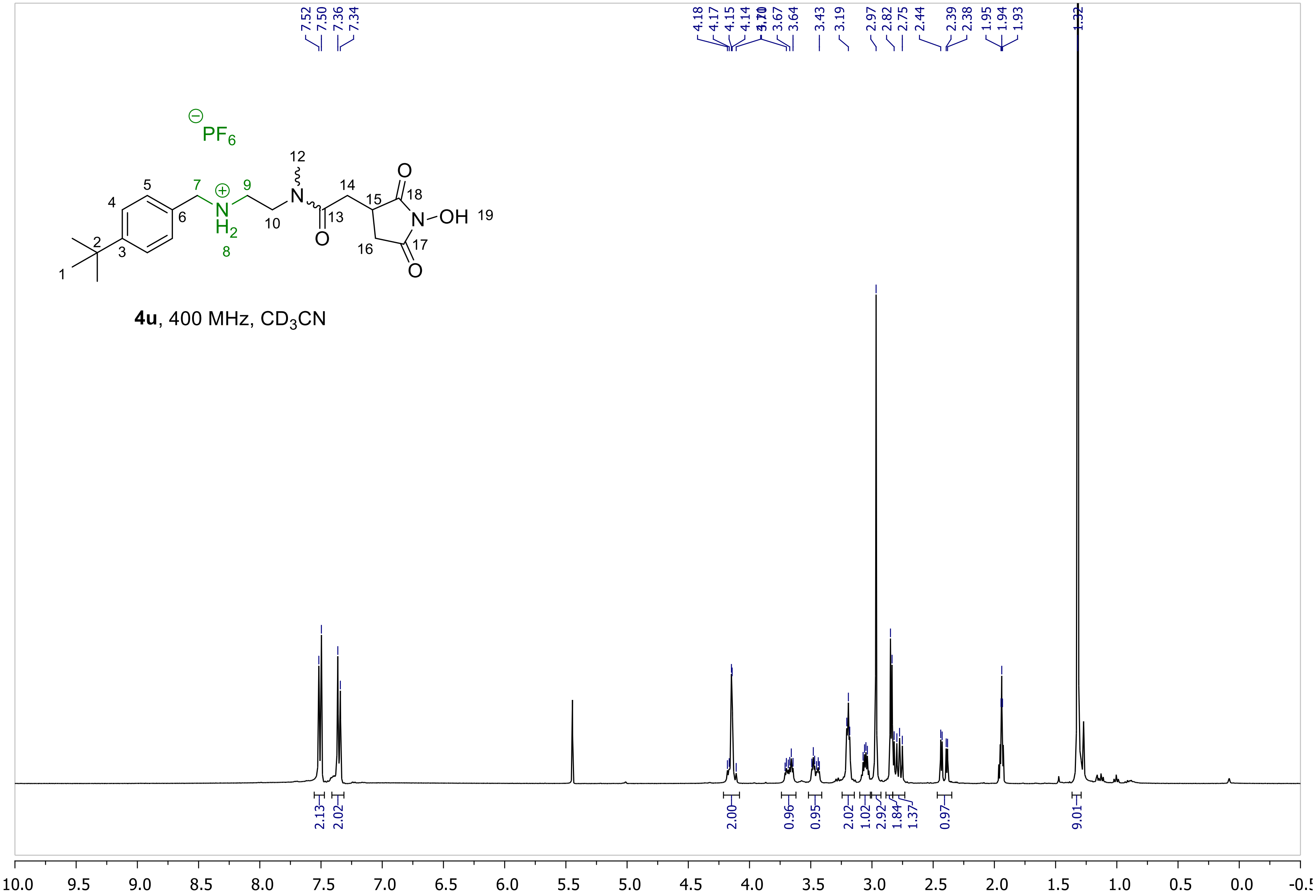
4D, 100 MHz, $CDCl_3$



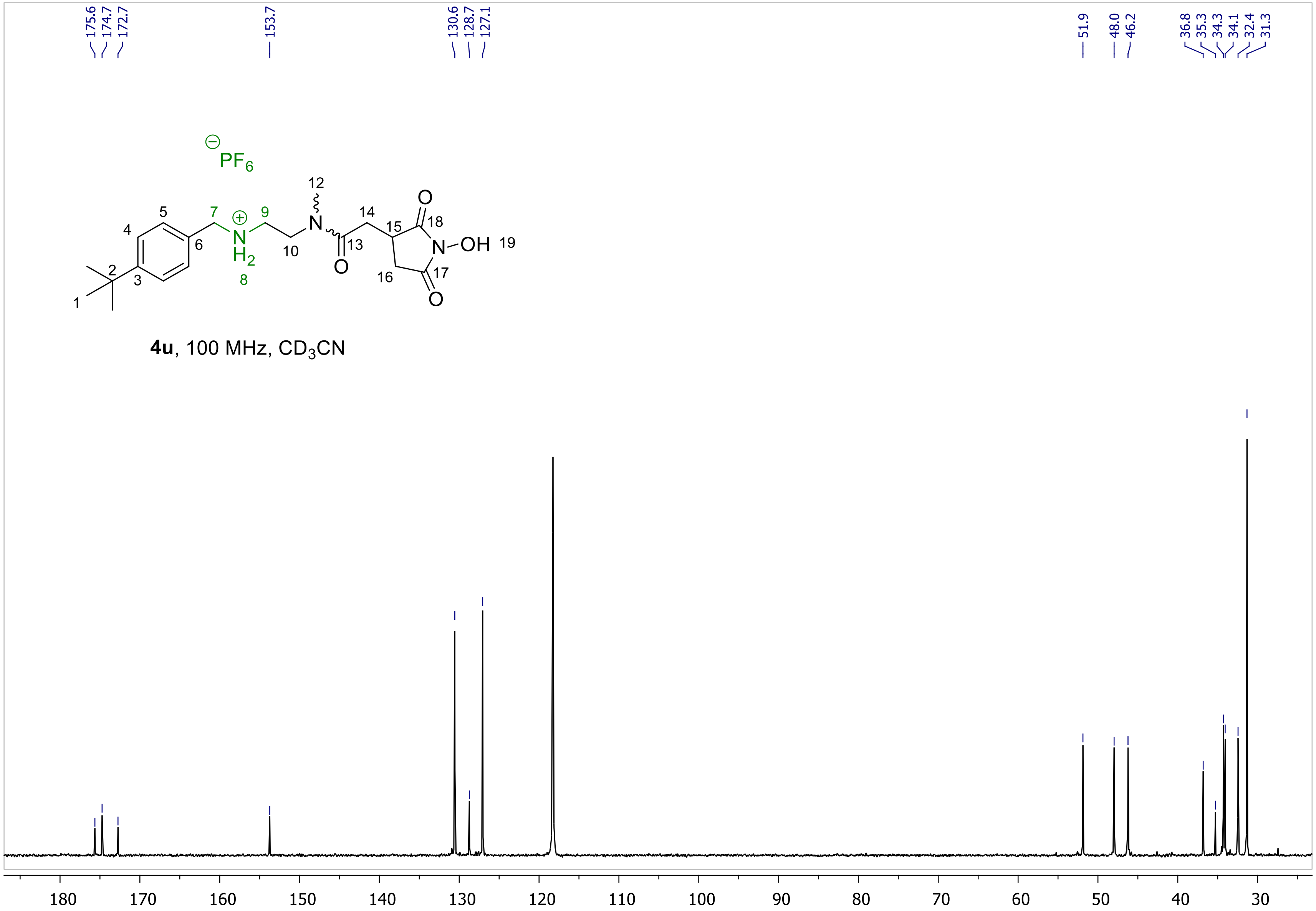
4E, 400 MHz, $CDCl_3$



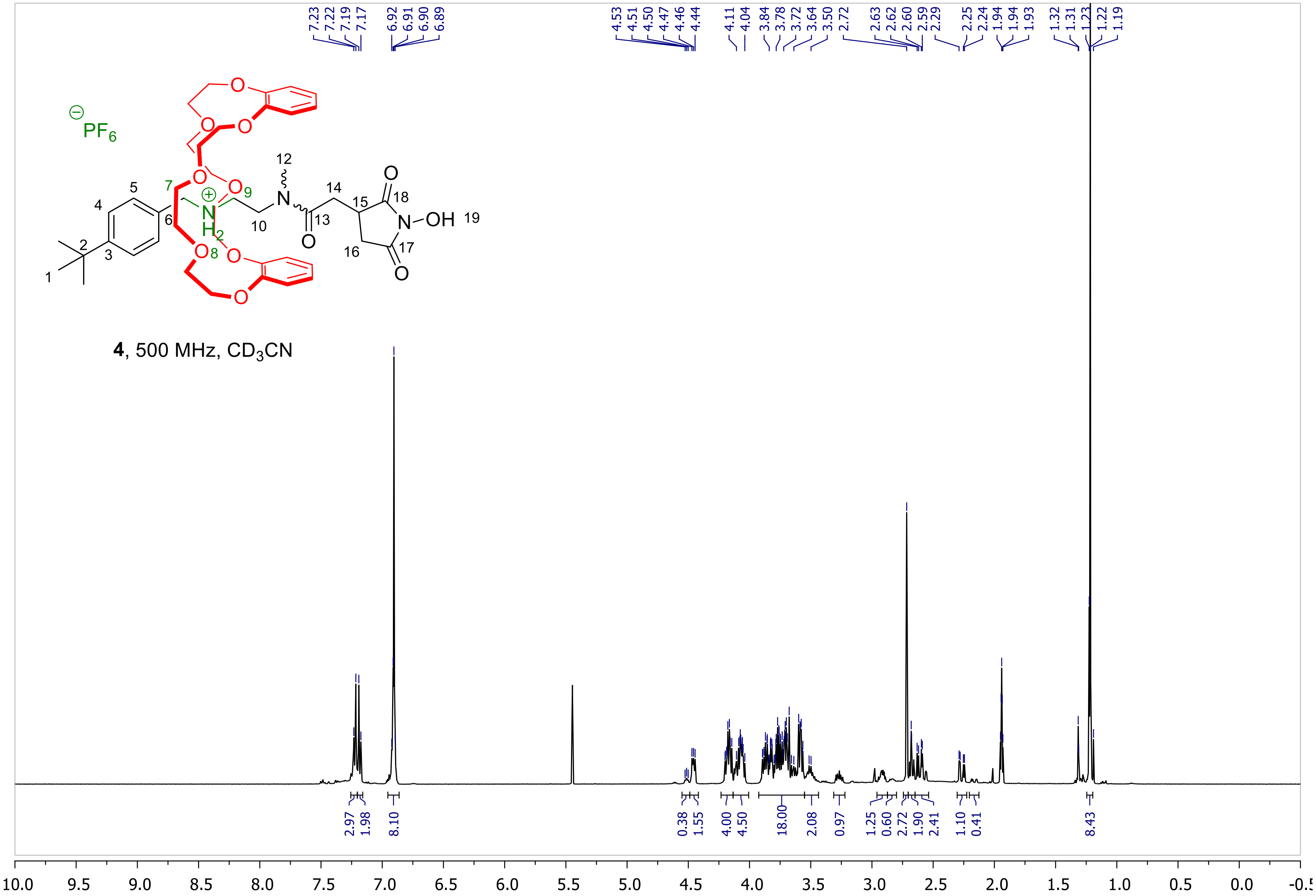
4E, 100 MHz, $CDCl_3$

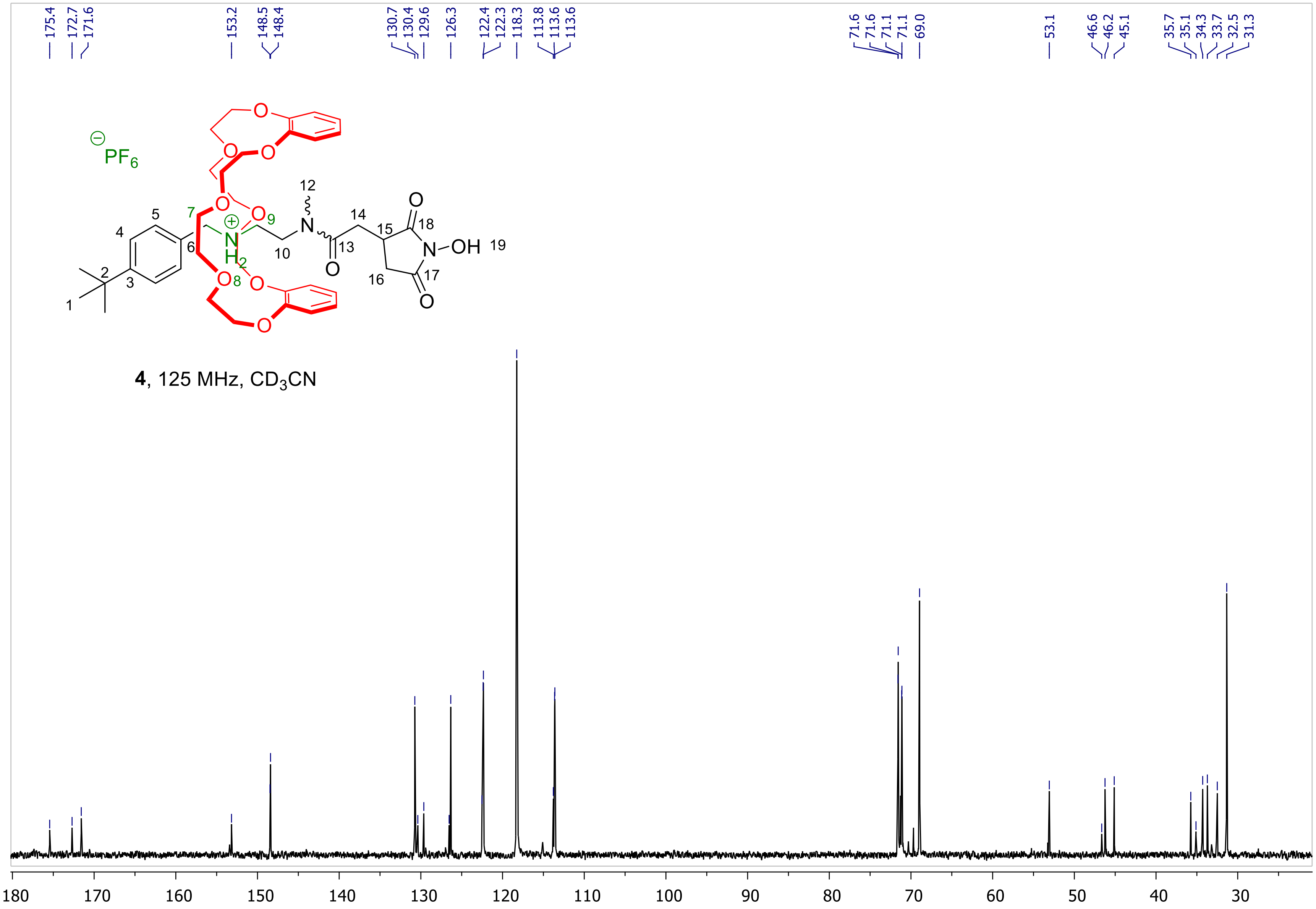


4u, 400 MHz, CD_3CN



4u, 100 MHz, CD_3CN


⊖
PF6
1
2
3
4
5
6
7
8
9
10
12
13
14
15
16
17
18
19
⊕
N
H2
N
O
N–OH
4, 500 MHz, CD3CN
7.23
7.22
7.19
7.17
6.92
6.91
6.90
6.89
4.53
4.51
4.50
4.47
4.46
4.44
4.11
4.04
3.84
3.78
3.72
3.64
3.50
2.72
2.63
2.62
2.60
2.59
2.29
2.25
2.24
1.94
1.94
1.93
1.32
1.31
1.23
1.22
1.19
2.97
1.98
8.10
0.38
1.55
4.00
4.50
18.00
2.08
0.97
1.25
0.60
2.72
1.90
2.41
1.10
0.41
8.43
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.



4, 125 MHz, CD$_3$CN

---

[1] S. Chao, C. Romuald, K. Fournel-Marotte, C. Clavel, F. Coutrot, *Angew. Chem. Int. Ed.* **2014**, *53*, 6914 –6919.