Supporting Information

$SmI_2(H_2O)_n$ Reductions of Electron Rich Enamines by Concerted Proton-Coupled Electron Transfer

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1. Instrumentation

All ^1H NMR spectra were recorded using Agilent 400 MHz, 500 MHz, or 600 MHz spectrometers in $CDCl_3$. All ^{13}C NMR spectra were recorded using an Agilent 600 MHz spectrometer in $CDCl_3$. LCMS measurements were made on an Agilent Technologies instrument (Agilent Technologies, Santa Clara, CA, USA), equipped with a Quadrupole LC/MS spectrometer and 64212B 1260 diode array detector, using a water/acetonitrile with 0.1% formic acid eluent. Automated chromatography was performed using a Teledyne ISCO Combiflash R_f instrument (Teledyne ISCO Inc., Lincoln, NE, USA), with samples loaded on a C-18 pre-column, purified with a 15.5g C-18 HP column, and eluted using a 30 mL/minute flow rate and a 5-90% water/methanol with 0.1% trifluoroacetic acid (TFA) eluent over 90 column volumes. Optical spectra and monitoring of reactions were done using Cary 5000 and Cary 60 UV-Vis spectrophotometers (Agilent Technologies, Santa Clara, CA, USA), which were connected to sample holders inside the N_2 filled glove box via fiber optic cables.

2. Materials

The following materials were used without any special purification. Samarium metal, 20-40 mesh, was purchased from Acros Organics. Iodine was purchased from Mallinckrodt. SmI_2 (s) was purchased from Santa Cruz Biotechnology Inc. Phenylacetaldehyde was purchased from Acros Organics. Acetophenone was purchased from Sigma Aldrich. Stilbene, *trans* 96%, was purchased from Aldrich. Anthracene was purchased from Eastman. Piperidine was purchased from American Bio. Morpholine was purchased from Acros Organics. 4-Isopropyl piperidine was purchased from TCI Chemicals. 4-Methoxyphenethyl alcohol was purchased from Aldrich. Trifluoroethanol was purchased from Aldrich. Chloroform-D and THF-d_8 were purchased from Cambridge Isotope Labs. Dichloromethane, ethyl acetate (EtOAc), and hexanes were purchased from Fisher Scientific. Benzene was purchased from Sigma Aldrich.

Tetrahydrofuran (THF) and diethyl ether (Et_2O) were purchased from Fisher Scientific and purified using a Glass Contour Solvent Purification System (Pure Process Technology, LLC, Nashua, NH). For experiments in the glove box these solvents were pumped directly into the N_2 filled glove box. H_2O was taken from a deionized water tap, then deoxygenated by the freeze pump thaw method and brought into the glove box in a solvent bomb. D_2O was purchased from Aldrich, then deoxygenated by the freeze-pump thaw method and brought into the glove box in a solvent bomb. All substrates were synthesized, then deoxygenated and stored in a N_2 glovebox prior to use.

Silica gel, 230-400 mesh, Grade 60, was purchased from Fisher Scientific. Aluminum oxide, activated, basic, Brockmann 1, was purchased from SigmaAldrich. Celite, 545 filter aid, was purchased from Fisher Scientific. Magnesium sulfate was purchased from Fisher Scientific. Silica plates, gel 60 F254, were purchased from Merck and visualized using a UV Lamp or by staining with a $KMnO_4$ solution. Basic alumina TLC plates, 250 micron, F-254, were purchased from Select

Scientific. Molecular Sieves, 4 Å, 3-5 mm, were purchased from Alfa Aesar and activated at 250 ^oC overnight before use.

3. Synthetic Procedures

Unless noted all procedures with SmI_2 were performed in a N_2 filled glovebox. Volumes for synthetic and kinetic procedures were measured using calibrated micropipettes.

3.1 SmI_2 Preparation and Titration

This procedure is adapted from a literature procedure.[1] A 500 mL two-neck round bottom flask with stir bar was flame dried and cooled under a flow of N_2 in a fume hood. The flask was charged with 2.06 g (13.7 mmol) 40-mesh samarium powder. One neck was equipped with an oven dried reflux condenser and the second neck with a rubber septum and the flask kept under flow of N_2. The flask was then charged with 115 mL THF, which was dispensed from a solvent system directly into a solvent bomb, by Luer lock syringe. The flask was then charged with 3.17 g (12.5 mmol) I_2 by quickly removing the rubber septum, pouring the powder in and replacing the septum under high flow of N_2. The solution began to turn brown-orange. The condenser flow was then turned on and the apparatus submerged in a mineral oil bath and heated to 70° C. After a few hours, the solution turned green, then dark blue. The solution was refluxed over-night, then cooled to room temperature and transferred by cannula under flow of N_2 into a flame dried 500 mL Schlenk flask, leaving a dark blue solid behind. The Schlenk flask was sealed and brought into a N_2 filled glovebox.

The SmI_2 solution was then titrated iodometrically or the optical spectrum measured inside the glovebox. The concentration was then calculated from the absorbance at λ= 618 nm using the reported absorptivity coefficient ε= 877 M^{-1} cm^{-1}.[2]

In a typical procedure for obtaining active concentration of SmI_2 (s), the active concentration of SmI_2 was measured spectroscopically. A quartz cuvette was charged with 1.97 mL THF followed by 30 µL of a 0.0189 M SmI_2/THF stock solution. The absorbance at 618 nm was measured to be 0.107 absorbance units, which using Beer's Law gives an active concentration in the cuvette of 0.0122 M. Back calculating to the stock solution, (0.0122 M* 0.002 L/ 0.00003 L= 0.00813 M) this gives an active concentration of 0.00813 M.

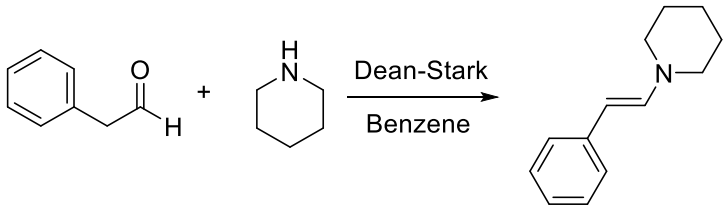
3.2 Substrate Syntheses

3.2.1. General procedure for the synthesis of enamines from aldehydes:

This procedure was adapted from a literature procedure.[3] A 25 mL round bottom flask with stir bar was charged with 5 mmol aldehyde, 7.5 or 10 mmol amine, and 10 mL benzene in air. The flask was then equipped with a 10 mL Dean-Stark trap and the trap fitted with a small reflux condenser. The apparatus was put under flow of N_2. The trap was then submerged in an ice water

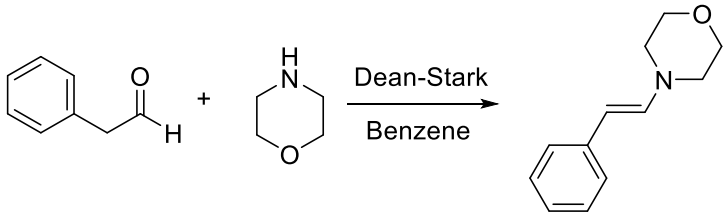
bath, the flask submerged in a mineral oil bath and heated to 100° C. The top of the round bottom and the neck of the apparatus was heated with a heat gun until all the benzene has boiled over and condensed into the trap. The resulting yellow oil was analyzed by ^{1}H NMR for consumption of aldehyde. The trap was then emptied, reattached to the reaction flask, and equipped with a rubber septum. The apparatus was put under 300 mTorr and heated to 80° C with stirring to remove residual amine and solvent. The residual yellow oil was analyzed by ^{1}H NMR, transferred to a 20 mL scintillation vial, and brought into the glovebox in the open vial, cycling in the antechamber five times to deoxygenate the oil. All spectral data matched literature data.

3.2.2. 1-(2-phenylethenyl)-piperidine **1p**



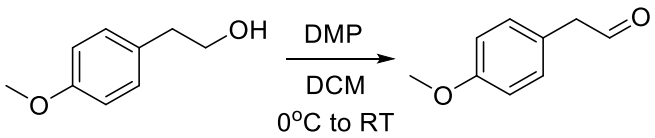
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.23-7.15 (4H, m), 7.03-6.96 (1H, m), 6.64 (1H, d), 5.38 (1H, d), 3.03 (4H, t), 1.67-1.52 (6H, m). Matched literature data.[4]

3.2.3. 4-(2-phenylethenyl)-morpholine **1m**



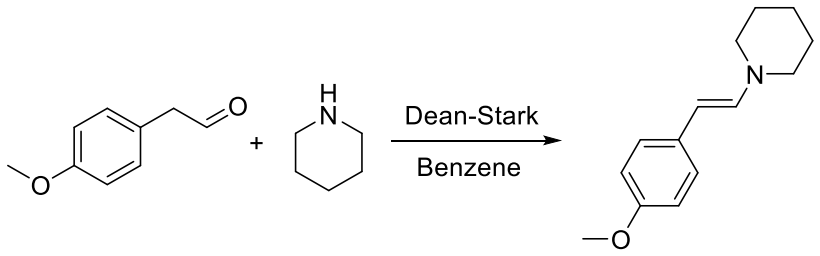
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.25-7.18 (4H, m), 7.07-7.02 (1H, t), 6.60 (1H, d), 5.46 (1H, d), 3.77 (4H, t), 3.04 (4H, t). Matched literature data.[4]

3.2.4. 2-(4-methoxyphenyl)acetaldehyde



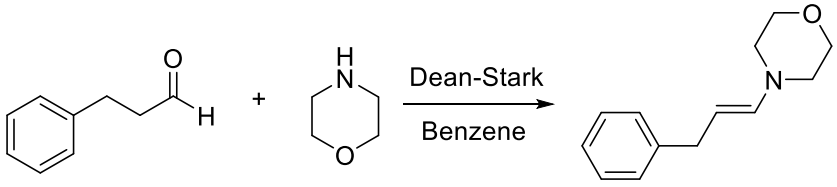
This procedure was adapted from a literature procedure.[5] A flame dried 100 mL round bottom flask with stir bar was cooled under N_2 then charged with 3.50 g (8.25 mmol) Dess-Martin periodinane, followed by 50 mL DCM, then sealed with a rubber septum and put under positive flow of N_2. The flask was then submerged in an ice-water bath and charged with 1.08 mL (7.5 mmol) 2-(4-methoxyphenyl)ethanol via syringe. After stirring for 15 minutes the flask was warmed to RT and stirred for an additional 2 hours. The flask was then charged with 30 mL saturated sodium carbonate and the organic and aqueous layers separated in a separatory funnel. The aqueous layer was extracted twice with 30 mL DCM, then the combined organic layers washed with 30 mL brine. The organic layers were then concentrated to give a white solid, which was then purified by column chromatography using 3:7 EtOAc:hexanes, isolating the spot with Rf = 0.37. The fractions were concentrated to give 708 mg of a yellow oil, which was analyzed by ^{1}H NMR. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 9.72 (1H, t), 7.12 (2H, d), 6.92 (2H, d), 3.80 (3H, s), 3.63 (2H, d). Matched literature data.[6]

3.2.5. 1-(4-methoxystyryl)piperidine **1pOMe**



^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.11 (2H, d), 6.79 (2H, d), 6.50 (1H, d), 5.37 (1H, d), 3.77 (3H, s), 2.98 (4H, t), 1.61 (6H, m). Matched literature data.[7]

3.2.6. 4-(3-phenyl-1-propen-1-yl)-morpholine **3**



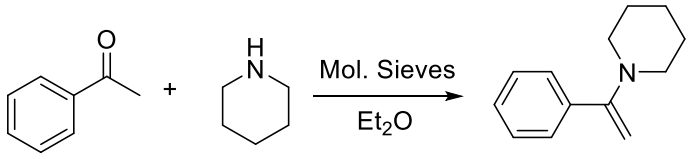
After condensation of the amine and aldehyde, attempts to remove residual amine and benzene under high vacuum resulted in significant decomposition of the enamine product. The crude enamine product was used in the $SmI_2(H_2O)_n$ reduction without application of vacuum to remove excess volatiles. Spectral data in the ^{1}H NMR thus show residual benzene, morpholine, and baseline impurities that increase the integration of the enamine peaks in the aromatic region. ^{1}H

NMR (400 MHz, $CDCl_3$) δ (ppm): 7.32-7.15 (5H, m), 5.89 (1H, d), 4.61 (1H, m), 3.73 (4H, t), 3.33 (2H, d), 2.82 (4H, t). Matched literature data.[8]

3.2.7. Procedure for synthesis of enamines from ketones:

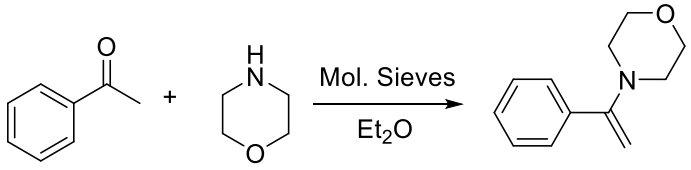
This procedure was adapted from a literature procedure.[9] A 250 mL round bottom flask with stir bar was charged with 5 mmol ketone, 20 mL Et_2O, 7.5 mmol amine, and 17 g 3 Å molecular sieves. The flask was then capped with a rubber septum, put under flow of N_2, and stirred at room temperature over-night. A sample of the solution was then analyzed by ^1H NMR to assess conversion. The resulting mixture was then concentrated on rotary evaporation under reduced pressure. The resulting yellow oil was transferred to a 25 mL round bottom flask with stir bar and distilled under 300-1000 mTorr vacuum using a short path distillation head and a mineral oil bath. The distillates were analyzed by ^1H NMR to identify the product, which was then transferred to a 20 mL scintillation vial and brought into the glovebox in the open vial, cycling in the antechamber five times to deoxygenate the oil.

3.2.8. 1-(1-phenylethenyl)-piperidine **2p**



The residual ketone starting material remaining from the above procedure was first distilled away at 85°C under 300 mTorr vacuum. The product was then distilled at 100°C under 300 mTorr vacuum. ^1H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.50-7.42 (2H, m), 7.35-7.27 (3H, m), 4.24 (1H, s), 4.14 (1H, s), 2.80 (4H, t), 1.62 (4H, m), 1.54 (2H, m). Matched literature data.[4]

3.2.9. 4-(1-phenylethenyl)-morpholine **2m**



The residual ketone and amine remaining from the above procedure were first distilled at 75°C under 1000 mTorr vacuum. The product was then distilled at 100°C under 300 mTorr vacuum. ^1H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.50-7.42 (2H, m), 7.37-7.30 (3H, m), 4.33 (1H, s), 4.19 (1H, s), 3.77 (4H, t), 2.84 (4H, t). Matched literature data.[4]

3.3 Reduction of Enamine Substrates with $SmI_2(H_2O)_n$

3.3.1. Procedure for SmI_2 (s) reduction of substrates (Table 1):

Inside an N_2 filled glovebox, a 20 mL scintillation vial was charged with 0.375 mmol (292 mg) SmI_2 (s) followed by 4.87 mL THF, making a dark blue solution. The vial was then charged with 0.125 mmol substrate, with no change in color observed. The vial was then charged with 18.7 mmol (0.337 mL) H_2O to trigger the reaction, turning the solution dark red. Once a color change to a colorless solution with white precipitate was observed, indicating Sm(II) oxidation, the vial was removed from the glovebox.

The solution was then filtered over a pad of non-acid washed Celite using a medium frit vacuum filter into a 100 mL round bottom flask, washing with 20-60 mL DCM. The resulting clear-yellow solution was then concentrated by rotary evaporation under reduced pressure. The resulting clear-yellow oil was then tested by LCMS and loaded onto a C-18 pre-column using 650 µL MeOH. The pre-column was attached to a Teledyne ISCO and the material purified by automated chromatography using a 10-90% H_2O/MeOH with 0.1% TFA eluent, testing fractions for pure product by LCMS.

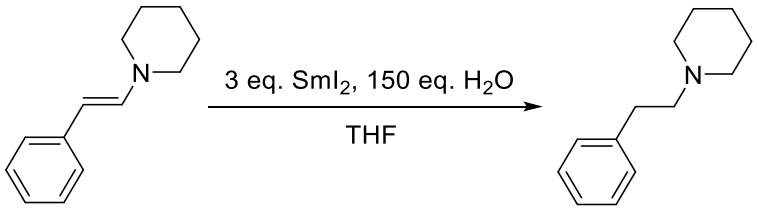
The fractions from the column were combined in a 250 or 500 mL round bottom flask, concentrated by rotary evaporation under reduced pressure to remove MeOH, and basified using 2M NaOH until the pH read >14 by pH paper. The solution was transferred to a 125 or 250 mL separatory funnel and extracted four times with 20 mL DCM. The combined DCM layers were washed with 40 mL saturated brine solution, dried over approximately 5 g $MgSO_4$ for 15 minutes, filtered over an oven dried medium frit vacuum filter into a 100 mL round bottom flask and concentrated by rotary evaporation under reduced pressure. The resulting colorless oil was weighed and analyzed by ^{1}H NMR, ^{13}C NMR, and LCMS.

3.3.2. Procedure for SmI_2 solution reduction of substrates:

Inside an N_2 filled glovebox, a 20 mL scintillation vial was charged with 0.375 mmol SmI_2 solution (4.87 mL), prepared and titrated as described in section 3.1, giving a dark blue solution. The vial was then charged with 0.125 mmol substrate, with no color change observed. The vial was then charged with 18.7 mmol (0.337 mL) H_2O to trigger the reaction, turning the solution dark red. The remaining procedure, workup and purification are identical to the procedure in Section 3.3.1.

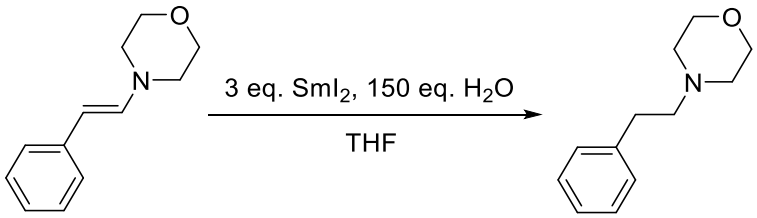
3.3.3. Procedures and data for reduction of enamines by $SmI_2(H_2O)_n$ (Table 1):

*3.3.3.1. Reduction of **1p** to 1-(2-phenylethyl)-piperidine*



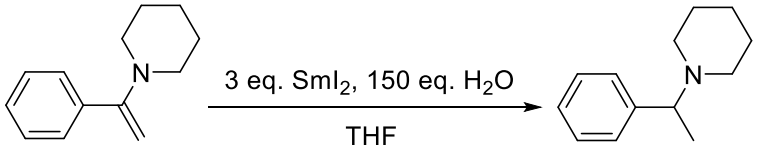
The procedure used 23.4 mg (0.10 mmol) enamine, 4.16 mL (0.30 mmol) 0.072 M SmI_2 solution, and 0.270 mL (15 mmol) H_2O. The product was purified by silica gel column chromatography using 9:1:0.01 hexanes/EtOAc/Et_3N, dry packing the column and pretreating with eluent to deactivate the silica gel. The product was isolated as the spot with Rf = 0.08, visualizing with $KMnO_4$ after thoroughly removing Et_3N from the plate with a heat gun. The procedure gave 18 mg colorless oil, 81% yield. ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.23-7.18 (2H, m), 7.15-7.09 (3H, m), 2.74 (2H, m), 2.48 (2H, m), 2.40 (4H, br), 1.62 (4H, quint), 1.40 (2H, m). ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 140.7, 128.7, 128.4, 125.9, 61.5, 54.6, 33.7, 26.0, 24.5. Matched literature data.[10]

*3.3.3.2. Reduction of **1m** to 4-(2-phenylethyl)-morpholine*



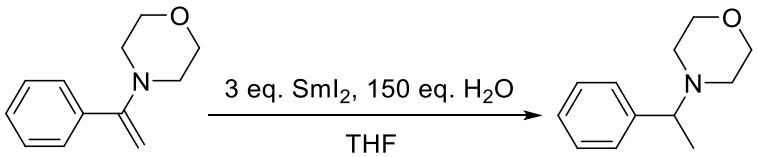
The procedure used 23.6 mg (0.125 mmol) enamine, 212 mg (0.375 mmol) SmI_2 (s), 0.337 mL (18.7 mmol) H_2O, and 4.87 mL THF. The procedure gave 21 mg white solid, 88% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.31-7.24 (2H, m), 7.22-7.17 (3H, m), 3.80 (4H, t), 2.87 (2H, m), 2.68 (2H, m), 2.62 (4H, br); ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 139.5, 128.8, 128.6, 126.5, 66.5, 60.7, 53.6, 32.9. Matched literature data.[10]

*3.3.3.3. Reduction of **2p** to 1-(1-phenylethyl)-piperidine*



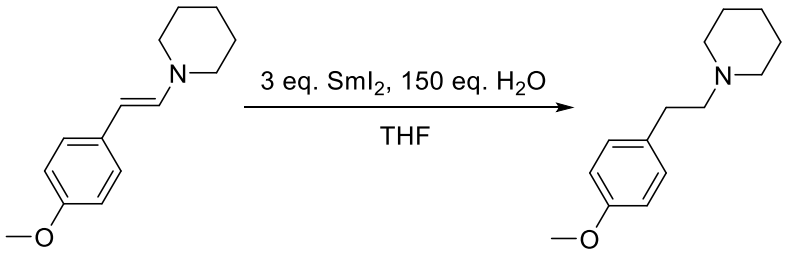
The procedure used 23.4 mg (0.125 mmol) enamine, 292 mg (0.375 mmol) SmI_2 (s), 0.337 mL (18.7 mmol) H_2O, and 4.87 mL THF. The procedure gave 20 mg clear oil, 87% yield. ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.33-7.28 (4H, m), 7.25-7.21 (1H, m), 3.42 (1H, q), 2.48-2.3 (4H, m), 1.56 (4H, m), 1.38 (5H, d); ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 128.0, 127.8, 126.7, 65.2, 51.5, 26.1, 24.5, 19.3. Matched literature data.[11]

*3.3.3.4. Reduction of **2m** to 4-(1-phenylethyl)-morpholine*



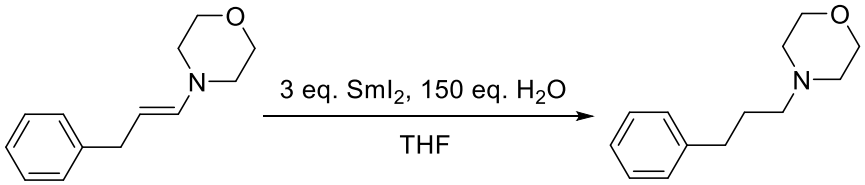
The procedure used 23.6 mg (0.125 mmol) enamine, 212 mg (0.375 mmol) SmI_2 (s), 0.337 mL (18.7 mmol) H_2O, and 4.87 mL THF. The procedure gave 18 mg clear oil, 75% yield. ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.33-7.28 (4H, m), 7.27-7.22 (1H, m), 3.69 (4H, t), 3.30 (1H, q), 2.48 (2H, br), 2.38 (2H, m), 1.36 (3H, d); ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 144.0, 128.4, 127.8, 127.1, 67.4, 65.6, 51.5, 20.0. Matched literature data.[11]

*3.3.3.5. Reduction of **1pOMe** to 1-(4-methoxyphenethyl)-piperidine*



The procedure used 21.7 mg (0.10 mmol) enamine, 4.16 mL (0.30 mmol) 0.072 M SmI_2 (sol), and 0.270 mL (15 mmol) H_2O. The product was purified by silica gel column chromatography using 9:1:0.01 hexanes/EtOAc/Et_3N, dry packing the column and pretreating with eluent to deactivate the silica gel. The product was isolated as the spot with Rf = 0.12, visualizing with $KMnO_4$ after thoroughly removing Et_3N from the plate with a heat gun. Procedure gave 18 mg clear oil, 81% yield. ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.12 (2H, d), 6.82, (2H, d), 3.77 (3H, s), 2.75 (2H, m), 2.52 (2H, m), 2.46 (4H, br), 1.62 (4H, quint), 1.45 (2H, m). ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 158.0, 132.8, 129.7, 113.9, 61.9, 55.4, 54.7, 32.9, 26.2, 24.6. Matched literature data.[11]

*3.3.3.6. Reduction of **3** to 4-(3-phenylpropyl)-morpholine*



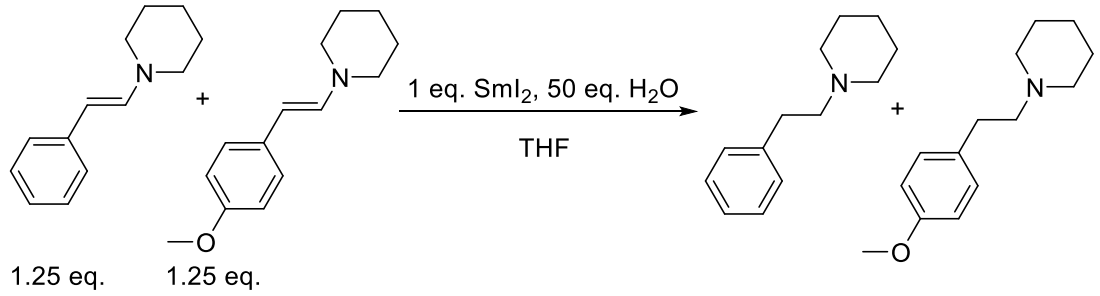
The procedure used 25 mg (0.062 mmol) (50 mol% as calculated from the ^{1}H NMR of the starting material) enamine, 212 mg (0.375 mmol) SmI_2 (s), 0.337 mL (18.7 mmol) H_2O, and 4.87 mL THF. The procedure gave 4 mg clear oil, 31% yield. The low yield is attributed to the difficulties in separating the starting material from amine and benzene. ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm): 7.35-7.22 (m, 2H), 7.22-7.07 (m, 3H), 3.82-3.65 (s, 4H), 2.72-2.55 (t, 2H), 2.50-2.38 (s, 4H), 2.40-2.25 (t, 2H), 1.90-1.75 (t, 2H). ^{13}C NMR (600 MHz, $CDCl_3$) δ (ppm): 142.2, 128.5, 125. Matched literature data.[11]

3.4 Procedures and data for substrate competition reactions with $SmI_2(H_2O)_n$

*3.4.1 General procedure for substrate competition experiments (**Table 2**):*

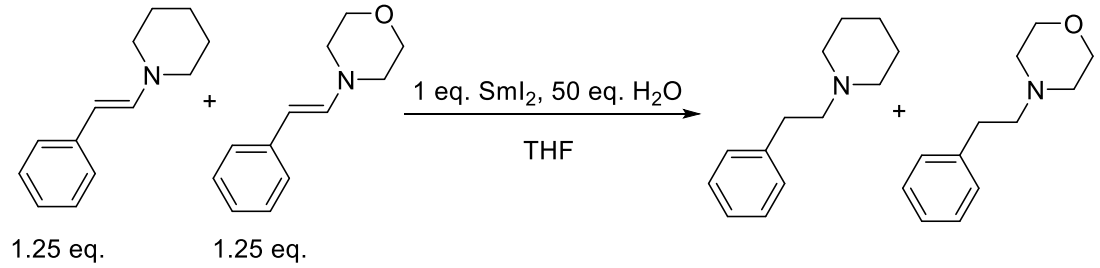
Inside an N_2 filled glovebox, a 20 mL scintillation vial was charged with 0.16 mmol solid SmI_2, titrated as noted in section 3.1. A one dram vial was charged with 0.20 mmol substrate **A** and transferred to the SmI_2 vial with 2 mL THF, then the **A** vial was washed with an additional 1 mL THF and this transferred. A second one dram vial was charged with 0.20 mmol substrate **B** and transferred to the SmI_2 vial with 2 mL THF, then washed with 1 mL THF and this transferred. The reaction vial was then charged with an additional 2 mL THF and then 8 mmol H_2O to start the reaction. Once a color change to a colorless solution with white precipitate was observed, indicating Sm(II) oxidation, the vial was removed from the glovebox, concentrated by rotary evaporation, and purified by basic alumina column chromatography to separate the unreacted starting materials and products. Yields are calculated with respect to SmI_2. Because each reduction requires two equivalents of SmI_2, 0.8 mmol total product corresponds to 100% yield.

*3.4.2. Reduction of **1p** and **1pOMe** to 1-(2-phenylethyl)-piperidine and 1-(4-methoxyphenethyl)-piperidine*



The procedure used 37 mg (0.20 mmol) 1-(2-phenylethenyl)-piperidine, 44 mg (0.20 mmol) 1-(4-methoxyphenethyl)-piperidine, 118 mg (0.16 mmol) SmI_2 (s), 0.144 mL (8 mmol) H_2O, and 8 mL THF. The mixture was purified by basic alumina column, eluting with 9:1 hexanes:EtOAc. All fractions containing 1-(2-phenylethyl)-piperidine and 1-(4-methoxyphenethyl)-piperidine were combined. To this mixture was added 1.6 mg (0.00951 mmol) trimethoxybenzene as standard, and the mixture analyzed by ^{1}H NMR. The mol ratio of trimethoxybenzene to 1-(2-phenylethyl)-piperidine was 1.0:3.1, which gave 5.4 mg (0.0292 mmol) 1-(2-phenylethyl)-piperidine, 36% yield. The mol ratio of trimethoxybenzene to 1-(4-methoxyphenethyl)-piperidine was 1.0:2.7, which gave 5.5 mg (0.0251) mmol 1-(4-methoxyphenethyl)-piperidine, 31% yield. This gives a 1.2:1.0 ratio of 1-(2-phenylethyl)-piperidine to 1-(4-methoxyphenethyl)-piperidine.

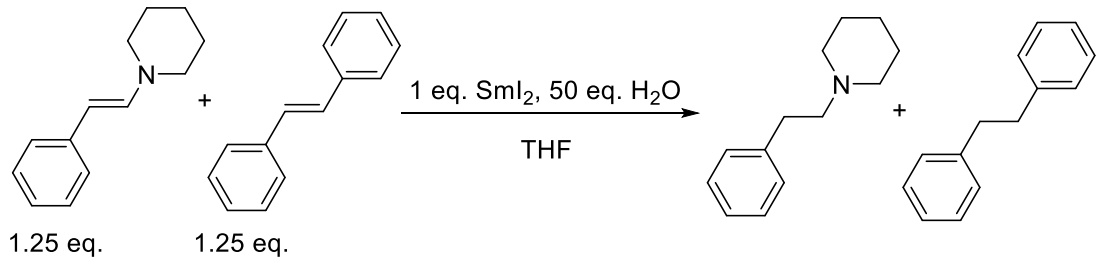
*3.4.3. Reduction of **1p** and **1m** to 1-(2-phenylethyl)-piperidine and 4-(2-phenylethyl)-morpholine*



The procedure used 37.4 mg (0.20 mmol) 1-(2-phenylethenyl)-piperidine, 37.8 mg (0.20 mmol) 4-(2-phenylethenyl)-morpholine, 118 mg (0.16 mmol) SmI_2 (s), 0.144 mL (8 mmol) H_2O, and 8 mL THF. The mixture was purified by basic alumina column chromatography, eluting with 1:1 hexanes:EtOAc. All fractions containing 1-(2-phenylethyl)-piperidine and 4-(2-phenylethyl)-morpholine were combined to give 15 mg. This mixture was analyzed by ^{1}H and ^{13}C NMR, and gave a 1.0:0.25 ratio of 1-(2-phenylethyl)-piperidine to 4-(2-phenylethyl)-morpholine. This ratio gave 12.1 mg (0.064 mmol) 1-(2-phenylethyl)-piperidine, 80% yield, and 3.0 mg (0.016 mmol) 4-

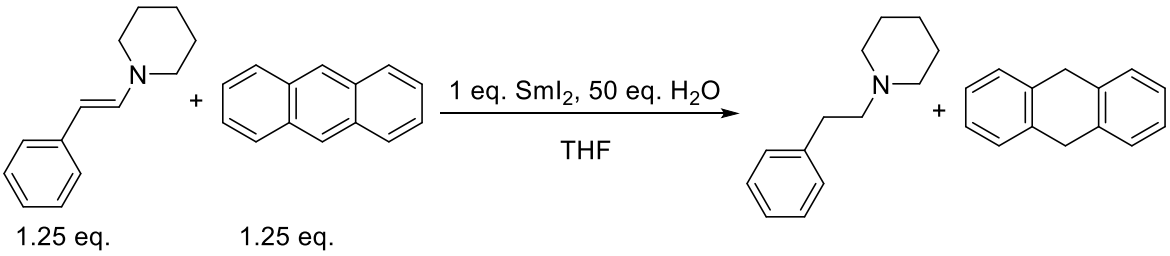
(2-phenylethyl)-morpholine, 20% yield. This gives 4.0:1.0 ratio of 1-(2-phenylethyl)-piperidine to 4-(2-phenylethyl)-morpholine.

*3.4.4. Reduction of **1p** and **S** to 1-(2-phenylethyl)-piperidine and 1,2-diphenylethane*



The procedure used 38 mg (0.20 mmol) 1-(2-phenylethenyl)-piperidine, 36 mg (0.20 mmol) stilbene, 118 mg (0.16 mmol) SmI_2 (s), 0.144 mL (8 mmol) H_2O, and 8 mL THF. The product mixture was purified by basic alumina column chromatography, eluting using 1:1 hexanes/EtOAc. Fractions containing stilbene and 1,2-diphenylethane were combined, giving 39 mg. This mixture was analyzed by ^{1}H NMR, and gave a 1:0.075 ratio of stilbene to 1,2-diphenylethane, which matched literature spectral data.[12] Fractions containing 1-(2-phenylethyl)-piperidine were combined, which gave 5 mg, matching previous spectral data. This mixture was analyzed by ^{1}H NMR, and gave a 1:0.10 ratio of 1-(2-phenylethyl)-piperidine to 1,2-diphenylethane. These ratios gave 11.8 mg (0.0630 mmol) 1-(2-phenylethyl)-piperidine, 78% yield, and 2.7 mg (0.0148 mmol) 1,2-diphenylethane, 18% yield. This gives a 4.3:1.0 ratio of 1-(2-phenylethyl)-piperidine to 1,2-diphenylethane.

*3.4.5. Reduction of **1p** and **A** to 1-(2-phenylethyl)-piperidine and dihydroanthracene*



The procedure used 37.4 mg (0.200 mmol) 1-(2-phenylethenyl)-piperidine, 35.6 mg (0.200 mmol) anthracene, 118 mg (0.16 mmol) SmI_2 (s), 0.144 mL (8 mmol) H_2O, and 8 mL THF. The product mixture was purified by basic alumina column chromatography, eluting with 1:1 hexanes/EtOAc. Fractions containing anthracene and 1,2-dihydroanthracene were combined. To this mixture was added 1.2 mg (0.00714 mmol) trimethoxybenzene as standard, and the mixture was analyzed by ^{1}H NMR, matching literature spectral data.[13] The mol ratio of trimethoxybenzene to dihydroanthracene was 1.0:7.5, which gave 9.6 mg (0.053 mmol) dihydroanthracene, 67% yield.

Fractions containing 1-(2-phenylethyl)-piperidine were combined to give 5 mg (0.026 mmol) 1-(2-phenylethyl)-piperidine, 33% yield. This gives a 1.0:2.0 ratio of 1-(2-phenylethyl)-piperidine to dihydroanthracene.

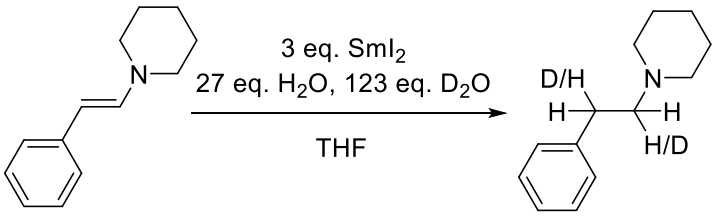
3.5. H_2O/D_2O competition experiments (KIEs) (Table 3)

3.5.1. General procedure

Inside an N_2 filled glovebox, a 20 mL scintillation vial was charged with 0.375 mmol solid SmI_2, titrated as noted in section 3.1. A one dram vial was charged with 0.125 mmol substrate A and transferred to the SmI_2 vial with 1 mL THF, then washed with 1 mL THF and this transferred. The reaction mixture was then charged with an additional 2 mL THF. A second one dram vial was charged with 9.35 mmol H_2O followed by 9.35 mmol D_2O and transferred to the SmI_2 vial, then washed with 0.87 mL THF and this transferred. Once a color change to a clear solution with white precipitate was observed, indicating Sm(II) oxidation, the vial was removed from the glovebox and purified as normal to isolate products. Uncertainty in KIE measurements was estimated to be equivalent to the uncertainty in an NMR measurement, 5%.

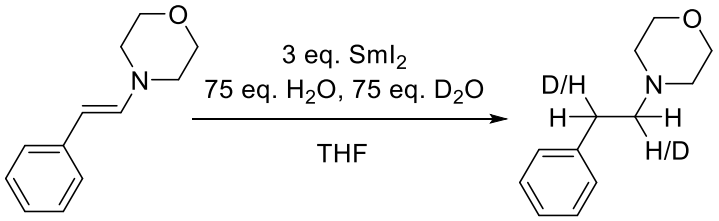
*Specific procedures and data for H_2O/D_2O competition reactions with $SmI_2(D/H_2O)_n$ (**Table 3**):*

*3.5.2. Reduction of **1p** to 1-(2-phenylethyl)-piperidine*



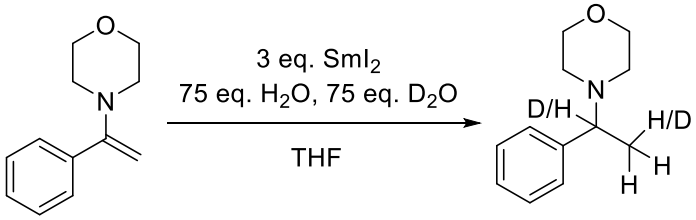
This procedure used 23.4 mg (0.125 mmol) 4-(2-phenylethenyl)-piperidine, 212 mg (0.375) SmI_2 (s), 61 μL (3.40 mmol) H_2O, 0.278 mL (15.3 mmol) D_2O, and 4.87 mL THF. The isolated product was analyzed by ^1H NMR (400 MHz, $CDCl_3$) δ (ppm): 7.32-7.25 (2H, m), 7.23-7.16 (3H, m), 2.84 (1.60H, m), 2.66-2.45 (5.09H, multiplet and br), 1.67 (4H, quintet), 1.48 (2H, m). From these data, the H/D ratio at the carbon α to the nitrogen is calculated to be 51:49 and the H/D ratio at the carbon β to the nitrogen is calculated to be 60:40. Multiplying each number by the ratio of D_2O:H_2O used in the experiment, 4.5:1, the KIE at the carbon β to the nitrogen is calculated to be 6.75±0.32.

*3.5.3. Reduction of **1m** to 4-(2-phenylethyl)-morpholine*



This procedure used 23.6 mg (0.125 mmol) 4-(2-phenylethenyl)-morpholine, 151 mg (0.375) SmI_2 (s), 0.168 mL (9.37 mmol) H_2O, 0.168 mL (9.37 mmol) D_2O, and 4.87 mL THF. The isolated product was analyzed by ^1H NMR (600 MHz, $CDCl_3$) δ (ppm): 7.32-7.28 (2H, m), 7.23-7.18 (3H, m), 3.75 (4H, t), 2.81 (1.88H, m), 2.63-2.47 (5.60H, two multiplets). From these data, the H/D ratio at the carbon α to the nitrogen is calculated to be 60:40 and the H/D ratio at the carbon β to the nitrogen is calculated to be 88:12. The KIE at the carbon β to the nitrogen is calculated to be 7.3±0.36.

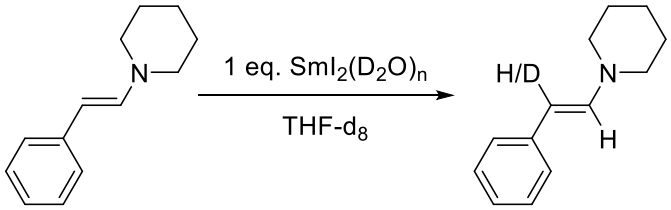
*3.5.4. Reduction of **2m** to 4-(1-phenylethyl)-morpholine*



This procedure used 23.6 mg (0.125 mmol) 4-(1-phenylethenyl)-morpholine, 151 mg (0.375) SmI_2 (s), 0.168 mL (9.37 mmol) H_2O, 0.168 mL (9.37 mmol) D_2O, and 4.87 mL THF. The isolated product was analyzed by ^1H NMR (600 MHz, $CDCl_3$) δ (ppm): 7.35-7.27 (4H, m), 7.25-7.20 (1H, m), 3.69 (4H, t), 3.29 (0.58 H, q), 2.48 (2H, br), 2.36 (2H, m), 1.34 (2.78 H, m). From these data, the H/D ratio at the tertiary carbon α to the amine is calculated to be 58:42 and the H/D ratio at the primary carbon β to the amine is calculated to be 78:22. The KIE at the carbon β to the nitrogen is calculated to be 3.54±0.17.

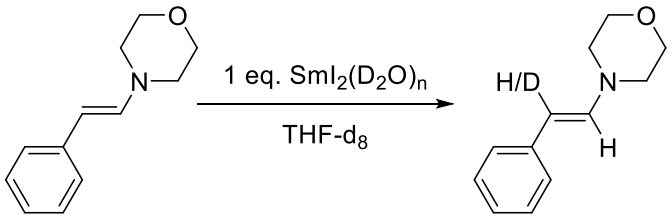
3.6 D_2O Exchange Experiments

*3.6.1. D_2O Exchange with **1p***



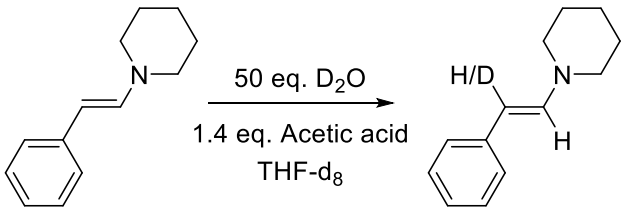
A J-Young tube was charged with 2.3 mg (0.0125 mmol) 1-(2-phenylethenyl)-piperidine, 9.3 mg (0.0125 mmol) SmI_2, 11.3 μL (0.625 mmol) D_2O, and 0.6 mL THF-d_8. The NMR tube was then sealed. After oxidation of SmI_2 had occurred the NMR tube was centrifuged to concentrate the Sm^{3+} precipitates in the bottom of the tube and the reaction mixture was analyzed by ^1H NMR. The integration of the alkenyl peaks in the remaining starting material are equal within error, showing that no deuteration has occurred at the carbon β to the nitrogen. One equivalent of SmI_2 was used so that conversion would be approximately 50% and remaining starting material could be analyzed.

*3.6.2. D_2O Exchange with **1m***



A J-Young tube was charged with 2.3 mg (0.0125 mmol) 1-(2-phenylethenyl)-morpholine, 9.3 mg (0.0125 mmol) SmI_2, 11.3 μL (0.625 mmol) D_2O, and 0.6 mL THF-d_8. The NMR tube was then sealed. After oxidation of SmI_2 had occurred the NMR tube was centrifuged to concentrate the Sm^{3+} precipitates in the bottom of the tube and the reaction mixture was analyzed by ^1H NMR. The integration of the alkenyl peaks in the remaining starting material are equal within error, showing that no deuteration has occurred at the carbon β to the nitrogen. One equivalent of SmI_2 was used so that conversion would be approximately 50% and remaining starting material could be analyzed.

*3.6.3. D_2O Exchange with **1p** and acetic acid*



An NMR tube was charged with 2.3 mg (0.0125 mmol) 1-(2-phenylethenyl)-piperidine, 11.3 μL (0.625 mmol) D_2O, 1 μL (0.0175 mmol) glacial acetic acid, and 0.6 mL THF-d_8. The ^1H NMR was measured after approximately 10 minutes. The integration of the enamine alkenyl peak at ~6.7 ppm is 1.19 with respect to the enamine alkenyl peak at ~5.3 ppm, indicating that some of the hydrogen at the carbon β to the nitrogen has been exchanged for deuterium.

4. Cyclic Voltammograms

4.1 Cyclic Voltammograms of 1p

4.1.1 General considerations.

Cyclic voltammetry was performed using a glassy carbon working electrode, platinum auxiliary electrode, and silver wire reference electrode. Experiments were performed in N_2 sparged THF solutions with 3.7 mM **1p** and 0.1 M tetrabutyl ammonium hexafluorophosphate ($TBAPF_6$). The surface of the working electrode was mechanically polished on felt pads with a coating of alumina slurry and electrochemically polished by cycling the potential of the electrode from 1.5 V to -3.5 V in N_2 sparged electrolyte solution without substrate. All cyclic voltammograms were referenced to the ferrocene$^{0/+}$ couple.

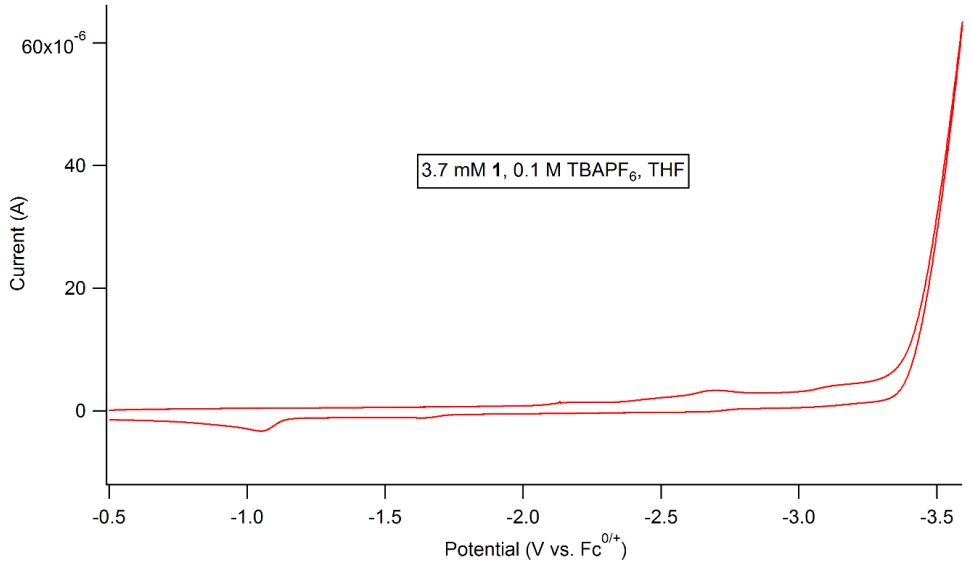


Figure S4.1.1. Cyclic voltammogram of 3.7 mM **1p** in THF.

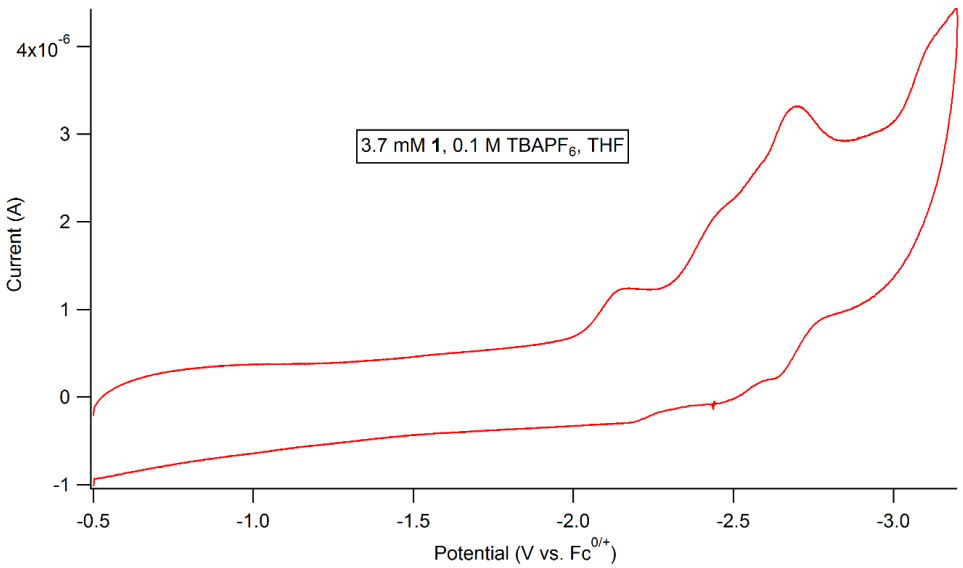


Figure S4.1.2. Cyclic voltammogram of 3.7 mM **1p** in THF, scan to –3.2 V.

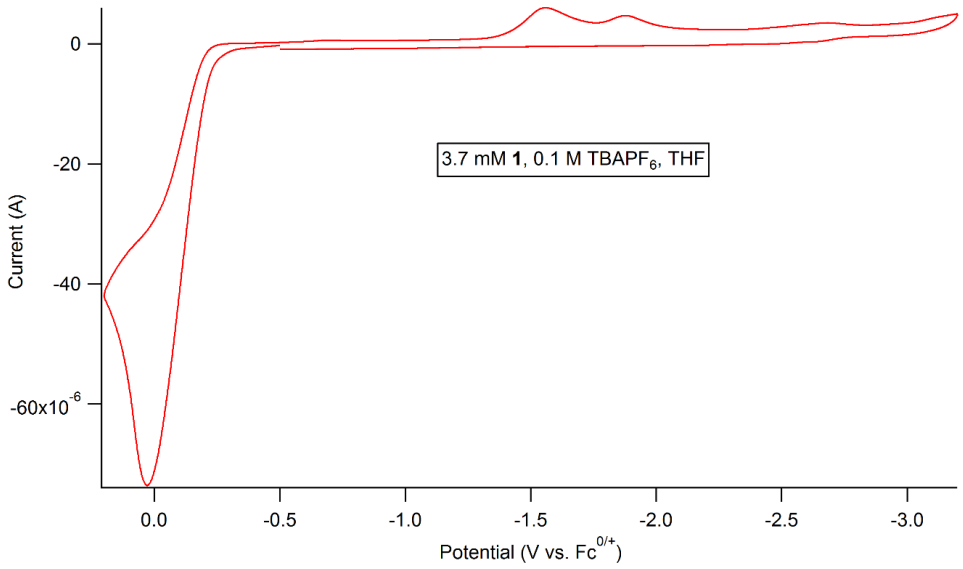


Figure S4.1.3. Cyclic voltammogram of 3.7 mM **1p** in THF, showing oxidation of the substrate at *ca.* 0.0 V vs. $Fc^{+/0}$.

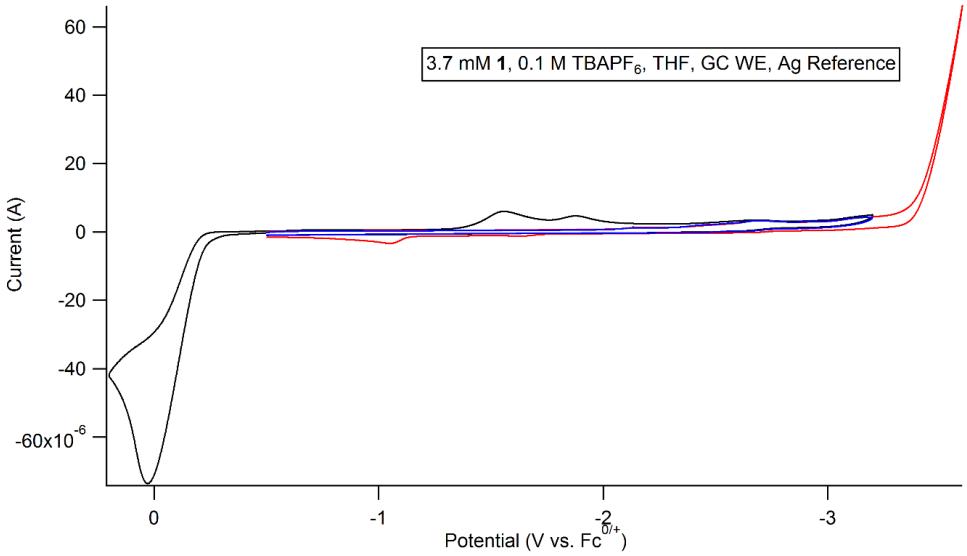


Figure S4.1.4. Overlay of the three cyclic voltammograms of 3.7 mM **1p** in THF.

5. Optical Monitoring of $SmI_2(H_2O)_n$ Reductions

5.1. Kinetics with Trifluoroethanol

5.1.1. General considerations.

Kinetic experiments were carried out inside an N_2 filled glovebox, with a cell holder connected to a Cary 60 UV-Vis spectrometer outside the glovebox by fiber optic cables. Quartz cuvettes were charged with SmI_2/THF, substrate/THF, and the reactions were triggered by addition of H_2O/THF or 1:1 H_2O:TFE/THF while stirring. The substrate was always held in at least 10-fold excess to SmI_2 to maintain pseudo first-order conditions. All additions were made using calibrated micropipettes. The consumption of $SmI_2(H_2O)_n$ was measured from the absorbance decay at 560 nm. Absorbance was normalized to the maximum absorbance of each trace. The traces did not fit exponential decay functions, so overlays for each pair of traces from 0-25 mM H_2O and TFE are presented here. In all cases the traces with H_2O are slower than the traces with 1:1 H_2O:TFE. By compressing the time axis of the slower trace to achieve overlay with the faster trace, it is apparent that differences in the reactions are less than a factor of 1.3 in all cases.

5.1.2. Overlays of kinetic traces.

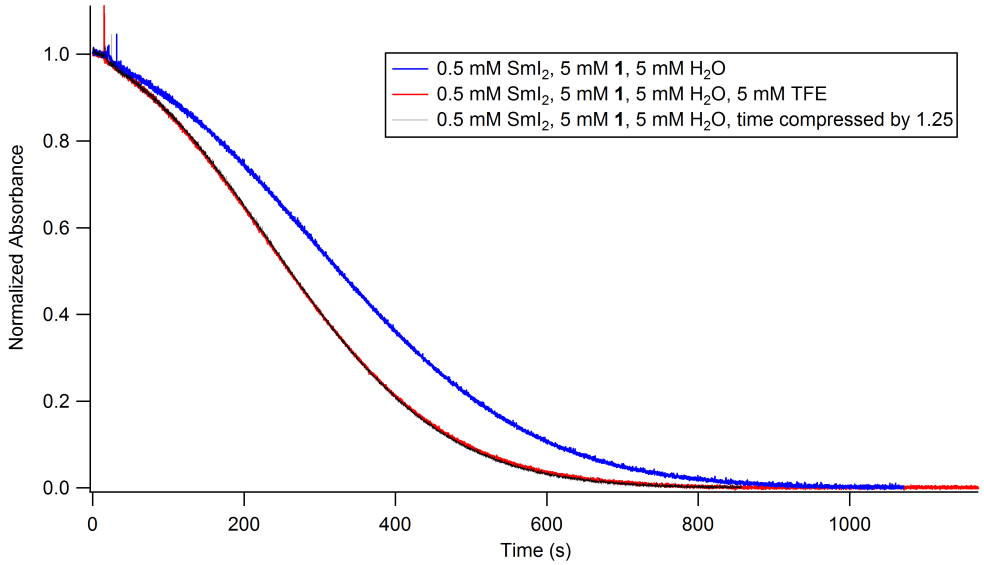


Figure S5.1.1. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (5 mM, blue trace) and 1:1 H_2O:TFE (5 mM:5 mM, red trace). The H_2O trace which is time compressed by 1.25 fold is shown in black.

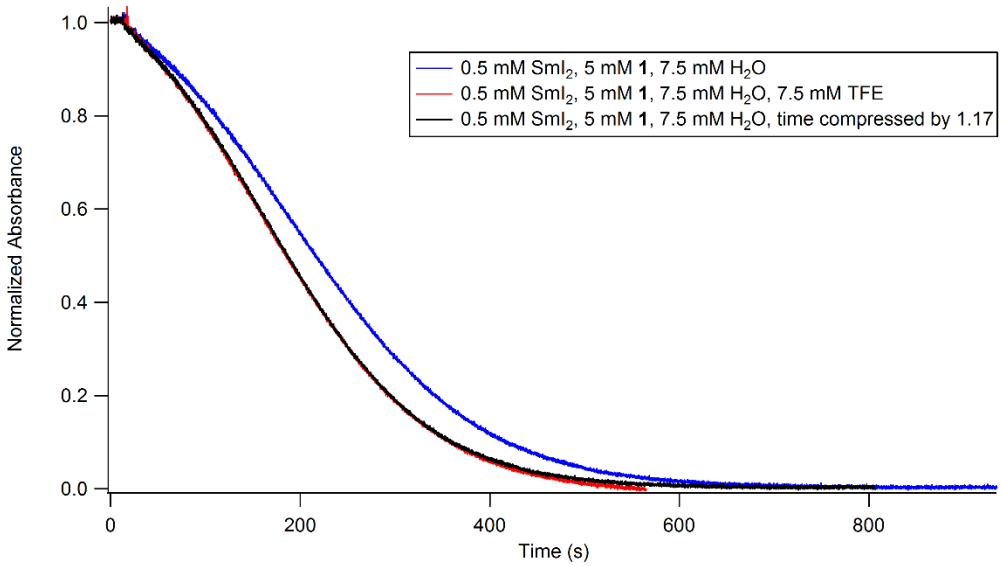


Figure S5.1.2. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (7.5 mM, blue trace) and 1:1 H_2O:TFE (7.5 mM:7.5 mM, red trace). The H_2O trace which is time compressed by 1.17 fold is shown in black.

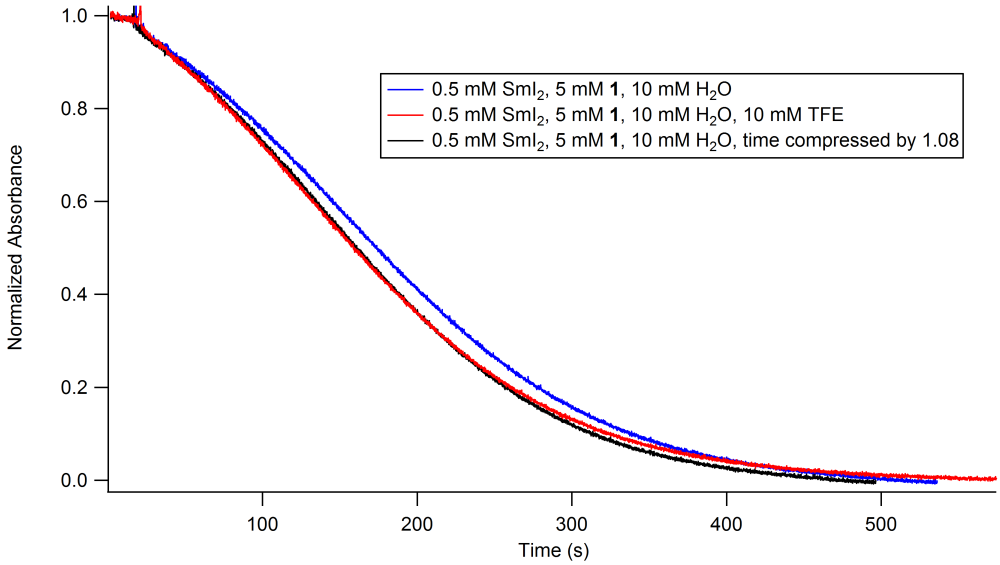


Figure S5.1.3. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (10 mM, blue trace) and 1:1 H_2O:TFE (10 mM:10 mM, red trace). The H_2O trace which is time compressed by 1.08 fold is shown in black.

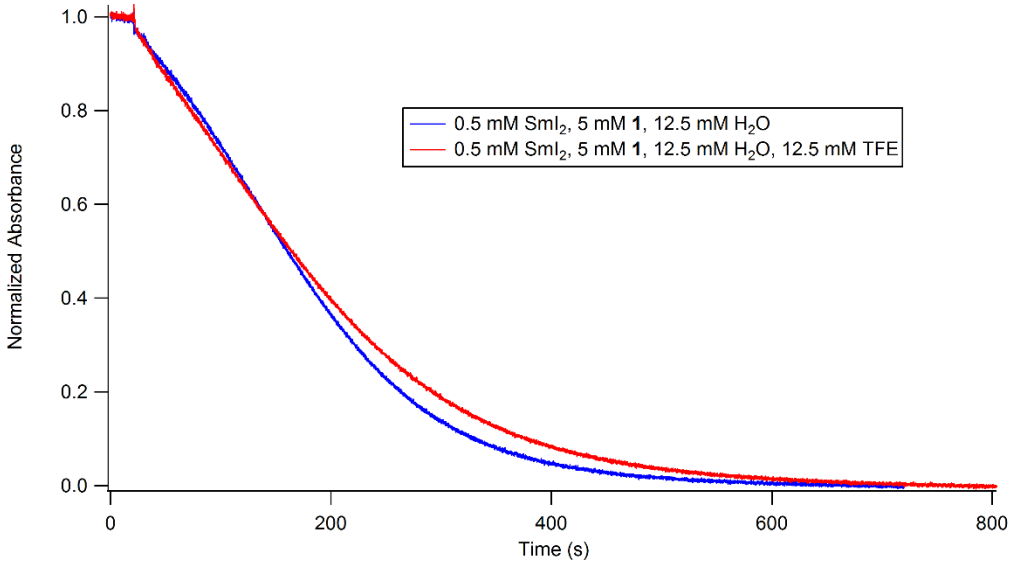


Figure S5.1.4. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (12.5 mM, blue trace) and 1:1 H_2O:TFE (12.5 mM:12.5 mM, red trace).

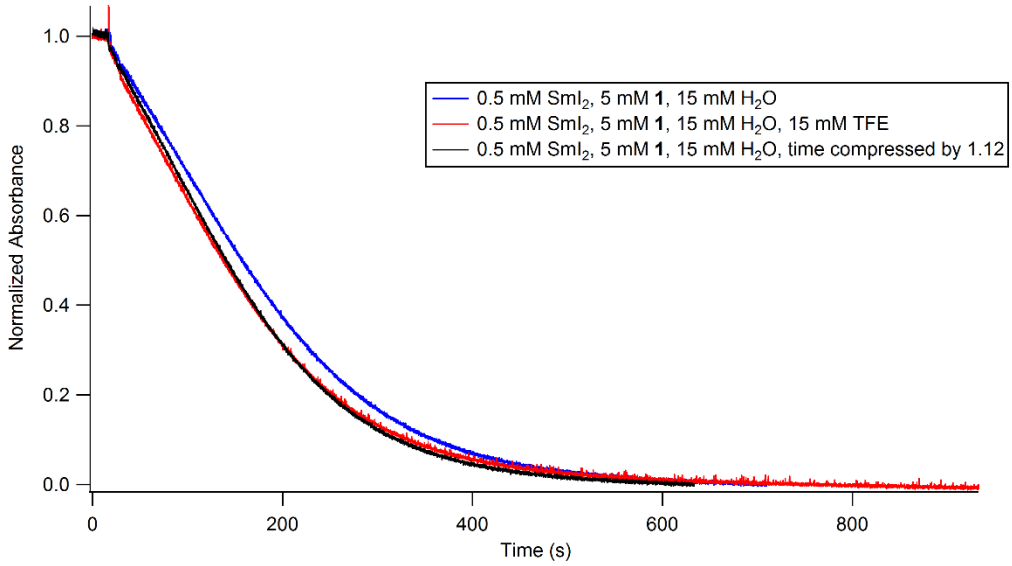


Figure S5.1.5. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (15 mM, blue trace) and 1:1 H_2O:TFE (15 mM:15 mM, red trace). The H_2O trace which is time compressed by 1.12 fold is shown in black.

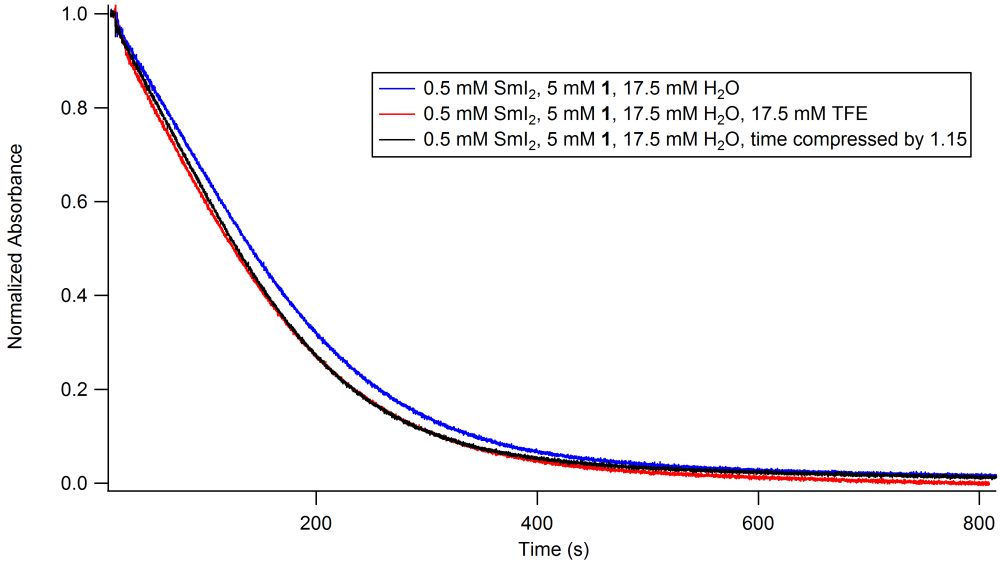


Figure S5.1.6. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (17.5 mM, blue trace) and 1:1 H_2O:TFE (17.5 mM:17.5 mM, red trace). The H_2O trace which is time compressed by 1.15 fold is shown in black.

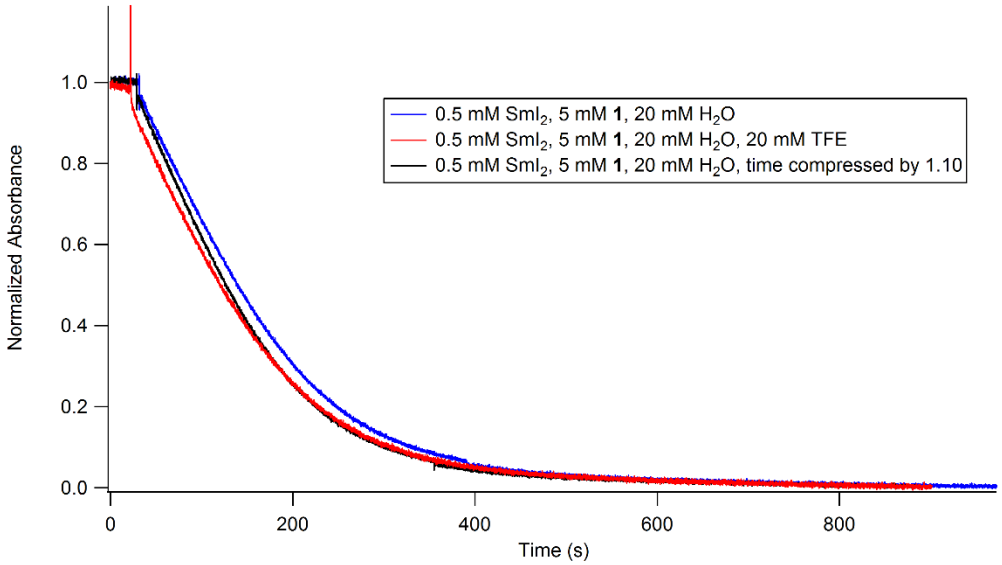


Figure S5.1.7. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (20 mM, blue trace) and 1:1 H_2O:TFE (20 mM:20 mM, red trace). The H_2O trace which is time compressed by 1.10 fold is shown in black.

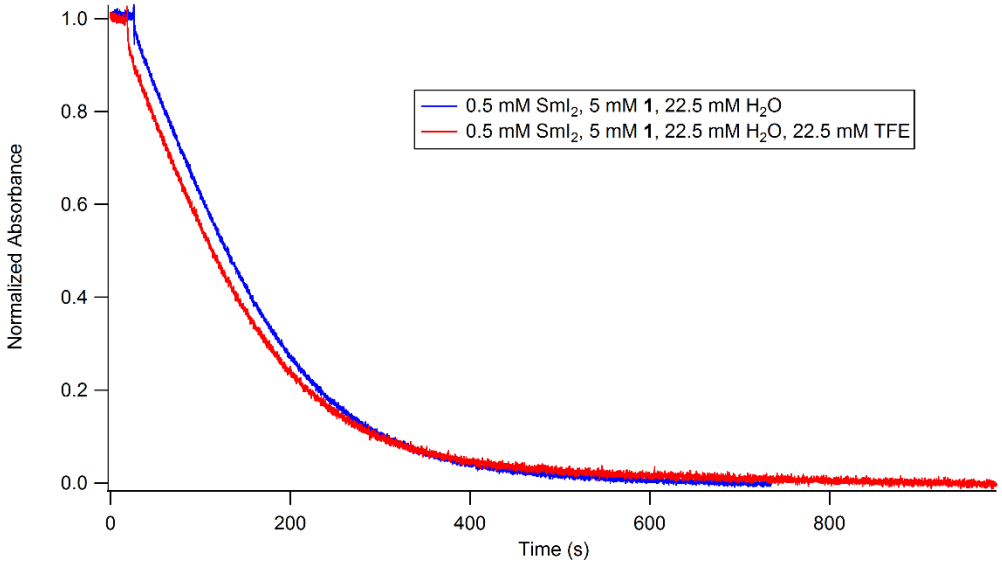


Figure S5.1.8. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (22.5 mM, blue trace) and 1:1 H_2O:TFE (22.5 mM:22.5 mM, red trace).

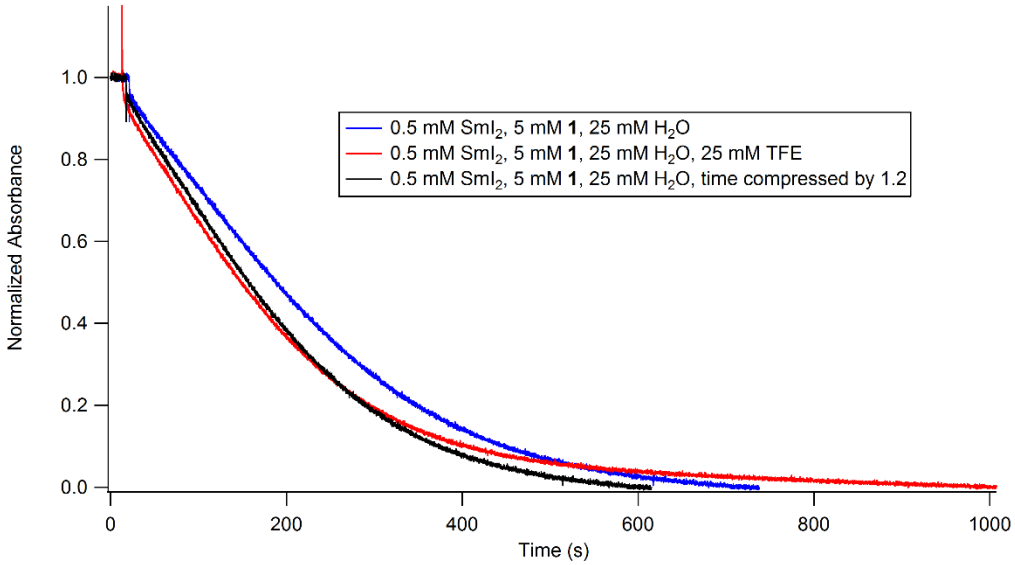


Figure S5.1.9. Plot of absorbance vs. time for the reduction of **1p** (5 mM) by SmI_2 (0.5 mM) with H_2O (25 mM, blue trace) and 1:1 H_2O:TFE (25 mM:25 mM, red trace). The H_2O trace which is time compressed by 1.20 fold is shown in black.

5.2 UV-vis analysis of $SmI_2(H_2O)_n$ and 1p reaction mixtures

UV-vis spectra are shown before and after (~10 seconds) the addition of 5 mM **1p** (50 µL 0.2 M **1p**) to 0.5 mM SmI_2 and 5 mM H_2O in THF (total volume after addition is 2 mL). Spectra are also shown before and after the addition of 5 mM **1p** (50 µL 0.2 M **1p**) to 0.5 mM SmI_2 and 75 mM H_2O (total volume after addition is 2 mL). The shape of the $SmI_2(H_2O)_n$ spectrum remains constant after addition of substrate, showing that the speciation of SmI_2 does not change during the reaction. The decrease in absorbance occurs because the reduction occurs on the seconds timescale.

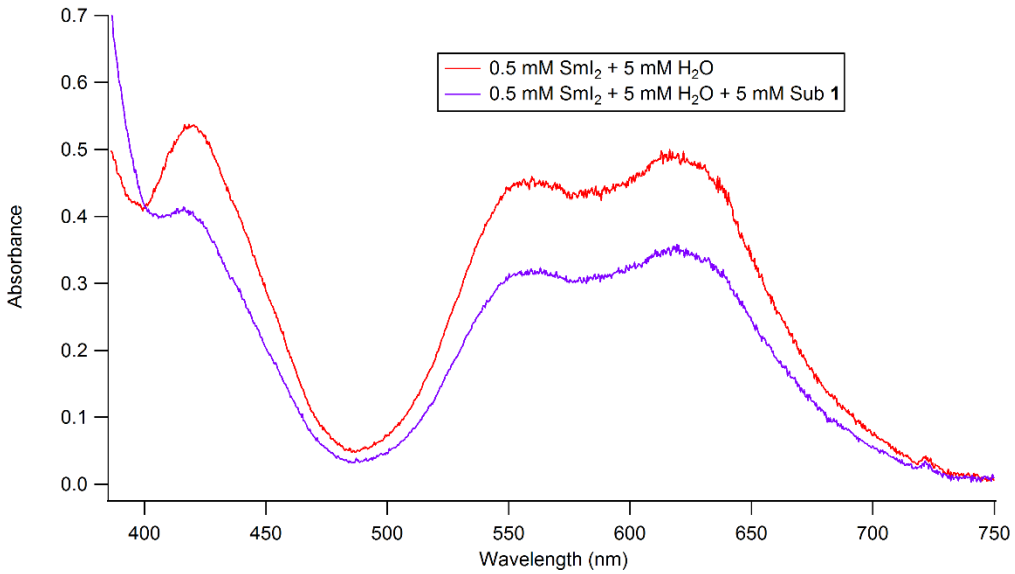


Figure S5.2.1. UV-vis spectra of 0.5 mM SmI_2 and 5 mM H_2O (red trace) and after the addition of 5 mM **1p** (blue).

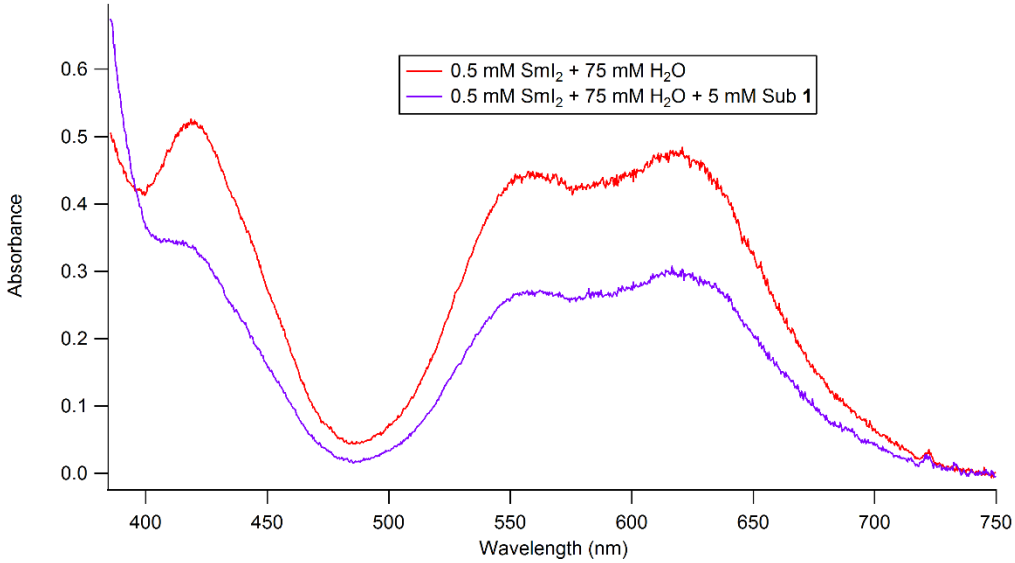


Figure S5.2.2. UV-vis spectra of 0.5 mM SmI_2 and 75 mM H_2O (red trace) and after the addition of 5 mM **1p**. (blue).

6. Thermochemical analyses

6.1 Estimation of the enthalpy and free energy of H-atom addition to cyclohexene

The BDE of the C–H bond shown below was estimated from the following thermochemical cycle depicted in Figure S6.1.1. The C-H BDE of the bond vicinal to the radical is 99.5 kcal mol^{-1},[14] the BDE of H2 is 104 kcal mol^{-1}, and the enthalpy of hydrogenation is 28.3 kcal mol^{-1}.[15] This analysis gives a BDE of 33 kcal mol^{-1}, which matches well with the computational value.[16] The difference between BDFE and BDE is $TS^0(H^{\bullet})_{solv}$, which is typically 4.6 kcal mol^{-1} in polar organic solvents.[17]

1)	C=C + H	=>	•C–CH	–BDE of interest
2)	•C–C–H + H	=>	HC–CH	–BDE = –99.5 kcal/mol
3)	H_2	=>	$2H^{\bullet}$	BDE = 104 kcal/mol
4)	C=C + H_2	=>	HCCH	ΔH(hyd) = –28.3 kcal/mol

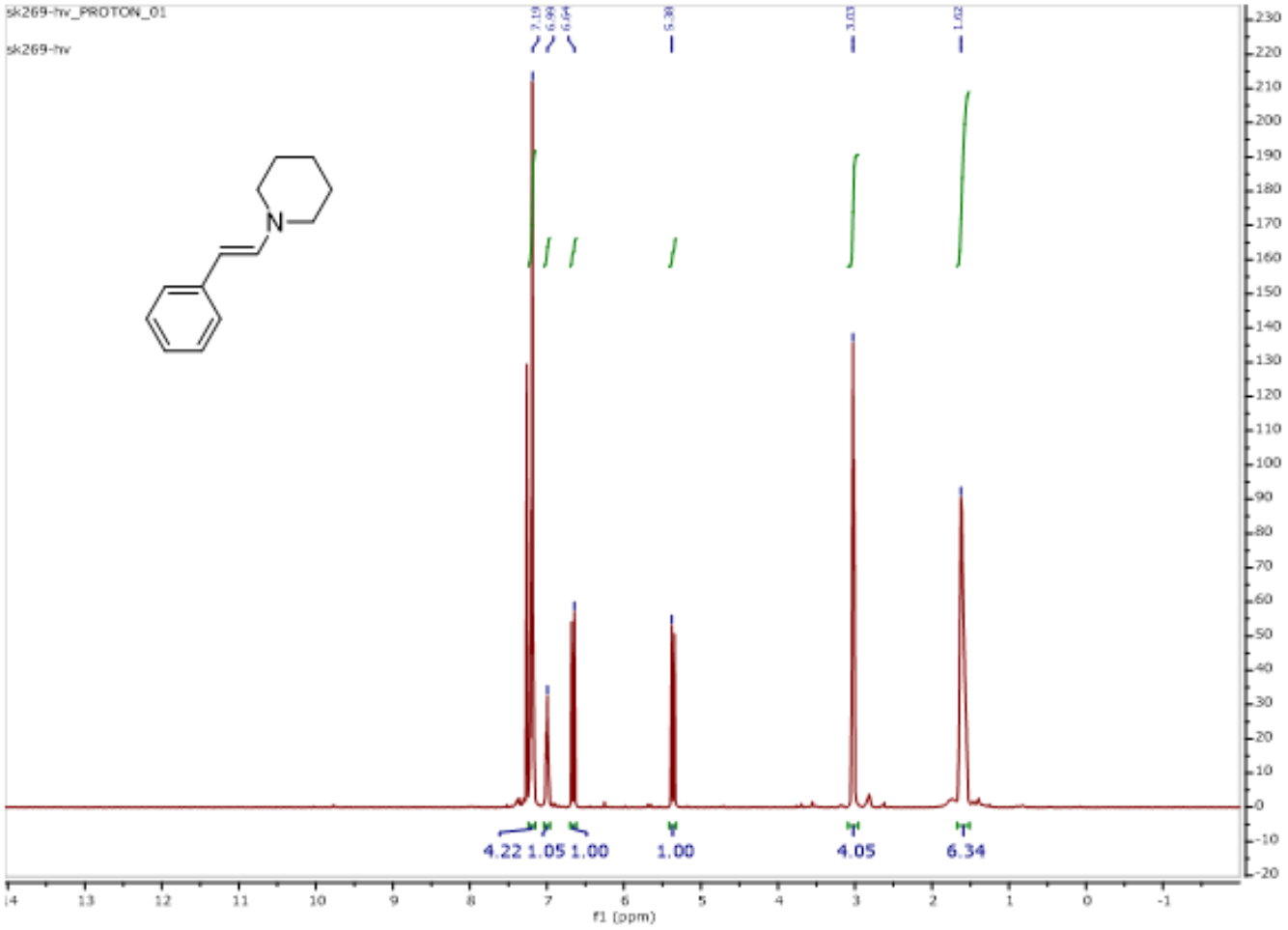
(1) + (2) + (3) = (4) so –BDE of interest – 99.5 + 104 = –28 implies BDE = 33 kcal/mol.

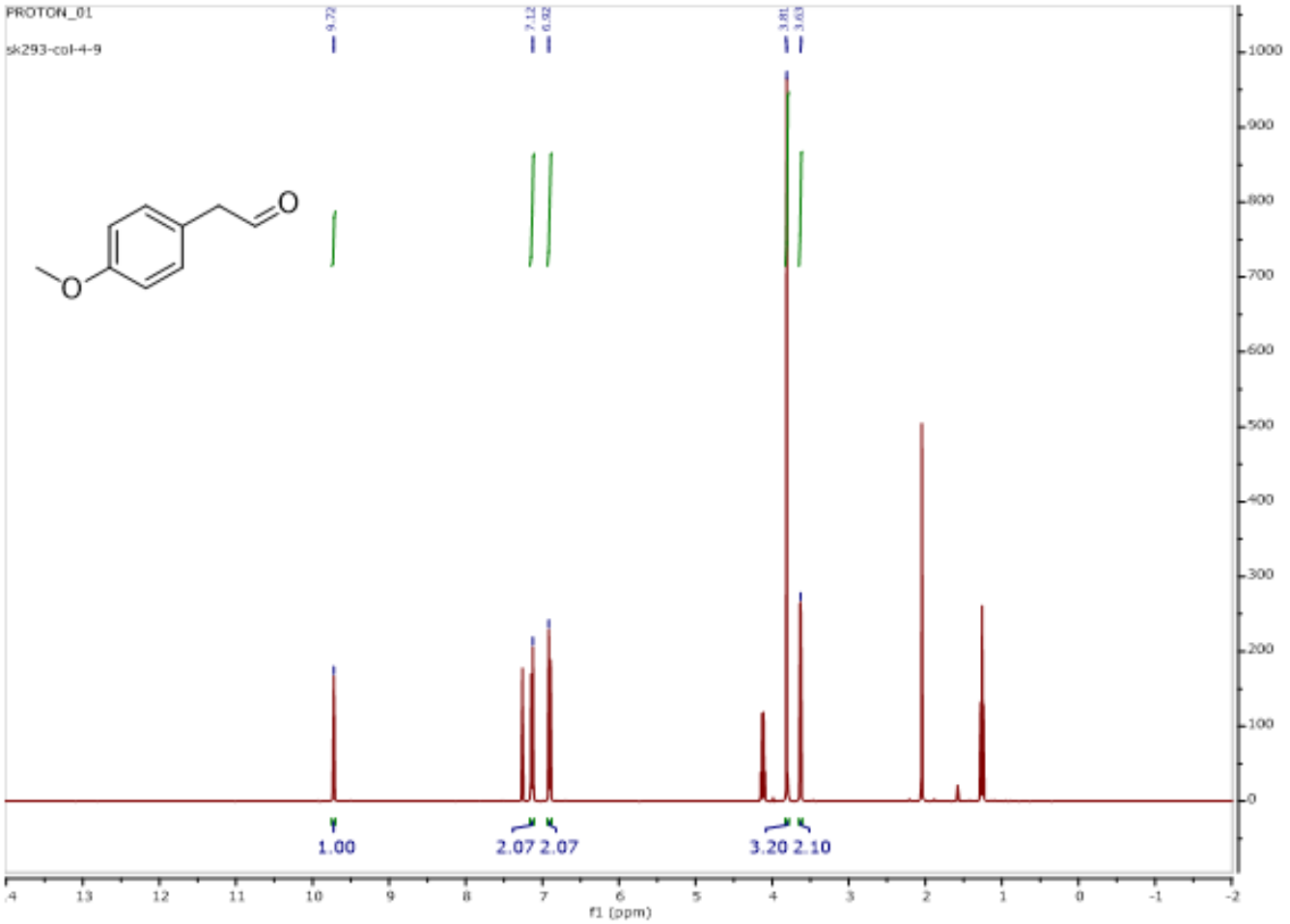
BDFE(R–H) ≅ BDE(R–H) – 4.6 kcal mol^{-1} so BDFE of interest = 28 kcal mol^{-1}

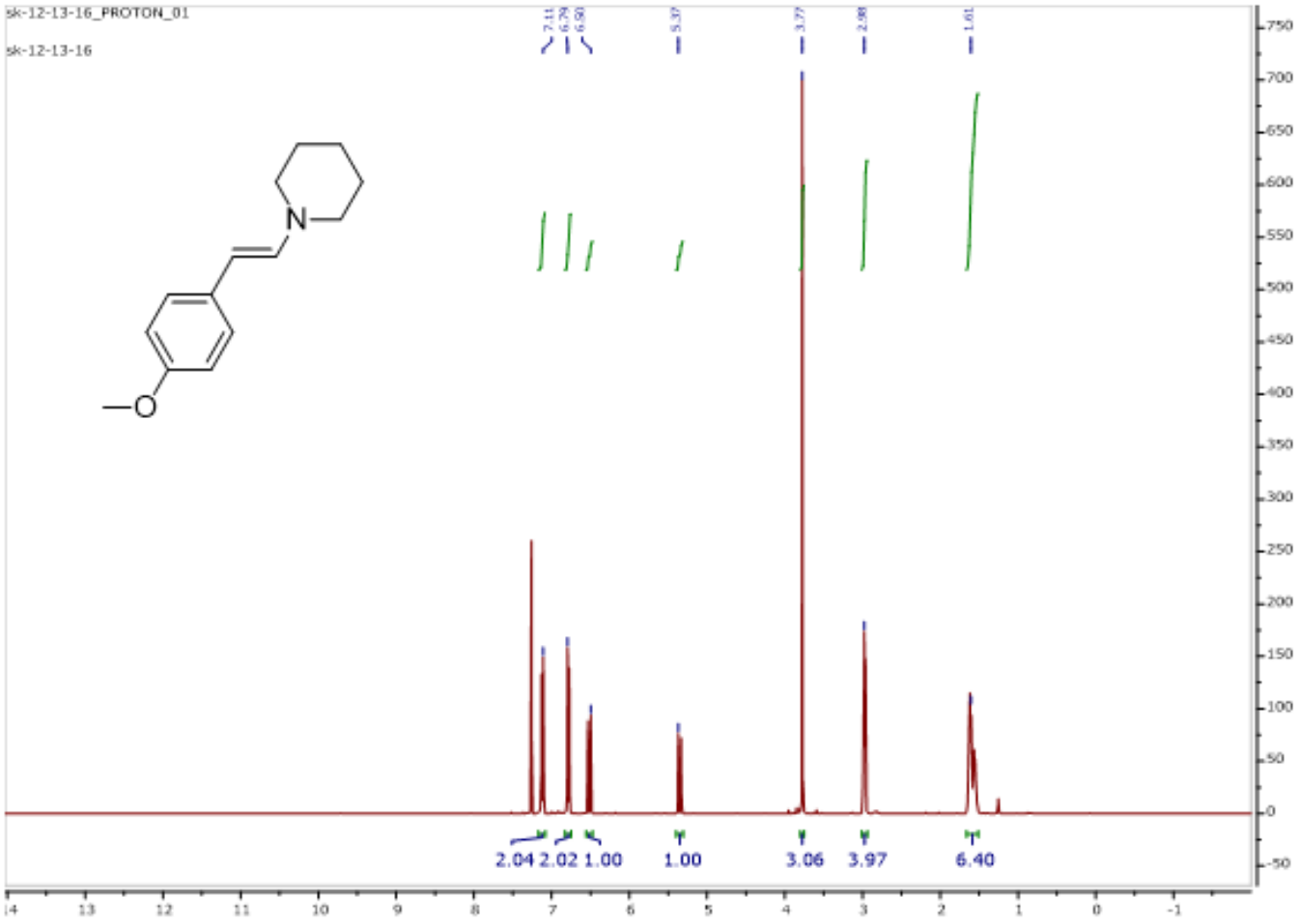
Figure S6.1.1. Thermochemical cycle to estimate the enthalpy and free energy of H-atom addition to cyclohexene.

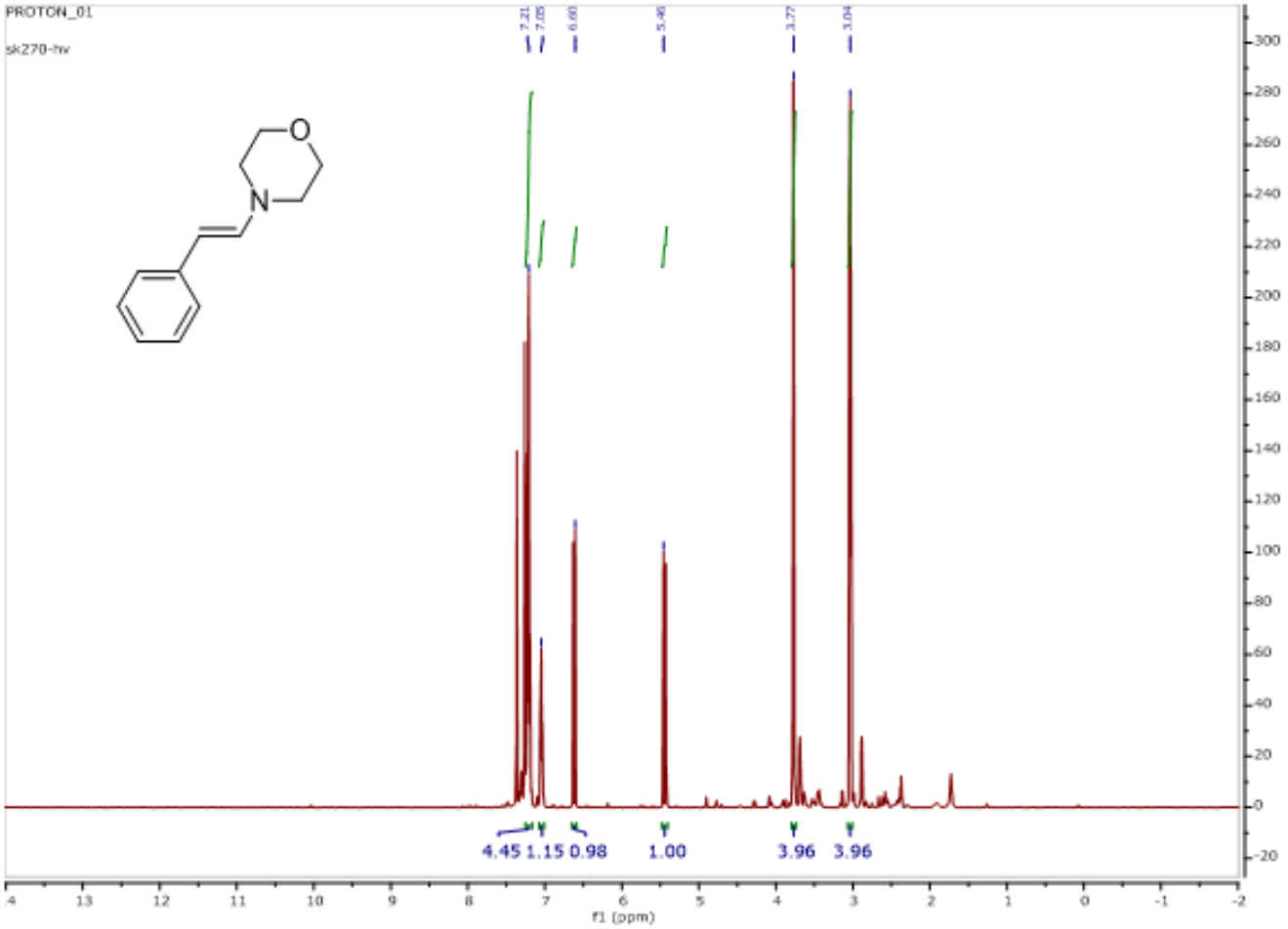
7. NMR Spectra

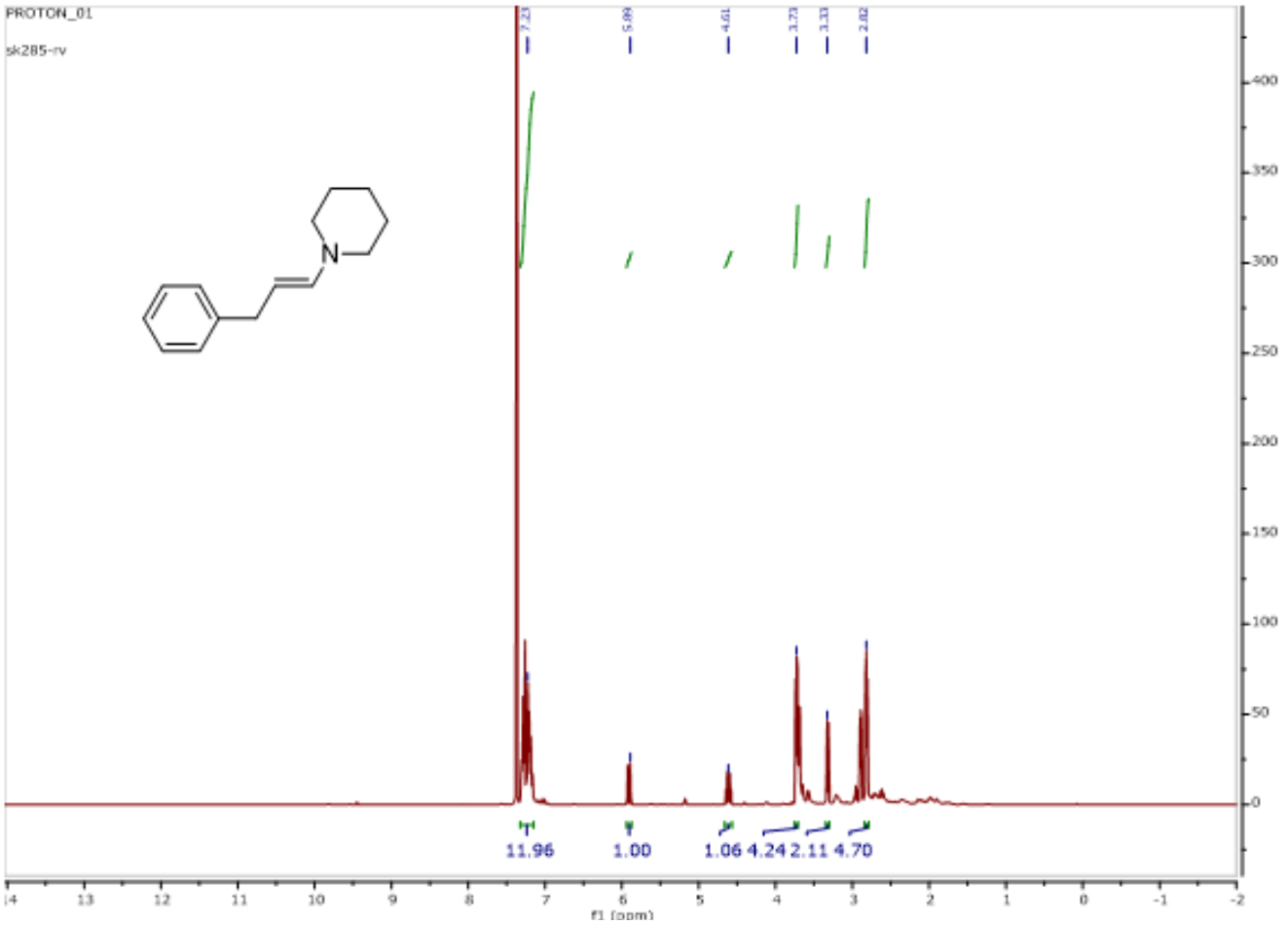
7.1 ^{1}H NMR Spectra of Substrates in $CDCl_3$

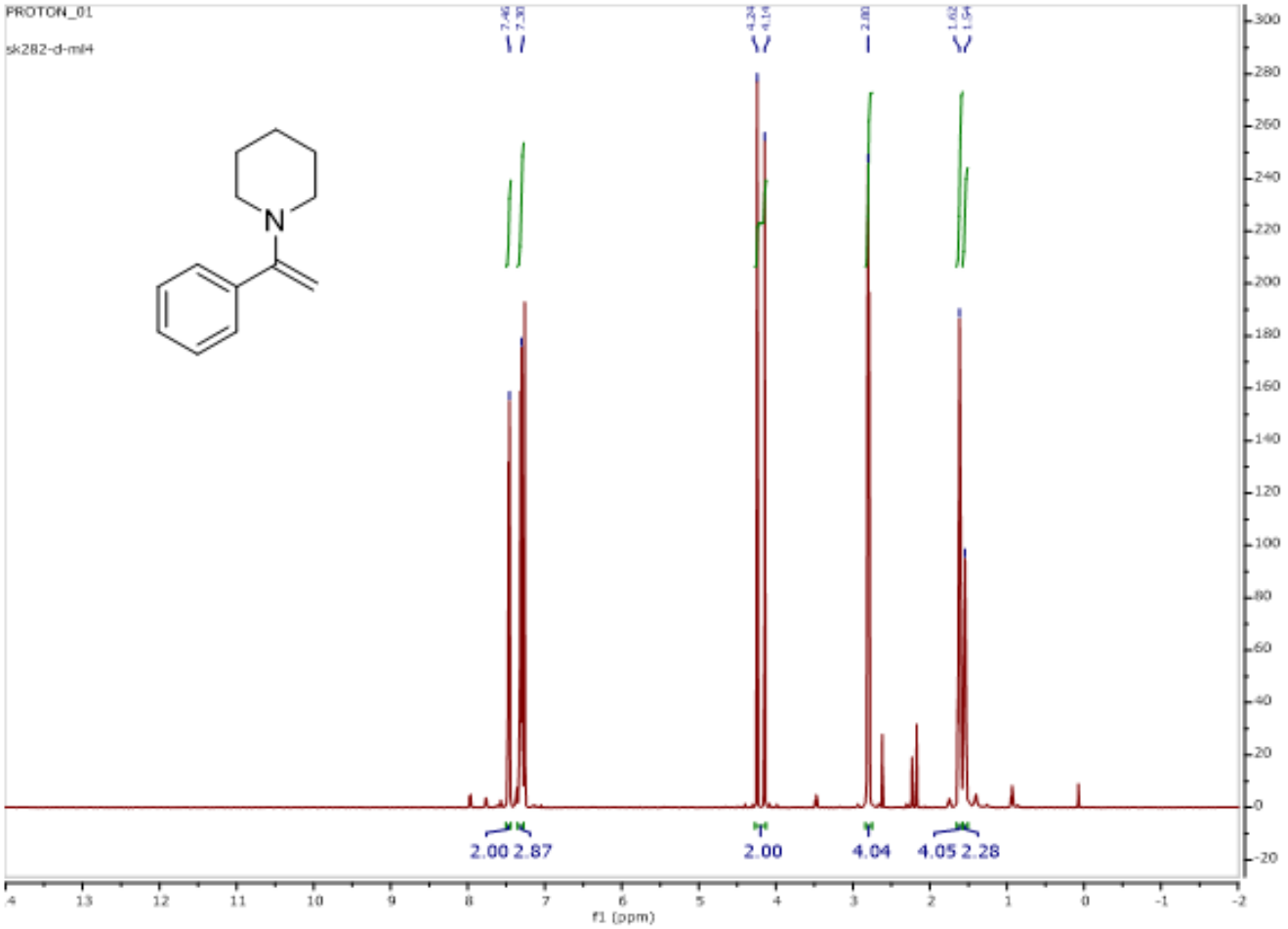


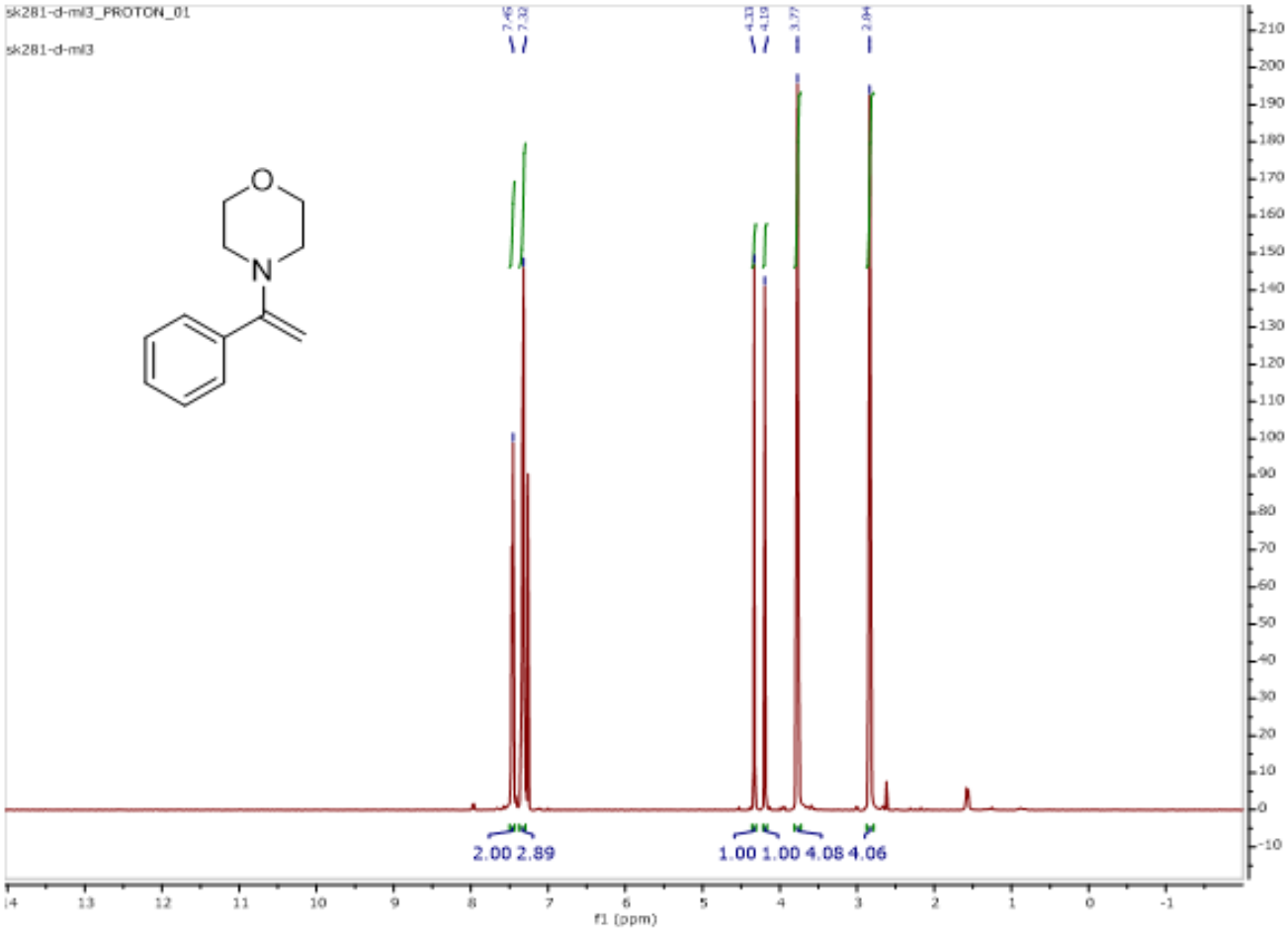

PROTON_01
sk293-col-4-9
9.72
7.12
6.92
3.81
3.63
O
O
1.00
2.07 2.07
3.20 2.10
f1 (ppm)


sk-12-13-16_PROTON_01
sk-12-13-16
7.11
6.79
6.50
5.37
3.77
2.98
1.61
N
O
2.04 2.02 1.00 1.00 3.06 3.97 6.40

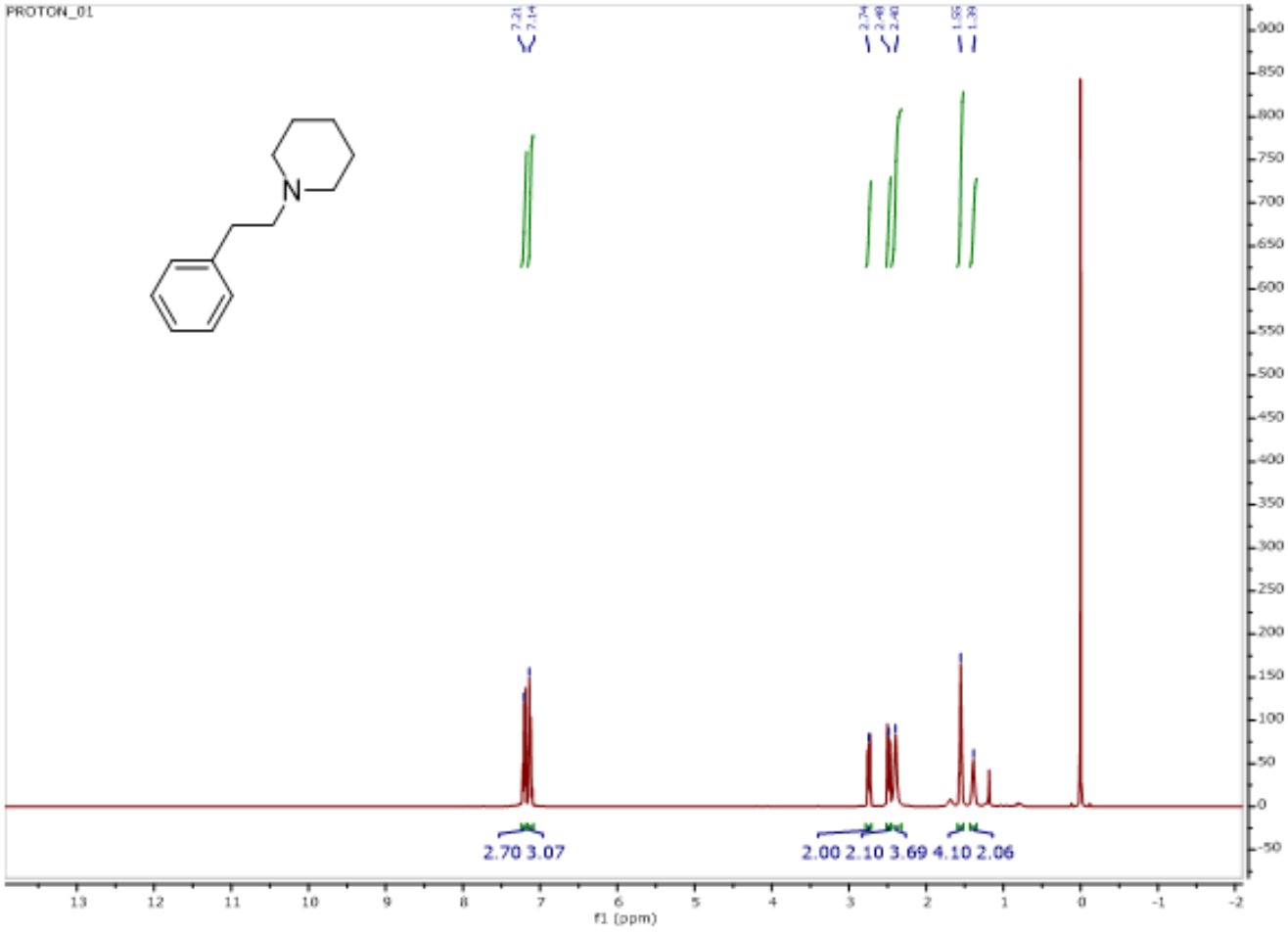

PROTON_01
sk270-hw
7.21
7.05
6.60
5.40
3.77
3.04
O
N
4.45 1.15 0.98 1.00 3.96 3.96
f1 (ppm)

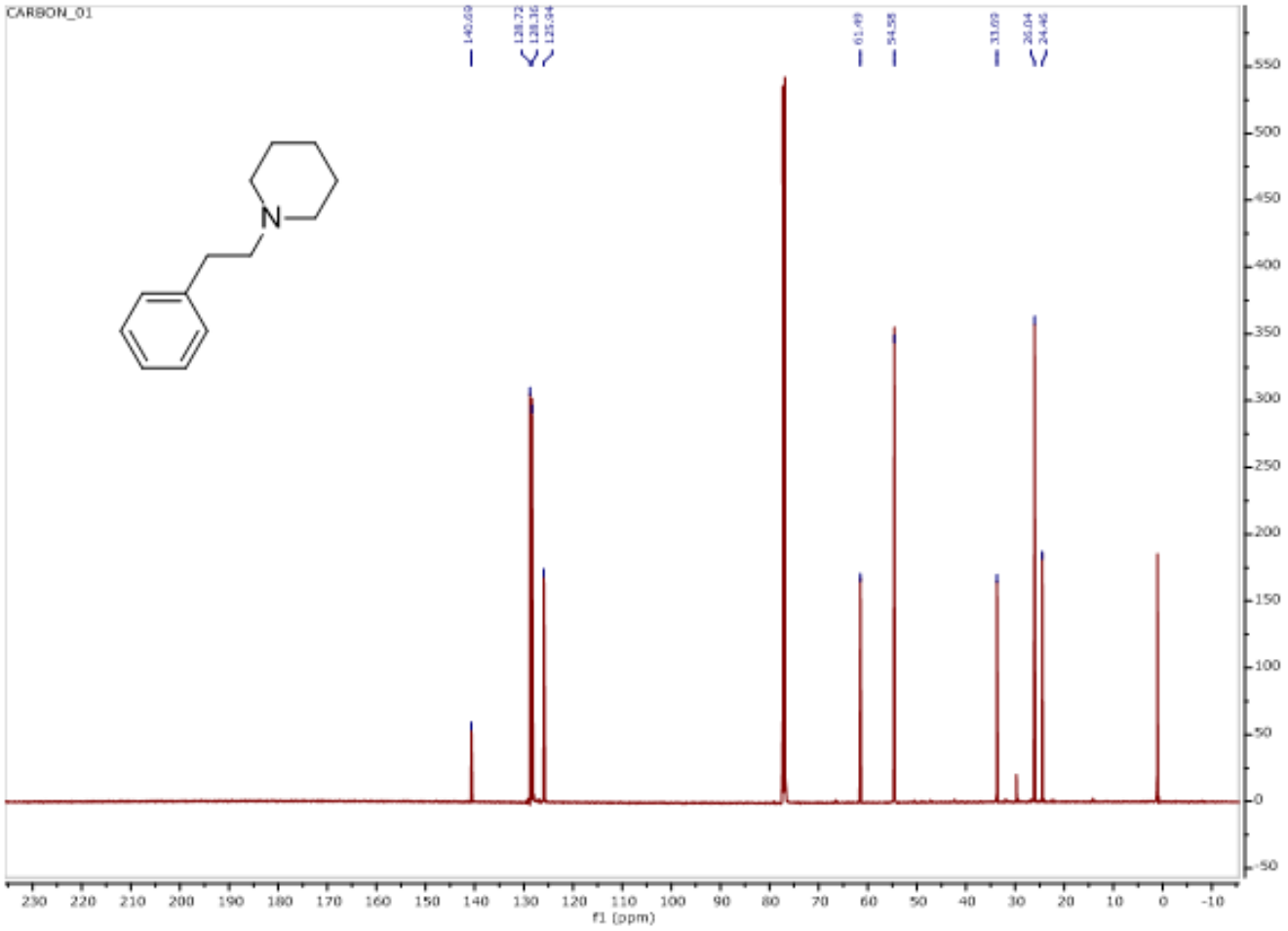

PROTON_01
sk285-rv
7.23
5.89
4.61
3.73
3.33
2.82
11.96
1.00
1.06
4.24
2.11
4.70
f1 (ppm)

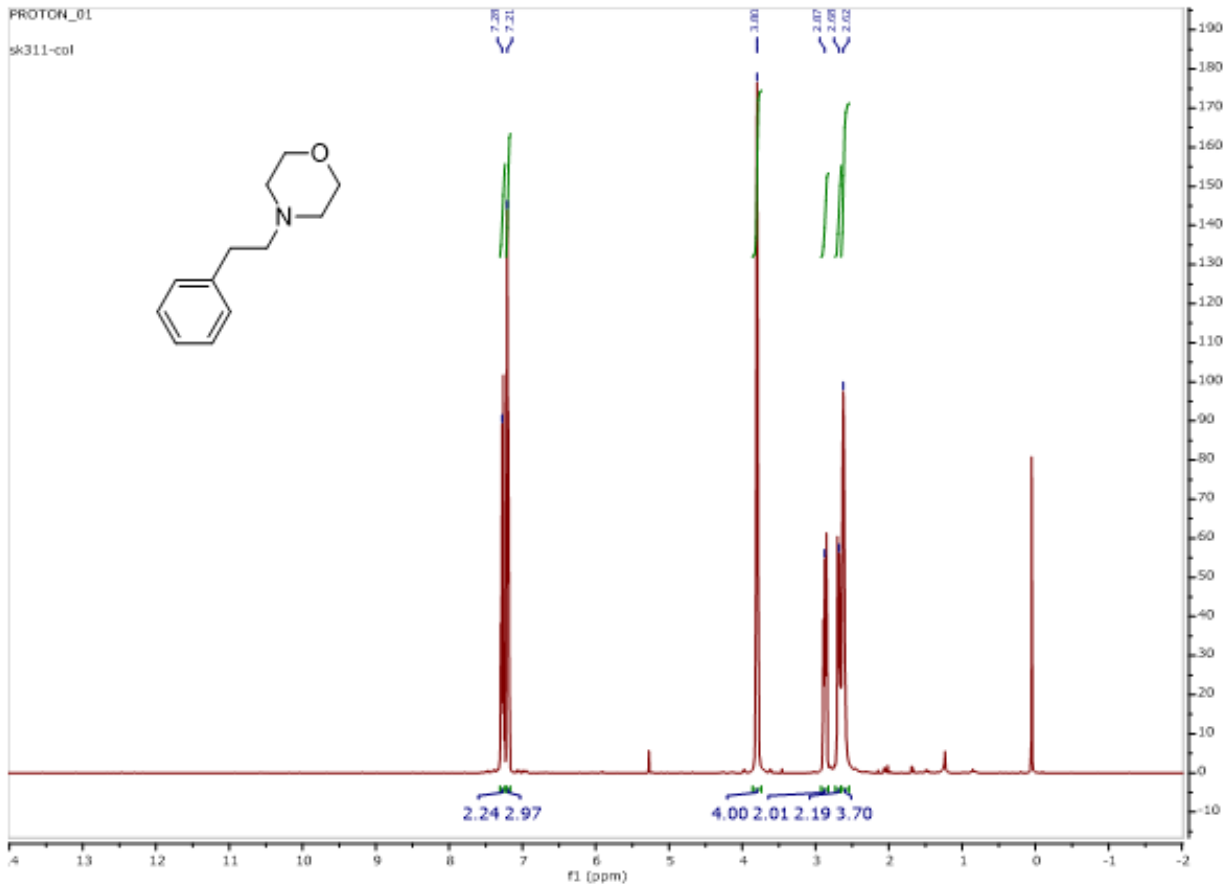

PROTON_01
sk282-d-ml4
7.46
7.30
4.24
4.14
2.80
1.62
1.54
N
2.00 2.87
2.00
4.04
4.05 2.28
f1 (ppm)

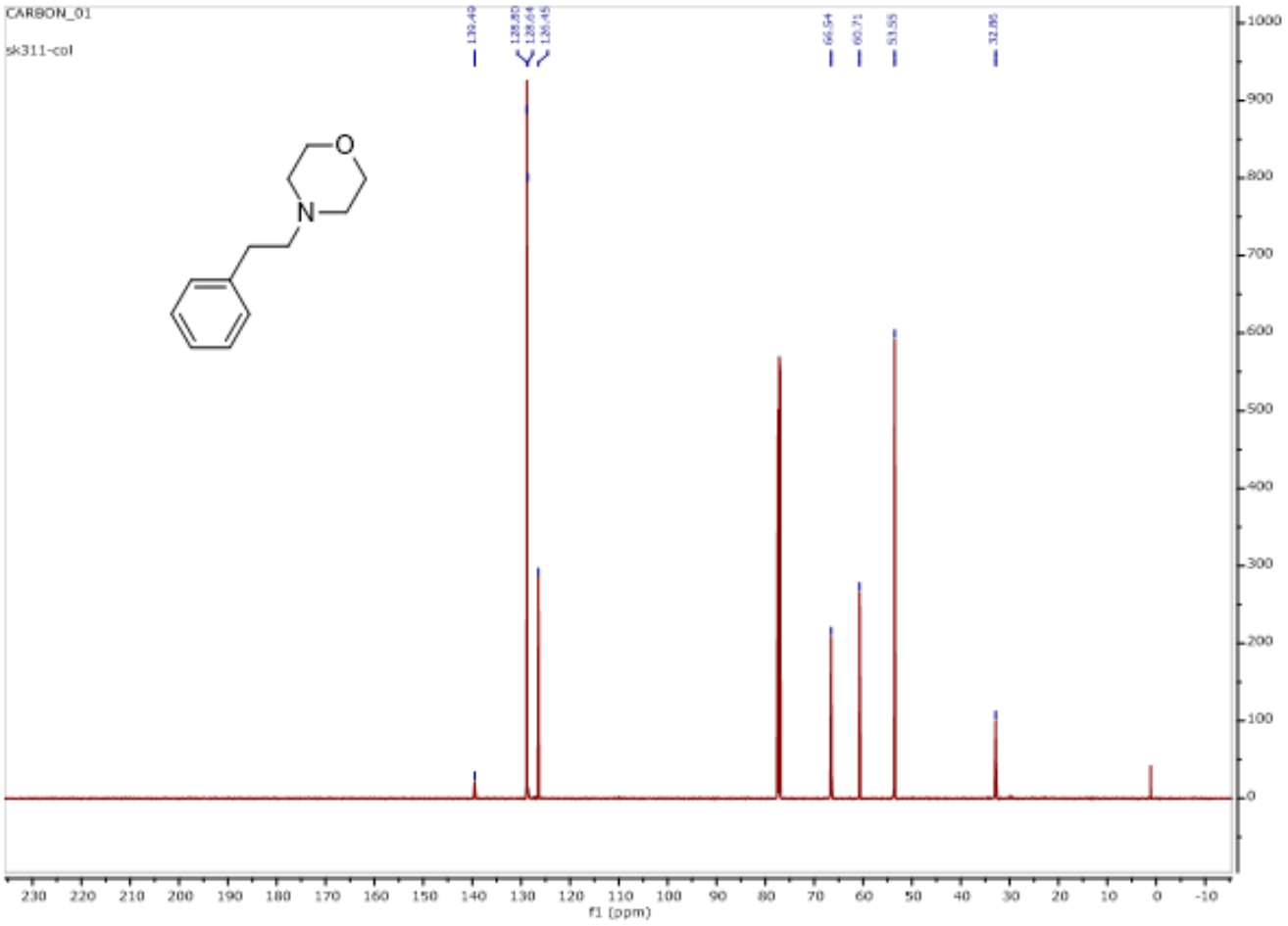

sk281-d-ml3_PROTON_01
sk281-d-ml3
7.46
7.32
4.33
4.19
3.77
2.04
O
N
2.00 2.89
1.00 1.00 4.08 4.06
f1 (ppm)

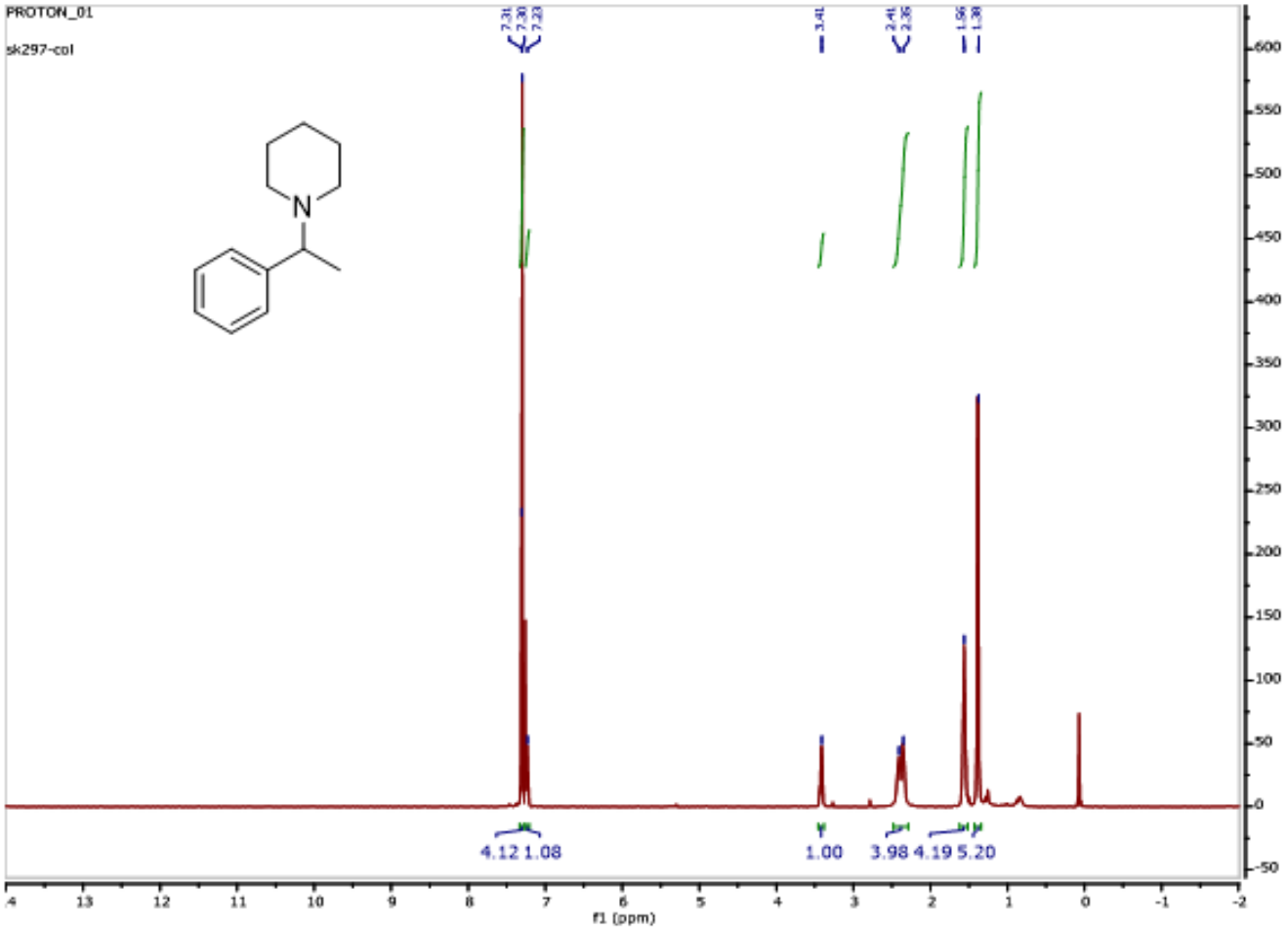
7.2 ^{1}H and ^{13}C NMR Spectra of Products in $CDCl_3$

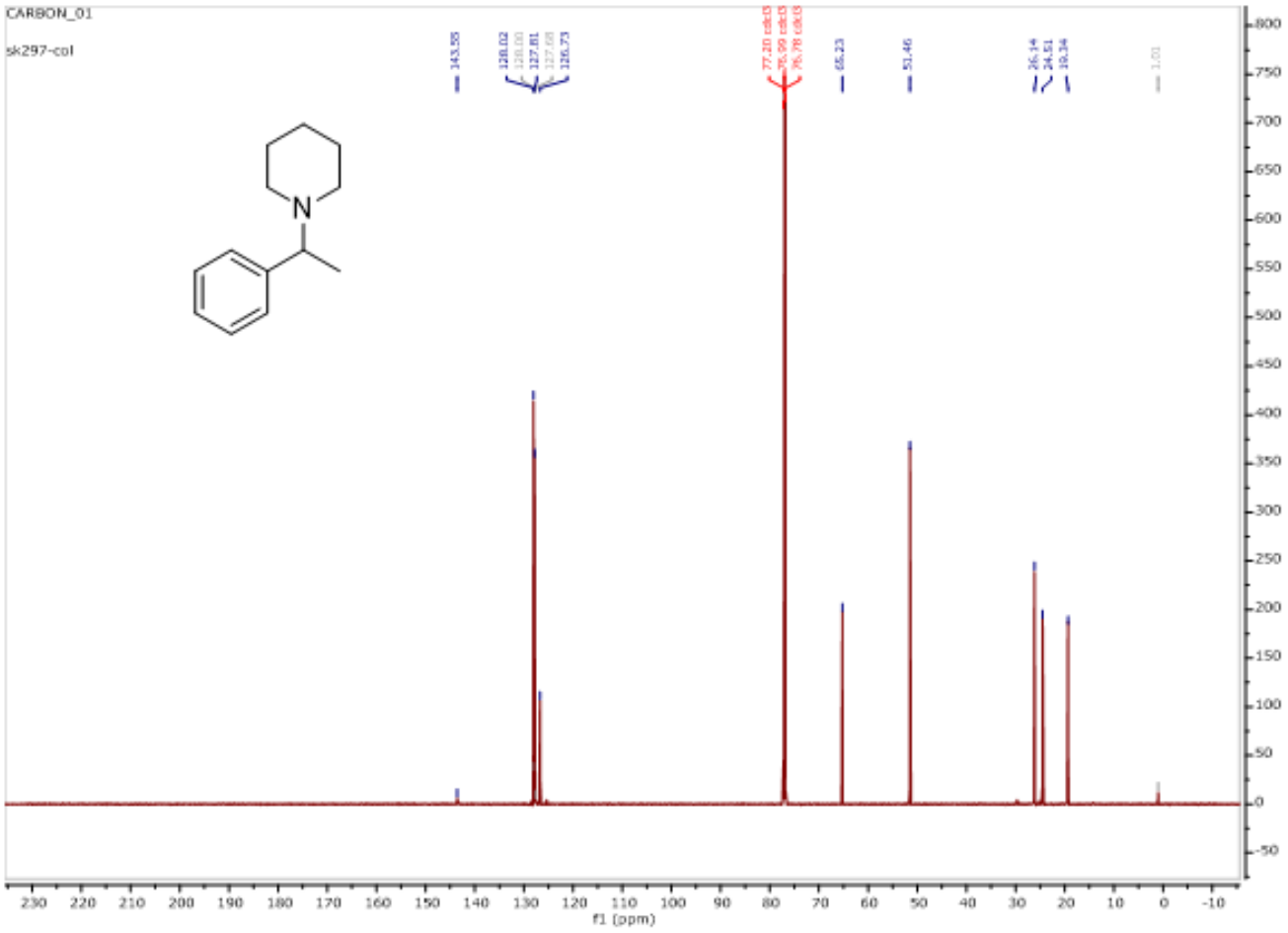


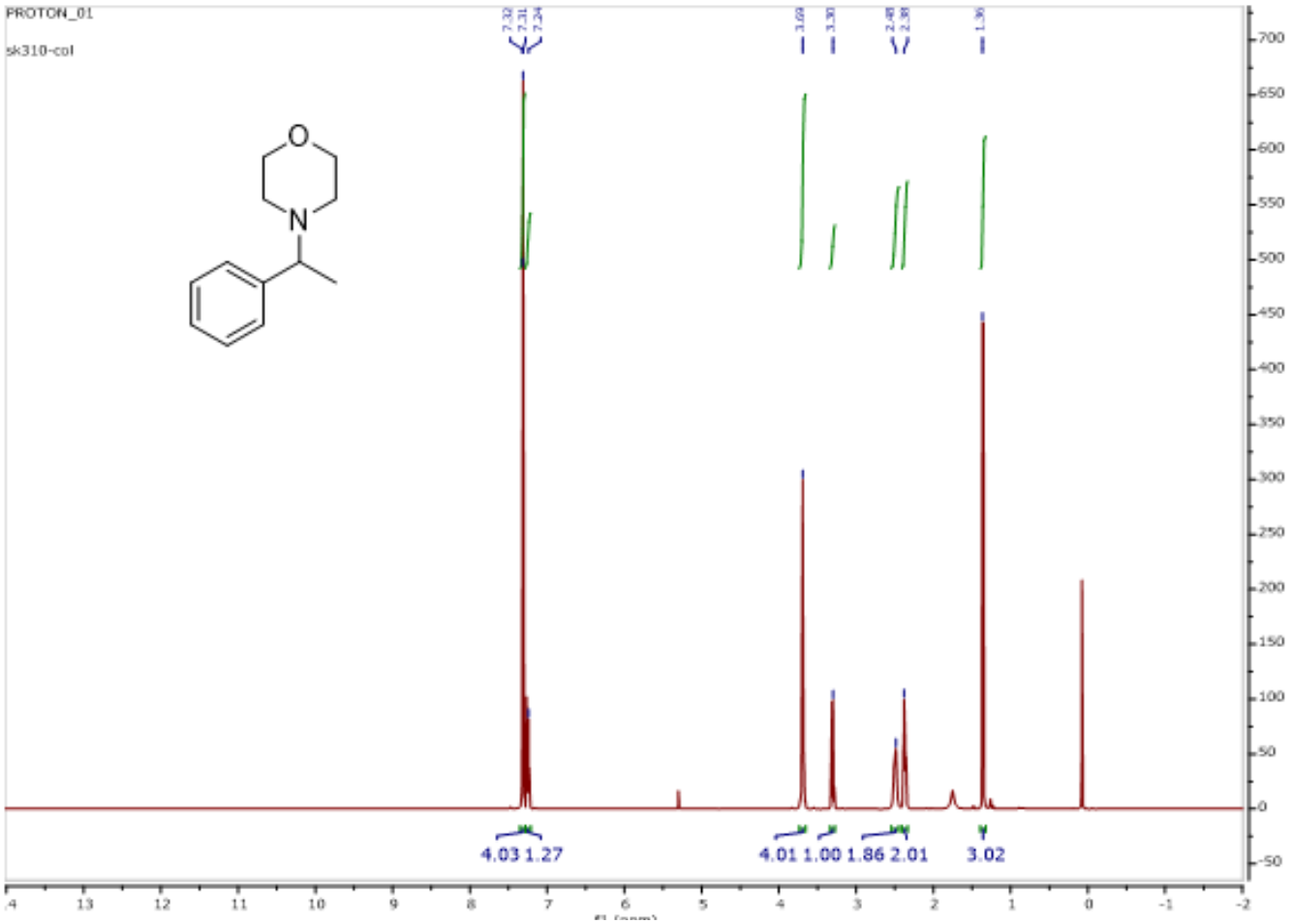

CARBON_01
140.69
128.72
128.36
125.94
61.49
54.58
33.69
26.04
24.46
N
f1 (ppm)

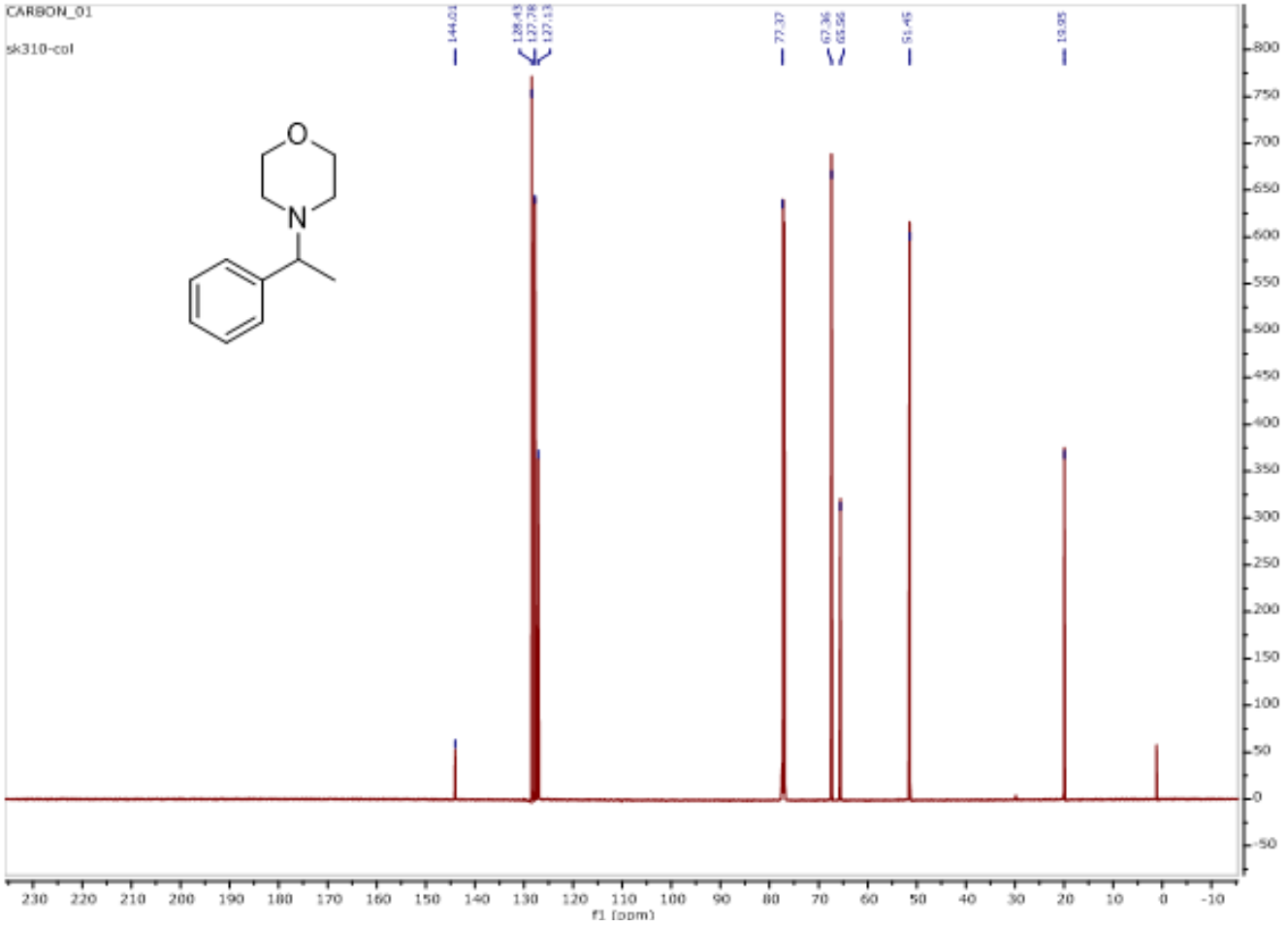

PROTON_01
sk311-col
7.28
7.21
3.80
2.67
2.65
2.62
O
N
2.24 2.97
4.00 2.01 2.19 3.70
f1 (ppm)

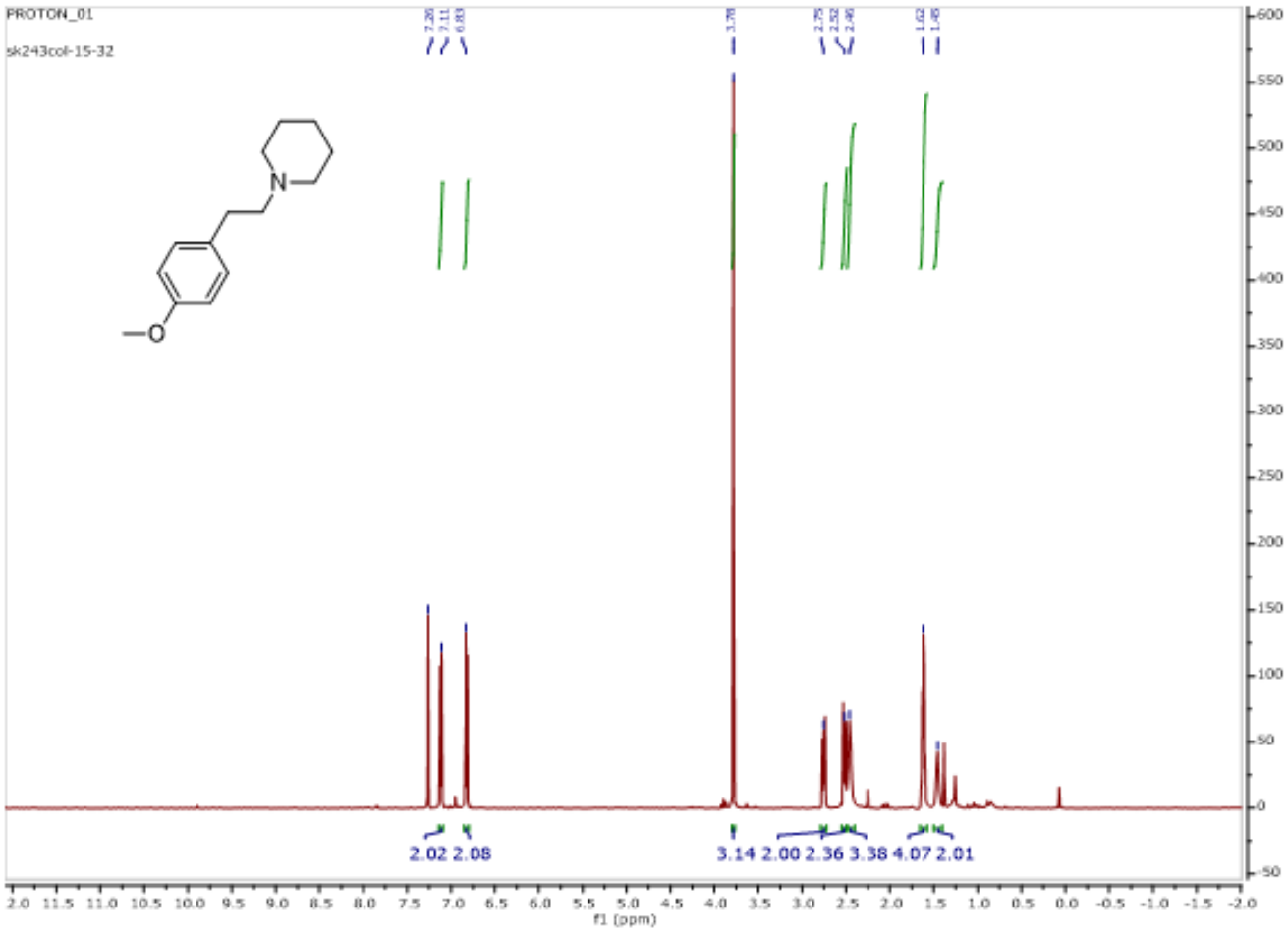

CARBON_01
sk311-col
139.49
128.80
128.64
126.45
66.54
60.71
53.55
32.86
O
N
1000
900
800
700
600
500
400
300
200
100
0
230 220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

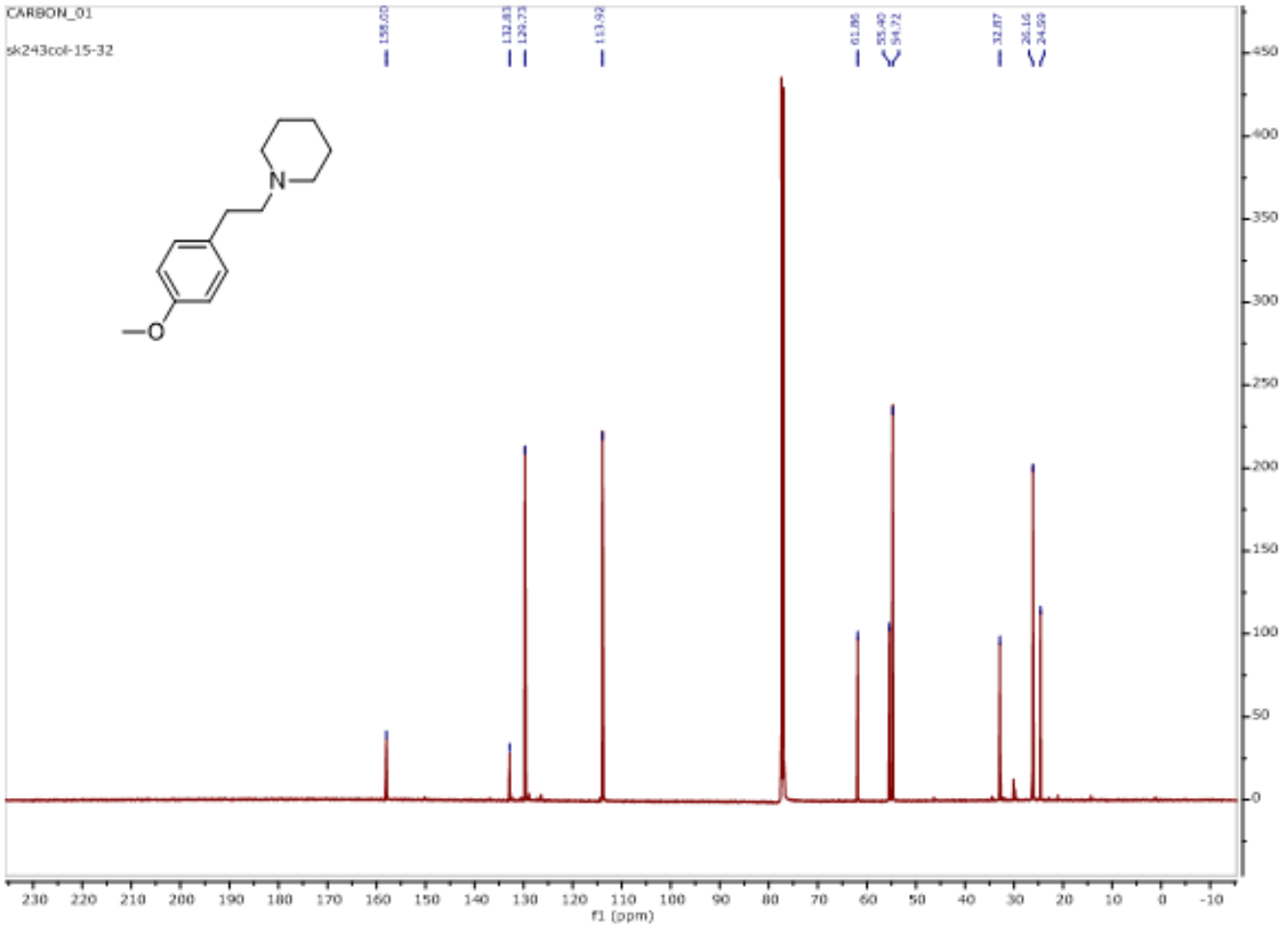

PROTON_01
sk297-col
7.31
7.30
7.23
3.41
2.41
2.35
1.96
1.38
4.12 1.08
1.00
3.98 4.19 5.20
f1 (ppm)

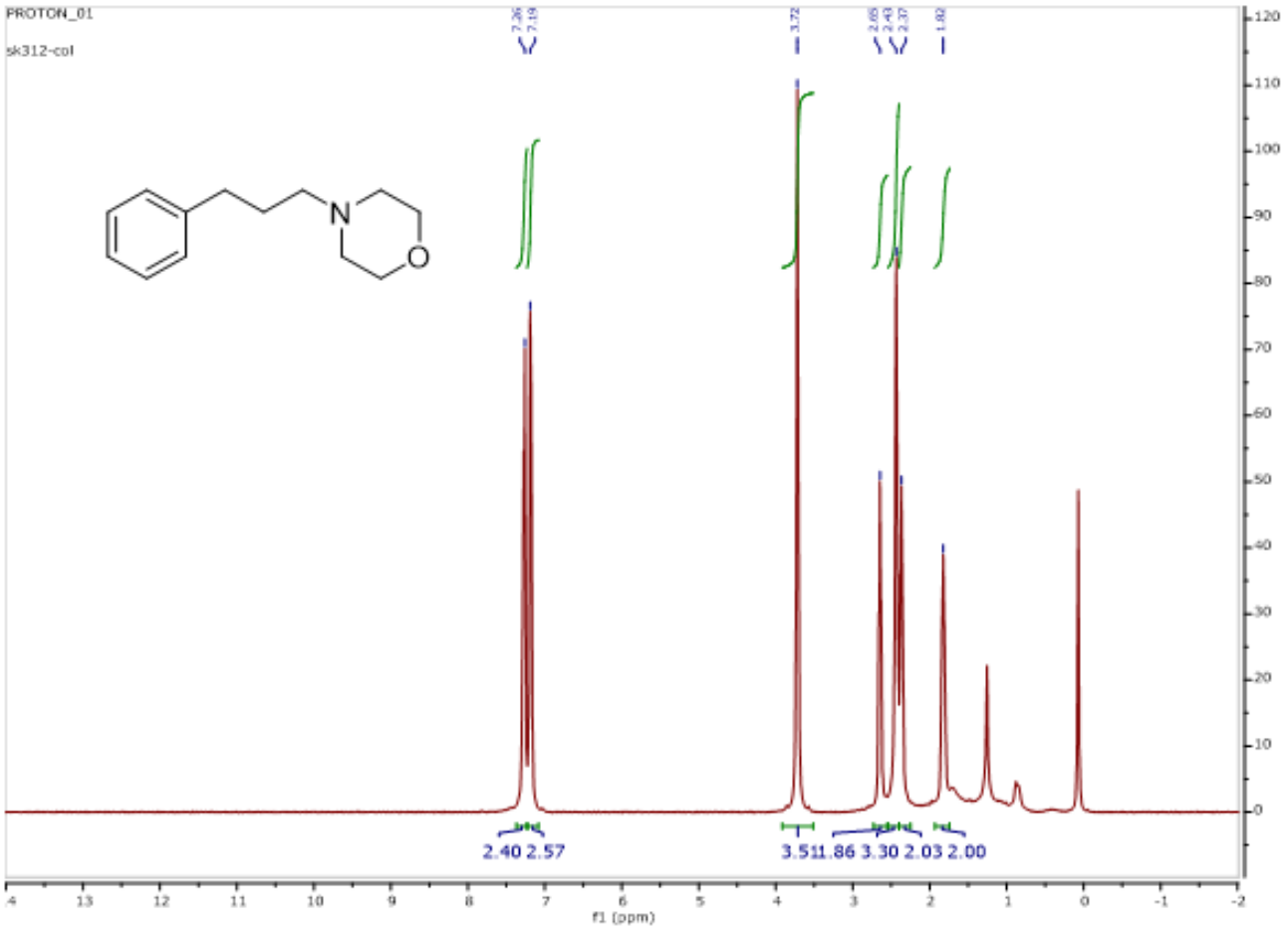

CARBON_01
sk297-col
143.55
128.02
128.00
127.81
127.66
126.73
77.20 cdcl3
76.99 cdcl3
76.78 cdcl3
65.23
51.46
26.14
24.51
19.34
1.01
f1 (ppm)

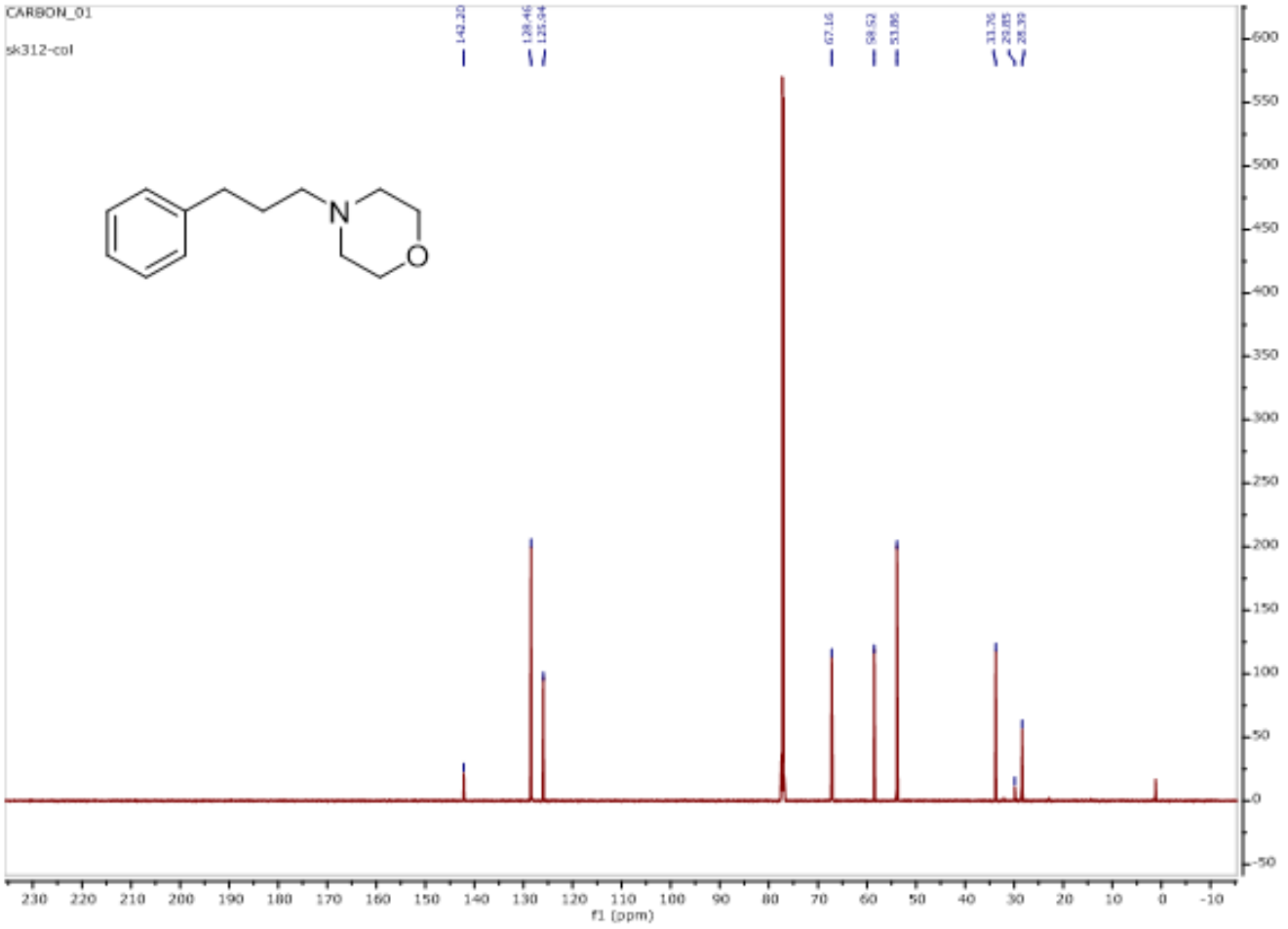

PROTON_01
sk310-col
7.32
7.31
7.24
3.69
3.30
2.48
2.39
1.36
4.03 1.27
4.01 1.00 1.86 2.01 3.02


CARBON_01
sk310-col
144.01
128.43
127.78
127.13
77.37
67.36
65.96
51.45
18.95
O
N
f1 (ppm)

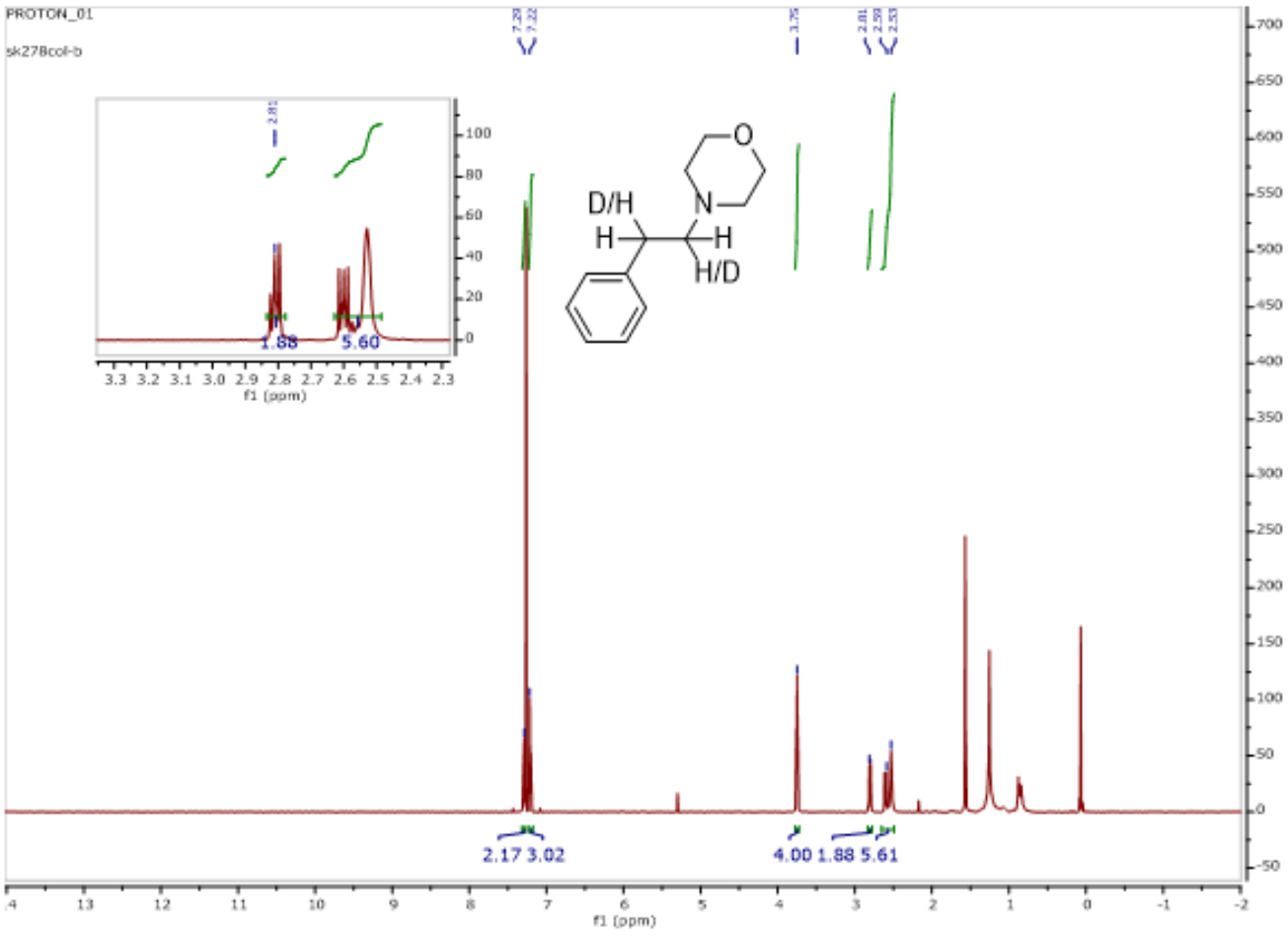

PROTON_01
sk243col-15-32
7.26
7.11
6.83
3.78
2.75
2.52
2.46
1.62
1.45
N
O
2.02 2.08
3.14 2.00 2.36 3.38 4.07 2.01
f1 (ppm)

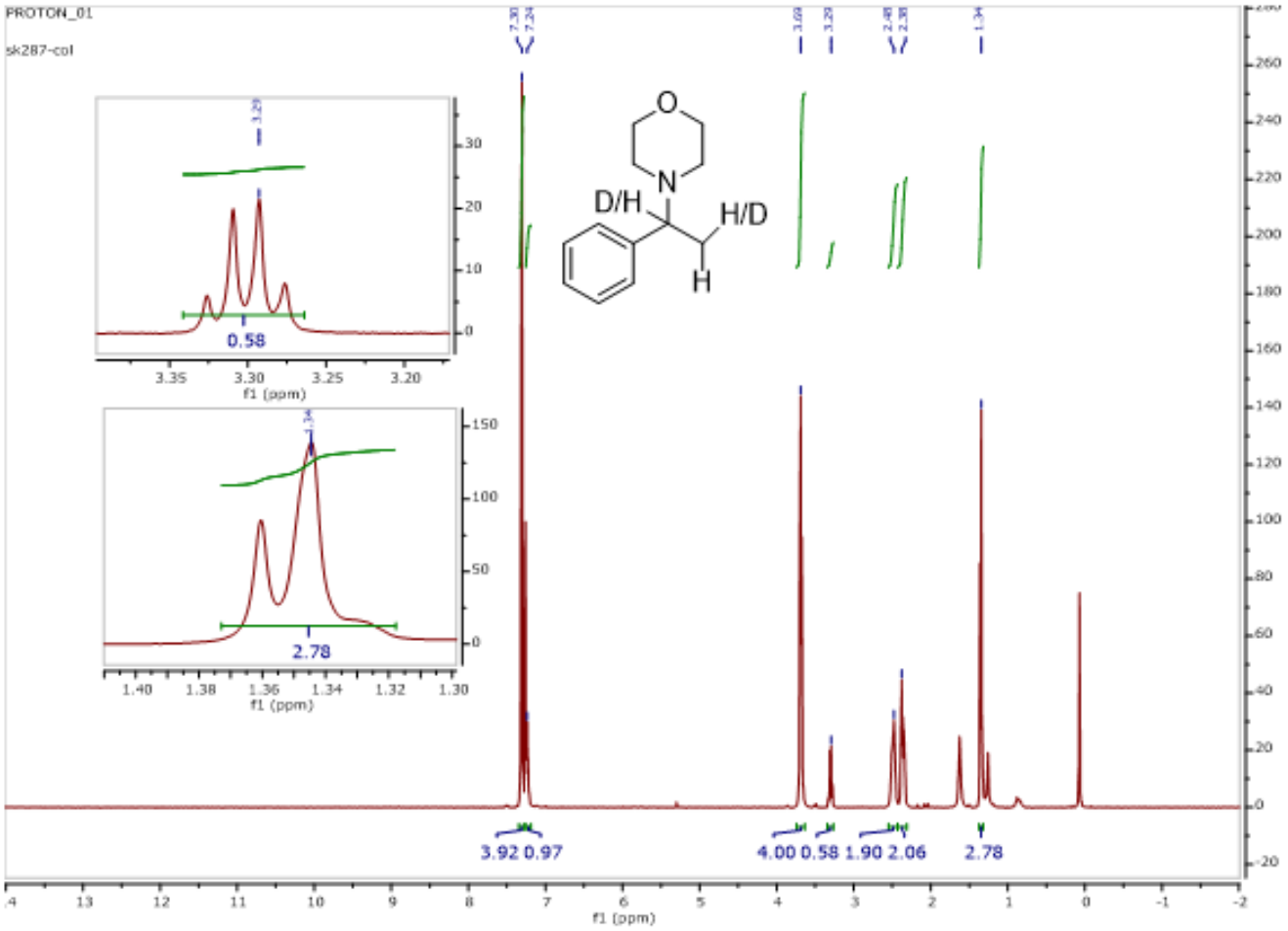

CARBON_01
sk243col-15-32
158.07
132.83
129.73
113.92
61.86
55.40
54.72
32.87
26.16
24.59
N
O
f1 (ppm)

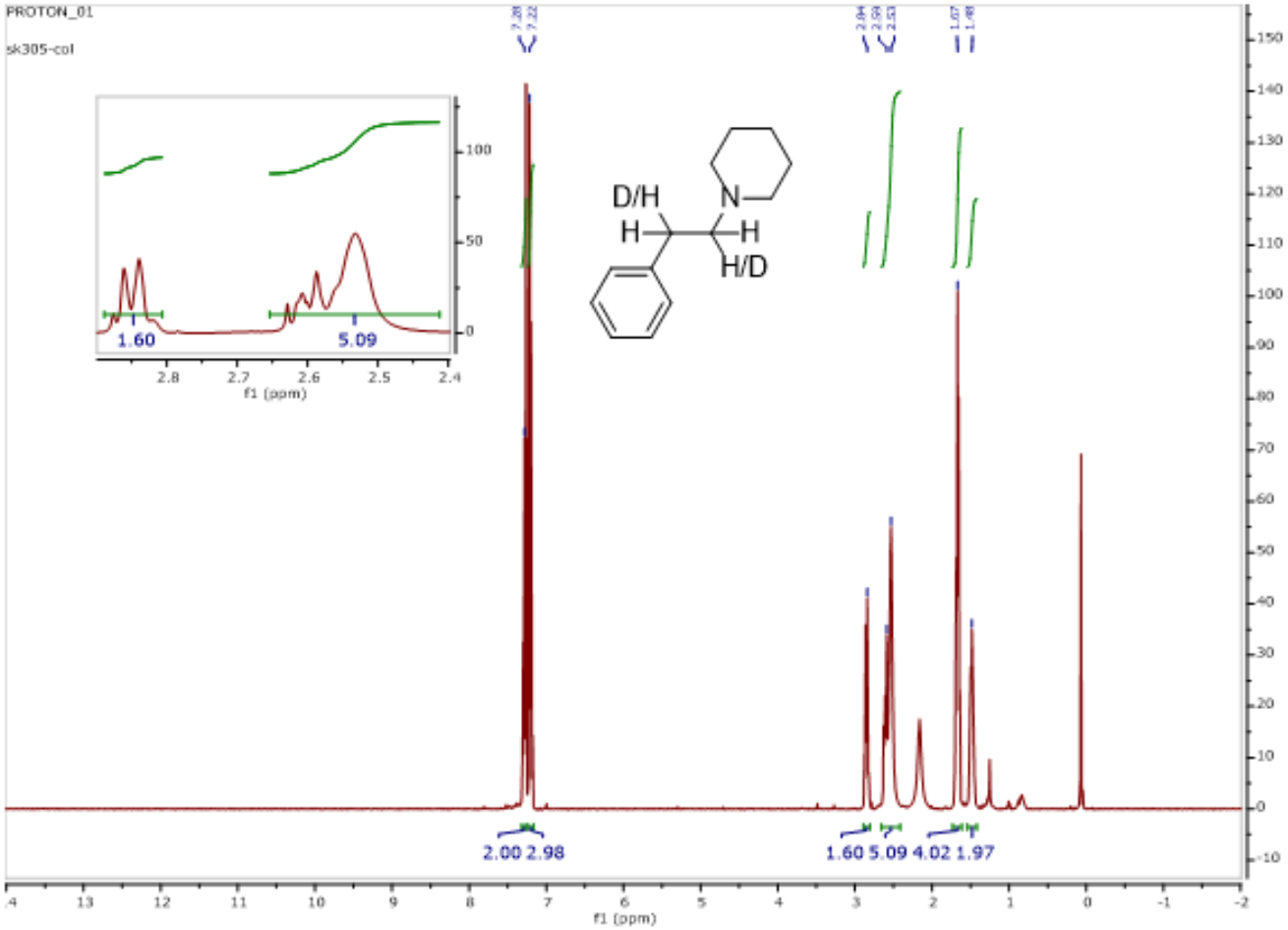

PROTON_01
sk312-col
7.26
7.19
3.72
2.65
2.43
2.37
1.82
2.40 2.57
3.51 1.86 3.30 2.03 2.00
f1 (ppm)


CARBON_01
sk312-col
142.20
128.46
125.94
67.16
58.52
53.86
31.76
29.85
28.39
N
O
f1 (ppm)

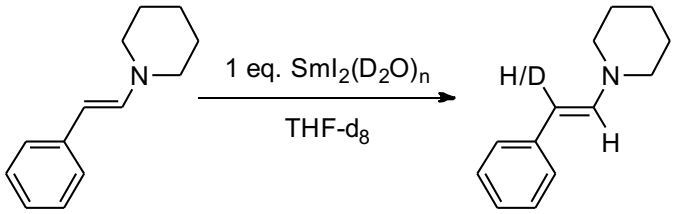
7.4 ^{1}H NMR Spectra of Partially Deuterated Products in $CDCl_3$

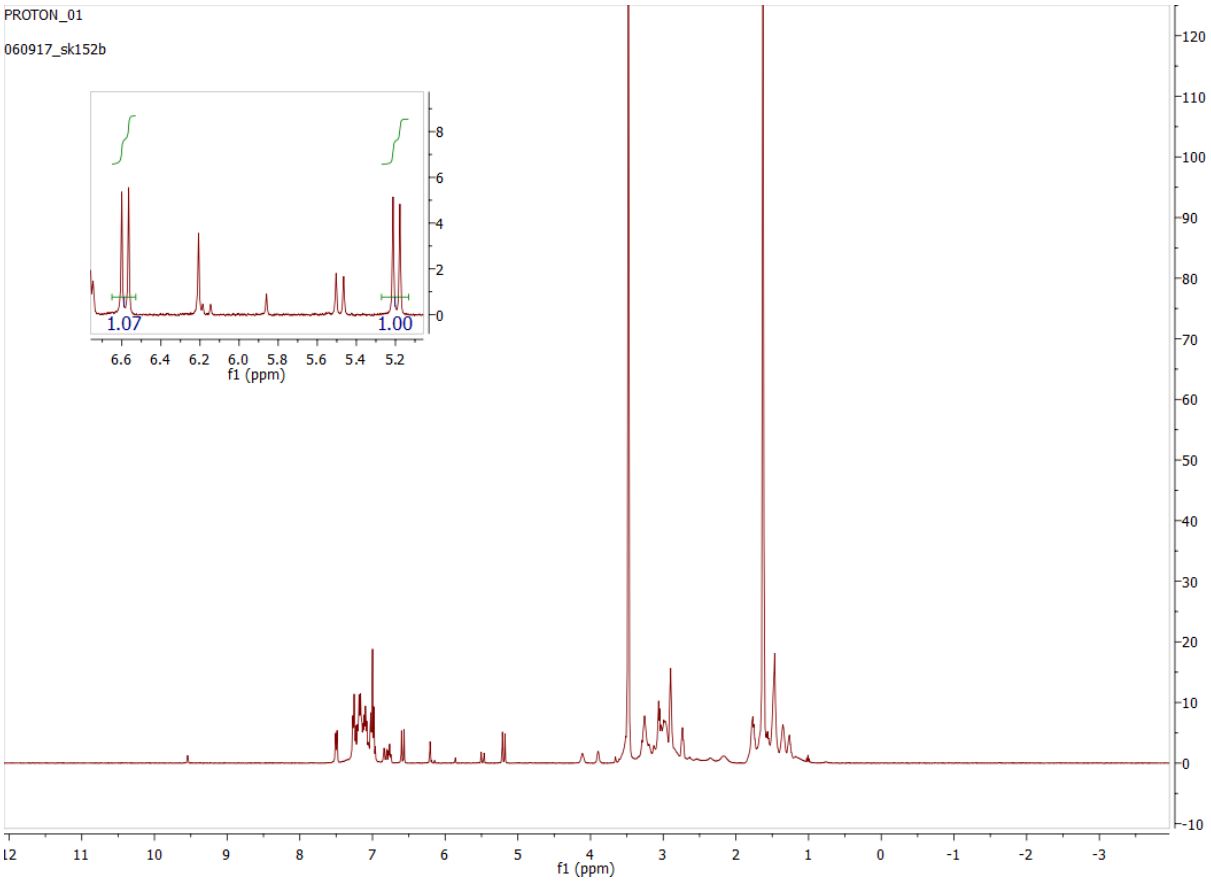


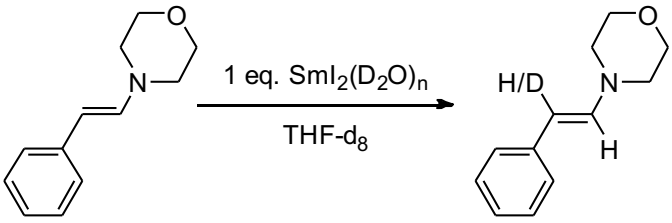

PROTON_01
sk287-col
O
N
D/H
H/D
H
0.58
2.78
3.92 0.97
4.00 0.58 1.90 2.06
2.78
f1 (ppm)

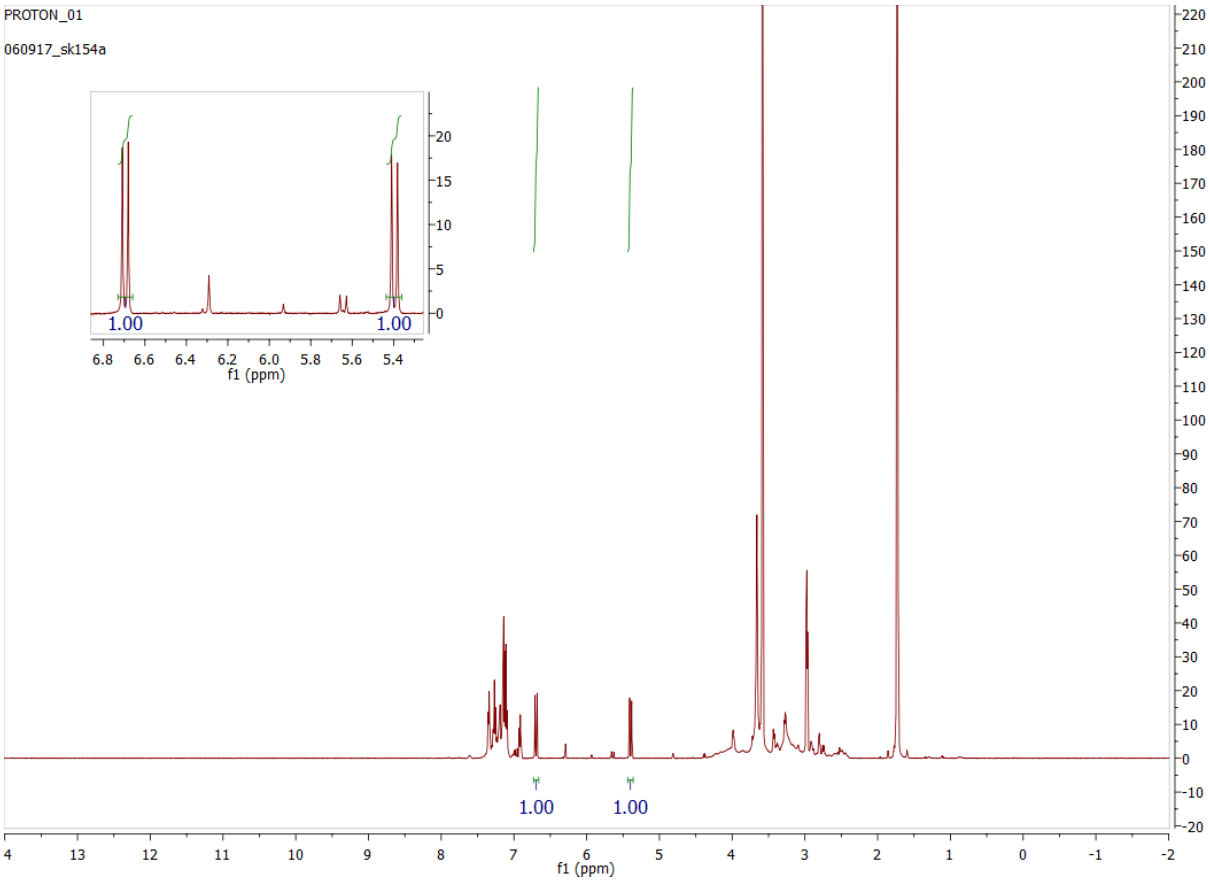

PROTON_01
sk305-col
D/H
H
N
H
H/D
1.60
5.09
f1 (ppm)
2.00 2.98
1.60 5.09 4.02 1.97
f1 (ppm)

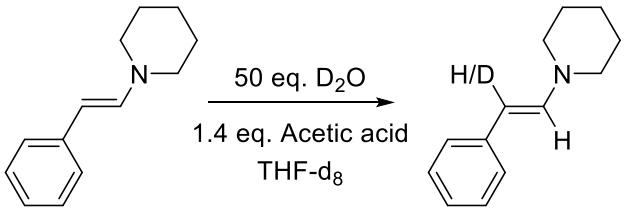
7.5 ^{1}H NMR Spectra of D_2O Exchange Experiments in THF-d_8

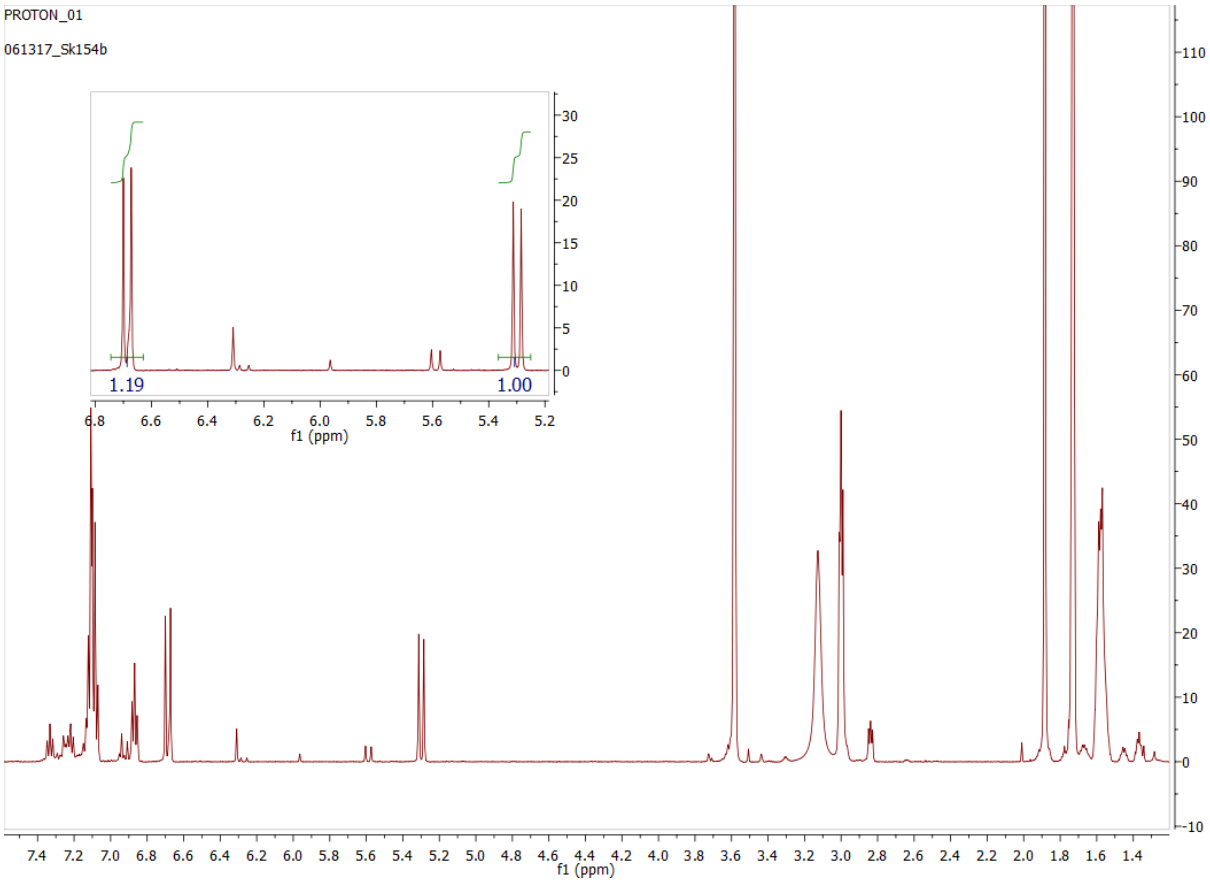





O
N
1 eq. $SmI_2(D_2O)_n$
THF-d_8
H/D
N
O
H


PROTON_01
060917_sk154a
1.00
1.00
f1 (ppm)
1.00
1.00
f1 (ppm)


N
50 eq. D_2O
1.4 eq. Acetic acid
$THF\text{-}d_8$
H/D
N
H


PROTON_01
061317_Sk154b
1.19
1.00
f1 (ppm)
f1 (ppm)

8. References

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