Supplementary Material (ESI) for Chemical Communications

Gold (I)-Catalyzed Intramolecular Hydroamination of Unactivated C=C Bonds with Alkyl Ammonium Salts

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Supporting Information

Experimental procedures, spectroscopic data, and scans of NMR spectra (15 pages).

General Methods

Reactions were performed under a nitrogen atmosphere using standard Schlenk line techniques or in a sealed vials. NMR spectra were obtained on Varian spectrometers operating at 400 MHz for ^{1}H NMR and 101 MHz for ^{13}C NMR in $CDCl_3$ at 25 °C unless noted otherwise. IR spectra were obtained on a Nicolet Avatar 360-FT IR spectrometer. Gas chromatography was performed on a HP 5890 gas chromatograph equipped with a 15 m or 25 m polydimethylsiloxane capillary column employing FID detection. Column chromatography was performed employing 230-400 mesh silica gel (Sorbent Technologies or Silicycle) or 150 mesh activated aluminum oxide, neutral, Brockmann I (Aldrich). Elemental analyses were performed by Complete Analysis Laboratories (Parsippany, NJ). Thin layer chromatography (TLC) was performed on silica gel 60 F254 (EMD Chemicals Inc.). Ambient laboratory temperature ranged from 22 to 24 °C.

Tetrahydrofuran (THF) and diethyl ether were distilled from sodium benzophenone ketyl under nitrogen, dichloromethane and $CDCl_3$ were distilled from CaH_2 under nitrogen. (**1**)AuCl,[1] (**2**)AuCl,[2] and (**5**)AuCl[2] were synthesized by previously reported methods. $NaAuCl_4 \cdot 2H_2O$ (Aldrich), **5** (Strem), AgOTf (Acros), and AgOTs (Acros) were used as received. Benzyl(1-allylcyclohexylmethyl)benzylamine (**3**), 2,2-diphenyl-4-pentenylamine (**6**), 1-but-3-enyl-cyclohexylmethylamine (**10**), and benzyl-(1-but-3-enyl-cyclohexylmethyl)amine (**12**) were synthesized employing published procedures.[3] All other solvents and reagents were purchased from major chemical suppliers and were used as received.

Synthesis of *N*-Alkenyl Ammonium Salts

Benzyl(1-allylcyclohexylmethyl)ammonium tetrafluroborate (3·HBF$_4$). $HBF_4 \cdot Et_2O$ (1.70 mL, 12.3 mmol) was added to a stirred solution of **3** (1.50 g, 6.16 mmol) in ether (50 mL) at 0 °C. Precipitation began within 20 s and the resultant white suspension was stirred for 5 min before the solid was isolated by vacuum filtration. The white solid was washed with ether (10 mL) and dried under vacuum to yield **3**·HBF$_4$ (1.76 g, 86%) as a white solid. ^{1}H NMR: δ 7.42-7.50 (m, 5 H), 6.68 (br s, 2 H), 5.47 (tdd, *J* = 7.7, 9.7, 17.1 Hz, 1 H), 4.88-5.00 (m, 2 H), 4.36 (t, *J* = 4.1 Hz, 2 H), 2.76-2.80 (m, 2 H), 2.14 (d, *J* = 7.5 Hz, 2 H), 1.30-1.44 (m, 10 H).

Tetrafluoroborate salts of **6**, **10**, and **12** were prepared as white solids from their corresponding amines by a method analogous to that used to prepare **3**·HBF$_4$.

For 6·HBF$_4$. 89%. ^{1}H NMR: δ 7.24-7.35 (m, 6 H), 7.11 (d, *J* = 8.03 Hz, 4 H), 5.73 (br s, 3 H), 5.07-5.34 (m, 3 H), 3.67 (q, *J* = 5.9 Hz, 2 H), 2.91 (d, *J* = 6.7 Hz, 2 H).

For 10·HBF$_4$. 70%. ^{1}H NMR: δ 6.05 (br s, 3 H), 5.82 (tdd, *J* = 6.5, 10.3, 17.1 Hz, 1 H), 4.96-5.10 (m, 2 H), 2.98-3.02 (m, 2 H), 1.94-2.00 (m, 2 H), 1.28-1.49 (m, 12 H).

For 12·HBF$_4$. 56%. ^{1}H NMR: δ 7.45-7.53 (m, 5 H), 6.72 (br s, 2 H), 5.66 (tdd, J = 6.5, 10.1, 17.1 Hz, 1 H), 4.84-4.93 (m, 2 H), 4.38 (t, *J* = 4.3 Hz, 2 H), 2.78-2.81 (m, 2 H), 1.23-1.64 (m, 14 H).

2-Allyl-2-(4-methoxyphenyl)-4-pentenylamine (8·HBF$_4$). 2-(4-Methoxyphenyl)-4-pentenenitrile (3.93 g, 21.0 mmol) was added dropwise to a solution of LDA [prepared from diisopropylamine (3.05 mL, 21.6 mmol) and *n*-BuLi (1.6 M in hexanes, 14.0 mL, 22.4 mmol) in THF (50 mL)] over 10 min at –78 °C and stirred for 1 h. The resulting solution was treated with allyl bromide (3.7 mL, 43 mmol) over 15 min at –78 °C and the reaction mixture was warmed to room temperature and stirred vigorously for 4 h. The reaction mixture was diluted with water (50 mL) and extracted with ether (2 × 50 mL). The combined organic extracts were dried ($MgSO_4$), and concentrated. The resulting

residue was chromatographed (ether–hexanes = 1:3) to give 2-allyl-2-(4-methoxyphenyl)-4-pentenenitrile (**S1**, 4.29 g, 90 %) as a colorless oil.

S1 was converted to **8** via a method analogous to that used to prepare **6**.[3]

$HBF_4{\cdot}Et_2O$ (195 mL, 143 mmol) was added to a solution of **8** (345 mg, 1.49 mmol) in CH_2Cl_2 (50 mL) at 0 °C over 5 min with stirring. After 30 min hexanes (50 mL) were added, the resultant white suspension was stirred for 5 min, and the solid was isolated by vacuum filtration. The white solid was triturated with hexanes (10 mL) and dried under vacuum to yield **8**·HBF_4 (292 mg, 64 %) as a white solid.

For S1: TLC (ether–hexanes = 1:3): R_f = 0.45. ^{1}H NMR: δ 7.29-7.33 (m, 2 H), 6.88-6.92 (m, 2 H), 5.60-5.71 (m, 2 H), 5.11-5.16 (m, 4 H), 3.81 (s, 3 H), 2.61-2.72 (m, 4 H). ^{13}C{^{1}H} NMR: δ 159.2, 131.9, 129.7, 127.5, 122.0, 120.2, 114.2, 55.4, 47.1, 44.4. IR (neat, cm^{-1}): 2937, 1610, 1512, 1521, 1184, 923. HRMS calcd (found) for $C_{15}H_{17}NO$ (M^+): 227.1310 (227.1312).

For 8. Colorless oil, 95%. TLC (MeOH–CH_2Cl_2 = 1:13): R_f = 0.18. ^{1}H NMR: δ 7.21-7.25 (m, 2 H), 6.86-6.90 (m, 2 H), 5.62 (tdd, J = 7.0, 10.1, 17.3 Hz, 2 H), 5.00-5.08 (m, 4 H), 3.80 (s, 3 H), 2.87 (s, 2 H), 2.39-2.49 (m, 4 H), 0.87 (br s, 2 H). ^{13}C{^{1}H} NMR: δ 157.8, 136.4, 134.7, 128.0, 117.7, 113.8, 55.3, 49.2, 45.1, 39.9. IR (neat, cm^{-1}): 2922, 1610, 1512, 1248, 1184, 911. HRMS calcd (found) for $C_{15}H_{29}NO$ (M^+): 231.1623 (231.1616).

For 8·HBF_4. ^{1}H NMR: δ 7.21 (d, *J* = 8.7 Hz, 2 H), 6.93 (d, *J* = 8.5 Hz, 2 H), 5.50-5.60 (m, 5 H), 5.10-5.19 (m, 4 H), 3.80 (s, 3 H), 3.23 (s, 2 H), 2.48 (d, *J* = 7.0 Hz, 4 H).

6·HOTf. Trifluormethanesulfonic acid (180 mL, 2.03 mmol) was added to a solution of **6** (474 mg, 2.00 mmol) in ether (10 mL) at 0 °C and stirred for 10 min. Hexanes (10 mL) were added, the resultant white suspension was stirred for 5 min, and

the solid was isolated by vacuum filtration. The white solid was triturated with hexanes (10 mL) and dried under vacuum to yield **6**·HOTf (685 mg, 89 %) as a white solid. ^{1}H NMR: δ 7.23-7.33 (m, 6 H), 7.08-7.10 (m, 4 H), 6.40 (br s, 3 H), 5.25 (tdd, *J* = 6.7, 9.9, 17.1 Hz, 1 H), 5.15-5.20 (m, 1 H), 5.04-5.07 (m, 1 H), 3.62 (q, *J* = 6.0 Hz, 2 H), 2.92 (d, *J* = 6.3 Hz, 2 H).

2-Allyl-benzylamine·HOTf (14). Oxalyl chloride (0.40 mL, 4.6 mmol) and DMF (1 drop) were added to a solution of 2-allylbenzoic acid (486 mg, 3.00 mmol) in toluene (10 mL) and the reaction stirred for 2 h at room temperature. The resultant yellow solution was concentrated to ~5 mL and was treated with a mixture of toluene (5 mL) and ammonia (2 mL) at –78 °C. The reaction mixture was warmed to room temperature overnight and concentrated. The resultant residue was partitioned between chloroform and 10% NaOH (50 mL) and the layers were separated. The aqueous fraction was extracted with chloroform (2 × 30 mL) and the combined organic extracts were washed with brine (20 mL), dried ($MgSO_4$), and concentrated to provide 2-allyl-benzamide (**S2**, 439 mg, 91 %) as a white solid.

A solution of **S2** (436 mg, 2.70 mmol) in ether and chloroform (1:2, *v*:*v*; 15 mL) was added dropwise to a suspension of $LiAlH_4$ (430 mg, 11.3 mmol) in ether (40 mL) at 0 °C, and the resultant suspension warmed to room temperature overnight with vigorous stirring. The reaction mixture was cooled to 0 °C and quenched by the successive addition of water (0.6 mL), 15% NaOH (0.6 mL), and water (0.6 mL). The resulting suspension was warmed to room temperature, filtered through Celite, eluted with ether (100 mL), and concentrated to provide **14** (327 mg, 82 %) as a colorless oil.

14·HOTf was prepared employing a procedure similar to that used to synthesize **6**·HOTf.

For S2.[4] ^{1}H NMR: δ. 7.49 (m, 1 H), 7.36-7.42 (m, 1 H), 7.24-7.28 (m, 2 H), 6.04 (tdd, *J* = 6.3, 10.2, 16.8 Hz, 1 H), 5.90 (br s, 2 H), 4.97-5.11 (m, 2 H), 3.62 (d, *J* = 6.0 Hz, 2 H). ^{13}C{^{1}H} NMR: δ 171.8, 137.8, 135.4, 130.9, 130.7, 127.7, 126.6, 116.4, 37.7.

For 14.[5] ^{1}H NMR: δ 7.16-7.35 (m, 4 H), 6.00 (tdd, *J* = 6.3, 10.2, 16.8 Hz, 1 H), 4.97-5.09 (m, 2 H), 3.88 (s, 2 H), 3.46 (d, *J* = 6.2 Hz, 2 H), 1.46 (br s, 2 H). ^{13}C{^{1}H} NMR: δ 141.3, 137.5, 137.4, 130.0, 127.9, 127.2, 126.9, 115.9, 43.8, 37.0.

For 14·HOTf. White solid, 69%. ^{1}H NMR (DMSO-d_6): δ 7.28 (m, 4 H), 6.00 (tdd, *J* = 6.1, 10.4, 17.1 Hz, 1 H), 4.94-5.12 (m, 2 H), 4.14 (s, 2 H), 3.51 (d, *J* = 6.1 Hz, 2 H).

Hydroamination of Alkenyl Ammonium Salts

2-Methyl-4,4-diphenyl-pyrrolidine (7). Toluene (0.50 mL) was added to a mixture of **6**·HBF_4 (85.6 mg, 0.253 mmol), (**5**)AuCl (7.9 mg, 0.012 mmol), and AgOTf (3.4 mg, 0.013 mmol) and the resulting suspension was stirred at 80 °C for 19 h. The resulting mixture was diluted with CH_2Cl_2/ether (1:4, *v*:*v*; 25 mL) and washed with 15% NaOH (5 mL). The layers were separated and the aqueous layer was extracted with ether (10 mL). The combined organic extracts were washed with 1 M HCl (5 × 5 mL). The combined aqueous extracts were basified with 15 % NaOH (15 mL) and extracted with CH_2Cl_2 (5 × 10 mL). The combined CH_2Cl_2 extracts were dried ($MgSO_4$) and concentrated to yield **7**[6] (58.7 mg, 94%) as a colorless oil. ^{1}H NMR: δ 7.14-7.32 (m, 10 H), 3.68 (dd, *J* = 1.4, 11.4 Hz, 1 H), 3.48 (d, *J* = 11.3 Hz, 1 H), 3.33-3.42 (m, 1 H), 2.75 (ddd, *J* = 1.2, 6.5, 12.6 Hz, 1 H), 2.03 (dd, *J* = 8.9, 12.6 Hz, 1 H), 1.88 (br s, 1 H), 1.21 (d, *J* = 6.3 Hz, 3 H). ^{13}C{^{1}H} NMR: δ 147.9, 147.2, 128.5, 128.4, 127.2, 127.1, 126.1, 126.1, 58.0, 57.4, 53.3, 47.2, 22.5.

2-Benzyl-3-methyl-2-aza-spiro[4.5]decane (**4**), 4-allyl-4-(4-methoxy-phenyl)-2-methyl-pyrrolidine (**9**), and 3-methyl-2-aza-spiro[5.5]undecane (**11**) were synthesized employing a procedure analogous to that used to synthesize **7**.

For 4.[3] TLC (EtOAc–hexanes = 1:4): R_f = 0.29**.** ^{1}H NMR: δ 7.21-7.34 (m, 5 H), 4.01 (d, *J* = 13.3 Hz, 1 H), 3.09 (d, *J* = 13.3 Hz, 1 H), 2.77 (d, *J* = 9.2 Hz, 1 H), 2.44-2.52 (m, 1 H), 1.86 (d, *J* = 9.2 Hz, 1 H), 1.76 (dd, *J* = 7.0, 12.5 Hz, 1 H), 1.25-1.45 (m, 11 H), 1.14 (d, *J* = 6.0 Hz, 3 H). ^{13}C{^{1}H} NMR: δ 140.1, 128.8, 128.2, 126.7, 66.8, 59.1, 58.1, 47.1, 39.4, 38.6, 26.2, 23.8, 23.6, 19.4.

For 9. Colorless oil, 1.9:1 mixture of diastereomers. ^{1}H NMR (major diastereomer): δ 7.09 (d, *J* = 8.7 Hz, 2 H), 6.85 (d, *J* = 8.9 Hz, 2 H), 5.45 (tdd, *J* = 7.3, 10.9, 15.5 Hz, 1 H), 4.91-4.96 (m, 2 H), 3.79 (s, 3 H), 3.41-3.50 (m, 1 H), 3.14-3.22 (m, 2 H), 2.37-2.48 (m, 2 H), 2.26 (dd, *J* = 6.5, 12.5 Hz, 1 H), 1.85 (br s, 1 H), 1.58 (dd, *J* = 9.2, 12.5 Hz, 1 H), 1.17 (d, *J* = 6.3 Hz, 3 H). ^{1}H NMR (minor diastereomer): δ 7.15 (d, *J* = 8.9 Hz, 2 H), 6.84 (d, *J* = 8.9 Hz, 2 H), 5.48 (tdd, *J* = 7.0, 11.8, 16.2 Hz, 1 H), 4.91-4.96 (m, 2 H), 3.79 (s, 3 H), 3.14-3.29 (m, 3 H), 2.37-2.48 (m, 2 H), 2.33 (dd, *J* = 7.7, 13.0 Hz, 1 H), 1.85 (br s, 1 H), 1.51 (dd, *J* = 8.4, 12.8 Hz, 1 H), 1.22 (d, *J* = 6.5 Hz, 3 H). ^{13}C{^{1}H} NMR (both diastereomers): δ 157.8, 135.4, 135.3, 128.0, 117.4, 117.3, 113.6, 113.5, 58.3, 57.5, 55.4, 54.2, 53.4, 51.5, 47.4, 46.2, 45.8, 45.6, 22.5, 22.3. IR (neat, cm^{-1}): 2955, 1512, 1401, 1246, 1033, 827. HRMS calcd (found) for $C_{15}H_{21}NO$ (M^+): 231.1623 (231.1617).

For 11.[7] Colorless oil. ^{1}H NMR: δ 2.88 (dd, *J* = 2.4, 12.3 Hz, 1 H), 2.49-2.57 (m, 1 H), 2.34 (d, *J* = 12.3 Hz, 1 H), 1.65-1.71 (m, 1 H), 1.09-1.50 (m, 14 H), 1.05 (d, *J* = 5.8 Hz, 3 H). ^{13}C{^{1}H} NMR: δ 56.8, 53.1, 39.1, 35.7, 31.6, 30.5, 27.2, 22.9, 21.8.

For 13. TLC (EtOAc–hexanes = 1:5): R_f = 0.73. ^{1}H NMR: δ 7.20-7.35 (m, 5 H), 4.00 (d, *J* = 13.8 Hz, 1 H), 3.05 (d, *J* = 13.8 Hz, 1 H), 2.52 (d, *J* = 11.4 Hz, 1 H), 2.21-

2.27 (m, 1 H), 1.62 (d, *J* = 11.6 Hz, 1 H), 1.04-1.57 (m, 17 H). $^{13}C\{^{1}H\}$ NMR: δ 140.8, 128.7, 128.1, 126.5, 61.8, 58.4, 57.4, 38.1, 34.9, 33.3, 31.0, 27.1, 21.8, 19.3. IR (neat, cm^{-1}): 2922, 2850, 2783, 1450, 735, 697. Anal. calcd (found) for $C_{18}H_{27}N$: H, 10.57 (10.72); C, 83.99 (83.96); N, 5.44 (5.36).

For 3-methyl-1,2,3,4-tetrahydroquinoline (15). The formation of **15** was established by comparison of the ^{1}H NMR spectrum of the crude reaction mixture to the published data.[8]

In Situ Generated Ammonium Salts

Tetrafluoroboric acid etherate (137 μL, 1.01 mmol) was added to a solution of **6** (239 mg, 1.01 mmol) in toluene and the mixture was stirred for 15 min at room temperature. (**5**)AuCl (31.9 mg, 4.96×10^{-2} mmol) and AgOTf (13.0 mg, 5.06×10^{-2} mmol) were added in one portion. The reaction vessel was evacuated at 77 K, backfilled with N_2, and heated at 80 °C with stirring for 20 h. Work up as described above gave **7** (221 mg, 93%).

Figure 1. ^{1}H NMR spectrum of **S1**.

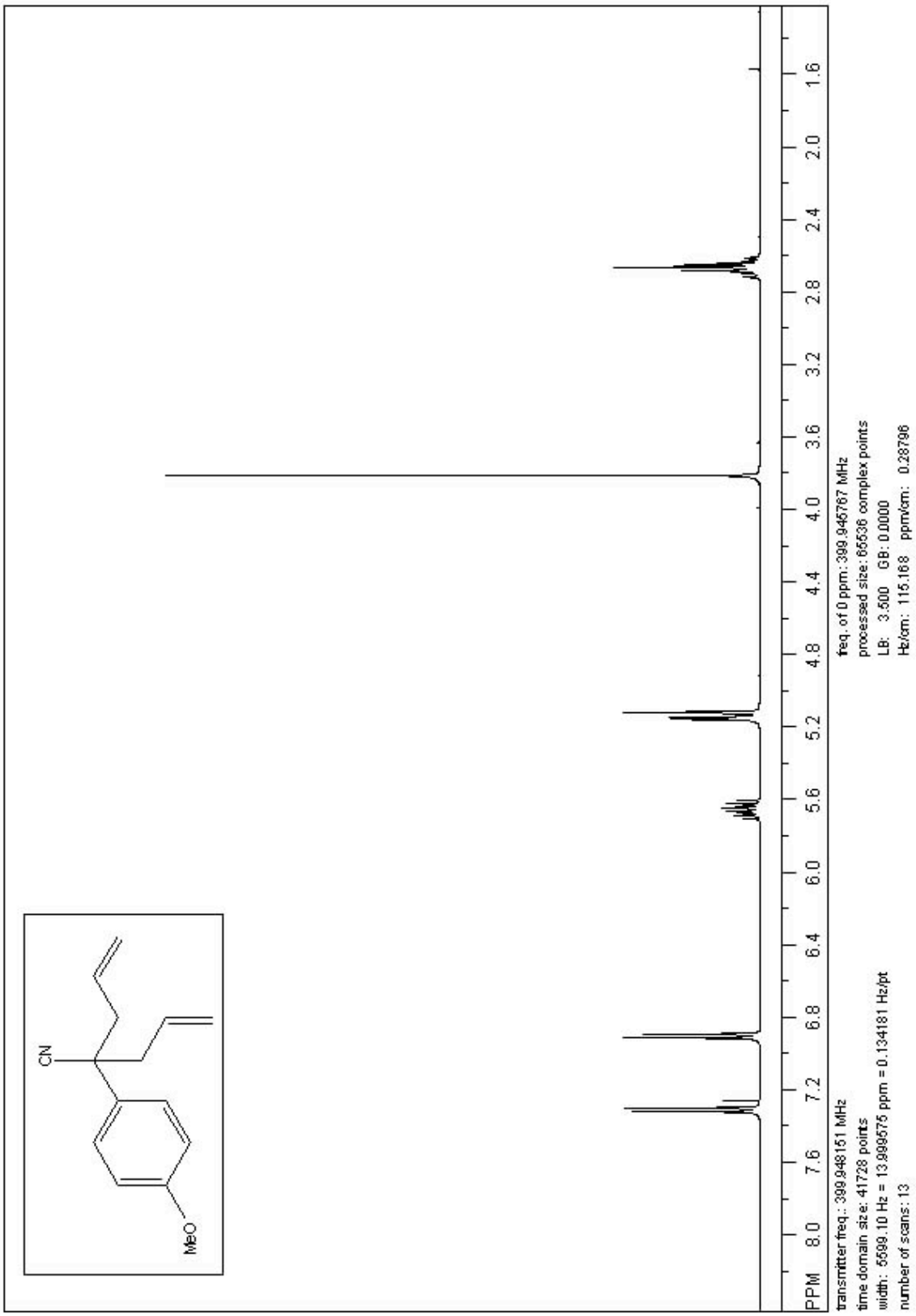


Figure 2. $^{13}C\{^{1}H\}$ NMR spectrum of **S1**.

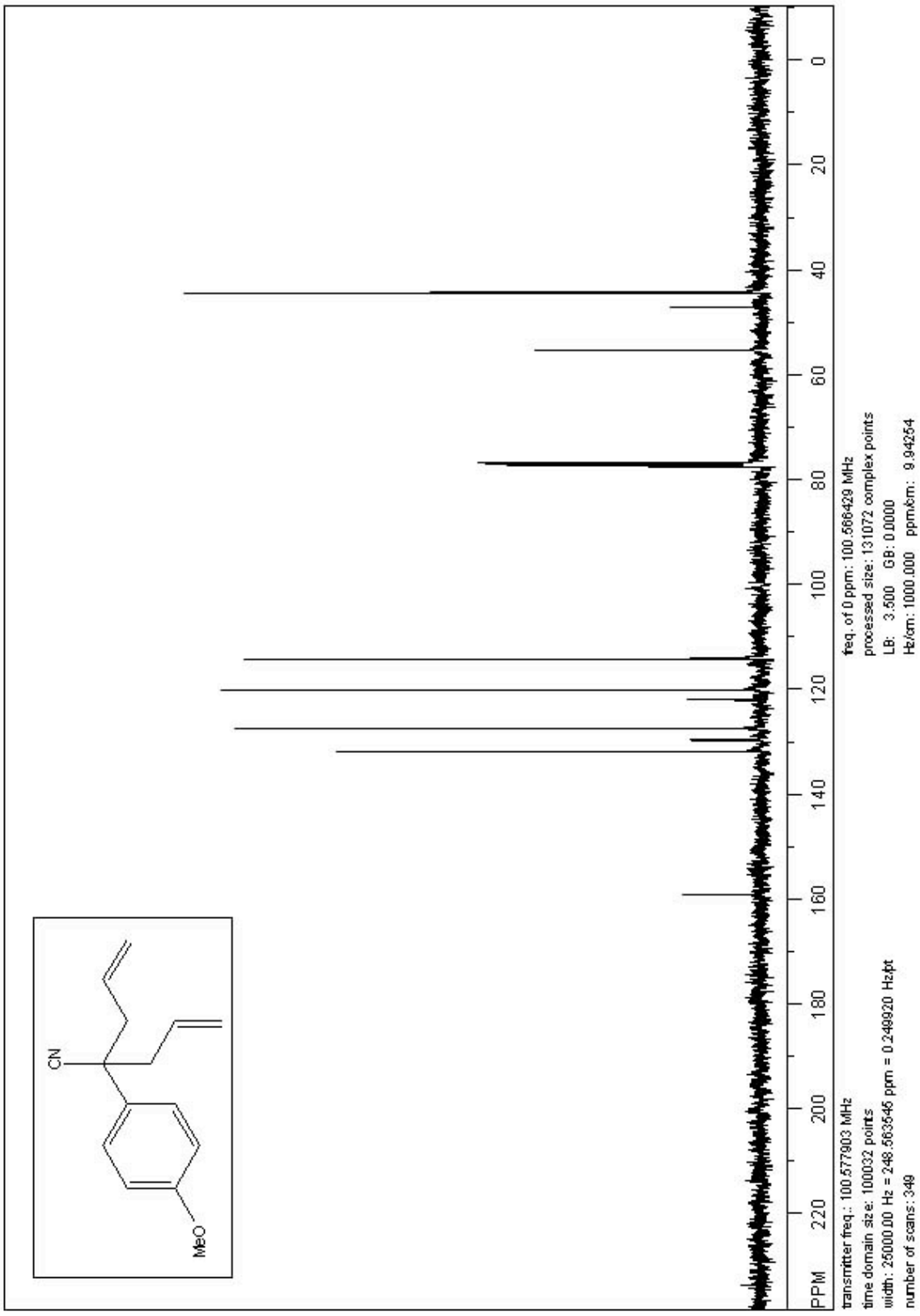


Figure 3. ^{1}H NMR spectrum of **8**.

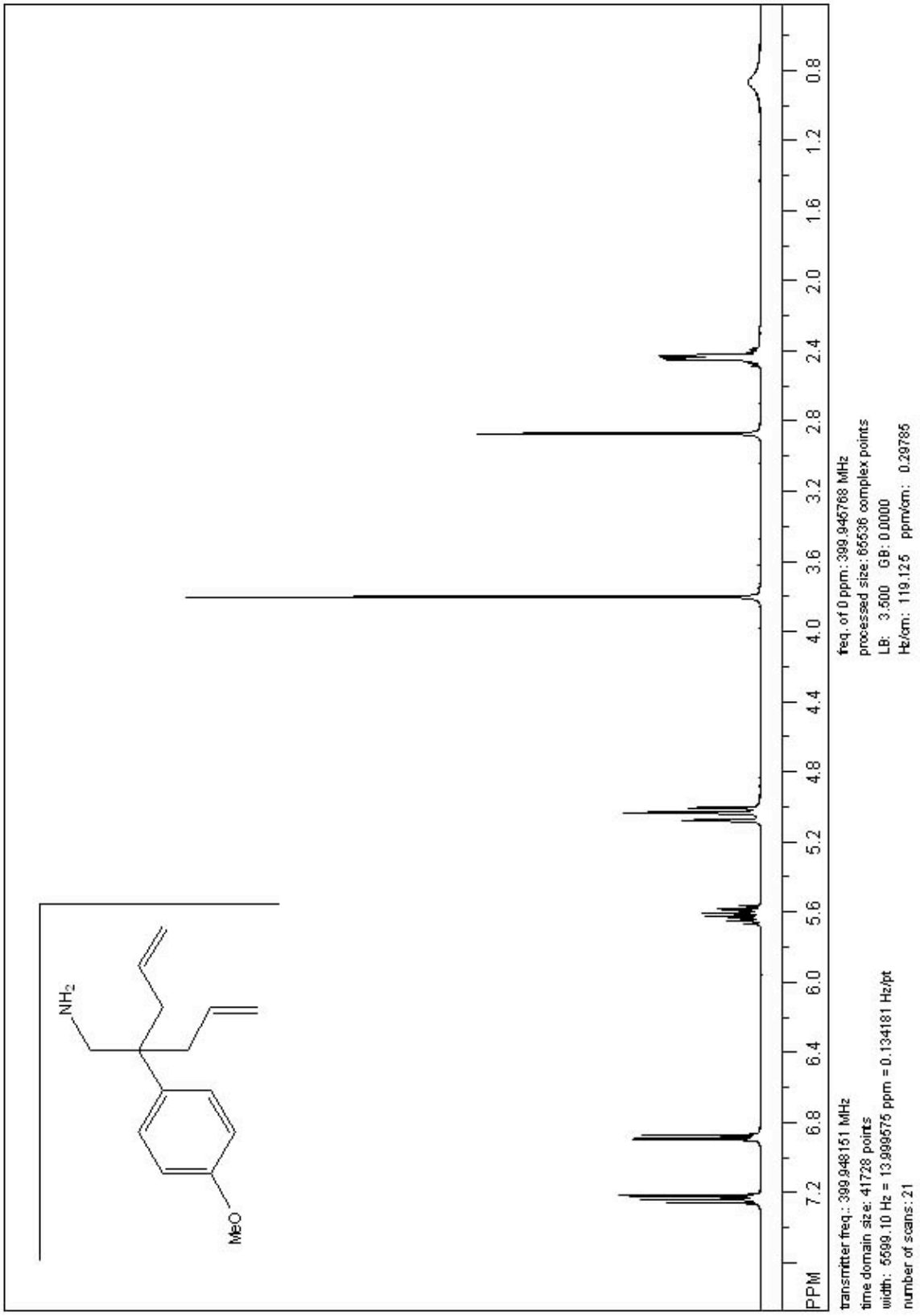


Figure 4. $^{13}C\{^{1}H\}$ NMR spectrum of **8**.

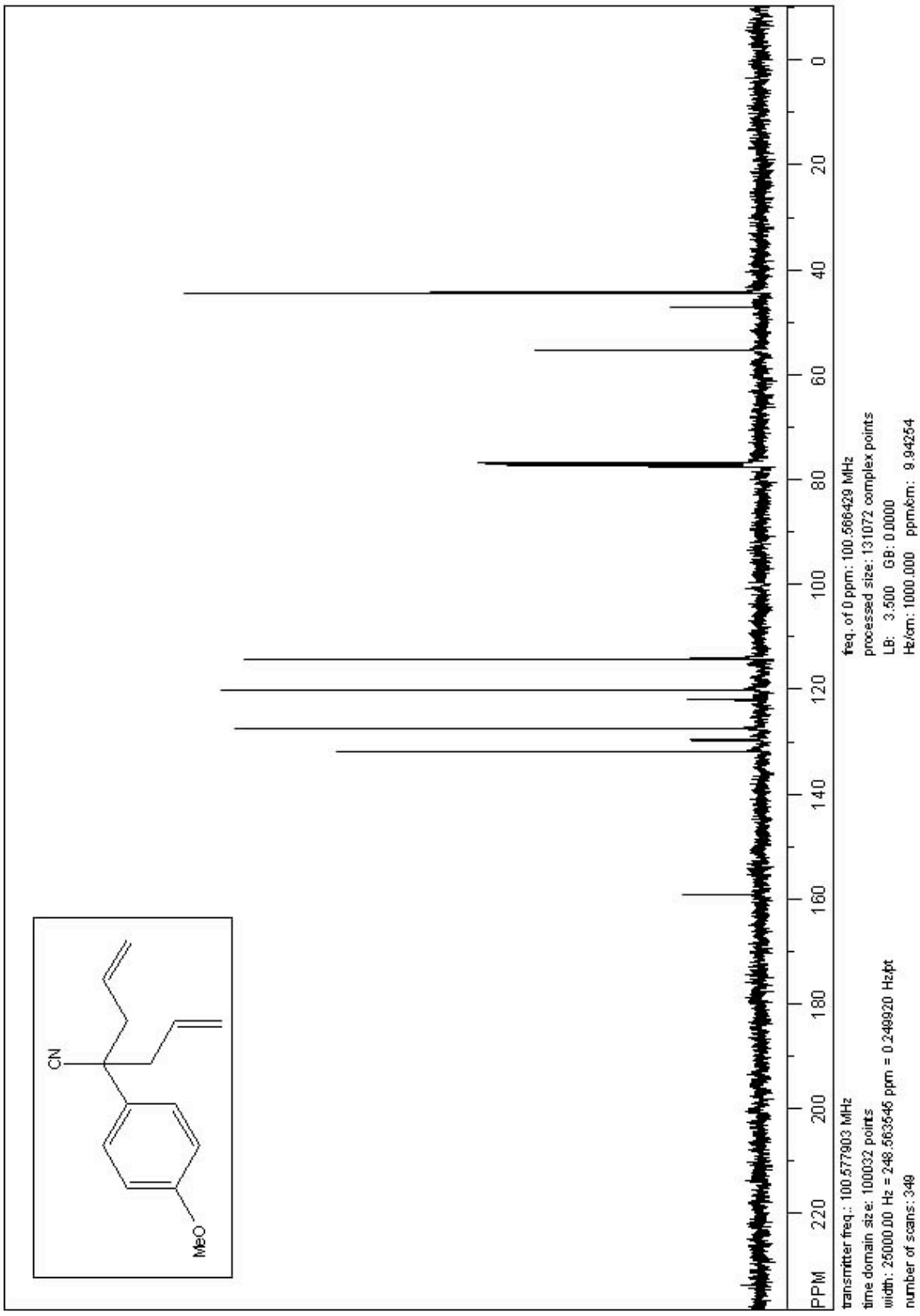


Figure 5. ^{1}H NMR spectrum of **9** (1.9:1 mixture of diastereomers).

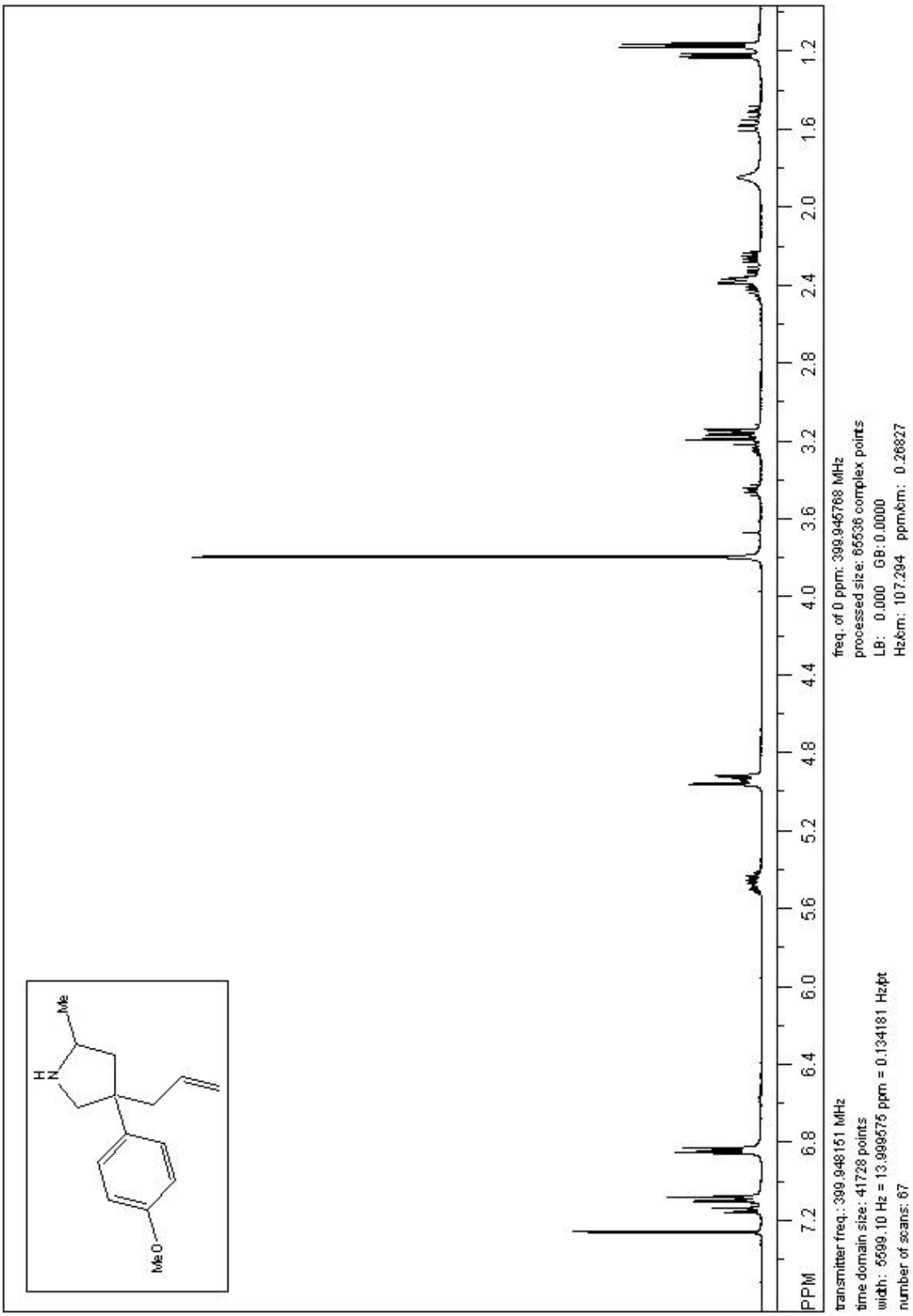
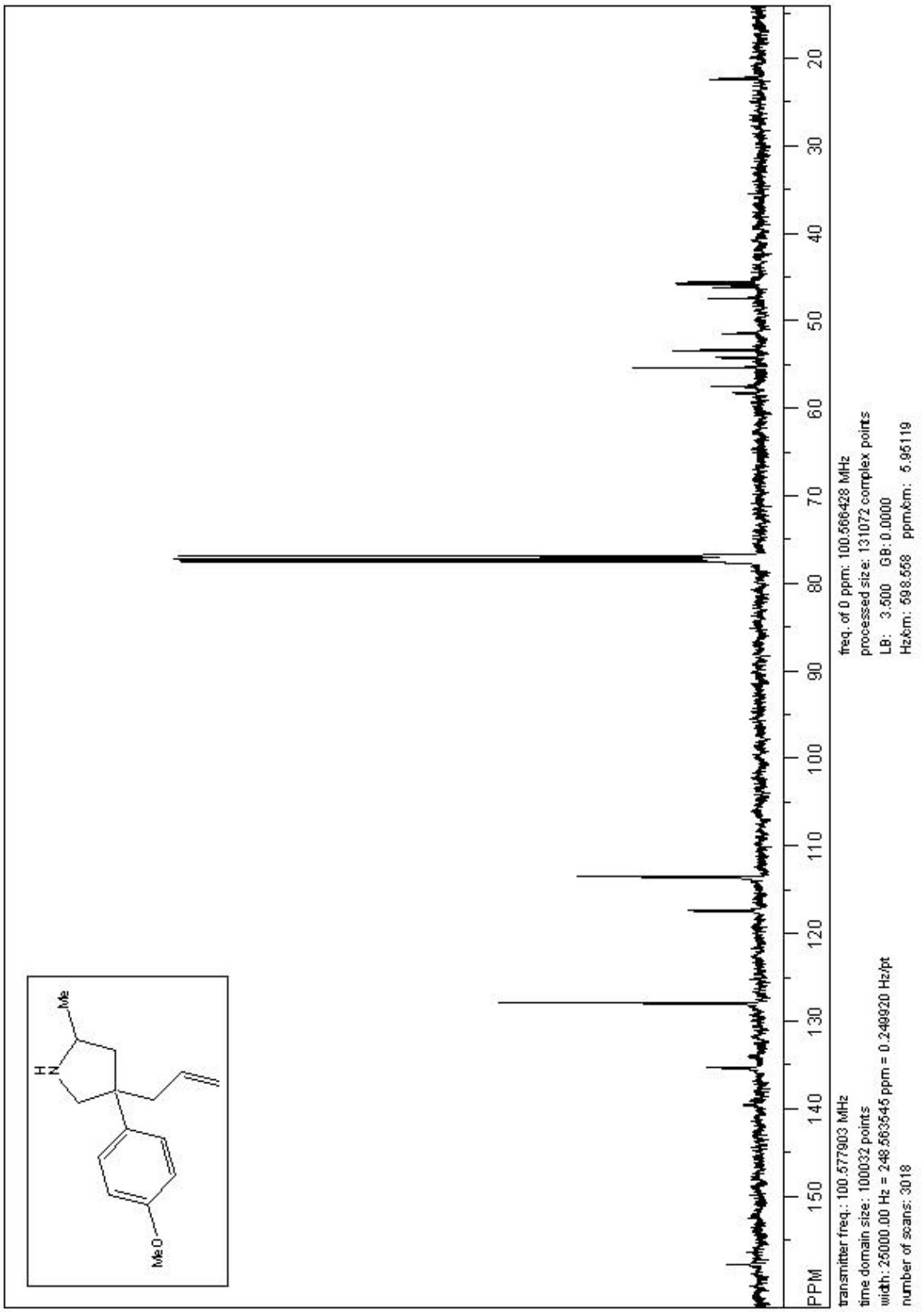


Figure 6. $^{13}C\{^{1}H\}$ NMR spectrum of **9** (1.9:1 mixture of diastereomers).



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