Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers.

Palladium-Catalyzed Amination of Allylic Carbonates with Ammonia: Access to Primary Amines

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Supporting Information

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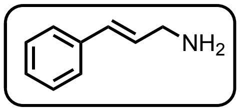
General Methods

Commercial solvents and reagents were used without further purification with the following exceptions: Hexane and ethyl acetate were fractionally distilled. Anhydrous 1,4-dioxane was purchased from Sigma-Aldrich. Anhydrous 99.99% ammonia was purchased from Singapore National Oxygen Pte Ltd. Analytical thin layer chromatography (TLC) was performed using Merck 60 F_{254} precoated silica gel plate (0.2 mm thickness). Subsequent to elution, TLC plates were visualized using UV radiation (254 nm) on Spectroline Model ENF-24061/F 254 nm. Further visualization was possible by staining with basic solution of potassium permanganate and iodine in the silica gel. Flash chromatography was performed using Merck silica gel 60 with freshly distilled solvents. Columns were typically packed as slurry and equilibrated with the appropriate solvent system prior to use. Proton nuclear magnetic resonance spectra (^{1}H NMR) were recorded on a Bruker AMX 400 spectrophoto-meters ($CDCl_3$ as solvent). Chemical shifts for ^{1}H NMR spectra are reported as δ in units of parts per million (ppm) downfield from $SiMe_4$ (δ 0.0) and relative to the signal of chloroform-d (δ 7.2600, singlet). Multiplicities were given as: s (singlet); d (doublet); t (triplet); q (quartet); qu (quintet); dd (doublets of doublet); ddd (doublets of doublets of doublet); dt (doublets of triplet); td (triplets of doublet) or m (multiplets). The number of protons (n) for a given resonance is indicated by nH. Coupling constants are reported as a *J* value in Hz. Carbon nuclear magnetic resonance spectra (^{13}C NMR) are reported as δ in units of parts per million (ppm) downfield from $SiMe_4$ (δ 0.0) and relative to the signal of chloroform-d (δ 77.03, triplet). High Resolution Mass (**HRMS**) spectra were obtained using Waters Q-Tof Permies Mass Spectrometer.

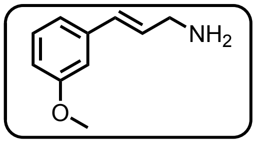
Cinnamyl alcohol and (*E*)-1,3-Diphenylallyl alcohol were bought from Sigma-Aldrich. Other allylic alcohols were prepared according to the literature procedures.[1] All allylic carbonates were synthesized from the reaction of the corresponding allylic alcohol with an alkyl chloroformate in the presence of pyridine in dichloromethane.[2]

General procedure for allylic amination using aq. NH_3: A 50 mL sealed tube was charged with PPh_3 (12 mg, 15 mol%), (SIPr)Pd(ally)Cl (9 mg, 5 mol%) and 6.8 mL 1,4-dioxane. The resulting solution was stirred at room temperature for 30 min. Then ethyl cinnamyl carbonate **1a** (62 mg, 0.3 mmol) and aqueous ammonia (3.4 mL, 25%) were added to the sealed tube. The reaction mixture was stirred at room temperature for 12 h.

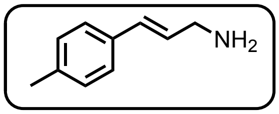
The reaction mixture was acidified by 3 M HCl to pH < 2 and extracted with dichloromethane three times. The aqueous layer was cooled in an ice bath and was made to be basic with solid NaOH until the pH value of the solution is more than 10 (the solution becomes cloudy from the insoluble free amine). The amine was extracted by dichloromethane three times. The combined organic layers were dried over anhydrous Na_2SO_4, the organic layer was filtered and concentrated under reduced pressure and the pure primary amine was obtained without further purification.



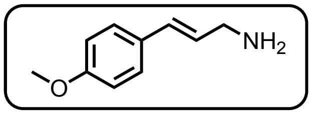
(*E*)-3-Phenylpro-2-en-1-amine (1b). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.36 (t, *J* = 7.63 Hz, 2H), 7.20 - 7.28 (m, 3H), 6.50 (d, *J* = 15.88 Hz, 1H) 6.30 (tt, *J* = 15.84, 5.88 Hz, 1H) 3.47 (dd, *J* = 1.22, 5.80 Hz, 2H), 1.45 (br. s., 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.2, 131.3, 129.5, 128.6, 127.3, 126.3, 44.4 ppm. FTIR (neat): *v* = 3017, 2924, 2855, 2253, 1651, 1636, 910, 733, 671, 648 cm^{-1}. HRMS (ESI, m/z): calculated for $C_9H_{11}N$ $[M+H]^+$: 134.0961, found $[M+H]^+$: 134.0970.



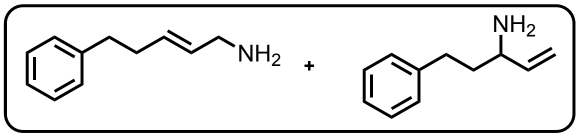
(E)-3-(3-Methoxyphenyl)prop-2-en-1-amine (3b). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.24 (t, *J* = 7.93 Hz, 1H), 6.89 - 6.97 (m, 2H), 6.78 (dd, *J* = 2.44, 8.24 Hz, 1H), 6.41 - 6.51 (m, 1H), 6.25 - 6.37 (m, 1H), 3.80 (s, 3H), 3.47 (d, *J* = 5.80 Hz, 2H), 1.37 (br. s., 2H) ppm; ^{13}C NMR(100 MHz, $CDCl_3$): δ = 159.8, 138.7, 131.7, 129.5, 129.3, 118.9, 113.0, 111.6, 55.2, 44.3 ppm; FTIR (neat): *v* = 3017, 2839, 2399, 2253, 1597, 1219, 910, 756, 733 cm^{-1}; HRMS (ESI, m/z): calculated for $C_{10}H_{13}NO$ $[M+Na]^+$: 186.0895, found $[M+Na]^+$: 186.0902.



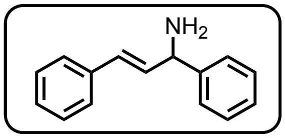
(*E*)-3-*p*-Tolylprop-2-en-1-amine (4b). ^{1}H NMR(400 MHz, $CDCl_3$): δ = 7.26 (d, *J* = 8.24 Hz, 2H), 7.11 (d, *J* = 7.93 Hz, 2H), 6.46 (d, *J* = 15.87 Hz, 1H), 6.23 - 6.28 (m, 1H), 3.45 (dd, *J* = 1.37, 5.95 Hz, 2H), 2.32 (s, 3H), 1.39 (br. s., 2H) ppm; ^{13}C NMR(100 MHz, $CDCl_3$): δ = 137.1, 134.4, 130.3, 129.4, 129.3, 126.2, 44.4, 21.2 ppm; FTIR (neat): *v* = 3017, 2361, 1651, 1636, 1219, 756, 671 cm^{-1}; HRMS (ESI, m/z): calculated for $C_{10}H_{13}N$ $[M+H]^+$: 148.1121, found $[M+H]^+$: 148.1119.



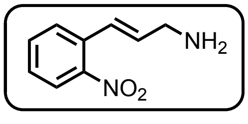
(*E*)-3-(4-Methoxyphenyl)prop-2-en-1-amine (5b). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.30 (d, *J* = 8.24 Hz, 2H), 6.85 (d, *J* = 8.85 Hz, 2H), 6.44 (d, *J* = 16.17 Hz, 1H), 6.10 - 6.24 (m, 1H), 3.80 (s, 3H), 3.44 (d, *J* = 5.80 Hz, 2H) ppm; ^{13}C NMR (100 MHz, CDCl$_3$): δ = 159.0, 142.6, 130.0, 129.2, 129.0, 127.4, 114.0, 113.4 55.3, 44.4 ppm; FTIR (neat): *v* = 3017, 2253, 1651, 1512, 1219, 910, 756, 733 cm^{-1}; HRMS (ESI, m/z): calculated for $C_{10}H_{13}NO$ [M+Na]$^+$: 186.0895, found [M+Na]$^+$: 186.0902.



(E)-5-Phenylpent-2-en-1-amine (6b) + 5-Phenylpent-1-en-3-amine (6b'). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.12 - 7.32 (m, 9.35H, **6b** + **6b'**), 5.76 - 5.89 (m, 0.87H, **6b'**), 5.55 - 5.61 (m, 2H, **6b**), 5.01 - 5.19 (m, 1.14H, **6b'**), 3.29 – 3.34 (m, 0.87H, **6b'**), 3.23 (d, *J* = 3.36 Hz, 2H, **6b**), 2.63 - 2.75 (m, 3.74H, **6b** + **6b'**), 2.34 – 2.36 (m, 2H, **6b**), 1.72 - 1.78 (m, 1.74H, **6b'**), 1.34 (br. s., 3.74H, **6b** + **6b'**) ppm; ^{13}C NMR (100 MHz, CDCl$_3$): δ = 143.2, 142.1, 141.9, 132.0, 129.7, 128.6, 128.5, 128.4, 128.4, 128.3, 125.8, 113.8, 54.1, 44.1, 39.2, 35.8, 34.1, 32.4 ppm; FTIR (neat): *v* = 3024, 2924, 2855, 2253, 1636, 1489, 1450, 910, 733, 702 cm^{-1}; HRMS (ESI, m/z): calculated for $C_{11}H_{15}N$ [M+H]$^+$: 162.1277, found [M+H]$^+$: 162.1290.



(*E*)-1,3-Diphenylprop-2-en-1-amine (7b). This compound was purified by purified on silica gel PTLC (hexane/*i*-PrNH$_2$ = 19/1).[3] ^{1}H NMR (400 MHz, CDCl$_3$) δ = 7.21 - 7.42 (m, 10H), 6.59 (d, *J* = 15.87 Hz, 1H), 6.37 (dd, *J* = 6.41, 15.87 Hz, 1H), 4.71 (d, *J* = 6.41 Hz, 1H), 1.66 (br. s., 2H) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ = 144.5, 137.0, 133.9, 129.2, 128.7, 128.6, 127.5, 127.2, 126.7, 126.5, 58.0 ppm; FTIR (neat): *v* = 3032, 2253, 1651, 910, 733, 648 cm^{-1}; HRMS (ESI, m/z): calculated for $C_{15}H_{15}N$ [M+H]$^+$: 210.1277, found [M+H]$^+$: 210.1290.



(*E*)-3-(2-Nitrophenyl)prop-2-en-1-amine (8b). ^{1}H NMR (400 MHz, CDCl$_3$) δ = 7.90 (d, *J* = 8.24 Hz, 1H), 7.51 - 7.65 (m, 2H), 7.31 - 7.43 (m, 1H), 6.98 (d, *J* = 15.87 Hz, 1H), 6.33 (dt, *J* = 5.76, 15.64 Hz, 1H), 3.54 (dd, *J* = 1.37, 5.65 Hz, 2H), 1.43 (br. s., 2H) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ = 147.8, 137.0, 133.0, 132.9, 128.6, 127.8, 124.5, 124.5, 44.3 ppm; FTIR (neat): *v* = 3156, 2963, 2855, 2253, 1519, 1350, 1119, 1096, 910, 733, 648 cm^{-1}; HRMS (ESI, m/z): calculated for $C_9H_{10}N_2O_2$ $[M+H]^+$: 179.0815, found $[M+H]^+$: 179.0813.

General procedure for allylic amination using Ammonia Gas: To a 50 mL sealed tube was added PPh_3 (24 mg, 30 mol%), (SIPr)Pd(ally)Cl (18 mg, 10 mol%) and 10 mL 1,4-dioxane. The sealed tube was evacuated and refilled with argon. This action was repeated three times. The mixture was stirred at room temperature for 30 min. Then ethyl cinnamyl carbonate **1a** (62 mg, 0.3 mmol) was added through syringe under the flow of argon. After stirring at room temperature for 10 min, the sealed tube was cooled to -78 ^{o}C in the acetone-dry ice bath. Liquid ammonia (4.4 mL, 500 equiv.) was quickly added through syringe to the sealed tube under the flush of argon. The reaction mixture was stirred at 50 ºC for indicated time.

The reaction mixture was cooled to room temperature and the cap of the sealed tube was slowly and carefully opened to release the ammonia gas. After the cap was totally opened, the mixture was stirred at room temperature for 10 min. The reaction mixture was acidified by 1 M HCl (pH < 2) and was extracted with dichloromethane three times. The aqueous layer was cooled in an ice bath and was made to be basic with solid NaOH (the solution becomes cloudy from the insoluble free amine). The amine was extracted by dichloromethane three times. The combined organic layers were dried over anhydrous Na_2SO_4, the organic layer was filtered and concentrated under reduced pressure and the pure primary amine was obtained without further purification.

References

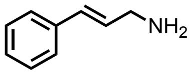
(1) Avery, T. D.; Caiazza, D.; Culbert, J. A.; Taylor, D. K.; Tiekink, E. R. T. *J. Org. Chem* .**2005**, *70*, 8344.

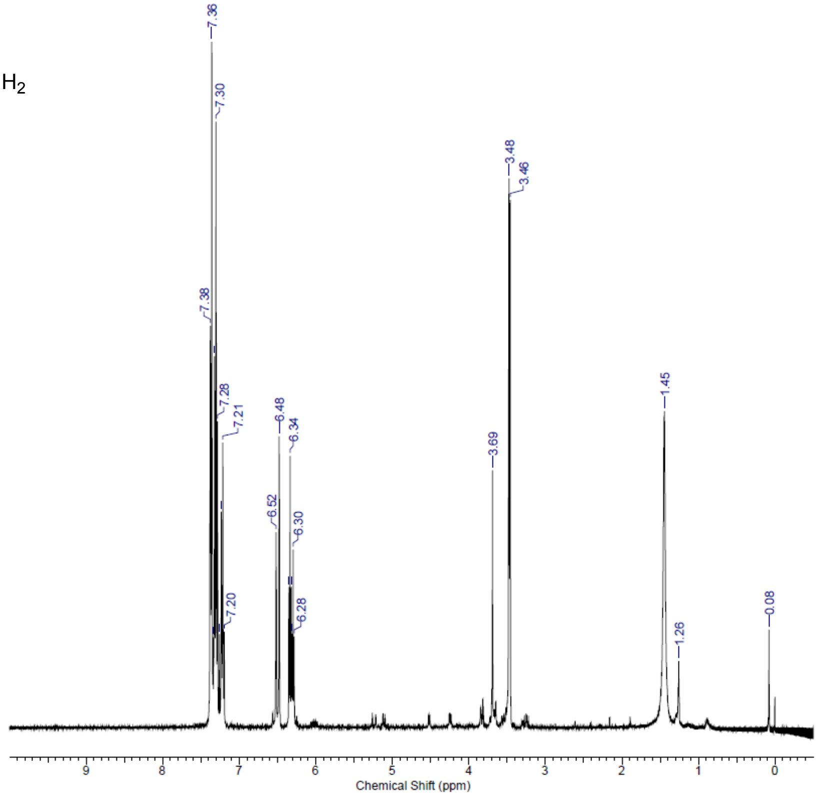
(2) Hayashi, T.; Yamamoto, A.; Ito, Y.; Nishioka, E.; Miura, H.; Yanagi, K. *J. Am. Chem. Soc.* **1989**, *111*, 6301.

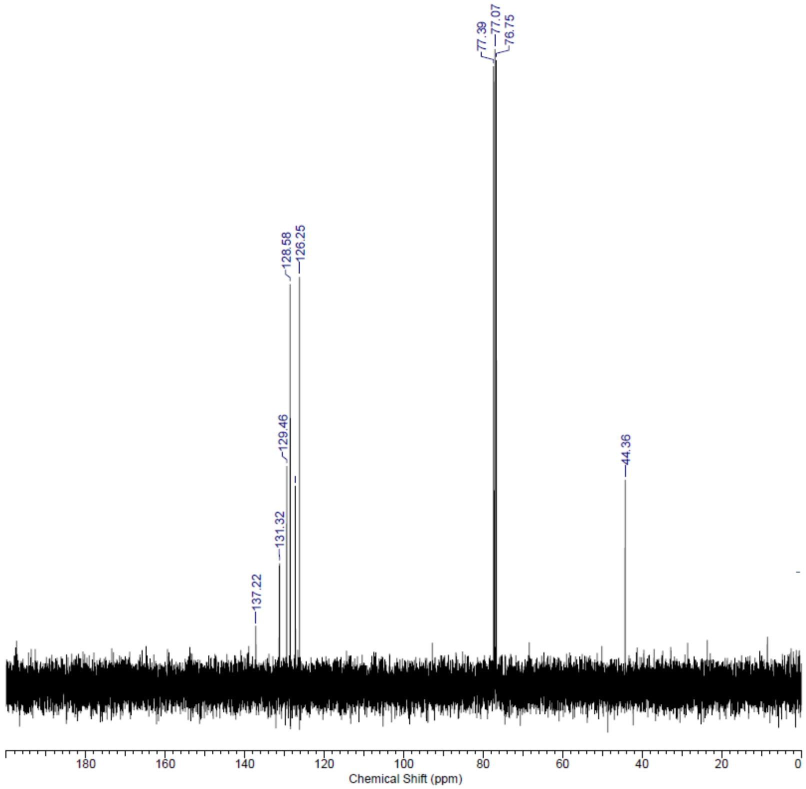
(3) Nagano, T.; Kobayashi, S. *J. Am. Chem. Soc.* **2009**, *131*, 4200.

NMR Spectra of Products:

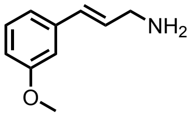
1b







3b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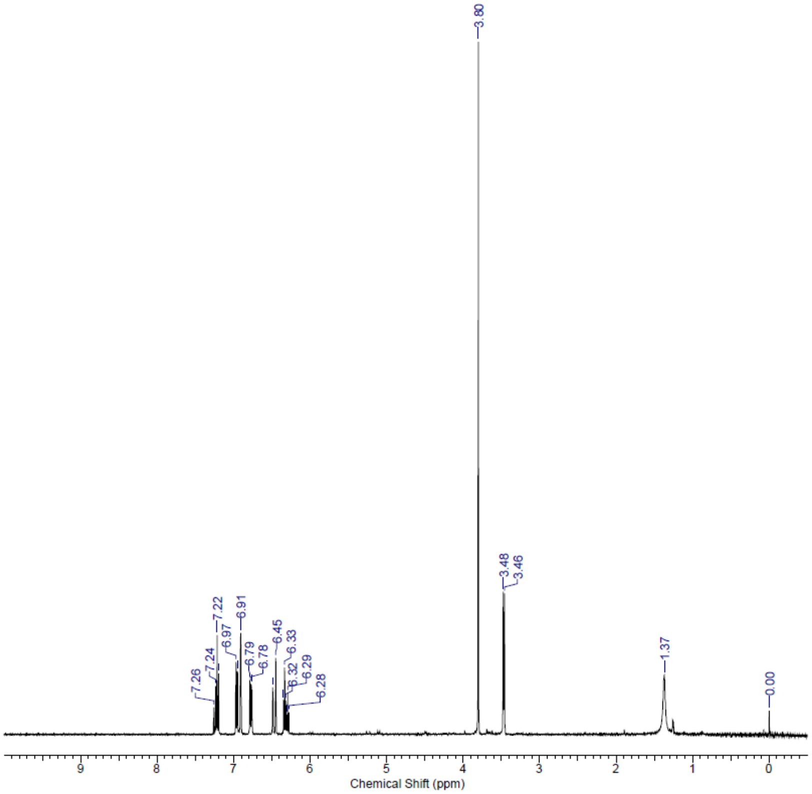
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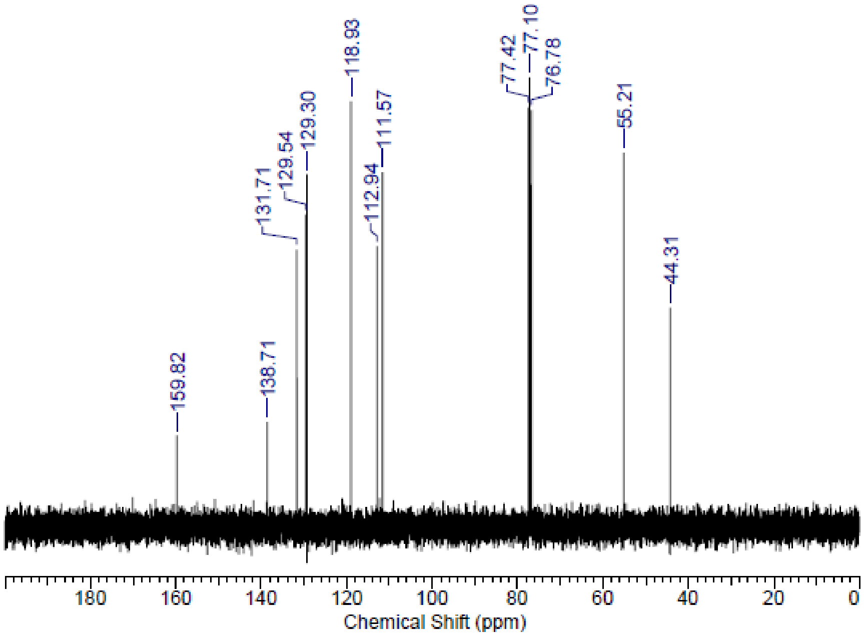
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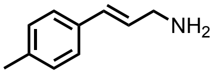
Chemical Shift (ppm)

4b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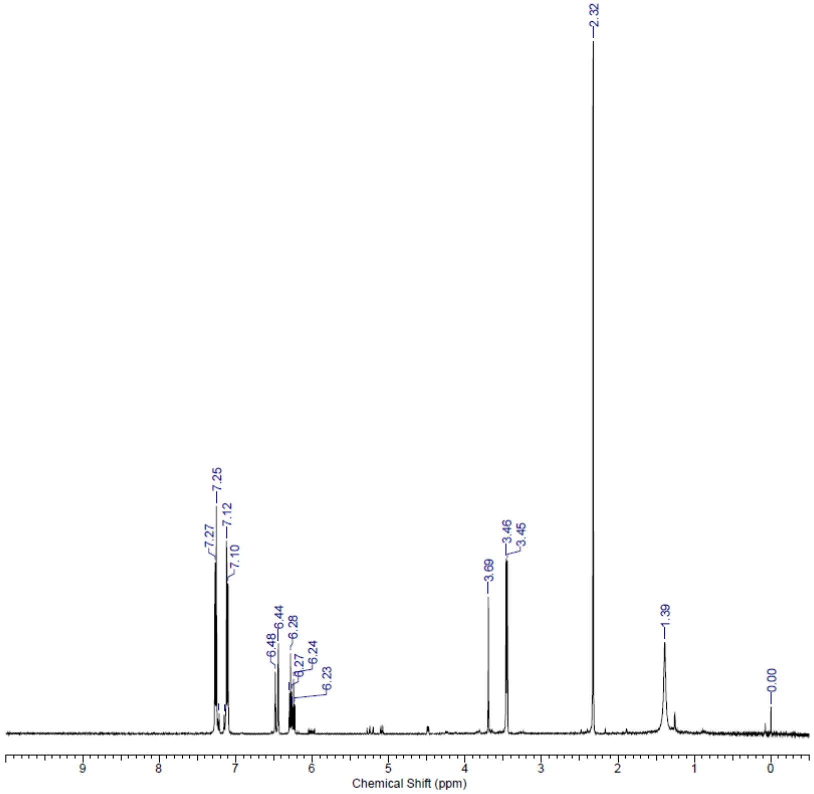
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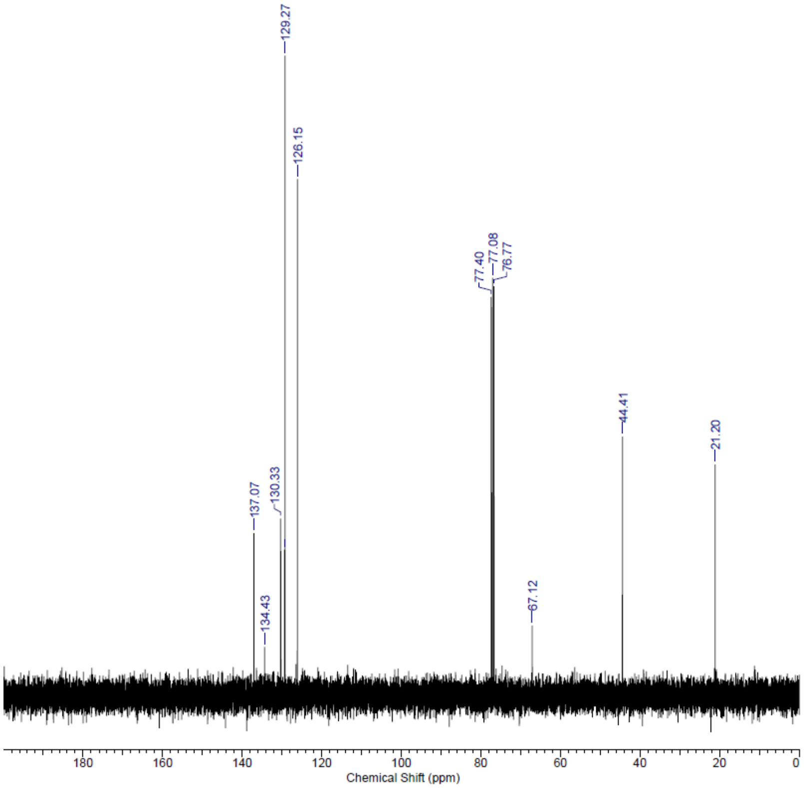
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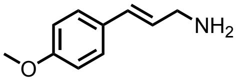
Chemical Shift (ppm)

5b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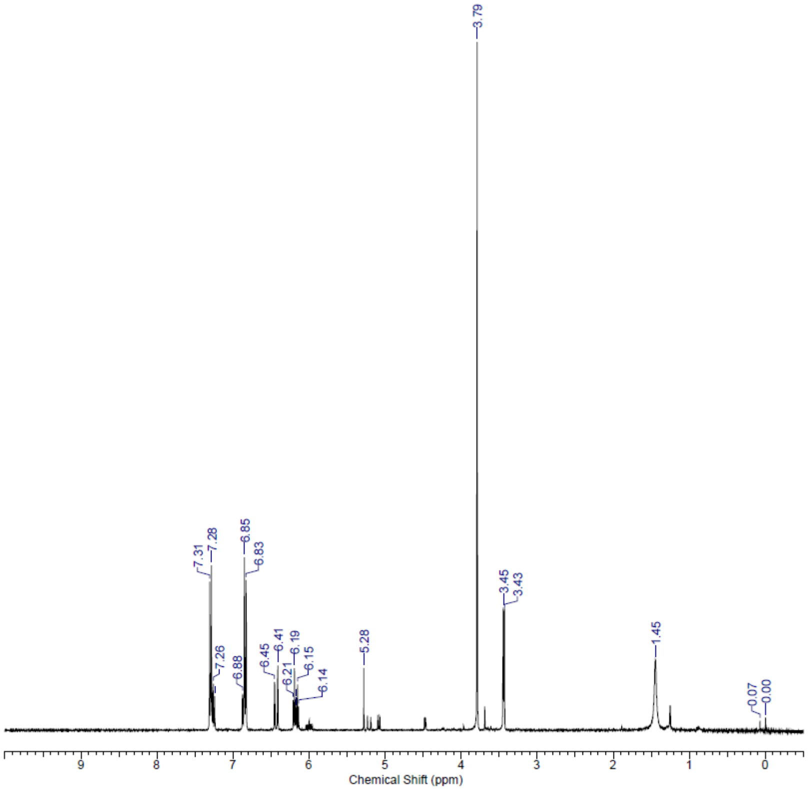
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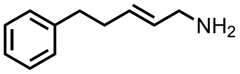
6b


NH2

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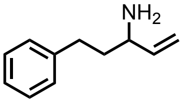
6b'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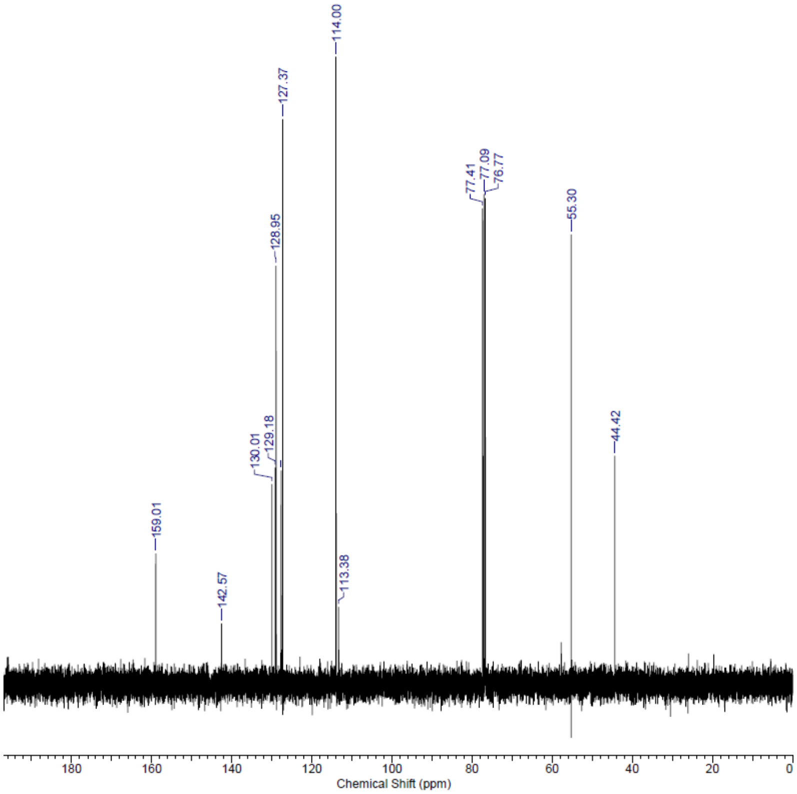
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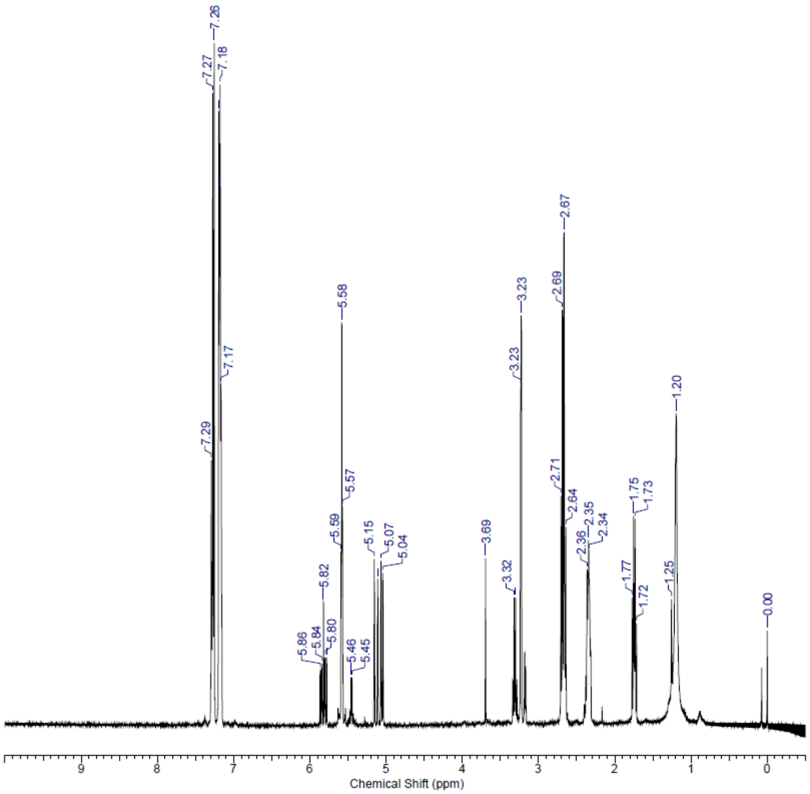
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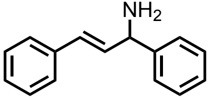
Chemical Shift (ppm)

7b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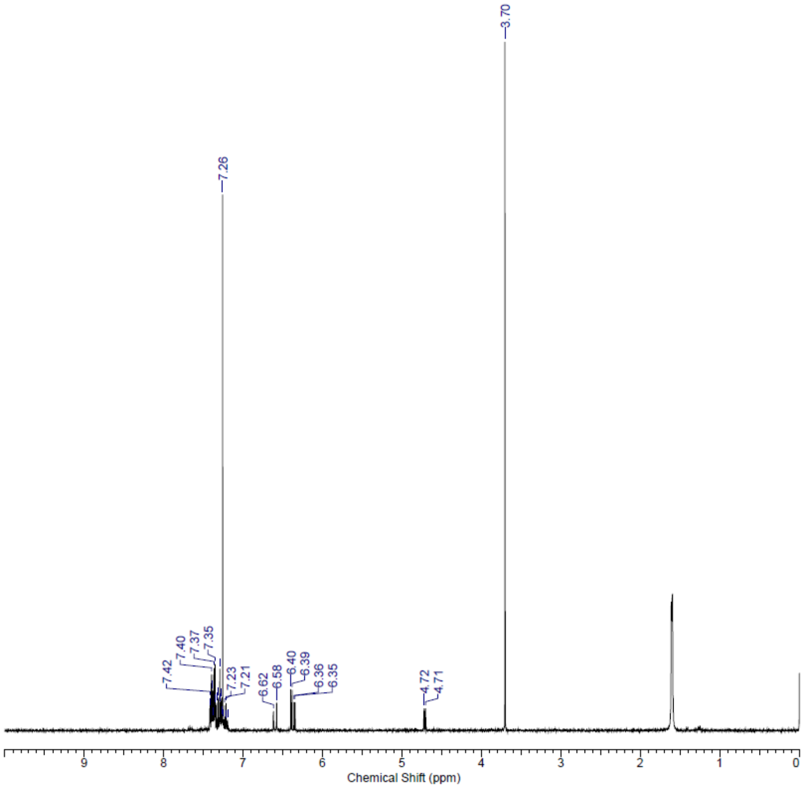
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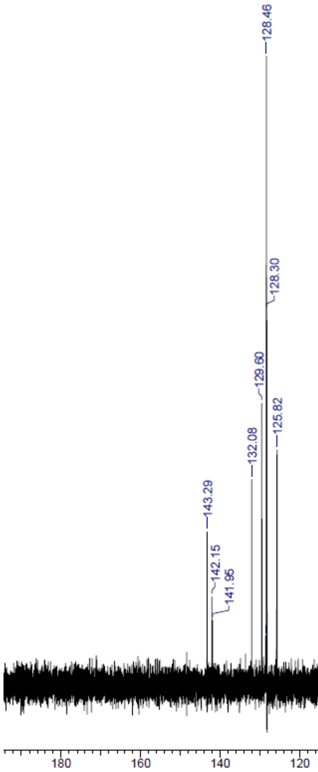
Chemical Shift (ppm)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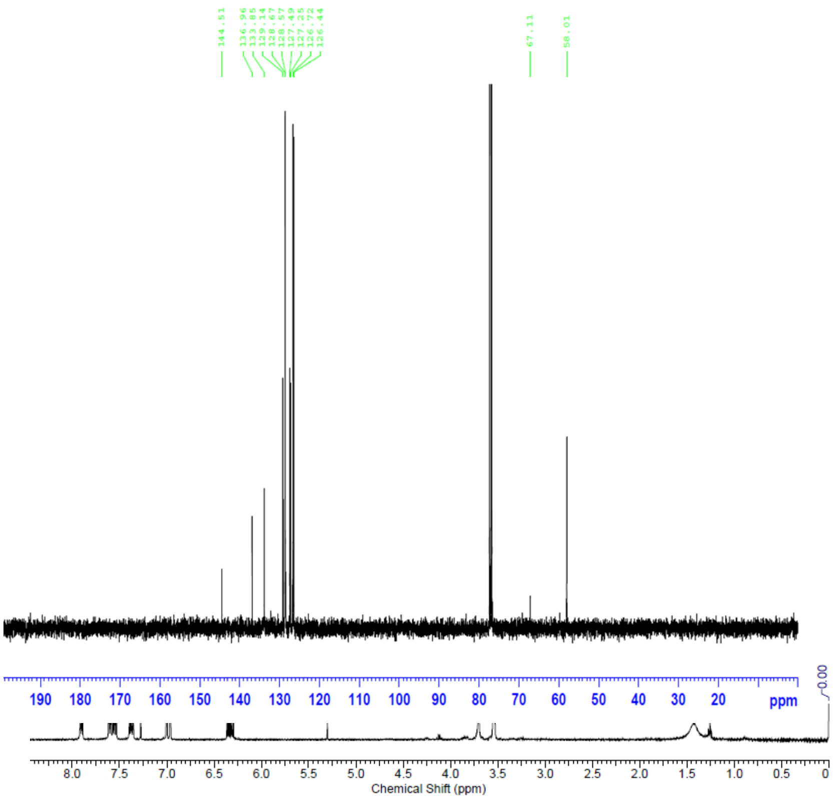
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50
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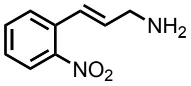
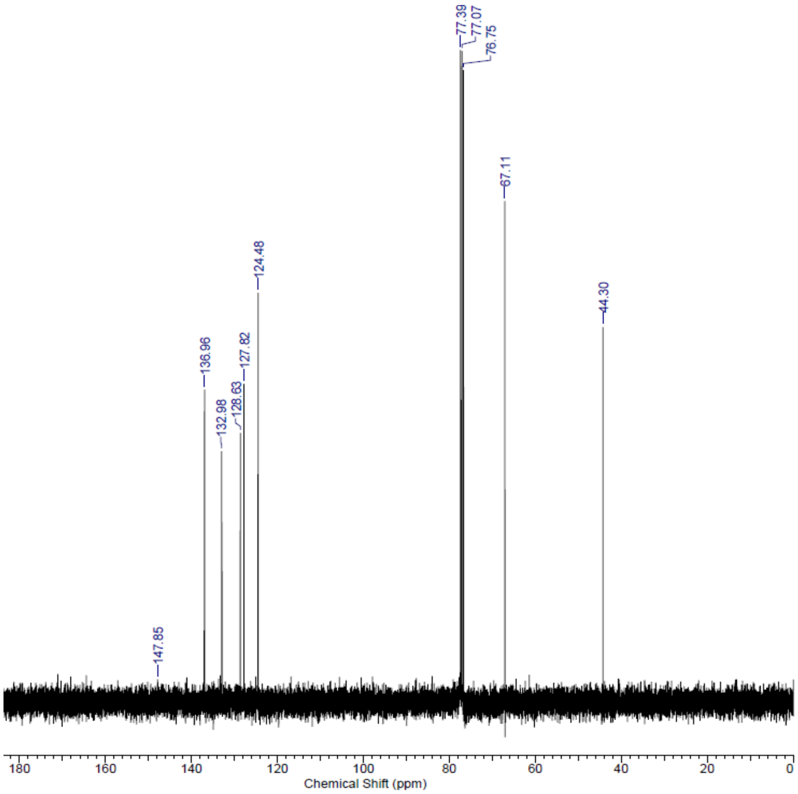
Chemical Shift (ppm)

8b


NH2
NO2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100
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Chemical Shift (ppm)