Electronic Supplementary Information for
Highly Stereoselective Michael Addition of Azlactones to Electoron-Deficient Triple Bonds under *P*-Spiro Chiral Iminophosphorane Catalysis: Importance of Protonation Pathway

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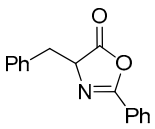
General Information: Infrared spectra were recorded on a Shimadzu IRAffinity-1 spectrometer. ^{1}H NMR spectra were recorded on a JEOL JNM-ECS400 (400 MHz). Chemical shifts are reported in ppm from the tetramethylsilane (0.0 ppm) resonance as the internal standard. Data are reported as follows: chemical shift, integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quin = quintet, sept = septet, m = multiplet) and coupling constants (Hz). ^{13}C NMR spectra were recorded on a JEOL JNM-ECS400 (101 MHz) spectrometer with complete proton decoupling. Chemical shifts are reported in ppm from the solvent resonance as the internal standard ($CDCl_3$; 77.16 ppm). Optical rotations were measured on a HORIBA SEPA-500 polarimeter. The high resolution mass spectra were conducted on Thermo Fisher Scientific Exactive. Analytical thin layer chromatography (TLC) was performed on Merck precoated TLC plates (silica gel 60 GF_{254}, 0.25 mm). Flash column chromatography was performed on silica gel 60 (spherical, 40-50 μm; Kanto Chemical Co., Inc.) and PSQ60AB (spherical, av. 55 μm; Fuji Silysia Chemical ltd.). Enantiomeric excesses were determined by HPLC analysis using chiral columns (ϕ 4.6 mm x 250 mm, DAICEL CHIRALPAK AD-H (ADH), CHIRALPAK AD-3 (AD3), CHIRALCEL OD-H (ODH), CHIRALCEL OD-3 (OD3), CHIRALCEL OZ-3 (OZ3), CHIRALPAK AS-H (ASH), CHIRALPAK IA (IA), or CHIRALPAK IC (IC)) with hexane (H) and 2-propanol (IPA) as eluent.

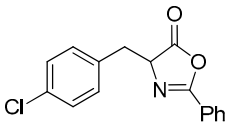
Toluene and dichloromethane (CH_2Cl_2) were supplied from Kanto Chemical Co., Inc. as "Dehydrated" and further purified by passing through neutral alumina under nitrogen atmosphere. Tetraaminophosphonium salts **1**·HCl,[1] iminophosphorane **2**,[1] cyanoacetylene,[2] and azlactones **3**, **5**[3] were prepared by following the literature procedure. Other simple chemicals were purchased and used as such.

Experimental Section:

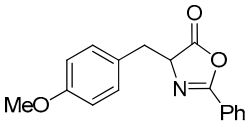
Characterization of Azlactones:



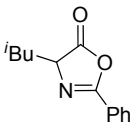
3a[4]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (2H, d, J = 7.6 Hz), 7.55 (1H, t, J = 7.6 Hz), 7.45 (2H, t, J = 7.6 Hz), 7.31-7.18 (5H, m), 4.70 (1H, dd, J = 6.8, 5.0 Hz), 3.38 (1H, dd, J = 14.2, 5.0 Hz), 3.19 (1H, dd, J = 14.2, 6.8 Hz).



3b[5]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (2H, d, J = 7.6 Hz), 7.57 (1H, t, J = 7.6 Hz), 7.46 (2H, t, J = 7.6 Hz), 7.23 (2H, d, J = 8.7 Hz), 7.20 (2H, d, J = 8.7 Hz), 4.66 (1H, dd, J = 6.4, 5.0 Hz), 3.35 (1H, dd, J = 14.2, 5.0 Hz), 3.16 (1H, dd, J = 14.2, 6.4 Hz).



3c[5]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (2H, d, J = 7.6 Hz), 7.55 (1H, t, J = 7.6 Hz), 7.45 (2H, t, J = 7.6 Hz), 7.17 (2H, d, J = 8.7 Hz), 6.78 (2H, d, J = 8.7 Hz), 4.66 (1H, dd, J = 6.4, 5.0 Hz), 3.75 (3H, s), 3.32 (1H, dd, J = 14.2, 5.0 Hz), 3.16 (1H, dd, J = 14.2, 6.4 Hz).



3d[4]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 (2H, d, J = 7.5 Hz), 7.58 (1H, t, J = 7.5 Hz), 7.49 (2H, t, J = 7.5 Hz), 4.43 (1H, dd, J = 9.2, 5.5 Hz), 2.08 (1H, nonet, J = 6.9 Hz), 1.85 (1H, ddd, J = 14.2, 6.9, 5.5 Hz), 1.69 (1H, ddd, J = 14.2, 9.2, 6.9 Hz), 1.05 (3H, d, J = 6.9 Hz), 1.02 (3H, d, J = 6.9 Hz).

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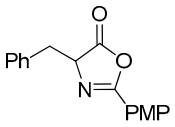
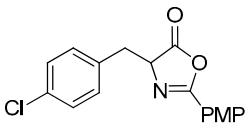
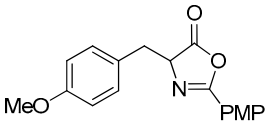
[1] a) D. Uraguchi, S. Sakaki, T. Ooi, *J. Am. Chem. Soc*. 2007, **129**, 12392. b) D. Uraguchi, S. Sakaki, Y. Ueki, T. Ito, T. Ooi, *Heterocycles* 2008, **76**, 1081. c) D. Uraguchi, Y. Ueki, T. Ooi, *J. Am. Chem. Soc*. 2008, **130**, 14088. d) D. Uraguchi, Y. Ueki, T. Ooi, *Science* 2009, **326**, 120. e) D. Uraguchi, K. Yoshioka, Y. Ueki, T. Ooi, *J. Am. Chem. Soc.* DOI: 10.1021/ja310209g.
[2] M. E. Jung, K. Buszek, *J. Am. Chem. Soc.* 1988, **110**, 3965.
[3] J. C. Ruble, G. C. Fu, *J. Am. Chem. Soc.* 1998, **120**, 11532.
[4] J. Liang, J. C. Ruble, G. C. Fu, *J. Org. Chem*. 1998, **63**, 3154.
[5] K. Gottwald, D. Seebach, *Tetrahedron* 1999, **55**, 723.



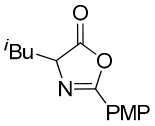
5a[3]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (2H, d, J = 9.2 Hz), 7.28-7.18 (5H, m), 6.94 (2H, d, J = 9.2 Hz), 4.66 (1H, dd, J = 6.9, 5.0 Hz), 3.86 (3H, s), 3.35 (1H, dd, J = 14.0, 5.0 Hz), 3.17 (1H, dd, J = 14.0, 6.9 Hz).



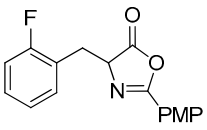
5b: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (2H, d, J = 8.7 Hz), 7.23 (2H, d, J = 8.7 Hz), 7.19 (2H, d , J = 8.7 Hz), 6.95 (2H, d, J = 8.7 Hz), 4.64 (1H, dd, J = 6.4, 5.0 Hz), 3.87 (3H, s), 3.33 (1H, dd, J = 14.2, 5.0 Hz), 3.14 (1H, dd, J = 14.2, 6.4 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.8, 163.4, 161.7, 133.9, 133.2, 131.1, 129.9, 128.7, 118.0, 114.3, 66.4, 55.6, 36.8; IR (film): 2920, 1802, 1651, 1607, 1508, 1254, 1171, 1028, 914, 829 cm^{-1}; HRMS (ESI) Calcd for $C_{17}H_{15}NO_3Cl$ ([M+H]$^+$) 316.0735. Found 316.0738.



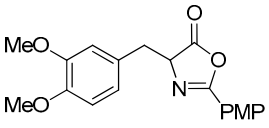
5c: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (2H, d, J = 8.7 Hz), 7.17 (2H, d, J = 8.7 Hz), 6.94 (2H, d, J = 8.7 Hz), 6.78 (2H, d, J = 8.7 Hz), 4.63 (1H, dd, J = 6.4, 4.8 Hz), 3.86 (3H, s), 3.75 (3H, s), 3.30 (1H, dd, J = 14.2, 4.8 Hz), 3.13 (1H, dd, J = 14.2, 6.4 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.1, 163.3, 161.5, 158.8, 130.8, 129.9, 127.4, 118.2, 114.3, 113.9, 66.8, 55.6, 55.3, 36.7; IR (film): 2936, 1800, 1645, 1609, 1512, 1308, 1250, 1043, 920, 818 cm^{-1}; HRMS (ESI) Calcd for $C_{18}H_{18}NO_4$ ([M+H]$^+$) 312.1230. Found 312.1230.



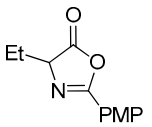
5d[3]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (2H, d, J = 8.7 Hz), 6.97 (2H, d, J = 8.7 Hz), 4.39 (1H, dd, J = 8.7, 6.0 Hz), 3.88 (3H, s), 2.06 (1H, nonet, J = 7.1 Hz), 1.83 (1H, ddd, J = 13.7, 7.1, 6.0 Hz), 1.67 (1H, ddd, J = 13.7, 8.7, 7.1 Hz), 1.03 (3H, d, J = 7.1 Hz), 1.01 (3H, d, J = 7.1 Hz).



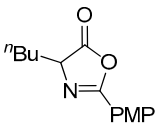
5e: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (2H, d, J = 8.7 Hz), 7.30 (1H, td, J = 7.8, 1.8 Hz), 7.23 (1H, tdd, J = 7.8, 5.5, 1.8 Hz), 7.08 (1H, t, J = 7.8 Hz), 7.04 (1H, t, J = 7.8 Hz), 6.95 (2H, d, J = 8.7 Hz), 4.67 (1H, dd, J = 7.3, 5.7 Hz), 3.87 (3H, s), 3.38 (1H, dd , J =14.2, 5.7 Hz), 3.15 (1H, dd, J = 14.2, 7.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.8, 163.3, 161.7, 161.3 (d, $J_{F\text{-}C}$ = 250.6 Hz), 131.7 (d, $J_{F\text{-}C}$ = 3.9 Hz), 130.0, 129.2 (d, $J_{F\text{-}C}$ = 8.7 Hz), 124.2 (d, $J_{F\text{-}C}$ = 2.9 Hz), 123.0 (d, $J_{F\text{-}C}$ = 15.5 Hz), 118.2, 115.6 (d, $J_{F\text{-}C}$ = 22.3 Hz), 114.3, 65.5, 55.6, 31.1; IR (film): 2924, 1796, 1645, 1510, 1302, 1263, 1233, 1049, 922, 843 cm^{-1}; HRMS (ESI) Calcd for $C_{17}H_{15}NO_3F$ ([M+H]$^+$) 300.1031. Found 300.1034.



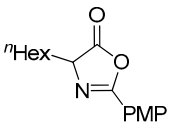
5f: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86 (2H, d, J = 9.2 Hz), 6.94 (2H, d, J = 9.2 Hz), 6.79 (1H, d, J = 7.8 Hz), 6.78 (1H, s), 6.74 (1H, d, J = 7.8 Hz), 4.66 (1H, dd, J = 6.4, 4.6 Hz), 3.86 (3H, s), 3.82 (3H, s), 3.76 (3H, s), 3.31 (1H, dd, J = 14.2, 4.6 Hz), 3.15 (1H, dd, J = 14.2, 6.4 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.9, 163.3, 161.5, 148.6, 148.2, 129.8, 127.7, 121.9, 118.1, 114.3, 112.8, 111.0, 66.7, 55.9, 55.8, 55.6, 37.0; IR (film): 2926, 1807, 1649, 1607, 1510, 1323, 1260, 1169, 1138, 1049, 1026, 935, 835 cm^{-1}; HRMS (ESI) Calcd for $C_{19}H_{20}NO_5$ ([M+H]$^+$) 342.1336. Found 342.1338.



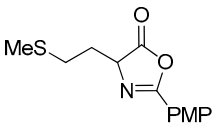
5g[3]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (2H, d, J = 8.9 Hz), 6.98 (2H, d, J = 8.9 Hz), 4.37 (1H, dd, J = 7.6, 5.7 Hz), 3.88 (3H, s), 2.07 (1H, dqd, J = 15.1, 7.6, 5.7 Hz), 1.94 (1H, d-quin, J = 15.1, 7.6 Hz), 1.04 (3H, t, J = 7.6 Hz).



5h[6]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (2H, d, J = 8.9 Hz), 6.98 (2H, d, J = 8.9 Hz), 4.39 (1H, dd, J = 6.8, 6.0 Hz), 3.88 (3H, s), 2.07-1.96 (1H, m), 1.91-1.80 (1H, m), 1.54-1.33 (4H, m), 0.92 (3H, t, J = 7.3 Hz).

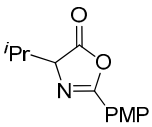


5i: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (2H, d, J = 8.9 Hz), 6.98 (2H, d, J = 8.9 Hz), 4.38 (1H, dd, J = 6.9, 5.8 Hz), 3.88 (3H, s), 2.06-1.95 (1H, m), 1.91-1.79 (1H, m), 1.54-1.42 (2H, m), 1.42-1.22 (6H, m), 0.87 (3H, t, J = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.0, 163.3, 161.4, 129.9, 118.4, 114.3, 65.5, 55.6, 31.8, 31.7, 29.0, 25.3, 22.7, 14.2; IR (film): 2918, 1809, 1651, 1514, 1310, 1260, 1043, 1022, 903, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{16}H_{22}NO_3$ ([M+H]$^+$) 276.1594. Found 276.1594.

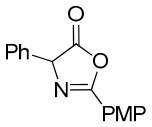


5j[3]**:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (2H, d, J = 8.9 Hz), 6.98 (2H, d, J = 8.9 Hz), 4.57 (1H, t, J = 6.9 Hz), 3.88 (3H, s), 2.73 (2H, t, J = 6.9 Hz), 2.30 (1H, dq, J = 14.2, 6.9 Hz), 2.13 (1H, dq, J = 14.2, 6.9 Hz), 2.12 (3H, s).

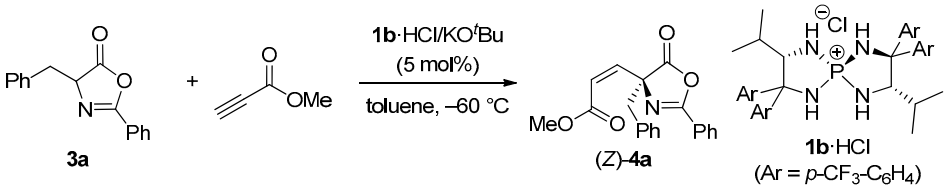
[6] C. Joannesse, C. P. Johnston, C. Concellón, C. Simal, D. Philip, A. D. Smith, *Angew. Chem. Int. Ed.* 2009, **48**, 8914.



5k: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (2H, d, J = 8.9 Hz), 6.98 (2H, d, J = 8.9 Hz), 4.26 (2H, d, J = 4.6 Hz), 3.88 (3H, s), 2.37 (1H, sept-d, J = 6.9, 4.6 Hz), 1.14 (3H, d, J = 6.9 Hz), 1.01 (3H, d, J = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.3, 163.3, 161.5, 129.9, 118.4, 114.3, 70.8, 55.6, 31.4, 18.9, 17.7; IR (film): 2924, 1811, 1645, 1510, 1304, 1261, 1043, 1006, 891, 833 cm^{-1}; HRMS (ESI) Calcd for $C_{13}H_{15}NO_3Na$ ([M+Na]$^+$) 256.0944. Found 256.0941.

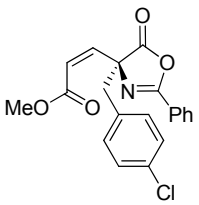


5l: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.04 (2H, d, J = 8.9 Hz), 7.47-7.33 (5H, m), 7.01 (2H, d, J = 8.9 Hz), 5.50 (1H, s), 3.90 (3H, s); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.6, 163.6, 162.4, 133.9, 130.1, 129.1, 128.8, 127.0, 118.1, 114.4, 68.2, 55.7; IR (film): 2938, 1815, 1641, 1603, 1508, 1323, 1256, 1171, 1047, 897, 847 cm^{-1}; HRMS (ESI) Calcd for $C_{16}H_{14}NO_3$ ([M+H]$^+$) 268.0968. Found 268.0965.

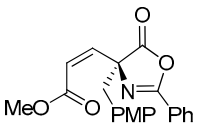


3a (Z)-4a 1b·HCl (Ar = p-CF_3-C_6H_4)

Representative Procedure for Asymmetric Michael Addition of Azlactone 3 to Methyl Propiolate Catalyzed by Chiral Iminophosphorane 1b prepared from 1b·HCl/KO^{t}Bu: A solution of **1b**·HCl (9.27 mg, 11.0 μmol) in toluene (1.5 mL) was treated with a 1.0 M THF solution of KO^{t}Bu (10.0 μL, 10.0 μmol) at –78 °C under Ar atmosphere and the mixture was stirred for 30 min at –40 °C. After cooling to –60 °C, methyl propiolate (18.5 mg, 0.22 mmol) and a solution of azlactone **3a** (50.3 mg, 0.20 mmol) in toluene (0.50 mL) were introduced dropwise sequentially, and stirring was continued for 12 h. The reaction was quenched by the addition of a toluene solution of trifluoroacetic acid (0.5 M, 80.0 μL) and the whole mixture was poured into ice-cooled 1 *N* hydrochloric acid. The aqueous phase was extracted with ethyl acetate (EA) twice and the organic phases were washed with brine. The combined organic extracts were dried over Na_2SO_4 and filtered. All volatiles were removed by evaporation and the *E*/*Z* ratio of **4a** was determined to be 1:>20 by ^{1}H NMR (400 MHz) analysis of the crude aliquot. Purification of the residue was performed by column chromatography on silica gel (H/EA = 5:1 as eluent) to give the adduct **4a** as a mixture of *E*/*Z* isomers in 92% yield (61.7 mg, 0.18 mmol). The enantiomeric excess of (*Z*)-**4a** was determined to be 90% by chiral stationary phase HPLC analysis. **4a:** HPLC ASH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 7.1 min (*S* of (*E*)-isomer), 8.3 min (*R* of (*E*)-isomer), 9.9 min (*R* of (*Z*)-isomer), 13.7 min (*S* of (*Z*)-isomer). (*Z*)-**4a:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (2H, d, J = 7.3 Hz), 7.51 (1H, t, J = 7.3 Hz), 7.40 (2H, t, J = 7.3 Hz), 7.24-7.11 (5H, m), 6.35 (1H, d, J = 11.9 Hz), 6.12 (1H, d, J = 11.9 Hz), 3.58 (3H, s), 3.40 (1H, d, J = 13.3 Hz), 3.30 (1H, d, J = 13.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.8, 165.4, 162.0, 140.5, 132.9, 132.6, 130.7, 128.7, 128.2, 127.9, 127.7, 125.8, 125.1, 72.1, 51.9, 46.3; IR (liq. film): 2951, 1817, 1724, 1645, 1207, 1090, 1059, 984, 899 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{17}NO_4Na$ ([M+Na]$^+$) 358.1050. Found 358.1054. (*E*)-**4a:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (2H, d, J = 7.8 Hz), 7.55 (1H, t, J = 7.8 Hz), 7.44 (2H, t, J = 7.8 Hz), 7.20-7.15 (5H, m), 7.14 (1H, d, J = 15.6 Hz), 6.26 (1H, d, J = 15.6 Hz), 3.76 (3H, s), 3.32 (1H, d, J = 13.3 Hz), 3.27 (1H, d, J = 13.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.2, 166.0, 160.8, 142.9, 133.2, 133.1, 130.4, 128.9, 128.4, 128.1, 127.8, 125.4, 123.2, 74.7, 52.1, 44.2; IR (liq. film): 2951, 1815, 1724, 1651, 1495, 1450, 1435, 1279, 1167, 1059, 970, 880 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{18}NO_4$ ([M+H]$^+$) 336.1230. Found 336.1231. Although >95% geometrically pure **4a** was obtained under the optimized conditions, the presence of the minor isomer was detected by ^{1}H NMR analysis (see the ^{1}H NMR trace shown below). Therefore, the isolated product should be regarded as a mixture of two diastereomers and thus specific rotation was not determined. In the following characterization of **4b**~**4d**, specific rotation was not determined either because of the slight contamination of the minor (*E*)-isomer.

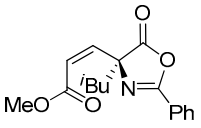


4b: HPLC AD3, H/IPA = 10:1, flow rate = 0.5 mL/min, λ = 254 nm, 16.7 min (major isomer of (*E*)-isomer), 17.2 min (minor isomer of (*E*)-isomer), 24.2 min (major isomer of (*Z*)-isomer), 27.3 min (minor isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*Z*)-isomer δ 7.87 (2H, d, J = 7.3 Hz), 7.55 (1H, t, J = 7.3 Hz), 7.44 (2H, t, J = 7.3 Hz), 7.16 (2H, d, J = 9.2 Hz), 7.13 (2H, d, J = 9.2 Hz), 6.31 (1H, d, J = 11.9 Hz), 6.13 (1H, d, J = 11.9 Hz), 3.60 (3H, s), 3.38 (1H, d, J = 13.5 Hz), 3.27 (1H, d, J = 13.5 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*Z*)-isomer δ 176.6, 165.4, 162.3, 140.1, 133.8, 132.9, 132.0, 131.5, 128.8, 128.5, 128.0, 125.6, 125.3, 72.0, 52.0, 45.4; IR (liq. film): 2951, 1817, 1724, 1645, 1491, 1437, 1209, 1092, 1065, 984, 901, 822 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{16}NO_4ClNa$ ([M+Na]$^+$) 392.0660. Found 392.0658.

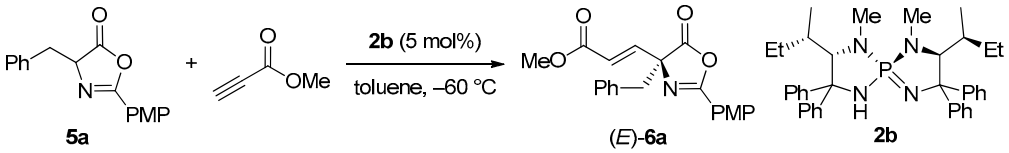


4c: HPLC OD3, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 7.3 min (major isomer of (*E*)-isomer), 8.3 min (minor isomer of (*E*)-isomer), 12.4 min (minor isomer of (*Z*)-isomer), 13.1 min (major isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*Z*)-isomer δ 7.86 (2H, d, J = 7.3 Hz), 7.52 (1H, t, J = 7.3 Hz), 7.42 (2H, t, J = 7.3 Hz), 7.12 (2H, d, J = 8.7 Hz), 6.70 (2H, d, J = 8.7 Hz), 6.34 (1H, d, J = 11.9 Hz), 6.11 (1H, d, J = 11.9 Hz), 3.70 (3H, s), 3.59 (3H, s), 3.34 (1H, d, J = 13.5 Hz), 3.25 (1H, d, J = 13.5 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*Z*)-isomer δ 177.0, 165.5, 162.1, 159.1, 140.5, 132.6, 131.8, 128.8, 128.0,

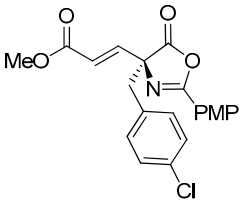
125.9, 125.1, 125.0, 113.7, 72.4, 55.2, 51.9, 45.5; IR (liq. film): 2953, 1817, 1724, 1645, 1512, 1438, 1250, 1209, 1065, 984, 822 cm^{-1}; HRMS (ESI) Calcd for $C_{21}H_{19}NO_5Na$ ([M+Na]$^+$) 388.1155. Found 388.1145.



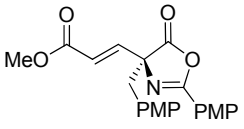
4d: HPLC OZ3, H/IPA = 10:1, flow rate = 0.5 mL/min, λ = 254 nm, 8.7 min (major isomer of (*E*)-isomer), 10.4 min (minor isomer of (*E*)-isomer), 12.0 min (minor isomer of (*Z*)-isomer), 13.1 min (major isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*Z*)-isomer δ 8.04 (2H, d, *J* = 7.3 Hz), 7.58 (1H, t, *J* = 7.3 Hz), 7.49 (2H, t, *J* = 7.3 Hz), 6.20 (1H, d, *J* = 11.9 Hz), 6.05 (1H, d, *J* = 11.9 Hz), 3.58 (3H, s), 2.07 (1H, dd, *J* = 14.2, 6.2 Hz), 1.93 (1H, dd, *J* = 14.2, 6.2 Hz), 1.76, (1H, nonet, *J* = 6.2 Hz), 0.97 (3H, d, *J* = 6.2 Hz), 0.95 (3H, d, *J* = 6.2 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*Z*)-isomer δ 177.9, 165.7, 161.7, 140.5, 132.8, 128.9, 128.1, 127.6, 126.0, 124.4, 71.2, 51.9, 49.2, 24.5, 23.8; IR (liq. film): 2934, 1817, 1726, 1647, 1450, 1437, 1290, 1209, 1179, 1146, 1047, 972, 885 cm^{-1}; HRMS (ESI) Calcd for $C_{17}H_{19}NO_4Na$ ([M+Na]$^+$) 324.1206. Found 324.1205.



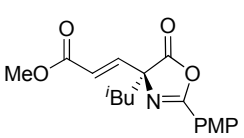
Representative Procedure for Asymmetric Michael Addition of Azlactone 5 to Methyl Propiolate Catalyzed by Chiral Iminophosphorane 2b: A solution of azlactone **5a** (28.1 mg, 0.10 mmol) in toluene (0.50 mL) was added to a solution of triaminoiminophosphorane **2b** (3.04 mg, 5.0 μmol) in toluene (0.50 mL) at –60 °C under Ar atmosphere. Methyl propiolate (9.24 mg, 0.11 mmol) was introduced dropwise slowly and stirring was continued for 13 h. A solution of trifluoroacetic acid in toluene (0.5 M, 80.0 μL) was then added to the reaction mixture for quenching the reaction. The mixture was poured into ice-cooled 1 *N* hydrochloric acid and the aqueous phase was extracted with EA twice. The combined organic phases were washed with brine, dried over Na_2SO_4, and filtered. All volatiles were removed under reduced pressure to give crude residue. The *E*/*Z* ratio of **6a** was determined to be >20:1 by ^{1}H NMR (400 MHz) analysis of the residue. Subsequent purification by column chromatography on silica gel (H/EA = 5:1 as eluent) afforded **6a** as a mixture of *E*/*Z* isomers in 97% yield (35.4 mg, 0.97 mmol). The enantiomeric excess of (*E*)-**6a** was determined to be 93% by chiral stationary phase HPLC analysis. **6a:** HPLC IA, H/IPA = 19:1, flow rate = 0.5 mL/min, λ = 210 nm, 26.2 min (major isomer of (*E*)-isomer), 34.2 min (minor isomer of (*E*)-isomer), 37.8 min (major isomer of (*Z*)-isomer), 54.1 min (minor isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*E*)-isomer δ 7.81 (2H, d, *J* = 8.7 Hz), 7.22-7.15 (5H, m), 7.14 (1H, d, *J* = 15.6 Hz), 6.92 (2H, d, *J* = 8.7 Hz), 6.26 (1H, d, *J* = 15.6 Hz), 3.86 (3H, s), 3.76 (3H, s), 3.30 (1H, d, *J* = 13.3 Hz), 3.25 (1H, d, *J* = 13.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*E*)-isomer δ 176.4, 166.1, 163.5, 160.5, 143.2, 133.3, 130.4, 130.0, 128.3, 127.7, 123.0, 117.6, 114.3, 74.6, 55.6, 52.0, 44.2; IR (liq. film): 2951, 1813, 1724, 1645, 1607, 1512, 1435, 1306, 1258, 1171, 972, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{21}H_{20}NO_5$ ([M+H]$^+$) 366.1336. Found 366.1346. Although >95% geometrically pure **6a** was obtained under the optimized conditions, the presence of the minor isomer was detected by ^{1}H NMR analysis (see the ^{1}H NMR trace shown below). Therefore, the isolated product should be regarded as a mixture of two diastereomers and thus specific rotation was not determined. Since **6b**~**6d** were also obtained as a mixture of two diastereomers in a varied ratio, their specific rotations were not provided either.



6b: HPLC OZ3, H/IPA =19:1, flow rate = 1.0 mL/min, λ = 210 nm, 12.0 min (minor isomer of (*E*)-isomer), 14.2 min (major isomer of (*E*)-isomer), 21.3 min (minor isomer of (*Z*)-isomer), 23.5 min (major isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*E*)-isomer δ 7.83 (2H, d, *J* = 9.2 Hz), 7.17 (2H, d, *J* = 8.7 Hz), 7.11 (2H, d, *J* = 8.7 Hz), 7.10 (1H, d, *J* = 15.8 Hz), 6.94 (2H, d, *J* = 9.2 Hz), 6.24 (1H, d, *J* = 15.8 Hz), 3.87 (3H, s), 3.76 (3H, s), 3.25 (1H, d, *J* = 13.3 Hz), 3.21 (1H, d, *J* = 13.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*E*)-isomer δ 176.2, 166.0, 163.7, 160.7, 142.9, 133.7, 131.9, 131.8, 130.1, 128.6, 123.3, 117.4, 114.4, 74.3, 55.7, 52.1, 43.3; IR (liq. film): 2953, 1815, 1724, 1647, 1609, 1512, 1491, 1437, 1308, 1260, 1171, 976, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{21}H_{18}NO_5ClNa$ ([M+Na]$^+$) 422.0766. Found 422.0763.

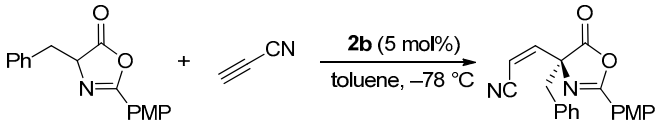


6c: HPLC OZ3, H/IPA =19:1, flow rate = 1.0 mL/min, λ = 210 nm, 17.2 min (minor isomer of (*E*)-isomer), 22.0 min (major isomer of (*E*)-isomer), 35.7 min (minor isomer of (*Z*)-isomer), 38.5 min (major isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*E*)-isomer δ 7.82 (2H, d, *J* = 8.7 Hz), 7.12 (1H, d, *J* = 16.0 Hz), 7.09 (2H, d, *J* = 9.2 Hz), 6.93 (2H, d, *J* = 9.2 Hz), 6.71 (2H, d, *J* = 8.7 Hz), 6.25 (1H, d, *J* = 16.0 Hz), 3.86 (3H, s), 3.76 (3H, s), 3.71 (3H, s), 3.24 (1H, d, *J* = 13.5 Hz), 3.19 (1H, d, *J* = 13.5 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*E*)-isomer δ 176.5, 166.2, 163.5, 160.5, 159.0, 143.3, 131.5, 130.0, 125.3, 123.0, 117.7, 114.3, 113.7, 74.8, 55.6, 55.2, 52.0, 43.4; IR (liq. film): 2953, 1813, 1724, 1645, 1609, 1510, 1464, 1435, 1304, 1250, 1171, 1030, 974, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{22}H_{22}NO_6$ ([M+H]$^+$) 396.1442. Found 396.1444.



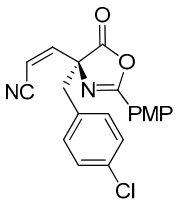
6d: HPLC ODH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 5.2 min (major isomer of (*E*)-isomer), 5.6 min (minor isomer of (*E*)-isomer), 7.8 min (minor isomer of (*Z*)-isomer), 10.0 min (major isomer of (*Z*)-isomer); ^{1}H NMR (400 MHz, $CDCl_3$) (*E*)-isomer δ 7.98 (2H, d, *J* = 8.9 Hz), 7.00 (1H, d, *J* = 15.8 Hz), 6.99 (2H, d, *J* = 8.9 Hz), 6.15 (1H, d, *J* = 15.8 Hz), 3.89 (3H, s), 3.74 (3H,

s), 2.02 (1H, dd, J = 14.2, 5.5 Hz), 1.85 (1H, dd, J = 14.2, 6.8 Hz), 1.74 (1H, octet-d, J = 6.8, 5.5 Hz), 0.92$_4$ (3H, d, J = 6.8 Hz), 0.91$_8$ (3H, d, J = 6.8 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) (*E*)-isomer δ 177.6, 166.2, 163.6, 160.3, 144.4, 130.1, 122.2, 117.9, 114.4, 73.1, 55.7, 52.0, 46.5, 25.2, 24.2, 23.2; IR (liq. film): 2951, 1815, 1724, 1647, 1609, 1508, 1489, 1458, 1310, 1265, 1169, 1153, 941, 883, 847 cm^{-1}; HRMS (ESI) Calcd for $C_{18}H_{21}NO_5Na$ ([M+Na]$^+$) 354.1312. Found 354.1311.

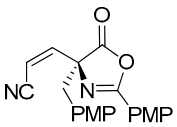


5a (*Z*)-**7a**

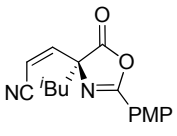
Representative Procedure for Asymmetric Michael Addition of Azlactone 5 to Cyanoacetylene Catalyzed by Chiral Iminophosphorane 2b: Azlactone **5a** (28.1 mg, 0.10 mmol) was placed in a dried test tube and dissolved into toluene (0.86 mL) under Ar atmosphere. After cooling to –78 °C, a 1 M toluene solution of cyanoacetylene (0.11 mL, 0.11 mmol) and a solution of triaminoiminophosphorane **2b** (3.04 mg, 5.0 μmol) in toluene (30.0 μL) were introduced dropwise sequentially to the solution and the reaction mixture was stirred for 4 h. A solution of trifluoroacetic acid in toluene (0.5 M, 80.0 μL) was added to the reaction mixture and the whole mixture was poured into an ice-cooled 1 *N* hydrochloric acid. The aqueous phase was extracted with EA twice and the organic phases were washed with brine. The combined organic extracts were dried over Na_2SO_4 and filtered. All volatiles were evaporated off to give the crude residue and the *E*/*Z* ratio of **7a** thus obtained was determined to be 1:>20 by ^{1}H NMR (400 MHz) analysis. Purification of the residue by column chromatography on silica gel (H/EA = 2:1 as eluent) afforded (*Z*)-**7a** in 87% yield (28.9 mg, 0.87 mmol), whose enantiomeric excess was determined to be 97% by chiral stationary phase HPLC analysis. (*Z*)-**7a:** HPLC IC, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 13.6 min (*R*), 14.8 min (*S*); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (2H, d, J = 9.2 Hz), 7.24-7.17 (5H, m), 6.94 (1H, d, J = 9.2 Hz), 6.59 (1H, d, J = 11.7 Hz), 5.60 (1H, d, J = 11.7 Hz), 3.85 (3H, s), 3.33 (1H, d, J = 13.5 Hz), 3.30 (1H, d, J = 13.5 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.0, 163.7, 161.0, 147.1, 132.7, 130.5, 130.4, 128.4, 127.9, 117.3, 114.9, 114.4, 102.3, 75.1, 55.6, 43.9; IR (liq. film): 2924, 1813, 1647, 1607, 1512, 1258, 1171, 1111, 976, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{16}N_2O_3Na$ ([M+Na]$^+$) 355.1053. Found 355.1049; $[\alpha]_D^{19}$ –170.3 (c = 1.6, $CHCl_3$) for 97% ee. The product (*Z*)-**7a** was obtained in a geometrically pure form and the minor (*E*)-isomer was not detected by ^{1}H NMR (see the ^{1}H NMR trace shown below) as well as HPLC analyses. Therefore, specific rotation was determined and this was also the case in the following characterization of **7b**~**7l**.



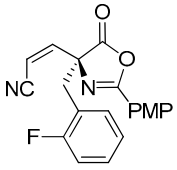
(*Z*)-**7b:** HPLC IC, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 13.5 min (minor isomer), 14.9 min (major isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (2H, d, J = 9.2 Hz), 7.19 (2H, d, J = 8.9 Hz), 7.15 (2H, d, J = 8.9 Hz), 6.95 (2H, d, J = 9.2 Hz), 6.56 (1H, d, J = 11.7 Hz), 5.61 (1H, d, J = 11.7 Hz), 3.86 (3H, s), 3.31 (1H, d, J = 13.7 Hz), 3.26 (1H, d, J = 13.7 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.8, 163.8, 161.2, 146.8, 133.9, 131.8, 131.3, 130.5, 128.6, 117.1, 114.8, 114.5, 102.5, 74.9, 55.6, 43.1; IR (film): 2922, 1813, 1647, 1607, 1512, 1258, 1171, 1117, 978, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{16}N_2O_3Cl$ ([M+H]$^+$) 367.0844. Found 367.0845; $[\alpha]_D^{20}$ –179.3 (c = 1.0, $CHCl_3$) for 96% ee.



(*Z*)-**7c:** HPLC ADH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 20.1 min (major isomer), 22.5 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (2H, d, J = 8.6 Hz), 7.13 (2H, d, J = 8.6 Hz), 6.93 (2H, d, J = 8.6 Hz), 6.72 (2H, d, J = 8.6 Hz), 6.57 (1H, d, J = 11.7 Hz), 5.58 (1H, d, J = 11.7 Hz), 3.83 (3H, s), 3.70 (3H, s), 3.27 (1H, d, J = 14.7 Hz), 3.24 (2H, d, J = 14.7 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.0, 163.6, 160.9, 159.1, 147.1, 131.5, 130.4, 124.6, 117.3, 114.9, 114.3, 113.7, 102.1, 75.2, 55.5, 55.2, 43.1; IR (film): 2934, 1813, 1647, 1607, 1510, 1303, 1248, 1171, 1028, 976, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{21}H_{18}N_2O_4Na$ ([M+Na]$^+$) 385.1159. Found 385.1155; $[\alpha]_D^{19}$ –173.7 (c = 3.8, $CHCl_3$) for 97% ee.

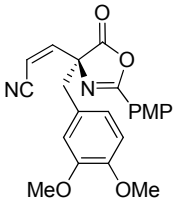


(*Z*)-**7d:** HPLC ADH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 9.4 min (major isomer), 10.1 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (2H, d, J = 9.2 Hz), 7.01 (2H, d, J = 9.2 Hz), 6.45 (1H, d, J = 11.9 Hz), 5.54 (1H, d, J = 11.9 Hz), 3.88 (3H, s), 2.07 (1H, dd, J = 13.8, 5.0 Hz), 1.86 (1H, dd, J = 13.8, 6.9 Hz), 1.80 (1H, octet-d, J = 6.9, 5.0 Hz), 0.96 (3H, d, J = 6.9 Hz), 0.95 (3H, d, J = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.1, 163.8, 160.8, 148.3, 130.6, 117.6, 115.1, 114.5, 101.3, 74.0, 55.7, 46.5, 25.2, 24.1, 23.2; IR (film): 2936, 1811, 1647, 1607, 1512, 1258, 1173, 1026, 966, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{17}H_{18}N_2O_3Na$ ([M+Na]$^+$) 321.1210. Found 321.1207; $[\alpha]_D^{20}$ –57.4 (c = 1.3, $CHCl_3$) for 92% ee.

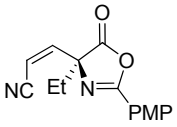


(*Z*)-**7e:** HPLC IC, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 16.3 min (minor isomer), 18.2 min (major isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (2H, d, J = 9.1 Hz), 7.30 (1H, td, J = 7.6, 1.8 Hz), 7.22 (1H, tdd, J = 7.6, 5.5, 1.8 Hz), 7.04 (1H, td, J = 7.6, 1.8 Hz), 7.00 (1H, t, J = 7.6 Hz), 6.96 (2H, d, J = 9.1 Hz), 6.59 (1H, d, J = 11.9 Hz), 5.57 (1H, d, J = 11.9 Hz), 3.86 (3H, s), 3.43 (1H, d, J = 14.0 Hz), 3.30 (1H, d, J = 14.0 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.9, 163.8, 161.2 (d, $J_{F\text{-}C}$ = 251.6 Hz), 161.1, 146.5, 132.6 (d, $J_{F\text{-}C}$ = 3.9 Hz), 130.5, 129.9 (d, $J_{F\text{-}C}$ = 7.7 Hz), 124.1 (d, $J_{F\text{-}C}$ = 3.9 Hz), 120.0 (d, $J_{F\text{-}C}$ = 15.5 Hz), 117.3, 115.5 (d, $J_{F\text{-}C}$ = 22.3 Hz), 114.7, 114.4, 102.7, 74.3, 55.6, 36.6; IR (film): 2936, 1813, 1647, 1607, 1512, 1258, 1171, 1123, 974, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{20}H_{16}N_2O_3F$ ([M+H]$^+$) 351.1140. Found 351.1151; $[\alpha]_D^{20}$

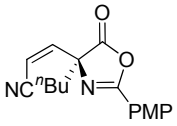
–43.6 (*c* = 1.0, $CHCl_3$) for 95% ee.



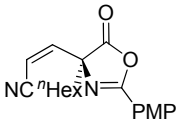
(*Z*)-**7f:** HPLC AD3, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 29.8 min (major isomer), 42.3 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (2H, d, *J* = 9.2 Hz), 6.94 (2H, d, *J* = 9.2 Hz), 6.77-6.73 (2H, m), 6.71 (1H, d, *J* = 8.7 Hz), 6.59 (1H, d, *J* = 11.9 Hz), 5.61 (1H, d, *J* = 11.9 Hz), 3.86 (3H, s), 3.80 (3H, s), 3.67 (3H, s), 3.29 (1H, d, *J* = 13.7 Hz), 3.25 (1H, d, *J* = 13.7 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.9, 163.7, 161.1, 148.6, 148.5, 147.2, 130.4, 125.1, 122.7, 117.4, 115.0, 114.5, 113.3, 110.9, 102.2, 75.5, 55.8, 55.6, 43.5, one carbon was not found probably due to overlapping; IR (film): 2938, 1817, 1651, 1514, 1260, 1238, 1144, 1022, 978, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{22}H_{20}N_2O_5Na$ ($[M+Na]^+$) 415.1264. Found 415.1260; $[\alpha]_D^{19}$ –201.4 (*c* = 1.3, $CHCl_3$) for 95% ee.



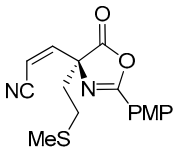
(*Z*)-**7g:** HPLC ADH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 11.1 min (major isomer), 13.1 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (2H, d, *J* = 8.9 Hz), 7.01 (2H, d, *J* = 8.9 Hz), 6.48 (1H, d, *J* = 11.9 Hz), 5.58 (1H, d, *J* = 11.9 Hz), 3.88 (3H, s), 2.10 (1H, dq, *J* = 14.6, 7.3 Hz), 2.06 (1H, dq, *J* = 14.6, 7.3 Hz), 0.97 (3H, t, *J* = 7.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.6, 163.8, 161.2, 147.6, 130.6, 117.5, 115.1, 114.5, 101.9, 74.5, 55.6, 31.6, 8.1; IR (liq. film): 2924, 1815, 1651, 1607, 1512, 1325, 1261, 1175, 1018, 939, 833 cm^{-1}; HRMS (ESI) Calcd for $C_{15}H_{14}N_2O_3Na$ ($[M+Na]^+$) 293.0897. Found 293.0890; $[\alpha]_D^{22}$ –51.6 (*c* = 1.7, $CHCl_3$) for 91% ee.



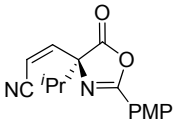
(*Z*)-**7h:** HPLC ADH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 9.4 min (major isomer), 10.9 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (2H, d, *J* = 8.9 Hz), 7.01 (2H, d, *J* = 8.9 Hz), 6.48 (1H, d, *J* = 11.7 Hz), 5.57 (1H, d, *J* = 11.7 Hz), 3.88 (3H, s), 2.11-1.93 (2H, m), 1.41-1.21 (4H, m), 0.88 (3H, t, *J* = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.7, 163.8, 161.1, 147.8, 130.6, 117.5, 115.1, 114.5, 101.7, 74.2, 55.7, 37.9, 25.8, 22.4, 13.9; IR (film): 2932, 1813, 1647, 1607, 1512, 1258, 1173, 1026, 962, 841 cm^{-1}; HRMS (ESI) Calcd for $C_{17}H_{18}N_2O_3Na$ ($[M+Na]^+$) 321.1210. Found 321.1206; $[\alpha]_D^{19}$ –21.1 (*c* = 1.0, $CHCl_3$) for 91% ee.



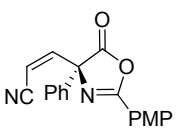
(*Z*)-**7i:** HPLC AD3, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 9.1 min (major isomer), 9.8 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (1H, d, *J* = 9.2 Hz), 7.01 (2H, d, *J* = 9.2 Hz), 6.47 (1H, d, *J* = 11.9 Hz), 5.56 (1H, d, *J* = 11.9 Hz), 3.88 (3H, s), 2.10-1.93 (2H, m), 1.40-1.19 (8H, m), 0.85 (3H, t, *J* = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.7, 163.8, 161.1, 147.8, 130.6, 117.5, 115.1, 114.5, 101.7, 74.2, 55.7, 38.2, 31.5, 28.9, 23.7, 22.6, 14.1; IR (film): 2922, 1813, 1647, 1607, 1512, 1323, 1260, 1173, 1020, 949, 843 cm^{-1}; HRMS (ESI) Calcd for $C_{19}H_{22}N_2O_3Na$ ($[M+Na]^+$) 349.1523. Found 349.1525; $[\alpha]_D^{21}$ –14.9 (*c* = 0.9, $CHCl_3$) for 93% ee.



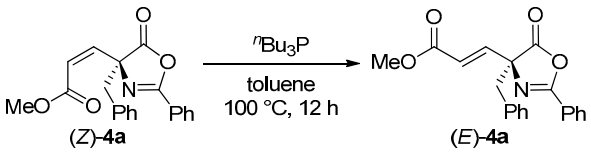
(*Z*)-**7j:** HPLC IA, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 15.1 min (major isomer), 17.7 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (2H, d, *J* = 9.2 Hz), 7.01 (2H, d, *J* = 9.2 Hz), 6.47 (1H, d, *J* = 11.4 Hz), 5.59 (1H, d, *J* = 11.4 Hz), 3.88 (3H, s), 2.57 (1H, dt, *J* = 13.6, 8.2 Hz), 2.53 (2H, dt, *J* = 13.6, 8.2 Hz), 2.35 (1H, dt, *J* = 13.6, 8.2 Hz), 2.31 (1H, dt, *J* = 13.6, 8.2 Hz), 2.08 (3H, s); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.3, 163.9, 161.8, 147.3, 130.7, 117.4, 114.9, 114.5, 102.0, 73.3, 55.7, 36.9, 28.5, 15.4; IR (film): 2922, 1811, 1645, 1609, 1510, 1323, 1263, 1173, 1016, 970, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{16}H_{16}N_2O_3SNa$ ($[M+Na]^+$) 339.0774. Found 339.0771; $[\alpha]_D^{21}$ –49.2 (*c* = 1.0, $CHCl_3$) for 90% ee.



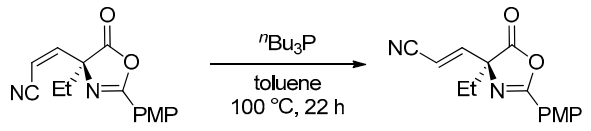
(*Z*)-**7k:** HPLC ADH, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 9.4 min (major isomer), 12.6 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 (2H, d, *J* = 9.1 Hz), 7.00 (2H, d, *J* = 9.1 Hz), 6.47 (1H, d, *J* = 11.7 Hz), 5.61 (1H, d, *J* = 11.7 Hz), 3.88 (3H, s), 2.36 (1H, sept, *J* = 6.9 Hz), 1.13 (3H, d, *J* = 6.9 Hz), 0.94 (3H, d, *J* = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.8, 163.8, 161.1, 147.8, 130.7, 117.6, 115.3, 114.5, 102.4, 77.9, 55.7, 36.8, 17.0, 16.7; IR (liq. film): 2934, 1813, 1647, 1607, 1512, 1321, 1261, 1016, 949, 839 cm^{-1}; HRMS (ESI) Calcd for $C_{16}H_{16}N_2O_3Na$ ($[M+Na]^+$) 307.1053. Found 307.1048; $[\alpha]_D^{20}$ –32.4 (*c* = 0.5, $CHCl_3$) for 96% ee.



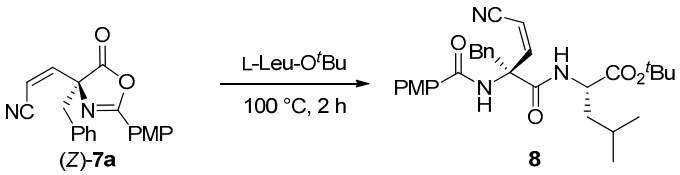
(*Z*)-**7l:** HPLC IC, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 254 nm, 15.0 min (major isomer), 17.1 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12 (2H, d, *J* = 9.2 Hz), 7.70 (2H, d, *J* = 7.6 Hz), 7.43 (2H, t, *J* = 7.6 Hz), 7.38 (1H, t, *J* = 7.6 Hz), 7.02 (2H, d, *J* = 9.2 Hz), 6.76 (1H, d, *J* = 11.4 Hz), 5.59 (1H, d, *J* = 11.4 Hz), 3.89 (3H, s); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.3, 164.0, 161.5, 148.3, 136.4, 130.8, 129.4, 129.3, 125.9, 117.5, 114.9, 114.6, 101.2, 74.9, 55.7; IR (film): 2940, 1813, 1647, 1607, 1512, 1323, 1260, 1169, 947, 843 cm^{-1}; HRMS (ESI) Calcd for $C_{19}H_{15}N_2O_3$ ($[M+H]^+$) 319.1077. Found 319.1087; $[\alpha]_D^{20}$ +31.2 (*c* = 0.7, $CHCl_3$) 90% ee.



Isomerization of (*Z*)-4a to (*E*)-4a: (*Z*)-**4a** (90% ee, 33.5 mg, 0.10 mmol) and tributylphosphine (246.7 mg, 1.0 mmol) were dissolved in toluene (2.0 mL) under Ar atmosphere. After being stirred for 12 h at 100 °C, water was added to the reaction mixture at room temperature. The aqueous phase was extracted with EA twice and the organic layers were washed with brine. The combined organic extracts were dried over Na_2SO_4 and filtered. All volatiles were removed by evaporation and the *E*/*Z* ratio of **4a** thus obtained was determined to be >20:1 by ^{1}H NMR (400 MHz) analysis of the crude residue. The residue was purified by column chromatography on silica gel (H/EA = 4:1 as eluent) to give (*E*)-**4a** in 77% yield (25.8 mg, 0.77 mmol), whose enantiomeric excess was determined to be 90% by chiral stationary phase HPLC analysis (see above for physical data of (*E*)-**4a**).



Isomerization of (*Z*)-7g to (*E*)-7g: A solution of (*Z*)-**7g** (91% ee, 20.3 mg, 0.067 mmol) and tributylphosphine (135.6 mg, 0.67 mmol) in toluene (1.4 mL) was stirred for 22 h at 100 °C under Ar atmosphere. After cooling to room temperature, water was added to the reaction mixture. The aqueous phase was extracted with EA twice and the organic layers were washed with brine. The combined organic extracts were dried over Na_2SO_4 and filtered. Concentration was performed under reduced pressure and the *E*/*Z* ratio of **7g** thus obtained was determined to be >20:1 by ^{1}H NMR (400 MHz) analysis of the crude residue. Purification of the residue by column chromatography on silica gel (H/EA = 4:1 as eluent) afforded (*E*)-**7g** in 71% yield (14.4 mg, 0.048 mmol) and its enantiomeric excess was determined to be 91% by chiral stationary phase HPLC analysis. (*E*)-**7g:** HPLC AD3, H/IPA = 10:1, flow rate = 1.0 mL/min, λ = 210 nm, 8.1 min (major isomer), 9.0 min (minor isomer); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (2H, d, J = 9.2 Hz), 7.00 (2H, d, J = 9.2 Hz), 6.81 (1H, d, J = 16.5 Hz), 5.81 (1H, d, J = 16.5 Hz), 3.90 (3H, s), 2.03 (1H, dq, J = 14.6, 7.3 Hz), 1.98 (1H, dq, J = 14.6. 7.3 Hz), 0.94 (3H, t, J = 7.3 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.2, 163.9, 161.4, 149.7, 130.3, 117.3, 116.4, 114.5, 102.5, 74.0, 55.7, 31.8, 8.2; IR (liq. film): 2922, 1813, 1649, 1605, 1510, 1321, 1258, 1165, 1024, 934, 845 cm^{-1}; HRMS (ESI) Calcd for $C_{16}H_{18}N_2O_4Na$ ([M+Na]$^+$) 325.1159. Found 325.1155; $[\alpha]_D^{20}$ +28.8 (c = 0.9, $CHCl_3$) for 91% ee.

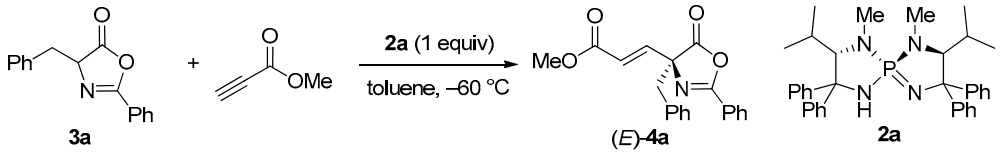


Procedure for Ligation from (*Z*)-7a to Dipeptide 8: A mixture of (*Z*)-**7a** (26.6 mg, 0.08 mmol) and L-Leu-O^{t}Bu (16.5 mg, 0.088 mmol) was stood at 100 °C for 2 h under Ar atmosphere. After cooling to room temperature, ^{1}H NMR (400 MHz) analysis of the crude residue showed complete conversion and also revealed the diastereomeric ratio of **8** to be >20:1. Subsequent purification by column chromatography on silica gel (H/EA = 1/1 as eluent) afforded pure **8** in 89% yield (37.0 mg, 0.71 mmol). **8:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (2H, d, J = 8.9 Hz), 7.40 (1H, d, J = 12.1 Hz), 7.36-7.28 (3H, m), 7.25-7.17 (3H, m), 6.92 (2H, d, J = 8.9 Hz), 6.29 (1H, d, J = 8.2 Hz), 5.51 (1H, d, J = 12.1 Hz), 4.49 (1H, td, J = 8.2, 5.9 Hz), 3.84 (3H, s), 3.49 (1H, d, J = 14.2 Hz), 3.44 (1H, d, J = 14.2 Hz), 1.67 (1H, nonet, J = 6.9 Hz), 1.56 (1H, ddd, J = 13.8, 8.2, 5.9 Hz), 1.51-1.42 (1H, m), 1.51-1.38 (1H, m) 1.44 (9H, s), 0.93 (3H, d, J = 6.9 Hz), 0.91 (3H, d, J = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 171.7, 169.2, 165.6, 162.9, 154.1, 133.5, 130.4, 129.3, 129.0, 128.2, 125.1, 115.5, 114.1, 98.6, 82.3, 63.6, 55.6, 52.0, 43.6, 42.1, 28.1, 24.8, 22.8, 22.2; IR (film): 3296, 2955, 1734, 1659, 1641, 1499, 1368, 1258, 1148, 1032, 849 cm^{-1}; HRMS (ESI) Calcd for $C_{30}H_{38}N_3O_5$ ([M+H]$^+$) 520.2806. Found 520.2812; $[\alpha]_D^{22}$ –23.9 (c = 0.6, $CHCl_3$).

Additional Experimental Data and Discussion:

Because both aminophosphonium ion **2a**·H and azlactone **3a** are possible proton donors to the intermediary allenic enolate in the asymmetric Michael reaction of **3a** to methyl propiolate catalyzed by **2a**, this reaction was conducted with stoichiometric amount of **2a** by following procedure 1 and 2, respectively (see below). These attempts led to the formation of product **4a** with comparable levels of *E*- and enantioselectivities to those of the catalytic reactions, thus confirming that

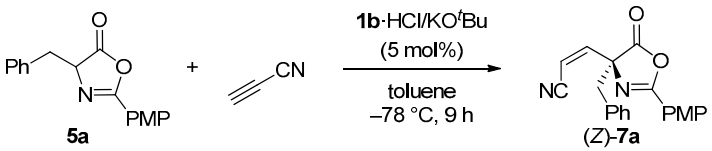
2a·H is an actual proton donor.



Procedures for Asymmetric Michael Addition of Azlactone 3a to Methyl Propiolate with Stoichiometric Amount of Chiral Iminophosphorane 2a:

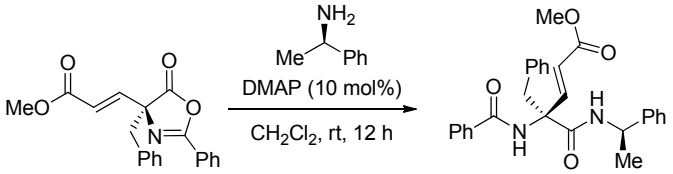
Procedure 1: To a solution of **2a** (29.0 mg, 0.055 mmol) in toluene (10.0 mL) was added methyl propiolate (4.60 mg, 0.055 mmol) at –60 °C. A solution of azlactone **3a** (12.6 mg, 0.050 mmol) in toluene (0.50 mL) was introduced slowly to the solution and the reaction mixture was then stirred for 12 h. The reaction was quenched by the addition of a solution of trifluoroacetic acid (0.5 M, 200 μL) and the whole mixture was poured into ice-cooled 1 *N* hydrochloric acid. The aqueous phase was extracted with EA twice and the organic layers were washed with brine. The combined organic extracts were dried over Na_2SO_4, filtered, and concentrated. The *E*/*Z* ratio of **4a** was determined to be 9:1 by ^{1}H NMR (400 MHz) analysis of the crude residue. The residue was purified by column chromatography on silica gel (H/EA = 5:1 as eluent) to give the adduct **4a** as a mixture of *E*/*Z* isomers in 97% yield (16.3 mg, 0.049 mmol). The enantiomeric excess of (*E*)-**4a** was determined to be 74% by HPLC analysis.

Procedure 2: To a solution of **2a** (29.0 mg, 0.055 mmol) in toluene (10.0 mL) was added methyl propiolate (4.60 mg, 0.055 mmol) at –60 °C. A solution of azlactone **3a** (12.6 mg, 0.050 mmol) in toluene (0.50 mL) was then introduced to the reaction mixture over a period of 12 h. Right after the addition completion, the reaction was quenched by the addition of a solution of trifluoroacetic acid (0.5 M, 200.0 μL) and the whole mixture was poured into ice-cooled 1 *N* hydrochloric acid. After the extractive workup was performed as described in **Procedure 1**, all volatiles were removed by evaporation and the *E*/*Z* ratio was determined to be 9:1 by ^{1}H NMR analysis of the crude aliquot. Purification of the residue was performed by silica gel column chromatography (H/EA = 5:1 as eluent) to afford the adduct **4a** as a mixture of *E*/*Z* isomers in 89% yield (14.9 mg, 0.044 mmol). The enantiomeric excess of (*E*)-**4a** was determined to be 73% by HPLC analysis.



Procedure for Chiral Phosphonium Salt 1b·HCl-Mediated Asymmetric Michael Addition of Azlactone 5a to Cyanoacetylene: A solution of **1b**·HCl (9.27 mg, 11.0 μmol) in toluene (1.5 mL) was treated with a 1.0 M THF solution of KO^{t}Bu (10.0 μL, 10.0 μmol) at –78 °C and the mixture was stirred for 30 min at –40 °C. After cooling again to –78 °C, a solution of azlactone **5a** (56.3 mg, 0.20 mmol) in toluene (0.40 mL) and a 1 M toluene solution of cyanoacetylene (0.22 mL, 0.22 mmol) were introduced dropwise sequentially, and stirring was continued for 9 h. A solution of trifluoroacetic acid (0.5 M, 80.0 μL) was added to the solution and the whole mixture was poured into ice-cooled 1 *N* hydrochloric acid. The aqueous phase was extracted with EA twice and the organic phases were washed with brine. The combined organic extracts were dried over Na_2SO_4, filtered, and concentrated. The *E*/*Z* ratio of **7a** was determined to be 1:>20 by ^{1}H NMR analysis of the crude aliquot. Purification of the residue by column chromatography on silica gel (H/EA = 2:1 as eluent) gave the adduct (*Z*)-**7a** in 85% yield (51.4 mg, 0.17 mmol), whose enantiomeric excess was determined to be 42% by HPLC analysis.

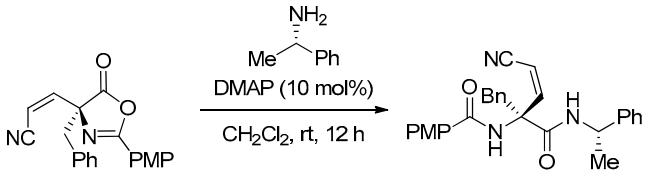
Crystallographic Structure Determination: The single crystal, which was obtained by the procedure exemplified below, was mounted on CryoLoop. Data of X-ray diffraction were collected at 153 K on a Bruker SMART APEX CCD diffractometer with graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). An absorption correction was made using SADABS. The structure was solved by direct methods and Fourier syntheses, and refined by full-matrix least squares on F^2 by using SHELXTL.[7] All non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms bonded to nitrogen atoms were located from a difference synthesis and their coordinates and isotropic thermal parameters refined. The other hydrogen atoms were placed in calculated positions and isotropic thermal parameters refined.



(*E*)-**4a** **9**

Procedure for Ring-opening Reaction of (*Z*)-4a to Amide 9: To a solution of (*Z*)-**4a** (67.1 mg, 0.20 mmol) in CH_2Cl_2 (0.67 mL) were added (*R*)-(+)-α-methylbenzylamine (26.7 mg, 0.22 mmol) and *N*,*N*-dimethylaminopyridine (2.4 mg, 0.020 mmol) at room temperature. After being stirred for 12 h, 1 *N* hydrochloric acid was introduced to the mixture. The aqueous phase was extracted with chloroform twice and the organic phases were washed with brine. The combined organic extracts were dried over Na_2SO_4 and filtered. After concentration, the residue was purified by column chromatography on silica gel (H/EA = 2:1 as eluent) and subsequent recrystallization (H/EtOH solvent system at room temperature) afforded stereochemically pure amide **9** in 22% yield (20.1 mg, 0.044 mmol). **9**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (2H, d, J = 7.5 Hz), 7.49 (1H, t, J = 7.5 Hz), 7.44-7.30 (8H, m), 7.29 (1H, d, J = 16.0 Hz), 7.16 (1H, t, J = 7.5 Hz), 7.06 (2H, t, J = 7.5 Hz), 6.84 (2H, d, J = 7.5 Hz), 6.44 (1H, brd, J = 6.9 Hz), 6.11 (1H, d, J = 16.0 Hz), 5.09 (1H, quin, J = 6.9 Hz), 3.78 (1H, d, J = 13.7 Hz), 3.75 (3H, s), 3.26 (1H, d, J = 13.7 Hz), 1.50 (3H, d, J = 6.9 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.5, 166.6, 166.4, 147.4, 142.3, 134.4, 134.2, 132.0, 130.2, 129.0, 128.8, 127.9, 128.5, 127.4, 127.1, 126.7, 122.1, 64.2, 52.1, 50.2, 40.9, 21.4; IR (film): 3352, 3319, 2984, 1720, 1699, 1654, 1636, 1504, 1476, 1290, 1123, 984 cm^{-1}; HRMS (ESI) Calcd for $C_{28}H_{29}N_2O_4$ ($[M+H]^+$) 457.2122. Found 457.2123.

Recrystallization of 9: Single crystals of **9** for X-ray diffraction analysis were obtained as mentioned in the above procedure. The crystallographic data were summarized in Table S1 and ORTEP diagram was shown in Fig. S1.



(*Z*)-**7a** **10**

10: **10** was prepared in 91% yield (28.5 mg, 0.063 mmol) from (*Z*)-**7a** (23.0 mg, 0.069 mmol) and (*S*)-(−)-α-methylbenzylamine by following the above procedure. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (2H, d, J = 9.2 Hz), 7.36 (1H, d, J = 11.9 Hz), 7.34-7.18 (9H, m), 7.10 (2H, d, J = 6.9 Hz), 6.92 (2H, d, J = 9.1 Hz), 6.05 (1H, d, J = 7.2 Hz), 5.48 (1H, d, J = 11.9 Hz), 5.11 (1H, quin, J = 7.2 Hz), 3.84 (3H, s), 3.49 (1H, d, J = 13.9 Hz), 3.39 (1H, d, J = 13.9 Hz), 1.45 (3H, d, J = 7.2 Hz); ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.6, 165.7, 163.0, 154.8, 142.3, 133.6, 130.4, 129.3, 129.0, 128.8, 128.1, 127.7, 126.5, 125.0, 115.5, 114.2, 98.6, 63.6, 55.6, 49.9, 43.6, 21.4; IR (film): 3279, 2938, 1659, 1632, 1605, 1531, 1504, 1258, 1175, 1022, 849 cm^{-1}; HRMS (ESI) Calcd for $C_{28}H_{27}N_3O_3Na$ ($[M+Na]^+$) 476.1945. Found 476.1944.

Recrystallization of 10: Recrystallization from a solution of **10** in H/EtOH solvent system at room temperature afforded single crystals of **10** suitable for X-ray diffraction analysis. The crystallographic data were summarized in Table S2 and ORTEP diagram was shown in Fig. S2.

[7] G. M. Sheldrick, *Acta Cryst.* **2008**, *A64*, 112.

Table S1a. Crystal data and structure refinement for **9** (CCDC 911536).

Empirical formula	C28 H28 N2 O4	
Formula weight	456.52	
Temperature	153(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	P2(1)2(1)2(1)	
Unit cell dimensions	a = 11.118(3) Å	α = 90°.
	b = 16.129(5) Å	β = 90°.
	c = 26.837(8) Å	γ = 90°.
Volume	4813(3) $Å^3$	
Z	8	
Density (calculated)	1.260 Mg/m^3	
Absorption coefficient	0.085 mm^{-1}	
F(000)	1936	
Crystal size	0.50 x 0.30 x 0.20 mm^3	
Theta range for data collection	1.47 to 28.49°.	
Index ranges	–14<=h<=14, –21<=k<=15, –35<=l<=35	
Reflections collected	36807	
Independent reflections	12079 [R(int) = 0.0825]	
Completeness to theta = 28.49°	99.4 %	
Absorption correction	Empirical	
Max. and min. transmission	0.9833 and 0.9589	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	12079 / 0 / 633	
Goodness-of-fit on F^2	1.085	
Final R indices [I>2sigma(I)]	R_1 = 0.0911, wR_2 = 0.1854	
R indices (all data)	R_1 = 0.1417, wR_2 = 0.2129	
Absolute structure parameter	2.1(15)	
Largest diff. peak and hole	0.510 and –0.282 e.$Å^{-3}$	

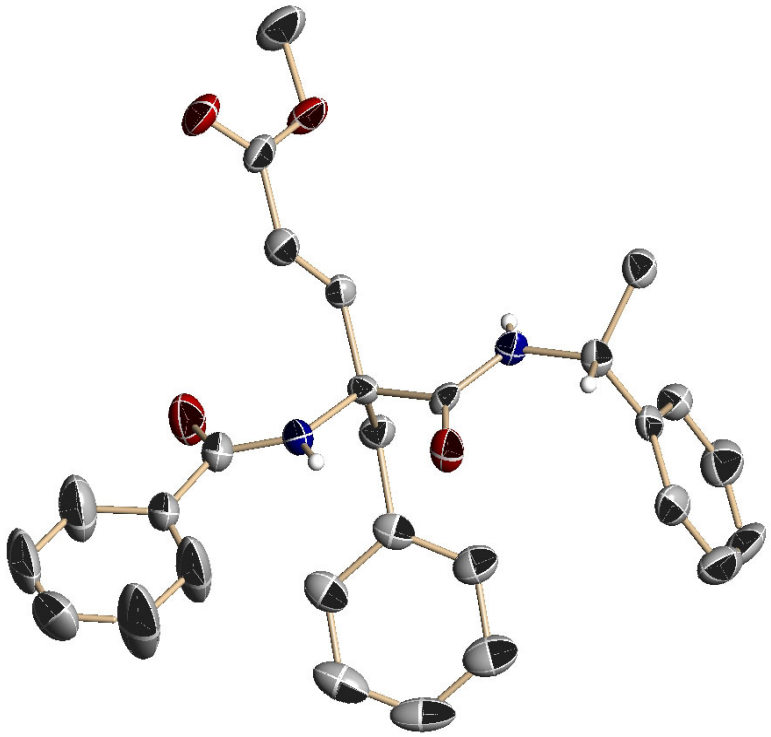


Fig. S1. ORTEP diagram of **9**. All calculated hydrogen atoms are omitted for clarity except for a hydrogen atom attached to the stereogenic carbon. Blue = nitrogen, red = oxygen, gray = carbon.

Table S2a. Crystal data and structure refinement for **10** (CCDC 911535).

Empirical formula	C28 H27 N3 O3	
Formula weight	453.53	
Temperature	153(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1	
Unit cell dimensions	a = 9.552(5) Å	α = 71.185(11)°.
	b = 10.569(6) Å	β = 76.497(11)°.
	c = 13.458(7) Å	γ = 77.422(11)°.
Volume	1235.5(12) $Å^3$	
Z	2	
Density (calculated)	1.219 Mg/m^3	
Absorption coefficient	0.080 mm^{-1}	
F(000)	480	
Crystal size	0.30 x 0.20 x 0.20 mm^3	
Theta range for data collection	1.62 to 28.46°.	
Index ranges	–11<=h<=12, –14<=k<=12, –17<=l<=17	
Reflections collected	8160	
Independent reflections	7116 [R(int) = 0.0360]	
Completeness to theta = 28.46°	95.5 %	
Absorption correction	Empirical	
Max. and min. transmission	0.9841 and 0.9764	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	7116 / 3 / 633	
Goodness-of-fit on F^2	0.999	
Final R indices [I>2sigma(I)]	R_1 = 0.0524, wR_2 = 0.1175	
R indices (all data)	R_1 = 0.1279, wR_2 = 0.1617	
Absolute structure parameter	1.0(16)	
Largest diff. peak and hole	0.287 and –0.294 e.$Å^{-3}$	

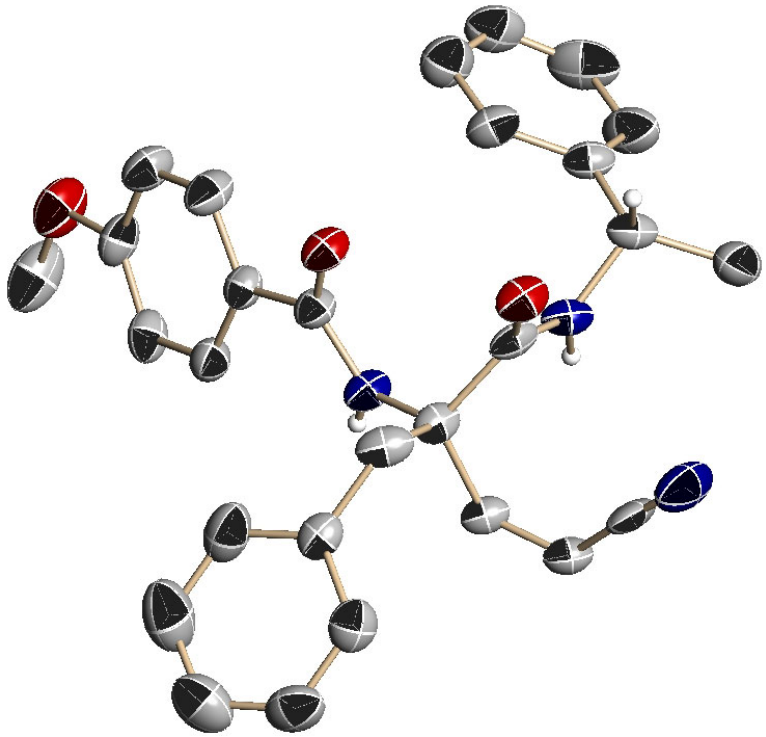
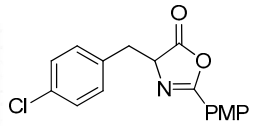
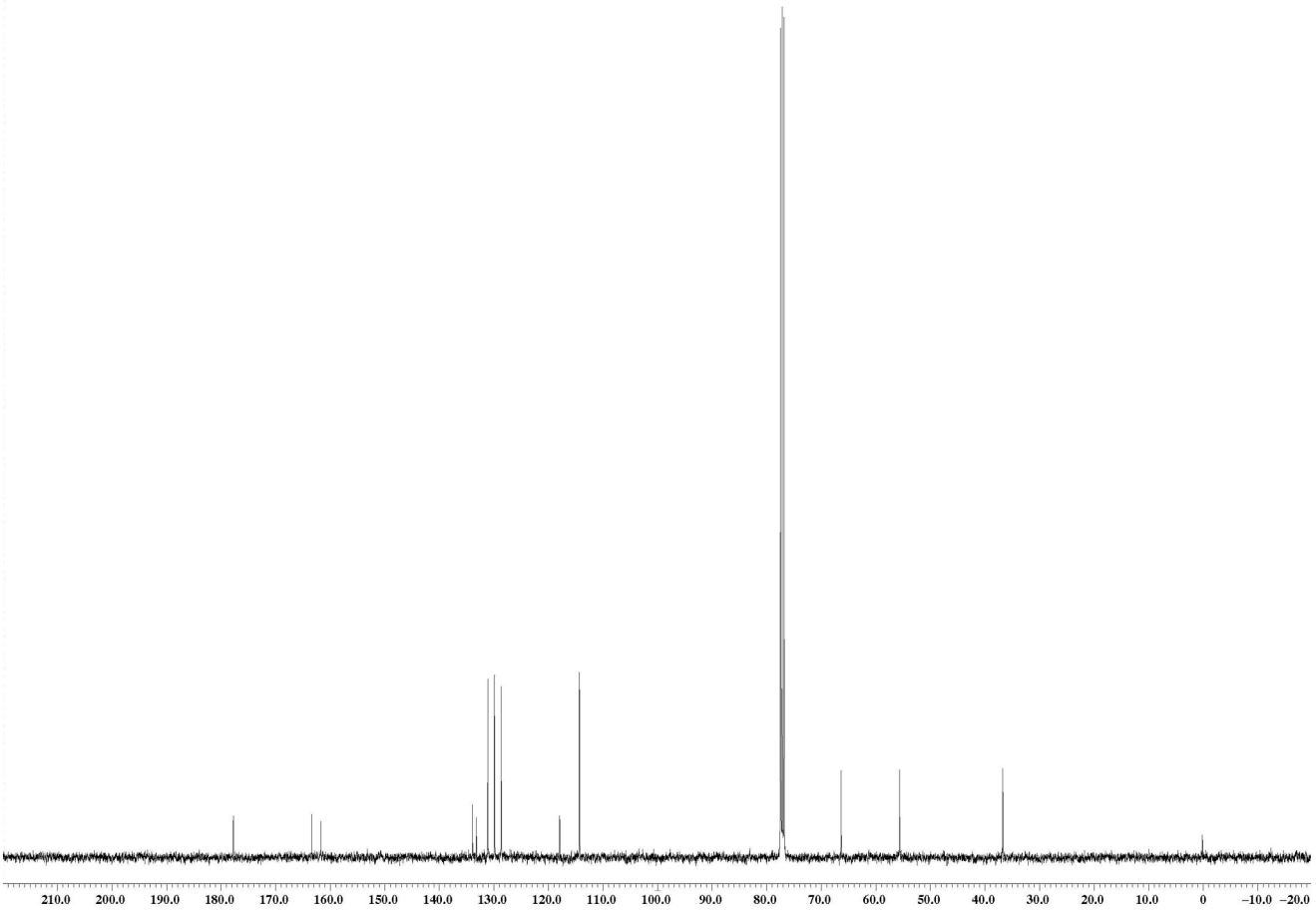


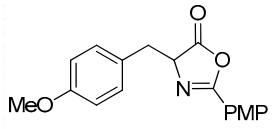
Fig. S2. ORTEP diagram of **10**. All calculated hydrogen atoms are omitted for clarity except for a hydrogen atom attached to the stereogenic carbon. Blue = nitrogen, red = oxygen, gray = carbon.

Copies of ^{1}H and ^{13}C NMR Spectra:



5b

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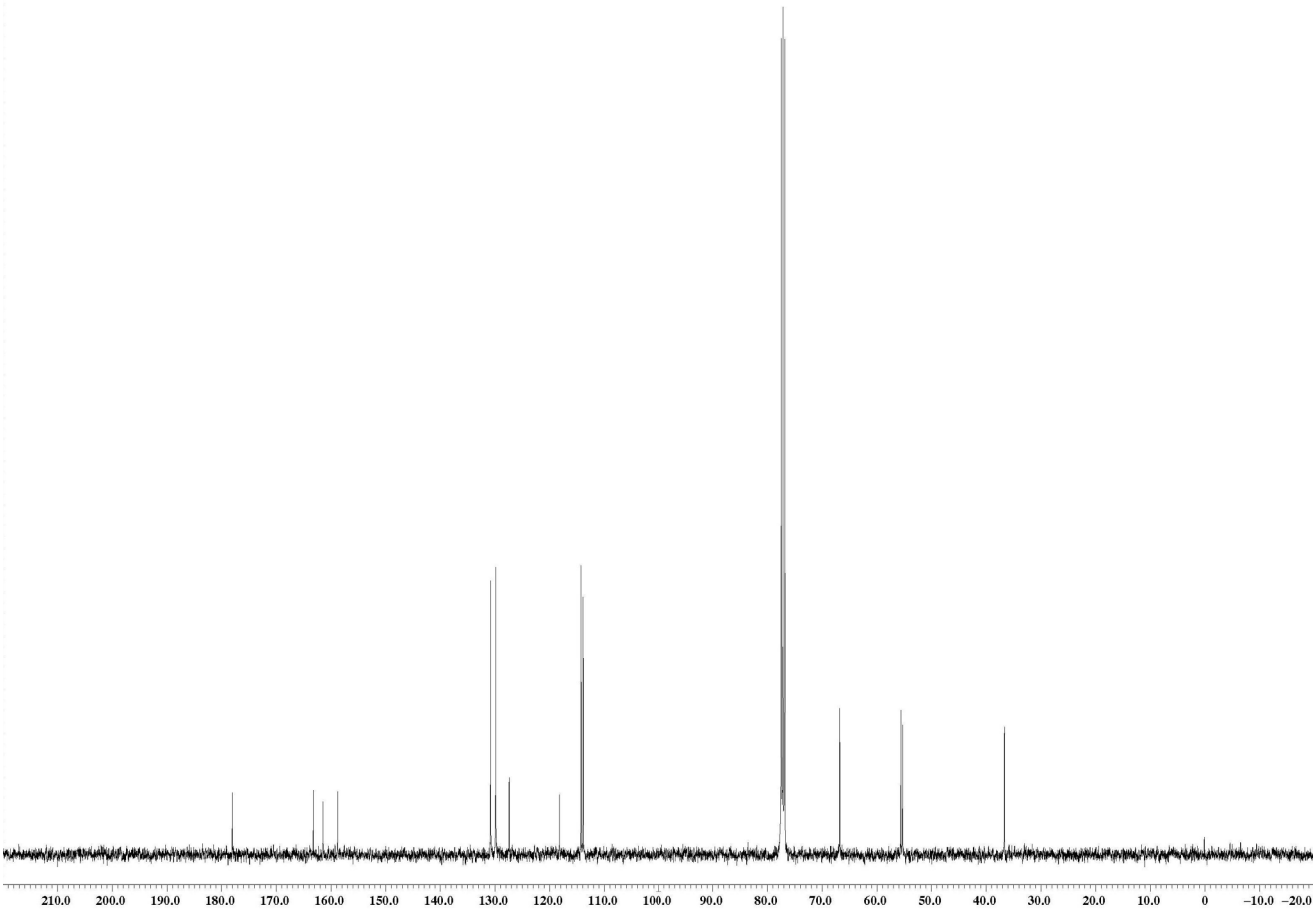
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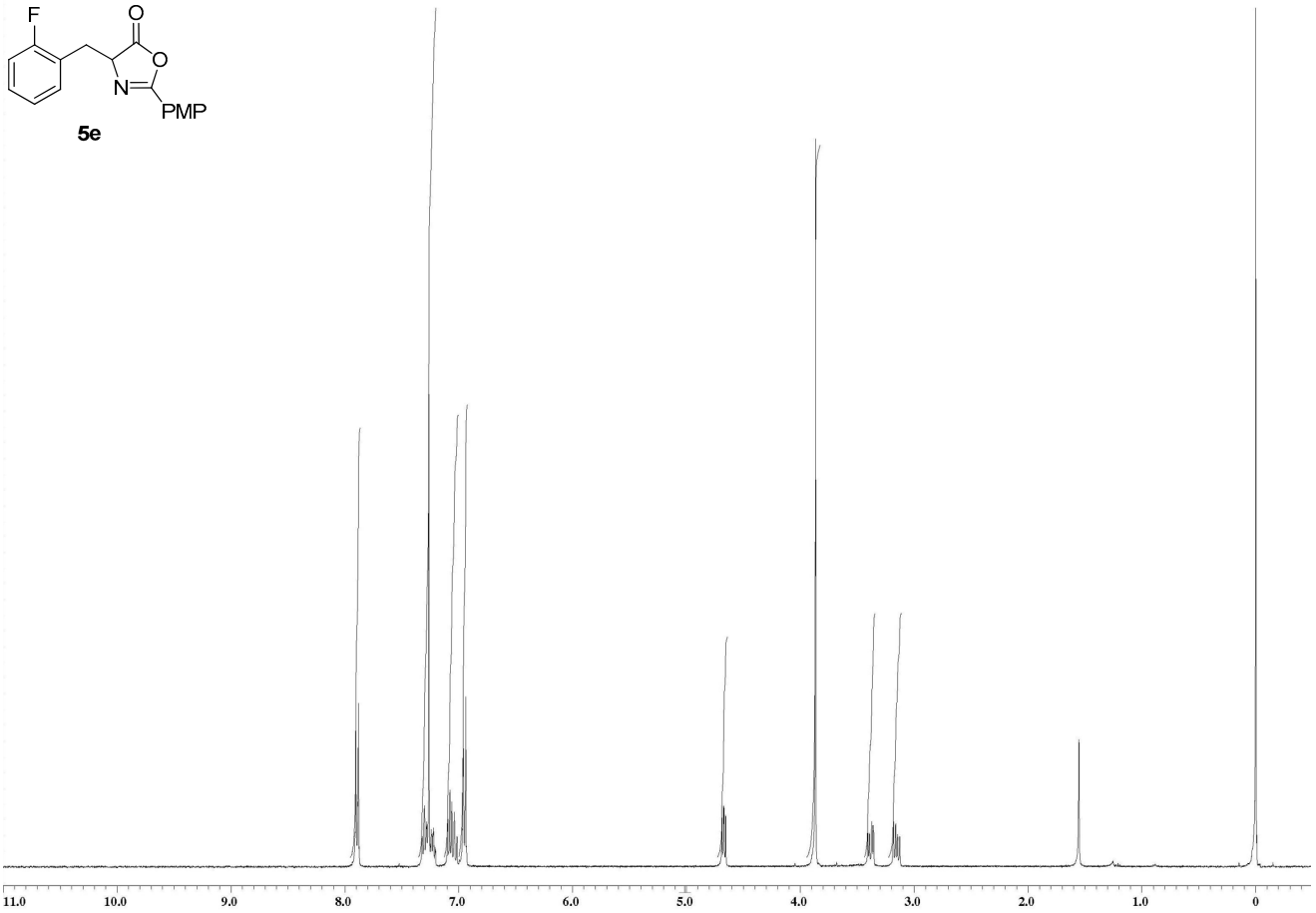
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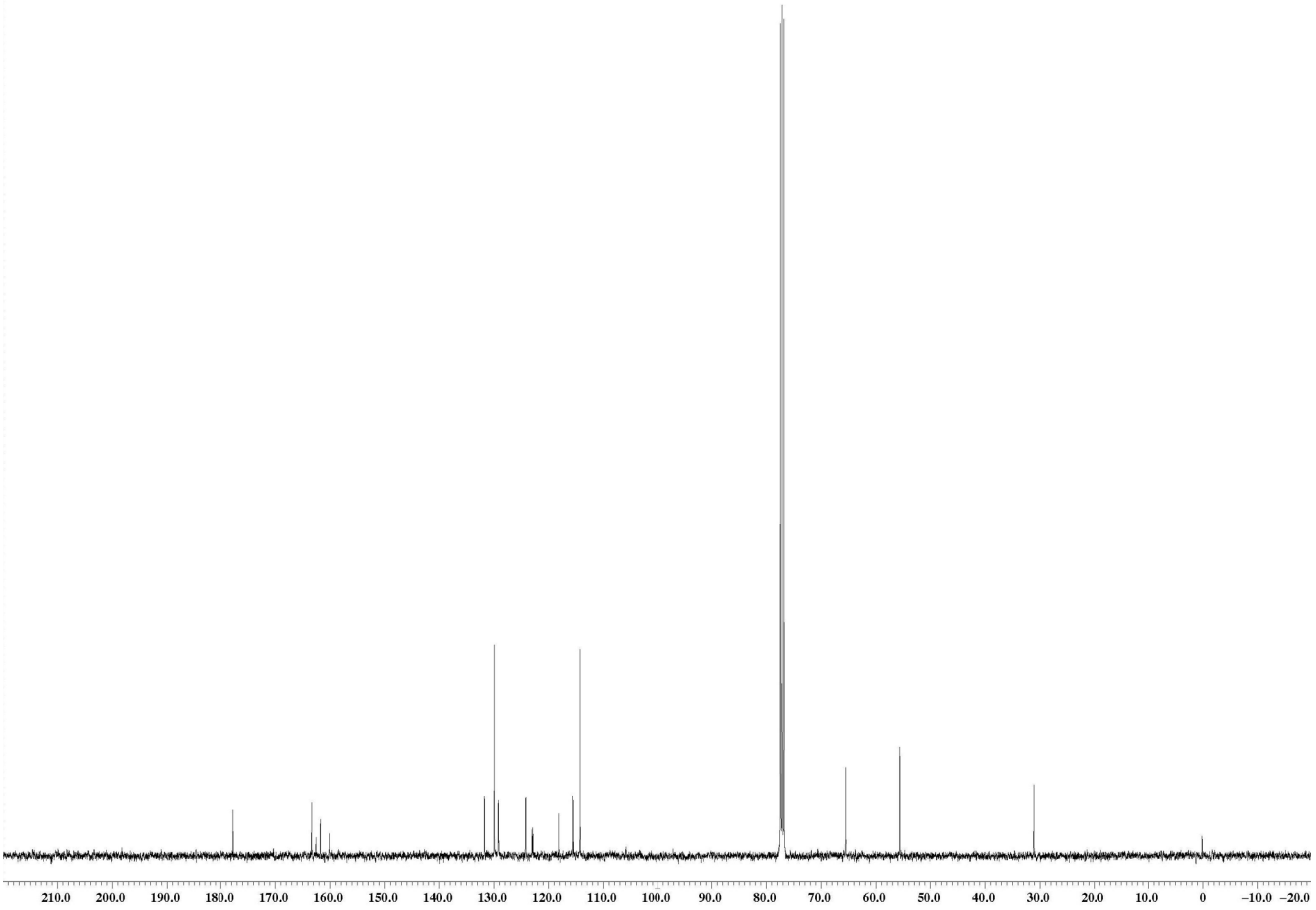
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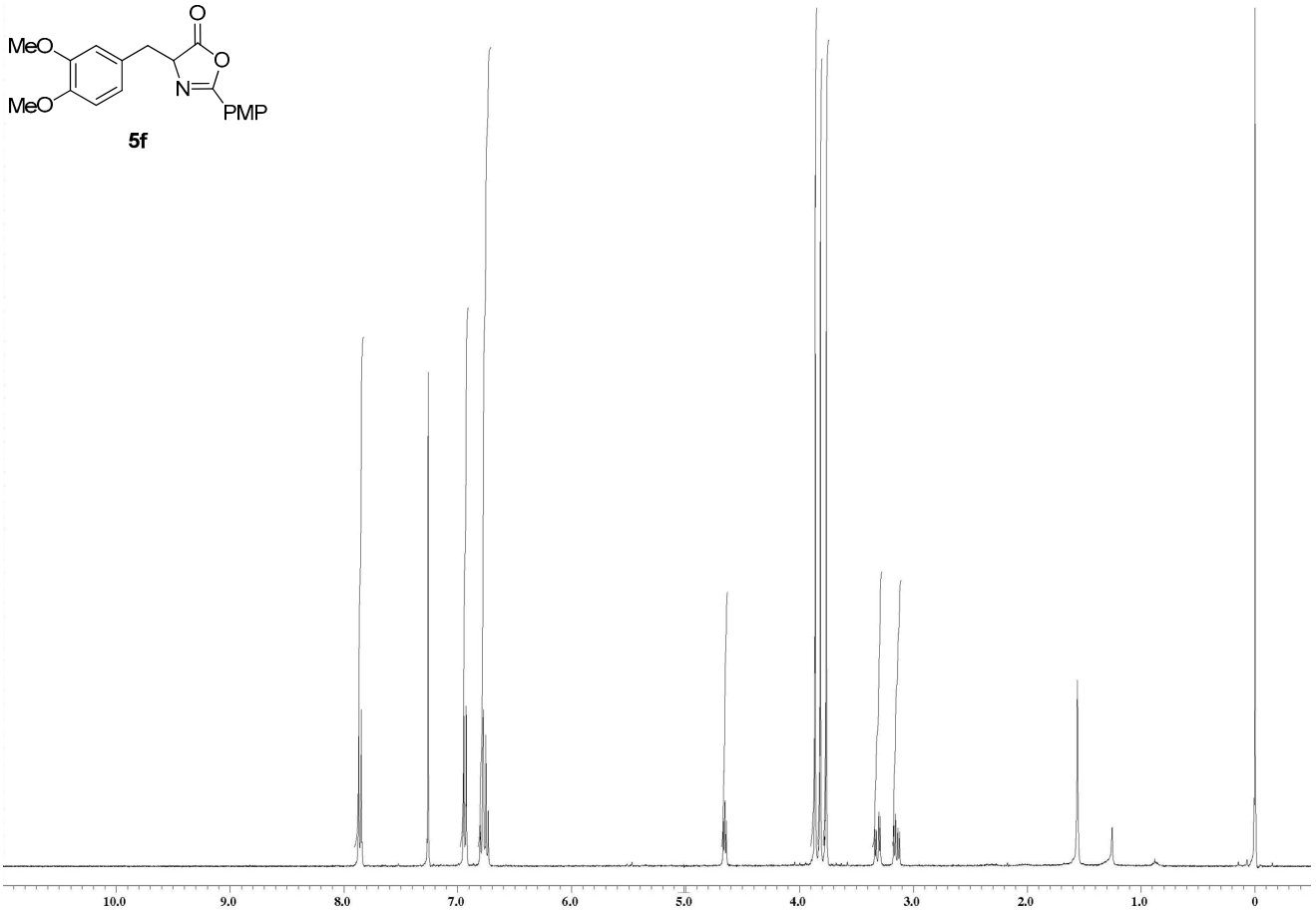

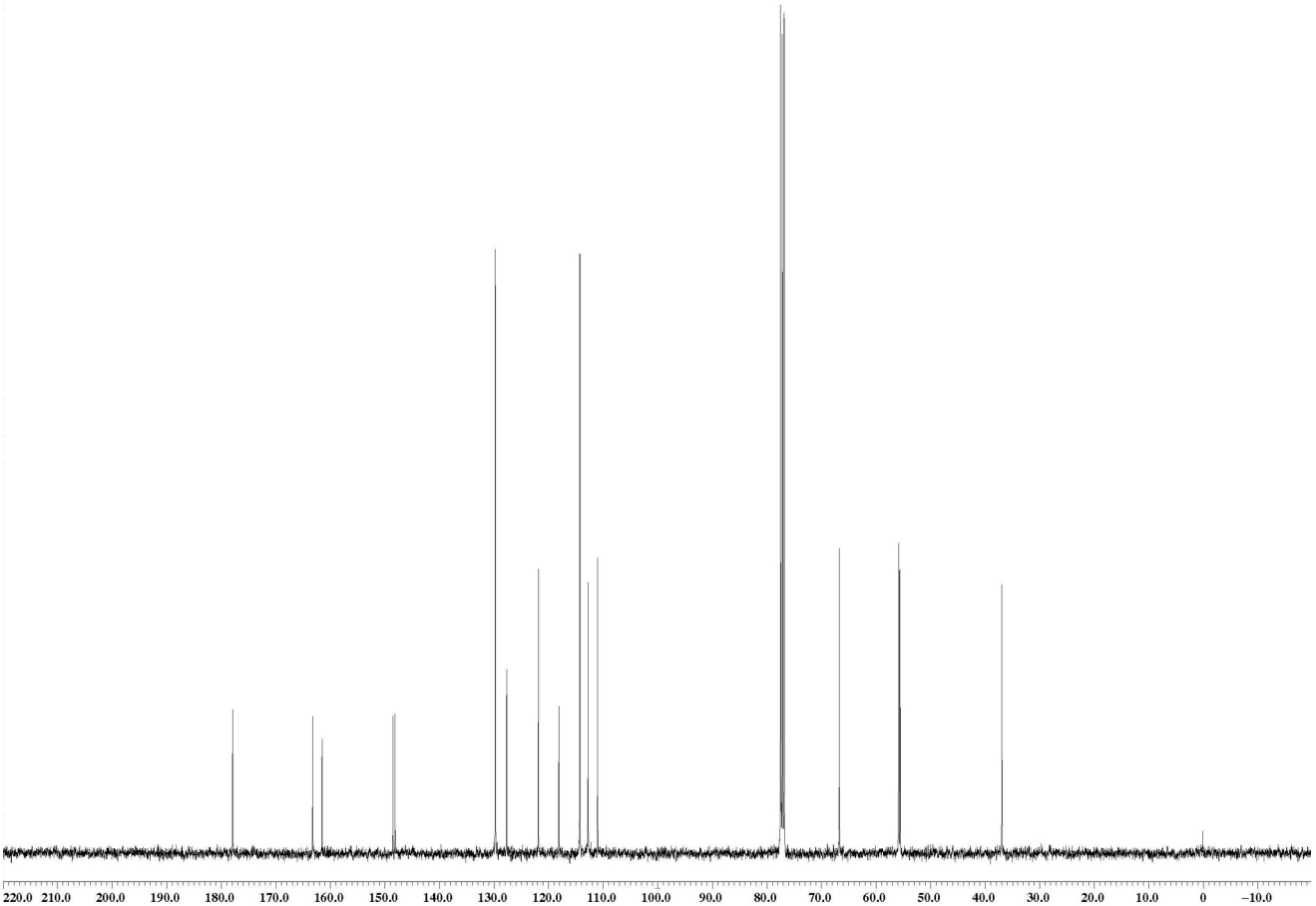

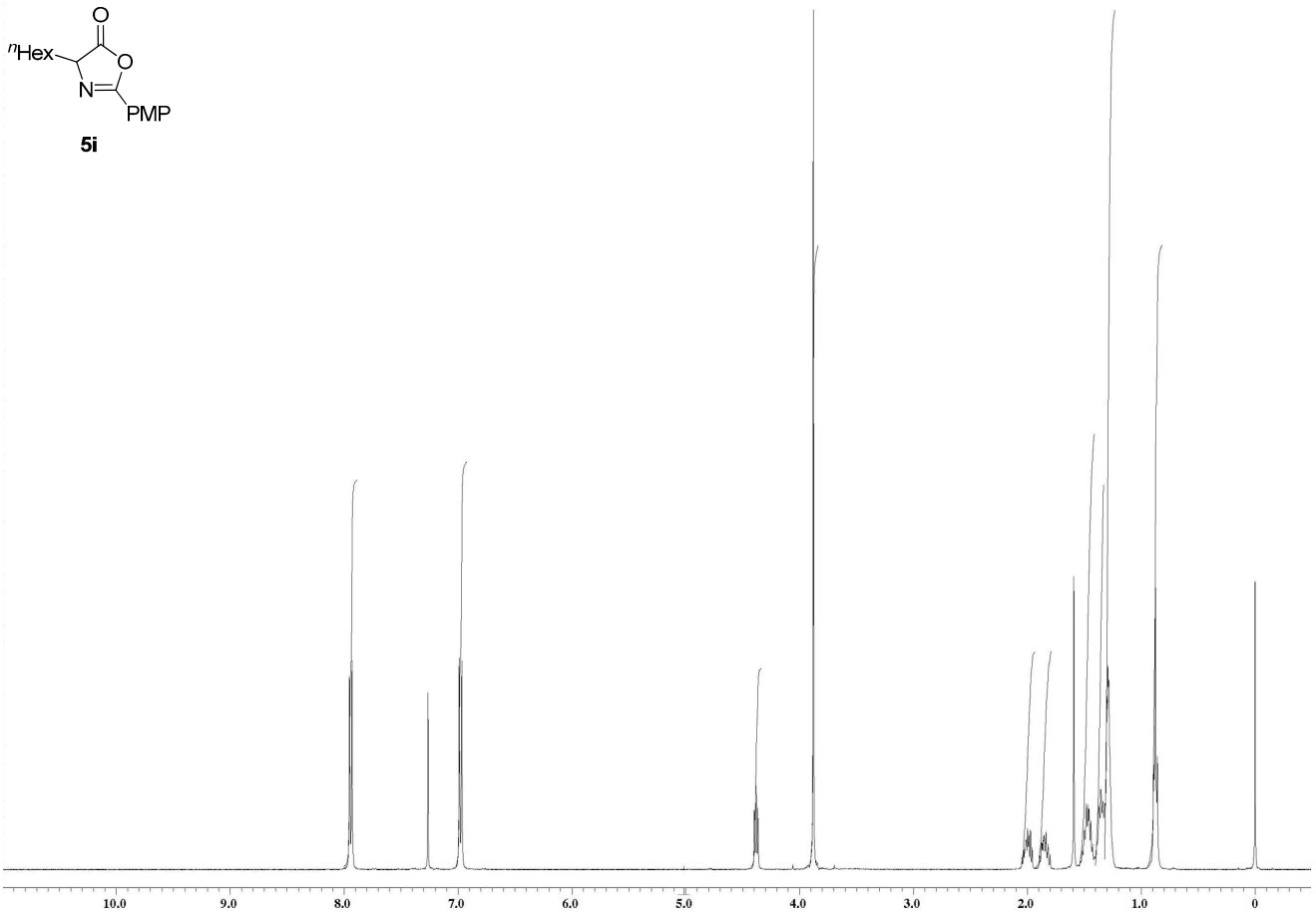
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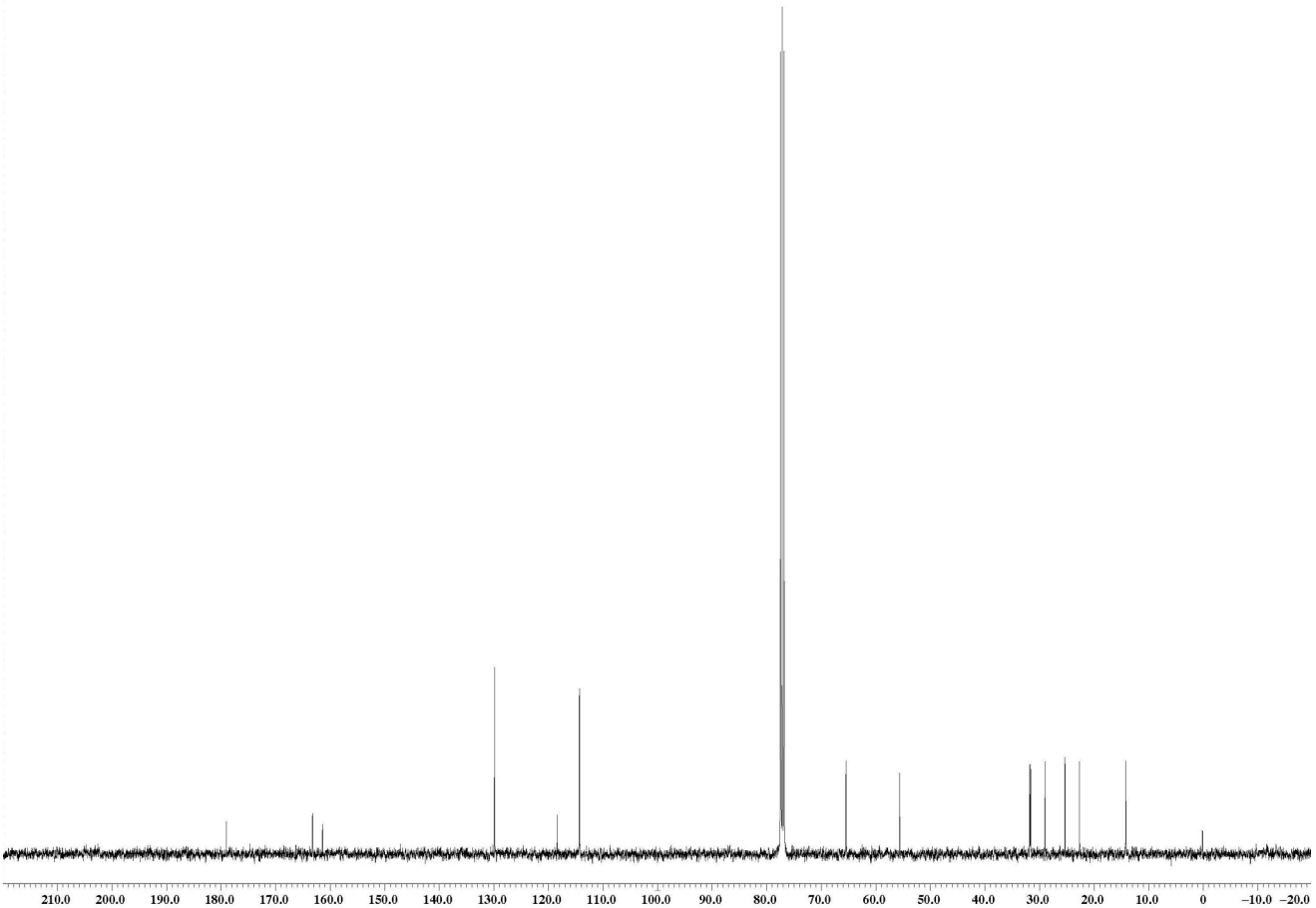
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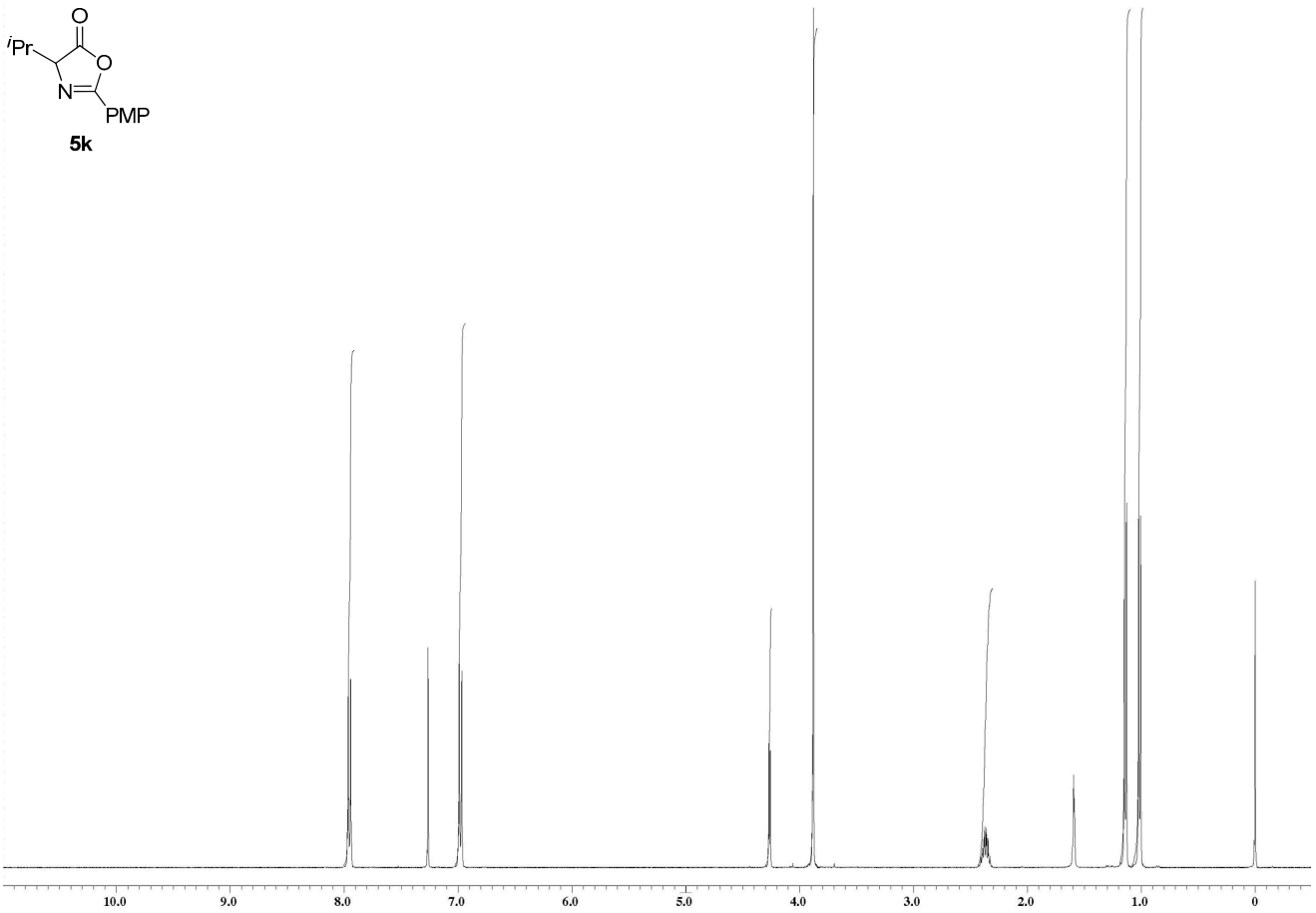
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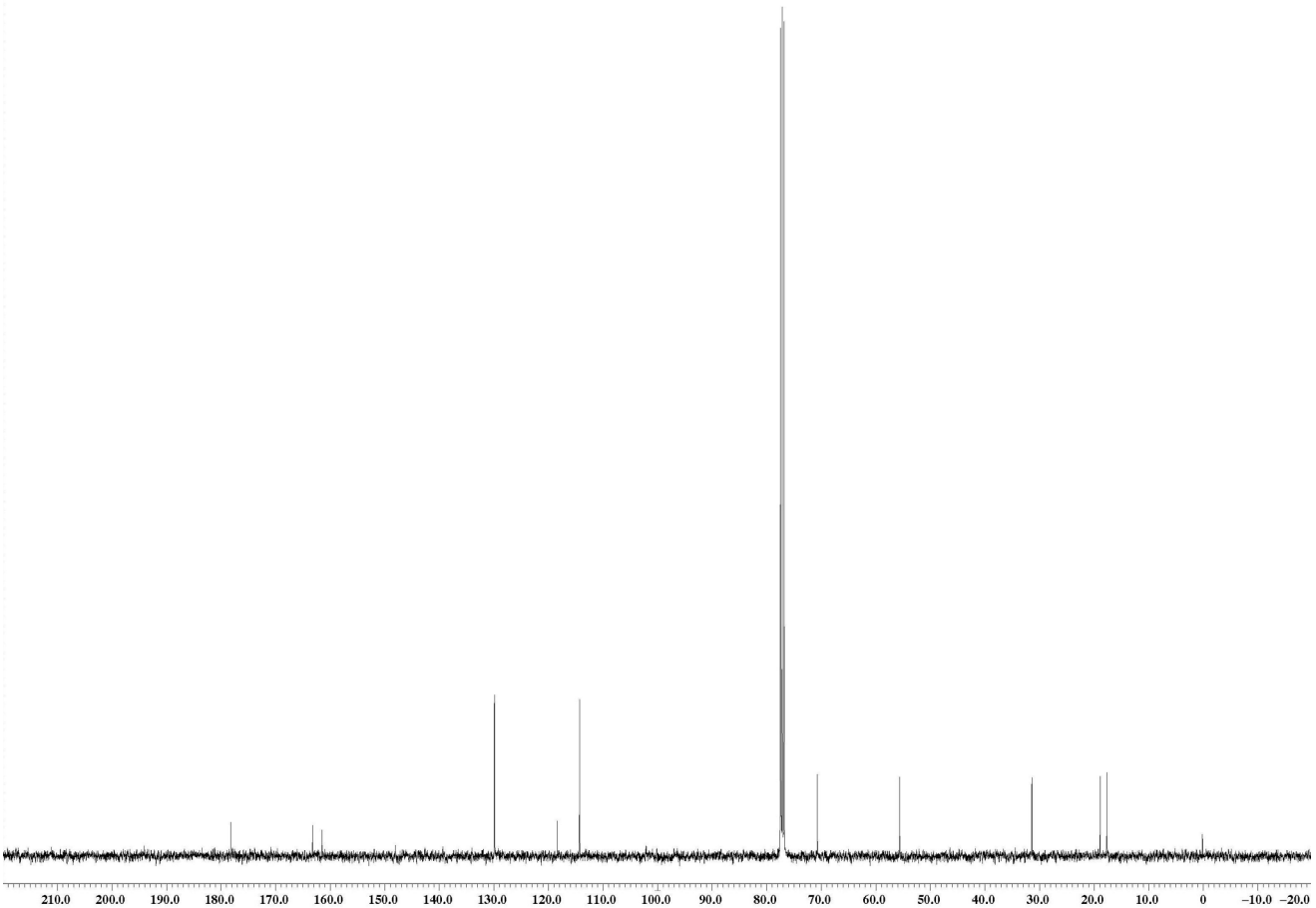
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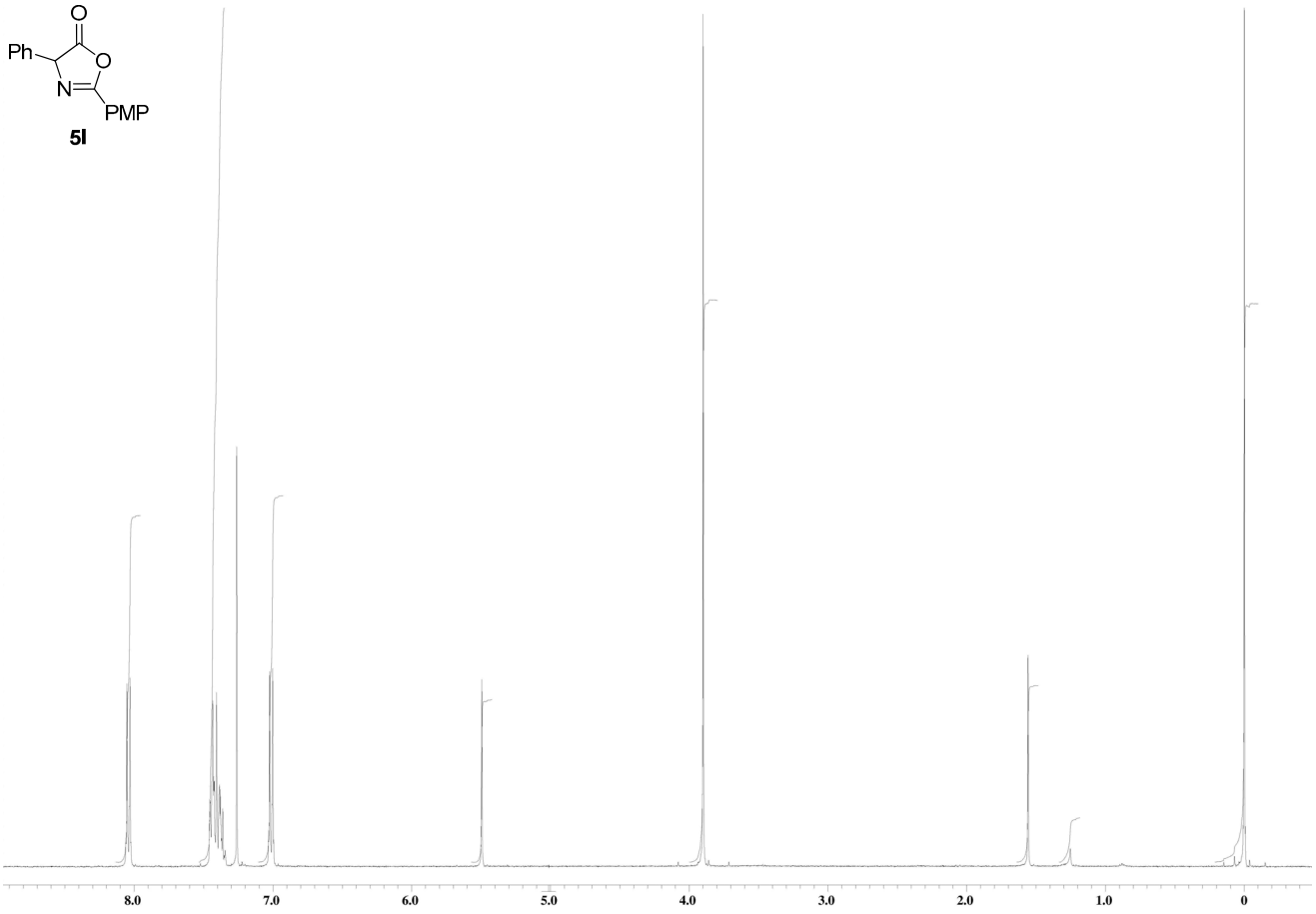

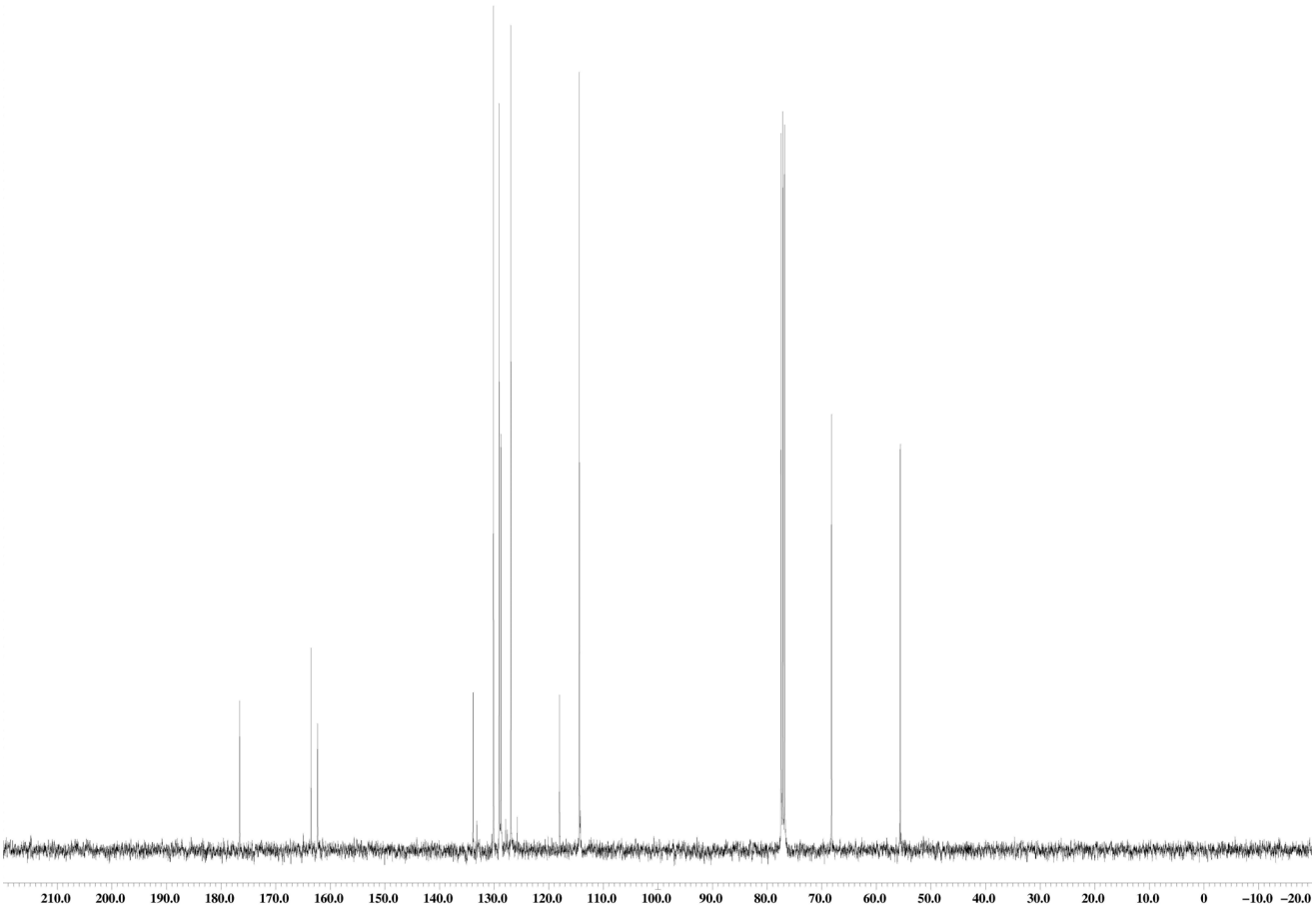

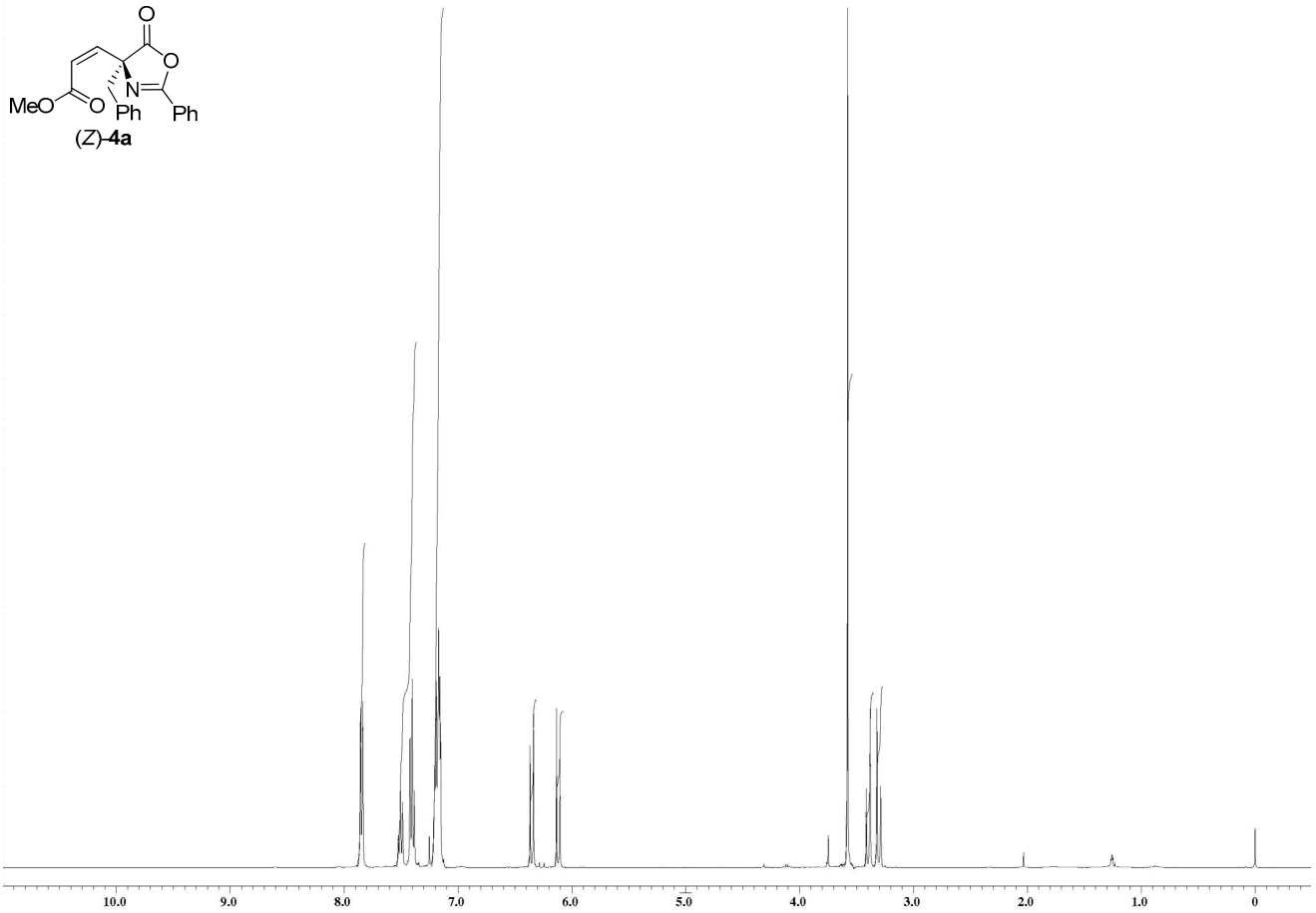
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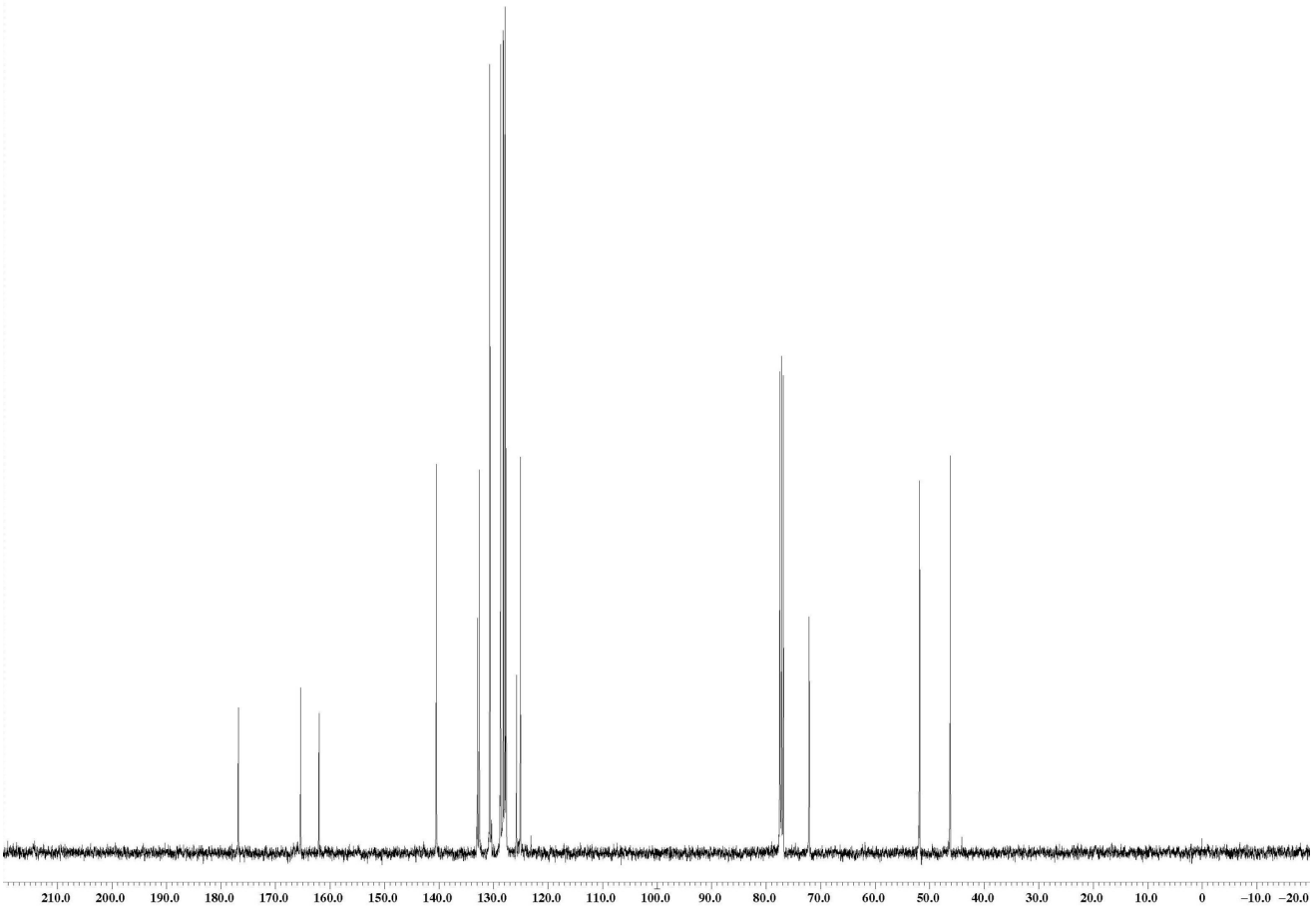
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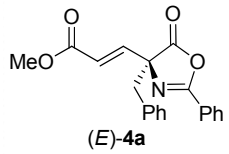
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(*E*)-**4a**

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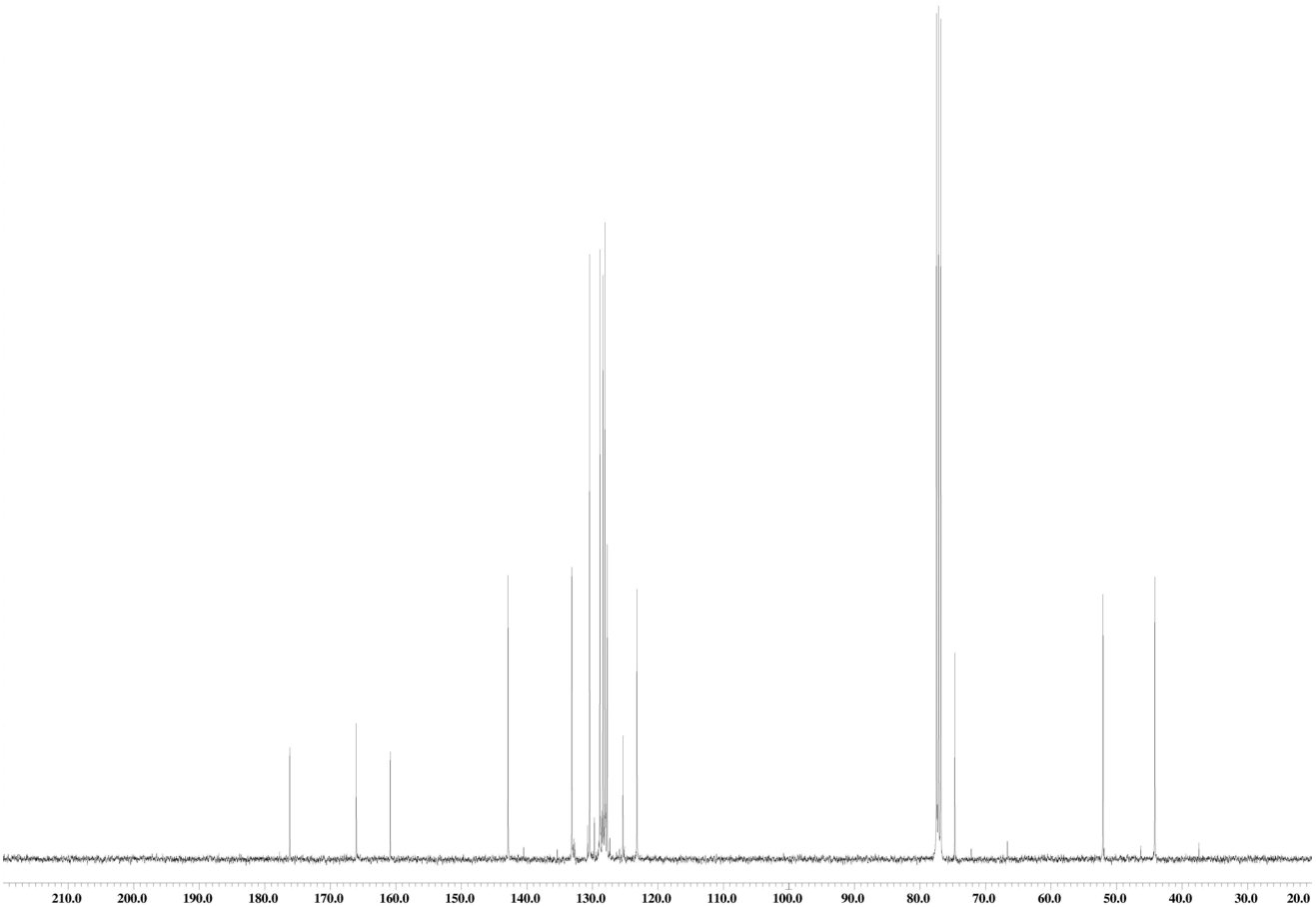
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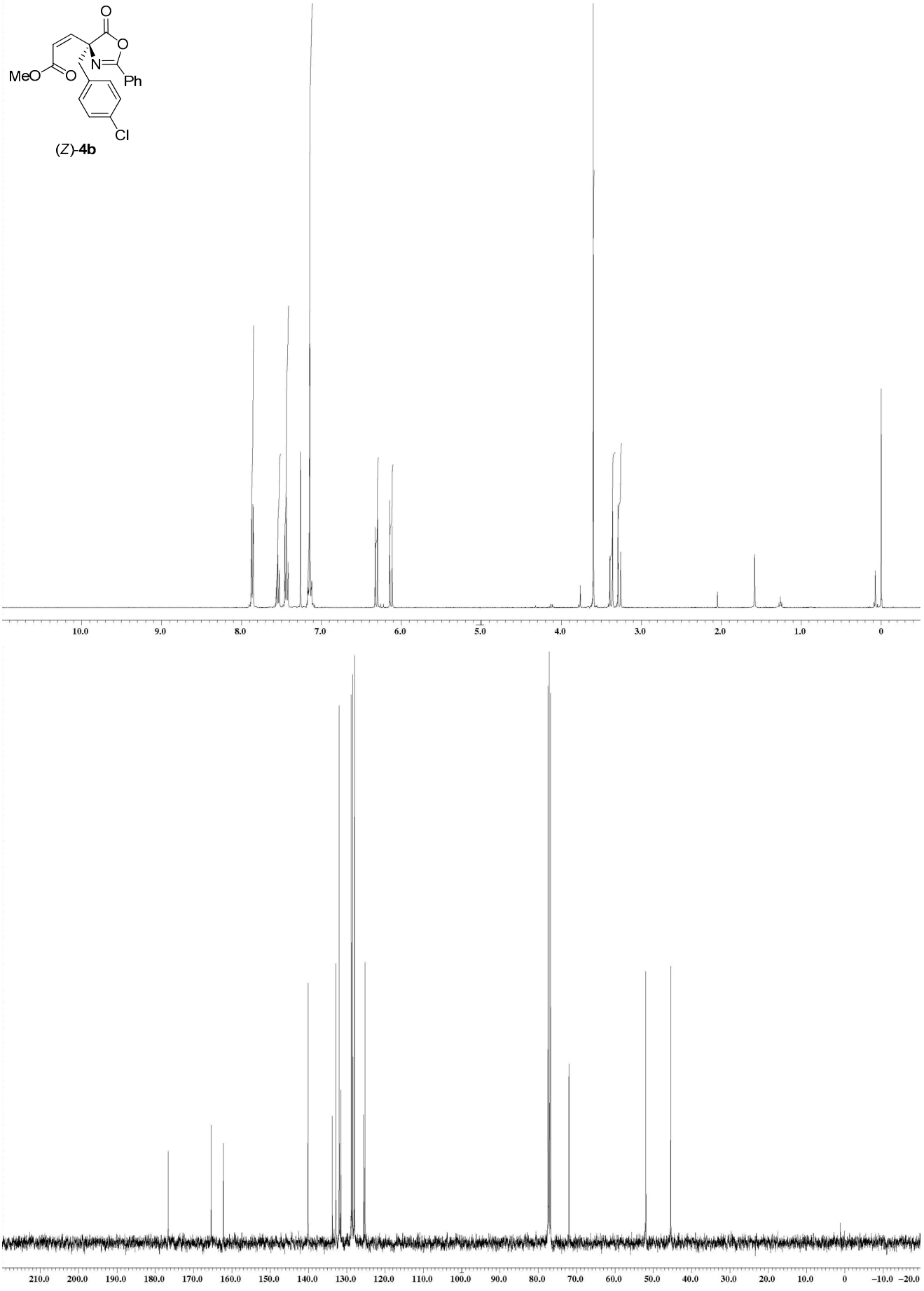
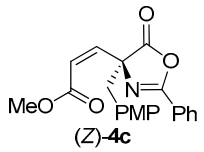
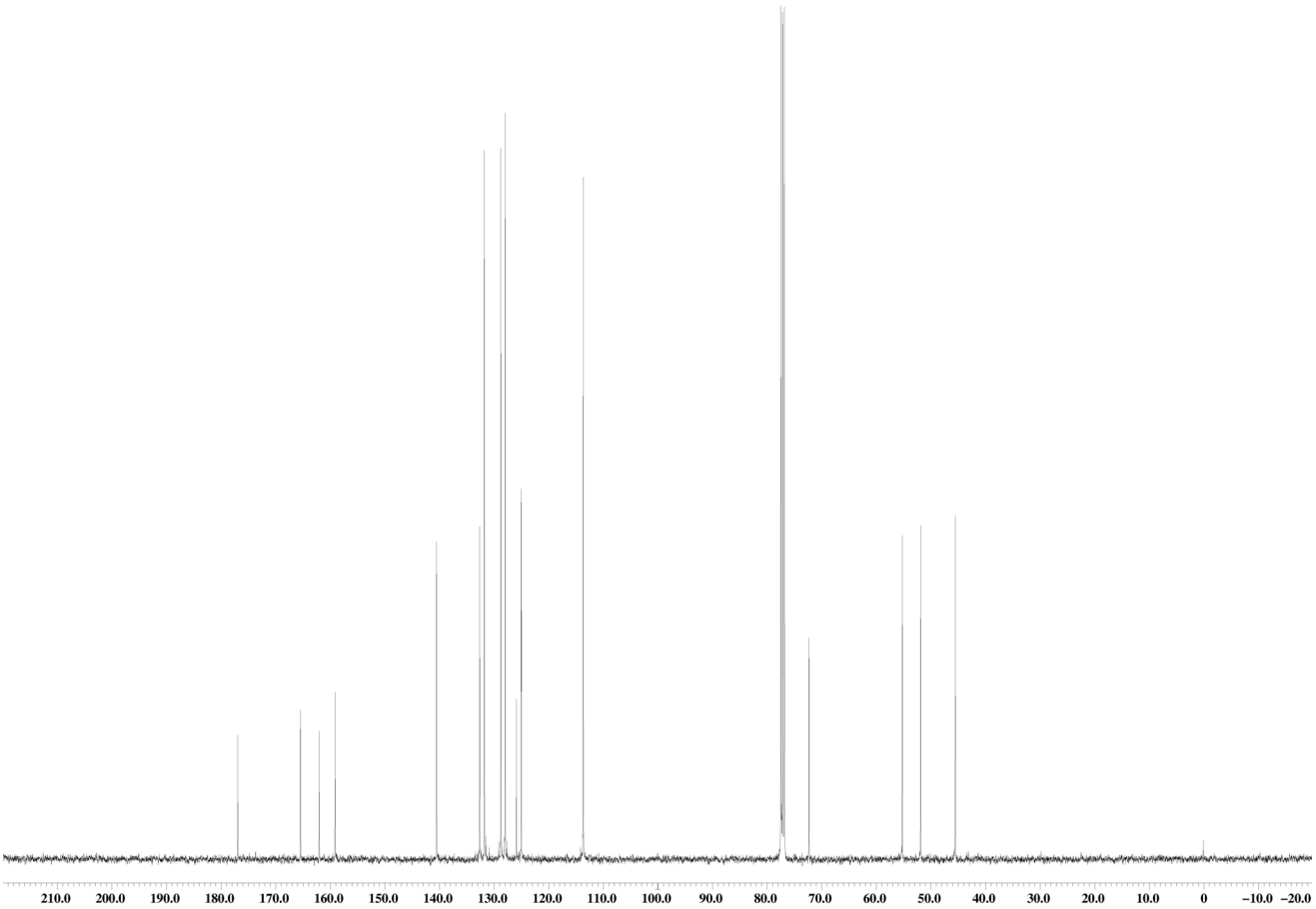
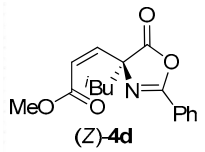


(*Z*)-**4b**



(*Z*)-**4c**

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(*Z*)-**4d**

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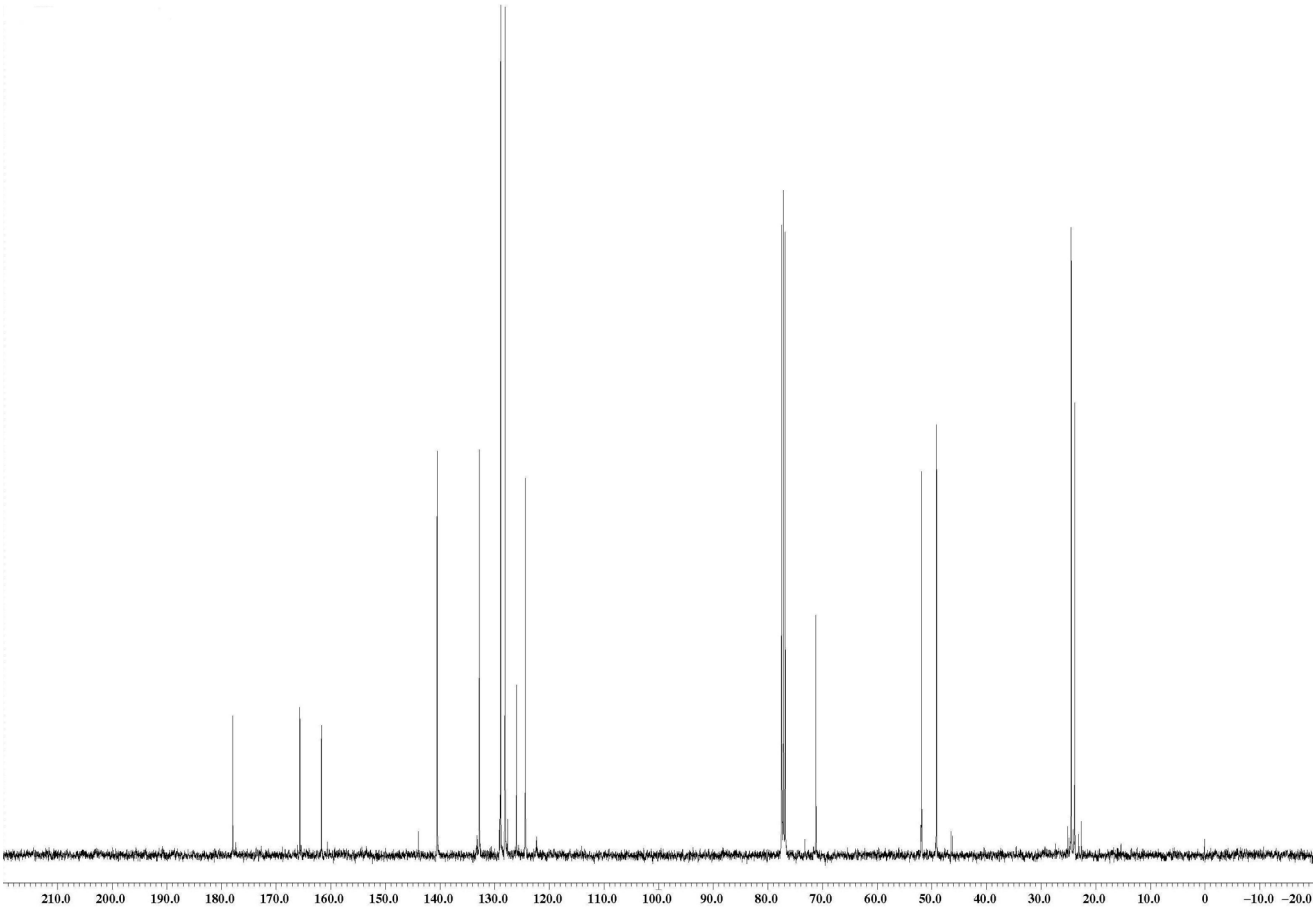
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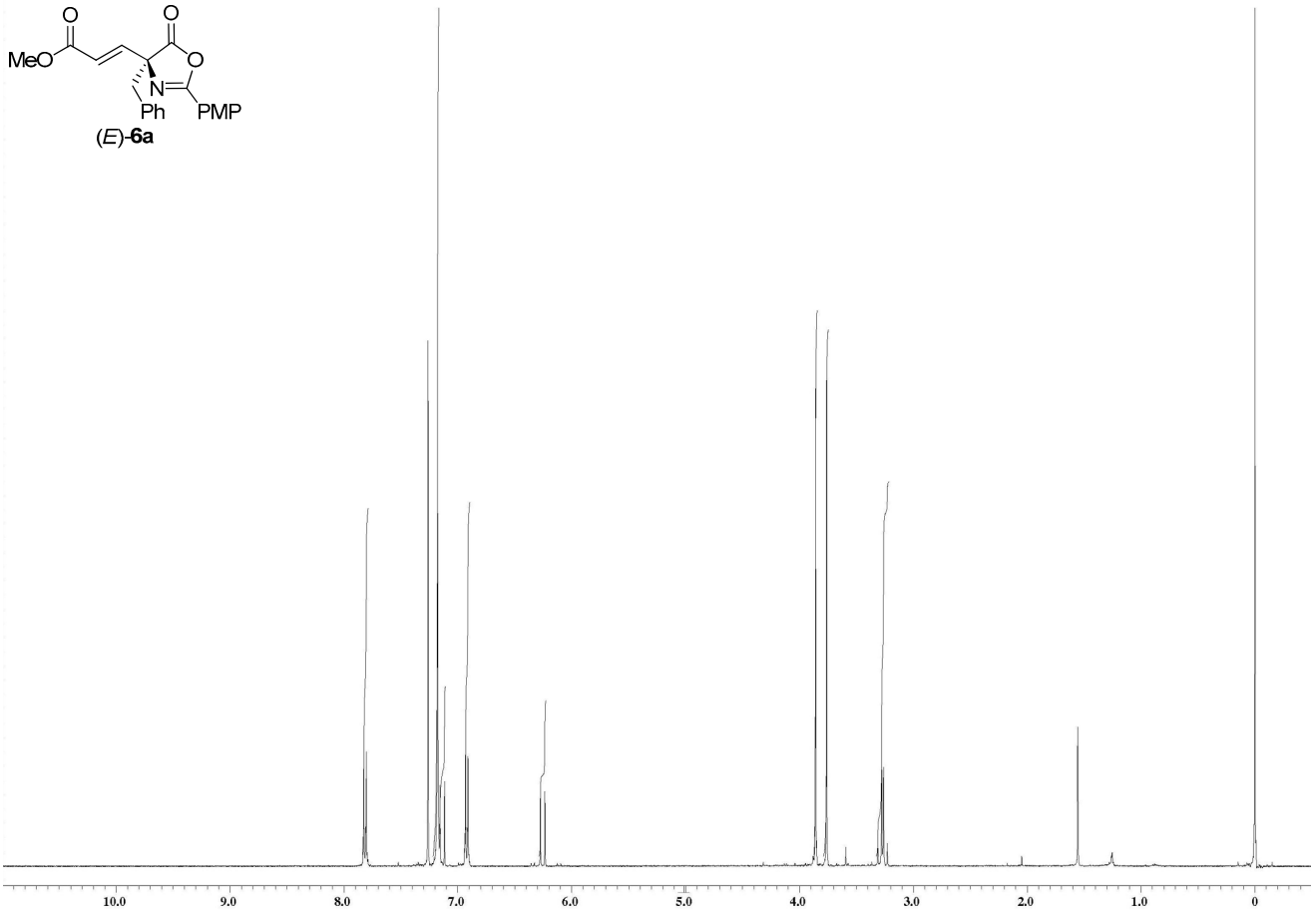

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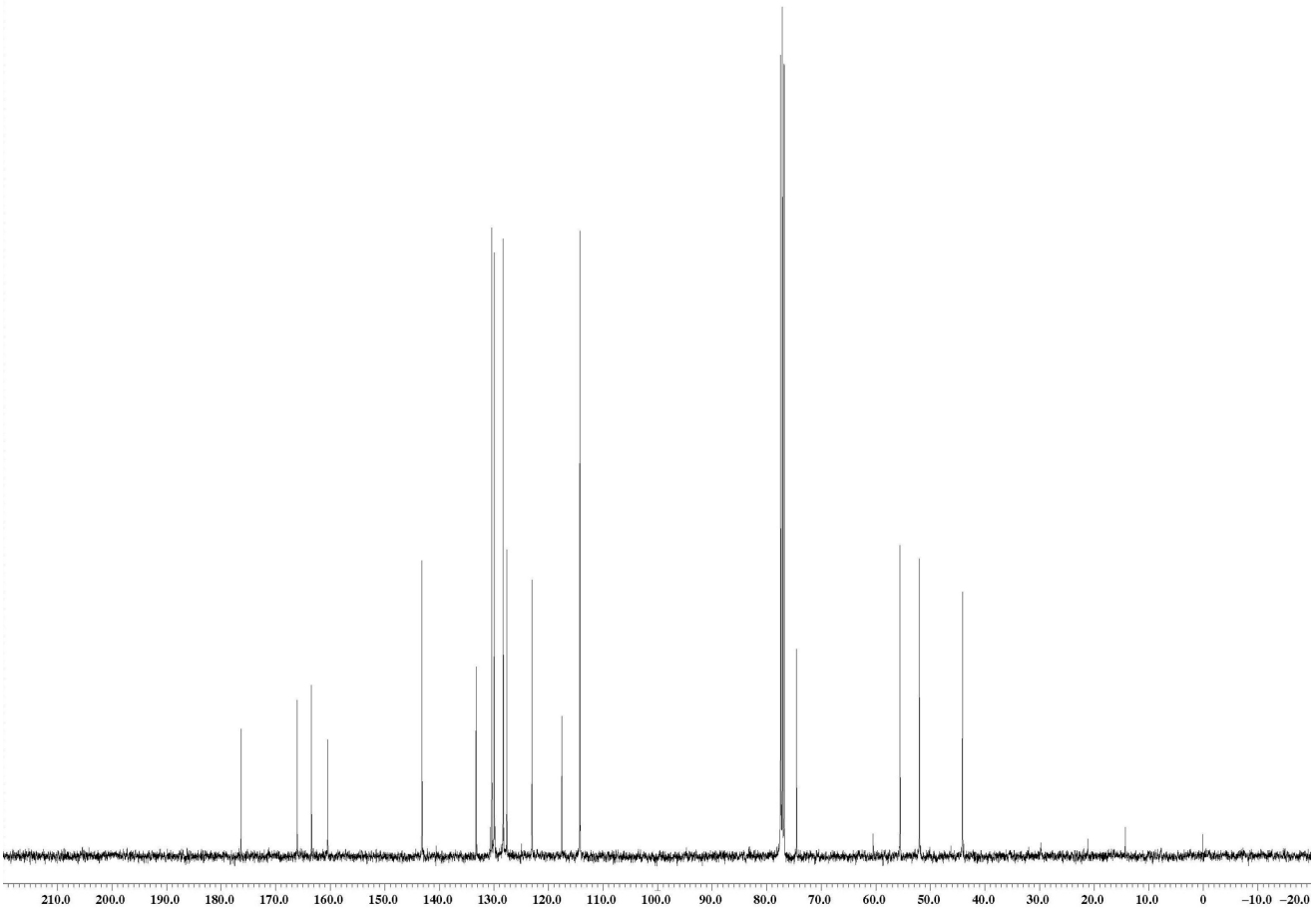

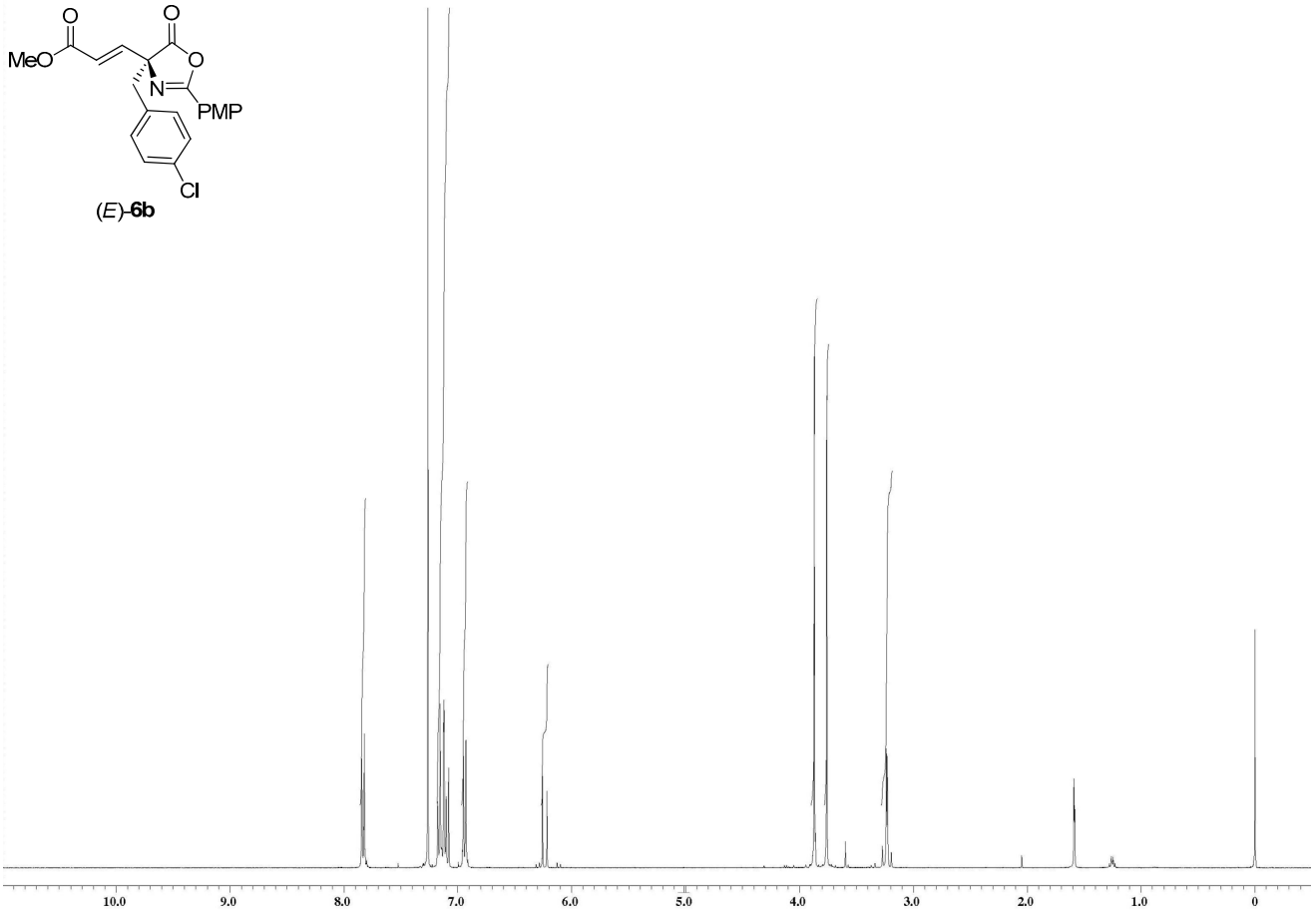
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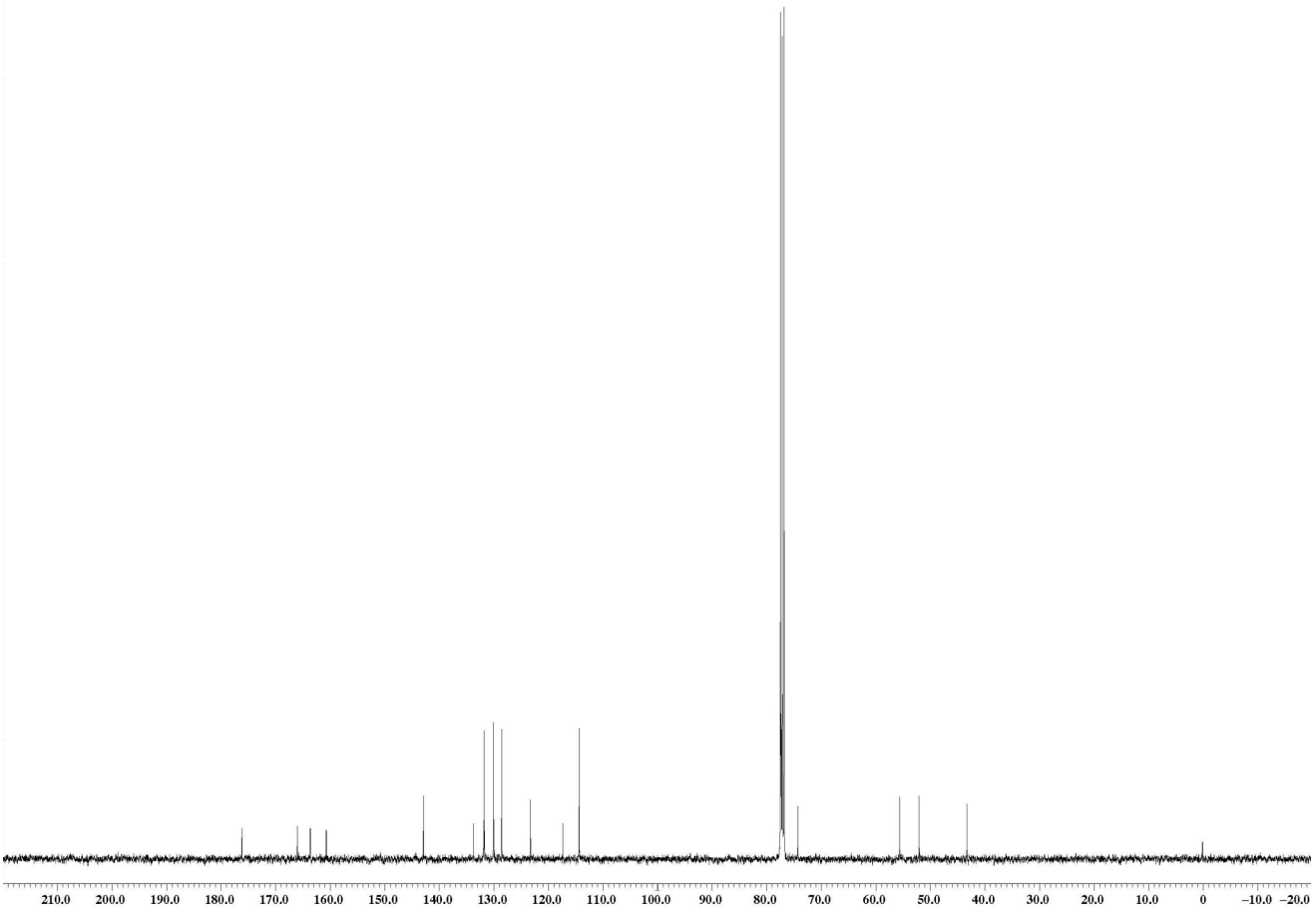
(*E*)-**6b**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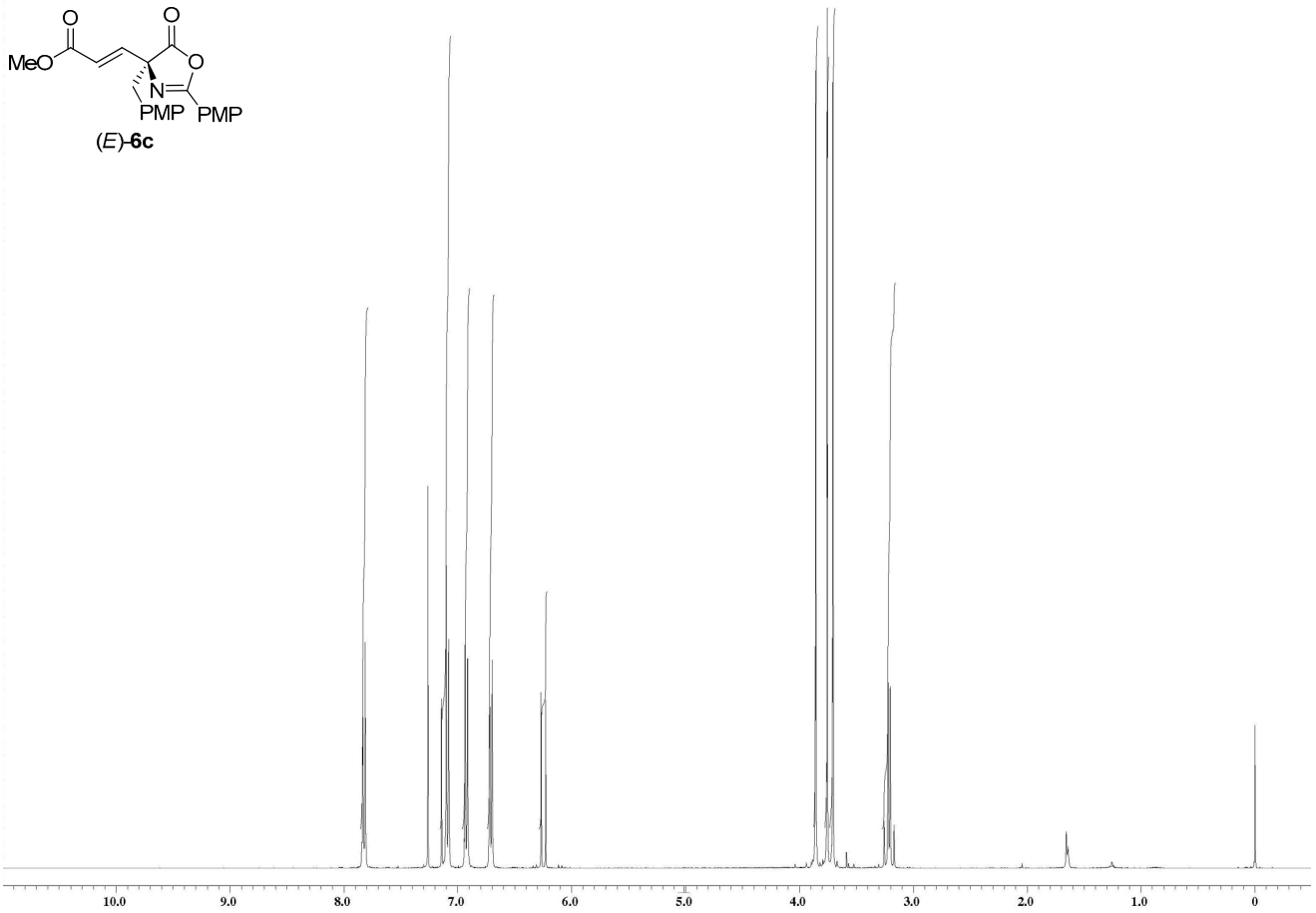
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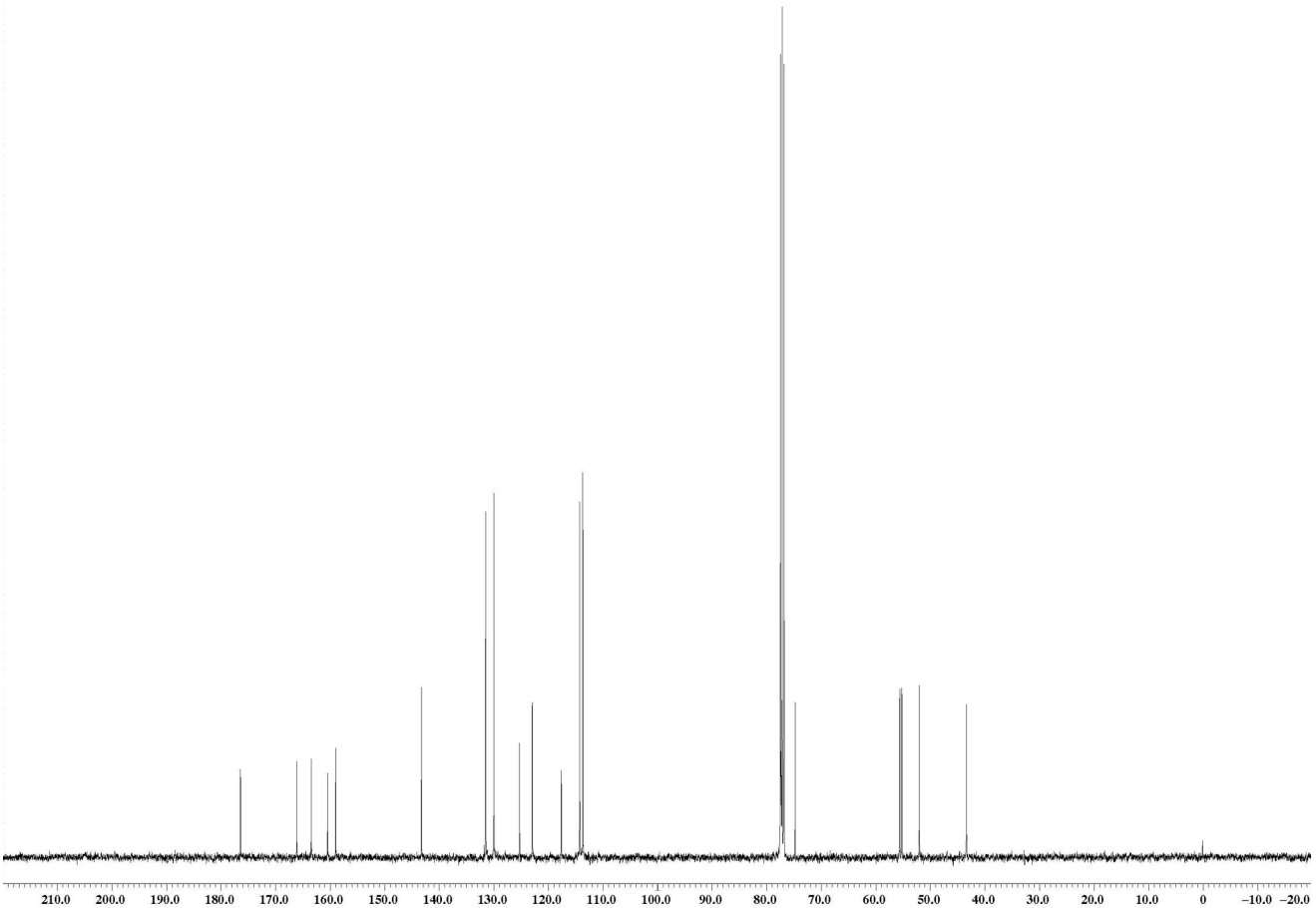
(*E*)-**6c**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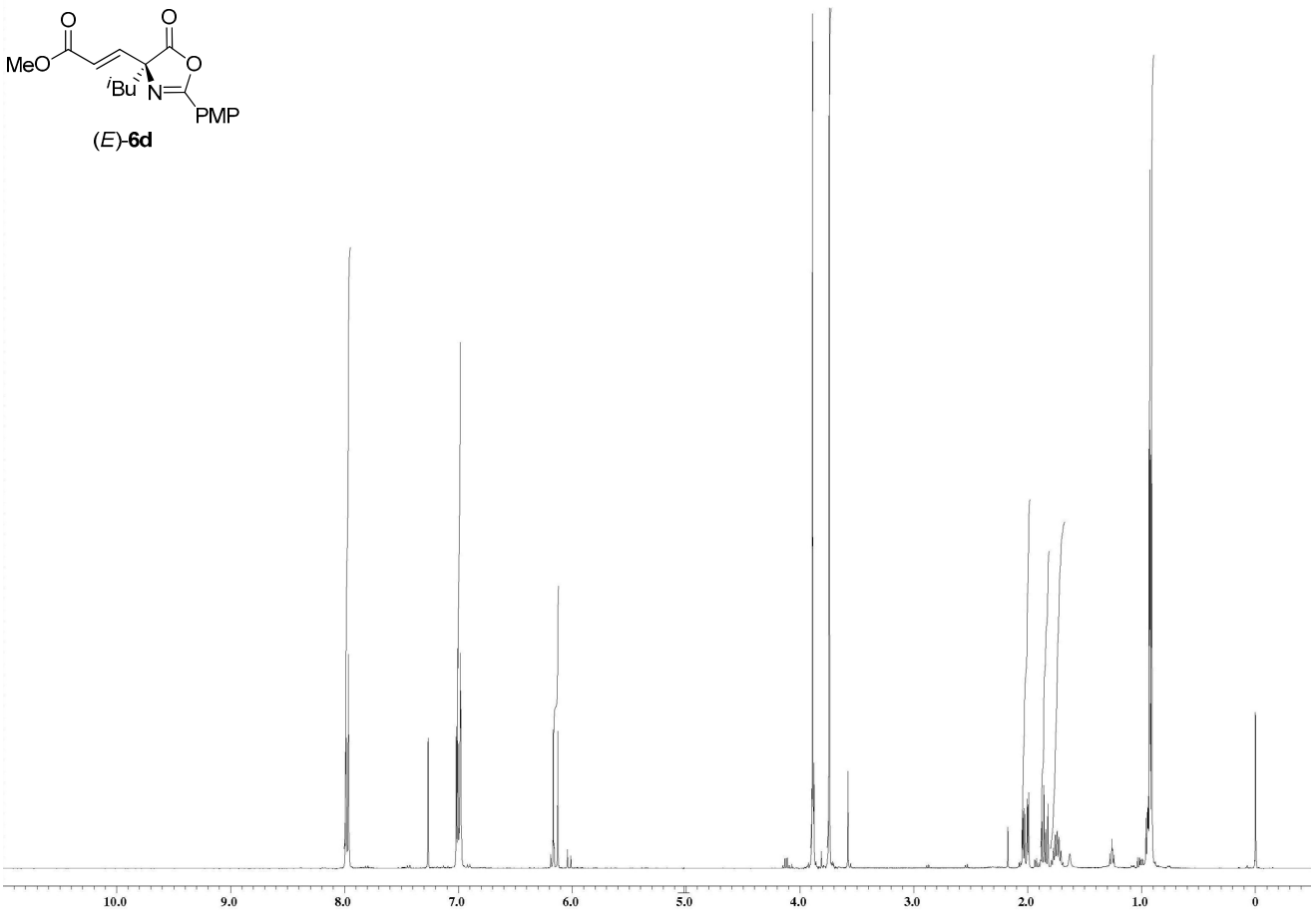

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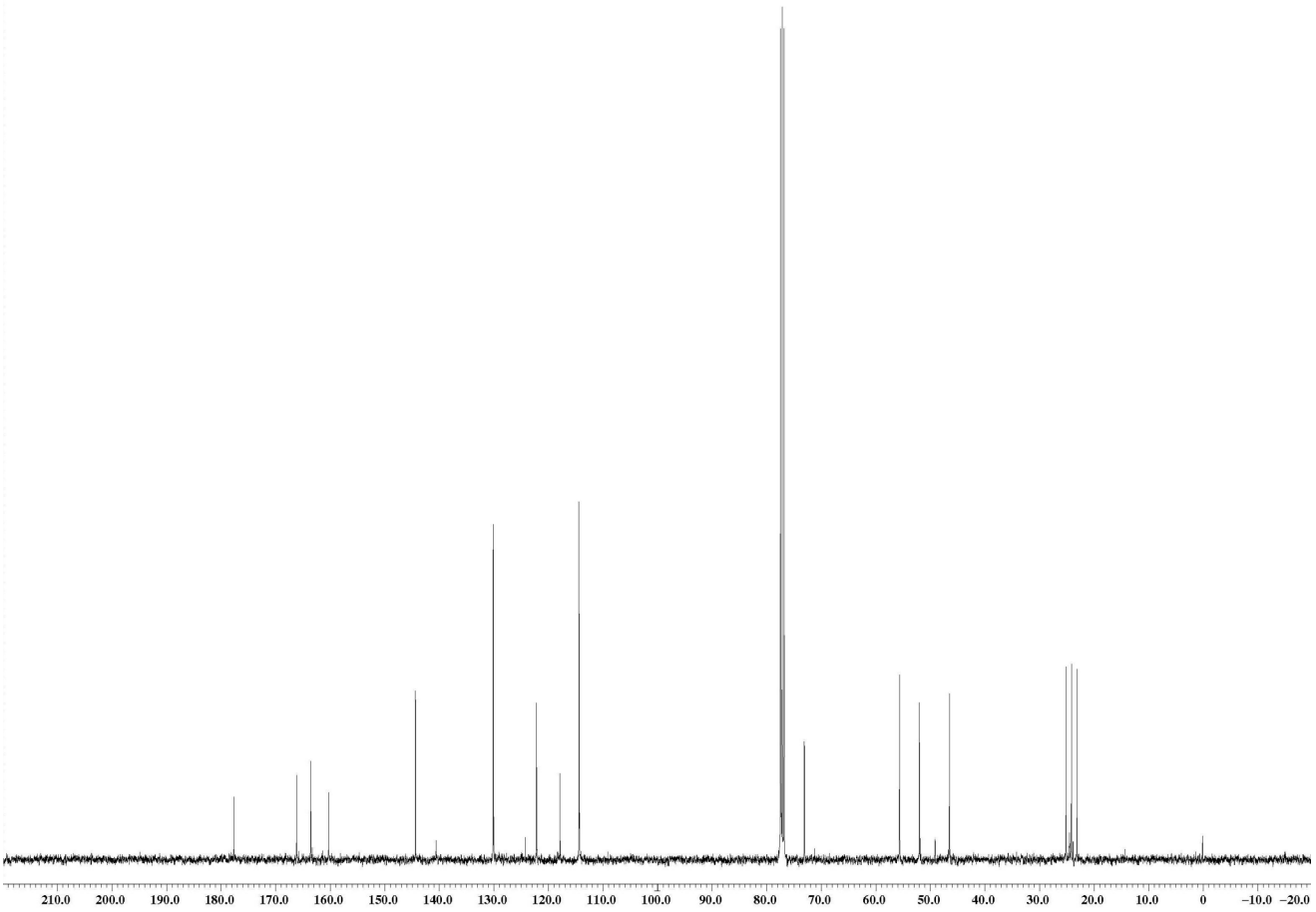

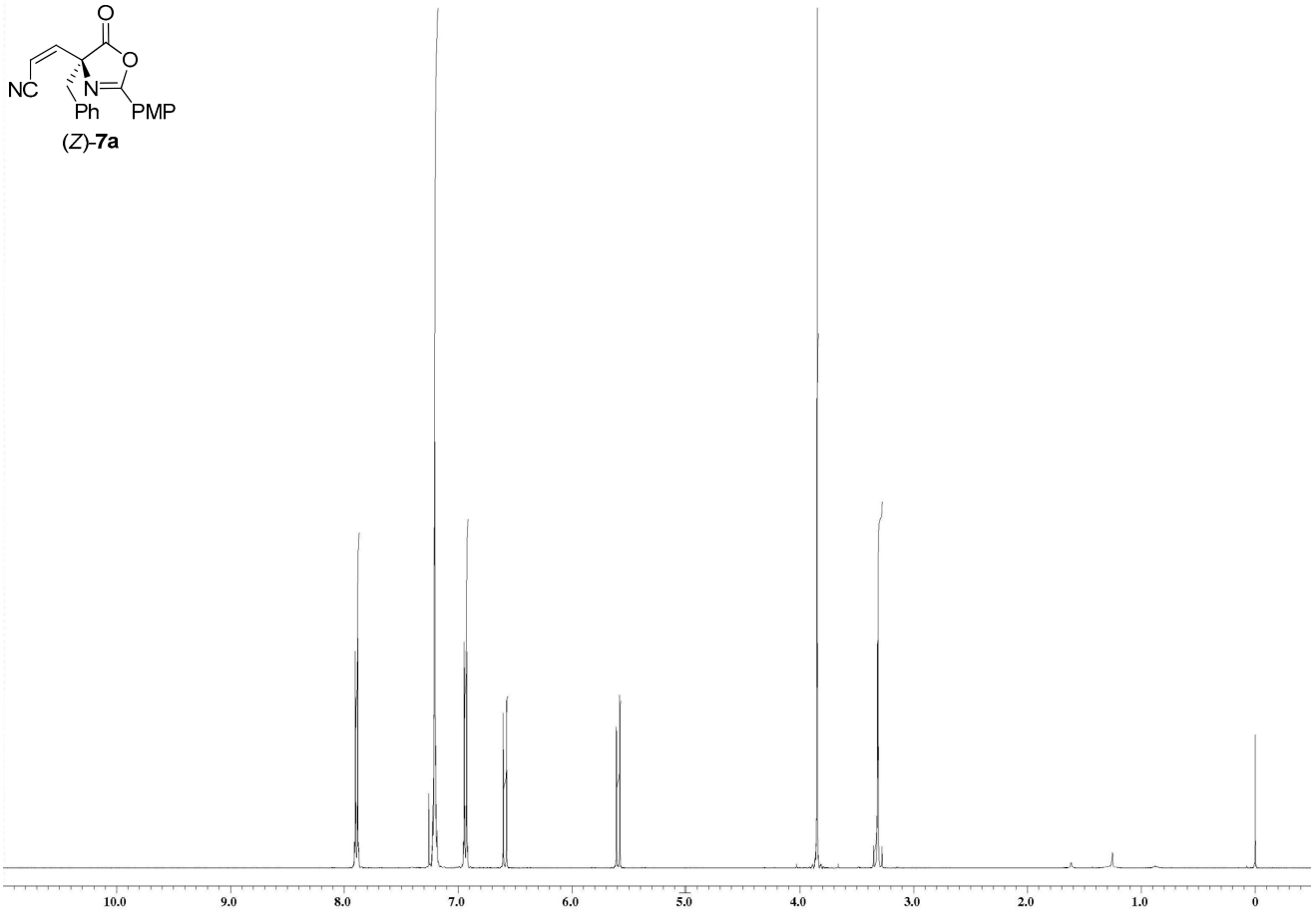
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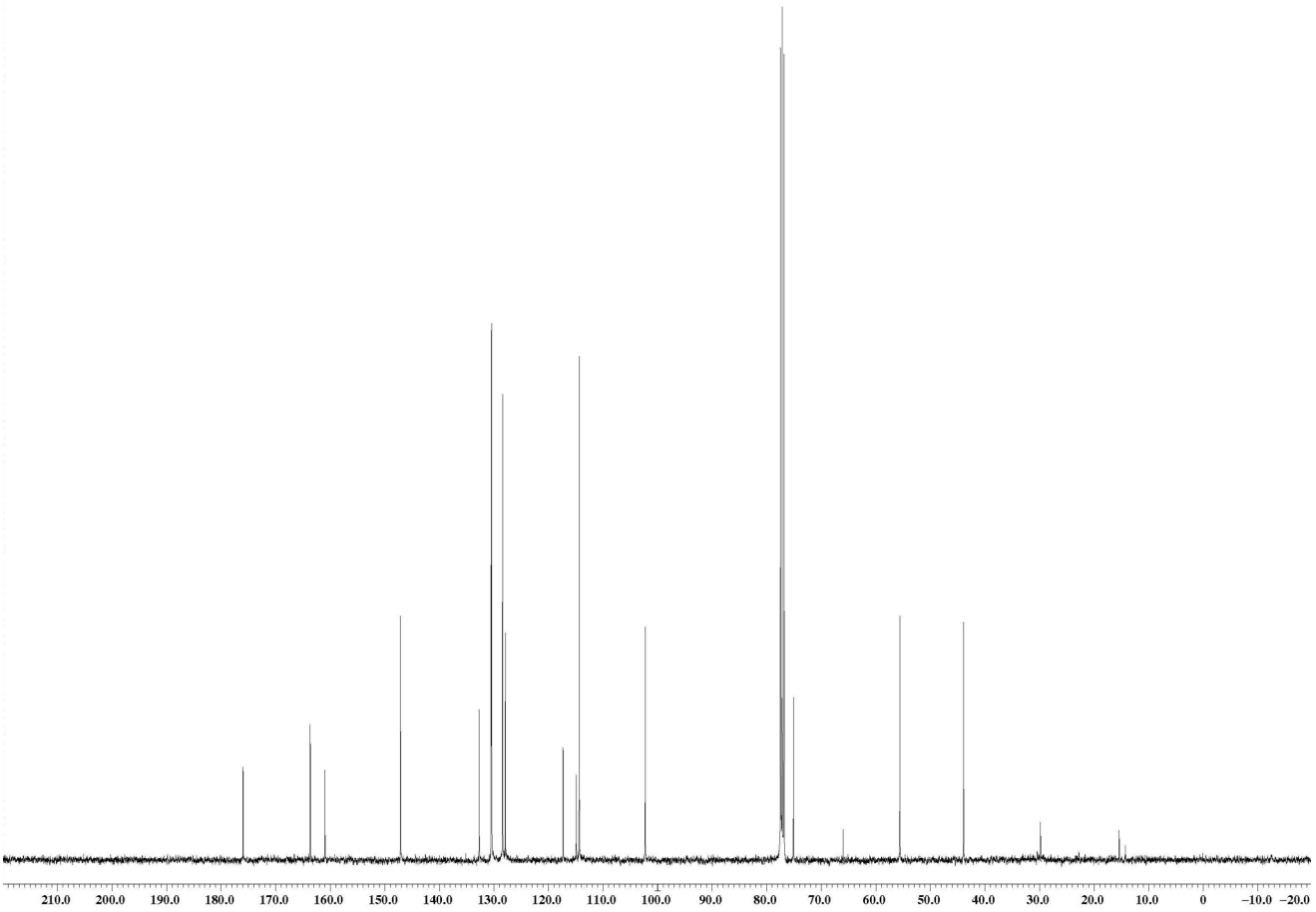
(*Z*)-**7a**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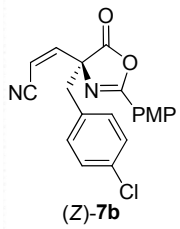

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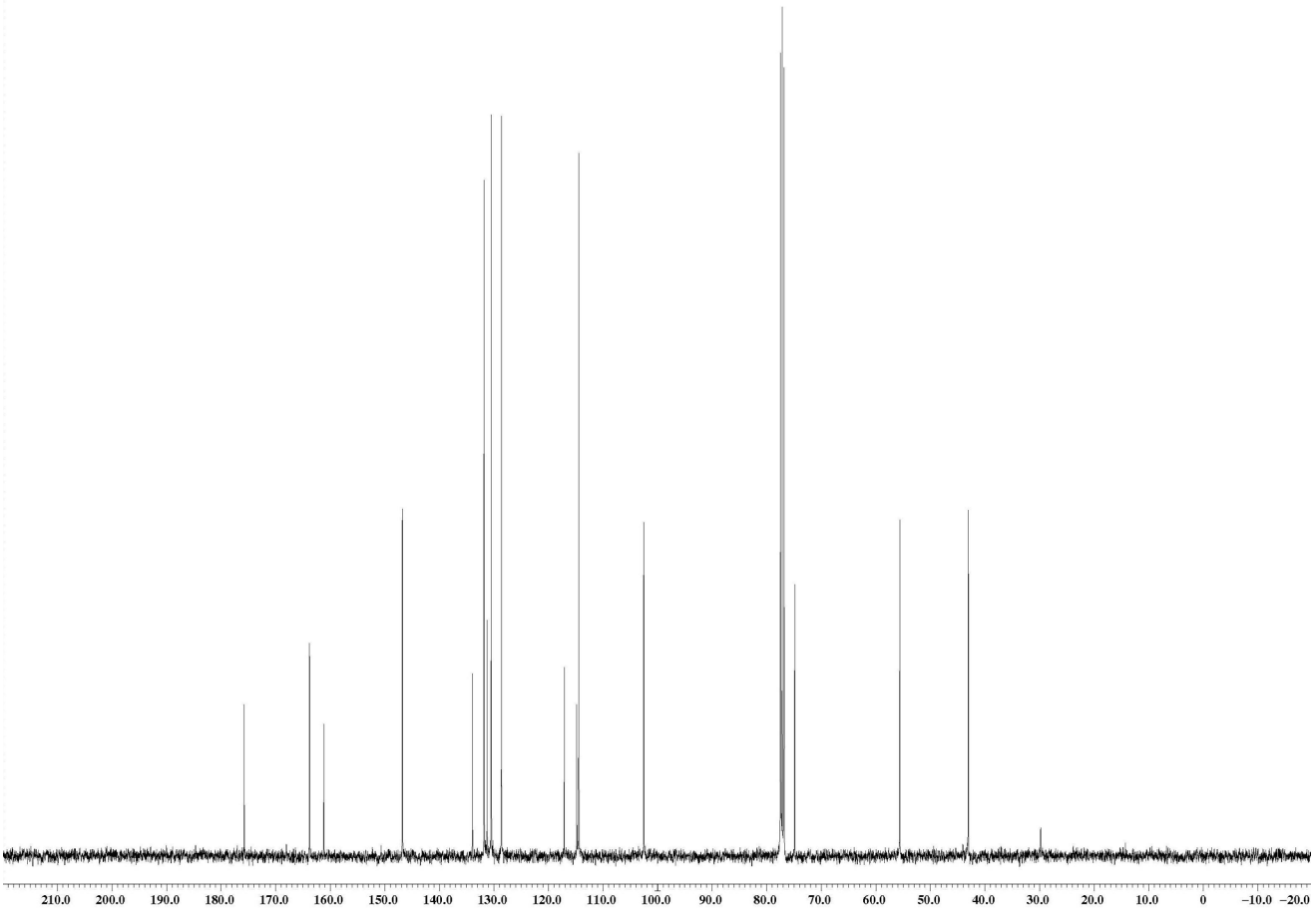

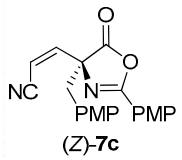
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(*Z*)-**7c**

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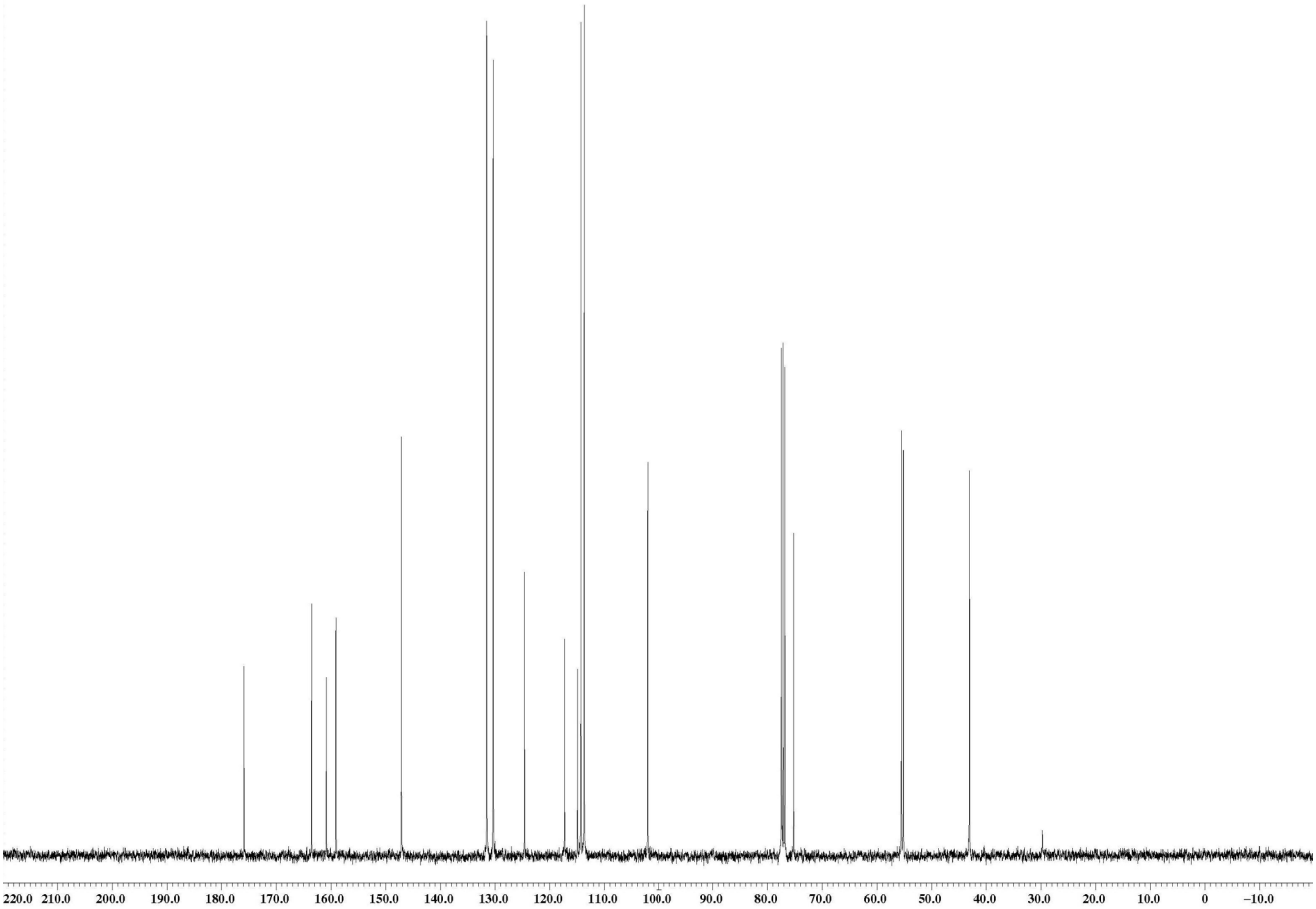
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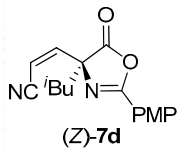
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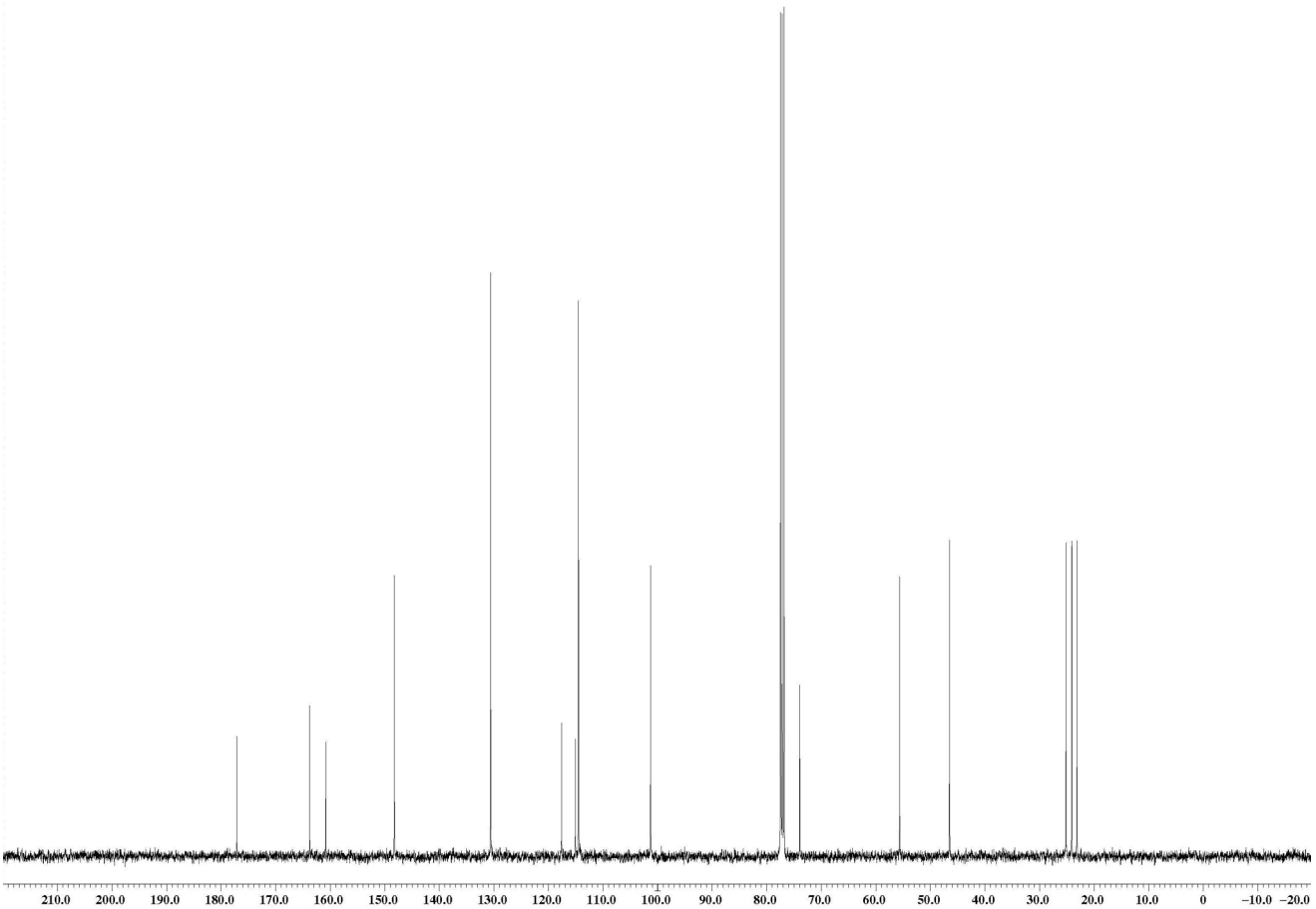
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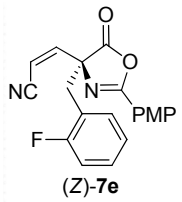

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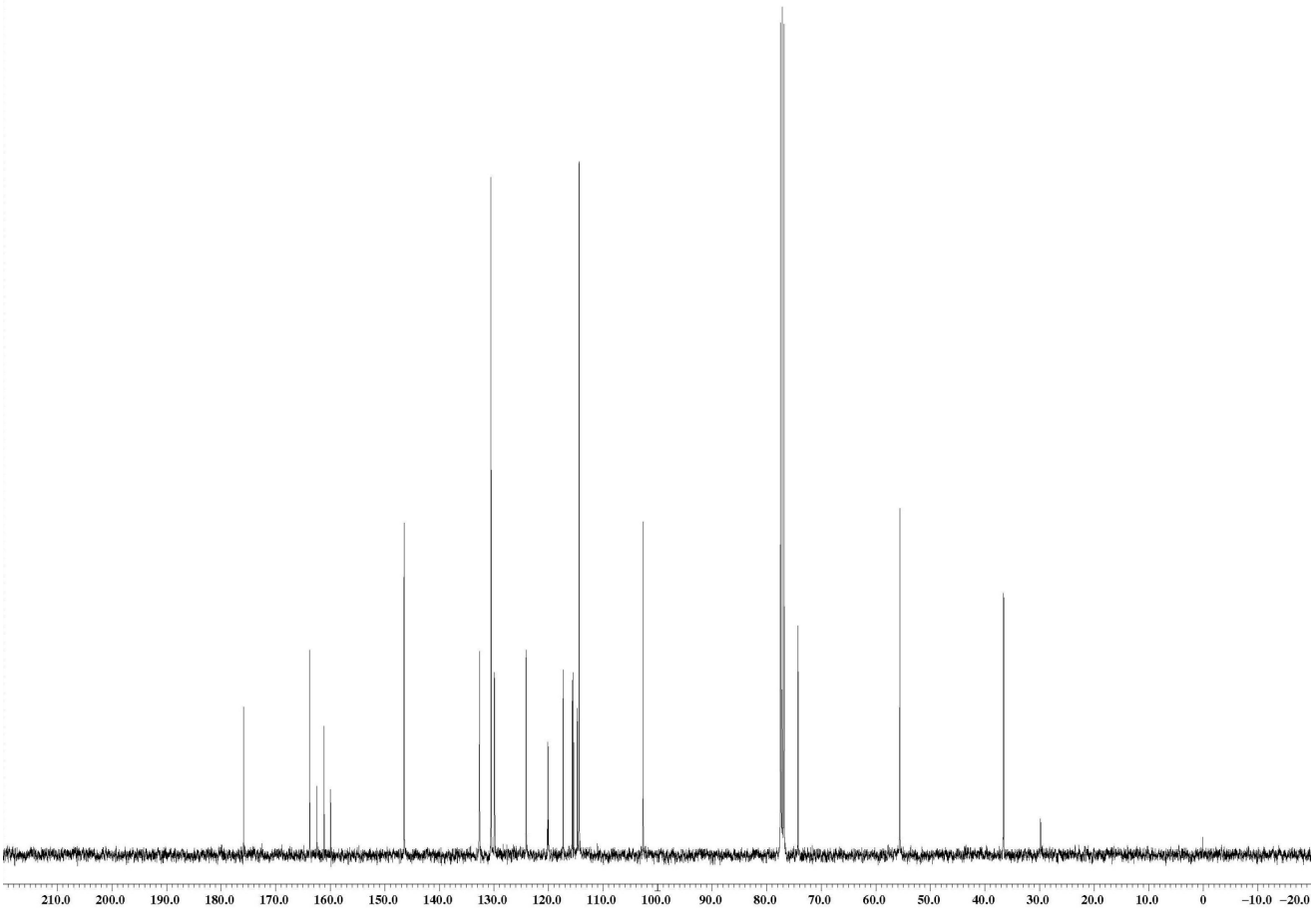

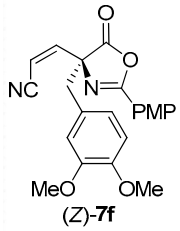

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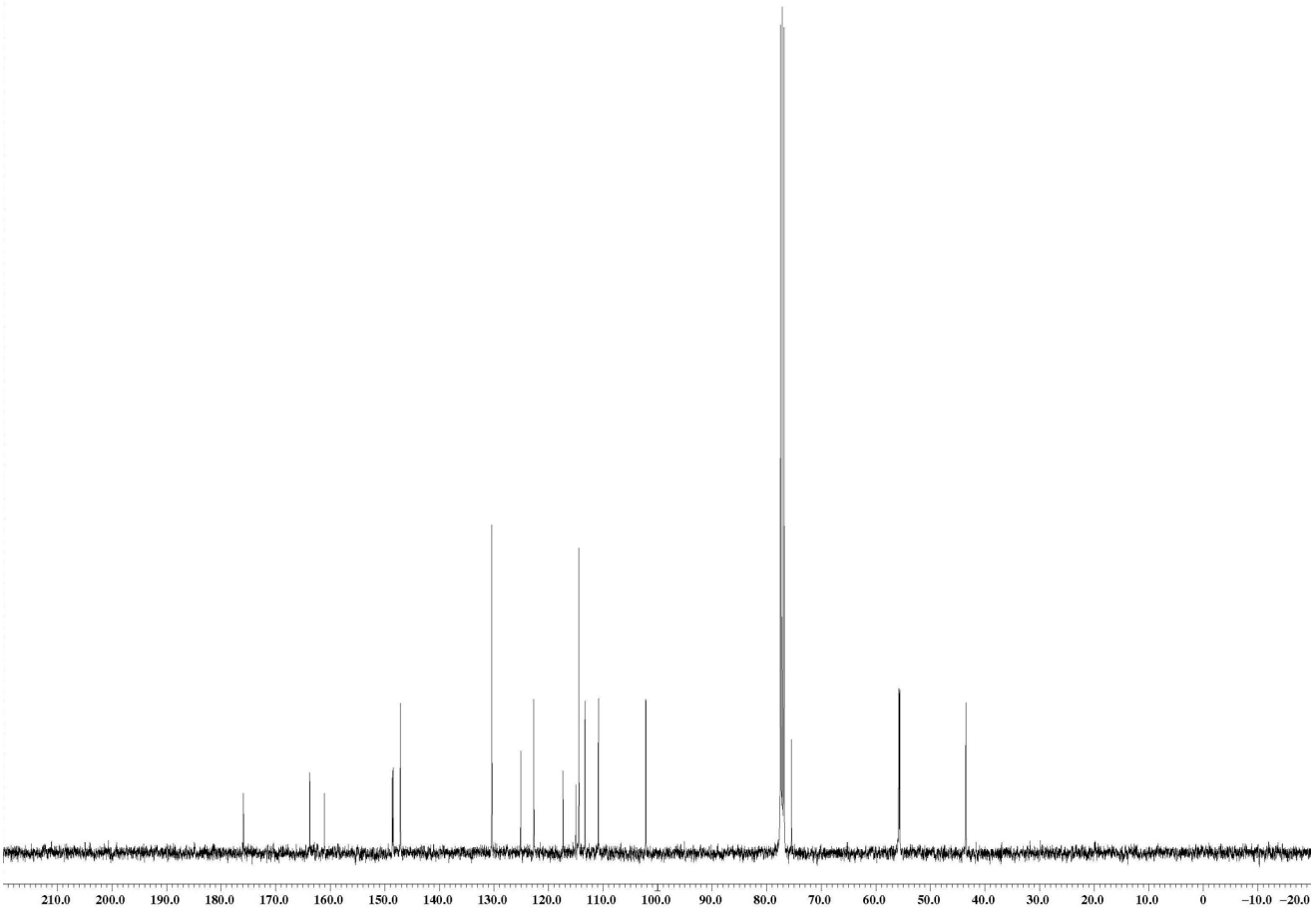

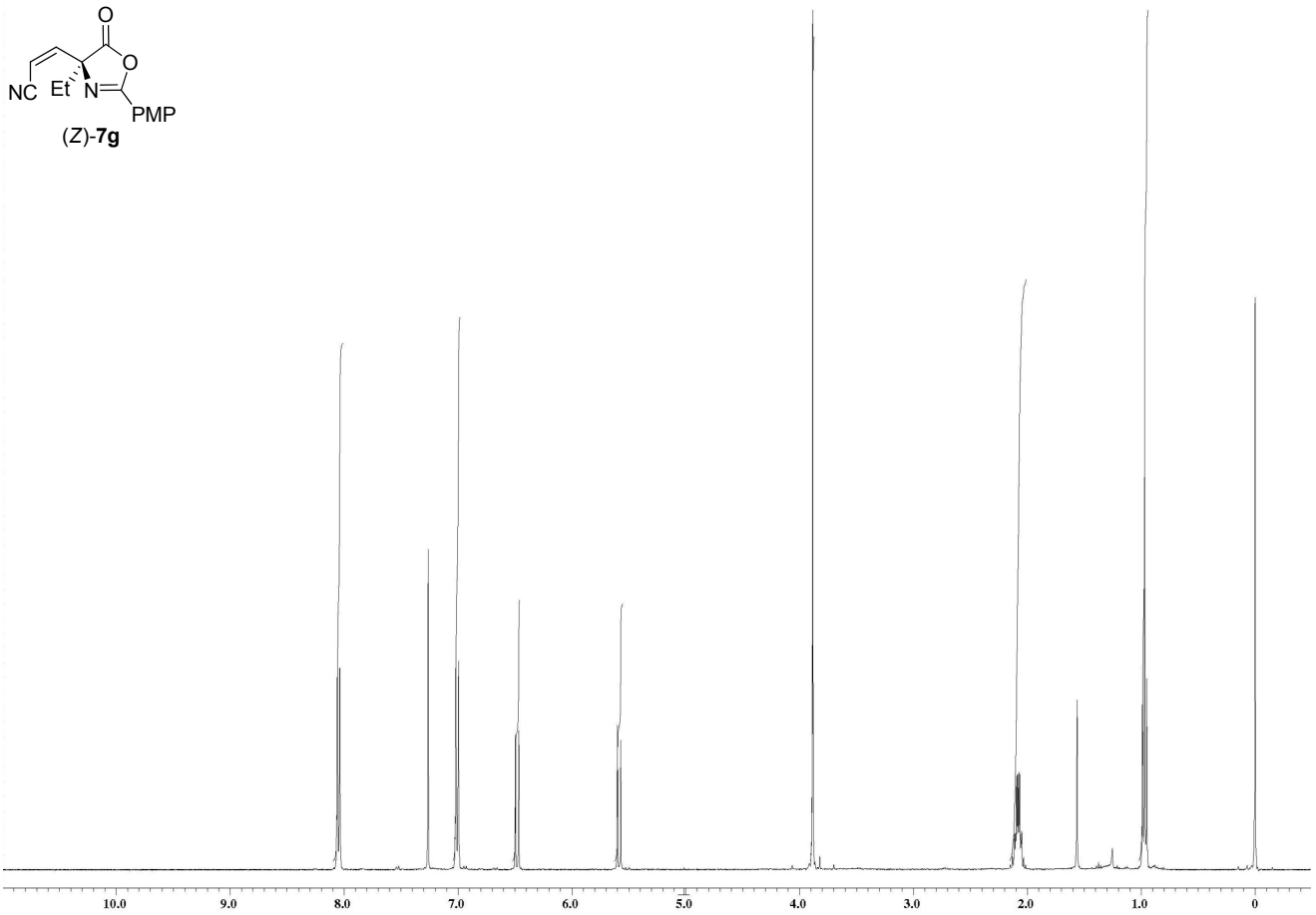
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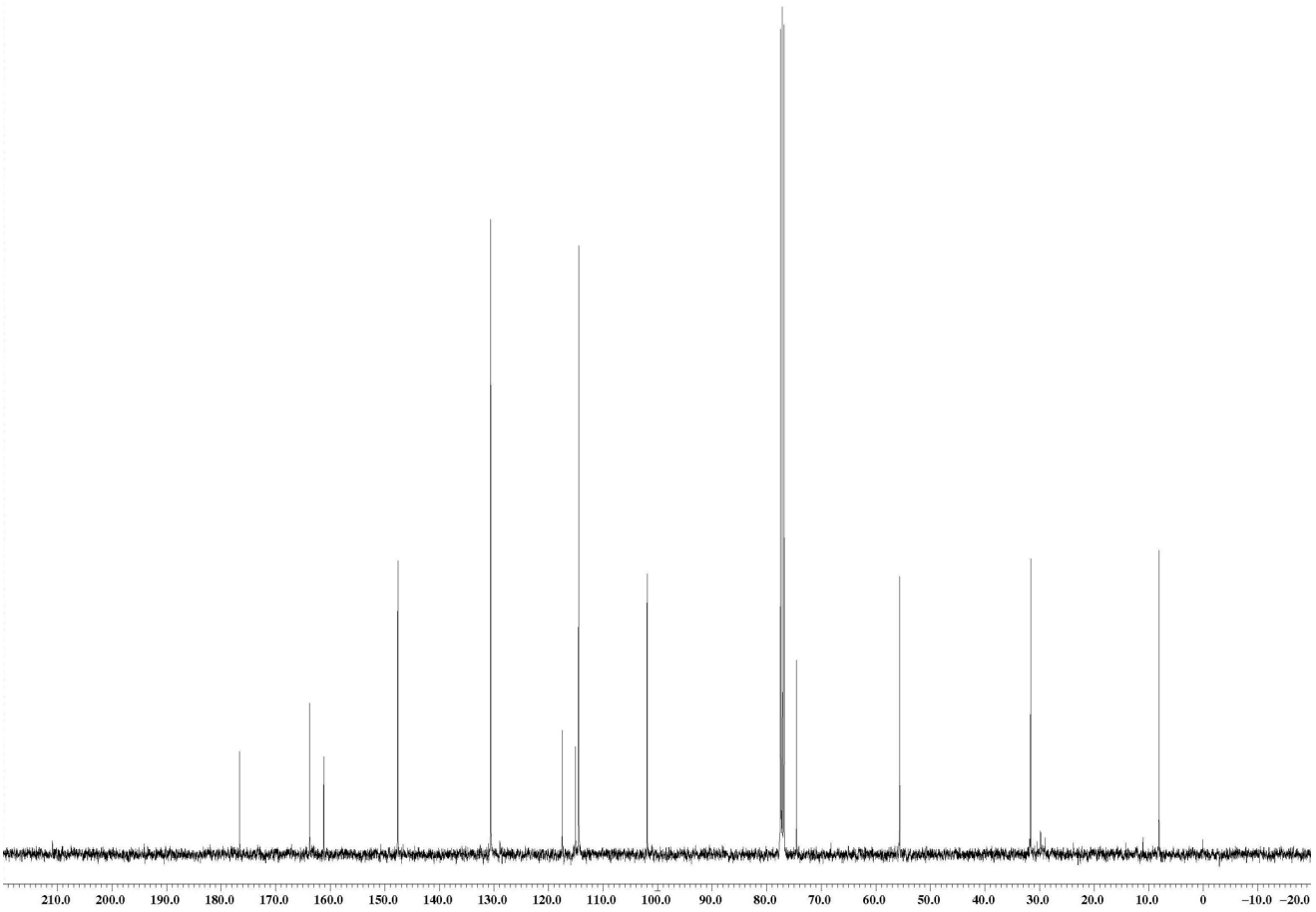
(*Z*)-**7g**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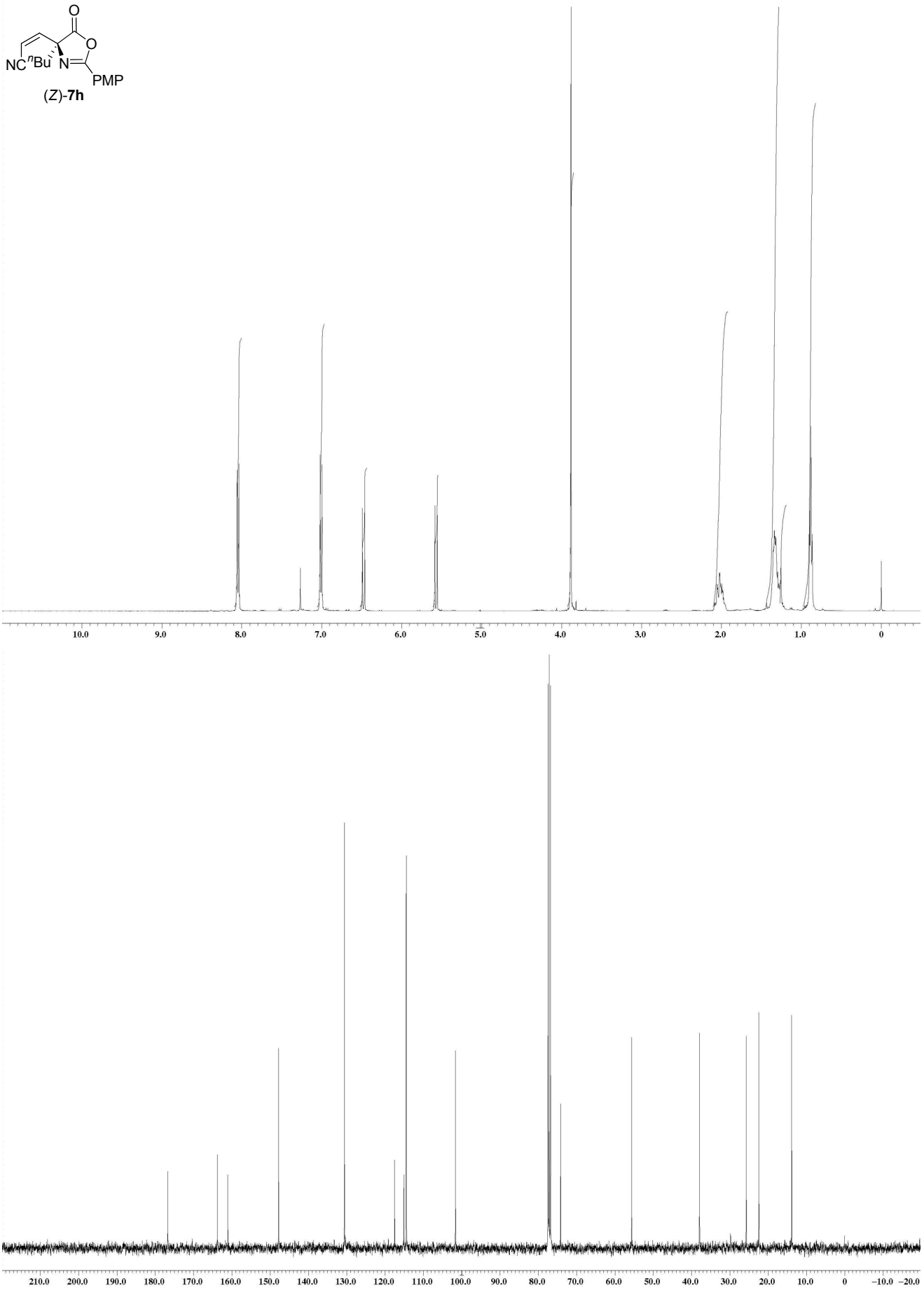
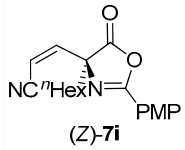


(*Z*)-**7h**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(*Z*)-**7i**

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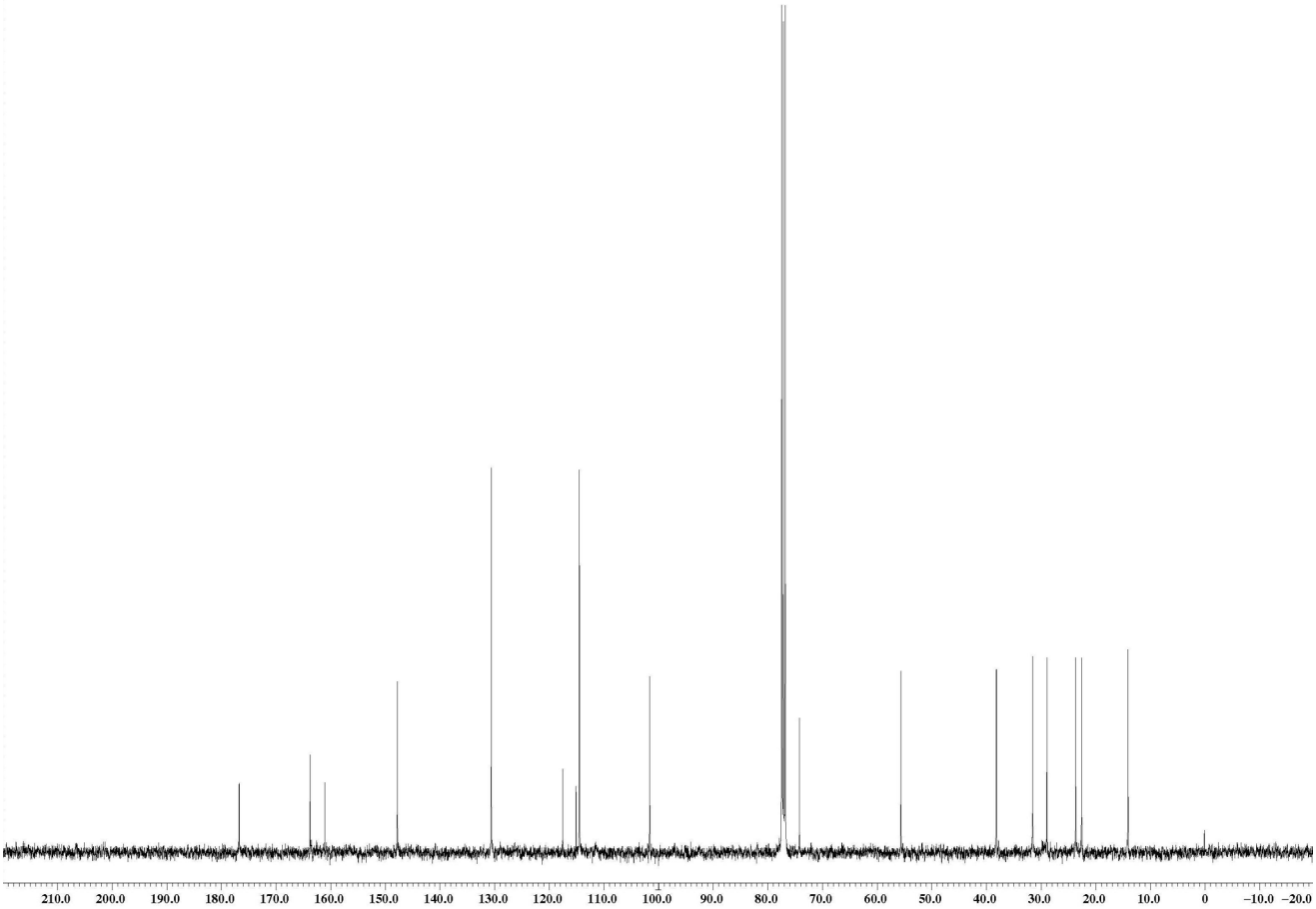
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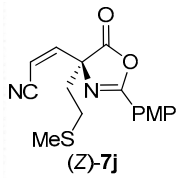

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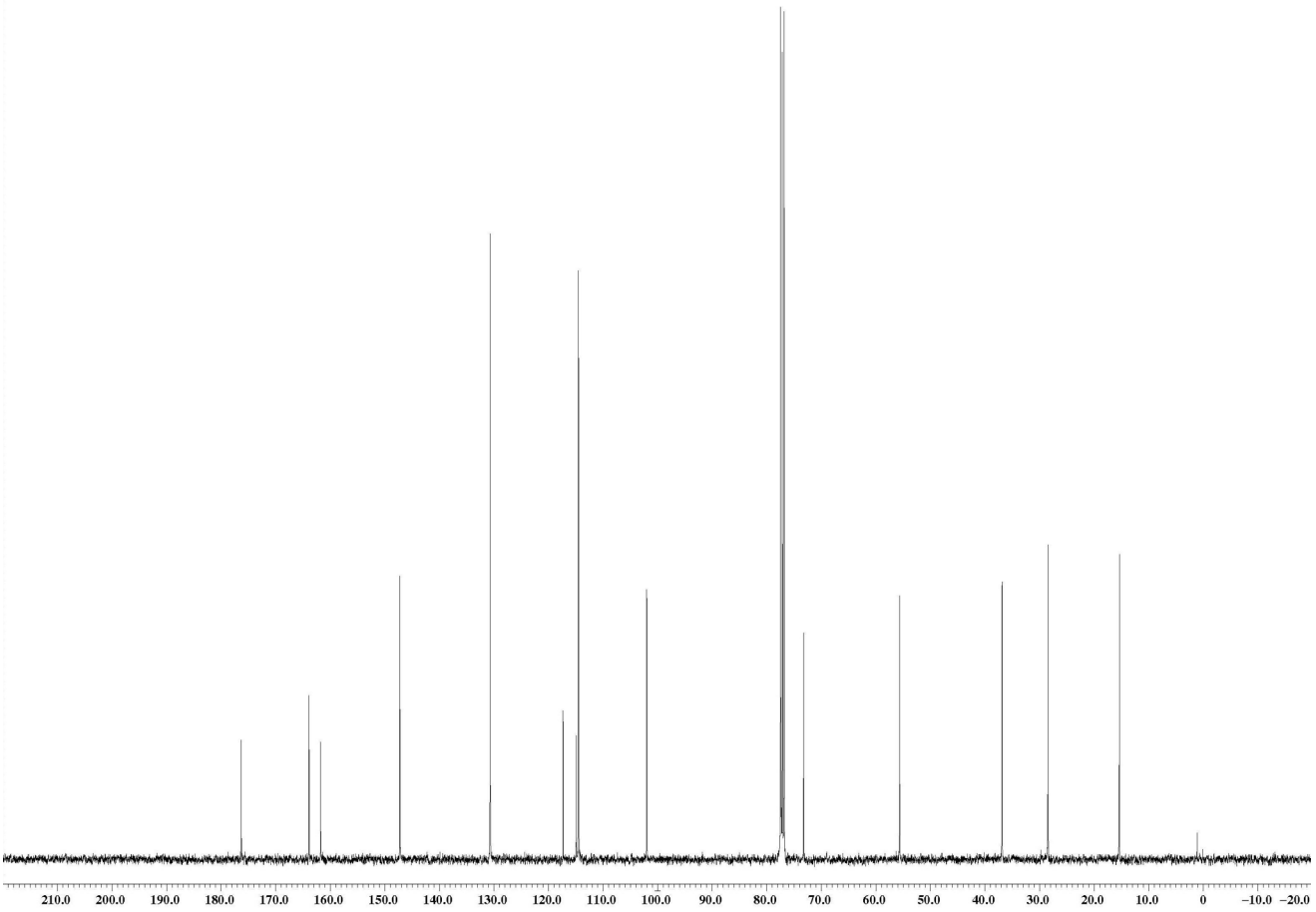

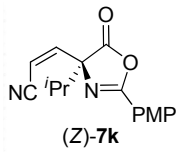
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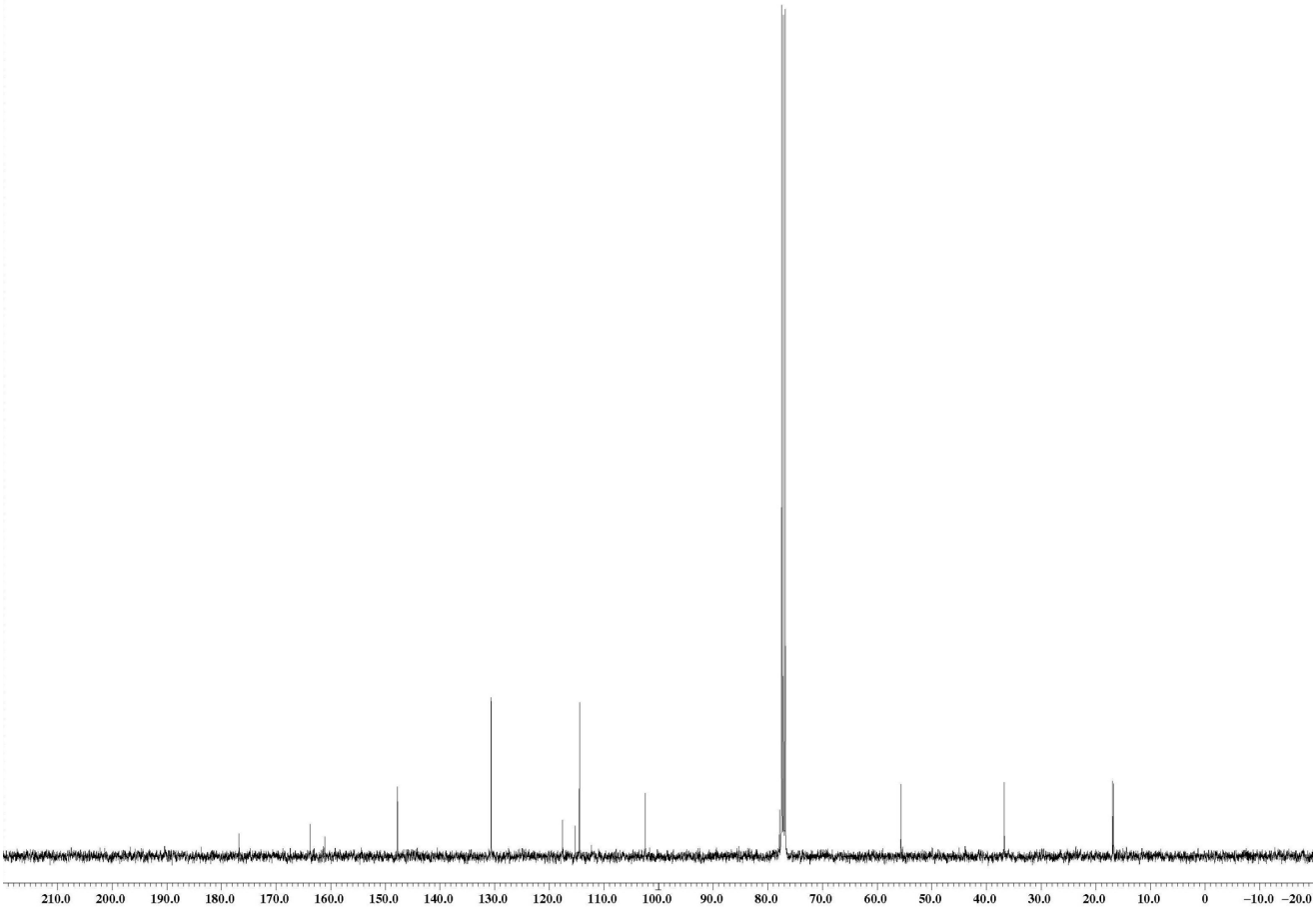
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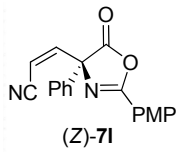

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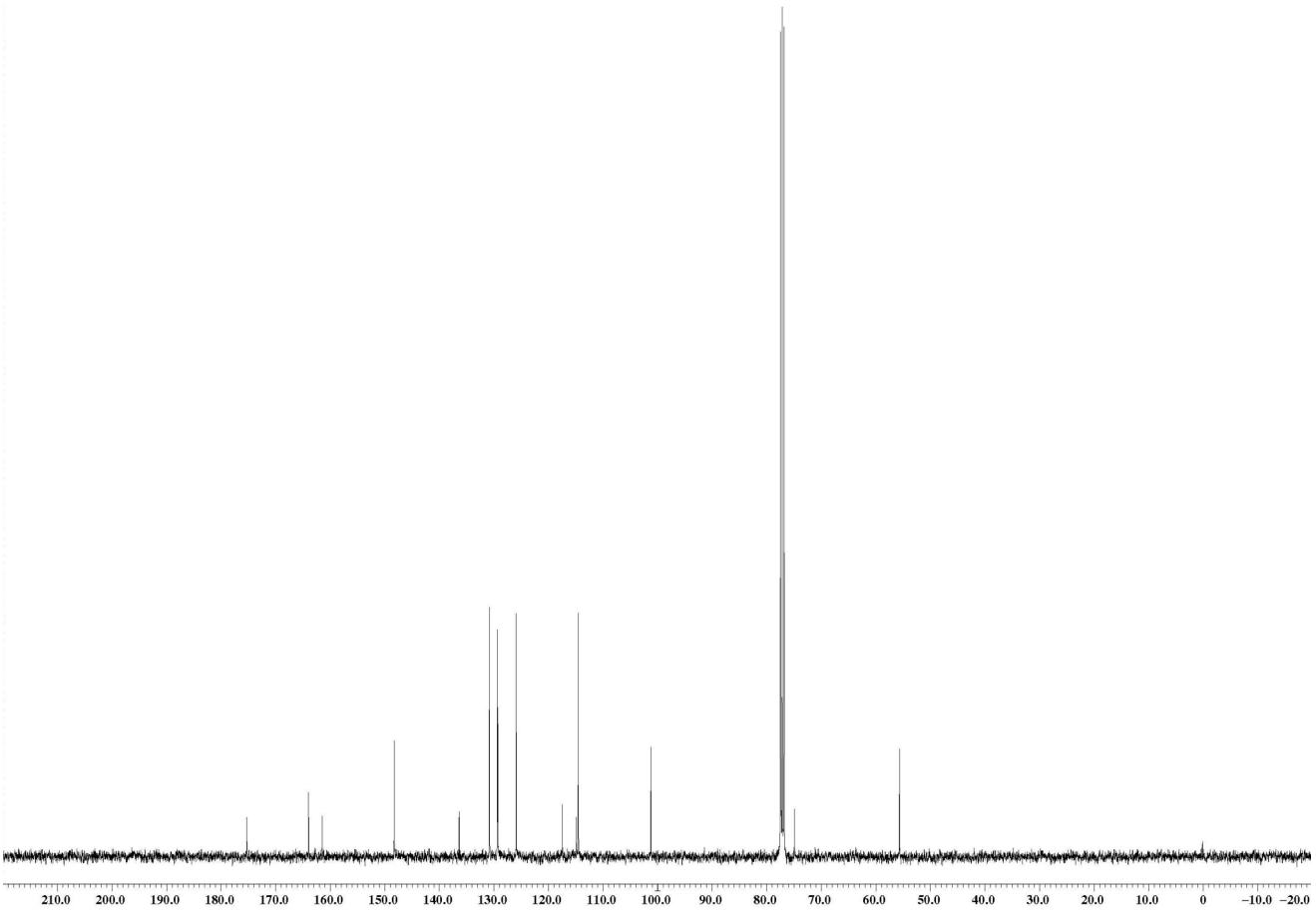

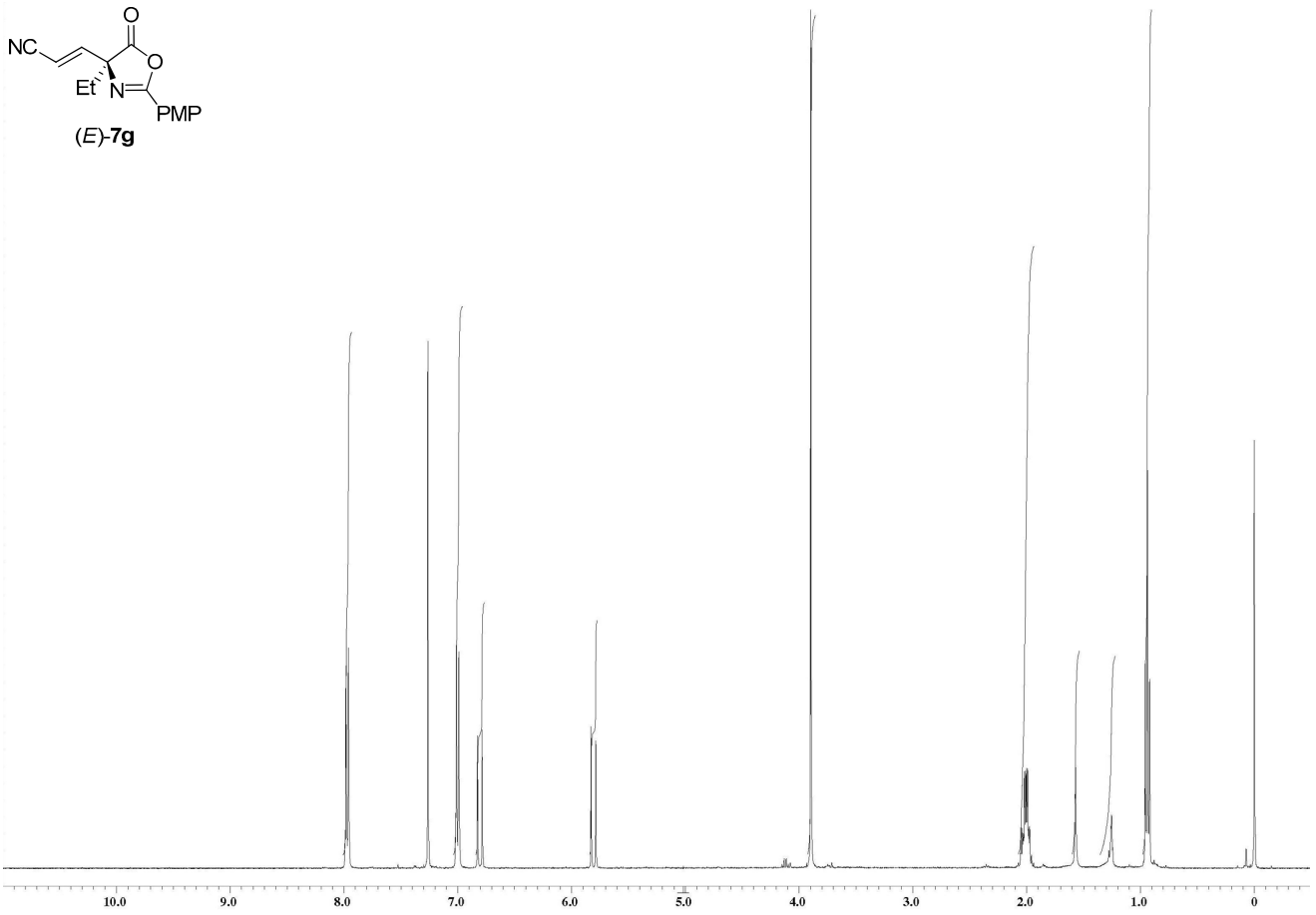
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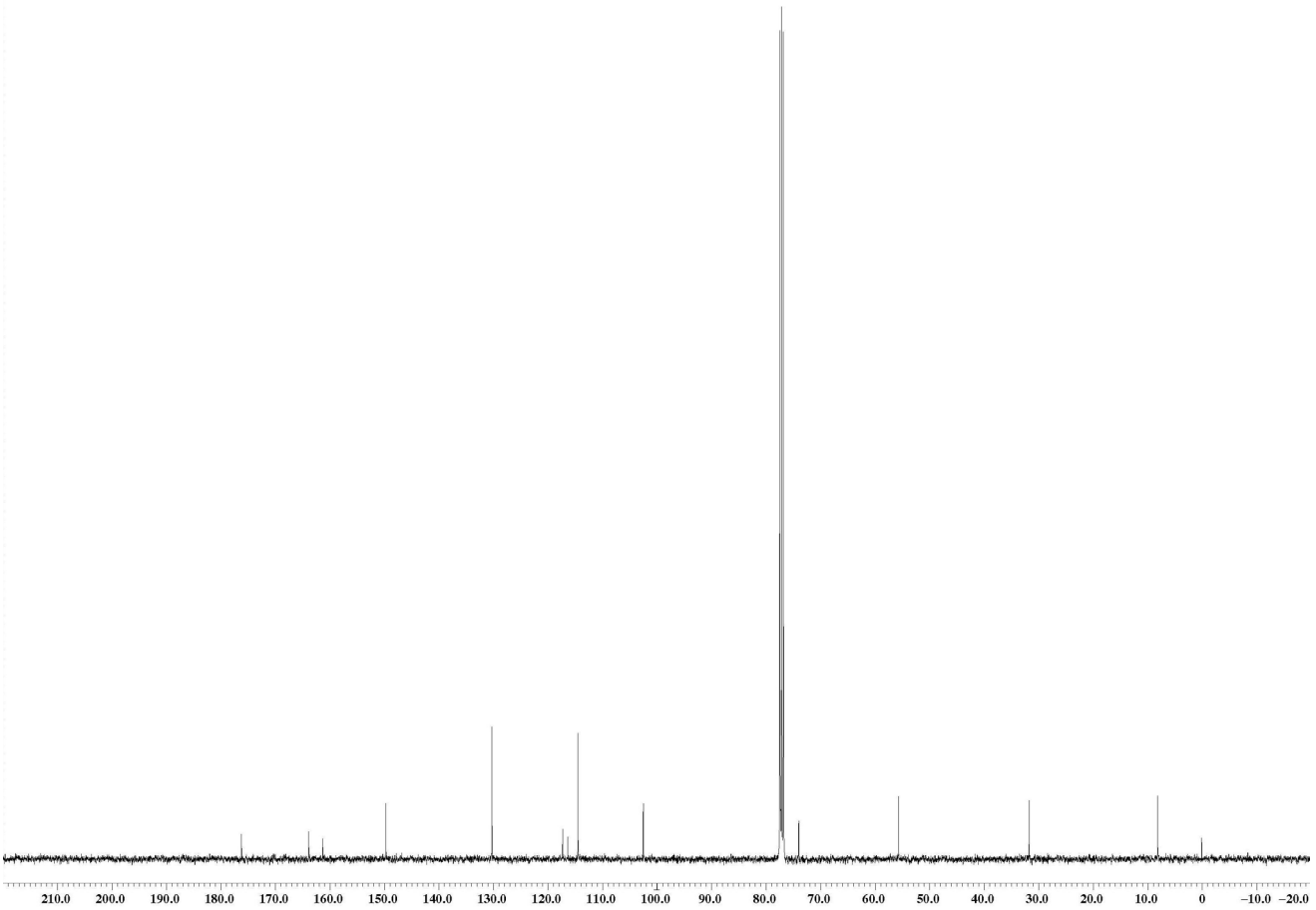
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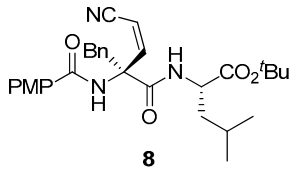

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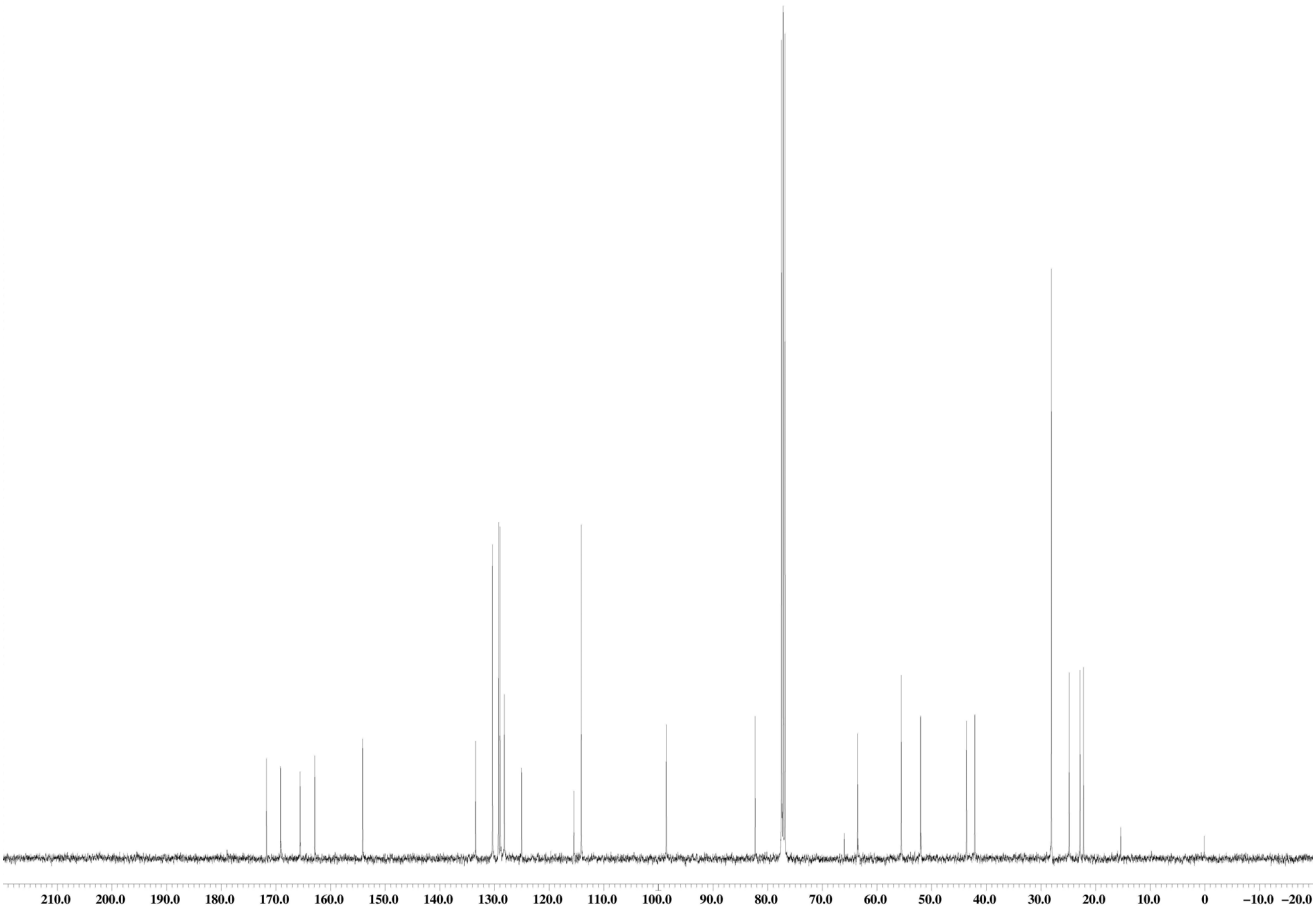

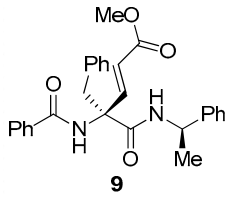
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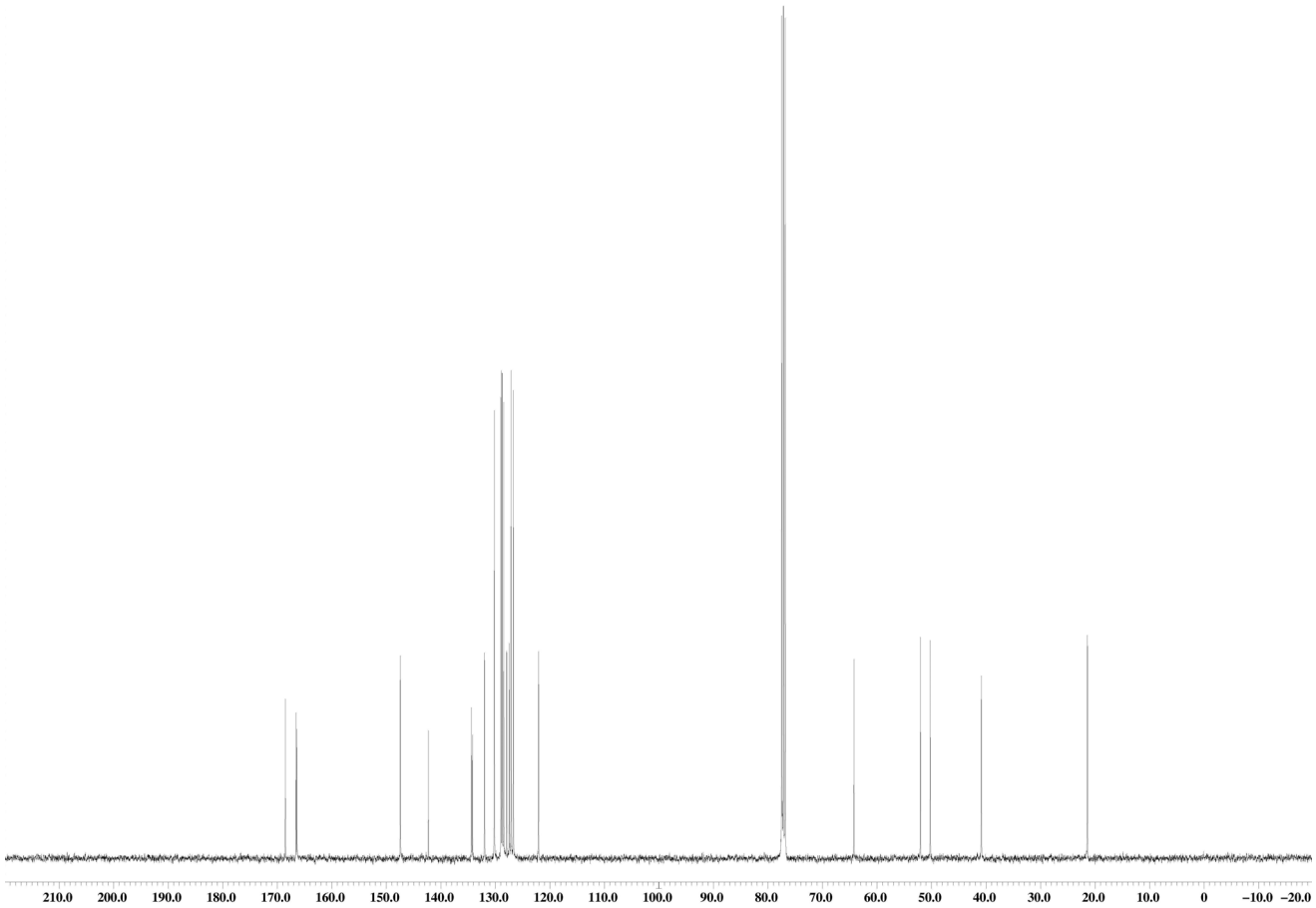
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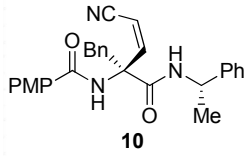

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