Electronic Supplementary Material (ESI) for Chemical Science

Highly enantioselective [4 + 2] annulations mediated by amino acid-based phosphines: synthesis of functionalized cyclohexenes and 3-spirocyclohexene-2-oxindoles

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SUPPORTING INFORMATION

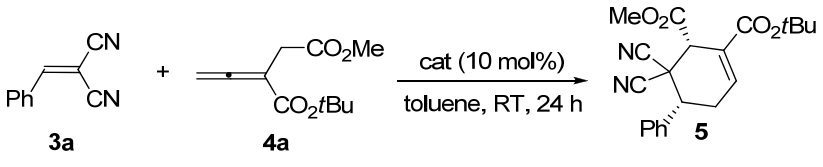
A. General Information

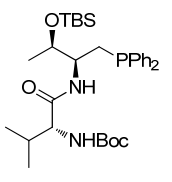
All the starting materials were obtained from commercial sources and used without further purification unless otherwise stated. THF and diethyl ether were dried and distilled from sodium benzophenone ketyl prior to use. $CHCl_3$ and CH_2Cl_2 were distilled from CaH_2 prior to use. Dioxane was dried and distilled from Na prior to use. All the solvents used in reactions involving phosphorous-containing compounds were de-gassed by dry N_2. ^1H and ^{13}C NMR spectra were recorded on a Bruker ACF300 or AMX500 (500 MHz) spectrometer. Chemical shifts were reported in parts per million (ppm), and the residual solvent peak was used as an internal reference: proton (chloroform δ 7.26), carbon (chloroform δ 77.0). Multiplicity was indicated as follows: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), dd (doublet of doublet), br s (broad singlet). Coupling constants were reported in Hertz (Hz). Low resolution mass spectra were obtained on a Finnigan/MAT LCQ spectrometer in ESI mode, and a Finnigan/MAT 95XL- T mass spectrometer in FAB mode. All high resolution mass spectra were obtained on a Finnigan/MAT 95XL- T spectrometer. For thin layer chromatography (TLC), Merck pre- coated TLC plates (Merck 60 F254) were used, and compounds were visualized with a UV light at 254 nm. Further visualization was achieved by staining with iodine, or ceric ammonium molybdate followed by heating on a hot plate. Flash chromatographic separations were performed on Merck 60 (0.040- 0.063 mm) mesh silica gel. The Enantiomerically excesses of products were determined by chiral-phase HPLC analysis, using a Daicel Chiralcel IC-H column (250 x 4.6 mm), or Chiralpak OD-H ncolumn, or IA column (250 x 4.6 mm).

α-Cyanoacrylonitriles **3**,[1] allenoates **4**,[2] 2-(2-oxoindolin-3-ylidene)malononitriles 7,[3] catalysts **1a-c**,[4] **1g**,[4] **1d-f**,[5] and **6a-e**[6] were prepared following the procedures reported in the literature. For all the [4+2] annulation products **5** and **8**, the two diastereomers were easily separated and only the major diastereomers were subjected to chiral HPLC analysis.

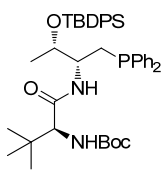
B. Optimization of Reaction Conditions

B1. The [4 + 2] annulation between benzylidenemalononitrile 3a and allenoate 4a catalyzed by dipeptide-based phosphines

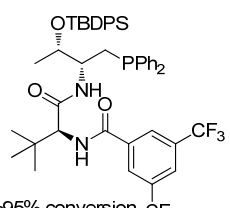




>95% conversion
cis/*trans* = 65/35
ee = 97%



>95% conversion
cis/*trans* = 74/26
ee = 99%

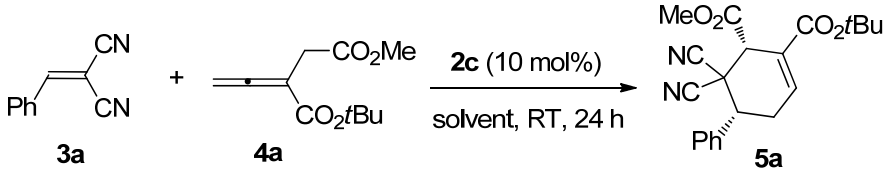


>95% conversion
cis/*trans* = 68/32
ee = 98%

Reactions were performed using **3a** (0.05 mmol), **4a** (0.075 mmol) and the catalyst (0.005 mmol) in toluene (0.50 mL) under Ar. The conversion and dr values were determined by ^{1}H NMR analysis of the crude products. Only the ee values of the major diastereomers were determined by HPLC analysis on a chiral stationary phase.

The results showed that peptide-based phosphines did not offer better diastereoselectivities for the cyclizations, compared to mono-amino acid-derived phosphines.

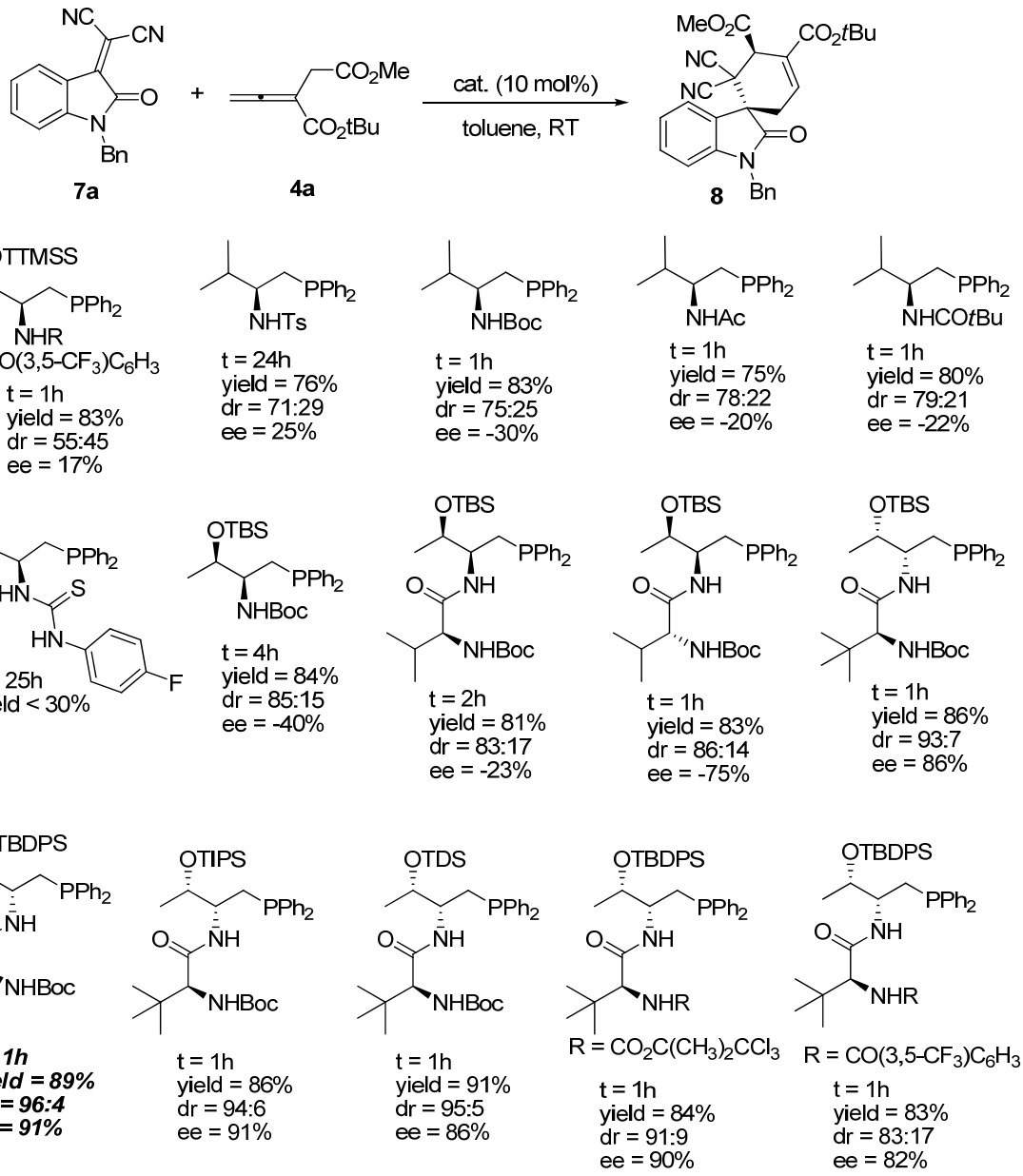
B2. Solvent screening for the [4 + 2] annulation between benzylidenemalononitrile 3a and allenoate 4a.



entry	solvent	conv (%)[b]	*cis*/*trans*[b]	ee (%)[c]
1[d]	toluene	>95	80:20	99
2	toluene	>95	83:17	99
3	THF	>95	***85:15***	***98***
4	CH_2Cl_2	>95	61:39	88
5	Hexane	>95	83:17	97
6	$CHCl_3$	>95	70:30	87
7	CH_3CN	<50	-	-
8	Et_2O	>95	83:17	87
9	xylene	>95	80:20	82
10	Ethyl acetate	>95	83:17	96
11	Dioxane	>95	82:18	98
12	Benzene	>95	70:30	98
13	Et_2O/THF (1:1)	>95	85:15	98
14	Ethyl acetate/THF (1:1)	>95	84:16	97
15	Hexane/THF (1:1)	91	85:15	98
16	Dioxane/THF (1:1)	>95	84:16	97
17	THF/10 mol% 2-naphthnol	>95	38:62	84
18	THF/10 mol% TEA	>95	52:48	91
19[d]	THF/3Å MS	>95	75:25	95
20[d]	THF/4Å MS	>95	75:25	94
21[d]	THF/5Å MS	>95	67:33	93
22[f]	***THF***	***92***[g]	***86:14***	***98***

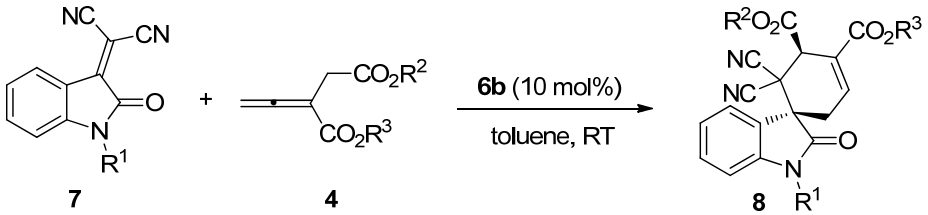
[a] Reactions were performed using **3a** (0.05 mmol), **4a** (0.075 mmol) and **2c** (0.005 mmol) in the solvent (0.5 mL) under Ar. [b] The conversion and dr values were determined by ^{1}H NMR analysis of the crude products. [c] The ee values of the *cis* isomers, determined by HPLC analysis on a chiral stationary phase. [d] The reaction was performed in the presence of 30 mg molecular sieve. [f] The best catalyst **2e** (0.005 mmol) was used. [g] isolated yield.

B3. Comprehensive catalyst screening for [4 + 2] annulation between 2-(2-oxoindolin-3-ylidene) -malononitriles 7a and allenoate 4a.



Reactions were performed with **7a** (0.03 mmol), **4a** (0.045 mmol) and the catalyst (0.003 mmol) in toluene (0.75 mL) under Ar. The dr values were determined by ^{1}H NMR analysis of the crude products. The ee values were determined by HPLC analysis on a chiral stationary phase.

B4. Optimization of the substrates for the [4 + 2] annulation between 2-(2-oxoindolin-3-ylidene)-malononitriles 7 and allenoate 4

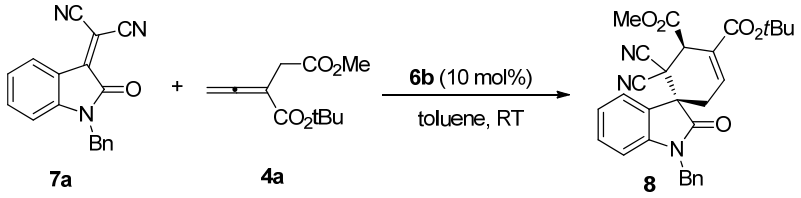


entry[a]	R^1	R^2	R^3	t (h)	Yield (%)[b]	dr[c]	ee (%)[d]
1	Bn	Et	Et	1	75	86:14	75
2	Bn	Et	*t*Bu	1	88	95:5	91
3	***Bn***	***Me***	***tBu***	***1***	***89***	***96:4***	***91***
4	Bn	Bn	*t*Bu	1	85	93:7	90
5	Me	Me	*t*Bu	1	75	84:16	73

6	PMB	Me	*t*Bu	1	83	95:5	89
7	Trt	Me	*t*Bu	12	62	94:6	78

[a] Reactions were performed with **7** (0.03 mmol), **4** (0.045 mmol) and **6b** (0.003 mmol) in toluene (0.75 mL) under Ar. [b] Isolated yield. [c] The dr values were determined by ^{1}H NMR analysis of the crude products. [d] The ee values were determined by HPLC analysis on a chiral stationary phase.

B5. Solvent screening for the [4 + 2] annulation between 2-(2-oxoindolin-3-ylidene)-malononitriles 7a and allenoate 4a

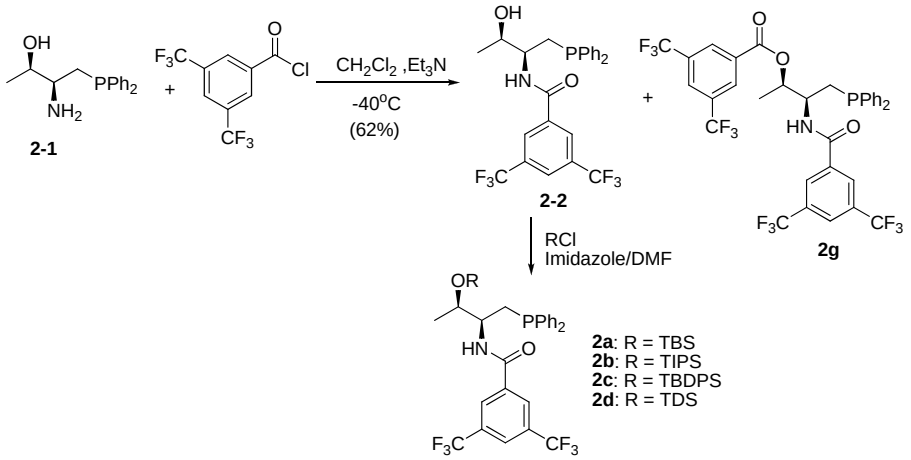


entry[a]	solvent	t (h)	Yield (%)[b]	dr[c]	Ee (%)[d]
1	toluene	1	89	95:5	91
2	THF	1	82	90:10	71
3	CH_2Cl_2	1	78	85:15	79
4	$CHCl_3$	1	83	91:9	82
5	Et_2O	1	80	91:9	81
6	xylene	1	85	93:7	78
7	CH_3CN	6	63	80:20	20
8[e]	toluene	2	88	95:5	91
9[f]	***toluene***	***3***	***91***	***97:3***	***93***

[a] Reactions were performed with **7a** (0.03 mmol), **4a** (0.045 mmol) and **6b** (0.003 mmol) in toluene (0.75 mL) under Ar. [b] Isolated yield. [c] The dr values were determined by ^{1}H NMR analysis of the crude product. [d] The ee values were determined by HPLC analysis on a chiral stationary phase. [e] The reaction was performed with 5 mol% **6b**. [f] The reaction was performed in toluene with 5 mol% **6b** and 30 mg 4Å molecular sieves in toluene (1.5 mL).

C. Preparation of the catalysts

Preparation of catalyst 2a-e & 2g



N-((2*S*,3*R*)-1-(Diphenylphosphino)-3-hydroxybutan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2-2

To a solution of **2-1** (546 mg, 2 mmol) and Et_3N (417 μL, 3 mmol) in anhydrous CH_2Cl_2 (30 mL) was slowly added a solution of 3,5-bis(trifluoromethyl)benzoyl chloride (360 μL, 2 mmol) in CH_2Cl_2 (30 mL) at -50°C over 30 min. The

resulting mixture was stirred at the same temperature for 1h and then warmed to room temperature. Water (45 mL) was added and the organic layer was separated. The aqueous phase was extracted with CH_2Cl_2 (2 x 15 mL). The combined organic layers were washed with brine and dried over Na_2SO_4. Solvent was removed under reduced pressure and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 25:1 to 8: 1) to afford **2-2** (630 mg, 62% yield) as a white solid and **2g** (350 mg, 23% yield) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.24 (d, *J* = 6.3 Hz, 3H), 2.55-2.65 (m, 2H), 3.08 (br, 1H), 4.23-4.24 (m, 1H), 4.32-4.35 (m, 1H), 6.69 (s, 1H), 7.29-7.31 (m, 6H), 7.45-7.52 (m, 4H), 7.98 (s, 1H), 8.04 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.52, 31.60 (d, *J* = 14.6 Hz), 53.72 (d, *J* = 14.6 Hz), 69.41 (d, *J* = 9.1 Hz), 119.57, 121.74, 123.92, 124.84 (d, *J* = 3.7 Hz), 124.89, 126.09, 127.20 (d, *J* = 2.7 Hz), 128.57 (d, *J* = 2.7 Hz), 128.62 (d, *J* = 2.7 Hz), 128.95 (d, *J* = 10.9 Hz), 132.13 (q, *J* = 33.7 Hz), 132.56 (d, *J* = 3.6 Hz), 132.71 (d, *J* = 3.6 Hz), 136.16, 137.35 (d, *J* = 11.9 Hz), 137.89 (d, *J* = 10.9 Hz), 164.51; ^{31}P NMR (121 MHz, $CDCl_3$) δ -22.8; HRMS (ESI) *m/z* calcd for $C_{25}H_{22}F_6NO_2P$ $[M+Na]^+$ = 536.1190, found = 536.1197.

(2R,3S)-3-(3,5-bis(trifluoromethyl)benzamido)-4-(diphenylphosphino)butan-2-yl 3,5-bis(trifluoromethyl)benzoate 2g

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.55 (d, *J* = 6.4 Hz, 3H), 2.51-2.55 (m, 1H), 2.67 (dd, *J* = 3.8 Hz, 14.5 Hz, 1H), 4.74-4.82 (m, 1H), 5.58-5.63 (m, 1H), 6.32 (br, 1H), 7.29-7.31 (m, 6H), 7.46-7.49 (m, 4H), 7.89 (s, 2H), 7.95 (s, 1H), 8.08 (s, 1H), 8.43 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.33, 31.17 (d, *J* = 16.4 Hz), 52.69 (d, *J* = 13.7 Hz), 74.79 (d, *J* = 10.0 Hz), 121.63 (d, *J* = 5.5 Hz), 123.80 (d, *J* = 5.5 Hz), 125.03, 125.98 (d, *J* = 5.5 Hz), 126.66, 126.95, 128.76 (q, *J* = 3.7 Hz), 129.16, 129.23, 129.64, 130.88, 131.64, 131.89, 132.20 (d, *J* = 4.6 Hz), 132.64 (q, *J* = 33.8 Hz), 135.78, 137.37 (d, *J* = 5.5 Hz), 137.44, 163.89; ^{31}P NMR (121 MHz, $CDCl_3$) δ -24.25; HRMS (ESI) *m/z* calcd $C_{34}H_{24}F_{12}NO_3P$ $[M+H]^+$ = 754.1380, found = 754.1393.

***N*-((2*S*,3*R*)-3-(*tert*-Butyldimethylsilyloxy)-1-(diphenylphosphino)butan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2a**

To a solution of **2-2** (61 mg, 0.12 mmol) in dry DMF (28 μL, 0.36 mmol) was added imidazole (25 mg, 0.36 mmol) and *tert*-butyldimethylsilyl chloride (22 mg, 0.15 mmol) at room temperature under N_2. The solution was stirred for 36 h, and the mixture was directly purified by column chromatography (hexane/ethyl acetate = 25:1) to afford **2a** as a white solid (61 mg, 81 % yield).

^{1}H NMR (500 MHz, $CDCl_3$) δ 0.14 (s, 3H), 0.16 (s, 3H), 0.94 (s, 9H), 1.16 (d, *J* = 7.7 Hz, 3H), 2.27 (dd, *J* = 7.7 Hz, 13.3 Hz, 1H), 2.64-2.68 (m, 1H), 4.15-4.18 (m, 1H), 4.31-4.35 (m, 1H), 6.66 (d, *J* = 8.9 Hz, 1H), 7.30-7.38 (m, 6H), 7.39-7.41 (m, 2H), 7.56-7.59 (m, 2H), 7.98 (s, 1H), 8.10 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.91, 21.26, 25.78, 29.65, 31.47 (d, *J* = 13.7 Hz), 53.40 (d, *J* = 15.6 Hz), 69.23 (d, *J* = 10.9 Hz), 123.99, 124.86, 127.08, 128.57 (d, *J* = 7.3 Hz), 128.69 (d, *J* = 7.3 Hz), 128.81, 129.18, 132.76 (q, *J* = 28.8 Hz), 136.52, 163.54; ^{31}P NMR (121 MHz, $CDCl_3$) δ -22.77; HRMS (ESI) *m/z* calcd for $C_{31}H_{36}F_6NO_2PSi$ $[M+H]^+$ = 628.2230, found = 628.2240.

Catalysts **2b-d** were prepared from **2-2**, following the same procedure described for the preparation of **2a.**

***N*-((2*S*,3*R*)-1-(Diphenylphosphino)-3-(triisopropylsilyloxy)butan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2b**

A white solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.11 (m, 21H), 1.23 (d, *J* = 6.3 Hz, 3H), 2.40-2.44 (m, 1H), 2.73-2.77 (m, 1H), 4.18-4.24 (m, 1H), 4.47-4.50 (m, 1H), 6.80 (br, 1H), 7.30-7.35 (m, 6H), 7.38-7.41 (m, 2H), 7.57-7.60 (m, 2H), 7.98 (s, 1H), 8.12 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.48, 27.80, 31.75 (d, *J* = 15.6 Hz), 36.34, 38.91, 40.91, 52.81 (d, *J* = 13.7 Hz), 71.58 (d, *J* = 10.0 Hz), 121.78, 123.95, 124.89, 127.09, 128.62, 128.67, 129.00 (d, *J* = 8.2 Hz), 132.00 (q, *J* = 33.7 Hz), 132.55, 132.71 (d, *J* = 3.6 Hz), 132.89, 136.10, 163.57, 177.41; ^{31}P NMR (121 MHz, $CDCl_3$) δ -24.10; HRMS (ESI) *m/z* calcd for $C_{34}H_{42}F_6NO_2PSi$ $[M+H]^+$ = 670.2699, found = 670.2723.

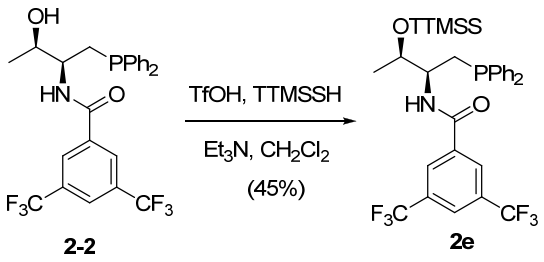
***N*-((2*S*,3*R*)-3-(*tert*-Butyldiphenylsilyloxy)-1-(diphenylphosphino)butan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2c**

A white solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.10 (d, *J* = 3.8 Hz, 3H), 1.14 (s, 9H), 2.23-2.27 (m, 1H), 2.57-2.61 (m, 1H), 4.24-4.30 (m, 1H), 4.35 (dd, *J* = 6.3 Hz, 12.6 Hz, 1H), 6.46 (d, *J* = 8.9 Hz, 1H), 7.29-7.30 (m, 5H), 7.37-7.50 (m, 10 H), 7.67 (dd, *J* = 1.3 Hz, 8.2 Hz, 2H), 7.72-7.76 (m, 3H), 8.02 (s, 1H), 8.06 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 19.42, 21.15, 26.58, 27.09, 32.47 (d, *J* = 15.5 Hz), 53.84 (d, *J* = 16.4 Hz), 71.40 (d, *J* = 10.0 Hz), 121.85, 124.02, 124.82, 127.04, 127.71, 127.87, 128.47 (d, *J* = 6.4 Hz), 128.90, 129.62, 130.02 (d, *J* = 8.2 Hz), 131.98, 132.53 (q, J = 32.8 Hz), 133.02, 133.13, 133.66, 134.80, 135.27, 135.82, 136.60, 138.58 (d, *J* = 12.8 Hz), 163.60; ^{31}P NMR (121 MHz, CDCl3) δ; -22.42; HRMS (ESI) *m/z* calcd for Chemical Formula: $C_{41}H_{40}F_6NO_2PSi$ $[M+H]^+$ = 752.2543, found = 752.2564.

***N*-((2*S*,3*R*)-3-((2,3-Dimethylbutan-2-yl)dimethylsilyloxy)-1-(diphenylphosphino)butan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2d**

A white solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.21 (s, 3H), 0.23 (s, 3H), 0.92 (d, *J* = 8.8 Hz, 6H), 0.96 (s, 3H), 0.97 (s, 3H), 1.19 (d, J = 6.4 Hz, 3H), 2.27 (dd, *J* = 7.6 Hz, 13.9 Hz, 1H), 2.71-2.75 (m, 1H), 4.18-4.24 (m, 1H), 4.34-4.38 (m, 1H), 6.68 (d, *J* = 8.2 Hz, 1H), 7.29-7.35 (m, 6H), 7.37-7.42 (m, 2H), 7.60-7.63 (m, 2H), 8.01 (s, 1H), 8.13 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ -2.64, -2.35, 18.55, 18.66, 20.33, 20.49, 21.32, 24.91, 32.11 (d, *J* = 12.3 Hz), 34.44, 53.42 (d, *J* = 16.4 Hz), 69.36 (d, *J* = 10.9 Hz), 124.83, 124.00, 124.84, 127.09, 128.57 (d, *J* = 6.4 Hz), 128.69 (d, *J* = 7.3 Hz), 128.80, 129.24, 132.23, 132.43, 132.71 (q, *J* = 25.2 Hz), 136.41, 163.53; ^{31}P NMR (121 MHz, $CDCl_3$) δ -22.45; HRMS (ESI) *m/z* calcd for $C_{33}H_{40}F_6NO_2PSi$ $[M+H]^+$ = 656.2543, found = 656.2568.

***N*-((2*S*,3*R*)-1-(Diphenylphosphino)-3-(1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yloxy)butan-2-yl)-3,5-bis(trifluoromethyl)benzamide 2e**



2-2 **2e**

To a solution of **2-2** (257 mg, 0.5 mmol) and Et_3N (139 μL, 1.0 mmol) in dry CH_2Cl_2 (5 mL) was slowly added TTMSSOTf (0.75 mmol, in CH_2Cl_2 solution, pre-prepared according to a known procedure described in ref. 7) at 0 °C. The resulting mixture was stirred at room temperature for 2 h, and water (5 mL) was added and the organic layer was separated. The aqueous phase was extracted with CH_2Cl_2 (2 x 5 mL). The combined organic layers were washed with brine and dried over Na_2SO_4. Solvent was removed under reduced pressure and the residue was purified column chromatography on silica gel (hexane/ethyl acetate = 50:1 to 5:1) to afford **2e** (170 mg, 45% yield) as a white solid, **2-2** (115 mg) was also recovered.

^{1}H NMR (500 MHz, $CDCl_3$) δ 0.24 (s, 27H), 1.15 (d, *J* = 5.7 Hz, 3H), 2.25-2.30 (m, 1H), 2.64-2.68 (m, 1H), 4.05 (dd, *J* = 6.3 Hz, 12.6 Hz, 1H), 4.17 (dd, *J* = 7.6 Hz, 15.1 Hz, 1H), 6.48 (d, *J* = 8.9 Hz, 1H), 7.27-7.32 (m, 6H), 7.39 (td, *J* = 7.6 Hz, 1.9 Hz, 2H), 7.55-7.58 (m, 2H), 7.98 (s, 1H), 8.06 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.85, 32.67 (d, *J* = 15.5 Hz), 53.45 (d, *J* = 15.5 Hz), 73.08 (d, *J* = 10.9 Hz), 121.82, 123.99, 124.79, 124.83 (d, *J* = 2.7 Hz), 127.01 (d, *J* = 2.7 Hz), 128.44 (d, *J* = 6.4 Hz), 128.51 (d, *J* = 7.3 Hz), 129.02, 132.07 (q, *J* = 33.6 Hz), 132.45 (d, *J* = 18.2 Hz), 133.00, 133.16, 136.40, 137.33 (d, *J* = 12.8 Hz), 138.65 (d, *J* = 11.9 Hz), 163.35; ^{31}P NMR (121 MHz, $CDCl_3$) δ -23.12; HRMS (ESI) *m/z* calcd for $C_{34}H_{48}F_6NO_2PSi_4$ $[M+H]^+$ = 760.2477, found = 760.2486.

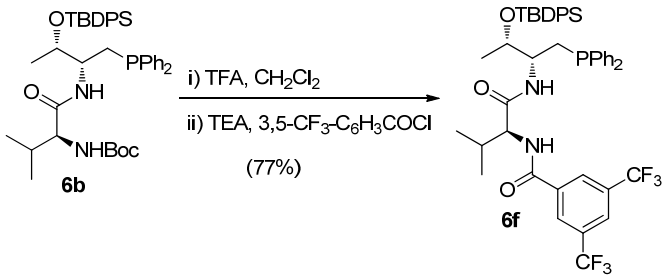
(3*R*,5*R*,7*R*)-(2*R*,3*S*)-3-(3,5-Bis(trifluoromethyl)benzamido)-4-(diphenylphosphino)butan-2-yl adamantane-1-carboxylate 2f

To solution of **2-2** (46 mg, 0.09 mmol) and Et_3N (25 μL, 0.18 mmol) in dry CH_2Cl_2 (1 mL) at 0 °C was added slowly 1-adamantanecarbonyl chloride. The resulting mixture was stirred at room temperature for 2 h, water (2 mL) was then added, and the organic layer was separated. The aqueous phase was extracted with CH_2Cl_2 (2 x 2 mL). The combined organic layers were washed with brine and dried over Na_2SO_4. Solvent was removed under reduced pressure and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 50:1 to 25:1) to afford **2f** (46 mg, 75% yield) as a white solid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.29 (d, *J* = 6.3 Hz, 3H), 1.64 (d, *J* = 12.0 Hz, 3H), 1.72 (d, *J* = 12.6 Hz, 3H), 1.83 (s, 6H), 1.99 (s, 3H), 2.39-2.44 (m, 1H), 2.50-2.54 (m, 1H), 4.48-4.55 (m, 1H), 5.26-5.30 (m, 1H), 6.21 (d, *J* = 8.9 Hz, 1H), 7.20-7.29 (m, 6H), 7.40-7.47 (m, 4H), 7.94 (s, 2H), 7.96 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ -2.64, -2.35, 18.55, 18.66, 20.33, 20.49, 21.32, 24.91, 32.11 (d, *J* = 12.3 Hz), 34.44, 53.42 (d, *J* = 16.4 Hz), 69.36 (d, *J* = 10.9 Hz), 124.83, 124.00, 124.84, 127.09, 128.57 (d, *J* = 6.4 Hz), 128.69 (d, *J* = 7.3 Hz), 128.80, 129.24, 132.23, 132.43, 132.71 (q, *J* = 25.2 Hz), 136.41, 163.53; ^{31}P NMR (121 MHz, $CDCl_3$) δ -22.45; HRMS (ESI) *m/z* calcd for $C_{36}H_{36}F_6NO_3P$ $[M+H]^+$ =

676.2410, found = 676.2416.

Preparation of dipeptide-based phosphine 6f.

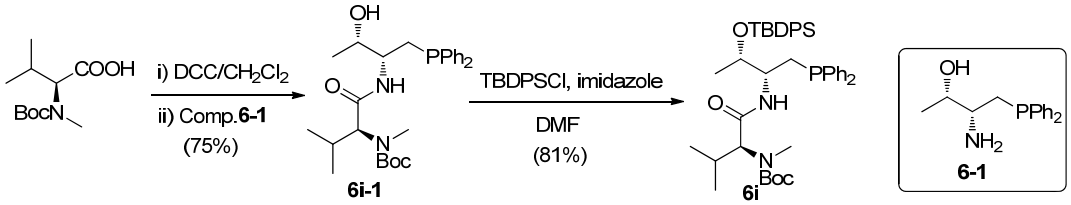


***N*-((*S*)-1-(((2*R*,3*S*)-3-((*tert*-Butyldiphenylsilyl)oxy)-1-(diphenylphosphino)butan-2-yl)amino)-3-methyl-1-oxobutan-2-yl)-3,5-bis(trifluoromethyl)benzamide 6f**

To a stirred solution of **6b** (36 mg, 0.05 mmol) in anhydrous CH_2Cl_2 (0.5 mL) was added TFA (0.1 mL), and the resulting mixture was stirred at room temperature for 2 hrs. The reaction was then quenched with saturated aqueous $NaHCO_3$ (5 mL), and extracted with CH_2Cl_2 several times (3 × 5 mL). The combined organic extracts were dried over Na_2SO_4, filtered and concentrated. The residue and Et_3N (14 µL, 0.1 mmol) were dissolved in anhydrous CH_2Cl_2 (0.5 mL) at 0 °C, 3,5-bis(trifluoromethyl)benzoyl chloride (11 µL, 0.06mmol) was added, and the mixture was stirred at 0 °C for 1 h. Solvent was removed and the residue was purified directly by flash column chromatography (hexane/ethyl acetate = 25 : 1 to 15 : 1) to afford **6f** as a white solid (33 mg, 77% yield).

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.03 (d, *J* = 6.3 Hz, 3H), 1.10 (s, 9H), 1.12 (s, 9H), 2.18 (dd, *J* = 6.9 Hz, 13.9 Hz, 1H), 2.37 (dd, *J* = 8.2 Hz, 12.6 Hz, 1H), 3.92-3.96 (m, 1H), 4.19 (dd, *J* = 6.3 Hz, 12.6 Hz, 1H), 6.05 (d, *J* = 9.5 Hz, 1H), 7.13 (d, *J* = 8.9 Hz, 1H), 7.21-7.25 (m, 4H), 7.28-7.34 (m, 4H), 7.36-7.40 (m, 5H), 7.43-7.45 (m, 2H), 7.67 (td, *J* = 1.3 Hz, 8.2 Hz, 4H), 7.71-7.73 (m, 1H), 8.03 (s, 1H), 8.29 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 19.37, 21.36, 26.88, 27.17, 32.77 (d, *J* = 13.7 Hz), 35.48, 52.97 (d, *J* = 16.4 Hz), 61.89, 70.85 (d, *J* = 9.1 Hz), 121.84, 124.01, 125.13, 127.49, 127.63, 127.70, 127.80, 128.46 (q, *J* = 6.4 Hz), 128.69 (d, *J* = 12.8 Hz), 129.63, 129.93 (d, *J* = 12.8 Hz), 132.51 (q, *J* = 33.7 Hz), 132.55 (d, *J* = 11.8 Hz), 132.71 (d, *J* = 11.9 Hz), 133.68, 134.79, 135.96, 135.99, 136.65, 164.32, 169.39; ^{31}P NMR (121 MHz, $CDCl_3$) δ -22.82; HRMS (ESI) *m/z* calcd for Chemical Formula: $C_{47}H_{51}F_6N_2O_3PSi$ $[M+H]^+$ = 887.3208, found = 887.3199.

Preparation of *N*-methylated dipeptide-based phosphine 6i



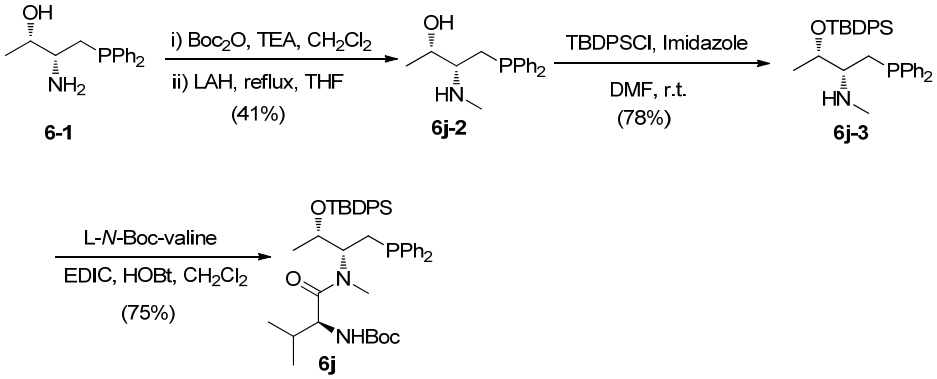
***tert*-Butyl ((*S*)-1-(((2*R*,3*S*)-3-((*tert*-butyldiphenylsilyl)oxy)-1-(diphenylphosphino)butan-2-yl)amino)-3-methyl-1-oxobutan-2-yl)(methyl)carbamate 6i**

To a stirred solution of *N*-methylated-*N*-Boc L-valine[8] (46 mg, 0.20 mmol) in anhydrous CH_2Cl_2 (1 mL) was added DCC (20 mg, 0.12 mmol), and the resulting mixture was stirred at room temperature for 2 hrs. The solution was then cooled down to 0 ^oC and a solution of **6-1** (27 mg, 0.10 mmol) in CH_2Cl_2 (0.5 mL) was added dropwise. The reaction mixture was further stirred for 0.5 h at 0 ^oC and 0.5 h at room temperature. Water (2 mL) was added to quench the reaction, and the resulting mixture was extracted with dichloromethane several times (3 x 2 mL). The combined organic extracts were dried over sodium sulfate, filtered and concentrated, and the residue was purified by column chromatography (hexane: ethyl acetate = 10:1) to afford **6i-1** (35 mg, 75%) as a colorless oil.

To a solution of **6i-1** in dry DMF (17 μL, 0.23 mmol) at room temperature under N_2 was added imidazole (15 mg, 0.23 mmol) and *tert*-butyldiphenylsilyl chloride (30 mg, 0.12 mmol). The resulting solution was stirred for 36 h, and the mixture was concentrated and the residue was purified directly by column chromatography (hexane/ethyl acetate = 25:1) to afford **6i** as a colorless oil (42 mg, 81 % yield).

^1H NMR (500 MHz, $CDCl_3$) δ 0.95 (d, J = 6.3 Hz, 3H), 0.98 (d, *J* = 6.3 Hz, 3H), 1.01 (d, *J* = 6.9 Hz, 3H), 1.11 (s, 9H), 1.43 (s, 9H), 2.18-2.25 (m, 1H), 2.32-2.38 (m, 1H), 2.92 (s, 3H), 3.85 (br, 1H), 4.04 (br, 1H), 4.24-4.26 (m, 1H), 6.72 (d, *J* = 8.9 Hz, 1H), 7.29-7.30 (m, 3H), 7.34-7.35 (m, 6H), 7.38-7.41 (m, 5H), 7.46 (t, *J* = 6.9 Hz, 2H), 7.71 (d, *J* = 6.3 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.40, 19.36, 19.91, 20.54 (rotamer), 25.46, 26.56 (rotamer), 27.11, 28.34, 33.33 (d, *J* = 13.8 Hz), 51.20 (d, *J* = 14.6 Hz), 64.49, 71.29, 79.97, 127.49, 127.67, 128.32 (d, *J* = 6.4 Hz), 128.59, 129.66 (d, *J* = 9.1 Hz), 132.24, 132.38, 133.19, 133.35, 133.45, 134.09, 134.80, 136.00, 138.56 (d, *J* = 13.8 Hz), 157.44, 169.96; ^{31}P NMR (121 MHz, $CDCl_3$) δ -23.37; HRMS (ESI) *m/z* calcd for $C_{43}H_{57}N_2O_4PSi$ $[M+H]^+$ = 725.3898, found = 725.3908.

Preparation of *N*-methylated dipeptide-based phosphine 6j.



(2*R*,3*S*)-4-(Diphenylphosphino)-3-(methylamino)butan-2-ol 6j-2

To solution of amino phosphine **2-2** (49 mg, 0.18 mmol) and Et_3N (50 μL, 0.36 mmol) in dry CH_2Cl_2 (2 mL) at 0 ^oC was added slowly Boc_2O, and the resulting mixture was stirred at room temperature for 2 h. Water (3 mL) was added and the organic layer was separated. The aqueous phase was extracted with CH_2Cl_2 (2 x 2 mL). The combined organic layers were washed with brine and dried over Na_2SO_4. Solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 10:1 to 5:1)

to afford carbamte intermediate (51 mg, 75% yield) as a colorless oil. To the solution of the carbamate intermediate in dry THF (10 mL) at 0 °C was added slowly LAH powder (30 mg, 0.81 mmol), and the resulting mixture was refluxed for 72 h. After cooling down to room temperature and further to 0 °C, the reaction mixture was quenched by addition of water and NaOH (1 N) solution. The insoluble slurry was filtrated off and washed with ethyl acetate. The filtrate was collected and the organic phase was separated. The aqueous layer was extracted with ethyl acetate several times, and the combined organic layers were washed with brine and dried over Na_2SO_4. Solvent was removed under reduced pressure, and the residue was purified column chromatography on silica gel (hexane/ethyl acetate = 5:1 to 1:1) to afford *N*-methylated phosphine **6j-2** as a colorless oil (21 mg, 41% yield for two steps).

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.13 (d, *J* = 6.3 Hz, 3H), 2.13-2.17 (m, 1H), 2.29-2.39 (m, 4H), 2.84 (br, 2H), 3.59-3.64 (m, 1H), 7.32-7.36 (m, 6H), 7.41-7.50 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.78, 30.03 (d, *J* = 13.7 Hz), 33.33 (d, *J* = 3.7 Hz), 62.59 (d, *J* = 11.9 Hz), 68.74 (d, *J* = 9.1 Hz), 128.46, 128.51, 128.57, 128.63 (d, *J* = 2.7 Hz), 128.99, 132.45, 132.60, 132.92, 133.07, 137.73 (d, *J* = 11.9 Hz), 138.68 (d, *J* = 12.3 Hz); ^{31}P NMR (121 MHz, $CDCl_3$) δ -23.7; HRMS (ESI) *m/z* calcd for $C_{17}H_{22}NOP$ $[M+H]^+$ = 288.1512, found = 288.1524.

(2*S*,3*R*)-3-((*tert*-Butyldiphenylsilyl)oxy)-1-(diphenylphosphino)-*N*-methylbutan-2-amine 6j-3

To a solution of **6j-2** (17 mg, 0.06 mmol) in dry DMF (14 μL, 0.18 mmol) at room temperature under N_2 was added imidazole (12 mg, 0.18 mmol) and *tert*-butyldiphenylsilyl chloride (19 mg, 0.07 mmol). The solution was stirred for 36 h, and the mixture was concentrated and purified directly by column chromatography (hexane/ethyl acetate = 25:1) to afford **6j-3** as a colorless oil (24 mg, 78 % yield).

^{1}H NMR (500 MHz, $CDCl_3$) δ 1.02 (s, 9H), 1.04 (d, *J* = 6.2 Hz, 3H), 1.86-1.94 (m, 1H), 2.07 (s, 3H), 2.36-2.41 (m, 1H), 2.59-2.63 (m, 1H), 3.98-4.01 (m, 1H), 7.24-7.27 (m, 2H), 7.30-7.34 (m, 8H), 7.39-7.40 (m, 2H), 7.47 (t, *J* = 7.0 Hz, 2H), 7.57 (dd, *J* = 1.9 Hz, 8.1 Hz, 2H), 7.60 (dd, *J* = 1.9 Hz, 8.2 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.09, 19.25, 27.08, 28.80 (d, *J* = 10.9 Hz), 62.06 (d, *J* = 12.8 Hz), 69.38 (d, *J* = 6.4 Hz), 127.46 (d, *J* = 7.3 Hz), 128.29, 128.35, 128.40, 128.43, 128.80, 129.53, 132.44 (d, *J* = 18.2 Hz), 133.37, 133.53, 134.27, 135.93 (d, *J* = 9.1 Hz), 137.89, 139.50; ^{31}P NMR (121 MHz, $CDCl_3$) δ -21.5; HRMS (ESI) *m/z* calcd for $C_{33}H_{40}NOPSi$ $[M+H]^+$ = 526.2690, found = 526.2684.

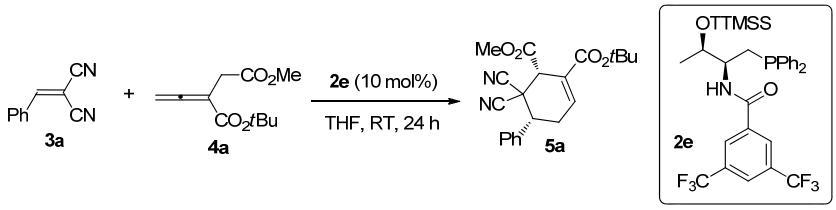
***tert*-Butyl ((*S*)-1-(((2*R*,3*S*)-3-((*tert*-butyldiphenylsilyl)oxy)-1-(diphenylphosphino)butan-2-yl)(methyl) amino)-3-methyl-1-oxobutan-2-yl)carbamate 6j**

To a solution of L-*N*-Boc-valine (8.7 mg, 0.04 mmol) in dry CH_2Cl_2 (0.5 mL) at 0 °C under argon was added HOBt (6.5 mg, 0.048 mmol), *N*,*N*-diisopropylethylamine (8.3 μL, 0.048 mmol) and EDCI (7.5 mg, 0.048 mmol). After stirring for 10 min, amine **6j-3** (21 mg, 0.04 mmol) in dry CH_2Cl_2 (0.5 mL) was introduced at the same temperature. The stirring was continued at 0 °C for 1 h and then at room temperature overnight. The mixture was diluted with

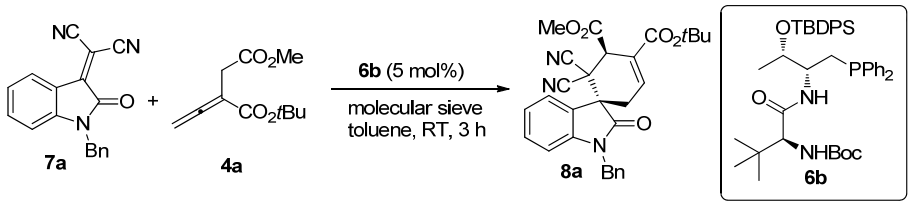
CH_2Cl_2, washed with saturated aqueous NH_4Cl solution, and the organic layer was dried over Na_2SO_4. Solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 25:1 to 10:1) to afford **6j** as a colorless oil (21 mg, 75% yield).

^{1}H NMR (500 MHz, d^6-DMSO) δ 0.81-0.82 (m, 6H), 0.83-0.88 (m, 3H), 0.96 & 0.98 (s, rotamers, 9H), 1.34 & 1.41 (s, rotamers, 9H), 1.93-2.00 (m, 1H), 2.33-2.40 (m, 1H), 2.86 & 3.14 (s,romaters, 3H), 4.08 (m, 1H), 4.25-4.28 (m, 1H), 4.44 (m, 1H), 6.52 (m, 1H), 7.26-7.34 (m, 8H), 7.38-7.50 (m, 8H), 7.61-7.63 (m, 4H); ^{31}P NMR (121 MHz, $CDCl_3$) δ -24.01 & -22.83 (rotamers); HRMS (ESI) *m/z* calcd for $C_{43}H_{57}N_2O_4PSi$ $[M+H]^+$ = 725.3898, found = 725.3905.

D. Representative procedure



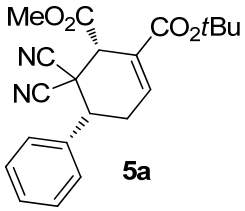
To a flame-dried round bottle flask with a magnetic stirring bar under Ar were added catalyst **2e** (3.8 mg, 0.005 mmol) and alkene **3a** (7.7 mg, 0.05 mmol), followed by the addition of dry THF (0.5 mL). After the mixture was stirred for 1 min, the allenoate **4a** (16 μL, 0.075 mmol) was added. The flask was sealed, and the reaction was stirred at room temperature for 24 hrs. THF was removed under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 25:1 to 15:1) to afford **5a** (16.8 mg, 92% yield) as a white solid.



To a flame-dried round bottle flask with a magnetic stirring bar at room temperature under argon were added catalyst **6b** (1.1 mg, 0.0015 mmol, in toluene), 4 Å molecular sieves (30 mg) and dicyanoalkene **7a** (15.8 mg, 0.05 mmol), followed by the addition of anhydrous toluene (1.5 mL). After the mixture was stirred for 2 minutes, the allenoate **4a** (9.5 μL, 0.045 mmol) was then added. The flask was sealed, and the reaction was stirred at room temperature for 3 hrs. Toluene was then removed under the reduced pressure, and the residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 15:1 to 10:1) to afford **8a** as a white solid (13.6 mg, 91% yield).

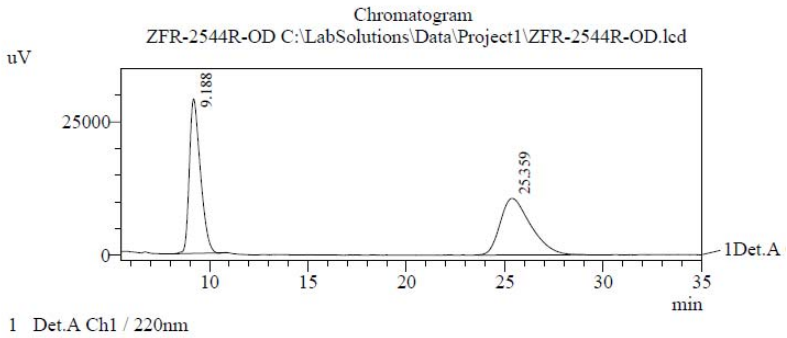
E. Analytical Data and HPLC Chromatogram of the catalysts and [4+2] annulation products

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-phenylcyclohex-2-ene-1,2-dicarboxylate **5a**



5a

A white solid; $[\alpha]^{25}_{D}$ = -90.0 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.66-2.73 (m, 1H), 3.03-3.11 (m, 1H), 3.25 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.86 (s, 3H), 4.15-4.16 (m, 1H), 7.17-7.19 (m, 1H), 7.43-7.49 (m, 5H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.92, 28.66, 41.15, 46.75, 51.36, 53.18, 82.45, 111.64, 113.36, 126.74, 128.45, 129.21, 129.64, 135.17, 138.43, 163.56, 168.00; HRMS (ESI) *m/z* calcd for $C_{21}H_{22}N_2O_4$ $[M+Na]^+$ = 389.1472, found = 389.1460; The ee value was 98%, t_R (major) = 25.3 min, t_R (minor) = 9.2 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

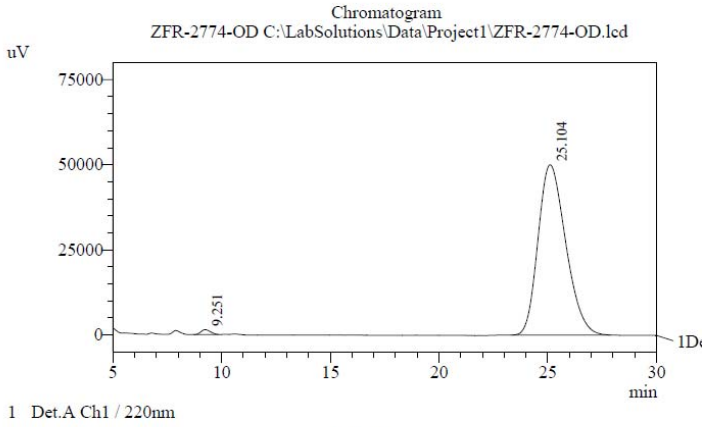


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.188	1131001	28978	49.653	73.166
2	25.359	1146819	10628	50.347	26.834
Total		2277820	39605	100.000	100.000

Racemic **5a**



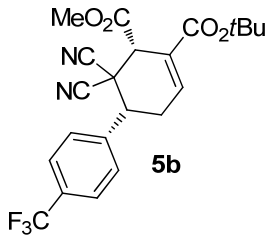
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.251	42479	1435	0.949	2.792
2	25.104	4433246	49980	99.051	97.208
Total		4475725	51416	100.000	100.000

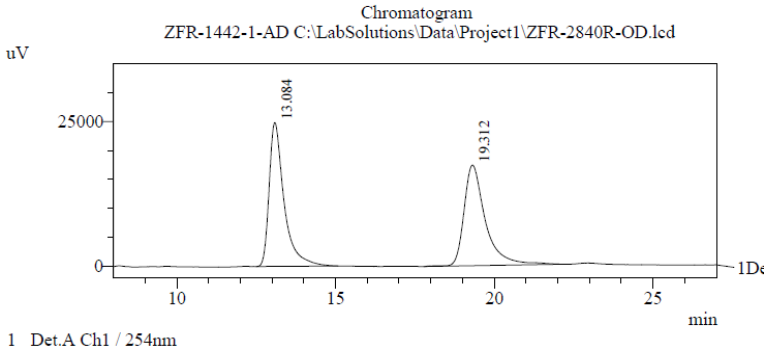
Enantiomerically enriched **5a**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(4-(trifluoromethyl)phenyl)cyclohex-2-ene-1,2-dicarboxylate **5b**



5b

A white solid; $[\alpha]^{25}_{D}$ = -61.5 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.68-2.74 (m, 1H), 3.03-3.11 (m, 1H), 3.33 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.88 (s, 3H), 4.17-4.18 (m, 1H), 7.17-7.19 (m, 1H), 7.61 (d, *J* = 8.2 Hz, 2H), 7.72 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.45, 40.72, 46.44, 51.20, 53.31, 82.67, 111.36, 113.09, 126.24 (q, *J* = 3.7 Hz), 126.90, 129.01, 131.76, 132.03, 137.75, 139.03, 163.38, 167.78; HRMS (ESI) *m/z* calcd for $C_{22}H_{21}F_3N_2O_4$ $[M+Na]^+$ = 457.1346, found = 457.1347; The ee value was 93%, t_R (major) = 19.3 min, t_R (minor) = 13.1 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

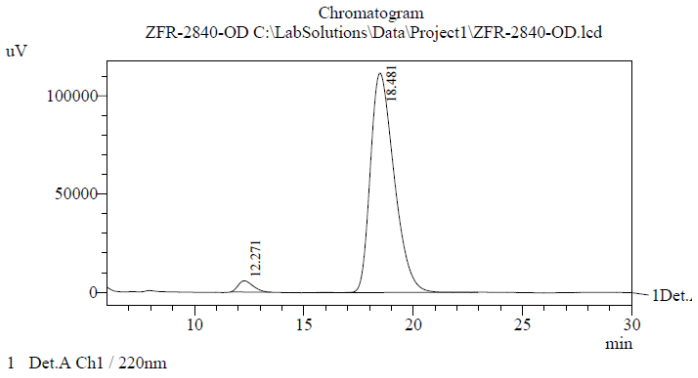


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	13.084	811838	24809	49.926	58.822
2	19.312	814260	17367	50.074	41.178
Total		1626098	42176	100.000	100.000

Racemic **5b**



PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
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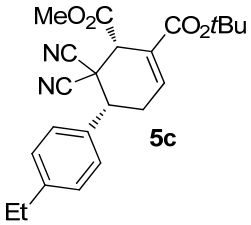
2	18.481	8430275	111660	96.857	95.122
Total		8703856	117386	100.000	100.000

Enantiomerically enriched **5b**

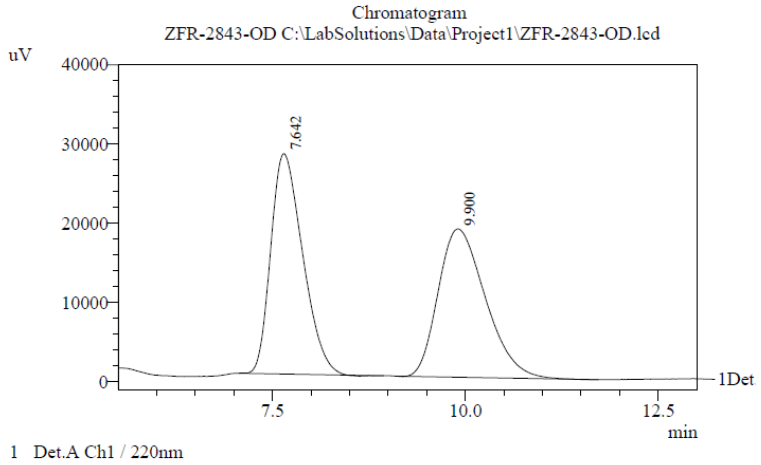
(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(4-ethylphenyl)cyclohex-2-ene-1,2-dicarboxylate **5c**



5c

A white solid; $[\alpha]^{25}_{D}$ = -95.1 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.25 (t, *J* = 7.6 Hz, 3H), 1.49 (s, 9H), 2.64-2.70 (m, 3H), 3.02-3.09 (m, 1H), 3.22 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.86 (s, 3H), 4.13-4.15 (m, 1H), 7.17-7.19 (m, 1H), 7.26 (d, *J* = 8.2 Hz, 2H), 7.38 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.23, 27.91, 28.48, 28.66, 41.28, 46.40, 51.30, 53.18, 82.41, 111.69, 113.46, 126.63, 128.38, 128.65, 132.30, 138.62, 145.81, 163.59, 168.08; HRMS (ESI) *m/z* calcd for $C_{23}H_{26}N_2O_4$ $[M+Na]^+$ = 417.1785, found = 417.1796; The ee value was 98%, t_R (major) = 9.9 min,

t_R (minor) = 7.6 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



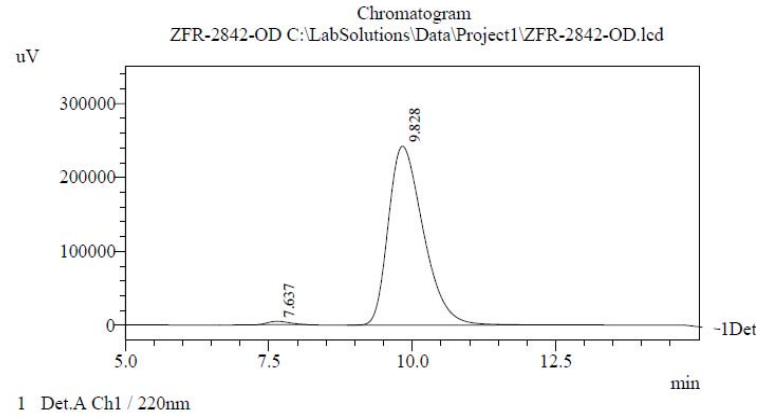
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.642	799757	27800	50.066	59.781
2	9.900	797655	18703	49.934	40.219
Total		1597412	46502	100.000	100.000

Racemic **5c**



1 Det.A Ch1 / 220nm

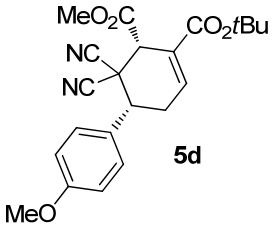
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.637	120947	4646	1.161	1.883
2	9.828	10292339	242070	98.839	98.117
Total		10413286	246716	100.000	100.000

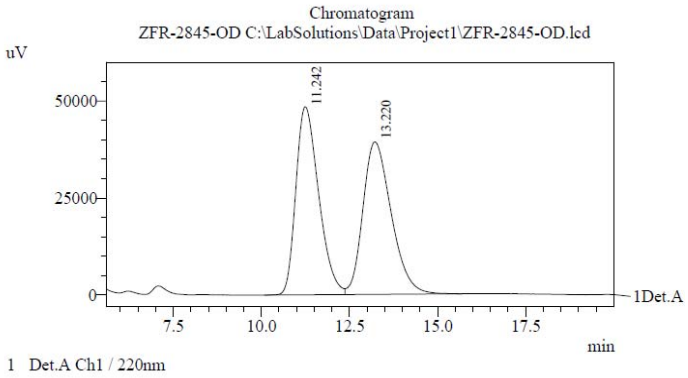
Enantiomerically enriched **5c**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(4-methoxyphenyl)cyclohex-2-ene-1,2-dicarboxylate **5d**



5d

A white solid; $[\alpha]^{25}_{D}$ = -85.6 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48 (s, 9H), 2.63-2.69 (m, 1H), 2.99-3.07 (m, 1H), 3.21 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.83 (s, 3H), 3.86 (s, 3H), 4.13-4.14 (m, 1H), 6.95 (d, *J* = 8.8 Hz, 2H), 7.16-7.18 (m, 1H), 7.39 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.71, 41.51, 46.06, 51.24, 53.19, 55.31, 82.42, 111.71, 113.52, 114.52, 126.63, 127.00, 129.64, 138.62, 160.45, 163.58, 168.08; HRMS (ESI) *m/z* calcd for $C_{22}H_{24}N_2O_5$ $[M+Na]^+$ = 419.1577, found = 419.1596; The ee value was 95%, t_R (major) = 13.2 min, t_R (minor) = 11.2 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

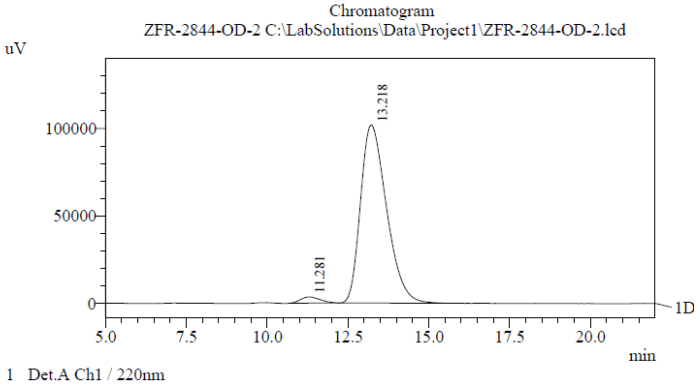


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	11.242	2186367	48529	49.812	55.238
2	13.220	2202876	39325	50.188	44.762
Total		4389242	87854	100.000	100.000

Racemic **5d**



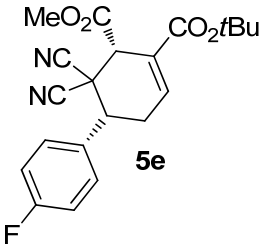
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	11.281	146898	3511	2.509	3.335
2	13.218	5707826	101767	97.491	96.665
Total		5854724	105278	100.000	100.000

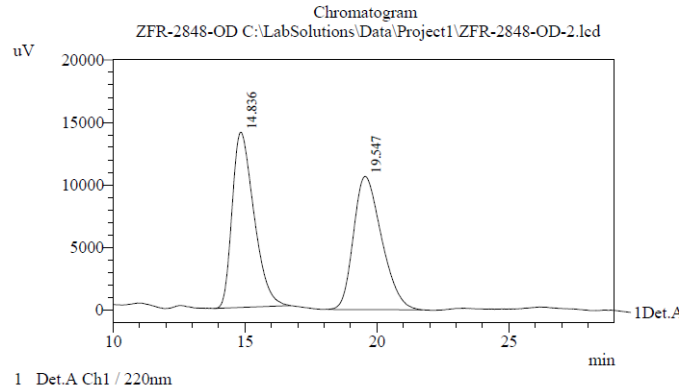
Enantiomerically enriched **5d**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(4-fluorophenyl)cyclohex-2-ene-1,2-dicarboxylate **5e**



5e

A white solid; $[\alpha]^{25}_{D}$ = -82.8 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.65-2.71 (m, 1H), 2.98-3.06 (m, 1H), 3.25 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.14-4.15 (m, 1H), 7.12-7.17 (m, 3H), 7.45-7.48 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.70, 41.23, 46.04, 51.22, 53.24, 82.55, 111.53, 113.31, 116.30 (d, *J* = 21.9 Hz), 126.80, 130.28 (d, *J* = 8.2 Hz), 130.96 (d, *J* = 3.7 Hz), 138.13, 163.37 (d, *J* = 247.8 Hz), 163.48, 167.91; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}FN_2O_4$ $[M+Na]^+$ = 407.1378, found = 407.1388; The ee value was 95%, t_R (major) = 19.5 min, t_R (minor) = 14.8 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

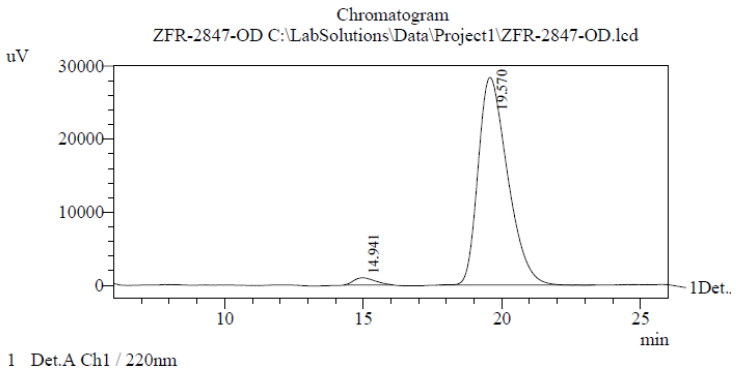


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.836	806283	14018	50.478	56.802
2	19.547	791024	10661	49.522	43.198
Total		1597307	24678	100.000	100.000

Racemic **5e**



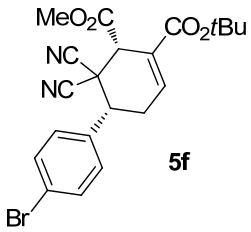
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.941	53029	1006	2.463	3.421
2	19.570	2100063	28410	97.537	96.579
Total		2153092	29416	100.000	100.000

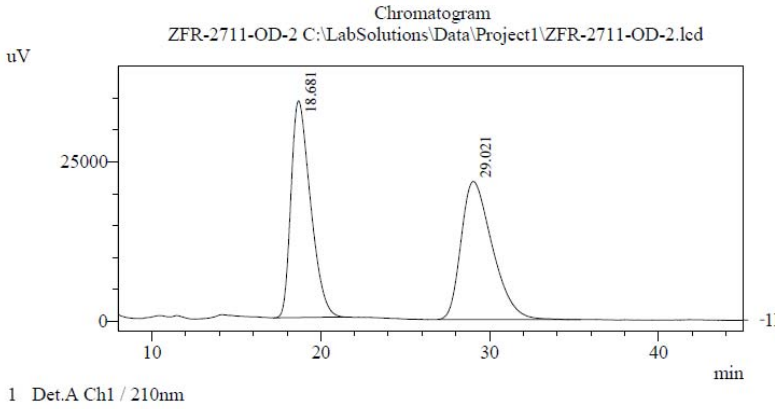
Enantiomerically enriched **5e**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 5-(4-bromophenyl)-6,6-dicyanocyclohex-2-ene-1,2-dicarboxylate **5f**



5f

A colorless oil; $[\alpha]^{25}_{D}$ = -18.3 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.64-2.71 (m, 1H), 2.98-3.05 (m, 1H), 3.22 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.13-4.15 (m, 1H), 7.15-7.17 (m, 1H), 7.35(d, *J* = 8.2 Hz, 2H), 7.58 (d, *J* = 8.9 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.49, 40.92, 46.23, 51.21, 53.27, 82.59, 111.45, 113.23, 123.98, 126.83, 130.07, 132.46, 134.11, 137.99, 163.43, 167.85; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}{}^{79}BrN_2O_4$ $[M+Na]^+$ = 467.0577, found = 467.0577; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}{}^{81}BrN_2O_4$ $[M+Na]^+$ = 469.0556, found = 469.0563; The ee value was 95%, t_R (major) = 29.0 min, t_R (minor) = 18.7 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

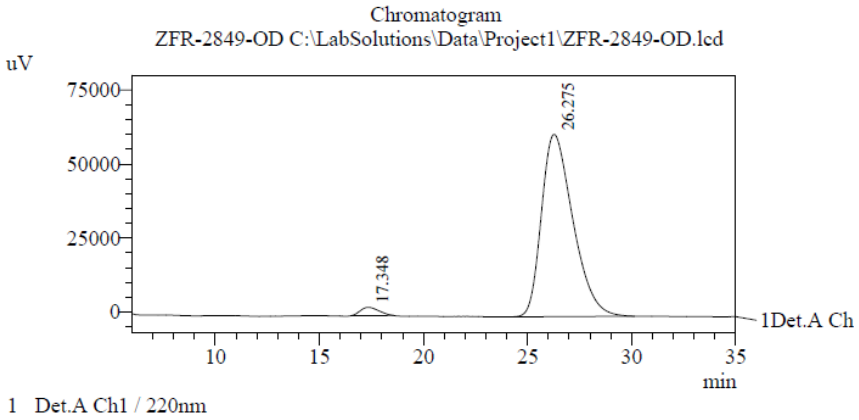


PeakTable

Detector A Ch1 210nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	18.681	2731068	34042	49.295	61.053
2	29.021	2809155	21716	50.705	38.947
Total		5540222	55758	100.000	100.000

Racemic **5f**



1 Det.A Ch1 / 220nm

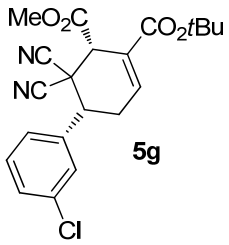
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	17.348	173288	2810	2.604	4.364
2	26.275	6480184	61566	97.396	95.636
Total		6653472	64376	100.000	100.000

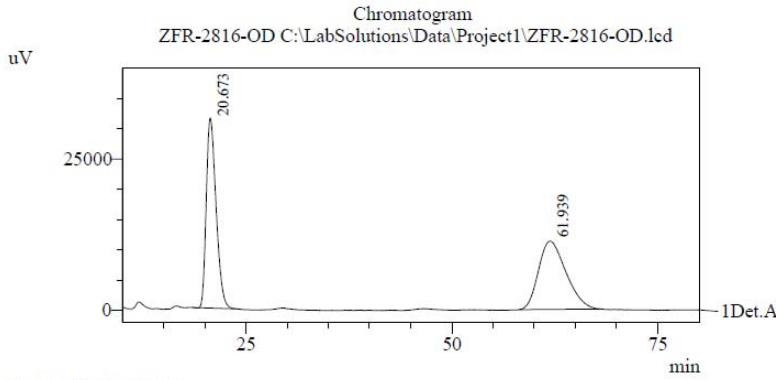
Enantiomerically enriched **5f**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 5-(3-chlorophenyl)-6,6-dicyanocyclohex-2-ene-1,2-dicarboxylate **5g**



5g

A white solid; $[\alpha]^{25}_{D}$ = -66.0 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.65-2.71 (m, 1H), 2.98-3.05 (m, 1H), 3.20 (dd, *J* = 4.5 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.13-4.15 (m, 1H), 7.15-7.17 (m, 1H), 7.32 (t, *J* = 7.9 Hz, 1H), 7.43 (d, *J* = 8.2 Hz, 1H), 7.57-7.60 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.60, 40.80, 46.28, 51.25, 53.30, 82.61, 111.35, 113.09, 123.20, 126.82, 127.06, 130.77, 131.53, 132.89, 137.35, 137.96, 163.42, 167.83; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}ClN_2O_4$ $[M+Na]^+$ = 423.1082, found = 423.1088; The ee value was 99%, t_R (major) = 61.9 min, t_R (minor) = 20.7 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



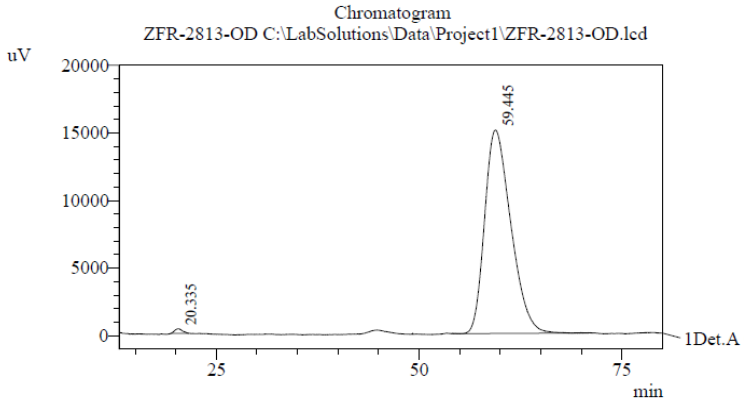
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	20.673	2600621	31413	49.833	73.574
2	61.939	2618056	11283	50.167	26.426
Total		5218677	42696	100.000	100.000

Racemic **5g**



1 Det.A Ch1 / 220nm

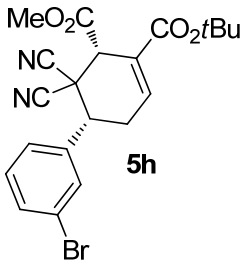
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	20.335	23168	347	0.679	2.255
2	59.445	3386580	15043	99.321	97.745
Total		3409748	15390	100.000	100.000

Enantiomerically enriched **5g**

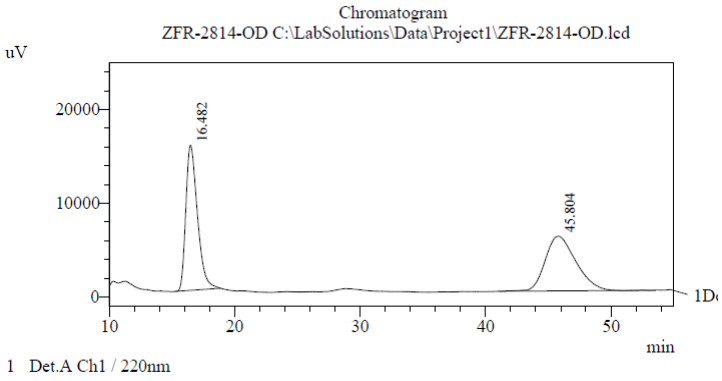
(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 5-(3-bromophenyl)-6,6-dicyanocyclohex-2-ene-1,2-dicarboxylate 5h



5h

A colorless oil; $[\alpha]^{25}_{D}$ = -97.5 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.66-2.72 (m, 1H), 2.98-3.06 (m, 1H), 3.22 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.08-4.10 (m, 1H), 6.43 (dd, *J* = 1.9 Hz, 3.2 Hz, 1H), 6.54 (d, *J*

= 3.8 Hz, 1H), 7.12-7.14 (m, 1H), 7.49 (d, *J* = 1.9 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.43, 27.91, 39.86, 40.64, 50.31, 53.26, 82.55, 109.89, 110.88, 111.21, 113.27, 126.69, 137.62, 143.72, 148.58. 163.41, 167.78; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}{}^{79}BrN_2O_4$ $[M+Na]^+$ = 467.0577, found = 467.0577; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}{}^{81}BrN_2O_4$ $[M+Na]^+$ = 469.0556, found = 469.0563; The ee value was 99%, t_R (major) = 45.8 min, t_R (minor) = 16.5 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

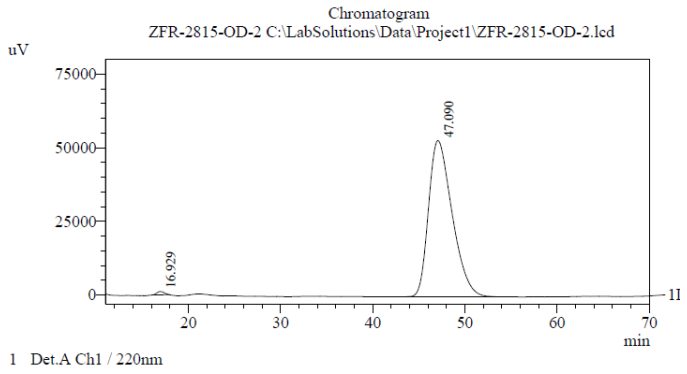


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	16.482	998649	15497	50.125	72.608
2	45.804	993686	5847	49.875	27.392
Total		1992335	21344	100.000	100.000

Racemic **5h**



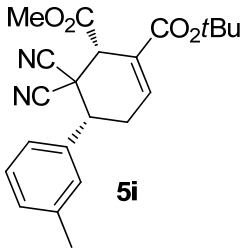
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	16.929	61708	1142	0.650	2.110
2	47.090	9434227	52993	99.350	97.890
Total		9495935	54136	100.000	100.000

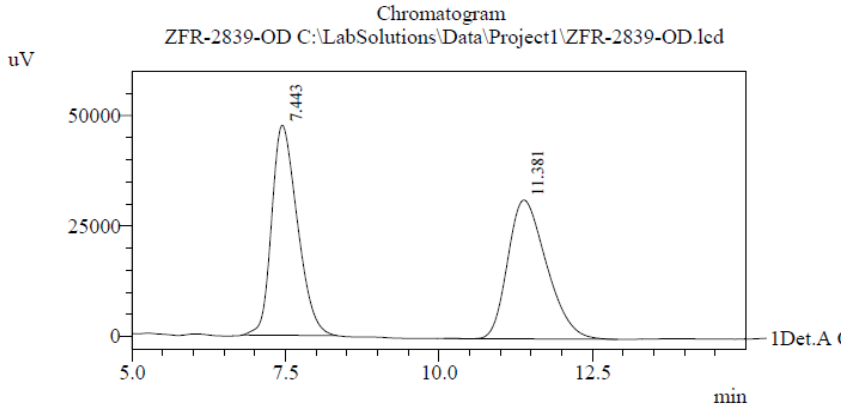
Enantiomerically enriched **5h**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-m-tolylcyclohex-2-ene-1,2-dicarboxylate **5i**



5i

A white solid; $[\alpha]^{25}_{D}$ = -106.9 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.39-2.71 (m, 1H), 3.01-3.09 (m, 1H), 3.20 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.13-4.15 (m, 1H), 7.17-7.19 (m, 1H), 7.23-7.27 (m, 3H), 7.31-7.34 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.48, 27.91, 28.74, 41.10, 46.69, 51.41, 53.20, 82.44, 111.66, 113.36, 125.49, 126.67, 129.01, 129.06, 130.39, 135.12, 138.60, 138.99, 163.58, 168.06; HRMS (ESI) *m/z* calcd for $C_{22}H_{24}N_2O_4$ $[M+Na]^+$ = 403.1628, found = 403.1632; The ee value was 98%, t_R (major) = 11.4 min, t_R (minor) = 7.4 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



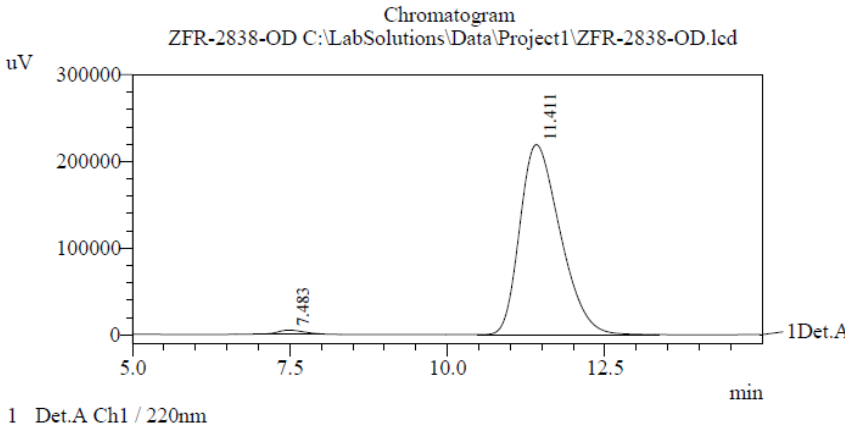
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.443	1390401	47531	50.153	60.205
2	11.381	1381941	31417	49.847	39.795
Total		2772342	78947	100.000	100.000

Racemic **5i**



1 Det.A Ch1 / 220nm

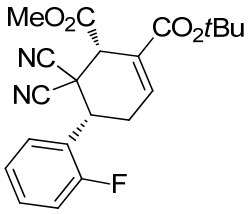
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.483	111188	4308	1.123	1.928
2	11.411	9785664	219115	98.877	98.072
Total		9896853	223423	100.000	100.000

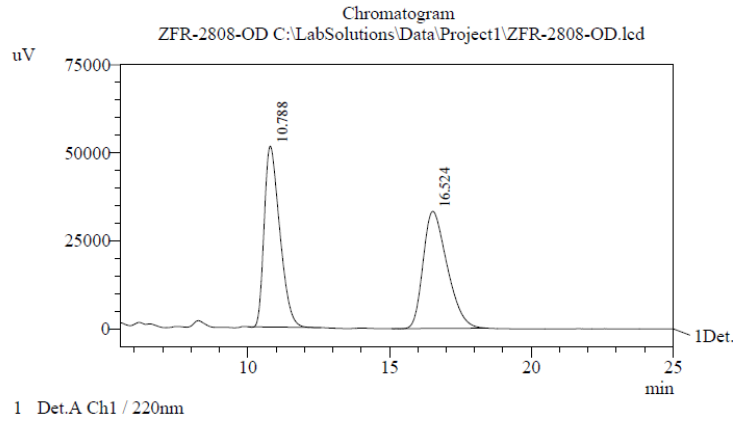
Enantiomerically enriched **5i**

(1*S*,5*S*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(2-fluorophenyl)cyclohex-2-ene-1,2-dicarboxylate **5j**



5j

A white solid; $[\alpha]^{25}_{D}$ = -71.7 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.61-2.67 (m, 1H), 2.99-3.06 (m, 1H), 3.83 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.88 (s, 3H), 4.18-4.20 (m, 1H), 7.16-7.20 (m, 2H), 7.25-7.28 (m, 1H), 7.42 (dt, *J* = 1.9 Hz, 7.9 Hz, 1H), 7.63-7.66 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 37.84, 37.87, 40.35, 51.22, 53.24, 82.55, 111.63, 112.87, 116.11 (d, *J* = 21.7 Hz), 122.66 (d, *J* = 12.8 Hz), 125.05 (d, *J* = 3.6 Hz), 126.90, 127.67 (d, *J* = 2.7 Hz), 131.11 (d, *J* = 9.1 Hz), 138.31, 160.66 (d, *J* = 246.9 Hz), 163.43, 167.95; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}FN_2O_4$ $[M+Na]^+$ = 407.1378, found = 407.1383; The ee value was 95%, t_R (major) = 16.5 min, t_R (minor) = 10.8 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

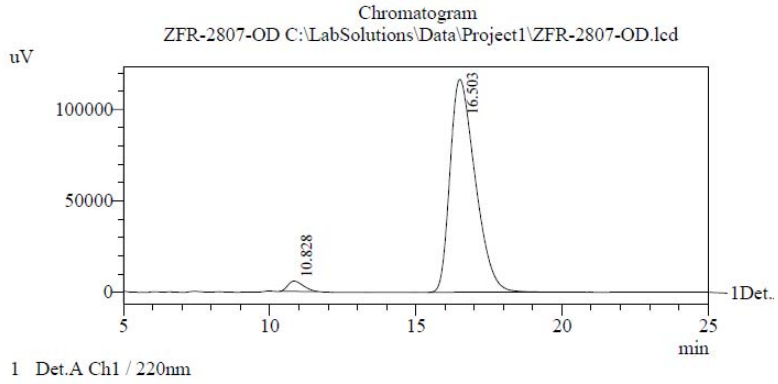


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	10.788	1957496	51336	49.939	60.714
2	16.524	1962262	33218	50.061	39.286
Total		3919758	84553	100.000	100.000

Racemic **5j**



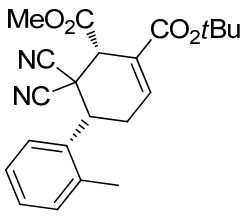
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	10.828	204685	5632	2.845	4.612
2	16.503	6990539	116476	97.155	95.388
Total		7195224	122108	100.000	100.000

Enantiomerically enriched **5j**

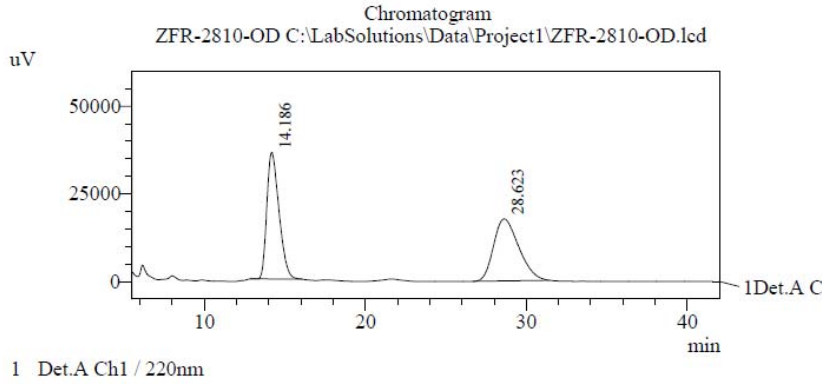
(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-o-tolylcyclohex-2-ene-1,2-dicarboxylate **5k**



5k

A white solid; $[\alpha]^{25}_{D}$ = -80.7 (c, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.44-2.64 (m, 1H), 2.99-3.06 (m, 1H), 3.64 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.88 (s, 3H), 4.16-4.17 (m, 1H), 7.19-7.20 (m, 1H), 7.27-7.33 (m, 3H), 7.64-7.65 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.09, 27.91, 29.30, 40.45, 41.23, 51.93, 53.21, 82.48, 111.83, 113.16,

126.12, 126.80, 127.14, 129.10, 131.40, 133.79, 136.90, 139.07, 163.62, 167.97; HRMS (ESI) *m/z* calcd for $C_{22}H_{24}N_2O_4$ $[M+Na]^+$ = 403.1628, found = 403.1624; The ee value was 99%, t_R (major) = 28.6 min, t_R (minor) = 14.2 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



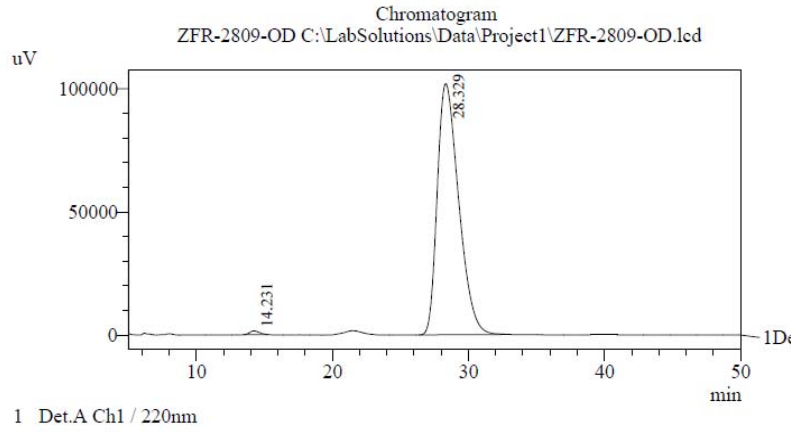
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.186	1899778	36077	49.690	67.094
2	28.623	1923500	17694	50.310	32.906
Total		3823278	53771	100.000	100.000

Racemic **5k**



1 Det.A Ch1 / 220nm

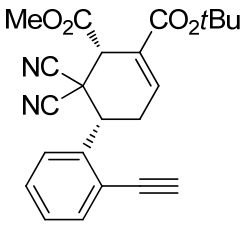
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	14.231	75635	1530	0.672	1.479
2	28.329	11171312	101908	99.328	98.521
Total		11246948	103438	100.000	100.000

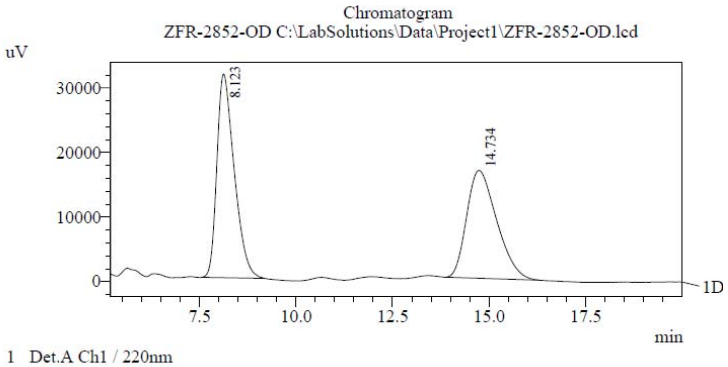
Enantiomerically enriched **5k**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(2-ethynylphenyl)cyclohex-2-ene-1,2-dicarboxylate **5l**



5l

A white solid; $[\alpha]^{25}_{D}$ = -182.8 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.65-2.73 (m, 1H), 2.93-3.03 (m, 1H), 3.41 (s, 1H), 3.88 (s, 3H), 4.12-4.17 (m, 2H), 7.17-7.19 (m, 1H), 7.39 (td, *J* = 2.6 Hz, 1.3 Hz, 1H), 7.47 (td, *J* = 2.6 Hz, 1.3 Hz, 1H), 7.63 (d, *J* = 8.2 Hz, 1H), 7.71 (td, *J* = 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.93, 29.06, 40.24, 43.00, 51.68, 53.20, 80.96, 82.54, 83.71, 111.86, 112.68, 123.36, 126.04, 126.97, 129.08, 129.86, 133.80, 137.43, 138.72, 163.60, 167.98; HRMS (ESI) *m/z* calcd for $C_{23}H_{22}N_2O_4$ $[M+Na]^+$ = 413.1472, found = 413.1478; The ee value was 91%, t_R (major) = 14.7 min, t_R (minor) = 8.1 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

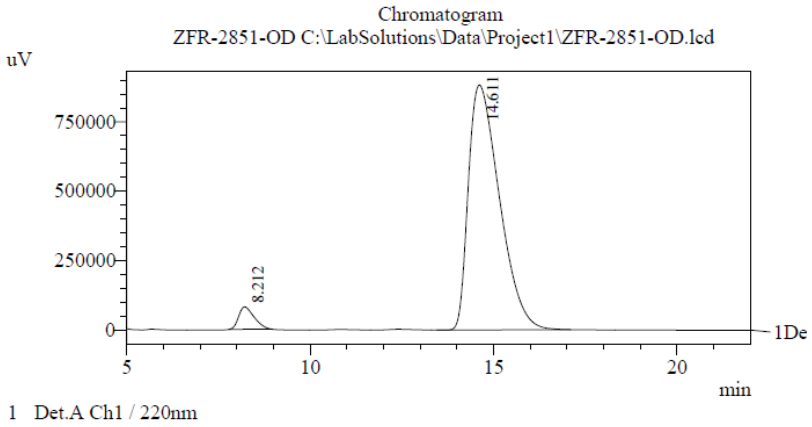


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.123	985848	31537	50.319	64.957
2	14.734	973365	17014	49.681	35.043
Total		1959213	48551	100.000	100.000

Racemic **5l**



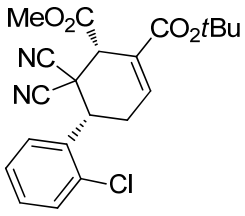
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.212	2366567	80791	4.356	8.395
2	14.611	51959484	881579	95.644	91.605
Total		54326051	962370	100.000	100.000

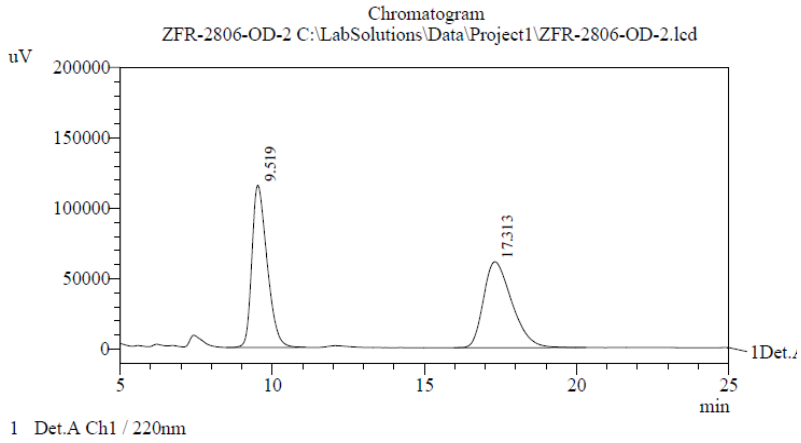
Enantiomerically enriched **5l**

(1*S*,5*S*)-2-*tert*-Butyl 1-methyl 5-(2-chlorophenyl)-6,6-dicyanocyclohex-2-ene-1,2-dicarboxylate **5m**



5m

A white solid; $[\alpha]^{25}_{D}$ = -47.3 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.63-2.69 (m, 1H), 2.92-2.99 (m, 1H), 3.88 (s, 3H), 4.10 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 4.19-4.20 (m, 1H), 7.17-7.19 (m, 1H), 7.35-7.42 (m, 2H), 7.50-7.52 (m, 1H), 7.73 (dd, *J* = 1.3 Hz, 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.90, 39.95, 41.43, 51.60, 53.24, 82.57, 111.75, 112.55, 127.00, 127.67, 130.45, 130.48, 133.08, 134.97, 138.51, 163.45, 167.90; HRMS (ESI) *m/z* calcd for $C_{21}H_{21}ClN_2O_4$ $[M+Na]^+$ = 423.1082, found = 423.1085; The ee value was 98%, t_R (major) = 17.3 min, t_R (minor) = 9.5 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



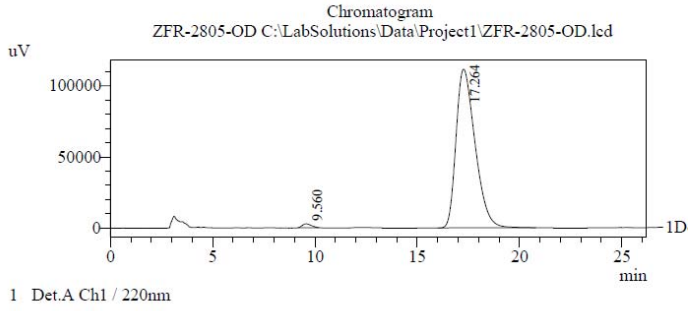
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.519	4008369	115204	50.375	65.392
2	17.313	3948660	60969	49.625	34.608
Total		7957029	176173	100.000	100.000

Racemic **5m**



1 Det.A Ch1 / 220nm

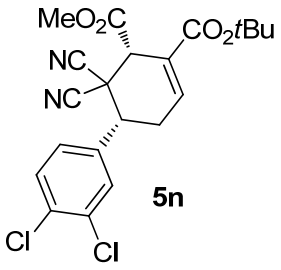
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.560	79133	2610	1.086	2.287
2	17.264	7206880	111516	98.914	97.713
Total		7286013	114125	100.000	100.000

Enantiomerically enriched **5m**

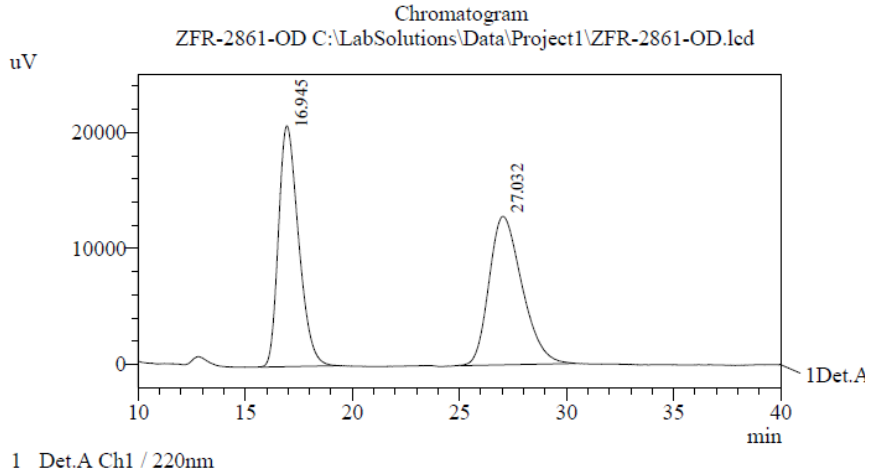
(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(3,4-dichlorophenyl)cyclohex-2-ene-1,2-dicarboxylate **5n**



5n

A white solid; $[\alpha]^{25}_{D}$ = -93.8 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.57-2.71 (m, 1H), 2.95-3.03 (m, 1H), 3.21 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.88 (s, 3H), 4.13-4.14 (m, 1H), 7.15-7.16 (m, 1H), 7.34 (d, *J* = 1.9 Hz, 8.2 Hz, 1H), 7.52-7.56 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91, 28.50, 40.72, 45.85, 51.15, 53.36, 82.70, 111.24,

113.04, 126.90, 127.66, 130.47, 131.25, 133.56, 134.22, 135.20, 137.65, 163.34, 167.73; HRMS (ESI) *m/z* calcd for $C_{21}H_{20}Cl_2N_2O_4$ $[M+Na]^+$ =457.0692, found = 457.0706; The ee value was 98%, t_R (major) = 27.0 min, t_R (minor) = 16.9 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



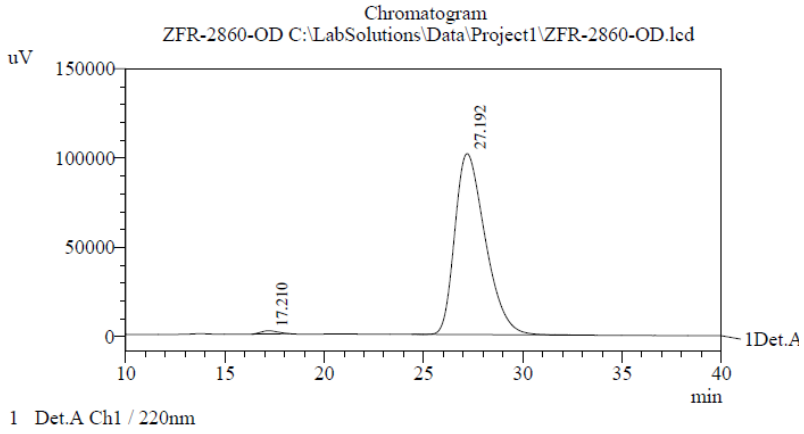
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	16.945	1355979	20782	49.715	61.876
2	27.032	1371545	12804	50.285	38.124
Total		2727524	33586	100.000	100.000

Racemic **5n**



1 Det.A Ch1 / 220nm

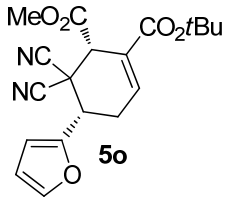
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	17.210	102652	1782	0.938	1.728
2	27.192	10837467	101349	99.062	98.272
Total		10940119	103131	100.000	100.000

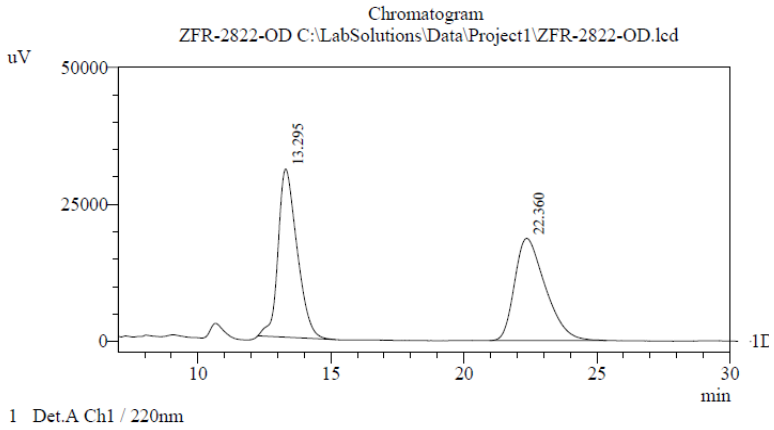
Enantiomerically enriched **5n**

(1*S*,5*S*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(furan-2-yl)cyclohex-2-ene-1,2-dicarboxylate **5o**



5o

A colorless oil; $[\alpha]^{25}_{D}$ = -26.3 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48 (s, 9H), 2.71-2.78 (m, 1H), 2.97-3.05 (m, 1H), 3.49 (dd, *J* = 4.5 Hz, 12.0 Hz, 1H), 3.86 (s, 3H), 4.08-4.10 (m, 1H), 6.43 (dd, *J* = 1.9 Hz, 3.2 Hz, 1H), 6.54 (d, *J* = 3.8 Hz, 1H), 7.12-7.14 (m, 1H), 7.49 (d, *J* = 1.9 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.43, 27.91, 39.86, 40.64, 50.31, 53.26, 82.55, 109.89, 110.88, 111.21, 113.27, 126.69, 137.62, 143.72, 148.58. 163.41, 167.78; HRMS (ESI) *m/z* calcd for $C_{19}H_{20}N_2O_5$ $[M+Na]^+$ = 379.1264, found = 379.1271; The ee value was 93%, t_R (major) = 22.3 min, t_R (minor) = 13.3 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



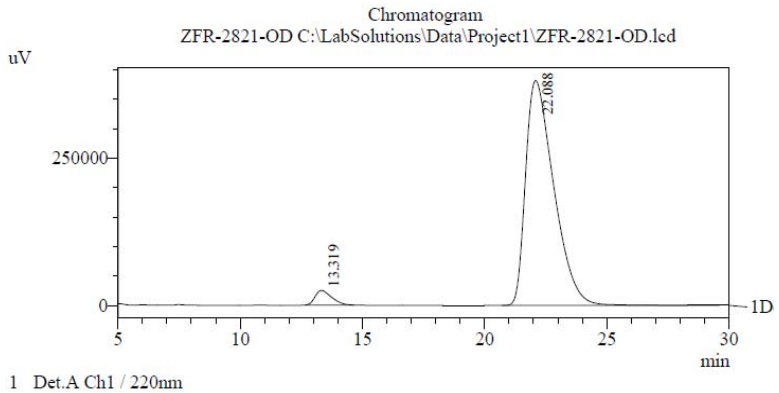
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	13.295	1527747	30707	50.444	62.202
2	22.360	1500854	18660	49.556	37.798
Total		3028601	49367	100.000	100.000

Racemic **5o**



1 Det.A Ch1 / 220nm

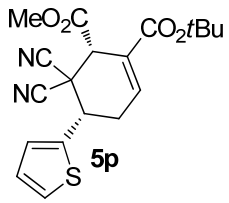
PeakTable

Detector A Ch1 220nm

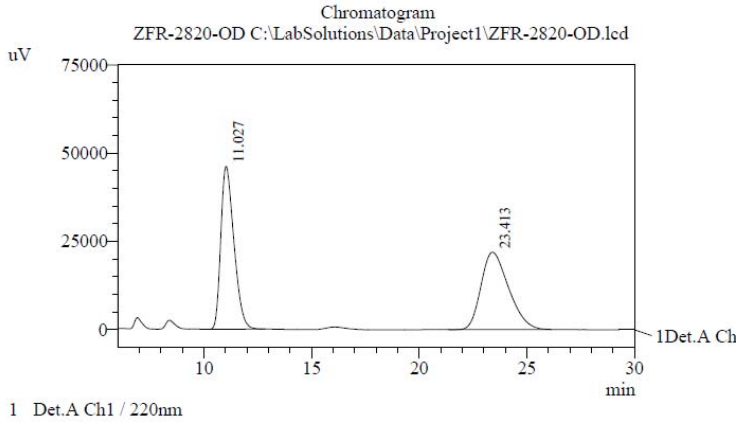
Peak#	Ret. Time	Area	Height	Area %	Height %
1	13.319	1162830	24858	3.653	6.113
2	22.088	30668983	381756	96.347	93.887
Total		31831813	406614	100.000	100.000

Enantiomerically enriched **5o**

(1*S*,5*S*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(thiophen-2-yl)cyclohex-2-ene-1,2-dicarboxylate **5p**



A colorless oil; $[\alpha]^{25}_{D}$ = -44.0 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48 (s, 9H), 2.80-2.87 (m, 1H), 2.96-3.054 (m, 1H), 3.60 (dd, *J* = 4.5 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.13-4.14 (m, 1H), 7.09 (t, *J* = 3.8 Hz, 1H), 7.13-7.14 (m, 1H), 7.28 (d, *J* = 3.2 Hz, 1H), 7.38 (d, *J* = 5.7 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.90, 30.56, 42.04, 42.46, 50.90, 53.27, 82.57, 111.38, 113.34, 126.47, 126.84, 127.45, 127.87, 137.15, 137.86, 163.41, 167.87; HRMS (ESI) *m/z* calcd for $C_{19}H_{20}N_2O_4S$ $[M+Na]^+$ = 395.1036, found = 395.1040; The ee value was 97%, t_R (major) = 23.4 min, t_R (minor) = 11.0 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

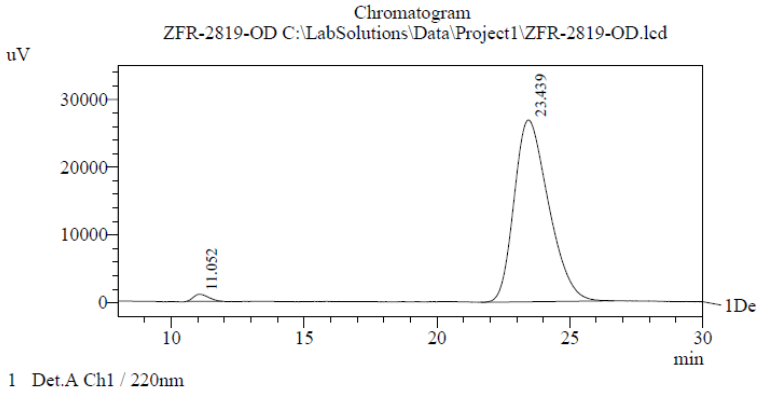


PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	11.027	1957896	46167	50.022	67.807
2	23.413	1956148	21919	49.978	32.193
Total		3914044	68086	100.000	100.000

Racemic **5p**



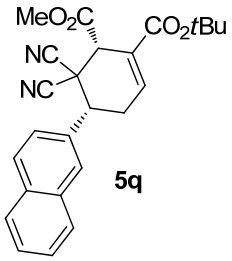
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	11.052	40331	1037	1.640	3.724
2	23.439	2418633	26810	98.360	96.276
Total		2458964	27847	100.000	100.000

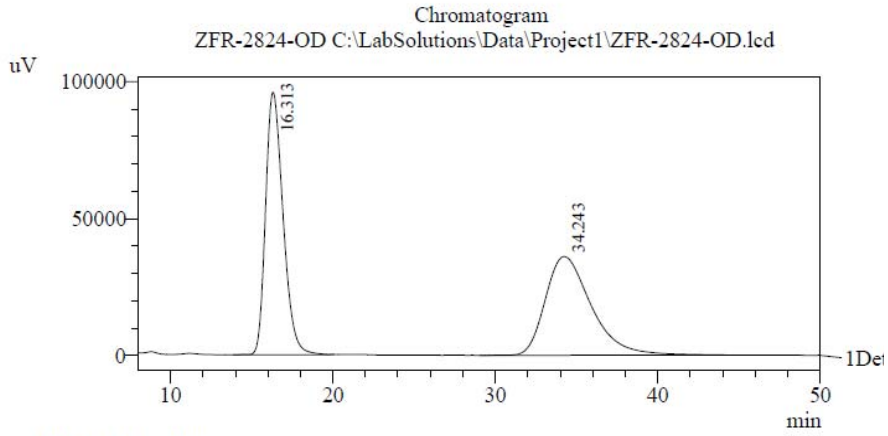
Enantiomerically enriched **5p**

(1*S*,5*R*)-2-*tert*-Butyl 1-methyl 6,6-dicyano-5-(naphthalen-2-yl)cyclohex-2-ene-1,2-dicarboxylate **5q**



5q

A white solid; $[\alpha]^{25}_{D}$ = -105.8 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.73-2.80 (m, 1H), 3.16-3.24 (m, 1H), 3.42 (dd, *J* = 4.4 Hz, 12.0 Hz, 1H), 3.87 (s, 3H), 4.20-4.21 (m, 1H), 7.22 (d, *J* = 6.3 Hz, 1H), 7.53-7.58 (m, 3H), 7.86-7.91 (m, 2H), 7.92 (d, *J* = 8.8 Hz, 1H), 7.95 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.93, 28.85, 41.13, 46.87, 51.42, 53.24, 82.50, 111.70, 113.37, 125.58, 126.76, 126.98, 127.72, 128.05, 128.29, 129.12, 132.54, 133.16, 133.66, 138.50, 163.58, 168.02; HRMS (ESI) *m/z* calcd for $C_{25}H_{24}N_2O_4$ $[M+Na]^+$ = 439.1628, found = 439.1636; The ee value was 97%, t_R (major) = 34.2 min, t_R (minor) = 16.3 min (Chiralcel OD-H, λ = 220 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



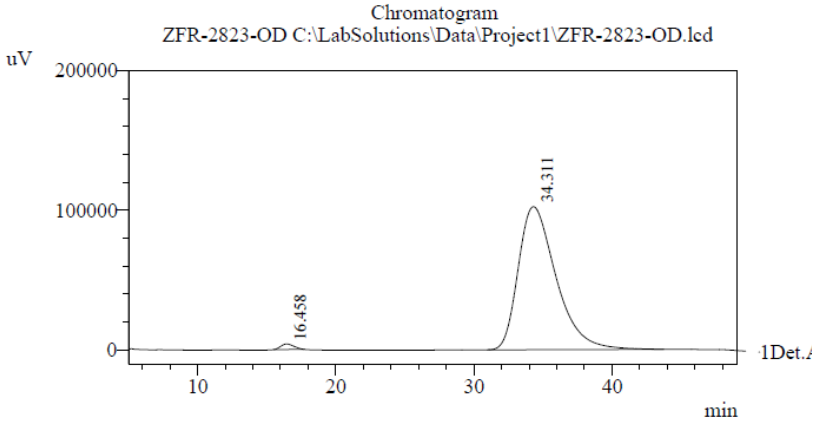
1 Det.A Ch1 / 220nm

PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	16.313	7168734	95821	50.282	72.659
2	34.243	7088464	36057	49.718	27.341
Total		14257198	131878	100.000	100.000

Racemic **5q**



1 Det.A Ch1 / 220nm

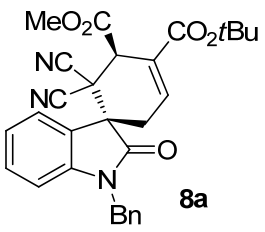
PeakTable

Detector A Ch1 220nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	16.458	262349	3937	1.325	3.698
2	34.311	19541057	102508	98.675	96.302
Total		19803406	106445	100.000	100.000

Enantiomerically enriched **5q**

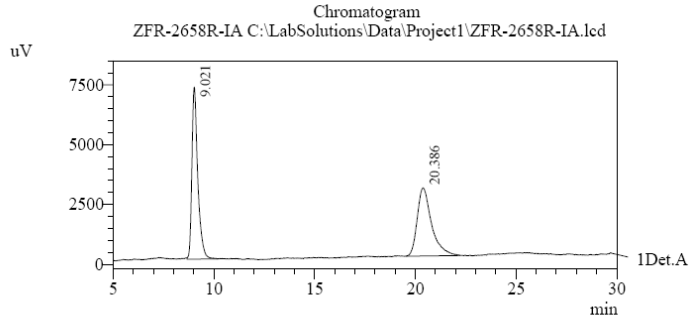
(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]-4,5-dicarboxylate **8a**



8a

A white solid; $[\alpha]^{25}_{D}$ = + 140.2 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.51 (s, 9H), 2.62-2.67 (m, 1H), 3.13 (dt, *J*

= 2.6 Hz, 20.2 Hz, 1H), 3.89 (s, 3H), 4.82 (s, 1H), 4.84 (d, *J* = 15.8 Hz, 1H), 5.02 (d, *J* = 15.8 Hz, 1H), 6.84 (d, *J* = 8.2 Hz, 1H), 7.04-7.06 (m, 1H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.28-7.37 (m, 6H), 7.79 (d, *J* = 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.96, 31.33, 40.63, 44.43, 46.90, 48.92, 53.17, 82.43, 110.24, 111.62, 111.70, 124.06, 124.43, 125.60, 127.25, 127.81, 128.06, 129.00, 131.11, 133.96, 134.50, 142.67, 163.30, 168.59, 172.61; HRMS (ESI) *m/z* calcd for $C_{29}H_{27}N_3O_5$ $[M+Na]^+$ = 520.1843, found = 520.1829; The ee value was 93%, t_R (major) = 9.0 min, t_R (minor) = 20.4 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



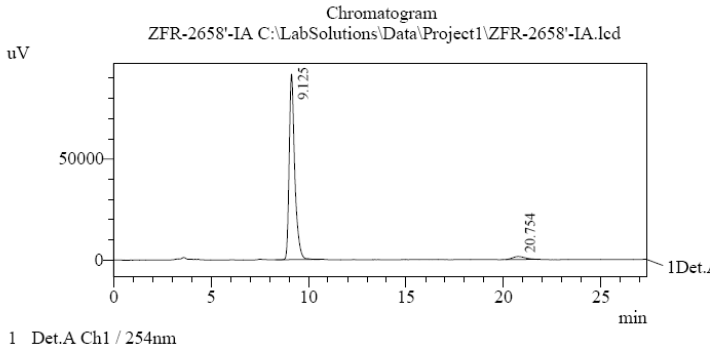
1 Det.A Ch1 / 254nm

PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.021	145711	7196	50.869	71.628
2	20.386	140732	2850	49.131	28.372
Total		286443	10046	100.000	100.000

Racemic **8a**



1 Det.A Ch1 / 254nm

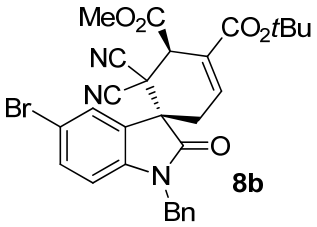
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.125	1822416	91695	96.642	98.453
2	20.754	63332	1441	3.358	1.547
Total		1885748	93137	100.000	100.000

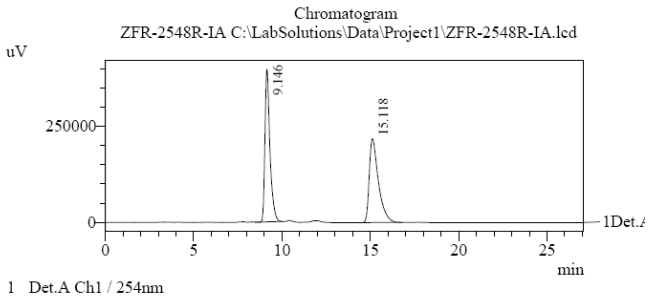
Enantiomerically enriched **8a**

(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-5'-bromo-6,6-dicyano-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]-4,5-dicarboxylate **8b**



8b

A white solid; $[\alpha]^{25}_{D}$ = +140.6 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.62-2.67 (m, 1H), 3.09 (dt, *J* = 3.2 Hz, 20.2 Hz, 1H), 3.90 (s, 3H), 4.78-4.80 (m, 1H), 4.83 (d, *J* = 15.8 Hz, 1H), 4.99 (d, *J* = 15.8 Hz, 1H), 6.70 (d, *J* = 8.2 Hz, 1H), 7.02-7.04 (m, 1H), 7.28-7.35 (m, 5H), 7.47 (dd, *J* = 1.9 Hz, 7.6 Hz, 1H), 7.88 (d, *J* = 1.9 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.94, 31.25, 40.37, 44.51, 46.84, 49.00, 53.24, 82.55, 111.29, 111.50, 111.70, 116.76, 127.19, 127.49, 127.65, 127.88, 128.24, 129.09, 133.43, 133.97, 134.13, 141.68, 163.17, 168.35, 171.99; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}{}^{79}BrN_3O_5$ $[M+Na]^+$ = 598.0948, found = 598.0926; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}{}^{81}BrN_3O_5$ $[M+Na]^+$ = 600.0933, found = 600.0906; The ee value was 90%, t_R (major) = 9.1 min, t_R (minor) = 15.1 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

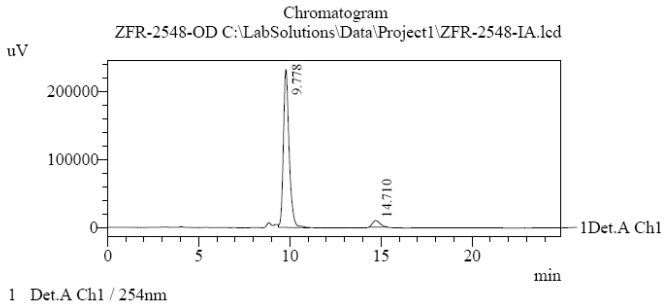


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.146	7753413	396180	49.694	64.552
2	15.118	7848914	217561	50.306	35.448
Total		15602327	613742	100.000	100.000

Racemic **8b**



PeakTable

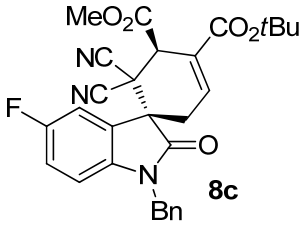
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.778	5074512	232715	94.793	96.032
2	14.710	278725	9615	5.207	3.968
Total		5353238	242330	100.000	100.000

Enantiomerically enriched **8b**

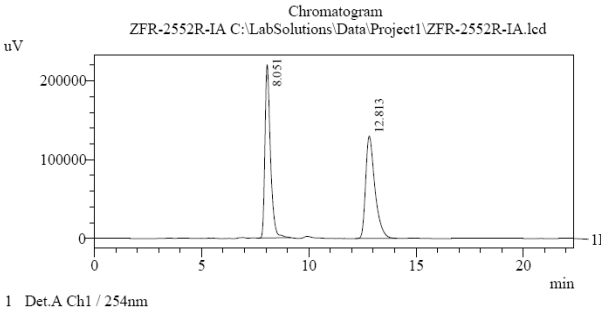
(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-5'-fluoro-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]

-4,5-dicarboxylate **8c**



8c

A white solid; $[\alpha]^{25}_{D}$ = +124.0 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.63-2.69 (m, 1H), 3.06-3.11 (m, 1H), 3.90 (s, 3H), 4.81-4.82 (m, 1H), 4.84 (d, *J* = 15.8 Hz, 1H), 5.02 (d, *J* = 15.8 Hz, 1H), 6.75-6.78 (m, 1H), 7.02-7.08 (m, 2H), 7.28-7.35 (m, 5H), 7.56 (dd, *J* = 2.6 Hz, 8.2 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.95, 31.29, 40.40, 44.57, 46.83, 49.17, 53.22, 82.54, 111.11 (d, *J* = 8.2 Hz), 111.38, 111.52, 112.83 (d, *J* = 26.4 Hz), 117.70 (d, *J* = 23.8 Hz), 127.02 (d, *J* = 7.3 Hz), 127.21, 127.90, 128.19, 129.08, 133.49, 134.14, 138.61, 159.55 (d, *J* = 242.3 Hz), 163.18, 168.41, 172.28; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}FN_3O_5$ $[M+Na]^+$ = 538.1749, found = 538.1729; The ee value was 91%, t_R (major) = 8.1 min, t_R (minor) = 12.8 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

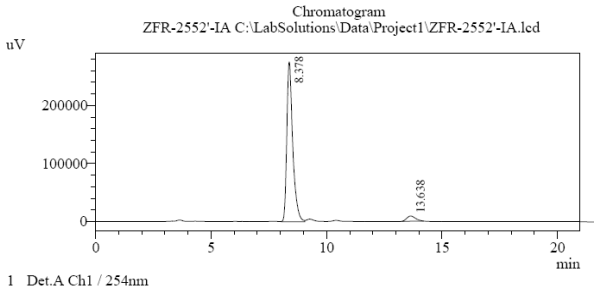


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.051	3907048	219800	50.114	62.844
2	12.813	3889239	129957	49.886	37.156
Total		7796287	349757	100.000	100.000

Racemic **8c**



PeakTable

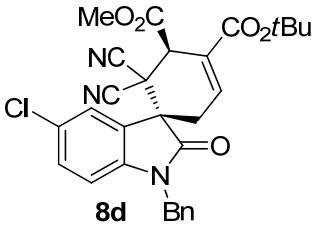
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.378	4907142	275282	95.486	96.854
2	13.638	232004	8942	4.514	3.146
Total		5139146	284224	100.000	100.000

Enantiomerically enriched **8c**

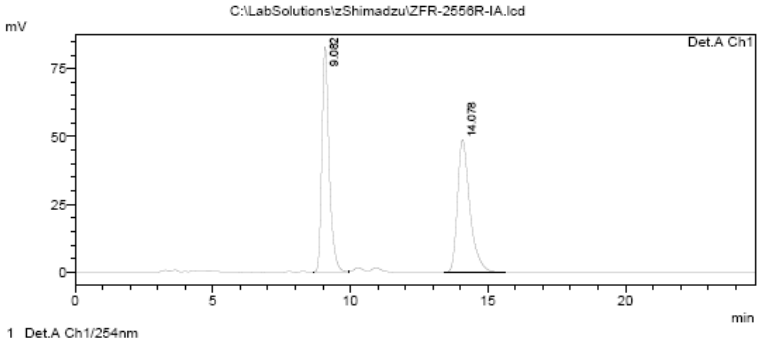
(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-5'-chloro-6,6-dicyano-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]

-4,5-dicarboxylate **8d**



8d

A white solid; $[\alpha]^{25}_{D}$ = +170.6 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.62-2.68 (m, 1H), 3.10 (dt, *J* = 3.2 Hz, 20.2 Hz, 1H), 3.90 (s, 3H), 4.79-4.80 (m, 1H), 4.84 (d, *J* = 15.8 Hz, 1H), 5.00 (d, *J* = 15.8 Hz, 1H), 6.75 (d, *J* = 8.2 Hz, 1H), 7.02-7.04 (m, 1H), 7.28-7.36 (m, 6H), 7.76 (d, *J* = 1.9 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.94, 31.24, 40.33, 44.53, 46.82, 49.04, 53.27, 82.56, 111.27, 111.49, 124.95, 127.12, 127.19, 127.84, 128.24, 128.97, 129.09, 129.64, 131.21, 133.48, 133.98, 141.15, 163.17, 168.39, 170.09; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}ClN_3O_5$ $[M+Na]^+$ = 554.1453, found = 554.1433; The ee value was 91%, t_R (major) = 9.1 min, t_R (minor) = 14.1 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

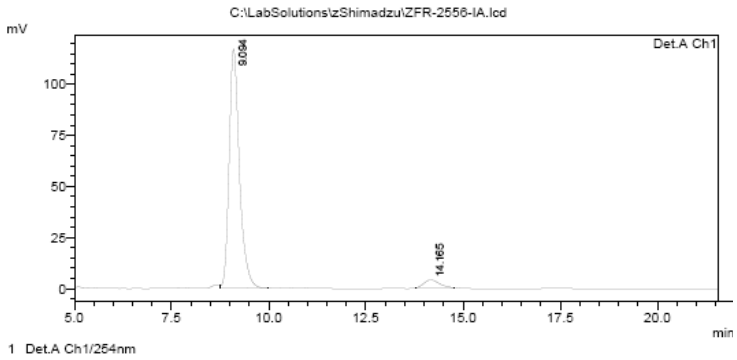


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.082	1524964	82867	49.958	62.947
2	14.078	1527516	48778	50.042	37.053
Total		3052479	131645	100.000	100.000

Racemic **8d**



PeakTable

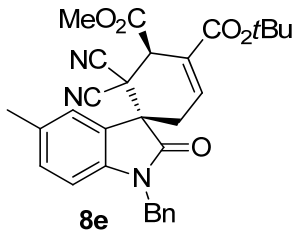
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.094	2158734	117078	95.312	96.755
2	14.165	106171	3927	4.688	3.245
Total		2264905	121005	100.000	100.000

Enantiomerically enriched **8d**

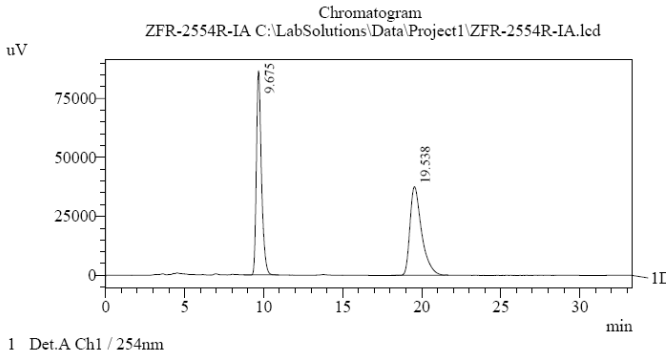
(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-5'-methyl-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]

-4,5-dicarboxylate **8e**



8e

A white solid; $[\alpha]^{25}_{D}$ = +127.0 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.36 (s, 3H), 2.60-2.65 (m, 1H), 3.11 (dt, *J* = 3.2 Hz, 20.2 Hz, 1H), 3.89 (s, 3H), 4.83 (s, 1H), 4.84 (d, *J* = 15.8 Hz, 1H), 4.99 (d, *J* = 15.8 Hz, 1H), 6.72 (d, *J* = 8.2 Hz, 1H), 7.04-7.06 (m, 1H), 7.14 (d, *J* = 7.6 Hz, 1H), 7.27-7.34 (m, 5H), 7.58 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.24, 27.94, 31.37, 40.60, 44.37, 46.90, 48.91, 53.19, 82.41, 109.99, 111.59, 111.74, 125.02, 125.54, 127.20, 127.73, 127.99, 128.95, 131.46, 133.93, 134.15, 134.58, 140.15, 163.31, 168.68, 172.52; HRMS (ESI) *m/z* calcd for $C_{30}H_{29}N_3O_5$ $[M+Na]^+$ = 534.1999, found = 534.1997; The ee value was 91%, t_R (major) = 9.7 min, t_R (minor) = 19.5 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

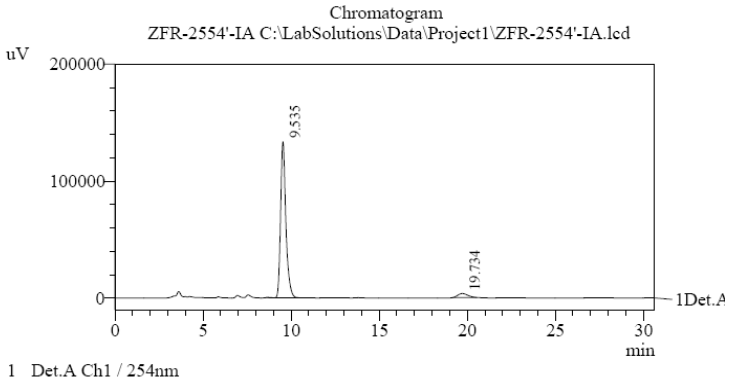


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.675	1915223	86510	49.935	69.719
2	19.538	1920193	37573	50.065	30.281
Total		3835416	124084	100.000	100.000

Racemic **8e**



PeakTable

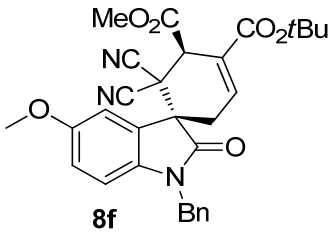
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	9.535	2765923	133315	95.279	97.471
2	19.734	137049	3459	4.721	2.529
Total		2902972	136773	100.000	100.000

Enantiomerically enriched **8e**

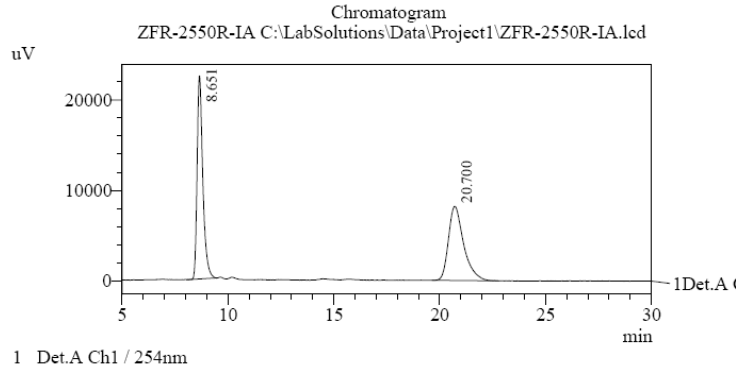
(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-5'-methoxy-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]

-4,5-dicarboxylate **8f**



8f

A white solid; $[\alpha]^{25}_{D}$ = +127.4 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.62-2.67 (m, 1H), 3.07-3.12 (m, 1H), 3.79 (s, 3H), 3.89 (s, 3H), 4.83-4.84 (m, 1H), 4.84 (d, *J* = 15.8 Hz, 1H), 5.00 (d, *J* = 15.8 Hz, 1H), 6.72 (d, *J* = 8.2 Hz, 1H), 6.85-6.87 (m, 1H), 7.03-7.05 (m, 1H), 7.28-7.33 (m, 5H), 7.39 (d, *J* = 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.98, 31.45, 40.65, 44.45, 46.96, 49.22, 53.13, 55.91, 82.41, 110.86, 111.51, 111.60, 111.73, 115.83, 126.73, 127.25, 127.87, 128.02, 128.98, 133.93, 134.62, 135.82, 156.86, 163.30, 168.59, 172.34; HRMS (ESI) *m/z* calcd for $C_{30}H_{29}N_3O_6$ $[M+Na]^+$ = 550.1949, found = 550.1934; The ee value was 91%, t_R (major) = 8.7 min, t_R (minor) = 20.1 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



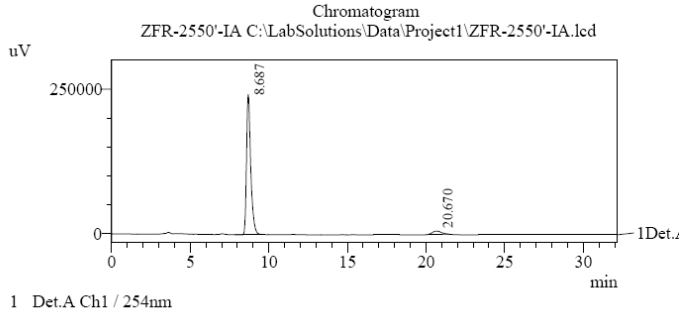
1 Det.A Ch1 / 254nm

PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.651	420154	22462	50.636	73.273
2	20.700	409595	8193	49.364	26.727
Total		829749	30655	100.000	100.000

Racemic **8f**



1 Det.A Ch1 / 254nm

PeakTable

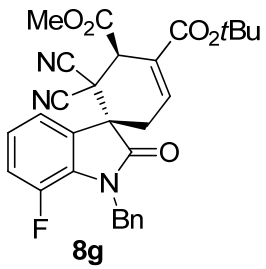
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.687	4470535	241790	95.264	97.701
2	20.670	222253	5690	4.736	2.299
Total		4692788	247480	100.000	100.000

Enantiomerically enriched **8f**

(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-7'-fluoro-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]

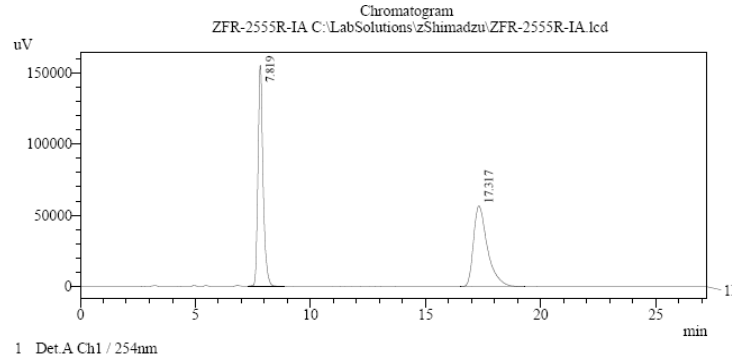
-4,5-dicarboxylate 8g



8g

A white solid; $[\alpha]^{25}_{D}$ = +154.2 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (s, 9H), 2.63 (dd, *J* = 5.7 Hz, 20.2 Hz, 1H), 3.07-3.11 (m, 1H), 3.89 (s, 3H), 4.79 (d, *J* = 6.9 Hz, 1H), 5.08 (s, 2H), 7.02-7.03 (m, 1H), 7.15-7.17 (m, 2H), 7.26-7.33 (m, 5H), 7.59-7.61 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.94, 31.41, 40.50, 45.99 (d, *J* = 4.6 Hz), 46.77, 49.07 (d, *J* = 1.8 Hz), 53.26, 82.55, 111.37, 111.43, 119.41 (d, *J* = 20.1 Hz), 120.32 (d, *J* = 3.6 Hz), 124.87 (d, *J* = 6.4 Hz),

127.41, 127.79, 127.98, 128.27 (d, *J* = 2.7 Hz), 128.77, 129.58 (d, *J* = 9.1 Hz), 133.60, 135.72, 147.47 (d, *J* = 245.0 Hz), 163.20, 168.46, 172.20; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}FN_3O_5$ $[M+Na]^+$ = 538.1749, found = 538.1727; The ee value was 93%, t_R (major) = 7.9 min, t_R (minor) = 17.3 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

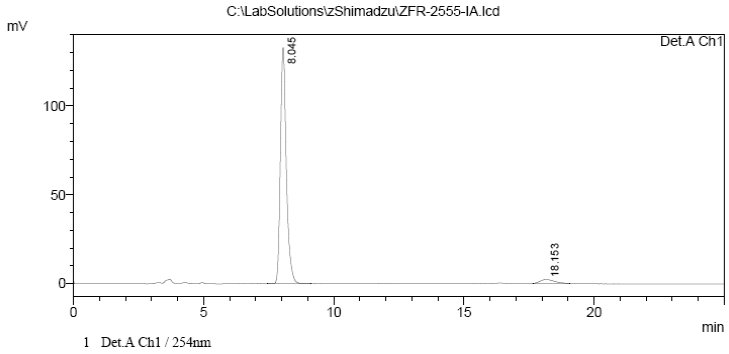


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.819	2388738	155399	50.114	73.327
2	17.317	2377898	56528	49.886	26.673
Total		4766636	211927	100.000	100.000

Racemic **8g**



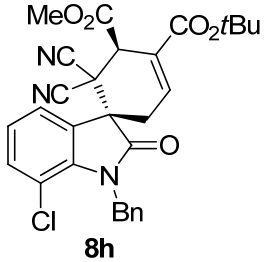
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.744	4788016	295644	96.356	98.084
2	16.992	181060	5774	3.644	1.916
Total		4969075	301418	100.000	100.000

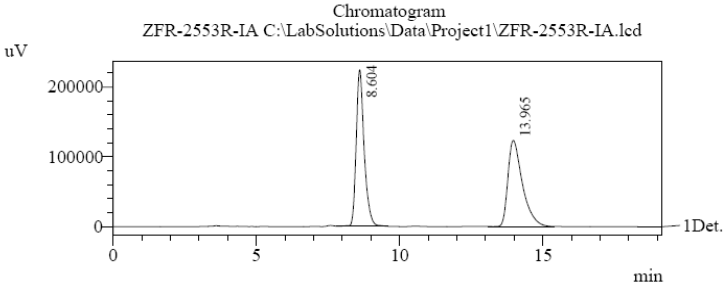
Enantiomerically enriched **8g**

(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-7'-chloro-6,6-dicyano-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]-4,5-dicarboxylate **8h**



8h

A white solid; $[\alpha]^{25}_{D}$ = +208.6 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.49 (s, 9H), 2.61-2.67 (m, 1H), 3.08-3.13 (m, 1H), 3.89 (s, 3H), 4.77 (d, *J* = 1.9 Hz, 1H), 5.35 (d, *J* = 16.4 Hz, 1H), 5.41 (d, *J* = 16.4 Hz, 1H), 7.00-7.02 (m, 1H), 7.16 (t, *J* = 7.8 Hz, 1H), 7.24-7.28 (m, 3H), 7.34-7.38 (m, 2H), 7.40 (d, *J* = 7.6 Hz, 1H), 7.76 (d, *J* = 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.92, 31.69, 40.51, 45.66, 46.94, 48.45, 53.27, 82.55, 111.45, 116.52, 122.99, 124.84, 126.29, 127.54, 127.86, 128.35, 128.75, 133.54, 133.82, 136.24, 138.94, 163.15, 168.42, 173.06; HRMS (ESI) *m/z* calcd for $C_{29}H_{26}ClN_3O_5$ $[M+Na]^+$ = 554.1453, found = 554.1433; The ee value was 92%, t_R (major) = 8.6 min, t_R (minor) = 14.0 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).



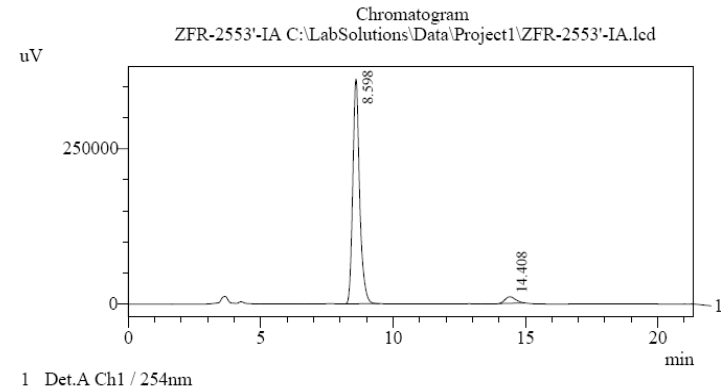
1 Det.A Ch1 / 254nm

PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.604	4317677	224039	49.904	64.494
2	13.965	4334362	123340	50.096	35.506
Total		8652039	347379	100.000	100.000

Racemic **8h**



1 Det.A Ch1 / 254nm

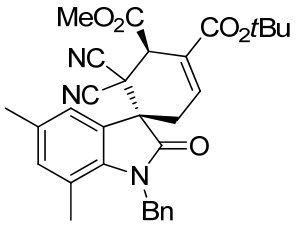
PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	8.598	6498774	361185	95.767	97.193
2	14.408	287233	10432	4.233	2.807
Total		6786007	371617	100.000	100.000

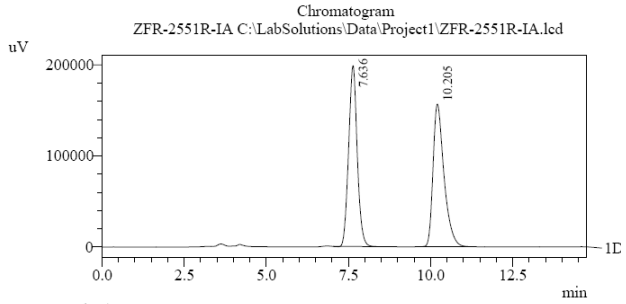
Enantiomerically enriched **8h**

(1*R*,5*R*)-4-*tert*-Butyl 5-methyl 1'-benzyl-6,6-dicyano-5',7'-dimethyl-2'-oxospiro[cyclohex[3]ene-1,3'-indoline]-4,5-dicarboxylate **8i**



8i

A white solid; $[\alpha]^{25}_{D}$ = +132.4 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48 (s, 9H), 2.27 (s, 3H), 2.34 (s, 3H), 2.61-2.66 (m, 1H), 3.09-3.14 (m, 1H), 3.89 (s, 3H), 4.81-4.82 (m, 1H), 5.14 (d, *J* = 17.0 Hz, 1H), 5.20 (d, *J* = 17.0 Hz, 1H), 6.95 (s, 1H), 7.02-7.04 (m, 1H), 7.19 (d, *J* = 7.6 Hz, 2H), 7.24-7.27 (m, 1H), 7.32 (t, *J* = 7.6 Hz, 2H), 7.49 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.64, 20.93, 27.91, 31.95, 40.77, 45.62, 47.13, 48.24, 53.16, 82.34, 111.61, 111.91, 120.56, 122.78, 125.51, 126.33, 127.50, 127.78, 129.01, 133.78, 134.20, 135.65, 136.43, 138.30, 163.32, 168.68, 173.51; HRMS (ESI) *m/z* calcd for $C_{31}H_{31}N_3O_5$ $[M+Na]^+$ = 548.2156, found = 548.2173; The ee value was 89%, t_R (major) = 7.6 min, t_R (minor) = 10.2 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

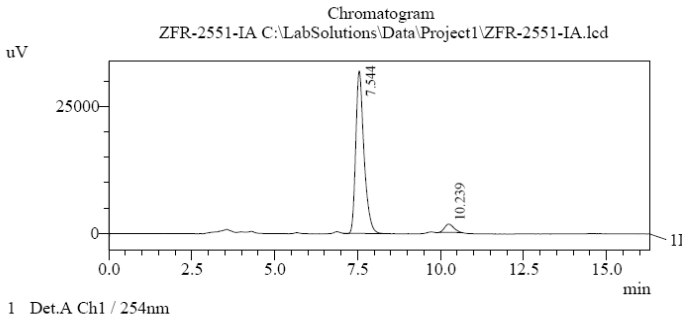


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.636	3609125	198652	49.852	55.941
2	10.205	3630557	156455	50.148	44.059
Total		7239682	355107	100.000	100.000

Racemic **8i**



PeakTable

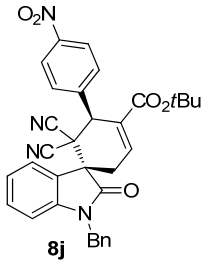
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	7.544	550317	31995	94.534	95.115
2	10.239	31818	1643	5.466	4.885
Total		582135	33638	100.000	100.000

Enantiomerically enriched **8i**

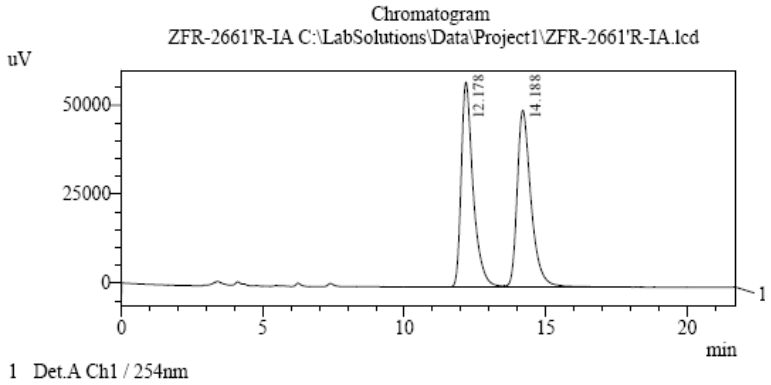
(2*R*,6*R*)-*tert*-Butyl 1'-benzyl-1,1-dicyano-6-(4-nitrophenyl)-2'-oxospiro[cyclohex[4]ene-2,3'-indoline]

-5-carboxylate **8j**



8j

A white solid; $[\alpha]^{25}_{D}$ = + 150.1 (c 0.75, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.18 (s, 9H), 2.72-2.77 (m, 1H), 3.22-3.27 (m, Hz, 1H), 4.94 (d, *J* = 15.2 Hz, 1H), 5.07 (d, *J* = 15.8 Hz, 1H), 5.27 (s, 1H), 6.86 (d, *J* = 8.2 Hz, 1H), 7.13-7.17 (m, 1H), 7.19 (d, *J* = 7.6 Hz, 1H), 7.31-7.37 (m, 6H), 7.65 (d, *J* = 7.6 Hz, 2H), 7.75 (d, *J* = 7.6 Hz, 1H), 8.30 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.66, 31.39, 44.44, 45.58, 46.05, 49.37, 82.33, 110.31, 112.12, 112.22, 123.86, 124.16, 124.40, 125.83, 127.17, 128.11, 129.04, 130.92, 131.10, 134.46, 134.98, 142.53, 143.37, 148.19, 163.67, 172.87; HRMS (ESI) *m/z* calcd for $C_{33}H_{28}N_4O_5$ $[M+Na]^+$ = 583.1952, found = 583.1958; The ee value was 84%, t_R (major) = 14.2 min, t_R (minor) = 12.1 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

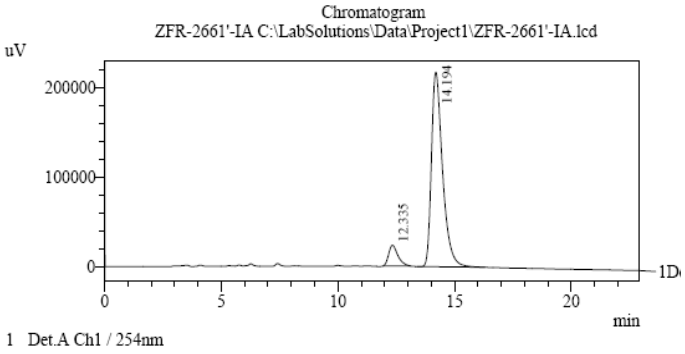


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	12.178	1677748	57550	49.820	53.672
2	14.188	1689865	49675	50.180	46.328
Total		3367613	107224	100.000	100.000

Racemic **8j**



PeakTable

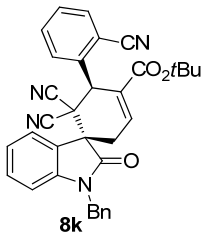
Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	12.335	636916	23156	8.109	9.611
2	14.194	7217670	217785	91.891	90.389
Total		7854586	240941	100.000	100.000

Enantiomerically enriched **8j**

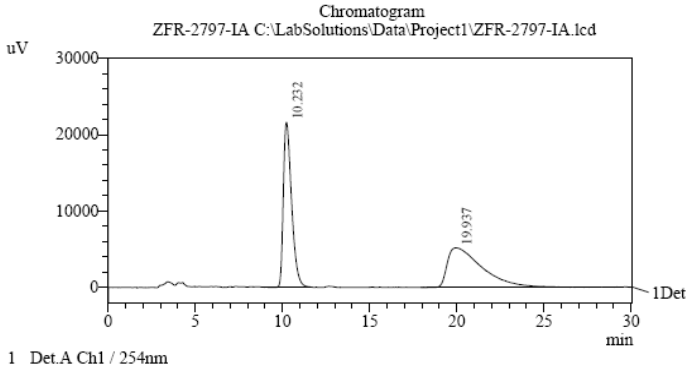
(2*R*,6*R*)-*tert*-Butyl 1'-benzyl-1,1-dicyano-6-(2-cyanophenyl)-2'-oxospiro[cyclohex[4]ene-2,3'-indoline]

-5-carboxylate **8k**



8k

A white solid; $[\alpha]^{25}_{D}$ = +195.5 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.13 (s, 9H), 2.74-2.79 (m, 1H), 3.22-3.28 (m, Hz, 1H), 4.86 (d, *J* = 15.2 Hz, 1H), 5.15 (d, *J* = 15.2 Hz, 1H), 5.85 (dd, *J* = 1.9 Hz, 3.8 Hz, 1H), 6.89 (d, *J* = 8.2 Hz, 1H), 7.10-7.12 (m, 1H), 7.16 (t, *J* = 7.6 Hz, 1H), 7.29 (d, *J* = 7.0 Hz, 1H), 7.33 (d, *J* = 1.3 Hz, 1H), 7.34-7.39 (m, 3H), 7.40 (d, *J* = 7.6 Hz, 2H), 7.51-7.55 (m, 1H), 7.65-7.69 (m, 2H), 7.73 (d, *J* = 7.6 Hz, 1H), 7.79 (d, *J* = 7.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.50, 31.32, 43.52, 44.56, 45.2, 49.33, 82.21, 110.19, 111.40, 112.51, 115.38, 116.89, 123.89, 124.24, 125.83, 127.66, 128.08, 129.00, 129.18, 129.29, 131.07, 131.55, 132.95, 133.42, 134.61, 134.99, 139.68, 142.69, 163.76, 172.71;; HRMS (ESI) *m/z* calcd for $C_{34}H_{28}N_4O_3$ $[M+Na]^+$ = 563.2054, found = 563.2046; The ee value was 90%, t_R (major) = 10.2 min, t_R (minor) = 19.9 min (Chiralcel IA-H, λ = 254 nm, 30% *i*-PrOH/hexanes, flow rate = 1.0 mL/min).

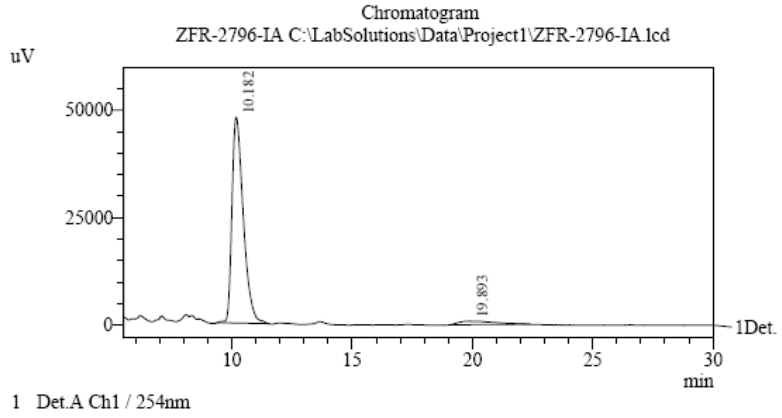


PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	10.232	705225	21567	49.996	80.714
2	19.937	705331	5153	50.004	19.286
Total		1410556	26721	100.000	100.000

Racemic **8k**



PeakTable

Detector A Ch1 254nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	10.182	1571767	47873	94.765	98.293
2	19.893	86820	831	5.235	1.707
Total		1658587	48704	100.000	100.000

Enantiomerically enriched **8k**

F. X-Ray Crystallographic Analysis and Determination of Configurations of the Products

The absolute configuration of the product **5f** (1*R*, 3*S*) was assigned by X-ray crystallographic analysis of a single crystal of **5f** (Figure S1). The configurations of other [4+2] products **5** were assigned by analogy.

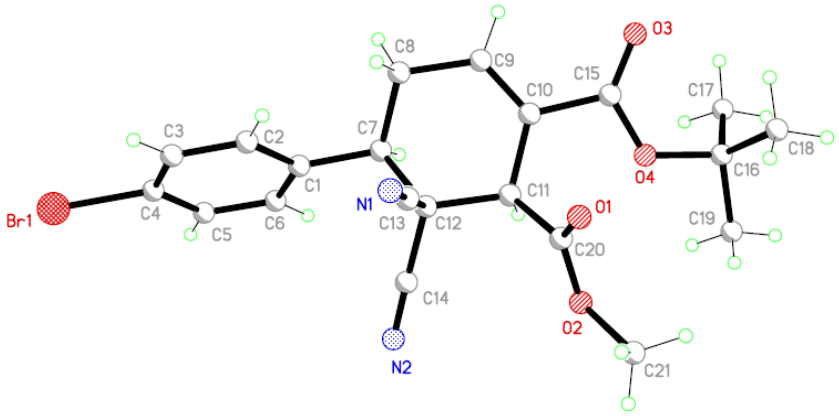


Figure S1. X-ray structure of **5f**.

Table S1.Crystal data and structure refinement for b478.

Identification code	b478	
Empirical formula	C21 H21 Br N2 O4	
Formula weight	445.31	
Temperature	223(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	C2	
Unit cell dimensions	a = 21.316(2) Å	α= 90°.
	b = 6.3205(6) Å	β= 112.859(2)°.
	c = 17.4926(17) Å	γ = 90°.
Volume	2171.6(4) $Å^3$	
Z	4	
Density (calculated)	1.362 Mg/m^3	
Absorption coefficient	1.920 mm^{-1}	
F(000)	912	
Crystal size	0.60 x 0.20 x 0.10 mm^3	
Theta range for data collection	1.26 to 27.50°.	
Index ranges	-27<=h<=27, -8<=k<=8, -22<=l<=22	
Reflections collected	13985	
Independent reflections	4967 [R(int) = 0.0454]	
Completeness to theta = 27.50°	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.8312 and 0.3921	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4967 / 1 / 257	
Goodness-of-fit on F^2	1.010	
Final R indices [I>2sigma(I)]	R1 = 0.0479, wR2 = 0.1018	
R indices (all data)	R1 = 0.0884, wR2 = 0.1286	

Absolute structure parameter	0.024(11)
Largest diff. peak and hole	0.362 and -0.328 e.Å^{-3}

The absolute configuration of the product **8d** (1*R*, 5*R*) was assigned by X-ray crystallographic analysis of a single crystal of **8d** (Figure S2). The configurations of other [4+2] products **8** were assigned by analogy.

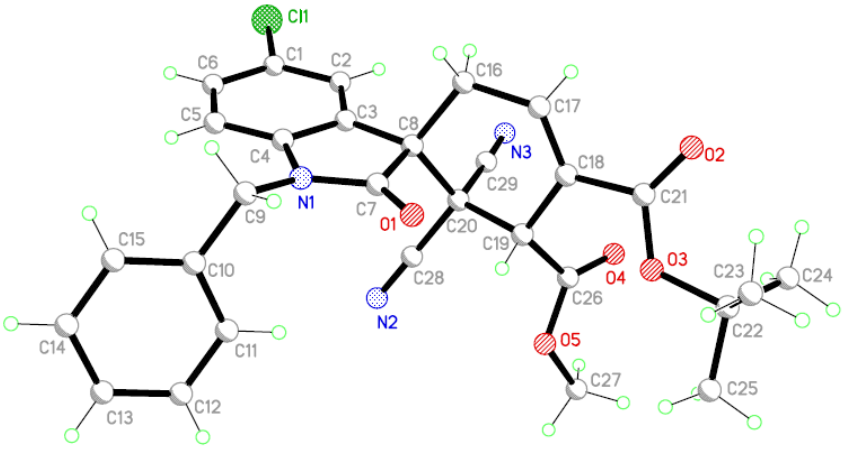


Figure S2. X-ray structure of **5f**.

Table S2. Crystal data and structure refinement for B286A.

Identification code	b286a	
Empirical formula	C29 H26 Cl N3 O5	
Formula weight	531.98	
Temperature	293(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	P2(1)2(1)2(1)	
Unit cell dimensions	a = 9.5107(4) Å	α= 90°.
	b = 10.1897(5) Å	β= 90°.
	c = 27.7823(13) Å	γ = 90°.
Volume	2692.4(2) Å^3	
Z	4	
Density (calculated)	1.312 Mg/m^3	
Absorption coefficient	0.186 mm^{-1}	
F(000)	1112	
Crystal size	0.60 x 0.60 x 0.12 mm^3	
Theta range for data collection	1.47 to 27.49°.	
Index ranges	-12<=h<=12, -12<=k<=13, -31<=l<=35	
Reflections collected	19080	
Independent reflections	6164 [R(int) = 0.0363]	
Completeness to theta = 27.49°	99.9 %	

Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9781 and 0.8968
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6164 / 0 / 347
Goodness-of-fit on F^2	1.097
Final R indices [I>2sigma(I)]	R1 = 0.0466, wR2 = 0.1076
R indices (all data)	R1 = 0.0510, wR2 = 0.1099
Absolute structure parameter	0.01(6)
Largest diff. peak and hole	0.304 and -0.173 e.$Å^{-3}$

References

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G. NMR Spectra of the Catalysts and Products

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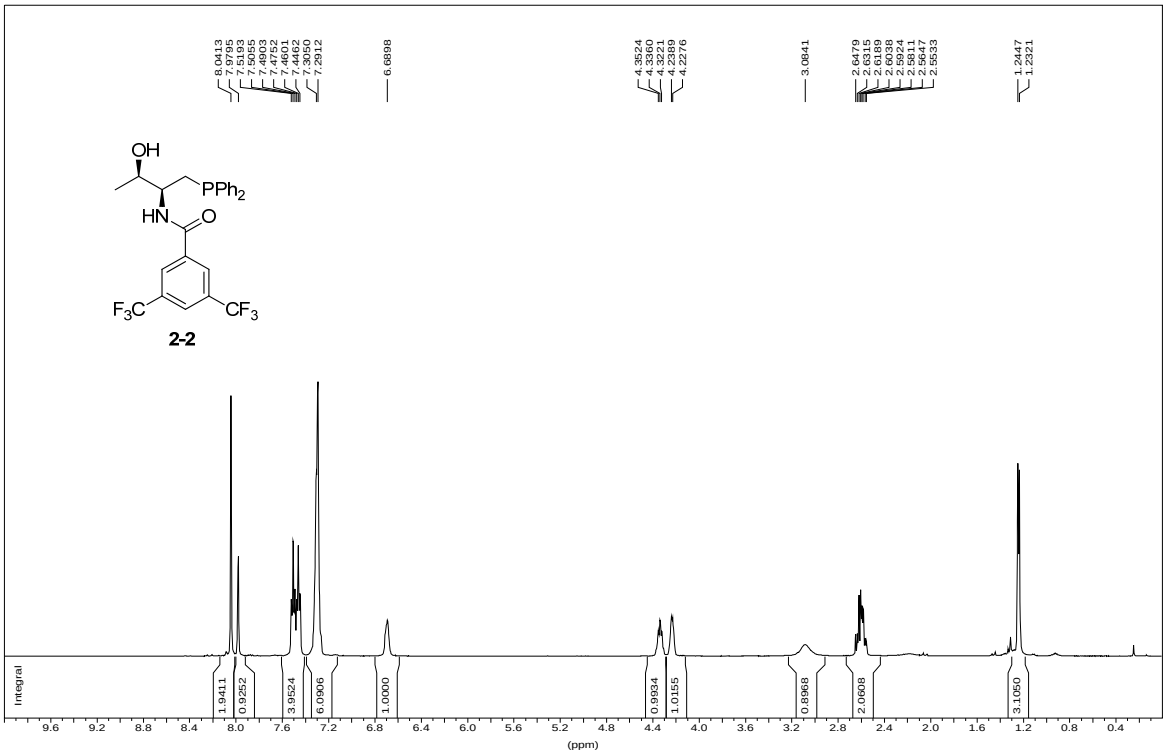

13C AMX500
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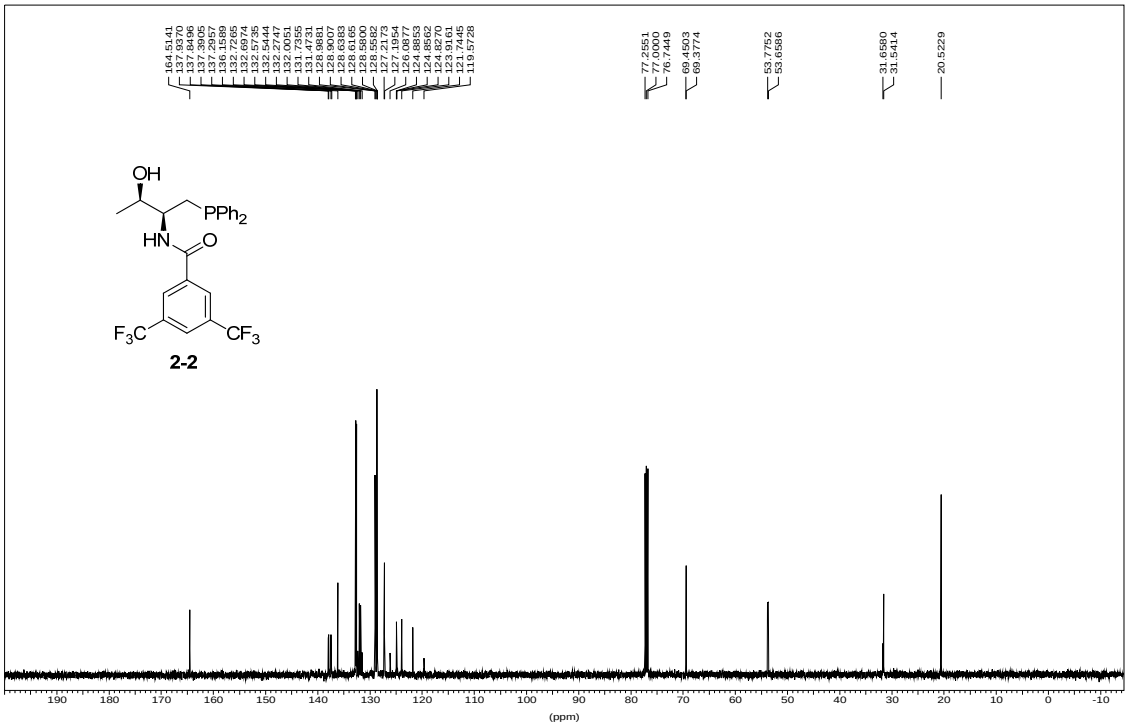
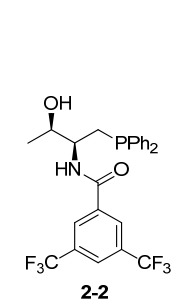


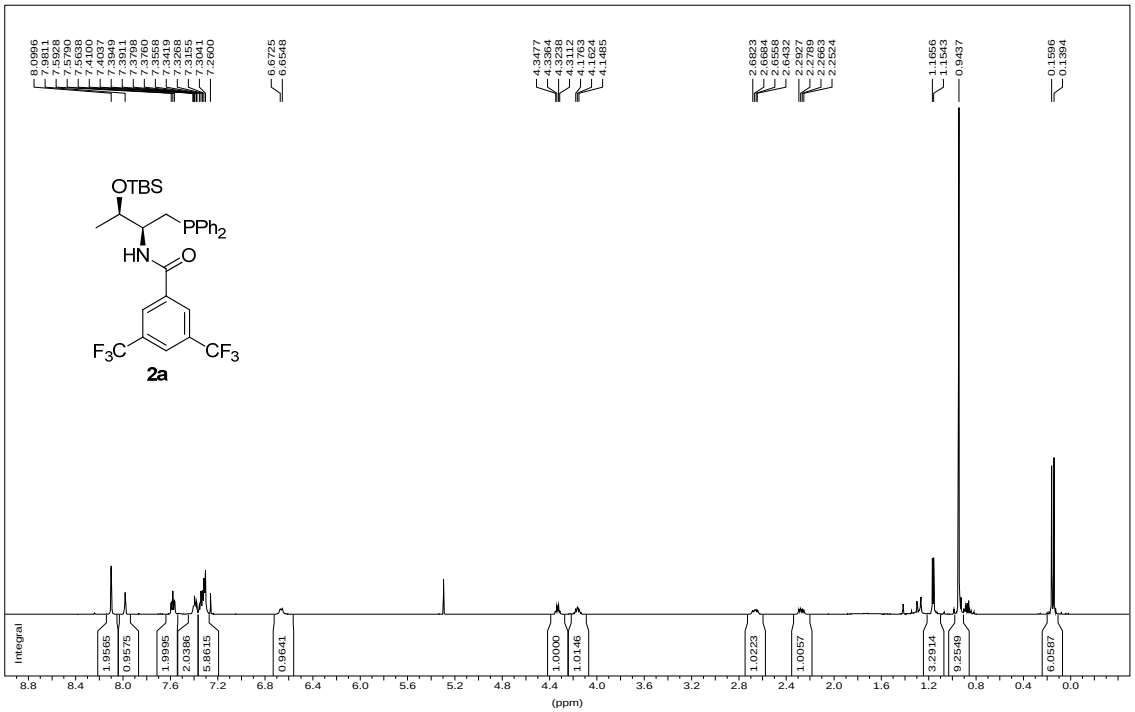
31P AC300
2694-2



2-2

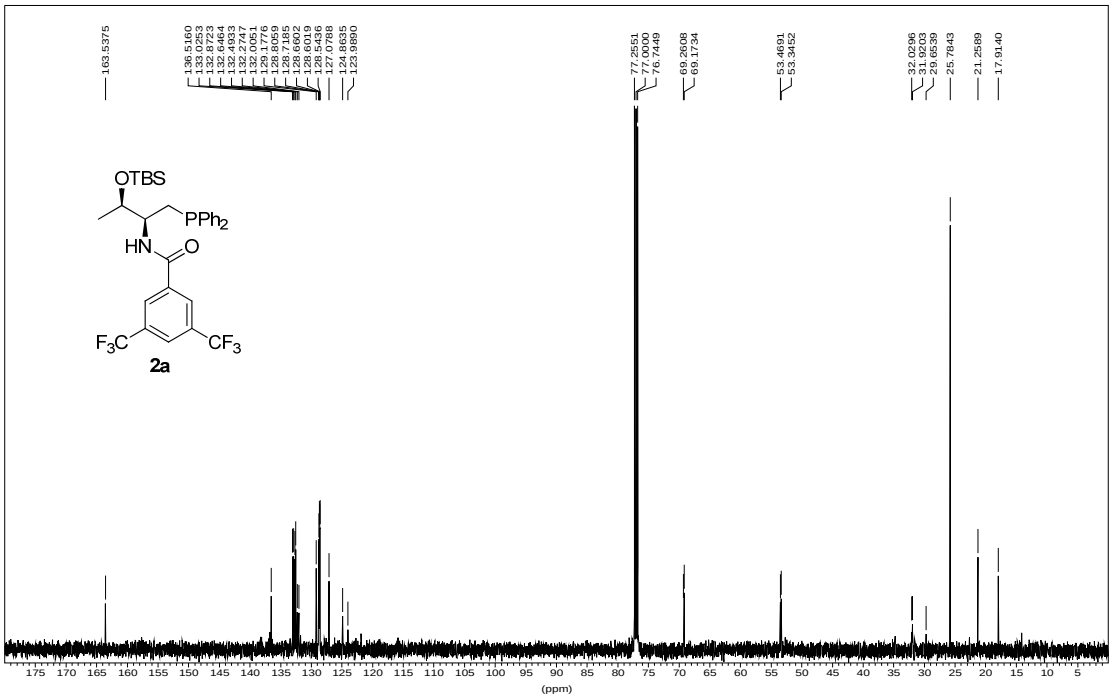
*** Current Data Parameters ***
NAME : ju01zfr
EXPNO : 1
PROCNO : 1
*** Acquisition Parameters ***
LOCNUC : 2H
NS : 5
NUCLEUS : off
O1 : -6074.78 Hz
PULPROG : zgpg30
SFO1 : 121.4887762 MHz
SOLVENT : Acetone
SW : 399.5734 ppm
TD : 65536
TE : 296.7 K
*** Processing Parameters ***
LB : 1.00 Hz
SF : 121.4947767 MHz
*** 1D NMR Plot Parameters ***
NUCLEUS : off

1H AMX500
2696(zfr0603-1)

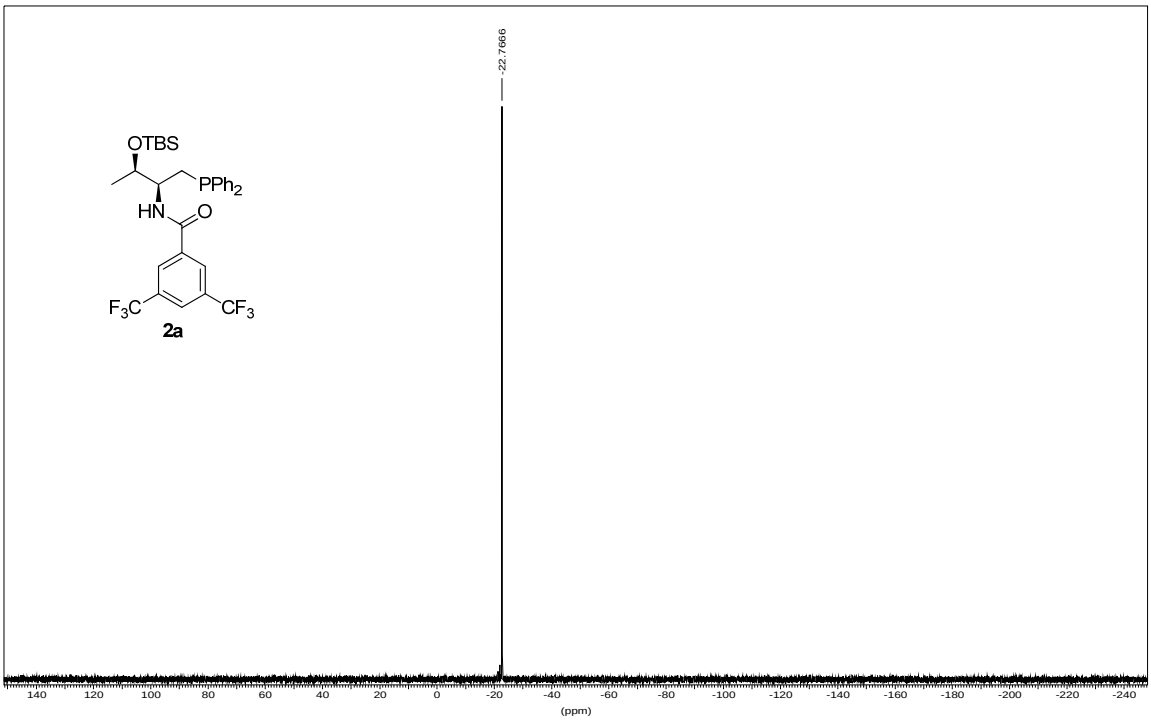


2a

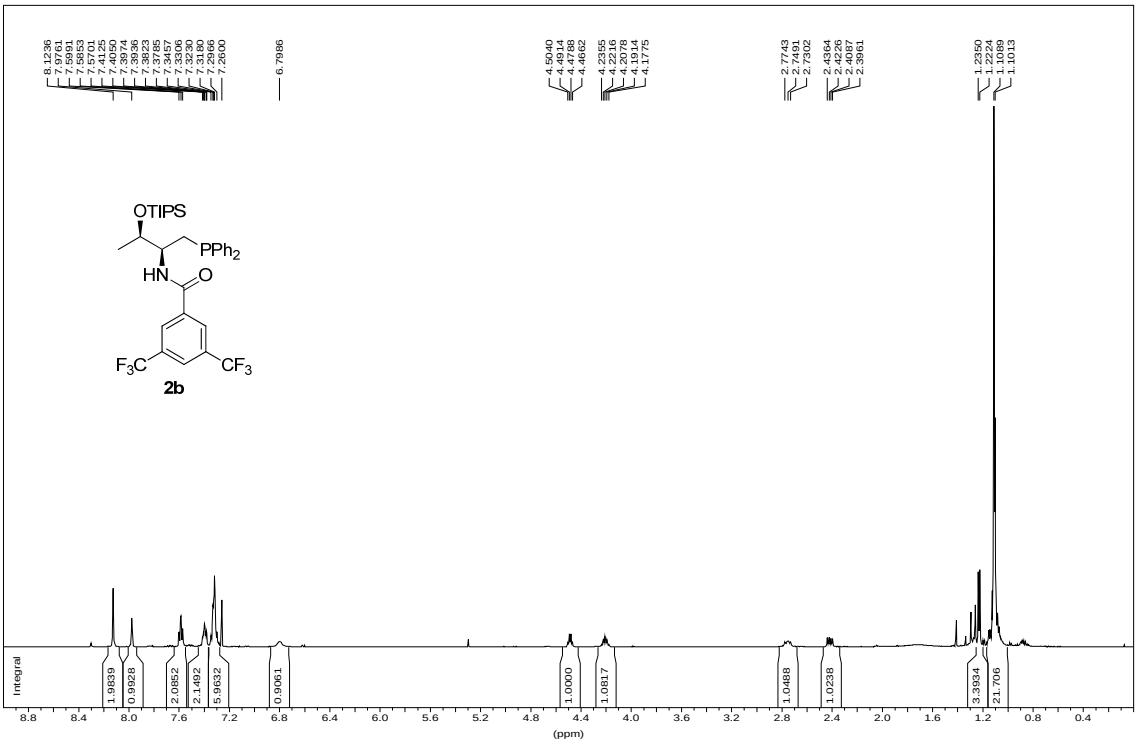
13C AMX500
zfr-2696(zfr0603-6)



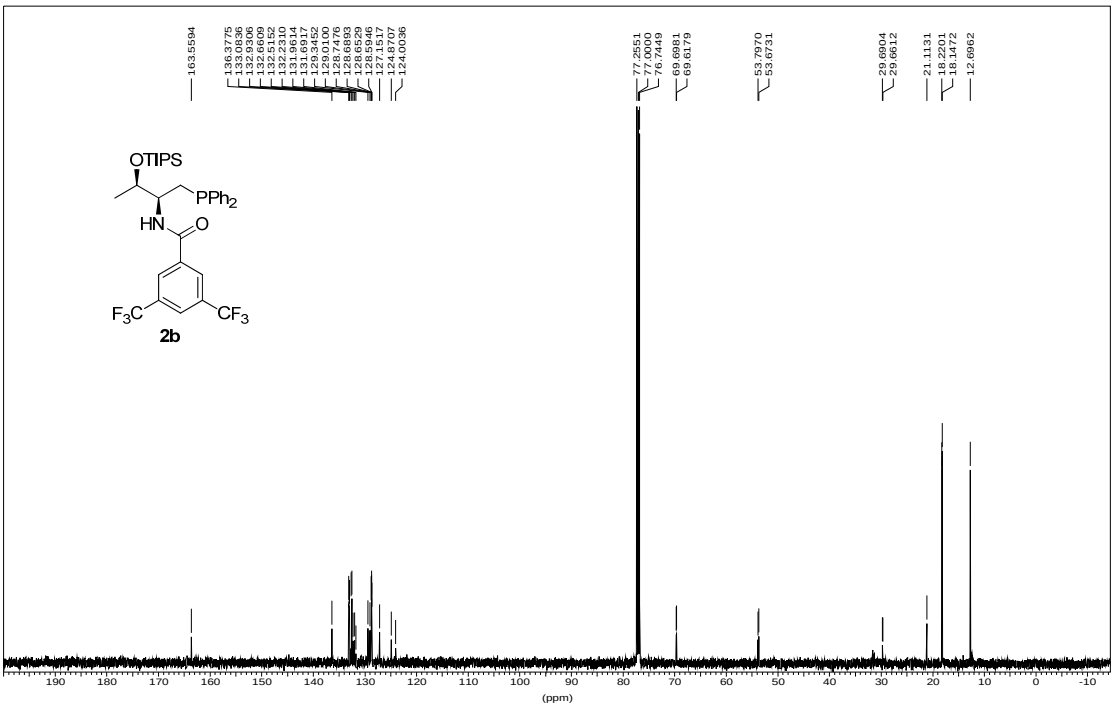
zfr2696(zfr0603-13)



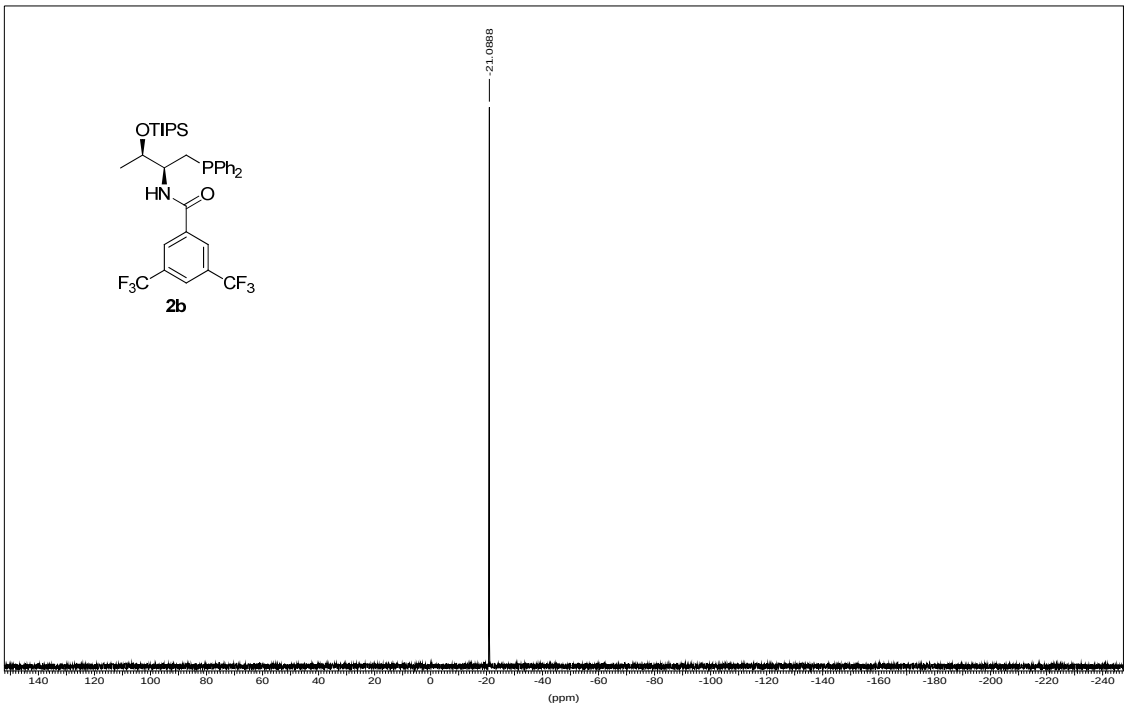
1H AMX500
2698(zfr0603-3)



13C AMX500
zfr-2698(zfr0603-10)

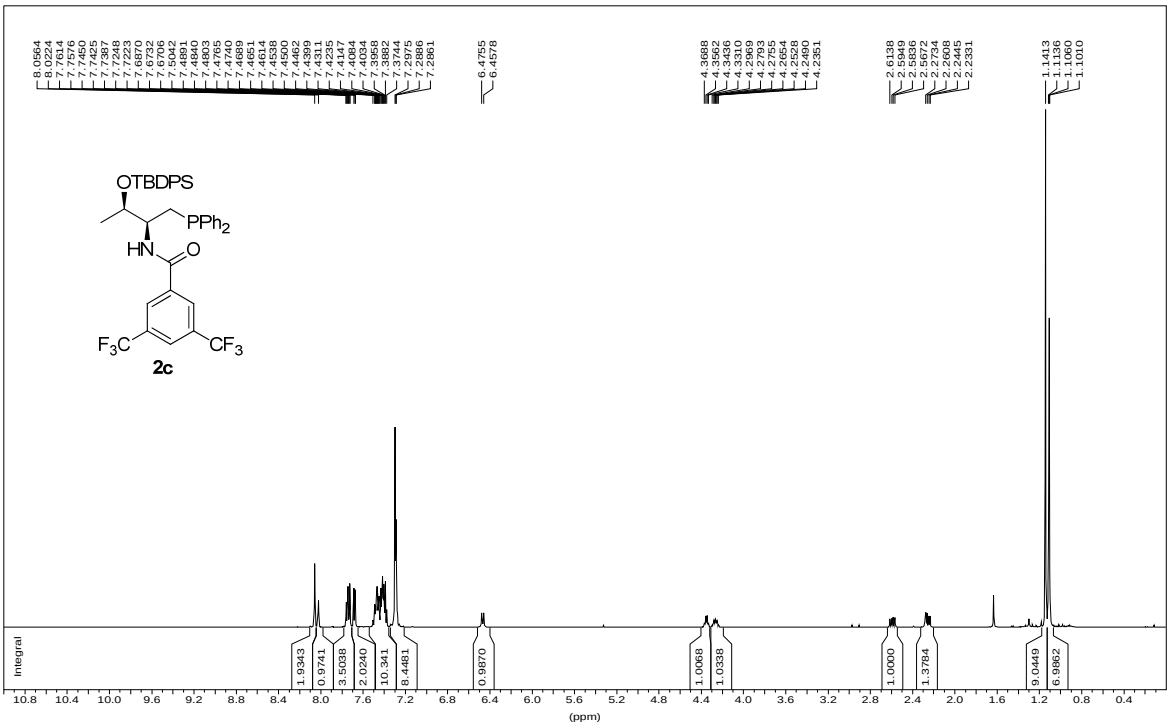


2698(zfr0603-11)

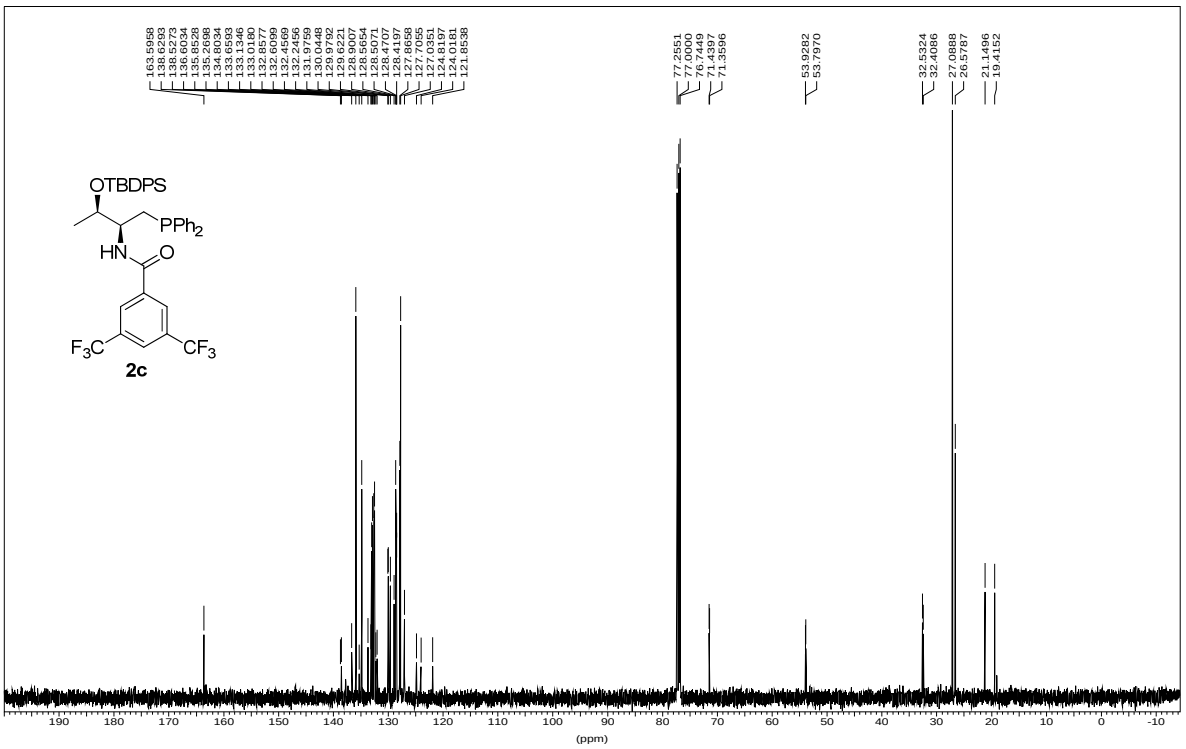


1H AMX500

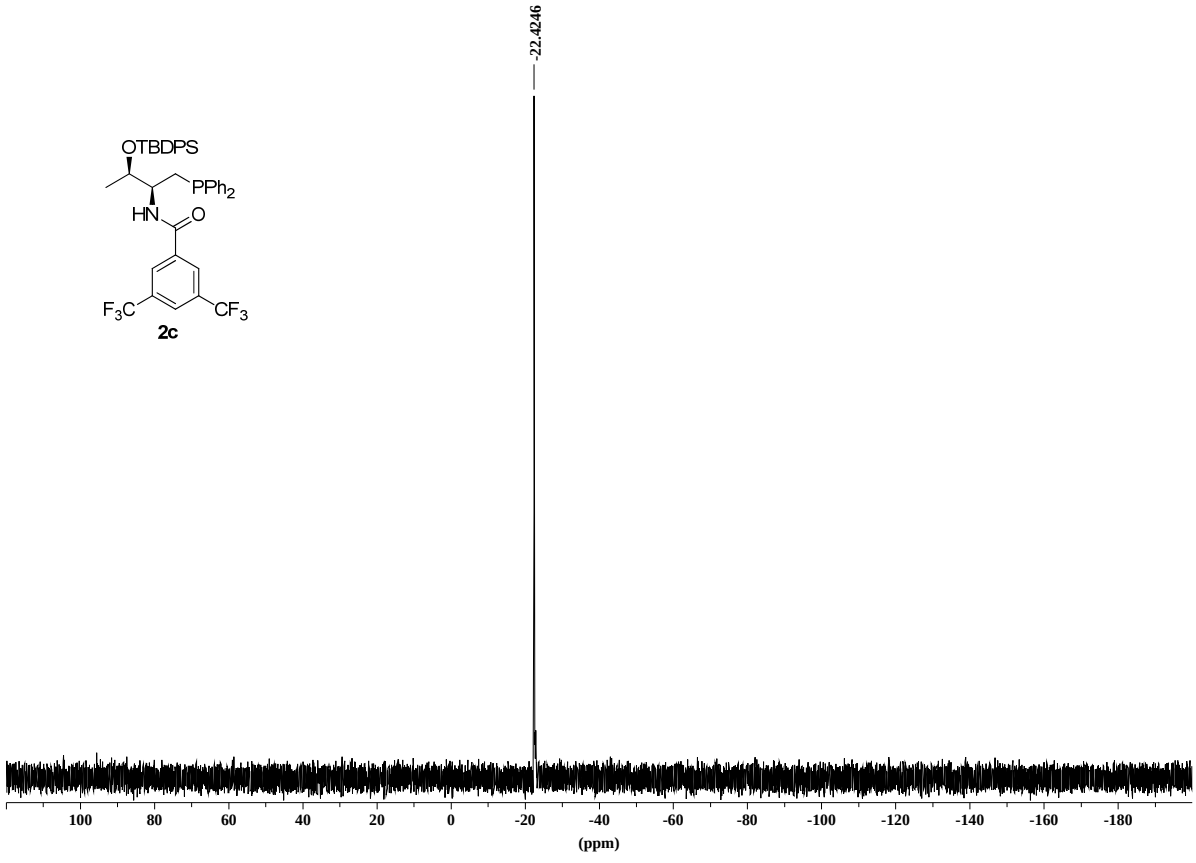
2530-TBDPS-cat



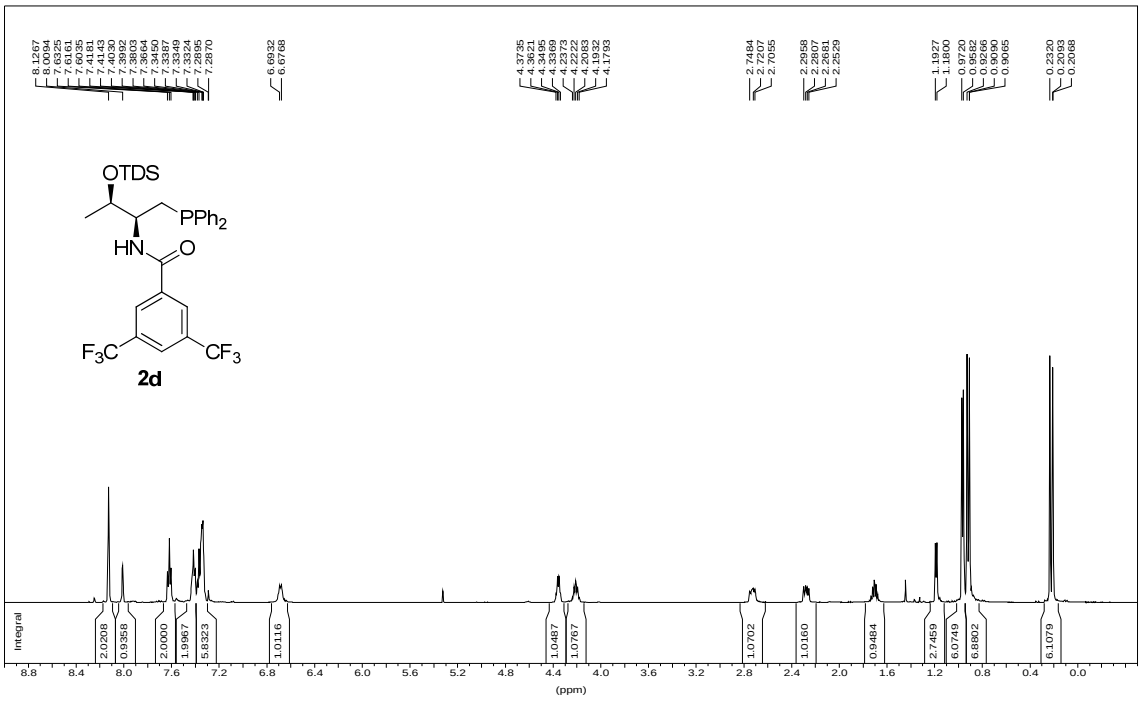
13C AMX500
zfr-2530(cat)(zfr0419-10)



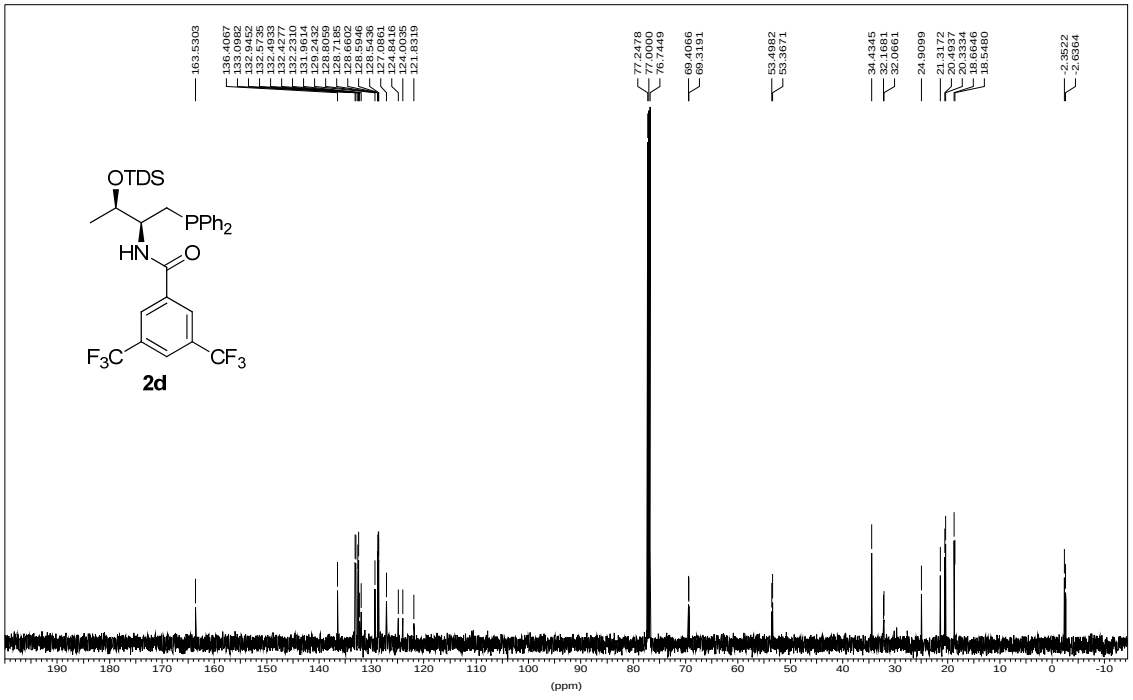
31p AMX500 wyq-B86



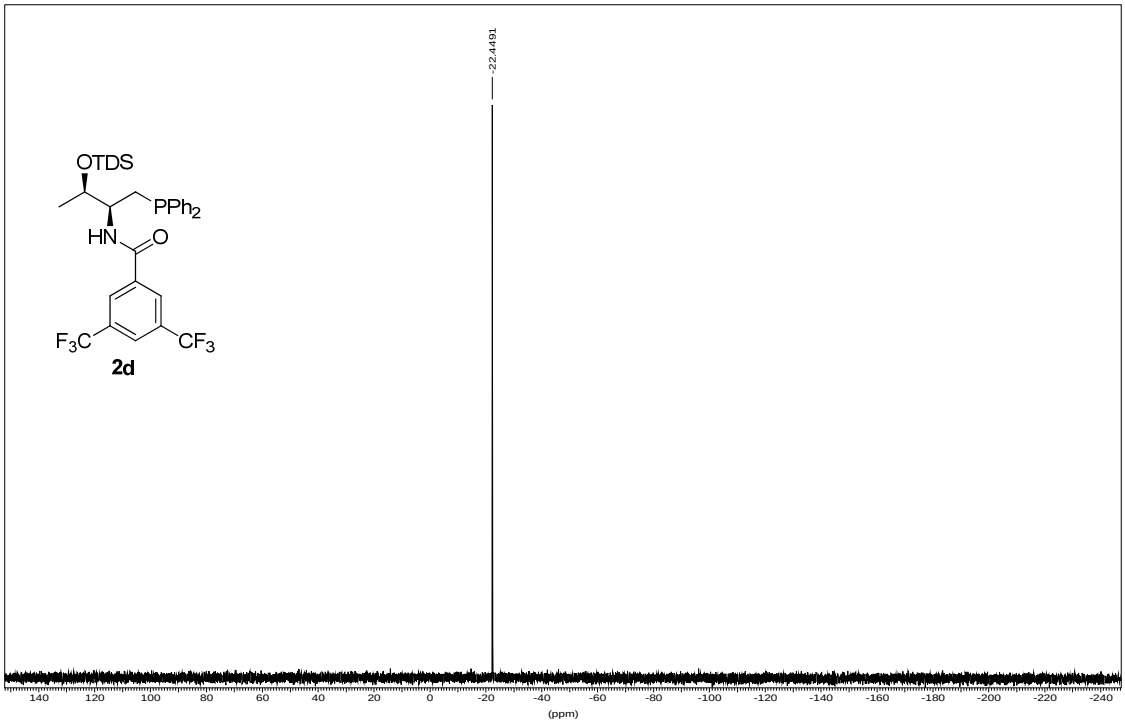
AMX500
2697(zfr0603-7)



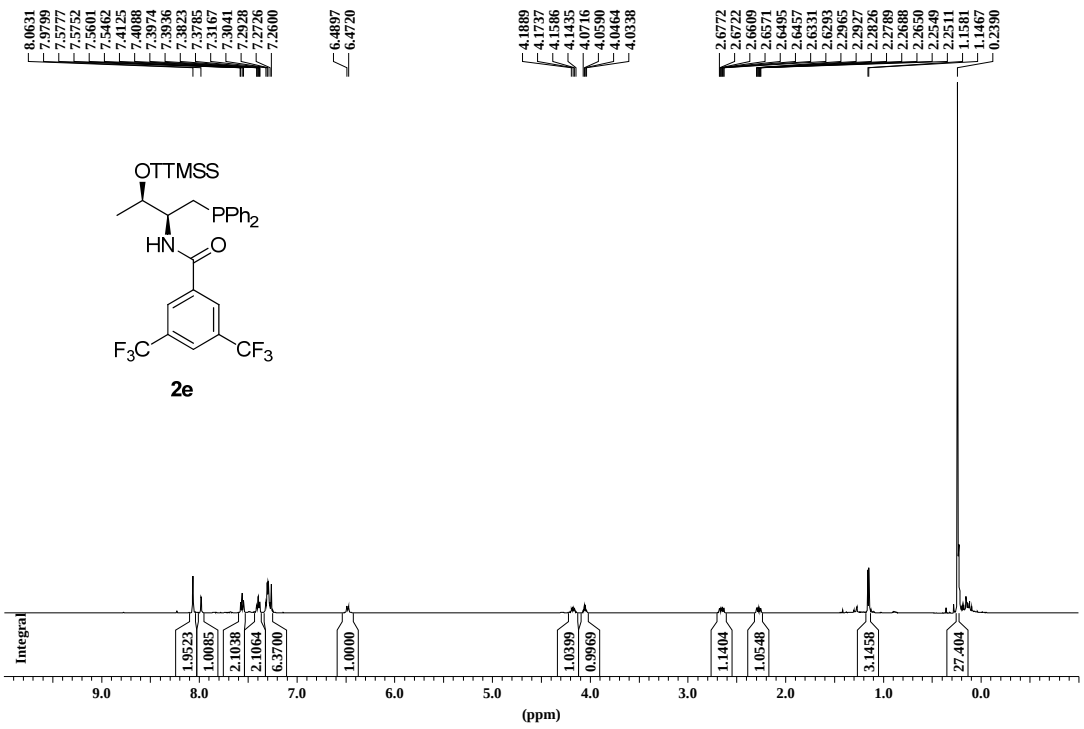
13C AMX500
zfr-2697(zfr0603-8)



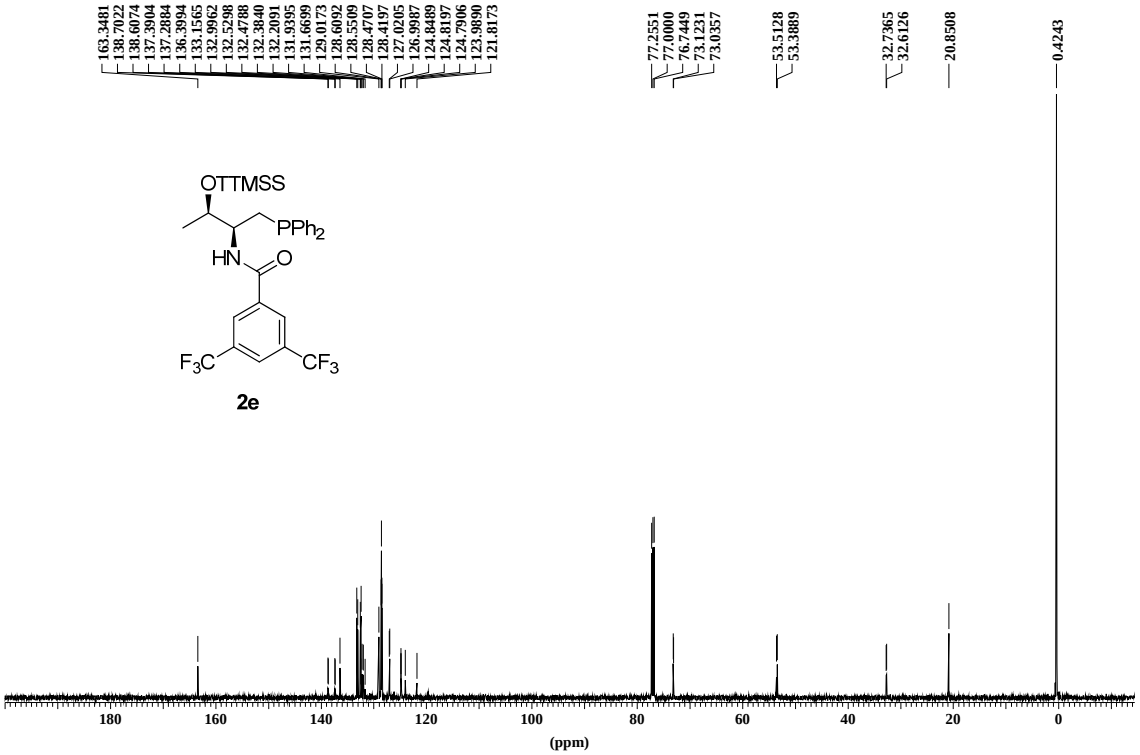
2697(zfr0603-12)



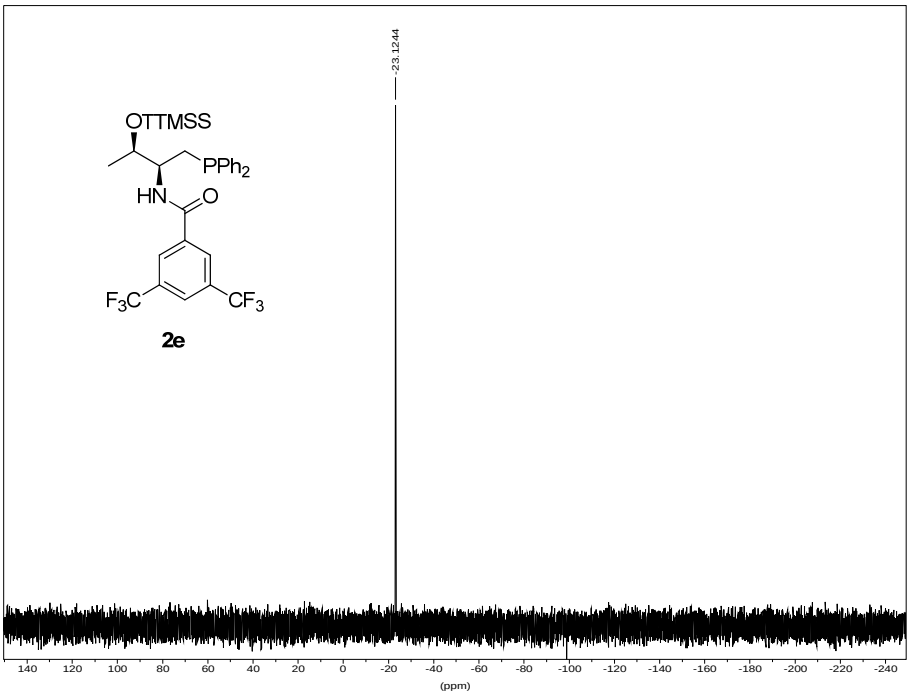
1H AMX500(zfr0621-1)
TTMS-cat



13C AMX500(zfr0621-2)
TTMS-cat



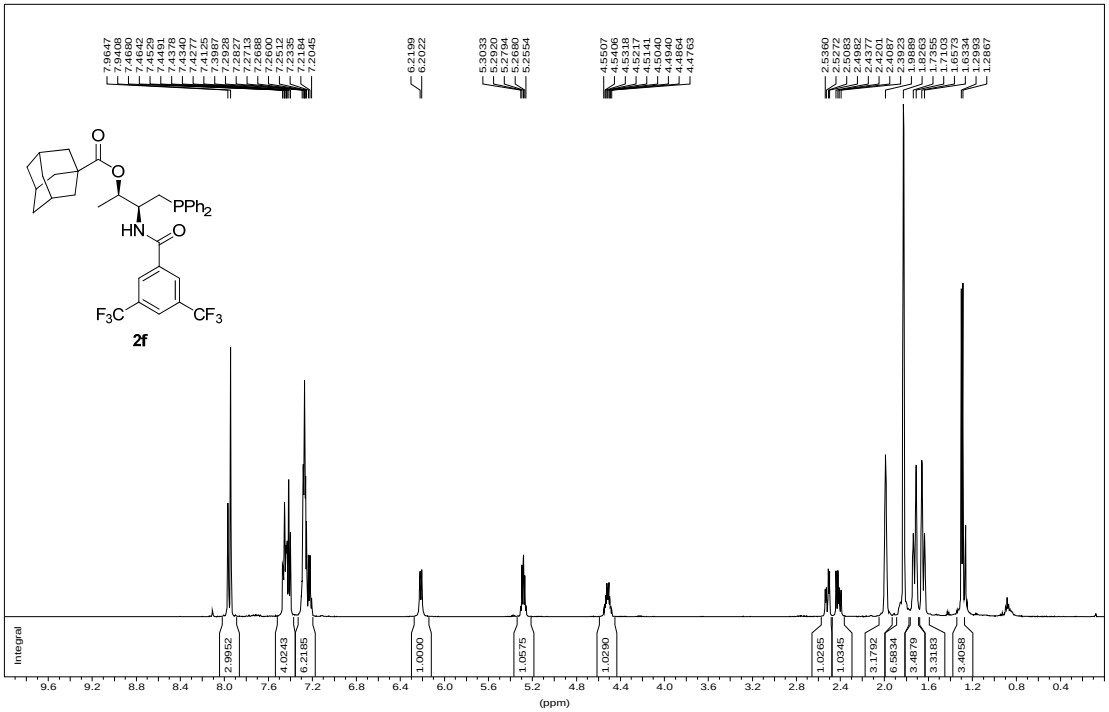
31P AC300
TMMS-L-Thr-COAr



*** Current Data Parameters ***
NAME : zfr0611
EXPNO : 5
PROCNO : 1
*** Acquisition Parameters ***
BF1 : 121.4948510 MHz
LOCNUC : 2H
NS : 5
O1 : -6074.78 Hz
PULPROG : zgpg30
SFO1 : 121.4887762 MHz
SOLVENT : Acetone
SW : 399.5734 ppm
*** Processing Parameters ***
LB : 1.00 Hz
PHC0 : 26.986 degree
PHC1 : 119.405 degree

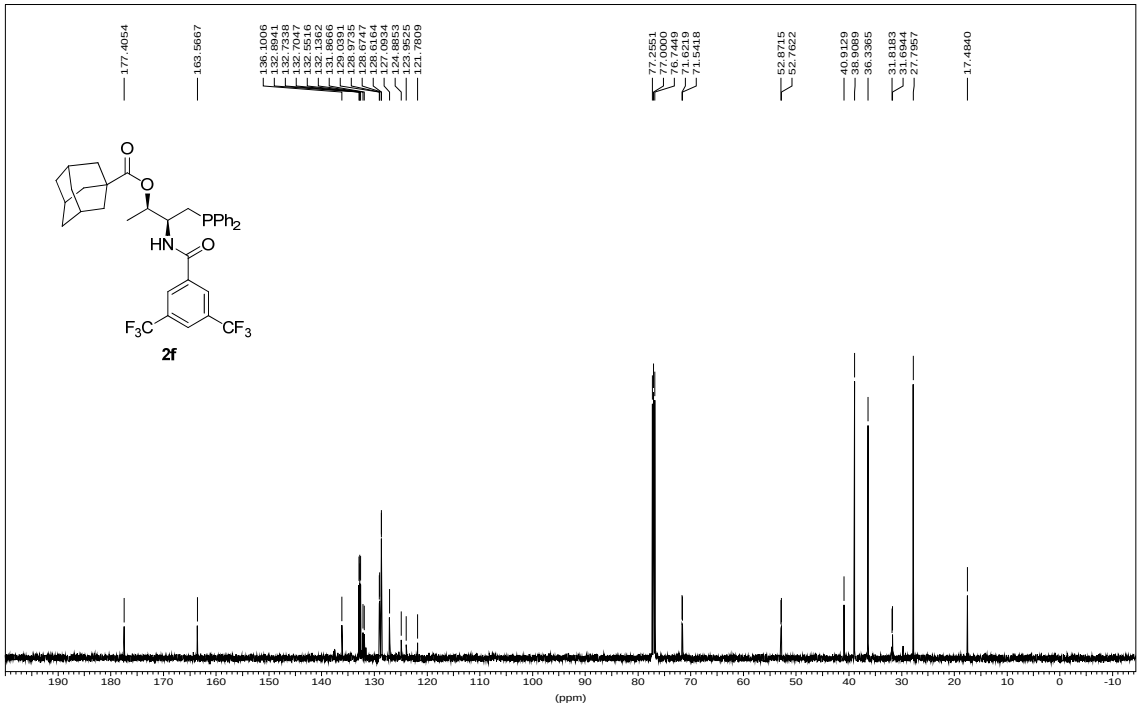
1H AMX500

Ad-phosphine-amide-cat



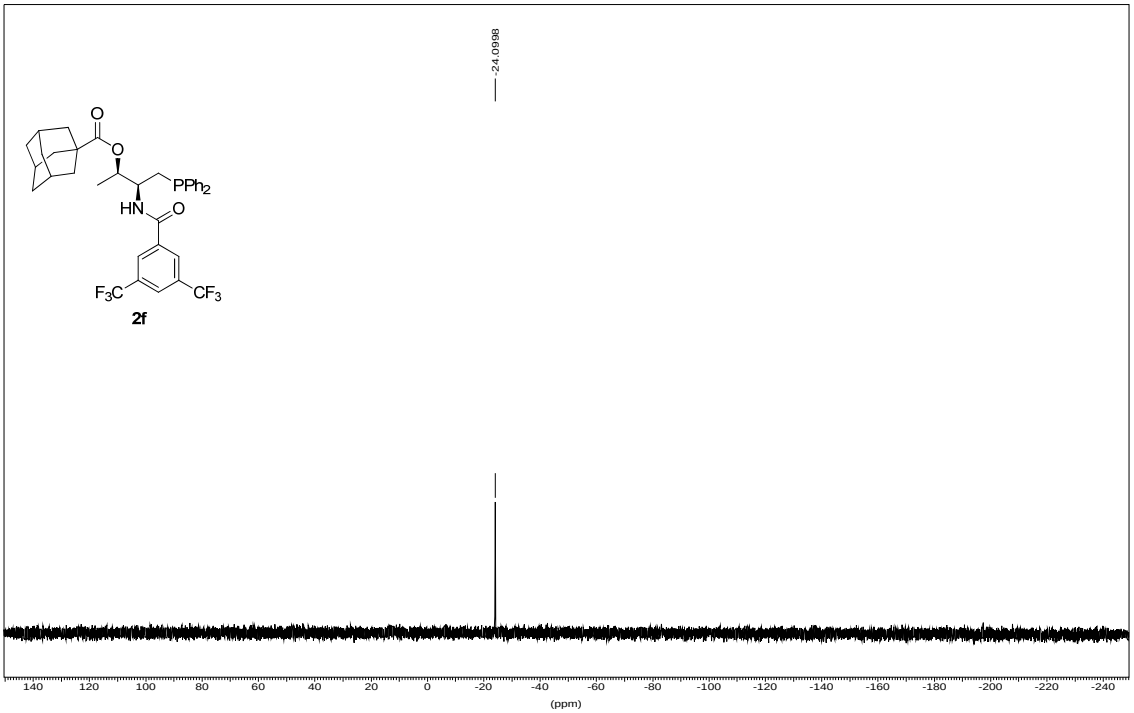
13C AMX500(zfr0606-4)

Ad-phosphine-amide-cat



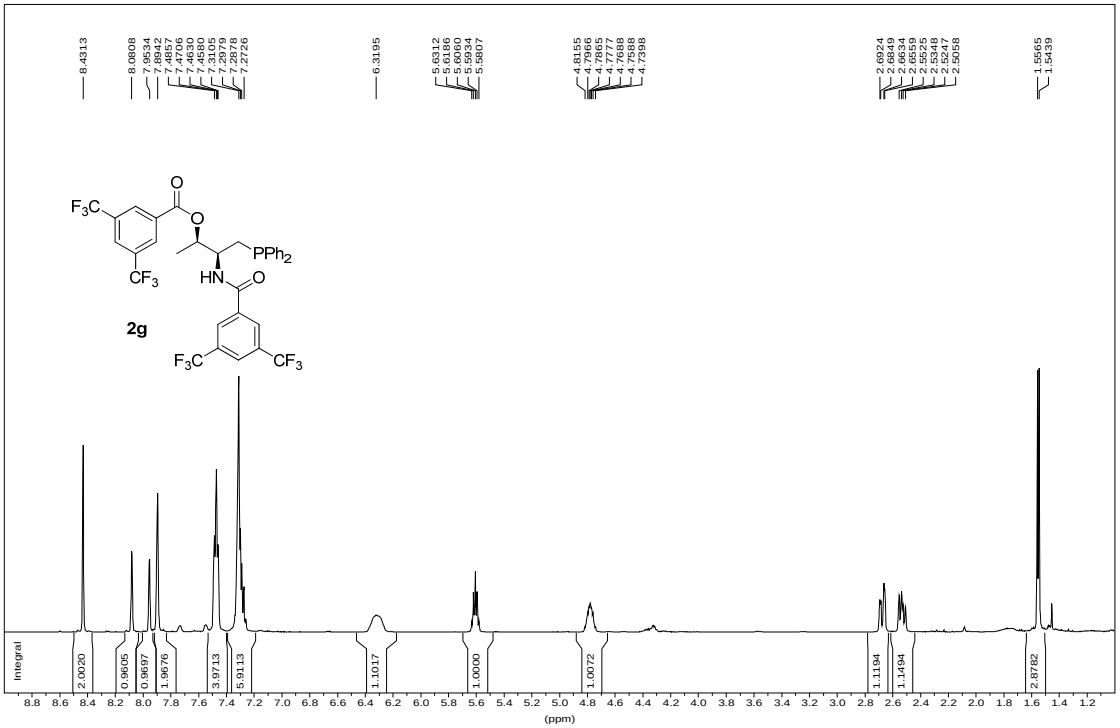
31P AC300

ad-phosphine-amide-cat

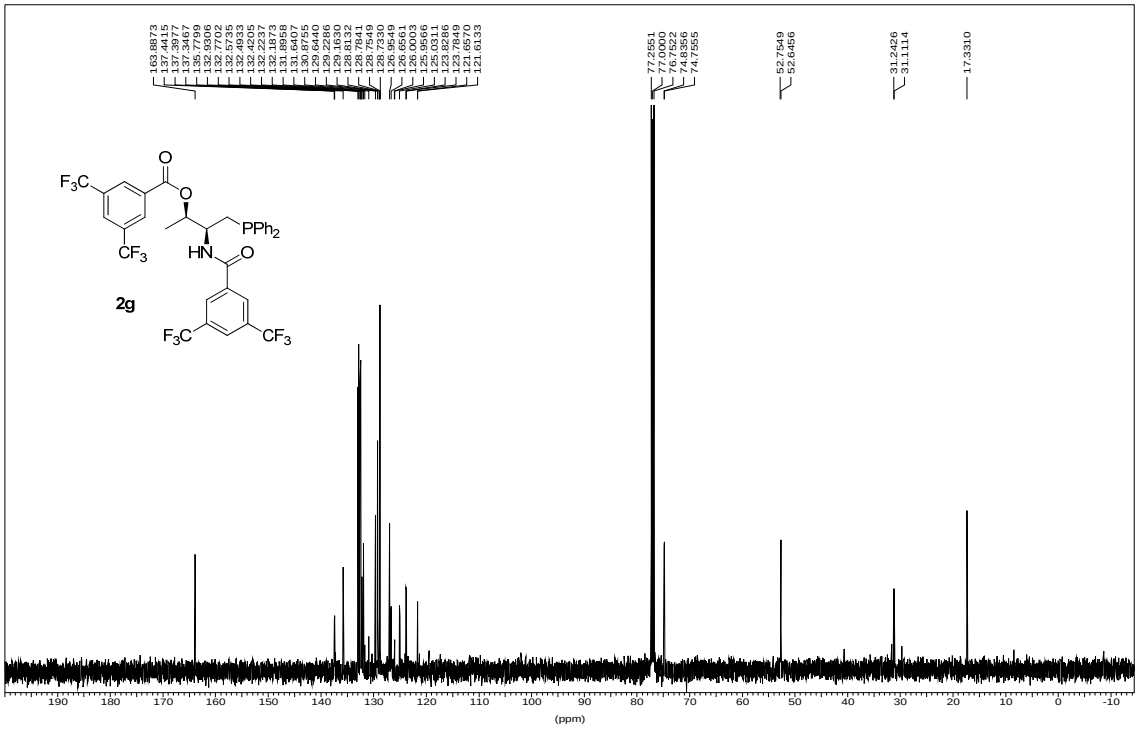


AMX500

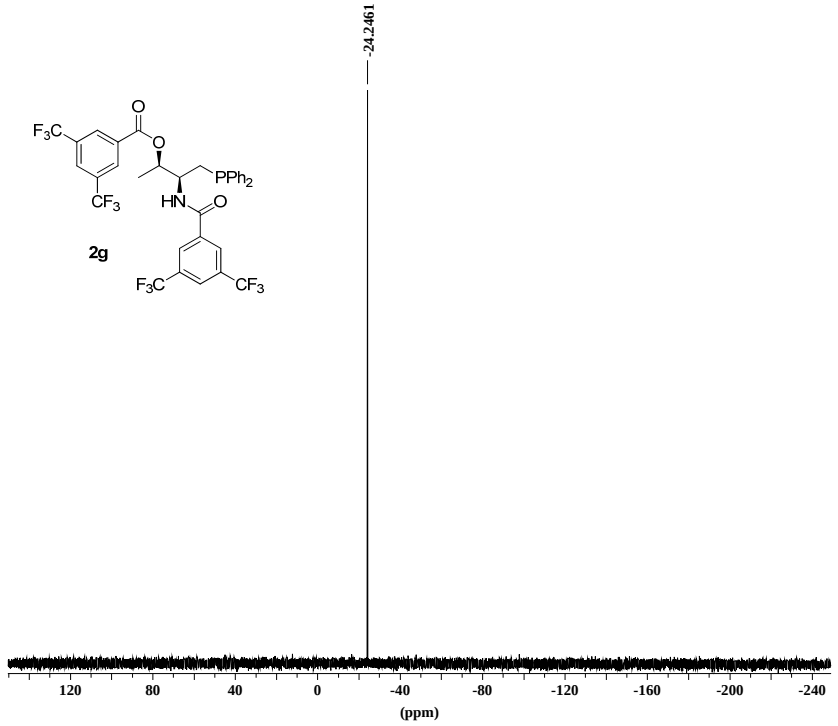
zfr-2694-1(zfr0601-8)



13C AMX500
2694-1(zfr0601-6)



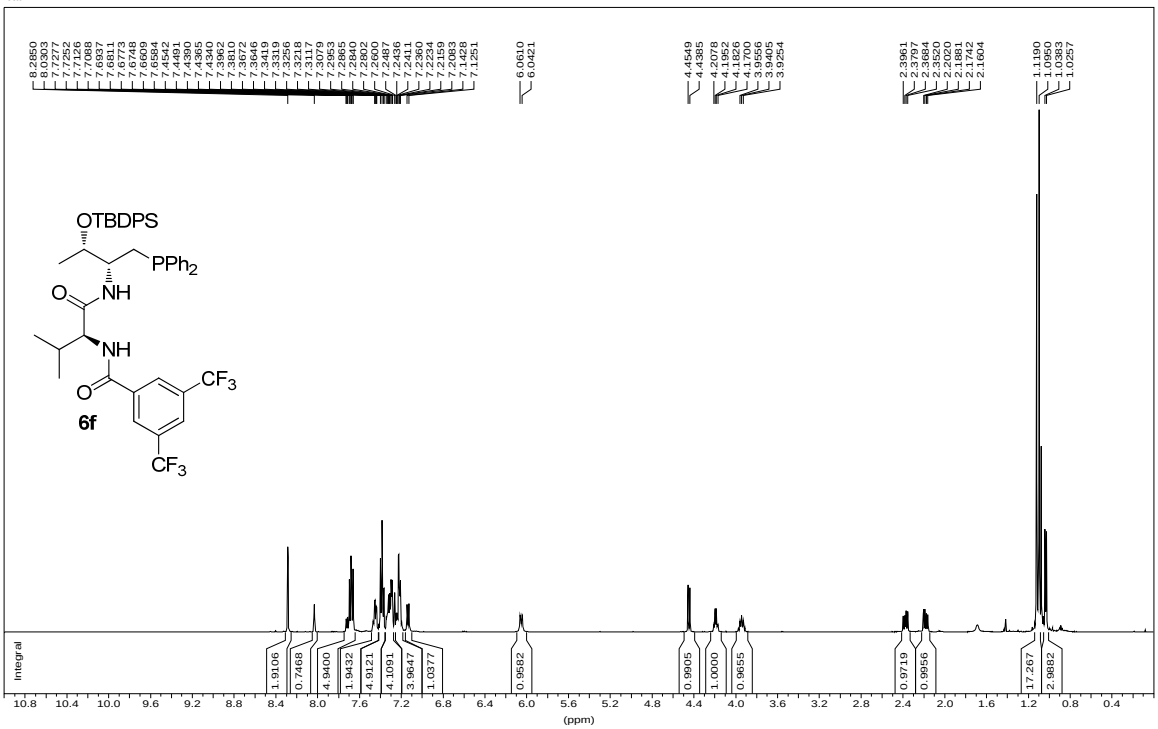
31P AC300
2694-1



*** Current Data Parameters ***
NAME : ju01zfr
EXPNO : 2
PROCNO : 1
*** Acquisition Parameters ***
LOCNUC : 2H
NS : 7
NUCLEUS : off
O1 : -6074.78 Hz
PULPROG : zgpg30
SFO1 : 121.4887762 MHz
SOLVENT : Acetone
SW : 399.5734 ppm
TD : 65536
TE : 296.8 K
*** Processing Parameters ***
LB : 1.00 Hz
SF : 121.4947767 MHz
*** 1D NMR Plot Parameters ***
NUCLEUS : off

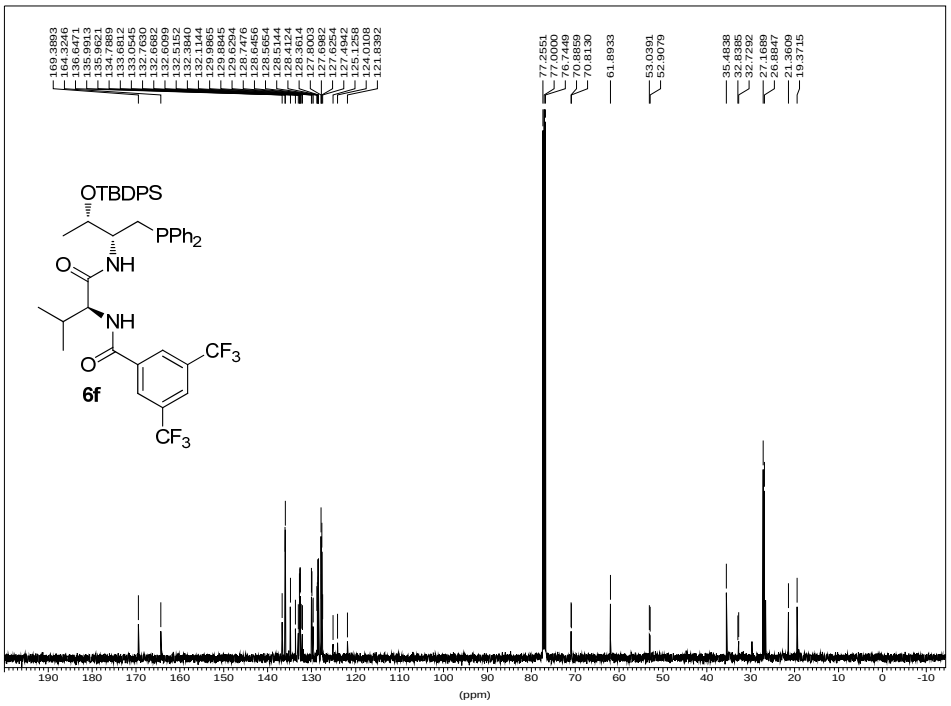
AMX500

cat



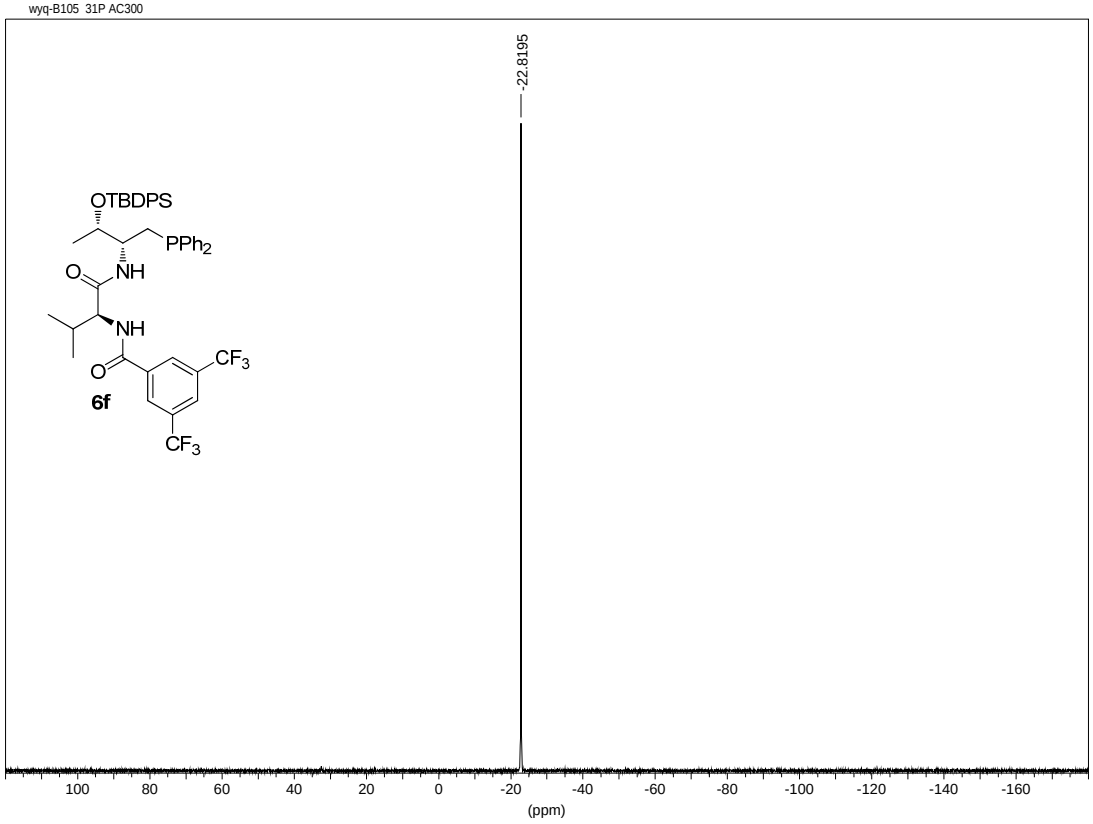
13C AMX500

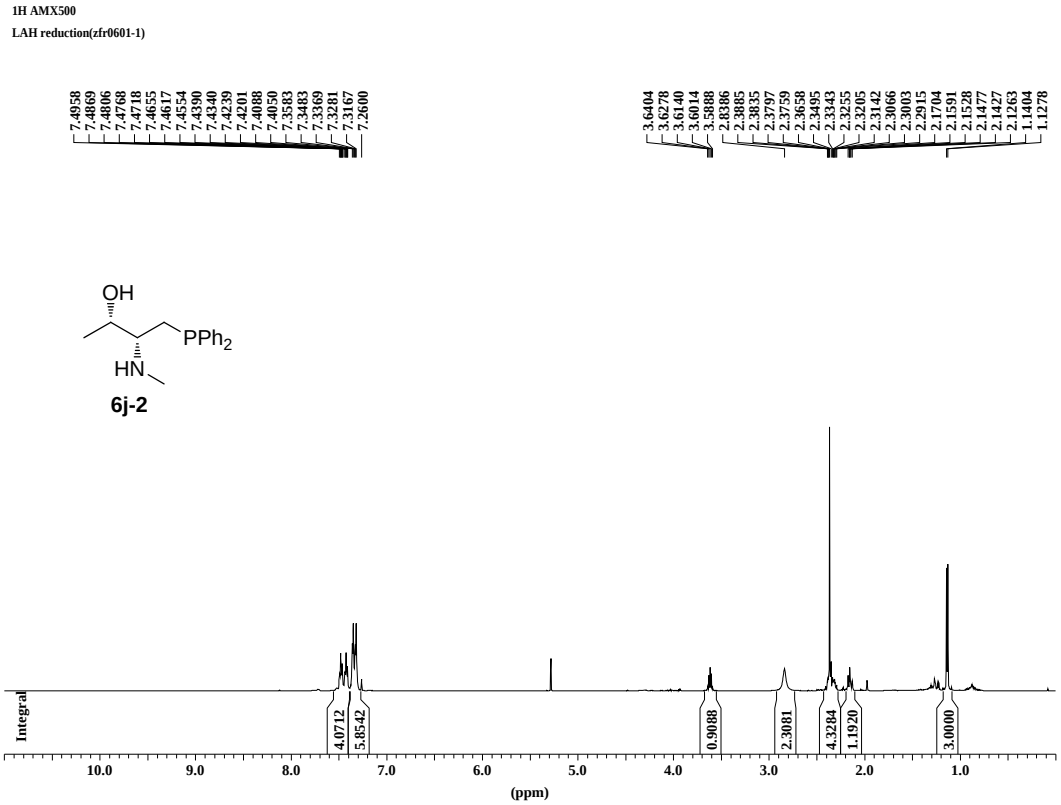
cat



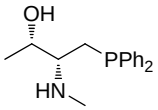
*** Current Data Parameters ***

NAME	:	zfr0610
EXPNO	:	9
PROCNO	:	1
*** Acquisition Parameters ***		
BF1	:	125.7577890 MHz
LOCNUC	:	2H
NS	:	567
O1	:	13204.57 Hz
PULPROG	:	zgpg30
SFO1	:	125.7709936 MHz
SOLVENT	:	CDCl3
SW	:	238.7675 ppm
*** Processing Parameters ***		
LB	:	1.00 Hz
PHC0	:	217.698 degree
PHC1	:	43.597 degree

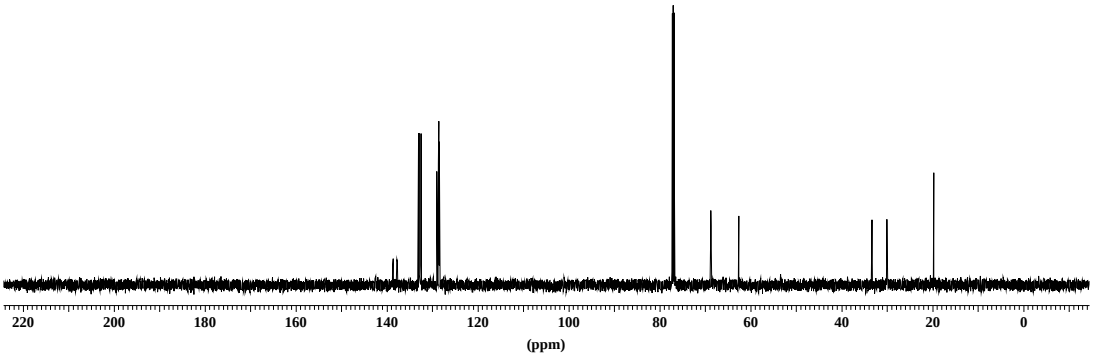

wyq-B105 31P AC300
-22.8195
OTBDPS
PPh2
O
NH
NH
O
CF3
CF3
6f
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
(ppm)


1H AMX500
LAH reduction(zfr0601-1)
7.4958
7.4869
7.4806
7.4768
7.4718
7.4655
7.4617
7.4554
7.4390
7.4340
7.4239
7.4201
7.4088
7.4050
7.3583
7.3483
7.3369
7.3281
7.3167
7.2600
3.6404
3.6278
3.6140
3.6014
3.5888
2.8386
2.3885
2.3835
2.3797
2.3759
2.3658
2.3495
2.3343
2.3255
2.3205
2.3142
2.3066
2.3003
2.2915
2.1704
2.1591
2.1528
2.1477
2.1427
2.1263
1.1404
1.1278
OH
PPh2
HN
6j-2
Integral
4.0712
5.8542
0.9088
2.3081
4.3284
1.1920
3.0000
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(ppm)

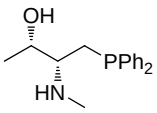
13C AMX500
LAH-reduction(zfr0601-2)



6j-2



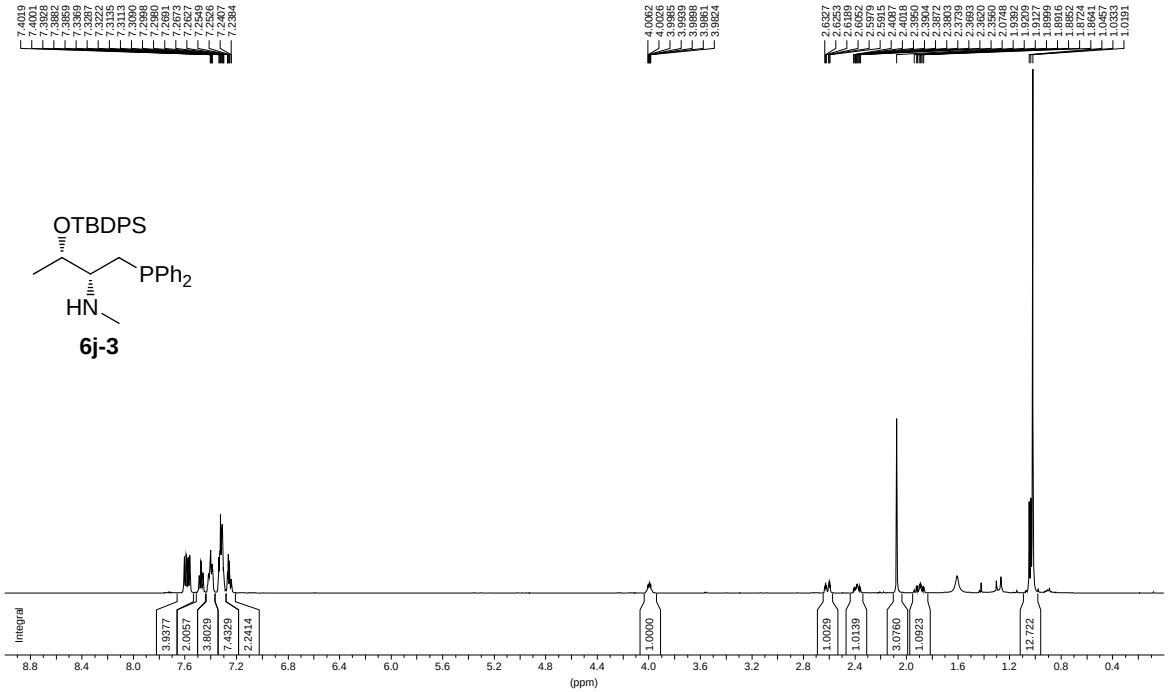
31P AC300
2694-LAH reduction



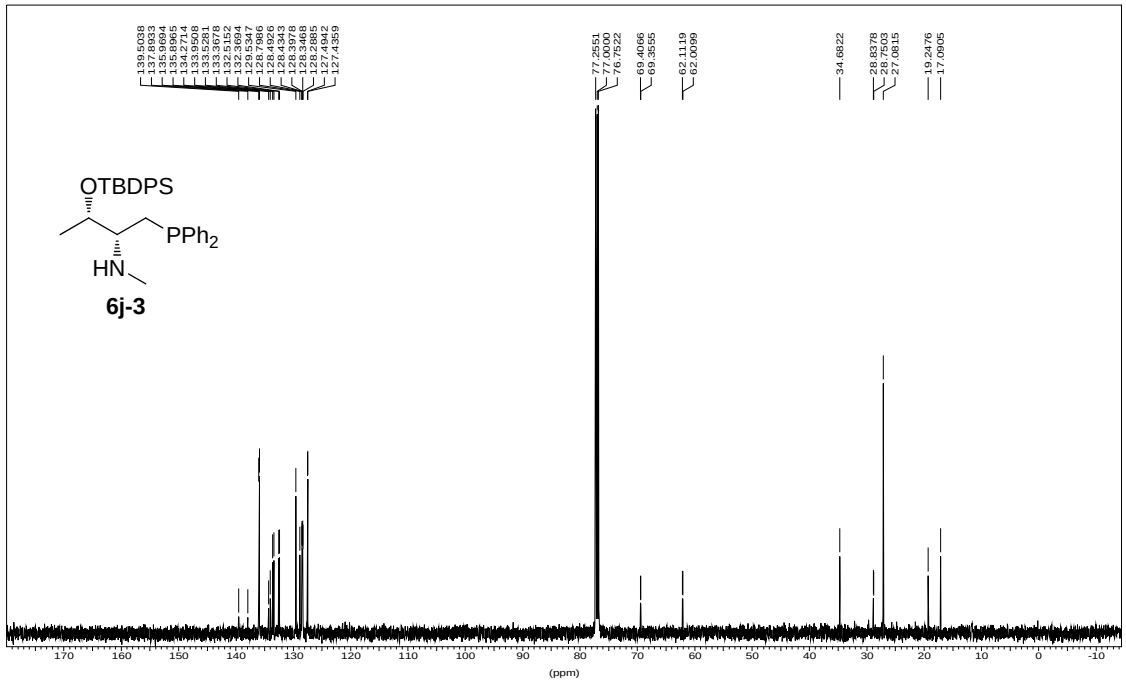
6j-2

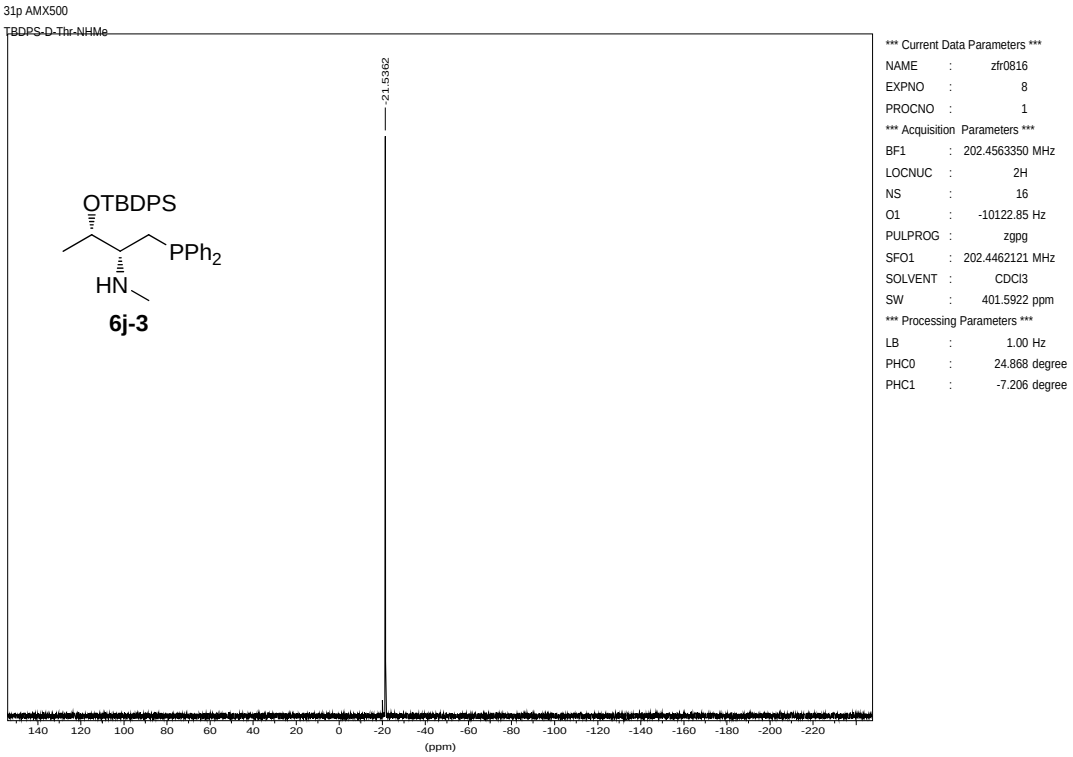
*** Current Data Parameters ***
NAME : ju01zfr
EXPNO : 3
PROCNO : 1
*** Acquisition Parameters ***
LOCNUC : 2H
NS : 12
NUCLEUS : off
O1 : -6074.78 Hz
PULPROG : zgpg30
SFO1 : 121.4887762 MHz
SOLVENT : Acetone
SW : 399.5734 ppm
TD : 65536
TE : 296.8 K
*** Processing Parameters ***
LB : 1.00 Hz
SF : 121.4947767 MHz
*** 1D NMR Plot Parameters ***
NUCLEUS : off

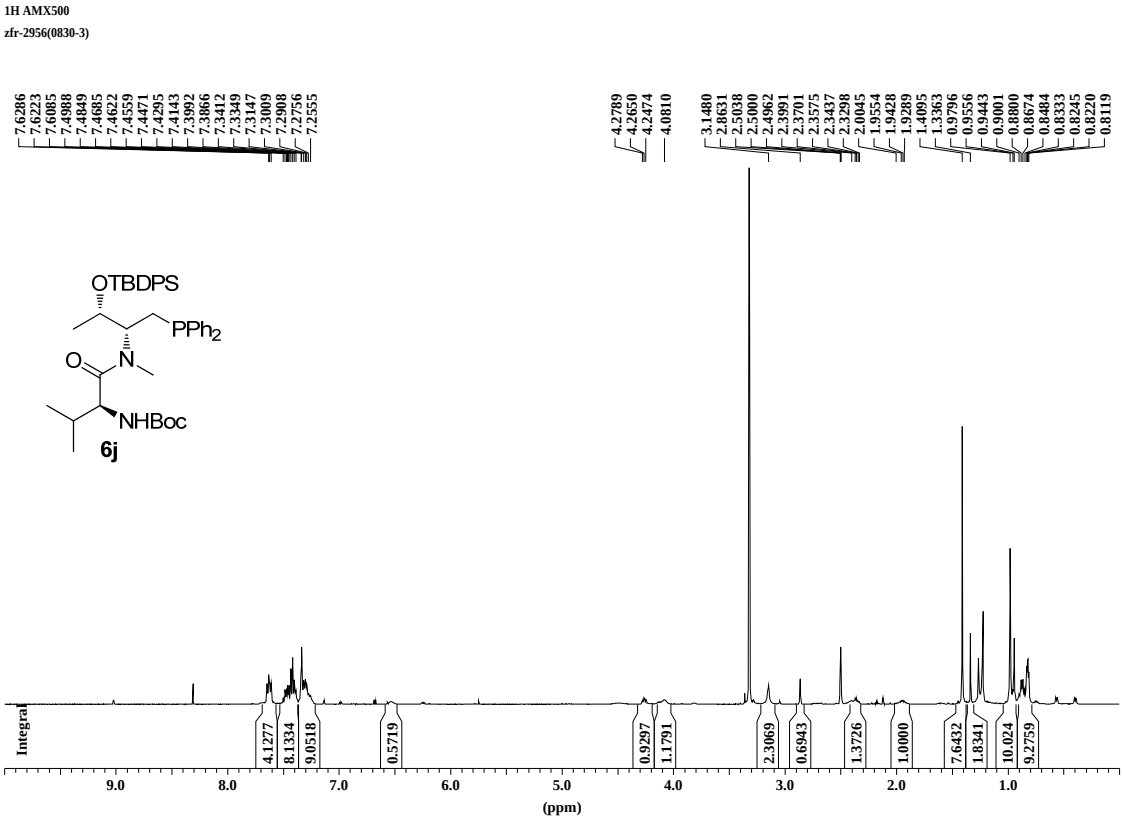
TBDPS-D-Thr-PPh2-NHMe



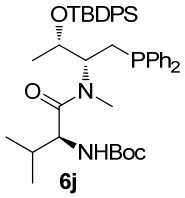
13C AMX500
TBDPS-D-Thr-NHMe(zfr0816-6)



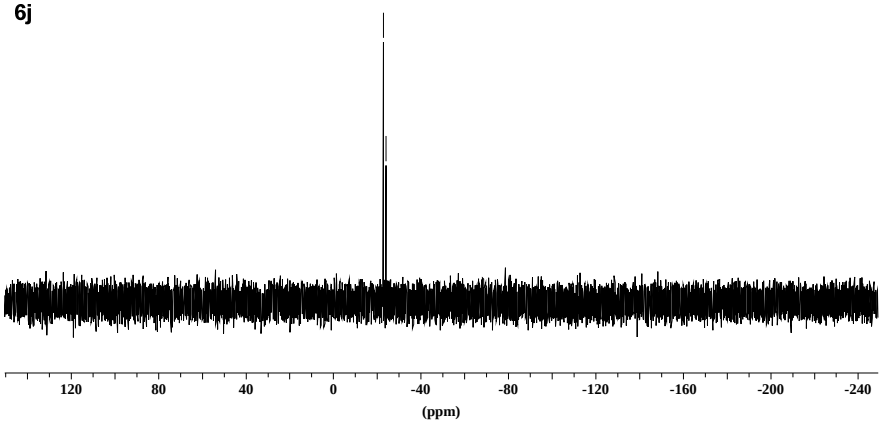

31p AMX500
TBDPS-D-Thr-NHMe
-21.5362
OTBDPS
PPh2
HN
6j-3
(ppm)
*** Current Data Parameters ***
NAME : zfr0816
EXPNO : 8
PROCNO : 1
*** Acquisition Parameters ***
BF1 : 202.4563350 MHz
LOCNUC : 2H
NS : 16
O1 : -10122.85 Hz
PULPROG : zgpg
SFO1 : 202.4462121 MHz
SOLVENT : CDCl3
SW : 401.5922 ppm
*** Processing Parameters ***
LB : 1.00 Hz
PHC0 : 24.868 degree
PHC1 : -7.206 degree


1H AMX500
zfr-2956(0830-3)
OTBDPS
PPh2
O
N
NHBoc
6j
Integral
(ppm)

31P AC300

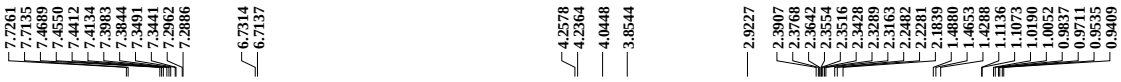


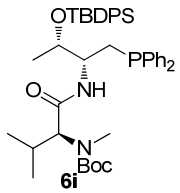
6j



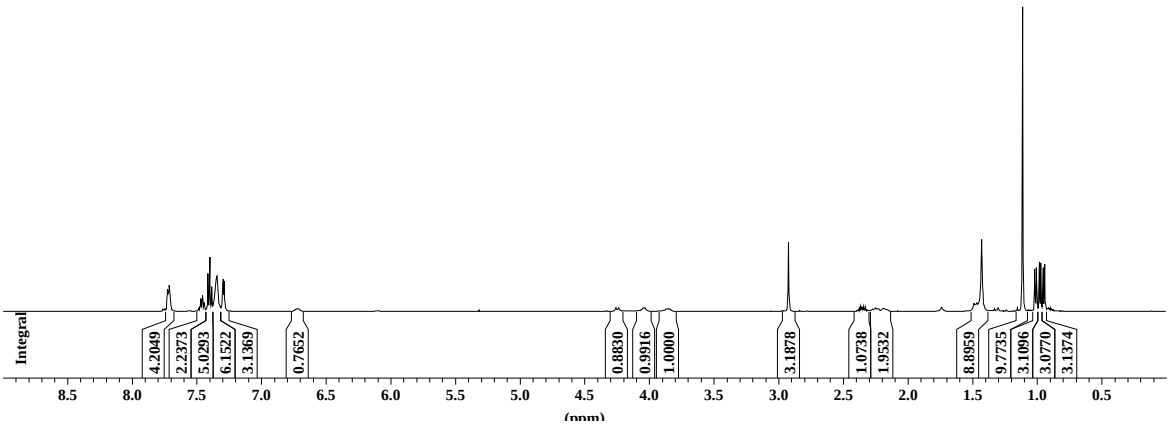
*** Current Data Parameters ***
NAME : ag30zfr
EXPNO : 3
PROCNO : 1
*** Acquisition Parameters ***
LOCNUC : 2H
NS : 52
NUCLEUS : off
O1 : -6074.78 Hz
PULPROG : zgpg30
SFO1 : 121.4887762 MHz
SOLVENT : DMSO
SW : 399.5734 ppm
TD : 65536
TE : 297.9 K
*** Processing Parameters ***
LB : 1.00 Hz
SF : 121.4947767 MHz
*** 1D NMR Plot Parameters ***
NUCLEUS : off

1H AMX500
zfr-2689(zfr-0531-1)

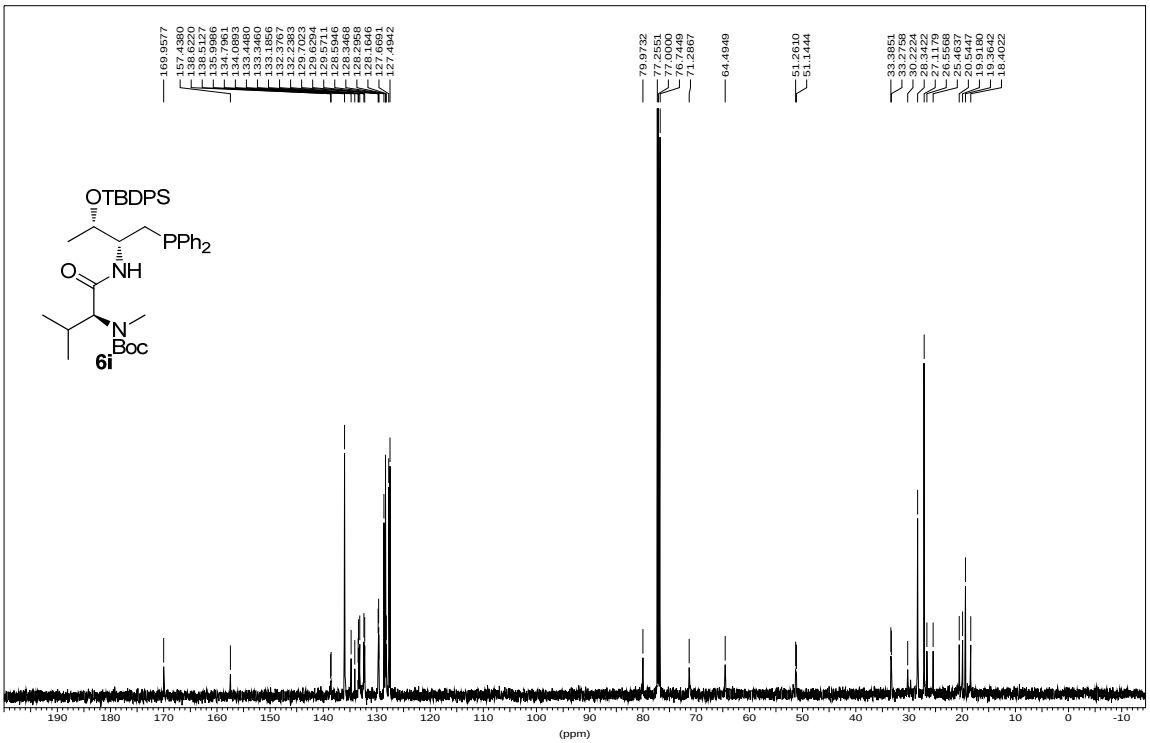




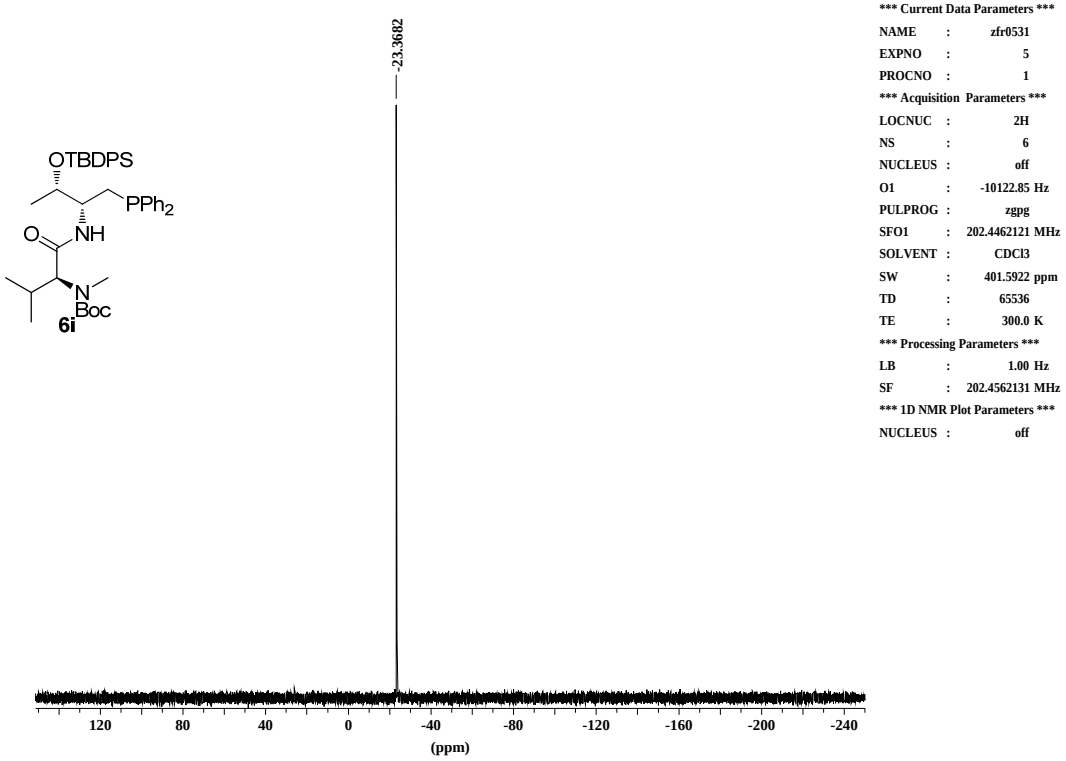
6i



13C AMX500
2689(zfr0601-10)

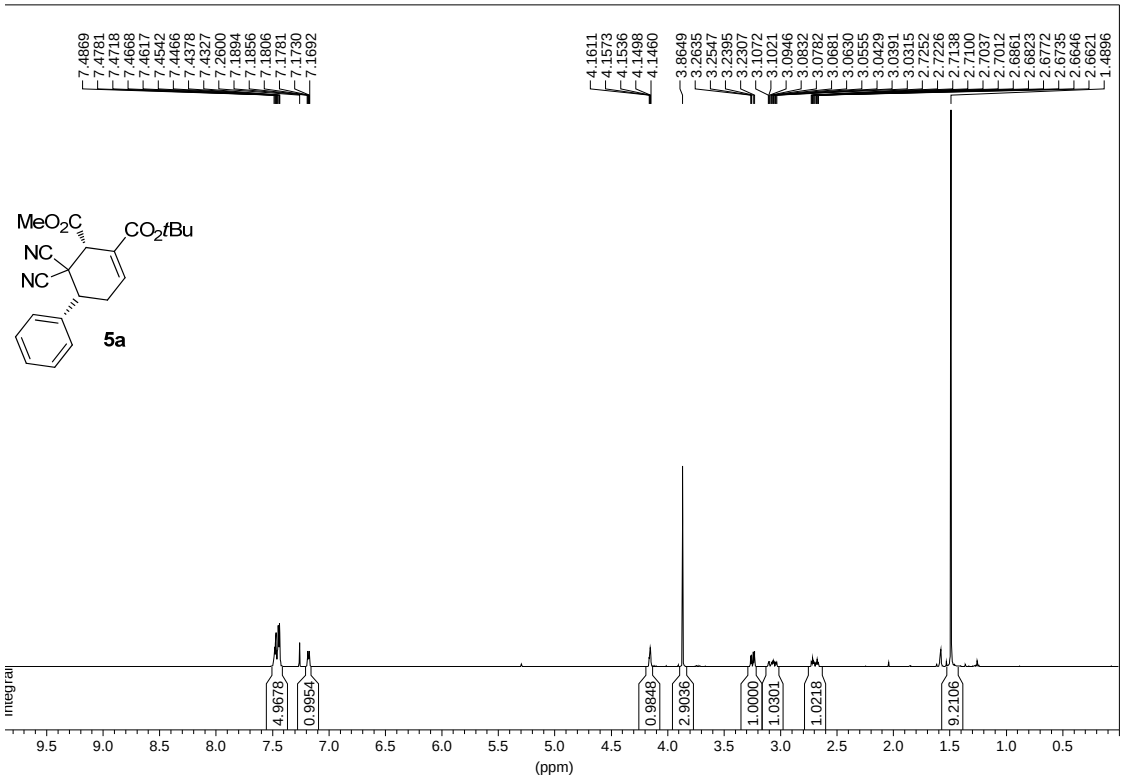


31p AMX500
2689

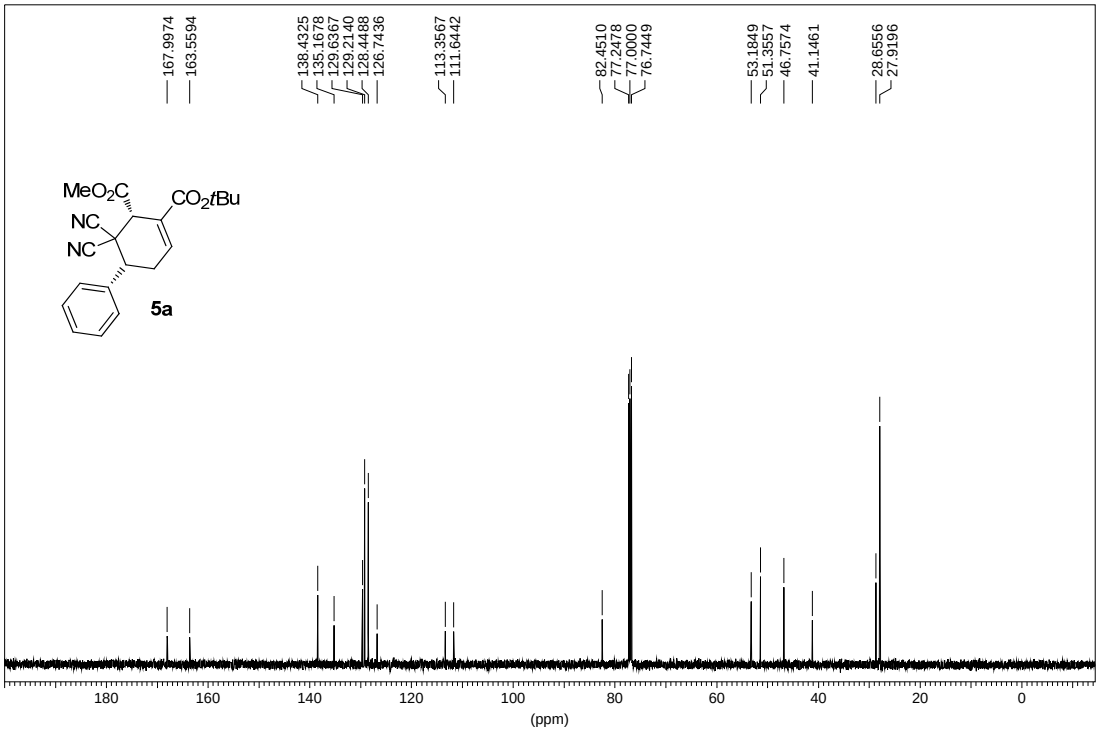


*** Current Data Parameters ***
NAME : zfr0531
EXPNO : 5
PROCNO : 1
*** Acquisition Parameters ***
LOCNUC : 2H
NS : 6
NUCLEUS : off
O1 : -10122.85 Hz
PULPROG : zgpg
SFO1 : 202.4462121 MHz
SOLVENT : CDCl3
SW : 401.5922 ppm
TD : 65536
TE : 300.0 K
*** Processing Parameters ***
LB : 1.00 Hz
SF : 202.4562131 MHz
*** 1D NMR Plot Parameters ***
NUCLEUS : off

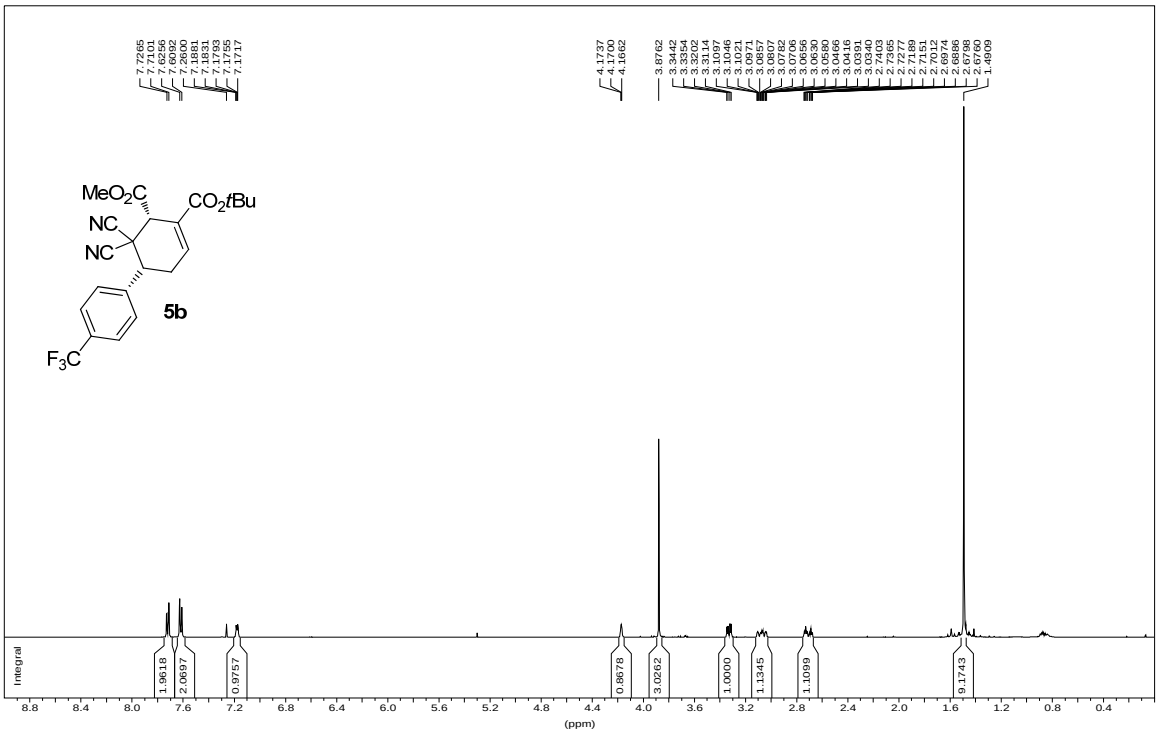
1H AMX500(zfr0608-15)
zfr-2709-2



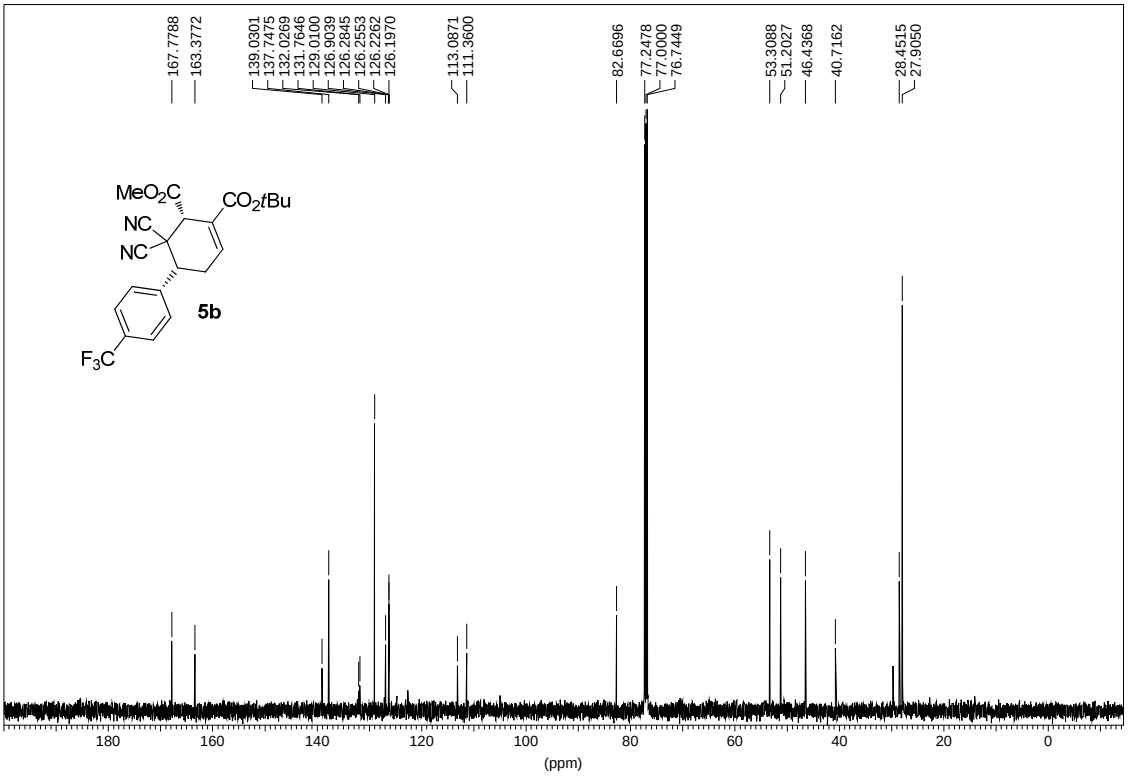
13C AMX500
zfr2709-2(zfr0608-14)



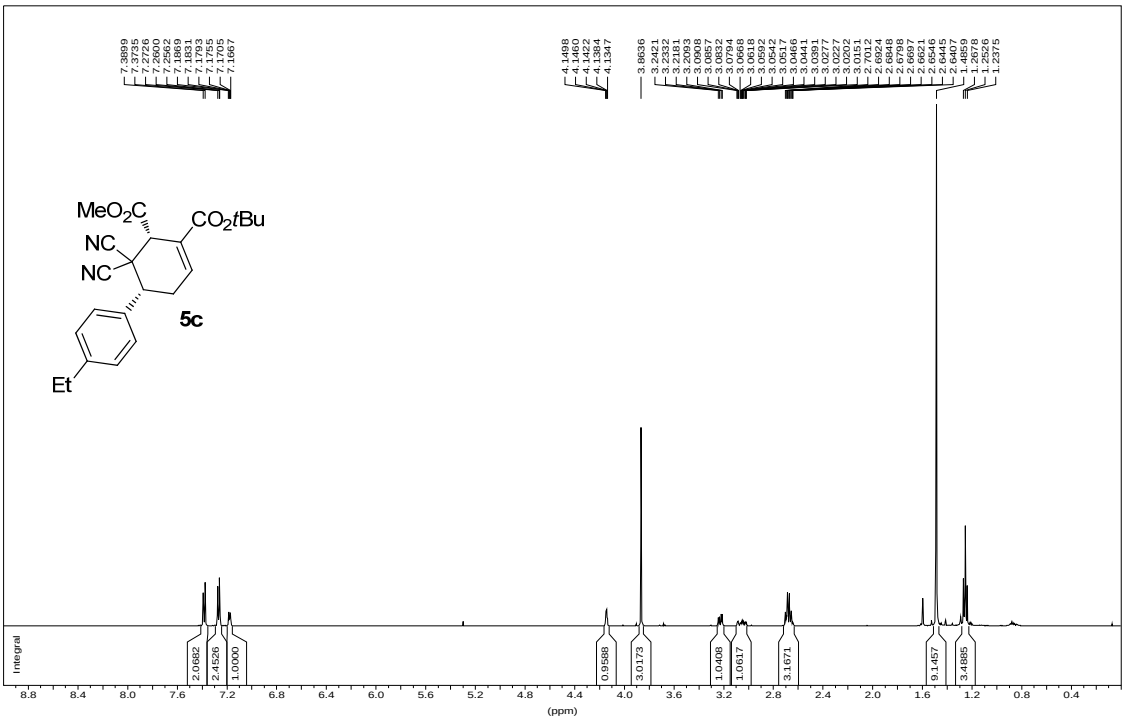
1H AMX500
2840(zfr0706-15)



13C AMX500
2840(zfr0712-10)



1H AMX500
2842(zfr0706-7)



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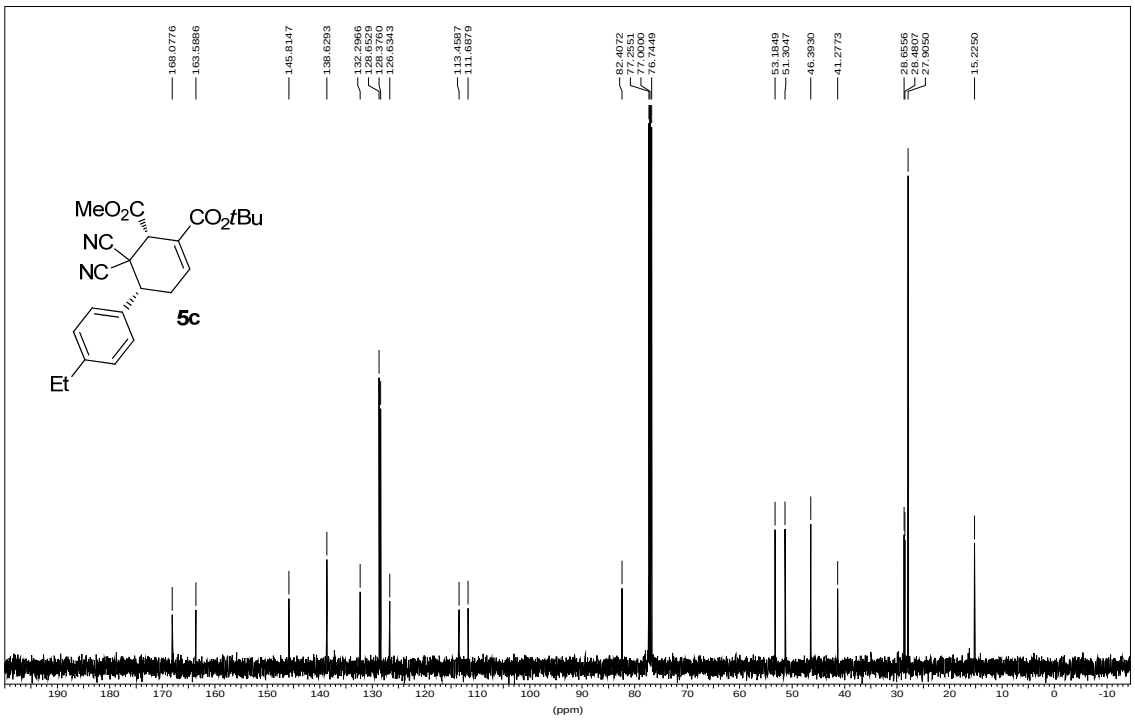

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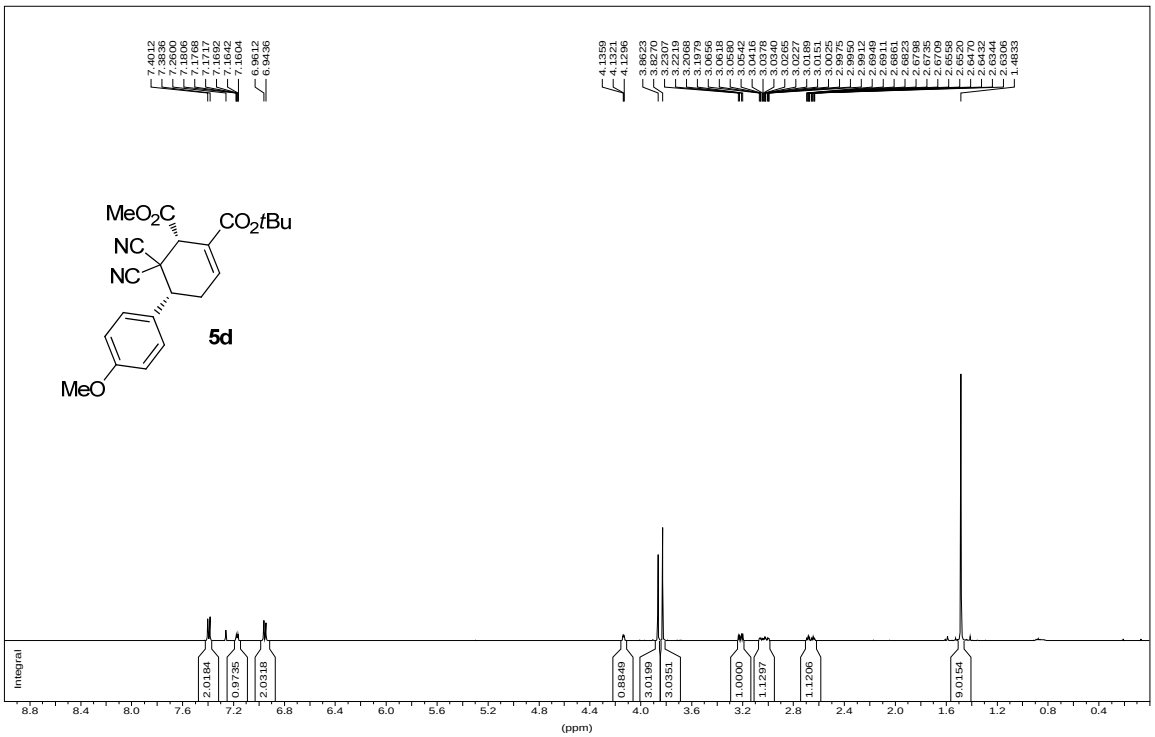

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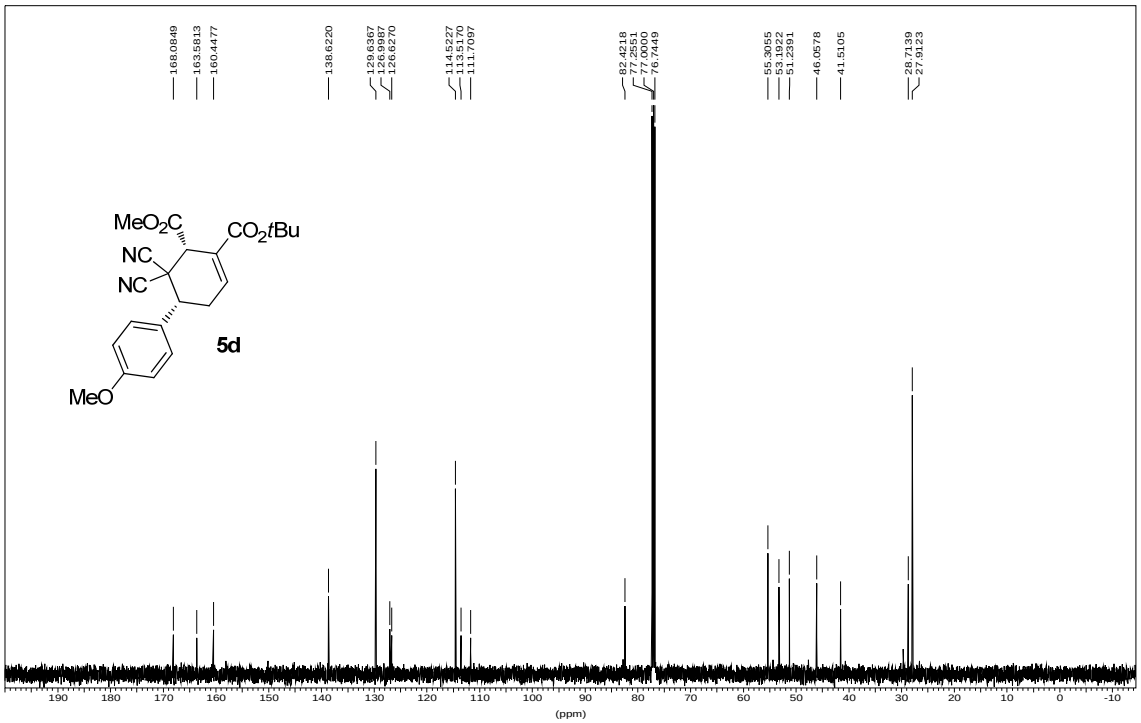

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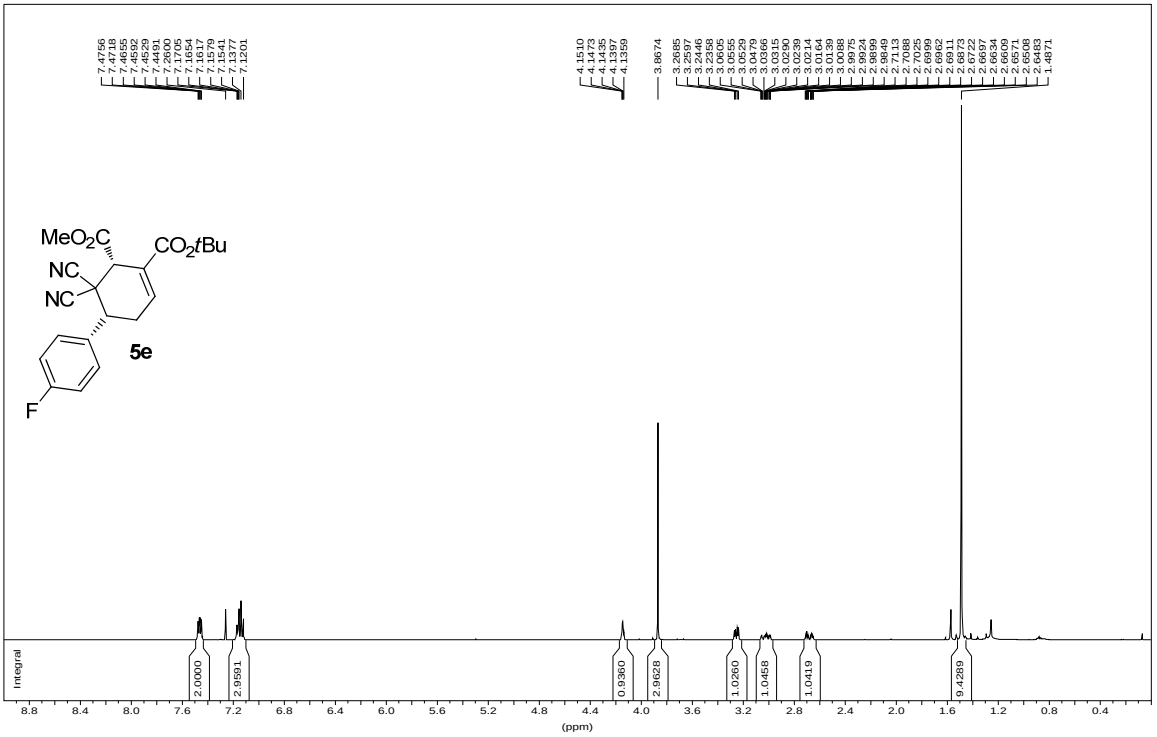

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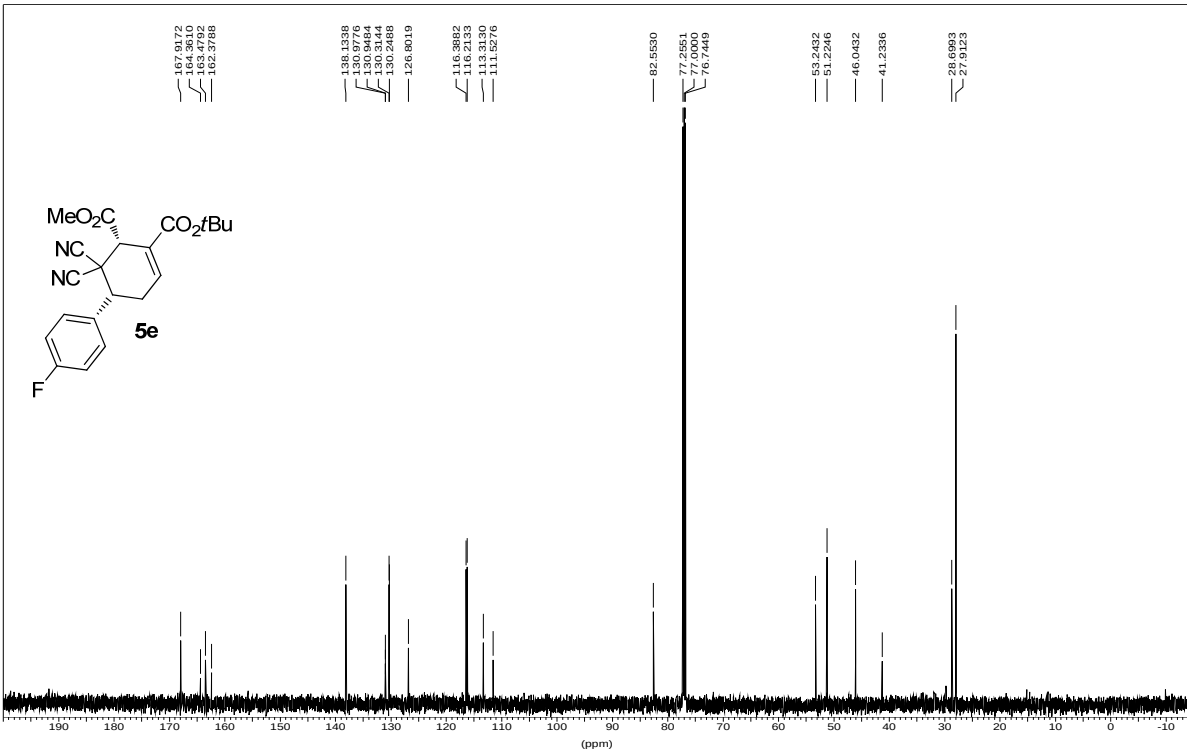

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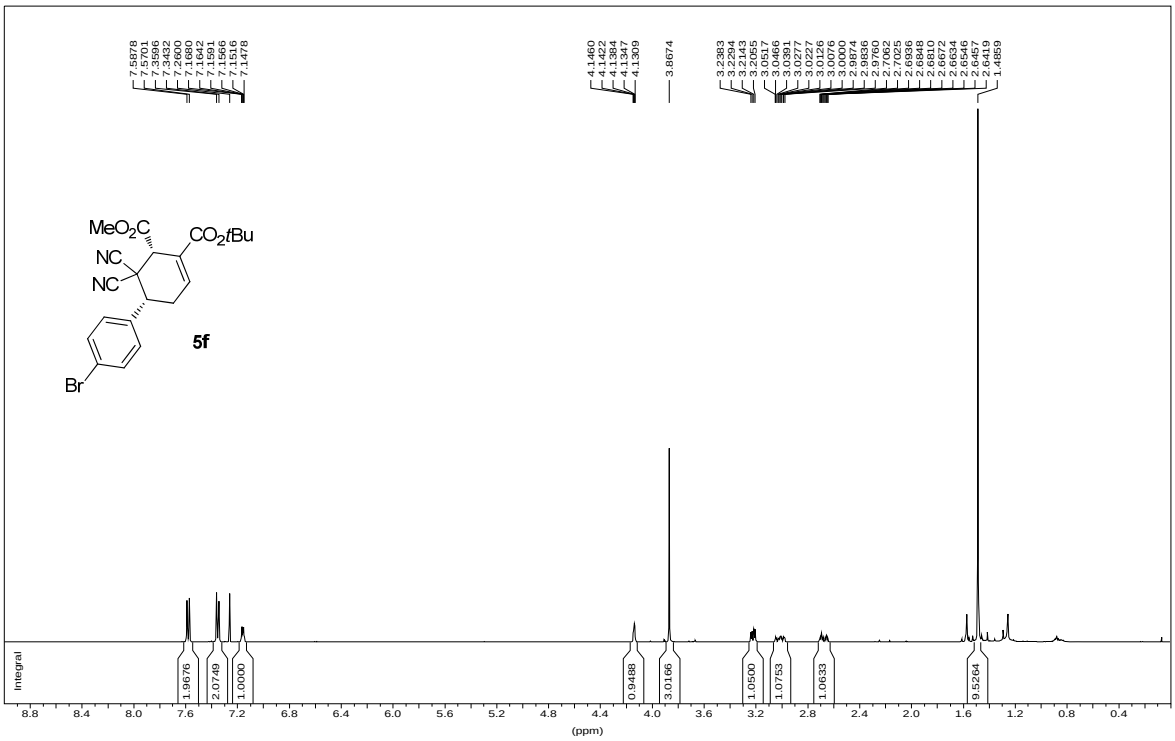

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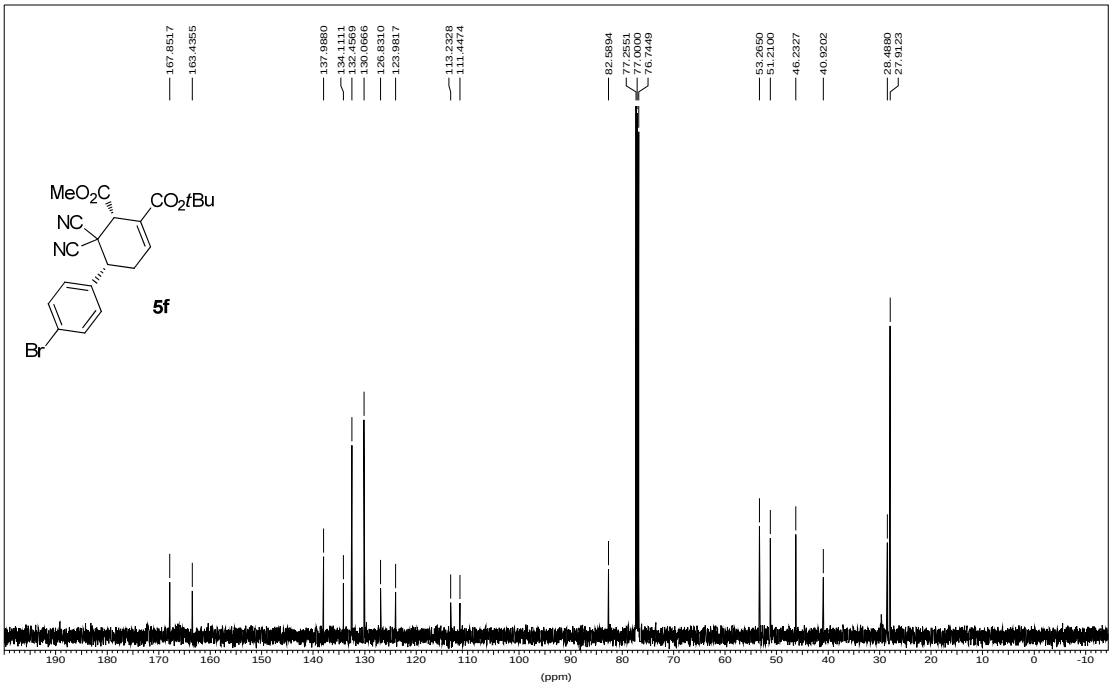

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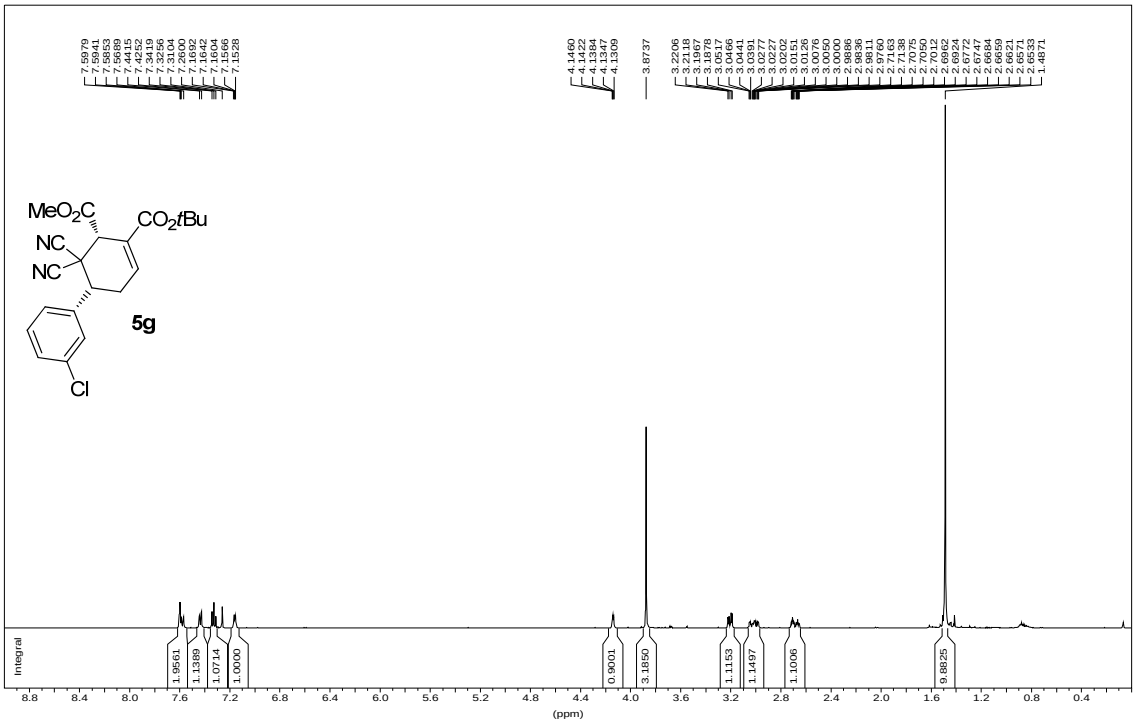

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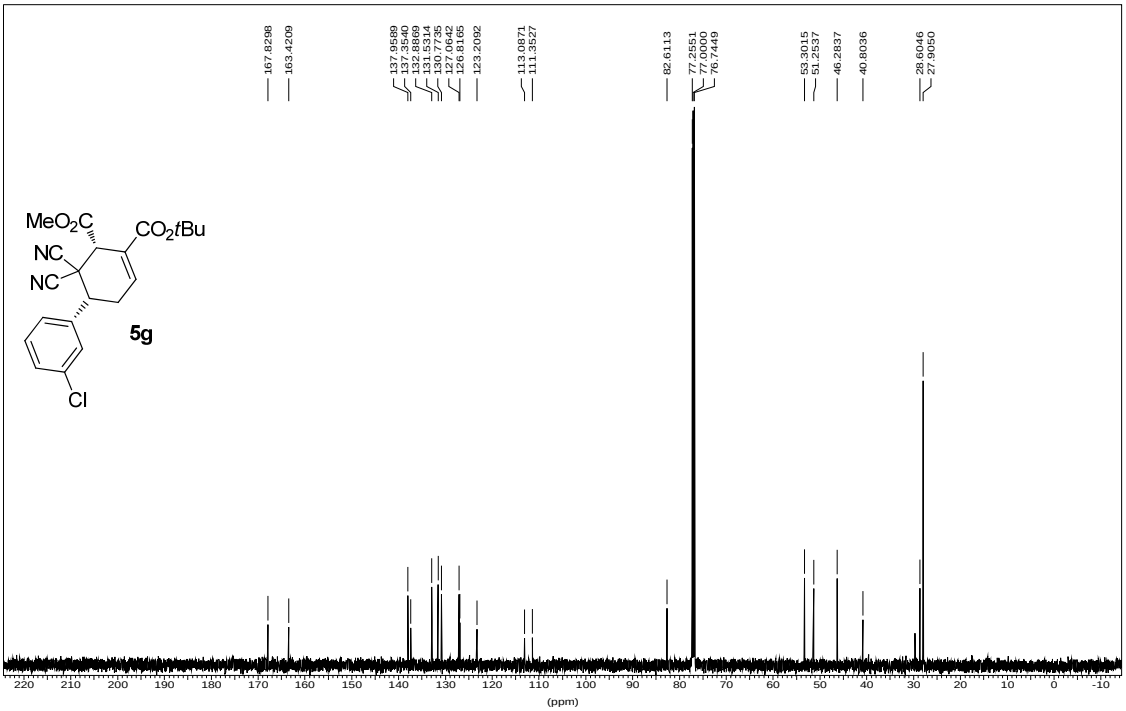

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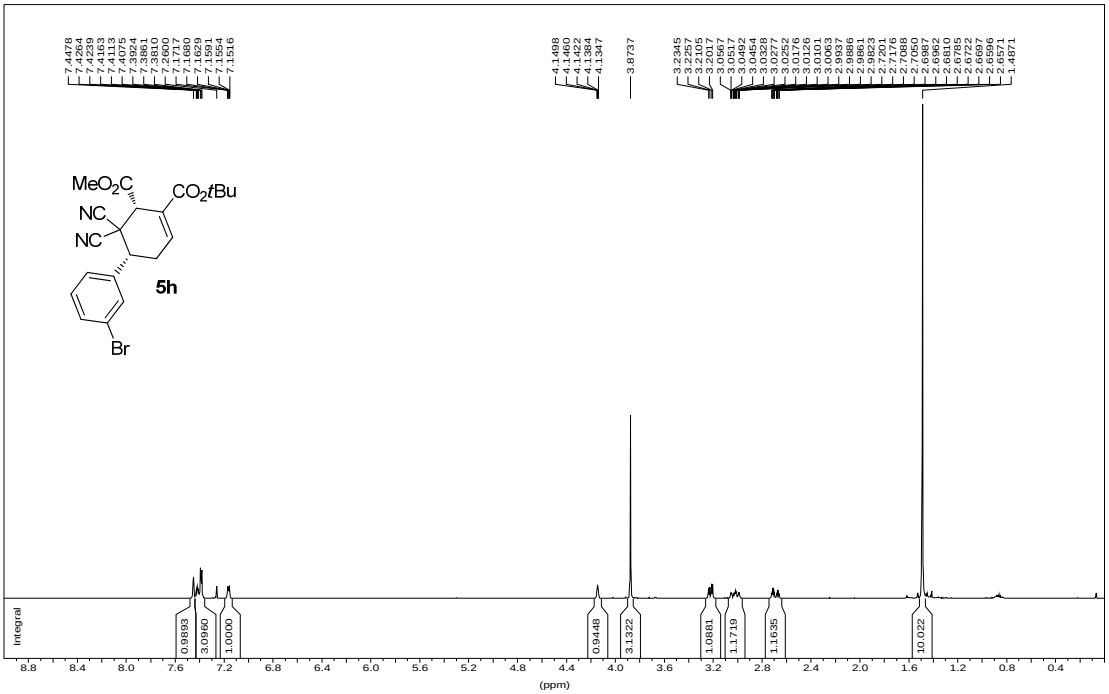

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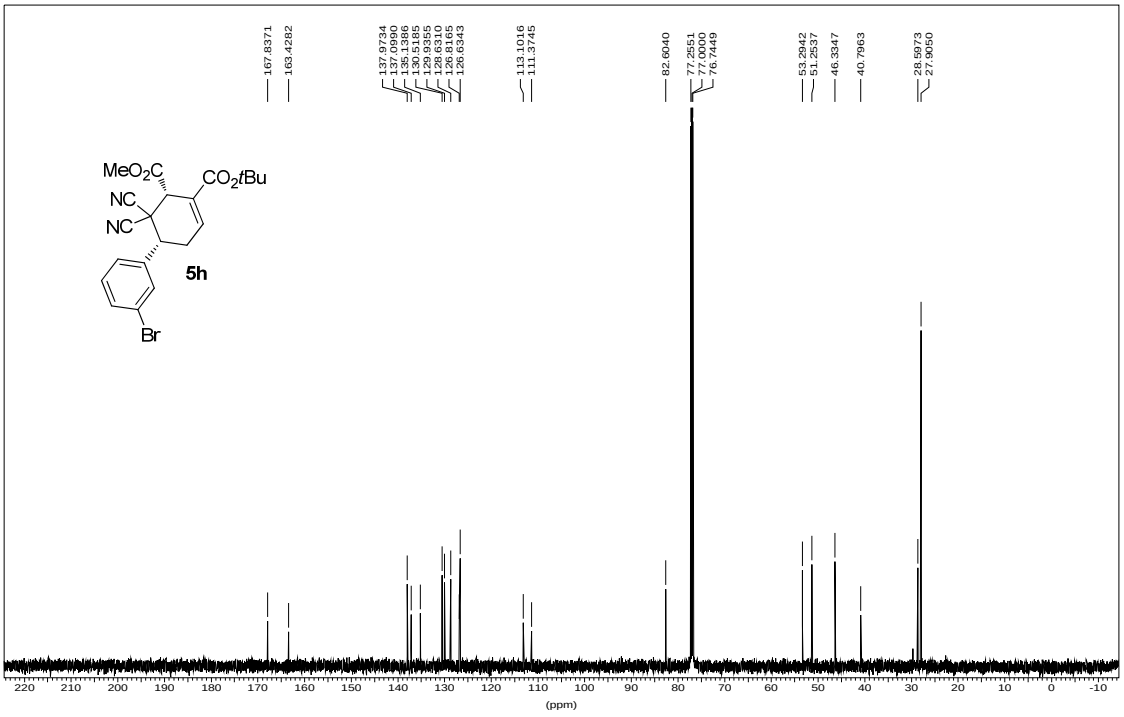

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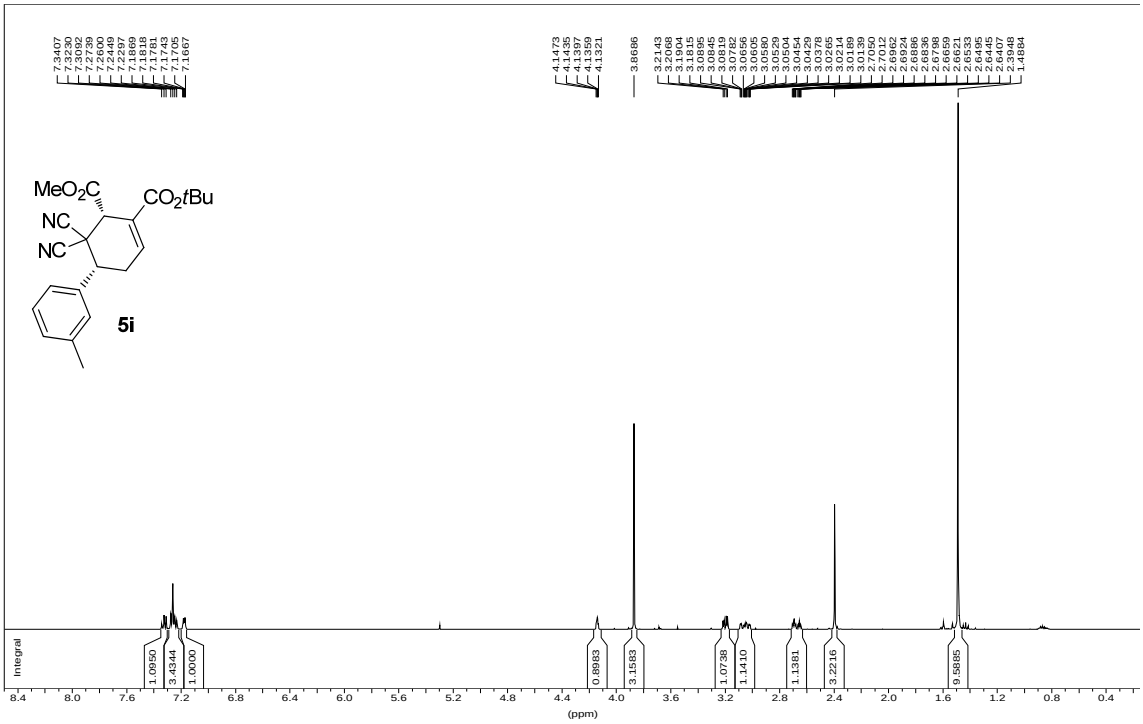

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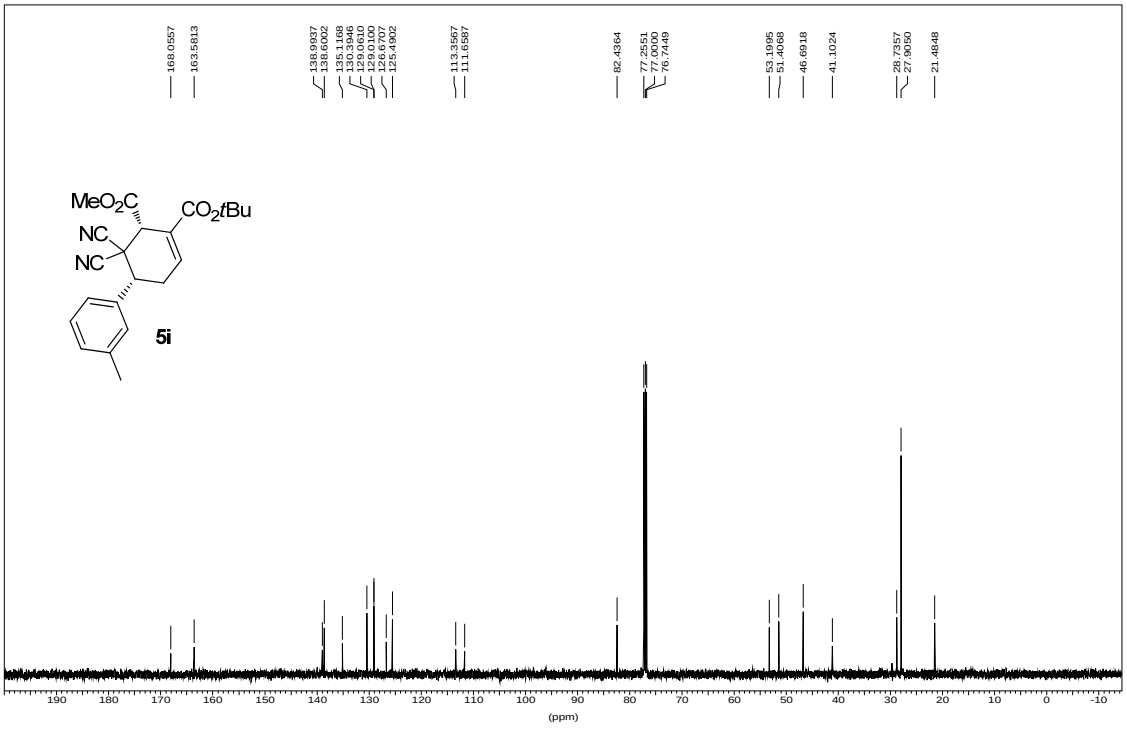

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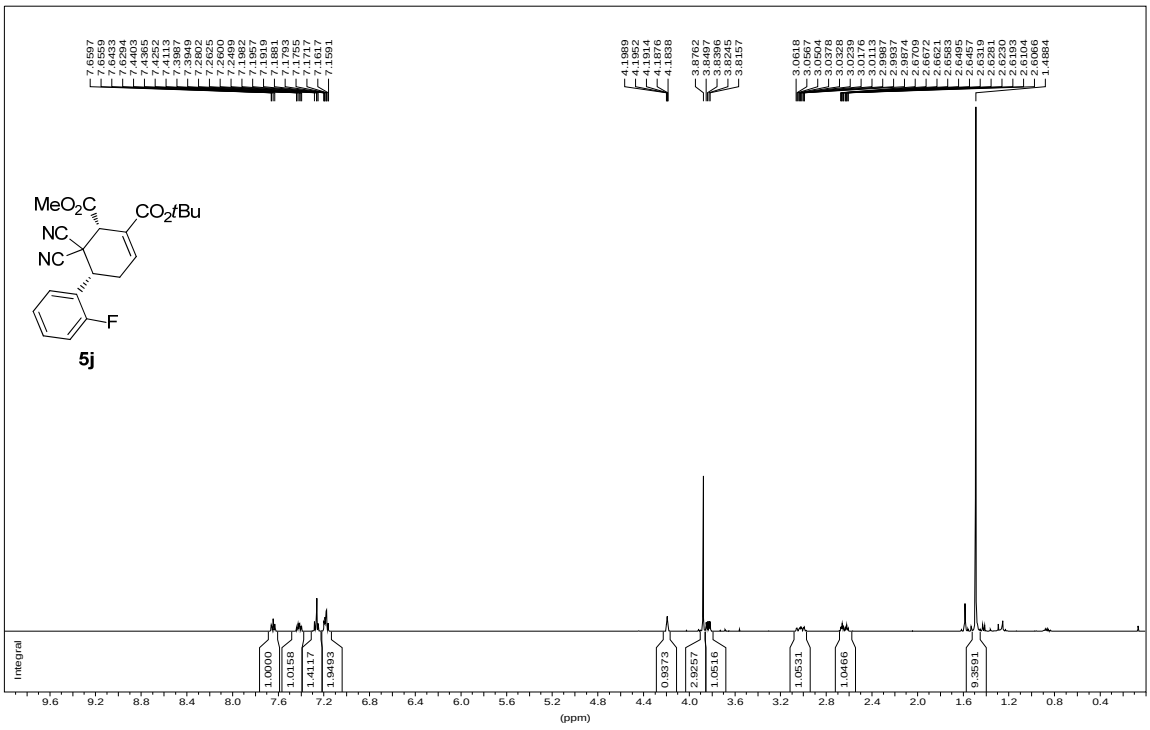

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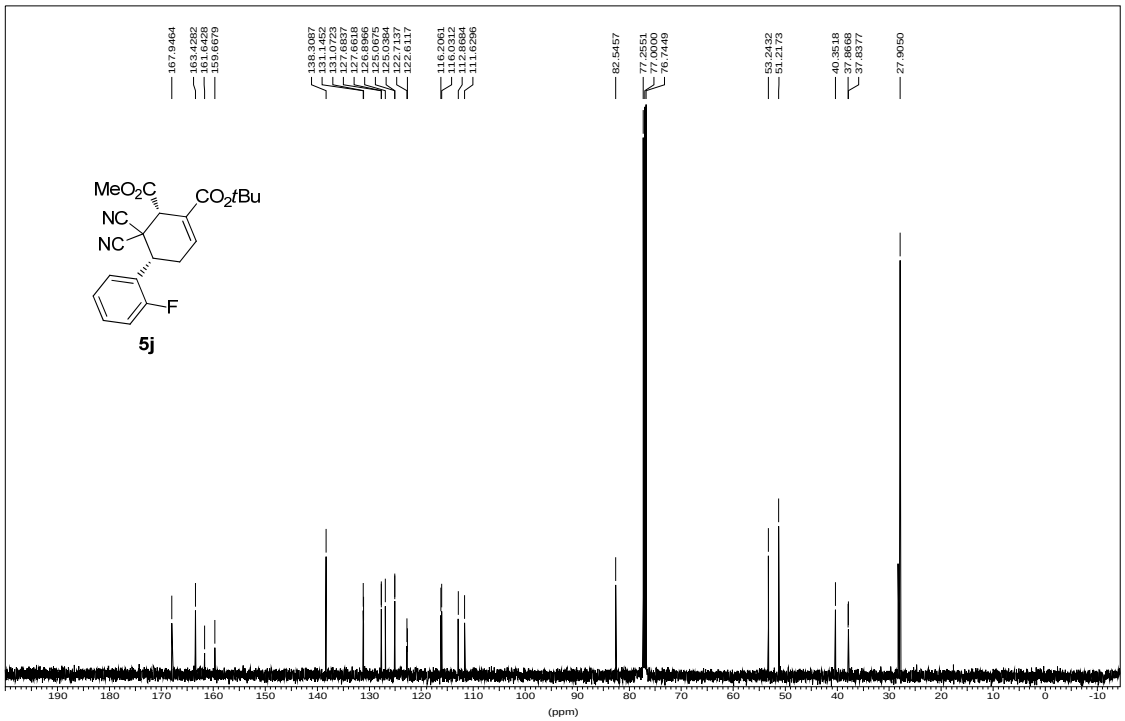

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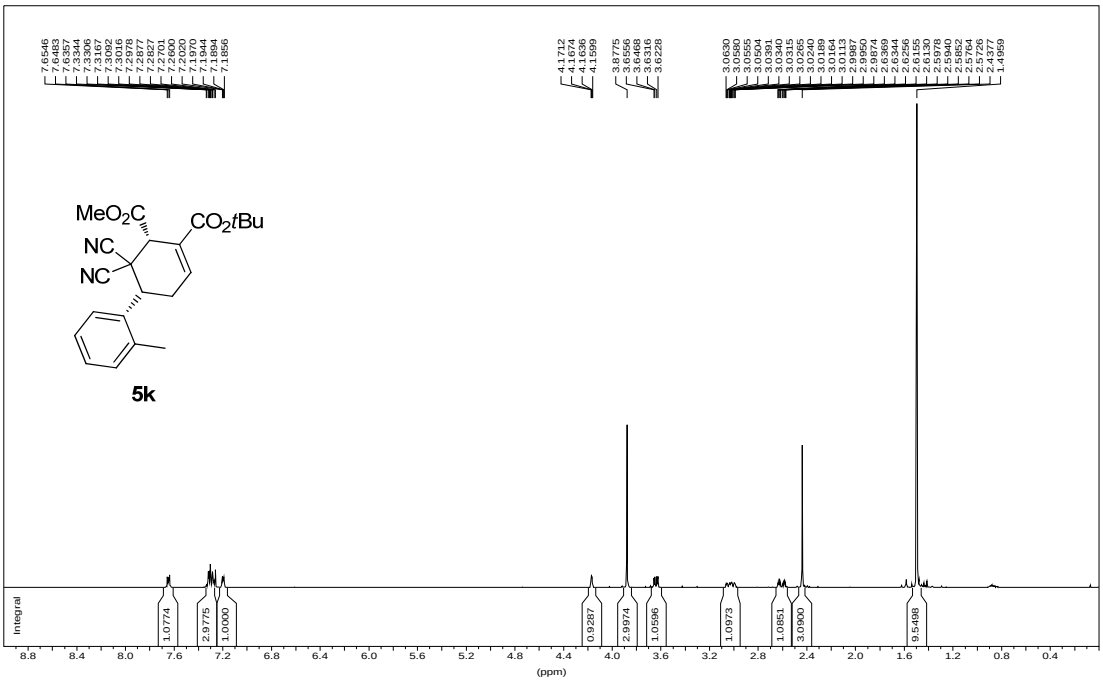

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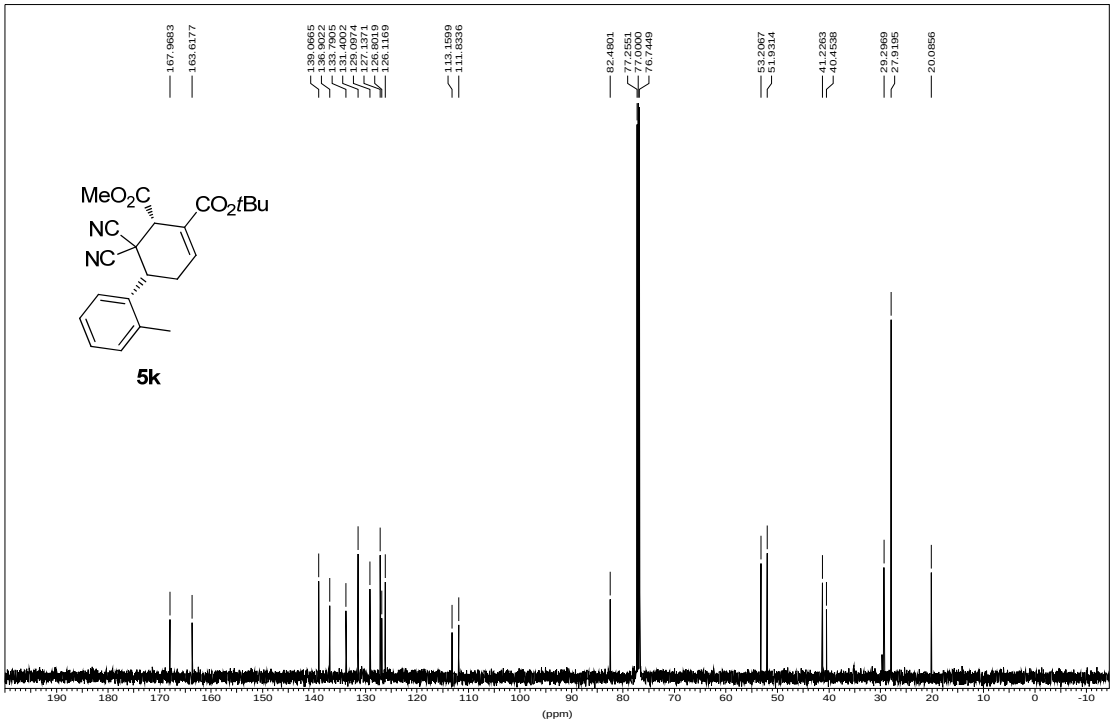

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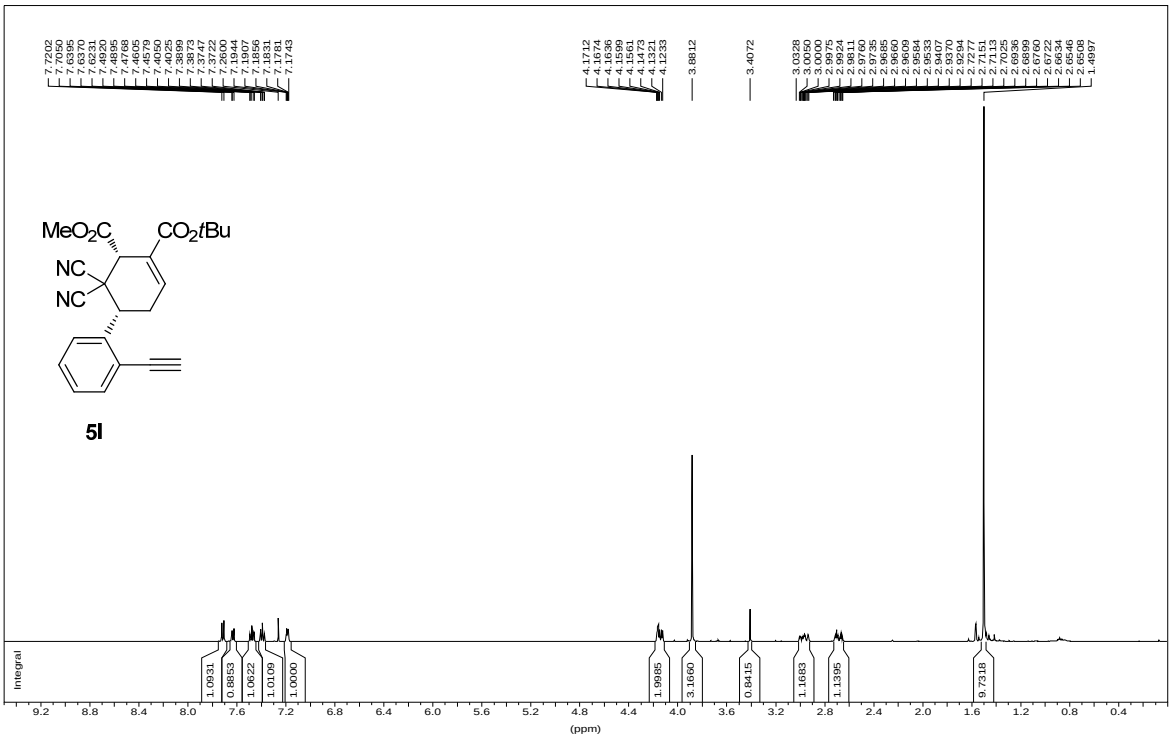

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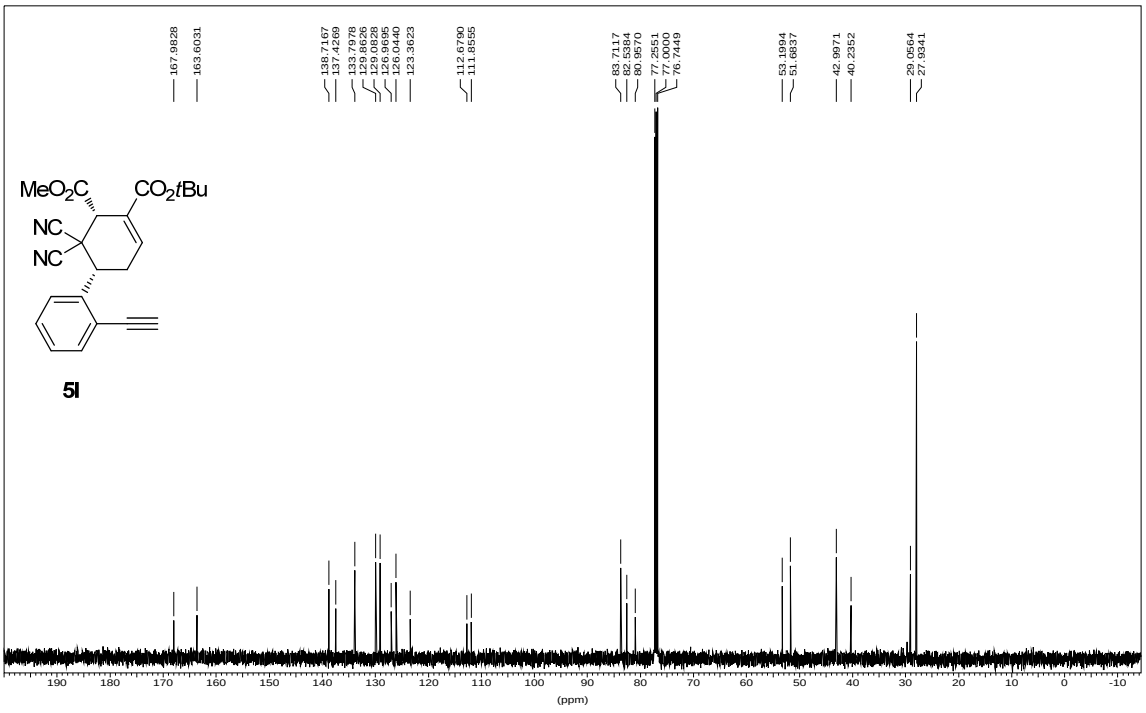

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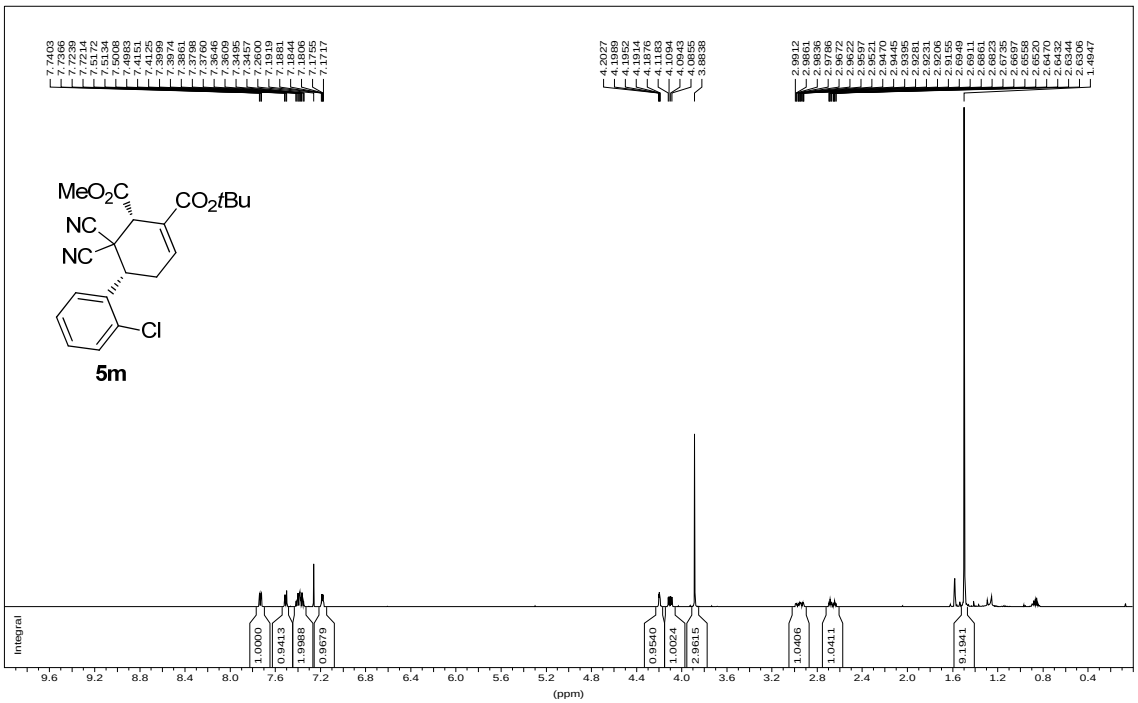

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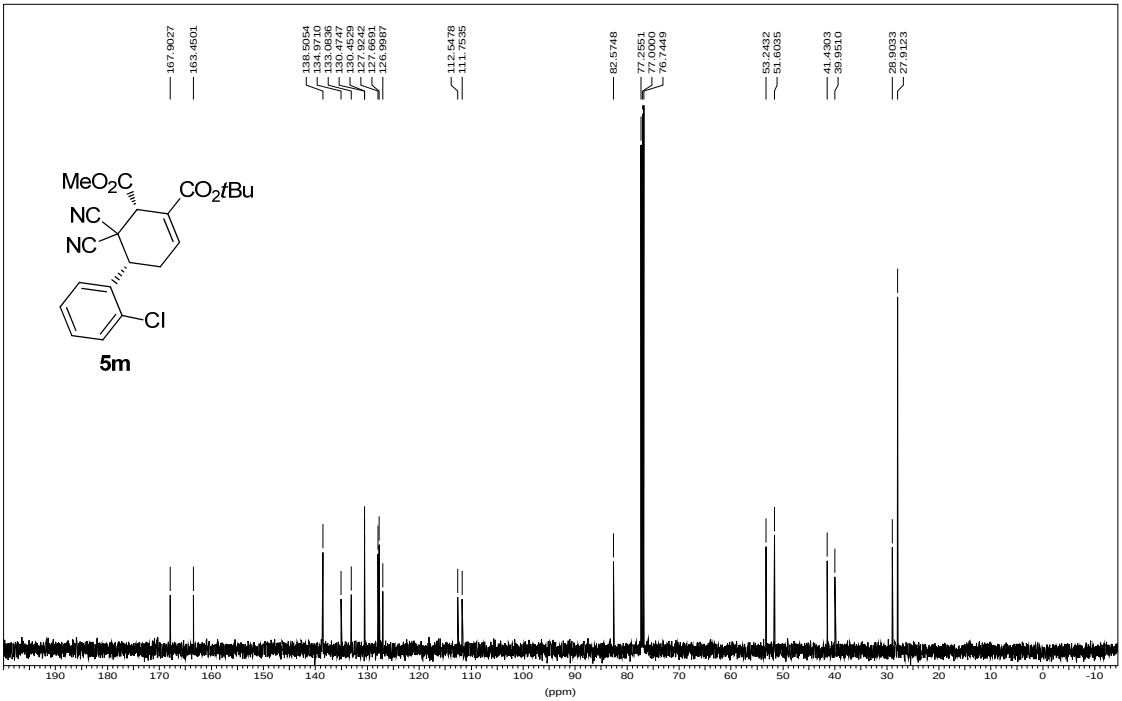

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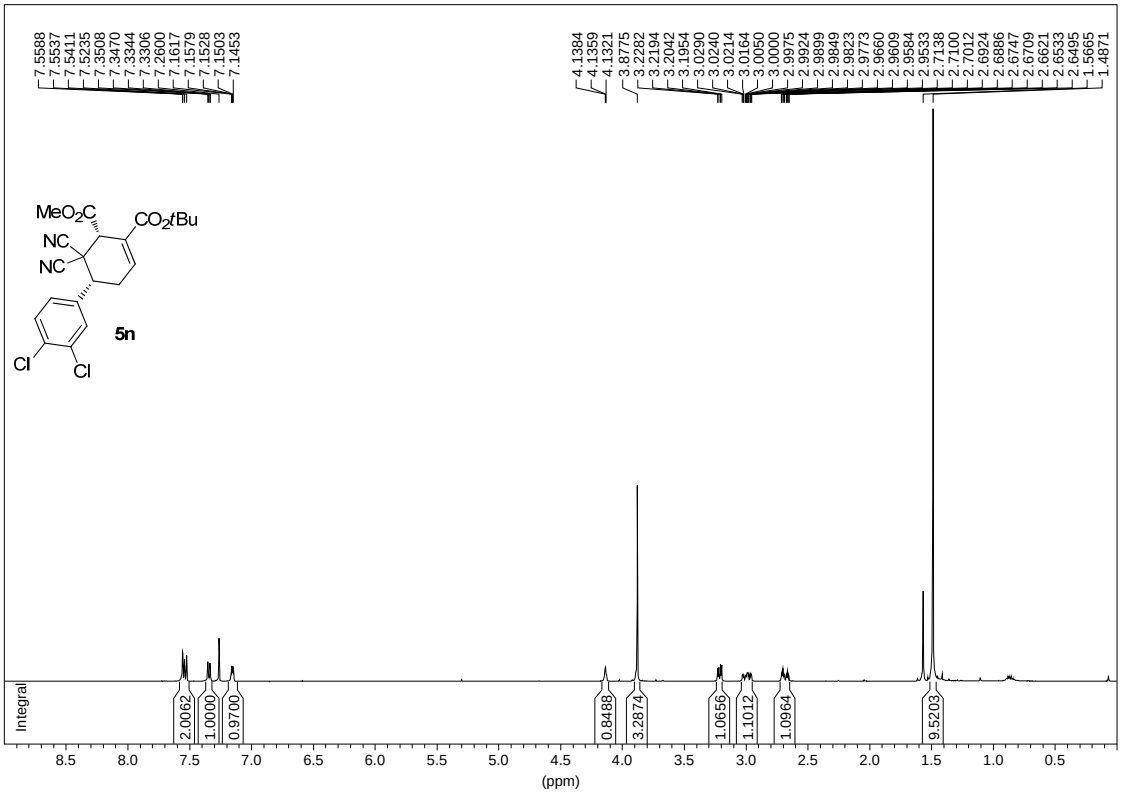

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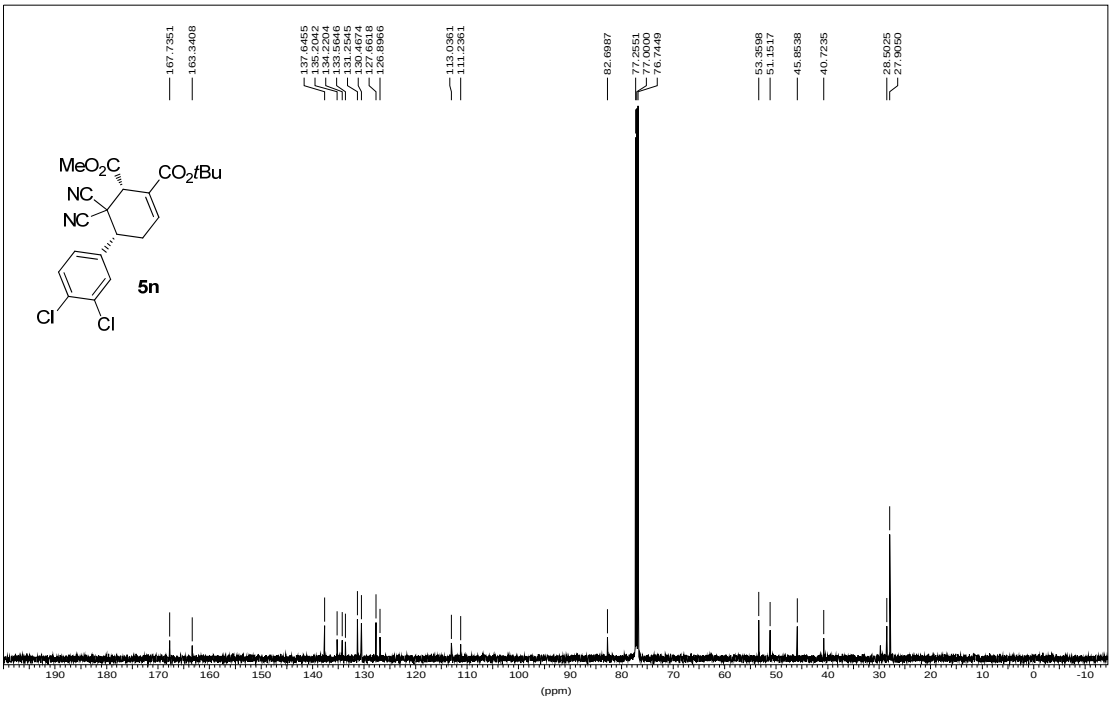

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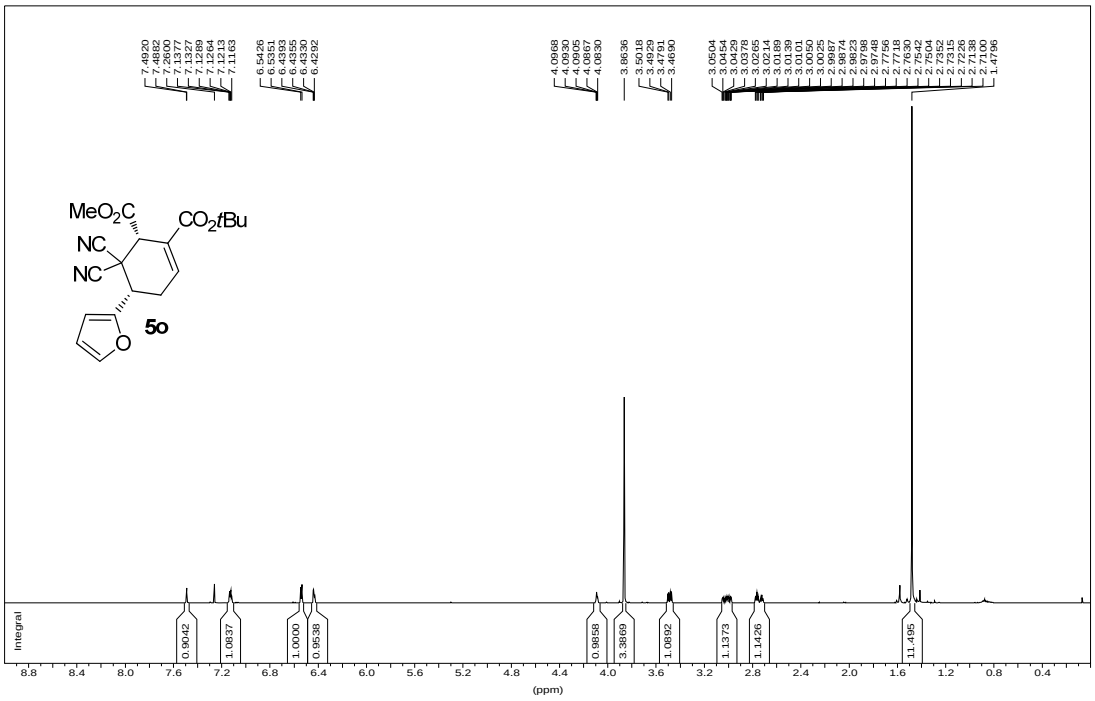

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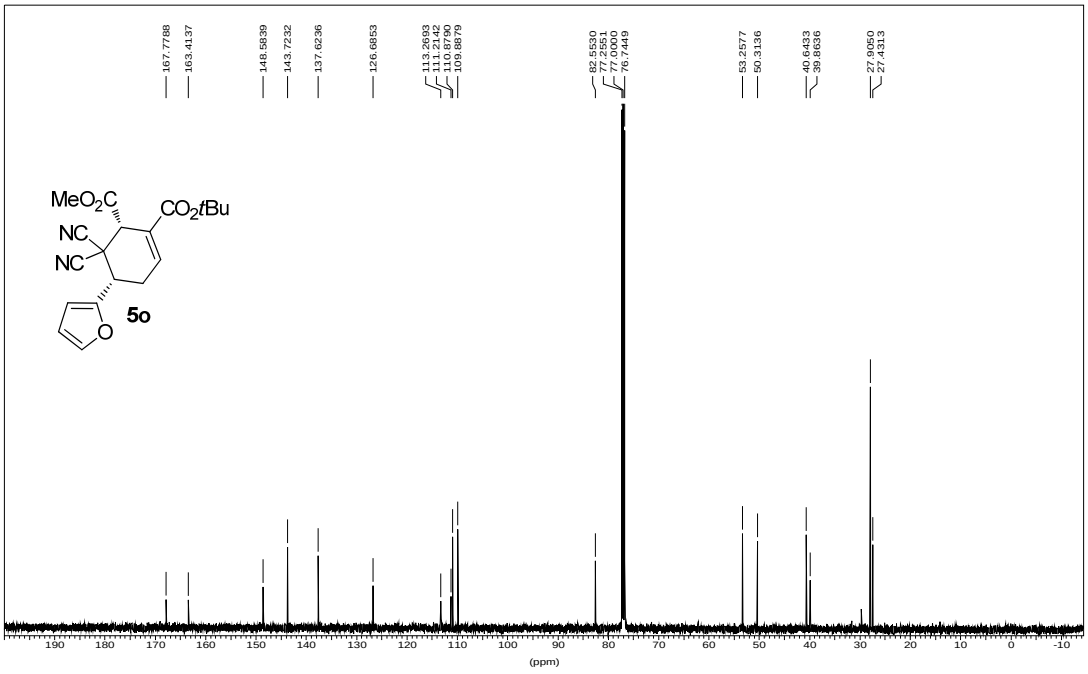

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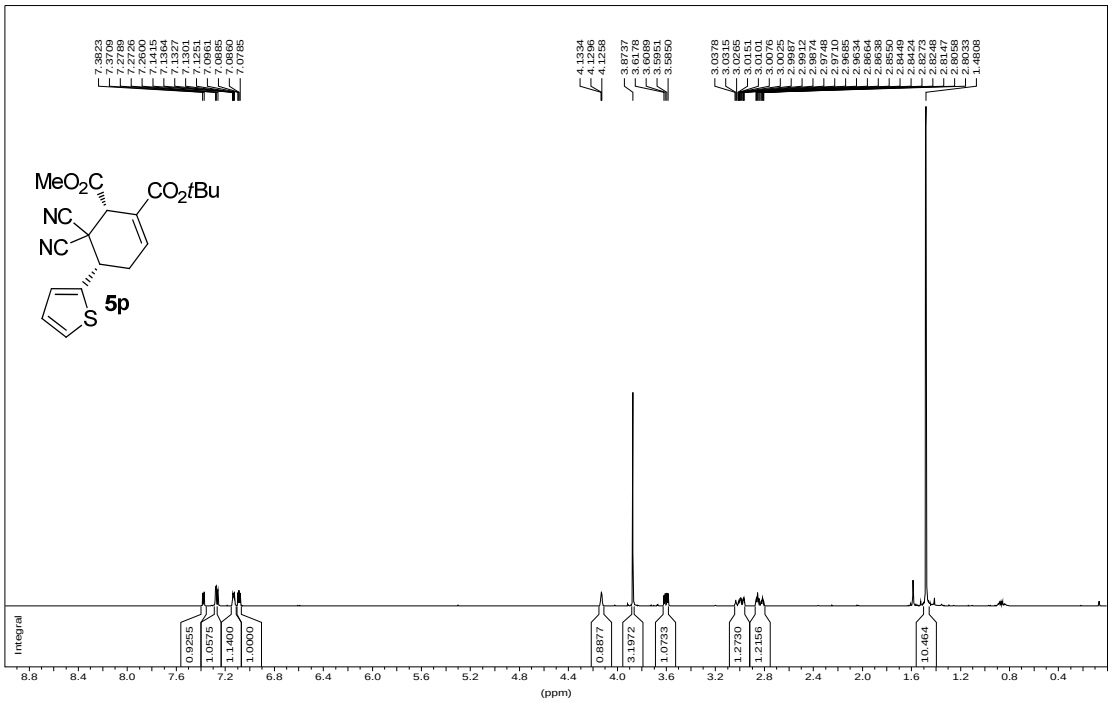

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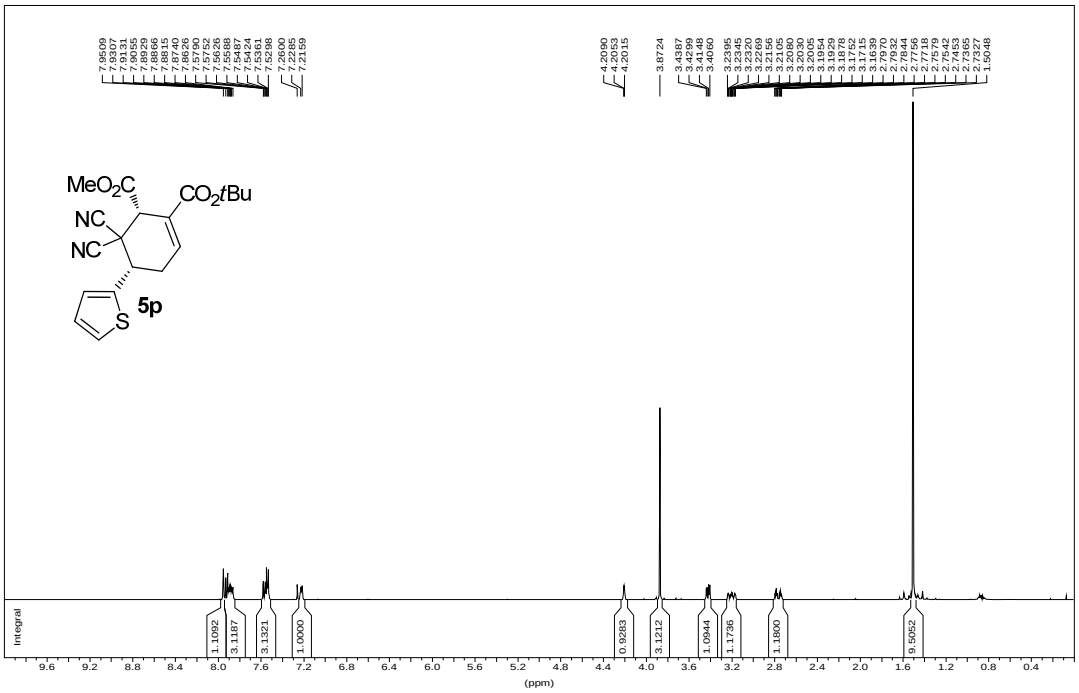

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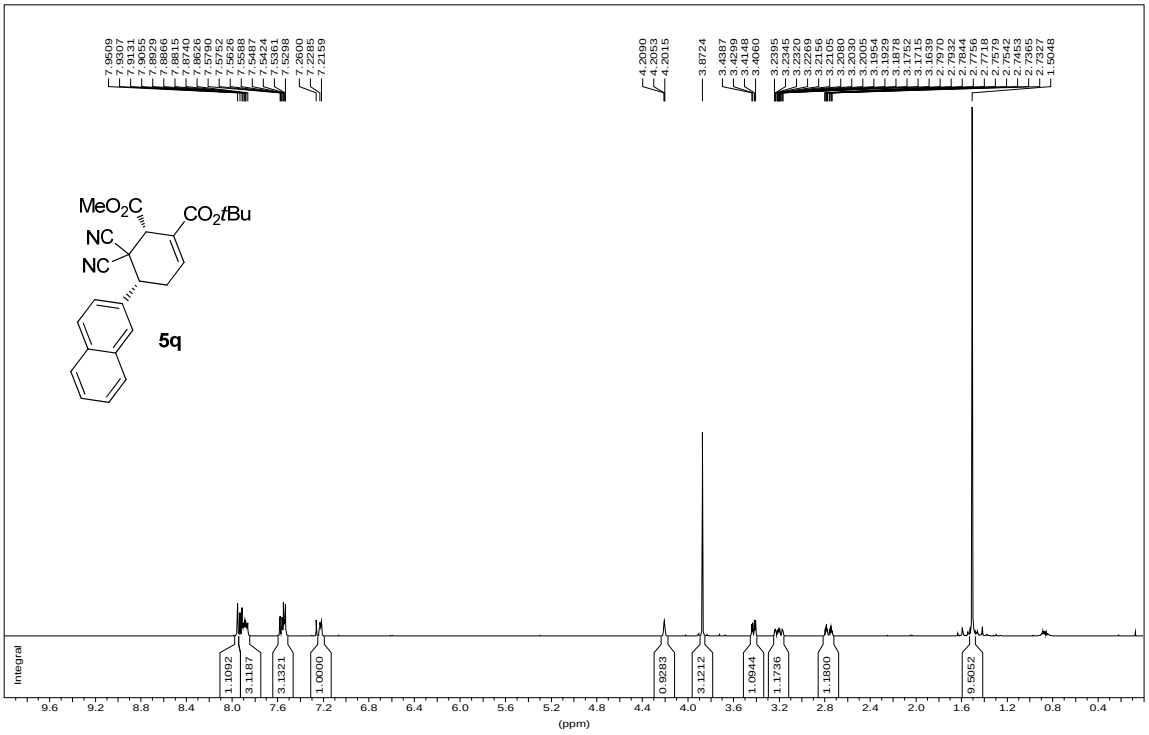

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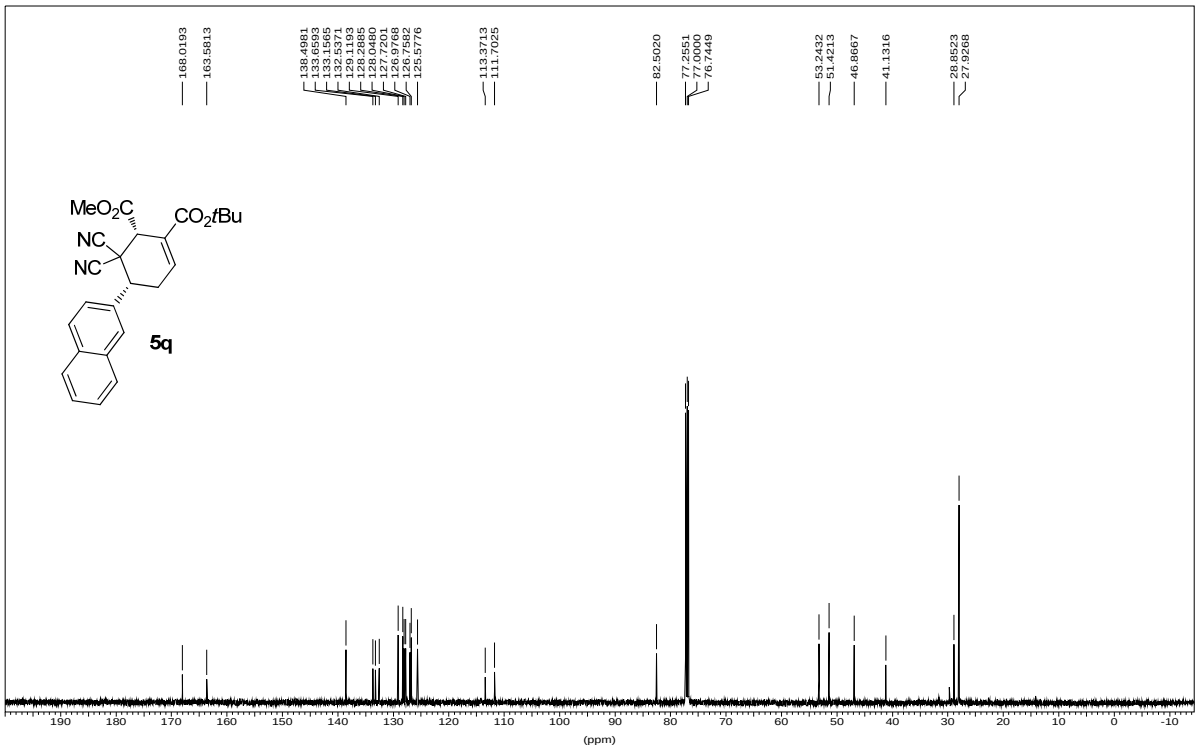

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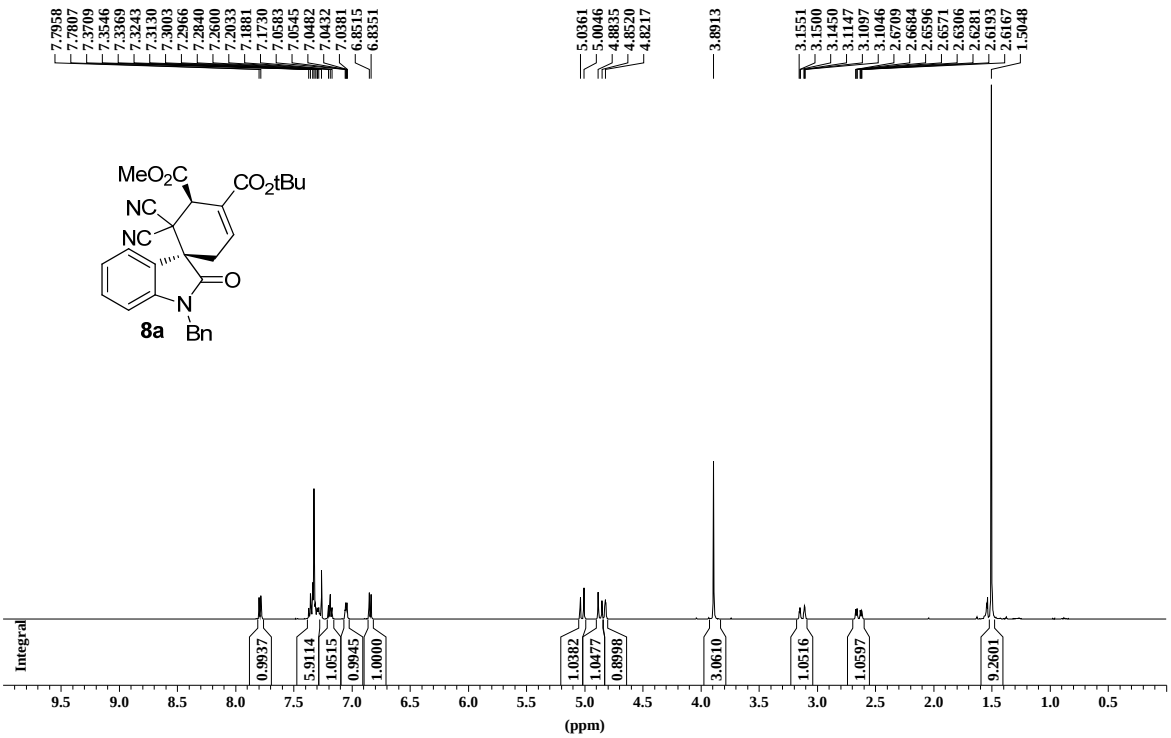

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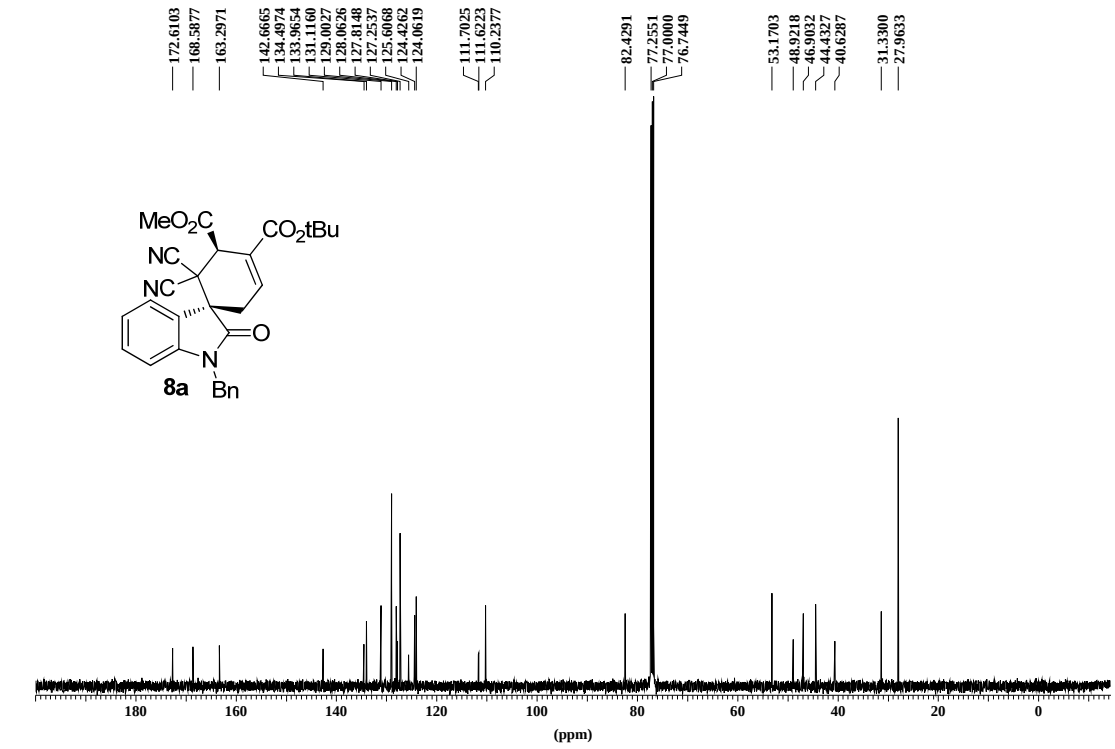

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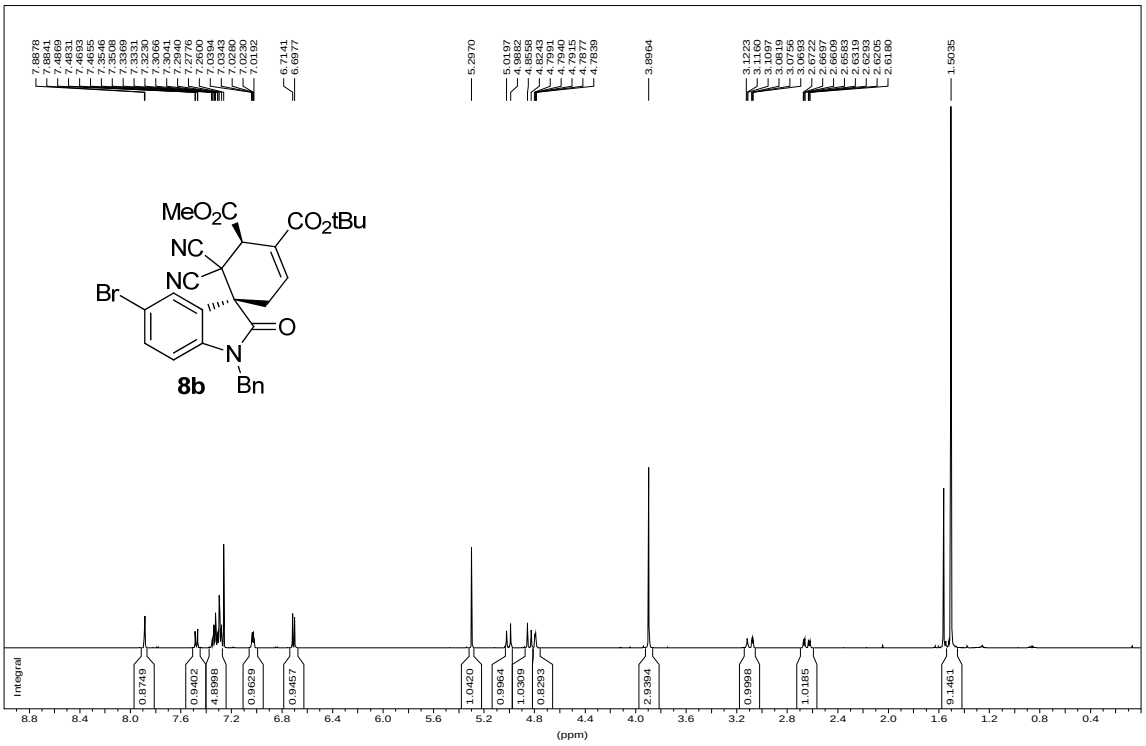
2548



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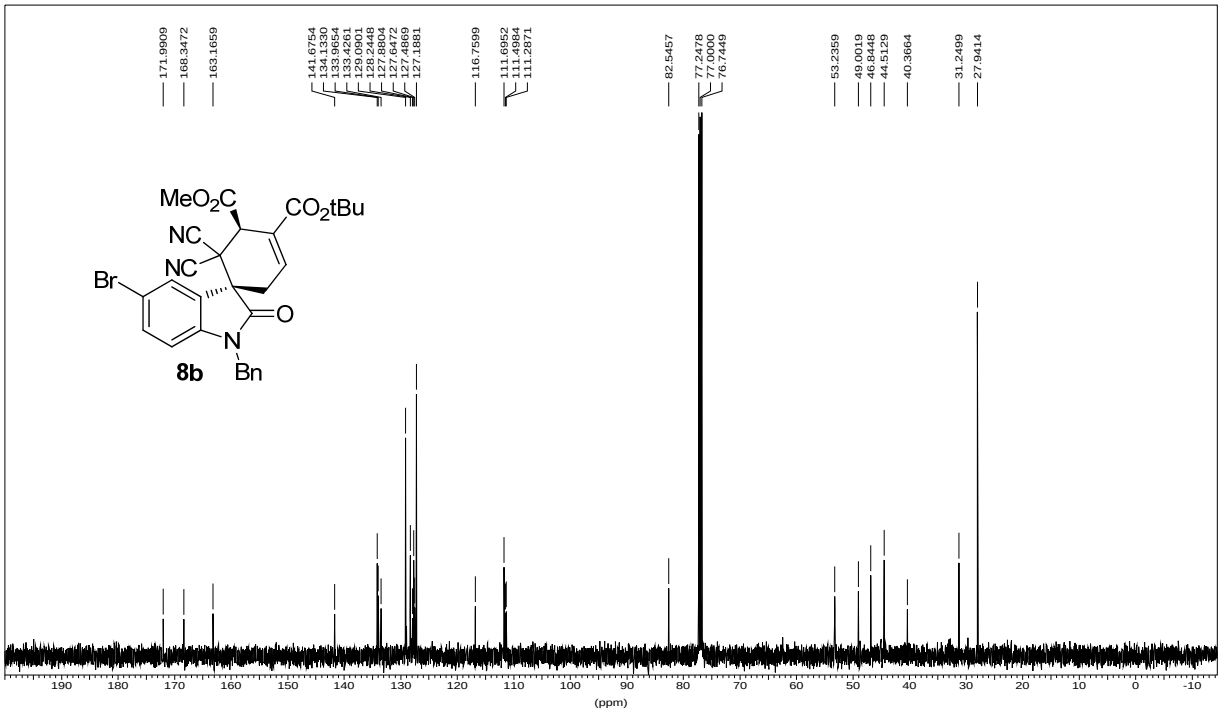

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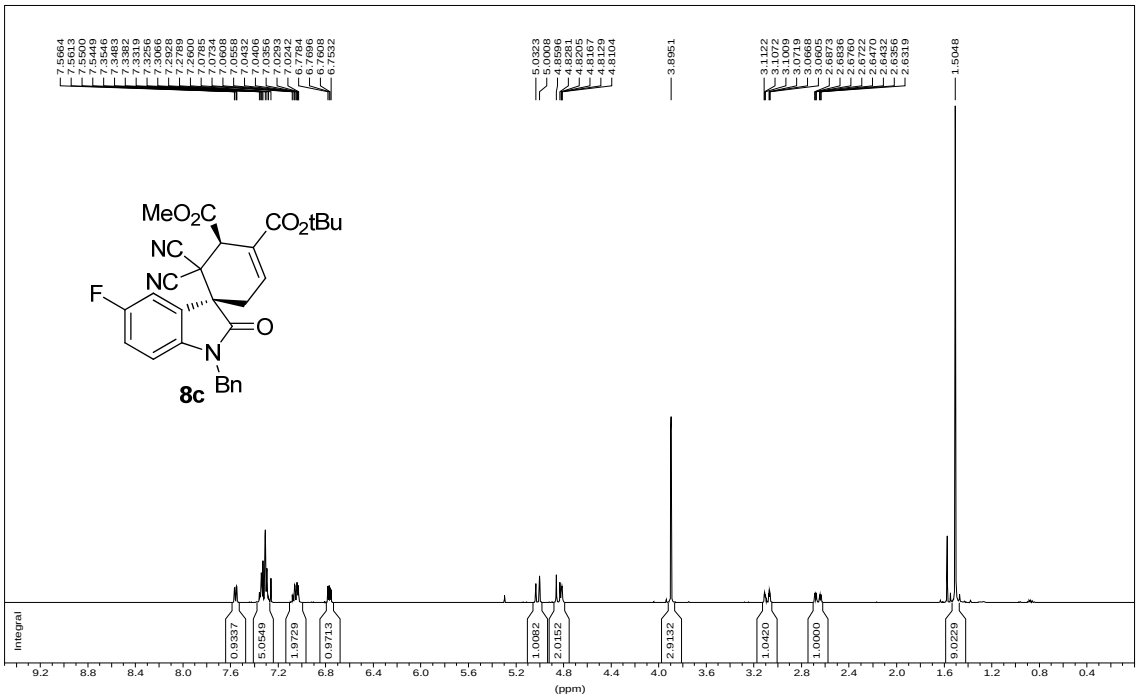

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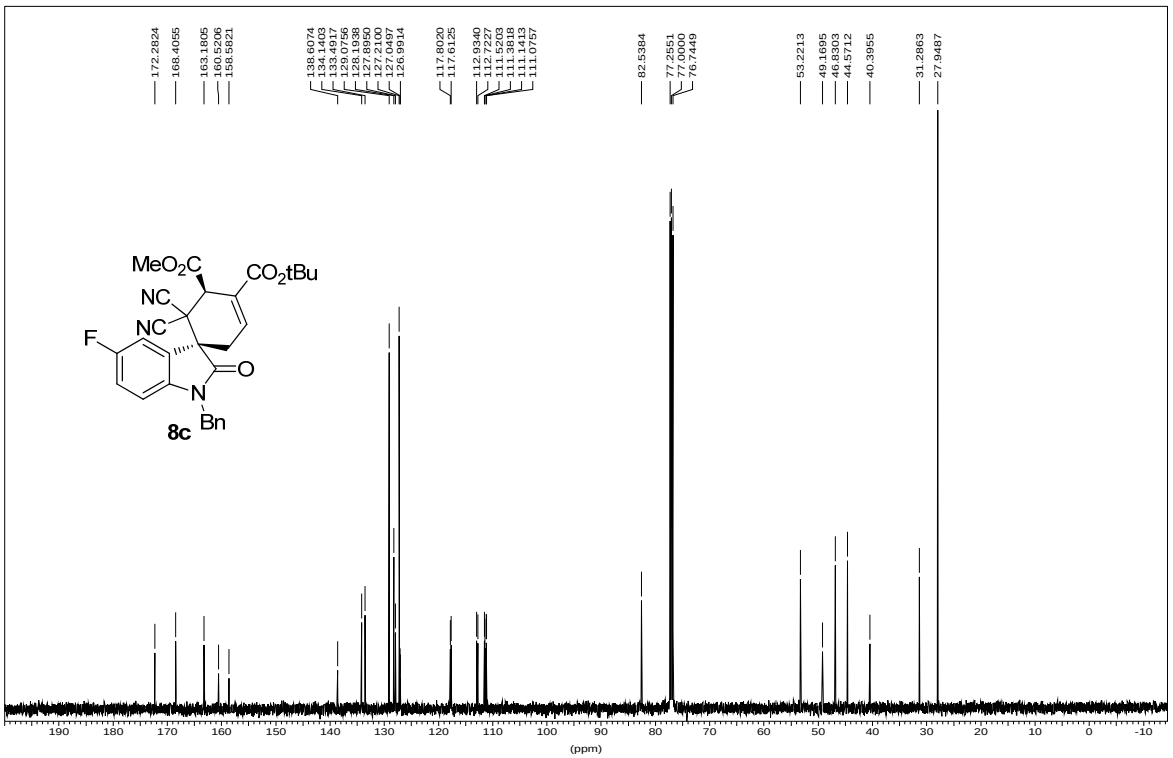

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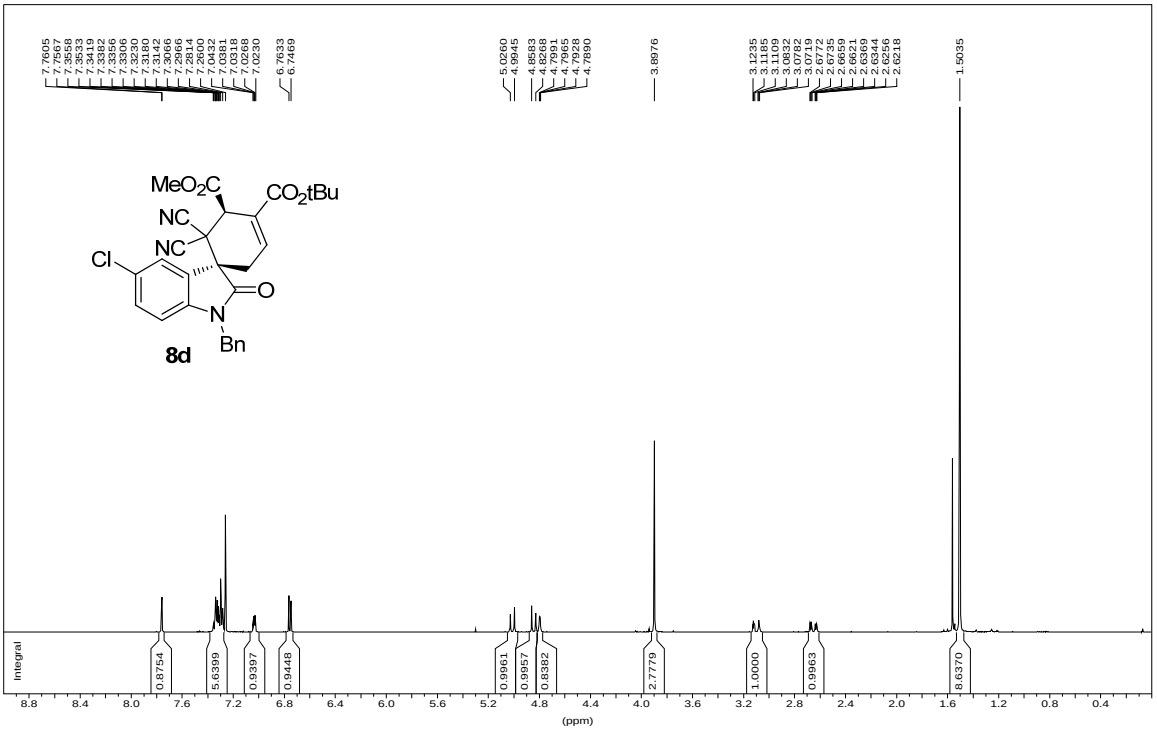

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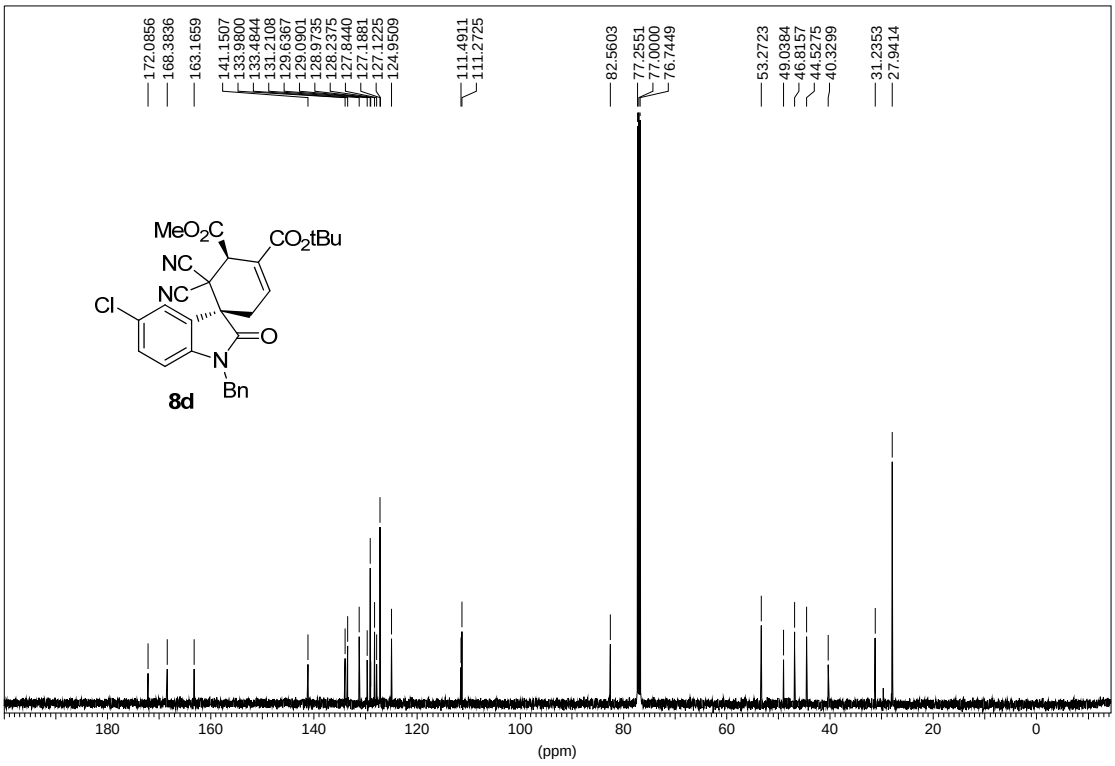

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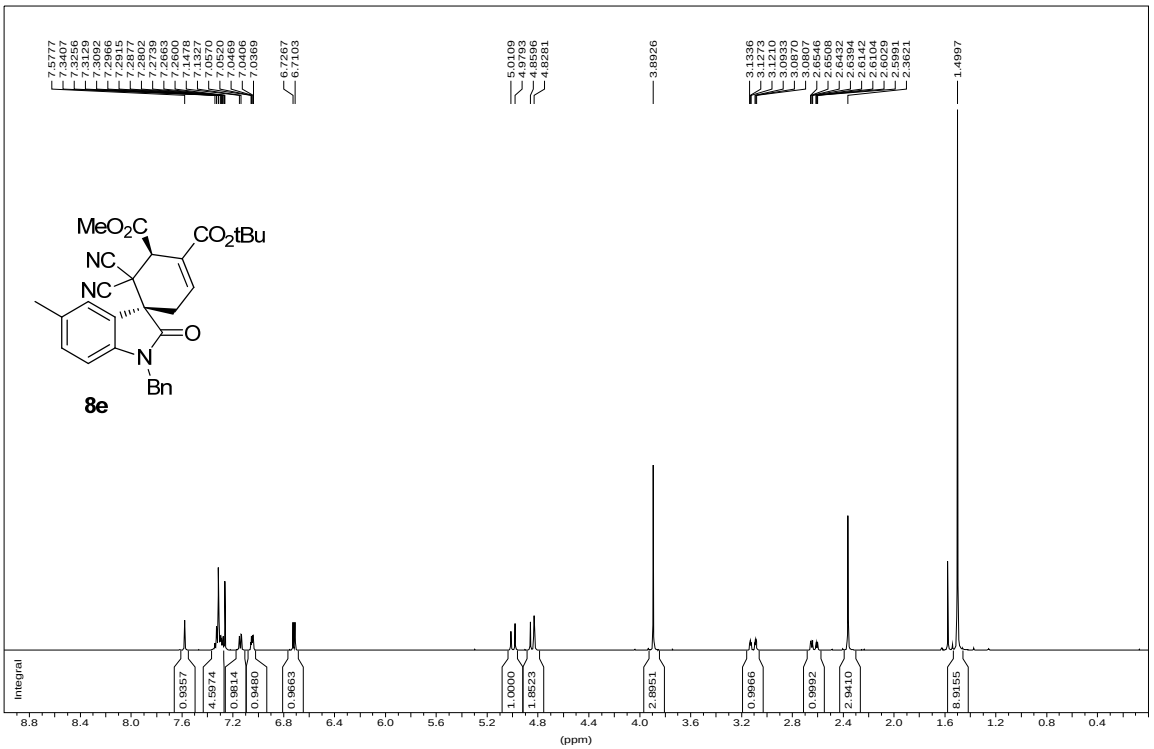

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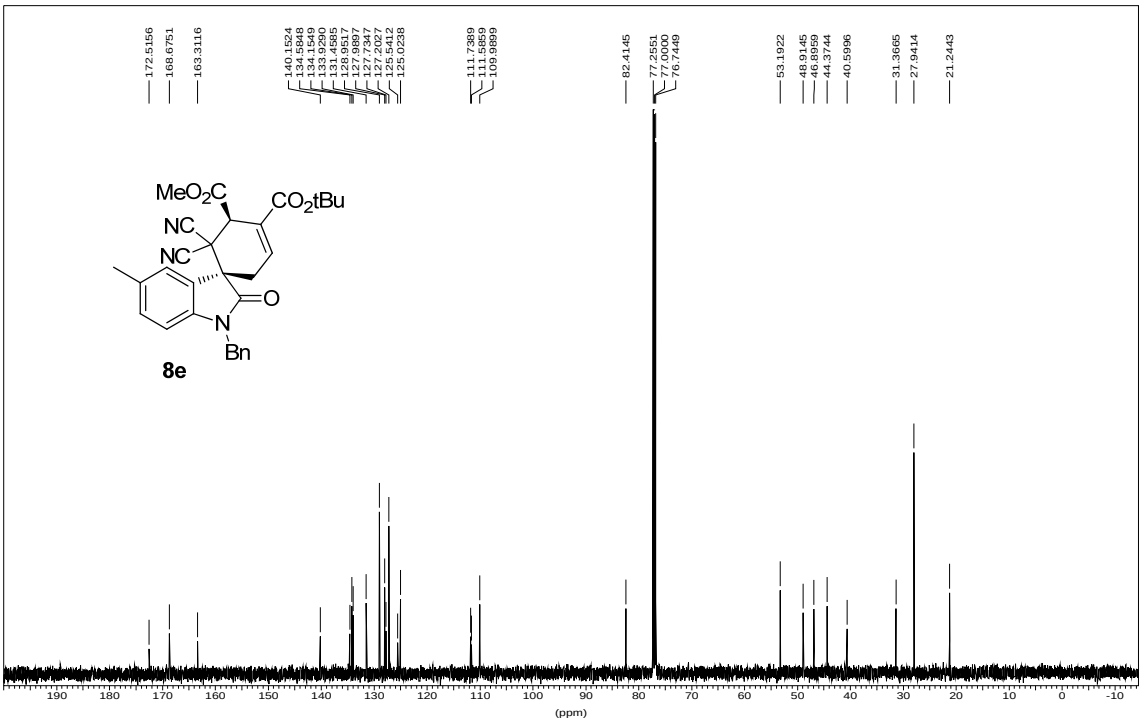

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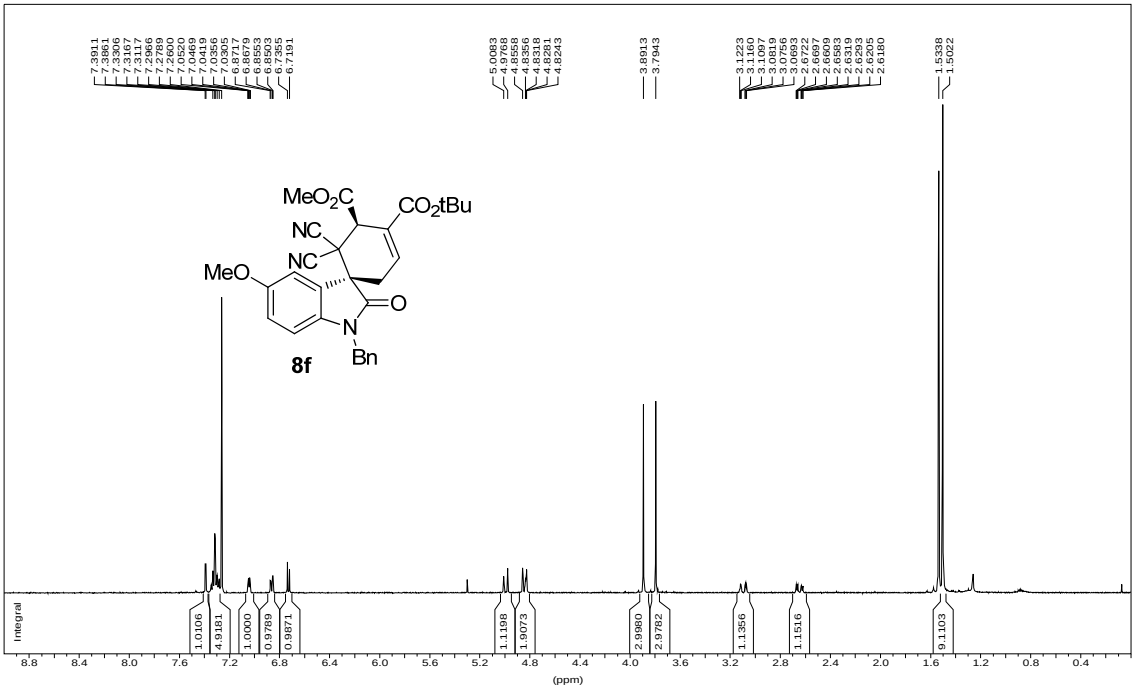

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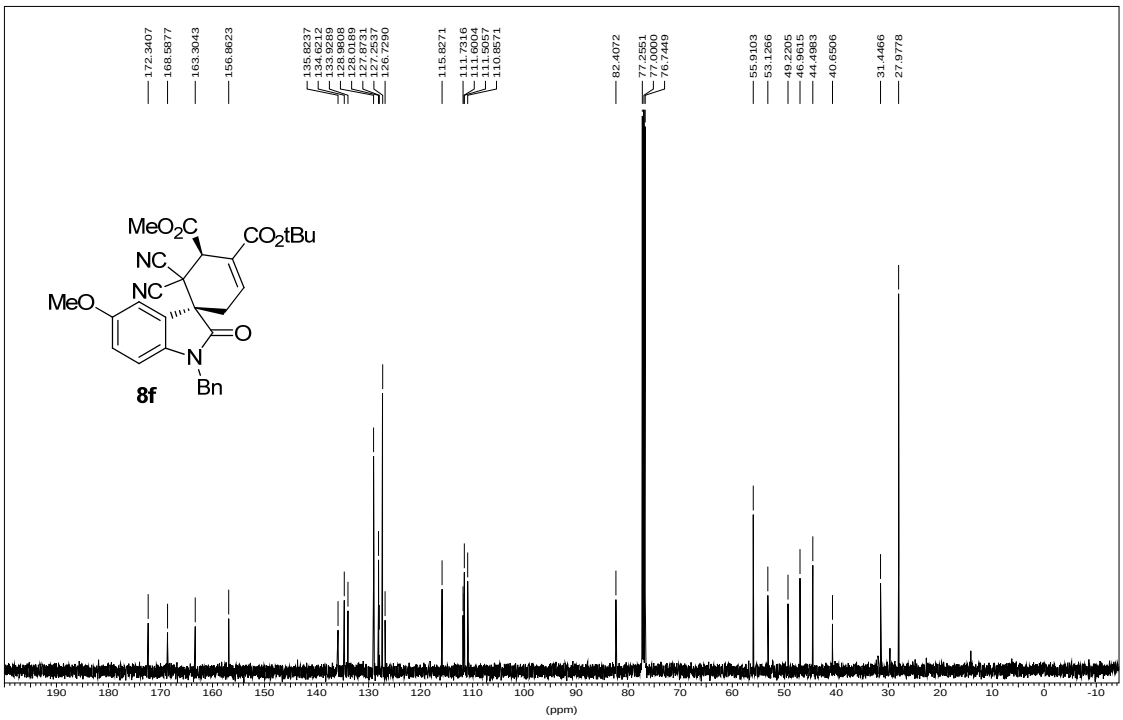

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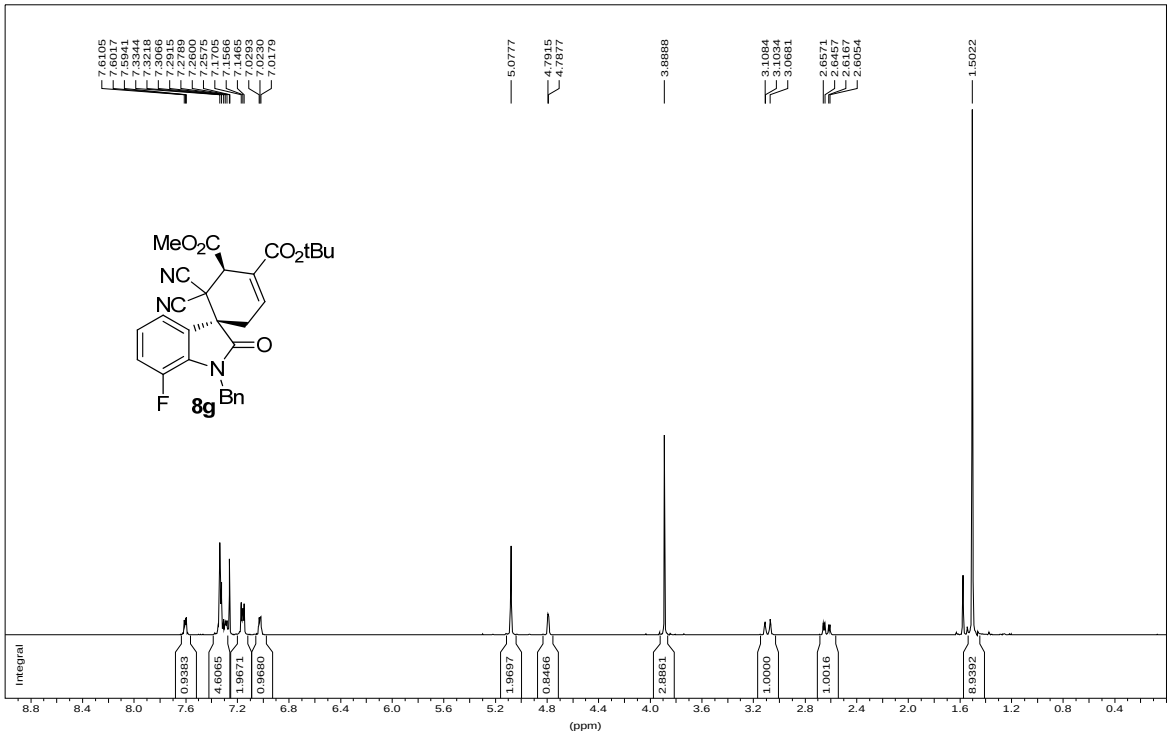

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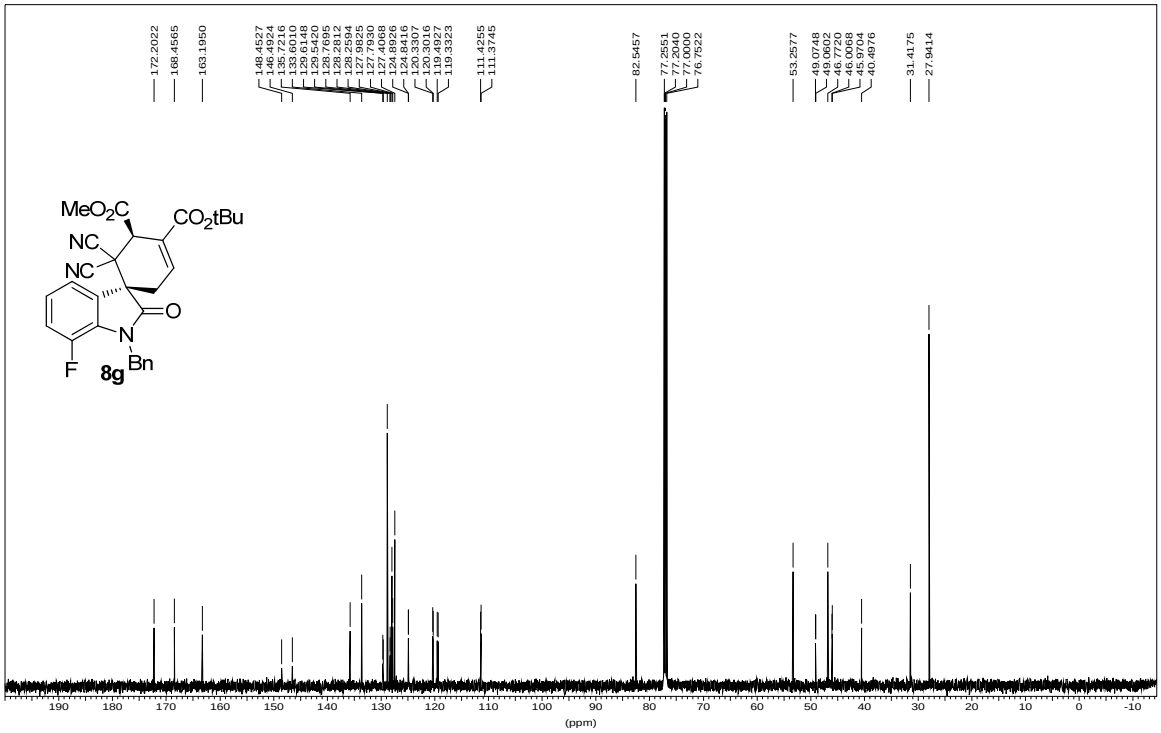

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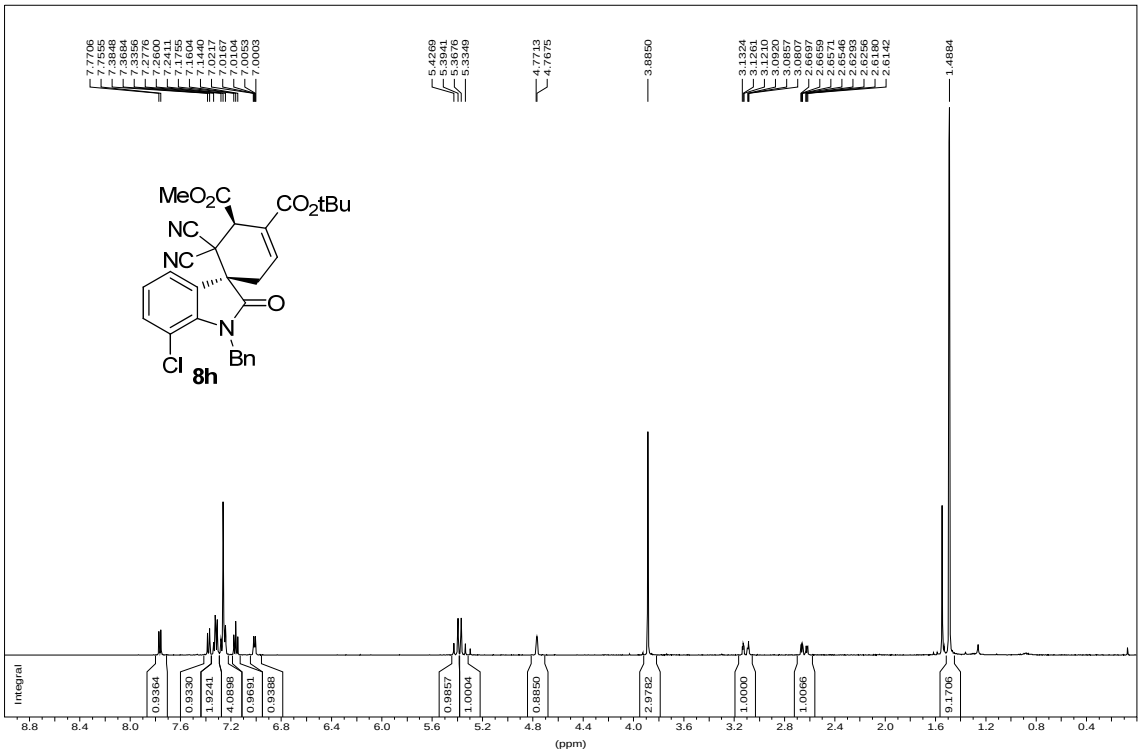

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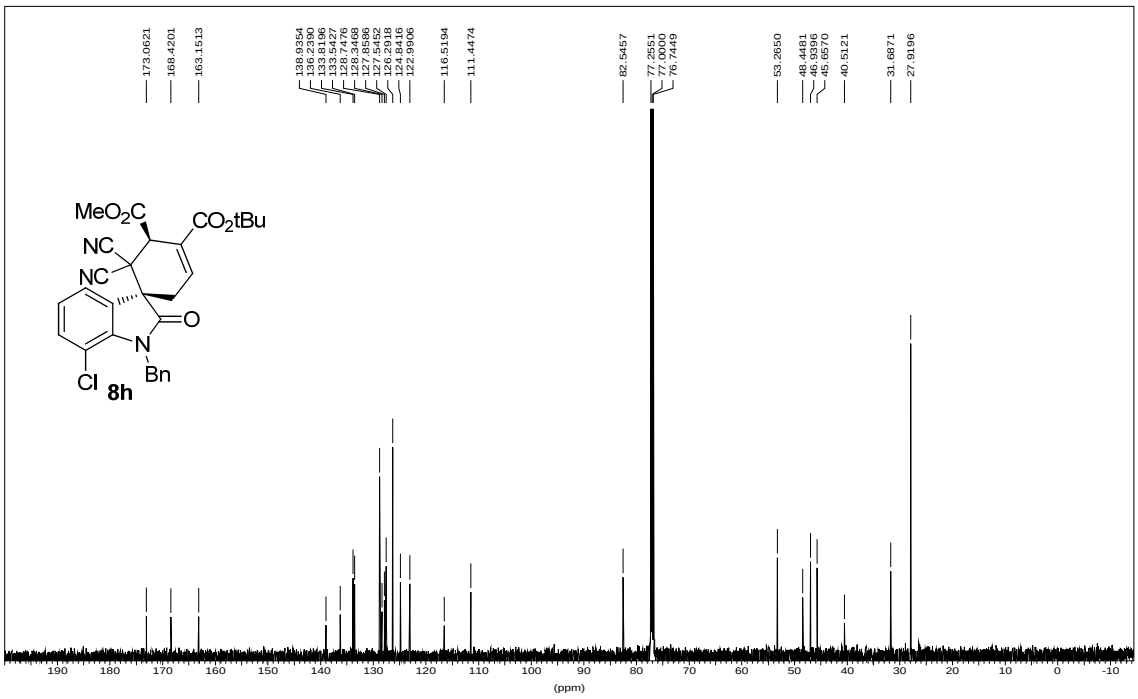

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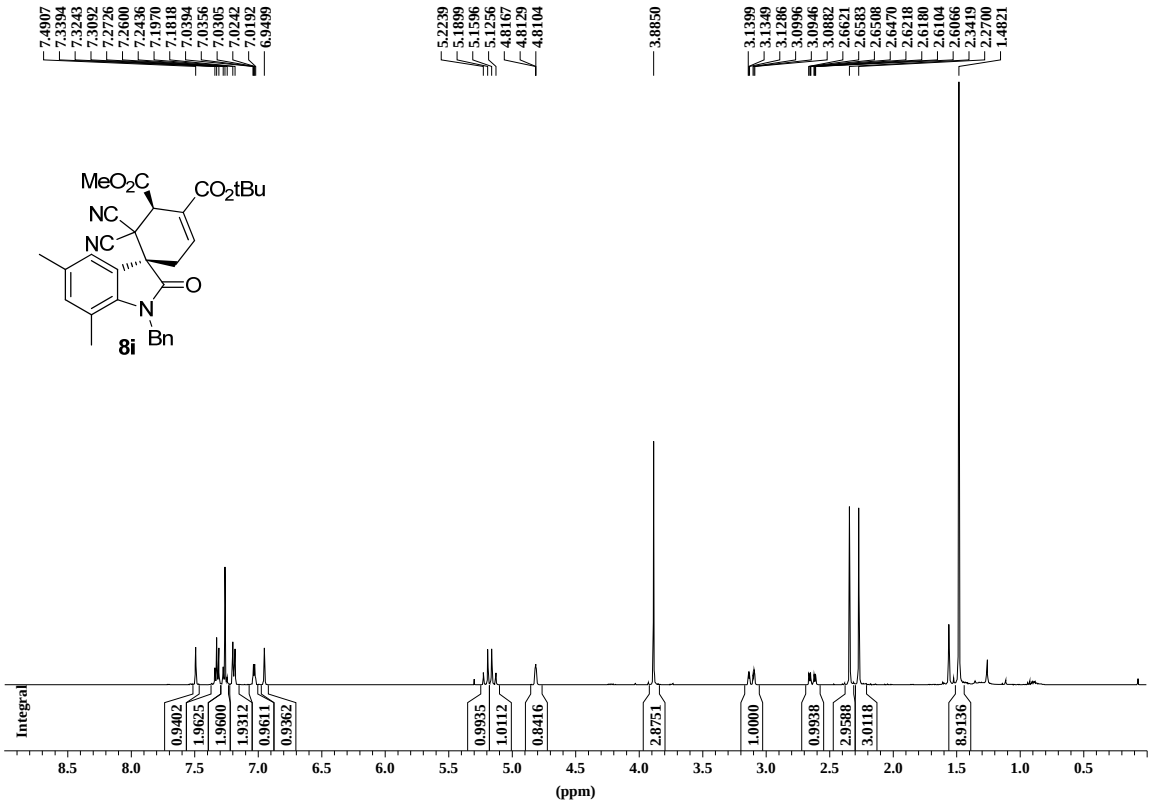

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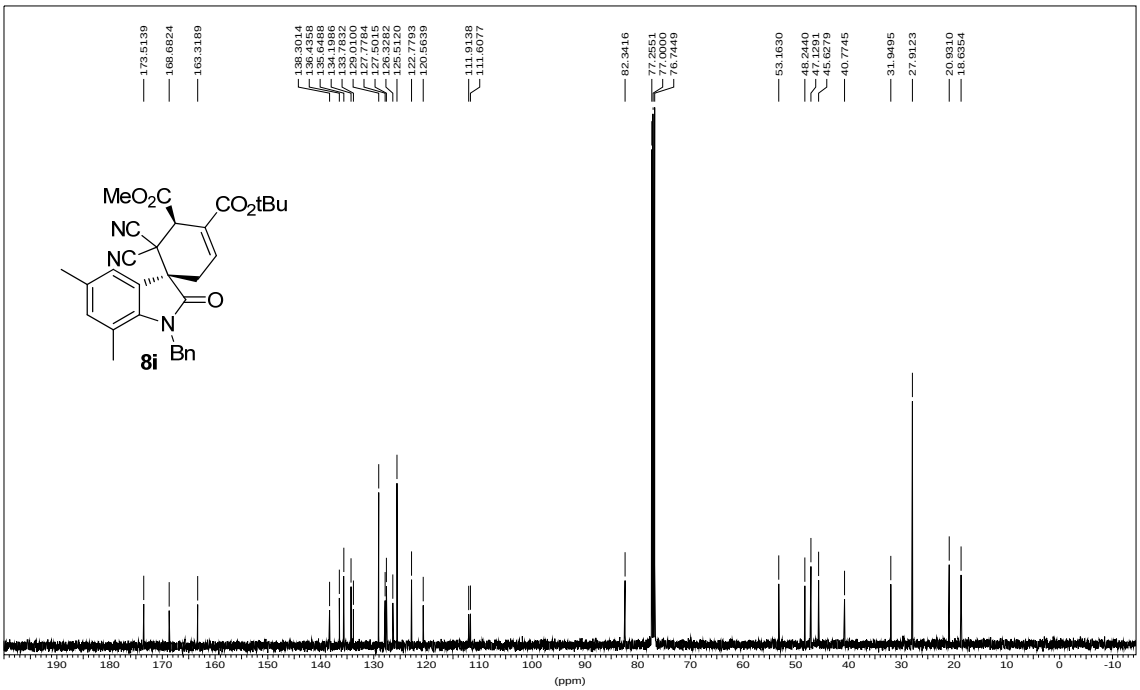

1H AMX500
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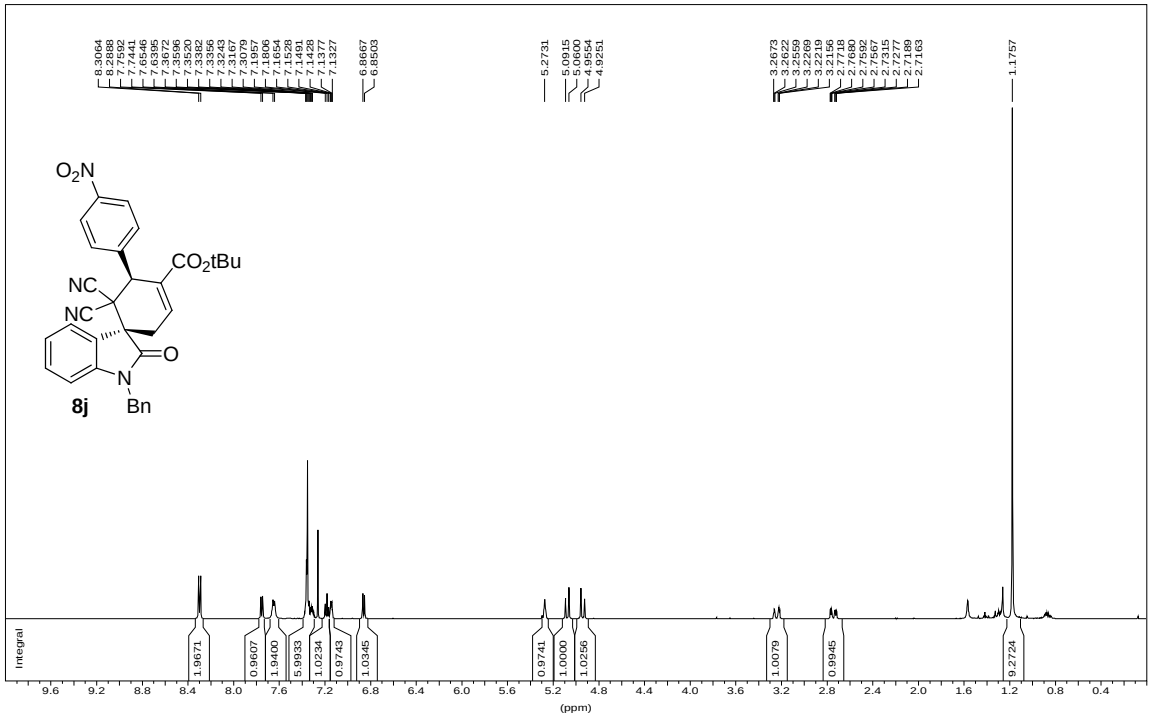

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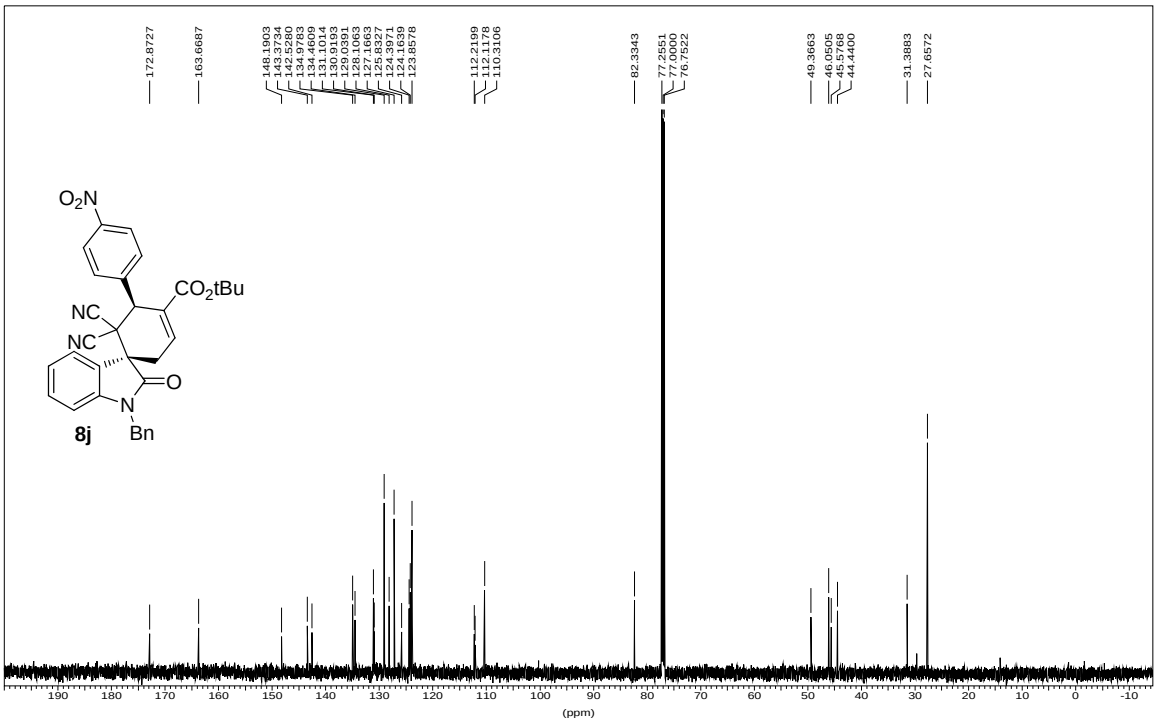

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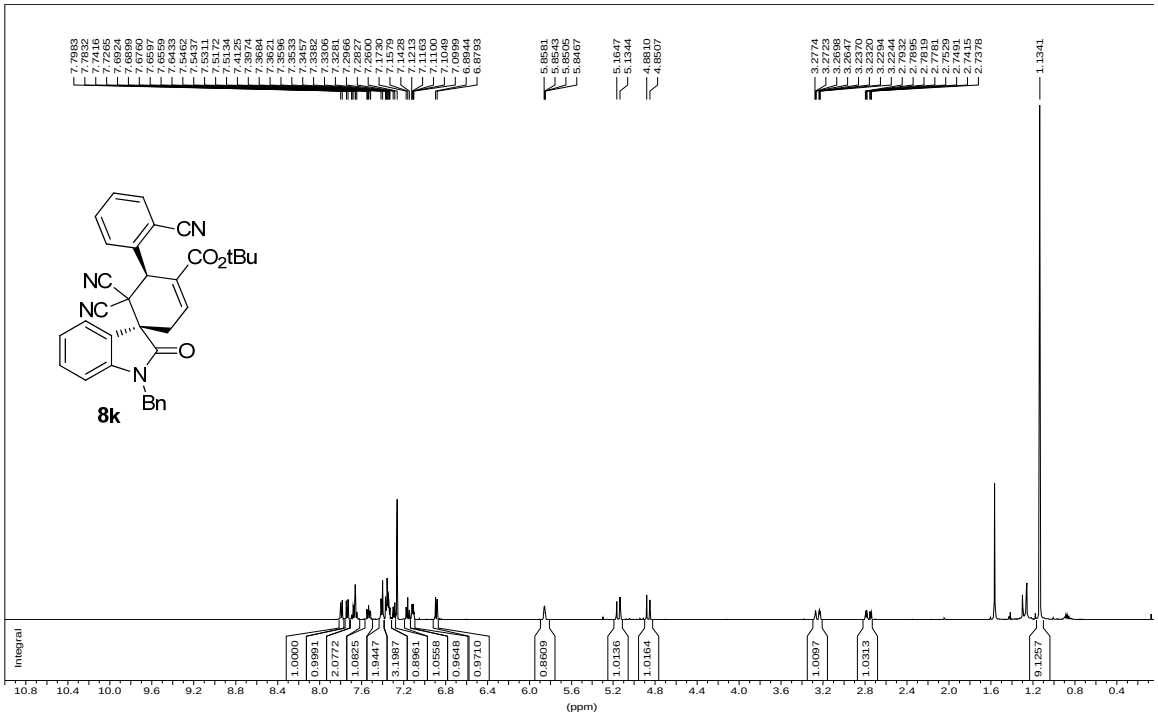

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