Electronic Supplementary Material (ESI) for Organic Chemistry Frontiers.

# Supporting Information

## Enantiodivergent Synthesis of 1,2-Bis(diphenylphosphino)ethanes via Asymmetric [3+2]-cycloaddition

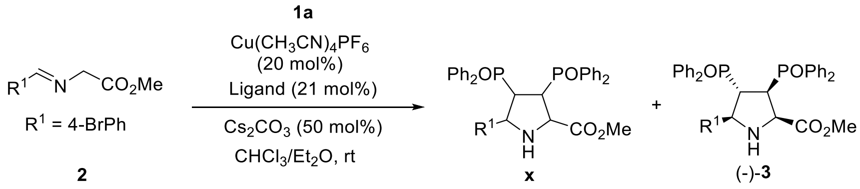
Bing Liu, Wenbo Li, Haihong Wu, and Junliang Zhang*

# Table Contents

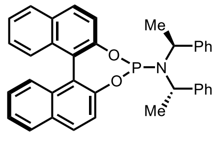
# 1. General Information

All reactions were carried out under an atmosphere of nitrogen in flame-dried glassware with magnetic stirring. $^{1}H$ NMR spectra, $^{19}F$ NMR spectra, $^{13}C$ NMR spectra were recorded on a Bruker 300, 400 and 500 MHz spectrometer in $CDCl_3$. All signals are reported in ppm with the internal TMS signal at 0 ppm as a standard. Data for $^{1}H$ NMR spectra are reported as follows: chemical shift (ppm, referenced to TMS; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, coupling constant(s) in Hz, integration), coupling constant (Hz), and intergration. Data for $^{13}C$ NMR are reported in terms of chemical shift (ppm) relative to residual solvent peak ($CDCl_3$: 77.0 ppm). Reactions were monitored by thin layer chromatography (TLC) using silica gel plates. Flash column chromatography was performed over silica gel (300-400 mesh). THF, $Et_2O$ and MTBE were freshly distilled from sodium metal prior to use. The ligands **L2**-**L13** were synthesized according to the procedure of reference.[1] Other known ligands were commercially available. The substrate **1a** were synthesized according to the procedure of references.[2] **2a**-**2o** were synthesized according to the procedure of references.[3]

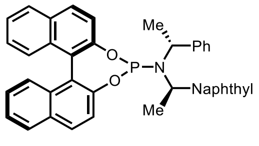
## 2. Table S1. Screening the Known Ligands[a]



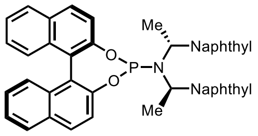
| Entry | Ligand | Yield (%)[b] | *Ee* (%)[c] (X/(-)-**3**) |
|---|---|---|---|
| 1 | **L6** | 100% conv. | -/42 |
| 2 | **L7** | 100% conv. | 51/27 |
| 3 | **L8** | trace | - |
| 4 | **L9** | 80% conv. | 42/15 |
| 5 | **L10** | 100% conv. | 25/31 |
| 6 | **L11** | 100% conv. | 30/18 |
| 7 | **L12** | trace | - |
| 8 | **L13** | 23% conv. | -/16 |



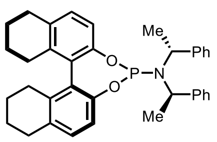
**L5**, (*R*,*S*,*S*)
100% Conv., /42% *ee*



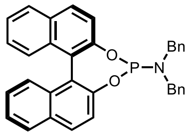
**L6**, *(S,R,R)*
100% conv., 51/27% *ee*



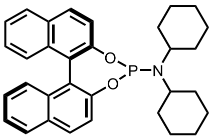
**L7**, *(R,R,R)*, *trace*



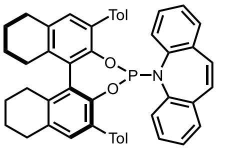
**L8**, *(S,R,R)*
80% conv., 42/15% *ee*



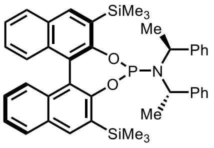
**L9**, *(R)*
100% conv., 25/31% *ee*



**L10**, *(R)*
100% conv., 30/18% *ee*



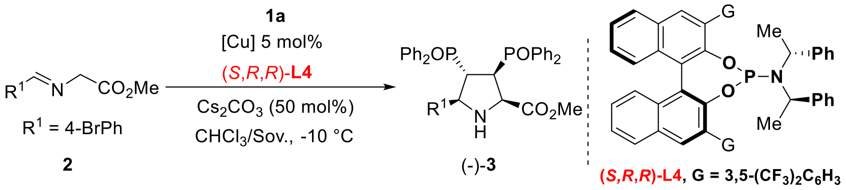
**L11**, *(R)*, trace



**L12**, (*R*,*S*,*S*)
23% conv., /16% *ee*

[a] All reactions were carried out with 0.025 mmol of **1a**, 0.2 mmol of **2a**, 20 mol% of catalyst ([Cu] to Ligand = 1:1.05), 50 mol% $Cs_2CO_3$ in 1.5 ml Solvent ($CHCl_3/Et_2O$ = 1) at rt for 24 h. [b] NMR yield with $CH_2Br_2$ as an internal standard. [c] Determined by chiral HPLC.

## 3. Table S2. Optimization of Reaction Conditions for (-)-3a [a]



| Entry | [Cu] | Solvent | Dr[b] (X/(-)-3) | Yield (%)[c] | *Ee* (%)[d] |
|---|---|---|---|---|---|
| 1 | $Cu(CH_3CN)_4BF_4$ | $CHCl_3/Et_2O$ = 1 |  | 30% conv. | 95% |
| 2 | $Cu(CH_3CN)_4NTf_2$ | $CHCl_3/Et_2O$ = 1 |  | 50% conv. | 98% |
| 3 | $Cu(CH_3CN)_4ClO_4$ | $CHCl_3/Et_2O$ = 1 |  | 60% conv. | 99% |
| 4 | $Cu(CH_3CN)_4PF_6$ | $CHCl_3/Et_2O$ = 1 | 1:13 | 100% conv. | >99% |
| 5 | $Cu(CH_3CN)_4PF_6$ | $CHCl_3$/THF = 1 |  | Trace |  |
| 6 | $Cu(CH_3CN)_4PF_6$ | $CHCl_3$/MTBE = 1 |  | 40% conv. | 97% |

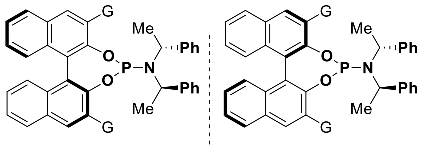
[a] All reactions were carried out with 0.025 mmol of **1a**, 0.2 mmol of **2a**, 20 mol% of catalyst ([Cu] to Ligand = 1:1.05), 50% $Cs_2CO_3$ in 1.5 ml Solvent at -10 °C for 24 h. [b] The diastereomeric ratios were determined by $^1H$, $^{31}P$ NMR analysis of the crude products. [c] NMR yield with $CH_2Br_2$ as an internal standard. [d] Determined by chiral HPLC.

## 4. General Procedure for the Synthesis of products 3-13

### Typical procedure for asymmetric copper-catalyzed cycloaddition of alkene with glycine ketoimino ester.

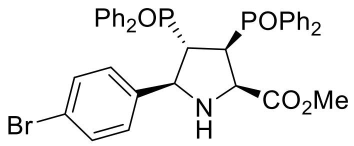
The solution of Ligand (21.0 mol%) and $Cu(CH_3CN)_4PF_6$ (20 mol%) in $CHCl_3/Et_2O$ = 1:1 (6 mL) was stirred at room temperature for 1 h. After the reaction temperature was dropped to -10 °C, azomethine ylides **2** (0.2 mmol), $Cs_2CO_3$ (0.05 mmol) and alkene **1** (0.1 mmol) were added sequentially. After the alkene **1** was consumed completely, remove the solvent under reduced pressure. The crude product was analyzed with $^1H$ NMR and $^{31}P$ NMR to determine the diastereomeric ratio. Then the crude product was purified by flash column chromatography on silica gel to afford the desired product. The enantionmeric excesses of the products were determined by chiral stationary phase HPLC.

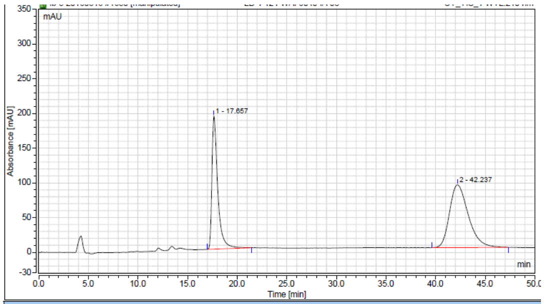
**Conditions A:** using (*S*, *R*, *R*)-**L4** as the ligand.
**Conditions B:** using (*R*, *R*, *R*)-**L4** as the ligand.


(*S*,*R*,*R*)-L4, G = 3,5-$(CF_3)_2C_6H_3$ (*R*,*R*,*R*)-L4, G = 3,5-$(CF_3)_2C_6H_3$

## 1. Synthesis of (-)-3a and (+)-3a.

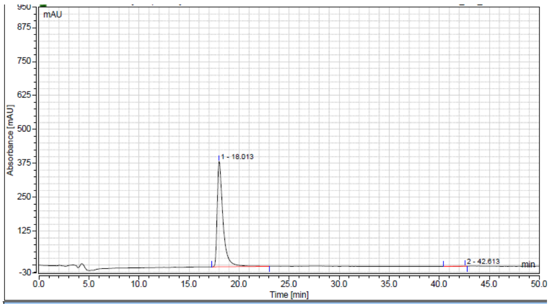
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2a** (51.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3a** as a white solid (58.7 mg, 86% yield) with 14:1 dr and 99% *ee*. mp: 220-221 ºC. $^1$H NMR (400 MHz, $CDCl_3$) δ 7.74 (t, $J$ = 8.7 Hz, 2H), 7.44 -7.36 (m, 8H), 7.33-7.26 (m, 6H), 7.23-7.12 (m, 8H), 4.45-4.34 (m, 2H), 3.76 (d, $J$ = 10.2 Hz, 1H), 3.49-3.43 (m, 1H), 3.27 (s, 1H), 2.88 (s, 3H). $^{31}$P NMR (162 MHz, $CDCl_3$) δ 33.37 (d, $J$ = 30.4 Hz), 33.13 (d, $J$ = 30.5 Hz). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 168.47 (d, $J$ = 3.6 Hz), 139.70 (d, $J$ = 2.2 Hz), 131.86, 131.41, 131.30, 131.28, 131.19, 130.51 (d, $J$ = 8.1 Hz), 130.32 (d, $J$ = 8.3 Hz), 129.99, 128.69 (t, $J$ = 9.0 Hz), 128.27 (t, $J$ = 11.2 Hz), 121.64, 65.15, 63.04, 51.09, 46.71 (dt, $J$ = 31.2, 17.5 Hz), 42.04 (dt, $J$ = 63.7, 16.1 Hz). ESI-MS calculated for $C_{36}H_{33}BrNO_4P_2$: m/z (%): 684.1063 (M+H$^+$), found: 684.1066. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 18.0 min, minor enantiomer tr = 42.6 min. $[\alpha]_D^{25}$ = -16.4 ($c$ = 0.25, $CHCl_3$).





Integration Results

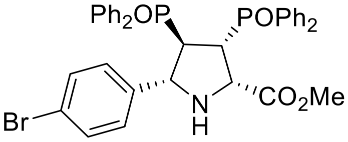
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>r |
|---|---|---|---|---|---|---|---|
| 1 |  | 17.657 | 130.975 | 192.160 | 39.73 | 67.95 | r |
| 2 |  | 42.237 | 198.709 | 90.633 | 60.27 | 32.05 | r |
| Total: |  |  | 329.684 | 282.793 | 100.00 | 100.00 |  |

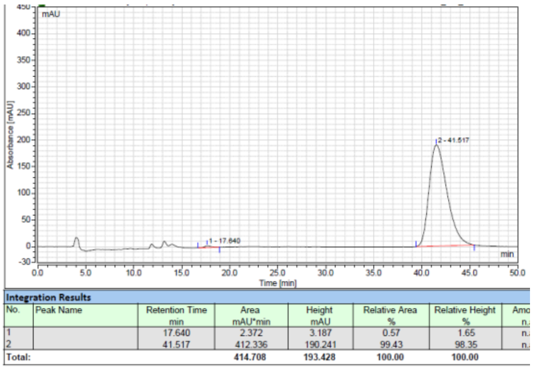


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>r |
|---|---|---|---|---|---|---|---|
| 1 |  | 18.013 | 259.744 | 388.455 | 99.90 | 99.95 | r |
| 2 |  | 42.613 | 0.269 | 0.177 | 0.10 | 0.05 | r |
| Total: |  |  | 260.013 | 388.633 | 100.00 | 100.00 |  |

**Under conditions B:** the product (+)-**3a** was obtained as a white solid (54.6 mg, 80% yield) with 11:1 dr and 99% *ee*. mp: 191-192 ºC. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 41.5 min, minor enantiomer tr = 17.6 min. $[\alpha]_D^{25}$ = +21.2 ($c$ = 0.25, $CHCl_3$).



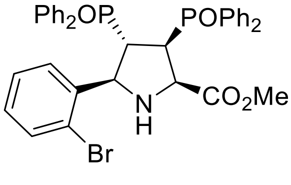


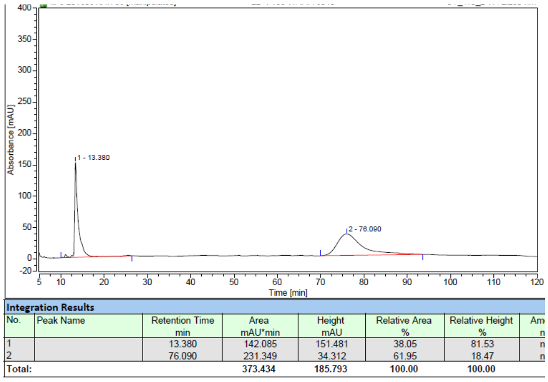
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 17.640 | 2.372 | 3.187 | 0.57 | 1.65 | n. |
| 2 | | 41.517 | 412.336 | 190.241 | 99.43 | 98.35 | n. |
| Total: | | | 414.708 | 193.428 | 100.00 | 100.00 | |

## 2. Synthesis of (-)-3b and (+)-3b.

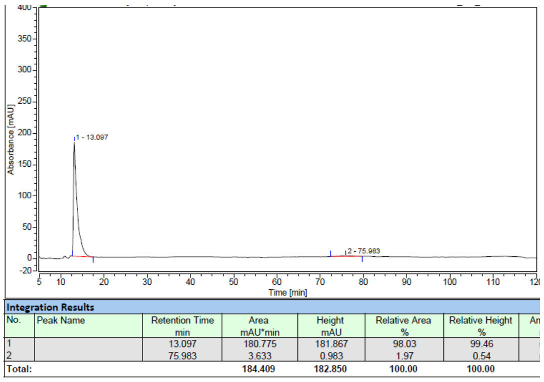
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2b** (51.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3b** as a white solid (60.1 mg, 88% yield) with >20:1 dr and 96% *ee*. mp: 231-232 °C. $^1$H NMR (500 MHz, $CDCl_3$) δ 8.61-8.59 (m, 1H), 7.75 (t, $J$ = 9.0 Hz, 2H), 7.53-7.38 (m, 10H), 7.33-7.23 (m, 4H), 7.19-7.05 (m, 7H), 5.04 (s, 1H), 4.44 (d, $J$ = 23.4 Hz, 1H), 3.89-3.81 (m, 2H), 3.13 (s, 1H), 2.90 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.67. $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.48, 139.62, 132.22, 131.73, 131.50 (dd, $J$ = 6.1, 3.0 Hz), 131.28, 130.99 (dd, $J$ = 6.3, 2.9 Hz), 130.47 (dd, $J$ = 5.9, 2.6 Hz), 130.32 (dd, $J$ = 6.2, 2.7 Hz), 129.66, 129.12, 128.73-128.40 (m), 128.28, 128.21-127.87 (m), 125.85, 65.23, 61.14, 51.09, 46.12 (dt, $J$ = 39.4, 13.4 Hz), 41.90 (dt, $J$ = 34.2, 12.6 Hz). ESI-MS calculated for $C_{36}H_{33}BrNO_4P_2$: m/z (%): 684.1063 (M+H$^+$), found: 684.1065. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 65:45 to 45:65, 0.8 mL/min, 230 nm); major enantiomer tr = 13.1 min, minor enantiomer tr = 76.0 min. $[\alpha]_D^{25}$ = -5.6 (*c* = 0.25, $CHCl_3$).





**Integration Results**

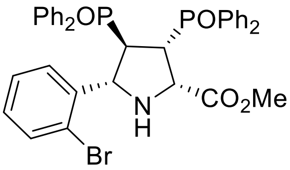
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 13.380 | 142.085 | 151.481 | 38.05 | 81.53 | n |
| 2 | | 76.090 | 231.349 | 34.312 | 61.95 | 18.47 | n |
| Total: | | | 373.434 | 185.793 | 100.00 | 100.00 | |

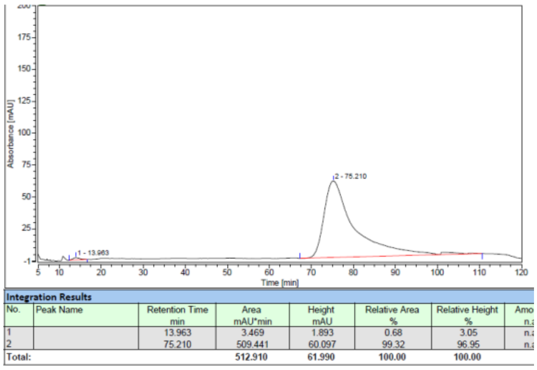


**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | An |
|---|---|---|---|---|---|---|---|
| 1 | | 13.097 | 180.775 | 181.867 | 98.03 | 99.46 | |
| 2 | | 75.983 | 3.633 | 0.983 | 1.97 | 0.54 | |
| Total: | | | 184.409 | 182.850 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3b** was obtained as a white solid (60.7 mg, 89% yield) with >20:1 dr and 99% *ee*. mp: 236-237 ºC. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 65:45 to 45:65, 0.8 mL/min, 230 nm); major enantiomer tr = 75.2 min, minor enantiomer tr = 14.0 min. $[\alpha]_D^{25}$ = +5.2 (*c* = 0.25, $CHCl_3$).





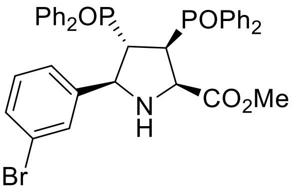
**Integration Results**

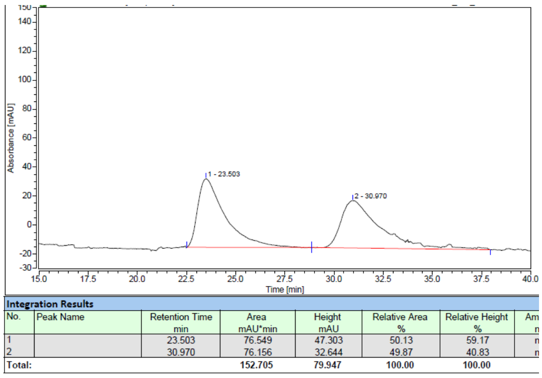
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 13.963 | 3.469 | 1.893 | 0.68 | 3.05 | n.a |
| 2 | | 75.210 | 509.441 | 60.097 | 99.32 | 96.95 | n.a |
| Total: | | | 512.910 | 61.990 | 100.00 | 100.00 | |

## 3. Synthesis of (-)-3c and (+)-3c.

**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2c** (51.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3c** as a white solid (60.1 mg, 88% yield) with 14:1 dr and 98% *ee*. mp: 115-116 ºC. $^1H$ NMR (400 MHz, $CDCl_3$) δ 7.70 (s, 2H), 7.51 (d, *J* = 6.6 Hz, 1H), 7.36 -7.26 (m, 11H), 7.24-7.19 (m, 4H), 7.11-7.05 (m, 5H), 6.98 (s, 1H), 4.38 (d, *J* = 23.0 Hz, 1H), 4.26 (d, *J* = 9.1 Hz, 1H), 3.72 (d, *J* = 13.5 Hz, 1H), 3.39 (d, *J* = 14.8 Hz, 1H), 3.26 (s, 1H), 2.85 (s, 3H). $^{31}P$ NMR (162 MHz, $CDCl_3$) δ 33.15 (q, *J* = 30.7 Hz). $^{13}C$ NMR (126 MHz, $CDCl_3$) δ 168.61 (d, *J* = 4.1 Hz), 142.97 (d, *J* = 2.7 Hz), 132.34 (d, *J* = 2.1 Hz), 131.97 (d, *J* = 2.0 Hz), 131.66 (d, *J* = 2.1 Hz), 131.58, 131.55, 131.36 (t, *J* = 7.9 Hz), 130.88, 130.67 (d, *J* = 8.2 Hz), 130.50 (d, *J* = 8.3 Hz), 130.26, 128.86 (t, *J* = 10.9 Hz), 128.39 (t, *J* = 10.4 Hz), 126.58, 122.11, 63.18, 51.22, 47.13 (dd, *J* = 59.4, 5.1 Hz), 42.10 (dd, *J* = 58.2, 7.2 Hz). ESI-MS calculated for $C_{36}H_{33}BrNO_4P_2$: m/z (%): 684.1063 (M+H$^+$), found: 684.1057. Enantiomeric excess was determined by

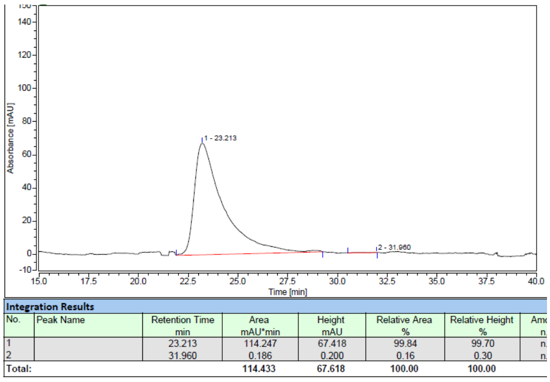
HPLC with a Chiralpak IA column (hexanes: 2-propanol = 70:30, 0.8 mL/min, 230 nm); major enantiomer tr = 23.2 min, minor enantiomer tr = 32.0 min. $[\alpha]_D^{25}$ = -14.4 (*c* = 0.25, $CHCl_3$).





Integration Results

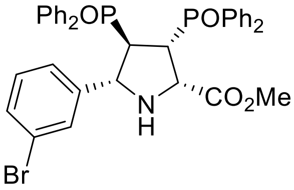
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 23.503 | 76.549 | 47.303 | 50.13 | 59.17 | n |
| 2 | | 30.970 | 76.156 | 32.644 | 49.87 | 40.83 | n |
| Total: | | | 152.705 | 79.947 | 100.00 | 100.00 | |

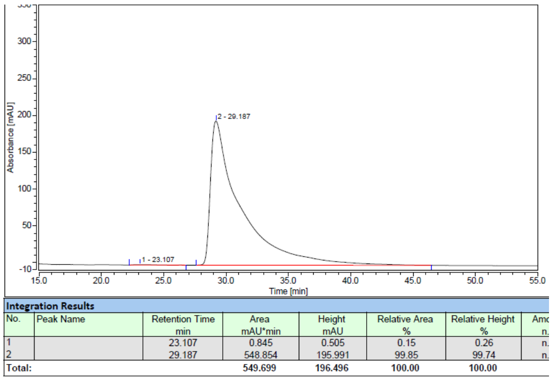


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 23.213 | 114.247 | 67.418 | 99.84 | 99.70 | n. |
| 2 | | 31.960 | 0.186 | 0.200 | 0.16 | 0.30 | n. |
| Total: | | | 114.433 | 67.618 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3c** was obtained as a white solid (64.8 mg, 95% yield) with >20:1 dr and >99% *ee*. mp: 121-122 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 70:30, 0.8 mL/min, 230 nm); major enantiomer tr = 29.2 min, minor enantiomer tr = 23.1 min. $[\alpha]_D^{25}$ = +13.2 (*c* = 0.25, $CHCl_3$).



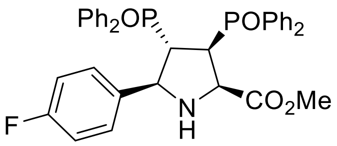


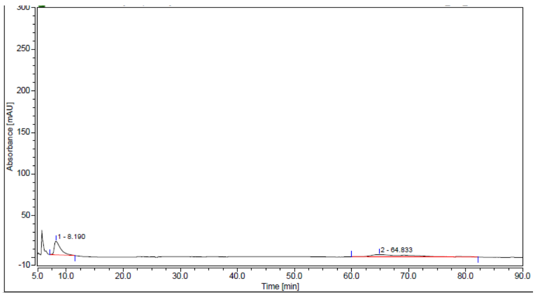
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 23.107 | 0.845 | 0.505 | 0.15 | 0.26 | n. |
| 2 | | 29.187 | 548.854 | 195.991 | 99.85 | 99.74 | n. |
| Total: | | | 549.699 | 196.496 | 100.00 | 100.00 | |

## 4. Synthesis of (-)-3d and (+)-3d.

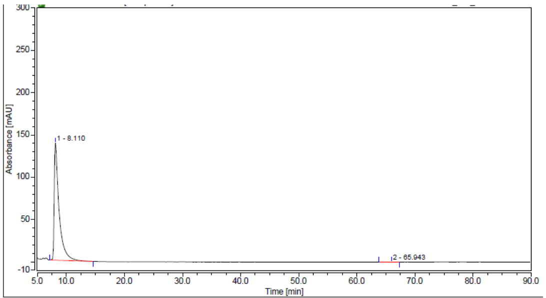
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2d** (39.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3d** as a white solid (56.7 mg, 91% yield) with 19:1 dr and >99% *ee*. mp: 212-213 °C. $^1H$ NMR (400 MHz, $CDCl_3$) δ 7.79-7.74 (m, 2H), 7.50-7.35 (m, 10H), 7.34-7.28 (m, 4H), 7.23 (t, *J* = 6.9 Hz, 2H), 7.15 (t, *J* = 7.7 Hz, 4H), 6.85 (t, *J* = 8.7 Hz, 2H), 4.43 (d, *J* = 21.3 Hz, 2H), 3.83-3.76 (m, 1H), 3.57-3.50 (m, 1H), 3.26 (s, 1H), 2.91 (s, 3H). $^{19}$F NMR (282 MHz, $CDCl_3$) δ -114.53. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 33.39 (d, $J$ = 2.7 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.65, 162.30 (d, $J$ = 246.3 Hz), 136.55, 131.96, 131.51, 131.44-131.25 (m), 130.76-130.59 (m), 130.59-130.34 (m), 130.10 (d, $J$ = 8.1 Hz), 129.05-128.63 (m), 128.38 (dd, $J$ = 11.8, 7.4 Hz), 115.38, 115.21, 65.24, 63.11, 51.24, 46.82 (dt, $J$ = 38.6, 13.9 Hz), 42.16 (dt, $J$ = 41.0, 12.6 Hz). ESI-MS calculated for $C_{36}H_{32}FNNaO_4P_2$: m/z (%): 646.1683 ($M+Na^+$), found: 646.1680. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 8.1 min, minor enantiomer tr = 65.9 min. $[\alpha]_D^{25}$ = -14.4 ($c$ = 0.25, $CHCl_3$).





Integration Results

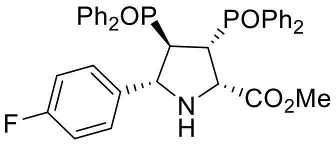
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 8.190 | 21.064 | 16.431 | 49.91 | 85.89 | n. |
| 2 | | 64.833 | 21.140 | 2.700 | 50.09 | 14.11 | n. |
| Total: | | | **42.204** | **19.130** | **100.00** | **100.00** | |

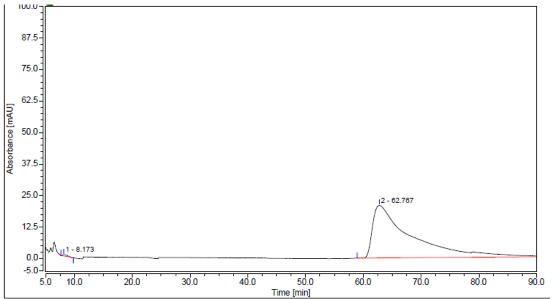


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 8.110 | 133.170 | 138.285 | 99.91 | 99.98 | n. |
| 2 | | 65.943 | 0.125 | 0.031 | 0.09 | 0.02 | n. |
| Total: | | | **133.295** | **138.316** | **100.00** | **100.00** | |

**Under conditions B:** the product (+)-**3d** was obtained as a white solid (54.2 mg, 87% yield) with >20:1 dr and 99% *ee*. mp: 203-204 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 62.8 min, minor enantiomer tr = 8.2 min. $[\alpha]_D^{25}$ = +14.4 ($c$ = 0.25, $CHCl_3$).



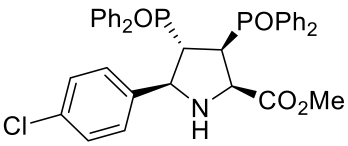


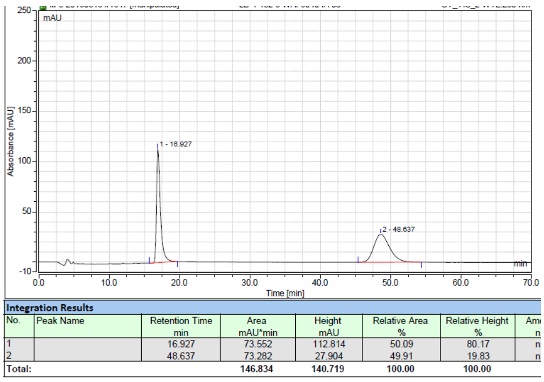
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 8.173 | 0.565 | 0.628 | 0.35 | 2.92 | n.a |
| 2 | | 62.767 | 161.988 | 20.882 | 99.65 | 97.08 | n.a |
| Total: | | | **162.553** | **21.510** | **100.00** | **100.00** | |

## 5. Synthesis of (-)-3e and (+)-3e.

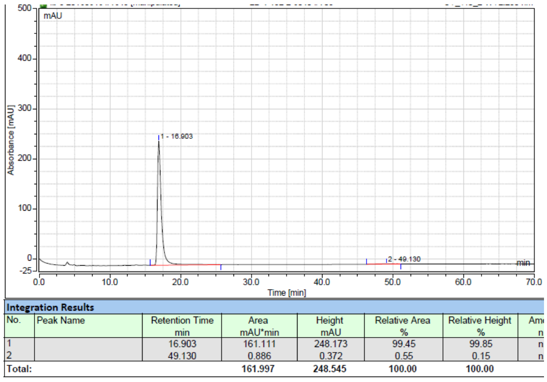
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2e** (42.2 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3e** as a white solid (46.6 mg, 73% yield) with 15:1 dr and 99% *ee*. mp: 111-112 °C. $^1$H NMR (500 MHz, $CDCl_3$) δ 7.77-7.34 (m, 2H), 7.48-7.38 (m, 8H), 7.37 -7.29(m, 4H), 7.26-7.21 (m, 4H), 7.17-7.12 (m, 6H), 4.46-4.34 (m, 2H), 3.81-3.77 (m, 1H), 3.52-3.48 (m, 1H), 3.29 (s, 1H), 2.90 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.37, 33.34. $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.62 (d, $J$ = 3.6 Hz), 139.30, 133.56, 132.00 (d, $J$ = 2.7 Hz), 131.54, 131.50, 131.39 (d, $J$ = 8.7 Hz), 130.68 (d, $J$ = 8.4 Hz), 130.48 (d, $J$ = 8.7 Hz), 129.79, 128.82 (dd, $J$ = 11.4, 9.1 Hz), 128.61, 128.55-128.18 (m), 65.29, 63.12, 51.25, 46.85 (dt, $J$ = 67.6, 16.2 Hz), 42.19 (dt, $J$ = 34.0, 14.3 Hz). ESI-MS calculated for $C_{36}H_{32}ClNNaO_4P_2$: m/z (%): 662.1387 (M+Na$^+$), found: 662.1385. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 16.9 min, minor enantiomer tr = 49.1 min. $[\alpha]_D^{25}$ = -22.0 ($c$ = 0.25, $CHCl_3$).





Integration Results

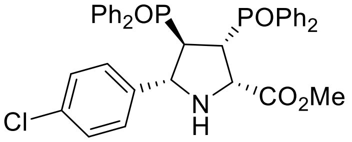
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>n |
|---|---|---|---|---|---|---|---|
| 1 | | 16.927 | 73.552 | 112.814 | 50.09 | 80.17 | n |
| 2 | | 48.637 | 73.282 | 27.904 | 49.91 | 19.83 | n |
| Total: | | | **146.834** | **140.719** | **100.00** | **100.00** | |

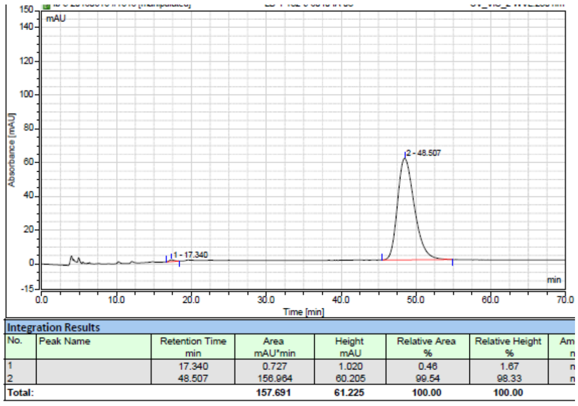


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>n |
|---|---|---|---|---|---|---|---|
| 1 | | 16.903 | 161.111 | 248.173 | 99.45 | 99.85 | n |
| 2 | | 49.130 | 0.886 | 0.372 | 0.55 | 0.15 | n |
| Total: | | | **161.997** | **248.545** | **100.00** | **100.00** | |

**Under conditions B:** the product (+)-**3e** was obtained as a white solid (55.0 mg, 86% yield) with >20:1 dr and 98% *ee*. mp: 97-98 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 48.5 min, minor enantiomer tr = 17.3 min. $[\alpha]_D^{25}$ = +20.0 ($c$ = 0.25, $CHCl_3$).



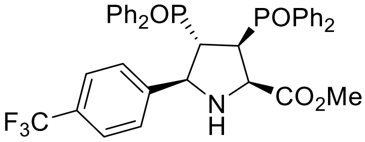


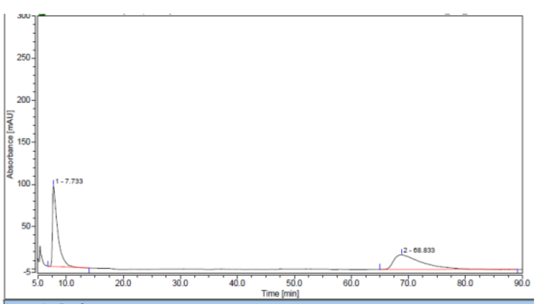
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 17.340 | 0.727 | 1.020 | 0.46 | 1.67 | n |
| 2 | | 48.507 | 156.964 | 60.205 | 99.54 | 98.33 | n |
| Total: | | | 157.691 | 61.225 | 100.00 | 100.00 | |

## 6. Synthesis of (-)-3f and (+)-3f.

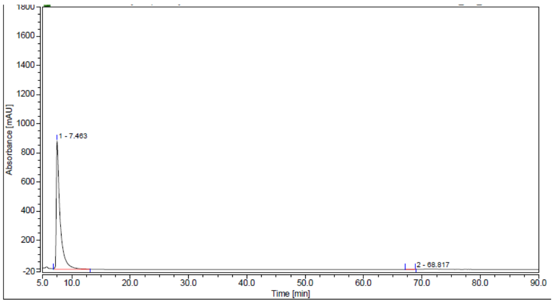
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2f** (49.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3f** as a white solid (61.9 mg, 92% yield) with 13:1 dr and >99% *ee*. mp: 224-225 $^{o}$C. $^{1}$H NMR (400 MHz, $CDCl_3$) δ 7.72-7.67 (m, 2H), 7.43-7.25 (m, 16H), 7.16-7.08 (m, 6H), 4.43-4.36 (m, 2H), 3.75-3.70 (m, 1H), 3.57-3.50 (m, 1H), 3.23 (s, 1H), 2.86 (s, 3H). $^{19}$F NMR (282 MHz, $CDCl_3$) δ -62.55. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 33.14 (dd, $J$ = 81.0, 30.1 Hz). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 168.54 (d, $J$ = 4.5 Hz), 144.77, 131.99 (dd, $J$ = 5.3, 2.5 Hz), 131.66 (q, $J_{C-F}$ = 281.4 Hz), 131.65, 131.56, 131.51, 131.31 (d, $J$ = 8.7 Hz), 130.67 (d, $J$ = 8.6 Hz), 130.48 (d, $J$ = 8.8 Hz), 128.87, 128.76 (t, $J$ = 5.6 Hz), 128.35 (t, $J$ = 11.0 Hz), 125.31 (d, $J$ = 3.8 Hz), 65.32, 63.08, 51.25, 46.76 (d, $J$ = 64.4 Hz), 42.22 (d, $J$ = 62.2 Hz). ESI-MS calculated for $C_{37}H_{32}F_3NNaO_4P_2$: m/z (%): 696.1651 (M+Na$^{+}$), found: 696.1651. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 210 nm); major enantiomer tr = 7.5 min, minor enantiomer tr = 68.8 min. $[\alpha]_D^{25}$ = -28.0 ($c$ = 0.25, $CHCl_3$).





**Integration Results**

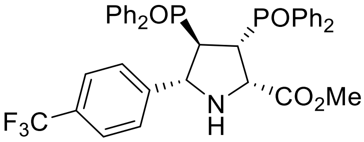
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amc n. |
|---|---|---|---|---|---|---|---|
| 1 | | 7.733 | 98.866 | 95.881 | 49.77 | 84.69 | n. |
| 2 | | 68.833 | 99.770 | 17.336 | 50.23 | 15.31 | n. |
| Total: | | | 198.636 | 113.217 | 100.00 | 100.00 | |

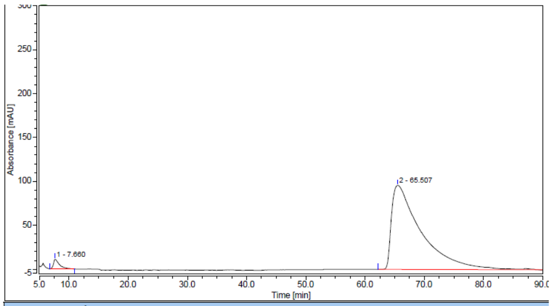


**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amc n. |
|---|---|---|---|---|---|---|---|
| 1 | | 7.463 | 662.321 | 883.763 | 99.95 | 99.99 | n. |
| 2 | | 68.817 | 0.311 | 0.063 | 0.05 | 0.01 | n. |
| Total: | | | 662.632 | 883.825 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3f** was obtained as a white solid (57.2 mg, 85% yield) with 18:1 dr and 96% *ee*. mp: 197-198 ºC. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 65.5 min, minor enantiomer tr = 7.7 min. $[\alpha]_D^{25}$ = +31.6 (*c* = 0.25, $CHCl_3$).



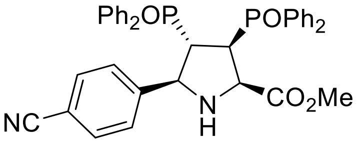


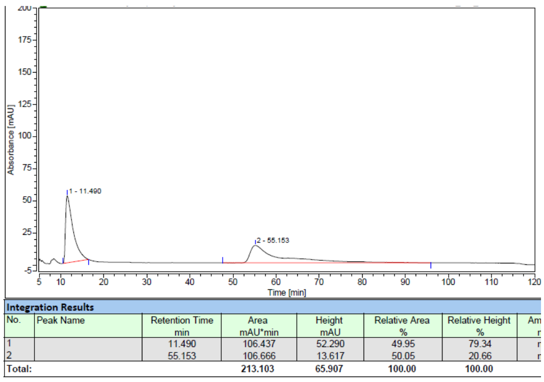
**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am |
|---|---|---|---|---|---|---|---|
| 1 | | 7.660 | 13.010 | 11.194 | 2.28 | 10.45 | |
| 2 | | 65.507 | 557.987 | 95.901 | 97.72 | 89.55 | |
| Total: | | | 570.997 | 107.095 | 100.00 | 100.00 | |

## 7. Synthesis of (-)-3g and (+)-3g.

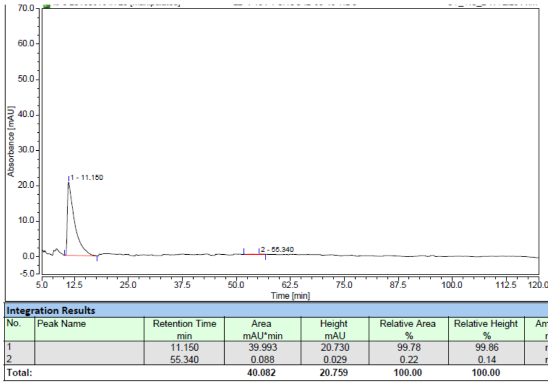
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2g** (40.4 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3g** as a white solid (59.2 mg, 94% yield) with >20:1 dr and >99% *ee*. mp: 86-87 ºC. $^1$H NMR (500 MHz, $CDCl_3$) δ 7.75-7.71 (m, 2H), 7.50-7.31 (m, 16H), 7.24-7.14 (m, 6H), 4.46 (d, *J* = 20.1 Hz, 2H), 3.77-3.72 (m, 1H), 3.61-3.55 (m, 1H), 3.27 (s, 1H), 2.91 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.16 (dd, *J* = 158.7, 30.1 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.45 (d, *J* = 4.6 Hz), 146.19 (d, *J* = 3.0 Hz), 132.23, 132.13 (dd, *J* = 9.5, 2.6 Hz), 131.64 (d, *J* = 9.2 Hz), 131.29 (d, *J* = 9.0 Hz), 131.47 (dd, *J* = 44.4, 9.1 Hz), 130.57 (dd, *J* = 21.5, 8.9 Hz), 129.21, 128.89 (dd, *J* = 11.5, 6.9 Hz), 128.45 (dd, *J* = 23.2, 11.6 Hz), 118.80, 115.66, 111.51, 65.27 (d, *J* = 3.0 Hz), 62.92, 51.32, 46.74 (d, *J* = 66.7 Hz), 42.21 (d, *J* = 65.3 Hz). ESI-MS calculated for $C_{37}H_{32}N_2NaO_4P_2$: m/z (%): 653.1730 (M+Na$^+$), found: 653.1737. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 210 nm); major enantiomer tr = 11.3 min, minor enantiomer tr = 76.9 min. $[\alpha]_D^{25}$ = -20.8 (*c* = 0.25, $CHCl_3$).





Integration Results

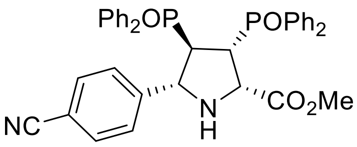
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>r |
|---|---|---|---|---|---|---|---|
| 1 |  | 11.490 | 106.437 | 52.290 | 49.95 | 79.34 | r |
| 2 |  | 55.153 | 106.666 | 13.617 | 50.05 | 20.66 | r |
| **Total:** |  |  | **213.103** | **65.907** | **100.00** | **100.00** |  |

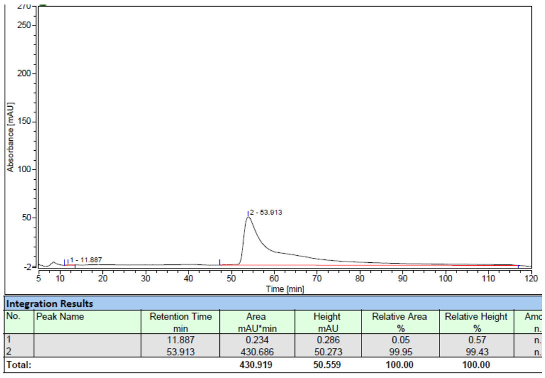


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>r |
|---|---|---|---|---|---|---|---|
| 1 |  | 11.150 | 39.993 | 20.730 | 99.78 | 99.86 | r |
| 2 |  | 55.340 | 0.088 | 0.029 | 0.22 | 0.14 | r |
| **Total:** |  |  | **40.082** | **20.759** | **100.00** | **100.00** |  |

**Under conditions B:** the product (+)-**3g** was obtained as a white solid (60.5 mg, 96% yield) with >20:1 dr and >99% *ee*. mp: 93-94 $^{o}$C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 53.9 min, minor enantiomer tr = 11.3 min. $[\alpha]_D^{25}$ = +24.8 (*c* = 0.25, $CHCl_3$).





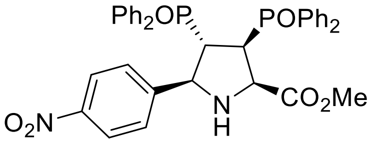
Integration Results

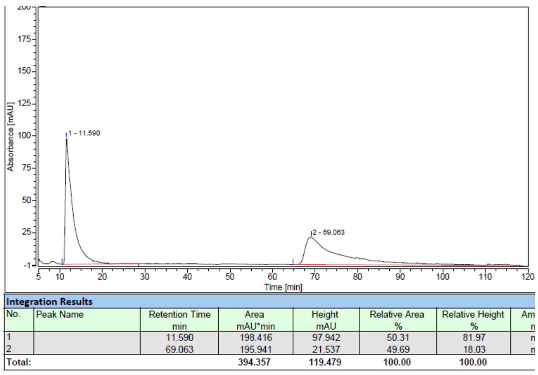
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n. |
|---|---|---|---|---|---|---|---|
| 1 |  | 11.887 | 0.234 | 0.286 | 0.05 | 0.57 | n. |
| 2 |  | 53.913 | 430.686 | 50.273 | 99.95 | 99.43 | n. |
| **Total:** |  |  | **430.919** | **50.559** | **100.00** | **100.00** |  |

## 8. Synthesis of (-)-3h and (+)-3h.

**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2h** (44.4 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3h** as a white solid (63.7 mg, 98% yield) with >20:1 dr and >99% *ee*. mp: 87-88 $^{o}$C. $^1$H NMR (500 MHz, $CDCl_3$) δ 8.01 (d, *J* = 8.7 Hz, 2H), 7.78-7.74(m, 2H), 7.53-7.34 (m, 14H), 7.26-7.18 (m, 6H), 4.57-4.48 (m, 2H), 3.82-3.76

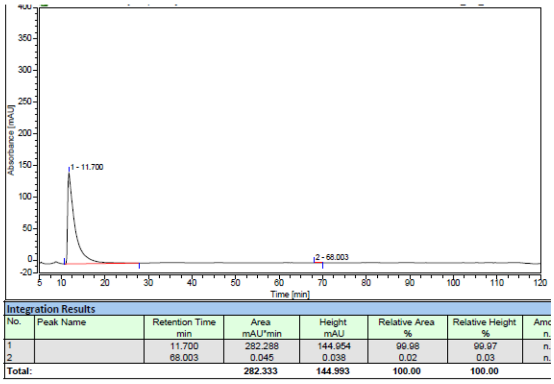
(m, 1H), 3.67-3.60 (m, 1H), 3.33 (s, 1H), 2.94 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.33 (dd, *J* = 157.7, 30.0 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.44 (d, *J* = 4.7 Hz), 147.40, 132.21 (d, *J* = 21.8 Hz), 131.70 (d, *J* = 9.3 Hz), 131.31 (d, *J* = 9.0 Hz), 130.69 (d, *J* = 8.8 Hz), 130.51 (d, *J* = 9.0 Hz), 128.92 (dd, *J* = 11.6, 6.8 Hz), 128.62 (d, *J* = 11.5 Hz), 128.39 (d, *J* = 11.8 Hz), 129.41, 123.57, 115.65, 65.28, 62.55, 51.37, 46.84 (d, *J* = 66.4 Hz), 42.28 (d, *J* = 65.2 Hz). ESI-MS calculated for $C_{36}H_{33}N_2O_6P_2$: m/z (%): 651.1808 (M+H$^+$), found: 651.1812. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 50:50, 0.8 mL/min, 230 nm); major enantiomer tr = 11.7 min, minor enantiomer tr = 68.0 min. $[\alpha]_D^{25}$ = -10.4 (*c* = 0.25, $CHCl_3$).





Integration Results

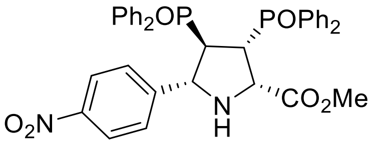
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 11.590 | 198.416 | 97.942 | 50.31 | 81.97 | n |
| 2 | | 69.063 | 195.941 | 21.537 | 49.69 | 18.03 | n |
| Total: | | | 394.357 | 119.479 | 100.00 | 100.00 | |

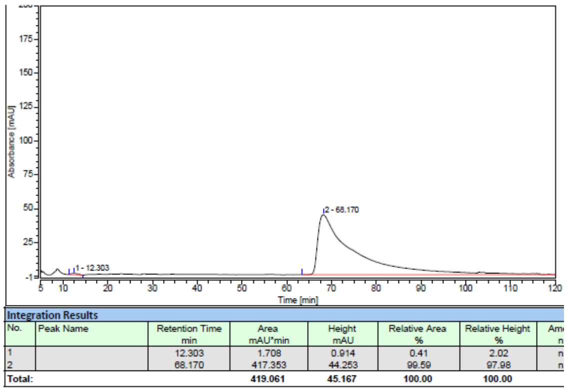


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amc n. |
|---|---|---|---|---|---|---|---|
| 1 | | 11.700 | 282.288 | 144.954 | 99.98 | 99.97 | n. |
| 2 | | 68.003 | 0.045 | 0.038 | 0.02 | 0.03 | n. |
| Total: | | | 282.333 | 144.993 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3h** was obtained as a white solid (59.2 mg, 91% yield) with >20:1 dr and 99% *ee*. mp: 116-117 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35, 0.8 mL/min, 230 nm); major enantiomer tr = 68.2 min, minor enantiomer tr = 12.3 min. $[\alpha]_D^{25}$ = +8.0 (*c* = 0.25, $CHCl_3$).



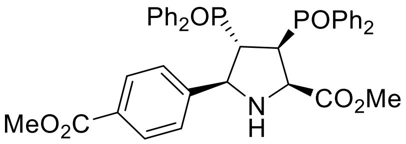


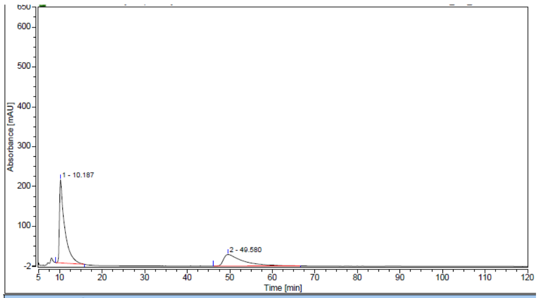
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 12.303 | 1.708 | 0.914 | 0.41 | 2.02 | n |
| 2 | | 68.170 | 417.353 | 44.253 | 99.59 | 97.98 | n |
| Total: | | | 419.061 | 45.167 | 100.00 | 100.00 | |

## 9. Synthesis of (-)-3i and (+)-3i.

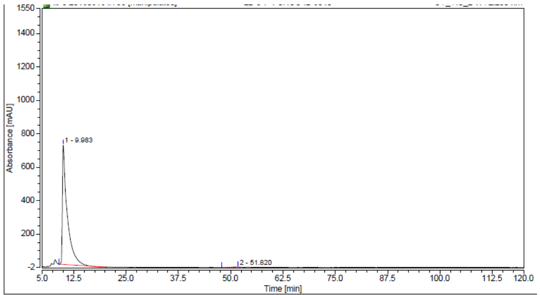
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2i** (47.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3i** as a white solid (61.7 mg, 93% yield) with >20:1 dr and >99% *ee*. mp: 120-121 $^{o}$C. $^{1}$H NMR (500 MHz, $CDCl_3$) δ 7.82 (d, *J* = 8.3 Hz, 2H), 7.77-7.73 (m, 2H), 7.49-7.29 (m, 14H), 7.20-7.12 (m, 6H), 4.48-4.41 (m, 2H), 3.89 (s, 3H), 3.82-3.77 (m, 1H), 3.55-3.49 (m, 1H), 3.35 (s, 1H), 2.90 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.36 (q, *J* = 30.3 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.60 (d, *J* = 4.1 Hz), 166.96, 145.75, 132.06 (d, *J* = 13.8 Hz), 131.53, 131.34 (d, *J* = 8.3 Hz), 130.71 (d, *J* = 8.0 Hz), 130.50 (d, *J* = 8.3 Hz), 129.77, 129.51, 128.84 (t, *J* = 10.6 Hz), 128.43 (dd, *J* = 15.3, 10.1 Hz), 128.40, 115.68, 65.39, 63.42, 52.14, 51.27, 46.93 (d, *J* = 64.5 Hz), 42.27 (d, *J* = 65.6 Hz). ESI-MS calculated for $C_{38}H_{35}NNaO_6P_2$: m/z (%): 686.1832 (M+Na$^{+}$), found: 686.1839. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 45:55, 0.8 mL/min, 230 nm); major enantiomer tr = 10.0 min, minor enantiomer tr = 51.8 min. $[\alpha]_D^{25}$ = -20.4 (*c* = 0.25, $CHCl_3$).





Integration Results

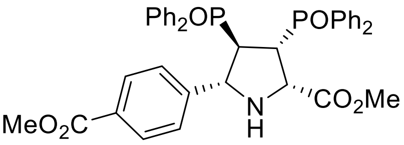
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 10.187 | 293.599 | 208.739 | 66.27 | 87.93 | n |
| 2 | | 49.580 | 149.425 | 28.665 | 33.73 | 12.07 | n |
| Total: | | | 443.024 | 237.404 | 100.00 | 100.00 | |

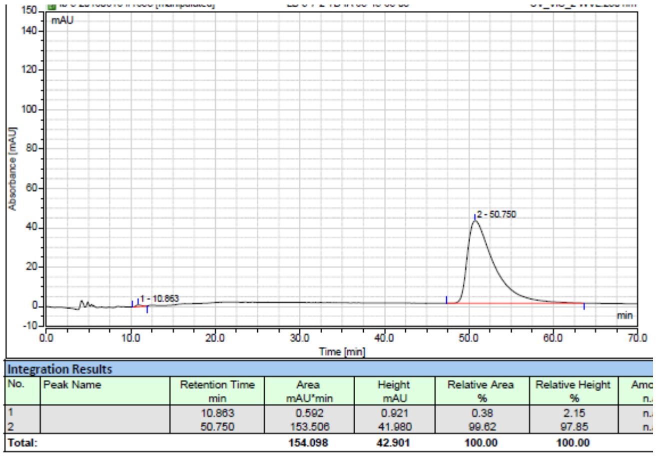


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n. |
|---|---|---|---|---|---|---|---|
| 1 | | 9.983 | 949.421 | 714.816 | 99.83 | 99.89 | n. |
| 2 | | 51.820 | 1.596 | 0.757 | 0.17 | 0.11 | n. |
| Total: | | | 951.016 | 715.573 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3i** was obtained as a white solid (61.0 mg, 92% yield) with >20:1 dr and 98% *ee*. mp: 111-112 $^{o}$C. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 45:55, 0.8 mL/min, 230 nm); major enantiomer tr = 50.8 min, minor enantiomer tr = 10.9 min. $[\alpha]_D^{25}$ = +24.4 (*c* = 0.25, $CHCl_3$).



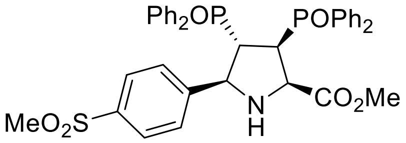


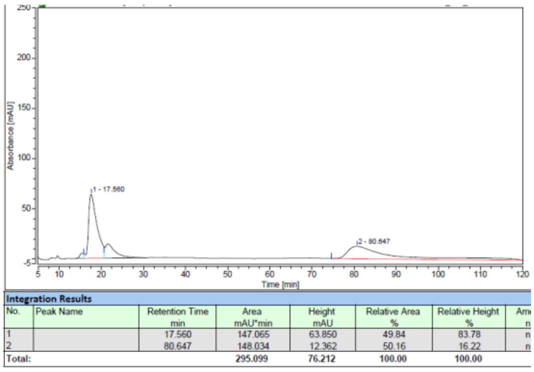
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 10.863 | 0.592 | 0.921 | 0.38 | 2.15 | n. |
| 2 | | 50.750 | 153.506 | 41.980 | 99.62 | 97.85 | n. |
| **Total:** | | | **154.098** | **42.901** | **100.00** | **100.00** | |

## 10. Synthesis of (-)-3j and (+)-3j.

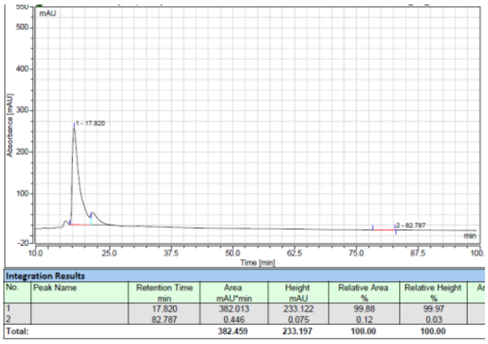
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2j** (51.0 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3j** as a white solid (54.0 mg, 79% yield) with 7:1 dr and >99% *ee*. mp: 101-102 ºC. $^1$H NMR (500 MHz, $CDCl_3$) δ 7.76-7.72 (m, 4H), 7.52 (d, *J* = 8.4 Hz, 2H), 7.49-7.33 (m, 12H), 7.23-7.14 (m, 4H), 4.51-4.44 (m, 2H), 3.79-3.73 (m, 1H), 3.55-3.49 (m, 1H), 3.33 (s, 1H), 3.01 (s, 3H), 2.90 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.98 (dd, *J* = 223.2, 33.7 Hz), 32.31 (dd, *J* = 178.8, 33.7 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 168.47 (d, *J* = 4.6 Hz), 147.12 (d, *J* = 3.1 Hz), 139.77, 132.19 (d, *J* = 21.6 Hz), 131.71, 131.55 (d, *J* = 9.0 Hz), 131.31 (d, *J* = 8.8 Hz), 130.56 (dd, *J* = 16.0, 8.9 Hz), 129.48, 128.94 (dd, *J* = 11.6, 4.4 Hz), 128.58 (d, *J* = 11.4 Hz), 128.40 (d, *J* = 11.6 Hz), 127.52, 65.35, 62.99, 51.30, 46.95 (d, *J* = 65.8 Hz), 44.49, 42.22 (d, *J* = 65.4 Hz). ESI-MS calculated for $C_{37}H_{35}NNaO_6P_2S$: m/z (%): 706.1553 ($M+Na^+$), found: 706.1551. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 45:55, 0.8 mL/min, 230 nm); major enantiomer tr = 18.0 min, minor enantiomer tr = 80.2 min. $[\alpha]_D^{25}$ = -24.4 (*c* = 0.25, $CHCl_3$).





Integration Results

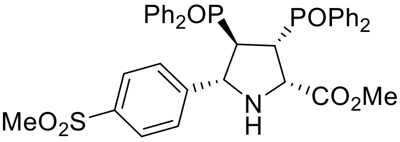
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 17.560 | 147.065 | 63.850 | 49.84 | 83.78 | n |
| 2 | | 80.647 | 148.034 | 12.362 | 50.16 | 16.22 | n |
| Total: | | | 295.099 | 76.212 | 100.00 | 100.00 | |

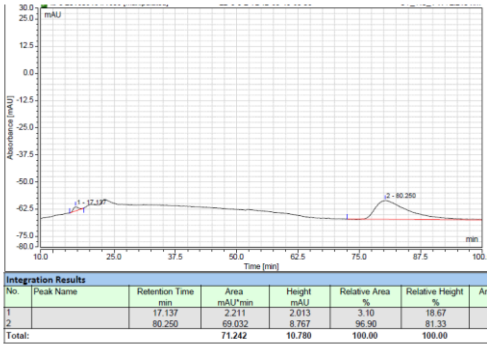


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Ar |
|---|---|---|---|---|---|---|---|
| 1 | | 17.820 | 382.013 | 233.122 | 99.88 | 99.97 | |
| 2 | | 82.787 | 0.446 | 0.075 | 0.12 | 0.03 | |
| Total: | | | 382.459 | 233.197 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3j** was obtained as a white solid (54.6 mg, 80% yield) with 10:1 dr and 94% *ee*. mp: 96-97 ºC. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 45:55, 0.8 mL/min, 230 nm); major enantiomer tr = 80.0 min, minor enantiomer tr = 18.3 min. $[\alpha]_D^{25}$ = +22.8 (*c* = 0.25, $CHCl_3$).



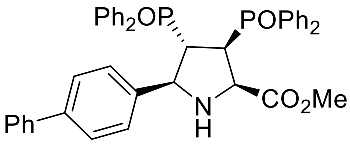


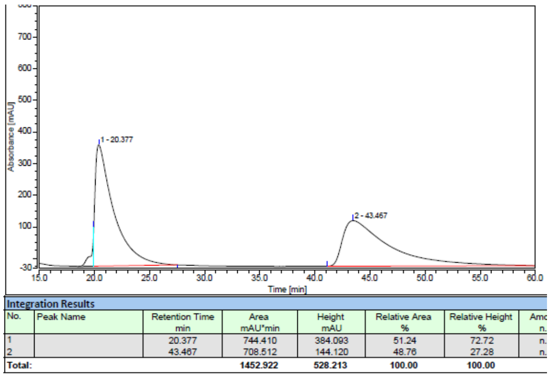
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Ar |
|---|---|---|---|---|---|---|---|
| 1 | | 17.137 | 2.211 | 2.013 | 3.10 | 18.67 | |
| 2 | | 80.250 | 69.032 | 8.767 | 96.90 | 81.33 | |
| Total: | | | 71.242 | 10.780 | 100.00 | 100.00 | |

## 11. Synthesis of (-)-3k and (+)-3k.

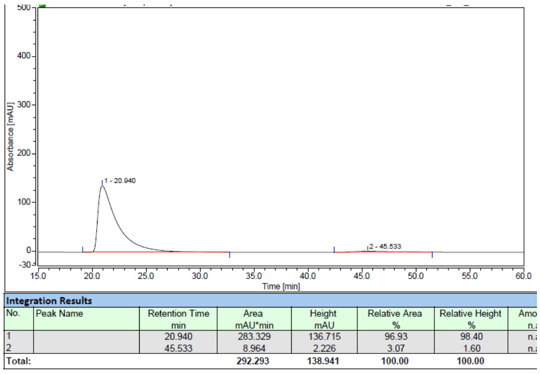
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2k** (50.6 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3k** as a white solid (55.2 mg, 81% yield) with 10:1 dr and 94% *ee*. mp: 95-96 ºC. $^1H$ NMR (500 MHz, $CDCl_3$) δ 7.82-7.78 (m, 1H), 7.57 (d, *J* = 7.5 Hz, 1H), 7.50-7.29 (m, 8H), 7.22-7.15 (m, 3H), 4.74-4.32 (m, 2H), 4.09-3.80 (m, 1H), 3.62 (dd, *J* = 18.8, 5.2 Hz, 1H), 3.36 (s, 1H), 2.92 (s, 3H). $^{31}P$ NMR (202 MHz, $CDCl_3$) δ 33.59 (q, *J* = 30.2 Hz). $^{13}C$ NMR (126 MHz, $CDCl_3$) δ 168.60, 140.71, 140.38, 131.81, 131.48, 131.40, 131.36, 131.34, 130.66 (d, *J* = 8.3 Hz), 130.42 (d, *J* = 8.5 Hz), 128.69, 128.67 (dd, *J* = 14.2, 6.4 Hz), 128.26 (dd, *J* = 11.1, 6.0 Hz), 127.22, 127.06, 126.92, 65.28, 63.51, 51.12, 46.76 (d, *J* = 64.5 Hz), 42.18 (d, *J* = 64.9 Hz). ESI-MS calculated for $C_{42}H_{38}NO_4P_2$: m/z (%): 682.2271 (M+Na$^+$), found: 682.2254. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 20.9 min, minor enantiomer tr = 45.5 min. $[\alpha]_D^{25}$ = -30.0 (*c* = 0.25, $CHCl_3$).





Integration Results

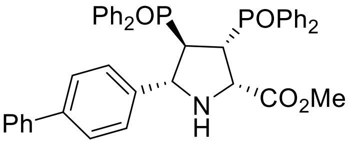
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amc<br>n. |
|---|---|---|---|---|---|---|---|
| 1 |  | 20.377 | 744.410 | 384.093 | 51.24 | 72.72 | n. |
| 2 |  | 43.467 | 708.512 | 144.120 | 48.76 | 27.28 | n. |
| Total: |  |  | 1452.922 | 528.213 | 100.00 | 100.00 |  |

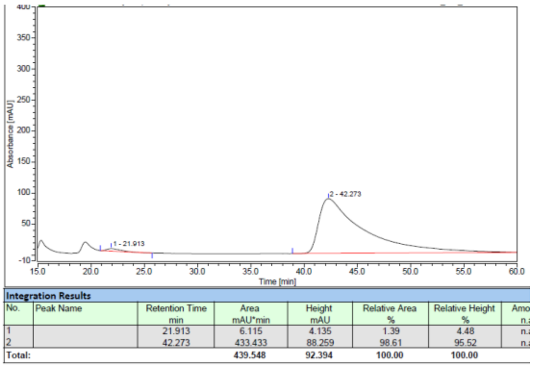


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 |  | 20.940 | 283.329 | 136.715 | 96.93 | 98.40 | n.a |
| 2 |  | 45.533 | 8.964 | 2.226 | 3.07 | 1.60 | n.a |
| Total: |  |  | 292.293 | 138.941 | 100.00 | 100.00 |  |

**Under conditions B:** the product (+)-**3k** was obtained as a white solid (42.2 mg, 62% yield) with 16:1 dr and 97% *ee*. mp: 110-111 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 42.3 min, minor enantiomer tr = 21.9 min. $[\alpha]_D^{25}$ = +32.8 (*c* = 0.25, $CHCl_3$).





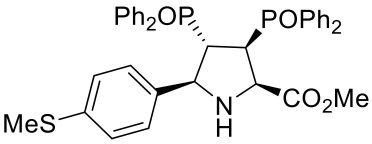
Integration Results

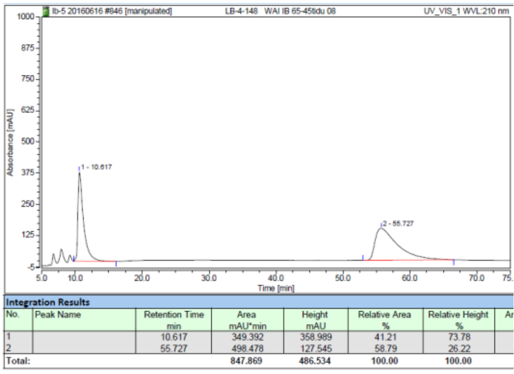
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 |  | 21.913 | 6.115 | 4.135 | 1.39 | 4.48 | n.a |
| 2 |  | 42.273 | 433.433 | 88.259 | 98.61 | 95.52 | n.a |
| Total: |  |  | 439.548 | 92.394 | 100.00 | 100.00 |  |

## 12. Synthesis of (-)-3l and (+)-3l.

**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2l** (44.6 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3l** as a white solid (44.3 mg, 68% yield) with 10:1 dr and >99% *ee*. mp: 95-96 °C. $^1$H NMR (300 MHz, $CDCl_3$) δ 7.82-7.76 (m, 2H), 7.51-7.34 (m, 12H), 7.29-7.19 (m, 8H), 7.09 (d, *J* = 8.0 Hz, 2H), 5.35 (s, 1H), 4.74-4.32 (m, 1H), 3.91 (d, *J* = 16.2 Hz, 1H), 3.49 (m, 1H), 2.93 (s, 3H), 2.47 (s, 3H). $^{31}$P NMR (122 MHz, $CDCl_3$) δ 33.69 (d, *J* = 109.2 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 167.12, 138.94, 132.12, 131.69, 131.33 (d, *J* = 9.1 Hz), 131.20 (d, *J* = 9.0 Hz), 130.43 (dd, *J* = 8.8, 6.2 Hz), 128.93, 128.82, 128.79, 128.48, 128.39, 126.45, 64.21, 62.68, 51.56, 15.56, 45.67

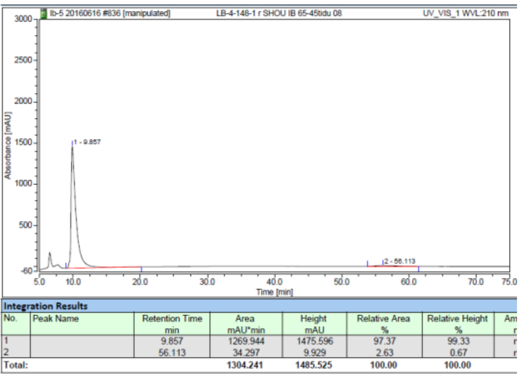
(d, $J = 62.3$ Hz), 40.97 (d, $J = 66.8$ Hz). ESI-MS calculated for $C_{37}H_{36}NO_4P_2S$: m/z (%): 652.1835 ($M+H^+$), found: 652.1818. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:45 to 45:65, 0.8 mL/min, 210 nm); major enantiomer tr = 9.9 min, minor enantiomer tr = 56.1 min. $[\alpha]_D^{25}$ = -77.1 (*c* = 0.25, $CHCl_3$).





Integration Results

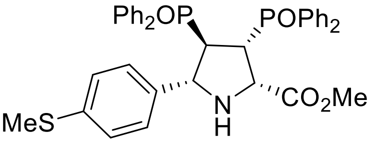
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % |
|---|---|---|---|---|---|---|
| 1 | | 10.617 | 349.392 | 358.989 | 41.21 | 73.78 |
| 2 | | 55.727 | 498.478 | 127.545 | 58.79 | 26.22 |
| Total: | | | 847.869 | 486.534 | 100.00 | 100.00 |

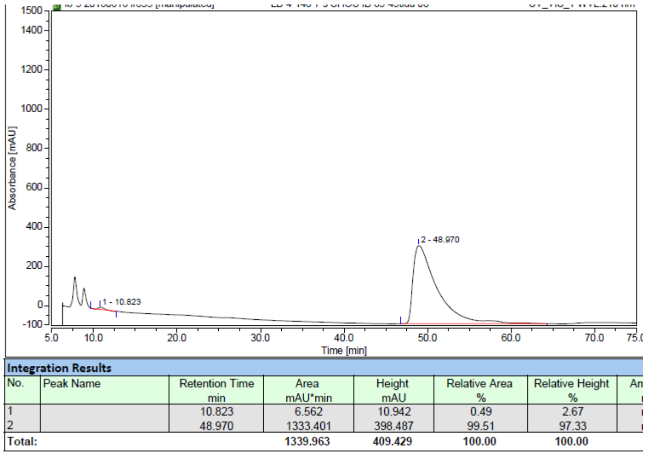


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % |
|---|---|---|---|---|---|---|
| 1 | | 9.857 | 1269.944 | 1475.596 | 97.37 | 99.33 |
| 2 | | 56.113 | 34.297 | 9.929 | 2.63 | 0.67 |
| Total: | | | 1304.241 | 1485.525 | 100.00 | 100.00 |

**Under conditions B:** the product (+)-**3l** was obtained as a white solid (52.7 mg, 81% yield) with 10:1 dr and 99% *ee*. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:45 to 45:65, 0.8 mL/min, 210 nm); major enantiomer tr = 49.0 min, minor enantiomer tr = 10.8 min. $[\alpha]_D^{25}$ = +63.4 (*c* = 0.25, $CHCl_3$).





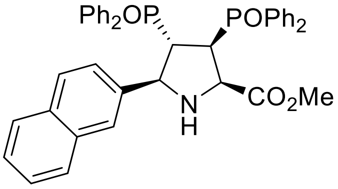
Integration Results

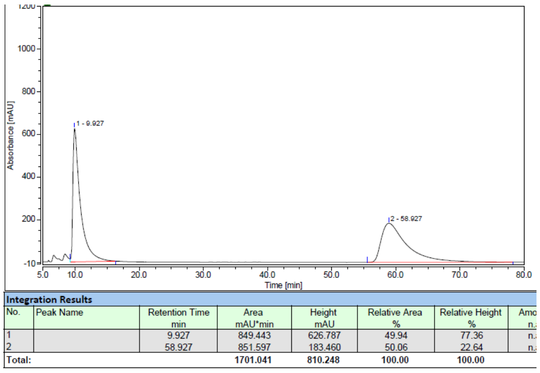
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % |
|---|---|---|---|---|---|---|
| 1 | | 10.823 | 6.562 | 10.942 | 0.49 | 2.67 |
| 2 | | 48.970 | 1333.401 | 398.487 | 99.51 | 97.33 |
| Total: | | | 1339.963 | 409.429 | 100.00 | 100.00 |

## 13. Synthesis of (-)-3m and (+)-3m.

**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2m** (45.4 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3m** as a white solid (49.8 mg, 76% yield) with 6:1 dr and

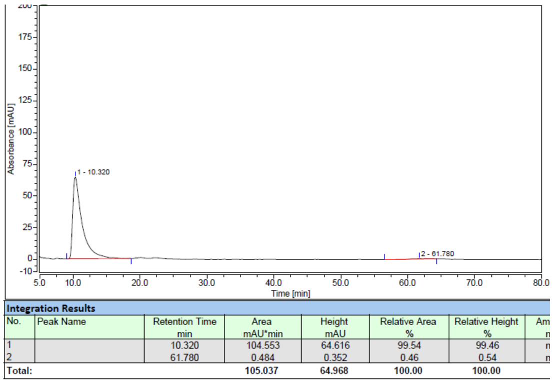
99% *ee*. mp: 133-134 °C. $^{1}$H NMR (500 MHz, CDCl$_3$) δ 7.89-7.79 (m, 5H), 7.57-7.28 (m, 17H), 7.15-7.11 (m, 5H), 4.59-4.50 (m, 2H), 3.91 (d, *J* = 15.7 Hz, 1H), 3.61-3.56 (m, 1H), 3.40 (s, 1H), 2.93 (s, 3H). $^{31}$P NMR (202 MHz, CDCl$_3$) δ 33.63 (q, *J* = 30.4 Hz). $^{13}$C NMR (126 MHz, CDCl$_3$) δ 168.67, 137.67, 132.87 (d, *J* = 4.3 Hz), 131.85, 131.40, 131.37, 130.48 (dd, *J* = 34.7, 8.3 Hz), 128.75, 128.67, 128.58, 128.49, 128.30, 128.21, 128.08, 127.80, 127.38, 125.83, 125.70, 125.32, 65.30, 64.00, 51.09, 46.68 (d, *J* = 58.1 Hz), 42.22 (d, *J* = 65.6 Hz). ESI-MS calculated for $C_{40}H_{35}NNaO_4P_2$: m/z (%): 678.1934 (M+Na$^+$), found: 678.1943. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 10.3 min, minor enantiomer tr = 61.8 min. $[\alpha]_D^{25}$ = -35.6 (*c* = 0.25, CHCl$_3$).





**Integration Results**

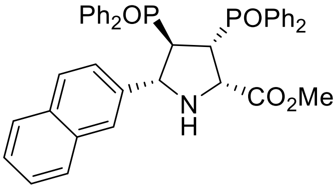
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 |  | 9.927 | 849.443 | 626.787 | 49.94 | 77.36 | n. |
| 2 |  | 58.927 | 851.597 | 183.460 | 50.06 | 22.64 | n. |
| Total: |  |  | **1701.041** | **810.248** | **100.00** | **100.00** |  |

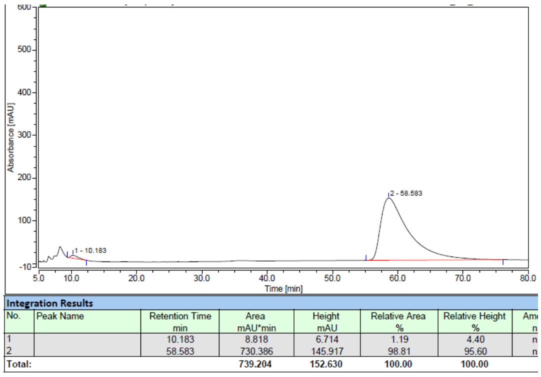


**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 |  | 10.320 | 104.553 | 64.616 | 99.54 | 99.46 | n |
| 2 |  | 61.780 | 0.484 | 0.352 | 0.46 | 0.54 | n |
| Total: |  |  | **105.037** | **64.968** | **100.00** | **100.00** |  |

**Under conditions B:** the product (+)-**3m** was obtained as a white solid (41.3 mg, 63% yield) with 11:1 dr and 98% *ee*. mp: 128-129 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 58.6 min, minor enantiomer tr = 10.2 min. $[\alpha]_D^{25}$ = +31.6 (*c* = 0.25, CHCl$_3$).



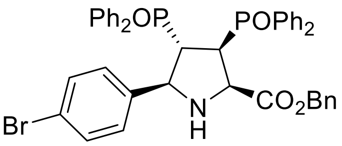


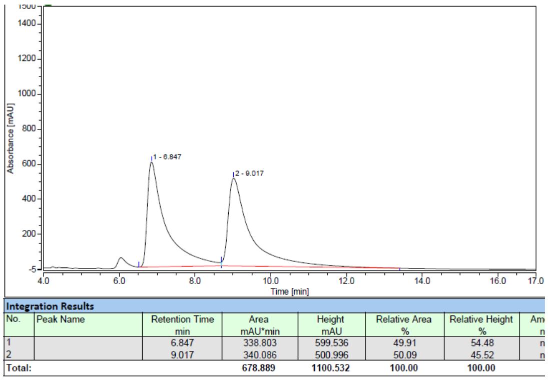
**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 10.183 | 8.818 | 6.714 | 1.19 | 4.40 | n |
| 2 | | 58.583 | 730.386 | 145.917 | 98.81 | 95.60 | n |
| Total: | | | 739.204 | 152.630 | 100.00 | 100.00 | |

## 14. Synthesis of (-)-3n and (+)-3n.

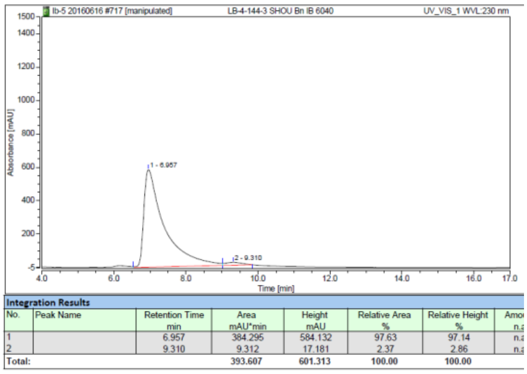
**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2n** (66.2 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3n** as a white solid (67.6 mg, 89% yield) with 15:1 dr and 95% *ee*. mp: 219-220 °C. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.81-7.77 (m, 2H), 7.51-7.38 (m, 10H), 7.33-7.25 (m, 7H), 7.25-7.21 (m, 4H), 7.19-7.11 (m, 6H), 4.53-3.87 (m, 2H), 4.45-4.35 (m, 1H), 3.83-3.77 (m, 1H), 3.68-3.61 (m, 1H). $^{31}$P NMR (162 MHz, CDCl$_3$) δ 33.24 (q, $J$ = 29.7 Hz). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 168.08 (d, $J$ = 4.3 Hz), 139.81 (d, $J$ = 2.7 Hz), 134.81, 131.86, 131.71 (d, $J$ = 8.6 Hz), 131.46, 131.40, 131.25 (d, $J$ = 8.5 Hz), 130.65 (d, $J$ = 8.1 Hz), 130.34 (d, $J$ = 8.3 Hz), 130.08, 128.85-128.46 (m), 128.45-128.17 (m), 128.32, 128.10, 128.04, 121.68, 66.14, 65.24, 62.87, 46.48 (d, $J$ = 64.7 Hz), 42.25 (d, $J$ = 65.9 Hz). ESI-MS calculated for $C_{42}H_{37}BrNO_4P_2$: m/z (%): 760.1376 (M+H$^+$), found: 760.1373. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 7.0 min, minor enantiomer tr = 9.3 min. $[\alpha]_D^{25}$ = -18.4 ($c$ = 0.25, CHCl$_3$).





**Integration Results**

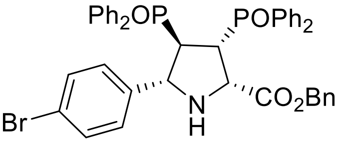
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>n |
|---|---|---|---|---|---|---|---|
| 1 | | 6.847 | 338.803 | 599.536 | 49.91 | 54.48 | n |
| 2 | | 9.017 | 340.086 | 500.996 | 50.09 | 45.52 | n |
| Total: | | | **678.889** | **1100.532** | **100.00** | **100.00** | |

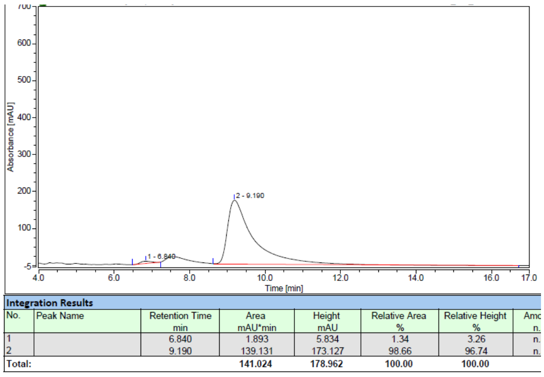


**Integration Results**

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 6.957 | 384.295 | 584.132 | 97.63 | 97.14 | n.a |
| 2 | | 9.310 | 9.312 | 17.181 | 2.37 | 2.86 | n.a |
| Total: | | | **393.607** | **601.313** | **100.00** | **100.00** | |

**Under conditions B:** the product (+)-**3n** was obtained as a white solid (63.0 mg, 83% yield) with 14:1 dr and 97% *ee*. mp: 205-206 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 9.2 min, minor enantiomer tr = 6.8 min. $[\alpha]_D^{25}$ = +18.4 (*c* = 0.25, $CHCl_3$).





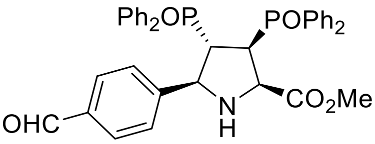
**Integration Results**

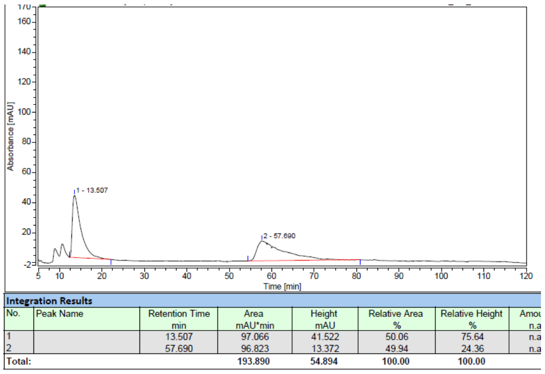
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n. |
|---|---|---|---|---|---|---|---|
| 1 | | 6.840 | 1.893 | 5.834 | 1.34 | 3.26 | n. |
| 2 | | 9.190 | 139.131 | 173.127 | 98.66 | 96.74 | n. |
| Total: | | | **141.024** | **178.962** | **100.00** | **100.00** | |

## 15. Synthesis of (-)-3o and (+)-3o.

**Under conditions A:** The reaction of alkene **1a** (42.8 mg, 0.1 mmol) and glycine imino ester **2o** (55.2 mg, 0.2 mmol), after a flash column chromatography (DCM: MeOH = 10:1) afforded the product (-)-**3o** as a white solid (53.2 mg, 84% yield) with 18:1 dr and 98% *ee*. mp: 95-96 °C. $^1$H NMR (300 MHz, $CDCl_3$) δ 9.96 (s, 1H), 7.75-7.66 (m, 4H), 7.49-7.31 (m, 14H), 7.22-7.16 (m, 6H), 4.51-4.44 (m, 2H), 3.83-3.77 (m, 1H), 3.65-3.56 (m, 1H), 3.33 (t, *J* = 10.5 Hz, 1H), 2.92 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 33.38 (dd, *J* = 93.8, 30.0 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 192.09, 168.53 (d, *J* = 4.6 Hz), 147.57, 135.76, 132.11 (d, *J* = 11.1 Hz), 131.62 (d, *J* = 9.1 Hz), 131.34 (d, *J* = 8.8 Hz), 130.62 (dd, *J* = 26.6, 8.8 Hz), 129.91, 129.09, 128.86 (dd, *J* = 11.4, 8.8 Hz), 128.45 (dd, *J* = 18.6, 11.4 Hz), 119.51, 115.66, 65.38, 63.25, 51.31, 46.83 (d, *J* = 64.9 Hz), 42.31 (d, *J* = 64.7 Hz). ESI-MS calculated for $C_{37}H_{33}NNaO_5P_2$: m/z (%): 656.1726 (M+Na$^+$), found: 656.1733. Enantiomeric excess was determined by HPLC with a

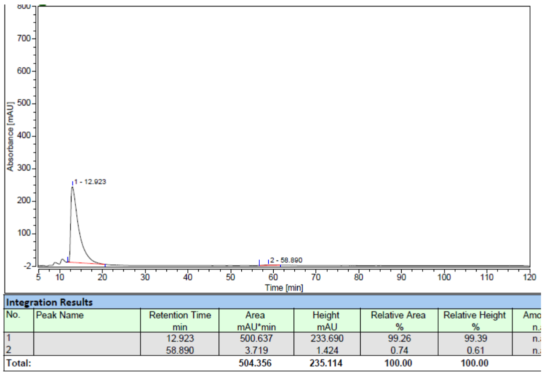
Chiralpak IB column (hexanes: 2-propanol = 65:35 to 50:50, 0.8 mL/min, 230 nm); major enantiomer tr = 12.9 min, minor enantiomer tr = 58.9 min. $[\alpha]_D^{25}$ = -12.4 (*c* = 0.25, $CHCl_3$).





Integration Results

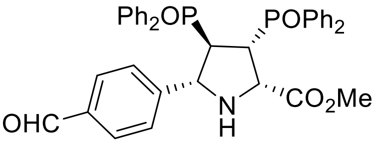
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amou n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 13.507 | 97.066 | 41.522 | 50.06 | 75.64 | n.a |
| 2 | | 57.690 | 96.823 | 13.372 | 49.94 | 24.36 | n.a |
| Total: | | | 193.890 | 54.894 | 100.00 | 100.00 | |

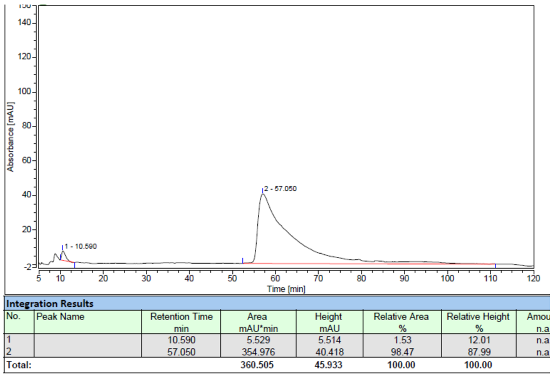


Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 12.923 | 500.637 | 233.690 | 99.26 | 99.39 | n. |
| 2 | | 58.890 | 3.719 | 1.424 | 0.74 | 0.61 | n. |
| Total: | | | 504.356 | 235.114 | 100.00 | 100.00 | |

**Under conditions B:** the product (+)-**3o** was obtained as a white solid (57.6 mg, 91% yield) with 24:1 dr and 97% *ee*. mp: 105-106 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IB column (hexanes: 2-propanol = 65:35 to 50:50, 0.8 mL/min, 230 nm); major enantiomer tr = 57.1 min, minor enantiomer tr = 10.6 min. $[\alpha]_D^{25}$ = +21.6 (*c* = 0.25, $CHCl_3$).



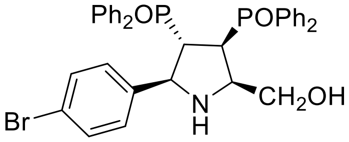


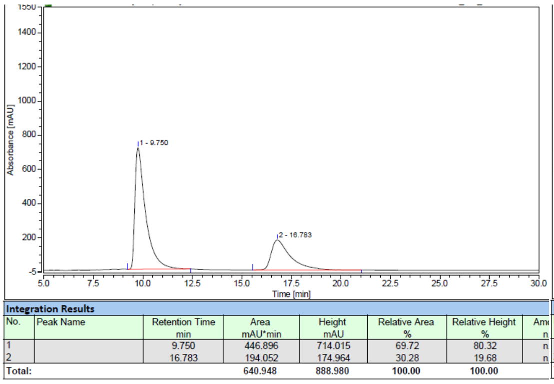
Integration Results

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amou n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 10.590 | 5.529 | 5.514 | 1.53 | 12.01 | n.a |
| 2 | | 57.050 | 354.976 | 40.418 | 98.47 | 87.99 | n.a |
| Total: | | | 360.505 | 45.933 | 100.00 | 100.00 | |

## 16. Synthesis of (-)-4 and (+)-4.

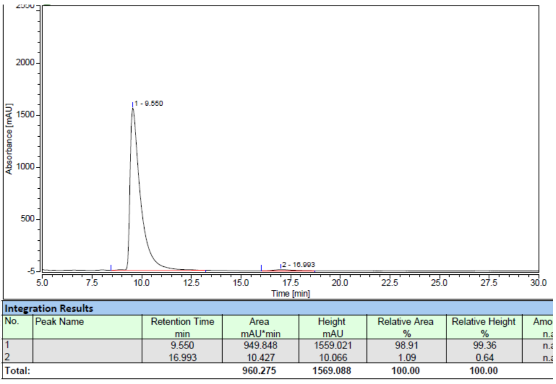
The solution of compound (-)-**3a** (68.3 mg, 0.1 mmol) in THF(2 mL) was stirred at -50 °C in a sealed tube. Subsequently, DIBAL-H ( 0.5 mmol) was added to the above solution. Then the reaction was determined by TLC analysis. After the (-)-**3a** was consumed completely, the reaction mixture was quenched by the addition of $NH_4Cl$ aq. and diluted with EtOAc. The organic layer was separated, and the aqueous layer was extracted twice with EtOAc. The combined organic layers were dried over $Na_2SO_4$, filtered, concentrated. Then the crude product was then purified by flash column chromatography on silica gel (DCM: MeOH = 10:1) afforded the product (-)-**4** as a white solid (44.6 mg, 68% yield) with 98% *ee*. mp: 266-267 °C. $^1$H NMR (400 MHz, $CDCl_3$) δ 7.85-7.80 (m, 2H), 7.56-7.52 (m, 3H), 7.46-7.19 (m, 15H), 7.14-7.09 (m, 4H), 4.35-4.29 (m, 1H), 3.95-3.88 (m, 1H), 3.73-3.65 (m, 2H), 3.48-3.43 (m, 2H), 3.24-3.13 (m, 1H). $^{31}$P NMR (162 MHz, $CDCl_3$) δ 35.57 (d, $J$ = 29.8 Hz), 33.28 (d, $J$ = 29.8 Hz). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 140.35, 131.81, 131.41 (d, $J$ = 20.2 Hz), 130.50 (d, $J$ = 8.7 Hz), 130.35-130.08 (m), 129.69, 128.93, 128.81, 128.78-128.58 (m), 128.32 (d, $J$ = 11.6 Hz), 125.15, 121.50, 67.44, 64.12, 61.58, 48.35 (d, $J$ = 65.0 Hz), 41.73 (d, $J$ = 66.5 Hz). ESI-MS calculated for $C_{37}H_{33}NNaO_5P_2$: m/z (%): 656.1726 (M+Na$^+$), found: 656.1733. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 9.6 min, minor enantiomer tr = 17.0 min. $[\alpha]_D^{25}$ = -52.8 ($c$ = 0.25, $CHCl_3$).





Integration Results

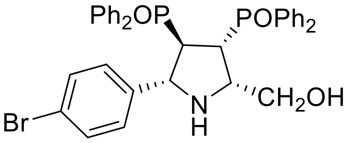
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>n. |
|---|---|---|---|---|---|---|---|
| 1 | | 9.750 | 446.896 | 714.015 | 69.72 | 80.32 | n. |
| 2 | | 16.783 | 194.052 | 174.964 | 30.28 | 19.68 | n. |
| Total: | | | 640.948 | 888.980 | 100.00 | 100.00 | |

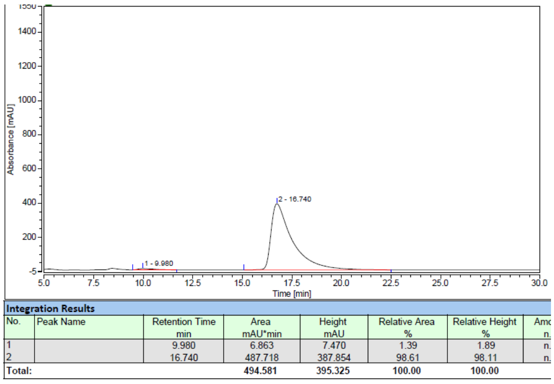


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 | | 9.550 | 949.848 | 1559.021 | 98.91 | 99.36 | n.a |
| 2 | | 16.993 | 10.427 | 10.066 | 1.09 | 0.64 | n.a |
| Total: | | | 960.275 | 1569.088 | 100.00 | 100.00 | |

The product (+)-**4** was obtained as a white solid (49.9 mg, 76% yield) with 97% *ee*. mp: 245-246 °C. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 16.7 min, minor enantiomer tr = 10.0 min. $[\alpha]_D^{25}$ = +48.8 ($c$ = 0.25, $CHCl_3$).



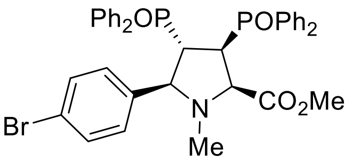


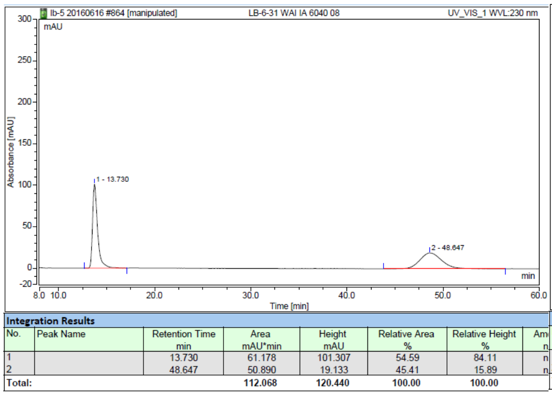
**Integration Results**

| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 |  | 9.980 | 6.863 | 7.470 | 1.39 | 1.89 | n. |
| 2 |  | 16.740 | 487.718 | 387.854 | 98.61 | 98.11 | n. |
| Total: |  |  | **494.581** | **395.325** | **100.00** | **100.00** |  |

## 17. Synthesis of (-)-5 and (+)-5.

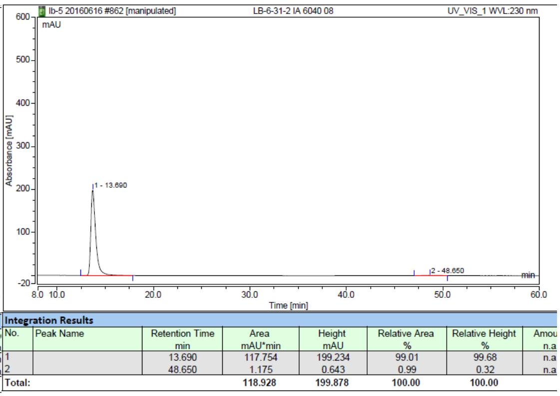
The solution of compound (-)-**3a** (68.3 mg, 0.1 mmol) and $K_2CO_3$ (6.0 eq) in DMF (2 mL) was stirred at rt in a sealed tube. Subsequently, MeI ( 2.0 eq) was added to the above solution. Then the reaction was determined by TLC analysis. After the (-)-**3a** was consumed completely, the reaction mixture was quenched by the addition of NaCl aq. and the aqueous layer was extracted three or more times with EtOAc. The combined organic layers were dried over $Na_2SO_4$, filtered, concentrated. Then the crude product was then purified by flash column chromatography on silica gel (DCM: MeOH = 10:1) afforded the product (-)-**5** as a white solid (66.9 mg, 96% yield) with 98% *ee*. mp: 65-66 °C. $^1$H NMR (400 MHz, $CDCl_3$) δ 7.66-7.61 (m, 2H), 7.48-7.39 (m, 7H), 7.35-7.26 (m, 5H), 7.21-7.13 (m, 6H), 7.04-6.97 (m, 4H), 3.88-3.77 (m, 2H), 3.69-3.62 (m, 1H), 3.54-3.47 (m, 1H), 2.90 (s, 3H), 2.13 (s, 3H). $^{31}$P NMR (162 MHz, $CDCl_3$) δ 34.52 (dd, $J$ = 416.8, 34.6 Hz), 30.27 (dd, $J$ = 673.2, 34.7 Hz). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 168.54 (d, $J$ = 5.0 Hz), 140.02 (d, $J$ = 3.1 Hz), 132.76 (d, $J$ = 9.7 Hz), 131.88, 131.60, 131.43, 131.32 (d, $J$ = 3.2 Hz), 131.22, 130.94, 130.80 (d, $J$ = 8.9 Hz), 128.46 (dd, $J$ = 17.0, 5.7 Hz), 128.00 (d, $J$ = 11.9 Hz), 121.54, 77.30 (d, $J$ = 3.1 Hz), 70.07, 69.66, 51.02 (d, $J$ = 3.1 Hz), 42.35 (dd, $J$ = 148.2, 66.0 Hz), 38.83 (d, $J$ = 3.6 Hz). ESI-MS calculated for $C_{37}H_{34}BrNNaO_4P_2$: m/z (%): 720.1039 (M+Na$^+$), found: 720.1031. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 13.7 min, minor enantiomer tr = 48.7 min. $[\alpha]_D^{25}$ = -14.9 ($c$ = 0.25, $CHCl_3$).





Integration Results

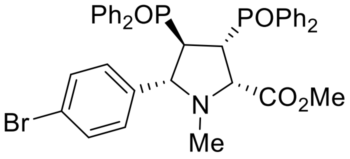
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>n |
|---|---|---|---|---|---|---|---|
| 1 |  | 13.730 | 61.178 | 101.307 | 54.59 | 84.11 | n |
| 2 |  | 48.647 | 50.890 | 19.133 | 45.41 | 15.89 | n |
| Total: |  |  | 112.068 | 120.440 | 100.00 | 100.00 |  |

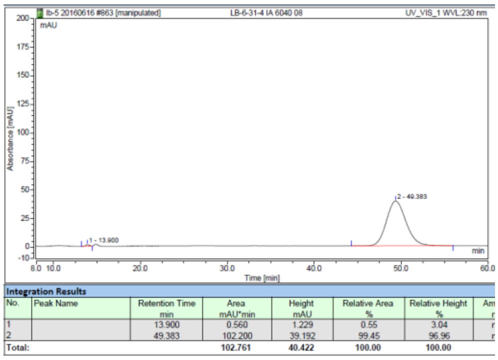


Integration Results

| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amou<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 |  | 13.690 | 117.754 | 199.234 | 99.01 | 99.68 | n.a |
| 2 |  | 48.650 | 1.175 | 0.643 | 0.99 | 0.32 | n.a |
| Total: |  |  | 118.928 | 199.878 | 100.00 | 100.00 |  |

The product (+)-**5** was obtained as a white solid (64.8 mg, 93% yield) with 99% *ee*. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 49.4 min, minor enantiomer tr = 13.9 min. $[\alpha]_D^{25}$ = +15.6 (*c* = 0.25, $CHCl_3$).





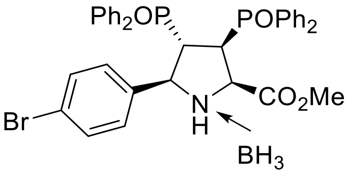
Integration Results

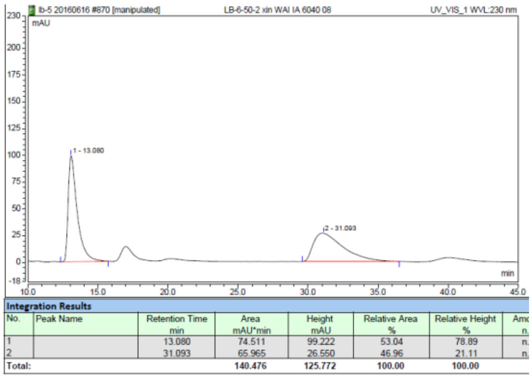
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am |
|---|---|---|---|---|---|---|---|
| 1 |  | 13.900 | 0.560 | 1.229 | 0.55 | 3.04 |  |
| 2 |  | 49.383 | 102.200 | 39.192 | 99.45 | 96.96 |  |
| Total: |  |  | 102.761 | 40.422 | 100.00 | 100.00 |  |

## 18. Synthesis of (-)-6 and (+)-6.

The solution of compound (-)-**3a** (68.3 mg, 0.1 mmol) in PhMe (2 mL) was stirred at 0 °C in a sealed tube. Subsequently, $BH_3$·THF (0.5 mmol) was added to the above solution. Then the reaction was determined by TLC analysis. After the (-)-**3a** was consumed completely, the reaction mixture was quenched by the addition of NaCl aq. and the aqueous layer was extracted twice with EtOAc. The combined organic layers were dried over $Na_2SO_4$, filtered, concentrated. Then the crude product was then purified by flash column chromatography on silica gel (DCM: MeOH = 10:1) afforded the product (-)-**6** as a white solid (68.3 mg, 98% yield) with 94% *ee*.$^1$H NMR (400 MHz, $CDCl_3$) δ 7.78-7.74 (m, 2H), 7.54-7.30 (m, 16H), 7.26-7.10 (m, 6H), 5.87 (t, *J* = 10.0

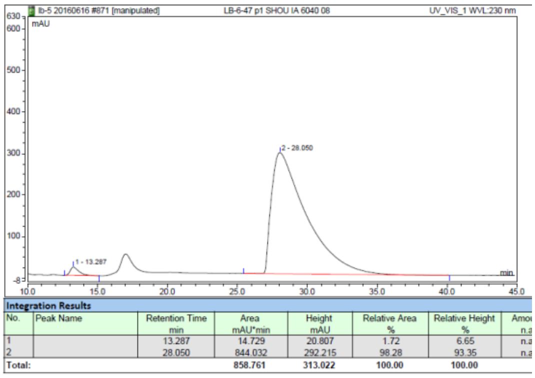
Hz, 1H), 4.53-4.41 (m, 1H), 4.32-4.23 (m, 1H), 3.91-3.82 (m, 1H), 3.44-3.38 (m, 1H), 2.91 (s, 3H). $^{31}$P NMR (162 MHz, $CDCl_3$) δ 33.06 (dd, *J* = 349.2, 27.7 Hz). $^{13}$C NMR (101 MHz, $CDCl_3$) δ 164.84 (d, *J* = 4.6 Hz), 135.25 (d, *J* = 3.2 Hz), 132.48 (d, *J* = 9.4 Hz), 132.04 (s), 131.83, 131.46 (d, *J* = 9.1 Hz), 130.81, 130.52 (d, *J* = 7.7 Hz), 130.27 (s), 129.04 (t, *J* = 9.9 Hz), 128.83 (d, *J* = 2.9 Hz), 128.71 (d, *J* = 2.9 Hz), 123.19, 77.20, 69.71 (d, *J* = 17.0 Hz), 51.70, 44.73 (d, *J* = 64.7 Hz), 38.74 (d, *J* = 65.7 Hz). ESI-MS calculated for $C_{36}H_{35}BBrNNaO_4P_2$: m/z (%): 720.1210 (M+Na$^+$), found: 720.1207. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 60:40, 0.8 mL/min, 230 nm); major enantiomer tr = 28.1 min, minor enantiomer tr = 13.3 min. $[\alpha]_D^{25}$ = -32.2 (*c* = 0.25, $CHCl_3$).





Integration Results

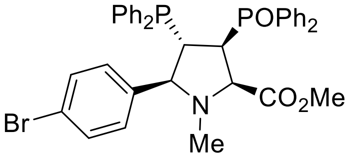
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amc<br>n. |
|---|---|---|---|---|---|---|---|
| 1 |  | 13.080 | 74.511 | 99.222 | 53.04 | 78.89 | n. |
| 2 |  | 31.093 | 65.965 | 26.550 | 46.96 | 21.11 | n. |
| Total: |  |  | 140.476 | 125.772 | 100.00 | 100.00 |  |



Integration Results

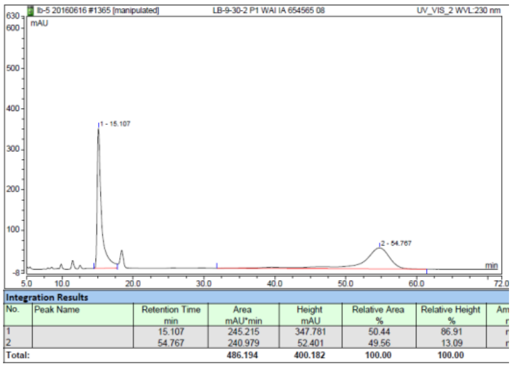
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n.a |
|---|---|---|---|---|---|---|---|
| 1 |  | 13.287 | 14.729 | 20.807 | 1.72 | 6.65 | n.a |
| 2 |  | 28.050 | 844.032 | 292.215 | 98.28 | 93.35 | n.a |
| Total: |  |  | 858.761 | 313.022 | 100.00 | 100.00 |  |

**19.** Synthesis of methyl (2*S*,3*S*,4*S*,5*S*)-5-(4-bromophenyl)-4-(diphenylphosphanyl)-3-(diphenylphosphoryl)-1-methylpyrrolidine-2-carboxylate (**7**).



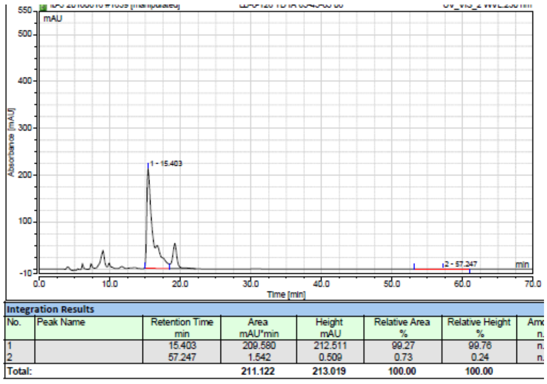
**7**

The reaction of (-)-**4a** (0.29 mmol, 200 mg) in THF (5.3 ml) was stirred at rt. Subsequently, $(Me_2HSi)_2O$ (0.33 ml, 6.0 equiv) and $Ti(O^iPr)_4$ (0.37 ml, 4.6 equiv) were added to the above solution. The solution was reacted at 65 °C for 12 h. Then the reaction was determined by TLC analysis. After the substrate was consumed completely, the reaction mixture was then purified by flash column chromatography on silica gel (PE: EA = 4:1 to 1:1) afforded the product **7** as white sollid (138 mg, 70% yield) with 97% *ee*. Mp = 88-89 ºC. $^1$H NMR (500 MHz, $CDCl_3$) δ 7.78-7.74 (m, 2H), 7.50-7.38 (m, 5H), 7.33-7.24 (m, 7H), 7.22-7.15 (m, 5H), 7.14-7.06 (m, 5H), 3.77 (m, 1H), 3.46-3.34 (m, 1H), 3.27 (m, 1H), 3.17 (m, 1H), 2.95 (s, 3H), 2.15 (s, 3H). $^{31}$P NMR (202 MHz, $CDCl_3$) δ 30.29 (d, *J* = 24.9 Hz), -1.04 (d, *J* = 24.8 Hz). $^{13}$C NMR (126 MHz, $CDCl_3$) δ 169.30 (d, *J* = 5.0 Hz),140.67 (d, *J* = 5.5 Hz), 135.07 (d, *J* = 21.2 Hz), 133.56 (d, *J* = 20.2 Hz), 131.84 (d, *J* = 8.8 Hz), 131.27 (d, *J* = 8.7 Hz), 130.97 (d, *J* = 10.0 Hz), 129.84, 128.95, 128.33 (dd, *J* = 6.6, 3.5 Hz), 128.14 (d, *J* = 11.5 Hz), 128.42, 121.16, 74.90 (d, *J* = 20.8 Hz), 69.09 (d, *J* = 2.1 Hz), 51.09, 44.37 (dd, *J* = 66.8, 20.5 Hz), 41.35 (d, *J* = 16.0 Hz), 39.38. ESI-MS calculated for $C_{37}H_{34}BrNNaO_3P_2$: m/z (%): 704.1090 ($M+Na^+$), found: 704.1082. Enantiomeric excess was determined by HPLC with a Chiralpak IA column (hexanes: 2-propanol = 65:35-45:55-65:35, 0.8 mL/min, 230 nm); major enantiomer tr = 15.1 min, minor enantiomer tr = 57.2 min. $[\alpha]_D^{25}$ = -74.7 (*c* = 0.25, $CHCl_3$).



Integration Results

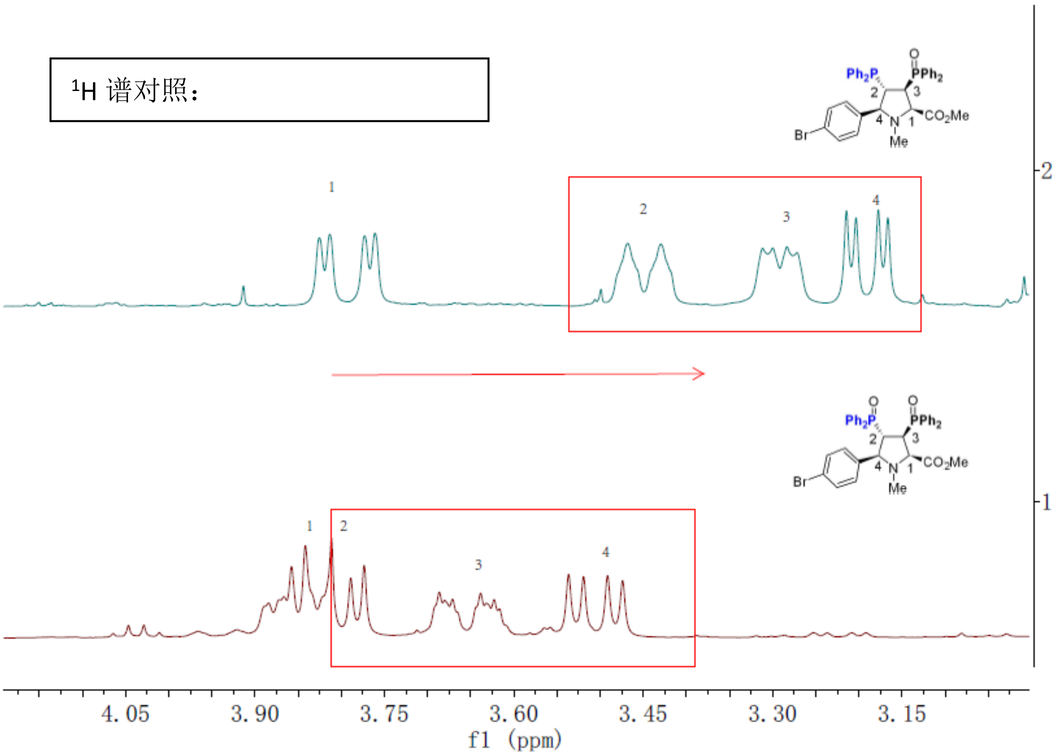
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Am<br>r |
|---|---|---|---|---|---|---|---|
| 1 | | 15.107 | 245.215 | 347.781 | 50.44 | 86.91 | r |
| 2 | | 54.767 | 240.979 | 52.401 | 49.56 | 13.09 | r |
| Total: | | | 486.194 | 400.182 | 100.00 | 100.00 | |



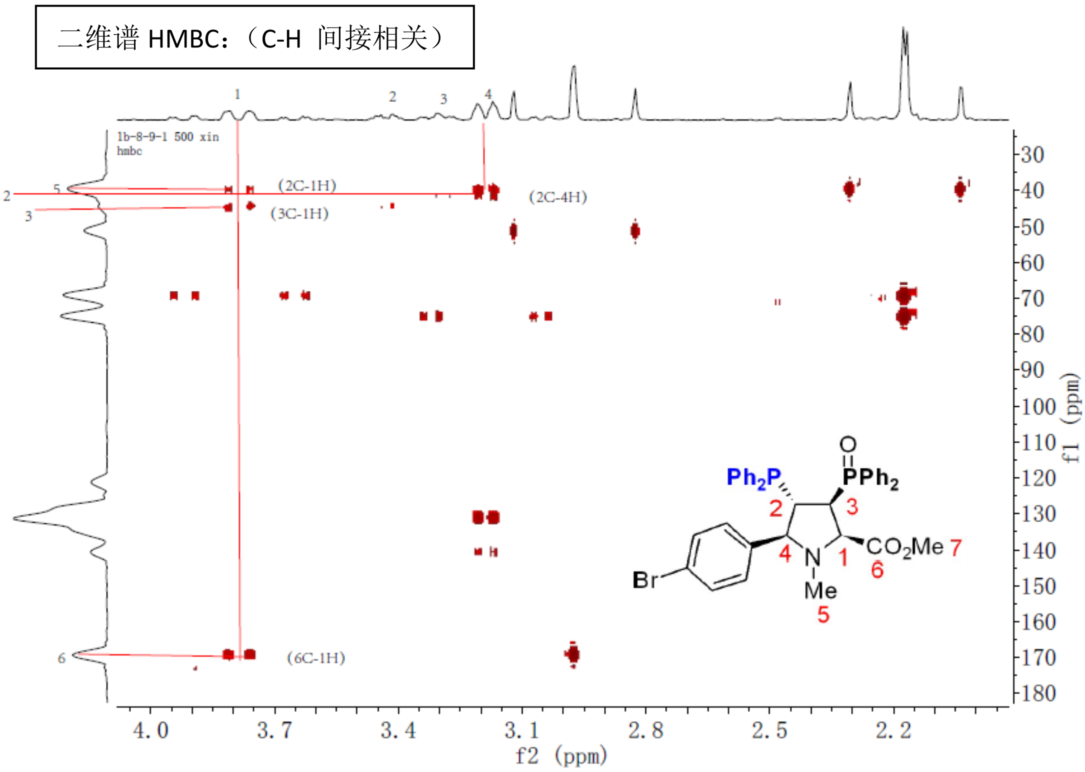
Integration Results

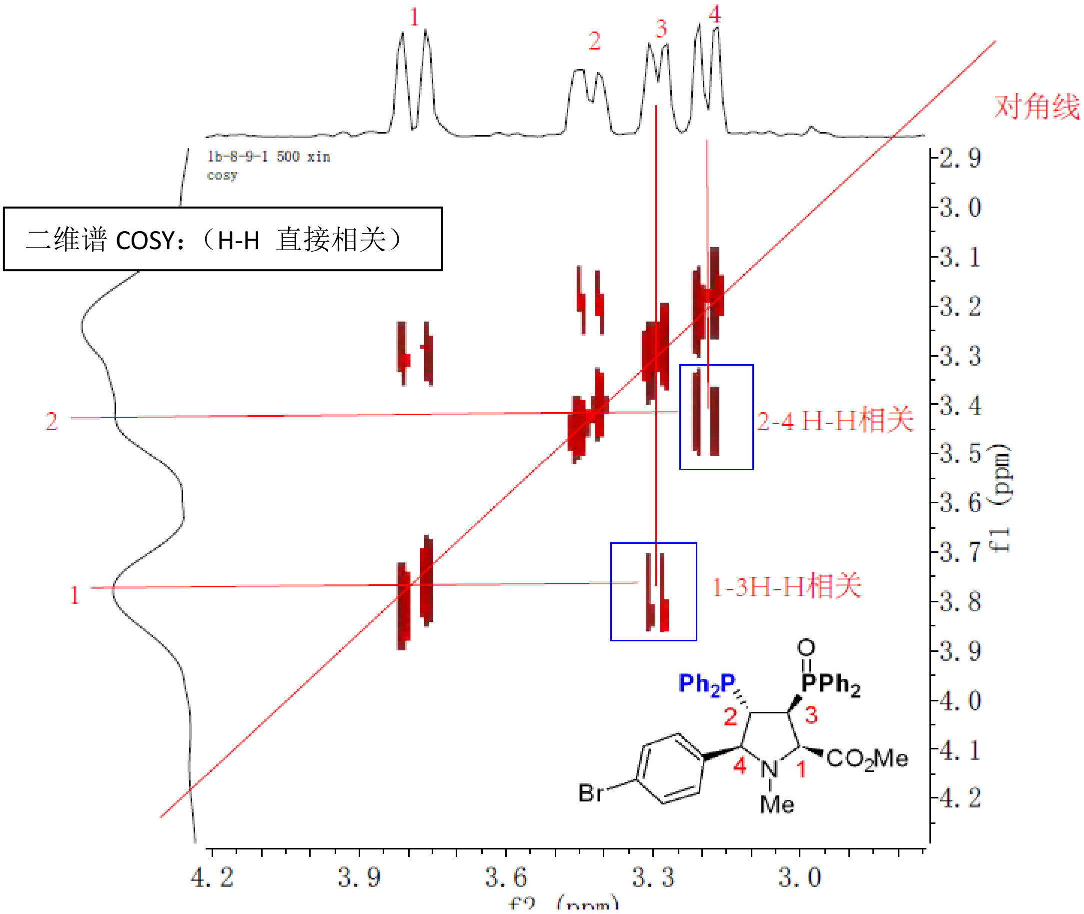
| No. | Peak Name | Retention Time<br>min | Area<br>mAU*min | Height<br>mAU | Relative Area<br>% | Relative Height<br>% | Amo<br>n. |
|---|---|---|---|---|---|---|---|
| 1 | | 15.403 | 209.580 | 212.511 | 99.27 | 99.76 | n. |
| 2 | | 57.247 | 1.542 | 0.509 | 0.73 | 0.24 | n. |
| Total: | | | 211.122 | 213.019 | 100.00 | 100.00 | |

### $^1$H 谱对照：



### 二维谱 HMBC：（C-H 间接相关）





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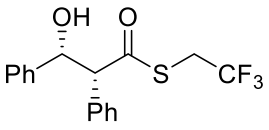
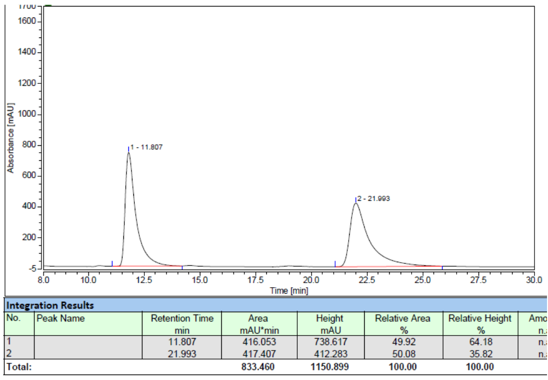
**20.** Synthesis of *S*-(2,2,2-trifluoroethyl) (2*R*,3*R*)-3-hydroxy-2,3-diphenylpropanethioate (**10**).



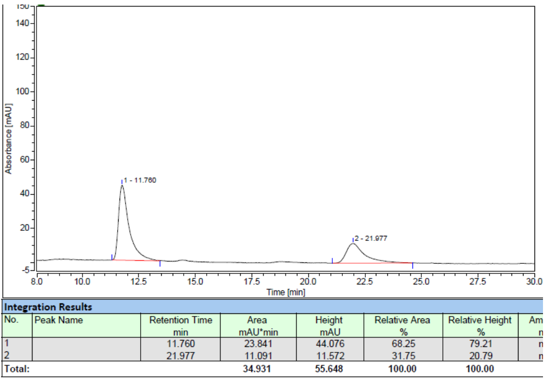
**10**

The reaction of ligand (–)-**3a** (10 mol%, 19.5 mg) and DIPEA (10.0 eq.) in $^{i}$PrCN (2 ml) was stirred at 0 $^{o}$C. Subsequently, (2,2,2-trifluoroethyl)-S-2-phenylethanethioate (140.4 mg, 0.6 mmol) and $SiCl_4$ (1.5 eq.) were added to the above solution. After 15 min, PhCHO (0.3 mmol) was added to the above solution. Stirred for overnight, $SiCl_4$ (1.5 eq.) was added to the above solution. Then the reaction was determined by TLC analysis. After the substrate was consumed completely, the reaction mixture was quenched by the addition of $NaHCO_3$ aq. and diluted with EtOAc. The organic layer was separated, and the aqueous layer was extracted twice with EtOAc. The combined organic layers were dried over $Na_2SO_4$, filtered, concentrated. Then the crude product was then purified by flash column chromatography on silica gel (PE: EA = 10:1) afforded the product **10** as liquid (66.3 mg, 65% yield) with 91:9 dr and 36% *ee*. $^1$H NMR (400 MHz, $CDCl_3$) δ 7.36-7.32 (m, 5H), 7.29-7.25 (m, 5H), 5.34 (d, $J = 7.6$ Hz, 1H), 4.06 (d, $J = 7.6$ Hz, 1H), 3.44-3.34 (m, 2H), 2.34 (s, 1H). $^{19}$F NMR (282 MHz, $CDCl_3$) δ -66.36. $^{13}$C NMR (101 MHz, $CDCl_3$) δ 195.38, 140.26, 133.59, 129.38, 128.84, 128.46, 128.34, 128.19, 126.61, 124.37 ($J_{C\text{-}F} = 277.1$ Hz), 74.95, 68.15, 30.63 (q, $J = 34.3$ Hz). ESI-MS calculated for $C_{17}H_{15}F_3NaO_2S$: m/z (%): 363.0637 (M+Na$^+$), found: 363.0637. Enantiomeric excess was determined by HPLC with a Chiralpak AD-H column (hexanes: 2-propanol = 90:10, 0.8 mL/min, 230 nm); major enantiomer tr = 11.8 min, minor enantiomer tr = 22.0 min. $[\alpha]_D^{25} = +2.8$ ($c$ = 0.25, $CHCl_3$).



Integration Results

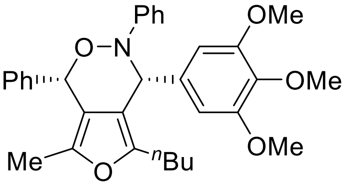
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Amo n. |
|---|---|---|---|---|---|---|---|
| 1 | | 11.807 | 416.053 | 738.617 | 49.92 | 64.18 | n. |
| 2 | | 21.993 | 417.407 | 412.283 | 50.08 | 35.82 | n. |
| Total: | | | 833.460 | 1150.899 | 100.00 | 100.00 | |



Integration Results

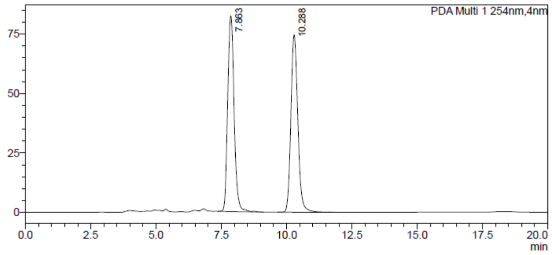
| No. | Peak Name | Retention Time min | Area mAU*min | Height mAU | Relative Area % | Relative Height % | Am n |
|---|---|---|---|---|---|---|---|
| 1 | | 11.760 | 23.841 | 44.076 | 68.25 | 79.21 | n |
| 2 | | 21.977 | 11.091 | 11.572 | 31.75 | 20.79 | n |
| Total: | | | 34.931 | 55.648 | 100.00 | 100.00 | |

## **21.** Synthesis of (1*S*,4*R*)-5-butyl-7-methyl-1,3-diphenyl-4-(3,4,5-trimethoxyphenyl)-3,4-dihydro-1*H*-furo[3,4-d][1,2]oxazine (**13**).



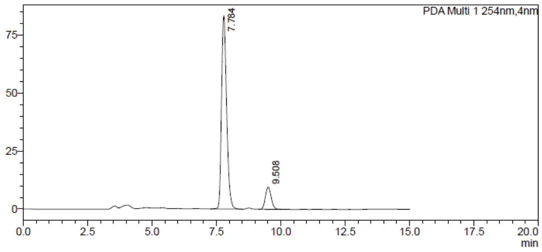
**13**

The reaction of AuCl($Me_2S$) (5 mol%) and ligand (-)-**3a** (5.5 mol%) in DCM (2 ml) was stirred at rt. After stirred for 1h, $AgSbF_6$ (5 mol%) was added above solution and continue stirred for 10 min in -50 $^{o}$C. Subsequently, 2-(1-alkynl)-alk-2-en-1-one **11** (0.1 mol) and nitrone **12** (2.0 equiv) were added to the above solution. After 48 h, then the reaction was determined by TLC analysis. After the substrate was consumed completely, the crude product was then purified by flash column chromatography on silica gel (PE: EA = 10:1) afforded the product **13** as liquid (37.4 mg, 73% yield) with >20:1 dr and 77% *ee*. Mp = 38-39 °C. $^1$H NMR (300 MHz, CDCl$_3$) δ 7.56-7.53 (m, 2H), 7.41-7.39 (m, 3H), 7.24-7.19 (m, 2H), 7.06 (d, *J* = 7.6 Hz, 2H), 6.92 (t, *J* = 7.3 Hz, 1H), 6.49 (s, 2H), 5.97 (d, *J* = 0.8 Hz, 1H), 5.63 (s, 1H), 3.79 (s, 3H), 3.69 (s, 6H), 2.50-2.45 (m, 2H), 1.82 (s, 3H), 1.53-1.45 (m, 2H), 1.32-1.22 (m, 2H), 0.84 (t, *J* = 7.3 Hz, 3H). $^{13}$C NMR (126 MHz, CDCl$_3$) δ 152.21, 148.45, 148.07, 143.26, 137.80, 137.17, 134.52, 129.14, 128.90, 128.39, 128.36, 122.12, 117.83, 116.85, 116.79, 106.45, 78.57, 62.50, 60.61, 55.82, 29.91, 26.24, 22.19, 13.62, 12.38. ESI-MS calculated for $C_{32}H_{35}NNaO_5$: m/z (%): 536.2407 (M+Na$^+$), found: 536.2410. Enantiomeric excess was determined by HPLC with a Chiralpak AD-H column (hexanes: 2-propanol = 90:10, 0.8 mL/min, 254 nm); major enantiomer tr = 7.8 min, minor enantiomer tr = 9.5 min. $[\alpha]_D^{25}$ = +88.6 (*c* = 0.25, CHCl$_3$).



**ak Table>** PDA Ch1 254nm

| Peak# | Ret. Time | Area | Height | Height% | Area% |
|---|---|---|---|---|---|
| 1 | 7.863 | 1407661 | 82278 | 52.446 | 50.508 |
| 2 | 10.288 | 1379346 | 74602 | 47.554 | 49.492 |
| Total |  | 2787007 | 156880 | 100.000 | 100.000 |



**ak Table>** PDA Ch1 254nm

| Peak# | Ret. Time | Area | Height | Height% | Area% |
|---|---|---|---|---|---|
| 1 | 7.784 | 1146924 | 83337 | 89.693 | 88.392 |
| 2 | 9.508 | 150626 | 9576 | 10.307 | 11.608 |
| Total |  | 1297549 | 92913 | 100.000 | 100.000 |

## 5. References

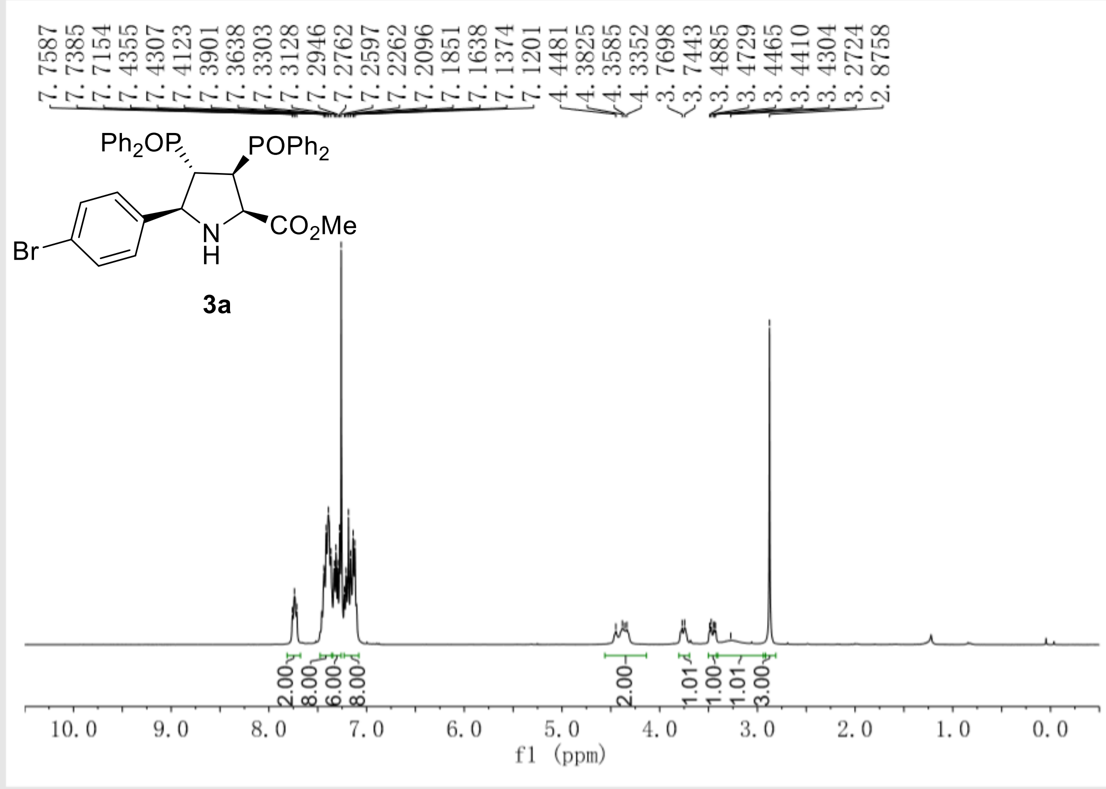
(1) (a) A. Z. González, D. Benitez, E. Tkatchouk, W. A. Goddard and F. D. Toste, *J. Am. Chem. Soc.*2011, **133**, 5500-5507. (b) I. Alonso, B. Trillo, F. López, S. Montserrat, G. Ujaque, L. Castedo, A. Lledós and J. L. Mascareñas, *J. Am. Chem. Soc.* 2009, **131**, 13020-13030. (c) A. Z. González and F. D. Toste, *Org. Lett.* 2010, **12**, 200-203.

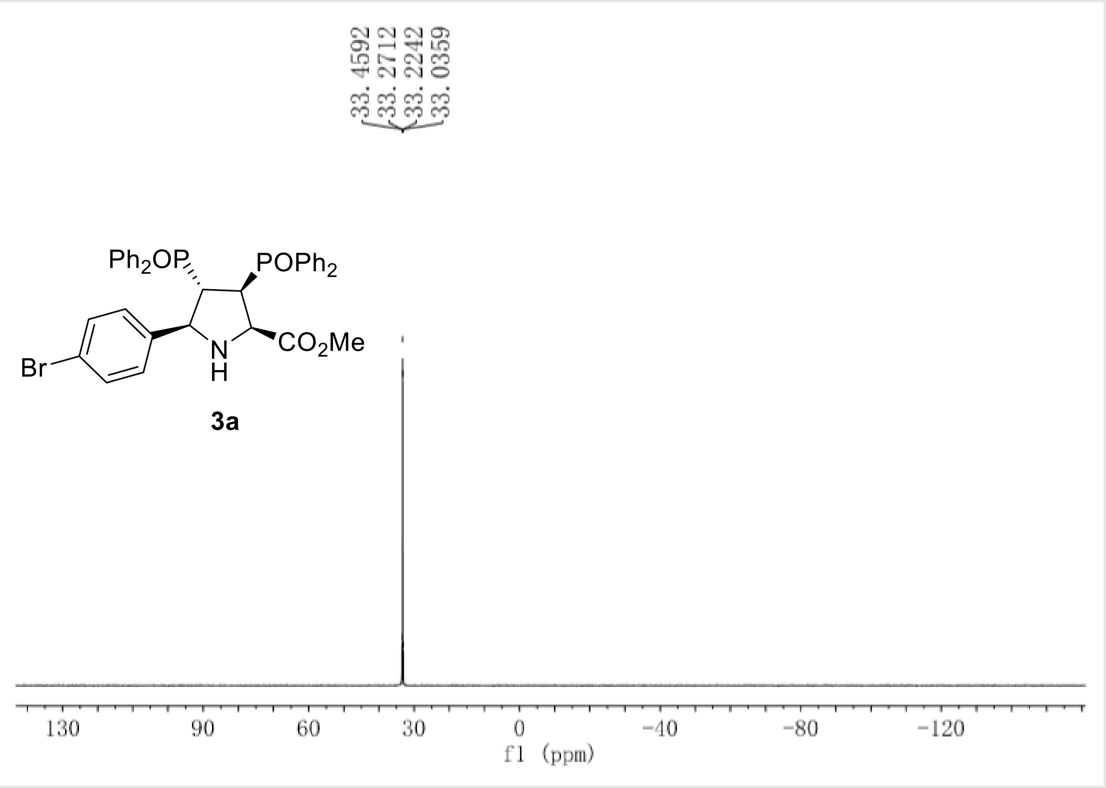
(2) M. Narsireddy and Y. Yamamoto, *J. Org. Chem.* 2008, **73**, 9698-9709.

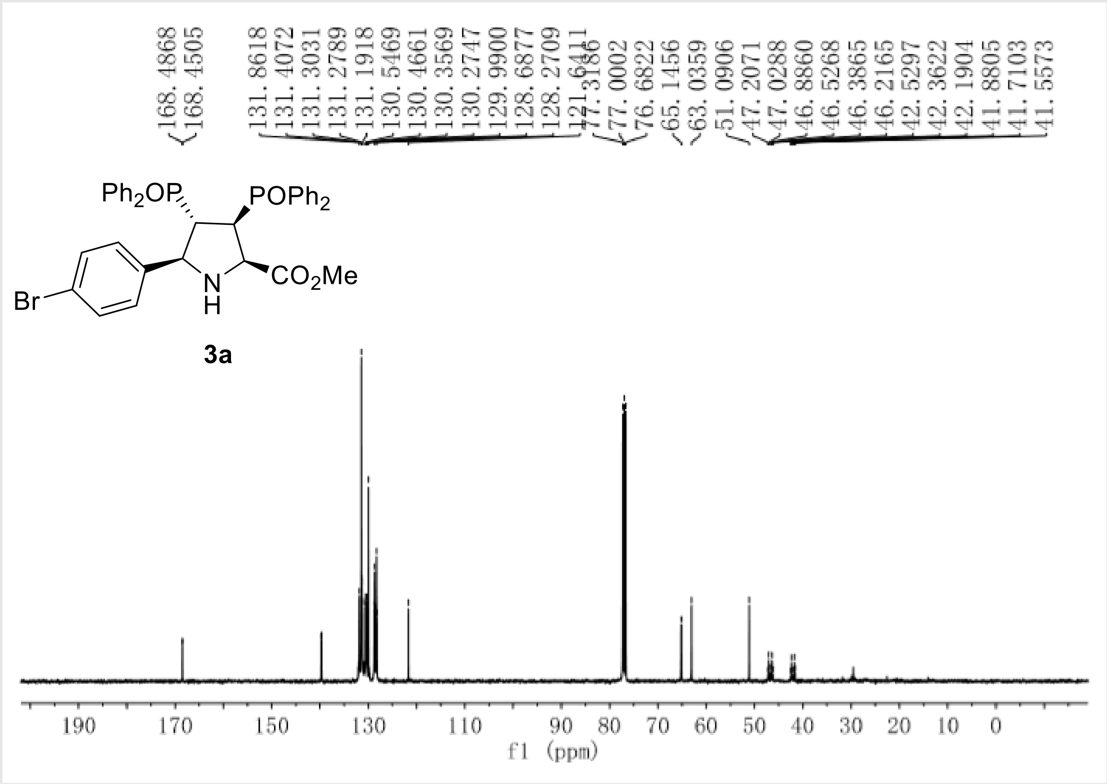
(3) (a) S. Cabrera, R. G. Arrayás, J. C. Carretero, *J. Am. Chem. Soc*, 2005, **127**, 16394. (b) C. Nájera, M. de Gracia Retamosa, J. M. Sansano, *Org. Lett.* 2007, **9**, 4025. (c) A. López-Pérez, J. Adrio, J. C. Carretero, *J. Am. Chem. Soc*, 2008, **130**, 10084.

## 6. $^{1}$H, $^{31}$P, $^{13}$C NMR and HPLC Spectra

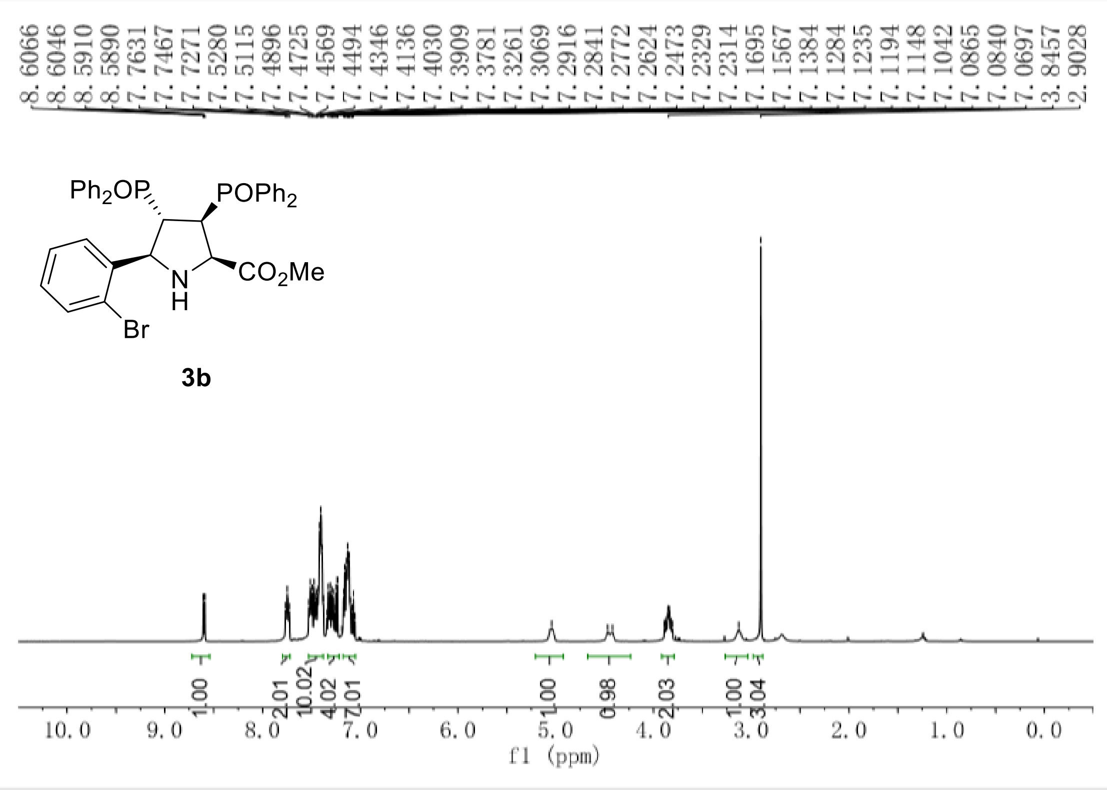
**$^{1}$H NMR** (400 MHz, $CDCl_3$), **$^{31}$P NMR** (162 MHz, $CDCl_3$) and **$^{13}$C NMR** (101 MHz, $CDCl_3$) of **3a**

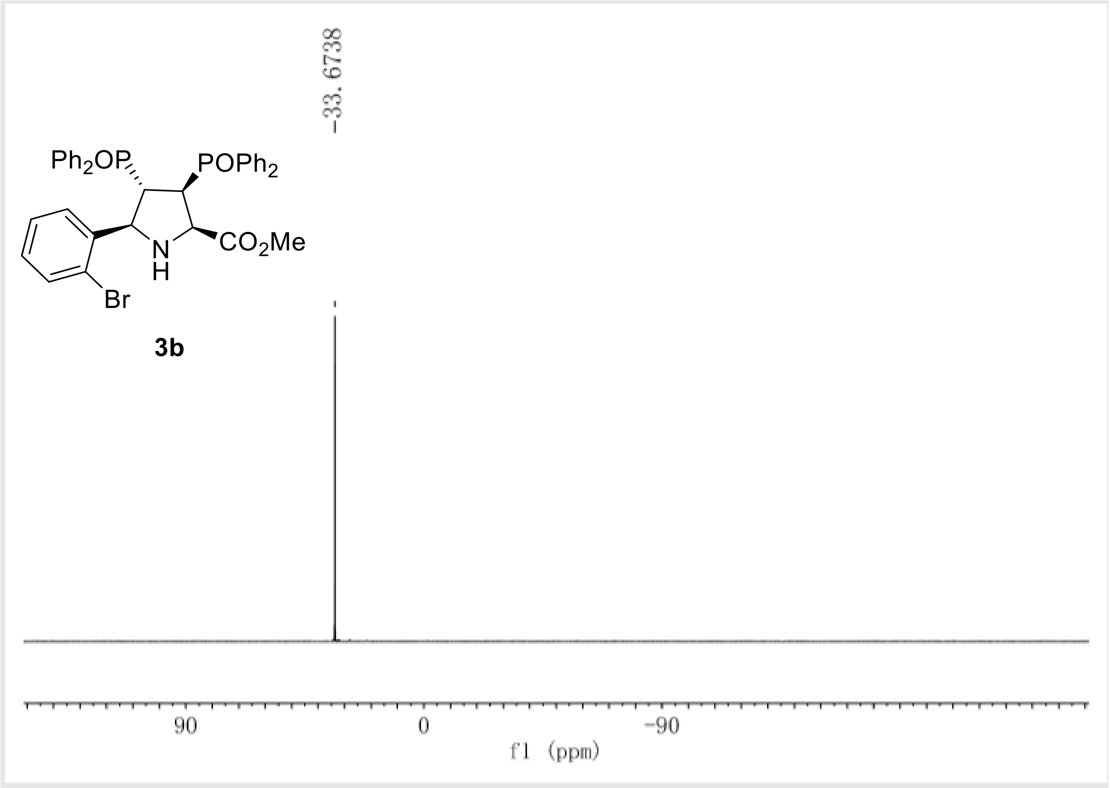


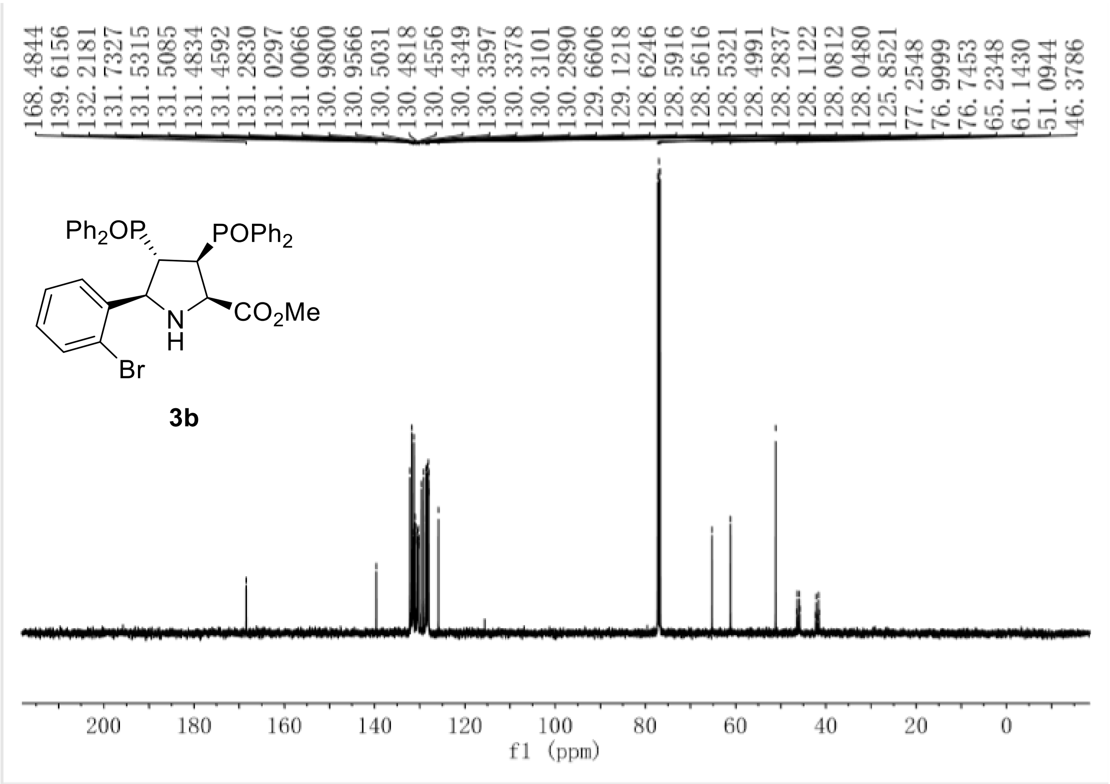




**$^{1}$H NMR** (500 MHz, CDCl$_3$), **$^{31}$P NMR** (202 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **3b**




-33.6738
Ph2OP
POPh2
N
H
CO2Me
Br
3b
90
0
-90
f1 (ppm)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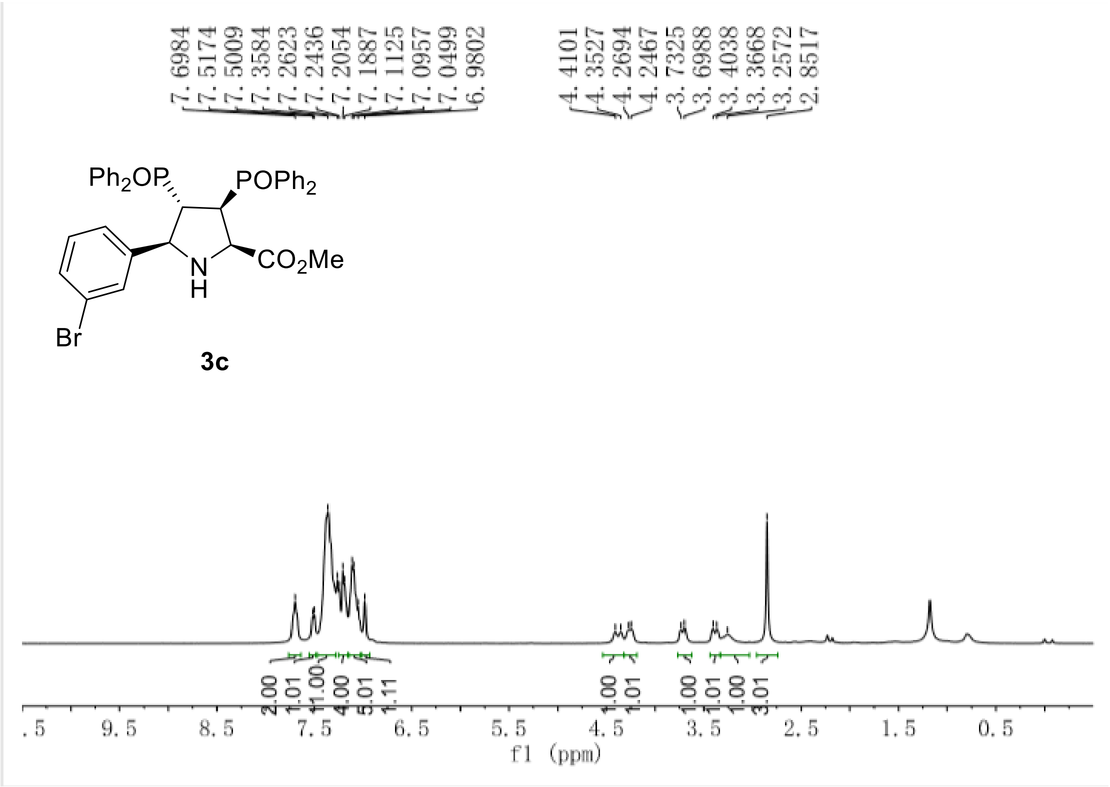
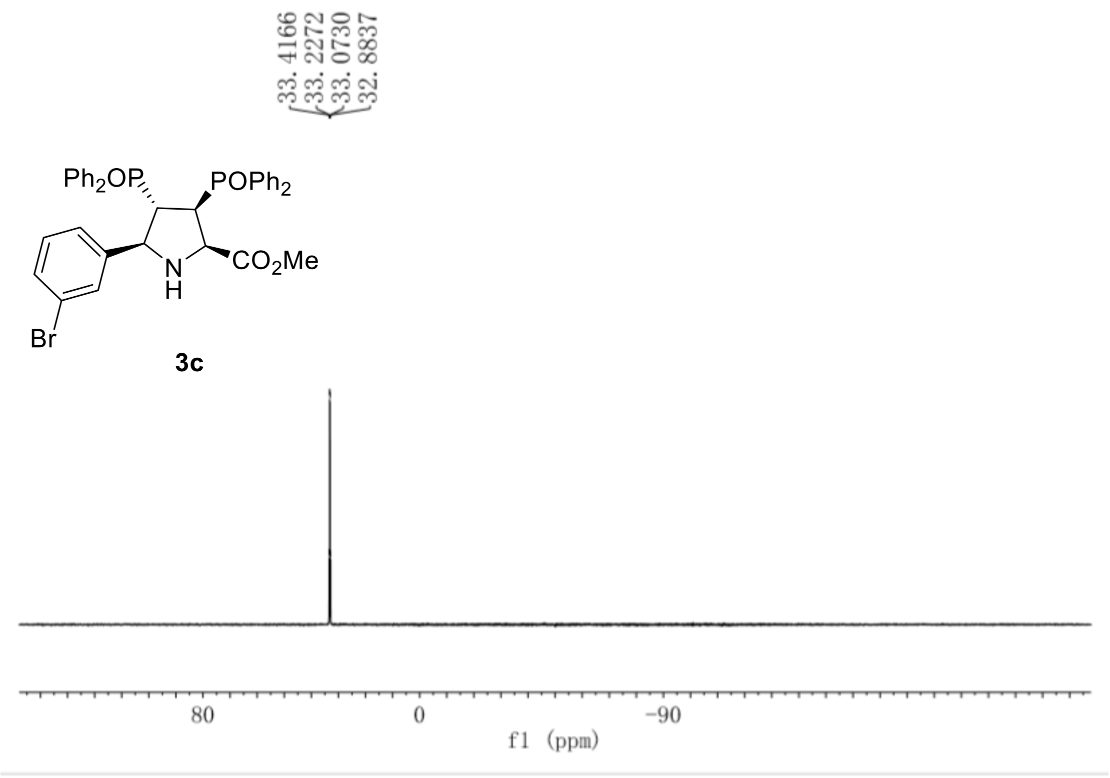
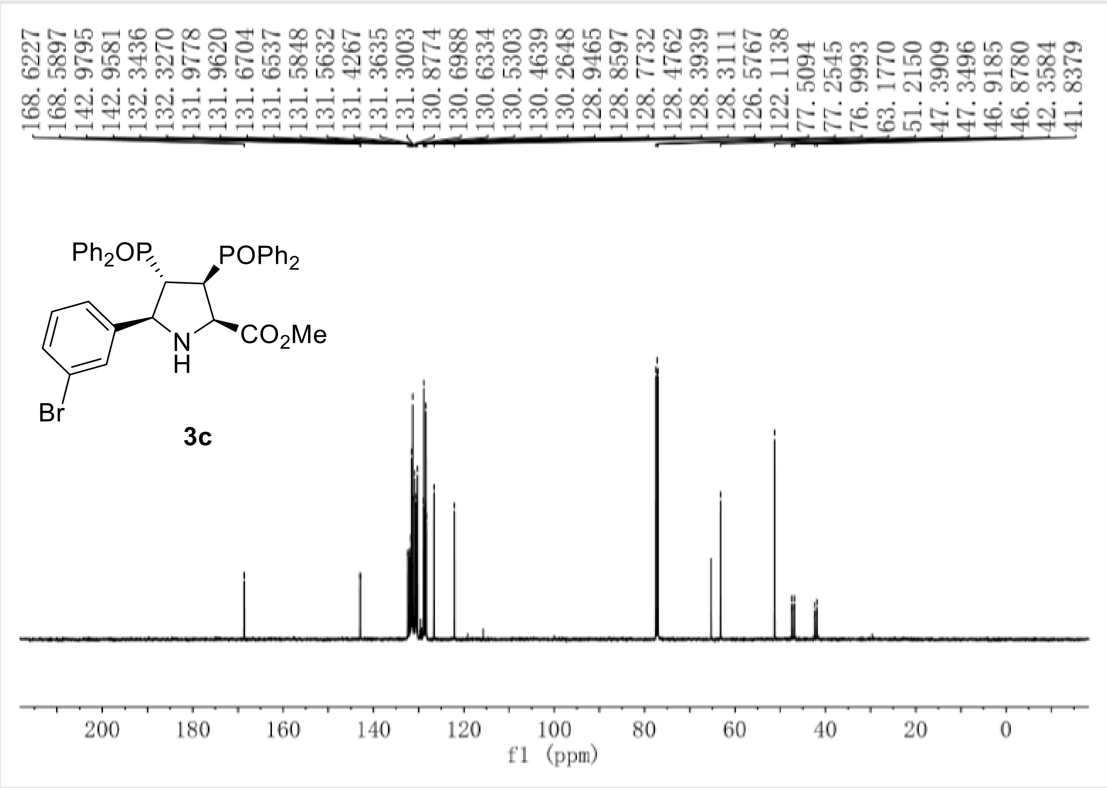
139.6156
132.2181
131.7327
131.5315
131.5085
131.4834
131.4592
131.2830
131.0297
131.0066
130.9800
130.9566
130.5031
130.4818
130.4556
130.4349
130.3597
130.3378
130.3101
130.2890
129.6606
129.1218
128.6246
128.5916
128.5616
128.5321
128.4991
128.2837
128.1122
128.0812
128.0480
125.8521
77.2548
76.9999
76.7453
65.2348
61.1430
51.0944
46.3786
Ph2OP
POPh2
N
H
CO2Me
Br
3b
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

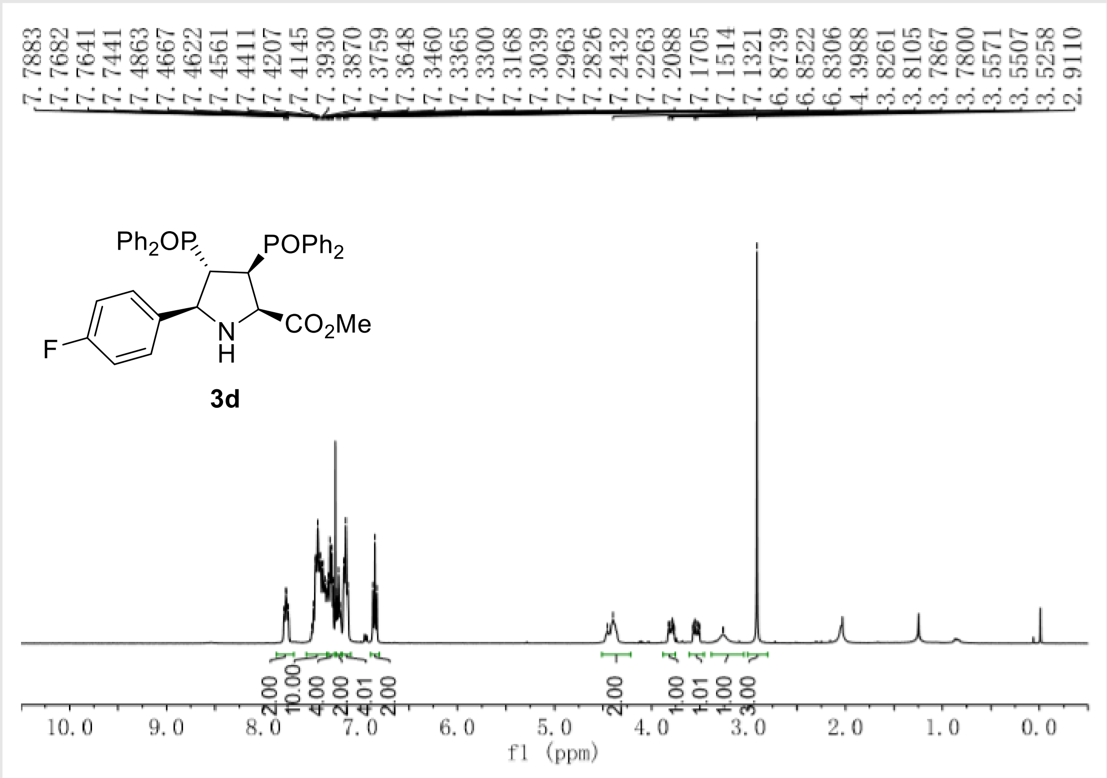
**$^1$H NMR** (400 MHz, $CDCl_3$), **$^{31}$P NMR** (162 MHz, $CDCl_3$) and **$^{13}$C NMR** (126 MHz, $CDCl_3$) of **3c**

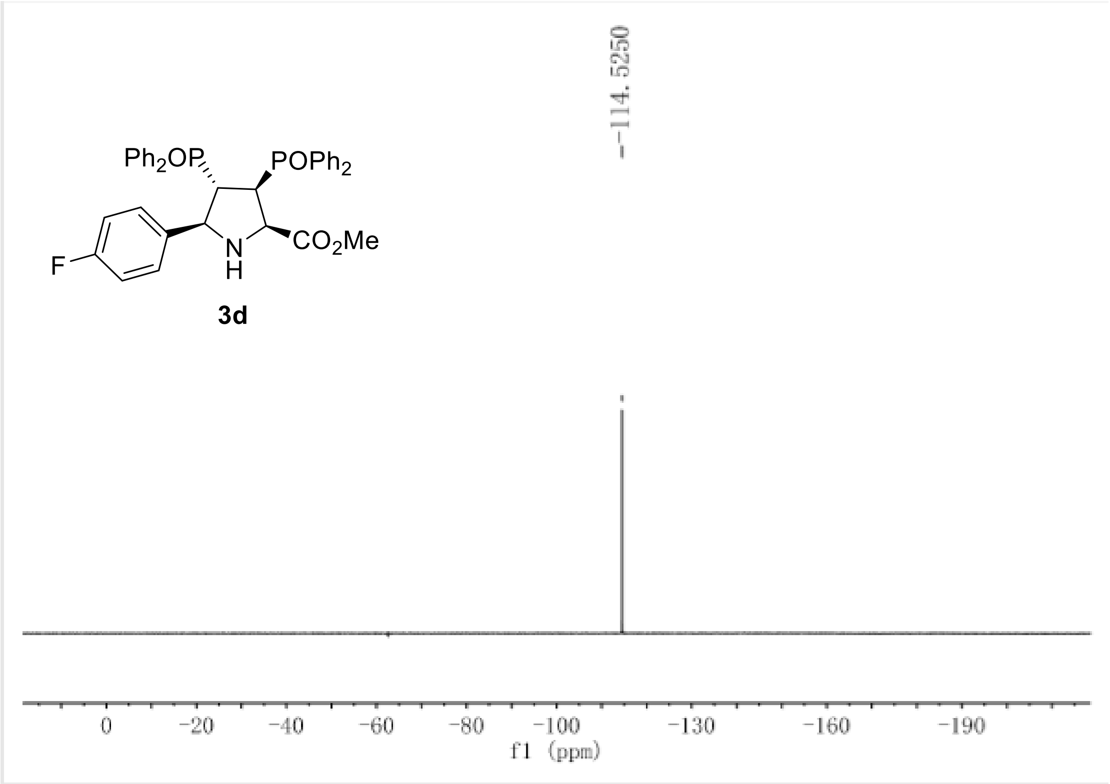






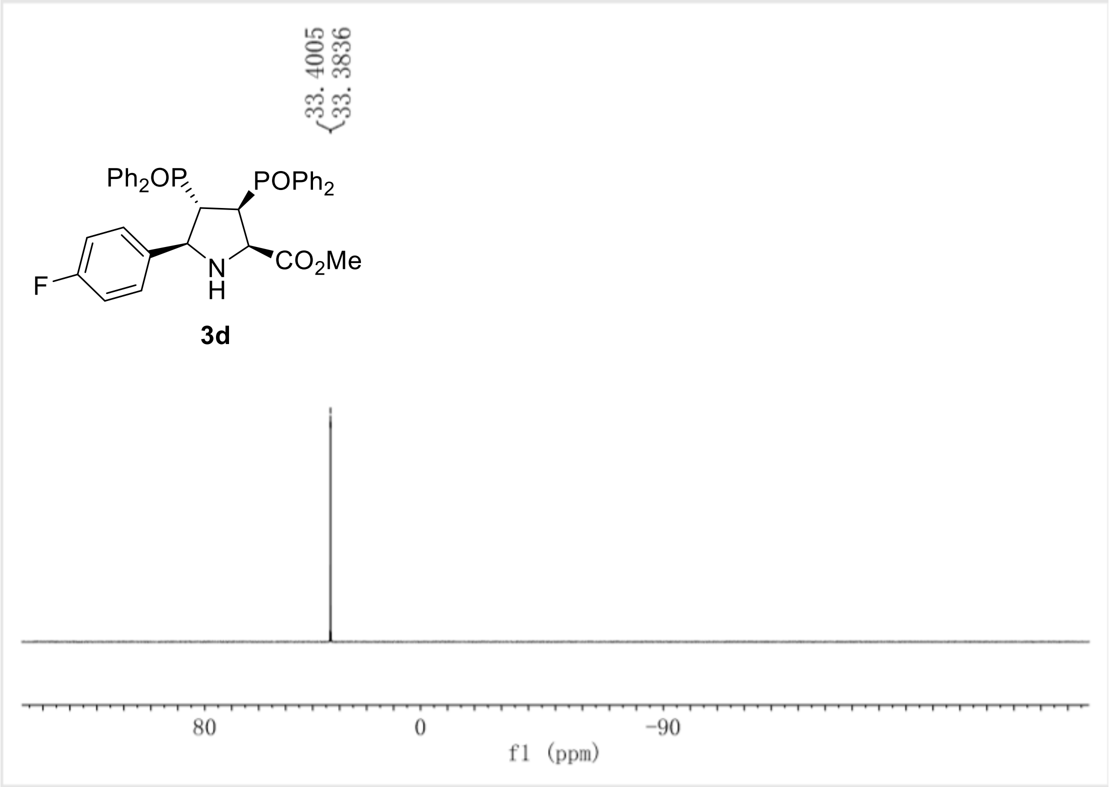
**$^1$H NMR** (400 MHz, CDCl$_3$), **$^{19}$F NMR** (282 MHz, CDCl$_3$), **$^{31}$P NMR** (162 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **3d**





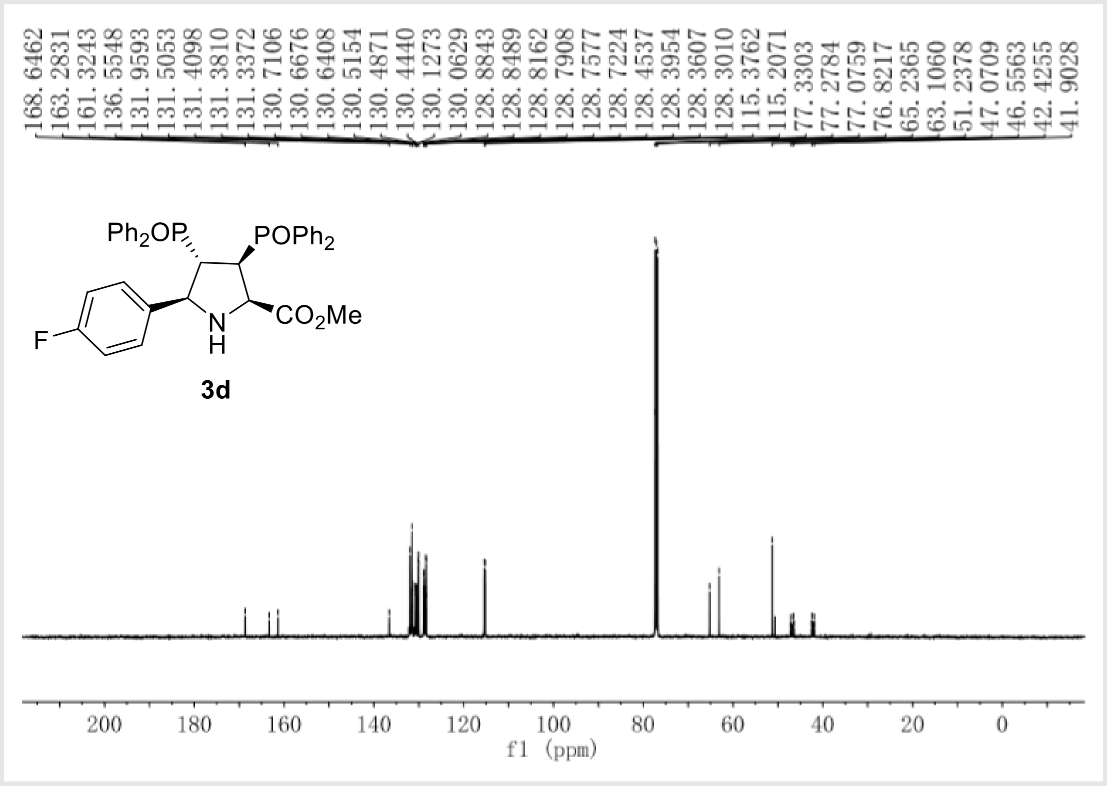
**3d**

-114.5250
Ph$_2$OP
POPh$_2$
CO$_2$Me
F
N
H
0
-20
-40
-60
-80
-100
-130
-160
-190
f1 (ppm)

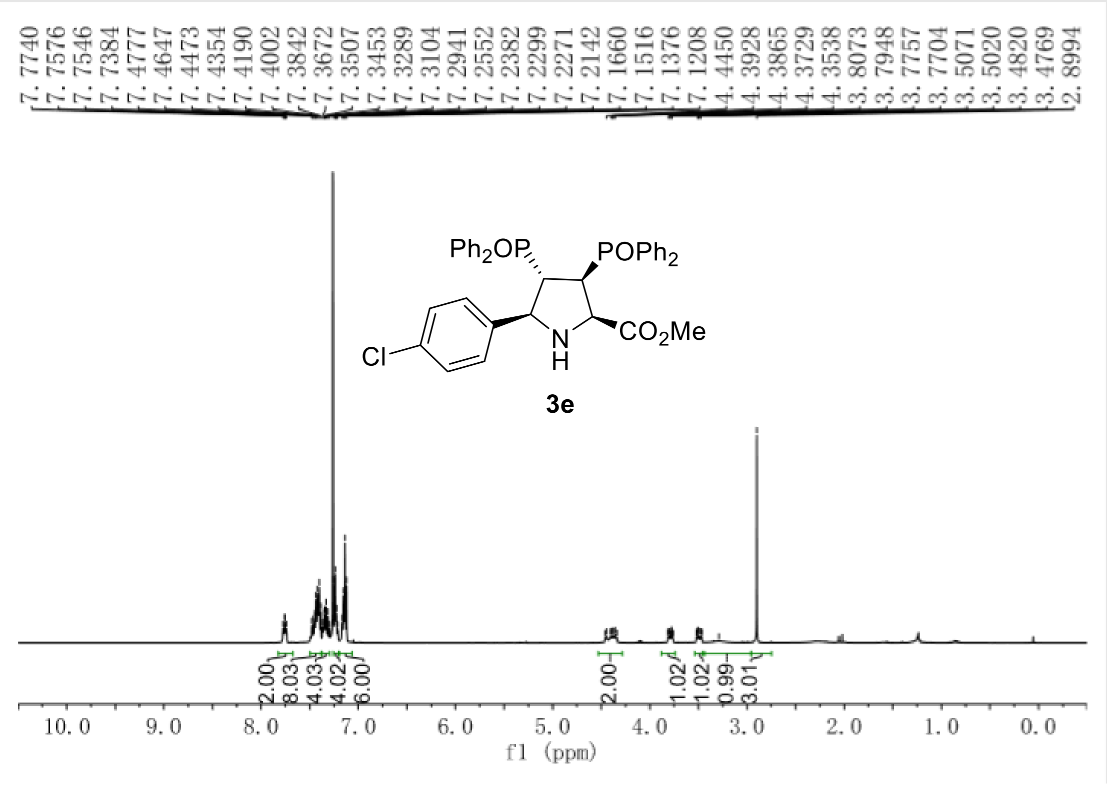


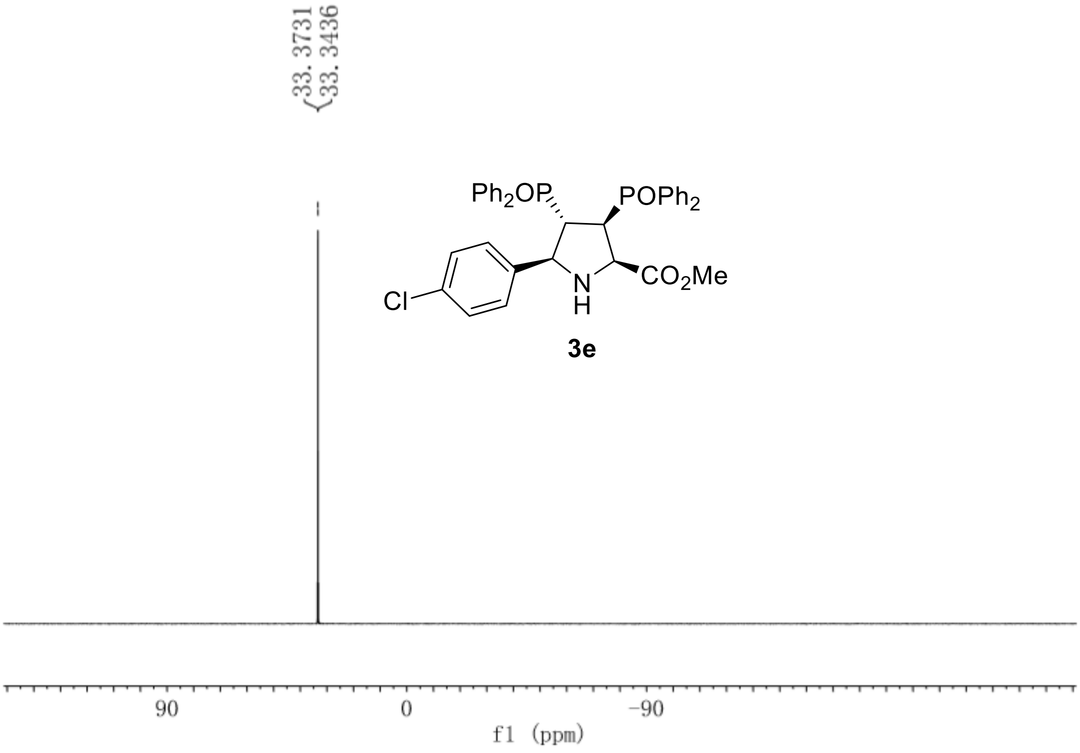
**3d**

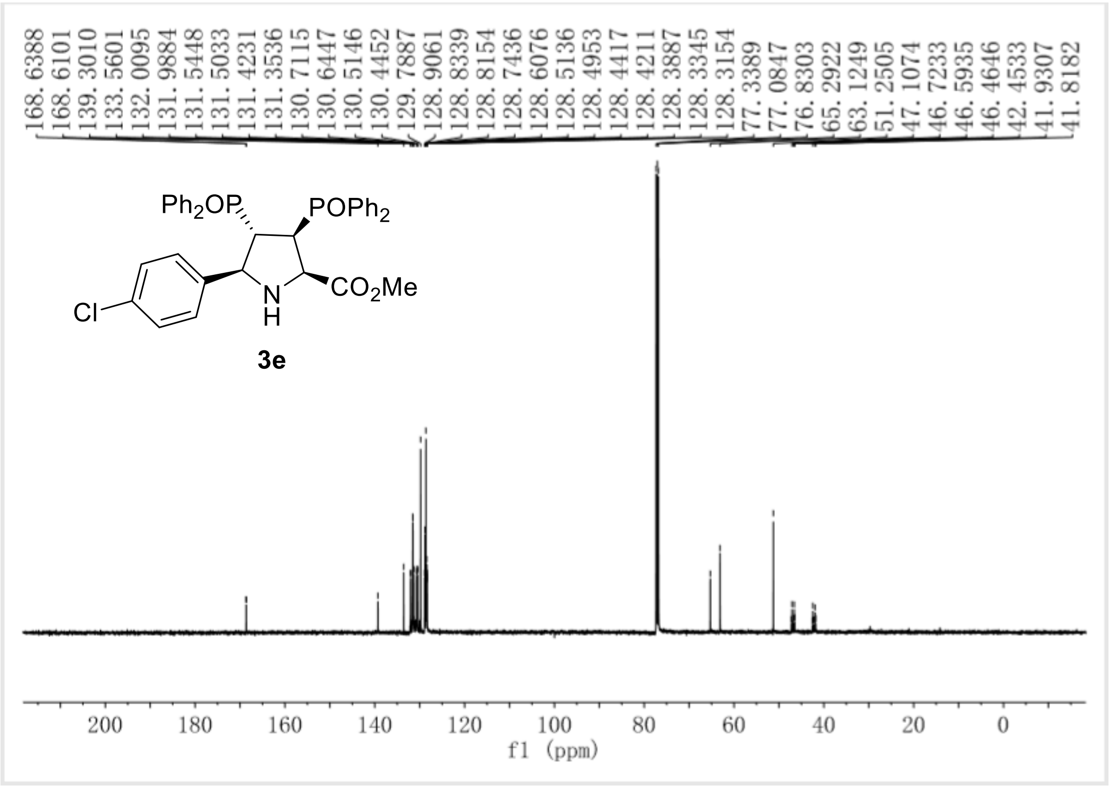
33.4005
33.3836
Ph$_2$OP
POPh$_2$
CO$_2$Me
F
N
H
80
0
-90
f1 (ppm)



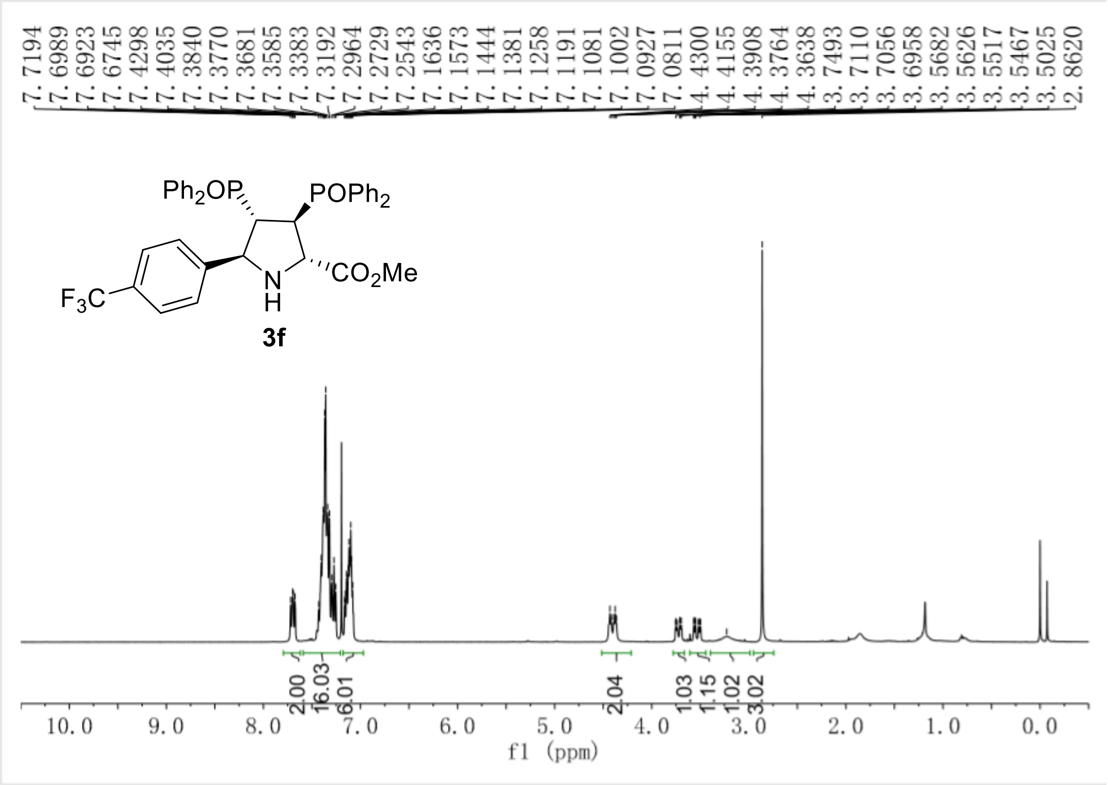
**$^{1}$H NMR** (400 MHz, CDCl$_3$), **$^{31}$P NMR** (162 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **3e**

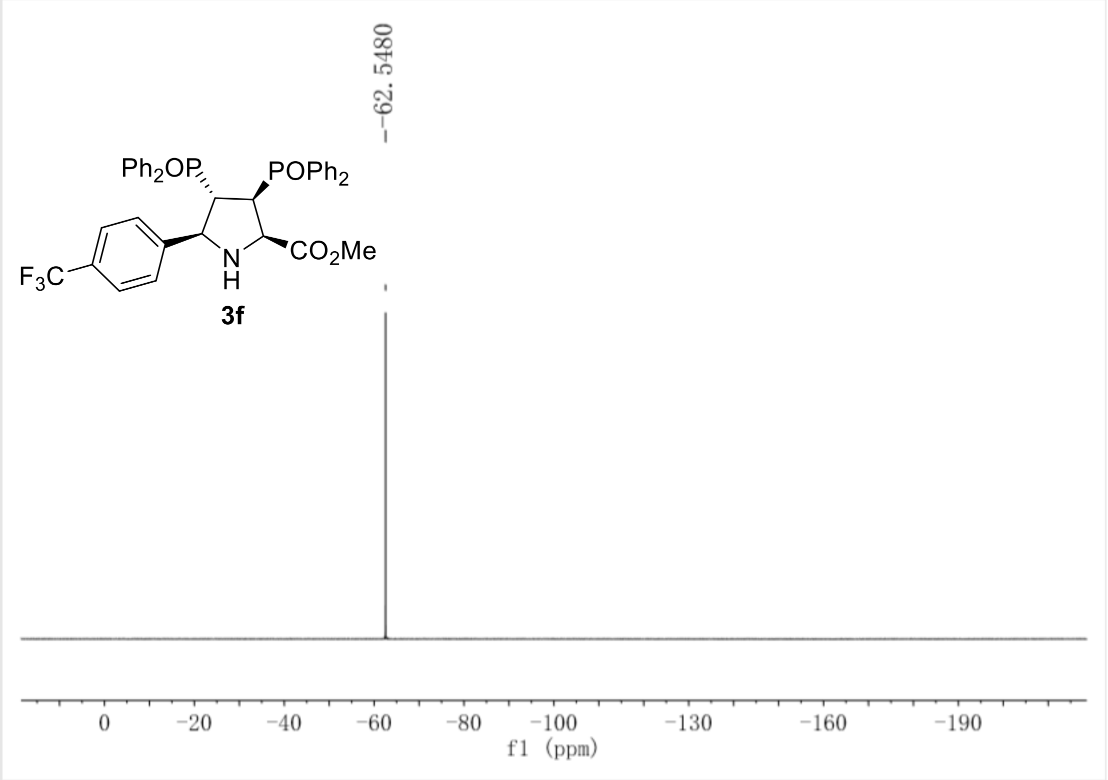


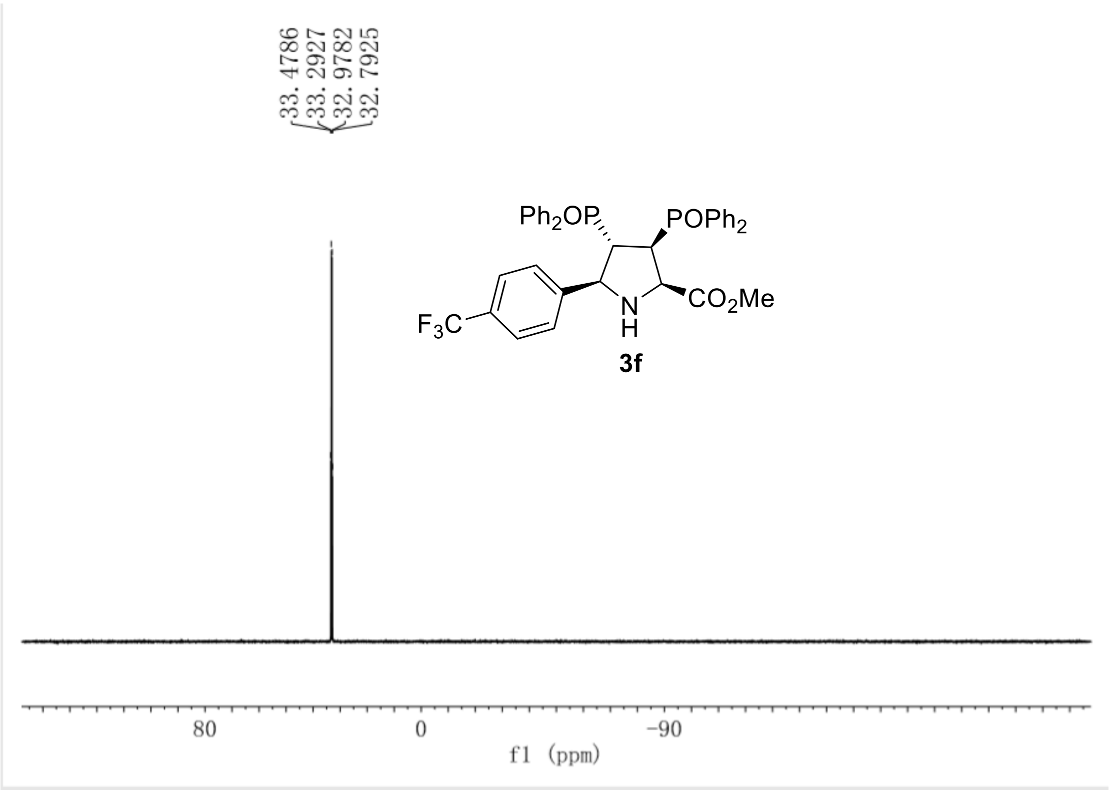

33.3731
33.3436
Ph$_2$OP
POPh$_2$
CO$_2$Me
N
H
Cl
3e
90
0
-90
f1 (ppm)

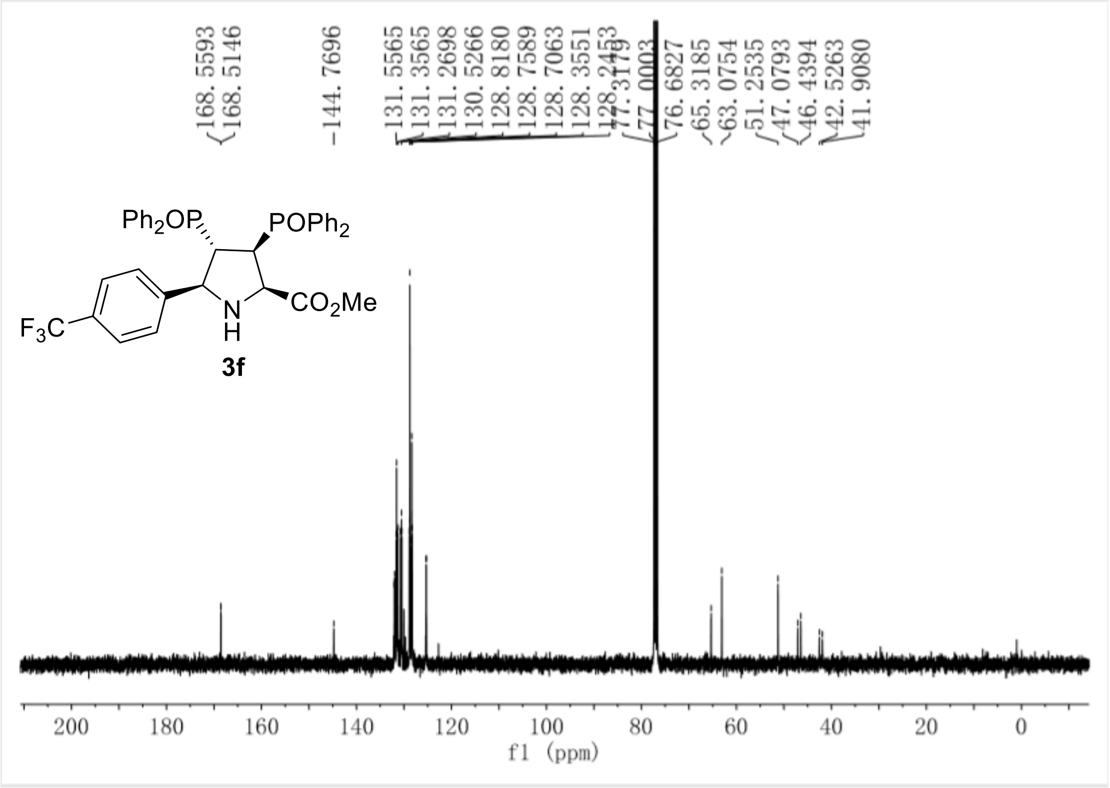

168.6388
168.6101
139.3010
133.5601
132.0095
131.9884
131.5448
131.5033
131.4231
131.3536
130.7115
130.6447
130.5146
130.4452
129.7887
128.9061
128.8339
128.8154
128.7436
128.6076
128.5136
128.4953
128.4417
128.4211
128.3887
128.3345
128.3154
77.3389
77.0847
76.8303
65.2922
63.1249
51.2505
47.1074
46.7233
46.5935
46.4646
42.4533
41.9307
41.8182
Ph$_2$OP
POPh$_2$
CO$_2$Me
N
H
Cl
3e
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

$^{1}$**H NMR** (400 MHz, $CDCl_3$), $^{19}$**F NMR** (282 MHz, $CDCl_3$), $^{31}$**P NMR** (101 MHz, $CDCl_3$) and $^{13}$**C NMR** (126 MHz, $CDCl_3$) of **3f**

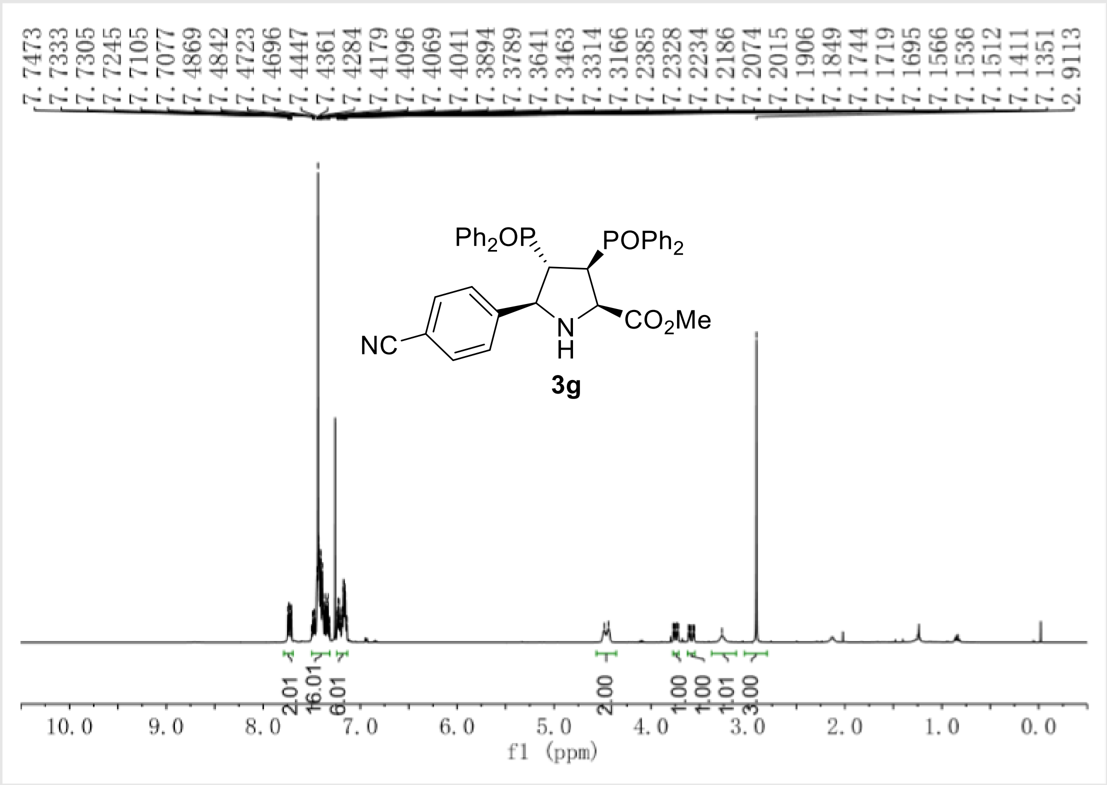


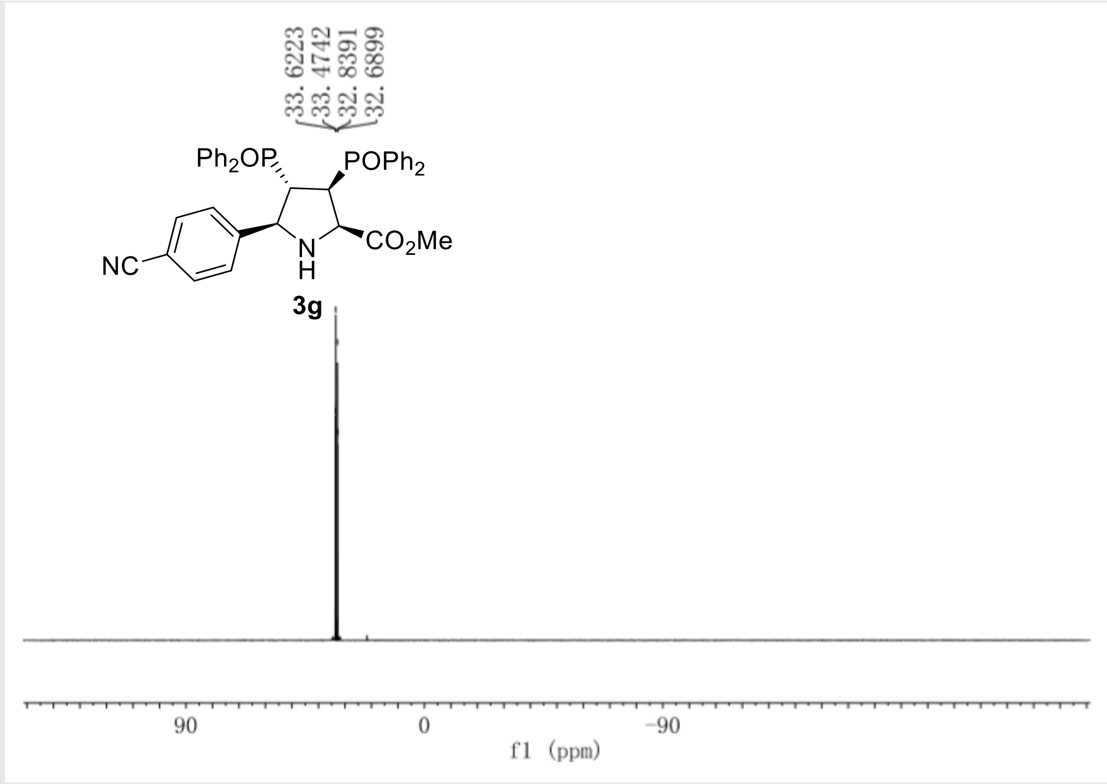


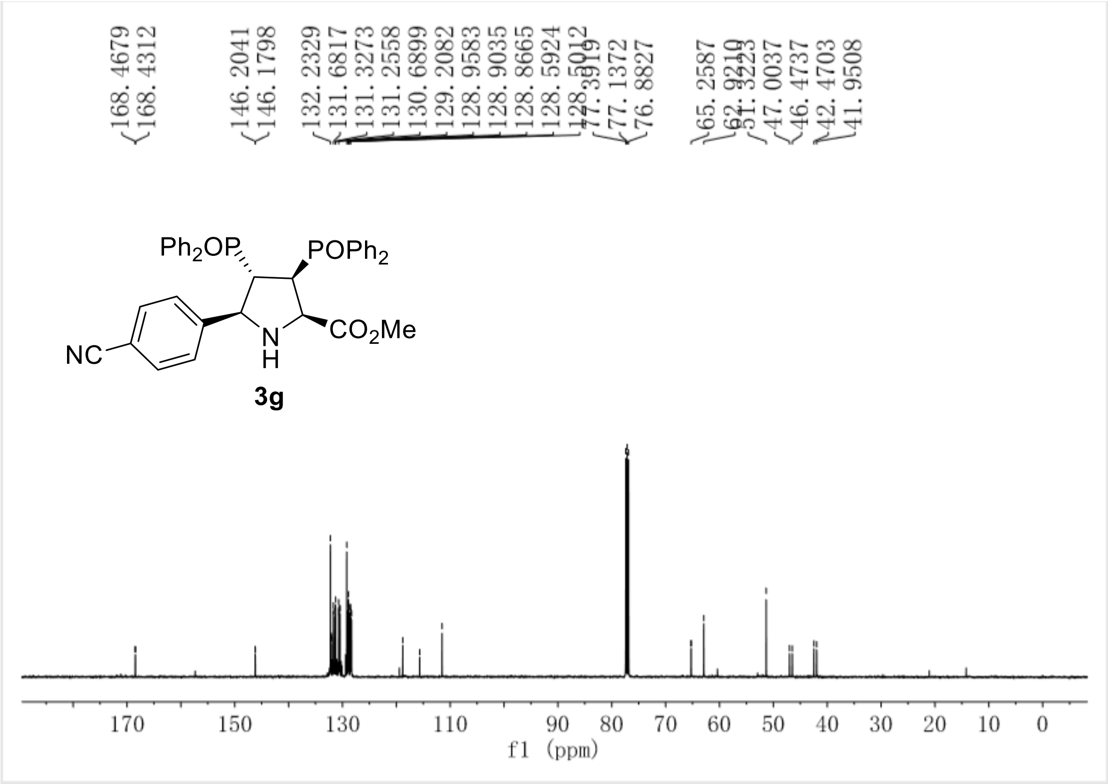

33.4786
33.2927
32.9782
32.7925
Ph₂OP
POPh₂
F₃C
N
H
CO₂Me
3f
80
0
−90
f1 (ppm)


168.5593
168.5146
144.7696
131.5565
131.3565
131.2698
130.5266
128.8180
128.7589
128.7063
128.3551
128.2453
77.3179
77.0003
76.6827
65.3185
63.0754
51.2535
47.0793
46.4394
42.5263
41.9080
Ph₂OP
POPh₂
F₃C
N
H
CO₂Me
3f
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

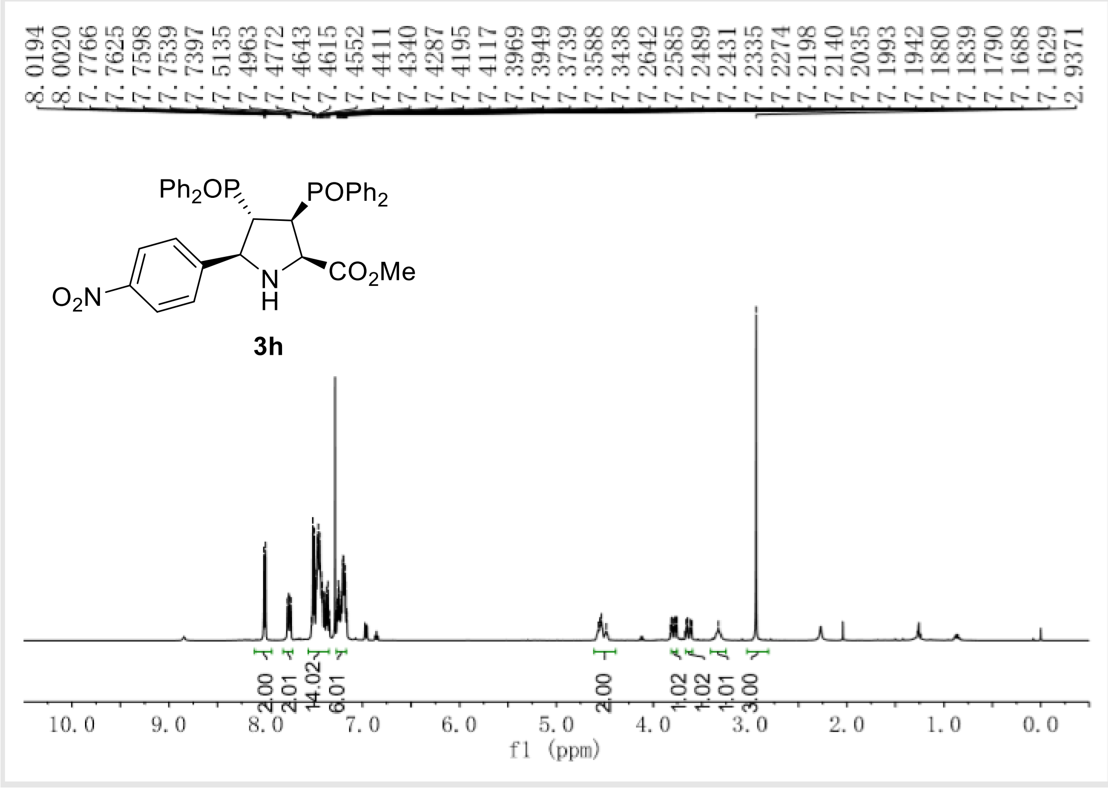
**$^{1}H$ NMR** (400 MHz, $CDCl_3$), **$^{31}P$ NMR** (202 MHz, $CDCl_3$) and **$^{13}C$ NMR** (126 MHz, $CDCl_3$) of **3g**

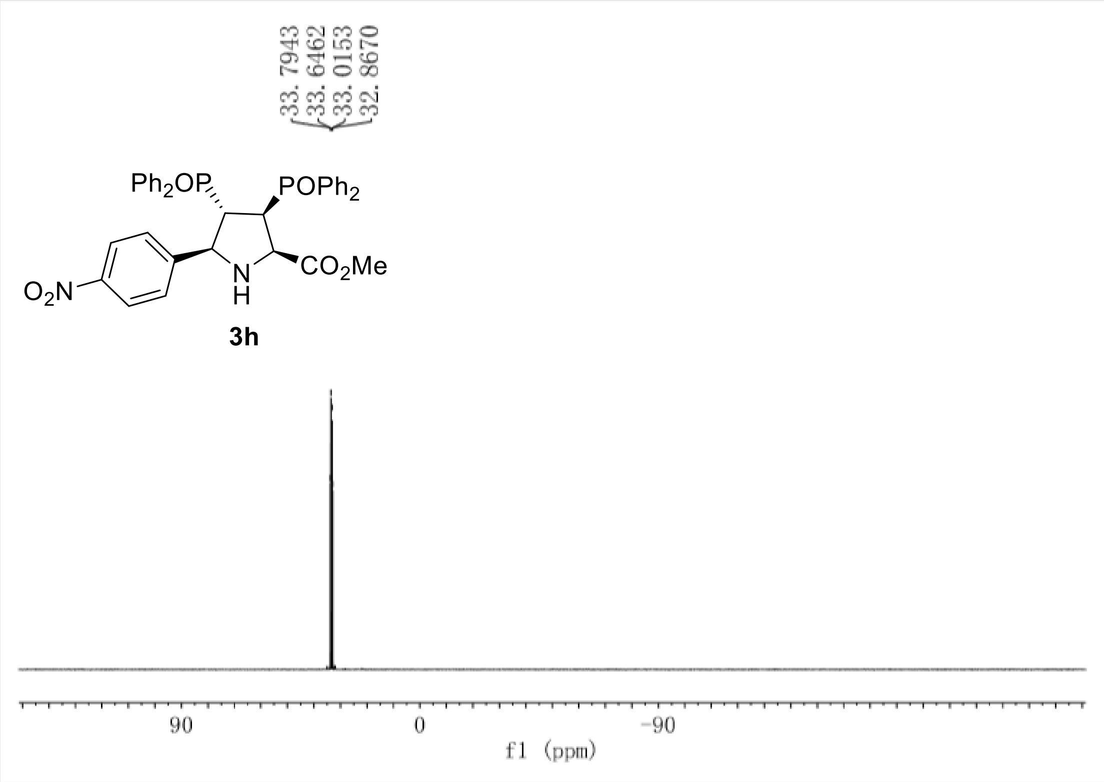


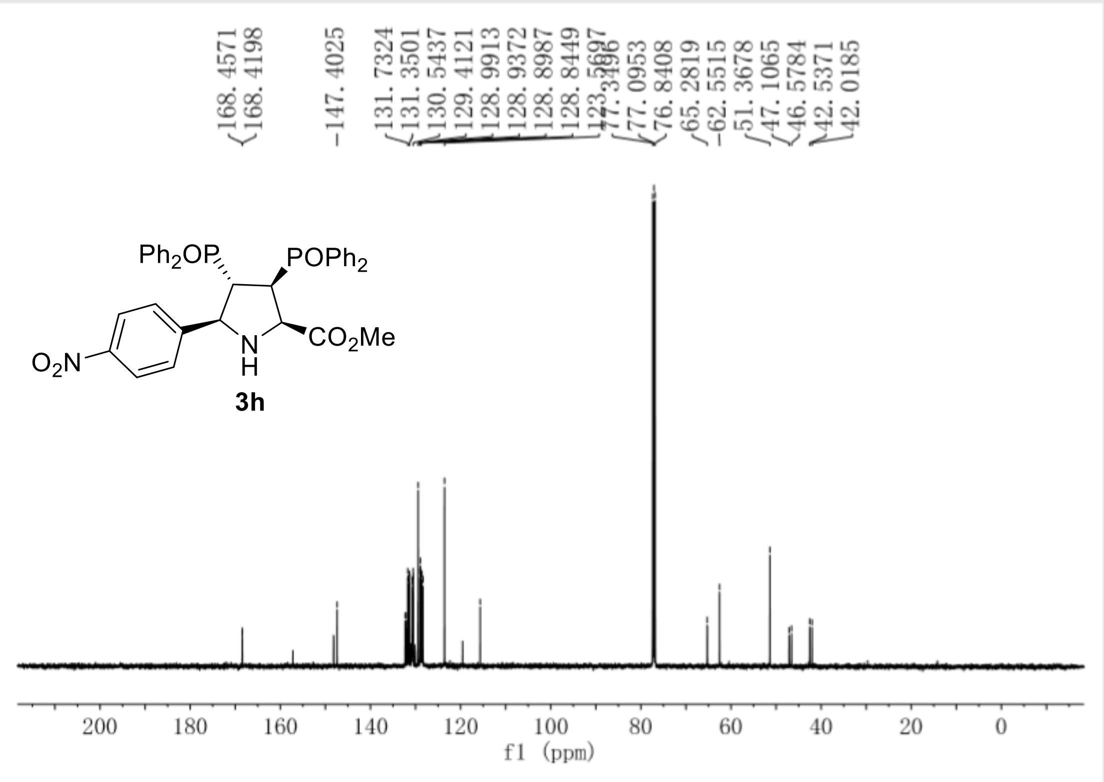




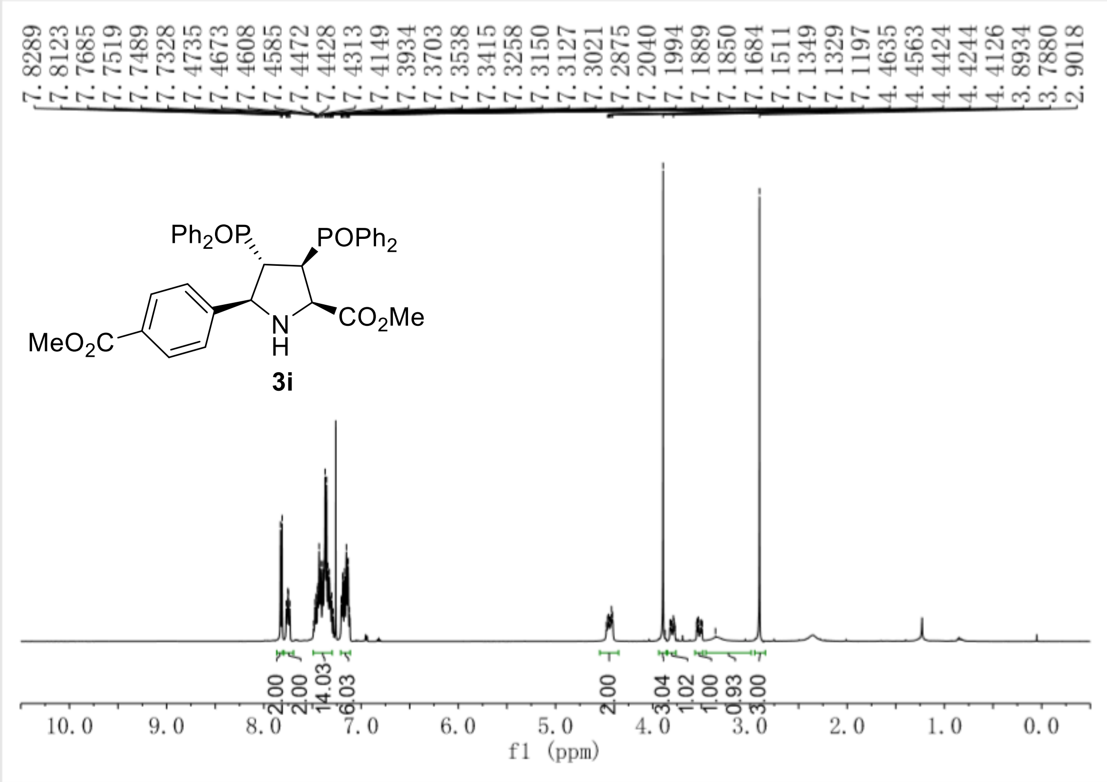
$^{1}$**H NMR** (500 MHz, $CDCl_3$), $^{31}$**P NMR** (202 MHz, $CDCl_3$) and $^{13}$**C NMR** (126 MHz, $CDCl_3$) of **3h**

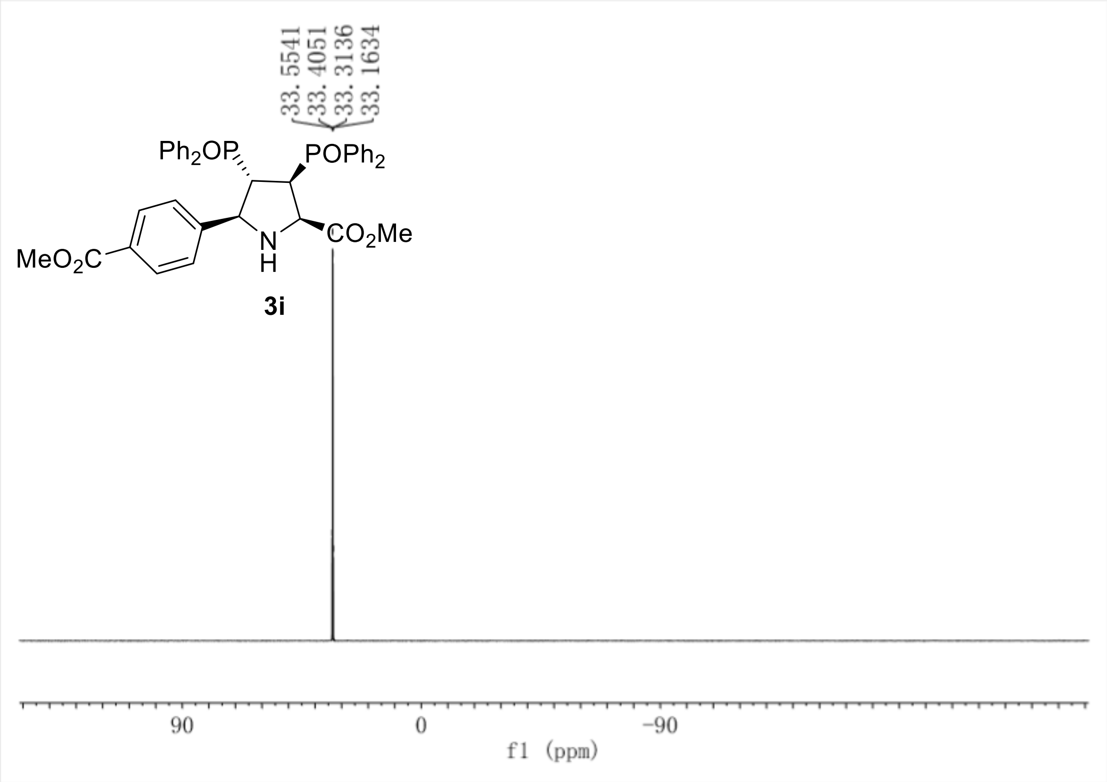


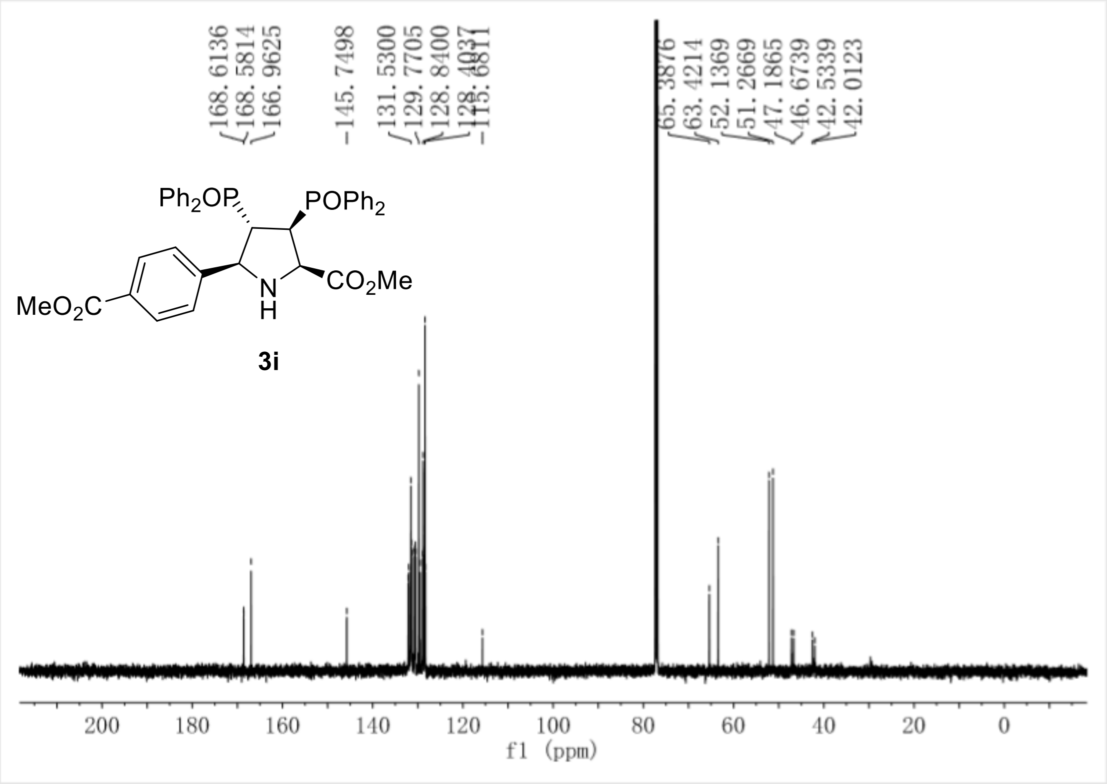

33. 7943
33. 6462
33. 0153
32. 8670
Ph₂OP
POPh₂
O₂N
N
H
CO₂Me
3h
90
0
−90
f1 (ppm)


168. 4571
168. 4198
147. 4025
131. 7324
131. 3501
130. 5437
129. 4121
128. 9913
128. 9372
128. 8987
128. 8449
123. 5697
77. 3496
77. 0953
76. 8408
65. 2819
62. 5515
51. 3678
47. 1065
46. 5784
42. 5371
42. 0185
Ph₂OP
POPh₂
O₂N
N
H
CO₂Me
3h
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

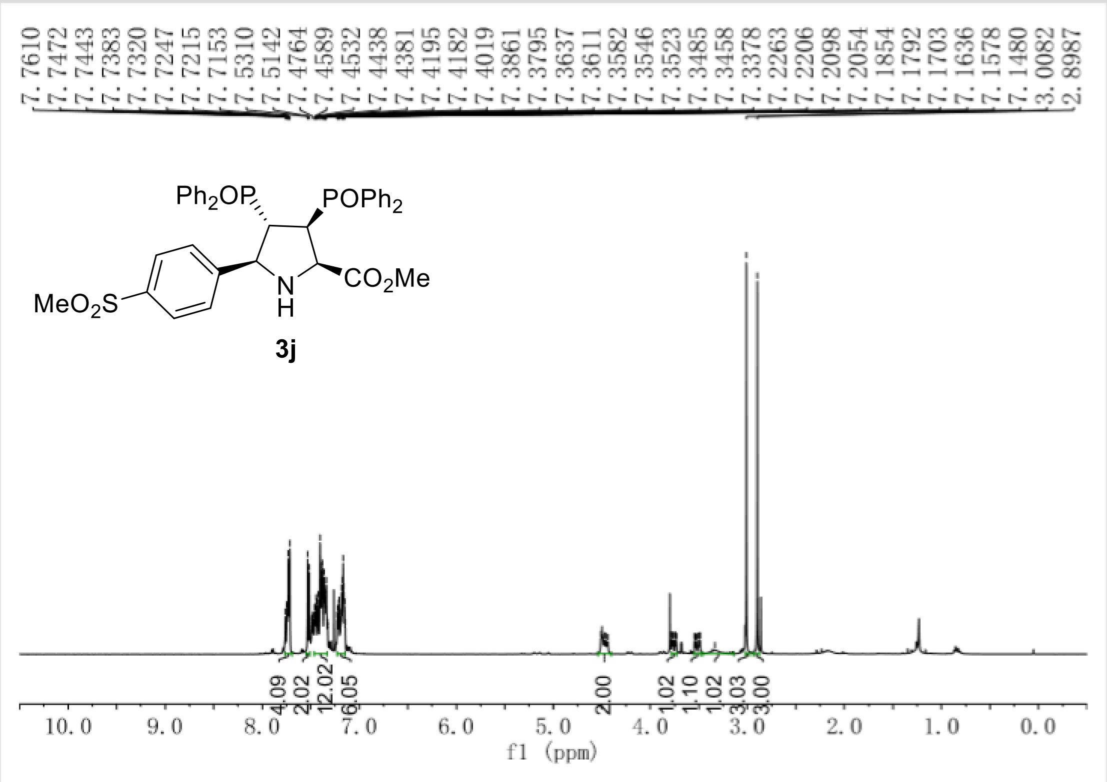
**$^{1}$H NMR** (500 MHz, $CDCl_3$), **$^{31}$P NMR** (202 MHz, $CDCl_3$) and **$^{13}$C NMR** (126 MHz, $CDCl_3$) of **3i**

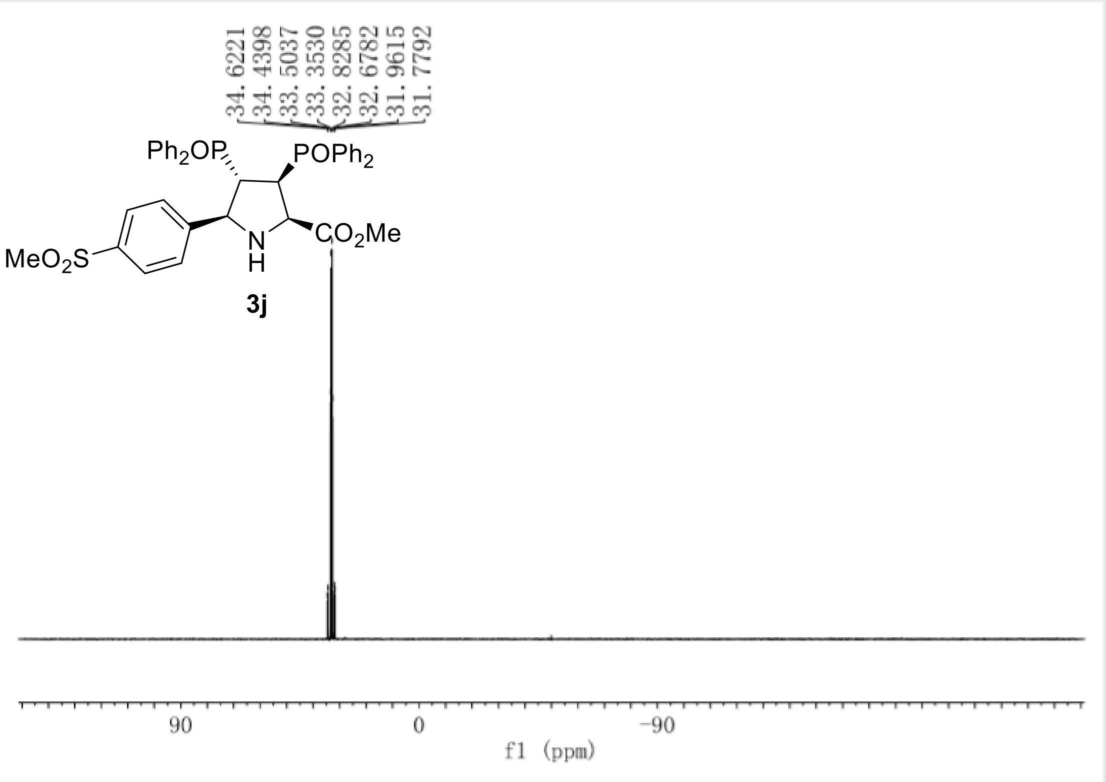


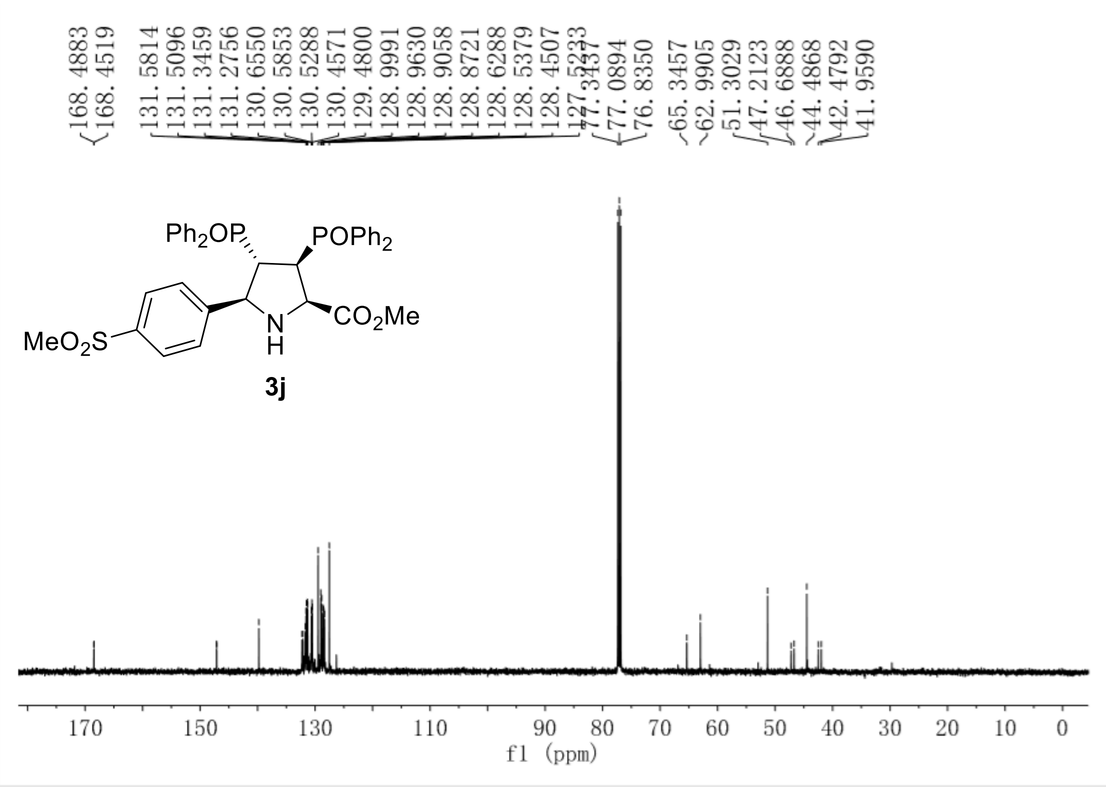




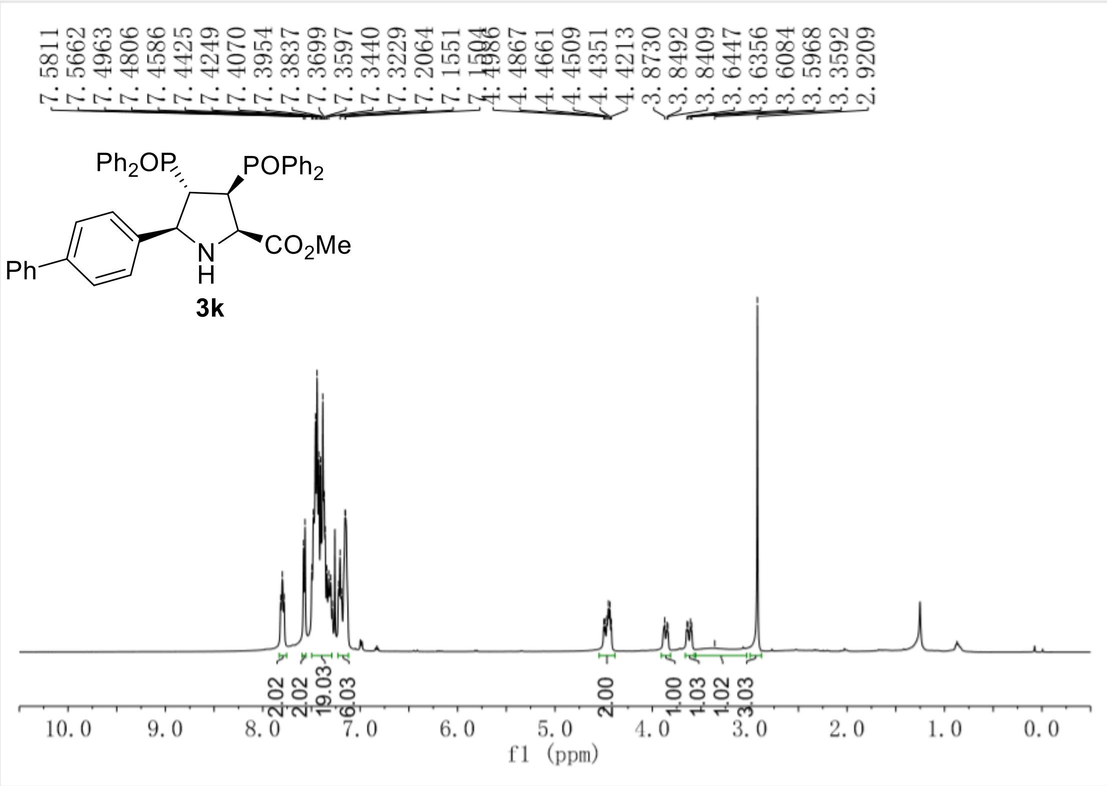
**$^{1}$H NMR** (500 MHz, $CDCl_3$), **$^{31}$P NMR** (202 MHz, $CDCl_3$) and **$^{13}$C NMR** (126 MHz, $CDCl_3$) of **3j**

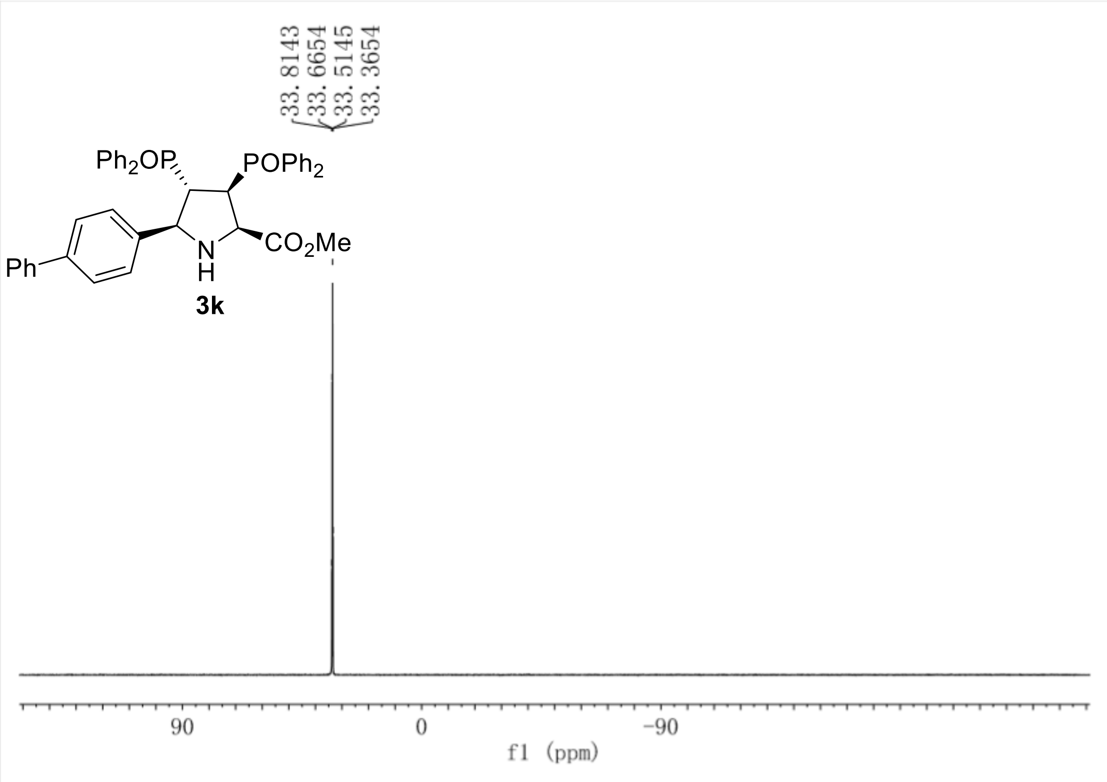


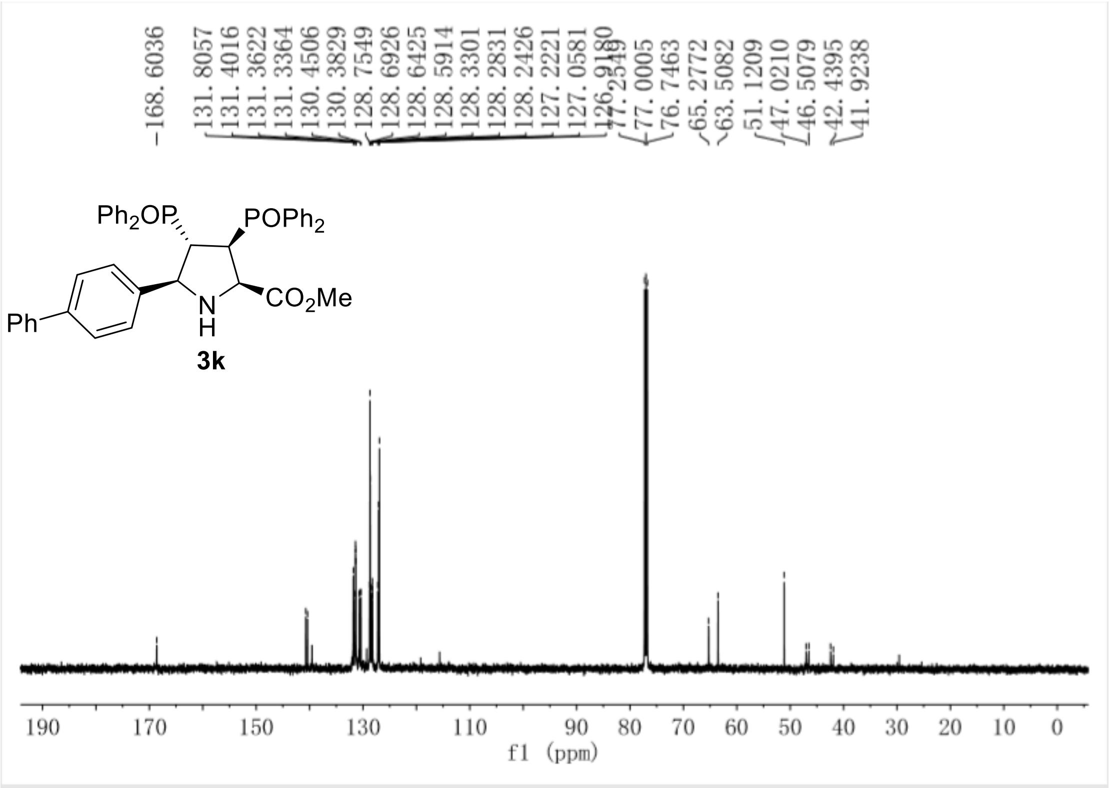

34.6221
34.4398
33.5037
33.3530
32.8285
32.6782
31.9615
31.7792
Ph2OP
POPh2
MeO2S
N
H
CO2Me
3j
90
0
-90
f1 (ppm)


168.4883
168.4519
131.5814
131.5096
131.3459
131.2756
130.6550
130.5853
130.5288
130.4571
129.4800
128.9991
128.9630
128.9058
128.8721
128.6288
128.5379
128.4507
127.5233
77.3437
77.0894
76.8350
65.3457
62.9905
51.3029
47.2123
46.6888
44.4868
42.4792
41.9590
Ph2OP
POPh2
MeO2S
N
H
CO2Me
3j
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

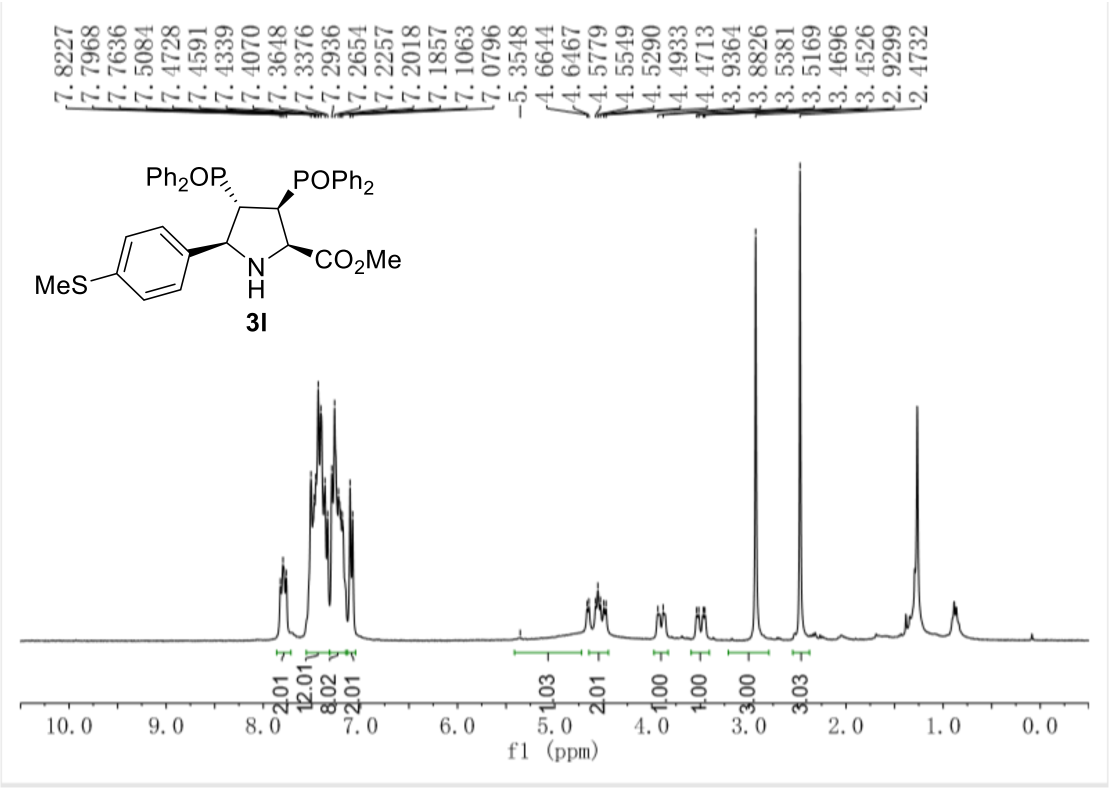
**$^{1}H$ NMR** (500 MHz, $CDCl_3$), **$^{31}P$ NMR** (202 MHz, $CDCl_3$) and **$^{13}C$ NMR** (126 MHz, $CDCl_3$) of **3k**

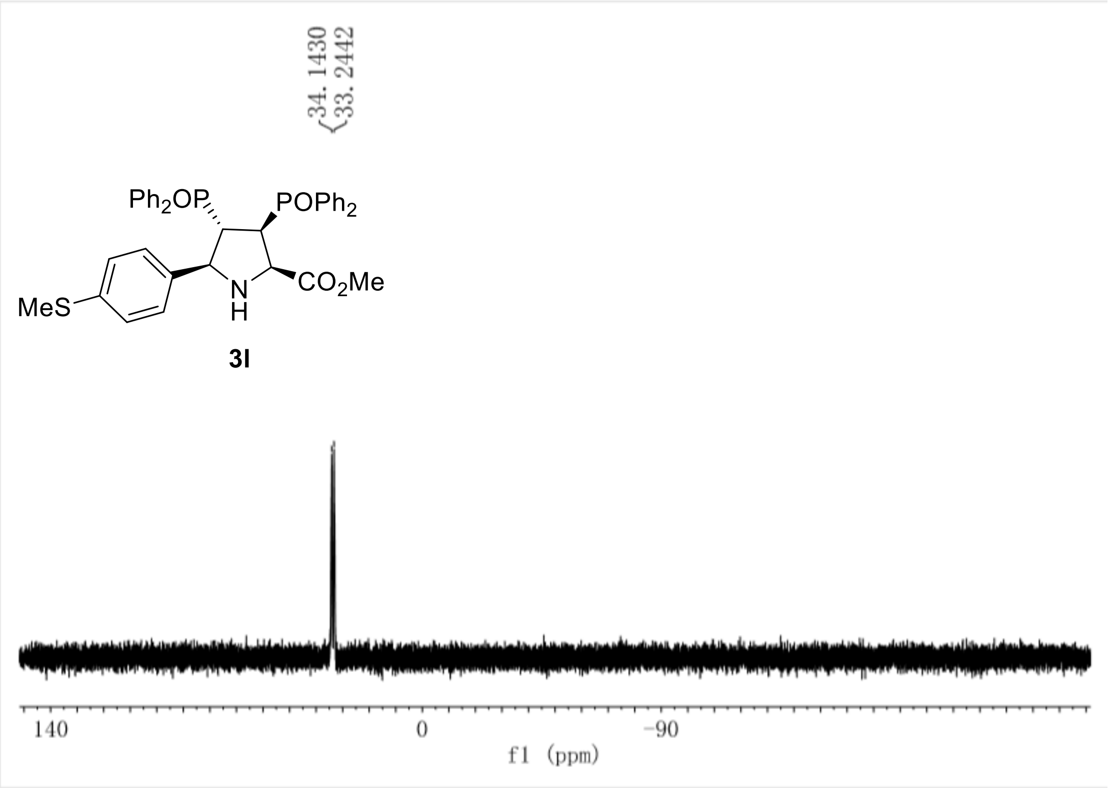


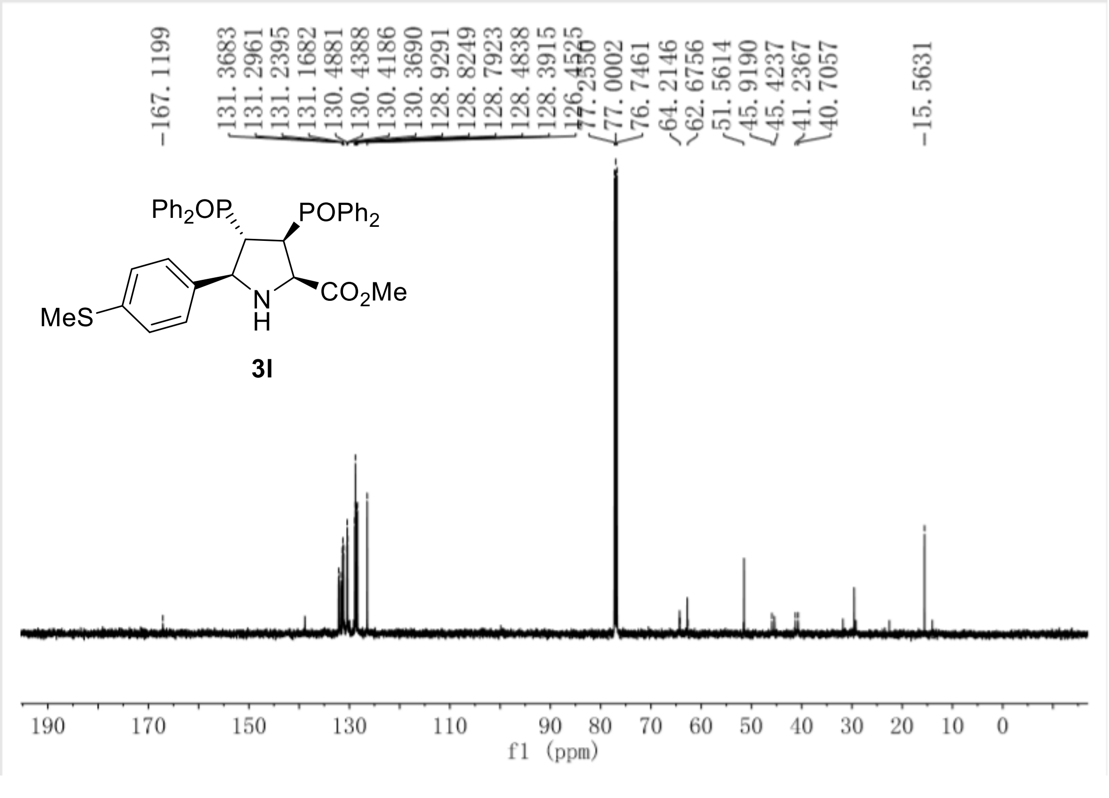




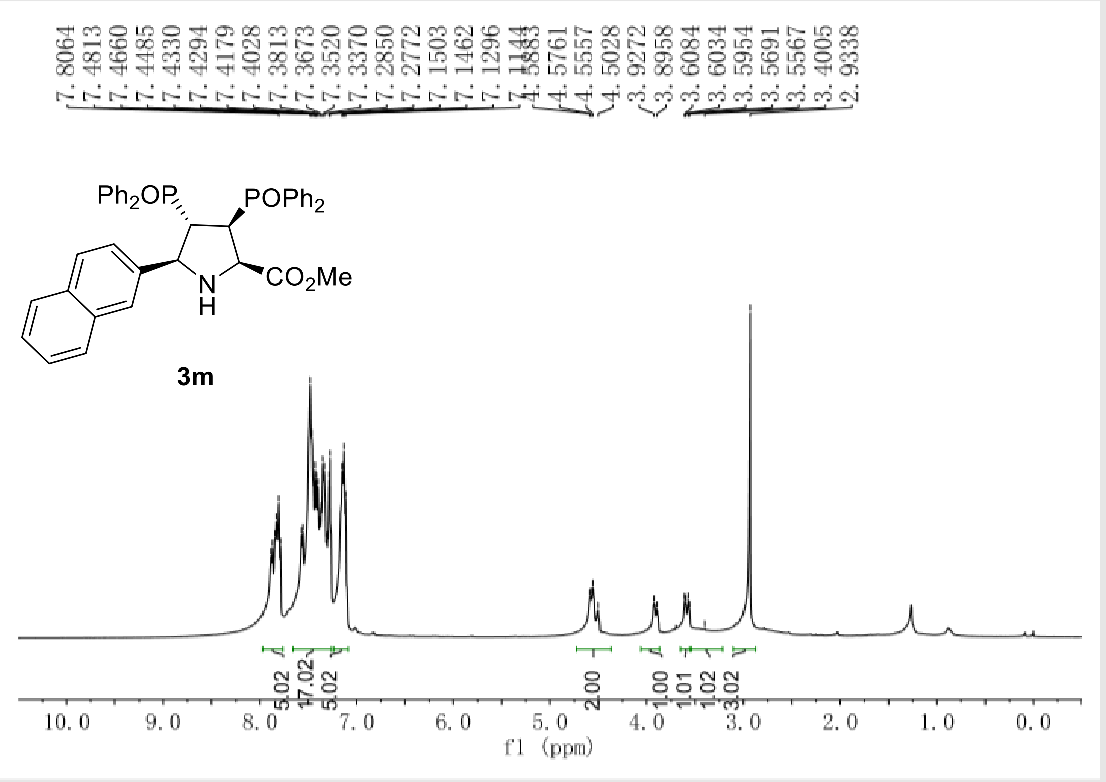
**$^{1}$H NMR** (300 MHz, CDCl$_3$), **$^{31}$P NMR** (122 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **3l**

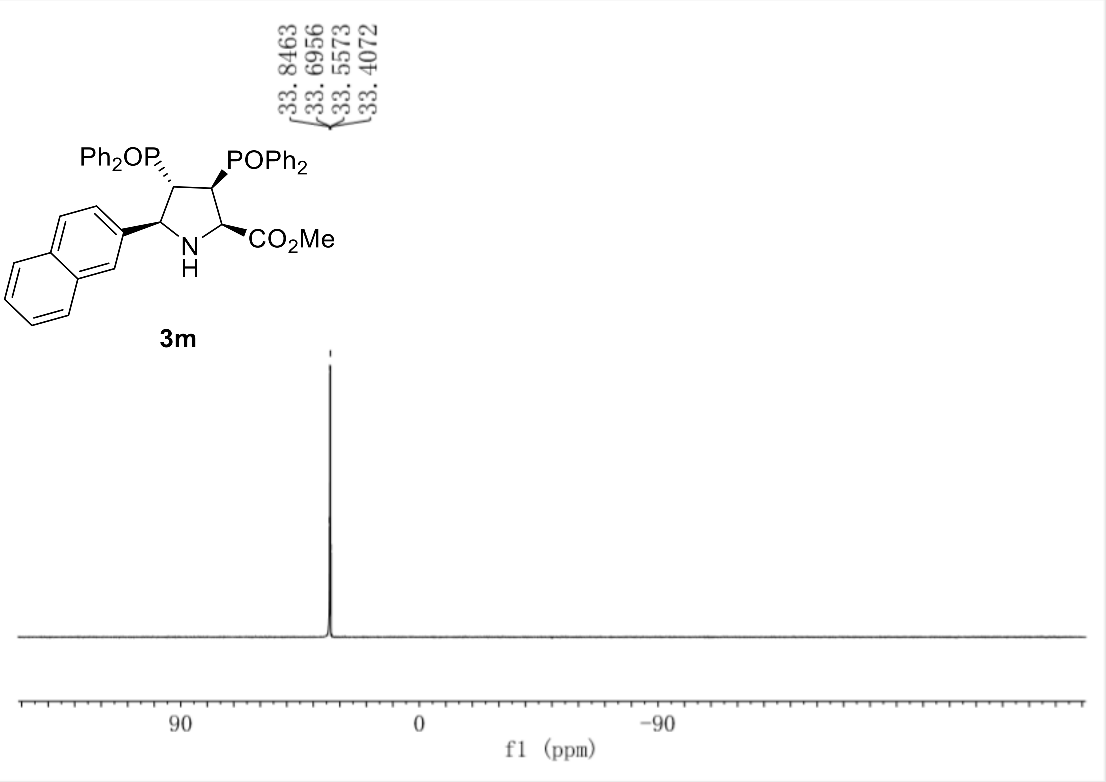


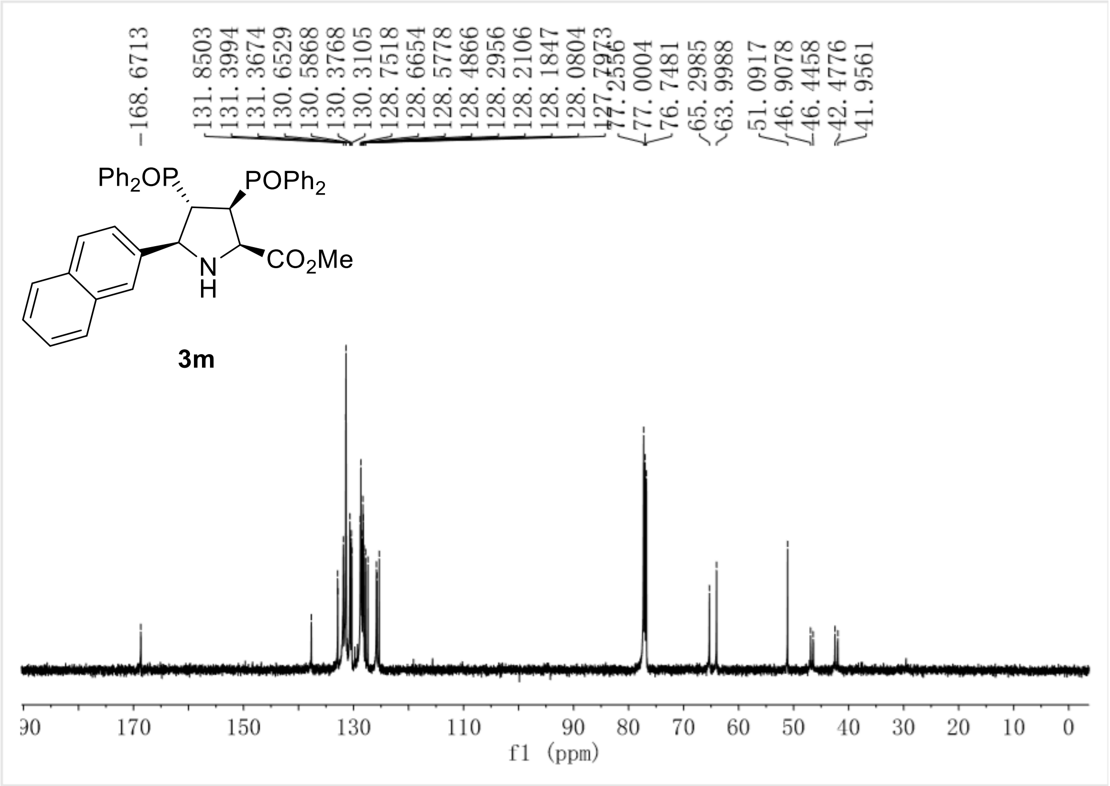

34.1430
33.2442
Ph$_2$OP
POPh$_2$
MeS
N
H
CO$_2$Me
3l
140
0
−90
f1 (ppm)


−167.1199
131.3683
131.2961
131.2395
131.1682
130.4881
130.4388
130.4186
130.3690
128.9291
128.8249
128.7923
128.4838
128.3915
126.4525
77.2550
77.0002
76.7461
64.2146
62.6756
51.5614
45.9190
45.4237
41.2367
40.7057
−15.5631
Ph$_2$OP
POPh$_2$
MeS
N
H
CO$_2$Me
3l
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

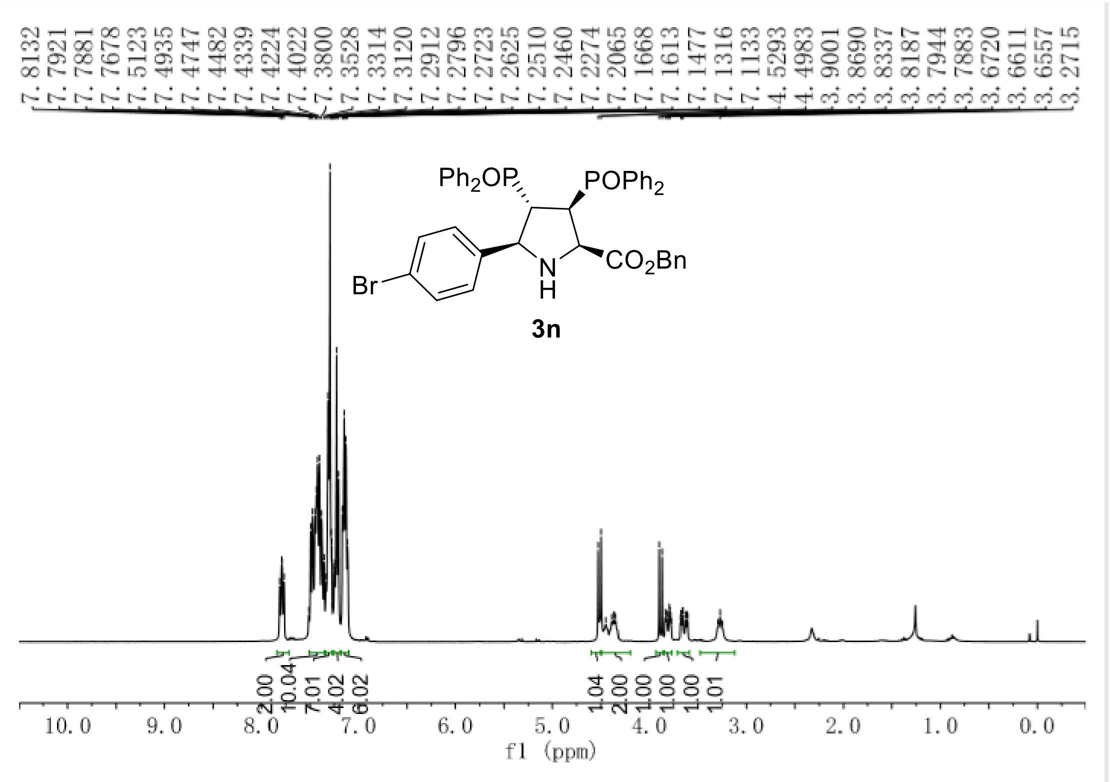
$^{1}$**H NMR** (500 MHz, CDCl$_3$), $^{31}$**P NMR** (202 MHz, CDCl$_3$) and $^{13}$**C NMR** (126 MHz, CDCl$_3$) of **3m**

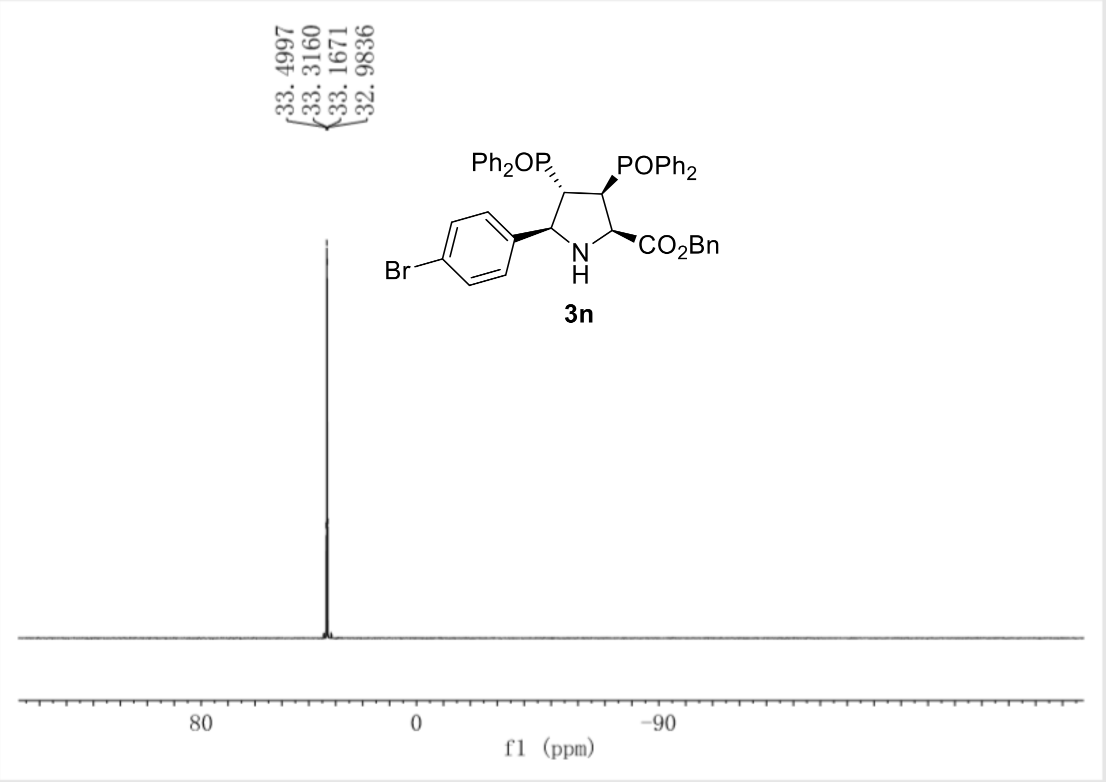


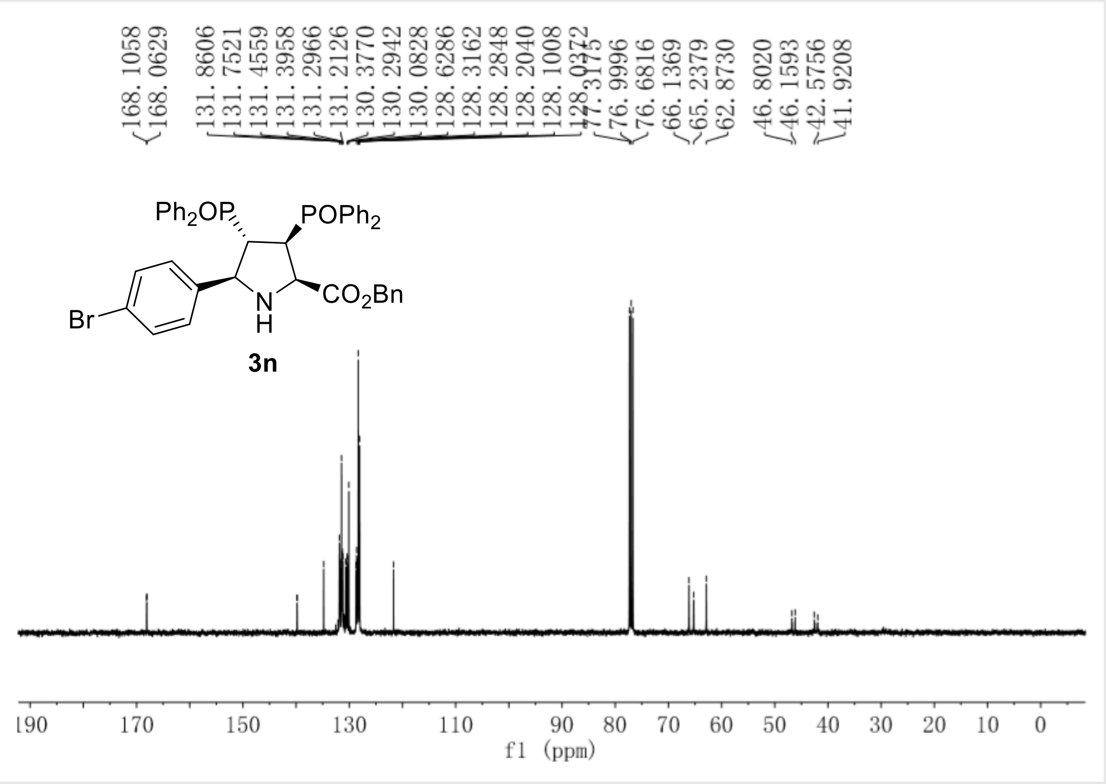




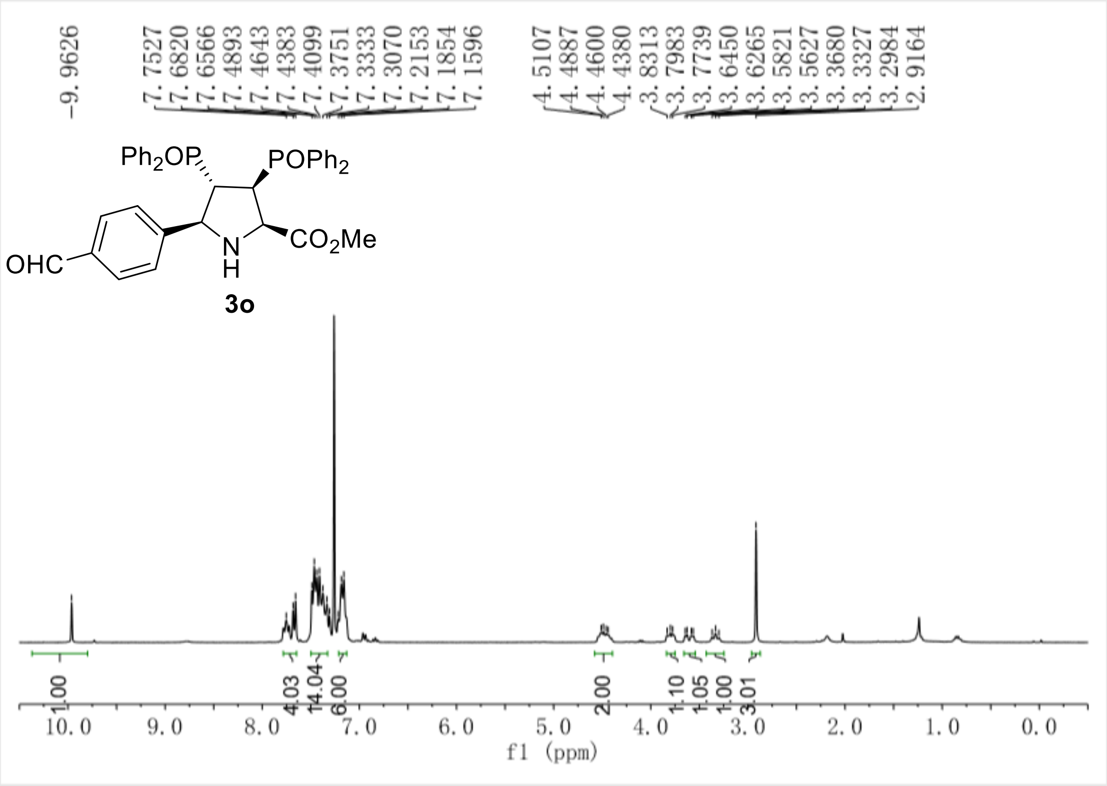
**$^1$H NMR** (400 MHz, CDCl$_3$), **$^{31}$P NMR** (162 MHz, CDCl$_3$) and **$^{13}$C NMR** (101 MHz, CDCl$_3$) of **3n**

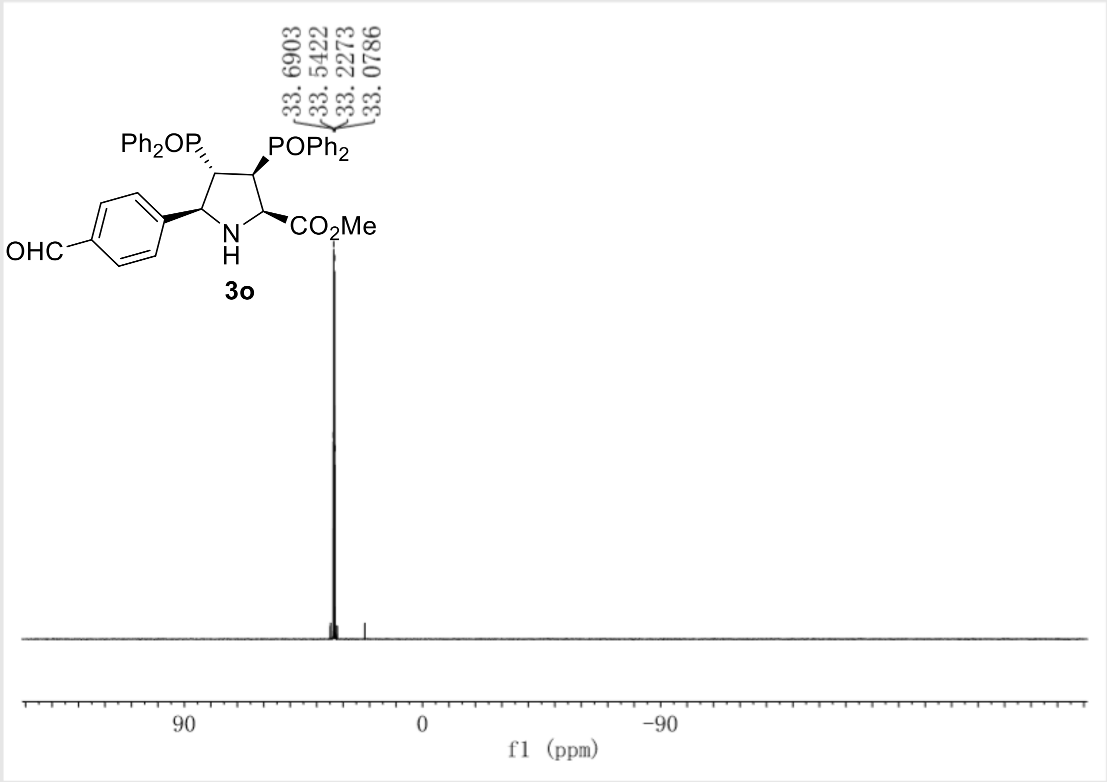


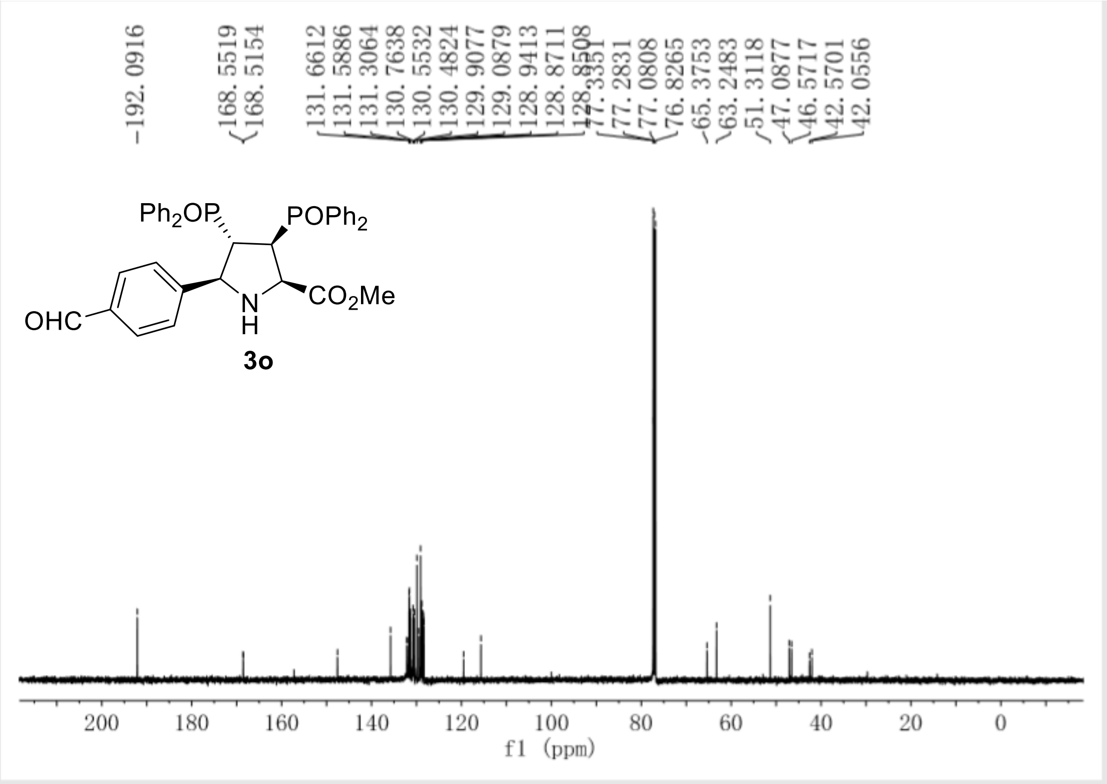

33. 4997
33. 3160
33. 1671
32. 9836
Ph2OP
POPh2
Br
N
H
CO2Bn
3n
80
0
−90
f1 (ppm)


168. 1058
168. 0629
131. 8606
131. 7521
131. 4559
131. 3958
131. 2966
131. 2126
130. 3770
130. 2942
130. 0828
128. 6286
128. 3162
128. 2848
128. 2040
128. 1008
128. 0372
77. 3175
76. 9996
76. 6816
66. 1369
65. 2379
62. 8730
46. 8020
46. 1593
42. 5756
41. 9208
Ph2OP
POPh2
Br
N
H
CO2Bn
3n
190
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

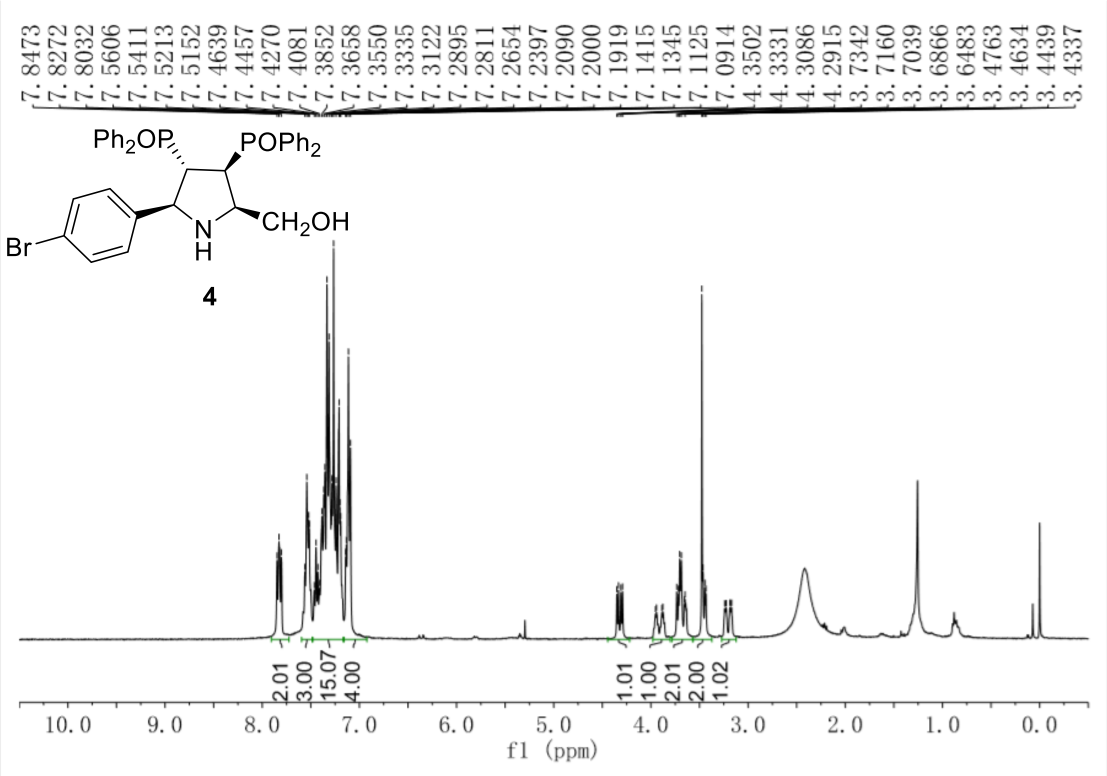
**$^{1}$H NMR** (300 MHz, CDCl$_3$), **$^{31}$P NMR** (202 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **3o**

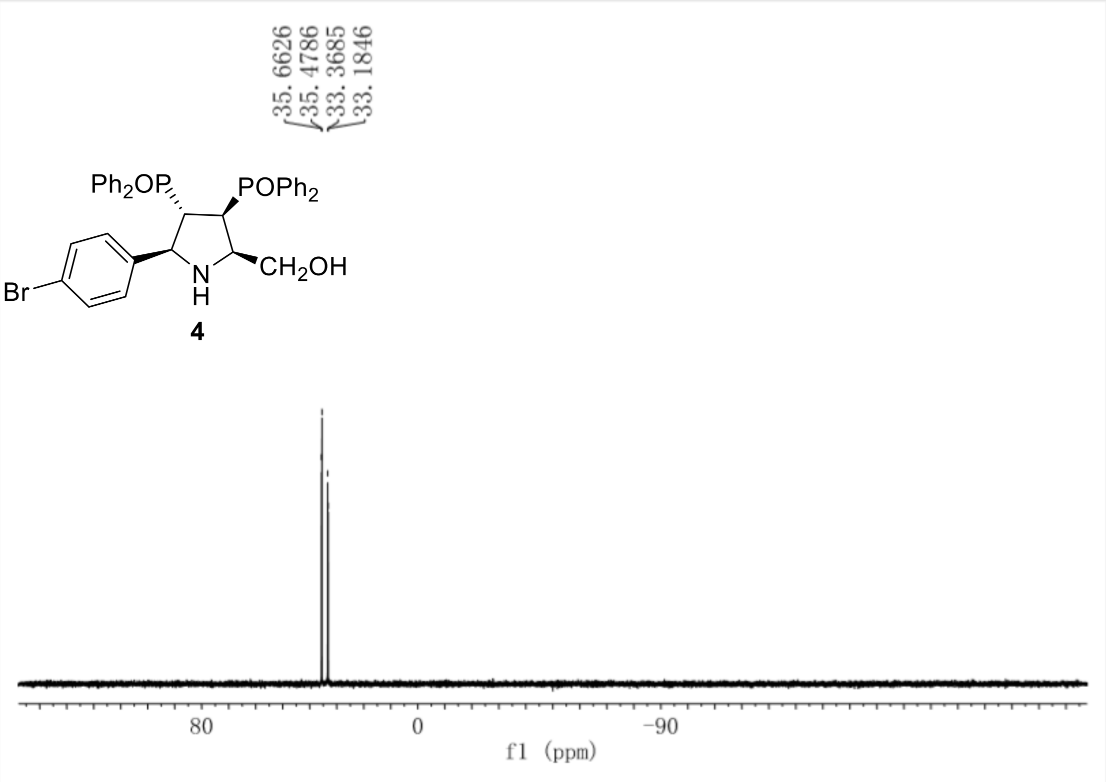


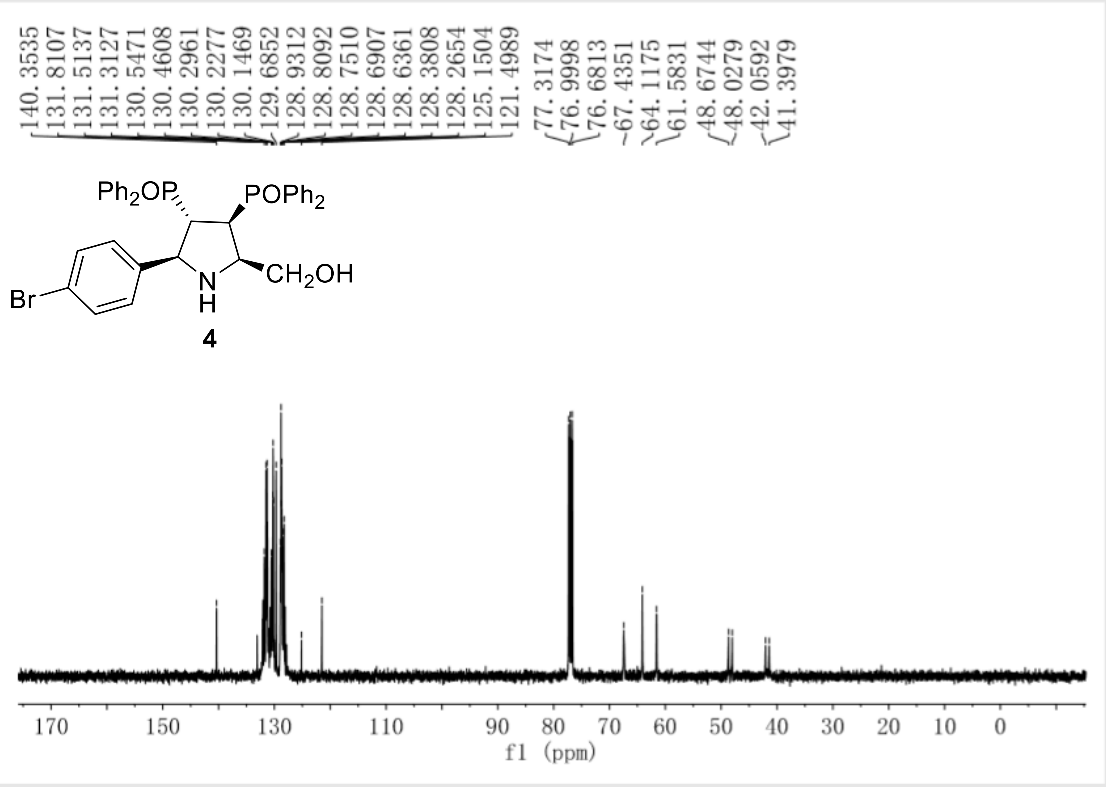




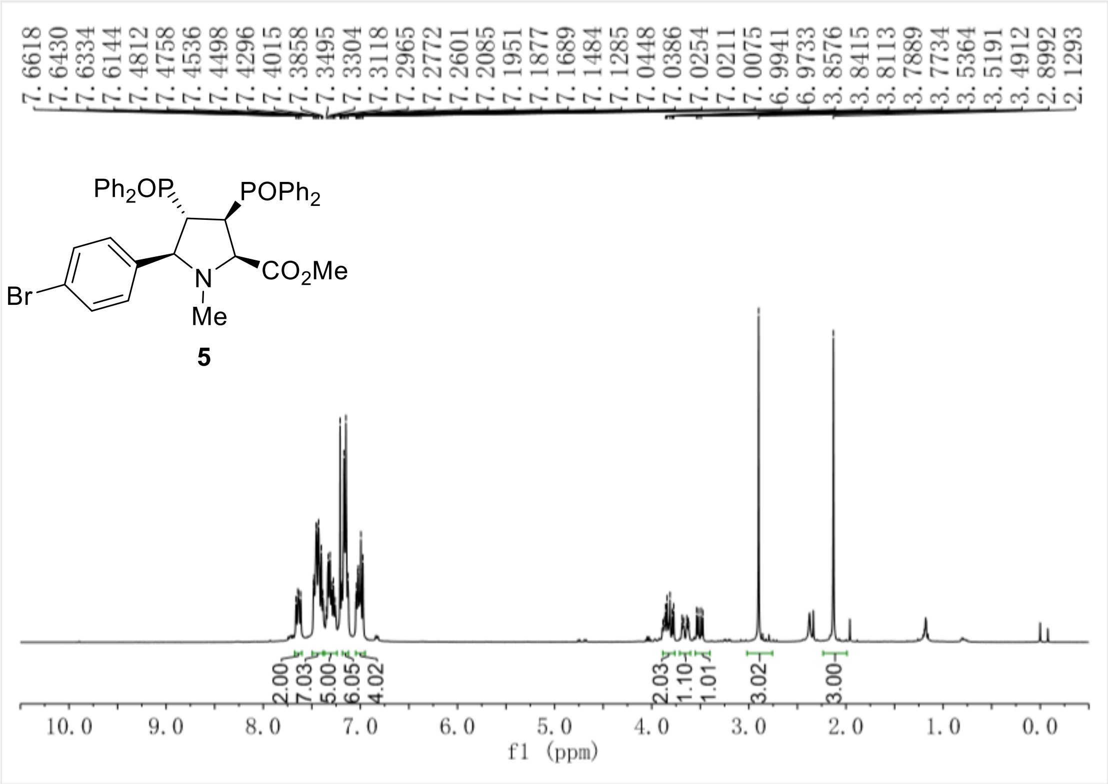
$^{1}$**H NMR** (400 MHz, CDCl$_3$), $^{31}$**P NMR** (162 MHz, CDCl$_3$) and $^{13}$**C NMR** (101 MHz, CDCl$_3$) of **4**

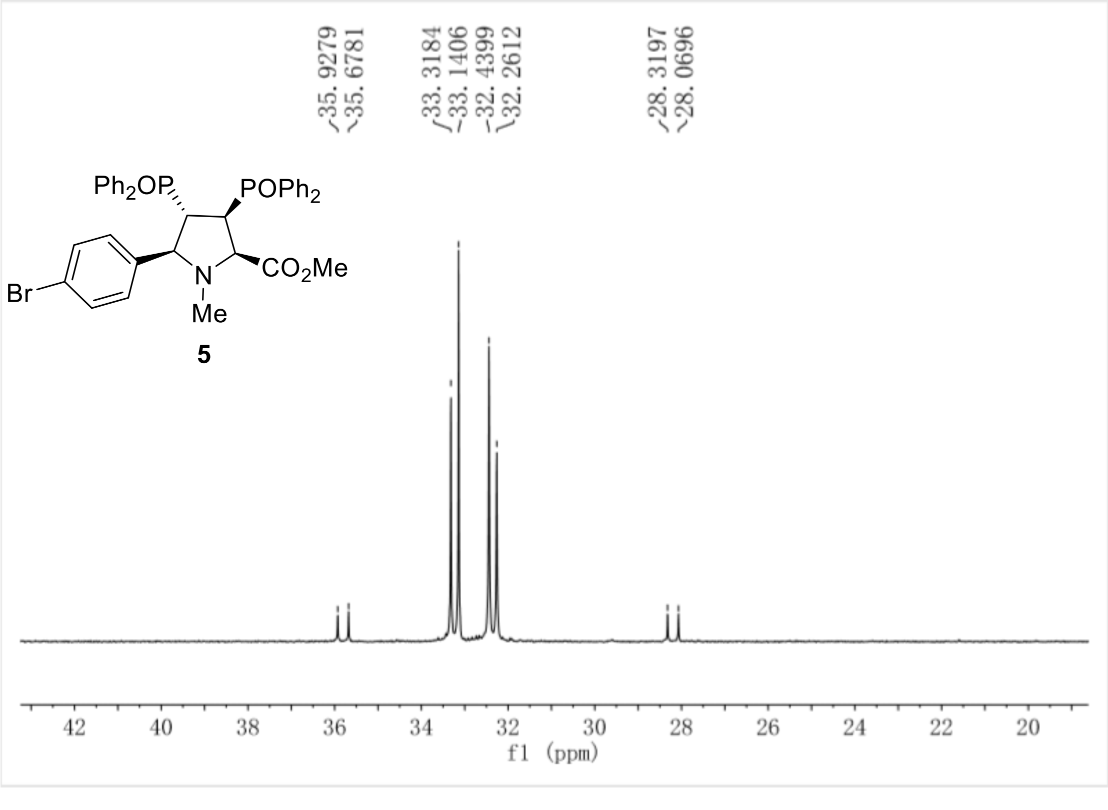


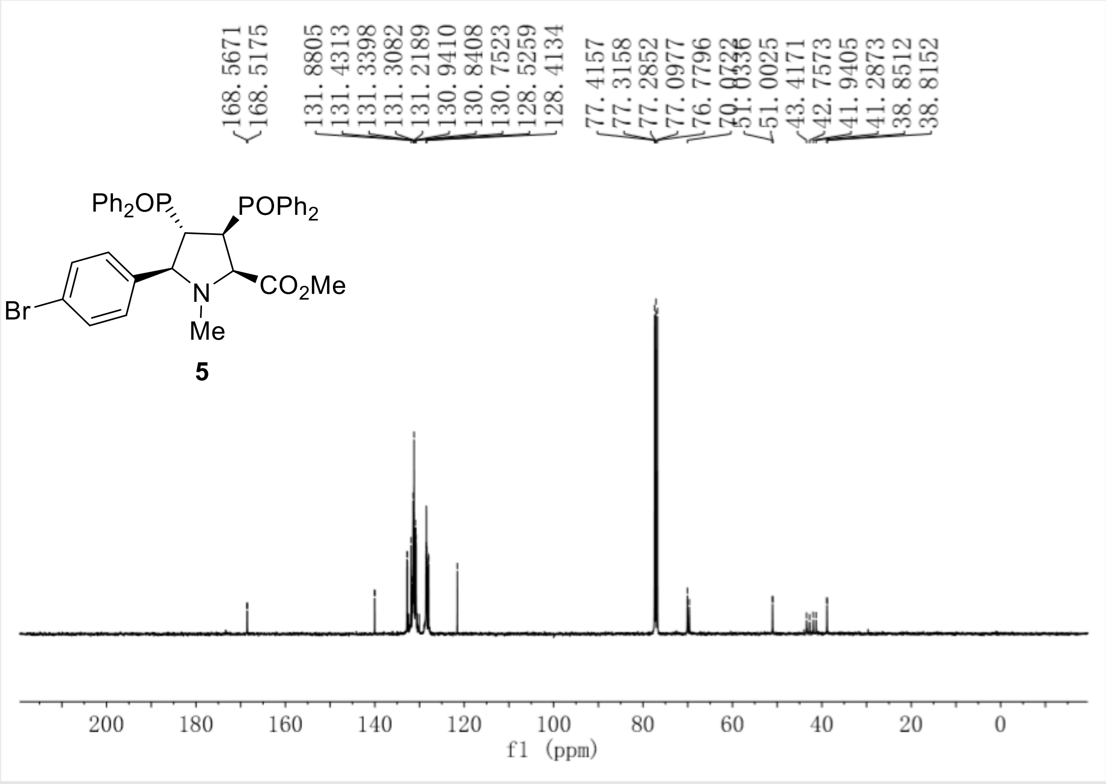

**4**
35. 6626
35. 4786
33. 3685
33. 1846
Ph$_2$OP
POPh$_2$
CH$_2$OH
N
H
Br
80
0
−90
f1 (ppm)


**4**
140. 3535
131. 8107
131. 5137
131. 3127
130. 5471
130. 4608
130. 2961
130. 2277
130. 1469
129. 6852
128. 9312
128. 8092
128. 7510
128. 6907
128. 6361
128. 3808
128. 2654
125. 1504
121. 4989
77. 3174
76. 9998
76. 6813
67. 4351
64. 1175
61. 5831
48. 6744
48. 0279
42. 0592
41. 3979
Ph$_2$OP
POPh$_2$
CH$_2$OH
N
H
Br
170
150
130
110
90
80
70
60
50
40
30
20
10
0
f1 (ppm)

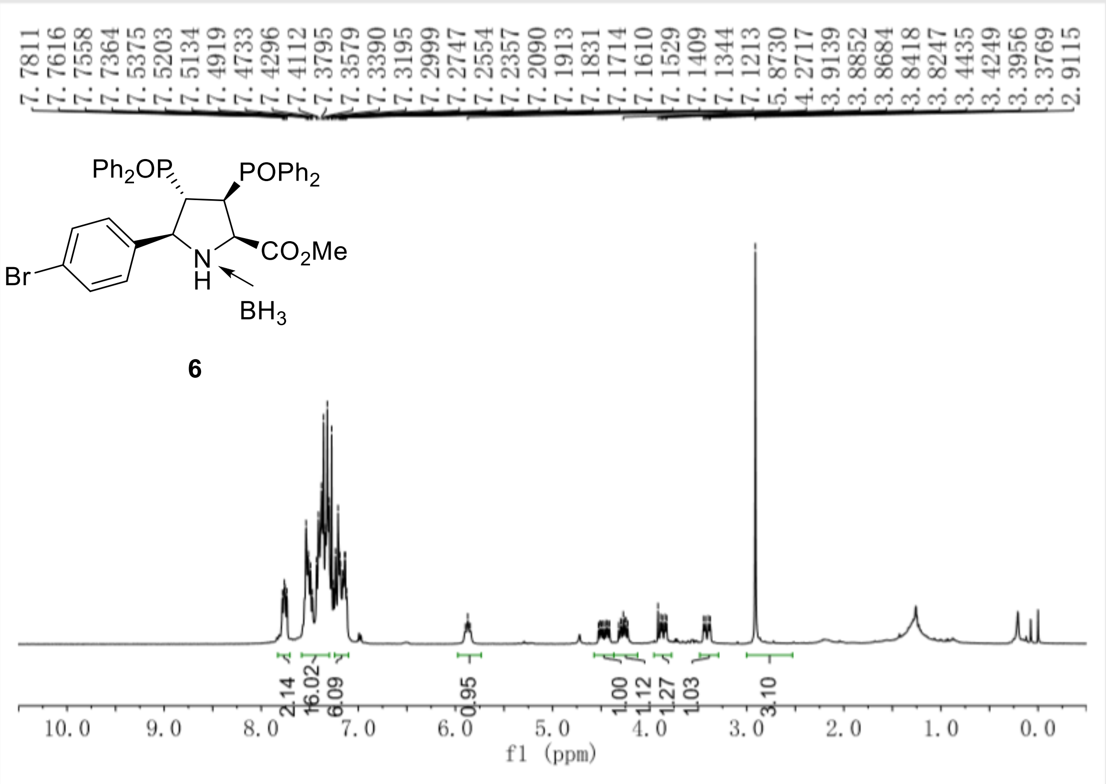
$^{1}$**H NMR** (400 MHz, CDCl$_3$), $^{31}$**P NMR** (162 MHz, CDCl$_3$) and $^{13}$**C NMR** (101 MHz, CDCl$_3$) of **5**

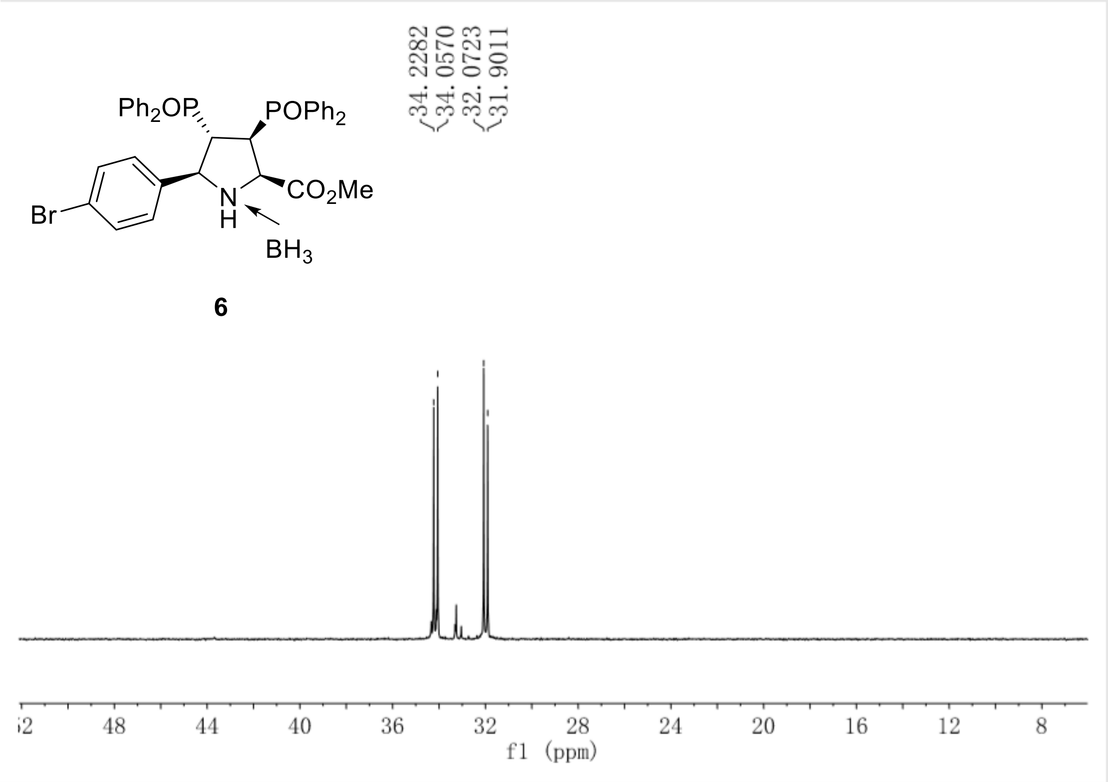




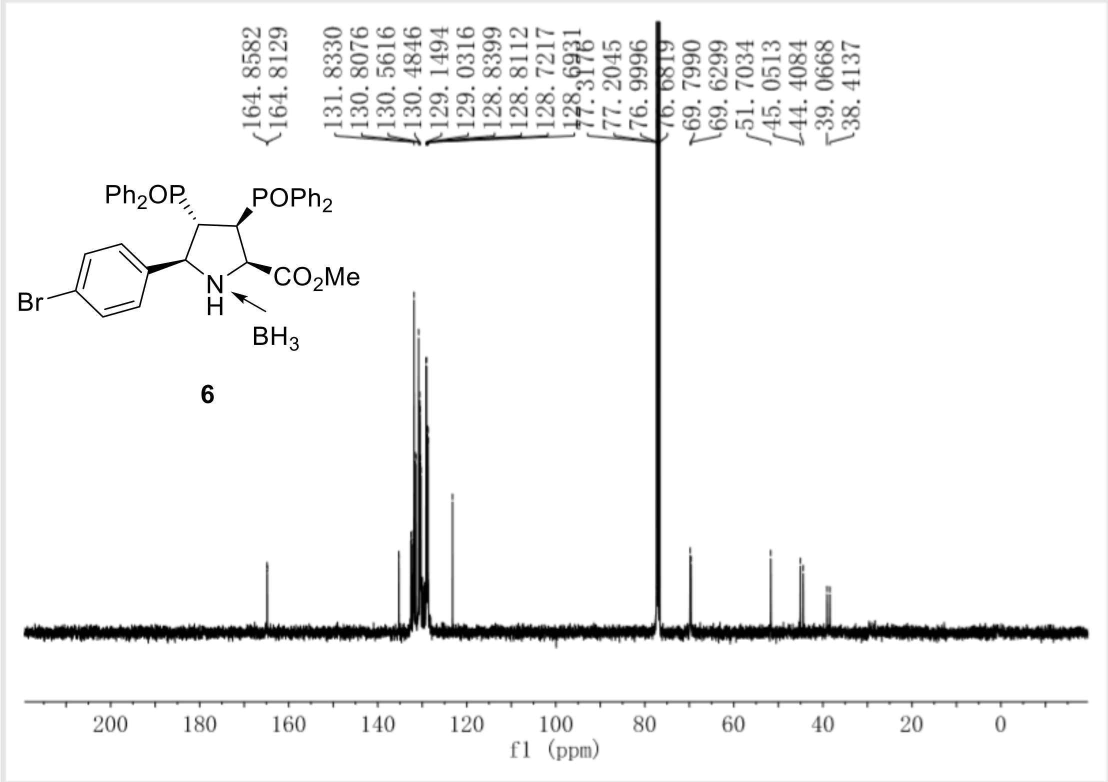


**$^1$H NMR** (400 MHz, CDCl$_3$), **$^{31}$P NMR** (162 MHz, CDCl$_3$) and **$^{13}$C NMR** (101 MHz, CDCl$_3$) of **6**



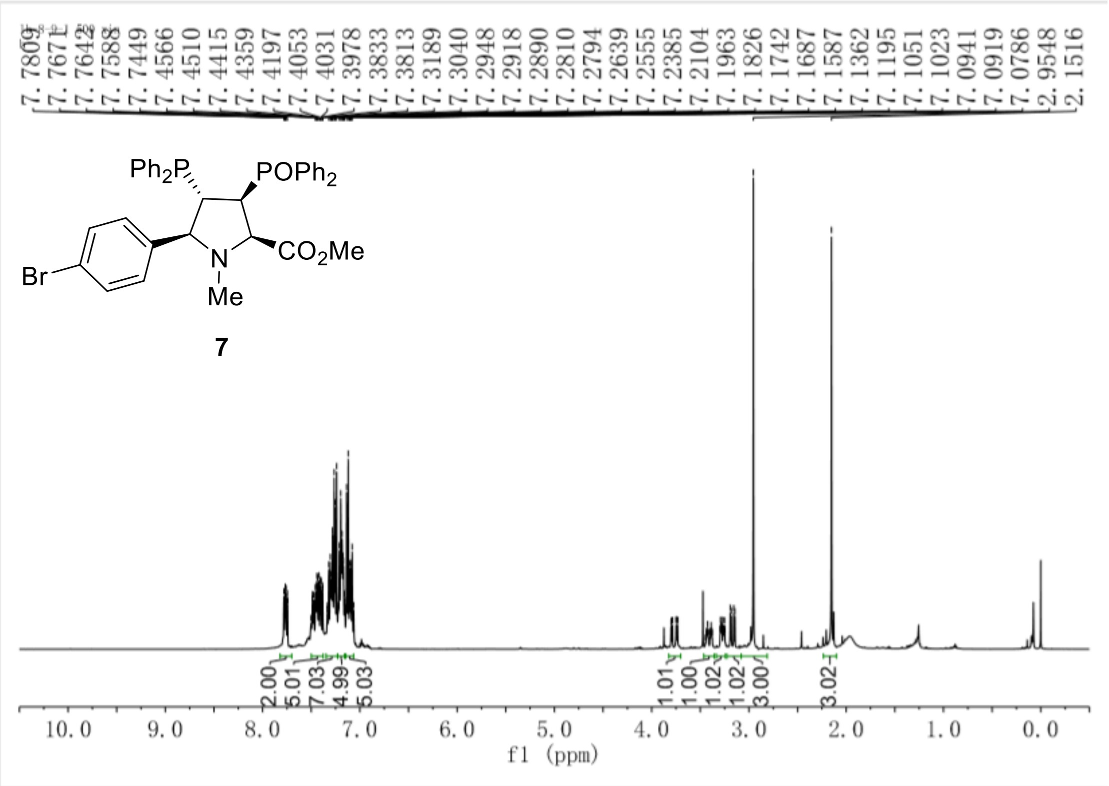


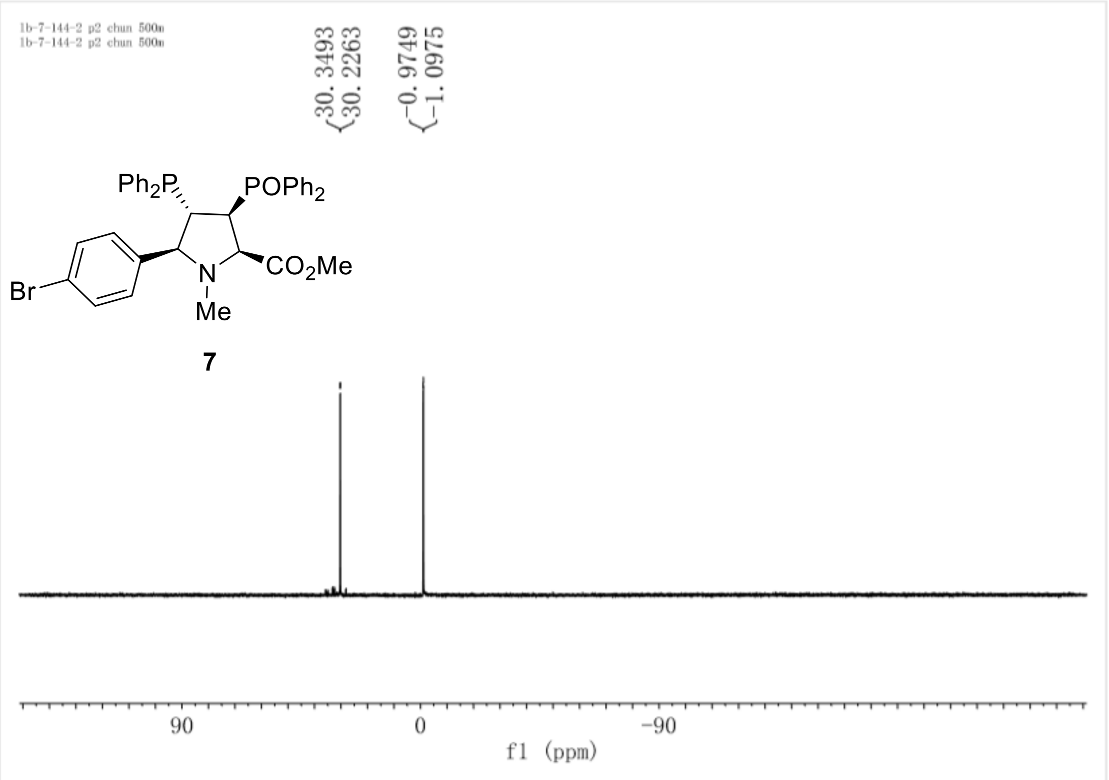
34.2282
34.0570
32.0723
31.9011
Ph2OP
POPh2
CO2Me
Br
N
H
BH3
6
52
48
44
40
36
32
28
24
20
16
12
8
f1 (ppm)

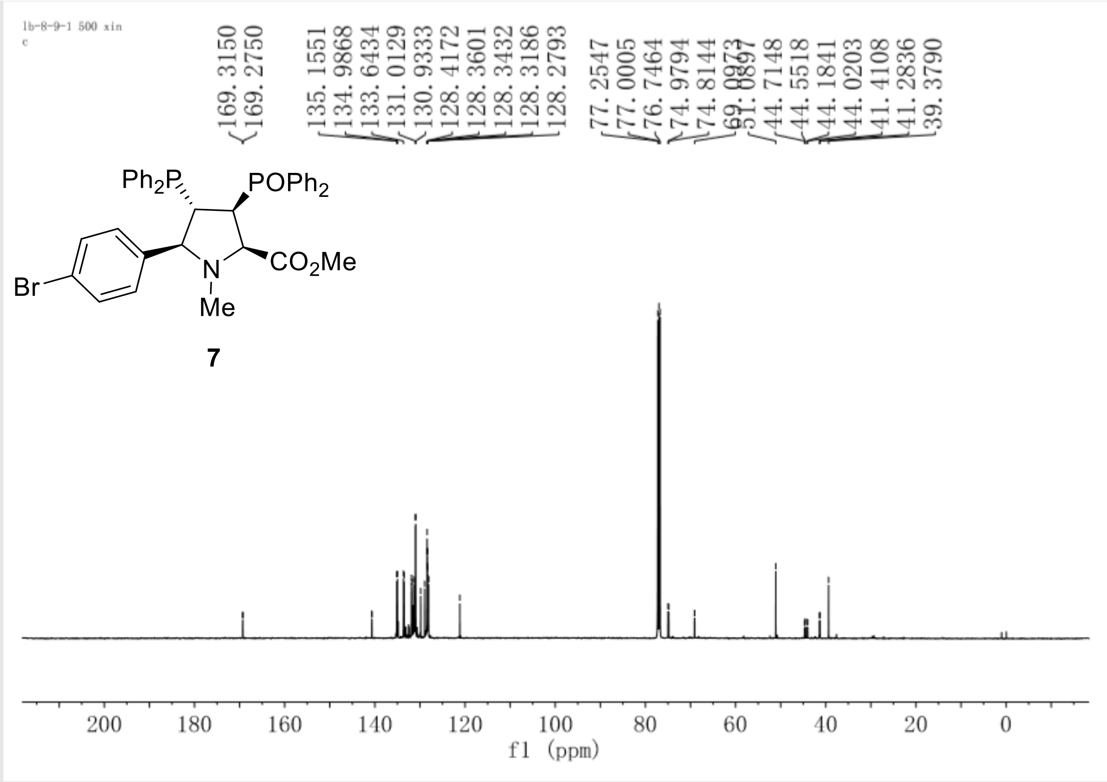


164.8582
164.8129
131.8330
130.8076
130.5616
130.4846
129.1494
129.0316
128.8399
128.8112
128.7217
128.6931
77.3176
77.2045
76.9996
76.6819
69.7990
69.6299
51.7034
45.0513
44.4084
39.0668
38.4137
Ph2OP
POPh2
CO2Me
Br
N
H
BH3
6
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

**$^{1}$H NMR** (500 MHz, CDCl$_3$), **$^{31}$P NMR** (202 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **7**

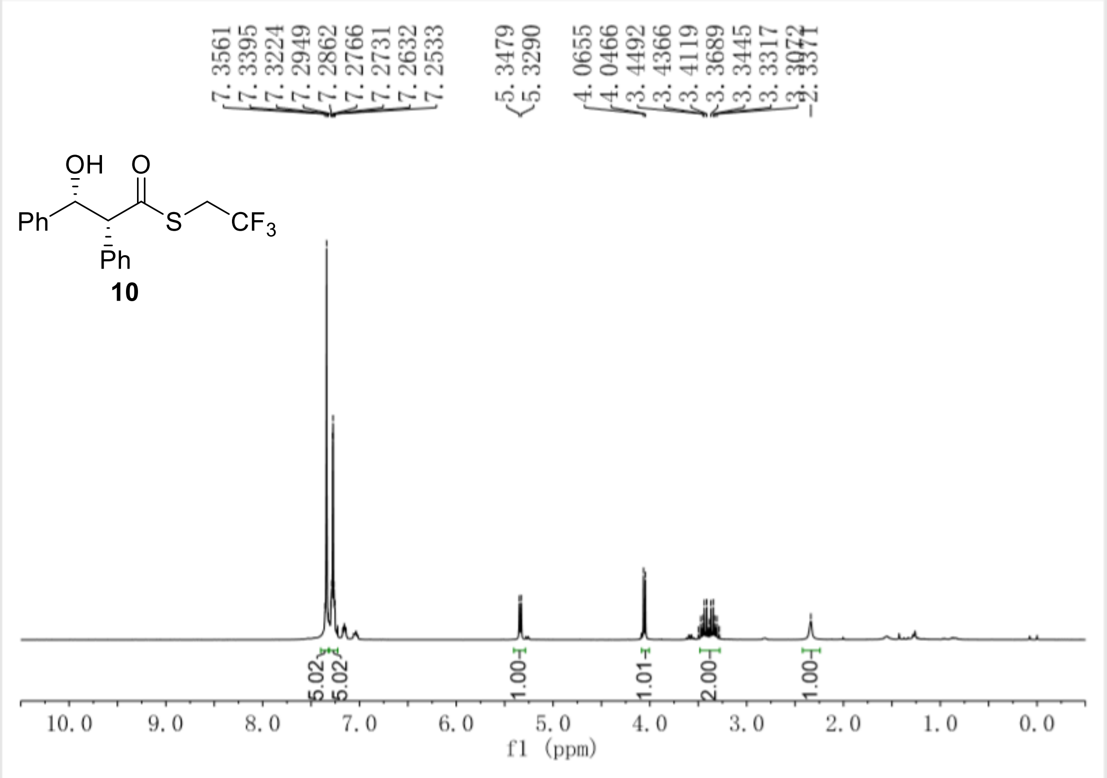




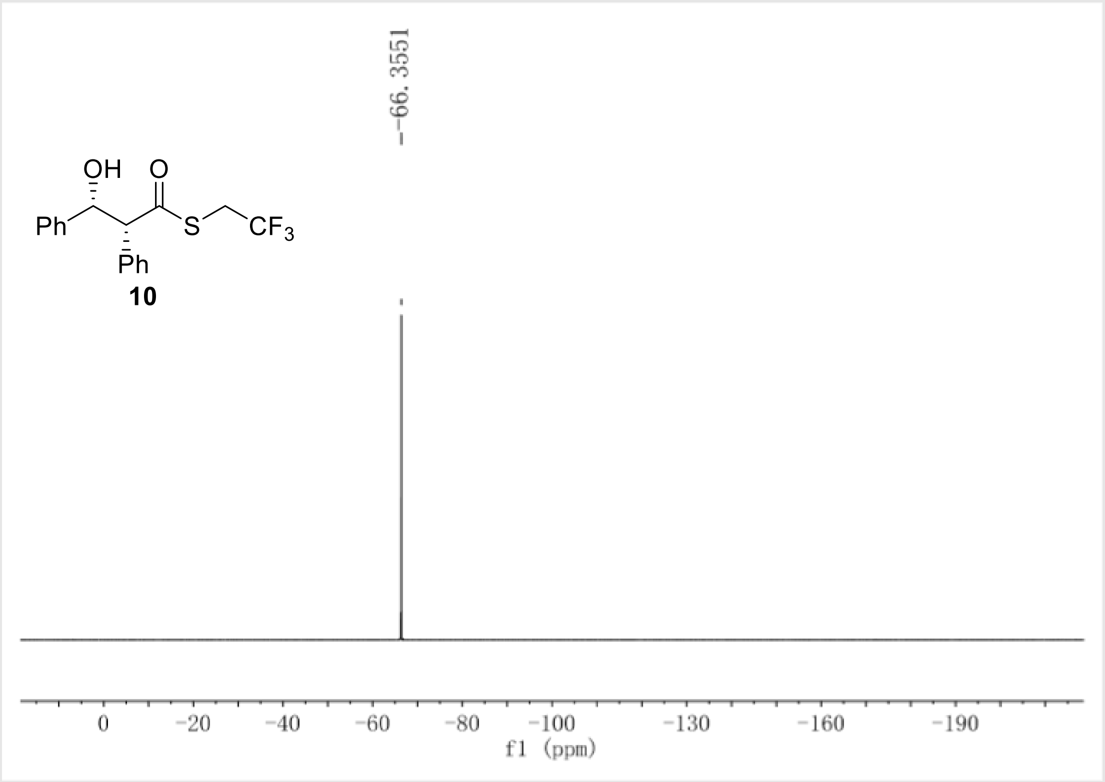


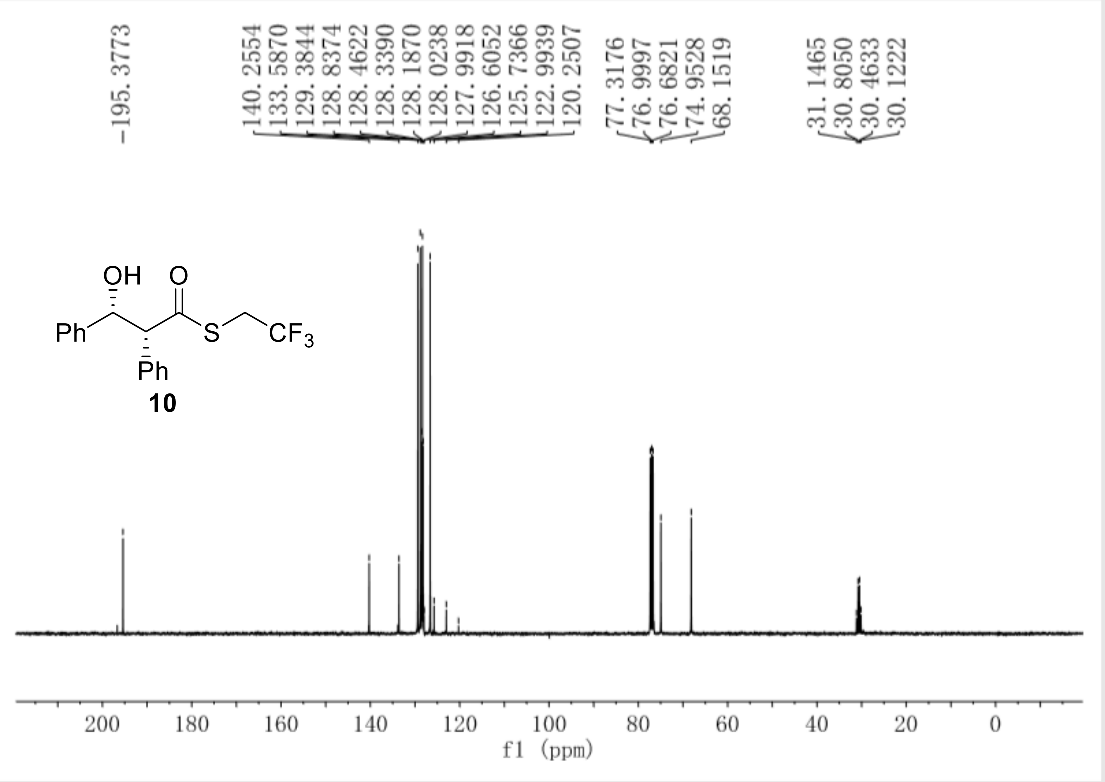
**7**

$^{1}$**H NMR** (400 MHz, CDCl$_3$), $^{19}$**F NMR** (282 MHz, CDCl$_3$) and $^{13}$**C NMR** (101 MHz, CDCl$_3$) of **10**



**10**


-66.3551
OH
O
Ph
S
CF3
Ph
10
0
-20
-40
-60
-80
-100
-130
-160
-190
f1 (ppm)


-195.3773
140.2554
133.5870
129.3844
128.8374
128.4622
128.3390
128.1870
128.0238
127.9918
126.6052
125.7366
122.9939
120.2507
77.3176
76.9997
76.6821
74.9528
68.1519
31.1465
30.8050
30.4633
30.1222
OH
O
Ph
S
CF3
Ph
10
200
180
160
140
120
100
80
60
40
20
0
f1 (ppm)

**$^{1}$H NMR** (300 MHz, CDCl$_3$) and **$^{13}$C NMR** (126 MHz, CDCl$_3$) of **13**