Supporting Information

Catalytic Enantioselective Fluorination and Amination of β-Keto Phosphonates Catalyzed by Chiral Palladium Complexes

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1.1. General

All reactions were carried out in oven-dried glassware under an atmosphere of dry nitrogen unless otherwise noted. All reaction were magnetically stirred and monitored by analytical thin layer chromatography using Merck pre-coated silica gel plates with F₂₅₄ indicator. Visualization was accomplished by UV light (256 nm), I₂, *p*-anisaldehyde, and phosphomolybdic acid, solution as an indicator. Flash column chromatography was performed according to the method of still using silicagel 60 (mesh 230-400) supplied by E. Merck. Yields refer to chromatographically and spectrographically pure compounds, unless otherwise noted.

¹H NMR and ¹³C NMR spectra were recorded on a Bruker AC 200 (200 MHz for ¹H, 50 MHz for ¹³C). Chemical shift values (δ) are reported in ppm relative to Me₄Si (δ 0.0 ppm). The proton spectra are reported as follows d (multiplicity, coupling constant *J*, number of protons). Multiplicities are indicated by s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet) and br (broad). Mass spectra were measured on a Jeol HX110/110A using electrospray ionization techniques. Optical rotations were measured with a JASCO-DIP-1000 digital polarimeter. Melting points were determined using an electrothermal apparatus and are uncorrected. High-performance liquid chromatography (HPLC) was performed on a Younglin M930 Series equipped with variable wavelength detector using chiral stationary column (250 mm, 4.6 mm) such as Chiralcel OD-H, OJ, Chiralpak AD, and Chiralhyun-Leu-1 columns. β-Keto phosphonates **3a-3g**,¹⁴ **3h-3i**,¹⁵ **3j-3p**¹⁶ were synthesized according to the literature procedures.

1.2. Preparation of Palladium complexes

Preparations of Palladium complexes were prepared according to the reported procedure.¹²

Pd((R)-Xylyl-BINAP)(H₂O)(CH₃CN)²⁺(BF₄⁻)₂ **1c:** To a solution of PdCl₂((R)-Xylyl-BINAP) (99.1 mg, 0.1086 mmol) in methylene chloride (6 mL) was added AgBF₄ (52.8 mg, 0.2715 mmol) in acetonitrile (3.0 mL) at room temperature. The reaction mixture was stirred at rt for 21 h. The precipitate AgCl was filtered off on celite, and the filtrate was evaporated under reduced pressure. The product was recrystallized from CH₂Cl₂-ether to afford **1c** (72.8 mg, 62 %): yellow powder; mp 159-160 °C (dec.); [α]_D²⁰ = +512.24 (c = 0.5, CHCl₃); ¹H NMR (200 MHz, CDCl₃) δ 1.98 (brs, 15H), 2.43 (s, 12H), 3.70 (brs, 2H), 6.38-6.58 (m, 4H), 7.12-7.77 (m, 20H).

1.3. General procedure for the fluorination of β -keto phosphonates: To a stirred solution of β -keto phosphonate (0.3 mmol) and catalyst **1c** (16.1 mg, 0.015 mmol) in MeOH (3 mL) was added NFSI (141.9 mg, 0.45 mmol) at room temperature. Reaction mixture was stirred for 3-94h at room temperature. The mixture was diluted with saturated NH₄Cl solution (30 mL) and extracted with ethyl ether (2 $\times$ 30 mL). The combined organic layers were dried over MgSO₄, filtered, concentrated, and purified by flash chromatography to afford the α -fluoro β -keto phosphonate.

2-(Diethoxyphosphinyl)-2-fluoro-1-oxo-1,2,3,4-tetrahydronaphthalene (4a**):** *R_f* 0.47 (EtOAc : CH₂Cl₂ = 1 : 4); [α]_D²³ = +46.64 (c = 1.0, CHCl₃, 97% ee); ¹H NMR (200 MHz, CDCl₃) δ 1.12 (t, *J* = 6.8 Hz, 3H), 1.36 (t, *J* = 6.9 Hz, 3H), 2.31-2.73 (m, 1H), 2.76-2.96 (m, 1H), 3.03-3.18 (m, 1H), 3.40-3.58 (m, 1H), 4.00-4.17 (m, 2H), 4.22-4.37 (m, 2H), 7.24-7.37 (m, 2H), 7.49-7.57 (m, 1H), 8.05 (dd, *J* = 7.8, 1.2 Hz, 1H); ¹³C NMR (50 MHz, CDCl₃) δ 16.0 (d, *J* = 6.2 Hz), 16.4 (d, *J* = 5.7 Hz), 26.0 (d, *J* = 11.0 Hz), 36.7 (d, *J* = 19.8 Hz), 63.9 (d, *J* = 7.2 Hz), 64.6 (dd, *J* = 9.1, 1.7 Hz), 95.6 (dd, *J* = 192.2, 156.5 Hz), 127.0, 128.0, 128.7, 131.5, 134.4, 143.3, 190.7 (dd, *J* = 14.3, 2.7 Hz); HRMS calcd for C₁₄H₁₈FO₄PNa ([M+Na]⁺) 323.0824, found 323.0816; *R_t* HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.2 mL/min) Chiralpak AD column, *t_R* = 6.6 min (major), *t_R* = 8.5 (minor).

2-(Dimethoxyphosphinyl)-2-fluoro-1-oxo-1,2,3,4-tetrahydronaphthalene (4b**):**

R_f 0.51 (EtOAc : CH₂Cl₂ = 1 : 3); [α]_D²³ = +51.36 (c = 1.0, CHCl₃, 93% ee); ¹H NMR (200 MHz, CDCl₃) δ

2.35-2.68 (m, 1H), 2.71-2.95 (m, 1H), 3.03-3.15 (m, 1H), 3.37-3.54 (m, 1H), 3.74 (d, $J = 10.8$ Hz, 3H), 3.93 (d, $J = 10.7$ Hz, 3H), 7.25-7.38 (m, 2H), 7.50-7.58 (m, 1H), 8.07 (dd, $J = 7.8, 1.0$ Hz, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 25.9 (d, $J = 11.1$ Hz), 31.7 (d, $J = 20.0$ Hz), 54.4 (d, $J = 7.2$ Hz), 55.0 (dd, $J = 6.8, 2.6$ Hz), 95.8 (d, $J = 192.0, 157.1$ Hz) 127.2, 128.3, 128.9, 131.3, 134.6, 143.3, 190.4 (d, $J = 11.1$ Hz); HRMS calcd for $\text{C}_{12}\text{H}_{14}\text{FO}_4\text{PNa}$ ($[\text{M}+\text{Na}]^+$) 295.0511, found 295.0523; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.2 mL/min) Chiralpak AD column, $t_R = 8.6$ min (major), $t_R = 10.2$ (minor).

2-(Diisopropoxyphosphinyl)-2-fluoro-1-oxo-1,2,3,4-tetrahydronaphthalene (4c);

R_f 0.51 (EtOAc : $\text{CH}_2\text{Cl}_2 = 1 : 3$); $[\alpha]_D^{23} = +30.04$ ($c = 1.0$, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.10 (d, $J = 6.2$ Hz, 3H), 1.15 (d, $J = 6.2$ Hz, 3H), 1.35 (s, 3H), 1.38 (s, 3H), 2.31-2.71 (m, 1H), 2.77-2.96 (m, 1H), 3.01-3.12 (m, 1H), 3.40-3.57 (m, 1H), 4.58-4.73 (m, 1H), 4.78-4.94 (m, 1H), 7.22-7.36 (m, 2H), 7.47-7.55 (m, 1H), 8.04 (d, $J = 7.8$ Hz, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 23.4 (d, $J = 3.5$ Hz), 23.5 (d, $J = 2.8$ Hz), 23.7 (d, $J = 3.6$ Hz), 24.2 (d, $J = 2.9$ Hz), 26.1 (d, $J = 11.3$ Hz), 31.6 (d, $J = 19.9$ Hz), 73.0 (d, $J = 7.7$ Hz), 73.6 (d, $J = 7.4$ Hz), 95.4 (dd, $J = 191.7, 158.8$ Hz) 126.8, 127.7, 128.5, 131.8, 134.1, 143.1, 190.7 (dd, $J = 14.0, 3.0$ Hz); HRMS calcd for $\text{C}_{16}\text{H}_{22}\text{FO}_4\text{PNa}$ ($[\text{M}+\text{Na}]^+$) 351.1137, found 351.1145; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.2 mL/min) Chiralpak AD column, $t_R = 5.4$ min (major), $t_R = 7.2$ (minor).

2-(Diethoxyphosphinyl)-5,7-dimethyl-2-fluoro-1-oxo-1,2,3,4-tetrahydronaphthalene (4d);

R_f 0.58 (EtOAc : $\text{CH}_2\text{Cl}_2 = 1 : 3$); $[\alpha]_D^{23} = +34.08$ ($c = 1.0$, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.12 (t, $J = 7.0$ Hz, 3H), 1.35 (t, $J = 7.1$ Hz, 3H), 2.27 (s, 3H), 2.33 (s, 3H), 2.38-2.69 (m, 1H), 2.77-3.05 (m, 2H), 3.12-3.29 (m, 1H), 3.95-4.16 (m, 2H), 4.19-4.37 (m, 2H), 7.22 (s, 1H), 7.73 (s, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.2 (d, $J = 5.9$ Hz), 16.5 (d, $J = 5.7$ Hz), 19.3, 21.0, 23.6 (d, $J = 11.1$ Hz), 31.2 (d, $J = 19.5$ Hz), 64.0 (d, $J = 7.1$ Hz), 64.7 (d, $J = 6.9$ Hz), 95.6 (dd, $J = 192.3, 157.0$ Hz) 126.1, 131.7, 136.3, 136.5, 137.0, 138.9, 190.7 (dd, $J = 13.7, 3.7$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 10.4$ min (major), $t_R = 13.6$ (minor).

2-(Diethoxyphosphinyl)-6-methoxy-2-fluoro-1-oxo-1,2,3,4-tetrahydronaphthalene (4e);

R_f 0.42 (EtOAc : CH₂Cl₂ = 1 : 3); $[\alpha]_D^{23} = +32.52$ ($c = 1.0$, CHCl₃, 95% ee); ¹H NMR (200 MHz, CDCl₃) δ 1.17 (t, $J = 6.9$ Hz, 3H), 1.37 (t, $J = 6.9$ Hz, 3H), 2.38-2.70 (m, 1H), 2.73-2.93 (m, 1H), 2.97-3.10 (m, 1H), 3.38-3.55 (m, 1H), 3.86 (s, 3H), 4.00-4.20 (m, 2H), 4.22-4.37 (m, 2H), 6.70 (d, $J = 2.4$ Hz, 1H), 6.90 (dd, $J = 8.8$, 2.5 Hz, 1H), 8.02 (d, $J = 8.8$ Hz); ¹³C NMR (50 MHz, CDCl₃) δ 16.2 (d, $J = 5.9$ Hz), 16.5 (d, $J = 5.6$ Hz), 26.4 (d, $J = 11.1$ Hz), 31.7 (d, $J = 20.0$ Hz), 55.6, 64.1 (d, $J = 7.1$ Hz), 64.6 (dd, $J = 7.3$, 1.6 Hz), 95.3 (dd, $J = 191.0$, 156.3 Hz), 112.4, 114.0, 125.1, 130.6, 145.9, 164.5, 189.1 (dd, $J = 14.3$, 2.7 Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.2 mL/min) Chiralpak AD column, $t_R = 10.1$ min (major), $t_R = 14.1$ (minor).

2-(Diethoxyphosphinyl)-2-fluoroindanone (4f);

R_f 0.51 (EtOAc : CH₂Cl₂ = 1 : 3); $[\alpha]_D^{23} = +66.12$ ($c = 1.0$, CHCl₃, 97% ee); ¹H NMR (200 MHz, CDCl₃) δ 1.22 (t, $J = 6.9$ Hz, 3H), 1.37 (t, $J = 6.9$ Hz, 3H), 3.28-3.62 (m, 1H), 3.87-4.08 (m, 1H), 4.11-4.40 (m, 4H), 7.40-7.49 (m, 2H), 7.63-7.72 (m, 1H), 7.80 (d, $J = 7.6$ Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 16.2 (d, $J = 5.3$ Hz), 16.4 (d, $J = 5.3$ Hz), 36.5 (d, $J = 21.2$ Hz), 64.3, 64.4, 95.9 (dd, $J = 199.5$, 163.8 Hz), 125.1, 126.4, 128.5, 134.1, 136.5, 149.7 (d, $J = 4.6$ Hz), 196.4 (d, $J = 14.4$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 9.1$ min (major), $t_R = 10.6$ (minor).

2-(Diethoxyphosphinyl)-5,6-dimethoxy-2-fluoroindanone (4g);

R_f 0.45 (EtOAc); $[\alpha]_D^{23} = +32.20$ ($c = 1.0$, CHCl₃, 95% ee); ¹H NMR (200 MHz, CDCl₃) δ 1.28 (t, $J = 6.9$ Hz, 3H), 1.39 (t, $J = 6.9$ Hz, 3H), 3.18-3.44 (m, 1H), 3.77-3.89 (m, 1H), 3.91 (s, 3H), 3.99 (s, 1H), 4.14-4.37 (m, 4H), 6.86 (s, 1H), 7.20 (s, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 16.3 (d, $J = 5.3$ Hz), 16.4 (d, $J = 7.6$ Hz), 36.2 (d, $J = 23.5$ Hz), 56.3 (dd, $J = 29.2$, 3.8 Hz), 64.4 (dd, $J = 26.6$, 6.9 Hz), 95.9 (dd, $J = 200.2$, 163.1 Hz), 105.1,

107.2, 126.8, 126.9, 128.2, 145.7, 150.2, 157.0, 194.6 (d, $J = 15.2$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 16.4$ min (major), $t_R = 21.2$ (minor).

2-(Diethoxyphosphinyl)-2-fluorocyclopentanone (4h);

R_f 0.39 (EtOAc : $\text{CH}_2\text{Cl}_2 = 1 : 3$); $[\alpha]_D^{23} = +225.6$ ($c = 1.0$, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.36 (t, $J = 7.2$ Hz, 3H), 1.39 (t, $J = 7.2$ Hz, 3H), 2.05-2.59 (m, 5H), 2.68-2.82 (m, 1H), 4.10-4.34 (m, 4H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.4 (dd, $J = 5.7, 2.9$ Hz), 16.9 (dd, $J = 5.2, 4.1$ Hz), 32.1 (dd, $J = 18.3, 2.7$ Hz), 35.4, 35.5, 64.1, 64.3 (d, $J = 2.1$ Hz), 96.3 (dd, $J = 200.3, 165.8$ Hz), 209.0 (d, $J = 10.2$ Hz). For the HPLC analysis, 2,4-dinitrophenylhydrazone derivatives were prepared according to the reported procedure.¹⁷

2-(Diethoxyphosphinyl)-2-fluoro-1-[(2,4-dinitrophenyl)hydrazone]cyclopentane;

R_f 0.50 (EtOAc : $\text{CH}_2\text{Cl}_2 = 1 : 3$); $[\alpha]_D^{23} = +58.96$ ($c = 0.5$, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.37-1.45 (m, 6H), 2.14-2.85 (m, 6H), 4.16-4.40 (m, 4H), 8.05 (d, $J = 9.3$ Hz, 1H), 8.36 (dd, $J = 9.5, 2.31$ Hz, 1H), 9.14 (d, $J = 2.6$ Hz, 1H), 10.93 (s, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.7 (dd, $J = 5.1, 5.0$ Hz), 20.5 (dd, $J = 7.8, 2.5$ Hz), 27.2, 27.3, 35.2 (dd, $J = 20.1, 3.7$ Hz), 63.8 (d, $J = 7.0$ Hz), 64.3 (d, $J = 6.7$ Hz), 97.9 (dd, $J = 193.4, 178.0$ Hz), 117.0, 123.4, 130.3, 139.1, 145.0, 158.5 (d, $J = 14.6$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 33.8$ min (major), $t_R = 48.3$ (minor).

2-(Diethoxyphosphinyl)-2-fluorocyclohexanone (4i);

R_f 0.61 (EtOAc); $[\alpha]_D^{23} = +155.04$ ($c = 1.0$, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.34 (t, $J = 7.0$ Hz, 3H), 1.39 (t, $J = 7.0$ Hz, 3H), 1.60-2.30 (m, 5H), 2.58-2.73 (m, 2H), 2.83-2.99 (m, 1H), 4.09-4.36 (m, 4H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.4 (dd, $J = 5.9, 3.6$ Hz), 21.4 (dd, $J = 7.6, 2.8$ Hz), 25.1, 26.8, 35.8 (d, $J = 19.6$ Hz), 40.7, 66.2 (d, $J = 3.0$ Hz), 66.3 (d, $J = 3.5$ Hz), 97.6 (dd, $J = 193.8, 165.0$ Hz), 202.5 (dd, $J = 15.6$,

4.3 Hz). For the HPLC analysis, 2,4-dinitrophenylhydrazone derivatives were prepared according to the reported procedure.¹⁷

2-(Diethoxyphosphinyl)-2-fluoro-1-[(2,4-dinitrophenyl)hydrazone]cyclohexane;

R_f 0.52 (EtOAc : CH_2Cl_2 = 1 : 3); $[\alpha]_D^{23}$; -43.76 (c = 0.5, CHCl_3 , 95% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.32-1.45 (m, 6H), 1.67-2.10 (m, 4H), 2.05-2.83 (m, 4H), 4.16-4.38 (m, 4H), 8.18 (d, J = 9.5 Hz, 1H), 8.36 (dd, J = 9.5, 2.2 Hz, 1H), 9.13 (d, J = 2.4 Hz, 1H), 11.25 (s, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.7 (d, J = 5.6 Hz), 20.3 (dd, J = 6.9, 5.4 Hz), 24.6, 24.7, 24.9, 34.7 (d, J = 14.9 Hz), 63.5 (d, J = 7.2 Hz), 64.1 (d, J = 6.0 Hz), 95.8 (dd, J = 182.9, 173.6 Hz), 117.5, 123.3, 130.4, 138.9, 145.4, 152.7 (d, J = 18.5 Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.2 mL/min) Chiralcel OD-H column, t_R = 20.6 min (major), t_R = 25.0 (minor).

Diethyl 1-fluoro-1-methyl-2-oxo-2-phenylethylphosphonate (4j);

R_f 0.42 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23}$ = -15.52 (c = 1.0, CHCl_3 , 91% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.34 (t, J = 6.7 Hz, 3H), 1.35 (t, J = 6.8 Hz, 3H), 1.92 (dd, J = 24.0, 15.1 Hz, 3H), 4.16-4.36 (m, 4H), 7.41-7.62 (m, 3H), 8.05-8.11 (m, 2H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.4, 16.6, 21.6 (d, J = 21.8 Hz), 64.2 (d, J = 1.5 Hz), 64.3 (d, J = 2.1 Hz), 100.6 (dd, J = 194.3, 160.6 Hz), 128.3, 130.1, 130.6, 133.5, 197.7 (dd, J = 23.0, 3.7 Hz); HRMS calcd for $\text{C}_{13}\text{H}_{18}\text{FO}_4\text{PNa}$ ($[\text{M}+\text{Na}]^+$) 311.0824, found 311.0834; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 0.5 mL/min) Chiralpak AD column, t_R = 13.4 min (minor), t_R = 14.1 (major).

Diethyl 1-fluoro-1-methyl-2-oxo-2-(4-chlorophenyl)ethylphosphonate (4k);

R_f 0.45 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23}$ = -20.12 (c = 1.0, CHCl_3 , 91% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.34 (t, J = 7.1 Hz, 3H), 1.37 (t, J = 7.0 Hz, 3H), 1.90 (dd, J = 24.2, 14.9 Hz, 3H), 4.13-4.36 (m, 4H), 7.43 (d,

$J = 8.7$ Hz, 2H), 8.05 (dd, $J = 8.6, 1.6$ Hz, 2H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.5 (d, $J = 1.5$ Hz), 16.6 (d, $J = 1.3$ Hz), 21.5 (d, $J = 21.8$ Hz), 64.4, 64.5, 100.7 (dd, $J = 193.7, 160.0$ Hz), 128.7, 131.8, 131.9, 140.2, 196.5 (dd, $J = 23.1, 3.8$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 0.5 mL/min) Chiralpak AD column, $t_R = 12.7$ min (minor), $t_R = 13.6$ (major).

Diethyl 1-fluoro-1-methyl-2-oxo-2-(4-nitrophenyl)ethylphosphonate (4l);

R_f 0.41 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23} = -34.24$ ($c = 1.0$, CHCl_3 , 87% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.36 (t, $J = 7.1$ Hz, 3H), 1.39 (t, $J = 6.9$ Hz, 3H), 1.93 (dd, $J = 24.1, 14.7$ Hz, 3H), 4.16-4.39 (m, 4H), 8.21-8.33 (m, 4H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.5 (d, $J = 2.7$ Hz), 16.6 (d, $J = 2.7$ Hz), 21.3 (d, $J = 21.8$ Hz), 64.6, 64.7, 100.7 (dd, $J = 192.4, 159.9$ Hz), 123.4, 131.2, 131.3, 150.3, 197.1 (d, $J = 28.5$ Hz); R_t HPLC (95:5, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralcel OJ column, $t_R = 27.0$ min (major), $t_R = 32.2$ (minor).

Diethyl 1-fluoro-1-methyl-2-oxo-2-(4-methoxyphenyl)ethylphosphonate (4m);

R_f 0.21 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23} = -6.72$ ($c = 0.5$, CHCl_3 , 91% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.34 (t, $J = 6.7$ Hz, 3H), 1.35 (t, $J = 6.7$ Hz, 3H), 1.91 (dd, $J = 24.2, 15.1$ Hz, 3H), 4.14-4.36 (m, 4H), 6.93 (d, $J = 9.1$ Hz, 2H), 8.14 (dd, $J = 7.3, 2.1$ Hz, 2H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.5, 16.7, 21.8 (d, $J = 21.9$ Hz), 55.7, 64.2, 64.4, 100.8 (dd, $J = 194.0, 160.7$ Hz), 113.7, 132.9, 133.1, 164.1, 195.5 (d, $J = 22.1$ Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 0.5 mL/min) Chiralpak AD column, $t_R = 19.2$ min (minor), $t_R = 24.9$ (major).

Diethyl 1-benzyl-1-fluoro-2-oxo-2-phenylethylphosphonate (4n);

R_f 0.41 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23} = +25.60$ ($c = 1.0$, CHCl_3 , 91% ee); ^1H NMR (200 MHz, CDCl_3)

δ 1.34 (t, J = 6.7 Hz, 3H), 1.36 (t, J = 6.7 Hz, 3H), 3.49 (ddd, J = 14.2, 13.1, 8.4 Hz, 1H), 3.77 (ddd, J = 39.1, 14.4, 5.2 Hz, 1H), 4.17-4.35 (m, 4H), 7.16-7.29 (m, 6H), 7.36-7.46 (m, 2H), 7.52-7.57 (m, 2H); ^{13}C NMR (50 MHz, CDCl_3) δ 16.5, 16.6, 40.6 (d, J = 19.5 Hz), 64.5 (d, J = 6.4 Hz), 64.6 (d, J = 6.4 Hz), 102.9 (dd, J = 200.7, 157.3 Hz), 127.4, 128.0, 128.5, 129.3, 129.4, 130.9, 132.8, 198.7 (dd, J = 24.5, 2.8 Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 0.5 mL/min) Chiralpak AD column, t_R = 15.3 min (minor), t_R = 17.1 (major).

Diethyl 1-fluoro-1-methyl-2-oxo-butylphosphonate (4o);

R_f 0.43 (EtOAc : CH_2Cl_2 = 1 : 3); $[\alpha]_D^{23}$ = +147.40 (c = 0.2, CHCl_3 , 87% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.08 (t, J = 7.1 Hz, 3H), 1.36 (t, J = 7.1 Hz, 6H), 1.71 (dd, J = 23.9, 15.6 Hz, 3H), 2.73-2.83 (m, 2H), 4.15-4.29 (m, 4H); ^{13}C NMR (50 MHz, CDCl_3) δ 7.0 (d, J = 2.7 Hz), 16.5, 16.6, 19.8 (d, J = 21.5 Hz), 31.6, 64.1 (d, J = 6.7 Hz), 64.3 (d, J = 6.8 Hz), 99.4 (dd, J = 189.3, 159.0 Hz), 208.1 (dd, J = 23.9, 3.6 Hz). For the HPLC analysis, 2,4-dinitrophenylhydrazone derivatives were prepared according to the reported procedure.¹⁷

Diethyl 1-fluoro-1-methyl-2-[(2,4-dinitrophenyl)hydrazono]butylphosphonate;

R_f 0.44 (EtOAc : n-hexane = 1 : 1); $[\alpha]_D^{23}$ = -170.24 (c = 0.5, CHCl_3 , 87% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.21-1.44 (m, 9H), 1.96 (dd, J = 24.9, 9.9 Hz, 3H), 2.57-2.87 (m, 2H), 4.07-4.31 (m, 4H), 7.95 (d, J = 9.5 Hz, 1H), 8.35 (dd, J = 9.5, 2.5 Hz, 1H), 9.15 (d, J = 2.9 Hz, 1H), 11.32 (s, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 9.7, 16.6, 16.7, 20.2 (d, J = 4.4 Hz), 21.5 (d, J = 18.8 Hz), 63.9 (d, J = 7.5 Hz), 64.1 (d, J = 7.7 Hz), 96.9 (dd, J = 176.0, 169.1 Hz), 116.8, 123.5, 130.4, 138.9, 145.2, 158.3 (d, J = 25.4 Hz); R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, t_R = 12.9 min (major), t_R = 17.0 (minor).

Diethyl 1-fluoro-1-methyl-2-oxo-pent-3-enylphosphonate (4p);

R_f 0.53 (EtOAc : CH_2Cl_2 = 1 : 3); $[\alpha]_D^{23}$ = -81.12 (c = 0.5, CHCl_3 , 93% ee); ^1H NMR (200 MHz, CDCl_3) δ

1.31-1.39 (m, 6H), 1.74 (dd, $J = 24.0, 15.3$ Hz, 3H), 1.96 (dd, $J = 6.9, 1.5$ Hz, 3H), 4.09-4.31 (m, 4H), 6.69-6.79 (m, 1H), 7.05-7.27 (m, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 16.4, 16.6, 18.9, 19.9 (d, $J = 21.5$ Hz), 64.3, 64.4, 98.8 (dd, $J = 190.8, 159.2$ Hz), 125.0, 146.9, 194.5 (d, $J = 22.0$ Hz); R_t HPLC (99:1, n-hexane : *iso*-PrOH, 254 nm, 0.5 mL/min) Chiralpak AD column, $t_R = 30.7$ min (major), $t_R = 32.2$ (minor).

1.4. General procedure for the amination of β -keto phosphonates: To a stirred solution of β -keto phosphonate (0.3 mmol) and catalyst **2c** (28.4 mg, 0.0075 mmol) in acetone (3 mL) was added diethyl azodicarboxylate (0.02 mL, 2.2 M in toluene, 0.45 mmol) at room temperature. Reaction mixture was stirred for 17-60h at room temperature. The mixture was concentrated and purified by flash chromatography to afford the α -amino β -keto phosphonate.

***N,N'*-Bis(ethoxycarbonyl)-2-hydrazino-2-(diethoxyphosphinyl)indanone (6a);** R_f 0.45 (EtOAc); $[\alpha]_D^{23} = +51.19$ ($c = 2.47$, CHCl_3 , 99% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.06-1.39 (m, 12H), 3.66-4.31 (m, 10H), 7.32-7.43 (m, 2H), 7.56-7.61 (m, 2H), 7.80 (d, $J = 7.4$ Hz, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 14.3, 15.7, 15.8, 15.9, 36.8, 62.0, 62.9, 63.4 (d, $J = 7.7$ Hz), 63.6 (d, $J = 7.7$ Hz), 73.3 (d, $J = 148.8$ Hz), 124.1, 125.5, 127.2, 127.4, 134.6, 134.7, 150.5, 156.0, 195.7; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralhyun-Leu-1 column, $t_R = 13.3$ min (major), $t_R = 16.5$ (minor).

***N,N'*-Bis(ethoxycarbonyl)-2-hydrazino-2-(dimethoxyphosphinyl)indanone (6b);** R_f 0.30 (EtOAc); $[\alpha]_D^{23} = +37.91$ ($c = 3.37$, CHCl_3 , 99% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.17-1.45 (m, 6H), 3.65-3.81 (m, 6H), 3.81-3.99 (m, 2H), 4.05-4.18 (m, 2H), 4.21-4.32 (m, 2H), 7.36-7.45 (m, 2H), 7.58-7.71 (m, 2H), 7.82 (d, $J = 7.5$ Hz, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 14.1, 14.5, 36.8, 54.1 (d, $J = 3.2$ Hz), 54.2 (d, $J = 2.4$ Hz), 62.2, 63.2, 74.9 (d, $J = 149.6$ Hz), 124.4, 125.6, 127.5, 127.8, 134.6, 135.1, 150.5, 156.3, 195.9; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 49.7$ min (minor), $t_R = 67.0$ (major).

***N,N'*-Bis(ethoxycarbonyl)-2-hydrazino-2-(diisopropoxyphosphinyl)indanone (6c);** R_f 0.53 (EtOAc); $[\alpha]_D^{23} = +54.03$ ($c = 0.59$, CHCl_3 , 99% ee); ^1H NMR (200 MHz, CDCl_3) δ 1.03-1.47 (m, 18H), 3.58-4.37 (m, 5H), 4.45-4.81 (m, 3H), 7.33-7.43 (m, 3H), 7.55-7.62 (m, 1H), 7.80 (d, $J = 7.5$ Hz, 1H); ^{13}C NMR (50 MHz, CDCl_3) δ 14.0, 14.5, 23.1, 23.3, 24.0, 24.3, 37.2, 62.2, 63.1, 72.7, 72.9, 73.4 (d, $J = 149.3$ Hz), 124.4, 125.8, 127.4, 127.6, 134.9, 135.1, 150.9, 156.1, 196.3; R_t HPLC (9:1, n-hexane : *iso*-PrOH, 254 nm, 1.0 mL/min) Chiralpak AD column, $t_R = 41.7$ min (minor), $t_R = 44.6$ min (major).

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