**Lewis Base Activation of Grignard Reagents with N-Heterocyclic Carbenes. Cu-Free
Catalytic Enantioselective Additions to γ -Chloro- α,β -Unsaturated Esters**

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SUPPORTING INFORMATION

General. Infrared (IR) spectra were recorded on a Nicolet 210 spectrophotometer, $\nu_{\max}$ in cm^{-1} . Bands are characterized as broad (br), strong (s), medium (m), and weak (w). ^1H NMR spectra were recorded on a Varian Unity INOVA 400 (400 MHz) spectrometer. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance as the internal standard (CDCl_3 : δ 7.26 ppm). Data are reported as follows: chemical shift, integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad, m = multiplet), and coupling constants (Hz). ^{13}C NMR spectra were recorded on a Varian Unity INOVA 400 (100 MHz) spectrometer with complete proton decoupling. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance as the internal standard (CDCl_3 : δ 77.16 ppm). High-resolution mass spectrometry were performed on a Micromass LCT ESI-MS (positive mode) at the Mass Spectrometry Facility, Boston College and at the University of Illinois Mass Spectrometry Laboratories (Urbana, Illinois). Elemental microanalyses were performed at Robertson Microlit Laboratories (Madison, NJ). Enantiomer ratios were determined by chiral GLC analysis (Alltech Associated Chiral dex GTA column (30 m x 0.25 mm) and Betadex 120 column (30 m x 0.25 mm) in comparison with authentic racemic materials. Optical rotations were measured on a Rudolph Research Analytical Autopol IV Polarimeter.

Unless otherwise noted, all reactions were carried out with distilled and degassed solvents under an atmosphere of dry N_2 in oven- (135 °C) and flame-dried glassware with standard dry box or vacuum-line techniques. Solvents were purified under a positive pressure of dry argon by a modified Innovative Technologies purification system: CH_2Cl_2 and Et_2O were purged with argon and purified by passage through two alumina columns. Tetrahydrofuran (Aldrich) was purified by distillation from sodium benzophenone ketal immediately prior to use unless otherwise specified. Methanol was distilled over CaH_2 . All work-up and purification procedures were carried out with reagent grade solvents (purchased from Doe & Ingalls) in air. All Grignard reagents were prepared in THF by addition of the corresponding chlorides onto magnesium

turnings, which was purchased from Strem Inc and used as received. Diisopropylmagnesium was prepared by a previously reported method.¹

■ Reagents and ligands:

Acetyl chloride was purchased from Aldrich and purified by distillation over PCl₅ before use.

Ag-complex 6 was prepared by a previously reported method.²

1-Chlorobutane was purchased from Aldrich and purified by distillation over CaCl₂ before use.

2-Chloropropane was purchased from Aldrich and purified by distillation over MgSO₄ before use.

Chlorocyclopentane was purchased from Aldrich and purified by distillation over CaCl₂ before use.

Cyclohexyl chloride was purchased from Acros and purified by distillation over CaCl₂ before use.

Imidazolinium salts 5,³ 7,² and 8⁴ were prepared by previously reported methods.

Modified imidazolinium salts 12 and 13 were prepared by previously reported methods.²

Trifluoroacetic acid was purchased from Acros and used as received.

Triphenylphosphine was purchased from Aldrich and recrystallized from hexanes.

Triphenylphosphine oxide was purchased from Aldrich and recrystallized from EtOH.

Imidazolinium chloride (12). mp: 148-150 °C; IR (neat): 3049 (w), 2936 (w), 2854 (w), 1633 (s), 1482 (m), 1457 (m), 1274 (m), 1211 (m), 1060 (m), 909 (w), 859 (w), 758 (m), 733 (s), 708 (s) cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 9.56 (1H, s, NCHN), 8.00 (1H, dd, *J* = 7.6 Hz, 1.6 Hz, ArH), 7.67-7.11 (16H, m, ArH), 6.89 (1H, s, ArH), 6.66 (1H, s, ArH), 6.57 (2H, d, *J* = 7.6 Hz, ArH), 5.40 (1H, d, *J* = 9.6 Hz, NCHCHN), 5.21 (1H, d, *J* = 9.6 Hz, NCHCHN), 2.57 (3H, s, CH₃), 2.17 (3H, s, CH₃), 1.85 (3H, s, CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ 158.4, 140.2, 139.0, 138.0, 135.5, 135.1, 135.0, 132.3, 131.8, 131.2, 130.7, 130.4, 130.2, 130.1, 130.1, 130.0, 129.9, 129.8, 129.8, 129.5, 129.1, 128.9, 128.8, 128.7, 128.0, 75.1, 72.7, 21.1, 19.3, 18.4; HRMS (ES⁺): Calcd for C₃₆H₃₃N₂: 493.2644, Found: 493.2645.

Imidazolinium chloride (13). mp: 157-159 °C; IR (neat): 3055 (w), 2945 (w), 2848 (w), 1620 (s), 1595 (m), 1488 (w), 1463 (m), 1274 (m), 1249 (m), 1218 (m), 1060 (m), 859 (w), 771 (m), 733 (m), 702 (m) cm⁻¹; NMR spectrum exists as a mixture of 2:1 atropisomers. ¹H NMR (CDCl₃, 400 MHz): δ 9.46 (0.5H, s, NCHN), 9.24 (1H, s, NCHN), 8.25 (1H, d, *J* = 8.4 Hz, ArH), 7.91-7.88 (0.5H, m, ArH), 7.68-7.61 (1.5H, m, ArH), 7.44-7.12 (21H, m, ArH), 6.92 (1H, s, ArH), 6.87 (0.5H, s, ArH), 6.62 (1.5H, s, ArH), 6.58 (1H, d, *J* = 8.0 Hz, ArH), 6.52 (2H, d, *J* = 8.0 Hz,

(1) Wakefield, B. J. *Organomagnesium Methods in Organic Synthesis*; Academic Press, 1995; pp 65-67.

(2) Van Veldhuizen, J. J.; Campbell, J. E.; Giudici, R. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2005**, *127*, 6877-6882.

(3) Arduengo III, A. J.; Krafczyk, R.; Schmutzler, R.; Craig, H. A.; Goerlich, J. R.; Marshall, W. J.; Unverzagt, M.; *Tetrahedron* **1999**, *55*, 14523-14534.

(4) Larsen, A. O.; Leu, W.; Nieto-Oberhuber, C.; Campbell, J. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2004**, *126*, 11130-11131.

ArH), 5.32 (0.5H, d, $J = 9.2$ Hz, NCHCHN), 5.37 (0.5H, d, $J = 9.2$ Hz, NCHCHN), 5.33 (2H, s, NCHCHN), 3.79 (1.5H, s, OCH₃), 3.76 (3H, s, OCH₃), 2.65 (3H, s, CH₃), 2.52 (1.5H, s, CH₃), 2.18 (3H, s, CH₃), 2.16 (1.5H, s, CH₃), 1.72 (1.5H, s, CH₃), 1.70 (3H, s, CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ 158.3, 157.1, 156.9, 140.1, 135.7, 135.7, 135.5, 135.4, 135.2, 135.1, 135.0, 134.3, 133.4, 133.0, 132.8, 132.8, 132.4, 132.3, 132.0, 131.4, 131.0, 130.9, 130.7, 130.6, 130.5, 130.3, 130.2, 130.1, 130.0, 130.0, 129.9, 129.8, 129.7, 129.6, 129.5, 129.1, 129.0, 128.8, 128.7, 128.2, 127.9, 127.2, 122.4, 121.9, 113.3, 112.0, 77.4, 75.1, 75.0, 73.4, 72.4, 57.2, 55.8, 21.1, 21.1, 19.4, 19.3, 18.4, 17.8; HRMS (ES⁺): Calcd for C₃₇H₃₅N₂O: 523.2749, Found: 523.2762.

■ Preparation and characterization of substrates:

(E)-tert-Butyl 4-chloro-2-methylbut-2-enoate (1a): All substrates were synthesized according to published procedures.⁵

Representative experimental procedures for the preparation of methyl ester substrates 1b:

(E)-4-Chloro-2-methylbut-2-enoic acid (A). Trifluoroacetic acid (2 mL) was added to **1a** (600 mg, 3.14 mmol) dissolved in CH₂Cl₂ (5 mL) at 22 °C. The mixture was allowed to stir for 5 h, at which time the reaction was quenched by addition of a saturated aqueous solution of NaHCO₃ at 0 °C until pH > 8. The mixture was acidified with an aqueous solution of 6M HCl until pH < 4 and washed with CH₂Cl₂ (3 x 10 mL). The combined organic layers were dried over MgSO₄, filtered and concentrated to yield 405 mg (3.00 mmol, 95% yield) of **A** as a white solid, which was used directly in the subsequent reaction.

(E)-Methyl 4-chloro-2-methylbut-2-enoate (1b). Acetyl chloride (1.5 mL) was dissolved in 15 mL of MeOH at 0 °C and the solution was allowed to stir at 0 °C. After 1 h, **A** (500 mg, 3.71 mmol) was added to the mixture. The mixture was then allowed to warm to 22 °C and stir for 12 h. At this time, the mixture was quenched by addition of a saturated aqueous solution of NaHCO₃ (10 mL) at 0 °C and washed with Et₂O (3x10 mL). The organic layers were dried over MgSO₄ and filtered. The filtrate was concentrated in vacuo to afford a colorless oil, which was purified by silica gel column chromatography (1:30 Et₂O:petroleum ether) to yield 494 mg (3.32 mmol, 90% yield) of **1b** as a clear oil. IR (neat): 2999 (m), 2955 (m), 2848 (w), 1715 (s), 1652 (m), 1438 (s), 1388 (w), 1356 (m), 1287 (s), 1199 (s), 1174 (s), 1123 (s), 1086 (m), 1010 (w), 947 (w), 758 (s) cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 6.81 (1H, t, $J = 8.0$ Hz, C=CH), 4.14 (2H, d, $J = 8.0$ Hz, CH₂Cl), 3.74 (3H, s, OCH₃), 1.90 (3H, s, CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ

(5) Stotter, P. L.; Hill, K. A. *Tetrahedron Lett.* **1975**, 21, 1679-1682.

167.8, 135.4, 131.8, 52.3, 39.3, 12.6; HRMS (EI⁺): Calcd for C₆H₉O₂Cl: 148.0291, Found: 148.0286; Elemental Analysis: Anal Calcd for C₆H₉O₂Cl: C, 48.50; H, 6.11; Found C, 48.45; H, 5.98.

(*E*)-Methyl 4-chloro-2-ethylbut-2-enoate (10). IR (neat): 2974 (m), 2955 (m), 2886 (w), 1715 (s), 1652 (m), 1463 (m), 1438 (s), 1381 (w), 1300 (s), 1243 (s), 1205 (s), 1174 (s), 1136 (s), 1098 (m), 1067 (m), 1035 (m), 997 (m), 916 (m), 771 (s) cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 6.77 (1H, t, *J* = 8.0 Hz, C=CH), 4.14 (2H, d, *J* = 8.0 Hz, CH₂Cl), 3.74 (3H, s, OCH₃), 2.35 (2H, q, *J* = 7.6 Hz, CH₂CH₃), 1.02 (3H, t, *J* = 7.6 Hz, CH₂CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ 167.5, 137.8, 135.0, 52.2, 39.1, 20.3, 14.1; HRMS (EI⁺): Calcd for C₇H₁₁O₂Cl: 162.0448, Found: 162.0448; Elemental Analysis: Anal Calcd for C₇H₁₁O₂Cl: C, 51.70; H, 6.82; Found C, 52.04; H, 6.77.

(*E*)-Methyl 2-(2-chloroethylidene)hexanoate (11). IR (neat): 2961 (m), 2930 (m), 2873 (w), 1721 (s), 1658 (w), 1438 (m), 1274 (s), 1211 (s), 1167 (m), 1135 (m), 1104 (m), 1048 (m), 928 (w), 777 (m) cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 6.77 (1H, t, *J* = 8.4 Hz, C=CH), 4.14 (2H, d, *J* = 8.4 Hz, CH₂Cl), 3.74 (3H, s, OCH₃), 2.33 (2H, t, *J* = 7.4 Hz, CH₂CH₂CH₂CH₃), 1.40-1.28 (4H, m, CH₂CH₂CH₂CH₃), 0.89 (3H, t, *J* = 7.2 Hz, CH₂CH₂CH₂CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ 167.7, 136.3, 135.3, 52.2, 39.3, 31.7, 26.8, 22.8, 14.0; HRMS (EI⁺): Calcd for C₉H₁₅O₂Cl: 190.0761, Found: 190.0764; Elemental Analysis: Anal Calcd for C₉H₁₅O₂Cl: C, 56.69; H, 7.93; Found C, 56.98; H, 8.00.

■ **Representative experimental procedures for enantioselective allylic alkylation of RMgCl to allylic chlorides:** An oven-dried 13 x 100 mm test tube was charged with a chiral imidazolinium salt **7** (8.6 mg, 1.5 x 10⁻² mmol), weighed out on the benchtop. THF (1.0 mL) and *i*-PrMgCl (1.47 M in THF, 0.42 mL, 0.62 mmol) were added and the mixture was allowed to cool to -78 °C (dry ice/acetone bath) and stir for 30 minutes. (*E*)-*tert*-Butyl 4-chloro-2-methylbut-2-enoate (60 mg, 0.31 mmol) in THF (0.20 mL) was added dropwise to the mixture through a syringe. The mixture was left at -78 °C (cryocool) for 24 hours. The reaction was quenched by the addition of a saturated aqueous solution of NH₄Cl (3 mL). After allowing the mixture to warm to 22 °C, it was washed with Et₂O (3 x 2 mL) and passed through a short plug (4 cm x 1 cm) of MgSO₄ eluted with Et₂O. The volatiles were removed in vacuo to yield a colorless oil, which was purified by silica gel column chromatography (1:50 Et₂O:pentane) to afford the pure S_N2' product (28 mg, 0.14 mmol) in 45 % yield as a clear oil.

(S)-tert-Butyl 2-isopropyl-2-methylbut-3-enoate (2a). IR (neat): 2972 (s), 2930 (m), 2874 (m), 1727 (s), 1643 (w), 1468 (m), 1370 (s), 1258 (s), 1139 (s), 1000 (w), 916 (m), 853 (m) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 5.95 (1H, dd, $J = 17.6, 10.8$ Hz, $\text{CH}=\text{CH}_2$), 5.09 (1H, dd, $J = 10.8, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.03 (1H, dd, $J = 17.6, 1.2$ Hz, $\text{CH}=\text{CHH}$), 2.12-2.05 (1H, m, $\text{CH}(\text{CH}_3)_2$), 1.41 (9H, s, $\text{C}(\text{CH}_3)_3$), 1.08 (3H, s, CH_3), 0.83 (3H, d, $J = 6.4$ Hz, $\text{CH}(\text{CH}_3)_2$), 0.79 (3H, d, $J = 7.2$ Hz, $\text{CH}(\text{CH}_3)_2$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 175.3, 141.8, 114.1, 80.3, 53.1, 34.7, 28.1, 17.8, 17.4, 14.3; HRMS (CI $^+$): Calcd for $\text{C}_{12}\text{H}_{23}\text{O}_2$ [$\text{M}^+ + 1$]: 199.1698. Found: 199.1700; Optical Rotation: $[\alpha]_D^{20} -23.2$ ($c=1.00$, CHCl_3) for an enantiomerically enriched sample of 96% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (93% ee shown; chiral dex GTA column, 10 psi, 40 $^\circ\text{C}$).

tert-Butyl 2-isopropyl-1-methylcyclopropanecarboxylate (4a) (Table 1, entry 1). IR (neat): 2961 (s), 2936 (m), 2879 (w), 1721 (s), 1469 (m), 1394 (w), 1369 (m), 1325 (m), 1268 (m), 1249 (m), 1155 (s), 853 (w) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 1.41 (9H, s, $\text{C}(\text{CH}_3)_3$), 1.23 (3H, s, CH_3), 1.22-1.07 (3H, m, CCHH , CCH , and $\text{CH}(\text{CH}_3)_2$), 1.02 (3H, d, $J = 6.4$ Hz, $\text{CH}(\text{CH}_3)_2$), 0.96 (3H, d, $J = 6.4$ Hz, $\text{CH}(\text{CH}_3)_2$), 0.28 (1H, dd, $J = 6.4, 6.0$ Hz, CHH); ^{13}C NMR (CDCl_3 , 100 MHz): δ 175.9, 79.8, 35.1, 29.3, 28.2, 24.0, 22.9, 22.8, 21.7, 14.3; HRMS (EI $^+$): Calcd for $\text{C}_{12}\text{H}_{22}\text{O}_2$: 198.1620, Found: 198.1618.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (<2% ee shown; chiral dex GTA column, 10 psi, 40 $^\circ\text{C}$).

tert-Butyl 2-methylbut-3-enoate (**9**) (Table 2, entry 1).⁶ IR (neat): 2974 (m), 2921 (s), 2855 (m), 1742 (s), 1462 (w), 1373 (w), 1260 (w), 1147 (s) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 5.90 (1H, ddd, $J = 7.6, 7.6, 10.0$ Hz, $\text{CH}=\text{CH}_2$), 5.10 (2H, m, $\text{CH}=\text{CH}_2$), 3.03 (1H, dq, $J = 7.2, 7.2$ Hz, $\text{CHCH}=\text{CH}_2$), 1.44 (9H, s, $\text{C}(\text{CH}_3)_3$), 1.22 (3H, d, $J = 7.2$ Hz, CH_3CH); ^{13}C NMR (CDCl_3 , 100 MHz): δ 174.0, 137.9, 115.5, 80.5, 44.8, 28.2, 16.6; Elemental Analysis: Anal Calcd for $\text{C}_9\text{H}_{16}\text{O}_2$: C, 69.19; H, 10.32; Found C, 69.27; H, 10.20.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (<2% ee shown; chiral dex GTA column, 10 psi, 40 $^\circ\text{C}$).

(*S*)-Methyl 2-isopropyl-2-methylbut-3-enoate (Table 3, entry 1).⁷ IR (neat): 2955 (s), 2931 (s), 2879 (m), 1733 (s), 1657 (w), 1633 (w), 1458 (w), 1434 (m), 1406 (w), 1373 (w), 1259 (m), 1150 (m), 1112 (m), 1017 (w), 927 (m) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.00 (1H, dd, $J = 17.6, 10.8$ Hz, $\text{CH}=\text{CH}_2$), 5.15 (1H, dd, $J = 10.8, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.08 (1H, dd, $J = 17.6, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.68 (3H, s, OCH_3), 2.14 (1H, dd, $J = 6.8, 6.8$ Hz, $\text{CH}(\text{CH}_3)_2$), 1.17, (3H, s, CH_3), 0.83 (3H, d, $J = 6.8$ Hz, $\text{CH}(\text{CH}_3)_2$), 0.82 (3H, d, $J = 6.8$ Hz, $\text{CH}(\text{CH}_3)_2$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.6, 141.1, 114.6, 52.7, 52.0, 34.9, 17.9, 17.4, 14.5; HRMS (EI+):

(6) Murphy, K. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2003**, 125, 4690-4691.

(7) Murphy, K. E.; Hoveyda, A. H. *Org. Lett.* **2005**, 7, 1255-1258.

Calcd for $C_9H_{16}O_2$: 156.1150, Found: 156.1150. Optical Rotation: $[\alpha]_D^{20}$ -37.9 ($c = 1.10$, $CHCl_3$) for an optically enriched sample of 95% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (97% ee shown; chiral dex GTA column, 10 psi, 35 °C).

(R)-Methyl 2-cyclopentyl-2-methylbut-3-enoate (Table 3, entry 2). IR (neat): 2955 (s), 2873 (m), 1734 (s), 1639 (w), 1463 (m), 1432 (m), 1375 (w), 1249 (s), 1199 (m), 1136 (m), 1104 (m), 1004 (w), 916 (m) cm^{-1} ; 1H NMR ($CDCl_3$, 400 MHz): δ 6.04 (1H, dd, $J = 17.6, 10.8$ Hz, $CH=CH_2$), 5.11 (1H, dd, $J = 10.8, 1.2$ Hz, $CH=CHH$), 5.03 (1H, dd, $J = 17.6, 1.2$ Hz, $CH=CHH$), 3.65 (3H, s, OCH_3), 2.30-2.25 (1H, m, CH), 1.59-1.22 (11H, m, CH_3 and $(CH_2)_4$); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 176.6, 140.6, 114.2, 52.0, 51.0, 47.3, 27.6, 27.4, 25.8, 25.8, 17.5; HRMS (EI+): Calcd for $C_{11}H_{18}O_2$: 182.1307, Found: 182.1308; Optical Rotation: $[\alpha]_D^{20}$ -18.9 ($c = 1.00$, $CHCl_3$) for an optically enriched sample of 73% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (74% ee shown; chiral dex GTA column, 10 psi, 50 °C).

(R)-Methyl 2-cyclohexyl-2-methylbut-3-enoate (Table 3, entry 3). IR (neat): 2993 (m), 2955 (s), 2854 (m), 1734 (s), 1633 (w), 1451 (m), 1438 (m), 1413 (w), 1375 (w), 1268 (m), 1230 (s), 1199 (m), 1167 (m), 1123 (m), 1098 (m), 1035 (w), 997 (w), 909 (m) cm^{-1} ; 1H NMR ($CDCl_3$,

400 MHz): δ 5.98 (1H, dd, J = 17.6, 10.8 Hz, CH=CH₂), 5.11 (1H, dd, J = 10.8, 1.2 Hz, CH=CHH), 5.03 (1H, dd, J = 17.6, 1.2 Hz, CH=CHH), 3.65 (3H, s, OCH₃), 1.75-0.88 (14H, m, CH₃ and CH(CH₂)₅); ¹³C NMR (CDCl₃, 100 MHz): δ 176.6, 141.3, 114.4, 52.7, 52.0, 45.5, 28.3, 27.6, 26.9, 26.9, 26.6, 15.3; HRMS (EI⁺): Calcd for C₁₂H₂₀O₂: 196.1463, Found: 196.1469; Optical Rotation: $[\alpha]_D^{20}$ -24.4 (c = 1.00, CHCl₃) for an optically enriched sample of 94% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (94% ee shown; chiral dex GTA column, 10 psi, 70 °C).

(S)-Methyl 2-methyl-2-vinylhexanoate (Table 3, entry 4). IR (neat): 2955 (s), 2886 (s), 2860 (m), 1740 (s), 1639 (w), 1469 (m), 1438 (m), 1262 (m), 1230 (m), 1211 (m), 1148 (m), 1092 (w), 991 (w), 916 (m) cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 5.99 (1H, dd, J = 17.6, 10.8 Hz, CH=CH₂), 5.11 (1H, dd, J = 10.8, 1.2 Hz, CH=CHH), 5.03 (1H, dd, J = 17.6, 1.2 Hz, CH=CHH), 3.65 (3H, s, OCH₃), 1.72-1.12 (9H, m, CH₃ and CH₂CH₂CH₂), 0.86 (3H, t, J = 7.2 Hz, CH₂CH₃); ¹³C NMR (CDCl₃, 100 MHz): δ 176.6, 142.0, 113.5, 52.0, 48.8, 39.1, 26.9, 23.2, 20.6, 14.1; HRMS (EI⁺): Calcd for C₁₀H₁₈O₂: 170.1307, Found: 170.1309; Elemental Analysis: Anal Calcd for C₁₀H₁₈O₂: C, 70.55; H, 10.66; Found C, 70.53; H, 10.95; Optical Rotation: $[\alpha]_D^{20}$ -7.67 (c = 1.00, CHCl₃) for an enantiomerically enriched sample of 58% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (63% ee shown; chiral dex GTA column, 10 psi, 35 °C).

(S)-Methyl 2-ethyl-2-isopropylbut-3-enoate (Table 3, entry 5). IR (neat): 3087 (w), 2974 (s), 2886 (m), 2841 (w), 1734 (s), 1639 (w), 1469 (m), 1432 (m), 1369 (m), 1287 (m), 1230 (s), 1130 (s), 1098 (m), 1004 (s), 909 (m), 809 (w) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 5.99 (1H, dd, $J = 18.0, 11.2$ Hz, $\text{CH}=\text{CH}_2$), 5.27 (1H, dd, $J = 11.2, 2.8$ Hz, $\text{CH}=\text{CHH}$), 5.01 (1H, dd, $J = 18.0, 2.8$ Hz, $\text{CH}=\text{CHH}$), 3.69 (3H, s, OCH_3), 2.08-2.04 (1H, m, CH), 1.80-1.66 (2H, m, CH_2), 0.83-0.75 (9H, m, CH_3 and $(\text{CH}_3)_2\text{CH}$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.3, 135.5, 115.7, 57.2, 51.7, 35.3, 26.6, 19.0, 16.9, 9.7; HRMS (CI⁺): Calcd for $\text{C}_{10}\text{H}_{19}\text{O}_2$ [$\text{M}^+ + 1$]: 171.1385, Found: 171.1383; Elemental Analysis: Anal Calcd for $\text{C}_{10}\text{H}_{18}\text{O}_2$: C, 70.55; H, 10.66; Found C, 70.51; H, 10.56; Optical Rotation: $[\alpha]_{\text{D}}^{20} +6.33$ ($c = 1.80$, CHCl_3) for an optically enriched sample of 97% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (97% ee shown; chiral dex GTA column, 10 psi, 40 $^\circ\text{C}$).

(S)-Methyl 2-isopropyl-2-vinylhexanoate (Table 3, entry 6). IR (neat): 3087 (w), 2961 (s), 2873 (m), 1740 (s), 1646 (m), 1463 (m), 1438 (m), 1388 (w), 1255 (m), 1211 (s), 1136 (s), 1016 (m), 922 (m), 752 (w) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.00 (1H, dd, $J = 18.0, 11.2$ Hz, $\text{CH}=\text{CH}_2$), 5.25 (1H, dd, $J = 11.2, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.00 (1H, dd, $J = 18.0, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.68 (3H, s, OCH_3), 2.07-2.04 (1H, m, CH), 1.69-1.61 (2H, m, CH_2), 1.29-0.75 (13H, m, $\text{CH}_2\text{CH}_2\text{CH}_3$ and $\text{CH}(\text{CH}_3)_2$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.4, 135.9, 115.5, 56.5, 51.7, 35.5, 33.8, 27.3, 23.4, 19.0, 16.9, 14.1; HRMS (CI⁺): Calcd for $\text{C}_{12}\text{H}_{23}\text{O}_2$ [$\text{M}^+ + 1$]: 199.1698, Found: 199.1693; Elemental Analysis: Anal Calcd for $\text{C}_{12}\text{H}_{22}\text{O}_2$: C, 72.68; H, 11.18; Found C, 72.90; H, 11.35; Optical Rotation: $[\alpha]_{\text{D}}^{20} +2.17$ ($c = 1.40$, CHCl_3) for an optically enriched sample of 98% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (98% ee shown; chiral dex GTA column, 10 psi, 70 $^\circ\text{C}$).

(R)-Methyl 2-cyclopentyl-2-ethylbut-3-enoate (Table 3, entry 7). IR (neat): 3081 (w), 2942 (s), 2873 (s), 1727 (s), 1639 (w), 1457 (m), 1432 (m), 1388 (w), 1356 (w), 1287 (m), 1224 (s), 1142 (s), 1117 (s), 1010 (m), 916 (m), 809 (m) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.01 (1H, dd, $J = 17.6, 10.8$ Hz, $\text{CH}=\text{CH}_2$), 5.24 (1H, dd, $J = 10.8, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.03 (1H, dd, $J = 17.6, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.68 (3H, s, OCH_3), 2.26-2.21 (1H, m, CH), 1.74 (2H, q, $J = 7.6$ Hz, CH_2CH_3), 1.61-1.20 (8H, m, $(\text{CH}_2)_4$), 0.79 (3H, t, $J = 7.2$ Hz, CH_3); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.1, 136.6, 115.7, 55.6, 51.7, 47.0, 28.1, 27.8, 26.9, 25.5, 25.3, 9.6; HRMS (EI⁺): Calcd for $\text{C}_{12}\text{H}_{20}\text{O}_2$: 196.1463, Found: 196.1459; Elemental Analysis: Anal Calcd for $\text{C}_{12}\text{H}_{20}\text{O}_2$: C, 73.43; H, 10.27; Found C, 73.19; H, 9.93; Optical Rotation: $[\alpha]_D^{20} -0.82$ ($c = 1.70$, CHCl_3) for an optically enriched sample of 90% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (90% ee shown; chiral dex GTA column, 10 psi, 80 °C).

(R)-Methyl 2-cyclopentyl-2-vinylhexanoate (Table 3, entry 8). IR (neat): 3081 (w), 2955 (s), 2867 (s), 1734 (s), 1633 (w), 1451 (m), 1432 (m), 1413 (w), 1243 (m), 1205 (s), 1148 (m), 1004 (w), 916 (m) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.03 (1H, dd, $J = 17.6, 11.2$ Hz, $\text{CH}=\text{CH}_2$), 5.24 (1H, dd, $J = 11.2, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.03 (1H, dd, $J = 17.6, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.67 (3H, s, OCH_3), 2.27-2.22 (1H, m, CH), 1.70-1.04 (14H, m, $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$ and $\text{CH}(\text{CH}_2)_4$), 0.86

(3H, t, $J = 7.2$ Hz, CH_3); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.3, 136.9, 115.5, 55.0, 51.8, 47.3, 35.0, 28.1, 27.2, 26.9, 25.5, 25.3, 23.4, 14.1; HRMS (EI⁺): Calcd for $\text{C}_{14}\text{H}_{24}\text{O}_2$: 224.1776, Found: 224.1775; Elemental Analysis: Anal Calcd for $\text{C}_{14}\text{H}_{24}\text{O}_2$: C, 74.95; H, 10.78; Found C, 74.85; H, 10.39; Optical Rotation: $[\alpha]_{\text{D}}^{20} -1.89$ ($c = 1.53$, CHCl_3) for an optically enriched sample of 83% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (85% ee shown; β -dex column, 10 psi, 90 °C).

(R)-Methyl 2-cyclohexyl-2-ethylbut-3-enoate (Table 3, entry 9). IR (neat): 3074 (w), 2930 (s), 2854 (s), 1734 (s), 1633 (w), 1457 (s), 1388 (w), 1350 (w), 1230 (s), 1199 (s), 1136 (s), 1054 (w), 1004 (s), 909 (m), 815 (w) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.01 (1H, dd, $J = 18.0$, 11.2 Hz, $\text{CH}=\text{CH}_2$), 5.23 (1H, dd, $J = 11.2$, 1.2 Hz, $\text{CH}=\text{CHH}$), 4.98 (1H, dd, $J = 18.0$, 1.2 Hz, $\text{CH}=\text{CHH}$), 3.68 (3H, s, OCH_3), 1.83-0.87 (13H, m, CH_2CH_3 and $\text{CH}(\text{CH}_2)_5$), 0.77 (3H, t, $J = 7.2$ Hz, CH_2CH_3); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.3, 136.5, 115.2, 57.3, 51.7, 46.0, 29.3, 27.2, 27.1, 26.8, 26.7, 26.1, 9.6; HRMS (EI⁺): Calcd for $\text{C}_{13}\text{H}_{22}\text{O}_2$: 210.1620, Found: 210.1624; Optical Rotation: $[\alpha]_{\text{D}}^{20} +17.3$ ($c = 1.85$, CHCl_3) for an optically enriched sample of 96% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (96% ee shown; chiral dex GTA column, 10 psi, 90 °C).

(R)-Methyl 2-cyclohexyl-2-vinylhexanoate (Table 3, entry 10). IR (neat): 3081 (w), 2930 (s), 2854 (s), 1734 (s), 1639 (w), 1451 (s), 1432 (m), 1356 (w), 1274 (m), 1237 (m), 1199 (s), 1136 (s), 1004 (m), 922 (m), 733 (w) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 6.02 (1H, dd, $J = 18.0, 11.2$ Hz, $\text{CH}=\text{CH}_2$), 5.21 (1H, dd, $J = 11.2, 1.2$ Hz, $\text{CH}=\text{CHH}$), 4.96 (1H, dd, $J = 18.0, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.66 (3H, s, OCH_3), 1.75-0.84 (20H, m, $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$ and $\text{CH}(\text{CH}_2)_5$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.1, 136.8, 115.0, 56.6, 51.7, 46.2, 33.4, 29.2, 27.3, 27.2, 27.1, 26.8, 26.7, 23.4, 14.1; HRMS (EI+): Calcd for $\text{C}_{15}\text{H}_{26}\text{O}_2$: 238.1933, Found: 238.1931; Elemental Analysis: Anal Calcd for $\text{C}_{15}\text{H}_{26}\text{O}_2$: C, 75.58; H, 10.99; Found C, 75.86; H, 10.66; Optical Rotation: $[\alpha]_{\text{D}}^{20} +11.2$ ($c = 1.00$, CHCl_3) for an optically enriched sample of 96% ee. Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (96% ee shown; chiral dex GTA column, 10 psi, 80 $^\circ\text{C}$).

(S)-Methyl 2-ethyl-2-vinylhexanoate (Table 3, entry 11). IR (neat): 2961 (s), 2936 (s), 2867 (m), 1746 (s), 1690 (m), 1639 (w), 1469 (m), 1432 (m), 1388 (w), 1249 (m), 1224 (m), 1142 (m), 1010 (m), 922 (m) cm^{-1} ; ^1H NMR (CDCl_3 , 400 MHz): δ 5.96 (1H, dd, $J = 18.0, 10.8$ Hz, $\text{CH}=\text{CH}_2$), 5.16 (1H, dd, $J = 10.8, 1.2$ Hz, $\text{CH}=\text{CHH}$), 5.05 (1H, dd, $J = 18.0, 1.2$ Hz, $\text{CH}=\text{CHH}$), 3.66 (3H, s, OCH_3), 1.71 (2H, q, $J = 7.6$ Hz, CH_2CH_3), 1.65 (2H, dd, $J = 8.8, 8.0$ Hz, $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$), 1.30-1.09 (4H, m, $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$), 0.86 (3H, t, $J = 7.2$ Hz, CH_2CH_3), 0.78 (3H, t, $J = 7.2$ Hz, $\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); ^{13}C NMR (CDCl_3 , 100 MHz): δ 176.3, 140.1, 114.5, 52.9, 51.9, 35.6, 28.8, 26.6, 23.3, 14.1, 8.9; HRMS (EI+): Calcd for $\text{C}_{11}\text{H}_{20}\text{O}_2$: 184.1463, Found: 184.1461; Optical Rotation: $[\alpha]_{\text{D}}^{20} +2.14$ ($c = 1.00$, CHCl_3) for an optically enriched sample of 79% ee.

Enantiomeric purity was determined by chiral GLC analysis in comparison with authentic racemic material (79% ee shown; chiral dex GTA column, 10 psi, 50 $^\circ\text{C}$).

■ **Proof of absolute stereochemistry:** The optical rotation of methyl 2-isopropyl-2-methylbut-3-enoate was compared to a previously reported value and optical rotation assignment. Thus, for a 95% ee sample of (*S*)-methyl 2-isopropyl-2-methylbut-3-enoate: $[\alpha]_D^{20} -37.9$ ($c = 1.10$, CHCl_3). Literature value is $[\alpha]_D^{20} -31.9$ ($c = 0.23$, CHCl_3) for a 54% ee sample enriched in the *S* enantiomer.⁷

Table 4. The representative data illustrated below indicate the alkylmagnesium bromides are less efficient than the corresponding chloride reagents.^a

CC(C)OC(=O)C=CCl
 $\xrightarrow[\text{THF, -78 } ^\circ\text{C, 24 h}]{\begin{array}{c} 5 \text{ mol } \% \text{ 7} \\ i\text{-PrMgBr} \end{array}}$
CC(C)OC(=O)C(C)(C)C=C

entry	equiv of <i>i</i> -PrMgBr	conv (%) ^b	S _N 2':S _N 2 ^b	cycloprop. product (%) ^b	ee (%) ^c
1	2	60	4:1	30	79
2	3	94	3.2:1	24	80

^aReactions run under N₂ atm. ^bDetermined by analysis of 400 MHz ¹H NMR spectra and chiral GLC. ^cDetermined by chiral GLC.

Table 5. The representative data illustrated below indicate the commercially available alkylmagnesium chlorides can be used for enantioselective alkylations.^a

entry	R	equiv of <i>i</i> -PrMgCl	conv (%) ^c	S _N 2':S _N 2 ^c	cycloprop. product (%) ^c	ee (%) ^d
1	Me	2	>98	4.6:1	18	95
2	<i>n</i> -Bu	3	>98	6.7:1	5	97

^aReactions run under N₂ atm. ^b*i*-PrMgCl 2.0 M in THF from Aldrich (packed under nitrogen in Sure/Pac metal cylinders). ^cDetermined by analysis of 400 MHz ¹H NMR spectra and chiral GLC. ^dDetermined by chiral GLC.