Ruthenium-catalyzed Decarboxylative Allylation of Nonstabilized Ketone Enolates.

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Supporting Information

Experimental

Materials. Methylene chloride and tetrahydrofuran were dried over activated alumina.¹ All other materials were used as received. β -ketoesters **1a-1j** were prepared by DMAP-catalyzed addition of diketene to the corresponding allylic alcohols.² β -ketoesters **4** and **6a** were prepared by the DMAP catalyzed condensation of β -ketoethylesters and allylic alcohols.³ ¹H NMR spectra were obtained on a Bruker Avance 400 or a Bruker Avance 500 DRX spectrometer and referenced to residual protio solvent signals. Structural assignments are based on ¹H, ¹³C, DEPT-135, COSY, and HMQC spectroscopies.

Catalyst Screening: An NMR tube was charged with **1a** (20 mg). The appropriate solvent, catalyst, and ligand were added. ¹H NMR spectra were recorded after 1.5, 4, and 16 h and the conversions determined by integration. Branched to linear ratios were determined by comparison of the ¹H NMR spectra with those of **2a** (vide infra) and **3a**.⁴

General procedure for catalytic Carroll rearrangements: In a Schlenk tube under argon, [Cp*RuCl]₄ (2.5 mol %) and bipyridine (10 mol %) were dissolved in 2 mL of methylene chloride. The resulting deep purple solution was allowed to stir briefly before addition of allyl- β -ketoester (1 mmol) in 3 mL of methylene chloride via cannula. The reaction was allowed to stir under Ar until the resulting dark burnt orange solution returned to purple. Following solvent evaporation the crude product was purified via flash chromatography (SiO₂, 15% Et₂O: Hex), providing the products in > 95% purity as determined by ¹H NMR spectroscopy.

¹ Pnagborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, *15*, 1518-20.

² Collado, I.; Pedregal, C.; Mazon, A.; Espinosa, J. F.; Blanco-Urgoiti, J.; Schoepp, D. D.; Wright, R. A.; Johnson, B. G.; Kingston, A. E. *J. Med. Chem.* **2002**, *45*, 3619-3629.

³ Gilbert, J. C.; Kelly, T. A. *J. Org. Chem.* **1998**, *63*, 449-450.

⁴ Oi, S.; Honma, Y.; Inoue, Y. *Org. Lett.* **2002**, *4*, 667 – 669.

2a:⁵ pale yellow oil : ¹H NMR (400 MHz, CDCl₃) δ 7.28 (m, 5H: arom H), 5.99 (ddd, *J* = 7 Hz, 11 Hz, 17 Hz, 1H: CH=CH₂), 5.08 (d, *J* = 11 Hz, 1H: CH=CH(*H*)_E), 5.04 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_Z) 3.94 (app. q, *J* = 7 Hz, 1H: CH), 2.91 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.84 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.12 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.50 (C=O), 143.19 (arom. C), 140.94 (CH=CH₂), 129.04 (arom. CH), 128.01 (arom. CH), 127.03 (arom. CH), 115.04 (CH=CH₂), 49.40 (CH₂), 44.95 (CH), 31.10 (CH₃). IR (CH₂Cl₂): ν_{max} 1716, 1157, 994, 922. HRMS calcd for C₁₂H₁₃O [M-H] 173.0966, found 173.0954.

2b: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.13 (m, 4H: arom H), 5.97 (ddd, *J* = 7 Hz, 10 Hz, 17 Hz, 1H: CH=CH₂), 5.07 (d, *J* = 10 Hz, 1H: CH=CH(*H*)_{cis}), 5.03 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_{trans}) 3.90 (app. q, *J* = 7 Hz, 1H: CH), 2.89 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.83 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.34 (s, 3H: Ph-CH₃) 2.11 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.63 (C=O), 141.18 (CH=CH₂), 140.161 (arom. C), 136.57 (arom. C), 129.73 (arom. CH), 127.68 (arom. CH), 114.81 (CH=CH₂), 49.48 (CH₂), 44.62 (CH), 31.09 (CH₃) 21.43 (Ph-CH₃). IR (CH₂Cl₂): ν_{max} 1716, 1352, 1157. HRMS calcd for C₁₃H₁₇O [M+H] 189.1279, found 189.1278.

2c: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.16 (m, 4H: arom H), 5.93 (ddd, *J* = 7 Hz, 10.3 Hz, 17 Hz, 1H: CH=CH₂), 5.06 (d, *J* = 10.3 Hz, 1H: CH=CH(*H*)_{cis}), 4.96 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_{trans}) 4.19 (app. q, *J* = 7 Hz, 1H: CH), 2.93 (dd, *J* = 7 Hz, 16.5 Hz, 1H: diastereotopic CH₂) 2.85 (dd, *J* = 7 Hz, 16.5 Hz, 1H: diastereotopic CH₂) 2.40 (s, 3H: Ph-CH₃) 2.14 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.50 (C=O), 141.15 (arom. C), 140.56 (CH=CH₂), 136.40 (arom. C), 131.04 (arom. CH), 126.80 (arom. CH),

⁵ Snider, B. B.; Patricia, J. J. *J. Org. Chem.* **1989**, *54*, 38-46.

126.76 (arom. CH), 126.62 (arom. CH) 114.97 (CH=CH₂), 48.84 (CH₂), 40.21 (CH), 31.05 (CH₃) 19.97 (Ph-CH₃). IR (CH₂Cl₂): $\nu_{\max}$ 1716, 1270, 1152. HRMS calcd for C₁₃H₁₇O [M+H] 189.1279, found 189.1289.

2d: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.14 (d, J = 6.5 Hz, 2H: 2 arom H), 6.87 (d, J = 6.5 Hz, 2H: 2 arom H), 5.97 (ddd, J = 7 Hz, 10.3 Hz, 17 Hz, 1H: CH=CH₂), 5.06 (d, J = 10.3 Hz, 1H: CH=CH(*H*)_{cis}), 5.02 (d, J = 17 Hz, 1H: CH=CH(*H*)_{trans}) 3.88 (app. q, J = 7 Hz, 1H: CH), 3.80 (s, 3H: OCH₃) 2.87 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.81 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.10 (s, 3H: CH₃). ¹³C NMR (M75 Hz, CDCl₃) δ 207.71 (C=O), 158.64 (arom. C-OCH₃), 141.28 (CH=CH₂), 135.18 (arom. C-CH₂) 128.97 (arom. CH), 114.67 (CH=CH₂), 114.39 (arom. CH), 55.65 (OCH₃), 49.55 (CH₂), 44.16 (CH), 31.11 (CH₃). IR (CH₂Cl₂): $\nu_{\max}$ 1710, 1244, 1117, 830. HRMS calcd for C₁₃H₁₆O₂ [M+] 204.1150, found 204.1146.

2e: clear oil: ¹H NMR (400 MHz, CDCl₃) δ 7.19 (m, 2H: arom H), 6.90 (d, 2H: 2 arom H), 6.04 (ddd, J = 7 Hz, 11 Hz, 17 Hz, 1H: CH=CH₂), 5.07 (d, J = 11 Hz, 1H: CH=CH(*H*)_{cis}), 5.04 (d, J = 17 Hz, 1H: CH=CH(*H*)_{trans}) 4.32 (app. q, J = 7 Hz, 1H: CH), 3.86 (s, 3H: OCH₃) 2.89 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.83 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.14 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 208.14 (C=O), 157.11 (arom. C-OCH₃), 140.20 (CH=CH₂), 131.45 (arom. C-CH₂) 128.54 (arom. CH), 128.06 (arom. CH), 121.08 (arom. CH), 115.03 (CH=CH₂), 111.16 (arom. CH), 55.79 (OCH₃), 48.57 (CH₂), 38.89 (CH), 30.58 (CH₃). IR (CH₂Cl₂): $\nu_{\max}$ 1710, 1234, 1163. HRMS calcd for C₁₃H₁₆O₂ [M+] 204.1150, found 204.1159.

2f: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 6.72 (m, 3H: arom H), 5.95 (ddd, J = 7 Hz, 10 Hz, 17 Hz, 1H: CH=CH₂), 5.96 (s, 2H: O-CH₂-O) 5.06 (d, J = 10 Hz, 1H:

CH=CH(*H*)_{cis}), 5.02 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_{trans}), 3.85 (app. q, *J* = 7 Hz, 1H: CH), 2.85 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.79 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.11 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.46 (C=O), 148.16 (arom. C), 146.55 (arom. C), 141.04 (CH=CH₂), 137.05 (arom. C) 121.00 (arom. CH), 114.85 (O-CH₂-O), 108.73 (arom. CH), 108.43 (arom. CH), 101.35 (CH=CH₂), 49.46 (CH₂), 44.58 (CH), 31.12 (CH₃). IR (CH₂Cl₂): ν_{max} 1710, 1152, 1040. HRMS calcd for C₁₃H₁₄O₃ [M+] 218.0943, found 218.0926.

2g: yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.28 (d, *J* = 8 Hz, 2H: 2 arom H), 7.18 (d, *J* = 8 Hz, 2H: 2 arom H), 5.94 (ddd, *J* = 7 Hz, 10.3 Hz, 17 Hz, 1H: CH=CH₂), 5.09 (d, *J* = 10.3 Hz, 1H: CH=CH(*H*)_{cis}), 5.02 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_{trans}) 3.92 (app. q, *J* = 7 Hz, 1H: CH), 2.89 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.81 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.12 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.03 (C=O), 141.67 (arom C), 140.50 (CH=CH₂), 132.73 (arom. C) 129.46 (arom. CH), 129.13 (arom CH), 115.40 (CH=CH₂), 49.18 (CH₂), 44.11 (CH), 31.11 (CH₃). IR (CH₂Cl₂): ν_{max} 1716, 1485, 1163, 1014. HRMS calcd for C₁₂H₁₄OCl [M+H] 209.0733, found 209.0728.

2h: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.58 (d, *J* = 8 Hz, 2H: 2 arom H), 7.35 (d, *J* = 8 Hz, 2H: 2 arom H), 5.51 (ddd, *J* = 7 Hz, 10.3 Hz, 17 Hz, 1H: CH=CH₂), 5.12 (d, *J* = 10.3 Hz, 1H: CH=CH(*H*)_{cis}), 5.05 (d, *J* = 17 Hz, 1H: CH=CH(*H*)_{trans}) 4.02 (app. q, *J* = 7 Hz, 1H: CH), 2.94 (dd, *J* = 7 Hz, 17 Hz, 1H: diastereotopic CH₂) 2.86 (dd, *J* = 7 Hz, 17 Hz, 1H: diastereotopic CH₂) 2.13 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 206.67 (C=O), 147.33 (arom C-CH), 140.07 (CH=CH₂), 129.28 (arom C-CF₃, q, *J*_{CF} = 54 Hz), 128.47 (arom. CH), 125.94 (CF₃, q, *J*_{CF} = 4 Hz), 115.84 (CH=CH₂), 48.98 (CH₂), 44.45 (CH), 31.06 (CH₃). IR (CH₂Cl₂): ν_{max} 1716, 1613, 1326, 1168. HRMS calcd for C₁₃H₁₂F₃O [M-H] 241.0840, found 241.0840.

2j:⁶ yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.30 (m, 10H: arom H), 6.38 (m, 2H: ambiguous CH=), 4.12 (app. q, J = 7 Hz, 1H: CH), 3.01 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂) 2.95 (dd, J = 7 Hz, 16 Hz, 1H: diastereotopic CH₂), 2.14 (s, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 207.36 (C=O), 143.35 (arom. C), 137.49 (arom. C), 132.76 (CH=), 130.39 (CH=), 129.13 (arom. CH), 128.91 (arom. CH), 128.06 (arom. CH), 127.75 (arom. CH), 127.12 (arom. CH), 126.65 (arom. CH), 49.82 (CH₂), 44.36 (CH), 31.20 (CH₃). IR (CH₂Cl₂): $\nu_{\max}$ 1710, 1490, 1255. HRMS calcd for C₁₈H₁₈O [M+] 250.1358, found 250.1352.

5: yellow oil: ¹H NMR (400 MHz, CDCl₃) Major Diastereomer: δ 7.27 (m, 5H: arom H), 6.07 (ddd, J = 7 Hz, 10 Hz, 17 Hz, 1H: CH=CH₂), 5.06 (m, 2H: CH=CH₂), 3.75 (t, J = 9 Hz, 1H: CH-CH=CH₂), 2.82 (m, 1H: COCH) 2.46-1.24 (broad m, overlapping cyclohexyl CH₂'s). Minor Diastereomer: δ 7.27 (m, 5H: arom H), 5.99 (ddd, J = 7 Hz, 10 Hz, 17 Hz, 1H: CH=CH₂), 5.06 (m, 2H: CH=CH₂), 3.83 (t, J = 9 Hz, 1H: CH-CH=CH₂), 2.82 (m, 1H: COCH) 1.84 (broad m, overlapping cyclohexyl CH₂'s). ¹³C NMR (75 MHz, CDCl₃) Major and Minor Diastereomer: δ 213.15; 212.17 (C=O), 143.67; 142.07 (arom. C), 140.52; 139.64 (CH=CH₂), 128.98; 128.85 (arom. CH), 128.24 (arom. CH), 126.94; 126.66 (arom. CH), 116.65; 115.34 (CH=CH₂), 55.80; 55.65 (COCH), 49.76; 49.44 (CH-CH=CH₂), 42.76; 42.51 (CH₂), 32.35; 32.03 (CH₂), 28.96; 28.80 (CH₂), 24.80; 24.14 (CH₂). IR (CH₂Cl₂): $\nu_{\max}$ 1705, 1445, 1214. HRMS calcd for C₁₅H₁₉O [M+H] 215.1436, found 215.1439.

9a: pale yellow oil: ¹H NMR (400 MHz, CDCl₃) δ 7.28 (m, 5H: arom H), 6.00 (ddd, J = 7 Hz, 10 Hz, 17 Hz, 1H: CH=CH₂), 5.08 (d, J = 10 Hz, 1H: CH=CH(H)_{cis}), 5.04 (d, J =

⁶ Oi, S.; Honma, Y.; Inoue, Y. *Org. Lett.* **2002**, *4*, 667-669.

17 Hz, 1H: CH=CH(*H*)_{trans}) 3.95 (app. q, *J* = 7 Hz, 1H: CH), 2.89 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH-CH₂) 2.82 (dd, *J* = 7 Hz, 16 Hz, 1H: diastereotopic CH-CH₂) 2.41 (dq, *J* = 7 Hz, 10 Hz, 1H: diastereotopic CH₂-CH₃) 2.33 (dq, *J* = 7 Hz, 10 Hz, 1H: diastereotopic CH₂-CH₃) 1.01 (t, *J* = 7 Hz, 3H: CH₃). ¹³C NMR (75 MHz, CDCl₃) δ 210.10 (C=O), 143.36 (arom. C), 141.08 (CH=CH₂), 129.01 (arom. CH), 128.03 (arom. CH), 126.98 (arom. CH), 114.97 (CH=CH₂), 48.22 (CH-CH₂), 45.00 (CH), 37.185 (CH₂-CH₃) 7.97 (CH₃). IR (CH₂Cl₂): ν_{max} 1716, 1449, 1106. HRMS calcd for C₁₃H₁₇O [M+H] 189.1279, found 189.1276. ¹H NMR spectroscopy of the crude mixture confirms that no 3-methyl-4-phenyl-5-hexene-2-one was produced.⁷

Figure 1. ¹H NMR spectrum of the crude mixture containing **9a**. The reported chemical shifts for the methyl ketone groups of the two diastereomers of 3-methyl-4-phenyl-5-hexene-2-one are δ 1.90 and 2.18. The absence of these peaks confirms that the enolate generated did not rearrange.

Crossover Experiment: An NMR tube was charged with approximately equal quantities of **8a** and **1g**. Bipyridine (10 mol%) and [Cp*RuCl]₄ (2.5 mol%) were added, followed by CD₂Cl₂ (550 μL). Upon reaction completion the mixture was analyzed by GC and MS. ¹H NMR spectroscopy of the mixture confirms that no 3-methyl-4-phenyl-5-hexene-2-one was produced.⁷

⁷ Daub, G. W.; McCoy, M. A.; Sanchez, M. G.; Carter, J. S. *J. Org. Chem.* **1983**, *48*, 3876-83.

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