

# Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral Allenes: a Synergistic Effect of Dibenzalacetone on High Enantioselectivity

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## Supporting Data

**General.** All anaerobic and/or moisture sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or with glovebox techniques under prepurified argon. Reaction progress was monitored by analytical thin-layer chromatography (TLC) using 0.25 mm Merck F-254 silica gel glass plates. NMR spectra were recorded on a JEOL JNM LA500 spectrometer ( $^1\text{H}$ , 500 MHz;  $^{13}\text{C}$ , 125 MHz;  $^{31}\text{P}$ , 202 MHz).  $^1\text{H}$  and  $^{13}\text{C}$  chemical shifts are reported in ppm downfield of internal tetramethylsilane.  $^{31}\text{P}$  NMR chemical shifts are externally referenced to 85%  $\text{H}_3\text{PO}_4$ . Optical rotations were measured with a JASCO DIP-370 polarimeter.

**Bromodienes (1).** The substrates were prepared from the commercially available corresponding aldehydes by a two-step sequence described in a previous report,<sup>1</sup> in which the preparation of **1a** was described in detail. The characterization data of the other substrates were described below. **2-Bromo-1-ferrocenyl-1,3-butadiene (1b).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  4.15 (s, 5H), 4.33 (br, 2H), 4.80 (br, 2H), 5.19 (d,  $J$  = 10.4 Hz, 1H), 5.57 (d,  $J$  = 16.2 Hz, 1H), 6.40 (dd,  $J$  = 16.2 and 10.4 Hz, 1H), 6.71 (s, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  69.40, 69.59, 70.35, 79.37, 116.18, 120.43, 131.94, 137.17. Anal. Calcd for  $\text{C}_{14}\text{H}_{13}\text{BrFe}$ : C, 53.04; H, 4.13. Found: C, 53.17; H, 4.19. **3-Bromo-5,5-dimethyl-1,3-hexadiene (1c).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  1.25 (s, 9H), 5.11 (d,  $J$  = 10.4 Hz, 1H), 5.55 (d,  $J$  = 16.2 Hz, 1H), 6.13 (s, 1H), 6.26 (dd,  $J$  = 16.2 and 10.4 Hz, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  29.74, 33.65, 116.48, 122.38, 137.61, 144.19. Anal. Calcd for  $\text{C}_8\text{H}_{13}\text{Br}$ : C, 50.81; H, 6.93. Found: C, 50.48; H, 7.16. **3-Bromo-1,3-dodecadiene (1d).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  0.88 (t,  $J$  = 7.1 Hz, 3H), 1.27-1.34 (m, 10H), 1.41-1.47 (m, 2H), 2.31 (apparent q,  $J$  = 7.4 Hz, 2H), 5.15 (d,  $J$  = 10.6 Hz, 1H), 5.52 (d,  $J$  = 16.4 Hz, 1H), 5.98 (t,  $J$  = 7.1 Hz, 1H), 6.31 (dd,  $J$  = 16.4 and 10.6 Hz, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  14.14, 22.71, 28.40, 29.27, 29.32, 29.44, 31.59, 31.91, 117.10, 125.81, 135.31, 135.94. Anal. Calcd for  $\text{C}_{12}\text{H}_{21}\text{Br}$ : C, 58.78; H, 8.63. Found: C, 58.62; H, 8.92.

**Palladium-Catalyzed Asymmetric Synthesis of Allenes.** The reaction conditions and the results are summarized in Table 2. A typical procedure is given for the preparation of diethyl 2-(4-phenyl-2,3-butadienyl)-2-acetylaminopropane-1,3-dioate (**3am**) (entry 3, Table 2): A mixture of  $\text{Pd}(\text{dba})_2$  (29 mg, 50  $\mu\text{mol}$ ), (*R*)-binap (34 mg, 55  $\mu\text{mol}$ ), and (*Z*)-2-bromo-1-phenyl-1,3-butadiene (**1a**, 105 mg, 0.502 mmol) was dissolved in  $\text{CH}_2\text{Cl}_2$  (5 mL) and the solution was added to a mixture of  $\text{HC}(\text{NHCMe})(\text{COOEt})_2$  (**2m**, 120 mg, 0.552 mmol) and  $\text{CsO}^t\text{Bu}$  (125 mg, 0.607 mmol) in  $\text{CH}_2\text{Cl}_2$  (2 mL) by cannula transfer under nitrogen. The mixture was stirred at 20  $^\circ\text{C}$  for 24 h, then filtered through a short pad of  $\text{Al}_2\text{O}_3$  to remove precipitated inorganic salts. The alumina pad was washed with small amount of  $\text{Et}_2\text{O}$  three times and the combined solution was evaporated to dryness under reduced pressure. The orange-yellow residue was chromatographed on  $\text{Al}_2\text{O}_3$  (hex/ $\text{Et}_2\text{O}$  = 1/4) to give the allene **3am** (130 mg, 75% yield) as pale yellow oil which crystallized slowly. The spectroscopic data of **3an** were described in the previous report,<sup>1</sup> and the characterization data of the other allenenes were described below. **Diethyl 2-(4-phenyl-2,3-**

**butadienyl)-2-acetylamino propane-1,3-dioate (3am).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  1.20 (t,  $J$  = 7.1 Hz, 3H), 1.27 (t,  $J$  = 7.1 Hz, 3H), 1.91 (s, 3H), 3.17 (dd,  $J$  = 7.7 and 2.4 Hz, 2H), 4.14–4.28 (m, 4H), 5.35 (td,  $J$  = 7.7 and 6.5 Hz, 1H), 6.12 (dt,  $J$  = 6.5 and 2.4 Hz, 1H), 6.83 (br, 1H), 7.18–7.31 (m, 5H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  13.91, 14.02, 22.89, 32.17, 62.73, 66.36, 88.12, 94.89, 100.59, 126.77, 127.14, 128.64, 134.04, 167.53, 167.57, 169.14, 207.15. Anal. Calcd for  $\text{C}_{19}\text{H}_{23}\text{O}_5\text{N}$ : C, 66.07; H, 6.71; N, 4.06. Found: C, 65.79; H, 6.63; N, 4.00.

**Diethyl 2-(4-ferrocenyl-2,3-butadienyl)-2-acetylamino propane-1,3-dioate (3bm).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  1.21 (t,  $J$  = 7.1 Hz, 3H), 1.27 (t,  $J$  = 7.1 Hz, 3H), 1.96 (s, 3H), 3.08 (dd,  $J$  = 7.8 and 2.8 Hz, 2H), 4.11 (s, 5H), 4.11–4.28 (m, 8H), 5.04 (td,  $J$  = 7.8 and 6.5 Hz, 1H), 5.82 (dt,  $J$  = 6.5 and 2.8 Hz, 1H), 6.79 (br, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  13.92, 14.01, 22.99, 32.38, 62.61, 62.62, 66.39, 66.45, 67.42, 68.40, 68.48, 69.15, 80.28, 86.26, 91.09, 167.62, 205.98. Anal. Calcd for  $\text{C}_{23}\text{H}_{27}\text{O}_5\text{NFe}$ : C, 60.94; H, 6.00; N, 3.09. Found: C, 60.73; H, 6.02; N, 3.12.

**Diethyl 2-(5,5-dimethyl-2,3-hexadienyl)-2-acetylamino propane-1,3-dioate (3cm).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  1.00 (s, 9H), 1.25 (t,  $J$  = 7.1 Hz, 3H), 1.26 (t,  $J$  = 7.1 Hz, 3H), 2.03 (s, 3H), 3.02 (ddd,  $J$  = 14.5, 7.7, and 2.3 Hz, 1H), 3.06 (ddd,  $J$  = 14.5, 7.7, and 2.3 Hz, 1H), 4.18–4.30 (m, 4H), 4.90 (td,  $J$  = 7.7 and 6.3 Hz, 1H), 5.07 (dt,  $J$  = 6.3 and 2.3 Hz, 1H), 6.78 (br, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  13.98, 14.02, 23.03, 30.06, 31.58, 33.06, 62.54, 62.60, 66.45, 85.72, 103.14, 167.65, 167.79, 168.88, 203.22. Anal. Calcd for  $\text{C}_{17}\text{H}_{27}\text{O}_5\text{N}$ : C, 62.75; H, 8.36; N, 4.30. Found: C, 62.98; H, 8.44; N, 4.37.

**Diethyl 2-(2,3-dodecadienyl)-2-acetylamino propane-1,3-dioate (3dm).**  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  0.88 (t,  $J$  = 7.1 Hz, 3H), 1.24–1.37 (m, 18H), 1.91–1.96 (m, 2H), 2.03 (s, 3H), 3.01 (dd,  $J$  = 7.7 and 2.2 Hz, 2H), 4.19–4.29 (m, 4H), 4.81–4.86 (m, 1H), 5.03–5.07 (m, 1H), 6.78 (br, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  14.00, 14.02, 14.12, 22.68, 23.02, 28.83, 29.16, 29.22, 29.30, 29.43, 31.89, 32.71, 62.53, 62.55, 66.51, 83.83, 91.22, 167.64, 167.71, 168.86, 205.92. Anal. Calcd for  $\text{C}_{21}\text{H}_{35}\text{O}_5\text{N}$ : C, 66.11; H, 9.25; N, 3.67. Found: C, 66.56; H, 9.58; N, 3.69.

**Preparation of Benzylidene- $\pi$ -allylpalladium Complexes (5).** A mixture of  $[\text{PdCl}(\eta^3\text{-C}_3\text{H}_5)]_2$  (90.6 mg, 495  $\mu\text{mol}$ /Pd), (*R*)-binap (315 mg, 506  $\mu\text{mol}$ ), and  $\text{Na}[\text{CMe}(\text{COOMe})_2]$  (86.0 mg, 512  $\mu\text{mol}$ ) was placed in a Schlenk flask and to this was added dry THF (5 mL) under nitrogen. The mixture was stirred at room temperature for 20 min, then **1a** (115 mg, 550  $\mu\text{mol}$ ) was added to the flask by means of syringe. After stirring the reddish-orange solution for 5 h at room temperature, all the volatiles were removed under reduced pressure. To the residue,  $\text{NaBAr}^{\text{F}_4}_2$  (489 mg, 552  $\mu\text{mol}$ ) and  $\text{CH}_2\text{Cl}_2$  (5 mL) were added and the mixture was stirred for 30 min at room temperature. The mixture was filtered and the filtrate was evaporated dryness under reduced pressure. The yellow residue was chromatographed on silica gel with  $\text{CHCl}_3$  as an eluent to give the complex **5** (715 mg, 84% yield) as yellow viscous oil. A satisfactory elemental analysis of the complex could not be obtained because of low crystallinity of the complex and difficulty to remove the remaining solvent.  $^1\text{H}$  NMR ( $\eta^3$ -benzylidene- $\pi$ -allyl region, 500 MHz,  $\text{CDCl}_3$ ):  $\delta$  3.01 (dd,  $J$  = 14.6 and 9.3 Hz, 1H of major isomer), 4.30–4.40 (overlap, 1H of major isomer and 2H of minor isomer), 4.72 (ddd,  $J$  = 12.5, 7.1, and 2.8 Hz, 1H of minor isomer), 5.41 (ddd,  $J$  = 11.2, 8.9, and 3.3 Hz, 1H of major isomer), 5.87–5.93 (m, 1H of minor isomer), 5.95 (ddd,  $J$  = 14.6, 8.5, and 3.3 Hz, 1H of major isomer).  $^{31}\text{P}\{^1\text{H}\}$  NMR (202 MHz,  $\text{CDCl}_3$ ):  $\delta$  16.97 (d,  $J$  = 46.6 Hz, 1P of major isomer), 18.61 (d,  $J$  = 46.6 Hz, 1P of minor isomer), 29.90 (d,  $J$  = 46.6 Hz, 1P of minor isomer), 29.94 (d,  $J$  = 46.6 Hz, 1P of major isomer).

**Stoichiometric Reactions of the Benzyldiene- $\pi$ -allylpalladium Complex **5** with Na[CMe(COOMe)<sub>2</sub>].** A mixture of **5** (250 mg, 145  $\mu$ mol), Na[CMe(COOMe)<sub>2</sub>] (26.7 mg, 159  $\mu$ mol), and dibenzalacetone (68.2 mg, 291  $\mu$ mol) was placed in a Schlenk flask and dissolved in dry THF (4 mL). After stirring for 12 h at 20 °C, the solution was filtered through a short pad of SiO<sub>2</sub>. The silica gel pad was washed with small amount of Et<sub>2</sub>O three times and the combined solution was evaporated to dryness under reduced pressure. The yellow residue was chromatographed on silica gel (hex/Et<sub>2</sub>O = 2/1) to give the allene **3an** (29.6 mg, 74% yield) as colorless oil. An analogous reaction was performed without dibenzalacetone and the allene **3an** was obtained in 62% yield.

**Measurements of the Exchange Rates between the Two Diastereomers of **5**.** Determination of the exchange rates between the two diastereomers was carried out according to the Forsén-Hoffman method<sup>3</sup> by <sup>1</sup>H NMR. The preparation of sample solutions of the complexes for NMR measurements was carried out under an argon atmosphere using air free CDCl<sub>3</sub> as a solvent. <sup>1</sup>H NMR *T*<sub>1</sub> determinations were performed with a standard 180°- $\tau$ -90° pulse sequence by the inversion-recovery method. Spin saturation transfer experiments were performed by irradiating the resonance of the minor isomer at  $\delta$  4.72. The exchange rates from the minor isomer to the major isomer, *k*<sub>1</sub>, were calculated from the following equation;

$$I'/I = \tau / (\tau + T_1)$$

where *I* and *I'* are the intensities of the signal of the major isomer at  $\delta$  5.41 without and with saturation of the signals of minor isomer at  $\delta$  4.72, respectively. *T*<sub>1</sub> is the spin-lattice relaxation time of the signal of the major isomer at  $\delta$  5.41 and  $\tau$  (= 1/*k*<sub>1</sub>) is the pre-exchange lifetime of this exchange system. The ratio *I'*/*I* were calculated from the difference spectrum recorded by subtracting the irradiated spectrum from the reference (nonirradiated) spectrum.

Similarly, the exchange rates from the major isomer to the minor isomer, *k*<sub>-1</sub>, were obtained from the experiments irradiating the signal of the major isomer at  $\delta$  5.41. The measurements were performed at 20 and 40 °C with or without dibenzalacetone (2 eq to **5**) and the results were summarized in Table 1.

## References

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