Catalytic Isomerization of 1,5-Enynes to Bicyclo[3.1.0]hexenes

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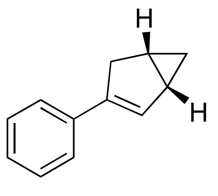
Supporting Information

General Information. Unless otherwise noted, all reagents were obtained commercially and used without further purification. ACS grade nitromethane was obtained from Aldrich Chemical Company. Tetrahydrofuran (THF), toluene, and ethyl ether were dried according to a procedure by Bergman.[1] $(Ph_3P)AuCl$ was prepared according to literature procedures.[2] Substrates **4**, **6**, **8**, **10**, **12**, **22** and **29** were prepared according to previous work.[3] Extracts were dried over $MgSO_4$ and solvents were removed *in vacuo* using a rotary evaporator at aspirator pressure. TLC analysis of reaction mixtures was performed on Merck silica gel 60 F254 TLC plates. Chromatography was carried out on ICN SiliTech 32-63 D 60 Å silica gel. ^1H and ^{13}C NMR spectra were recorded with Bruker AMX-300 and AMX-400 spectrometers and referenced to $CDCl_3$ unless otherwise noted. Mass spectral and CHN data were obtained *via* the Micro-Mass/Analytical Facility operated by the College of Chemistry, University of California, Berkeley.

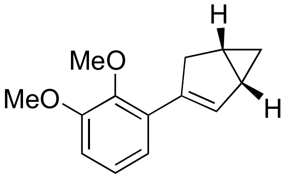
Representative procedure for Gold(I) synthesis of Bicyclo[3.1.0]-hexene.
To a 1 dram vial with a threaded cap containing a magnetic stir bar and 1,5-enyne (100 mg, 1 eq.) in CH_2Cl_2 (0.5 M) was added $AgSbF_6$ (1-5 mol%) and $(Ph_3P)AuCl$ (1-5 mol%) sequentially. A cloudy white mixture formed during the course of the reaction. The mixture was stirred at room temperature and monitored by TLC analysis. Upon completion, the mixture was filtered through a short silica plug and eluted with CH_2Cl_2. Evaporation of the solvent, followed by column chromatography afforded the desired bicyclo[3.1.0]hexene.



(**5**)

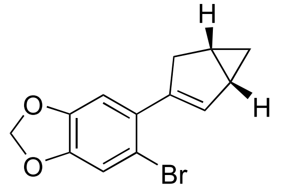
5: Prepared using 1% $(Ph_3P)AuPF_6$ and isolated as a clear solid (99%) after purification by chromatography on silica gel (hexanes); ^1H NMR ($CDCl_3$, 300 MHz) ∂ 7.44 (dt, 2H, J = 8.1, 1.5 Hz), 7.36 (tt, 2H, J = 7.2, 1.5 Hz), 7.27 (tt, 1H, J = 7.2, 1.2 Hz), 6.48 (dd, 1H, J = 2.1, 1.8 Hz), 3.09 (dd, 1H, J = 16.8, 7.2 Hz), 2.80 (d, 1H, J = 16.8 Hz), 2.05-1.98 (m, 1H), 1.84-1.75 (m, 1H), 1.01 (td, 1H, J = 7.8, 3.6 Hz), 0.17 (q, 1H, J = 3.3 Hz) ppm; ^{13}C

NMR ($CDCl_3$, 75 MHz) ∂ 140.1, 137.0, 130.0, 128.7, 127.1, 125.5, 36.7, 24. 6, 18.0, 15.9 ppm; Anal. calc'd for $C_{12}H_{12}$: C, 92.26; H, 7.74. Found: C, 91.92; H, 7.72.



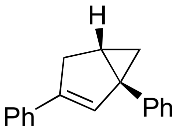
(**7**)

7: Prepared using 2% $(Ph_3P)AuPF_6$ and isolated as a clear solid (99%) after purification by chromatography on silica gel (20:1 hexanes: diethyl ether); ^{1}H NMR ($CDCl_3$, 300 MHz) ∂ 6.98 (t, 1H, *J* = 8.1 Hz), 6.81 (qd, 2H, *J* = 8.1, 1.5 Hz), 6.59 (q, 1H, *J* = 2.1 Hz), 3.85 (s, 3H), 3.75 (s, 3H), 3.07 (dd, 1H, *J* = 16.8, 5.7 Hz), 2.75 (d, 1H, *J* = 17.1), 1.98-1.91 (m ,1H), 1.72-1.63 (m, 1H), 0.92 (td, 1H, *J* = 7.5, 3.6 Hz), 0.06 (q, 1H, *J* = 3.6 Hz) ppm; ^{13}C NMR (CDCl3, 75 MHz) ∂ 153.5, 147.4, 136.5, 134.6, 131.5, 124.0, 120.8, 111.1, 60.0, 56.1, 38.6, 24.8, 17.5, 15.3 ppm; Anal. calc'd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 78.06; H, 7.76.



(**9**)

9: Prepared using 1% $(Ph_3P)AuSbF_6$ and isolated as a colorless oil (95%) after purification by chromatography on silica gel (20:1 hexanes: diethyl ether); ^{1}H NMR (400 MHz, $CDCl_3$) ∂ 6.98 (s, 1H), 6.65 (s, 1H), 6.16 (d, 1H, *J* = 0.2 Hz), 5.95 (s, 2H), 2.99 (dd, 1H, *J* = 17.2, 7.2 Hz), 2.65 (d, 1H, *J* = 17.2 Hz), 1.93-1.89 (m, 1H), 1.69-1.58 (m 1H), 0.88 (td, 1H, *J* = 7.6, 3.6 Hz), 0.17 (dd, 1H, *J* = 7.2, 3.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) ∂ 147.0, 146.9, 139.6, 134.5, 132.1, 112.9, 112.7, 109.7, 101.6, 39.2, 23.9, 16.3, 15.1; Anal. calc'd for $C_{13}H_{11}BrO_2$: C, 55.94; H, 3.97. Found: C, 55.72; H, 3.95; HRMS (EI) calc'd for $C_{13}H_{11}BrO_2$: 277.9942, found: 277.9944.

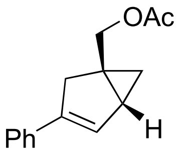


(**11**)

10: Prepared using 1% $(Ph_3P)AuSbF_6$ and isolated as a colorless oil (94%) after purification by chromatography on silica gel (hexanes); ^{1}H NMR (400 MHz, $CDCl_3$) ∂ 7.51-7.46 (m, 2H), 7.41-7.21 (m, 8H), 6.65 (s, 1H), 3.25 (dd, 1H, *J* = 17.2, 8.8 Hz), 2.86 (d, 1H, *J* = 16.8 Hz), 1.98 (dd, 1H, *J* = 12.4, 7.6 Hz), 1.66 (dd, 1H, *J* = 8.0, 2.4 Hz), 0.80 (dd, 1H, *J* = 4.4, 4.4 Hz) ^{13}C NMR (100 MHz, $CDCl_3$) ∂ 142.4, 139.7, 136.3, 130.9, 128.4, 128.3, 127.1, 126.3, 125.7, 125.3, 39.7, 26.8, 25.1; Anal. calc'd for $C_{18}H_{16}$: C, 93.06; H, 6.94. Found: C, 93.10; H, 7.15; HRMS (EI) calc'd for $C_{18}H_{16}$: 232.1252; found: 232.1249.

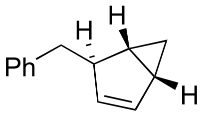
One pot synthesis of 1,3-Diphenyl-bicyclo[3.1.0]hex-2-ene (11)

To a stirring solution of (dppm)ReOCl$_3$ (3.4 mg, 0.0050 mmol) and silver hexafluoroantimonate (1.71 mg, 0.0050 mmol) in nitromethane (1 mL) in a 1 dram vial was added trimethyl allylsilane (175□L, 1.10 mmol) then 1,3-diphenyl-prop-2-yn-1-ol (208 mg 1.00 mmol). The vial was submerged in a 60 ºC oil bath for 10 minutes then allowed to cool to 22 ºC. The contents of the vial were transferred via pipette – assisted with 0.5 mL nitromethane – to a 1-dram vial containing chloro(triphenylphosphine)gold (25 mg, 0.050 mmol) and silver hexafluoroantimonate (17 mg, 0.050 mmol). After stirring for 30 minutes at 22 ºC, the solvent was removed under reduced pressure and silica gel chromatography with hexanes eluent afforded compound **11** (209 mg, 89%).

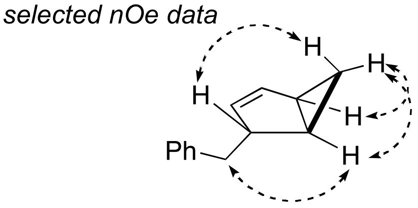


(**13**)

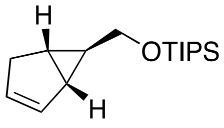
13: Prepared using 1% (Ph$_3$P)AuSbF$_6$ and isolated as a white solid (96%) after purification by chromatography on silica gel (10:1 hexanes: diethyl ether); ^{1}H NMR (400 MHz, CDCl$_3$) □ 7.29 (d, 2H, *J* = 9.2 Hz), 6.83 (d, 2H, *J* = 8.8Hz), 6.20 (s, 1H), 4.22 (s, 2H), 3.79 (s, 3H), 2.98 (dd, 1H, *J* = 16.8, 1.6 Hz), 2.81 (d, 1H, *J* = 16.8 Hz) 2.09 (s, 3H), 1.93-1.91 (m, 1H), 1.05 (dd, 1H, *J* = 7.2, 4.4 Hz), 0.41 (dd, 1H, *J* = 3.8, 3.8 Hz); ^{13}C (100 MHz, CDCl$_3$) □ 171.3, 158.7, 140.0, 129.0, 128.3, 126.3, 113.7, 69.5, 55.2, 39.9, 29.1, 26.7, 22.8, 22.7; Anal. calc'd for $C_{16}H_{18}O_3$: C, 73.39; H, 7.02. Found: C, 73.31; H, 7.13; HRMS (EI) calc'd for $C_{16}H_{18}O_3$: 258.1256; found: 258.1259.



(**15**)



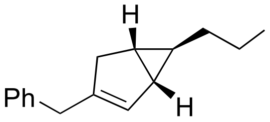
15: Prepared using 3% (Ph$_3$P)AuSbF$_6$ and isolated as a colorless oil (82%, 10:1 dr) after purification by chromatography on silica gel (hexanes); Major diastereomer ^{1}H NMR (CDCl$_3$, 400 MHz) ∂ 7.42-7.29 (m, 5H), 6.08 (dd, 1H, *J* = 5.6, 1.6 Hz), 5.45 (d, 1H, *J* = 4.4 Hz), 2.87-2.76 (m, 2H), 2.69-2.64 (m, 1H), 1.90 (broad s, 1H), 1.55 (m, 1H), 0.93-0.91 (m, 1H), -0.04 (broad s, 1H) ppm; ^{13}C NMR (CDCl$_3$, 100 MHz) ∂ 142.1, 134.8, 131.5, 129.2, 128.3, 125.9, 49.9, 43.1, 22.8, 20.8, 17.8 ppm; Anal. calc'd for $C_{13}H_{14}$: C, 91.71; H, 8.29. Found: C, 91.52; H, 8.23.



(**17**)

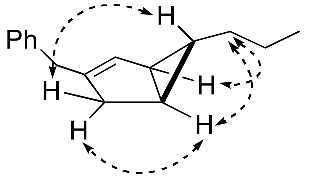
17: Prepared using 2% (Ph$_3$P)AuSbF$_6$ and isolated as a colorless oil (61%) after purification by chromatography on silica gel (99:1 hexanes: diethyl ether); ^{1}H NMR (400 MHz, CDCl$_3$) ∂ 5.92-5.88 (m, 1H), 5.43-5.39 (m, 1H), 3.66-3.54 (m, 2H), 2.57 (dd, *J* = 18.0, 7.2 Hz, 1H), 2.34 (d, *J* = 18.0 Hz, 1H) 1.80-1.76 (m, 1H), 1.54-1.48 (m, 1H), 1.06

(s, 18H), 1.05 (s, 3H), 0.51-0.45 (m, 1H); ^{13}C (100 MHz, $CDCl_3$) ∂ 133.7, 128.5, 65.0, 35.7, 32.0, 29.0, 20.2, 18.0, 12.1.

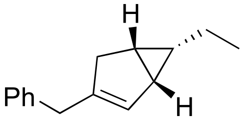


(**19**)

selected nOe data

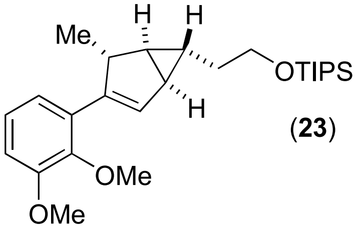


19: Prepared using 1% $(Ph_3P)AuSbF_6$ and isolated as a colorless oil (99%, >99:1 dr) after purification by chromatography on silica gel (hexanes); ^{1}H NMR (400 MHz, $CDCl_3$) ∂ 6.98 (s, 1H), 6.65 (s, 1H), 6.16 (d, 1H, J = 0.2 Hz), 5.95 (s, 2H), 2.99 (dd, 1H, J = 17.2, 7.2 Hz), 2.65 (d, 1H, J = 17.2 Hz), 1.93-1.89 (m, 1H), 1.69-1.58 (m 1H), 0.88 (td, 1H, J = 7.6, 3.6 Hz), 0.17 (dd, 1H, J = 7.2, 3.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) ∂ 147.0, 146.9, 139.6, 134.5, 132.1, 112.9, 112.7, 109.7, 101.6, 39.2, 23.9, 16.3, 15.1; HRMS (EI) calc'd for $C_{16}H_{20}$: 212.1565, found: 212.1567.



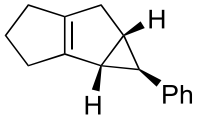
(**21**)

21: Prepared using 1% $(Ph_3P)AuSbF_6$ and isolated as a colorless oil (96%, 95:5 dr) after purification by chromatography on silica gel (hexanes); ^{1}H NMR (400 MHz, $CDCl_3$) ∂ 7.33-7.16 (m, 5H), 5.33 (bs, 1H), 3.40-3.31 (m, 2H), 2.42 (dd, 1H, J = 17.6, 7.6 Hz), 1.97-1.87 (m, 2H), 1.58-1.52 (m, 1H), 1.17-1.05 (m, 1H), 1.05-0.92 (m, 1H), 0.90 (t, 3H, J = 7.2 Hz), 0.86-0.79 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) ∂ 144.4, 140.1, 128.8, 128.2, 125.8, 123.7, 37.3, 33.8, 27.4, 24.2, 19.6, 14.3, 13.9. Anal. calc'd for $C_{15}H_{18}$: C, 90.88; H, 9.15. Found: C, 91.33; H, 9.23.



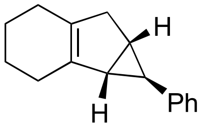
(**23**)

23: Prepared using 3% $(Ph_3P)AuPF_6$ and isolated as a clear oil (99%) after purification by chromatography on silica gel (1:3 ethyl acetate: hexanes). ^{1}H NMR ($CDCl_3$, 400 MHz) ∂ 7.01 (t, 1H, J = 8.0 Hz), 6.84-6.80 (m, 2H), 6.33 (s, 1H), 3.89 (s, 3H), 3.83 (t, 2H, J = 6.8 Hz), 3.26-3.24 (broad m, 1H), 1.78-1.75 (m, 1H), 1.62-1.52 (m, 2H), 1.31 (dd, 1H, J = 6, 3.6 Hz), 1.20-1.10 (m, 21H), 1.05 (d, 3H, J = 7.2 Hz), 0.55-0.53 (m, 1H) ppm; ^{13}C NMR ($CDCl_3$, 100 MHz) ∂ 153.1, 146.9, 143.6, 132.2, 131.6, 123.7, 121.5, 110.4, 63.2, 59.9, 55.8, 43.8, 36.0, 29.9, 28.1, 21.2, 18.1, 12.1 ppm; Anal. calc'd for $C_{26}H_{42}O_3Si$: C, 72.51; H, 9.83. Found: C, 72.33; H, 10.08. 91% ee by HPLC analysis using a Chiralcel OD column, eluting with 97:3 hexanes:2-propanol, 1.0 mL/min (λ = 250 nm); retention times 3.76 min. for major enantiomer and 4.13 min for minor enantiomer.



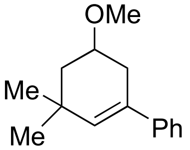
(**32a**)

32a: Prepared using 10% $(\mathrm{Ph_3P})\mathrm{AuBF_4}$ and isolated as a clear oil (72%) after purification by chromatography on silica gel (hexanes); ^{1}H NMR ($\mathrm{CDCl_3}$, 400 MHz) ∂ 7.29 (t, 2H, J = 8.0 Hz), 7.14 (t, 1H, J = 7.6 Hz), 7.05 (d, 2H, J = 6.8 Hz), 2.60 (dd, 1H, J = 17.6, 6.0 Hz), 2.40 (d, 1H, J = 18.0 Hz), 2.32-2.23 (m, 5H), 2.18-2.10 (m, 2H), 2.00-2.98 (m, 1H), 1.51 (t, 1H, J = 3.2 Hz) ppm; ^{13}C NMR ($\mathrm{CDCl_3}$, 100 MHz) ∂ 149.2, 145.0, 143.5, 128.2, 125.3, 125.2, 34.5, 33.3, 33.0, 31.7, 29.1, 28.7, 28.5 ppm; HRMS (EI) calc'd for $\mathrm{C_{15}H_{16}}$: 196.1247, found: 196.1252



(**32b**)

32b: Prepared using 3% $(\mathrm{Ph_3P})\mathrm{AuBF_4}$ and isolated as a white solid (62%) after purification by chromatography on silica gel (hexanes); ^{1}H NMR ($\mathrm{CDCl_3}$, 400 MHz) ∂ 7.26 (t, 2H, J = 7.2 Hz), 7.14 (t, 1H, J = 7.2 Hz), 7.02 (d, 2H, J = 7.6 Hz), 2.70 (d, 1H, J = 16.4 Hz), 2.40 (d, 1H, J = 17.6 Hz), 2.14-2.12 (m, 2H), 2.00-1.98 (m, 2H), 1.90-1.80 (m, 2H), 1.68-1.54 (m, 4H), 1.39 (t, 1H) ppm; ^{13}C NMR ($\mathrm{CDCl_3}$, 100 MHz) ∂ 143.8, 138.0, 133.5, 128.2, 125.1, 125.0, 40.0, 38.4, 34.3, 26.6, 25.5, 25.4, 23.1, 22.9 ppm; Anal. calc'd for $\mathrm{C_{16}H_{18}}$: C, 91.37; H, 8.63. Found: C, 91.24; H, 8.85.



(**30**)

30: To a filtered solution of $\mathrm{Ph_3PAuCl}$ (12 mg, 0.025 mmol) and $\mathrm{AgSbF_6}$ (8.6 mg, 0.025 mmol) in methanol (1 mL) was added 1,5-enyne **29** (92 mg, 0.50 mmol). After stirring for 12 hours at room temperature the methanol was removed under reduced pressure. Flash chromatography eluting with 50:1 hexanes: ethyl acetate afforded **30** (92 mg, 85%) as a colorless oil. ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) ∂ 7.48 (d, J = 8.8 Hz, 2H), 7.30 (t, J = 8.8 Hz, 2H), 7.26 (t, J = 8.8 Hz, 1H), 5.84 (t, J = 1.2 Hz, 1H), 3.71-3.64 (m, 1H), 3.47 (s, 3H), 2.84 (dd, J = 16, 4.8 Hz, 1H), 2.33 (ddd, J = 16, 9.6, 2.4 Hz, 1H), 1.95 (d, J = 12.4 Hz, 1H), 1.44, (app. t, J = 12.4 Hz, 1H), 1.16 (s, 3H), 1.14 (s, 3H); ^{13}C NMR (100 MHz, $\mathrm{CDCl_3}$) 141.6, 134.5, 131.5, 128.2, 126.8, 125.2, 55.8, 42.0, 34.2, 33.9, 31.3, 29.5; HRMS (EI) calc'd for $\mathrm{C_{15}H_{20}O}$: 216.1514, found: 216.1513.

References:

1. Alaimo, P. J.; Peters, D. W.; Arnold, J.; Bergman, R.G. *J. Chem. Ed.* **2001**, *78*, 64.
2. Bruce M. I.; Nicholson B. K.; Binshawkataly O.; Shapley Jr., Henly T. *Inorg. Syn.* **1989**, *26*, 324.
3. Luzung, M. R.; Toste, F. D. *J. Am. Chem. Soc.* **2003,** *125* **,** 15760.