Supporting Information for
Cleavage of a Carbon-carbon Triple Bond via Gold-catalyzed Cascade
Cyclization/Oxidative Cleavage Reactions of (Z)-Enynols with Molecular Oxygen

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Experimental section

All reactions were carried out using standard Schlenk techniques under nitrogen. THF was distilled from sodium and benzophenone. Zirconocene dichloride and EtMgBr (1.0 M solution in THF) were purchased from Aldrich Chemical Company. Alkynes such as 4-Octyne or diphenylacetylene were purchased from Acros Co. Ltd. (Z)-Enynols **1** were prepared by the published method¹ from readily available alkynes, ketones, and alkynyl bromides mediated by zirconium. Gold complexes of AuCl(PPh₃),² [(Ph₃PAu)₃O]BF₄³ and AuCIP(*p*-CF₃C₆H₄)₃⁴ were prepared according to the published method.

¹H and ¹³C NMR spectra were recorded at room temperature in CDCl₃ (containing 1% TMS) solutions on Varian XL-300 MHz spectrometer. For ³¹P NMR (121.45 MHz) spectroscopy, the spectra was referenced to 85% H₃PO₄ (external standard). GC analysis was performed on SHIMADZU GC-14B equipped with fused silica capillary column SHIMADZU CBP1-M25-O25 and SHIMADZU CR8A-Chromatopac integrator. Mass spectra and High-resolution mass spectra were obtained by using HP5989A and Waters Micromass GCT mass spectrometers or IonSpec 4.7 Tesla FTMS mass spectrometers. Elemental analyses were performed on an Italian Carlo-Erba 1106 analyzer. Single crystal X-ray diffraction data were collected on Bruker SMART APEX diffractometers with molybdenum cathodes.

The characterization data of (Z)-enynols **1a**, and **1d-i** have been reported.¹

(Z)-6-(4-Methoxyphenyl)-2,3,4-triphenylhex-3-en-5-yn-2-ol (**1b**)

Column chromatography on Al₂O₃ (petroleum ether / ethyl acetate =10:1) afforded the title product in 70% isolated yield. ¹H NMR (CDCl₃, Me₄Si) δ 1.64 (s, 3H), 3.77 (s,

3H), 4.07 (s, 1H), 6.76 (d, $J = 9.0$ Hz, 2H), 7.02-7.10 (m, 7H), 7.11-7.15 (m, 5H), 7.24-7.31 (m, 1H), 7.36-7.41 (m, 2H), 7.72-7.76 (m, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 31.05, 55.09, 77.75, 88.09, 99.89, 113.73, 114.52, 123.22, 125.77, 126.52, 126.71, 126.74, 127.44, 127.48, 128.02, 129.30, 130.07 (bs), 132.66, 139.14, 139.70, 148.56, 155.56, 159.72. HRMS (EI) for $\text{C}_{31}\text{H}_{26}\text{O}_2$: calcd 430.1933, found 430.1938.

(Z)-6-(4-Chlorophenyl)-2,3,4-triphenylhex-3-en-5-yn-2-ol (1c)

Column chromatography on Al_2O_3 (petroleum ether / ethyl acetate =12:1) afforded the title product in 40% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.68 (s, 3H), 3.70 (s, 1H), 7.00-7.34 (m, 15H), 7.36-7.41 (m, 2H), 7.70-7.74 (m, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 30.92, 77.74, 90.20, 98.38, 120.97, 122.82, 125.77, 126.67, 126.84, 126.91, 127.53, 128.12, 128.41, 129.26, 129.97 (bs), 132.35, 134.43, 138.82, 139.37, 148.33, 156.88. HRMS (EI) for $\text{C}_{30}\text{H}_{23}\text{ClO}$: calcd 434.1437, found 434.1434.

(Z)-2-Phenyl-3,4-dipropyldec-3-en-5-yn-2-ol (1j)

Column chromatography on Al_2O_3 (petroleum ether / ethyl acetate =10:1) afforded the title product in 42% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.84 (t, $J = 6.9$ Hz, 3H), 0.89 (t, $J = 6.9$ Hz, 3H), 0.92 (t, $J = 6.9$ Hz, 3H), 1.18-1.46 (m, 6H), 1.49-1.61 (m, 2H), 1.70 (s, 3H), 2.06-2.25 (m, 6H), 4.43 (s, 1H), 7.16-7.20 (m, 1H), 7.24-7.31 (m, 2H), 7.42 (d, $J = 7.8$ Hz, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 13.40, 13.65, 14.50, 19.00, 21.60, 21.77, 23.44, 28.88, 30.30, 33.10, 35.52, 77.82, 80.47, 98.65, 119.58, 125.55, 126.17, 127.48, 149.08, 152.01. HRMS (EI) for $\text{C}_{22}\text{H}_{32}\text{O}$: calcd 312.2453, found

312.2447.

(E)-3-Methyl-2-phenyl-4-(trimethylsilyl)dec-3-en-5-yn-2-ol (1k)

Column chromatography on neutral Al_2O_3 (ethyl acetate/petroleum ether:1:15) afforded **1k** in 62% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.23 (s, 9H), 0.84 (t, $J = 7.1$ Hz, 3H), 1.23-1.39 (m, 4H), 1.67 (s, 3H), 1.94 (s, 3H), 2.23 (t, $J = 6.9$ Hz, 2H), 5.22 (s, 1H), 7.21-7.44 (m, 5H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 0.03, 13.52, 19.41, 21.92, 21.95, 28.39, 30.55, 79.20, 81.09, 102.92, 118.19, 125.31, 126.53, 127.80, 147.91, 163.51. HRMS (EI) calcd for $\text{C}_{20}\text{H}_{30}\text{OSi}$: calcd 314.2066, found 314.2064.

(Z)-1-(1,2-Diphenyloct-1-en-3-ynyl)cyclohexanol (1l)

Column chromatography on neutral Al_2O_3 (ethyl acetate/petroleum ether:1:15) afforded **1l** in 67% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.92 (t, $J = 7.2$ Hz, 3H), 1.03-1.13 (m, 1H), 1.39-1.85 (m, 11H), 2.00-2.04 (m, 2H), 2.41 (t, $J = 9.6$ Hz, 2H), 4.23 (s, 1H), 6.91-7.11 (m, 10H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 13.49, 19.42, 21.60, 21.98, 25.27, 30.43, 36.46, 74.66, 80.64, 101.30, 120.51, 126.10, 126.30, 127.23, 129.11, 129.56, 139.17, 140.31, 157.62. HRMS (MALDI/DHB) for $\text{C}_{26}\text{H}_{30}\text{ONa}$ $[\text{M}+\text{Na}]^+$: calcd 381.2189, found 381.2192.

(Z)-1-(4-ethyldec-3-en-5-yn-3-yl)-1,2,3,4-tetrahydronaphthalen-1-ol (1m)

Column chromatography on neutral Al₂O₃ (ethyl acetate/petroleum ether:1:15) afforded **1m** in 51% isolated yield. ¹H NMR (CDCl₃, Me₄Si) δ 0.83 (t, *J* = 6.9 Hz, 3H), 1.08 (t, *J* = 7.5 Hz, 6H), 1.17-1.32 (m, 4H), 1.76-1.83 (m, 1H), 1.91-2.06 (m, 4H), 2.09-2.31 (m, 5H), 2.74-2.88 (m, 3H), 7.01-7.23 (m, 4H); ¹³C NMR (CDCl₃, Me₄Si) δ 13.47, 13.57, 14.75, 19.20, 19.32, 21.96, 23.15, 27.19, 29.99, 30.67, 37.25, 76.94, 80.29, 97.65, 119.65, 126.25, 126.62, 128.03, 128.40, 137.21, 142.44, 153.39. HRMS (EI) for C₂₂H₃₀O : calcd 310.2297, found 310.2305.

A typical procedure for gold-catalyzed carbon-carbon triple bond cleavage reactions of (Z)-enynols 1a: A solution of AuCl(PPh₃) in THF (0.05 M) and AgOTf in THF (0.05 M) were prepared. To a solution of (Z)-enynols **1a** (0.4 mmol) in 10 mL THF was added 2 mol% AuCl(PPh₃) followed by AgOTf (2 mol%). Oxygen was gently bubbled through the resulting solution at 50 °C until the reaction was complete as monitored by thin-layer chromatography. The solvent was removed in vacuo and the residue was purified by chromatography on silica gel. The butenolide derivative **2a** was obtained in 97% yield.

To isolate the byproduct of benzoic acid, the reaction was quenched with 10% of NaOH solution. The aqueous solution was washed with Et₂O, acidified with 3N HCl solution to PH < 2, and extracted with Et₂O. The organic layer was dried over anhydrous Na₂SO₄. The solvent was removed in vacuo and the residue was purified by flash chromatography on silica gel. The benzoic acid was obtained in 64% yield.

A partial oxidation of THF was also observed, ca. 419 mg was obtained as a mixture of several products in the case of **1a** (one of the product was defined as 2-hydroperoxytetrahydrofuran,⁵ 243 mg). The amount of these byproducts was reduced if the reaction time was shorter, for example, ca. 96 mg THF oxidation products were obtained in the case of **1f**.

5-Methyl-3, 4, 5-triphenyl-5H-furan-2-one (2a)

Column chromatography on silica gel (petroleum ether / ethyl acetate =30:1) afforded the title product in 97% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.93 (s, 3H), 6.74-6.78 (m, 2H), 7.16-7.30 (m, 6H), 7.31-7.45 (m, 7H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 23.18, 87.50, 125.75, 126.03, 128.20, 128.25, 128.50, 128.53, 128.66, 128.69, 129.21, 129.26, 129.62, 131.66, 137.71, 165.30, 171.90. HRMS (EI) for $\text{C}_{23}\text{H}_{18}\text{O}_2$: calcd 326.1307, found 326.1302.

5-(4-Fluorophenyl)-5-methyl-3, 4-dipropyl-5H-furan-2-one (2b)

Column chromatography on Al_2O_3 (petroleum ether / ethyl acetate =35:1) afforded the title product in 80% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.83 (t, $J = 7.5$ Hz, 3H), 0.96 (t, $J = 7.5$ Hz, 3H), 1.03-1.08 (m, 1H), 1.21-1.38 (m, 1H), 1.54-1.67 (m, 2H), 1.84 (s, 3H), 2.14(dd, $J = 8.4$, 8.1 Hz, 2H), 2.27(dd, $J = 9.3$, 8.1 Hz, 2H), 7.03 (t, $J=8.4\text{Hz}$, 2H), 7.24-7.30 (m, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 13.88, 14.35, 21.24, 21.58, 23.12, 25.75, 28.33, 87.20, 115.22, 115.50, 126.37, 127.22, 127.33, 134.40, 134.45, 160.81, 164.10, 167.35, 173.82. HRMS (EI) for $\text{C}_{17}\text{H}_{21}\text{FO}_2$: calcd 276.1526, found 276.1527.

5-(4-Fluorophenyl)-5-methyl-3, 4-diphenyl-5H-furan-2-one (2c)

Column chromatography on silica gel (petroleum ether / ethyl acetate =30:1) afforded

the title product in 96% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.92 (s, 3H), 6.76-6.80 (m, 2H), 7.02-7.10 (m, 2H), 7.19-7.35 (m, 8H), 7.40-7.46 (m, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 23.30, 86.94, 115.39, 115.68, 125.64, 127.84, 127.95, 128.07, 128.15, 128.38, 128.54, 129.08, 129.31, 131.36, 133.50, 133.54, 160.94, 164.24, 164.96, 171.61. Anal. calcd for $\text{C}_{23}\text{H}_{17}\text{FO}_2$: C, 80.22; H, 4.98; F, 5.52; O, 9.29 found C, 79.75; H, 5.04; F, 5.09.

5-(2-Chlorophenyl)-5-methyl-3,4-diphenyl-5H-furan-2-one (2d)

Column chromatography on silica gel (petroleum ether / ethyl acetate =30:1) afforded the title product in 82% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.97 (s, 3H), 6.76-6.79 (m, 2H), 7.12-7.22 (m, 2H), 7.22-7.32 (m, 5H), 7.34-7.37 (m, 1H), 7.40-7.46 (m, 4H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 26.48, 87.00, 126.97, 127.92, 128.22, 128.43, 128.49, 128.57, 129.14, 129.29, 129.85, 129.92, 130.48, 131.52, 132.21, 133.30, 134.10, 162.55, 172.09. Anal. calcd for $\text{C}_{23}\text{H}_{17}\text{ClO}_2$: C, 76.56; H, 4.75; Cl, 9.83; O, 8.87 found C, 76.72; H, 4.96; Cl, 9.88.

5-(2-Bromophenyl)-5-methyl-3,4-diphenyl-5H-furan-2-one (2e)

Column chromatography on silica gel (petroleum ether / ethyl acetate =40:1) afforded the title product in 81% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.99 (s, 3H), 6.74-6.78 (m, 2H), 7.13-7.19 (m, 2H), 7.22-7.36 (m, 6H), 7.40-7.48 (m, 3H), 7.69 (dd, J = 7.5, 1.5 Hz, 1H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 27.03, 87.49, 122.51, 127.54, 127.96, 128.25, 128.53, 128.59, 129.07, 129.18, 129.32, 129.74, 130.34, 130.63, 131.47, 134.38, 135.99, 162.41, 172.34. Anal. calcd for $\text{C}_{23}\text{H}_{17}\text{BrO}_2$: C, 68.16; H,

4.23; Br, 19.72; O, 7.90 found C, 68.22; H, 4.26; Br, 19.80.

5-Methyl-3, 4-diphenyl-5-(2-thienyl)-5H-furan-2-one (2f)

Column chromatography on silica gel (petroleum ether / ethyl acetate =25:1) afforded the title product in 91% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.97 (s, 3H), 6.89-6.93 (m, 2H), 7.00-7.06 (m, 2H), 7.20-7.35 (m, 6H), 7.36-7.38 (m, 1H), 7.41-7.47 (m, 2H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 24.11, 85.30, 125.64, 126.45, 126.90, 127.14, 128.30, 128.44, 128.57, 128.67, 129.32, 129.54, 131.20, 142.54, 163.71, 171.00. HRMS (EI) for $\text{C}_{21}\text{H}_{16}\text{O}_2\text{S}$: calcd 332.0871, found 332.0867.

5, 5-Diethyl-3, 4-diphenyl-5H-furan-2-one (2g)

Column chromatography on silica gel (petroleum ether / ethyl acetate =25:1) afforded the title product in 92% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.95 (t, J = 7.2 Hz, 6H), 1.81-1.93 (m, 2H), 1.98-2.10 (m, 2H), 7.17-7.27 (m, 5H), 7.35-7.39 (m, 5H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 7.34, 29.50, 91.12, 127.80, 128.15, 128.35, 128.98, 129.24, 129.28, 129.33, 129.86, 132.27, 162.16, 171.88. HRMS (EI) for $\text{C}_{20}\text{H}_{20}\text{O}_2$: calcd 292.1463, found 292.1466.

5-Methyl-5-phenyl-3, 4-dipropyl-5H-furan-2-one (2h)

Column chromatography on Al_2O_3 (petroleum ether / ethyl acetate =35:1) afforded the title product in 70% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.81 (t, J = 7.5 Hz, 3H),

0.96 (t, $J = 7.5$ Hz, 3H), 1.02-1.19 (m, 1H), 1.20-1.35 (m, 1H), 1.55-1.67 (m, 2H), 1.85 (s, 3H), 2.14 (dd, $J = 8.1, 7.8$ Hz, 2H), 2.27 (dd, $J = 9.6, 7.8$ Hz, 2H), 7.27-7.38 (m, 5H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 13.91, 14.38, 21.27, 21.57, 23.00, 25.78, 28.38, 87.72, 125.30, 126.19, 128.24, 128.47, 138.55, 167.61, 174.10. HRMS (EI) for $\text{C}_{17}\text{H}_{22}\text{O}_2$: calcd 258.1620, found 258.1614.

4,5-Dimethyl-5-phenyl-3-(trimethylsilyl)-5H-furan-2-one (**2i**)

Column chromatography on silica gel (ethyl acetate/petroleum ether:1:10) afforded **2i** in 41% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 0.31 (s, 9H), 1.82 (s, 3H), 1.91 (s, 3H), 7.26-7.36 (m, 5H); ^{13}C NMR (CDCl_3 , Me_4Si) δ -1.01, 13.65, 22.69, 89.56, 125.25, 128.26, 128.62, 138.55, 179.99. HRMS (MALDI/DHB) for $\text{C}_{15}\text{H}_{20}\text{SiO}_2\text{Na}$ $[\text{M}+\text{Na}]^+$: calcd 283.1125, found 283.1137.

3,4-Diphenyl-1-oxa-spiro[4,5]dec-3-en-2-one (**2j**)

Column chromatography on silica gel (ethyl acetate/petroleum ether:1:15) afforded **2j** in 66% isolated yield. ^1H NMR (CDCl_3 , Me_4Si) δ 1.10-1.18 (m, 1H), 1.69-1.90 (m, 9H), 7.15-7.23 (m, 5H), 7.36-7.40 (m, 5H); ^{13}C NMR (CDCl_3 , Me_4Si) δ 21.98, 24.33, 33.53, 87.38, 126.43, 127.78, 127.98, 128.22, 128.80, 129.01, 129.61, 132.72, 166.78, 171.52. Anal. calcd for $\text{C}_{21}\text{H}_{20}\text{O}_2$: C, 82.86; H, 6.62 found C, 82.80; H, 6.71.

Column chromatography on neutral Al₂O₃ (ethyl acetate/petroleum ether:1:30) afforded **2k** in 52% isolated yield. ¹H NMR (CDCl₃, Me₄Si) δ 1.03 (t, *J* = 7.5 Hz, 3H), 1.23 (t, *J* = 7.5 Hz, 3H), 1.89-2.30 (m, 6H), 2.42 (q, *J* = 7.5 Hz, 2H), 2.77-2.95 (m, 2H), 6.91 (d, *J* = 7.5 Hz, 1H), 7.09-7.27 (m, 3H); ¹³C NMR (CDCl₃, Me₄Si) δ 12.85, 13.03, 17.33, 19.58, 19.97, 29.59, 34.02, 86.62, 126.34, 127.03, 128.76, 129.56, 129.93, 131.91, 138.57, 166.74, 173.75. HRMS (EI) for C₁₇H₂₀O₂: calcd 256.1463, found 256.1455.

(Z)-2-Methyl-5-pentylidene-3,4-diphenyl-2-(2-thienyl)-2,5-dihydrofuran (3h**)**⁶

Column chromatography on Al₂O₃ (petroleum ether / ethyl acetate =30:1) afforded the title product in 84% isolated yield. ¹H NMR (CDCl₃, Me₄Si) δ 0.86 (t, *J* = 7.2 Hz, 3H), 1.25-1.38 (m, 4H), 1.92 (s, 3H), 2.17-2.26 (m, 2H), 4.45 (t, *J* = 7.8 Hz, 1H), 6.78-6.82 (m, 2H), 6.95-7.00 (m, 2H), 7.02-7.11 (m, 3H), 7.21-7.31 (m, 6H); ¹³C NMR (CDCl₃, Me₄Si) δ 13.98, 22.29, 24.89, 24.97, 32.10, 89.59, 99.79, 124.34, 125.86, 126.59, 127.42, 127.63, 127.83, 128.24, 129.05, 129.78, 133.04, 133.08, 133.36, 144.67, 148.60, 157.26. HRMS (EI) for C₂₆H₂₆OS: calcd 386.1704, found 386.1714.

A typical procedure for gold-catalyzed oxidative cleavage reactions of dihydrofurans **3a.** A solution of AuCl(PPh₃) in THF (0.05 M) and AgOTf in THF (0.05 M) were prepared. To a solution of dihydrofuran **3a** (0.4 mmol) in 10 mL THF was added 2 mol% AuCl(PPh₃) followed by AgOTf (2 mol%). Oxygen was gently bubbled through the resulting solution at 50 °C until the reaction was complete as monitored by thin-layer chromatography. The solvent was removed in vacuo and the residue was purified by flash chromatography on silica gel. The butenolide derivative **2a** was obtained in 90% yield. The representative results are shown in Table 1.

Table 1, Formation of butenolides from dihydrofurans

R ¹	R ²	R ³	product	time	yield% ^a
Ph	Ph	Ph	2a	21 h	90
<i>p</i> -FC ₆ H ₄	Pr	Ph	2b	14 h	69
<i>o</i> -ClC ₆ H ₄	Ph	Bu	2d	3 h	86
2-thienyl	Ph	Bu	2f	3 h	84

^aIsolated yields.

A typical procedure for gold-catalyzed oxidative cleavage reaction of an enol ether. A solution of AuCl(PPh₃) in THF (0.05 M) and AgOTf in THF (0.05 M) were prepared. To a solution of (2-butoxyvinyl)benzene (a mixture of *cis*/*trans* isomers) (0.5 mmol) in 10 mL THF was added 2 mol% AuCl(PPh₃) followed by AgOTf (2 mol%). Oxygen was gently bubbled through the resulting solution at 50 °C for 10 h. The reaction was quenched with 10% of NaOH solution. The aqueous solution was washed with Et₂O, acidified with 3N HCl solution to PH < 2, and extracted with Et₂O. The organic layer was dried over anhydrous Na₂SO₄. The solvent was removed in vacuo and the residue was purified by flash chromatography on silica gel. The benzoic acid was obtained in 29% yield.

³¹P NMR study of the reaction mixture.

(1) To probe the stability of AuCl(PPh₃) in THF under the atmosphere of O₂.

It was found that there is no change of the chemical shift (33.8 ppm in THF, literature,^{7a} 32.9 ppm in CDCl₃) after 24 h. This result indicated that AuCl(PPh₃) is

stable under the atmosphere of O₂.

(2) To probe the stability of AuCl(PPh₃)/AgOTf^{7b} in THF under the atmosphere of O₂.

Figure S1. a) ³¹P NMR spectra of the reaction mixture of AuCl(PPh₃)+AgOTf in THF. (literature,^{7b} 28.8 ppm in CDCl₃) b) Stirring of the mixture for 24 h under O₂. c) Stirring of the mixture for 48 h under O₂. d) ³¹P NMR spectra of the reaction mixture in CDCl₃ (24 h, THF was removed by vacuum pump).

Figure S2. The MS (MALDI-TOF) spectra of the reaction mixture of $\text{AuCl}(\text{PPh}_3) + \text{AgOTf}$ in THF under O_2 after 24 h. The principal ion of m/z 720.9 was assigned to be “ $(\text{PPh}_3)_2\text{Au}^+$ ” (calcd: m/z 721.1).

The result indicated that cationic gold(I) complex is unstable and a new phosphorus species was generated. The new species at 45.4 ppm was suggested to be $(\text{PPh}_3)_2\text{Au}^+$ according to MS result and the same chemical shift found in literature (45.6 ppm in CDCl_3).^{7b}

(3) Monitoring of the reaction mixture of **1f**.

Figure S3. a) ^{31}P NMR spectra of the reaction mixture of **1f** and 2% $\text{AuCl}(\text{PPh}_3)/\text{AgOTf}$ (stirring for 5 min under O_2). b) Stirring of the mixture for 1.5 h under O_2 . c) After the reaction finished (3 h).

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X-ray single-crystal structure of **2d**.