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π-Extended DPCB for Activation-Free Homogeneous Gold Catalysis**

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The catalytic properties of bis[chlorogold(I)] complexes that bear the 3,4-bis(2,4,6-tri-*tert*-butylphenyl)-3,4-diphosphinidenecyclobutene (DPCB) ligand could be improved by suitable extension of the π-conjugation. If the 1-naphthyl substituent was employed in the 1,2-positions in the kinetically stabilized DPCB skeleton, high catalytic activity of the DPCB-bis(chlorogold) complex was induced in the intermolecular alkoxycyclization of 1,6-enyne without activation by a Ag cocatalyst. DFT calculations of the 1,2-diaryl-substituted DPCB derivatives indicated that both suitable energetic reduction of the LUMO level and steric characteristics of the ligand structure are important for the high catalytic activity. The optimized 1-naphthyl-substituted DPCB-chlorogold(I) complex was further employed for catalytic intramolecular cyclizations to afford heterocyclic structures by the activation of terminal acetylene and allene moieties and the hydration of terminal acetylene under the mild conditions.

Introduction

In the past decades the chemistry of homogenous Au catalysts has grown tremendously. Various homogenous Au catalysts have been employed widely for organic synthesis,[1–8] and consequently, precise mechanistic analyses have been developed.[9–13] One of the popular procedures for the generation of the catalytically active Au species is the exchange of the chloride in LAuCl precursors [L = phosphine, N-heterocyclic carbene (NHC), etc] by treatment with Ag salts as the LAuCl species normally showed low or almost no catalytic functionality because of the insufficient activity of the Cl-coordinated Au centers except for a few examples.[14–16] This conventionally utilized procedure for homogeneous Au catalysis, however, often exhibits remarkable dependence on the "Ag effect". Shi and coworkers proved that several Au-catalyzed organic transformations scarcely worked in the absence of silver halides.[17] One of the effective procedures that excludes the Ag effect is to employ isolable and catalytically active LAuX complexes such as Gagosz-type complexes [LAu(NTf_2)].[18,19] Recently Nolan and co-workers reported Ag- and acid-free procedures by using a diaurated structure for highly catalytically active Au species.[20] These "Ag-free" processes still require the addition of a Ag salt to exchange the chloride of the LAuCl precursors with anionic ligands X, and the Ag effect could exist unless the resultant Ag salt was removed properly in the purification of the catalysts.[21,22]

An alternative method for Ag-free homogeneous Au catalysis is to use LAuCl complexes directly. Previously, we found that several phosphaalkene-chlorogold(I) structures could exhibit catalytic activity for molecular transformations through the activation of the terminal alkyne without exchange of the chloride anion.[23–25] This unique catalytic activity would correspond to the strong π-accepting ability of the P=C bond based on its low LUMO level.[26,27] 3,4-Diphosphinidenecyclobutenes (DPCBs) possess a unique, almost planar π-conjugate system that includes two P=C moieties and provides relatively rigid and suitable chelate structures for remarkable catalytic activity. To date, Ozawa and Yoshifuji have utilized DPCB chelate complexes for unique transition-metal catalysis.[28] Moreover, DPCBs can also be utilized for bis(chlorogold) complexes to induce considerable distortion of the planar ligand skeleton,[23,29] and homogeneous catalytic activity is displayed in 1,6-enyne cycloisomerizations without any Ag activator (Figure 1).[23] The remarkable short Au–Au distance caused by the DPCB distortion reinforces the aurophilic interaction,[30] which leads to the resultant catalytic activity.

As Ozawa and co-workers have revealed, the catalytic activity of the mononuclear DPCB chelate complexes depends considerably on the 1,2-diaryl substituents.[31,32] Therefore, the tuning of the 1,2-diaryl groups is a promising approach to improve and understand the catalytic activity of DPCB-bis(chlorogold) complexes. Furthermore, the tuning method for the ho-

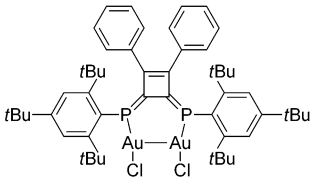

Figure 1. A catalytically active DPCB-bis(chlorogold) complex.

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[**] *DCPB = 3,4-bis(2,4,6-tri-tert-butylphenyl)-3,4-diphosphinidenecyclobutene*

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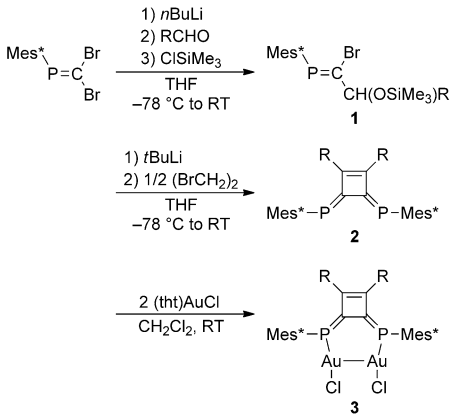
mogeneous chlorogold catalysis is expected to be applicable to other DPCB-coordinated transition-metal catalysts.

In this paper we demonstrate the synthesis of various 1,2-diaryl-substituted DPCB derivatives, and their structural and physical properties are discussed based on the observed catalytic activity of the DPCB-bis(chlorogold) complexes in the alkoxycyclization of 1,6-enyne, the intramolecular cyclization of propargylic amide and allenyl alcohol, and the acetyl-assisted hydration of terminal alkynes without activation. The structural and physicochemical properties suggest that moderate extension of the π conjugation of the 1,2-diaryl substituents and the corresponding steric effects were able to improve the catalytic activity. In addition to the 1,2-diaryl-substituted DPCB derivatives, the related 1,2-cycloalkyl-substituted derivatives were also employed for activation-free chlorogold catalysis.

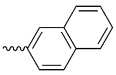
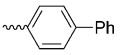
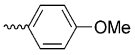
Results and Discussion

As displayed in Scheme 1, 2-bromo-1-phosphapopenes **1** were synthesized by the regioselective halogen–metal exchange of a kinetically stabilized 2,2-dibromo-1-phosphaethene (dibromomethylenephosphine; Mes* = 2,4,6-*t*Bu$_3$C$_6$H$_2$),[33] and the subsequent coupling of the anionic organophosphorus intermediates afforded the corresponding DPCB derivatives (**2**) together with small amounts of the *E,Z* isomers.[23,29] Aromatic hydrocarbons and the related aliphatic cyclic structures were employed as the substituents at the 1,2-positions (R; Table 1). Additionally, the 4-methoxyphenyl derivative **2f** that was successful to improve the catalytic activity of chelate Pd complexes[31,32,34,35] was also examined. Although yields of the 1,2-cycloalkyl-substituted **2g**[29] and **2h** were low, probably because of the instability of the organophosphorus intermediates, the 1,2-diaryl derivatives **2a**–**f** were obtained in high yields. DPCBs **2** were successfully converted to the corresponding bis(chlorogold(I)) complexes (**3**) by reaction with two equivalents of (tht)AuCl (tht = tetrahydrothiophene) in good yields. The *E,Z* isomers were consumed in the course of complexation.



Scheme 1. Preparation of DPCB derivatives.

Table 1. Synthesis of **2** and **3** via 2-bromo-1-phosphapropene **1**.

Compound	R	Yield of **1** [%]	Yield of **2** [%][a]	Yield of **3** [%]
a		85	80	83
b		96	97	82
c		77	87	85
d		83	85	89
e		97	85	80
f		86	90	82
g		95	21	82
h		66	14	86

[a] Combined yield of *E,E* and *E,Z* isomers.

The structures of **2** and **3** were determined from the spectroscopic data, and the structures of **2b** and **3b** were further confirmed by X-ray crystallography (Figures 2 and 3). The metric parameters of the DPCB skeleton are compared in Table 2.[34] Most of the metric parameters of **2b** are comparable to the 1,2-diaryl DPCB derivatives reported previously.[34,36] However, the P1–C1–C2–P2 skeleton of **2b** showed a slightly twisted conformation, and correspondingly, the four aryl rings formed a propeller-like structure. Although the Mes* groups are nearly perpendicular to the P–C1–C2–P2 plane (A), the dihedral angles between the 1-naphthyl planes (C and D) and the four-membered ring B indicate the possible extension of the conjugation effect. The LUMO plots of **2b** show the remarkable contribution of the 1-naphthyl groups (Figure 4), and the UV/Vis spectroscopic study also supports a reduction of the HOMO–LUMO energetic difference (Figure S1). The X-ray structure of **3b** indicated that the dual coordination of the AuCl moiety induced a remarkable distortion of the P=C–C=P skeleton to construct the C_2-type structure.[23,29] The increase of the P1–C1–C2 and P2–C2–C1 angles also indicates the effect

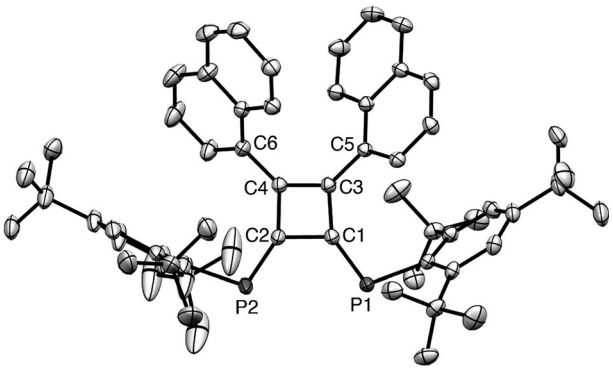


Figure 2. An ORTEP drawing of **2d** (40% probability levels). Hydrogen atoms are omitted for clarity. The torsion angle of P1–C1–C2–P2 is 7.7(4)°.

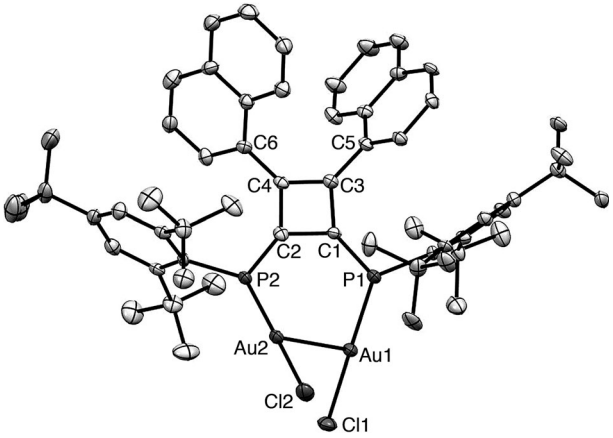
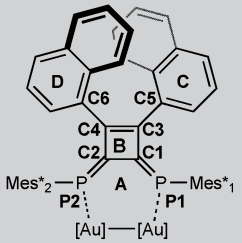


Figure 3. An ORTEP drawing of **3b** (50% probability levels). One of the two independent molecules is shown. Hydrogen atoms and solvent molecules (acetonitrile) are omitted for clarity. Bond distances [Å]: P1–Au1 2.232(1)/2.231(1), P2–Au2 2.228(1)/2.229(1), Au1–Cl1 2.283(1)/2.286(1), Au2–Cl2 2.285(1)/2.281(1), Au1–Au2 2.9719(3)/3.0014(2). The torsion angle of P1–C1–C2–P2 is 18.3(4)/21.4(7)°

Table 2. Comparison of bond distances [Å] and angles [°] in the DPCB skeleton.



Description	2b	3b
P1–C1	1.679(3)	1.670(5)/1.668(4)
P2–C2	1.669(3)	1.684(4)/1.675(4)
P1–Mes*$_1$	1.843(2)	1.828(4)/1.818(4)
P2–Mes*$_2$	1.851(3)	1.818(4)/1.826(4)
C1–C2	1.521(4)	1.504(6)/1.508(5)
C1–C3	1.480(4)	1.470(6)/1.481(6)
C2–C4	1.483(4)	1.467(6)/1.467(6)
C3–C4	1.397(3)	1.399(6)/1.400(5)
C3–C5	1.468(4)	1.466(6)/1.456(6)
C4–C6	1.468(4)	1.461(6)/1.477(6)
C1–P1–Mes*$_1$	104.6(1)	110.5(2)/110.3(2)
C2–P2–Mes*$_2$	105.3(2)	110.7(2)/112.5(2)
P1–C1–C2	124.4(2)	131.6(3)/129.9(3)
P2–C2–C1	124.4(2)	128.2(3)/129.0(3)
C3–C4–C6	134.6(2)	134.8(4)/133.7(4)
C4–C3–C5	135.8(2)	134.2(4)/135.1(4)
A–B	3.3	7.6/7.7
A–Mes*$_1$	75.1	84.5/80.2
B–Mes*$_2$	77.4	78.4/80.4
B–C	47.0	53.9/43.8
B–D	42.9	47.4/45.3

of the dual coordination of Au, whereas the chelation of DPCB reduced the corresponding parameters.[34]

The catalytic activity of **3** was monitored in the Ag-activator-free (phosphaalkene)AuCl-catalyzed alkoxycyclization of 1,6-enyne **4**.[38] Under the reaction conditions that used a 1:1 mixture of methanol and dichloromethane, **3a** afforded the cyclization product **5** but in a low yield (Table 3, Entry 1), whereas the intramolecular cycloisomerization of **4** was catalyzed quantitatively.[23] The π-extended 1,2-substituents were then employed for the chlorogold catalysis. To our delight, 1-naphthyl-substituted **3b** showed quite a high activity for the alkoxycyclization, and **5** was obtained almost quantitatively (Entry 2). Conversely, **3c**, which bears 2-naphthyl groups, showed a lower catalytic activity than **3b** (Entry 3), although the levels of the frontier orbitals of **2c** were almost same as those of **2b** (Supporting Information). However, the extension of the conjugation was basically effective, and complexes **3d** and **3e** showed a high activity (Entries 4 and 5). 4-Methoxyphenyl-substituted DPCB was also effective, and **3f** catalyzed the alkoxycyclization to afford **5** in good yield (Entry 6). Cyclopropyl-substituted DPCB **3g** improved the catalytic activity in comparison with **3a** (Entry 7), whereas **3h**, which bears cyclohexyl groups, showed a comparable activity to **3a** (Entry 8). Therefore, the cyclopropyl conjugation effect[39] would be somewhat useful for the activation-free Au-catalyzed reaction. DFT calculation of **2g** indicated a large contribution of the cyclopropyl group to the LUMO (Supporting Information). The most active catalyst **3b** permitted the reduction of the catalytic amount up to 0.5 mol%, although an extension of the reaction time was required (Entries 9 and 10; turnover number (TON) = 92 and 170, respectively). Very recently Hashmi and co-workers developed quite active Au catalysts by the use of sterically bulky phosphite ligands and accomplished TONs up to 420 for the rele-

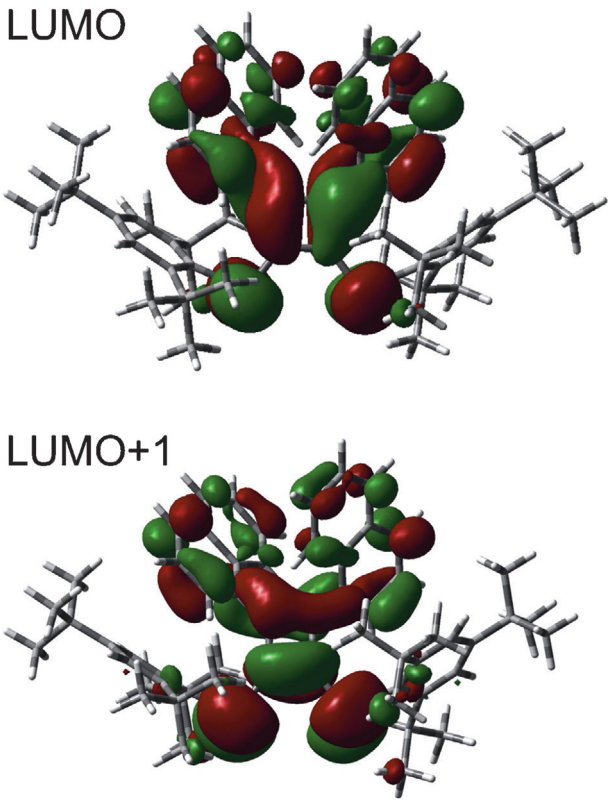
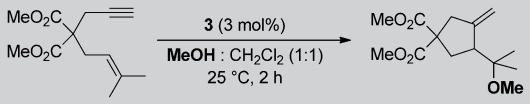


Figure 4. Plots of the LUMO and LUMO+1 for **2b** [M06-2X/6-31G(d)].[37]

Table 3. Catalytic activity of **3**.



4 5

Entry	Catalyst	R	Yield of **5** [%]	Recovery of **4** [%]
1	**3a**	Ph	45	55
2	**3b**	1-Naph	99	<1
3	**3c**	2-Naph	67	32
4	**3d**	4-PhC_6H_4	88	8
5	**3e**	2-PhC_6H_4	92	6
6	**3f**	4-MeOC_6H_4	87	11
7	**3g**	*c*Pr	75	20
8	**3h**	*c*Hex	55	45
9	**3b**[a]	1-Naph	92	7
10	**3b**[b]	1-Naph	85	15
11	**3b**[c]	1-Naph	81	18

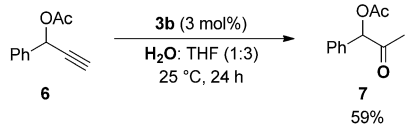
[a] 1 mol% of **3b**, 4 h. [b] 0.5 mol% of **3b**, 24 h. [c] Reaction without dichloromethane for 24 h.

vant 1,6-enyne cycloisomerization.[40] Thus, **3b**, which shows a comparable catalytic efficiency to the phosphite-gold catalysts, might be effective for practical homogeneous Au catalysis. Additionally, **3b** catalyzed the alkoxycyclization in the absence of dichloromethane (Entry 11). The dual coordination of Au with the DPCB ligand is also decisive for the Ag-free Au-catalyzed reaction.[41]

As described above, the remarkable difference of catalytic activity between **3b** and **3c** could not be explained only by the electronic properties. UV/Vis spectra of **3c** show larger absorption coefficients and indicate a higher planarity between the four-membered ring and 2-naphthyl groups, whereas **3b** displayed slightly redshifted absorptions. However, **3b** showed somewhat better solubility under the conditions employed in comparison with other DPCB-bis(chlorogold) complexes. Complex **3b** showed enough solubility in methanol, which would be advantageous for catalytic activity under CH_2Cl_2-free conditions (Table 1, Entry 11). However, the possibly more planar skeleton and relatively rigid structure of **2c** indicates the disadvantageous character of **3c** for the homogeneous reaction conditions.

The results of the alkoxycyclization, which include the intermolecular formation of the C–O bond stimulated us to use **3b** for other reactions, and we next examined intramolecular cyclizations that afford heterocyclic structures. A propargylic amide could be cyclized in the presence of **3b** to give the corresponding methylene-3-oxazoline derivative[42] under AgX-free conditions at 25 °C, although a low yield (29%) was observed (Table S1). The intramolecular cyclization of a hydroxyallene (hexa-4,5-dien-1-ol) could also be catalyzed by **3b** without a AgX cocatalyst, and the corresponding furan derivative[43] was isolated in 26% yield (Table S2). Almost every **3** except **3b** showed a low catalytic activity. However, the catalytic activity of **3e** was slightly superior in comparison with other DCPB-bis(chlorogold) complexes, and thus the 2-phenylphenyl group might also be available to the phosphaalkene-chlorogold catalysis because of the suitable level of conjugation and steric hindrance to the Au catalyst (Supporting Information).[44,45]

Next we attempted to develop intermolecular reactions by using **3b** and we found that the acetyl-supported hydration of **6**[46] was catalyzed successfully under the mild conditions. The corresponding methylketone derivative **7** was obtained in a moderate yield (Scheme 2). Although activation with Ag salts



6 7
59%

Scheme 2. Acetyl-assisted hydration of terminal acetylene.

such as $AgSbF_6$ normally accompanies the Au-catalyzed hydration reaction, the use of small Au clusters was developed recently and achieved high TONs.[47] However, the Au-catalyzed processes without any activation process would also be attractive synthetic approaches in terms of simplified reaction conditions and the avoidance of residual contamination of the products.

Conclusions

Adequate π-conjugation effects were effective to enforce activity of the homogeneous chlorogold catalyst that bears the 3,4-bis(2,4,6-tri-*tert*-butylphenyl)-3,4-diphosphinidenecyclobutene (DPCB) ligand system. The 1-naphthyl structure could be employed as the optimized DPCB ligand, which enables several activation-free Au-catalyzed cyclization and hydration reactions. The structural characteristics of the 1-naphthylated DPCB derivatives would also be advantageous to understand the detailed mechanism of the activation-free Au-catalyzed reactions. Phosphaalkene-chlorogold complexes have not catalyzed reactions by the activation of inner alkynes to date, which is an important aspect of these particular homogeneous Au-catalyzed reactions. However, the bis(chlorogold) structure of **3** is applicable for further development based on dual Au catalysis[5,8,21] and the helically distorted molecular skeleton. The exploration of Au-catalyzed reactions by using complexes **3** and the related phosphaalkene-gold complexes under the activation-free conditions is in progress.

Experimental Section

All manipulations with organolithium reagents were performed under an Ar atmosphere using standard Schlenk techniques, and the solvents were dried by appropriate methods. ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$ NMR spectra were recorded by using a Bruker AV300M spectrometer in $CDCl_3$ at 298 K with internal Me_4Si (^1H, ^{13}C) or external 85% H_3PO_4 (^{31}P) standards. MS spectra were taken by using a JEOL T100 LC spectrometer. XRD data were collected by using a Rigaku RAXIS-Rapid diffractometer, and structures were solved by direct methods (SHELXL-97).[48] The X-ray structure solution and refinement were performed by using the Yadokari-XG software.[49] DFT calculations for a single isolated species were performed by

using the Gaussian 09 program package.[50] UV/Vis spectra were recorded by using a Jasco V570 spectrometer. 2,2-Dibromo-1-(2,4,6-tri-*tert*-butylphenyl)-1-phosphaethene was synthesized according to our previous report.[33]

Preparation of 1 b

To a solution of 2,2-dibromo-1-(2,4,6-tri-*tert*-butylphenyl)-1-phosphaethene (Mes*P=CBr_2; 2.24 g, 5.00 mmol) in THF (40 mL) was added butyllithium (5.50 mmol, 1.6 M solution in hexane, 1 M = 1 mol dm^{-3}) at −78 °C, and the mixture was stirred for 15 min. 1-Naphthaldehyde (5.50 mmol) was added at −78 °C, and the mixture was stirred for 15 min. After the reaction mixture was warmed to 0 °C, chlorotrimethylsilane (0.58 mL, 6.0 mmol) was added, and the reaction mixture was stirred for 3 h at 40 °C. After the residue was extracted with hexane, and the solvent was removed in vacuo. The resultant residue was purified by silica-gel column chromatography (hexane/AcOEt = 30:1) to afford **1 b** as a colorless solid (2.9 g, 96%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.50 (d, J = 8.2 Hz, 1 H, arom.), 7.98–7.92 (m, 2 H, arom.), 7.86 (d, J = 8.4 Hz, 1 H, arom.), 7.63–7.52 (m, 3 H, arom.), 7.44 (d, J = 14.7 Hz, 2 H, arom.), 6.51 (d, J = 13.5 Hz, 1 H, CH), 1.52 (s, 9 H, *o*-*t*Bu), 1.38 (s, 9 H, *o*-*t*Bu), 1.35 (s, 9 H, *p*-*t*Bu), 0.25 ppm (s, 9 H, TMS); ^{31}P{^{1}H} NMR (121 MHz, $CDCl_3$): δ = 258.1 ppm; ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ = 167.4 (d, $^1J_{PC}$ = 63.6 Hz, P=C), 153.4 (d, J_{PC} = 2.5 Hz), 153.3 (d, J_{PC} = 2.2 Hz), 150.8, 140.8, 137.6, 137.1 (d, J_{PC} = 10.4 Hz), 136.9, 133.7, 130.3, 128.9, 126.0, 125.9, 125.2 (d, J_{PC} = 13.2 Hz), 124.2 (d, J_{PC} = 4.9 Hz), 122.2 (d, J_{PC} = 5.3 Hz), 71.4, 37.9 (d, J_{PC} = 13.4 Hz), 35.1, 32.8 (d, J_{PC} = 7.1 Hz), 32.5 (d, J_{PC} = 6.9 Hz), 31.4, 0.33 ppm; HRMS (atmospheric pressure chemical ionization; APCI): *m*/*z*: calcd for $C_{33}H_{47}BrOPSi$: 597.2317 $[P+H]^+$; found 597.2362.

Preparation of 2 b

To a solution of **1 b** (0.600 g, 1.00 mmol) in THF (15 mL) was added *tert*-butyllithium (2.1 mmol, 1.55 M solution in pentane) at −78 °C, and the mixture was stirred for 15 min. The reaction mixture was warmed to 0 °C, and 1,2-dibromoethane (43 μL, 0.5 mmol) was added. The reaction mixture was warmed to 40 °C and stirred for 4 h. After concentration in vacuo, the residue was extracted with hexane, and the solvent was removed in vacuo. The crude residue was purified by silica-gel column chromatography (hexane/ethyl acetate = 20:1) to give **2 b** (0.83 g, 97%, (*E*,*E*)/(*E*,*Z*) = 76:24) as a yellow solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.38 (d, J = 7.8 Hz, 4 H, arom.), 7.26 (s, 4 H, arom.), 7.05 (d, J = 8.6 Hz, 2 H, arom.), 6.95 (t, J = 7.2 Hz, 2 H, arom.), 6.89 (t, J = 7.7 Hz, 2 H, arom.), 6.73 (d, J = 7.1 Hz, 2 H, arom.) 6.63 (t, J = 7.7 Hz, 2 H, arom.), 1.62 (s, 36 H, *o*-*t*Bu), 1.36 ppm (s, 18 H, *p*-*t*Bu); ^{31}P{^{1}H} NMR (121 MHz, $CDCl_3$): δ = 168.3 [(*E*,*Z*) isomer: 193.1 (d, $^3J_{PP}$ = 13.3 Hz), 173.5 ppm (d, $^3J_{PP}$ = 13.3 Hz)]; ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ = 177.0 (dd, J_{PC} = 16.8 Hz and 9.2 Hz), 156.7 (d, $^2J_{PC}$ = 5.0 Hz), 154.7, 150.1, 124.5–130.3 (m, 8C), 121.5, 119.5, 38.4, 34.9, 33.4, 31.5 ppm; HRMS (APCI): *m*/*z*: calcd for $C_{60}H_{73}P_2$: 855.5188 $[P+H]^+$; found: 855.5225.

Preparation of 3 b

A mixture of **2 b** (86.0 mg, 0.100 mmol), (tht)AuCl (0.195 mmol), and CH_2Cl_2 (1 mL) was stirred for 1 h at RT. After evaporation under reduced pressure, the resultant residue was dissolved in CH_2Cl_2 (0.2 mL), and the resulting mixture was recrystallized from hexane to afford **3 b** (108 mg, 82%) as a red solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.48 (d, J = 8.4 Hz, 2 H, arom.), 7.43 (d, J = 8.1 Hz, 2 H, arom.), 7.17 (t, J = 2.1 Hz, 4 H, arom.), 7.00 (t, J = 7.8 Hz, 2 H, arom.), 6.84 (t, J = 7.2 Hz, 2 H, arom.), 6.76 (d, J = 8.7 Hz, 2 H, arom.), 6.71 (d, J = 6.9 Hz, 2 H, arom.), 6.58 (t, J = 8.3 Hz, 2 H, arom.), 1.57 (s, 36 H, *o*-*t*Bu), 1.21 ppm (s, 18 H, *p*-*t*Bu); ^{31}P{^{1}H} NMR (121 MHz, $CDCl_3$): δ = 132.9 ppm; ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ = 167.9 (dd, J_{PC} = 29.4 Hz and 8.5 Hz), 157.1 (d, J_{PC} = 13.0 Hz), 156.9, 132.6, 130.4, 129.0, 128.0, 127.3, 126.4, 125.8 (d, J_{PC} = 4.1 Hz), 124.7 (d, J_{PC} = 2.3 Hz), 123.2 (t, J_{PC} = 5.0 Hz), 120.5 (t, J_{PC} = 14.3 Hz), 39.3, 35.2, 34.7, 31.1 ppm; HRMS (APCI): *m*/*z*: calcd for $C_{60}H_{73}Au_2Cl_2NaP_2$: 1341.3715 $[M+Na]^+$; found: 1341.3749.

Alkoxycyclization of 4 (Table 3, Entry 1–8)

To a solution of **3** (3 mol%) in dichloromethane (0.5 mL) and methanol (0.5 mL) was added a solution of **4** (25.3 mg, 0.10 mmol) in methanol (0.5 mL) at RT. After it was stirred for 2 h, the reaction mixture was loaded directly onto a silica-gel column (hexane/ethyl acetate 6:1) to give **5** as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 5.02 (s, 1 H, =CH), 4.96 (s, 1 H, =CH), 3.70 (s, 6 H, CO_2Me), 3.17 (s, 3 H, OMe), 2.79–2.92 (m, 3 H, CH_2), 2.53 (dd, J = 13.4 Hz and 8.6 Hz, 1 H, CH_2), 1.98 (dd, J = 13.4 Hz and 9.4 Hz, 1 H, CH_2), 1.16 (s, 3 H, Me), 1.10 ppm (s, 3 H, Me); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ = 172.0, 171.9, 148.2, 110.5, 58.6, 52.69, 52.65, 49.1, 49.0, 43.4, 36.0, 22.6, 22.2 ppm.

Hydration of 6

To a solution of **3 b** (4.0 mg, 3 μmol) in 1,4-dioxane (0.5 mL) was added a solution of 1-phenylprop-2-yn-1-yl acetate (17.4 mg, 0.10 mmol) in 1,4-dioxane (0.25 mL) and H_2O (0.25 mL) at 25 °C. After it was stirred for 24 h, the reaction mixture was loaded directly onto a silica-gel column and eluted with hexane/ethyl acetate 10:1 to give 2-oxo-1-phenylpropyl acetate as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.40 (brs, 5 H, arom.), 5.97 (s, 1 H, CH), 2.19 (s, 3 H, CH_3), 2.11 ppm (s, 3 H, CH_3); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ = 201.7, 170.3, 133.1, 129.4, 129.1, 128.1, 81.0, 26.2, 20.8 ppm.

X-ray crystallography of 2 b

$C_{60}H_{72}P_2$, yellow prisms (CH_2Cl_2), M_W = 855.12, crystal dimensions = 0.38 × 0.35 × 0.23 mm^3, monoclinic, space group $P2_1/a$ (#14), a = 19.9929(6), b = 12.9744(4), c = 20.4275(6) Å, β = 100.2460(10)°, V = 5214.3(3) Å^3, Z = 4, λ = 0.71075 Å, T = 123 K, ρ_{calcd} = 1.089 g cm^{-3}, μ_{MoK_α} = 0.119 mm^{-1}, F_{000} = 1848, 49892 total reflections ($2\theta_{max}$ = 54.96°), index ranges = $-25 \le h \le 25$, $-16 \le k \le 16$, $-26 \le l \le 26$, 11948 unique reflections (R_{int} = 0.0712), $R1$ = 0.0908 ($I > 2\sigma(I)$), 0.1023 (all data), $wR2$ = 0.2806 ($I > 2\sigma(I)$), 0.2873 (all data), S = 2.000 (812 parameters).

X-ray Crystallography of 3 b

$C_{60}H_{72}P_2Au_2Cl_2{\cdot}C_2H_3N$, yellow prisms ($CH_2Cl_2$/MeCN), M_W = 1361.00, crystal dimensions = 0.28 × 0.22 × 0.15 mm^3, triclinic, space group $P\bar{1}$ (#2), a = 14.6352(5), b = 16.4465(5), c = 25.2864(7) Å, α = 90.0373(8), β = 95.3300(11), γ = 107.1027(12)°, V = 5789.6(3) Å^3, Z = 4, λ = 0.71075 Å, T = 123 K, ρ_{calcd} = 1.561 g cm^{-3}, μ_{MoK_α} = 5.248 mm^{-1}, F_{000} = 2704, 52162 total reflections ($2\theta_{max}$ = 54.96°), index ranges = $-18 \le h \le 18$, $-18 \le k \le 21$, $-32 \le l \le 32$, 25865 unique reflections (R_{int} = 0.0680), $R1$ = 0.0412 ($I > 2\sigma(I)$), 0.0501 (all data), $wR2$ = 0.1136 ($I > 2\sigma(I)$), 0.1290 (all data), S = 0.814 (1368 parameters).

CCDC 990816 (for **2b**) and CCDC 990817 (for **3b**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data request/cif.

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[1] *Modern Gold Catalyzed Synthesis* (Eds.: A. S. K. Hashmi, F. D. Toste), Wiley-VCH, Weinheim, **2012**.
[2] A. S. K. Hashmi, *Top. Organomet. Chem.* **2013**, *44*, 143 – 164.
[3] "Golden Opportunities in the Synthesis of Natural Products and Biologically Active Compounds": F. Gagosz in *Modern Tools for the Synthesis of Complex Bioactive Molecules* (Eds.: J. Cossy, S. Arseniyadis), Wiley, Hoboken, **2012**, pp. 111 – 154.
[4] C. Obradors, A. M. Echavarren, *Chem. Commun.* **2014**, *50*, 16 – 28.
[5] N. D. Shapiro, F. D. Toste, *Synlett* **2010**, 675 – 691.
[6] M. Rudolph, A. S. K. Hashimi, *Chem. Soc. Rev.* **2012**, *41*, 2448 – 2462.
[7] A. S. K. Hashmi, M. Rudolph, *Chem. Soc. Rev.* **2008**, *37*, 1766 – 1775.
[8] A. Fürstner, *Acc. Chem. Res.* **2014**, *47*, 925 – 938.
[9] A. S. K. Hashmi, *Acc. Chem. Res.* **2014**, *47*, 864 – 876.
[10] A. Gómez-Suárez, S. P. Nolan, *Angew. Chem.* **2012**, *124*, 8278 – 8281; *Angew. Chem. Int. Ed.* **2012**, *51*, 8156 – 8159.
[11] A. Fürstner, L. Morency, *Angew. Chem.* **2008**, *120*, 5108 – 5111; *Angew. Chem. Int. Ed.* **2008**, *47*, 5030 – 5033.
[12] D. Benitez, N. D. Shapiro, E. Tkatchouk, Y. Wang, W. A. Goddard III, F. D. Toste, *Nat. Chem.* **2009**, *1*, 482 – 486.
[13] A. S. K. Hashmi, *Angew. Chem.* **2010**, *122*, 5360 – 5369; *Angew. Chem. Int. Ed.* **2010**, *49*, 5232 – 5241.
[14] Ph_3PAuCl catalyzed the cyclization of a 2-(2-propynyl)pyridine N-oxide to afford the corresponding indolizinone in 29% yield: M. Murai, S. Kitabata, K. Okamoto, K. Ohe, *Chem. Commun.* **2012**, *48*, 7622 – 7624.
[15] An (NHC)AuCl-catalyzed carboxylative cyclization of propargylic amines: S. Hase, Y. Kayaki, T. Ikariya, *Organometallics* **2013**, *32*, 5285 – 5288.
[16] A. S. K. Hashmi, B. Bechem, A. Loos, M. Hamzic, F. Rominger, H. Rabaa, *Aust. J. Chem.* **2014**, *67*, 481 – 499.
[17] D. Wang, R. Cai, S. Sharma, J. Jirak, S. K. Thummanapelli, N. G. Akhmedov, H. Zhang, X. Liu, J. L. Petersen, X. Shi, *J. Am. Chem. Soc.* **2012**, *134*, 9012 – 9019.
[18] N. Mézailles, L. Ricard, F. Gagosz, *Org. Lett.* **2005**, *7*, 4133 – 4136.
[19] L. Ricard, F. Gagosz, *Organometallics* **2007**, *26*, 4704 – 4707.
[20] A. Gómez-Suárez, Y. Oonishi, S. Meiries, S. P. Nolan, *Organometallics* **2013**, *32*, 1106 – 1111.
[21] Y. Zhu, C. S. Day, L. Zhang, K. J. Hauser, A. C. Jones, *Chem. Eur. J.* **2013**, *19*, 12264 – 12271.
[22] Isolation of Ag-free catalytically active dual Au complexes: A. S. K. Hashmi, T. Lauterbach, P. Nösel, M. H. Vilhelmsen, M. Rudolph, F. Rominger, *Chem. Eur. J.* **2013**, *19*, 1058 – 1065. See also Ref. [8] and A. S. K. Hashmi, I. Braun, P. Nösel, J. Schädlich, M. Wieteck, M. Rudolph, F. Rominger, *Angew. Chem.* **2012**, *124*, 4532 – 4536; *Angew. Chem. Int. Ed.* **2012**, *51*, 4456 – 4460.
[23] M. Freytag, S. Ito, M. Yoshifuji, *Chem. Asian J.* **2006**, *1*, 693 – 700.
[24] S. Ito, S. Kusano, N. Morita, K. Mikami, M. Yoshifuji, *J. Organomet. Chem.* **2010**, *695*, 291 – 296.
[25] S. Ito, L. Zhai, K. Mikami, *Chem. Asian J.* **2011**, *6*, 3077 – 3083.
[26] P. Le Floch, *Coord. Chem. Rev.* **2006**, *250*, 627 – 681.
[27] K. B. Dillon, F. Mathey, J. F. Nixon, *Phosphorus: The Carbon Copy*, Wiley, Chichester, **1998**.
[28] F. Ozawa, M. Yoshifuji, *Dalton Trans.* **2006**, 4987 – 4995.
[29] S. Ito, M. Freytag, M. Yoshifuji, *Dalton Trans.* **2006**, 710 – 713.
[30] H. Schmidbaur, W. Graf, G. Müller, *Angew. Chem.* **1988**, *100*, 439 – 441; *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 417 – 419.
[31] T. Minami, H. Okamoto, S. Ikeda, R. Tanaka, F. Ozawa, M. Yoshifuji, *Angew. Chem.* **2001**, *113*, 4633 – 4635; *Angew. Chem. Int. Ed.* **2001**, *40*, 4501 – 4503.
[32] F. Ozawa, H. Okamoto, S. Kawagishi, S. Yamamoto, T. Minami, M. Yoshifuji, *J. Am. Chem. Soc.* **2002**, *124*, 10968 – 10969.
[33] H. Sugiyama, S. Ito, M. Yoshifuji, *Chem. Eur. J.* **2004**, *10*, 2700 – 2706.
[34] F. Ozawa, S. Kawagishi, T. Ishiyama, M. Yoshifuji, *Organometallics* **2004**, *23*, 1325 – 1332.
[35] F. Ozawa, T. Ishiyama, S. Yamamoto, S. Kawagishi, H. Murakami, M. Yoshifuji, *Organometallics* **2004**, *23*, 1698 – 1707.
[36] R. Appel, V. Winkhaus, F. Knoch, *Chem. Ber.* **1987**, *120*, 243 – 245.
[37] Y. Zhao, D. G. Truhler, *Theor. Chem. Acc.* **2008**, *120*, 215 – 241.
[38] C. Nieto-Oberhuber, M. P. Muñoz, S. López, E. Jiménez-Núñez, C. Nevado, E. Herrero-Gómez, M. Raducan, A. M. Echavarren, *Chem. Eur. J.* **2006**, *12*, 1677 – 1693.
[39] S. Kimura, S. Ito, M. Yoshifuji, T. Veszprémi, *J. Org. Chem.* **2003**, *68*, 6820 – 6823.
[40] M. C. Blanco Jaimes, F. Rominger, M. M. Pereira, R. M. B. Carriho, S. A. C. Carabineiro, A. S. K. Hashmi, *Chem. Commun.* **2014**, *50*, 4937 – 4940. A TON of 2.8×10^7 was also reported for the twofold hydroalkoxylation.
[41] Bis(chlorogold)complexes that bear a 2-silyl-1,3-diphosphapropene (Ref. [25]) showed almost no catalytic activity in the intermolecular alkoxycyclization.
[42] A. S. K. Hashmi, J. P. Weyrauch, W. Frey, J. W. Bats, *Org. Lett.* **2004**, *6*, 4391 – 4394.
[43] Z. Zhang, C. Liu, R. E. Kinder, X. Han, H. Qian, R. A. Widenhoefer, *J. Am. Chem. Soc.* **2006**, *128*, 9066 – 9073.
[44] The LUMO of **2f** (−1.07 eV) is lower than that of **3a** (−1.13 eV) [M06-2X/6-31G(d)], and the DFT-optimized P=C–C=P dihedral angle of **2f** is smaller (3.3°) than that of **3b**. However, **2c** and **2d** showed remarkably large P=C–C=P dihedral angles. See Supporting Information.
[45] In the ^1H and ^{13}C NMR spectra, the *o-tert*-butyl groups in **2f** and **3f** were not equivalent because of steric hindrance. See Supporting Information.
[46] N. Ghosh, S. Nayak, A. K. Sahoo, *J. Org. Chem.* **2011**, *76*, 500 – 511.
[47] J. Oliver-Meseguer, J. R. Cabrero-Antonino, I. Domínguez, A. Leyva-Pérez, A. Corma, *Science* **2012**, *338*, 1452 – 1455. See also: A. S. K. Hashmi, *Science* **2012**, *338*, 1434.
[48] G. Sheldrick, T. Schneider, *Methods Enzymol.* **1997**, *277*, 319.
[49] Yadokari-XG, Software for Crystal Structure Analyses, K. Wakita (2001); Release of Software (Yadokari-XG 2009) for Crystal Structure Analyses, C. Kabuto, S. Akine, T. Nemoto, E. Kwon, *J. Crystallogr. Soc. Jpn.* **2009**, *51*, 218 – 224.
[50] Gaussian 09 (Revision B.01), M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox, Gaussian, Inc., Wallingford CT, **2010**.

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