Gold Catalysis

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Highly Enantioselective Transfer Hydrogenation of Quinolines Catalyzed by Gold Phosphates: Achiral Ligand Tuning and Chiral-Anion Control of Stereoselectivity**

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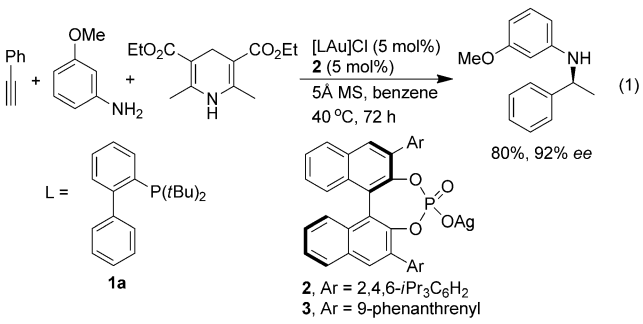
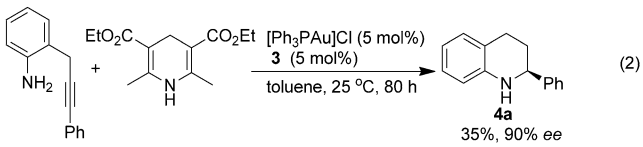
The prevalence of 1,2,3,4-tetrahydroquinoline as a key structural element in numerous natural alkaloids, bioactive molecules, and clinical pharmaceuticals has led to a great demand for the efficient construction of this skeleton.[1] As a consequence, a great deal of effort has been devoted to the development of stereoselective methods for the manufacture of highly enantioenriched tetrahydroquinolines.[2] Among the available enantioselective approaches, the asymmetric hydrogenation of quinolines is one of the most important methods. Zhou and co-workers have described the use of a chiral iridium catalyst for the hydrogenation of quinolines.[3] The combined chiral catalyst system, which consists of [{Ir(cod)Cl}$_2$] with MeO-Biphep and I_2, enabled the catalytic generation of tetrahydroquinolines with high enantioselectivity. Subsequent investigation into the iridium-catalyzed hydrogenation of quinolines led to a number of highly enantioselective variants by tuning of the chiral ligands.[4] Recently, Fan demonstrated that the chiral ruthenium catalyst Ru/Ts-dpen is highly enantioselective for the hydrogenation of quinolines (up to 99% *ee*).[5] Subsequently, Xiao and co-workers showed that the rhodium catalyst Rh/Ts-dpen affords the highly enantioselective hydrogenation of quinolines in water.[6] Rueping and co-workers established the first organocatalytic asymmetric transfer hydrogenation of quinolines by using chiral phosphoric acid catalysts.[2d] Although the methods are elegant, the catalytic efficiency still needs to be improved. Moreover, the transition-metal-catalyzed hydrogenation of quinolines exclusively relies on the use of chiral ligands to control the stereochemistry and the metals generally used are group VIII elements. Herein, we report the transfer-hydrogenation of quinolones, with enantioselectivities of up to 98% *ee* and a TON of > 10000, catalyzed by gold phosphates. Moreover, the stereoselectivity of the reaction was solely controlled by the chiral anion, and the tuning of achiral ligands was able to modulate catalytic efficiency.

Gold complexes have proven to be suitable catalysts for a large number of carbon–carbon and carbon–heteroatom bond-forming reactions.[7] Furthermore, gold complexes using either chiral ligands[8] or chiral anions[9] to control stereochemistry have been increasingly applied in asymmetric catalysis. However, the effectiveness of gold complexes as catalysts for hydrogenation has been much less recognized.[10] In particular, even fewer reports describe the hydrogenation of imines.[10a,d,e] Recently, Liu and Che found that a gold phosphate prepared in situ from [(**1a**)Au]Cl and **2** could catalyze a cascade hydroamination and asymmetric transfer hydrogenation in high yield [Eq. (1)].[11] Just a little earlier we



had also found that 2-(3-phenylprop-2-ynyl)aniline underwent a consecutive hydroamination and asymmetric transfer hydrogenation reaction under catalyzed by a gold phosphate prepared from [Ph_3PAu]Cl with **3**, but the reaction was incomplete [Eq. (2)].[12] A comparison of these reactions



indicated that the different catalytic activity of the gold complexes may originate from the phosphine ligands. Thus, we envisioned that tuning of the achiral ligands coordinated to chiral gold phosphates might lead to the discovery of an efficient chiral gold-phosphate catalyst for transfer hydrogenation.

The initial investigation was focused on the evaluation of achiral ligands coordinated to gold phosphates for the transfer hydrogenation of 2-phenylquinoline (**5a**; Figure 1). Indeed, the achiral ligands exerted considerable effect on the

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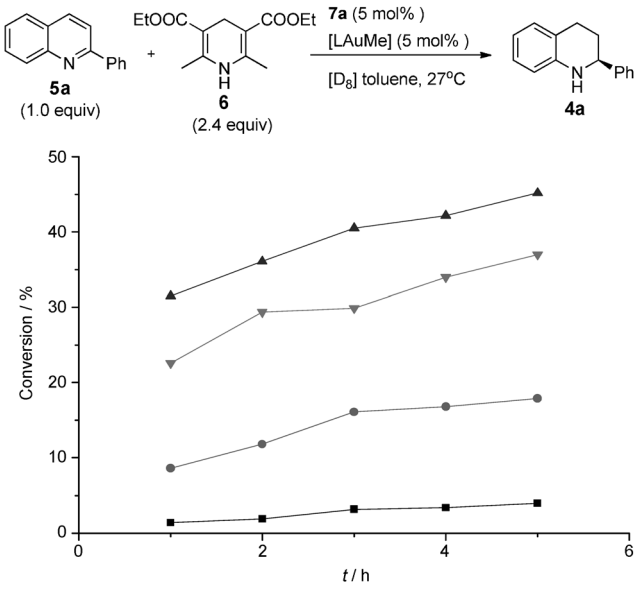
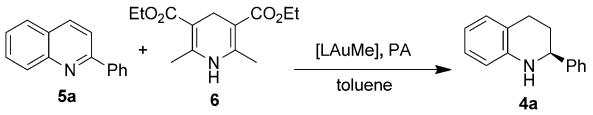


Figure 1. Kinetic studies on the effect of achiral Ligand on the catalytic activity of gold phosphate: The reduction was performed in the presence of **7a** (5 mol%) and [LAuMe] (5 mol%); without [LAuMe] (▼), L = IMes (▲), L = PPh_3 (●), and L = PCy_3 (■).

reaction. The use of a gold phosphate generated in situ from [Ph_3PAuMe] and chiral phosphoric acid **7a**[12,13] led to an incomplete reaction.[14] The replacement of triphenylphosphine (Ph_3P) with the more electron-rich tricyclohexylphosphine (PCy_3) resulted in an even slower reaction. Interestingly, the use of ligand **1a**,[15] which was a good ligand for the cascade hydroamination/asymmetric transfer hydrogenation,[11] gave almost no reaction. In contrast, the use of 5 mol% chiral phosphoric acid **7a** provided a much faster reaction than gold phosphates coordinated with phosphine ligands, as reported previously.[16] The carbene IMes (**1b**; see Table 1 for structure)[17] was identified as the best ligand for the gold phosphate complex, which showed more catalytic activity than with the corresponding phosphoric acid **7a**. However, [(IMes)AuMe] alone did not catalyze the transfer hydrogenation under the same conditions, indicating that the counteranion also plays a crucial role in the catalytic activity.

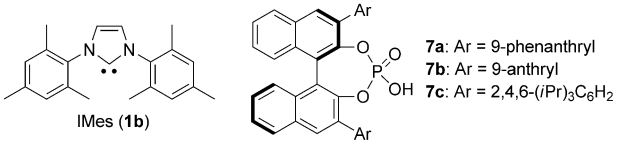
The chiral gold phosphate complex provided a high enantioselectivity of 91% *ee* (Table 1, entry 1), indicating that the chiral phosphate anion was able to efficiently control the stereoselectivity in the transfer hydrogenation.[9,18] Thus, we subsequently screened chiral gold phosphates generated in situ from a variety of binol-based phosphoric acids **7** and [(IMes)AuMe]. Among the chiral phosphoric acids screened (entries 1–3), **7c** improved the stereochemical outcome to 95% *ee* (entry 3). An examination of solvents found that toluene was still a suitable reaction medium in terms of stereoselectivity (entries 4–6 vs. entry 3). Elevating the temperature from 40 to 90 °C not only dramatically facilitated the reaction, but also turned out to be beneficial for stereochemical control (entries 6–8). As a result, an excellent stereoselectivity of 96% *ee* was obtained in the presence of only 0.01 mol% of the optimized gold phosphate at 90 °C (TON = 10000; entry 8). Such a low catalyst loading is unusual, both in

Table 1: Evaluation of gold complexes and optimization of reaction conditions.[a]



Entry	L/PA (mol%)[b]	*t* [h]	*T* [°C]	*ee* [%][c]
1	IMes/**7a** (5)	18	40	91
2	IMes/**7b** (5)	18	40	91
3	IMes/**7c** (5)	22	40	95
4	IMes/**7c** (5)	22	40	92[d]
5	IMes/**7c** (5)	22	40	92[e]
6	IMes/**7c** (5)	22	40	93[f]
7	IMes/**7c** (0.05)	11	80	96
8	IMes/**7c** (0.01)	12	90	96
9	IMes/**7c** (0.001)	24	100	20
10	IMes/**7c** (0.01)	12	90	96[g]

[a] Unless indicated otherwise, the reaction of **5a** (0.1 mmol) and Hantzsch ester **6** (0.24 mmol) was carried out in toluene (2.0 mL) under argon; > 99% yield. [b] Ligand/phosphoric acid (L/PA) used in a 1:1 ratio. [c] Determined by HPLC analysis on a chiral stationary phase (Chiralcel OD-H). [d] In *o*-xylene. [e] In *m*-xylene. [f] In chlorobenzene. [g] In toluene (1.0 mL).

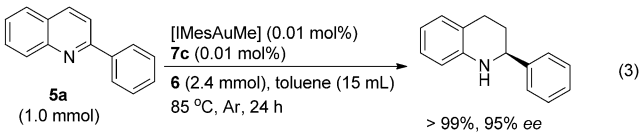


gold-catalyzed organic transformations and in the asymmetric hydrogenation of quinolines.[19] However, further decreasing the catalyst loading to 0.001 mol% resulted in a significant erosion of stereoselectivity (entry 9). However, when the reaction was conducted at a higher concentration, the enanatioselectivity was retained (entry 10).

Under the optimized reaction conditions, we investigated the reaction scope for different quinoline derivatives in the presence of 0.01 mol% of chiral gold phosphate formed from [(IMes)AuMe] and **7c** (Table 2). Gratifyingly, a range of 2-aryl quinolones, from electron-deficient to electron-rich, could be efficiently reduced in high yields and excellent enantioselectivities (up to > 99% yields, 98% *ee*). A loading of 0.01 mol% of phosphoric acid **7c** was found to be sufficient to catalyze the reaction, but provided a slightly lower enantioselectivity than the gold phosphate, as seen in entries 1, 3, 6, 10, and 12 (data in parentheses). Quinolines with a 2,3-disubstitution pattern also underwent the reaction, but the stereoselectivity was unsatisfactory.[20]

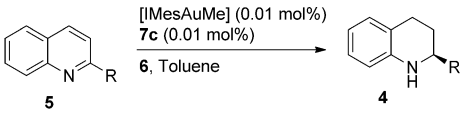
The reaction could also be successfully scaled up. The transfer hydrogenation of 2-phenyl quinoline **5a** in 1.0 mmol scale still proceeded cleanly in the presence of 0.01 mol% of the chiral gold phosphate, to give the product in quantitative yield and with the enantioselectivity maintained at 95% *ee* [Eq. (3)].

A gold(I) complex is essentially a kind of Lewis acid, and therefore able to coordinate to unsaturated carbon–carbon bonds and heteroatoms. In particular, gold complexes have been found to coordinate to pyridine-type compounds.[21] Thus, chiral-phosphate-catalyzed transfer hydrogenation of



(3)

Table 2: Reaction scope for quinoline derivatives.[a]

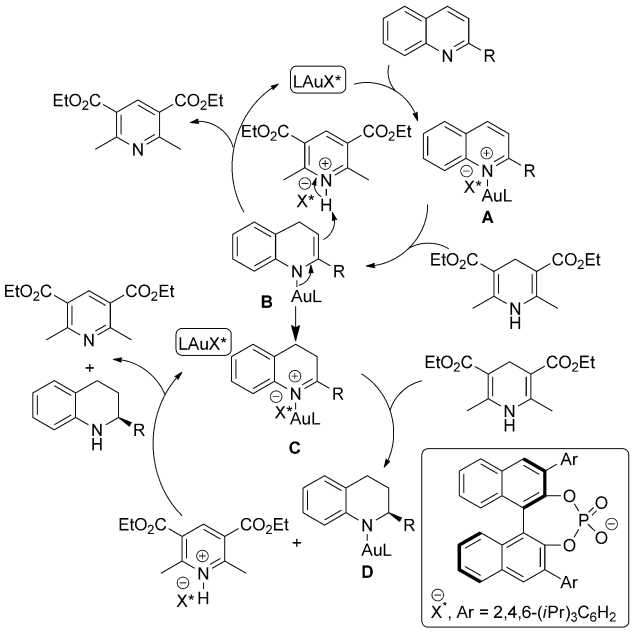


Entry	R	*t* [h]	Yield [%][b]	*ee* [%][c,d]
1	C_6H_5	12	>99	96 (95)
2	4-PhC_6H_4	48	89	97[e]
3	2-naphthyl	18	>99	98 (90)[f]
4	2-FC_6H_4	36	93	96[e]
5	4-$CF_3C_6H_4$	12	97	98
6	4-FC_6H_4	12	89	96 (93)
7	3-ClC_6H_4	22	99	95
8	3-FC_6H_4	12	>99	98
9	3-BrC_6H_4	12	93	94
10	4-$MeOC_6H_4$	18	>99	96 (88)[f]
11	3-$MeOC_6H_4$	18	>99	93
12	$CH_3CH_2CH_2$	6	82	54[g] (12)[f]

[a] Unless otherwise noted, the reaction of **5** (0.1 mmol), catalyst (0.01 mol%) and Hantzsch ester **6** (0.24 mmol) was carried out in toluene (1.0 mL) at 90 °C under argon. [b] Yield of isolated product after column chromatography. [c] Determined by HPLC analysis on a stationary chiral phase. [d] Numbers given in parentheses are for reactions using 0.01 mol% **7c** as catalyst. [e] 80 °C, toluene (1.5 mL). [f] Average of two experiments. [g] 70 °C, toluene (1.5 mL).

quinolines might commence with the coordination of the gold phosphate to quinoline to form active complex **A** (Scheme 1), which principally undergoes asymmetric transfer hydrogenation with a Hantzsch ester to generate intermediate **B** and a pyridine salt. Subsequently, the protonation of intermediate **B** with the pyridine salt occurs to produce dihydroquinoline **C**, which undergoes enantioselective transfer hydrogenation with a Hantzsch ester to form intermediate **D**. Once again, a metathesis reaction between intermediate **D** and a pyridine salt proceeds to furnish the tetrahydroquinoline product and to release the chiral gold phosphate catalyst. In light of this proposed mechanism, the reaction could be considered to be a gold-catalyzed asymmetric cascade reaction with the stereoselectivity solely controlled by the chiral anion.

In conclusion, we have found that chiral gold phosphate complexes are able to serve as highly efficient catalysts for the asymmetric transfer hydrogenation of quinolines,[22] with the stereoselectivity controlled by the chiral anion. Only 0.01 mol% of the gold phosphate is needed to effectively afford the highly enantioselective transfer hydrogenation of quinolines. Tuning of the achiral ligands had a great impact on the catalytic activity, with the chiral gold phosphate exhibiting high catalytic efficiency when the carbene IMes was used as a ligand. Facile scale-up makes this method of practical interest.



Scheme 1. Proposed mechanism for gold-phosphate-catalyzed transfer hydrogenation of quinolines. L = IMes (**1b**).

Experimental Section

A mixture of [(IMes)AuMe] (0.002 mmol) and phosphoric acid **7c** (0.002 mmol) was flushed with argon and suspended in toluene (0.8 mL) in a screw-capped vial. The resulting mixture was stirred at 25 °C for 5 h to form the catalyst solution, which was then added (1×10^{-5} mmol, 0.0025 M, 4 μL) to a mixture of quinoline **5** (0.1 mmol) and **6** (0.24 mmol) in toluene (1.0 mL) in a dry vial under Ar. The reaction was stirred at 90 °C until the quinoline was consumed, as indicated by TLC. The crude product was purified by column chromatography on silica gel (ethyl acetate/petroleum ether 1:20) to afford the pure tetrahydroquinoline.

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[20] The reduction of 1,2,3,4-tetrahydroacridine gave > 99% yield, 1:1 d.r., 66/18% *ee* (*trans*/*cis*).

[21] a) J. A. Flores, H. V. Rasika Dias, *Inorg. Chem.* **2008**, *47*, 4448 – 4450; b) H. V. Rasika Dias, J. Wu, *Angew. Chem.* **2007**, *119*, 7960 – 7962; *Angew. Chem. Int. Ed.* **2007**, *46*, 7814 – 7816; c) M. A. Cinellu, G. Minghetti, S. Stoccoro, A. Zucca *a*, M. Manassero, *Chem. Commun.* **2004**, 1618 – 1619; d) M. A. Cinellu, G. Minghetti, F. Cocco, S. Stoccoro, A. Zucca *a*, M. Manassero, *Angew. Chem.* **2005**, 117, 7052 – 7055; *Angew. Chem. Int. Ed.* **2005**, *44*, 6892 – 6895; e) M. A. Cinellu, G. Minghetti, F. Cocco, S. Stoccoro, A. Zucca, M. Manassero, *Dalton Trans.* **2006**, 5703 – 5716; f) H. Schmidbaur, A. Schier, *Organometallics* **2010**, *29*, 2 – 23.

[22] For selected examples of other metal-catalyzed transfer hydrogenations with Hantzsch esters as the hydrogen source, see: a) S. Zehani, G. Gelbard, *J. Chem. Soc. Chem. Commun.* **1985**, 1162 – 1163; b) J. W. Yang, B. List, *Org. Lett.* **2006**, *8*, 5653 – 5655; c) D.-W. Wang, W. Zeng, Y.-G. Zhou, *Tetrahedron: Asymmetry* **2007**, *18*, 1103 – 1107.

