Efficient addition of alcohols, amines and phenol to unactivated alkenes by Au^{III} or Pd^{II} stabilized by $CuCl_2$†

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The nucleophilic addition of alcohols, amines and phenol to unactivated alkenes catalyzed by cationic gold and palladium becomes limited due to the fast reduction into metallic gold under reaction conditions. The presence of $CuCl_2$ retards the reduction of Au^{III} and Pd^{II}, strongly increasing the turnover number of gold and palladium catalysts. It is shown that new Au^{III}–$CuCl_2$ and Pd^{II}–$CuCl_2$ catalysts are active and selective for the nucleophilic addition of alcohols, amines and phenol to unactivated alkenes.

Introduction

Interest in the catalytic chemistry of gold has undergone a marked increase in recent years.[1] Cationic gold (Au^I and Au^{III}) salts and organic complexes have emerged as powerful homogeneous and heterogeneous catalysts for the activation of C–C multiple bonds.[1–3] The major virtue of gold salts in homogenous catalysis is their unique ability to activate C–C multiple bonds as soft, carbophilic Lewis acids, allowing for the formation of new C–C, C–O, C–N, and C–S bonds by nucleophilic attack at these activated substrates. While there are many reports[1,2] about the activation of alkynes and allenes, activation of less active substrates, *e.g.*, alkenes, by cationic gold salts have remained relatively unexplored.[4] It is also important to consider that cationic gold salts and organic complexes are easily reduced by alkynes, alkenes, alcohols, CO, and phosphines, present in the reaction medium.[1,5] In fact, even the addition of water and methanol to alkyne catalyzed by Au^{III} catalysts ($Na[AuCl_4]$), which has become a kind of benchmark for gold catalysts,[1c,5c] presents the serious drawback of the reduction of gold(III) into inactive metallic gold under the reaction conditions. In this sense Fukuda and his coworkers[5d–f] found that gold(III)-catalyzed ($AuCl_3$ and $Na[AuCl_4]$) hydroamination of alkynylamines required to work at high dilution levels to prevent catalyst decomposition into metallic gold, and furthermore their system was not effective for the hydroamination of arylacetylenes. Mizushima *et al.*[6] discovered that the low activity for gold(I) $[(Ph_3P)AuCH_3]$ catalyzed hydration of alkynes was due to the decomposition of the catalyst to metallic particles. Therefore the reduction of cationic gold species to metallic gold often results in deactivation of cationic gold salts, which unambiguously weaken their utilization.

Efforts to enhance the use of cationic gold catalysts have long been sought. The simple methodology involves employing the cationic gold under very mild reaction conditions (*e.g.*, room temperature), however the low activity at low reaction temperatures requires the use of very reactive substrates. This is probably a reason why most reports on cationic gold catalysis are limited to activation of alkynes and allenes[1,2] Teles *et al.*[5b] found that by using gold(I) complexes in the presence of a strong acid as cocatalyst, instead of using Au^{III} ($Na[AuCl_4]$), the efficiency of gold(I) catalyst was greatly improved. Mizushima *et al.*[6] found that the efficiency of the Au^I catalyst was significantly enhanced by addition of large amounts of appropriate ligands (*e.g.*, $(PhO)_3P$), which improved the stability of the catalyst.

Activation of alkenes catalyzed by cationic gold remains one of the most significant challenges and is regarded as the gate to catalytic asymmetric synthesis in homogenous gold catalysis.[1] Recently, Yao and Li[4a] reported that Au^{III} catalyzes the addition of β-diketone to alkenes with Ag^I as co-catalyst. An interesting Au^I-mediated addition of phenols, carboxylic acids, and amines to alkenes was also shown.[4b,4c] However in most cases the stability of the catalyst is a major issue.

In the present work we will show that Au^{III} as well as Pd^{II} when used in combination with $CuCl_2$ are able to catalyze efficiently the nucleophilic addition of alcohols, amines and phenol to unactivated alkenes. The stabilizing role of $CuCl_2$ for cationic gold species is investigated.

Results and discussion

The role of $CuCl_2$ on stabilizing Au^{III} active species during reaction conditions: addition of methanol to styrene

Fukuda and Utimoto[5c] first reported on the nucleophilic addition of alcohols and water to alkynes by means of Au^{III} catalyst ($Na[AuCl_4]$) under refluxing conditions. However, the catalyst was soon deactivated under the reaction conditions due to formation of metallic gold particles. Teles *et al.*[5b] overcame the drawback by using cationic gold(I) complexes (phosphane/phosphite–Au^+) to replace $Na[AuCl_4]$ and found the cationic gold(I) to be highly active for addition of alcohols to alkynes at 20–50 °C using strong acid (CH_3SO_3H) as the co-catalyst. Nevertheless, the authors reported that alkenes did not react.[1c] Based on this, we thought that since alkenes are much less reactive than alkynes, the addition of alcohols (*e.g.*, methanol) to alkenes (*e.g.*, styrene) could be carried

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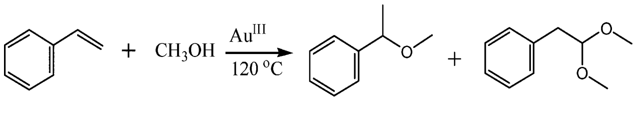
out at higher temperatures provided that the rapid reduction of Au^{III} could be avoided or, at least, slow down.

Addition of methanol to styrene catalyzed by the gold(III) salts occurred at 120 °C, giving main products of 1-methoxyethylbenzene and 2,2-dimethoxyethylbenzene (Scheme 1).[4d] Fig. 1 compares styrene conversion and 1-methoxyethylbenzene selectivity over cationic gold (Au^{III}, Au^{I}), and Pd^{II}. The maximum styrene conversion obtained was 46, 38, 23, 5, and 29% on $HAuCl_4$, $AuCl_3$, $Na[AuCl_4]$, AuCl, and $PdCl_2$ catalysts, respectively (Fig. 1a). It is evident that cationic gold(III) salts (*e.g.*, $HAuCl_4$, $AuCl_3$) show much higher activity than AuCl, or $PdCl_2$. The selectivity to the adduct (1-methoxyethylbenzene) was in the range of 70–80% with all cationic gold catalysts, while some lower selectivity (62%) was found with $PdCl_2$ (Fig. 1b), and 18–35% of 2,2-dimethoxyethylbenzene was also found with all cationic gold and palladium catalysts.



Scheme 1 Addition of methanol to styrene on Au^{III} salts.

The major adduct (1-methoxyethylbenzene) was achieved by nucleophilic addition of one molecule of methanol to styrene which was activated by cationic gold and/or palladium. Fukuda and Utimoto[5c] reported that the direct formation of dimethyl acetals (*e.g.*, 2,2-dimethoxyethylbenzene) were achieved from alkynes by addition of two moles of methanol mediated by Au^{III} catalyst (*e.g.*, $Na[AuCl_4]$). However, the direct formation of acetal from alkenes and alcohols on cationic gold catalyst was not reported, to the best of our knowledge. Taking into account that palladium(II) complex (π-$C_2H_4{\cdot}PdCl_2$) is facially formed when refluxing an aqueous solution of $PdCl_2$, alkene, and alcohols, and that palladium(II) alkene π-complexes have been reported[7] to undergo redox decomposition in alcohol solutions to give acetals and Pd metal (Scheme 2a). We thought that Au^{III} by being "isoelectronic" with Pd^{II} should follow, a similar reaction scheme (Scheme 2b).

$$C_2H_4 + PdCl_2 \longrightarrow \left[\ \pi\text{-}C_2H_4{\cdot}Pd^{II}\right] \xrightarrow{2ROH} CH_3CH(OR)_2 + Pd^0 + 2HCl \quad (\mathbf{a})$$

$$C_2H_4 + AuCl_3 \longrightarrow \left[\ \pi\text{-}C_2H_4{\cdot}Au^{III}\right] \xrightarrow{2ROH} CH_3CH(OR)_2 + Au^0 + 2HCl \quad (\mathbf{b})$$

Scheme 2 Formation of palladium(II) alkene π-complexes (a) and gold(III) alkene π-complexes (b) and then converted to acetals by redox decomposition.

Indeed, as shown in Fig. 1A the maximum conversion at 120 °C is obtained within 2 h on all cationic gold and palladium catalysts, while the formation of gold and palladium metals was evident. The result indicated that the reaction stops after ~2 h because catalyst deactivation is due to the reduction of cationic gold (Au^{III}, Au^{I}) and Pd^{II} to metallic Au^0 and Pd^0, respectively. At this point, we thought that the great success of the Wacker process[8] relies on its ingenious catalytic cycle, in which the reduced Pd^0 is reoxidized *in situ* to Pd^{II} by $CuCl_2$ which is reduced to CuCl. In turn, CuCl is easily reoxidized to $CuCl_2$ with oxygen. Although in a first approximation it appears difficult that the oxidation of Au^0 and Pd^0 can be carried out by $CuCl_2$, taking into account the redox potentials,[8a,9] it should be considered that cationic gold(III) and palladium(II) species can be easily stabilized by complex formation in the presence of chloride ions,[1,6,8a] and the initially reduced Au^{I} and metallic Au nanoparticles should have lower redox potential.[10] Then, the effect of adding $CuCl_2$ on styrene conversion and 1-methoxyethylbenzene selectivity was studied and the results were shown in Fig. 2 and 3, respectively. After addition of 8, 16, and 32 mol% of $CuCl_2$ to $AuCl_3$, the styrene conversion increased from 38 to 62, 82, and 89% (Fig. 2A); and the conversion also significantly increased from 29 to 55, 87 and 93% in the case of $PdCl_2$ (Fig. 3A). It should be noted that styrene conversion is only about 1 and 15% with 8 and 16 mol% of $CuCl_2$ alone at 2 and 5.7 h, respectively (Fig. 2A). The greatly enhanced activity of both $AuCl_3$ and $PdCl_2$ after addition of $CuCl_2$ demonstrated that the key role of $CuCl_2$ is to stabilize Au^{III} and Pd^{II} species. In comparison with the products of the reaction catalyzed by only $AuCl_3$ and/or $PdCl_2$, the addition of $CuCl_2$ also results in significant increase of 1-methoxyethylbenzene selectivity (Fig. 2B and Fig. 3B), with a sharp decrease of 2,2-dimethoxyethylbenzene. The result indicated that the formation of acetal and Au/Pd metal by redox decomposition of gold(III) and/or palladium(II) complexes[8] (Scheme 2) was greatly retarded after addition of $CuCl_2$. Nevertheless a further increase in the amount of $CuCl_2$ from 16 to 32 mol% can not improve the selectivity to 1-methoxyethylbenzene, since the formation of 1,2-dichloroethylbenzene by chlorination of styrene also increased.

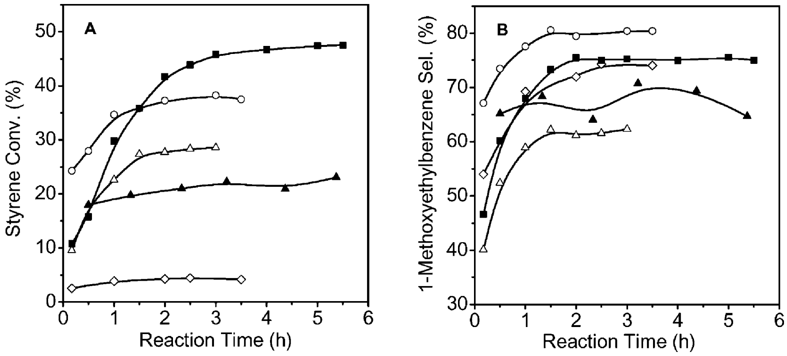


Fig. 1 Styrene conversion (A) and 1-methoxyethylbenzene selectivity (B) over 8 mol% of: (○) $AuCl_3$, (■) $HAuCl_4$, (▲) $NaAuCl_4$, (◇) AuCl, and (△) $PdCl_2$ catalysts.

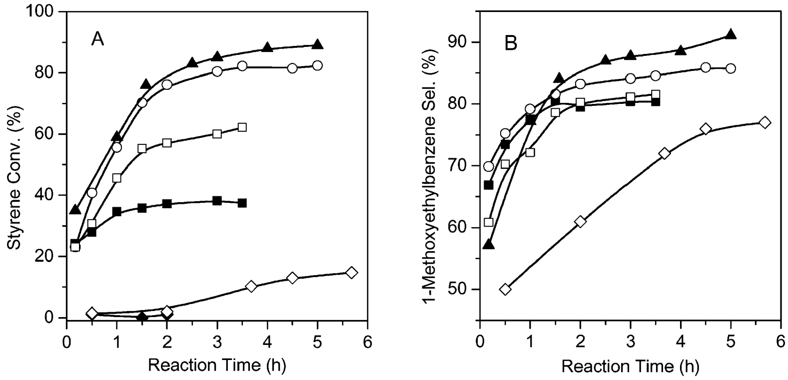


Fig. 2 Effect of $CuCl_2$ amount on styrene conversion (A) and 1-methoxyethylbenzene selectivity (B) over: (◇) 8 mol% $CuCl_2$, (◆) 16 mol% $CuCl_2$, (■) 8 mol% $AuCl_3$, (□) 8 mol% $AuCl_3$–8 mol% $CuCl_2$, (○) 8 mol% $AuCl_3$–16 mol% $CuCl_2$, and (▲) 8 mol% $AuCl_3$–32 mol% $CuCl_2$ catalysts.

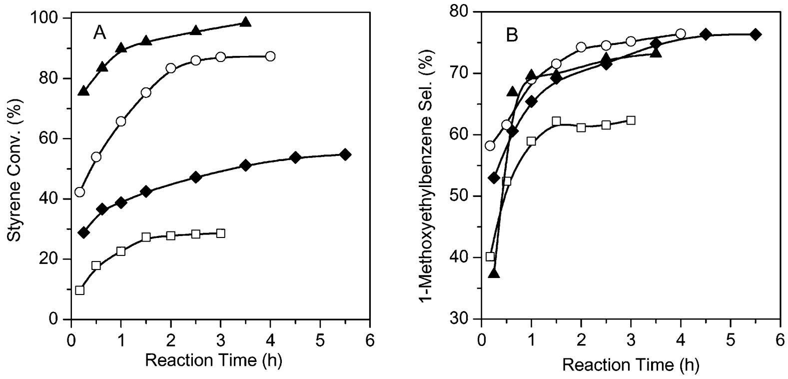


Fig. 3 Effect of $CuCl_2$ amount on styrene conversion (A) and 1-methoxyethylbenzene selectivity (B) over (□) 8 mol% $PdCl_2$, (◆) 8 mol% $PdCl_2$–8 mol% $CuCl_2$, (○) 8 mol% $PdCl_2$–16 mol% $CuCl_2$, and (▲) 8 mol% $PdCl_2$–32 mol% $CuCl_2$ catalysts.

The stabilizing effect was proven through the observation that $AuCl_3$ (0.1 mmol) in 1.0 mL of methanol at 120 °C starts to form metallic particles after 2 min, while in the presence of $CuCl_2$ (0.2 mmol), no metallic particles were observed after 1 h. The same occurs in the case of $PdCl_2$.

It is expected that the stabilizing role of $CuCl_2$ will be lost when $CuCl_2$ is reduced to CuCl. Indeed a green-tinged white precipitate formed due to the reduction of $CuCl_2$ to CuCl was observed when the catalytic activity stopped. However, since as mentioned earlier, the reduced CuCl is reoxidized to $CuCl_2$ with oxygen in the Wacker process,[8] we have studied the effect of the reaction atmosphere (N_2, air, O_2) on the catalytic performance of $AuCl_3$–$CuCl_2$ and $PdCl_2$–$CuCl_2$ (Fig. 4, and 5 respectively). In agreement with the hypothesis, the styrene conversion over $PdCl_2$ increased from 80, 87 to 98% when the reaction atmosphere was changed from N_2, air, to oxygen, respectively (Fig. 5A). This result shows that introduction of O_2 significantly improves the activity of $PdCl_2$. On the contrary, the reaction under O_2 led to a distinct decrease in the catalytic activity of $AuCl_3$ compared with N_2 and air (Fig. 4A). And the 1-methoxyethylbenzene selectivity also sharply decreased (Fig. 4B). The different catalytic result between $AuCl_3$ and $PdCl_2$ under O_2 is due to their different stability to air (and/or O_2). It is

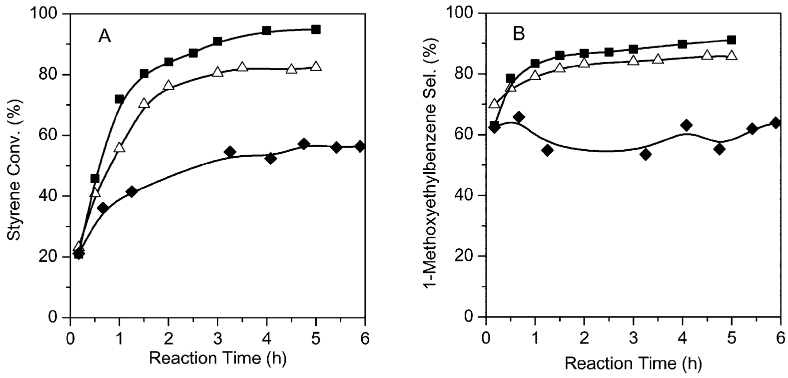


Fig. 4 Styrene conversion (A) and 1-methoxyethylbenzene selectivity (B) over 8 mol% $AuCl_3$–16 mol% $CuCl_2$ catalyst under different reaction atmospheres: (■) N_2; (△) air; (◆) O_2.

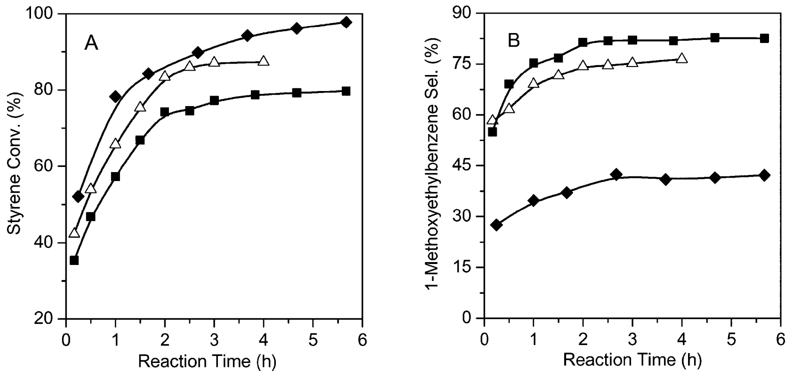


Fig. 5 Styrene conversion (A) and 1-methoxyethylbenzene selectivity (B) over 8 mol% $PdCl_2$–16 mol% $CuCl_2$ catalyst under different reaction atmospheres: (■) N_2; (△) air; (◆) O_2.

well known that $PdCl_2$ are air stable, while the gold salts are air sensitive, and this matter is now under investigation.

The effect of chloride ions on the catalytic performance has also been considered, due to the stabilizing effect by complex formation with cationic gold(III) and palladium(II).[1,6,8a] However, the catalytic activity of $AuCl_3$ was not improved after introduction of 0.16 mmol NaCl. The result indicates the importance of Cu^{II} on stabilizing the Au^{III}.

The simple methodology by addition of $CuCl_2$ which retards the reduction of the gold salt and/or oxidizes it back to gold(III) will unambiguously enhance the utilization of cationic gold salts to activate alkenes. The following are three examples in such a direction.

Addition of alcohols to alkenes

The nucleophilic addition of various alcohols to alkenes over Au^{III}–$CuCl_2$ was shown in Table 1. Addition of 16 mol% of $CuCl_2$ into 8 mol% of $AuCl_3$, $Na[AuCl_4]$, $HAuCl_4$, sharply increased styrene conversion from 38, 23 and 46% to 82, 65 and 88%, respectively. The 1-methoxyethylbenzene selectivity also increased from 80, 65, 75% to 85, 86, 83%, respectively (Fig. 1, and entries 1–3, Table 1). We find that the primary alcohols (such as ethanol, 1-propanol, and 1-butanol) work successfully on 8 mol% $AuCl_3$–16 mol% $CuCl_2$ and give yields up to 80% (entries 4, 5, 7, Table 1). The secondary alcohols (such as 2-propanol and 2-butanol) react more slowly than primary alcohols and give yields of up to 60% (entries 6, 8, Table 1), while the tertiary alcohol (*e.g.*, *tert*-butyl alcohol) failed in this reaction due to steric inhibition (entry 9, Table 1).[5b] Interestingly, addition of ethylene glycol is also effective, and gives 88% styrene conversion and 71% yield to 2-(1-phenylethoxy)ethanol (entry 10, Table 1). Both electron-rich and electron-deficient styrene derivatives serve as good substrates (entries 11, 12, Table 1). The alcohols can also be added to the straight-chain and cyclo-alkenes, but a higher reaction temperature (150 °C) is needed (entry 14, Table 1). It has to be remarked that all the products are formed following Markovnikov's rule.

Addition of amines to alkenes

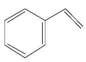
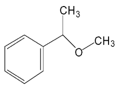
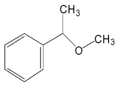
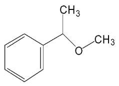
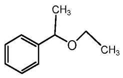
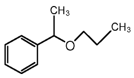
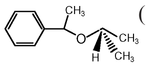
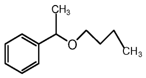
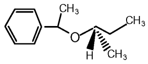
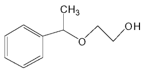
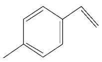
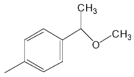
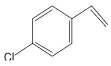
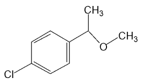
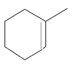
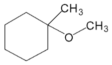
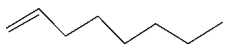
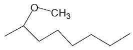
Acyclic amines are an important class of compounds widely present in nature and they are common components of pharmaceuticals, agrochemicals, cosmetics, and important intermediates for a number of industrial processes.[11] Therefore, the catalytic addition of N–H to a C–C multiple bond (hydroamination) has received considerable attention.[11,12] It was reported[5c,d] that the Au^{III} salts ($Na[AuCl_4]$ and $AuCl_3$) catalyze intramolecular hydroamination of 5-alkynylamines to form tetrahydropyridine derivatives. Unfortunately, Au^{III} salts catalyzed hydroamination of alkynylamines requires high dilution to prevent catalyst decomposition and was not effective for the hydroamination of acrylacetylenes.[5e] Recently, an interesting gold(I)-catalyzed ($Ph_3PAuOTf$) hydroamination of alkenes,[4c] and 1,3-dienes[13] was shown using *p*-toluenesulfonamide, and benzyl carbamate as the main nucleophiles, respectively.

We find that as shown in Table 2 the direct nucleophilic addition of aniline to styrene can be realized at 150 °C on 8 mol% of $AuCl_3$, $Na[AuCl_4]$, and $HAuCl_4$ catalysts after addition of 16 mol% of $CuCl_2$, giving up to 60–70% yield of phenyl-(1-phenyl-ethyl)-amine (entries 2–4, Table 2). The electron rich styrene substrate (*e.g.*, 4-methylstyene) gives a higher yield (88%, entry 4, Table 2). Remarkably, less than 21% yields of phenyl-(1-phenylethyl)-amine was found solely on $AuCl_3$ (entry 1, Table 2). These results demonstrate that the efficiency of cationic gold(III) for hydroamination of alkenes has greatly improved after addition of $CuCl_2$. Luo *et al.*[14] recently reported 88% yield of phenyl-(1-phenylethyl)-amine obtained by two steps in a sequential hydroamination–reduction of phenylacetylene with aniline using $AuCl_3$ and $NaBH_4$ at room temperature. We have seen that although $AuCl_3$ gives only 32% yield of 4-methyl-*N*-(1-phenylethyl)-benzenesulfonamide for hydroamination of *p*-toluenesulfonamide with styrene (entry 6, Table 2) the yield was significantly increased (*ca.* 60%) with the Au^{III}–$CuCl_2$ catalysts (entries 7–9, Table 2). A higher yield (71%) was also obtained when the addition of benzyl carbamate to 1-methyl-1-cyclohexene was carried out on 8 mol% $AuCl_3$–16 mol% $CuCl_2$ instead of solely $AuCl_3$ (35% yield) (entries 10, 11, Table 2). It should be pointed that less than 8% yield was found with solely $CuCl_2$ under the same reaction conditions. Clearly, the presence of $CuCl_2$ also stabilizes cationic gold(III) during the nucleophilic addition of amines to alkenes.

Addition of phenol to alkenes

Nucleophilic addition of phenols to unsaturated carbon–carbon bonds provides one of the simplest methods to construct valuable

Table 1 Nucleophilic addition of alcohols to alkenes over Au^{III}–$CuCl_2$ catalysts[a]

Entry	Alkene	Alcohol	*t*/h	Conv. (%)	Product (sel.) (%)	Yield[b](%)
1	 **1a**	Methanol	3.5	82	 (85)	70
2[c]	**1a**	Methanol	3.5	65	 (86)	56
3[d]	**1a**	Methanol	3.5	88	 (83)	73
4	**1a**	Ethanol	4.0	93	 (86)	80
5	**1a**	1-Propanol	4.0	95	 (84)	80
6	**1a**	2-Propanol	4.0	67	 (74)	50[e]
7	**1a**	1-Butanol	4.0	95	 (87)	83
8	**1a**	2-Butanol	4.0	69	 (84)	58[e]
9	**1a**	*tert*-Butyl alcohol	4.0	3	—	—
10	**1a**	Glycol	5.7	88	 (81)	71
11	 **2a**	Methanol	2.5	93	 (86)	80
12	 **3a**	Methanol	8.0	75	 (79)	59
13	 **4a**	Methanol	12	60	 (93)	56
14[f]	 **5a**	Methanol	12	52	 (68)	35

[a] Without specified, reactions were performed on 8 mol% $AuCl_3$–16 mol% $CuCl_2$ at 120 °C. [b] GC yield. [c] 8 mol% $Na[AuCl_4]$–16 mol% $CuCl_2$. [d] 8 mol% $HAuCl_4$–16 mol% $CuCl_2$. [e] Mixture of distereoisomers. [f] Reaction temperature: 150 °C.

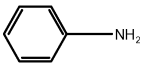
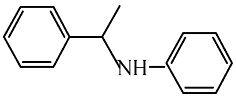
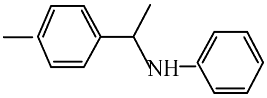
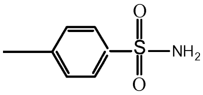
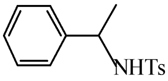
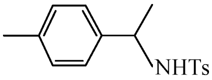
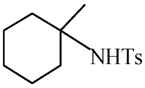
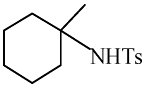
synthetic building blocks.[15] The use of metal-based catalysts is promising for enantioselective additions. Recently, Yang and He[4b] attempted the gold(I)-catalyzed ($Ph_3PAuCl/AgOTf$) intermolecular addition of phenols to alkenes at 85 °C, and claimed that 5 mol% $AuCl_3$–15 mol% AgOTf failed to give the desired product (yield < 5%).

We found that 40% yield of 1-methoxy-4-(1-phenyl-ethoxy)-benzene can be obtained on 8 mol% $AuCl_3$ at 120 °C using toluene as solvent (entry 1, Table 3). However, after addition of 16 mol% $CuCl_2$, the yields were sharply increased to 63%, and 80% on 8 mol% of $AuCl_3$, and $HAuCl_4$, respectively (entry 2, 3, Table 3). Using 4-methylstyrene as a substrate gave excellent yields (85–93%) on 8 mol% of $AuCl_3$, $HAuCl_4$, or $Na[AuCl_4]$ together with 16 mol% of $CuCl_2$ (entry 4–6, Table 3). It should be remarked that the reaction works almost exclusively with styrene derivatives and the attempt to react 1-methyl-1-cyclohexene failed to give the desired product (entry 7, Table 3).

Conclusion

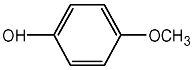
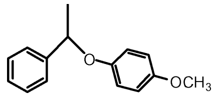
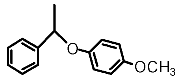
We have comparatively investigated the role of $CuCl_2$ for $AuCl_3$, $PdCl_2$ catalyzed addition of methanol to styrene. The results show that the catalytic performance of gold(III) and palladium(II) has greatly improved after addition of small amounts of $CuCl_2$, which can retard reduction of the gold(III) and/or oxidizes it back to gold(III). This is even more notorious in the case of the $PdCl_2$–$CuCl_2$ system where the presence of air in the reaction system improves the process, as it occurs within the Wacker process. The Au^{III}–$CuCl_2$ catalysts presented allow nucleophilic addition of alcohols, amines, and phenol to simple unactivated alkenes. Good to excellent yields were obtained in most cases and unambiguously demonstrated that $CuCl_2$ stabilizes cationic gold(III) and Pd(II) and should also allow the expansion of the use of gold salts to other reactions in which the cationic gold becomes reduced, and therefore deactivated, under reaction conditions.

Table 2 Nucleophilic addition of amines to alkenes over Au^{III}–$CuCl_2$ catalysts[a]

Entry	Alkene	Nucleophile	t/h	Product	Yield[b] (%)
1[c]	**1a**	 **1b**	12	 **1c**	<21
2	**1a**	**1b**	12	**1c**	67
3[d]	**1a**	**1b**	12	**1c**	59
4[e]	**1a**	**1b**	12	**1c**	73
5	**2a**	**1b**	8	 **2c**	88
6[c]	**1a**	 **2b**	12	 **3c**	32
7	**1a**	**2b**	12	**3c**	57
8	**2a**	**2b**	12	 **4c**	59
9	**4a**	**2b**	12	 **5c**	61
10[c]	**4a**	**3b**	12	 **6c**	35
11	**4a**	**3b**	12	**6c**	71

[a] Reactions were carried out at 150 °C with toluene (1.5 mL) as solvent using 8 mol% $AuCl_3$–16 mol% $CuCl_2$ as catalyst (if not specified). [b] GC yield, entries 1–8 contain mixtures of distereoisomers. [c] Using 8 mol% $AuCl_3$ as catalyst. [d] Using 8 mol% $Na[AuCl_4]$–16 mol% $CuCl_2$ as catalyst. [e] Using 8 mol% $HAuCl_4$–16 mol% $CuCl_2$ as catalyst.

Table 3 Nucleophilic addition of phenol to alkenes over Au^{III}–$CuCl_2$ catalysts[a]

Entry	Alkenes	Nucleophile	t/h	Product	Yield[b] (%)
1[c]	**1a**	 **4b**	7	 **7c**	40
2	**1a**	**4b**	7	**7c**	63
3[d]	**1a**	**4b**	12	**7c**	80
4	**2a**	**4b**	7	 **8c**	90
5[d]	**2a**	**4b**	12	**8c**	93
6[e]	**2a**	**4b**	12	**8c**	85
7	**4a**	**4b**	12	—	—

[a] Reactions were carried out at 120 °C with toluene (1.5 mL) as solvent using 8 mol% $AuCl_3$–16 mol% $CuCl_2$ as catalyst (if not specified). [b] GC yield. [c] Using 8 mol% $AuCl_3$ as catalyst. [d] Using 8 mol% $HAuCl_4$–16 mol% $CuCl_2$ as catalyst. [e] Using 8 mol% $Na[AuCl_4]$–16 mol% $CuCl_2$ as catalyst.

Experimental

Materials

Commercially available reagents including gold(III) chloride ($AuCl_3$, 99%), hydrogen tetrachloroaurate(III) trihydrate ($HAuCl_4 \cdot 3H_2O$, 99.9+%), sodium tetrachloroaurate(III) dihydrate ($Na[AuCl_4] \cdot 2H_2O$, 99%), gold(I) chloride (AuCl, 99.9+%), palladium(II) chloride ($PdCl_2$, 99.9%) were purchased from Sigma-Aldrich and used as received. Copper(II) chloride dehydrate ($CuCl_2 \cdot 2H_2O$, 98%, Panreac), methanol (CH_3OH, 99.9+%, Merck), ethanol (C_2H_5OH, 99.9%, Scharlau), 1-propanol (C_3H_7OH, 99.5+%, Aldrich), 2-propanol ($CH_3(CH)OHCH_3$, 99.9%, Scharlau), 1-butanol (C_4H_9OH, 99.4+%, Sigma-Aldrich), 2-butanol ($CH_3CH_2(CH)OHCH_3$, 99%, Aldrich), *tert*-butyl alcohol ($(CH_3)_3C(OH)$, 99+%, Aldrich), ethylene glycol ($CH_2(OH)CH_2(OH)$, 99+%, Aldrich), styrene ($C_6H_5CHCH_2$, 99+%, Aldrich), 4-methylstyrene ($CH_3C_6H_4CHCH_2$, 96%, Aldrich), 4-chlorostyrene ($ClC_6H_4CHCH_2$, 97%, Aldrich), 1-methyl-1-cyclohexene ($C_6H_9CH_3$, 97%, Aldrich), 1-octene (C_8H_{16}, 97%, Acros), aniline ($C_6H_5NH_2$, 99%, Aldrich), *p*-toluenesulfonamide ($C_7H_9NO_2S$, 99+%, Aldrich), benzyl carbamate

($NH_2COOCH_2C_6H_5$, 99%, Aldrich), 4-methoxyphenol ($CH_3OC_6H_4OH$, 99%, Aldrich), and toluene ($C_6H_5CH_3$, 97+%, Aldrich) were used as received without further purification.

Reaction Test: Nucleophilic addition of alcohols, amines, and phenol to alkenes were performed in a closed glass reactor (2.0 mL, Supelco®) equipped with a micro-syringe which allows sample (20 μL) uptake through to analysis at the desired time. Certain reactant mixtures were put into the reactor and closed tightly. After extensive mixing under magnetic stirring at room temperature, the reaction was assumed to start after the reactor was put into the oil bath at the desired temperature and stirred extensively.

A typical procedure for the addition of alcohols to alkenes is: the gold or palladium(II) catalyst (0.10 mmol) and/or a proper amount (without specifying, the amount is equal to two moles of gold, *i.e.*, 0.20 mmol) of $CuCl_2$ was added into 1.5 mL of the mixtures of the alcohol and alkene (1.21 mmol). Then the reactor was closed tightly and the reactants mixed in the room temperature. Specifically, for the addition of methanol to styrene in different atmospheres (N_2, air, O_2), the reactor was further purged with the desired gas (*e.g.*, N_2) three times, then the reactants were kept at 3.0 bar of the desired gas. The reaction was assumed to start when the reactor was put into the oil bath at 120 °C (unless otherwise specified) and stirred extensively.

A typical procedure for the addition of amines to alkenes is: The reactants contain a mixture of alkene (0.50 mmol) and amine (2.0 mmol for aniline, the others 1.0 mmol) and gold(III) salts (8 mmol%, *i.e.* 0.04 mmol)-$CuCl_2$ (16 mmol%, *i.e.* 0.08 mmol) in toluene (1.5 mL). The reaction temperature is 150 °C.

A typical procedure for the addition of phenol to alkenes is: The reactants contain a mixture of alkene (0.50 mmol) and 4-methoxphenol (1.0 mmol) and gold(III) salts (8 mmol%, *i.e.* 0.04 mmol)–$CuCl_2$ (16 mmol%, *i.e.* 0.08 mmol) in toluene (1.5 mL). The reaction temperature is 120 °C.

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References

1 For selected reviews, see: (*a*) A. S. K. Hashmi and G. J. Hutcings, *Angew. Chem., Int. Ed.*, 2006, **45**, 7896–7936; (*b*) A. S. K. Hashmi, *Chem. Rev.*, 2007, **107**, 3180–3211; (*c*) A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2005, **44**, 6990–6993; (*d*) A. Hoffmann-Röder and N. Krause, *Org. Biomol. Chem.*, 2005, **3**, 387–391; (*e*) X. Zhang, H. Shi and B.-Q. Xu, *Angew. Chem., Int. Ed.*, 2005, **44**, 7132; (*f*) A. Corma and P. Serna, *Science*, 2006, **313**, 332–334; (*g*) X. Zhang, H. Shi and B.-Q. Xu, *Catal. Today*, 2007, **122**, 330–337; (*h*) D. J. Gorin and F. D. Toste, *Nature*, 2007, **446**, 395–403.

2 For selected recent examples, see: (*a*) A. S. K. Hashmi, J. P. Weyrauch, E. Kurpejović, T. M. Frost, B. Miehlich, W. Frey and J. W. Bats, *Chem.–Eur. J.*, 2006, **12**, 5806–5814; (*b*) G. Lemière, V. Gandon, N. Agenet, J.-P. Goddard, A. Kozak, C. Aubert, L. Fensterbank and M. Malacria, *Angew. Chem., Int. Ed.*, 2006, **45**, 7596–7599; (*c*) J. Barluenga, A. Diéguez, A. Fernández, F. Rodríguez and F. J. Fananás, *Angew. Chem., Int. Ed.*, 2006, **45**, 2091–2093; (*d*) E. Genin, P. Y. Tullec, S. Antoniotti, C. Brancour, J.-P. Genêt and V. Michelet, *J. Am. Chem. Soc.*, 2006, **128**, 3112–3113; (*e*) A. W. Sromek, M. Rubina and V. Gevorgyan, *J. Am. Chem. Soc.*, 2005, **127**, 10500–10501; (*f*) E. Mizushima, K. Sato, T. Hayashi and M. Tanaka, *Angew. Chem., Int. Ed.*, 2002, **41**, 4563–4565.

3 (*a*) C. González-Arellano, A. Corma, M. Iglesias and F. Sanchez, *J. Catal.*, 2006, **238**, 497–501; (*b*) C. González-Arellano, A. Corma, M. Iglesias and F. Sanchez, *Chem. Commun.*, 2005, **27**, 3451–3453; (*c*) C. González-Arellano, A. Abad, A. Corma, H. García, M. Iglesias and F. Sánchez, *Angew. Chem., Int. Ed.*, 2007, **46**, 1536–1538.

4 (*a*) X. Yao and C.-J. Li, *J. Am. Chem. Soc.*, 2004, **126**, 6884–6885; (*b*) C.-G. Yang and C. He, *J. Am. Chem. Soc.*, 2005, **127**, 6966–6967; (*c*) J. Zhang, C.-G. Yang and C. He, *J. Am. Chem. Soc.*, 2006, **128**, 1798–1799; (*d*) X. Zhang and A. Corma, *Chem. Commun.*, 2007, 3080–3082.

5 (*a*) R. A. Widenhoefer and X. Han, *Eur. J. Org. Chem.*, 2006, 4555–3082; (*b*) J. H. Teles, S. Brode and M. Chabanas, *Angew. Chem., Int. Ed.*, 1998, **37**, 1415–1418; (*c*) Y. Fukuda and K. Utimoto, *J. Org. Chem.*, 1991, **56**, 3729–3731; (*d*) Y. Fukuda, K. Utimoto and H. Nozaki, *Heterocycles*, 1987, **25**, 297–300; (*e*) Y. Fukuda and K. Utimoto, *Synthesis*, 1991, 975–978; (*f*) T. E. Müller, *Tetrahedron Lett.*, 1998, **39**, 5961–5962; (*g*) *Handbook of Reagents for Organic Synthesis: Reagents, Auxiliaries, and Catalysts for C–C Bond Formation*, R. M. Coates and S. E. Denmark, John Wiley & Sons, Ltd., UK, 1999, p. 566.

6 E. Mizushima, K. Sato, T. Hayashi and M. Tanaka, *Angew. Chem., Int. Ed.*, 2002, **41**, 4563–4565.

7 I. I. Moiseev and M. N. Vargaftik, *Coord. Chem. Rev.*, 2004, **248**, 2381–2391.

8 (*a*) J. Tsuji, *Transition Metal Reagents and Catalysts: Innovations in Organic Synthesis*, John Wiley & Sons, Ltd., UK, 2000, p. 420; (*b*) J. E. Bäckvall, B. Åkermark and S. O. Ljunggren, *J. Am. Chem. Soc.*, 1979, **101**, 2411–2416.

9 *Handbook of Chemistry and Physics*, ed. D. R. Lide, CRC Press, Boca Roton, FL, USA, 80th edn, 1999, pp. 8–21.

10 (*a*) S. Carrettin, J. Guzman and A. Corma, *Angew. Chem., Int. Ed.*, 2005, **44**, 2242–2245; (*b*) L. D. Burke, A. J. Ahern and A. P. O'Mullane, *Gold Bull.*, 2002, **35**, 3–10.

11 R. A. Widenhoefer and X. Han, *Eur. J. Org. Chem.*, 2006, 4555–4563.

12 T. E. Müller and M. Beller, *Chem. Rev.*, 1998, **98**, 675–703.

13 C. Brouwer and C. He, *Angew. Chem., Int. Ed.*, 2006, **45**, 1744–1747.

14 Y. Luo, Z. Li and C. J. Li, *Org. Lett.*, 2005, **7**, 2675–2678.

15 Z. Li, J. Zhang, C. Brouwer, C. G. Yang, N. W. Reich and C. He, *Org. Lett.*, 2006, **8**, 4175–4178.