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# **FULL PAPER**

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## **Regiospecific Hydroamination of Unsymmetrical Electron-Rich and Electron-Poor Alkynes with Anilines Catalyzed by Gold(I) Immobilized in MCM-41**

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**Abstract:** The first heterogeneous gold(I)-catalyzed regiospecific hydroamination of ynamides and propiolic acid derivatives with anilines has been achieved by using a diphenylphosphine-functionalized MCM-41-supported gold (I) complex and AgNTf<sub>2</sub> as catalysts under mild conditions, yielding the corresponding (*E*)-*N*-arylimines and (*Z*)-enamines in good to excellent yields with broad substrate scope. The new heterogeneous gold(I) complex can easily be prepared via a two-step procedure from commercially

available reagents and recovered by simple filtration of the reaction mixture. The recovered catalyst ( $Ph_2P$ -MCM-41-AuNTf<sub>2</sub>) can be reused at least seven times without addition of AgNTf<sub>2</sub> as a co-catalyst and its catalytic efficiency remains unaltered.

**Keywords:** gold; hydroamination; ynamide; propiolic acid derivative; heterogeneous catalysis

## Introduction

Substituted amine, enamine or imine moieties are widely encountered in the scaffolds of many complex molecules such as natural products and synthetic drugs. Besides their relevance as part of bioactive naturally occurring products, amines, enamines and imines are important intermediates in the synthesis of natural products, pharmacological agents, N-heterocycles, and fine chemicals.<sup>[1]</sup> Hydroamination of alkynes is of great importance in synthetic organic chemistry since this reaction offers an atom-economical route to various amine derivatives and provides a convenient and practical method for the preparation of numerous important synthetic intermediates and fine chemicals.<sup>[2]</sup> A wide range of metal catalysts of titanium,<sup>[3]</sup> zirconium,<sup>[4]</sup> ruthenium,<sup>[5]</sup> rhodium,<sup>[6]</sup> palladium,<sup>[7]</sup> iridium,<sup>[8]</sup> platinum,<sup>[9]</sup> zinc,<sup>[10]</sup> nickel,<sup>[11]</sup> copper,<sup>[12]</sup> silver,<sup>[13]</sup> lanthanide,<sup>[14]</sup> and actinide<sup>[15]</sup> have been developed to catalyze this transformation. The catalysts based on late transition metals are preferred due to their lower oxophilicity and the majority of the metal-catalyzed hydroaminations of alkynes provide enamine or imine products. However, in many cases, high catalyst loadings, elevated temperatures and long reaction times are usually required to achieve acceptable conversions. Furthermore, for intermolecular hydroamination of unsymmetrical internal alkynes, a mixture of regioisomers is often formed with poor to moderate regioselectivity.

Homogeneous catalysis of organic reactions by gold complexes is a landmark addition to the field of synthetic organic chemistry and has been developed into a highly efficient and powerful tool for the construction of various important building blocks.<sup>[16]</sup> Recently, homogeneous gold(I)-catalyzed reactions of ynamides have gained much attention due to their high efficiency for the synthesis of nitrogen-containing heterocycles.<sup>[17]</sup> Gold complexes are considered as excellent candidates for hydroamination catalysts of alkynes due to their very low oxophilicity. Cationic gold(I) or gold(III) complexes have been shown to be highly efficient catalysts for the intermolecular hydroamination of terminal alkynes<sup>[18]</sup> and internal alkynes.<sup>[19]</sup> However, applications of these homogeneous gold complexes in large-scale synthesis or multistep syntheses remain a challenge because gold is an expensive metal and the catalyst is difficult to separate and recycle. The heterogenization of the existing homogeneous gold catalysts appears to be an attractive solution to this problem.<sup>[20]</sup> Although gold nanoparticles supported on different matrices or

gold clusters have been used as heterogeneous catalysts for the intermolecular hydroamination of terminal alkynes in recent years,<sup>[21]</sup> only an example of intermolecular hydroamination of terminal alkynes catalyzed by supported gold complexes has been described<sup>[20a]</sup> and no examples of intermolecular hydroamination of internal alkynes catalyzed by supported gold complexes have been reported so far. Mesoporous MCM-41 materials have recently been shown to be powerful supports for immobilization of homogeneous catalysts due to their outstanding advantages such as extremely high surface areas, large and defined pore sizes, big pore volumes and the presence of a large number of silanol (Si-OH) groups on the inner surface, compared with other solid supports.<sup>[22]</sup> In continuation of our efforts to develop economical and eco-friendly synthetic pathways for organic transformations,<sup>[20f-h]</sup> we here report the first synthesis of diphenylphosphinefunctionalized MCM-41-supported gold(I) complex [Ph<sub>2</sub>P-MCM-41-AuCl] and its successful application to the intermolecular hydroamination of unsymmetrical electron-rich and electron-poor alkynes with anilines leading to the corresponding (E)-N-arylimines and (Z)-enamines in good to excellent yields with 100% regioselectivity under mild conditions (Scheme 1). The new heterogeneous gold(I) catalyst can easily be recovered by a simple filtration and its catalytic efficiency remains unaltered even after recycling eight times.



**Scheme 1.** Heterogeneous gold(I)-catalyzed intermolecular hydroamination of unsymmetrical electron-rich and electron-poor alkynes with anilines.

#### **Results and Discussion**

# Preparation of Ph<sub>2</sub>P-MCM-41-AuCl Complex and Optimization of Reaction Conditions

The diphenylphosphine-functionalized MCM-41-supported gold(I) complex [Ph<sub>2</sub>P-MCM-41-AuCl] was easily prepared according to the procedure shown in Scheme 2. Firstly, the mesoporous MCM-41<sup>[20f]</sup> was condensed with commercially available 2-(diphenylphosphino)ethyltriethoxysilane in toluene under reflux for 24 h, followed by silylation with Me<sub>3</sub>SiCl at room temperature for 24 h to generate diphenylphosphine-functionalized MCM-41 (Ph<sub>2</sub>P-MCM-41). The latter was subsequently treated with Me<sub>2</sub>SAuCl in dichloromethane (DCM) at room temperature to afford the diphenylphosphine-functionalized MCM-41-supported gold(I) complex [Ph<sub>2</sub>P-MCM-41-AuCl] as a gray powder, the gold content of the complex was found to be 0.36 mmol g<sup>-1</sup> according to the ICP-AES analyses.



Scheme 2. Synthesis of the Ph<sub>2</sub>P-MCM-41-AuCl complex.

The Ph<sub>2</sub>P-MCM-41-AuCl complex was characterized by various physico-chemical techniques. The small angle X-ray powder diffraction (XRD) patterns of the parent MCM-41 and the Ph<sub>2</sub>P-MCM-41-AuCl complex are illustrated in Fig. 1. XRD pattern of the parent MCM-41 gave three peaks corresponding to hexagonally ordered mesoporous phases. For the Ph<sub>2</sub>P-MCM-41-AuCl, the (100) reflection of the MCM-41 with decreased intensity was remained after grafting phosphine-gold(I) complex, while the (110) and (200) reflections became weak and diffuse, which may be mainly due to contrast matching between the silicate framework and organic moieties which are located inside the channels of MCM-41 These results indicate that the structure of the mesoporous MCM-41 remains unchanged through the grafting procedure and the formation of the gold(I) catalyst has taken place preferentially inside the pore system of MCM-41.



**Fig. 1.** XRD patterns of the parent MCM-41 (1) and  $Ph_2P-MCM-41$ -AuCl (2). a.u.: arbitrary units.

The  $N_2$  adsorption-desorption isotherms and pore size distributions for the parent MCM-41 and the Ph<sub>2</sub>P-MCM-41-AuCl complex are presented in Fig. 2 and Fig. 3, respectively. As expected, the isotherms in Fig. 2 have remarkable changes before and after grafting the gold(I) complex because the organic moieties entered the channels, but both samples

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showed type IV isotherms, characteristic of mesoporous materials according to the IUPAC classification. As shown in Fig. 3, the pore volume and size of the Ph<sub>2</sub>P-MCM-41-AuCl complex reduced apparently compared with the parent MCM-41, also indicating that the organic moieties were introduced into the inner channels, but the pore still remained a narrow distribution. After the grafting the phosphine gold(I) complex onto MCM-41, the surface area and pore diameter decreased from 896 m<sup>2</sup>/g and 2.7 nm to 574 m<sup>2</sup>/g and 1.8 nm, respectively, demonstrating that the ordered mesostructure of the parent MCM-41 remained almost unchanged.



**Fig. 2.** N<sub>2</sub> adsorption/desorption isotherms of MCM-41 and Ph<sub>2</sub>P-MCM-41-AuCl. STP: standard temperature and pressure.



Fig. 3. Pore size distributions of MCM-41 and Ph<sub>2</sub>P-MCM-41-AuCl.



**Fig. 4.** Energy dispersive spectra (EDS) of Ph<sub>2</sub>P-MCM-41-AuCl.

The energy dispersive X-ray spectroscopy (EDS) shows the elements present in the material. EDS analysis of fresh Ph<sub>2</sub>P-MCM-41-AuCl complex indicates the presence of Si, O, C, P, Cl and Au elements (Fig. 4). The structure of supported phosphine gold(I) catalyst was also verified by X-ray photoelectron spectroscopy (XPS). The XPS spectra of the fresh Ph<sub>2</sub>P-MCM-41-AuCl (Fig. 5) displayed the spin orbit pair at 84.8 eV (Au  $4f^{7/2}$ ) and 88.5 eV (Au  $4f^{5/2}$ ) that can be assigned to Au(I).



**Fig. 5.** XPS spectra of the Ph<sub>2</sub>P-MCM-41-AuCl complex. a.u.: arbitrary units.

The Ph<sub>2</sub>P-MCM-41-AuCl was then used as the catalyst for the intermolecular hydroamination of unsymmetrical electron-rich or electron-poor alkynes with anilines. Initial experiments with 2-iodoaniline (1a) and 3-(phenylethynyl)oxazolidin-2-one (2a) were performed to optimize the reaction conditions. and the results are listed in Table 1. At first, various heterogeneous gold(I) complexes as catalysts were tested at room temperature in DCE as solvent (entries 1-5). When Ph<sub>2</sub>P-MCM-41-AuCl was used as catalyst, only trace of the desired product 3a was detected (entry 1). To our delight, when various silver salts such as AgOTf, AgNTf<sub>2</sub>, AgSbF<sub>6</sub>, and AgBF<sub>4</sub> were used as co-catalysts, the reaction gave the desired **3a** in 45-95% isolated yields and AgNTf<sub>2</sub> was the best choice (entries 2-5). The use of AgNTf<sub>2</sub> alone as the catalyst only afforded a low yield (entry 6) and no reaction was observed in the absence of any catalyst (entry 7). These results indicated that the real catalyst was Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub>, generated in situ from Ph<sub>2</sub>P-MCM-41-AuCl and AgNTf<sub>2</sub>. In order to furthe confirm that the supported AuNTf<sub>2</sub> is the real catalyst, we prepared Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> by the reaction of Ph<sub>2</sub>P-MCM-41-AuCl with AgNTf<sub>2</sub> in DCM at 25 °C for 0.5 h and used it as the catalyst, the desired product **3a** was isolated in 96% yield after 4 h (entry 8). Our next studies focused on the effect of solvent on the model reaction and a significant solvent effect was observed (entries 9-14). Among the solvents examined, DCM, MeCN, toluene and dioxane also afforded the desired **3a** in good to excellent yields, and DCM gave the best result, while DMF and DMSO were less effective. Finally, we screened the

amount of the supported gold catalyst and were pleased to find that the reaction still proceeded smoothly even with only 0.5 mol% catalyst (entry 15). But further reducing the amount of the catalyst to 0.2 mol% resulted in a lower yield and a long reaction time was required (entry 16). When a homogeneous gold(I) complex was used as catalyst, the desired **3a** was also isolated in 97% yield (entry 17), indicating that the catalytic activity of Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> was comparable to that of Ph<sub>3</sub>PAuNTf<sub>2</sub>. Thus, the optimized conditions for this hydroamination reaction are the Ph<sub>2</sub>P-MCM-41-AuCl/AgNTf<sub>2</sub> (1 mol%) in DCM as solvent at room temperature for 4 h (Table 1, entry 9).

Table 1. Optimization of the reaction conditions<sup>[a]</sup>

		Ph <sub>2</sub> P-MCM-41-AuCl (1 mol%)		Ph 0
l 1a	+ PhN O NH <sub>2</sub> s	≓ ilver salt, solvent, rt	N <sup>2</sup> 3a	N N
Entry	Silver salt (mol%)	Solvent	t [h]	Yield [%] <sup>[b]</sup>
1	_	DCE	12	trace
2	AgOTf (1)	DCE	12	52
3	$\operatorname{AgNTf}_{2}(1)$	DCE	4	95
4	$AgSbF_{6}(1)$	DCE	8	73
5	$AgBF_{4}(1)$	DCE	12	45
6 <sup>[c]</sup>	$AgNTf_{2}(1)$	DCE	12	27
7 <sup>[c]</sup>	_	DCE	24	0
8 <sup>[d]</sup>	_	DCE	4	96
9	$AgNTf_{2}(1)$	DCM	4	97
10	$\operatorname{AgNTf}_{2}(1)$	MeCN	4	91
11	$\operatorname{AgNTf}_{2}(1)$	toluene	4	87
12	$\operatorname{AgNTf}_{2}(1)$	dioxane	4	75
13	$\operatorname{AgNTf}_{2}(1)$	DMF	12	16
14	$\operatorname{AgNTf}_{2}(1)$	DMSO	12	12
15	AgNTf <sub>2</sub> (0.5)	DCM	12	92
16	AgNTf <sub>2</sub> (0.2)	DCM	24	81
17 <sup>[e]</sup>	_	DCM	4	97

<sup>[a]</sup> Reaction conditions: **1a** (1.1 mmol), **2a** (1.0 mmol), Ph<sub>2</sub>P-MCM-41-AuCl (1 mol%) in solvent (1.0 mL), stirred at room temperature. <sup>[b]</sup> Isolated yield. <sup>[c]</sup> Without Ph<sub>2</sub>P-MCM-41-AuCl. <sup>[d]</sup> Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> (1 mol%) was used. <sup>[e]</sup> Ph<sub>3</sub>PAuNTf<sub>2</sub> (1 mol%) was used.

#### Scope of the Reaction Catalyzed by Ph<sub>2</sub>P-MCM-41-AuCl Complex

With the optimal reaction conditions (1 mol% of  $Ph_2P$ -MCM-41-AuCl/AgNTf<sub>2</sub> in DCM at room temperature for 4 h) in hand, we started to investigate the scope of this heterogeneous gold(I)-catalyzed hydro-amination reaction by using various anilines and ynamides as substrates, and the results are summarized in Table 2. First, the scope of anilines was examined with 3-(phenylethynyl)oxazolidin-2-one

(2a) as substrate. Substituted benzenamines bearing either electron-donating or electron-withdrawing groups 1b-1f can undergo the hydroamination with 2a smoothly under mild conditions to give the corresponding (E)-N-arylimines 3b-3f in good to excellent yields. But anilines bearing strong electronwithdrawing groups 1e and 1f showed lower reactivity and afforded the desired products 3e and 3f in slightly lower yields on longer reaction time or by using 2 mol% of catalysts. Alkyl-substituted 3ethynyloxazolidin-2-ones 2b and 2c proved to be also suitable substrates and the reactions with 2-iodoaniline (1a) furnished the desired 3g and 3h in 92% and 95% yield, respectively. This heterogeneous hydroamination reaction was also applicable to the ynamides comprising tosyl-substituted sulfonamide. For example, *N*,4-dimethyl-*N*-(phenylethynyl)benzenesulfonamide (2d) underwent the intermolecular hydroamination with electron-rich or electron-defi cient anilines efficiently to give the corresponding (E)-N-arylimines **3i-3m** in excellent yields. When alkyl-substituted N-ethynyl-N,4-dimethylbenzenesulfonamides 2e and 2f were used as substrates, the reactions with various anilines proceeded smoothly to afford the expected products **3n** and **3o** in 90-93% yields. In addition to 3-alkynyloxazolidin-2-ones 2a-**2c** and *N*-alkynyl-*N*,4-dimethylbenzenesulfonamides **2d-2f**, the hydroamination reaction worked equally well with alkyl- or aryl-substituted N-ethynyl-Nmethylmethanesulfonamides 2g-2j, thus furnishing the desired (E)-N-arylimines **3p-3s** in 89-94% yields. In all cases, (E)-N-arylimine was isolated as the solution product and no other isomers were observed, which should be attributed to the presence of strongly polarized C-C triple bond in ynamide thereby ensuring full regioselectivity. The results above prompted us to investigate the intermolecular hydroamination of ynamides with aliphatic amines, unfortunately, aliphatic amines were not reactive under the conditions optimized for anilines even at higher temperatures. Interestingly, this heterogeneous gold(I)-catalyzed intermolecular hydroamination reaction also worked well for allenamides. Under the optimized conditions for ynamides, the reactions of 3-(propa-1,2-dienyl)oxazolidin-2-one with anilines 1a and 1f proceeded smoothly to give the corresponding hydroaminated products A and B in excellent yields (Scheme 3). The enamides were obtained exclusively as the *E*-isomers, and the addition of N-H bond to the activated allenamide gave the Markovnikov product.





**Table 2.** Heterogeneous gold(I)-catalyzed regiospecific hydroamination of anilines with ynamides<sup>[a,b]</sup>



<sup>[a]</sup> Reaction conditions: **1** (1.1 mmol), **2** (1.0 mmol),  $Ph_2P-MCM-41$ -AuCl (1 mol%), AgNTf<sub>2</sub> (1 mol%) in DCM (1.0 mL) at room temperature for 4 h. <sup>[b]</sup> Isolated yield. <sup>[c]</sup> For 8 h. <sup>[d]</sup> 2 mol% of catalysts were used.

Encouraged by the above results, we next applied this catalytic system to the intermolecular hydroamination of propiolic acid derivatives with anilines, and the results are summarized in Table 3. Generally, these unsymmetrical electron-deficient alkynes displayed a lower reactivity than the electron-rich ones. So, longer reaction times and higher catalyst loading (2 mol%) were required for these substrates, but in all cases examined, high yields of the (Z)enamines were isolated as the sole products. For example, ethyl 3-phenylpropiolate (4a) can undergo the intermolecular hydroamination smoothly with anilines bearing various substituents, regardless of their electronic properties and substitution positions, yielding the corresponding (Z)-enamines **5a-5f** in good to excellent yields within 6-24 h. Alkylsubstituted ethyl propiolates 4b and 4c showed a similar reactivity with 4a and afforded the desired (Z)-enamines 5g-5l in 85-89% yields. Besides propiolates, propiolamides 4d and 4e also proved to be suitable substrates and the reactions with various anilines gave the expected products 5m-5r in high yields within 24 h. Interestingly, the intermolecular hydroamination of sterically hindered 2-iodoaniline with sterically hindered ethyl propiolate 4f furnished exclusively a 95% yield of the (Z)-enamine 5s resulting from attack on the more sterically hindered carbon of strongly polarized C-C triple bond in 4f, which indicating that the electronics of the alkynes can be used to ensure full regioselctivity overruling steric effects. These results show how the electronic effects of unsymmetrical internal alkynes strongly influence the regioselectivity in the heterogeneous gold(I)-catalyzed intermolecular hydroaminations. In principle, these (Z)-enamine products could also result from a Michael addition of anilines to propiolic acid derivatives. However, control experiments showed that the reaction at 60 °C did not occur at all in the absence of the catalyst. We also performed the reaction of propiolic acid derivatives with aliphatic amines such as isobutylamine and benzylamine under the optimized conditions, but the hydroamination reaction did not work. In addition, common terminal alkynes such as phenylacetylene proved to be also compatible with the standard reaction conditions. In the presence of Ph<sub>2</sub>P-MCM-41-AuCl (2 mol%) and Ag $NTf_2$  (2 mol%), the reaction of phenylacetylene with 2-iodoaniline (1.1 equiv) in DCM proceeded smoothly at room temperature to afford the Markovnikov addition product (E)-2-iodo-N-(1-phenylethy lidene)aniline ( $\mathbf{C}$ ) in 90% yield within 5 h.

To ensure that the observed catalysis arises from the heterogeneous catalyst Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> and not from the leached gold species in solution, we performed the addition of 2-iodoaniline (1a) to 3-(phenylethynyl)oxazolidin-2-one (2a) and removed the catalyst from the reaction mixture by filtration at approximately 50% conversion of 2a. After removal of the Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> catalyst, the filtrate was again stirred at room temperature for 4 h. In this case, no significant increase in conversion of 2a was observed, indicating that leached gold species from the catalyst (if any) are not responsible for the observed activity. It was further confirmed by ICP-AES analysis that no gold species could be detected in the filtrate (below the detection limit). These results rule out any contribution to the observed catalysis from a homogeneous gold species demonstrating that the observed catalysis was intrinsically heterogeneous.

Next, we carried out palladium(0)-catalyzed ring closing reaction of (E)-*N*-arylimine **3a** and (Z)-enamine **5a** to prepare indole derivatives (Scheme 4). In the presence of 5 mol% Pd(dba)<sub>2</sub> and 6 mol% XPhos, the cyclization reactions of compounds **3a** and **5a** proceeded smoothly at 80 °C in dioxane with K<sub>3</sub>PO<sub>4</sub> as base to give the desired indole derivatives **6a** and **6b** in 87% and 97% yield, respectively.



Scheme 4. Pd(0)-catalyzed indole synthesis

**Table 3.** Heterogeneous gold(I)-catalyzed regiospecific hydroamination of various anilines with propiolic acid derivatives<sup>[a,b]</sup>



<sup>[a]</sup> Reaction conditions: 1 (1.1 mmol), 4 (1.0 mmol),  $Ph_2P-MCM-41$ -AuCl (2 mol%), AgNTf<sub>2</sub> (2 mol%) in DCM (1.0 mL) at room temperature. <sup>[b]</sup> Isolated yield.

Under the optimized conditions, the stability and recyclability of Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> were evaluated in the reaction between 2-iodoaniline (1a) and 3-(phenylethynyl)oxazolidin-2-one (2a). Filtration of the crude mixture followed by washing of the resulting solid with NH<sub>3</sub>·H<sub>2</sub>O, distilled water and acetone allowed the easy recovery of the gold(I) catalyst. The recovered catalyst could be recycled up to seven times, and almost the same yield of 3a was observed (Fig. 6). It is noteworthy that the reaction catalyzed by the recovered catalyst didn't need the addition of AgNTf<sub>2</sub> because the Ph<sub>2</sub>P-MCM-41-AuCl had been changed to the Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> after the first cycle. In addition, ICP-AES analysis was conducted on the recovered catalyst after eight consecutive runs, the gold content was found to be 0.35 mmol g<sup>-1</sup>, which revealing almost the same gold content as the fresh one. In our opinion, the high catalytic activity and excellent reusability of the gold catalyst relates to the efficient site isolation, to the optimal dispersion of the active sites on the inner channel walls and to the relatively strong interaction between the phosphine ligand and the gold centre supported on the MCM-41.



Fig. 6. Recycle of the Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub> catalyst.

## Conclusions

In conclusion, we have developed a highly regioselective heterogeneous gold(I)-catalyzed intermo lecular hydroamination of ynamides and propiolic acid derivatives with anilines, leading to only one of the two possible regioisomers. This heterogeneous intermolecular hydroamination has many attractive features, such as: (1) the substrate scope is broad, and a wide range of ynamides and propiolic acid derivatives are allowed; (2) a variety of (E)-N-arylimines and (Z)-enamines were obtained in mostly excellent yields; (3) the reaction proceeds smoothly at room temperature under air; (4) this new heterogeneous gold(I) catalyst can easily be prepared via a simple procedure from commercially available reagents and recovered by filtration of the reaction solution. The recovered catalyst (Ph<sub>2</sub>P-MCM-41-AuNTf<sub>2</sub>) can be reused at least seven times without any loss of activity. Our catalytic system not only solves the basic problems of catalyst separation and recovery but also avoids the use of AgNTf<sub>2</sub> as a co-catalyst in recycling process. This makes our protocol facile, economical, and environmentally benign.

#### **Experimental Section**

#### **General Comments**

All chemicals were reagent grade and used as purchased. Mesoporous MCM-41,<sup>[20f]</sup> ynamides **2a-j**,<sup>[23]</sup> propiolic acid derivatives **4d-f**<sup>[24]</sup> and 3-(propa-1,2-dienyl)oxazolidin-2-one<sup>[25]</sup> were prepared according to literature procedures. DCM was dried over CaH<sub>2</sub> and distilled before use. All

reactions were carried out at room temperature under air in oven-dried glassware. The products were purified by flash chromatography on silica gel. Mixture of EtOAc and light petroleum ether was generally used as eluent. All products were characterized by comparison of their spectra and physical data with authentic samples. IR spectra were recorded on an FT-IR spectrometer. <sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded at 400 or 100 MHz with CDCl<sub>3</sub> as the solvent and TMS as an internal standard. Chemical shifts are reported in  $\delta$  (ppm) relative to TMS. HRMS spectra were recorded on a Q-Tof spectrometer with micromass MS software using electro-spray ionization (ESI). Melting points are uncorrected. Gold content was determined with inductively coupled plasma atom emission spectrometry (ICP-AES). X-ray diffraction (XRD) measurements were carried out at room temperature using an X-ray powder diffractmeter. X-ray energy dispersive spectroscopy (EDS) was performed using a microscope. Nitrogen adsorption/desorption isotherms were measured at 77K, using a gravimetric adsorption apparatus equipped with a CI electronic MK2-M5 microbalance and an Edwards Barocel pressure sensor. X-ray photoelectron spectra (XPS) were recorded on a Kratos Axis Ultra Imaging X-ray photoelectron spectrometer equipped with a Mg anode and a multichannel detector.

#### Preparation of Ph<sub>2</sub>P-MCM-41-AuCl Complex

2-(Diphenylphosphino)ethyltriethoxysilane (0.565 g, 1.5 mmol) was added to a suspension of 2.0 g of the MCM-41 in 120 mL of dry toluene. The mixture was stirred at 100 °C for 24 h under Ar. Then the solid was filtered, washed with CHCl<sub>3</sub> (20 mL), and dried in vacuum at 140 °C for 5 h. The dried white solid was then soaked in a solution of 2.8 g of Me<sub>3</sub>SiCl in 100 mL of dry toluene at room temperature under stirring for 24 h. The solid product was filtered, washed with acetone (3 × 20 mL), and dried in vacuum at 120 °C for 3 h to obtain 2.413 g of hybrid material Ph<sub>2</sub>P-MCM-41. The phosphine content was found to be 0.43 mmol g<sup>-1</sup> by elemental analysis.

In a small Schlenk tube, 1.00 g of the above-functionalized MCM-41 (Ph<sub>2</sub>P-MCM-41) was mixed with Me<sub>2</sub>SAuCl (112 mg, 0.38 mmol) in 30 mL of dry CH<sub>2</sub>Cl<sub>2</sub>. The mixture was stirred at room temperature for 8 h under an argon atmosphere. The solid product was filtered, washed with CH<sub>2</sub>Cl<sub>2</sub> and dried under vacuum to give 1.046 g of a gray gold complex (Ph<sub>2</sub>P-MCM-41-AuCl). The gold content was found to be 0.36 mmol g<sup>-1</sup> by ICP-AES.

#### General Procedure for the Heterogeneous Gold(I)-Catalyzed Intermolecular Hydroamination of Anilines with Ynamides or Allenamide.

A small Schlenk tube was charged with Ph<sub>2</sub>P-MCM-41-AuCl (28 mg, 0.01 mmol), AgNTf<sub>2</sub> (3.9 mg, 0.01 mmol) and dry DCM (0.5 mL) and the resulting mixture was stirred at room temperature for 30 min. To this mixture was added the aniline 1 (1.1 mmol), the ynamide 2 or allenamide (1.0 mmol), and dry DCM (0.5 mL) and the tube was sealed. Then the reaction mixture was stirred at room temperature for 4 h, unless otherwise noted, and diluted with ethyl acetate (10 mL) and filtered. The gold

catalyst was washed with NH<sub>3</sub>·H<sub>2</sub>O ( $2 \times 3$  mL), distilled water (3 mL), and acetone ( $2 \times 3$  mL) and reused in the next run. The filtrate was concentrated under reduced pressure and the residue was purified by chromatography on silica gel (eluent: light petroleum ether/ethyl acetate) to afford the desired product.

#### General Procedure for the Heterogeneous Gold(I)-Catalyzed Intermolecular Hydroamination of Propiolic Acid Derivatives or Phenylacetylene with Anilines.

A small Schlenk tube was charged with Ph<sub>2</sub>P-MCM-41-AuCl (56 mg, 0.02 mmol), AgNTf<sub>2</sub> (7.8 mg, 0.02 mmol) and dry DCM (0.5 mL) and the resulting mixture was stirred at room temperature for 30 min. To this mixture was added the aniline **1** (1.1 mmol), the propiolic acid derivative **4** or phenylacetylene (1.0 mmol), and dry DCM (0.5 mL) and the tube was sealed. The reaction mixture was stirred at room temperature for 5-24 h and then diluted with ethyl acetate (10 mL) and filtered. The gold catalyst was washed with NH<sub>3</sub>·H<sub>2</sub>O (2 × 3 mL), distilled water (3 mL), and acetone (2 × 3 mL) and reused in the next run. The filtrate was concentrated under reduced pressure and the residue was purified by chromatography on silica gel (eluent: light petroleum ether/ethyl acetate) to afford the desired product.

# General Procedure for the Pd(0)-Catalyzed Indole Synthesis

The hydroamination product **3a** or **5a** (0.5 mmol), Pd(dba)<sub>2</sub> (5 mol%), XPhos (6 mol%), and K<sub>3</sub>PO<sub>4</sub> (1.5 mmol) were dissolved in dioxane (1.0 mL) under Ar and the reaction. mixture was stirred at 80 °C for 24 h. Then the reaction mixture was allowed to cool to room temperature, quenched with sat. NH<sub>4</sub>Cl (aq.) and extracted with EtOAc ( $3 \times 10$  mL). The combined organic phases were washed with brine, dried over MgSO<sub>4</sub>, filtered, and evaporated in vacuo. The crude mixture was purified by chromatography on silica gel (eluent: light petroleum ether/ethyl acetate) to afford the desired product **6a** or **6b**.

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Regiospecific Hydroamination of Unsymmetrical Electron-Rich and Electron-Poor Alkynes with Anilines Catalyzed by Gold(I) Immobilized in MCM-41

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