Synthesis of bifunctional Au–Sn organic–inorganic catalysts for acid-free hydroamination reactions†‡

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Gold(III) complexes heterogenized on the surface of a Sn-containing MCM-41 are efficient recyclable catalysts for hydroamination reactions, without requiring any acid promoters.

Hydroaminations are chemical reactions with high atom economy, in which an amine N–H bond adds to an alkene or alkyne.[1,2] Since the activation energy for the uncatalyzed reaction is high, a large number of transition-metal based catalysts such as zinc, cadmium, mercury, thallium, zirconium, titanium, lanthanides, rhodium, ruthenium and palladium have been tested for hydroamination reactions.[3,4] Unfortunately, the results are generally not satisfactory in terms of yields, catalytic efficiency and simplicity of procedure.

Cationic gold(I) and gold(III), either in the form of salts or as Au(PPh₃) derivatives, and Au(III) porphyrins have been used for the hydroamination of alkynes and alkenes;[4–9] however, in most cases an acid has to be added to the reaction medium to achieve conversion. Furthermore, none of the catalysts reported up to now could be recovered but, in many cases, they decompose to give the inactive metal.

In the present work, we present a bifunctional organic–inorganic solid catalyst that combines, in one material, the hydroamination catalyst and the acid component. It is formed by phosphine-free gold(I) and gold(III) complexes on a tin-silicate MCM-41 mesostructured inorganic material. In this system the gold complex acts as catalyst and the Sn Lewis site in Sn-MCM-41 as co-catalyst or promoter for hydroamination of alkynes and alkenes in absence of liquid acids.

The phosphine-free Au(I) and Au(III) complexes used in this work for the hydroaminations of alkynes are shown in Fig. 1 and the synthesis and characterization is given as ESI.†[10]
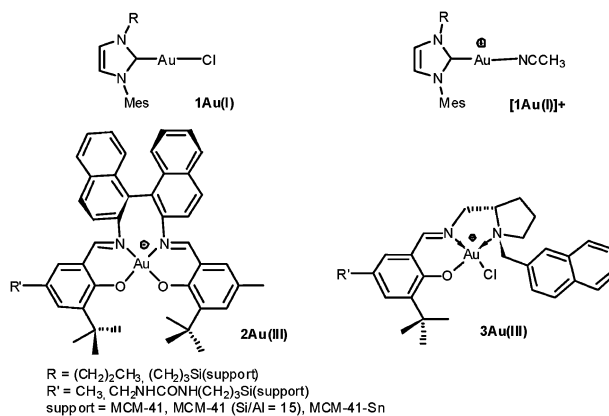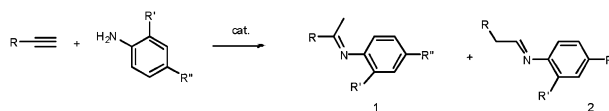
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‡ Typical experimental procedure for hydroamination reactions: A mixture of phenylacetylene (102 mg, 1.0 mmol), aniline (111.6 mg, 1.2 equiv.), gold catalyst (5%), and NH₄PF₆ (5%) in tetrahydrofuran (2 ml) was stirred at 70 °C for 24 h. The mixture was cooled and filtered through a pad of Celite. The progress of the reaction was monitored by gas chromatography.

Fig. 1 Complexes used in this study.

Scheme 1 Hydroamination of alkynes.

When they were used as homogeneous catalysts together with NH₄PF₆ as acid promoter for hydroamination of alkynes (see experimental), the reactions were highly regioselective, and only the Markovnikov addition product was observed (Scheme 1).

The results in Table 1 show that the presence of an acidic promoter (NH₄PF₆), together with Au(I) and Au(III) homogeneous catalysts, was necessary for the hydroamination to take place. Catalyst decomposition was not observed during the reaction. In any case, we have checked that colloidal gold is completely inactive for catalyzing hydroaminations (see Table 1).

From a chemical point of view it would be of much interest to avoid the use of NH₄PF₆ or any soluble acid promoter in solution. However, this has not been possible thus far, and protons are used as a co-catalyst in all the reports of hydroamination using gold catalysts. We thought we might be able to avoid the use of acid-promoters in solution by preparing a bifunctional organic–inorganic catalyst in which the gold complex 2Au(III) was supported on a solid containing Brønsted acid sites. Thus two ordered mesoporous MCM-41 materials were prepared in the form of pure silicate (non-acid reference support), and as an aluminosilicate (acid support with the same structure and textural properties as the previous one). The MCM-41 supports have a pore diameter of 3.5 nm.

Table 1 Homogeneous gold-catalyzed hydroamination of alkynes[a]

	Catalyst	R	R′	R″	t (h)	Yield (%)[b]
1	1Au(I)	Ph	H	H	15	50
2	[1Au(I)]⁺	Ph	H	H	15	95
3	2Au(III)	Ph	H	H	0.3	100[c]
4	3Au(III)	Ph	H	H	1	100
5	2Au(III)	Ph	Br	H	15	60
6	2Au(III)	Ph	H	CH_3	15	100
7	2Au(III)	Ph	H	OMe	4	100
8	2Au(III)	Ph	H	NO_2	15	100
9	2Au(III)	p-MeC_6H_4	H	H	15	50
10	2Au(III)	C_6H_{13}	H	H	15	100
11	2Au(III)	$C(CH_3)_2OH$	H	H	15	100
12	Au(0) (coll.)	Ph	H	H	15	0

[a] Reaction conditions: 1.0 mmol of alkyne, 1.2 equiv. of amine, 5 mol% of NH_4PF_6 and catalyst (gold(I) 10%, gold(III) 5%) in THF at 70 °C. [b] GC and ^1H NMR. [c] With $Sn(Bu)_3Cl$ as promoter, there was 0% conversion.

The Brønsted acidity of the supports was measured by pyridine adsorption,[11] and it is possible to see in Fig. S1† that pyridine was protonated by Brønsted acid sites from the aluminosilicate support, forming a pyridinium ion that is characterized by the corresponding IR band at ~1545 cm^{-1}. In the case of pure silica MCM-41 no band corresponding to pyridinium ions was observed, as could be expected taking into account the non-acid character of the sample. Then, 1–2 mol% of gold complex was anchored on the surface of the two supports, *i.e.* pure silica and silica–alumina MCM-41 mesoporous materials, following the technique reported before,[10] and described in the ESI† for the specific cases. We have checked by means of FTIR, DFTR and ^{13}C NMR spectroscopy that the complexes are anchored to the OH groups of the support, (0.10–0.60 mmol metal/g support) and maintain the geometry and electronic surrounding after heterogenization without significant distortion (see Fig. S2–S7 and description in the ESI†).

From the catalytic point of view we have a bifunctional catalyst that combines the activity of the gold metal complex, with the promoting effect of the Brønsted acid sites of the support. If this was the case and taking into account the acidity of the support, the Au(III) complex anchored on the pure non-acidic silica MCM-41 should not be active, while when on the aluminosilicate the hydroamination reaction should proceed.

The results from Table 2 clearly show that 2Au(III) complexes anchored on the pure silica support (entry 1) do not catalyze the hydroamination of alkynes under our reaction conditions. On the other hand, when the 2Au(III) complex was anchored on the aluminosilicate that contains Brønsted acidity, the reaction proceeds very efficiently, while the acid support was almost inactive by it self (entries 2 and 3). Unfortunately, the gold aluminosilicate catalyst becomes de-activated during the reaction owing to reactant polymerization, and shows very low activity upon recycling, though the gold complex was not leached out (entry 2).

Since it appears that the role of the acidic promoter is, in general, to increase the density of positive charge by subtracting electrons from one of the carbons of the acetylenic group that is interacting with gold,[9] we thought of using a Lewis acid

Table 2 Supported gold-catalyzed hydroamination of phenyl acetylene with aniline[a]

	Catalyst	Promoter	t (h)	Yield (%)[b]
1	2Au(III)-(MCM-41) (pure silica)	NH_4PF_6	24	0
2	2Au(III)-(MCM-41) (Si/Al ≈ 15)	—	0.3	100
	2Au(III)-(MCM-41) (Si/Al ≈ 15) recycled	—	24	20
3	MCM-41 (Si/Al ≈ 15)	—	24	<10
4	2Au(III)-(MCM-41-Sn_G)	—	1.5	100[c]
5	2Au(III)-(MCM-41-Sn_S)	—	1	100
6	3Au(III)-(MCM-41-Sn_G)	—	1	100[c]
7	3Au(III)-(MCM-41-Sn_S)	—	1	100
8	MCM-41-Sn_G	—	24	<10
9	2Au(III)-(MCM-41)	MCM-41-Sn_G	24	Trace

[a] Reaction conditions: 1.0 mmol of alkyne, 1.2 equiv. of amine, and catalyst (5 mol%) in THF at 70 °C. [b] GC and ^1H NMR. [c] After four cycles.

instead of the Brønsted acid site. We expected that a Lewis acid would also be less prone than a Brønsted acid to make polymers, and also will adsorb less strongly the products formed. To check this hypothesis, a Sn-silicate support with Lewis acidity rather than Brønsted acidity (see Fig. S1†) was prepared[12] with MCM-41 by direct synthesis (Sn_S) or by a post-treatment grafting (Sn_G) (see ESI†).

The results presented in Table 2 show that MCM-41-Sn_G (entry 8) by itself gives very low conversion, while the bifunctional 2 and 3Au(III)-(MCM-41-$Sn_{G/S}$) catalysts can give 100% yield after one hour reaction time in the absence of any other acid promoter (entries 4–7, Table 2).

Table 3 shows that supported catalyst on MCM-41-Sn catalyzes the hydroamination reaction with different anilines. In this reaction, both electron-donating and -withdrawing substituents gave good results, and the catalyst retains full activity after four recycles (entries 4 and 6, Table 2). Thus, a new recyclable solid catalyst has been obtained that does not require the presence of acid-promoters in solution to carry out the hydroamination of alkynes.

Reactions with a wide series of acetylenes and aniline have been performed with 2Au(III)-(MCM41-Sn_G) under standard conditions (Table 4). The reactivity of aromatic terminal alkynes (entries 1–4) was sensitive to the substituents of the aromatic ring. Thus the product yield from a 4-methylalkyne (entry 2) was 85%, increasing to 98% when the reaction was performed with 10 mol% of catalyst and at 100 °C. Good yields were obtained with terminal alkynes having *n*-alkyl chains if 10 mol% catalyst and 100 °C were employed. The product yields decreased as the primary alkyl groups were substituted by bulky tertiary groups (entries 9 and 10).

Table 3 2Au(III)-(MCM-41-Sn_G)-catalyzed hydroamination of phenyl acetylene with aromatic amines[a]

	Amine	t (h)	Yield (%)[a]
1	Aniline	1.5	100
2	4-Methylaniline	15	100
3	4-Methoxyaniline	15	100
4	4-Nitroaniline	15	100

[a] Determined by ^1H NMR.

Table 4 2Au(III)-(MCM-41-Sn$_G$)-catalyzed reaction of aniline with various alkynes[a]

	Alkyne	Au-cat (%)	t (h)	Conv. (%)[a]
1	1-Ethynylbenzene	5	1.5	100
2	1-Ethynyl-4-methylbenzene	5	15	85
3		10[b]	15	98
4	1-Ethynyl-4-methoxybenzene	5	15	60
5	1-Octyne	5	24	75
6		10[b]	20	95
7	1-Decyne	5	24	50
8	2-Methylbut-3-yn-2-ol	5	20	40
9	3,3-Dimethylbut-1-yne	5	20	30
10		10[b]	20	80

[a] Determined by GC. [b] In toluene at 100 °C.

Table 5 Supported gold-catalyzed hydroamination of styrene[a]

	Catalyst	Promoter	t (h)	Yield (%)[b]
1	1Au(I)-(MCM-41) (pure silica)	NH$_4$PF$_6$	24	60
2	1Au(I)-(MCM-41-Sn$_G$)	—	24	70
3	2Au(III)-(MCM-41)(pure silica)	—	24	0
4	2Au(III)-(MCM-41) (pure silica)	NH$_4$PF$_6$	10	60
5	2Au(III)-(MCM-41) (Si/Al ≈ 15)	—	15	20[c]
6	MCM-41 (Si/Al ≈ 15)	—	24	5
7	2Au(III)-(MCM-41-Sn$_G$)	—	1.5	100
8	3Au(III)-(MCM-41-Sn$_G$)	—	1	100[d]
9	3Au(III)-(MCM-41-Sn$_S$)	—	1.5	100[d]
10	MCM-41-Sn$_G$	—	24	30
11	Au(0) (colloidal)	NH$_4$PF$_6$	15	0

[a] *Reaction conditions*: 1.0 mmol of alkyne, 1.2 equiv. of amine, and catalyst (gold(I) 10%, gold(III) 5%) in THF at 70 °C. [b] GC and ^{1}H NMR. [c] Deactivation of catalyst after 1 run (without leaching). [d] After four cycles.

For testing the synthetic application of these catalysts, we performed a reaction (1-ethynylbenzene and aniline, 24 h) on a 3 mmol scale, obtaining 100% conversion and 96% yield of isolated pure imine.

The reaction of aniline and styrene proceeds to give *N*-(1-phenylethyl)aniline, with 5% 2Au(III) homogeneous catalyst and NH$_4$PF$_6$ as co-catalyst. In this case, unlike with alkynes, [1Au(I)]$^+$ was more active than 2 and 3Au(III) and, as observed before for alkynes, anilines with electron-donating substituents react much faster than those with electron-withdrawing substituents (see Table S1†). Moreover, the substituents did not influence the regioselectivity of the reaction, since the Markovnikov product remained the exclusive product in all cases.

As with alkynes, the presence of an acid co-catalyst in solution could be avoided by anchoring the 2 and 3Au(III) complex on Sn-containing MCM-41. Indeed, the results in Table 5 clearly demonstrate that the reaction of aniline and styrene occurs faster with 2 and 3Au(III)-(MCM-41-Sn$_{G/S}$) than with the 2Au(III)-(MCM-41) (pure silica)/NH$_4$PF$_6$ catalytic system. Furthermore, the 2 and 3Au(III)-(MCM-41-Sn$_G$) catalyst can be recycled four times without any observable loss in conversion. As with alkynes, we have found that colloidal gold is not active for the hydroamination of alkenes. Although the catalysts are chiral and some substrates prochiral, in no case we have obtained an ee larger than 5% measured by GC.

In conclusion, we have found that the phosphine-free gold(I) and gold(III) homogeneous catalysts presented here are active alkyne and alkene hydroamination catalysts in the presence of added acid promoters. The use of acid promoters could be avoided by preparing bifunctional catalysts formed by the gold complexes anchored to the surface of an aluminosilicate or a tin silicate MCM-41 support. In this case either the Brønsted or the Lewis acid sites on the support are able to promote the hydroamination reaction, but the gold complexes on the aluminosilicate catalyst containing Brønsted acid sites rapidly deactivate. On the order hand, with Lewis acid sites on the support (MCM-41-Sn), the catalyst can be recycled at least 4 times without loss of activity or selectivity.

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