

Powerful Amide Synthesis from Alcohols and Amines under Aerobic Conditions Catalyzed by Gold or Gold/Iron, -Nickel or -Cobalt Nanoparticles

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S Supporting Information

ABSTRACT: Considering the importance of the development of powerful green catalysts and the omnipresence of amide bonds in natural and synthetic compounds, we report here on reactions between alcohols and amines for amide bond formation in which heterogeneous gold and gold/iron, -nickel, or -cobalt nanoparticles are used as catalysts and molecular oxygen is used as terminal oxidant. Two catalysts show excellent activity and selectivity, depending on the type of alcohols used. A wide variety of alcohols and amines, including aqueous ammonia and amino acids, can be used for the amide synthesis. Furthermore, the catalysts can be recovered and reused several times without loss of activity.

The amide is one of the most important functional groups in chemistry.¹ It plays a major role in the elaboration and composition of biological and chemical systems and polymer compounds. While amide bond formation remains a fundamental reaction in organic chemistry,² it is usually created by reactions of carboxylic acids with amines using coupling reagents or by prior conversion of carboxylic acids to derivatives such as acid chlorides or anhydrides (Figure 1 (1)).³ Over the past few years, chemists have made great efforts to develop suitable and environmentally friendly processes,⁴ and in this context, the development of new methodologies for amide bond formation represents a major socioeconomic stake for chemical companies and an important challenge for academic research groups.⁵

In 2007, an important discovery was made by the research group of Milstein et al.⁶ They described the first coupling between an alcohol and an amine for the amide bond formation catalyzed by a ruthenium pincer complex, with molecular hydrogen being the only byproduct (Figure 1 (2)). This direct catalytic conversion of alcohols and amines into amides and dihydrogen (molecular hydrogen) is a particularly desirable reaction due to its high atom efficiency, and this clean and simple reaction has inspired several other research groups to further develop the reactions.⁷ However, although several efforts have been made, the limited availability of substrates remains a disadvantage. Although the catalysts showed excellent activity with sterically unhindered alcohols and amines, limited activity was observed with sterically hindered alcohols and amines, less basic amines, and secondary amines. Moreover, since the reactions were conducted under reductive conditions (hydrogen is formed), unsaturated bonds such as C=C were not tolerated (they were

reduced).^{7a,b,e} Furthermore, special handling of expensive metal complexes and ligands is required in many cases. On the other hand, so far, relatively little work has been carried out on the oxidative transformations. A rhodium catalyst was developed, but a large amount of hydrogen acceptor is required.^{7d} The oxidation pathway (Figure 1 (3)) starting from aldehydes⁸ or alcohols requires one or more equivalents of an oxidant.⁹ We planned to use an alternative pathway for the amide formation from an alcohol and an amine, namely via a tandem oxidative process (TOP) (Figure 1 (4)).¹⁰ TOP is clearly different from the dehydrogenative pathway (Figure 1 (2)) in that the reaction proceeds under oxidative conditions and the only byproduct is water. On the other hand, this oxidation process is very challenging, because there are many possible side-reaction pathways and many byproducts, such as IX,¹¹ X,¹² XI,¹³ XII,¹⁴ XIII, and XI,¹⁵ might be obtained. Some groups recently studied this process; however, yields of the desired compounds (IV) were low, and applicable substrates were very limited.^{14,16} We envisioned that the key step was the oxidation of carbinolamine VII generated from aldehyde VI (formed in situ from alcohol V) and an amine (Figure 1 (4)), and that this step might be catalyzed by gold nanoparticle catalysts. Our group has recently developed gold nanoparticle catalysts immobilized on polystyrene-based polymers with cross-linked moieties, namely polymer-incarcerated (carbon black) catalysts (PI or PICB catalysts), which show excellent activity for the aerobic oxidation of alcohols to carbonyl compounds^{13c,17} and amines to imines.^{15c} These catalysts are quite efficient and can be recycled many times, which makes them one of the most important green catalysts.¹⁸ We have also recently demonstrated a remarkable effect of bimetallic complexes with gold and other noble metals like palladium or platinum for the selective oxidation of alcohols to aldehydes, carboxylic acids, or esters, depending on different combinations of alloy nanoparticles.^{18a,19}

Here, we report the first selective and general amidation using TOP starting from an alcohol and an amine, in a one-to-one equivalent, in the presence of PICB-Au or a new generation of bimetallic nanoparticle catalysts consisting of gold and inexpensive metals, such as iron, nickel, or cobalt, under mild conditions with water being the only byproduct.

First, we investigated the amidation of 3-phenylpropan-1-ol (for an aliphatic case) and 4-methylbenzyl alcohol (for a benzylic alcohol case) in the presence of one equivalent of benzylamine with O₂ and PICB catalysts (Table 1).²⁰ We found that such

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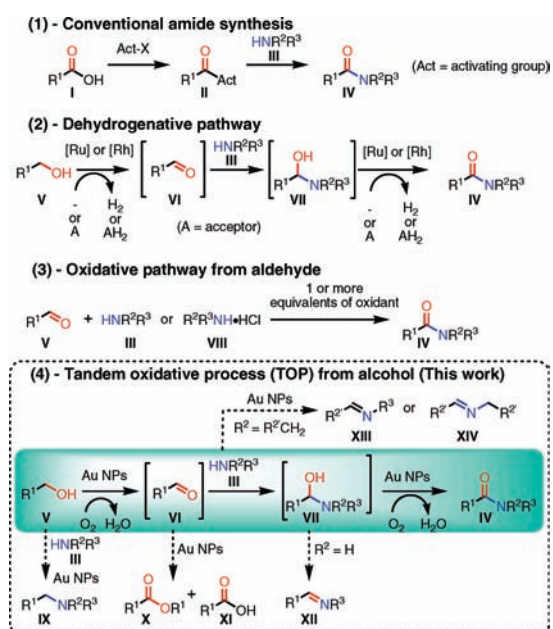


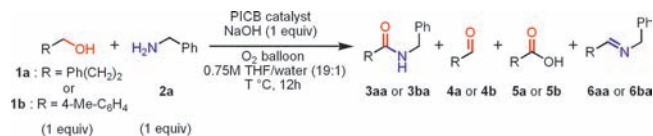
Figure 1. Different pathways for the amide bond formation.

reactions proceeded when one equivalent of NaOH in a mixed solvent, THF/water in a 19:1 ratio, was used.²¹ We initially investigated PICB-Au catalysts prepared by a procedure published previously.^{17b} However, we found that the catalysts were not very active for the amidation of an aliphatic alcohol and not selective for a benzylic alcohol (Table 1, entries 1 and 10). For the aliphatic case, a low conversion (53%) but high selectivity of the amide product **3aa** was obtained. The first oxidation of an alcohol **1a** to an aldehyde **4a** was found to be more difficult in the presence of one equivalent of an amine than in the absence of an amine (Table 1, entries 1,2). To improve the activity, we raised the temperature from room temperature to 40 °C, and good conversion and good selectivity were observed (Table 1, entry 6). For the benzylic alcohol, good conversion but low selectivity was obtained with PICB-Au at room temperature. The yield of amide **3ba** was only 45%, and imine **6ba** was the major byproduct.

To improve the amide yield and the selectivity, we searched for other catalysts. We found that PICB-Au/Pt and PICB-Au/Pd did not exhibit good activity for this reaction (Table 1, entries 11,12). However, we established that a new association between gold and inexpensive metals of period 4 (nickel, iron, or cobalt) has a positive effect on the amide selectivity (Table 1, entries 13–15). In these new catalysts, the association of gold and cobalt is the best combination, and the desired amide **3ba** was obtained in 94% isolated yield. To the best of our knowledge, this is the first example of a positive effect of gold nanoparticles doped with cobalt, nickel, or iron.

To confirm this observation, we conducted several control experiments. First, the activity of Co²⁺ ions in the presence of PICB-Au (Table 1, entry 21) was examined, and different selectivity in favor of amide **3ba** was observed. Results indicated that the active species was not the Co²⁺ ions. Second, we carried out this reaction using two catalysts prepared independently (Table 1, entry 20). In this case, lower selectivity compared with that obtained when using PICB-Au/Co, but better selectivity compared with that obtained when using PICB-Au only was observed. The reaction between 4-methylbenzaldehyde **4b** and

Table 1. Optimization of Reaction Conditions^f



Entry	Substrate	Catalyst (%)	T (°C)	Conv. [%] ^a	3aa or 3ba [%] ^a	4a or 4b [%] ^a	5a or 5b [%] ^b	6aa or 6ba [%] ^a
1	1a	PICB-Au (1)	25	53	50	n.d.	n.d.	n.d.
2 ^c	1a	PICB-Au (1)	25	100	n.d.	n.d.	100	n.d.
3	1a	PICB-Au/Pd (1)	25	n.r.	n.d.	n.d.	n.d.	n.d.
4	1a	PICB-Au/Pt (1)	25	n.r.	n.d.	n.d.	n.d.	n.d.
5	1a	PICB-Au/Co (1)	25	14	10	n.d.	n.d.	3
6	1a	PICB-Au (1.5)	40	86	85 (83)	n.d.	n.d.	1
7 ^d	1a	PICB-Au (1.5)	40	84	84	n.d.	n.d.	n.d.
8	1a	PICB-Au (1.5)	50	87	80	n.d.	6	1
9	1a	PICB-Au/Co (1)	40	44	44	n.d.	n.d.	n.d.
10	1b	PICB-Au (1)	25	95	45	n.d.	n.d.	50
11	1b	PICB-Au/Pd (1)	25	75	2	n.d.	n.d.	73
12	1b	PICB-Au/Pt (1)	25	80	5	n.d.	n.d.	75
13	1b	PICB-Au/Ni (1)	25	100	87	n.d.	n.d.	13
14	1b	PICB-Au/Fe (1)	25	100	94	n.d.	n.d.	6
15	1b	PICB-Au/Co (1)	25	100	96 (94)	n.d.	n.d.	4
16 ^d	1b	PICB-Au/Co (1)	25	94	94	n.d.	n.d.	n.d.
17 ^e	1b	PICB-Au/Co (1)	25	100	n.d.	n.d.	100	n.d.
18	1b	PICB-Au (1.5)	40	100	25	n.d.	12	63
19	1b	PICB-Co (1)	25	n.r.	n.d.	n.d.	n.d.	n.d.
20	1b	PICB-Au (1) and PICB-Co (1)	25	100	76	15	n.d.	9
21	1b	PICB-Au (1) and CoCl ₂ (1)	25	100	43	30	n.d.	27
22	4b	PICB-Au/Co (1)	25	100	45	n.d.	n.d.	55
23	5b	PICB-Au/Co (1)	25	n.r.	n.d.	n.d.	100	n.d.
24	6ba	PICB-Au/Co (1)	25	n.r.	n.d.	n.d.	n.d.	100
25 ^e	-	PICB-Au/Co (1)	25	n.r.	n.d.	n.d.	n.d.	n.d.

^a Determined by gas chromatography (GC) analysis using dodecane as an internal standard. Number in parentheses is isolated yield. ^b Determined by ¹H NMR. ^c The reaction was performed without amine. ^d Reaction was performed under an atmosphere of air for 24 h. ^e 4-Methylbenzyl 4-methylbenzoate was used instead of **1b**. ^f (n.d. = not detected, n.r. = no reaction).

benzylamine **2a** under the same conditions (Table 1, entry 22) led to formation of the corresponding imine as major product. The imine did not react under these conditions (Table 1, entry 24). These results suggest that a low concentration of aldehyde during the reaction is required to obtain a high selective reaction. On the other hand, when the reaction was conducted with 4-methylbenzoic acid **5b** or 4-methylbenzyl-4-methylbenzoate instead, no reactions were observed (Table 1, entries 23 and 25). These results suggest that benzoic acid and ester are not intermediate in this reaction and the reaction proceeds by a carbinolamine. At this stage, we thought that cobalt might stabilize the carbinolamine and inhibit the dehydration process and that, if cobalt and gold particles were in close proximity, the reaction would then proceed with a better selectivity.

The catalyst was recovered by simple filtration and reused without significant loss of activity.²² The recovered catalyst could

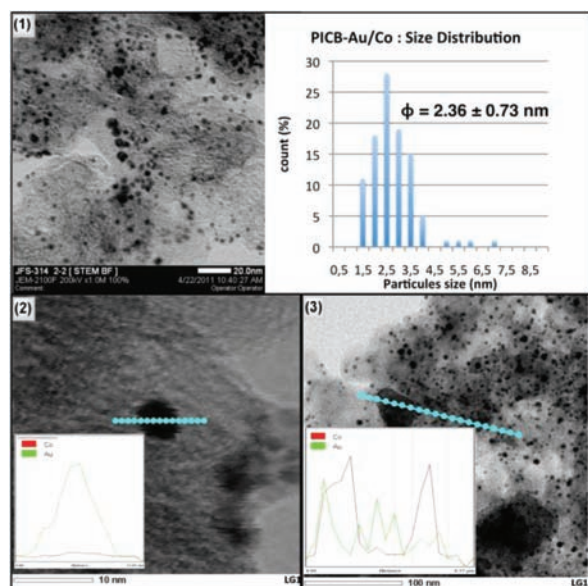


Figure 2. STEM and EDS analyses of PICB-Au/Co catalysts. (1) Typical STEM image and size distribution. (2) EDS line analysis of a cluster (green: Au; red: Co). (3) EDS line analysis of several clusters (green: Au; red: Co).

be washed with water, THF, or CH_2Cl_2 and then heated at 170 °C for 5 h to facilitate its reuse.²¹ Finally, we examined the TOP using air (under balloon pressure) as the terminal oxidant and found that the reaction proceeded smoothly under our optimized reaction conditions (Table 1, entries 7 and 16).

Next, we conducted scanning transmission electron microscopy (STEM) and energy dispersive spectroscopy (EDS) analyses to characterize the newly prepared bifunctional composite catalyst PICB-Au/Co (Figure 2). EDS line analysis revealed the following: a single Gaussian distribution of X-rays of Au across the nanoparticle (5 nm) and independent multiple Gaussian distributions of X-rays of Au and Co. This observation indicated the random arrangement of Au and Co atoms without formation of Au/Co alloys as previously reported in the case of PICB-Au/Pt or PICB-Au/Pd.^{19b,c} Moreover, these results suggested that Co does not exist inside the Au nanoparticles but is dispersed throughout the polymer/CB composite material, and Au and Co lie in close proximity. Additional proof of this proximity between Au and Co is provided by EDS mapping analysis.²¹ At this stage, we think that Co has two effects: (a) with an electronic interaction between Au and Co (Table 1, substrate = **1a**, entries 1 and 4) the reactivity of Au is decreased, and (b) Co can stabilize the carbinolamine during the oxidation step (Table 1, substrate = **1b**, entries 10 and 15. See also Figure 1).

To demonstrate the general applicability of the PICB-Au/X system, various alcohols were tested in amidation reactions with benzylamine **2a**. In general, the catalytic experiments were conducted under a dioxygen atmosphere in the presence of 1 mol % PICB-Au/Co catalyst at 25 °C (conditions A) for benzylic alcohols, and 1.5 mol % PICB-Au at 40 °C (conditions B) for nonbenzylic alcohols. It was found that both electron-poor and -rich benzylic alcohols (Table 2, entries 2–4) were successfully converted to the corresponding amides **3ba–da** in good to excellent yields. We also determined that the reactions of alcohols bearing heterocycles and naphthalene proceeded very well to afford the corresponding amides in good yields (Table 2, entries 5–7).

Table 2. Scope of the Reaction

R-OH (1x) + HNR^1R^2 (2y) (1 equiv) (1 equiv)		$\xrightarrow[\text{O}_2, \text{ balloon}]{\text{PICB catalyst NaOH (1 equiv)}} \text{R-NR}^1\text{R}^2$ (3xy) 0.75M THF/water (19:1) T °C, 12h isolated yield (conditions)
Conditions A : PICB-Au/Co (1 mol%), 25 °C Conditions B : PICB-Au (1.5 mol%), 40 °C		
1	2	3
3aa; 10% (A), 85% (B)	3ba; 95% (A), 45% (55%) ^a (B)	3ca; 95% (A)
4	5	
3da; 87% (A)	3ea; 89% (A)	
6	7	8
3fa; 92% (A)	3ga; 85% (A)	3ha; 65% (A), 39% (B)
9	10	
3ia; 54% (60%) ^b (A)	3ja; 89% (B)	
11	12	13
3ka; 71% (B)	3la; 95% (B)	3ma; 95% (A), 45% (55%) ^a (B)
14	15	
3mb; 93% (A)	3mc; 96% (A)	
16	17	18
3md; 97% (A)	3me; 96% (A)	3mf; 93% (A)
19	20	
3mg; 79% (A)	3mh; 68% (A)	
21	22	23
3mi; 0% (A)	3mj; 75% (A)	3mk; 89% (A) ^c
24	25	
3bl; trace (A), 70% (B)	3mm; 84% (B)	
26	27	28
3mn; 72% (B)	3mo; 66% (B)	3mp; 72% (A) ^d , 73% (B) ^d
29	30	
3mq; 87% (B) ^d	3mr; 69% (A)	

^a Yield of corresponding imines. ^b 2 equiv of alcohol was used. ^c 6 equiv of aqueous ammonia was used. ^d 2 mol% of catalyst was used, and the reaction was performed in THF/water (9:1) in the presence of 2 equiv of base.

Next, allylic alcohols were also tried. Using cinnamyl alcohol, conditions A furnished a moderate yield; however, a poor yield (39%) was observed under conditions B (Table 2, entries 8–9). Allylic alcohol was also tried, and a 60% yield of amide **3ia** was obtained.²³ It was noted that the C=C double bond moieties were tolerant in the present amide formation, whereas the reduction of double bond moieties occurred in alternative processes using ruthenium catalysts. When aliphatic alcohols **1a** and **1j–I** were used as coupling partners, conditions B were used, and the desired amides **3aa** and **3ka–la** were obtained in good yields (Table 2, entries 1 and 10–12).

We also investigated the amines. Excellent yields were obtained with benzylic amine **2a** or aliphatic amines (Table 2, entries 14–19). Steric effects of the amine may play a key role. A bulky group, such as C_5H_{11} **2g**, afforded amide **3mg** in moderate yield (Table 2, entry 19), but no product was obtained when using a bulkier amine (Table 2, entry 21). The reaction with a primary aromatic amine (Table 2, entry 22) proceeded smoothly to afford the amide **3mj** in good yield. When using an aqueous solution of ammonia, this TOP can directly provide the primary amide **3mk** in good yield. To the best of our knowledge, this free amidation reaction, using aqueous ammonia and starting from an alcohol, is the first reported. With a secondary amine, only a trace of amide **3bl** was observed when PICB-Au/Co was used. We then decided to optimize the reaction conditions. When conditions B were used, amide **3bl** was isolated in 70% yield. Cyclic

secondary amines such as piperidine and morpholine (Table 2, entries 26 and 25, respectively) offered better yields than the simple secondary amines (Table 2, entries 24 and 27). Interestingly, when the oxidative amidation reaction was applied to an optically active amino acid and its derivatives, the reaction proceeded smoothly with yields of 73% and 69% (Table 2, entries 28 and 30). No racemization occurred in this reaction, and a free amino acid could be used directly.

Currently available data do not allow one to explain clearly the several remarkable effects of the bimetallic Au/Co complex for the selective formation of amide products and the difference in activities for PICB-Au and PICB-Au/Co, but there are several possibilities. The cobalt center may stabilize the carbinolamine form and decrease the activity of gold nanoparticles in the first oxidation step. Although the mechanistic issues are yet to be resolved, the results of this work have demonstrated that, depending on the catalyst system, the amide bond formation from alcohols and amines when using molecular oxygen as a terminal oxidant can be conducted with high selectivity and in high yields when using heterogeneous catalysts. These catalysts can be reused several times. The method has been generalized and a wide variety of substrates has been tested (benzylic, allylic, and aliphatic alcohols; primary and secondary amines; aniline; aqueous ammonia; and amino acids), and these have shown good activity in this coupling. Our results indicate that this is one of the greenest and most general methods for amide bond formation from alcohols and amines.

■ ASSOCIATED CONTENT

S Supporting Information. Reaction procedure and spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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■ REFERENCES

- (1) (a) Larock, R. C. *Comprehensive Organic Transformations: A Guide to Functional Group Preparations*, 2nd ed.; Wiley-VCH: New York, 1999; (b) Allen, C. L.; Williams, J. M. J. *Chem. Soc. Rev.* **2011**, *40*, 3405–3415.
- (2) Valeur, E.; Bradley, M. *Chem. Soc. Rev.* **2009**, *38*, 606–631.
- (3) Smith, M. B. *Compendium of Organic Synthetic Methods*; Wiley: New York, 2001; Vol. 9.
- (4) Anastas, P.; Eghbali, N. *Chem. Soc. Rev.* **2010**, *39*, 301–312.
- (5) Constable, D. J. C.; Dunn, P. J.; Hayler, J. D.; Humphrey, G. R.; Leazer, J. J. L.; Linderman, R. J.; Lorenz, K.; Manley, J.; Pearlman, B. A.; Wells, A.; Zaks, A.; Zhang, T. Y. *Green Chem.* **2007**, *9*, 411–420.
- (6) (a) Gunanathan, C.; Ben-David, Y.; Milstein, D. *Science* **2007**, *317*, 790–792. (b) Naota, T.; Murahashi, S. I. *Synlett* **1991**, 693–694.

- (7) (a) Nordström, L. U.; Vogt, H.; Madsen, R. *J. Am. Chem. Soc.* **2008**, *130*, 17672–17673. (b) Ghosh, S. C.; Muthaiah, S.; Zhang, Y.; Xu, X. Y.; Hong, S. H. *Adv. Synth. Catal.* **2009**, *351*, 2643–2649. (c) Watson, A. J. A.; Maxwell, A. C.; Williams, J. M. J. *Org. Lett.* **2009**, *11*, 2667–2670. (d) Zweifel, T.; Naubron, J.-V.; Grützmacher, H. *Angew. Chem., Int. Ed.* **2009**, *48*, 559–563. (e) Muthaiah, S.; Ghosh, S. C.; Jee, J. E.; Chen, C.; Zhang, J.; Hong, S. H. *J. Org. Chem.* **2010**, *75*, 3002–3006. (f) Zhang, Y.; Chen, C.; Ghosh, S. C.; Li, Y.; Hong, S. H. *Organometallics* **2010**, *29*, 1374–1378. (g) Shimizu, K.; Ohshima, K.; Satsuma, A. *Chem.—Eur. J.* **2009**, *15*, 9977–9980.
- (8) Yoo, W.-J.; Li, C. J. *J. Am. Chem. Soc.* **2006**, *128*, 13064–13065.
- (9) Reddy, K. R.; Maheswari, C. U.; Venkateshwar, M.; Kantam, M. L. *Eur. J. Org. Chem.* **2008**, 3619–3622.
- (10) Taylor, R. J. K.; Reid, M.; Foot, J.; Raw, S. A. *Acc. Chem. Res.* **2005**, *38*, 851–869.
- (11) (a) He, L.; Lou, X.-B.; Ni, J.; Liu, Y.-M.; Cao, Y.; He, H.-Y.; Fan, K.-N. *Chem.—Eur. J.* **2010**, *16*, 13965–13969. (b) Ishida, T.; Kawakita, N.; Akita, T.; Haruta, M. *Gold Bull.* **2009**, *42*, 267–274.
- (12) Abad, A.; Concepcion, P.; Corma, A.; Garcia, H. *Angew. Chem., Int. Ed.* **2005**, *44*, 4066–4069.
- (13) (a) Prati, L.; Rossi, M. *J. Catal.* **1998**, *176*, 552–560. (b) Bianchi, C.; Porta, F.; Prati, L.; Rossi, M. *Top. Catal.* **2000**, *13*, 231–236. (c) Carrettin, S.; McMorn, P.; Johnston, P.; Griffin, K.; Hutchings, G. J. *Chem. Commun.* **2002**, 696–697. (d) Tsunoyama, H.; Sakurai, H.; Negishi, Y.; Tsukuda, T. *J. Am. Chem. Soc.* **2005**, *127*, 9374–9375. (e) Miyamura, H.; Matsubara, R.; Miyazaki, Y.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2007**, *46*, 4151–4154.
- (14) Kegnaes, S.; Mielby, J.; Mentzel, U. V.; Christensen, C. H.; Riisager, A. *Green Chem.* **2010**, *12*, 1437–1441.
- (15) (a) Aschwanden, L.; Mallat, T.; Krumeich, F.; Baiker, A. *J. Mol. Catal. A: Chem.* **2009**, *309*, 57–62. (b) Gorrane, A.; Corma, A.; Garcia, H. *J. Catal.* **2009**, *264*, 138–144. (c) Miyamura, H.; Morita, M.; Inasaki, T.; Kobayashi, S. *Bull. Chem. Soc. Jpn.* **2011**, *84*, 588–599. (d) So, M.-H.; Liu, Y.; Ho, C.-M.; Che, C.-M. *Chem. Asian J.* **2009**, *4*, 1551–1561. (e) Zhu, B.; Angelici, R. J. *Chem. Commun.* **2007**, 2157–2159.
- (16) (a) Klitgaard, S. K.; Egeblad, K.; Mentzel, U. V.; Popov, A. G.; Jensen, T.; Taarning, E.; Nielsen, I. S.; Christensen, C. H. *Green Chem.* **2008**, *10*, 419–423. (b) Ishida, T.; Haruta, M. *ChemSusChem* **2009**, *2*, 538–541. (c) Xu, B.; Zhou, L.; Madix, R. J.; Friend, C. M. *Angew. Chem., Int. Ed.* **2010**, *49*, 394–398. (d) Zhou, L.; Freyschlag, C. G.; Xu, B. J.; Friend, C. M.; Madix, R. J. *Chem. Commun.* **2010**, 46, 704–706. (e) Preedasuriyachai, P.; Kitahara, H.; Chavasiri, W.; Sakurai, H. *Chem. Lett.* **2010**, *39*, 1174–1176.
- (17) (a) Miyamura, H.; Yasukawa, T.; Kobayashi, S. *Green Chem.* **2010**, *12*, 776–778. (b) Lucchesi, C.; Inasaki, T.; Miyamura, H.; Matsubara, R.; Kobayashi, S. *Adv. Synth. Catal.* **2008**, *350*, 1996–2000.
- (18) (a) Enache, D. I.; Edwards, J. K.; Landon, P.; Solsona-Espriu, B.; Carley, A. F.; Herzing, A. A.; Watanabe, M.; Kiely, C. J.; Knight, D. W.; Hutchings, G. J. *Science* **2006**, *311*, 362–365. (b) Tsukuda, T.; Tsunoyama, H.; Sakurai, H. *Chem. Asian J.* **2011**, *6*, 736–748. (c) Della Pina, C.; Falletta, E.; Prati, L.; Rossi, M. *Chem. Soc. Rev.* **2008**, *37*, 2077–2095. (d) Polshettiwar, V.; Varma, R. S. *Green Chem.* **2010**, *12*, 743–754.
- (19) (a) Landon, P.; Collier, P. J.; Papworth, A. J.; Kiely, C. J.; Hutchings, G. J. *Chem. Commun.* **2002**, 2058–2059. (b) Kaizuka, K.; Miyamura, H.; Kobayashi, S. *J. Am. Chem. Soc.* **2010**, *132*, 15096–15098. (c) Yoo, W.-J.; Miyamura, H.; Kobayashi, S. *J. Am. Chem. Soc.* **2011**, *133*, 3095–3103.
- (20) The effect of carbon black (CB) on catalytic activity was discussed in previous reports (refs 17b and 19c): it prevents aggregation of clusters and enlarges surface area.
- (21) See Supporting Information.
- (22) Examination by Inductively Coupled Plasma (ICP) analysis of the resulting filtrate of the reaction mixture revealed no leaching of either cobalt or gold under the two conditions.
- (23) Because of the instability of acrolein, 2 equiv of allylic alcohol was used.