DOI: 10.1002/chem.201001915

Organic Ligand-Free Alkylation of Amines, Carboxamides, Sulfonamides, and Ketones by Using Alcohols Catalyzed by Heterogeneous Ag/Mo Oxides

Xinjiang Cui,[a, b] Yan Zhang,[a] Feng Shi,*[a] and Youquan Deng[a]

Abstract: Complicated and expensive organic ligands are normally essential in fine chemical synthesis at preparative or industrial levels. The synthesis of fine chemicals by using heterogeneous catalyst systems without additive organic ligand is highly desirable but severely limited due to their poor generality and rigorous reaction conditions. Here, we show the results of carbon–nitrogen or carbon–carbon bond formation catalyzed by an Ag/Mo hybrid material with specific $Ag_6Mo_{10}O_{33}$ crystal structure. 48 nitrogen- or oxygen-containing compounds, that is, amines, carboxamides, sulfonamides, and ketones, were successfully synthesized through a borrowing-hydrogen mechanism. Up to 99% isolated yields were obtained under relatively mild conditions without additive organic ligand. The catalytic process shows promise for the efficient and economic synthesis of amine, carboxamide, sulfonamide, and ketone derivatives because of the simplicity of the system and ease of operation.

Keywords: Ag/Mo · amines · carboxamides · ketones · sulfonamides

Introduction

One of the most fundamental transformations in chemistry is C–N bond formation, which plays a major role in the elaboration and composition of biological and chemical systems.[1] In the past decades, transition-metal-catalyzed C–N bond-forming reactions have emerged as a potent tool for amine synthesis. With the exception of the great achievements obtained by reacting amines with aryl halides and amines,[2] hydroaminations[3] and hydroaminomethylation,[4] coupling amines with alcohols could be one of the most promising routes for amine synthesis.[5] Alcohols are readily available, nonexpensive, nontoxic, and water is the only byproduct theoretically; thus, the reaction is intrinsically environmentally friendly. However, employing alcohols as alkylation reagents is severely limited because of the poor electrophilicity of most alcohols. Recently, the N-alkylations of sulfonamides and carboxamides with alcohols were realized successfully through a carbocation mechanism.[6] Unfortunately, only benzylic and allylic alcohols could be activated and the formation of undesired byproducts and tar is unavoidable. The borrowing-hydrogen technology makes the direct use of alcohol as an alkylation reagent more facile. Since the early reports by Grigg[7] and Watanabe[8] in the 1980s, until today, various transition-metal catalysts including ruthenium[9] and iridium[10] complexes have been successfully developed for the alkylation of amines with alcohols. Although elegant results were reported, the application of expensive noble metal catalysts results in complicated reaction systems. Other than noble metal catalysts, the use of an organic ligand is a more serious problem. Sometimes the synthesis of organic ligands is difficult and the ligands are hard to recover. Therefore, the whole process is uneconomic especially when it is applied in industry. Thus enormous efforts have been spent in the last decades for the heterogenization of homogeneous catalysts.[11] Most study in this area is to immobilize the organic ligand or metal complex onto the support through chemical bonds.[12] Unfortunately, this technology is commonly of scientific interest because of the enormous complexity in ligand preparation and immobilization. What is worse is the deactivation after immobilization and the often common loss of catalytically active components. In comparison with the homogeneous or heterogen-

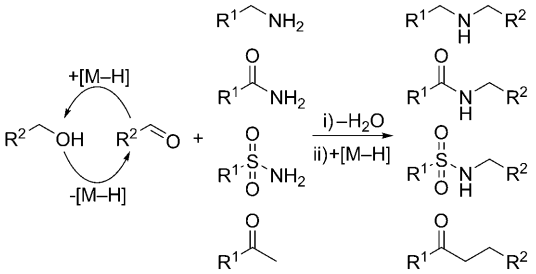
[a] X. Cui, Dr. Y. Zhang, Dr. F. Shi, Prof. Y. Deng
Centre for Green Chemistry and Catalysis
Lanzhou Institute of Chemical Physics
Chinese Academy of Sciences Middle Tianshui Road
18, Lanzhou, 730000 (China)
Fax: (+86) 931-8277088
E-mail: fshi@licp.cas.cn

[b] X. Cui
Graduate School of Chinese Academy of Sciences
Beijing, 100049 (China)

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201001915.

ized catalysts, heterogeneous catalysts have advantages for product and catalyst isolation, catalyst reuse, and operational handling and some nice results were obtained recently.[13] Nevertheless, till today, the development of heterogeneous catalyst systems was severely limited due to its poor generality or its specific catalytic activity for specific reactions, especially in fine-chemical synthesis. For example, the newly reported iron oxide supported nanoruthenium could be an active catalyst in sulfonamide alkylation with alcohols.[14] However, this catalyst has no activity in the alkylation of carboxamides, amines, and ketones. Also, there is no possibility to use aliphatic alcohols as starting materials. Therefore, one of the major tasks for catalyst researchers is to develop more active and general heterogeneous catalysts for the N-alkylation reactions with alcohol without the addition of organic ligand.

According to the mechanistic investigation, the key steps for the reaction are the activation or dehydrogenation of alcohol to form the carbonyl compound and the hydrogenation of the imine intermediate to yield the product (Scheme 1).[5a,9b,15] Up-to-now, one of the most active catalysts, that is, hydrotalcite-supported silver, for the dehydrogenation of alcohols has been reported.[16] Meantime, molybdenum complex was found to be active for the nuclephilic addition or reduction of imines.[17] Possibly a new and simple catalyst could be designed for the N-alkylation of amines with alcohol if we can combine silver and molybdenum together through a suitable method. Here, we report our new findings on the selective growth of Ag/Mo hybrid materials, that is, $Ag_6Mo_{10}O_{33}$ and its catalytic activity in the coupling reactions of amines, carboxamides, sulfonamides, and ketones with alcohols (Scheme 1).



Scheme 1. Amine, carboxamide, sulfonamide, and ketone alkylation with alcohol (M = Ag/Mo).

Results and Discussion

Initially, the catalytic activity of commercially available Ag_2O, MoO_3, and Ag_2MoO_4 were tested (Table 1). Clearly, only *N*-benzylideneaniline formed in the presence of Ag_2O or MoO_3 (Table 1, entries 1 and 2). As we imagined, the catalytic activity was efficiently improved with Ag_2MoO_4 as the catalyst. Although the conversion was not high, 24% *N*-benzyl aniline was observed (entry 3).

Inspired by these interesting results, we tried to find a suitable method to prepare Ag/Mo hybrid material catalysts for the N-alkylation of amines. The Ag/Mo hybrid materials were prepared through a hydrothermal method with slight modification.[18] All the materials were characterized by BET, XPS, XRD, SEM, and TEM. BET measurements showed that the BET surface area was 1.5–4.5 $m^2 g^{-1}$ for all the samples (see Table S1 in the Supporting Information). XPS analysis confirmed the presence of Ag^+ and Mo^{6+} species (Figure 1).

Table 1. Reaction condition optimization with a Ag/Mo hybrid material as the catalyst.[a]

Entry	Cat.	Base	Conv. [%][b]	Sel. [%][c]
1	Ag_2O	K_2CO_3	41	0
2	MoO_3	K_2CO_3	13	0
3	Ag_2MoO_4	K_2CO_3	36	24
4	Ag-Mo-22	K_2CO_3	82	82
5	Ag-Mo-5	K_2CO_3	32	35
6	Ag-Mo-15	K_2CO_3	48	50
7	Ag-Mo-20	K_2CO_3	72	76
8	Ag-Mo-25	K_2CO_3	44	51
9	Ag-Mo-22	K_2CO_3	85	85
10	Ag-Mo-22	Na_2CO_3	17	0
11	Ag-Mo-22	$NaHCO_3$	24	0
12	Ag-Mo-22	KO*t*Bu	≈95 (≈95)[d]	≈95 (≈ 95)[d]
13	Ag-Mo-22	KOH	88	92
14	Ag-Mo-22	Cs_2CO_3	89	80

[a] Reaction conditions: aniline (2 mmol, 186 mg), benzyl alcohol (10 mmol, 1080 mg), catalyst (40 mg), base (20 mol%), 12 h, 140°C (entries 1–4), 160°C (entries 5–14). Conversion of aniline was determined by GC-FID. [b] Conversion of aniline. [c] Selectivity to *N*-benzyl aniline determined by GC-FID. The major byproduct derived from aniline is *N*-benzylideneaniline. [d] The catalyst was recovered and reused for the second time.

The SEM and TEM pictures showed that the sample was closed packed and confirmed the formation of the $Ag_6Mo_{10}O_{33}$ crystal for sample Ag-Mo-22 (Figure 2 and Figure S1 in the Supporting Information). XRD analysis gave more interesting results (Figure 3). Normally, $Ag_2Mo_2O_7$ crystals could be obtained with a pH value of about 0.90–1.50 after the addition of nitric acid (samples Ag-Mo-5, -15, and -20). After finely tuning the acidity, $Ag_6Mo_{10}O_{33}$ crystal, that is, Ag-Mo-22, could be selectively synthesized by the addition of nitric acid (22 mL, 2 M), although the pH value of the reaction mixture with the addition of 20–25 mL nitric acid could not be measured accurately by a pH meter. The crystal structure of $Ag_6Mo_{10}O_{33}$ was different from former reports,[18a] which was denoted as Ag-Mo-R and prepared in solution with pH 2 and the ratio of Ag to Mo was 1:1 (see Figure S2 in the Supporting Information).

By applying these Ag/Mo hybrid materials in the reaction of aniline alkylation with benzyl alcohol, nice results were achieved (Table 1, entries 5–14). The conversion of aniline and the selectivity of *N*-benzyl aniline were all above 90% with Ag-Mo-22 as the catalyst and no deactivation occurred when it was recovered and reused with KO*t*Bu as additive base. For comparison, the Ag-Mo-R prepared by the reported procedure was also tested under the same reaction conditions (not shown in Table 1). The conversion was 52% with 56% selectivity, which suggests that Ag-Mo-R was also a

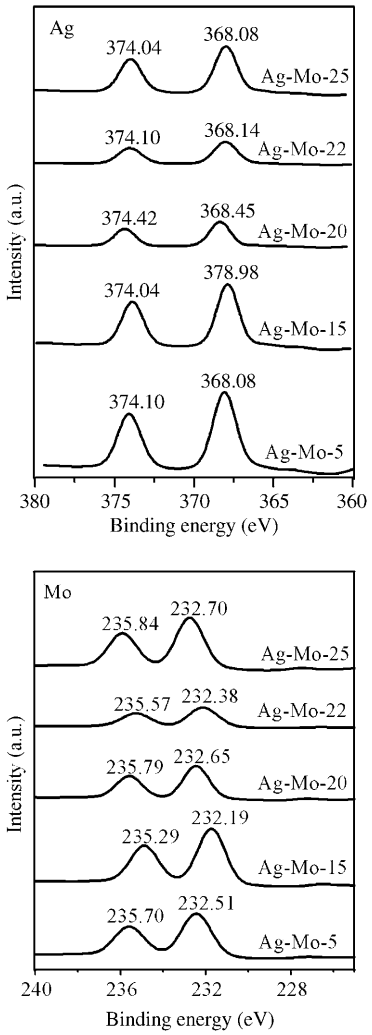


Figure 1. XPS spectra of Ag/Mo hybrid materials.

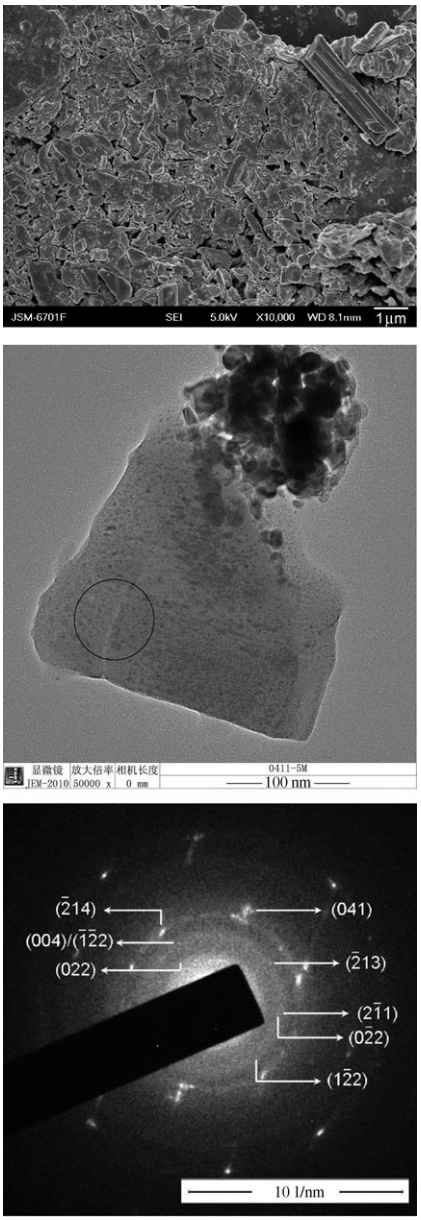


Figure 2. SEM and TEM images and selected-area electron diffraction patterns of Ag-Mo-22 catalyst.

good catalyst for the N-benzylation of aniline with benzyl alcohol but not as active as our catalyst. Therefore, a heterogeneous Ag/Mo catalyst was successfully developed for the aniline alkylation with alcohol without the addition of any organic ligand.

Under the optimized reaction conditions, the Ag/Mo hybrid catalyst was further applied in the alkylation of different amines, carboxamides, sulfonamides, and ketones.[5a,d,9b] By alcohol variation, 82–90% yields were obtained with 3-methyl benzyl alcohol, 3-methoxy benzyl alcohol, and 4-isopropyl benzyl alcohol as the alkylation reagents (Table 2, entries 1–4). Interestingly, excellent yields were obtained for the reactions of aniline with 2-ethylbutan-1-ol and 1-decanol (entries 5 and 6). The yields to *N*-(2-*e*thylbutyl)-aniline and *N*-decylaniline were 80 and 84%, respectively. Amines with a different structure, that is, aniline, 4-chloroaniline, *p*-methyl aniline, 2-aminonaphthalene, and 2-aminopyridine, could also react with benzyl alcohol to afford the *N*-benzyl amine (entries 7–10). The yields to the products were all >90%. If 1-octyl amine was employed as the starting material, no *N*-benzyl-1-octyl amine was observed, although the 1-octyl amine was totally converted into the corresponding imine, that is, *N*-benzylideneoctan-1-amine (entry 11). Therefore, the alkylation of amines with aliphatic alcohols was successfully realized under organic ligand-free conditions by using heterogeneous catalysts.

The alkylation of carboxamide with alcohol was further explored. With benzamide as the starting material, the coupling reactions could be realized by using benzyl alcohols with different substitution groups, that is, methyl, isopropyl, chloro, and methoxy (Table 3, entries 1–5). The yields were normally >90%. Excellent results were achieved when using heterocyclic aromatic alcohols as alkylation reagents. The yield of *N*-(pyridin-2-ylmethyl)benzamide was 89% (entry 6). The variation of carboxamide was also tolerated.

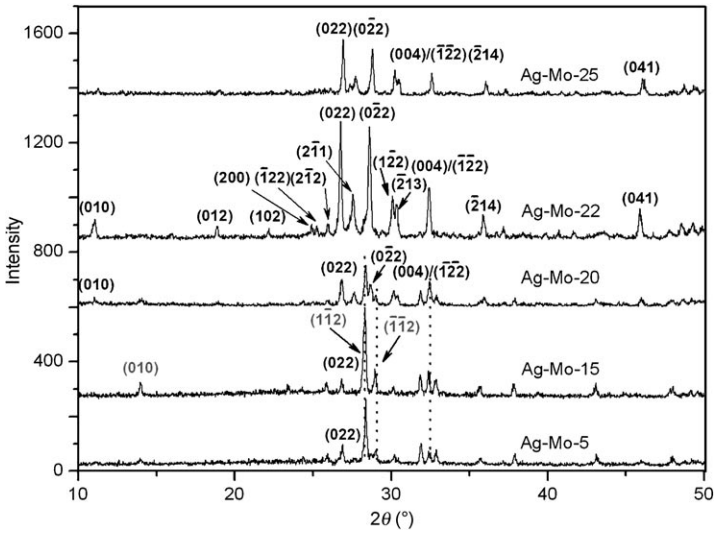


Figure 3. XRD patterns of Ag/Mo hybrid materials prepared under different conditions (Black: $Ag_6Mo_{10}O_{33}$, gray: $Ag_2Mo_2O_7$).

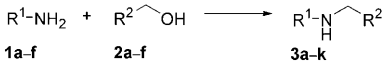
Yields of 70–98% of the desired products were obtained when applying 4-methylbenzamide, 3-methoxybenzamide, 4-chlorobenzamide, picolinamide, thiophene-2-carboxamide, and cinnamamide as starting materials (entries 7–12).

This Ag/Mo hybrid material was also active for the alkylation of sulfonamides. Various alcohols, that is, benzyl alcohol derivatives and 2-thiophene methanol, could react with *p*-toluenesulfonamide to generate the N-alkylated *p*-toluenesulfonamide in excellent yields, which were normally ~90% (Table 4, entries 1–9). Other sulfonamides, such as benzenesulfonamide, methylsulfonamide, and 2-naphthalenesulfonamide, can also produce the alkylation products with 95–99% yields (entries 10–12). Importantly, ~90% yields could be achieved when using 5-methylpyridine-2-sulfonamide, 5-dichlorothiophene-2-sulfonamide, and 4,5-dichlorothiophene-2-sulfonamide as the starting materials (entries 13–15). Therefore, here we offer an effective method for the synthesis of organic compounds containing sulfonamide and the thiophene moiety.

Apart from the alkylation of amines, carboxamides, and sulfonamides, this Ag/Mo hybrid material could be applied to the alkylation of aromatic ketones.[19] Firstly, the reactions of acetophenone with different benzylic alcohols including benzyl alcohol, [4-(methylthio)phenyl]methanol, (4-isopropylphenyl)methanol, 2-pyridinyl methanol, 3-methoxy benzyl alcohol, 3-methyl benzyl alcohol, and piperitol were performed. To our delight, the yields to the alkylated ketones were 86–98% (Table 5, entries 1–6). Moreover, other ketones, such as 1-(4-ethoxyphenyl)ethanone, 1-*p*-tolylethanone, 1-(naphthalen-2-yl)ethanone, and 1-(4-chlorophenyl)-ethanone, could react with benzyl alcohol to create the target products and the yields were 87–92% (entries 7–10).

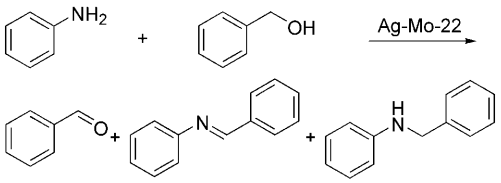
Next, the mechanism of the reaction was explored. By tracing the reaction of aniline with benzyl alcohol by GCMS, it was found that benzaldehyde formed at the initial stage and *N*-benzylideneaniline was observed. Finally, *N*-benzylideneaniline was converted into *N*-benzylaniline. These results suggest that the formation of benzaldehyde was the first step of the reaction and imine should be the possible intermediate (Scheme 2). Moreover, the reaction was also performed with a sealed Scheck tube and the gas

Table 2. Results of amine alkylation with alcohol.[a]



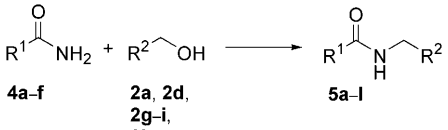
Entry	Reactants		Products	Yield [%][b]
1	**1a**	**2a**	**3a**	93
2	**1a**	**2b**	**3b**	84
3	**1a**	**2c**	**3c**	90
4	**1a**	**2d**	**3d**	82
5[c]	**1a**	**2e**	**3e**	80
6[c]	**1a**	**2f**	**3f**	84
7	**1b**	**2a**	**3g**	93
8	**1c**	**2a**	**3h**	84
9	**1d**	**2a**	**3i**	94
10	**1e**	**2a**	**3j**	90
11	**1f**	**2a**	**3k**	>99[d]

[a] Reaction conditions: 2 mmol amine, 10 mmol benzylic alcohol, 40 mg Ag-Mo-22, 20 mol% (45 mg) KO*t*Bu, 160°C, 12 h. [b] Isolated yields. [c] 40 mol% (90 mg) KO*t*Bu, 160°C, 20 h. [d] determined by GC-MS.

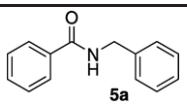
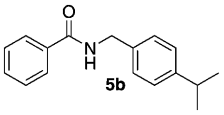
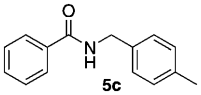
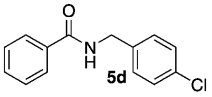
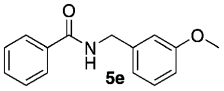
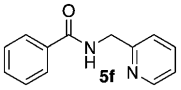
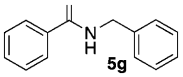
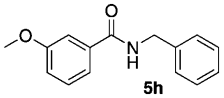
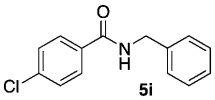
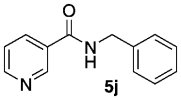
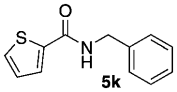
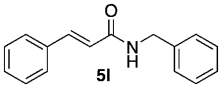


Scheme 2. Reaction of aniline with benzyl alcohol at the initial stage.

Table 3. Results of carboxamide alkylation with alcohol.[a]



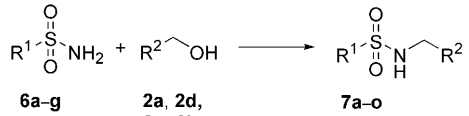
4a–f **2a**, **2d**, **2g–i**, **2l** **5a–l**

Entry	Reactants		Products	Yield [%][b]
1	**4a**	**2a**	 **5a**	96
2	**4a**	**2d**	 **5b**	90
3	**4a**	**2g**	 **5c**	97
4	**4a**	**2h**	 **5d**	98
5	**4a**	**2i**	 **5e**	97
6	**4a**	**2l**	 **5f**	89
7	**4a**	**2a**	 **5g**	98
8	**4b**	**2a**	 **5h**	95
9	**4c**	**2a**	 **5i**	85
10	**4d**	**2a**	 **5j**	82
11	**4e**	**2a**	 **5k**	70
12	**4f**	**2a**	 **5l**	85

[a] Reaction conditions: 2 mmol carboxamide, 10 mmol benzylic alcohol, 40 mg Ag-Mo-22, 20 mol% (56 mg) K_2CO_3, 160 °C, 12 h. [b] Isolated yields.

phase of the reaction mixture was checked after reaction by MS with pulse-injection (DM 300, AMETEK, USA). This confirmed the formation of molecular hydrogen. Thus small amounts of hydrogen were released and were not transferred into the product. This also can explain the formation of a detectable amount of aldehyde after the reaction.

Table 4. Results of sulfonamide alkylation with alcohol.[a]



6a–g **2a**, **2d**, **2g**, **2j**, **2l–o** **7a–o**

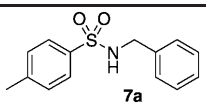
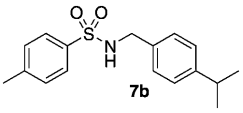
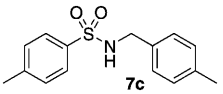
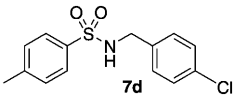
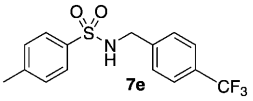
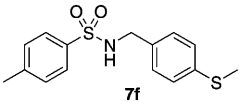
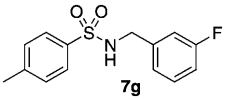
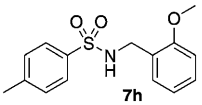
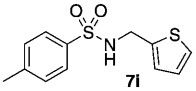
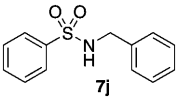
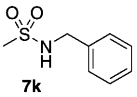
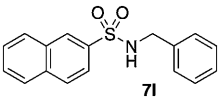
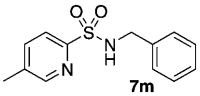
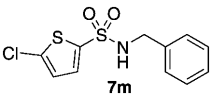
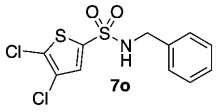
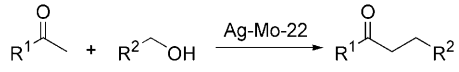
Entry	Reactants		Products	Yield [%][b]
1	**6a**	**2a**	 **7a**	98
2	**6a**	**2d**	 **7b**	93
3	**6a**	**2g**	 **7c**	91
4	**6a**	**2h**	 **7d**	88
5	**6a**	**2l**	 **7e**	86
6	**6a**	**2m**	 **7f**	95
7	**6a**	**2n**	 **7g**	84
8	**6a**	**2o**	 **7h**	91
9	**6a**	**2j**	 **7i**	78
10	**6b**	**2a**	 **7j**	96
11	**6c**	**2a**	 **7k**	95
12	**6d**	**2a**	 **7l**	99
13	**6e**	**2a**	 **7m**	92
14	**6f**	**2a**	 **7m**	89

Table 4. (Continued)

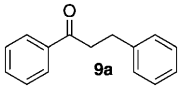
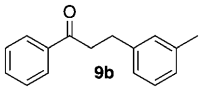
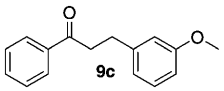
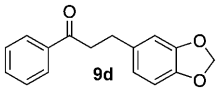
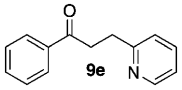
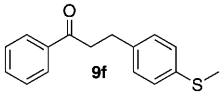
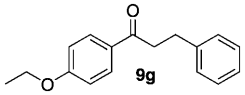
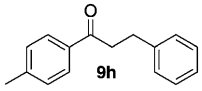
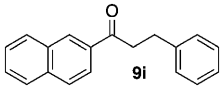
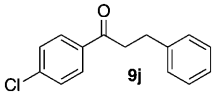
Entry	Reactants		Products	Yield [%][b]
15	**6g**	**2a**	 **7o**	87

[a] Reaction conditions: sulfonamide (2 mmol), benzylic alcohol (10 mmol), Ag-Mo-22 (40 mg), K_2CO_3 (20 mol%, 56 mg), 160 °C, 12 h. [b] Isolated yields.

Table 5. Results of ketone alkylation with alcohol.[a]

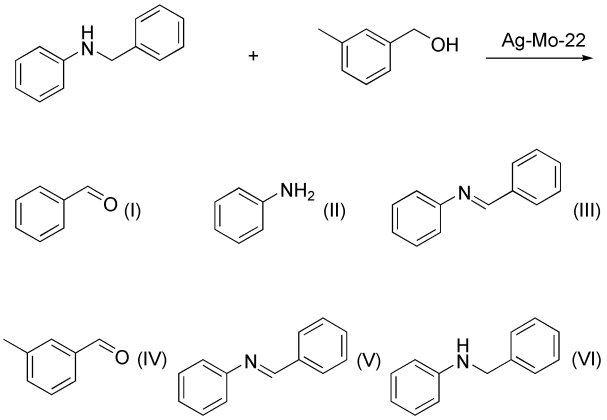


8a–e **2a–d**, **2i**, **2l**, **2n** **9a–k**

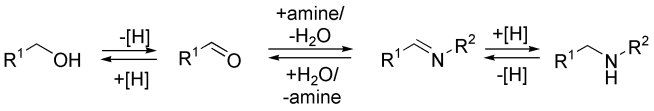
Entry	Reactants		Products	Yield [%][b]
1	**8a**	**2a**	 **9a**	97
2	**8a**	**2b**	 **9b**	96
3	**8a**	**2c**	 **9c**	95
4	**8a**	**2j**	 **9d**	86
5	**8a**	**2l**	 **9e**	96
6	**8a**	**2n**	 **9f**	95
7	**8b**	**2a**	 **9g**	95
8	**8c**	**2a**	 **9h**	93
9	**8d**	**2a**	 **9i**	93
10	**8e**	**2a**	 **9j**	95

[a] Reaction conditions: ketone (2 mmol), benzylic alcohol (10 mmol), Ag-Mo-22 (40 mg), K_2CO_3 (20 mol%, 56 mg), 135 °C, 12 h. [b] Isolated yields.

The reaction of *N*-benzylaniline with *p*-methyl benzyl alcohol revealed the reversibility of the whole reaction. Benzaldehyde, *p*-methyl benzaldehyde, aniline, *N*-benzylideneaniline, *N*-(4-*m*ethylbenzylidene)aniline, and *N*-(4-*m*ethylbenzyl)aniline were formed (Scheme 3). A possible mechanism could be given as shown in Scheme 4.



Scheme 3. Reaction of *N*-benzyl aniline with *p*-methyl benzyl alcohol.



Scheme 4. A possible mechanism of the amine alkylation with alcohol.

Conclusion

A simple and general Ag/Mo hybrid material ($Ag_6Mo_{10}O_{33}$) catalyst was successfully prepared for the alkylation of amines, carboxamides, sulfonamides, and aromatic ketones with alcohols. The yields for the reactions are normally ~90% under reaction conditions as mild as conventional homogeneous systems without additional organic ligand. This result should be an inspiration for designing practically valuable catalysts for fine chemical synthesis.

Experimental Section

Materials and methods: All solvents and chemicals were obtained commercially and were used as received. NMR spectra were measured by using a Bruker ARX 400 or ARX 100 spectrometer at 400 (^{1}H) and 100 MHz (^{13}C). All spectra were recorded in $CDCl_3$ and chemical shifts (δ) are reported in ppm relative to tetramethylsilane referenced to the residual solvent peaks. Mass spectra were in general recorded on an HP 6890/5973 GCMS. High-resolution TEM analysis was carried out on a JEM 2010 operating at 200 KeV. The catalyst samples after pretreatment were dispersed in methanol and the solution was mixed ultrasonically at room temperature. A part of the solution was dropped on the grid for the measurement of TEM images. SEM was performed with a Hitachi S4800 with a cold FEG (Field Emission Gun). The setup was equipped with an Energy Dispersive X-ray system EDAX Genesis 4.52; the EDX detector consists of Si(Li) crystals and a SUTW (Super Ultra Thin Window). Samples were mounted on an Al-holder with conducting carbon tape. XRD measurements are conducted by a STADI P automated transmission diffractometer (STOE) equipped with an incident beam curved germanium monochromator selecting $Cu_{K\alpha1}$ radiation and a 6° po-

sition sensitive detector (PSD). The XRD patterns are scanned in the 2θ range of 10–50°. For the data interpretation, the software WinXpow (STOE) and the database of Powder Diffraction File (PDF) of the International Centre of Diffraction Data (ICDD) were used. The XPS measurements were performed with a VG ESCALAB 210 instrument provided with a dual Mg/Mg anode X-ray source, a hemispherical capacitor analyzer and a 5 keV Ar^+ ion-gun. All spectra were recorded by using non-monochromatic $Mg_{K\alpha}$ (1253.6 eV) radiation. Nitrogen adsorption–desorption isotherms were measured at 77 K by using a Micromeritics 2010 instrument. The pore-size distribution was calculated by the Barrett, Joyner, and Halenda (BJH) method from a desorption isotherm. The Ag and Mo contents of the catalysts were measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES), by using an Iris advantage Thermo Jarrel Ash device.

Preparation of Ag/Mo hybrid materials: Firstly, $AgNO_3$ (60 mL, 0.25 M) was added dropwise into $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ solution (60 mL of 0.0175 M) under magnetic stirring over 10 min ([Ag]/[Mo] = 2:1). Then the acidity of the solution was finely tuned in the pH value range of 0.8–1.5 with the addition nitric acid (5, 15, 20, 22, and 25 mL, 2 M) to form a green/yellow solution. Then, the resulting precursor solution was transferred into a Teflon-lined stainless autoclave. After being hydrothermally treated at 140 °C for 12 h, the reaction mixture was cooled to room temperature, filtrated, and washed with distilled water (50 mL × 3). The straw-yellow solid sample was further dried at 100 °C in air for 4 h and calcined at 450 °C for 4 h to give the final Ag/Mo hybrid material. The Ag/Mo hybrid materials were denoted as Ag-Mo-5, Ag-Mo-15, Ag-Mo-20, Ag-Mo-22, and Ag-Mo-25. For comparison, Ag-Mo-R was prepared by the reported literature method.[18a]

Representative procedure for the alkylation of carboxamides or amines with alcohols: The representative amine or carboxamide (2 mmol) and representative alcohol (10 mmol) were added to an ovendried, argon-purged reaction tube containing Ag-Mo-22 (40 mg) and K_2CO_3 (55 mg, 0.4 mmol). Then, the tube was installed on the top-cooled carousel 12 reaction station and the reaction mixture was stirred at 160 °C for 12 h. The mixture was then cooled to room temperature and acetone (~20 mL) was added to dissolve the reaction mixture, which was subsequently filtered by Celite. The crude reaction mixture was concentrated in vacuo and purified by column chromatography (petroleum ether (b.p. 30–60 °C)/ethyl acetate) to give the corresponding secondary amine in good yields.

Representative procedure for the alkylation of sulfonamides with alcohols: The representative sulfonamides (2 mmol) and representative alcohol (10 mmol) were added to an ovendried, argon-purged reaction tube containing Ag-Mo-22 (40 mg) and K_2CO_3 (55 mg, 0.4 mmol). Then, the tube was installed on the top-cooled carousel 12 reaction station and the reaction mixture was stirred at 160 °C for 12 h. The mixture was cooled to room temperature and acetone (~20 mL) was added to dissolve the reaction mixture, which was subsequently filtered by Celite. The acetone and alcohol were removed under vacuum and a white solid was obtained. It was further washed by diethyl ether/hexane to remove benzyl alcohol residue and soluble impurities. After it was further dried under reduced pressure a white solid was obtained.

Representative procedure for the alkylation of ketones with alcohols: Ag-Mo-22 (40 mg), K_2CO_3 (55 mg, 0.4 mmol), the representative ketone (2 mmol), and representative alcohol (10 mmol) were added to an ovendried, argon-purged reaction tube. Then, the tube was installed on the top-cooled carousel 12 reaction station and the reaction mixture was stirred at 135 °C for 12 h. The mixture was then cooled to room temperature and acetone (~20 mL) was added to dissolve the reaction mixture, which was subsequently filtered by Celite. The crude reaction mixture was concentrated in vacuo and purified by column chromatography (petroleum ether (b.p. 30–60 °C)/ethyl acetate) to give the corresponding secondary amine in good yields.

Acknowledgements

This work was financially supported by the "Hundred Talents Program" of the Chinese Academy of Sciences.

[1] a) J. F. Hartwig, *Handbook of Organopalladium Chemistry for Organic Synthesis, Vol. 1* (Eds.: E. Negishi, A. Meijere), Wiley Interscience, New York **2002**; b) S. A. Lawrence, *Amines: Synthesis Properties and application* (Ed.: S. A. Lawrence), Cambridge University Press, Cambridge, **2004**.

[2] a) D. L. Guo, H. Huang, Y. Zhou, J. Y. Xu, H. Jiang, K. X. Chen, H. Liu, *Green Chem.* **2010**, *12*, 276; b) D. L. Guo, H. Huang, J. Y. Xu, H. L. Jiang, H. Liu, *Org. Lett.* **2008**, *10*, 4513; c) J. P. Schulte II, S. R. Tweedie, *Synlett* **2007**, 2331; d) S. L. Buchwald, C. Mauger, G. Mignani, U. Scholz, *Adv. Synth. Catal.* **2006**, *348*, 23; e) M. Yoshida, N. Hara, S. Okuyama, *Chem. Commun.* **2000**, 151; f) M. S. Driver, J. F. Hartwig, *J. Am. Chem. Soc.* **1996**, *118*, 7217.

[3] a) L. Troisi, C. Granito, F. Rosato; V. Videtta, *Tetrahedron Lett.* **2010**, *51*, 371; V. Videtta, *Tetrahedron Lett.* **2010**, *51*, 371; b) K. D. Hesp, S. Tobisch, M. Stradiotto, *J. Am. Chem. Soc.* **2010**, *132*, 413; c) N. R. Perl, N. D. Ide, S. Prajapati, H. H. Perfect, S. G. Duron, D. Y. Gin, *J. Am. Chem. Soc.* **2010**, *132*, 1802; d) X. Q. Shen, S. L. Buchwald, *Angew. Chem.* **2010**, *122*, 574; *Angew. Chem. Int. Ed.* **2010**, *49*, 564; e) M. C. Wood, D. C. Leitch, C. S. Yeung, J. A. Kozak, L. L. Schafer, *Angew. Chem.* **2009**, *121*, 7071; *Angew. Chem. Int. Ed.* **2009**, *48*, 6937; f) A. Seayad, M. Ahmed, H. Klein, R. Jackstell, T. Gross, M. Beller, *Science* **2002**, *297*, 1676.

[4] a) T. O. Vieira, H. Alper, *Chem. Commun.* **2007**, 2710; b) M. Ahmed, C. Buch, L. Routaboul, R. Jackstell, H. Klein, A. Spannenberg, M. Beller, *Chem. Eur. J.* **2007**, *13*, 1594; c) Y. Y. Wang, J. H. Chen, M. M. Luo, H. Chen, X. J. Li, *Catal. Commun.* **2006**, *7*, 979; d) M. Ahmed, A. M. Seayad, R. Jackstell, M. Beller, *J. Am. Chem. Soc.* **2003**, *125*, 10311.

[5] a) G. Guillena, D. J. Ramon, M. Yus, *Chem. Rev.* **2010**, *110*, 1611; b) S. Farhadi, M. Zaidi, *J. Mol. Catal. A* **2009**, *299*, 18; c) P. R. Likhar, R. Arundhathi, M. L. Kantam, P. S. Prathima, *Eur. J. Org. Chem.* **2009**, 5383; d) K. Shimizu, K. Ohshima, A. Satsuma, *Chem. Eur. J.* **2009**, *15*, 9977; e) T. Ohshima, Y. Miyamoto, J. Ipposhi, Y. Nakahara, M. Utsunomiya, K. Mashima, *J. Am. Chem. Soc.* **2009**, *131*, 14317; f) N. Iranpoor, H. Firouzabadi, N. Nowrouzi, D. Khalili, *Tetrahedron* **2009**, *65*, 3893; g) L. U. Nordstrøm, H. Vogt, R. Madsen, *J. Am. Chem. Soc.* **2008**, *130*, 17672.

[6] a) U. Jana, S. Maiti, S. Biswas, *Tetrahedron Lett.* **2008**, *49*, 858; b) B. Sreedhar, P. S. Reddy, M. A. Reddy, B. Neelima, R. Arundhathi, *Tetrahedron Lett.* **2007**, *48*, 8174; c) J. S. Yadav, B. V. S. Reddy, T. S. Rao, B. Bala, M. Krishna, G. G. K. S. N. Kumar, *Chem. Lett.* **2007**, *36*, 1472; d) H. B. Qin, N. Yamagiwa, S. Matsunaga, M. Shibasaki, *Angew. Chem.* **2007**, *119*, 413; *Angew. Chem. Int. Ed.* **2007**, *46*, 409; e) K. Motokura, N. Nakagiri, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Org. Chem.* **2007**, *72*, 6006; f) V. Terrasson, S. Marque, M. Georgy, J. Campagne, D. Prim, *Adv. Synth. Catal.* **2006**, *348*, 2063.

[7] R. Grigg, T. R. B. Mitchell, S. Sutthivaiyakit, N. Tongpenyai, *J. Chem. Soc. Chem. Commun.* **1981**, 611.

[8] Y. Watanabe, Y. Tsuji, H. Ige, Y. Ohsugi, T. Ohta, *J. Org. Chem.* **1984**, *49*, 3359.

[9] a) S. C. Ghosh, S. Muthaiah, Y. Zhang, X. Y. Xu, S. H. Hong, *Adv. Synth. Catal.* **2009**, *351*, 2643; b) J. W. Kim, J. He, K. Yamaguchi, N. Mizuno, *Chem. Lett.* **2009**, *38*, 920; c) M. H. S. A. Hamid, C. L. Allen, G. W. Lamb, A. C. Maxwell, H. C. Maytum, A. J. A. Watson, J. M. J. Williams, *J. Am. Chem. Soc.* **2009**, *131*, 1766; d) A. Tillack, D. Hollmann, K. Mevius, D. Michalik, S. Bahn, M. Beller, *Eur. J. Org. Chem.* **2008**, 4745; e) D. Hollmann, A. Tillack, D. Michalik, R. Jackstell, M. Beller, *Chem. Asian J.* **2007**, *2*, 403; f) C. Gunanathan, Y. Ben-David, D. Milstein, *Science* **2007**, *317*, 790.

[10] a) B. Blank, S. Michlik, R. Kempe, *Chem. Eur. J.* **2009**, *15*, 3790; b) D. Gnanamgari, E. L. O. Sauer, N. D. Schley, C. Butler, C. D. Incarvito, R. H. Crabtree, *Organometallics* **2009**, *28*, 321; c) B. Blank,

M. Madalska, R. Kempe, *Adv. Synth. Catal.* **2008**, *350*, 749; d) K. I. Fujita, Y. Enoki, R. Yamaguchi, *Tetrahedron* **2008**, *64*, 1943.
[11] a) P. Barbaro, F. Liguori, *Chem. Rev.* **2009**, *109*, 515; b) M. H. Valkenberg, W. F. Holderich, *Catal. Rev.* **2002**, *44*, 321; c) X. Huang, H. Wu, X. P. Liao, B. Shi, *Catal. Commun.* **2010**, *11*, 487; d) Y. Cao, J. C. Hu, P. Yang, W. L. Dai, K. N. Fan, *Chem. Commun.* **2003**, 908; e) K. Mukhopadhyay, R. V. Chaudhari, *J. Catal.* **2003**, *213*, 73.
[12] a) M. A. M. Gijs, F. Lacharme, U. Lehmann, *Chem. Rev.* **2010**, *110*, 1518; b) W. Wang, Y. Xu, D. I. C. Wang, Z. Li, *J. Am. Chem. Soc.* **2009**, *131*, 12892; c) A. Dyal, K. Loos, M. Noto, S. W. Chang, C. Spagnoli, K. V. P. M. Shafi, A. Ulman, M. Cowman, R. A. Gross, *J. Am. Chem. Soc.* **2003**, *125*, 1684.
[13] a) S. Shylesh, V. Schuenemann, W. R. Thiel, *Angew. Chem.* **2010**, *122*, 3504; *Angew. Chem. Int. Ed.* **2010**, *49*, 3428; b) M. Campelo, D. Luna, R. Luque, J. M. Marinas, A. A. Romero, *ChemSusChem* **2009**, *2*, 18.
[14] F. Shi, M. K. Tse, S. L. Zhou, M. M. Pohl, J. Radnik, S. Hubner, K. Jahnisch, A. Bruckner, M. Beller, *J. Am. Chem. Soc.* **2009**, *131*, 1775.
[15] a) J. W. Kim, K. Yamaguchi, N. Mizuno, *J. Catal.* **2009**, *263*, 205; b) X. J. Cui, F. Shi, M. K. Tse, D. Gordes, K. Thurow, M. Beller, Y. Deng, *Adv. Synth. Catal.* **2009**, *351*, 2949; c) K. Fujita, A. Komatsubara, R. Yamaguchi, *Tetrahedron* **2009**, *65*, 3624.
[16] T. Mitsudome, Y. Mikami, H. Funai, T. Mizugaki, K. Jitsukawa, K. Kaneda, *Angew. Chem.* **2008**, *120*, 144; *Angew. Chem. Int. Ed.* **2008**, *47*, 138.
[17] G. Zhu, K. Pang, G. Parkin, *J. Am. Chem. Soc.* **2008**, *130*, 1564.
[18] a) X. J. Cui, S. H. Yu, L. L. Li, L. Biao, H. B. Li, M. S. Mo, X. M. Liu, *Chem. Eur. J.* **2004**, *10*, 218; b) G. Nagaraju, G. T. Chandrappa, J. Livage, *Bull. Mater. Sci.* **2008**, *31*, 367; c) H. S. Lin, B. B. Yan, P. D. Boyle, P. A. Maggard, *J. Solid State Chem.* **2006**, *179*, 217.
[19] a) T. D. Nixon, M. K. Whittlesey, J. M. J. Williams, *Dalton Trans.* **2009**, 753; b) M. H. S. A. Hamid, P. A. Slatford, J. M. J. Williams, *Adv. Synth. Catal.* **2007**, *349*, 1555.

Received: July 7, 2010
Published online: November 9, 2010

