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Mesoporous Materials

Bifunctionalized Mesoporous Materials with Site-Separated Brønsted Acids and Bases: Catalyst for a Two-Step Reaction Sequence**

Yulin Huang, Shu Xu, and Victor S.-Y. Lin*[†]

Mesoporous silica has been regarded as an ideal support for heterogeneous catalysts because of its high surface area and tunable pore size. This interest has increased since the discovery of the ordered mesoporous material MCM-41,[1] which led to a range of possibilities for the chemical design of novel heterogeneous catalysts.[2] There has been rapid development of immobilized, reusable organocatalysts, and one of the major research interests is the functionalization of mesoporous silica with organic functional groups. The functionalization can be accomplished by using either postsynthesis grafting or co-condensation.[3–27] The design and synthesis of bi- or multifunctionalized mesoporous silica containing multiple types of functional groups is appealing because these functional groups might be used as catalysts for a multistep reaction sequence requiring either a cooperative or independent catalytic performance.[3,7,9–14,16,28] Actually, in biological systems, there are many interesting examples of multifunctional catalysts—enzymes such as α-amylases,[29] as they can catalyze different reactions using different catalytic active sites.

There are many examples of bifunctionalized mesoporous material catalysts in which two different organic functional groups, such as amines with silanols,[16,30] amines with thiols,[31,32] amines with ureas,[3,7] amines with Lewis acids,[33–37] sulfonic acid with thiols[9,11,14] and adjacent sulfonic acid functional groups,[28] are incorporated and are compatible with each other. Recently different catalysts, each located on a mesoporous silica nanoparticle, have been used as catalysts in a one-pot reaction sequence.[38] As we know, many enzymes can immobilize mutually incompatible catalytic groups, such as a Brønsted acid and a Brønsted base, on a single molecule in a site-separated manner that maintains their independent function to catalyze one step in a multistep reaction sequence. Up to now, there are only few samples of mesoporous materials displaying two functional groups that cannot otherwise coexist in solution. For example, both Davis and co-workers[10] and Thiel and co-workers[39] reported on mesoporous silica materials functionalized with sulfonic acid and amine groups; there were limited amounts of each acid and base group to neutralize each other during the one-pot reaction. Mehdi and co-workers[23] reported another bifunctionalized mesoporous silica material having sulfonic acid groups within its framework and basic groups within the channel pores, but the sulfonic acid groups were not accessible to reactants. Thiel and co-workers[40] also recently reported a functionalized periodic mesoporous organosilica (PMO) having the acidic groups within the framework walls and the basic groups directed into the channel pores. However, there is no report on selective dual-functionalization of a single mesoporous silica nanoparticle with Brønsted acid and Brønsted base groups on the external and internal mesoporous silica surface, respectively; this is presumably a result of the incompatibility of these groups and the difficulty of independently controlling reactions on both the external and internal surfaces.[41–49]

Herein we report two mesoporous silica nanoparticles (MSNs) that were functionalized with both a Brønsted acid and Brønsted base; one group was attached on the internal surface of the MSN through co-condensation and the second group was tethered onto the external surface of the MSN by postsynthesis grafting. Both of these functional groups on one particle could catalyze each step of a two-step reaction sequence; for example, sulfonic acid catalyzed hydrolysis of 4-nitrobenzaldehyde dimethyl acetal and the subsequent amine-catalyzed Henry reaction of 4-nitrobenzaldehyde with nitromethane, a sequence that cannot be achieved when the catalysts are combined in a one-pot homogeneous system. These novel materials were synthesized by co-condensation of tetraethyl orthosilicate (TEOS) and 3-aminopropyltrimethoxysilane (APTMOS) [or 3-mercaptopropyltrimethoxysilane (STMOS)] in the presence of cetyltrimethylammonium bromide (CTAB) as a template under basic reaction conditions, and subsequent post-treatment for grafting another functional group onto the external surface.

Typically, these bifunctional mesoporous materials were synthesized by co-condensation of one of the two functional groups onto the internal channels[4] and subsequent grafting of the second group onto the external surface; since template CTAB is still in the mesoporous channels only the external surface is exposed to the grafting reagent.[48–51] The bifunctional mesoporous silica nanoparticle with sulfonic acid on its internal surface and amine groups on its external surface was labeled as SAMSN-AP (Figure 1). Another bifunctional mesoporous silica nanoparticle with amine groups on its internal surface and sulfonic acid groups on its external surface was labeled as APMSN-SA (see Figure S1 in the Supporting Information). For each of the bifunctionalized

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[*] Dr. Y. Huang, Dr. S. Xu, Prof. Dr. V. S.-Y. Lin
Department of Chemistry and
Ames Laboratory – U.S. Department of Energy
Iowa State University, Ames, IA 50011 (USA)
E-mail: ylhuang@iastate.edu

[†] Deceased May 4, 2010.

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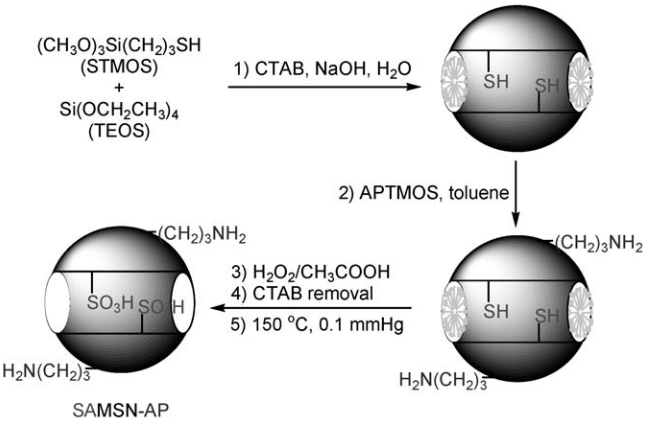


Figure 1. Syntheses of bifunctional mesoporous silica nanoparticles having sulfonic acid groups on the internal surface and organic amine groups on the external surface.

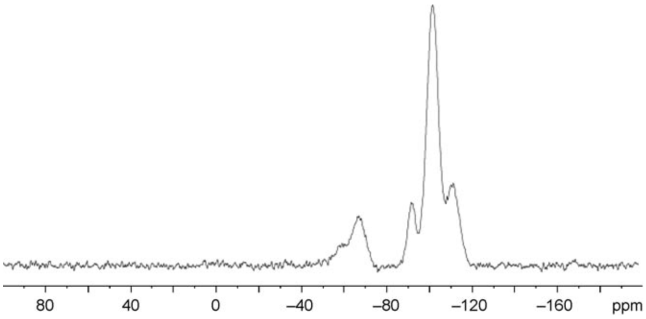


Figure 2. ^{29}Si solid-state NMR spectrum of SAMSN-AP. (T^2: −59 ppm; T^3: −68 ppm; Q^2: −90 ppm; Q^3: −100 ppm; Q^4: −110 ppm).

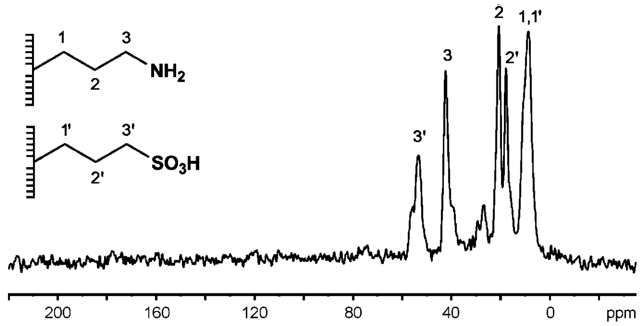


Figure 3. ^{13}C solid-state NMR spectrum of SAMSN-AP. (chemical shift at $\delta = 29.5$ ppm was from CTAB; chemical shift at $\delta = 26.0$ ppm was from the 3-mercaptopropyl group of the starting material).

MSNs (Figures S2–S5), the functionalization of the external surface through postsynthesis grafting was successful because the mesopores of the material were blocked by surfactant during the grafting process, and it is even possible that partial displacement of surfactant during the grafting was limited because of the lost condensation steps around $P/P_0 = 0.3$ (P/P_0: relative pressure; insets of Figures S2–S5).

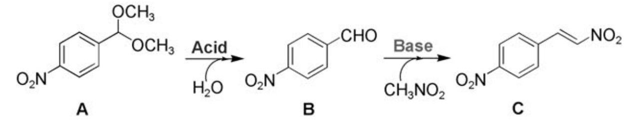
These materials [MSN, SAMSN (sulfonic acid functionalized MSN), APMSN (amine-functionalized MSN)] were analyzed by N_2 adsorption/desorption, X-ray powder diffraction (XRD), and ^{13}C and ^{29}Si solid-state NMR spectroscopy.

The N_2 adsorption/desorption measurements for SAMSN-AP and APMSN-SA showed type IV isotherms, which have very clear H_1-hysteresis loops at a relatively high pressure, characteristic of mesoporous materials, having BET surface areas over 853 $m^2 g^{-1}$ for SAMSN-AP, and 934 $m^2 g^{-1}$ for APMSN-SA; additionally the total pore volume for SAMSN-AP was 0.8 $cm^3 g^{-1}$, and for APMSN-SA was 0.9 $cm^3 g^{-1}$. There was also a very narrow pore-size distribution centered at 2.8 nm for SAMSN-AP, and at 2.6 nm for APMSN-SA (Figures S6 and S7, and Table S1). Small-angle X-ray scattering patterns indicated highly ordered structures with d_{100} values of 4.1 nm and 4.2 nm for SAMSN-AP and APMSN-SA, respectively (Figure S8 and Table S1). The TEM images in Figure S10 confirmed the mesoporous structures as having parallel channels as well as a uniform pore size.

T^2 and T^3 peaks in the ^{29}Si solid-state NMR spectra (Figure 2 and Figure S11) indicated the incorporation of sulfonic acid and amine groups. The ^{13}C solid-state NMR spectra (Figure 3 and Figure S12) indicated the presence of the intact organic functional groups and the removal of the surfactant. Elemental analyses of SAMSN-AP and APMSN-SA showed that each of the materials contained 0.35 $mmol\,g^{-1}$ of sulfur and 0.35 $mmol\,g^{-1}$ of nitrogen, which means the concentration of sulfonic acid on MSN particles is equal to that of the amine, and has a sulfur/nitrogen ratio around 1.0.

The activities of these immobilized bifunctional catalysts were tested in a one-pot reaction sequence involving the hydrolysis of an acetal and subsequent Henry reaction (Table 1). In all experiments, the amount of either the amine or sulfonic acid functional groups was kept at 2.3 mol %. After the two-step reaction sequence had been run using either SAMSN-AP or APMSN-SA as the catalyst, the conversion of the starting material was 100 % and more than 97 % of the mixture was the desired product **C** (Table 1, entries 1 and 2). These results were consistent with the result

Table 1: One-pot reaction cascades composed of acid-catalyzed hydrolysis and base-catalyzed Henry reaction.[a]



Entry	Catalyst	**B** [%]	**C** [%]	Conv. of **A** [%]
1	SAMSN-AP	2.3	97.7	100
2	APMSN-SA	1.9	98.1	100
3	SAMSN/APMSN	4.5	95.5	100
4	SAMSN	100	0	100
5	APMSN	0	0	0
6	SAMSN-AP/AP	0	0	0
7	SAMSN-AP/PTSA	100	0	100
8	APMSN-SA/AP	0	0	0
9	APMSN-SA/PTSA	100	0	100
10	MSN	0	0	0

[a] Reaction conditions: Catalyst: **A** (100.0 mg, 1.5 mmol), H_2O (1.5 mmol) CH_3NO_2 (1.0 mL), 80 °C, 48 h. Conversion and yields were determined using GC data. AP: 1-aminopropane, PTSA: *p*-toluenesulfonic acid.

in entry 3 wherein the amine and sulfonic acid were each located on different mesoporous silica nanoparticles, SAMSN and APMSN. However, neither SAMSN nor APMSN showed any conversion of the reactant **A** into the product **C** (Table 1, entries 4 and 5) even though SAMSN could catalyze the first step of this two-step sequence. Interestingly, no conversion of the starting material to the final product was observed when either of the homogeneous analogues of the sulfonic acid or amine was used with the SAMSN-AP or APMSN-SA (Table 1, entries 6–9); this behavior results from the fact that the functionalities neutralized each other. The pure MSN, as an experimental control, led to no conversion (Table 1, entry 10).

These bifunctionalized MSNs (SAMSN-AP and APMSN-SA) can be recycled five by simple filtration after each use without any detectable decrease in catalytic activity (Table S2), thus confirming that these two functional groups were quite stable and appropriately site-separated on the different MSN surfaces.

Although the one-pot reaction sequence including acetal hydrolysis and a Henry reaction was studied to establish proof of our site-separation of a Brønsted acid and base on a single mesoporous silica nanoparticle, we investigated the kinetics of these catalysts (Figure 4) to provide a comparison to our earlier reported results.[38] The reactivity (TOF: turnover frequency) of both the acid and base decreased with increasing reaction time because of the decreased concentration of the reactant. Although silanol groups on the external surface of MCM-41 were more kinetically accessible than those on the internal surface,[44,52,53] both the acid and base introduced by co-condensation methods onto the internal surface of the MSNs showed higher reactivity (TOF) than their counterparts, wherein the groups were grafted onto the external surface of the MSNs.

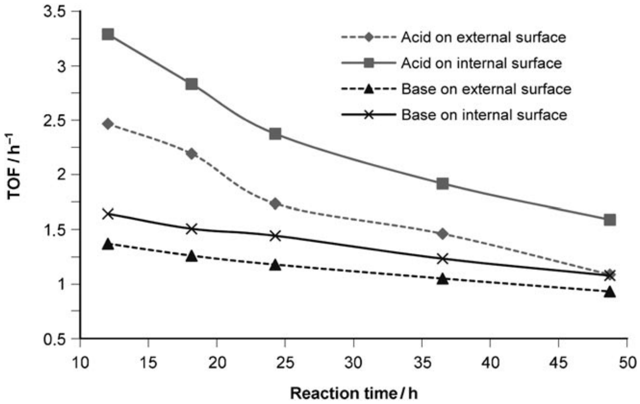
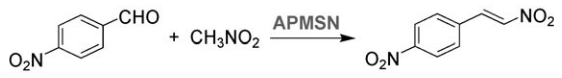


Figure 4. Turnover frequency of the acid and base catalysts that are located on either the internal or external surfaces of SAMSN-AP and APMSN-SA.

These kinetic results indicate that 1) there may not be any diffusion limitation in our MSN-based catalysts and 2) the reactivity of the acid and base might be related to the dispersion or surface coverage of the catalytic sites which differs for the acid or base catalysts that are located on either internal or external surfaces. Therefore, a series of Henry reactions catalyzed by five different 3-aminopropyl-functionalized MSNs with different concentrations of the surface-bound amines (Figures S13–S15) were investigated (Scheme 1 and Figure 5). From the fitted curve of TOF versus the concentration of the base on the MSN surface (mmol amine per square meter surface), the catalytic activity (TOF) decreased dramatically when the surface coverage of catalyst was increased; the same trend was observed in the APMSN-catalyzed Henry reaction at different reaction times (Figures S16–S19). Furthermore, the relationship between the TOF and the functional-group concentration was investigated for the one-pot reaction sequence catalyzed by the bifunctional materials (Table S3); overall, the yield of the final product was increased and the TOF decreased when the concentration of basic sites was increased.



Scheme 1. Henry reaction catalyzed by APMSN.

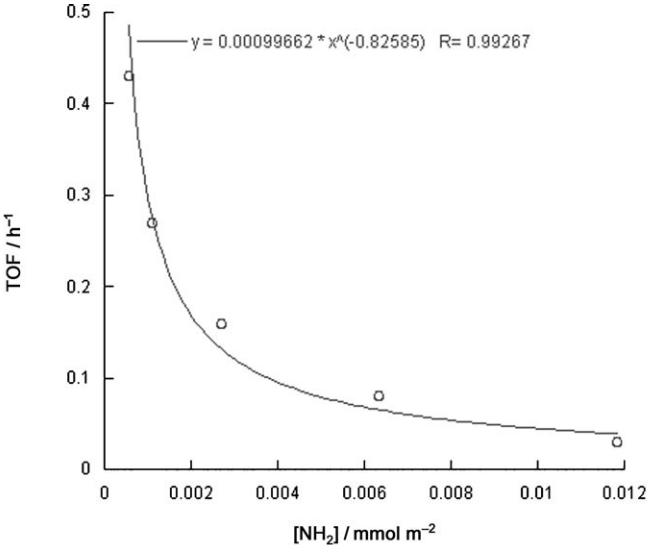


Figure 5. Fitted curve of base activity versus base concentration on the APMSN surface (reaction conditions were the same as those used in Table 1).

In conclusion, by combining co-condensation to functionalize the internal surface of MSNs and postsynthesis grafting to functionalize the external surface, we have shown that site-separation of Brønsted acid and Brønsted base sites on a single mesoporous silica nanoparticle was successful. As a result of this ideal site-separation, reaction sequences requiring two or more catalysts, which are incompatible with each other in a homogenous solution, were carried out successfully using our bifunctionalized particle. This model is useful for systems in which a series of reactions are catalyzed by only one multifunctional enzyme or catalyst. At the same time, we also demonstrated that the activity of the catalyst on the surface of the mesoporous silica nanoparticle was closely related to the coverage of catalytic sites on the MSN surface; therefore we have a better understanding of the catalysis on the MSN surface and can envision better control of the kinetics and efficiency of a catalyst by changing the number of catalytic sites on every unit surface of MSN.

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