Nanoscale Organization of Thiol and Arylsulfonic Acid on Silica Leads to a Highly Active and Selective Bifunctional, Heterogeneous Catalyst

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Abstract: Ordered mesoporous silicas functionalized with alkylsulfonic acid and thiol group pairs have been shown to catalyze the synthesis of bisphenols from the condensation of phenol and various ketones, with activity and selectivity highly dependent on the distance between the acid and thiol. Here, a new route to thiol/sulfonic acid paired catalysts is reported. A bis-silane precursor molecule containing both a disulfide and a sulfonate ester bond is grafted onto the surface of ordered mesoporous silica, SBA-15, followed by simultaneous disulfide reduction and sulfonate ester hydrolysis. The resulting catalyst, containing organized pairs of arylsulfonic acid and thiol groups, is significantly more active than the alkylsulfonic acid/thiol paired catalyst in the synthesis of bisphenol A and Z, and this increase in activity does *not* lead to a loss of regioselectivity. The paired catalyst has activity similar to that of a randomly bifunctionalized arylsulfonic acid/thiol catalyst in the bisphenol A reaction but exhibits greater activity and selectivity than the randomly bifunctionalized catalyst in the bisphenol Z reaction.

Introduction

Organic–inorganic hybrid materials represent an attractive class of solids that allows for molecular-level fine-tuning of catalytic materials.[1] Of current interest in the design and synthesis of solid catalysts is the creation of materials that contain multiple types of active centers.[2] These functionalities may be used to perform several steps in a reaction sequence or work in a cooperative manner to alter the characteristics (rates, selectivities) of a single reaction. Logically, cooperative behavior between functional groups should depend on the control of the distance between the reactive groups in order to optimize the catalysis for a particular reaction. We have been developing positioned monofunctional and bifunctional catalytic materials where the functional groups are present in a highly ordered fashion at predefined distances. The synthetic route to these materials involves the integration of incipient functional groups, in a protected form, positioned around a central spacer during the synthesis of the solid. When the spacer is removed by deprotection, one is left with the positioned functional group pair.[2g]

One reaction where cooperative, heterogeneous catalysis has been established is the synthesis of bisphenols. Bisphenols, such as bisphenol A (BPA) and bisphenol Z (BPZ), are important industrial feedstocks, especially as monomers in polycarbonate materials and epoxy resins. They are synthesized by the acid-catalyzed condensation between a ketone and phenol, yielding the desired *p,p′* isomer and a byproduct, the *o,p′* isomer (Scheme 1). The addition of thiols as a cocatalyst is known to improve both the rate of reaction and the selectivity to the desired isomer.[3,4]

Mineral acids can be used to catalyze the bisphenol condensation reaction, but solid acid catalysts such as polymeric ion-exchange resins are typically used for commercial bisphenol A production due to their recyclability. Thiols have been either added as a homogeneous feed additive[4] or bound to the resin surface by ion-pairing.[5] Several solid catalysts bearing both acid and thiol groups covalently attached to a solid support have been reported. Thiols have been covalently tethered to polymeric resins containing sulfonic acid groups,[6,7] and polysiloxane catalysts containing randomly organized alkylsulfonic acid and alkylthiol groups have also been reported to have good catalytic

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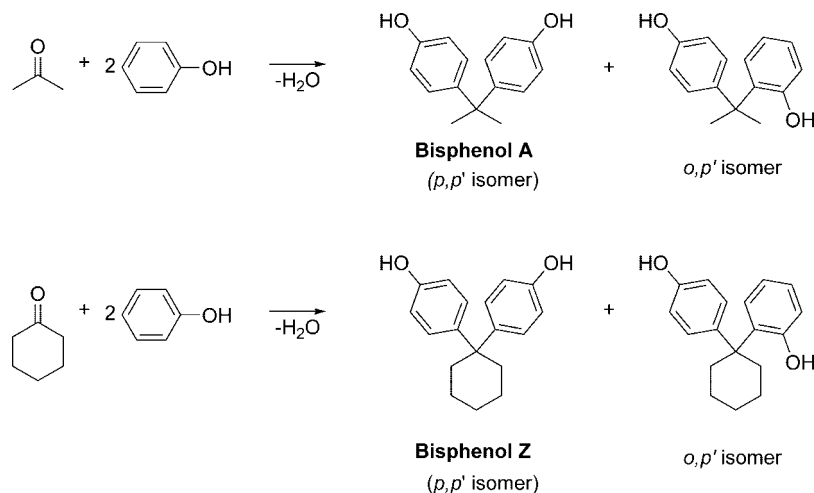
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(5) McNutt, B. W.; Gammill, B. B. U.S. Patent 3,394,089, 1968.
(6) Apel, F. N.; Conte, L. B.; Bender, H. L. U.S. Patent 3,153,001, 1964.
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Scheme 1. Synthesis of Bisphenol A (Top) and Bisphenol Z (Bottom) from Phenol and Either Acetone or Cyclohexanone

activity,[8] but the thermal stability of polymeric resins is a key limitation of these materials.

Catalytic materials bearing multiple sulfonic acid functional groups positioned at varying distances from one another on the surface of mesoporous solids have been prepared to explore the effects that the spatial arrangement of active sites have on catalytic activity and selectivity.[9] A series of organosilane precursors containing either disulfide or sulfonate ester functionalities (synthons of the eventual sulfonic acid groups) were synthesized. From these molecular precursors, a variety of organic−inorganic hybrid, mesostructured SBA-15 silica materials were prepared using a postsynthetic grafting procedure that led to disulfide- and sulfonate ester-modified silicas, which were subsequently converted to sulfonic acid-modified materials. The sulfonic acid-containing SBA-15 silica materials were tested as catalysts for the condensation reaction of phenol and acetone to bisphenol A, and positive cooperative effects were demonstrated, although the origin of the effects was not determined.

We have investigated the addition of thiol to the sulfonic acid-catalyzed reactions by using homogeneous and SBA-15-immobilized sulfonic acids.[10] Inclusion of homogeneous thiol catalysts along with either type of sulfonic acid catalyst accelerated the rate of reaction and shifted the regioselectivity to favor the formation of the *p,p'*-bisphenol isomer (bisphenol A) over the unwanted *o,p'*-bisphenol isomer. By immobilizing the thiol on the same solid as the sulfonic acid, reaction rates and regioselectivities were enhanced even further from those obtained from using mixtures of these two functional groups (when they are both homogeneous, or a combination of homogeneous and heterogeneous). These observations led us to design SBA-15 catalysts functionalized with discrete alkylsulfonic acid/thiol pairs formed from a sultone intermediate (see Scheme 2).[11] The activity and selectivity of these catalysts were found to increase markedly as the acid/thiol distance decreased. Furthermore, the catalyst in which the acid and thiol groups were separated by three carbon atoms was 3 times more active than a material containing randomly distributed acid and thiol groups in the synthesis of bisphenol A and 14 times more active

Scheme 2. Synthesis of Previously Reported[11] Catalysts **SBA-a**, Containing Alkylsulfonic Acid Sites, and **SBA-at-p**, Containing Alkylsulfonic Acids Paired with Alkyl Thiols
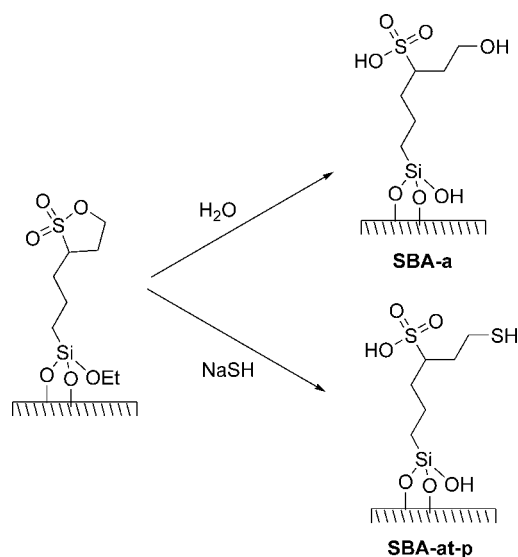
in the synthesis of bisphenol Z.[11] These results highlight how the nanoscale organization of catalytic surfaces can be tuned to provide a level of reactivity control unachievable through traditional random functionalization approaches.

Here, we report a new route to acid/thiol paired catalysts involving the design of an organosilane precursor which is grafted to a surface at two points and then cleaved to deprotect the catalytic site. The precursor, bis-silane **3** containing a disulfide group and an aryl sulfonate ester separated by two carbon atoms, was prepared according to Scheme 3. After this molecule was grafted onto the silica surface, reduction of the disulfide bond and hydrolysis of the sulfonate ester afforded a thiol and arylsulfonic acid group, respectively, in close proximity on the silica surface (Scheme 4). This material was used to catalyze the condensation between phenol and either acetone or cyclohexanone, and its performance was compared to those of the randomly bifunctionalized analogue and the alkylsulfonic acid/thiol paired catalyst obtained by the sultone route.[11] Typically, increasing the strength of an acid catalyst increases catalytic activity at the expense of selectivity. It was hoped that,

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(9) Dufaud, V.; Davis, M. E. *J. Am. Chem. Soc.* **2003**, *125*, 9403–9413.
(10) Zeidan, R. K.; Dufaud, V.; Davis, M. E. *J. Catal.* **2006**, *239*, 299–306.
(11) Margelefsky, E. L.; Zeidan, R. K.; Dufaud, V.; Davis, M. E. *J. Am. Chem. Soc.* **2007**, *129*, 13691–13697.

Scheme 3. Synthesis of Disulfide Silane **2** and Bis-silane **3**
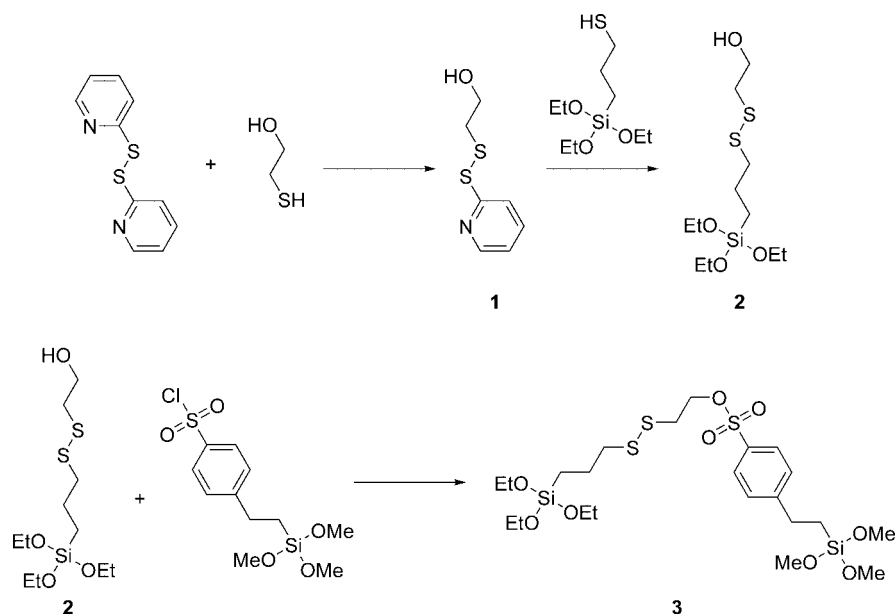
Scheme 4. Synthesis of Paired Acid/Thiol Catalyst **SBA-AT-p** by Deprotection from Grafted Disulfide/Sulfonate Ester Intermediate **SBA-g3**
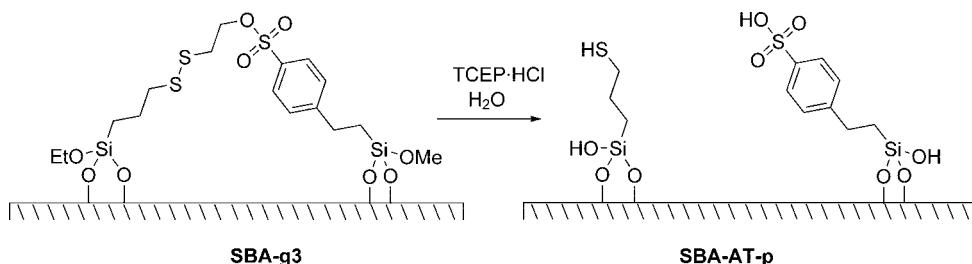
through careful positioning of the acid and thiol groups, higher activity can be achieved without sacrificing selectivity.

Results and Discussion

Synthesis of Molecular Precursor. The synthesis of a precursor containing both a disulfide linkage and a sulfonate group bearing two terminal trialkoxysilane groups was accomplished in three steps (Scheme 3). The unsymmetrical disulfide 2-(pyridin-2-yldisulfanyl)ethanol, **1**, was obtained in 68% yield from 2-mercaptoethanol, $HO(CH_2)_2SH$, with 2,2′-dithiodipyridine via a thiol−disulfide interchange reaction.[12] The pyridyl group, which is a well-known reversible blocking reagent for thiol functionalities, was then easily removed by reaction with (3-mercaptopropyl)triethoxysilane, leading to the formation of 2-((3-(triethoxysilyl)propyl)disulfanyl)ethanol, **2**, in 60% yield. The last step involves the esterification of the commercially available 2-(4-chlorosulfonylphenyl)ethyltrimethoxysilane with **2** in the presence of an excess of triethylamine. The reaction leads to bis-silane **3** in a relatively low yield (40%), probably due to the impurities present in the commercial sulfonyl chloride reagent (mainly free sulfonic acid). **3** was characterized by ^{1}H and ^{13}C NMR. Note, in particular, in the ^{13}C NMR spectrum (Figure 1, top) the peaks characteristic of the mercaptoethanol spacer at 36.6 and 68 ppm that correspond respectively to the

carbon adjacent to the disulfide and the carbon adjacent to the arylsulfonate ester group.

Synthesis of Organic−Inorganic Hybrid Materials. SBA-15 was functionalized with bis-silane **3** by grafting in refluxing toluene. The resulting material is denoted **SBA-g3**. The loading was deliberately kept very low so that the effect of pairing could be seen: the loading used was ∼0.2 mmol/g (the same loading used for the previously reported alkylsulfonic acid/thiol paired catalysts).[11] SBA-15[13] was chosen as a support because of its high surface area, large pore diameter (∼6 nm), and ease of functionalization. The rigidity of the silica matrix ensures also that the bound functional groups do not change their positioning during surface chemical transformations or catalysis.

SBA-g3 was characterized by X-ray diffraction (XRD), nitrogen adsorption/desorption porosimetry, [13]C{[1]H} and [29]Si{[1]H} cross-polarization/magic-angle spinning (CP/MAS) NMR, and thermogravimetric analysis (TGA).

The X-ray diffraction pattern of **SBA-g3** (see Supporting Information) exhibits three clear peaks in the 2θ range of 0.6−3°, characteristic of hexagonally ordered mesophases with a $d(100)$ spacing of 96.4 Å. The structure of the mesoporous material is thus preserved throughout the grafting process.

(12) (a) Guo, W.; Pleasants, J.; Rabenstein, D. L. *J. Org. Chem.* **1990**, *55*, 373–376. (b) Houk, J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1987**, *109*, 6825–6836.

(13) (a) Zhao, D.; Feng, J.; Huo, Q.; Melosh, N.; Fredrickson, G. H.; Chmelka, B. F.; Stucky, G. D. *Science* **1998**, *279*, 548–552. (b) Zhao, D.; Huo, Q.; Feng, J.; Chmelka, B. F.; Stucky, G. D. *J. Am. Chem. Soc.* **1998**, *120*, 6024–6036. (c) Zhao, D.; Sun, J.; Li, Q.; Stucky, G. D. *Chem. Mater.* **2000**, *12*, 275–279. (d) Kruk, M.; Jaroniec, M. *Chem. Mater.* **2000**, *12*, 1961–1968.
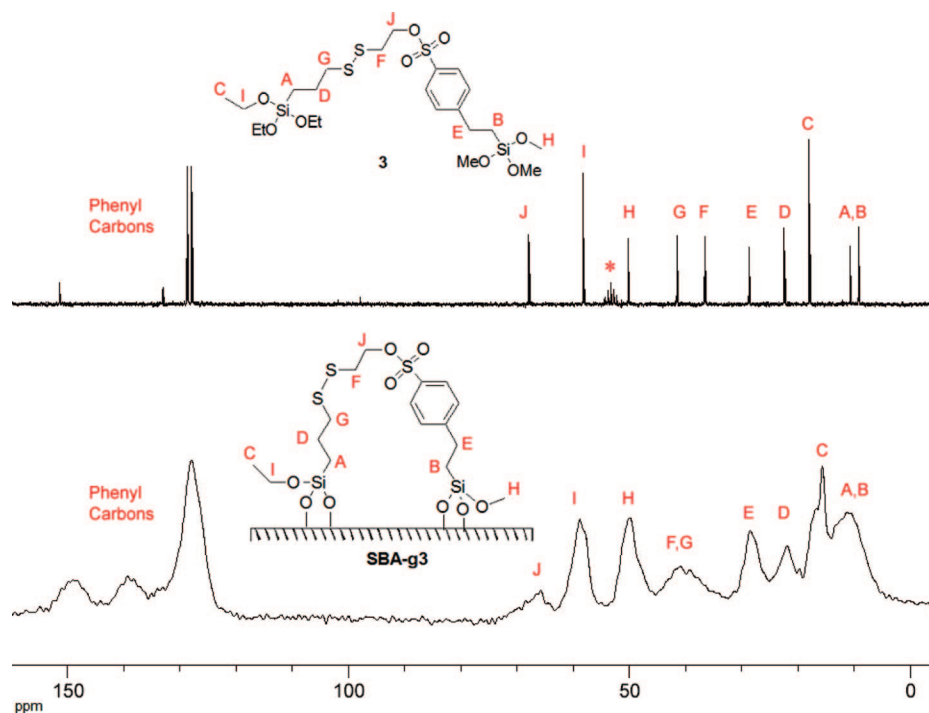
Figure 1. ^{13}C NMR spectrum of bis-silane **3** (top) and ^{13}C{^{1}H} CP/MAS spectrum of **SBA-g3** (bottom). * indicates solvent peak (DMSO-d_6).

Table 1. Catalyst Characterization Data

entry	material	S_{BET}[a] (m²/g)	D_p[b] (nm)	H⁺[c] (mmol/g)	SH[d] (mmol/g)	SH/H⁺
1	**SBA-15**	860	6.3			
2	**SBA-g3**	230	5.8			
3	**SBA-A**			0.20		
4	**SBA-AT-p**	430	6.0	0.21	0.19	0.90
5	**SBA-AT-r**			0.13	0.12	0.92
6	**SBA-T**				0.32	

[a] Specific surface area, calculated using the BET method. [b] Average pore diameter, calculated from adsorption isotherm using the BJH method. [c] Acid loading, measured by ion exchange/titration. [d] Thiol loading, measured by reaction with Ellman's reagent.

Nitrogen adsorption−desorption results (Table 1, Supporting Information) show a type IV isotherm, typical of mesoporous solids. The unfunctionalized SBA-15 has a surface area of 860 m²/g. After grafting with the large bis-silane **3**, the surface area decreases to 230 m²/g, and the pore size is reduced from 6.3 to 5.8 nm. While the surface area of SBA-15 would be expected to decrease after grafting with a large organosilane such as **3**, the nearly 4-fold decrease observed is too large to be attributed only to the presence of organic surface groups. It is also likely that some of the pore mouths are blocked by organic species, rendering those pores inaccessible to adsorbent.

The integrity of the organic fragment after grafting was confirmed by ^{13}C CP/MAS NMR spectroscopy. The ^{13}C CP/MAS spectrum of the grafted molecule corresponds to the solution-phase spectrum of **3**, confirming that the molecule remains intact upon grafting (see Figure 1). In particular, the presence of the central spacer that determines the distance between the masked functionalities is observed at 68 ppm as a resolvable peak in the solid-state NMR spectrum.

The tertiary silicon peaks in the ^{29}Si CP/MAS spectrum confirm the presence of covalently bonded organic groups (Figure 2, top). T^1, T^2, and T^3 peaks can be seen, corresponding to organosilanes grafted to the surface at one, two, and three points, respectively. Of these three peaks, the largest is T^2,

indicating that most of the grafted silanes are covalently bonded to the surface at two points, as shown in Scheme 4. Because **3** contains two trialkoxysilane groups, it is possible that one end could graft to the silica surface, leaving the other end free. This would be evidenced by a T^0 peak in the ^{29}Si spectrum at −41 ppm, but since no such peak is seen, it appears that nearly every precursor molecule is grafted to the surface at both ends.

Quantitative determination of the organic content of **SBA-g3** was performed by thermogravimetric analysis in air. The TGA profile (see Supporting Information) showed three weight loss regions. At temperatures up to about 200 °C, weight loss was observed, accompanied by an endothermic DSC peak, presumably due to the desorption of water. A second region of weight loss followed at temperatures ranging from 200 to 600 °C, presumably arising from the decomposition and desorption of volatile organics. This weight loss was taken as an estimate of the total amount of the organic. Thus, the functional group loading for **SBA-g3** was found to be ~0.4−0.5 mmol/g, depending on how many residual methoxy/ethoxy groups are left on the surface. Note also that the grafted complex is thermally stable up to 220 °C. Further weight loss occurred at temperatures above 600 °C, likely due to the condensation of silanols of the silica framework.

Generation of Catalytic Solids and Characterization of Active Sites. Since the two types of functional groups are introduced in a protected form, they must be deprotected in order to remove the spacer and generate the active catalytic material. This sequence requires that the deprotection of one functional group does not degrade the other. Fortuitously in this case, the deprotection of the disulfide and sulfonate ester groups of **SBA-g3** could be accomplished in one step using aqueous tris(2-carboxyethyl)phosphine hydrochloride (TCEP·HCl). The phosphine reduces the disulfide to a thiol,[14] and the weakly acidic aqueous solution hydrolyzes the sulfonate ester to a sulfonic

(14) Burns, J. A.; Butler, J. C.; Moran, J.; Whitesides, G. M. *J. Org. Chem.* **1991**, *56*, 2648–2650.
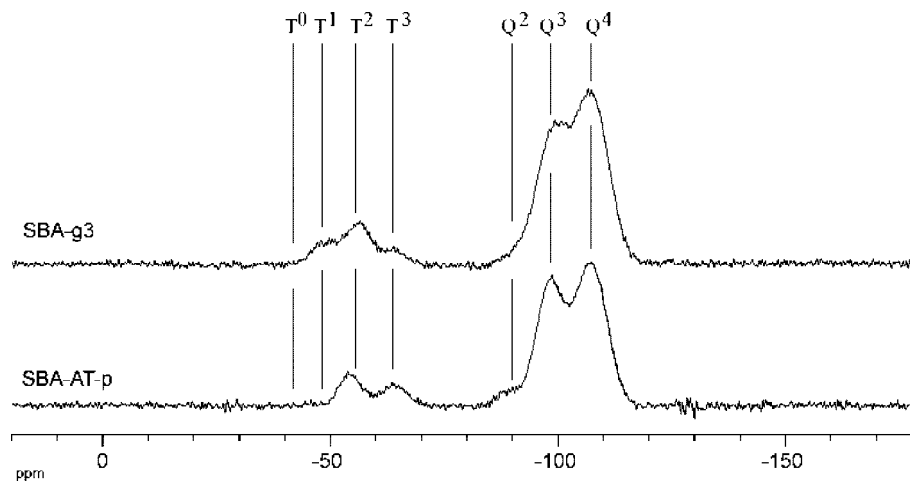
Figure 2. ^{29}Si{^{1}H} CP/MAS spectrum of **SBA-g3** (top), showing T^1, T^2, and T^3 peaks corresponding to silanes covalently bonded to the surface at one, two, and three points, respectively. Following the cleavage of the mercaptoalcohol linker to form **SBA-AT-p** (bottom), the T^3 peak is larger, the T^2 peak is shifted slightly downfield, and the T^1 peak is nearly absent.
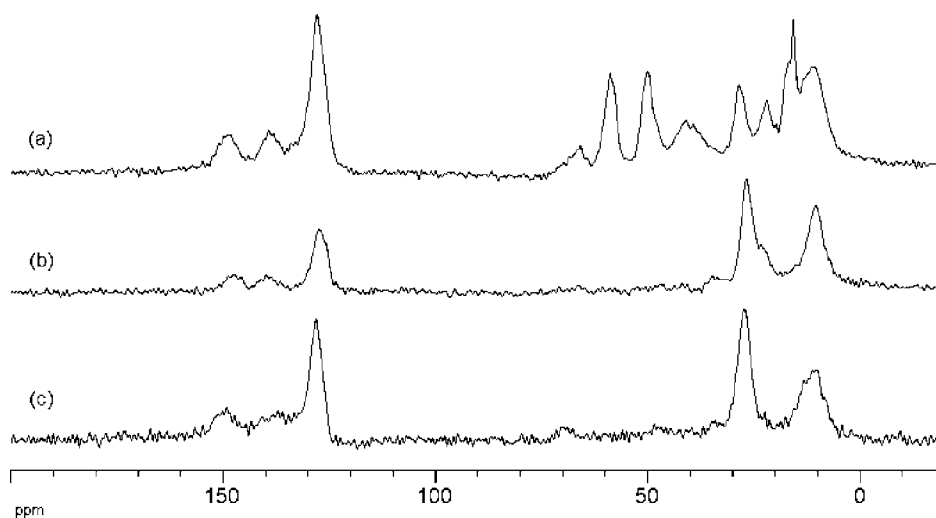

Figure 3. ^{13}C{^{1}H} CP/MAS NMR spectra of (a) **SBA-g3**, (b) **SBA-AT-p**, and (c) **SBA-AT-r**. For peak assignments, see Supporting Information, Figures S6 and S8.

acid. The mercaptoalcohol linker is then free to diffuse away from the acid/thiol site. The resulting deprotected material is denoted **SBA-AT-p** (for acid/thiol paired).

The ^{13}C CP/MAS spectrum of **SBA-AT-p** is shown in Figure 3b. The peaks corresponding to the mercaptoethanol linker (37 and 68 ppm) are absent, confirming that the deprotection step is complete. The residual alkoxy peaks are also absent, as these groups are also hydrolyzed during the aqueous reaction. The ^{29}Si CP/MAS spectrum (Figure 2, bottom) shows an increase in the T^3 signal and a decrease in the T^1 signal; thus, the aqueous deprotection reaction appears to further condense the alkoxysilane moieties with the surface.[15]

The surface area measurements show that the BET surface area increased from 230 (**SBA-g3**) to 430 m^2/g (**SBA-AT-p**) after the deprotection step (Table 1, entries 2, 4). This is due to the removal of the mercaptoethanol linker and also likely to the unblocking of some of the blocked pore mouths. The median pore diameter did not change significantly during deprotection

(5.8−6.0 nm). The powder XRD pattern of **SBA-AT-p** (Supporting Information) indicates that the hexagonal ordering is maintained.

The acid content of **SBA-AT-p** was measured by ion-exchange with NaCl, followed by titration of the HCl with NaOH. Thiol content was measured by reaction with Ellman's reagent,[16] followed by spectrophotometric quantification of the liberated 2-nitro-5-mercaptobenzoate. The catalyst characterization data are summarized in Table 1. The acid/thiol ratio was nearly unity, as expected (0.21 mmol/g acid, 0.19 mmol/g thiol).

Catalysts containing only thiols, only arylsulfonic acids, and randomly distributed arylsulfonic acid and thiol groups were also synthesized (denoted **SBA-T**, **SBA-A**, and **SBA-AT-r**, respectively) according to Scheme 5. The acid groups were generated by sulfonate ester hydrolysis, using the same aqueous TCEP·HCl treatment employed for **SBA-AT-p**. The disulfide silane **2** was used as the source of thiol groups for **SBA-AT-r** because a free thiol could attack the sulfonate ester during the

(15) The same phenomenon was noted by Dufaud and Davis.[9] for a similar aqueous TCEP treatment of organic functionalized SBA-15.

(16) Badyal, J. P.; Cameron, A. M.; Cameron, N. R.; Coe, D. M.; Cox, R.; Davis, B. G.; Oates, L. J.; Oye, G.; Steel, P. G. *Tetrahedron Lett.* **2001**, *42*, 8531–8533.

Scheme 5. Synthesis of **SBA-T**, **SBA-A**, and **SBA-AT-r**[a]
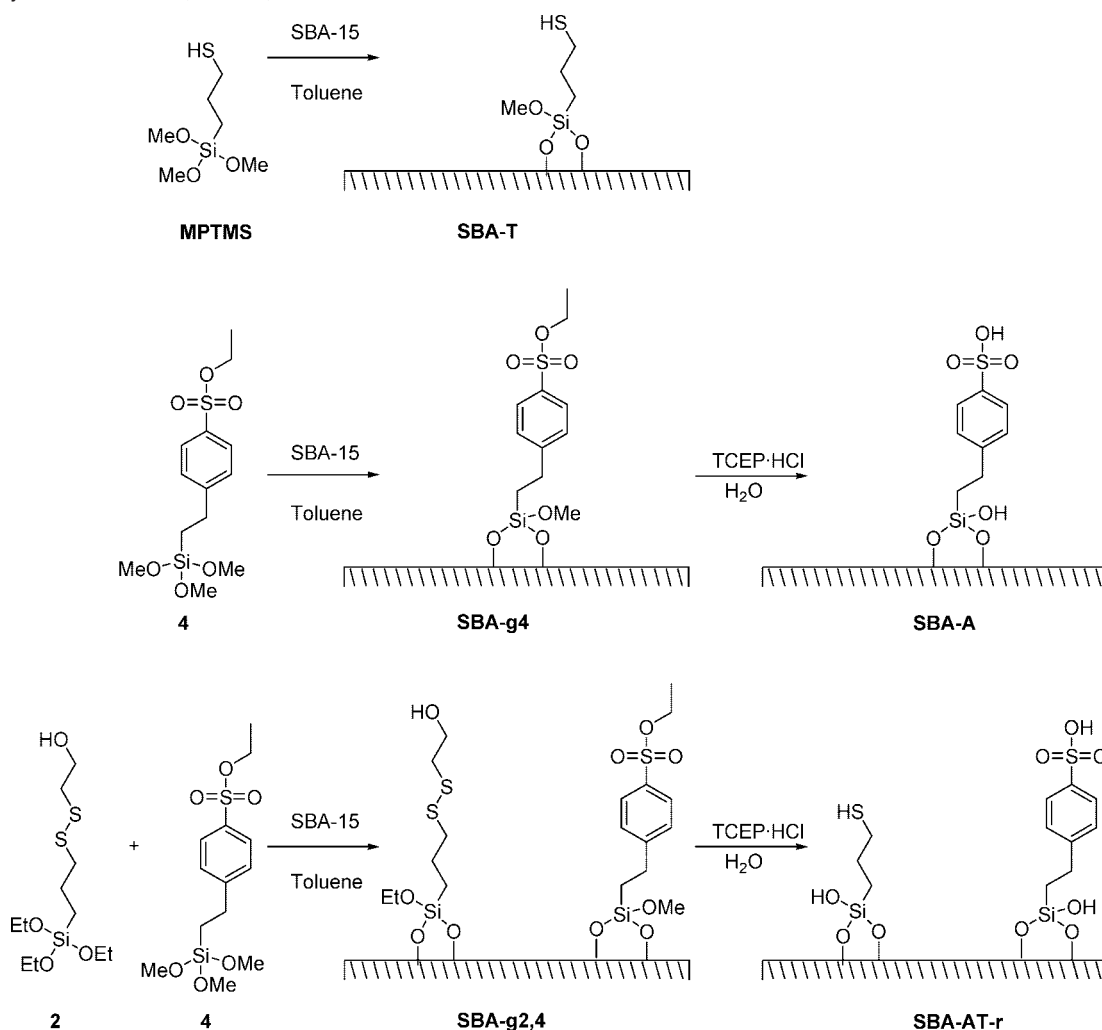
[a] (Top) Grafting 3-mercaptopropyltrimethoxysilane (MPTMS) onto SBA-15 generates **SBA-T**, containing only thiol sites. (Middle) Grafting sulfonate ester precursor **4** generates intermediate **SBA-g4**, which is hydrolyzed to **SBA-A**, containing only acid sites. (Bottom) Grafting both disulfide **2** and sulfonate ester **4** generates intermediate **SBA-g2,4** which is deprotected to form **SBA-AT-r**, containing randomly distributed acid and thiol sites.

grafting process. ^{13}C CP/MAS NMR spectroscopy indicates that, in all cases, the cleavage of the protected groups is quantitative to yield clean thiol- and/or sulfonic acid-functionalized hybrid materials (see Supporting Information). As expected, the ^{13}C NMR spectrum of **SBA-AT-r** is essentially that of **SBA-AT-p** (Figure 3c) because the same functional groups are present on the surface of both materials; the only difference is the spatial positioning of these groups. It is also worth noting that the thiol/acid ratio was fixed at unity in this randomly bifunctionalized material to provide comparison with the organized thiol/acid solid.

Catalytic Reactions. The above materials were used to catalyze the synthesis of bisphenols A and Z. The catalytic tests were carried out under the same reaction conditions as those reported in ref 11.

The catalytic data for the bisphenol A reaction are summarized in Table 2. As expected, **SBA-T** was almost completely inactive due to its lack of acid sites (entry 1). **SBA-A** exhibited some catalytic activity, but very low selectivity due to its lack of thiol sites (entry 2). When a physical mixture of these two catalysts was employed (entry 3), the activity and selectivity improved only slightly beyond that for **SBA-A** alone, because the acid and thiol groups are spatially isolated and unable to

Table 2. Catalytic Data for Bisphenol A Synthesis[a]

		per-site yield			
entry	catalyst(s)	p,p′	o,p′	total	isomer ratio
1	**SBA-T**[b]	<0.1	<0.1	<0.2	
2	**SBA-A**	23	11	34	2.1
3	**SBA-A** + **SBA-T**	28	11	39	2.6
4	pTSA	21	13	34	1.6
5	pTSA + **SBA-T**	35	12	47	2.9
6	**SBA-AT-r**	106	7	113	15.2
7	**SBA-AT-p**	108	6	114	19.3
8	**SBA-a**[c]	2	1.1	3.1	1.8
9	**SBA-at-p**[c]	78	5.6	83	14.0

[a] Reaction conditions: 0.02 mmol of H$^+$, 6 mmol of acetone, 24 mmol of phenol, 90 °C, 24 h. Per-site yield calculated as mmol of product/mmol of H$^+$. [b] 0.02 mmol of SH was used; per-site yield calculated on the basis of thiol sites instead of acid sites. [c] Data taken from ref 11.

interact except at the outer surfaces of the particles. When a homogeneous acid, *p*-toluenesulfonic acid (pTSA), was used, the activity was very close to that of **SBA-A**, albeit with an even lower selectivity (entry 4). pTSA and **SBA-T** used together (entry 5) gave somewhat improved activity and selectivity, as the acid was able to enter the silica pores and interact with the surface-bound thiols. The catalysts containing both acid and thiol

Table 3. Catalytic Data for Bisphenol Z Synthesis[a]

		per-site yield			
entry	catalyst(s)	*p,p′*	*o,p′*	total	isomer ratio
10	**SBA-T**[b]	0	0	0	
11	**SBA-A**	8.1	3.8	11.9	2.1
12	**SBA-A + SBA-T**	7.9	3.6	11.4	2.2
13	**SBA-A** + PrSH	7.3	4.2	11.5	1.8
14	pTSA	3.2	2.6	5.8	1.2
15	pTSA + **SBA-T**	4.5	3.0	7.5	1.5
16	**SBA-AT-r**	17	4.0	21	4.3
17	**SBA-AT-p**	27	2.0	29	13.6
18	**SBA-a**[c]	0.3	0[d]	0.3	N/A[d]
19	**SBA-at-p**[c]	13	0.9	14	14.3

[a] Reaction conditions: 0.02 mmol of H^{+}, 6 mmol of cyclohexanone, 24 mmol of phenol, 90 °C, 24 h. Per-site yield calculated as mmol of product/mmol of H^{+}. [b] 0.02 mmol of SH was used; per-site yield calculated on the basis of thiol sites instead of acid sites. [c] Data taken from ref 11. [d] *o,p′* isomer below detection limit.

sites in close proximity on the same silica support exhibited very high activity and good selectivity to the desired *p,p′* isomer. Whether they are organized or randomly distributed, the 1:1 thiol/acid materials (entries 6, 7) exhibited very similar activity (total yield ~113−114 per acid site), despite the difference in the spatial positioning of the acid and thiol groups. The paired catalyst was, however, the more selective (isomer ratio of 19.3 versus 15.2). Compared to the alkylsulfonic acid-containing catalysts **SBA-a** and **SBA-at-p** obtained via the sultone route[11] (entries 8, 9), it is clear that the greater acid strength of the arylsulfonic acid groups leads to greater overall activity without sacrificing selectivity.

The heterogeneous acid/thiol catalysts were also tested in the condensation of cyclohexanone with phenol to form bisphenol Z. This reaction is slower and has been previously shown to be more highly sensitive to acid/thiol positioning than the bisphenol A reaction.[11] The catalytic results are shown in Table 3.

The yield of bisphenol Z is 3−6 times lower than that of bisphenol A at the same reaction conditions due to the lower reactivity of the cyclohexanone reactant. **SBA-A** gives a per-site yield of only 11.9 (entry 11), and no improvement is seen when a physical mixture of **SBA-A** and **SBA-T** is used (entry 12). Notably, no cooperativity is seen when a homogeneous thiol is used in conjunction with **SBA-A** (entry 13), and only a minor improvement is seen with the homogeneous acid catalyst when heterogeneous thiol is added (entries 14, 15). Only when the acid and thiol groups are both immobilized on the silica surface does cooperativity become evident. **SBA-AT-r** (entry 16) has a yield (21) and selectivity (4.3) approximately twice those of **SBA-A**. Organizing the acid and thiol sites into pairs (entry 17) further increases the yield to 29 and imparts a very high selectivity (13.6). Compared to the alkylsulfonic acid-containing catalyst **SBA-at-p** (entry 19), the arylsulfonic acid/thiol paired catalyst **SBA-AT-p** is twice as active while retaining the same high selectivity.

These data demonstrate that catalytic cooperativity in the synthesis of bisphenol Z is much more dependent on acid/thiol distance than for bisphenol A. Combining a homogeneous acid with a heterogeneous thiol (or vice versa) does not provide the necessary proximity for good catalytic activity because the homogeneous component is dispersed throughout the liquid phase. Immobilizing both the acid and thiol onto silica fixes the groups on the two-dimensional surface, leading to greater proximity and catalytic performance. Finally, organizing the acid and thiol groups into closely spaced surface pairs leads to a

further improvement in activity and a dramatic increase in selectivity that is not seen in the bisphenol A reaction.

Conclusions

An ordered mesoporous silica catalyst containing arylsulfonic acid and alkylthiol groups organized in pairs was synthesized by grafting a designed bis-silane precursor onto SBA-15, followed by linker cleavage. In the bisphenol A reaction, the random and paired arylsulfonic acid/thiol catalysts exhibit similar catalytic performance, whereas in the slower bisphenol Z reaction, the paired catalyst outperforms the randomly distributed catalyst. Compared to catalysts containing weaker alkylsulfonic acid sites, the arylsulfonic acid catalysts are more active while maintaining similar selectivities. Thus, it appears that the common tradeoff between activity and selectivity can be circumvented by appropriate catalyst design.

The acid/thiol distance in **SBA-AT-p** was set by the mercaptoethanol spacer used in the precursor. Other mercaptoalcohol linkers could be used, allowing the acid/thiol distance to be tuned. Replacing the alkyl spacer (which is somewhat flexible) with a more rigid one might also lead to a greater uniformity in acid/thiol distance. This fine-tuning of acid/thiol distance would be expected to be especially important for even slower bisphenol condensations and could potentially catalyze the condensation of phenol with less-reactive ketones without requiring very high reaction temperatures.

Experimental Section

Materials. Dichloromethane, pentane, and toluene were dried by distillation over CaH$_2$, CaSO$_4$, and Na, respectively, and stored over activated 4 Å molecular sieves. All other solvents were analytical grade and used as received. Tris(2-carboxyethyl)phosphine hydrochloride was purchased from Alfa Aesar. Tetraethoxysilane (TEOS), 2-mercaptoethanol, and 2-(4-chlorosulfonylphenyl)ethyltrimethoxysilane (50% in dichloromethane) were obtained from Acros Organics. (3-Mercaptopropyl)triethoxysilane was purchased from Gelest. All other chemicals were purchased from Aldrich and used as received. All reactions were performed under an argon atmosphere.

2-(Pyridin-2-yldisulfanyl)ethanol, 1. A solution of 2-mercaptoethanol (0.87 g, 11.1 mmol) in dry CH$_2$Cl$_2$ (10 mL) was added dropwise at room temperature to a solution of 2,2′-dithiopyridine (4.89 g, 22.2 mmol) in CH$_2$Cl$_2$ (20 mL). After complete addition of the mercaptoethanol, the solution was stirred for 3 h at room temperature. The initially colorless solution turned yellow due to the production of pyridine-2-thione. After the solvent was removed *in vacuo*, chromatography on silica gel (8:2 pentane/ethyl acetate) afforded 2-(pyridin-2-yldisulfanyl)ethanol (1.4 g, 68% yield) as a yellow oil.

^{1}H NMR, CDCl$_3$, δ 2.71 ppm (t, *J* = 5.5 Hz, 2H, C$_5$H$_4$NS$_2$-*CH$_2$*CH$_2$OH), 3.59 ppm (q, *J* = 5.5 Hz, 2H, SSCH$_2$*CH$_2$*OH), 5.5 ppm (t, *J* = 6.4 Hz, 1H, SSCH$_2$CH$_2$*OH*), 6.89, 7.33, 8.2 ppm (m, 4H, pyridyl); ^{13}C NMR, CDCl$_3$, δ 42.1 ppm (SS*CH$_2$*CH$_2$OH), 58.9 ppm (SSCH$_2$*CH$_2$*OH), 120.9, 121.3, 137.1, 149.2, and 159.2 ppm (pyridyl carbons).

2-((3-(Triethoxysilyl)propyl)disulfanyl)ethanol (Organosilane 2). A solution of (3-mercaptopropyl)triethoxysilane (1.61 g, 6.74 mmol) in dry CH$_2$Cl$_2$ (10 mL) was added slowly via syringe to a solution of **1** (1.40 g, 7.49 mmol) in CH$_2$Cl$_2$ (20 mL). The yellow solution was stirred at room temperature overnight. The crude product was purified by chromatography on silica gel (6:4 cyclohexane/ethyl acetate) to afford **2** (1.27 g, 60% yield).

^{1}H NMR, CDCl$_3$, δ 0.6 ppm (m, 2H, Si*CH$_2$*CH$_2$), 1.1 ppm (t, *J* = 7 Hz, 9H, SiOCH$_2$*CH$_3$*), 1.6 ppm (m, 2H, SiCH$_2$*CH$_2$*), 2.6 ppm (t, *J* = 7 Hz, 2H, SS*CH$_2$*CH$_2$CH$_2$), 2.7 ppm (t, *J* = 6 Hz, 2H, HOCH$_2$*CH$_2$*SS), 3.4 ppm (br, 1H, O*H*), 3.7 ppm (m, 8H,

SiOCH_2CH$_3$ and HOCH_2CH$_2$SS); ^{13}C NMR, CDCl$_3$, δ 9.2 ppm (SiCH_2CH$_2$), 17.7 ppm (SiOCH$_2$$CH_3$), 22.4 ppm (SS$CH_2CH_2CH_2$), 40.9 ppm (SS$CH_2$$CH_2CH_2$), 41.5 ppm (HO$CH_2CH_2$SS), 58.3 ppm (SiO$CH_2CH_3$), 60.3 ppm (HO$CH_2CH_2$SS); HRMS (ESI+) *m/z* (M + Na$^+$) (C$_{11}$H$_{27}$SiS$_2$O$_4$) calcd 337.0939, found 337.0942.

2-((3-(Triethoxysilyl)propyl)disulfanyl)ethyl 4-(2-(Trimethoxysilyl)ethyl)benzenesulfonate (Bis-silane 3). A solution of **2** (1.23 g, 3.93 mmol) and dry triethylamine (1.02 g, 10.1 mmol) in dry CH$_2$Cl$_2$ (20 mL) was cooled to 0 °C, and 2-(4-chlorosulfonylphenyl)ethyltrimethoxysilane (50% in CH$_2$Cl$_2$, 1.4 mL, 2.8 mmol) was added dropwise via syringe. The mixture was allowed to warm slowly to room temperature and stirred overnight. The solvent was removed *in vacuo*, and the crude product was purified by chromatography on tetramethylorthosilicate-passivated silica gel (6:4 CH$_2$Cl$_2$/ethyl acetate) to afford **3** (0.67 g, 40% yield).

^{1}H NMR, CD$_2$Cl$_2$, δ 0.7 ppm (m, 2H, SiCH_2CH$_2$CH$_2$), 1.0 ppm (m, 2H, SiCH_2CH$_2$), 1.2 ppm (t, *J* = 7 Hz, 9H, SiOCH$_2$$CH_3$), 1.8 ppm (m, 2H, SiCH$_2$$CH_2CH_2$), 2.7 ppm (t, *J* = 7 Hz, 2H, SiCH$_2$$CH_2$), 2.8 ppm (m, 4H, SO$_2OCH_2$$CH_2$SS and SiCH$_2CH_2$$CH_2$), 3.6 ppm (s, 9H, SiO$CH_3$), 3.8 ppm (q, *J* = 7 Hz, 6H, SiOCH_2CH$_3$), 4.3 ppm (t, *J* = 7 Hz, 2H, SO$_2$OCH_2CH$_2$SS), 7.4 (d, *J* = 8.5 Hz, 2H, phenyl proton β to ethyl chain) and 7.8 ppm (d, *J* = 8.5 Hz, 2H, phenyl proton β to sulfonate ester group); ^{13}C NMR, CD$_2$Cl$_2$, δ 9.2 ppm (SiCH_2CH$_2$CH$_2$), 10.7 ppm (SiCH_2CH$_2$), 17.7 ppm (SiOCH$_2$$CH_3$), 22.5 ppm (SiCH$_2CH_2$$CH_2$), 28.8 ppm (SiCH$_2$$CH_2$), 36.6 ppm (SO$_2OCH_2$$CH_2$SS), 41.6 ppm (SiCH$_2CH_2$$CH_2$), 50.3 ppm (SiO$CH_3$), 58.2 ppm (SiO$CH_2CH_3$), 68.0 ppm (SO$_2OCH_2CH_2$SS), 127.8 and 128.8 ppm (aromatic carbons), 133.0 ppm (aromatic carbon attached to ethyl group), 151.4 ppm (aromatic carbon attached to sulfonate ester); HRMS (ESI+) *m/z* (M + Na$^+$) (C$_{22}$H$_{42}$Si$_2$S$_3$O$_9$) calcd 625.1427, found 625.1427.

Ethyl 4-(2-(Trimethoxysilyl)ethyl)benzenesulfonate (Organosilane 4). 2-(4-Chlorosulfonylphenyl)ethyltrimethoxysilane (50% in dichloromethane, 1.9 mL, 3.8 mmol) was added dropwise through a septum to a solution of dry ethanol (0.88 g, 19 mmol) and triethylamine (1.56 g, 15.4 mmol) at 0 °C. After the addition, the mixture was allowed to warm slowly to room temperature. The reaction mixture was stirred at 25 °C overnight. After the solvent was removed *in vacuo*, filtration on silica gel (ethyl acetate) afforded **4** (0.5 g, 40% yield).

^{1}H NMR, CDCl$_3$, δ 0.9 ppm (m, 2H, SiCH_2CH$_2$), 1.21 ppm (t, *J* = 7 Hz, 3H, CH_3CH$_2$O), 2.74 ppm (m, 2H, C$_6$H$_4$$CH_2$), 3.5 ppm (s, 9H, SiO$CH_3$), 4.0 ppm (q, *J* = 7 Hz, 2H, CH$_3$$CH_2$O), 7.33 ppm (d, *J* = 8.2 Hz, 2H, phenyl protons β to ethyl chain), 7.7 ppm (d, *J* = 8.2 Hz, 2H, phenyl protons β to sulfonate ester group); ^{13}C {^{1}H} NMR, CDCl$_3$, δ 10.8 (SiCH_2CH$_2$) ppm, 14.6 ppm (CH_3CH$_2$O), 28.7 ppm (C$_6$H$_4$$CH_2$), 50.4 ppm (SiO$CH_3$), 66.8 ppm (CH$_3$$CH_2$O), 127.8 and 128.8 (aromatic carbons), 133.0 (aromatic carbon attached to ethyl group), 150.8 ppm (aromatic carbon attached to sulfonate group).

Organic-Functionalized SBA-15 Materials. SBA-15 (1.0 g, synthesized according to the literature procedure[15]) was suspended in dry toluene (40 mL). A solution of organosilane in toluene (10 mL) was added dropwise via syringe. The suspension was stirred for 2 h at room temperature and then refluxed overnight. After cooling to room temperature, the solids were filtered, washed several times with toluene, and dried under high vacuum.

When two organosilanes were grafted onto the same SBA-15 material, two separate solutions of organosilane in toluene were prepared and were added dropwise simultaneously to the SBA-15 suspension.

Surface Disulfide Reduction and Sulfonate Ester Hydrolysis. Functionalized silica (0.5 g) containing disulfide and/or sulfonate ester surface groups was suspended in an aqueous solution of TCEP·HCl (16 mM, 50 mL) and stirred at 50 °C for 48 h. After filtration, the solids were washed with water (5 × 100 mL) and then suspended in 0.5 N HCl for ∼1 h to acidify, followed by washing with water (5 × 100 mL). The material was then dried under high vacuum.

Quantification of Acid Sites. Acid-containing silica (40 mg) and 2 N aqueous NaCl (4 mL) were stirred at room temperature for 24 h. The solids were filtered off using positive air pressure filtration and were washed with water (4 × 2 mL). The combined filtrate was titrated with 0.01 N NaOH using phenol red as indicator.

Quantification of Thiol Sites. The procedure developed by Badyal et al.[16] was followed for quantification of resin-bound thiols in organic solvents. Thiol-containing silica (5 mg) was suspended in methanol (4 mL), and 1 mL of a solution containing Ellman's reagent (4 mg/mL) and diisopropyl ethylamine (0.05 mL/mL) was added. After stirring at room temperature for 4 h, the solids were removed by syringe filtration, and the absorbance of the filtrate was measured at 412 nm, using an experimentally determined extinction coefficient of 11 mM^{-1}.

Catalytic Reaction: Condensation of Phenol and Ketone. An amount of catalyst corresponding to 0.02 mmol of H$^+$ (∼100−200 mg) was added to a vial and dried under high vacuum at 80 °C overnight. Phenol (2.2 g, 24 mmol) and ketone (6 mmol) were added, the vial was sealed under argon, and the contents were stirred at 90 °C for 24 h. The catalyst was removed by filtration and washed with acetonitrile to a total filtrate volume of 25 mL, and the products were quantified by HPLC analysis. Per-site yield was calculated on the basis of the number of acid sites present, and selectivity was defined as the ratio of bisphenol isomers (*p,p′/o,p′*).

When homogeneous catalysts were used, the homogeneous catalyst was dissolved in ketone and then added to the phenol and heterogeneous catalyst.

Supporting Information Available: ^{13}C{^{1}H} CP/MAS NMR spectra of **SBA-g4**, **SBA-A**, **SBA-g2,4**, **SBA-AT-r**, and **SBA-T**; N$_2$ adsorption/desorption isotherms of **SBA-15**, **SBA-g3**, and **SBA-AT-p**; X-ray diffraction data of **SBA-15**, **SBA-g3**, and **SBA-AT-p**; TGA data of **SBA-g3** and **SBA-AT-p**. This material is available free of charge via the Internet at http://pubs.acs.org.

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