Synthesis of Ordered Mesoporous Silica with Tunable Morphologies and Pore Sizes via a Nonpolar Solvent-Assisted Stöber Method

Xiqing Wang,† Yu Zhang,† Wei Luo,‡ Ahmed A. Elzatahry,‖ Xiaowei Cheng,† Abdulaziz Alghamdi,§ Aboubakr M. Abdullah,⊥ Yonghui Deng,*†,# and Dongyuan Zhao†

†Department of Chemistry, State Key Laboratory of Molecular Engineering of Polymers, Shanghai Key Laboratory of Molecular Catalysis and Innovative Materials, State Key Laboratory of ASIC & System, Collaborative Innovation Center of Chemistry for Energy Materials, Fudan University, Shanghai 200433, China
‡College of Materials Science and Engineering, Donghua University, Shanghai 201620, China
§Materials Science and Engineering, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
‖Center for Advanced Materials, Qatar University, P.O. Box 2713, Doha, Qatar
⊥Center for Advanced Materials, Qatar University, Doha 2713, Qatar
#State Key Lab of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
*Supporting Information

ABSTRACT: A facile nonpolar solvent-assisted Stöber method has been developed to synthesize ordered mesoporous silica materials with tunable pore size and diverse morphologies and mesostructures by using cetyltrimethylammonium bromide as the template and tetraethyl orthosilicate as silica precursor in a simple aqueous-phase synthesis system. By simply changing the amount of n-hexane and ammonia−water in the system, ordered mesoporous silica with pore sizes of 2.7−10.5 nm, various morphologies (nanocubes, truncated nanocubes, core−shell microspheres, and twisted nanorods), a high surface area up to 888 m²/g, and a large pore volume of 1.55 cm³/g are synthesized. Owing to their highly hydrophilic surface, large and accessible pores, and high surface area, the mesoporous silica materials exhibit an excellent performance in adsorption of dye molecules of large dimension (1.6 nm) with a maximum adsorption capacity of 106 mg/g in 10 min at 200 mg/L initial Rhodamine B concentration.

INTRODUCTION

Because of their outstanding physicochemical properties stemming from their periodically arranged uniform pores in the sub-50 nm regime, ordered mesoporous materials have attracted considerable attention in various fields, including catalysis, energy storage and conversion, biomedicine, environmental remediation, and many multidisciplinary fields. Tremendous efforts have been devoted to synthesizing mesoporous materials with different pore sizes, mesostructures, framework compositions, surface functionalities, and morphologies to realize their promising applications. Variuos methods with different synthesis strategies such as low-temperature synthesis, hydrothermal treatment, and auxiliary organics-assisted synthesis have been developed to achieve the controlled synthesis of mesoporous silica with respect to their morphology and pore sizes by using cheap small surfactants or expensive amphiphilic block copolymers as the structure directing agent. Che et al. synthesized monodisperse rodlike chiral mesoporous silica by using N-miristoyl-L-alanine sodium salt (C14-L-AlaS) and N-trimethoxysilylpropyl-N,N,N-trimethylammonium chloride or 3-aminopropytrimethoxysilane. Kim et al. reported mesoporous silica MCM-48 (Ia̅3d symmetry) with a decaoctahedron shape templated by CTAB in the presence of various kinds of alcohol. Bruinsma et al. synthesized mesoporous silica fibers by dry spinning of alkoxide-cetyltrimethylammonium chloride (CTAC) solutions. Ting et al. reported mesoporous silica nanocubes by using dodecyltrimethylammonium as the template. In addition to the templating synthesis based on small surfactants, amphiphilic block copolymers have been widely employed to synthesize mesoporous silica with large pores and various morphologies since 1998. For example, rodlike mesoporous silica SBA-15 with a 2-D hexagonal mesostructure and rhombdodecahedron-shaped single crystals of mesoporous...
silica with a body-centered cubic mesostructure were synthesized by controlling the ionic strength of synthetic solutions using nonionic block copolymers P123 and F108 as the template, respectively. Ordered mesoporous silica materials with large pores are highly desirable for applications involving the host–guest interaction with large molecules or functional nanoparticles, because large mesopores can avoid the problem of pore blockage during interaction with guest species of large molecules or nanoparticles and provide unique and effective confinement for host–guest chemistry at mesoscale. Additionally, the morphology plays an important role in their applications. For example, mesoporous films have been demonstrated as good candidates for use in membrane separation. Spherical mesoporous silica is an attractive stationary-phase material in high-performance liquid chromatography. Rodlike mesoporous silica SBA-15 materials have shown much improved immobilization ability for lysozymes over that of conventional SBA-15 materials. Ordered mesoporous silica fibers have been demonstrated to be a potential for application as high-surface-area optical waveguides and construction of new laser materials. Despite the aforementioned advances, most previous reports succeeded in morphology or pore size controlled synthesis of mesoporous silica materials in different synthetic systems, and they failed to simultaneously tune the morphology and mesopore size of mesoporous silica materials in a simple synthesis system. Particularly, little work has been done to realize a facile, mild and cost-efficient synthesis of mesoporous silica materials with tunable morphology and pore size in a simple aqueous system.

Herein, we report a simple, but efficient, synthesis of mesoporous silica with tunable mesopore sizes and various morphologies via a modified Stöber process using cheap CTAB as the template and n-hexane as the pore expanding agent and tetraethyl orthosilicate (TEOS) as the silicon source. By simply changing the amount of n-hexane and the dosage of ammonia–water in the synthesis system, ordered mesoporous silica materials with tunable pore sizes (2.7–10.5 nm), various morphologies (nanocubes, truncated nanocubes, microspheres, and twisted nanorods), high surface area up to 888 m$^2$/g, and a large pore volume of 1.55 cm$^3$/g were synthesized. Because of the mild solvent extraction of CTAB for generation of mesopores, the obtained mesoporous silica particles not only have large and accessible mesopores but also possess good water dispersibility and rich surface active sites (i.e., ionizable silanol groups), which enables an excellent adsorption performance for adsorption of cationic polycyclic aromatic dye molecules with a maximum adsorption capacity of 124 mg/g at 200 mg/L initial Rhodamine B concentration.

**EXPERIMENTAL SECTION**

**Chemicals.** All the chemicals were of analytical grade and used as received without further purification. Cetyltrimethylammonium bromide (CTAB) was purchased from Sinopharm Chemical Reagent Co., Ltd. (China). Tetraethyl orthosilicate (TEOS), Rhodamine B (Rh B), and n-hexane were of analytical grade purchased from Shanghai Lingfeng Chemical Reagent Co., Ltd. (China). Concentrated ammonia–water (28 wt %) was purchased from Jiangsu Tongsheng Chemical Reagent Co., Ltd. (China). Deionized water was used for all experiments.

**Synthesis of Ordered Mesoporous Silica Cubic Particles (MS-C).** The synthesis is based on a similar Stöber process in an alkali ethanol/water solution. Typically, 1.0 g of CTAB was dissolved in 160 mL of deionized water under stirring. Then, 7.0 mL of concentrated ammonia–water (28 wt %) was added, forming a clear solution. After that, a mixture solution of n-hexane (20 mL) and TEOS (5 mL) was added into the solution dropwise in 30 min under continuous stirring. As the reaction proceeds at 35 °C, a homogeneous milky colloidal solution was gradually formed under continuous stirring (200 rpm). After stirring for 12 h, the product was collected by centrifugation and washed with deionized water and ethanol. After that, the collected solid sample (i.e., the as-made mesostructured CTAB/silica composite) was submitted to solvent extraction treatment to remove CTAB templates by redispersing in a mixture of 1 M HCl (3.5 mL) and ethanol (100 mL) at 80 °C for 8 h. The solvent extraction was repeated 6 times, and the sample was collected by centrifugation, followed with washing with ethanol 6 times, and finally vacuum-dried overnight. Ordered mesoporous silica cubic particles (MS-C) were thus obtained.

Additionally, ordered mesoporous silica nanocubes with a partially hydrophobic surface were synthesized by calcination of the as-made CTAB/silica composite with a cubic mesostructure in air at 550 °C instead of solvent extraction for removal of CTAB. The obtained sample was denoted as C-MS-C.

**Synthesis of Mesoporous Silica Spheres (MS-S).** The synthesis procedure is similar to that for mesoporous silica nanocubes, except that the dosage of catalyst was reduced by decreasing the amount of concentrated ammonia–water from 7.0 to 3.0 mL.

**Synthesis of Twisted Mesoporous Silica Rods (MS-R).** The synthesis procedure is similar to that of mesoporous silica nanocubes, except that the amount of ammonia–water was increased to 20 mL and meanwhile the amount of n-hexane was decreased from 20 to 6 mL.

**Dye Adsorption Study Using Rh B as a Probe.** An adsorption study was carried out by dispersing MS-C (0.05 g) and C-MS-C (0.05 g) in an aqueous solution of Rh B with a concentration of 200 mg/L (pH 7.0, 50 mL), respectively. The mixture was kept stirring at 200 rpm at 25 °C. Next, 1 mL of the solution was withdrawn at a time interval of 5 min and submitted to centrifugation to separate the mesoporous silica particles, and the concentration of Rh B in the supernatant solution was determined on a UV–vis spectrophotometer by measuring the absorbance at the wavelength of 554 nm, which is the characteristic absorption peak for Rh B.

**Measurement and Characterization.** Field-emission scanning electron microscopy (FESEM) images were collected on the Hitachi model S-4800 field emission scanning electron microscope. The dried samples were directly used for the observation without any treatment. Transmission electron microscopy (TEM) images were taken with a JEOL 2011 microscope (Japan) operating at 200 kV. For the TEM measurements, the samples were dispersed in ethanol and then dried on a holey carbon film Cu grid. Small-angle X-ray scattering (SAXS) measurements were taken on a NanoStar U small-angle X-ray scattering system (Bruker, Germany) using Cu Kα radiation (40 kV, 35 mA). The formula $d = 2\piq/a$ was used to calculate the $d$-spacing values. Nitrogen adsorption-desorption isotherms were measured at 77 K with a QuadraSorb SI analyzer (USA). Before measurement, the samples were degassed in vacuum at 180 °C for at least 6 h. The Brunauer–Emmett–Teller (BET) method was utilized to calculate the specific surface areas, with $P/P_0$ in the range of 0.04–0.2, and the correlation coefficient for the multipoint BET plot is not lower than 0.999. By using the Broekhoff de Boer (BdB) spherical model, the pore volumes and pore size distributions were derived from the adsorption branches of isotherms, and the total pore volumes ($V$) were estimated from the adsorbed amount at a relative pressure $P/P_0$ of 0.992. The calibration curve was obtained by using the carbon black (part no. 004-16833-00) as a reference material and nitrogen as an adsorption gas. The zeta potentials of the materials were measured by a Malvern Zetasizer Nano-ZS90. The UV–vis spectra were recorded on a UV–vis spectrometer (Jasco V-550) at 25 °C. Fourier transform infrared (FTIR) spectra were collected on a Nicolet Fourier spectrophotometer using KBr pellets. Water contact angles of mesoporous silica samples were measured on a contact angle system (XG-CAMC3). Before measurements, the powder sample (50 mg) was pressed to form a pellet at 5 MPa.
RESULTS AND DISCUSSION

SEM observation reveals that the obtained MS-C sample consists of nanocubes of 400–800 nm (Figure 1a). Despite the polydispersity of the particle size, the nanocubes possess clear edges and corners and six equivalent \([100]\) planes, indicating a well-faceted single crystal morphology (Figure 1a, inset).

The SAXS patterns (Figure 1c) of the obtained mesoporous silica nanocubes exhibit well-resolved diffraction peaks which can be indexed to the \([200]\), \([210]\), \([211]\), \([220]\), \([310]\), \([321]\), \([400]\), \([420]\), and \([422]\) faces of a highly ordered cubic mesostructure of \(Pm\overline{3}n\), similar to the well-known mesoporous silica SBA-1.

The cell parameter \((a_0)\) is 15.93 nm, calculated from the formula \(a = d_{210} (5)^{1/2}\). TEM characterization (Figure 1b) indicates that the obtained mesoporous silica nanocubes are highly dispersed without aggregation and have a regular cubic morphology with a diameter ranging from 400 to 800 nm, agreeing well with the SEM results. The highly ordered arrays of uniform spherical mesopores can be unambiguously visible in the TEM images recorded on a single nanocube viewed along \([100]\), \([110]\), \([111]\), and \([210]\) directions, respectively (Figure 2), which confirms a highly ordered cubic mesostructure of \(Pm\overline{3}n\). The mesopores’ size is about 7.5 nm, as estimated from the TEM image (Figure 2a), much larger than those of typical mesoporous silica materials (~2.5 nm) directly templated from CTAB molecules mainly due to the pore expanding effect of nonpolar \(n\)-hexane.

FTIR characterization shows that the CTAB template can be completely removed by the repeated ethanol extraction treatment (Figure S1).

The \(N_2\) adsorption–desorption isotherms of the obtained mesoporous silica nanocubes (Figure 3a) exhibit a type IV isotherm as defined by IUPAC. A large and clear \(H_2\) hysteresis loop is observed, indicating that the single crystal nanocubes possess relatively large cage-type mesopores. The total pore volume is 1.06 cm\(^3\) g\(^{-1}\), and the BET specific surface area is 801 m\(^2\) g\(^{-1}\), indicative of a high porosity of the MS-C materials. The pore size calculated using the BdB spherical model from the adsorption branch is 7.8 nm with a relatively narrow pore size distribution (Figure 3b).

The amount of concentrated ammonia–water plays a particularly important role in determining the morphology and mesostructure of the obtained mesoporous silica materials. As the amount of ammonia solution decreases from 7 to 5 mL, truncated mesoporous silica nanocubes with a particle size ranging from 200 to 420 nm were obtained (Figure 4a), and each particle exhibits a defect-free single crystal with well-ordered spherical mesopores (Figure 4b). Although the particle morphology changed slightly, the obtained truncated MS-C materials retain the \(Pm\overline{3}n\) mesostructure (Figure S2a). Further decrease of the basic catalyst to 3 mL results in uniform mesoporous silica spheres (hereafter denoted as MS-S-100) with a rough surface and mean diameter of ~100 nm. TEM observation shows that the microspheres have an interesting core–shell structure, wherein the core has mesopores aligned in a cubic structure and the shell exhibits radially aligned mesopores (Figure 4c,d).
MS-S-100 as indicated by the SAXS patterns (Figure S2b). By further decreasing the amount of ammonia−water to 1.5 mL, core−shell microspheres with a diameter of about 80 nm were obtained (hereafter denoted as MS-S-80). Compared to MS-S-100, the core of MS-S-80 is much smaller and shows a poorly defined mesoporous structure, while the shell still has radial pore channels (Figure S3a,b). The MS-S-80 materials display a much deteriorated mesostructure (Figure S2c). It implies that a fast hydrolysis and condensation process under higher concentration of basic catalyst is favorable for the formation crystal-like cubic mesoporous silica materials with a highly ordered mesostructure (i.e., MS-C), while slowing down the reaction rate at lower concentrations of basic catalyst can cause stepwise growth of the mesostructure by gradual deposition of a layer of porous shell with radially aligned mesopores on MS-C nanoseeds. The nitrogen adsorption−desorption isotherm of truncated MS-C shows a type IV isotherm and exhibits an H2 hysteresis loop (Figure S4A). The samples obtained by using different amounts of basic catalyst have pore sizes of about 8.3−10.5 nm, specific surface areas of 620−888 m2/g, and total pore volumes of 0.90−1.55 cm3/g (Table S1). Notably, the MS-S samples have two sets of mesopores which can be attributed to the smaller mesopores in the core and larger ones in the shell. Such a pore size distribution feature is similar to that of previously reported dendritic mesoporous silica nanospheres with a core−shell structure by Shen et al.36

Interestingly, by increasing the amount of ammonia−water from 7 to 20 mL and simultaneously reducing the amount of n-hexane from 20 to 6 mL, twisted hexagonal mesoporous silica rods (denoted as MS-R) with a width of about 500 nm and a length of about 1.2 μm can be obtained (Figure 5a). SEM observation indicates that the twisted mesoporous silica rods seem to be formed through an instantaneous reversion of the growth direction of the rods and twisting a certain angle around their center axis, and finally merging at the starting point of the growth for the mesostructured “crystals” with a paperclip-like pore orientation (Figure 5b). Such a growth manner is totally different from the helical growth mode of chiral mesoporous silica as reported before.37 The high quality morphology of the twisted hexagonal mesoporous silica rods can be also clearly visible under TEM (Figure 5c,d), and the 2-dimensional hexagonal arrays of the cylindrical pore channels of the mesoporous silica nanorods can be seen in the TEM images taken along different directions (Figure 5e,f). The SAXS pattern shows two broad peaks at 0.093 and 0.145 nm−1, respectively, which can be indexed as [100] and [110] planes of p6mm structure (Figure S5). The broadening of the scattering peaks is mainly due to the existence of the twisted pore channels. The nitrogen adsorption−desorption isotherms (Figure S6) show a type IV adsorption isotherm with a small H2 hysteresis loop, which is typical for twisted cylindrical mesopores. The pore size distribution curve (Figure S6, inset) indicates a mean pore size of 2.7 nm. The total pore volume and the specific surface area are calculated to be 0.26 cm3g−1 and 351 m2g−1 for the twisted mesoporous silica rods. The results presented above indicate that, in the simple system of ammonia−water solution/TEOS/CTAB/n-hexane, varying the addition amount of ammonia−water can dramatically tune the morphology from nanocubes to truncated nanocubes, to microspheres and to twisted nanorods, and through combining the adjustment of the amount of n-hexane, the mesopores size

Figure 4. (a, c) SEM and (b, d) TEM images of truncated mesoporous silica nanocubes (a, b) and mesoporous silica microspheres (c, d) synthesized using different amounts of n-hexane and concentrated ammonia−water. The insets in panel (a, c) show the corresponding structure models. The inset in panel (d) is the fast Fourier transform diffractogram of the selected particle.

Figure 5. SEM (a, b), TEM (c, d), and high-resolution TEM (e, f) images of the twisted mesoporous silica nanorods (MS-R) synthesized using 20 mL of ammonia−water and 6 mL of n-hexane. The insets in panels (e) and (f) show the structural models of MS-R viewed from different directions and the corresponding fast Fourier transform image.
can be readily adjusted in the range of 2.7-10.5 nm. In order to gain more insight about the formation process of the mesoporous silica colloids, a series of reaction solutions were withdrawn during the synthesis of the MS-C sample at high concentration of ammonia-water for TEM observation (Figure S7). A fast nucleation of the CTAB–silica composite particles was found in the synthesis system. After reaction for 30 min, quasi-sphere-like particles with a mean diameter of 140 nm were observed (Figure S7a). As the reaction proceeds, the particles grow gradually into regular cubes with a mean diameter of 580 nm at 10 h (Figure S7f), and the well-aligned mesopores can be clearly visible from a certain plane (Figure S7f, inset). It indicates that high concentration of ammonia–water favors a rapid nucleation and the formation of cubic mesoporous silica particles by preferably growing along the [100] directions. In the case of the synthesis system with lower concentration of ammonia–water, the nucleation rate is relatively slow and only small spherical nanoseeds were observed in the early stage of synthesis, and they further grow into core–shell mesoporous silica spheres with shells consisting of perpendicularly aligned mesopores by isotropical deposition of the CTAB–silica composite shell on the nanoseeds. These results shown above indicate that the kinetically controlled coassembly of the n-hexane swelled CTAB molecules and silicate oligomers and the solid (nuclear)–liquid interfacial growth contributes to the morphological evolution of the mesoporous silica materials, while the swelling degree of the silicate-locked CTAB micelles determines the pore sizes of the mesoporous silica materials. More detailed and time-resolved morphology evolution of the mesoporous silica colloids in the synthesis system is yet to be studied by other advanced techniques like in-liquid atomic force microscopy.

Notably, since the solvent extraction method was employed in this study to gently remove the CTAB template and n-hexane during the synthesis, the obtained mesoporous silica particles possess a high surface area, highly hydrophilic surface, and excellent dispersibility in water at a pH value of 4–8. These features make them ideal host materials in host–guest chemistry, particularly in fast adsorption of guest molecules. In this study, we investigated the performance of the hydrophilic mesoporous silica nanocubes obtained by solvent extraction (i.e., MS-C) in adsorption of cationic Rhodamine B (a water-soluble polycyclic aromatic hydrocarbon derivative; see molecular structure in Figure S8) in its aqueous solutions. For comparison, mesoporous silica nanocubes with less hydrophilic surface (C-MS-C) were synthesized by a calcination method. Similar to the MS-C sample, the C-MS-C sample shows N2 adsorption–desorption isotherms with type IV curves, indicating a similar mesoporous structure (Figure S9). Compared to the MS-C sample, the C-MS-C sample has a smaller pore size of 6.2 nm due to the structure shrinkage during calcination, a slightly lower specific surface area of 667 m2/g, and a pore volume of 0.79 cm3/g (Table S2). Upon incubation in Rh B aqueous solution, the MS-C sample requires about 50 min to reach the adsorption equilibrium with a maximum adsorption capacity of 124 mg/g, while C-MS-C reaches the saturated adsorption of about 70 mg/g only in 20 min (Figure 6A). For the MS-C sample, the adsorption amount of Rh B sharply jumps to 106 mg/g in 10 min, and then gradually increases to 124 mg/g in the following 30 min, close to the plateau value of 124 mg/g at 50 min (Figure 6A, a). By contrast, C-MS-C quickly reaches an adsorption of 66 mg/g in 10 min and a 69.3 mg/g in the following 20 min (Figure 6A, b). It indicates that, due to their large and highly opened mesopores, both samples display a fast adsorption rate, with MS-C exhibiting a higher adsorption capacity.

Considering the similar surface area and pore size, such a dramatically different adsorption behavior can be mainly related to the surface property of the two absorbents. At pH 7.0, the MS-C sample was measured to have a zeta potential of −39.8 eV, much higher than that of the C-MS-C sample (−14.8 eV). To further study their surface properties, water contact angle measurements were carried out for the pressed powder sample of MS-C and C-MS-C sample, respectively. The water contact angles of MS-C and C-MS-C were measured to be 17° and 39°, respectively (Figure S10), indicating a more hydrophilic surface of the MS-C sample. Such results are reasonable because the former has numerous silanol groups that can be ionized at pH 7.0 in the pore wall due to the incomplete condensation reaction during the mild sol–gel process. By contrast, the silanol groups can be almost completely eliminated during calcination treatment at high temperature for C-MS-C. The numerous silanol groups providing a negatively charged surface for MS-C serve as active sites for adsorption of cationic Rh B molecules through an electrostatic attraction.

To further investigate their adsorption behavior, a pseudo-second-order model was adopted to examine the adsorption process,38 which can be expressed as follows

\[
\frac{dq}{dt} = \kappa (q_e - q)^2
\]

where \( \kappa \) is the equilibrium rate constant, \( q_e \) is the adsorption amount of Rh B when equilibrium is reached, and \( q \) is the adsorption amount of Rh B at time \( t \).

After being integrated with the boundary conditions of \( t = 0 \) to \( t = t \), and \( q = 0 \) to \( q = q_e \), the model can be linearly expressed as follows:

\[
\frac{t}{q} = \frac{1}{kq_e^2} + \frac{t}{q_e}
\]

The points of \( t/q \) versus \( t \) and respective linear fitting lines are shown in Figure 6B. The equilibrium adsorption amount of Rh B could be calculated from the slope; then \( \kappa \) could be calculated from the intercept and \( q_e \). The parameters of the kinetic model and correlation coefficient \( R^2 \) were calculated and then listed in Table 1, which indicates that the adsorption behavior of Rh B on MS-C and C-MS-C samples fits the pseudo-second-order kinetic model very well. It implies that the rate-controlling step of adsorptions is largely the interaction...
between the negatively charged pore walls and the positively charged Rh B molecules in the neutral solutions. The C-MS-C sample has a larger $\kappa$ value than that of MS-C, implying a faster uptake of Rh B, and the reason is that C-MS-C has a relatively lower density of active sites (i.e., silanol groups) in the pore wall’s surface, particularly in the region around the nanocube’s surface, which provides a smoother path for the diffusion of Rh B molecules.

**CONCLUSION**

A facile and efficient n-hexane-assisted Stöber method approach was demonstrated for the controlled synthesis of ordered mesoporous silica materials with various morphologies, pore sizes, and hydrophilic surface in a simple modified Stöber synthesis system. By changing the amount of n-hexane and ammonia solution, ordered mesoporous silica particles with different morphologies and pore structures (such as nanocubes with $Pm3n$ mesostructure, truncated nanocubes, core−shell microspheres with a core of cubic mesopores and a shell of radial mesopores, and twisted mesoporous silica nanorods with $p6mm$ mesostructure) were obtained. The mesoporous silica particles have a tunable pore size of 2.7–10.5 nm, a high surface area up to 888 $m^2/g$, a large pore volume of 1.55 $cm^3/g$, and a highly hydrophilic surface stemming from their rich ionizable silanol groups, which endows them with excellent host−guest chemistry performance in adsorption of cationic dye molecules.

Because of the simplicity and cost-effectiveness of the synthesis system, it is expected that this synthesis method can be scaled up for production of mesoporous silica materials with customer-tailoring pore parameters and surface properties for various practical applications, such as drug delivery, environmental remediation, and catalysis.

**ASSOCIATED CONTENT**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemmater.6b00499.

**REFERENCES**


**AUTHOR INFORMATION**

**Corresponding Author**

*E-mail: yhdeng@fudan.edu.cn.*

**Author Contributions**

The manuscript was written by contributions of all authors.

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported by the State Key 973 Program of PRC (2013CB934104), the NSF of China (51372041, 51422202, 51402049, and 51432004), the innovation program of Shanghai Municipal Education Commission (13ZZ004), the Program for New Century Excellent Talents in University (NCET-12-0123), the “Shu Guang” Project (13SG02) supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation, the State Key Laboratory of ASIC & System (2015KF002), the Foundation of State Key Laboratory of Pollution Control and Resource Reuse (Tongji University), China (PCRF14017), and Qatar University grant # QUUG-CAS-DMST-15.16-18. We extend our appreciation to the Deanship of Scientific Research at King Saud University for funding the work through the research group project No. RGP-227. We thank Prof. Guangrong Zhou for TEM characterization.
Chemistry of Materials


(28) Stöber, W.; Fink, A.; Bohn, E. Controlled growth of monodisperse silica spheres in the micrometer size range. J. Colloid Interface Sci. 1968, 26, 62–69.
