J|A|C|S
COMMUNICATIONS

Published on Web 09/09/2003

Thermally-Regulated Molecular Selectivity of Organosilica Sol−Gels

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Regulation of molecular events by external physical/chemical signals or stimuli is an exquisite strategy for allosteric regulation of biological processes.[1a] In this context, temperature is a ubiquitous and perennial stimulus. Consequently, thermal regulation remains an intrinsic control mechanism in biology from the modulation of ion transport,[1b,c] and binding/catalysis[1d] at molecular level to expression of genetic information[1e,f] at cellular level. As such, design of artificial systems (that can mimic thermally regulated control mechanisms with temperature-dependent selectivity at the molecular level) remains a particularly attractive goal. Here we report a novel system that exhibits unique temperature-dependent molecular selectivity and is able to interact preferentially with its environment with respect to thermal variations. We show that sol−gel-derived porous glasses act as thermoresponsive materials, which selectively bind, sequester, and release distinct molecules as a function of temperature. Furthermore, a particularly remarkable feature of this system is that the temperature-dependent molecular selectivity of the gels is reversible and can be efficiently modulated by simply changing the temperature.

Selectivity at the molecular level is a key factor in recognition, sensing, and separation phenomena.[2] Selectivity is most often due to functional groups, which can preferentially interact with an extrinsic molecule via specific noncovalent/covalent interactions.[3] However, such interactions are usually fixed, and the native affinity of the material is largely independent of external influences. Materials wherein the molecular interactions can be varied by modification of the external environment can provide an attractive pathway to the design of smart[4] or intelligent systems with precisely controlled molecular selectivity. We have recently demonstrated variations in hydrophobicity of organically modified silica gels by means of temperature.[5] Herein, we present results on thermally regulating the selectivity of these gels for specific molecules and demonstrate the feasibility of using temperature as a control mechanism for altering the selectivity. The porous sol−gels act as reversible thermoresponsive materials which become hydrophobic at high temperature and hydrophilic at low temperature.[5a] A particularly remarkable feature of these gels is their ability to preferentially sequester the hydrophobic molecule at high temperature and the hydrophilic species at low temperature.

The gels were made from bis[3-(trimethoxysilyl)propyl]ethylenediamine (enTMOS).[6] Typical preparations involved mixing 0.4 mL of precursor with 0.4 mL of water to obtain gels with approximate dimensions of 40 mm × 10 mm × 2 mm. The gel was then kept in contact with 3.5 mL of dye mixture (the concentration of each dye in the mixture was 500 μM) to study the selective intake of dyes. The release of dyes was studied by making enTMOS gels with the dye mixture encapsulated such that the concentration of each dye in the gel was 250 μM.

The selectivity of these gels (after an aging period of about 30 min) was evaluated by monitoring their affinity toward a dye pair as a function of change in temperature. The structures of dye molecules—brilliant blue G (BBG) and phenol red (PR)—used in this study are shown in Figure 1a. We used dye molecules that possess similar structures; however, they differ in the overall content of hydrophobic groups.[7] Thus, with the BBG+PR dye pair, the BBG molecule is the more hydrophobic of the two molecules. The intake/release of dye molecules was monitored by taking optical spectra of the outside solution at different time intervals to determine the changes in relative concentrations of each dye. For the dye pair, the ratio of absorbance at 432 nm (for PR) and 595 nm (for BBG) was measured, and the thermal selectivity of the gels under conditions of thermal equilibrium was estimated using the following equation:

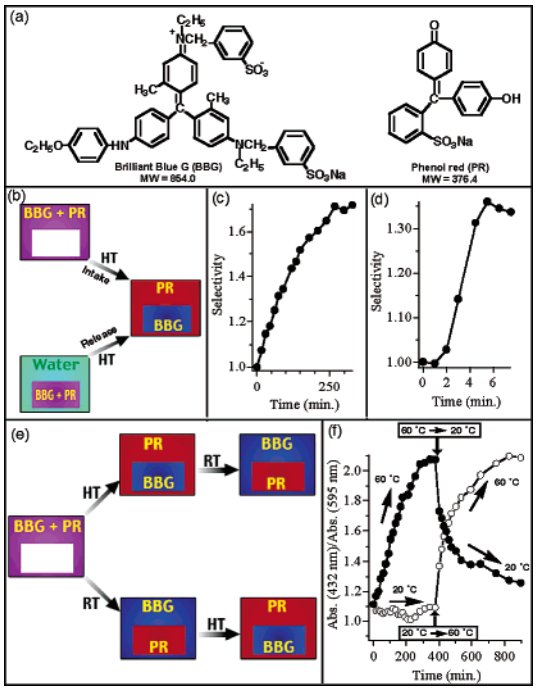

Figure 1. (a) Structures of dyes. (b) Schematic depiction of processes associated with selective intake and release of dyes. (c) Changes in thermal selectivity during intake. (d) Changes in thermal selectivity during release. (e) Schematic representation of processes associated with selective intake/release due to sequential changes in temperature. (f) Variation in absorbance ratio of dyes with respect to sequential change in temperature.

$$\text{thermal selectivity} = [\text{absorbance ratio}]_{HT}/[\text{absorbance ratio}]_{RT}$$

$$= [\{A_{(PR)}/A_{(BBG)}\}]_{HT}/[\{A_{(PR)}/A_{(BBG)}\}]_{RT}$$

where HT is high temperature (60 °C) and RT is room temperature (20 °C), and A corresponds to the absorbance maximum. As such, thermal selectivity increases as the gels preferentially absorb BBG at elevated temperature.

Parts b−d of Figure 1 show the results on selectivity of the gels with respect to temperature. The overall processes that take place

10.1021/ja0352348 CCC: $25.00

as a result of changing the temperature are summarized in Figure 1b. The enTMOS gels exhibit an enhanced selectivity toward the more hydrophobic BBG molecule at high temperature as compared to room temperature. Figure 1c shows the changes in thermal selectivity with respect to time as the pristine enTMOS gels—when exposed to a mixture of BBG and PR—show an increased affinity for the hydrophobic BBG dye at HT relative to RT.[8] Similarly, enTMOS gels containing encapsulated dye pair (250 μM each) preferentially release the less hydrophobic molecule (PR) and retain the more hydrophobic BBG dye at HT. Figure 1d shows the changes in thermal selectivity value due to *relative* increase in concentration of PR in the external solution at HT compared to RT. Thus, overall the results show that exposure of enTMOS samples to high temperature stimulus makes them hydrophobic, causing them to interact preferentially with the hydrophobic dye and exhibit enhanced thermal selectivity.[9]

Next, we investigated the feasibility of switching the selectivity of enTMOS gels by changing the temperature. The overall process of thermally modulating selectivity is schematically depicted in Figure 1e. When pristine enTMOS gels are exposed to an equimolar mixture (500 μM each) of dyes, they selectively intake the less hydrophobic molecule (PR) at RT. However, upon the increasing the temperature to 60 °C, the gels exhibit pronounced affinity toward the more hydrophobic BBG and retain it better in preference to the other molecule. The results on changes in selectivity accompanying these processes are shown in Figure 1f. The ratio of absorption maxima of the two dyes is used to estimate relative concentration of dyes in the external solution with respect to change in temperature. Thus, for the gels at RT, the ratio remains largely unchanged with time indicating equal concentration of dyes. However, when the temperature is increased, the ratio increases dramatically indicating a relative excess of PR in the external solution due to intake of BBG by the gels. Conversely, the gel sample initially kept at 60 °C shows an increase in the ratio with respect to time as the gels absorb BBG, leaving an excess of PR in the external solution. When the temperature is lowered, the gels begin to release BBG and start taking in PR, causing the absorption ratio to decrease dramatically. Thus, the results indicate the feasibility of reversibly switching the selectivity of the enTMOS gels by simply changing the temperature.

Taken together, the results suggest a unique temperature-controlled selectivity of enTMOS sol−gels.[10] These characteristics of the gels are due to several factors that elicit themoresponsive selectivity. First, these gels undergo a structural transition from a hydrophilic to a hydrophobic state when the temperature is increased.[5a] This change in hydrophobicity makes these gels interact favorably with hydrophobic molecules at HT and hydrophilic molecules at RT. Second, the temperature induced structural changes in these gels accompany volume shrinkage and an overall expulsion of water from the gel at HT.[5] The removal of water from the gel allows the hydrophilic molecules to be expelled from the gels with retention of the hydrophobic species. Third, the more compact structure of the gels at HT possibly favors better noncovalent interactions between pore walls of the gel and the dye molecule. Finally, lowering the temperature results in overall swelling of the gels along with reabsorption of water molecules,[5] which favors selective intake of the hydrophilic (or less hydrophobic) molecule of the dye pair by the gel. It is particularly important to note that the selectivity of these gels is not due to size-specific (or permiselective) interactions[11] since the gels at HT preferentially take in BBG which has a considerably high molecular weight (MW = 854) as compared to PR (MW = 376). Likewise, the gels at RT release the bigger BBG molecule in preference to PR. These observations rule out shape-selective interactions. Additionally, the fact that the selectivity of the enTMOS gels can be altered by simply changing the temperature (with all other conditions remaining constant) indicates that the thermal selectivity of the gels is strongly coupled with thermoresponsivity of the materials and the concomitant changes in hydrophobicity. As such, the observed results are consistent with selectivity originating as a result of thermally regulated noncovalent interactions.

In conclusion, we have established the ability of enTMOS sol−gels to exhibit thermally regulated selectivity. The enTMOS gels undergo temperature-controlled variations in hydrophobicity, which allows a subtle fine-tuning of noncovalent interactions with other molecules, leading to thermoregulated selectivity. The observed selectivity is reversible such that by changing the temperature, the affinity of the gels can be modified. Such a modulation of interactions is quite reminiscent of allosteric regulation in biology wherein an external influence can significantly alter binding and selectivity.[1a] An important aspect of these selective interactions is that the gels preferentially sequester the more hydrophobic molecule at higher temperature and subsequently release it at lower temperature. This feature may find potential applications in thermally regulated separation, release, detection, and sensing of different molecules as well as in designing novel devices such as temperature regulated molecular flow pumps, molecular filters, separators, and molecular sorters.

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(7) Similar results on thermal selectivity were also obtained with mixtures of thymol blue with phenol red and bromophenol red. The gels showed enhanced thermal selectivity for thymol blue (data not shown).

(8) The samples were kept in a controlled-temperature circulating bath maintained at the desired temperature.

(9) The dye molecules are distributed throughout the bulk of the material. Visual inspection of deliberately fragmented monoliths showed uniformity of color within the entire sample.

(10) Thermal selectivity is not observed with plain (TMOS-derived) silica gels.

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JA0352348