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Highly Precise Detection, Discrimination, and Removal of Anionic Surfactants over the Full pH Range via Cationic Conjugated Polymer: An Efficient Strategy to Facilitate Illicit-Drug Analysis

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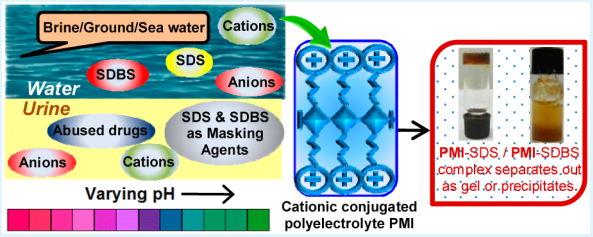
Supporting Information

ABSTRACT: A water-soluble cationic conjugated polyelectrolyte (CPE), poly(1,4-bis(6-(1-methylimidazolium)-hexyloxy)-benzene bromide) (PMI) displays extraordinary stability over the full pH range of 1−14 as well as in seawater, brine, urine, and other solutions and carries out efficient detection, discrimination, and removal of moderately dissimilar anionic surfactants (viz., sodium dodecyl benzenesulfonate (SDBS) and sodium dodecyl sulfate (SDS)) at very low levels (31.7 and 17.3 parts per billion (ppb), respectively). PMI formed stable hydrogels in the presence of SDS that remained unaffected by strong acids/bases, heating, ultrasonication, or exposure to light, whereas SDBS formed precipitate with PMI as a result of its different interpolymer cofacial arrangement via Columbic attraction. The complex-forming ability of PMI with SDS and SDBS facilitated their elimination from water or drug-doped urine samples without the use of any organic solvent, chromatographic technique, or solid support. This protocol, the first of its kind for the removal of anionic surfactants at very low concentrations from any type of solution and competitive environments, demonstrates an original application using a CPE. The surfactant-free sample solutions could be precisely analyzed for the presence of illicit drugs by any standard methods. Using PMI, a newly developed CPE, a rapid and practical method for the efficient detection, discrimination, and removal of SDS and SDBS at ppb levels from water and urine, under harsh conditions, and in natural chemical environments is demonstrated.



KEYWORDS: *conjugated polyelectrolyte, surfactants, sensors, fluorometric, illicit drugs, masking agents*

INTRODUCTION

Anionic surfactants that possess hydrophobic alkyl chains (nonpolar) and hydrophilic groups (polar) are indispensable in the detergent industry; for emulsification, lubrication, and catalysis; and for their well-known interaction with biomolecules such as proteins, DNA, and peptides, even possessing the ability to penetrate cell membranes.[1−5] Because of their large application base and extensive industrial scale production, it has become extremely important to determine their presence in pharmaceutical and food formulations, as drug-abuse-masking agents, in wastewater treatment plants, in the environment, and in biological fluids as well as to analyze them in trace quantities because they are well-recognized contaminants.[6,7] Another critical problem associated with anionic surfactants (viz., sodium dodecyl benzenesulfonate (SDBS) and sodium dodecyl sulfate (SDS)) is their extensive misuse as adulterants and masking agents, along with abused and performance-enhancing drugs, to evade detection by doping tests.[8,9] It is estimated that approximately 20 million individuals are screened each year in the United States alone for illicit drug abuse. Thus, adulterants are a severe challenge when testing for abused drugs. Detergents containing SDS and SDBS have also been found to be one of the most common specimens in adulterated forensic urine drug tests because they can interfere with the immunoassay/initial test via a combination of pH and ionic strength, remove the drug by forming an insoluble complex, or cause impediments with gas chromatography−mass spectrometry (GC-MS) confirmation procedures.[9−12] Most of the fluorometric sensors developed for anionic surfactants have been employed for either the analysis of industrial samples in quality control processes or environmental monitoring. To the best of our knowledge, no conjugated polymers/polyelectrolytes (CPE) platforms, recognized for their superior chemical stability, tunable photophysical properties, and high sensitivity, have been developed to detect and to distinguish among anionic surfactants in water, urine, and biological fluids or under extremely harsh conditions such as seawater and brine as well as over the full pH range of 1−14. This unique property of poly(1,4-bis(6-(1-methylimidazolium)-hexyloxy)-benzene bromide) (PMI) was utilized to efficiently remove anionic surfactants used as masking agents in drug testing by simple gelation or by precipitation, thereby enabling efficient and error-free analysis of the illicit drugs and demonstrating a novel application of CPEs that has not previously been realized with any synthetic material.

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Several surfactant-analysis techniques, such as the methylene blue active substances (MBAS) method,[13] ion-selective electrodes, capillary electrophoresis,[14] high-performance liquid chromatography[15] (HPLC), gas chromatography and mass spectroscopy[16] (GC-MS) are widely used but have multiple limitations in their applicability, owing to tedious procedures, irreproducibility, and signal instability as well as requiring the use of large amounts of chlorinated solvents that are not readily biodegradable. Despite the enormity of the problem, the limitations in the existing surfactant-analysis systems, and the necessity to have efficient alternate detection platforms, very few reports on the use of fluorescence and/or UV/vis spectra have been developed to detect anionic surfactants.[17−19] In addition, these surfactants tend to form micelles or to accumulate at the air−water interface as a stable foam, with the hydrophobic tail in the air and hydrophilic head in the water, posing serious separation problems; as a result, no existing methods can remove these large organic contaminants, e.g., SDS and SDBS. Therefore, the development of superior probes and efficient methods to detect anionic surfactants at low concentrations in water, under acidic/basic conditions, and in a competitive environment and to remove them from biological fluids or effluent wastes has immense technological significance, yet remains an unsolved problem.

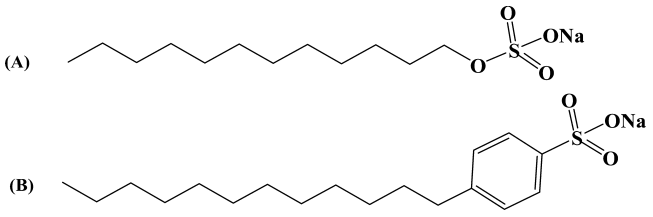
Charged polyelectrolytes have a strong tendency to form stable complexes with oppositely charged surfactant molecules, and the resulting complexes may have different conformations than the free polymer.[20−24] Among the various anion receptors, imidazolium has been widely reported as a suitable coordination site for anions via both electrostatic and hydrogen-bonding interactions.[25,26] Recent studies have also shown their ability for the recognition of anionic surfactants.[17,18,27,28]

Herein, we report the synthesis and characterization of PMI, a new cationic CPE, that neither degrades nor shows loss of activity over the full pH range of 1−14 and that displays significant photophysical and conformational changes in the presence of anionic surfactants SDBS and SDS with precise and highest selectivity. This PMI system was found to be highly effective at detecting and distinguishing SDS and SDBS in aqueous media, most notably, over the full working pH range at which the solubilities of both surfactants are very high; this has not been perceived with any synthetic sensors in prior instances. We also demonstrate that by combining the CPE (PMI) with dissimilar anionic surfactants, the geometric conformation of the CPE is altered, thereby bringing significant photophysical changes that in principle form the basis on which to distinguish anionic surfactants with minor structural variations. On the basis of this principle, the PMI system was utilized to detect the presence of anionic surfactants in aqueous samples, random urine specimens, and drug formulations and to remove them efficiently.

EXPERIMENTAL SECTION

Materials and Instruments. Chemicals (viz., SDBS, triton-X-100, tween-20, cetyltrimethylammonium bromide (CTAB), sodium laurate, sodium stearate, sodium *p*-toluenesulfinate, sodium *p*-toluenesulfonate, 1,6-dibromohexane, 1-methyl imidazole, and metal salts (used as their perchlorates)) were purchased from Aldrich chemicals. SDS was purchased from Merck. Scheme 1 shows the structures of SDS and SBDS. Four different classes of benzodiazepines that are available as commercial drugs were purchased and used. UV/vis and PL spectra were recorded on a PerkinElmer Lambda-25 spectrophotometer and a Horiba Fluoromax-4 spectrofluorometer using 10 mm path length quartz cuvettes with a slit width of 2 nm at 298 K. Atomic force microscopy images were recorded on an Agilent 5500-STM instrument. FT−IR spectra were recorded on a PerkinElmer spectrometer with samples that were prepared as KBr pellets. ^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded with a Varian-AS400 NMR spectrometer. GPC data was recorded with a Waters-2414 instrument (polystyrene calibration). Urine specimens were collected by a laboratory from different individuals at different time intervals.

Scheme 1. Structures of Anionic Surfactants (A) Sodium Dodecyl Sulfate (SDS) and (B) Sodium Dodecyl Benzene Sulfonate (SDBS)



Synthesis of 1,4-Bis(6-bromohexyloxy)-benzene (M1) and Poly(1,4-bis(6-bromo-hexyloxy)-benzene) (PBr). Synthesis of monomer M1 and polymer PBr were carried out by using a previously established procedure.[29−33] To prepare PBr, anhydrous ferric chloride (0.74 g, 4.57 mmol) was dissolved in 10 mL of nitrobenzene and transferred to a three-necked round-bottomed flask that was equipped with a nitrogen inlet. Using a syringe, M1 (1.0 g, 2.03 mmol, dissolved in 15 mL of nitrobenzene) was introduced into the flask. The reaction mixture was then stirred for 36 h at room temperature, followed by precipitation from methanol. The reaction mixture was centrifuged and washed repeatedly with methanol. The resulting polymer was finally dried under reduced pressure to obtain a brown-colored powder. Yield: 70%. ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.07 (s, 2H), 3.94 (m, 4H), 3.36 (m, 4H), 1.81 (m, 4H), 1.69 (m, 4H), 1.52 (m, 4H), 1.41 (m, 4H). GPC in THF, polystyrene standard: $M_w = 2.32 \times 10^4$, PDI = 1.7.

Synthesis of Poly(1,4-bis(6-(1-methylimidazolium)-hexyloxy)-benzene bromide) (PMI). To a 100 mL round-bottomed flask, PBr (0.12 mmol, 1equiv) and an excess of 1-methyl imidazole were added and kept at reflux under stirring in an oil bath at 80 °C for 24 h. The reaction mixture was then poured into an of excess chloroform and stirred for 1 h to obtain a precipitate. The process was repeated twice to remove excess 1-methyl imidazole and PBr. The precipitate was filtered out and dried to get a brownish-colored sticky product. Yield: 85%. ^{1}H NMR (400 MHz, CD_3OD, δ): 9.0 (s, 1H), 7.70 (d, 1H), 7.59 (d, 1H), 7.10 (s, 2H), 4.62 (m, 4H), 4.23 (m, 4H), 3.96 (m, 6H), 1.90 (m, 4H), 1.70 (m, 4H), 1.39 (m, 4H). FT−IR (ν_{max}/cm^{-1}): 2928.08, 2855.31, 1634.02, 1571.27, 1463.99, 1381.17, 1206.33, 1168.33, 1021.93, 757.54.

Method of Calculating Fluorescence Quantum Yield. Fluorescence quantum yield of PMI in water and methanol was determined using quinine sulfate ($\Phi_r = 0.54$ in 0.1 M H_2SO_4) as the standard and was calculated from the following equation.[34]

$$\Phi_s = \Phi_r(A_rF_s/A_sF_r)(\eta_s^2/\eta_r^2)$$

Here, s and r denote the sample and reference, respectively; A is the absorbance, F is the relative integrated fluorescence intensity, and η is the refractive index of the solvent used.

Preparation of Stock Solutions and Fluorescence and Absorbance Studies of PMI. Surfactants, anions, and various metal stock solutions were prepared (10.0×10^{-3} M in Milli-Q water). The stock solutions were diluted to the desired concentrations with Milli-Q water when needed. A solution of PMI (2×10^{-5} M) in repeat units in HEPES buffer (pH 7.2, 10 mM) was placed in a 3 mL cuvette (10.0 mm width) and then the fluorescence spectrum was recorded. Different analyte solutions were introduced, and the changes in the fluorescence intensity were recorded at room temperature each time (excitation wavelength = 325 nm). Similarly, the absorbance of PMI (2×10^{-5} M in HEPES buffer (pH 7.2, 10 mM)) was recorded at room

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temperature, and the stock solutions of SDS and SDBS were introduced separately to observe the change in absorbance induced by each.

Methods for Calibration Curve and Detection Limit. Different solutions of PMI (2×10^{-5} M), each containing SDBS (0, 2, 4, 6, 8, 10, 12, 14, and 16 μM) or SDS (0, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 μM), were prepared separately in HEPES buffer (pH 7.2, 10 mM). The fluorescence spectrum was then recorded for each sample by excitation at 325 nm. The calibration curve for SDBS/SDS was obtained by plotting change in the fluorescence intensity versus the concentration of SDBS/SDS. The curve demonstrates a linear relationship, and the correlation coefficient (R^2), determined via linear regression analysis, was calculated to be 0.9900 (SDBS) and 0.9893 (SDS). The limit of detection (LOD) was calculated on the basis of the standard method reported in the literature[35] using the equation

$$\text{LOD} = 3 \times \text{S.D.}/k$$

where k is the slope of the curve equation and S.D. represents the standard deviation for the intensity of the PMI solution in the absence of these analytes.

Gel Formation and Precipitation. Stock solutions of PMI and surfactants SDS and SDBS (0.05 M) were prepared separately in Milli-Q water. Similarly, 0.05 M solutions of SDS and SDBS were prepared in untreated urine as well as in drug-doped specimens. Mixing was done by dropwise addition of the homogeneous surfactant solutions to the aqueous polyelectrolyte solutions. The PMI−SDS complex formed a gel, whereas the PMI−SDBS separated out as a precipitate. Microcentrifugation of the PMI−SDS complex at 14 000 rpm produced a highly stable hydrogel. The hydrogel and the precipitate complexes of anionic surfactants with PMI were separated and the aqueous solution was analyzed by thin layer chromatography analysis to confirm the presence of the drug.

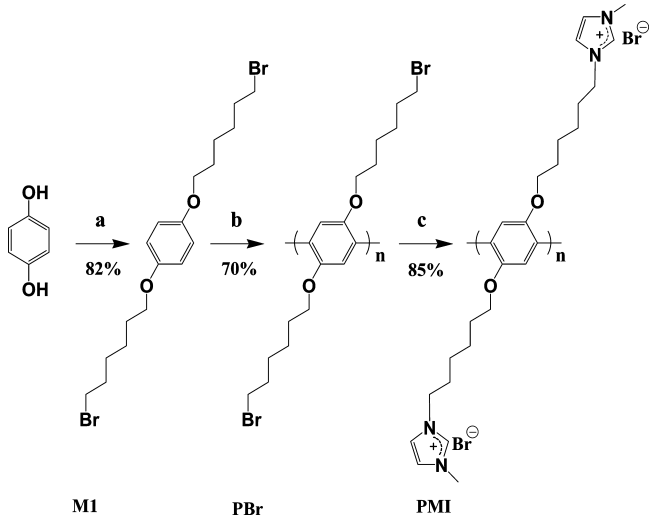
Control Experiment Using Drug-Doped Urine Specimens. Tablets (viz., Lonazep (0.25 mg of clonazepam), Nitrest (5 mg of zolpidem), Alzolam (0.25 mg of alprazolam) and Clampose (5 mg of diazepam)) were crushed and independently mixed with 3 mL of a urine specimen and then subjected to Whattman filtration to remove any insoluble components. A total of 50 μL of each sample was added to an aqueous solution of PMI, and changes in fluorescence were recorded. Each sample was then independently doped with SDBS (10^{-2} M) or SDS (10^{-2} M) to prepare standard stock solutions, set aside for 2 d, and used for sensing purposes.

RESULTS AND DISCUSSION

Synthesis and Characterization of PMI. The synthesis of PMI is shown in Scheme 2. *N*-Methyl imidazole was introduced onto the terminal bromide atoms of the neutral conjugated polymer (PBr), using postpolymerization functionalization, resulting in 85% yield of cationic polymer PMI. All of the products were well characterized by NMR, FT−IR, and GPC (Figures S1−S3). The molecular weight (M_w) of the polymer PBr was found to be 2.32×10^4, PDI = 1.7 (GPC in THF, PS standard). Fluorescence quantum yield (Φ_s) of PMI was calculated in water and methanol and found to be 0.32 and 0.36, respectively.

Effect of pH on the Emission of PMI. Water-soluble cationic polymer PMI shows an absorption maximum at 325 nm and an emission maximum at 406 nm (325 nm excitation) in aqueous media. The pH studies using NaOH/HCl and a buffer demonstrated that the fluorescence of PMI is retained over the full pH range of 1−14, with negligible fluorescence quenching of 2−12% observed at higher pH (Figure S4). Furthermore, no changes in the emission maxima and shape of the spectra were observed over the full pH range studied here. Because the pH stability of PMI is extraordinarily high, the application of PMI could be extended over the full pH range;

Scheme 2. Synthesis of Poly(1,4-bis(6-(1-methylimidazolium)-hexyloxy)-benzene bromide) (PMI)



[a] K_2CO_3, dry acetone, 1,6-dibromohexane, 70 °C. [b] $FeCl_3$, nitrobenzene, room temperature, 36 h. [c] 1-methyl imidazole, reflux, 24 h.

this range was previously not accessible with any other synthetic probes. This also confirms that irrespective of the environment or sample source the loss of PMI activity would be insignificant.

Optical Sensing of SDBS and SDS. At the outset, the photophysical changes of PMI were studied in the presence of the surfactants to demonstrate its detection ability. The fluorescence intensity of PMI decreased after the addition of successive aliquots of surfactants to the PMI solution (2×10^{-5} M in HEPES buffer (pH 7.2, 10 mM)). The addition of only 1 equiv of SDBS or SDS (2×10^{-5} M) to the solution of PMI caused a decrease (~90%) in the fluorescence intensity (λ_{ex} = 325 nm), with a red shift of ~12 and ~21 nm with SDBS and SDS, respectively (Figure 1a,b). In addition to the red shift, the emission spectrum of the PMI−SDS complex (Figure 1b) shows a well-defined vibrational structure as a result of interchain charge-transfer reactions and excimer formation.[36,37] However, no such change was observed in the spectrum of the PMI−SDBS complex (Figure 1a). To calculate the lower LOD, a curve was created by plotting the maximum emission intensity of PMI versus the concentration of SDBS/SDS in aqueous solution (Figures 2 and S5 and S6). The curve demonstrates a linear relationship with a correlation coefficient (R^2) value of 0.9860 and 0.9775 for SDBS and SDS, respectively. The detection limits calculated for SDBS and SDS were found to be 110 nM (31.7 ppb) and 61 nM (17.3 ppb), respectively, which confirms the ability of PMI to detect surfactants in aqueous media at very low levels that were previously inaccessible.[17,18,27,28]

Selectivity Studies. Other widely used surfactants (viz. triton-X-100, tween-20, cetyltrimethylammonium bromide (CTAB)) and several anions, including those found in urine such as halides (Cl^-), phosphates (PO_4^{3-}), and sulfates (SO_4^{2-}), did not cause any significant changes in the fluorescence emission of PMI (Figure 1c) when compared with the spectra of PMI with added SDS and SDBS. To identify the effect of the hydrophobic chains of SDS and SDBS on the photophysical properties of PMI, the sodium salts of SO_4^-, SO_4^{2-}, *p*-toluenesulfinate (SO_2^-), and *p*-toluenesulfonate

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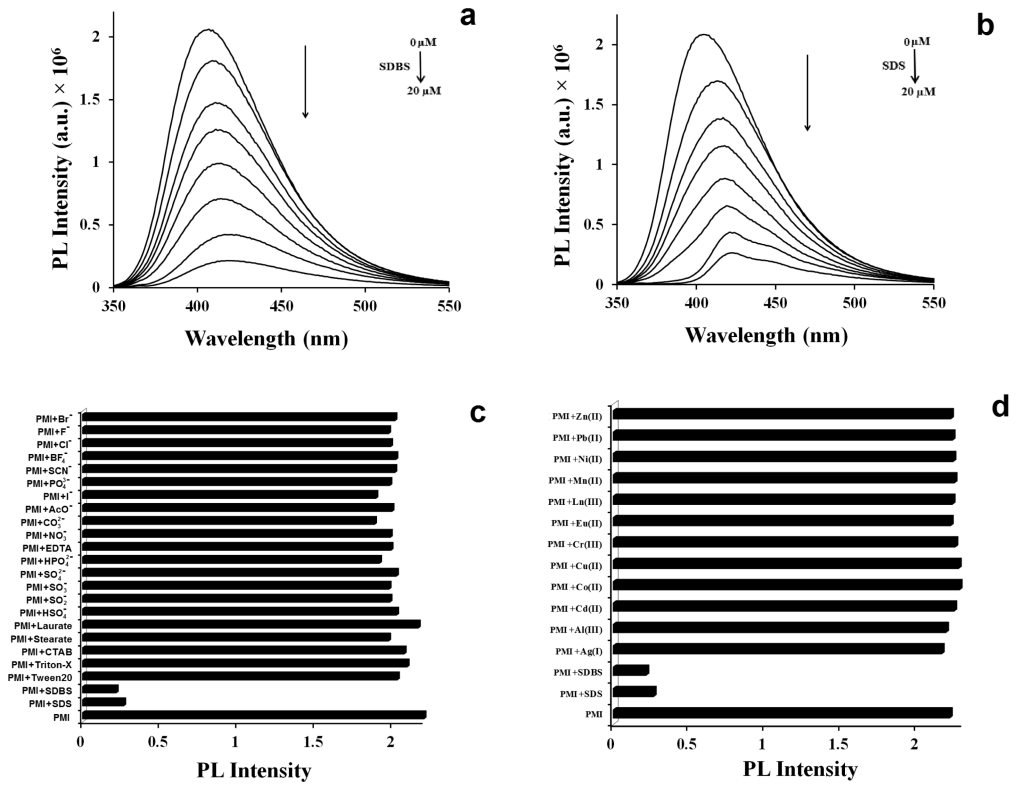

Figure 1. PL spectra of PMI with increasing concentration of (a) SDBS (λ_{ex} = 325 nm) and (b) SDS (λ_{ex} = 325 nm) in HEPES buffer (pH 7.2, 10 mM). Fluorescence quenching was found to be ~90%. Concentration of PMI inside the cuvette was 2×10^{-5} M. Final concentration of SDBS and SDS was 2×10^{-5} M. Bar diagrams depicting the effect of various (c) anions and surfactants and (d) metal ions on the fluorescence intensity of PMI in water. Concentration of PMI and other analytes are 2×10^{-5} and 2×10^{-4} M, respectively.

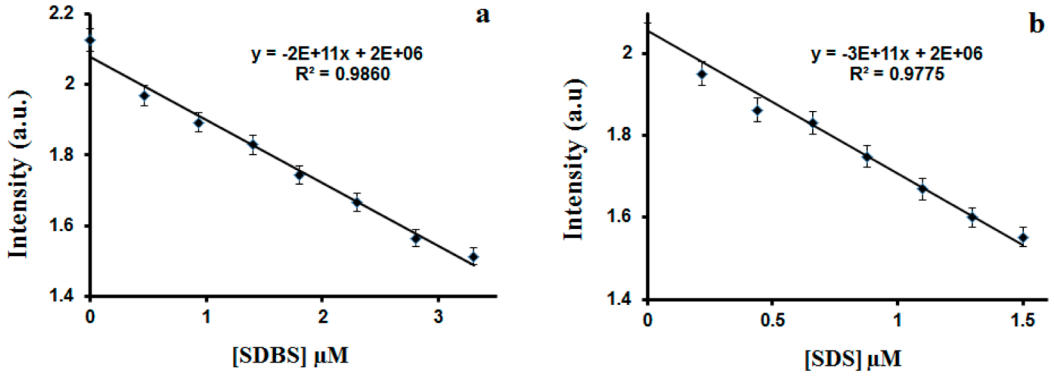

Figure 2. Detection limit plots, obtained after the addition of various concentrations of (a) SDBS and (b) SDS to a solution of PMI (2×10^{-5} M in HEPES buffer (pH 7.2, 10 mM)).

(SO_3^-) were titrated with PMI. However, no noticeable changes were observed in the fluorescence emission peaks of PMI after the addition of these anionic salts (Figures 1c and S7). Fluorometric titration of PMI with anionic surfactants (viz. sodium laurate and sodium stearate) were also carried out to ascertain the effect of polar head groups with characteristics (i.e., charge distribution and hydrophobic chain length) similar to those of SDS, but no remarkable changes in the fluorescence emission of PMI were observed, suggesting a lesser preference for carboxylate salts (Figures 1c and S7). Common metal ions, such as Cu^{2+}, Co^{2+}, Ni^{2+}, Pb^{2+}, Cr^{3+}, Mn^{2+}, Cd^{2+}, Ln^{3+}, Zn^{2+}, Eu^{3+}, Ag^{+} and Al^{3+}, were also ineffectual toward the fluorescence quenching of PMI (Figures 1d and S8). These results confirm that the combination of the hydrophobic chains and the polar head groups of surfactants plays a key role in the assembly of PMI toward an interchain cofacial arrangement[19,23,36] and is vital for both sensitive and selective detection and conformational changes.

Monitoring Complexation via UV/Vis Spectroscopy. The interaction of anionic SDBS and SDS with cationic PMI was also studied by UV/vis spectroscopy to gain further insight into the polymer−surfactant interactions. Significant shifts in the absorption peaks occurred after the addition of these two surfactants to the aqueous solution of PMI (2×10^{-5} M). The absorption maximum peak of PMI was red-shifted by 15 nm (Figure 3a) after the addition of a total of 1 equiv of SDBS, with the clear formation of isosbestic point at 330 nm. However, the presence of SDS had a more remarkable effect on the structure of PMI, as observed by the significant 55 nm redshift of the 325 nm peak to 380 nm, with the formation of

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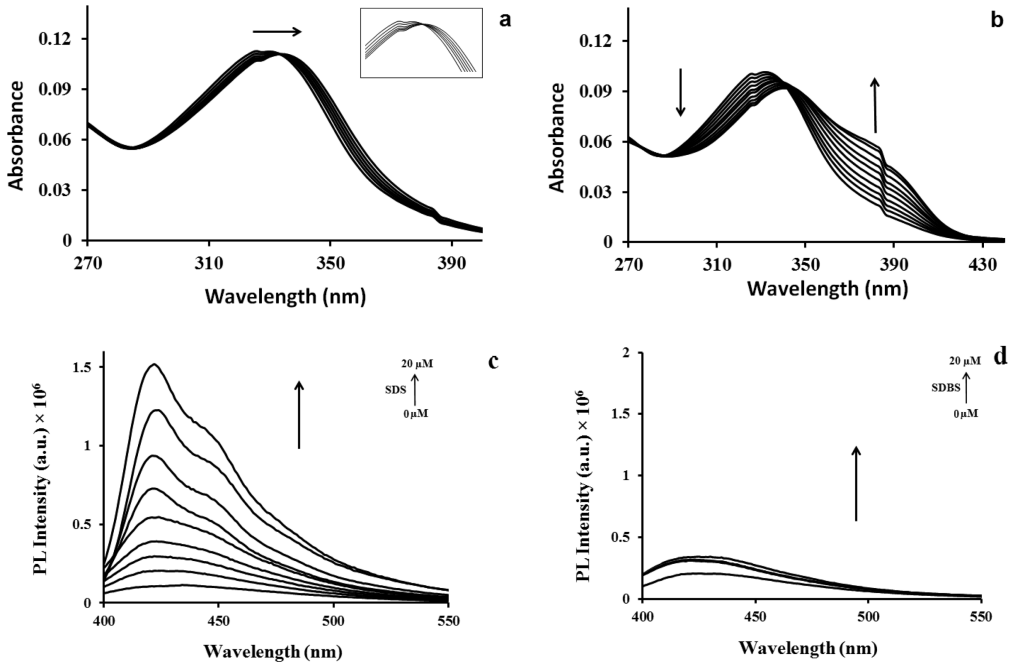

Figure 3. UV/vis titration spectra of PMI (2×10^{-5} M) with increasing concentrations of (a) SDBS (2×10^{-5} M) and (b) SDS (2×10^{-5} M). PL spectra of PMI (2×10^{-5} M) with increasing concentrations of (c) SDS (λ_{ex} = 380 nm) and (d) SDBS (λ_{ex} = 380 nm) in HEPES buffer (pH 7.2, 10 mM). Fluorescent enhancement was found to be ~90% after the addition of 1 equiv of SDS. SDBS did not cause any significant change in fluorescence.

an isosbestic point at 345 nm after continuous addition of up to 1 equiv of SDS (Figure 3b). These redshifts are attributed to the J-type aggregation of PMI upon binding with SDBS or SDS as a result of an interpolymer cofacial arrangement; J-type aggregates generally display bathochromic shifted bands because of increased chain or aggregate length.[38] The appearance of isosbestic points in the absorption spectra with increasing SDBS/SDS concentration also provides strong evidence for an equilibrium between the polymer PMI and each surfactant.

Discrimination between SDBS and SDS. Interestingly, when PMI (2×10^{-5} M in HEPES buffer (pH 7.2, 10 mM)) was excited at 380 nm, the emission spectra showed remarkable fluorescent enhancement at 424 nm after the addition of SDS, with a well-defined vibrational structure (Figure 3c). Enhancement of PMI fluorescence was found to be ~90% at 2×10^{-5} M SDS concentration. These spectral changes suggest that after the addition of SDS to the aqueous solution of PMI the polymer shifts to a different conformation that has an emission peak at 424 nm. PMI starts out as the first species, but when the concentration of SDS reaches 2×10^{-5} M, the polymer shifts to a different conformation, i.e., a polymer–SDS complex that induces the formation of an excimer. However, no such fluorescent enhancement was observed in the emission spectra of PMI after the addition of SDBS (Figure 3d), indicating that excimer forms with PMI–SDS but not with PMI–SDBS. On the basis of these observations, moderately dissimilar anionic surfactants (viz., SDBS and SDS) can be easily discriminated in aqueous media by tuning the excitation wavelength of PMI.

Because the emission spectra changes with the excitation wavelength, a thorough study was carried out that monitored the change in emission spectra of both the PMI–SDBS and PMI–SDS complexes at different excitation wavelengths (300–400 nm). It was found that the PMI–SDBS complex does not show significant enhancement of fluorescence at any excitation (300–400 nm, Figure S9a). However, substantial fluorescence enhancement at 424 nm was observed in case of the PMI–SDS complex when changing the excitation wavelength (300–400 nm, Figure S9b). The intensity of the emission maxima at 424 nm was highest when recorded at 380 nm, indicating that the PMI–SDS complex induces excimer formation at this emission wavelength. Similarly, excitation spectra were also monitored at different emission wavelengths (400–500 nm) to examine the species present in the system. The excitation spectra of the PMI–SDBS complex (Figure S10a) has a peak at ~340 nm (at any emission between 400–500 nm), confirming the formation of a new species. However, the PMI–SDS excitation spectra (Figure S10b) showed a peak at ~380 nm (at any emission between 400–500 nm), indicating the formation of a complex between PMI and SDS. These results are in good agreement with the UV/vis studies and confirm the formation of a new species between PMI and SDBS/SDS detectable at 340 and 380 nm, respectively.

We have also demonstrated that the polymer PMI can efficiently distinguish between SDBS and SDS in a mixed and competitive environment. To confirm this unique ability of PMI to differentiate between moderately dissimilar anionic surfactants, the following experiment was carried out. A solution of SDS and SDBS in Milli-Q water (pH 7) was prepared by adding equimolar concentrations (10 mM each) of these surfactants, and the solution was incubated for 2 d at room temperature. When this mixture (2×10^{-5} M) was added to a solution of PMI (2×10^{-5} M, 325 nm excitation), ~90% fluorescent quenching was observed. However, when PMI was excited at 380 nm, the fluorescent enhancement was found to be ~55%. This result postulates that SDS and SDBS interact almost equally with PMI and that they can be distinguished by PMI even in a mixed environment.

Mechanistic Studies of Complexation. Generally, CPEs are present as weak aggregates in aqueous solution, with ionic

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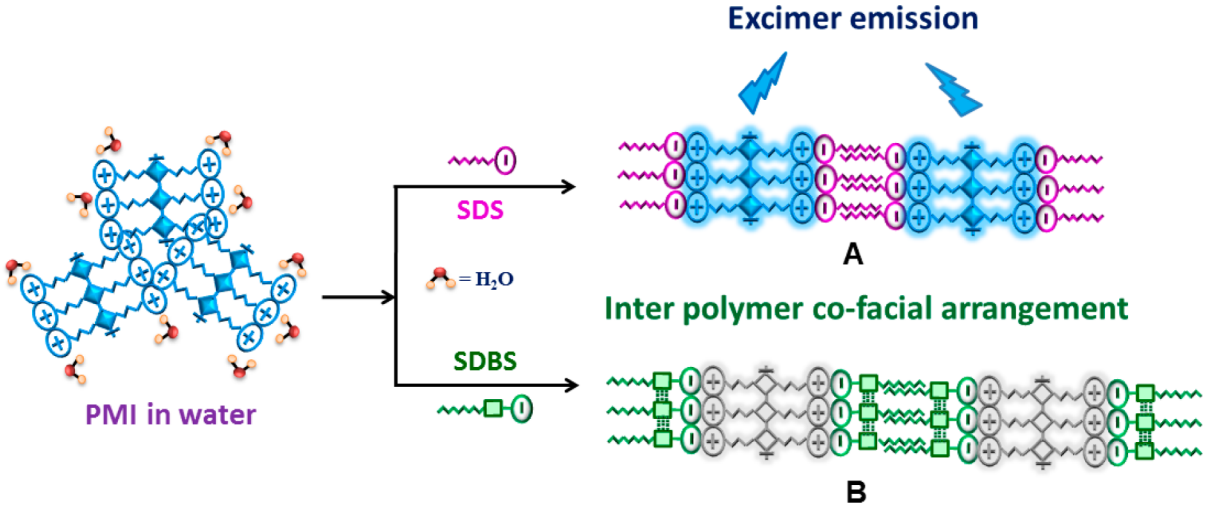

Figure 4. Schematic representation of the aggregation behavior of the (A) PMI–SDS and (B) PMI–SDBS complexes.

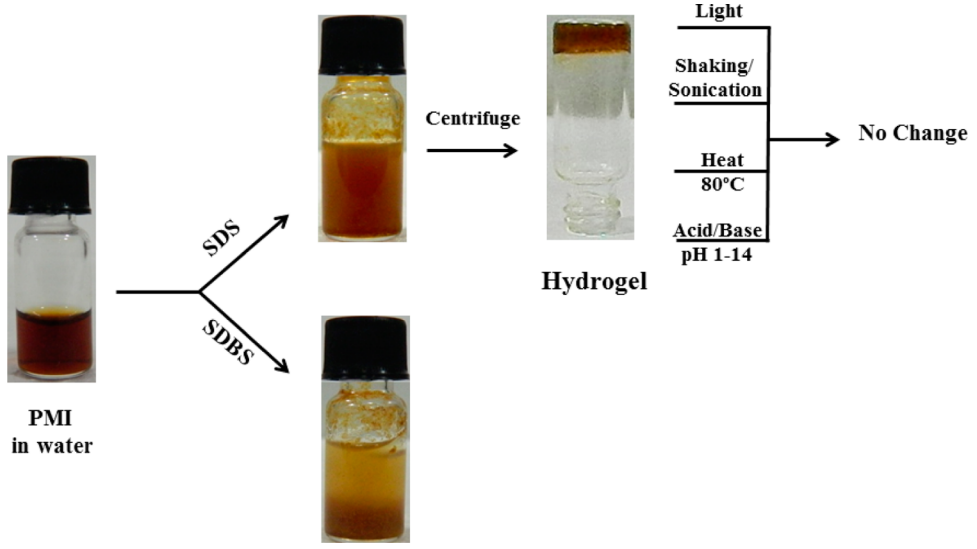

Figure 5. Solutions of PMI and SDS/SDBS in water were mixed and kept standing for a few minutes. PMI–SDS forms a stable hydrogel when this is followed by centrifugation, whereas PMI–SDBS separated out as a precipitate. The hydrogel showed very high stability when subjected to thermal, chemical, photo, and mechanical stresses and displayed irreversible behavior.

side chains facing the water–polymer interface and π–π stacking occuring between the backbones within.[39] The complexation between PMI and surfactants SDBS and SDS via interpolymer cofacial arrangement and the interaction of hydrophobic chains with these anionic surfactants is driven by Columbic interactions. Consequently, the interfacial water molecules are released during complexation, which may further assist the extension of the polymer chains by reducing conformation disorders.[19] After the addition of SDS to the aqueous solution of PMI, the extended chains promote interchain packing via the PMI–SDS complex and overlap to form excimers[36] that emit fluorescence at a longer wavelength (Figure 4A). The large redshift in the absorption spectra and the emission at a longer wavelength can be attributed to this observation. However, the SDBS/PMI mixture failed to show any excimer emission, which indicates that the aromatic rings present in SDBS restrict the interchain packing of the PMI–SDBS complex (Figure 4B).

Gel Formation and Precipitation. To gain a better understanding of the complexation process, the polymer and the surfactants were mixed at higher concentrations of 0.05 M (1:1 mol ratio of PMI/surfactant) by dropwise addition of the surfactants to the PMI solution. When SDS (10^{-5} M) was added to the clear solution of PMI, the mixture became more viscous, resulting from intermolecular association and cross-linking via Columbic attraction (Movie 1). As the SDS concentration is increased, a self-assembled 3D network with high viscosity and a semisolid-gel nature was formed[40] (Figure S11) because of the intermolecular association between PMI and SDS via hydrophobic chain interactions and efficient interchain interdigitations. The hydrogel thus obtained displayed extraordinary chemical, thermal, and optical stability for a prolonged period of over six months. A similar observation was reported[23] for a P3KHT–CTAB complex, formed by the interaction of anionic polythiophene and cationic surfactant. Because of this high stability, the gel showed irreversible behavior when subjected to thermal, chemical, optical, and mechanical stresses (Figure 5). Interestingly, this irreversible PMI–SDS hydrogel does not collapse even under extremely acidic or basic conditions (pH

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1−14), at high temperature, in the presence of light, or under prolonged shaking/sonication. However, PMI did not form a gel in the presence of SDBS (10^{-5} M); instead, the complex precipitated out of the solution, a behavior of PMI with SDBS that clearly distinguishes it from the gel-forming PMI−SDS complex. The amount of PMI−SDBS precipitate that was formed further increased at higher SDBS concentration (10^{-5}−10^{-2} M) and could be easily separated from the clear liquid after standing. It may be presumed that after the addition of SDBS to PMI the complex is favored to remain in a planar conformation rather than forming a 3D network.[23]

It has been reported earlier that anionic surfactants present at levels of 10^{-4} M or greater interfered with and gave false negative results in immunoassay and GC-MS procedures during drug-analysis tests[41] with several urine specimens. Hence, alternate strategies that can overcome the limitations in the existing methods with regard to eliminating anionic surfactants SDS or SDBS from the drugs are indispensable for the accurate analysis of illicit doping. Experiments utilizing PMI confirmed that it is possible to easily remove both SDS and SDBS from water and urine containing illicit drugs (Figures 5 and S12, respectively) at concentrations much lower than those allowed by existing methods because both the PMI−SDS gel and the PMI−SDBS precipitate form rapidly at room temperature without the use of any chromatographic technique or solid support; this demonstrates a practical application of PMI that was previously unfeasible with any other material.

Detection of SDBS/SDS at Varying pH. Furthermore, PMI showed extraordinarily high detection ability over the full pH range of 1−14, a range over which synthetic sensors are rarely recognized to operate. This unique feature of PMI was further verified by carrying out detection under harsh and unfavorable conditions, i.e., highly acidic and basic environments as well as seawater and brine samples. The quenching efficiency of PMI remained unperturbed over the full pH range, with a very negligible decrease of 2−12% at pH 8−14 in the presence of SDBS and SDS (Figure S13). Such high stability demonstrated by the PMI system has not previously been perceived with synthetic sensors and is a unique feature of PMI.

Detection of SDBS and SDS in Brine, Groundwater, Seawater, and Urine Specimens. To further confirm the feasibility of PMI as a sensor in practical applications, we carried out detection studies of SDBS and SDS under competitive-environment conditions and natural samples because these surfactants are categorized as the most common pollutants to be found in technogenic water and natural water and as adulterants in urine specimens.[28] In a typical experiment, various groundwater, seawater, brine, and random urine samples were independently spiked with known concentrations of SDBS and SDS and utilized for sensing experiments. Experiments carried out using various groundwater, seawater, and brine samples confirm the practicability of PMI to detect both these surfactants efficiently under competitive-environment conditions at very low ppb levels (Figures S14−S19 and Tables S1−S3). This protocol demonstrated enhanced features for the detection of anionic surfactants (viz., SDBS/SDS) in aqueous media without the use of hazardous chlorinated organic solvents.[13,41] Likewise, seawater is known to have high salinity and an excess of dissolved ions, yet PMI showed no loss of activity under such harsh environmental conditions and was able to detect both SDS and SDBS efficiently.

Similarly, six urine specimens (pH 6−7) were collected from different consenting individuals at varying time intervals and used without further treatment. Fluorometric titration was carried out by adding aliquots of urine to a solution of PMI (2×10^{-5} M in HEPES buffer (pH 7.2, 10 mM)). It was found that the interference of urine on the fluorescence emission of PMI was negligible (Figure S20). To acquire enhanced and accurate results, three samples that caused a minimum change in the fluorescence emission of PMI were then separately spiked with known concentration of SDBS and SDS (10^{-3} and 10^{-3} M, respectively). After adding known volumes of these spiked samples to a solution of PMI (2×10^{-5} M), the fluorescence spectra were then recorded (Figures S21 and S22), and the peaks were compared with the standard calibration curves (Table 1) after taking three replicate measurements. It

Table 1. Determination of Anionic Surfactants in Urine Specimens

urine sample	SDBS added (10^{-7} M)	SDBS found (10^{-7} M)[a]	SDS added (10^{-7} M)	SDS found (10^{-7} M)[a]
U1	40.00	33.40 ± 2.00	50.00	51.51 ± 1.73
U2	90.00	86.05 ± 2.64	33.33	30.70 ± 1.00
U3	123.33	122.67 ± 3.60	90.00	85.40 ± 3.00

[a]An average of three replicate measurements with standard deviation.

could be established from these experiments that even in urine samples PMI can detect and estimate the presence of SDBS and SDS at very low levels (10^{-7} M) that were inaccessible in the past with any sensors.[17,28] This study formed the basis for carrying out further analysis of surfactants with high stability that are used as adulterants and masking agents in biological fluids.

Detection of SDBS and SDS in Drug-Doped Urine Specimens. To determine the ability of PMI to detect SDS and SDBS being used as adulterants and masking agents with recreational, abused, and performance-enhancing drugs, we carried out detection experiments by spiking these surfactants with several prescription drugs commonly used as abused agents. The most popular recreational drugs used worldwide include amphetamines, cocaine, cannabinoids, and heroin. Subjects abusing these drugs may adulterate the urine specimens with anionic surfactants to mask them and to evade illicit drug detection during testing[12] because these surfactants are stable in a biological environment for extended periods. Benzodiazepines are also considered to be one of the most commonly abused[42,43] drugs because of their high misuse as a medical prescription and their categorization as Schedule IV controlled drugs[44] by the International Narcotics Control Board. They enhance the effect of the neurotransmitter γ-aminobutyric acid, resulting in sedative, anxiolytic (antianxiety), and muscle-relaxant properties. They generally have long detection periods in urine (up to 7 d with therapeutic use and 4 to 6 weeks with chronic use). Urinalysis is the most common type of test employed for drug testing because drug metabolites can be detected for a longer time in urine than in other biological specimens such as blood, saliva, and sweat.[45] Hence, control studies were carried out by doping urine specimens separately with a few medically prescribed and commercially available benzodiazepines (viz., clonazepam (D1), zolpidem (D2), alprazolam (D3), and diazepam (D4); Figures 6a,b,c,d and S23).

It has been found that when these drugs are mixed with urine specimens they have an insignificant effect on the fluorescence emission of PMI. However, surfactants doped with these

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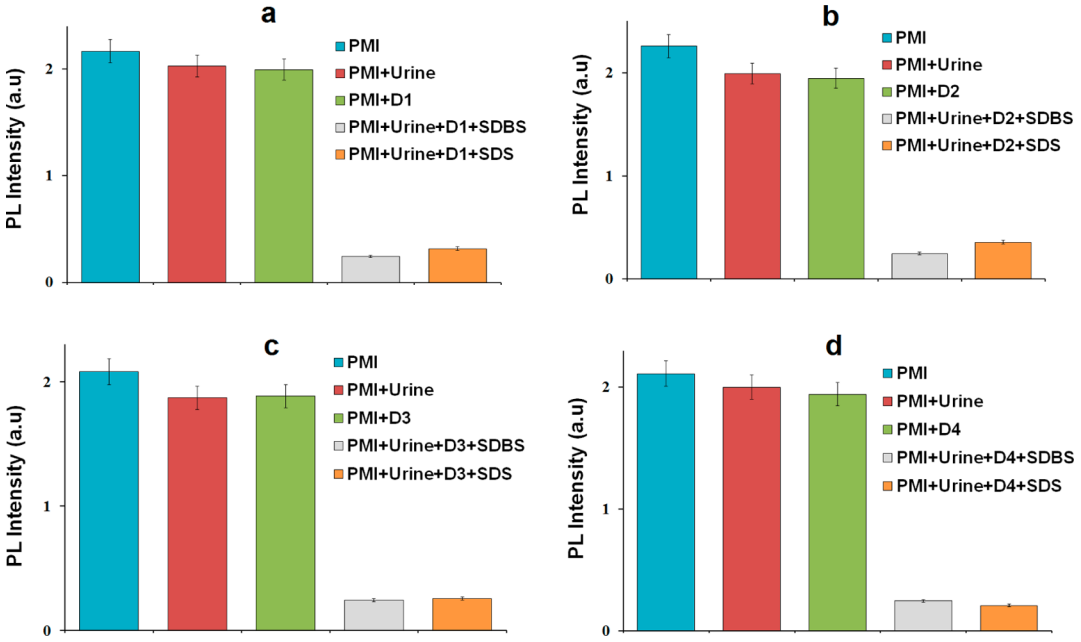

Figure 6. (a), (b), (c), and (d) Fluorescence changes observed after the addition of urine samples, various drugs (clonazepam (D1), zolpidem (D2), alprazolam (D3), and diazepam (D4)), and drug-doped urine samples that contained SDBS and SDS to a solution of PMI in HEPES buffer (pH 7.2, 10 mM). Concentration of PMI inside the cuvette was 2×10^{-5} M. Final concentration of SDBS and SDS after the addition of drug-doped urine samples was 2×10^{-5} M. Error bars = ±5%.

recreational drugs in urine showed significant fluorescence quenching, even after a prolonged time of 2−7 d. These results confirm that this PMI-based system can efficiently detect anionic surfactants, i.e., SDBS and SDS, that are exploited as adulterants in urine with recreational drugs at concentrations as low as 10^{-7} M in a highly competitive environment, containing drug formulations and components of urine, under varying pH conditions. SDS molecules form ion pairs with the cationic side chains of PMI via Columbic attraction, leading to an increase in the conjugation length. The extended chains can then overlap and form excimers that emit fluorescence at a longer wavelength. PMI forms complexes with SDS and SDBS and separates them efficiently in the form of hydrogels or precipitates from water or urine samples, thereby facilitating analysis of illicit drugs that remain in the analysis fluid and are utilized for confirmation tests. The PMI-based probe carried out multiple tasks to detect, discriminate, and eliminate SDS and SDBS from drugs rapidly and with superior activity, even under competitive conditions.

CONCLUSIONS

An efficient strategy for the detection, discrimination, and removal of anionic surfactants having very small structural variation (viz., sodium dodecyl benzenesulfonate (SDBS) and sodium dodecyl sulfate (SDS)) is developed on the basis of different aggregation behavior via interpolymer cofacial arrangement. PMI is a highly effective CPE and is viable over the full pH range of 1−14 for the detection and removal of these moderately dissimilar surfactants, even at parts per billion levels (SDS = 17.3 ppb and SDBS = 31.7 ppb) in urine specimens, under acidic and basic conditions, in seawater, brine, and aqueous media. The removal of these surfactants irrespective of the fluid in which they exist has remained an unresolved problem; hence, they are frequently exploited by doping suspects as the most common masking agents and adulterants in urine specimens to elude detection in drug testing. PMI demonstrated high optical activity in the presence of these surfactants and facilitated the rapid elimination of both SDS and SDBS in the form of gel or precipitate from water and biological medium, thereby enabling accurate analysis of illicit drugs. This simple approach provides for the first time a highly stable and practical method that rapidly detects and discriminates SDS and SDBS, eliminates them from urine samples without the use of hazardous organic solvents, and facilitates the precise investigation of illicit drugs by doping suspects at very low concentrations.

ASSOCIATED CONTENT

Supporting Information

Characterization data of polymers; pH study of PMI; detection-limit plots for SDS/SDBS; excitation and emission spectra of PMI−SDBS/SDS; atomic force microscopy image of hydrogel; quenching efficiency of PMI/surfactants at various pH; detection studies of SDS/SDBS in brine, groundwater, and urine specimens; and a movie representing the formation of PMI−SDS hydrogel. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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