J|A|C|S
COMMUNICATIONS

Published on Web 10/13/2007

Kinetic Trapping of Large Amount of Long Polymers in Nanopores

Andrzej Żywociński,[†] Anna Korda,[§] Joanna Gosk,[||] Stefan A. Wieczorek,[†] Agnieszka Wilk,[‡] and Robert Hołyst*[,†,||]

Department III, Institute of Physical Chemistry and Institute of Organic Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw, Poland, Institute of Physics, A. Mickiewicz University, Umultowska 85 61-614 Poznań, Poland, and Cardinal Stefan Wyszyński University, WMP-SNS, Dewajtis 5, Warsaw, Poland

Received August 20, 2007; E-mail: holyst@ptys.ichf.edu.pl

We demonstrate that long hydrophilic polymers (PEG 6000, 8000, 20000) with a minor hydrophobic modification (anthraquinone attached to one of its terminal groups) can be trapped inside very narrow water channels (size $l = 1.5$ nm, much smaller than the polymer radius of gyration) in the hexagonal phase of nonionic surfactant $C_{12}E_6$ (*n*-dodecyl hexaoxyethylene monoether). The equilibrium partition coefficient of the polymers between a bulk water solution and a hexagonal phase is given by $K = [x]_{pore}/[x]_{bulk} = \exp(\Delta\mu/kT)$, where $\Delta\mu$ is the change of the chemical potential upon transfer of a polymer chain from the bulk solution into the nanopores.[1] For the Gaussian chain $\Delta\mu \approx -kT(\pi R_g/l)^2$, where $R_g = 0.02M^{0.58}$ [nm] is the radius of gyration[2] of PEG and M is PEG molecular mass. From this estimate we find $K \approx 10^{-76}$ (for PEG 20000). A small hydrophobic group attached at one end of the polymer increases $\Delta\mu$ by a few percent and therefore, from the equilibrium theory, we still get that for $R_g \gg l$ 100% of the polymer should remain in the bulk solution.[1] In our experiment we used the phase separation kinetics to trap modified PEG in the nanopores. We obtained $K > 4$ for modified PEG 20000 (85% of PEG inside the hexagonal phase) and found that the amount of trapped polymers increases with PEG molecular mass. The experiment is based on the observation that hydrophobically modified PEG (M-PEG) anchors at the micellar surface with high affinity in dilute solution. Subsequently it can be permanently trapped in the surfactant-rich phase during quick phase separation. In short the phase separation "freezes" the equilibrium association partition of M-PEG between micelles/M-PEG complexes and free M-PEG in water. Our observation can be used in the timely problem of encapsulation techniques.[3]

PEG molecules were hydrophobically modified in a reaction with anthraquinone.[1] More details about synthesis and NMR analysis of the products can be found in supporting materials. The collective diffusion coefficient was the same for modified and unmodified PEG as measured by the dynamic light scattering and as shown in Figure 1, meaning that modified PEG (M-PEG) and PEG have the same radius of gyration. Moreover it demonstrates that M-PEG does not form aggregates in the bulk solution. Modified PEG in surfactant solutions shows mobility which is smaller than in pure water and is independent of its molecular mass indicating that it forms complexes with micelles as verified by the fluorescence correlation spectroscopy (Figure 1). The surfactant $C_{12}E_6$ in water solution forms a hexagonal phase at 39% w/w below 38 °C and phase separates from water by dehydration of polar heads for the temperatures above 50 °C. The hexagonal phase has the following characteristics: $d = 5.9$ nm is the size of the unit cell; $a = 2.2$ nm

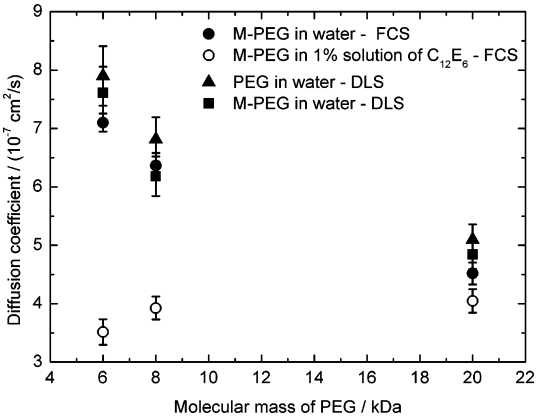

Figure 1. Diffusion coefficient vs molecular mass of PEG/modified PEG molecules obtained from dynamic light scattering measurements and from fluorescence correlation spectroscopy

is the average size of the molecule in the hexagonal column; and $l = 1.5$ nm is the width of water nanopores between surfactant cylinders.[4] PEG added to the surfactant/water solutions induces phase separation into surfactant-rich and polymer-rich phase at room temperature or below (e.g., for 3% $C_{12}E_6$ and 10% percent of PEG 20000 the separation temperature was below 10 °C), and at high concentration of PEG the separated surfactant phase forms the hexagonal phase.[5] The separation is caused by the depletion interactions.[6]

We performed the following experiments (the results of partition coefficients from UV-spectroscopy are shown in Figure 2): (a) we mixed 10% of PEG/0.2% of M-PEG with 10% of surfactant and induced a phase separation into isotropic PEG-rich phase and hexagonal surfactant-rich phase (supporting material gives the equation for the amount of PEG needed to induce hexagonal ordering[5]); (b) we mixed 3 to 6% of PEG with 0.2% of M-PEG and 3% of surfactant and induced a phase separation into PEG-rich phase and micellar surfactant-rich phase; (c) we mixed 4 to 2% of PEG/6 to 8% of M-PEG with 10% of surfactant and performed temperature cycle (jump−quench) to induce phase separation and hexagonal ordering; (d) to check the equilibrium partition between the nanopores of the hexagonal phase and the bulk water, we added 0.1 to 0.3% of M-PEG directly to the bulk solution of PEG-rich phase coexisting with the surfactant hexagonal phase (in a 10% PEG/10% surfactant water mixture). In all cases we monitored the amount of M-PEG in both phases by UV spectroscopy. Additionally M-PEG absorbs visible light and gives colors in the pipet, therefore we also verified the amount of M-PEG in a visible light (PEG is colorless). Figure 2 shows the M-PEG partition coefficients obtained in the experiments. It demonstrates that trapping is kinetic in nature. M-PEG does not enter into the

[†] Institute of Physical Chemistry, PAS.
[‡] A. Mickiewicz University.
[§] Institute of Organic Chemistry, PAS.
[||] Cardinal Stefan Wyszyński University.

10.1021/ja0762590 CCC: $37.00

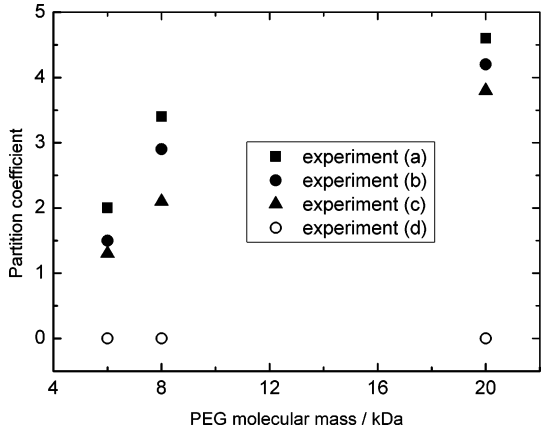

Figure 2. Partition coefficient $K = [x]_{pore}/[x]_{bulk}$ vs molecular mass of modified PEG calculated as a ratio of M-PEG concentration in the hexagonal/micellar (upper, surfactant-rich) phase, $[x]_{pore}$, and M-PEG concentration, $[x]_{bulk}$, in the isotropic (lower, PEG-rich) phase.

hexagonal phase from the bulk solution as demonstrated in the experiment d. In the experiments a and c we found that most of M-PEG is trapped inside the hexagonal phase. The partition coefficient does not change with the amount of M-PEG. Also from the experiment b we found that approximately the same amount of M-PEG appears in the micellar phase, where there is a free exchange of M-PEG between the M-PEG/micellar complexes and water. It supports our conclusion that the original amount of M-PEG trapped inside the hexagonal phase results from the equilibrium partition of M-PEG between M-PEG/micelles complexes and water.

Since pure M-PEG does not separate at room temperature from the surfactant solutions (in fact M-PEG stabilizes the micellar solution by the formation of complexes with micelles) thus in the experiment c we had to induce the phase separation by the temperature jump−quench method explained in the Supporting Information (Figure S3). We heated M-PEG/surfactant/water samples above the separation line for binary surfactant/water mixture and separated the mixture into almost pure water and concentrated $C_{12}E_6$/M-PEG phase. The concentration of $C_{12}E_6$ in this phase exceeded 39% w/w, but it did not order owing to high temperature. In the next step a sudden drop of temperature below 38 °C induced a hexagonal phase. The M-PEG was trapped during the process between the micelles with hydrophobic anchors attached to the micelles. The ordering was faster than the escape rate of polymers from the space confined by the ordering micelles. The obtained phase was metastable and dissolved slowly in the excess of water over the period of two weeks. However, additional unmodified PEG added to the solution stabilized the hexagonal phase. In the experiment d we first induced phase separation into PEG-rich and $C_{12}E_6$-rich phase. Next, M-PEG was added into the former phase and left for 4 weeks for equilibration. We found no M-PEG in the hexagonal phase as we had expected on the basis of the equilibrium partition coefficient *K*. Figure 3 shows a photo of the two samples prepared as described in the experiments c and d. The images of upper (hexagonal) phases observed with a polarizing microscope at crossed polarizers are also presented together with the UV spectra of both phases in two samples.

We have presented a simple method of introducing large amount of long polymers into the nanopores (of sizes much smaller than the radius of gyration) formed in ordered surfactant phases using the phase separation. The method "freezes" the equilibrium partition of a polymer between polymer/micelle complexes and bulk water in the phase separation process. The previous attempts to introduce

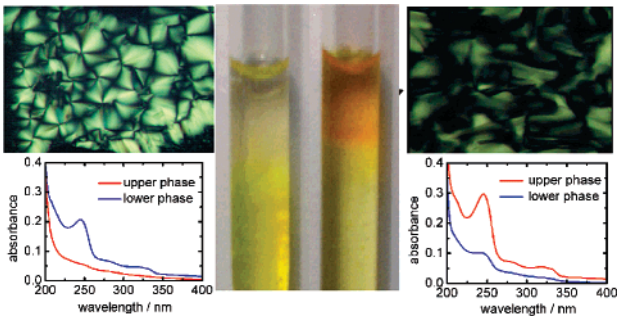

Figure 3. Visualization of the experiments c and d performed for PEG (M-PEG) 8000 and described in the text: (experiment d) direct injection of M-PEG into the isotropic (lower) phase obtained by earlier phase separation of PEG/water/surfactant mixture; (experiment c) temperature jump−quench method applied to a mixture containing PEG doped with M-PEG. The images of hexagonal phases (in polarized light with crossed polarizers) as well as the UV spectra of both phases. In experiment d the upper phase (hexagonal) is depleted from M-PEG (shown on UV spectrum and visible as lack of color); in experiment c most of M-PEG is encapsulated in the hexagonal phase.

long polymers with hydrophobic anchors into the surfactant phases ended with the conclusion that a stable polymer/ordered surfactant phase is formed providing that the size of a nanopore is larger than the radius of gyration of the polymer.[7] Our method might find applications in the timely problem of polymer encapsulation in the confined space of vesicles.[3]

Acknowledgment. This work was supported as a scientific Project 2006-2008 and the SONS (SCALES) scientific Project 2006-2009 from the budget of the Ministry of Science and Higher Education.

Supporting Information Available: Characteristics of chemical compounds, description of dynamic light scattering and fluorescence correlation spectroscopy measurements, discussion of depletion interactions, equation for the amount of PEG needed to induce hexagonal ordering in PEG/water/surfactant mixture, description of temperature jump−quench technique used to induce hexagonal ordering in M-PEG/surfactant/water mixture. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Teraoka, I. *Prog. Polym. Sci.* **1996**, *21*, 89−149. (b) Cifra, P.; Bleha, P. *Polymer* **2000**, *41*, 1003−1009. (c) Bleha, T.; Cifra, P. *Polymer* **2005**, *46*, 10996−11002.

(2) (a) Devanand, K.; Selser, J. C. *Macromolecules* **1991**, *24*, 5943−5947. (b) Kawaguchi, S.; Imai, G.; Suzuki, J.; Miyahara, A.; Kitano, T.; Koichi, I. *Polymer* **1997**, *38*, 2885−2891.

(3) (a) Ruyssachaert, T.; Sonnen, A. F. P.; Haefele, T.; Meier, W.; Winterhaltert, M.; Fournier, D. *J. Am. Chem. Soc.* **2005**, *127*, 6242−6247. (b) Discher, D. E.; Eisenberg, A. *Science* **2002**, *297*, 967−973.

(4) (a) Constantin, D.; Oswald, P.; Imperor-Clerc, M.; Davidson, P.; Sotta, P. *J. Phys. Chem. B* **2001**, *105*, 668−673. (b) Constantin, D. Ph.D. Thesis. ENS-Lyon, Lyon, Cedex 07, 2002. (c) Mitchell, D. J.; Tiddy, G. J. T.; Waring, L.; Bostock, T.; McDonald, M. P. J. *J. Chem., Faraday Trans.* **1983**, *79*, 975−1000.

(5) (a) Hoyst, R.; Staniszewski, K.; Demyanchuk, I. *J. Phys. Chem. B* **2005**, *109*, 4881−4886. (b) Hoyst, R.; Staniszewski, K.; Patkowski, A.; Gapiński, J. *J. Phys. Chem. B* **2005**, *109*, 8533−8537. (c) Demyanchuk, I.; Staniszewski, K.; Hoyst, R. *J. Phys. Chem. B* **2005**, *109*, 4419−4424.

(6) (a) Asakura, S.; Oosawa, F. *J. Chem. Phys.* **1954**, *22*, 1255−1256. (b) Vrij, A. *Pure Appl. Chem.* **1976**, *48*, 471−483. (c) Lekkerkerker, H. N. W.; Poon, W. C. K.; Pusey, P. N.; Stroobants, A.; Warren, P. B. *Europhys. Lett.* **1992**, *20*, 559−563. (d) Lekkerkerker, H. N. W. *Physica A* **1997**, *244*, 227−237.

(7) (a) Yang, B. S.; Lal, J.; Kohn, J.; Huang, J. S.; Russel, W. B.; Prud'homme, R. K. *Langmuir* **2001**, *17*, 6692−6698. (b) Yang, B. S.; Lal, J.; Richetti, P.; Marques, C. M.; Russel, W. B.; Prud'homme, R. K. *Langmuir* **2001**, *17*, 5834−5841.

JA0762590