Mesoporous Films and Polymer Brushes Helping Each Other To Modulate Ionic Transport in Nanoconfined Environments. An Interesting Example of Synergism in Functional Hybrid Assemblies

Alejandra Calvo,[†] Basit Yameen,[‡] Federico J. Williams,[§] Galo J.A.A. Soler-Illia,*,[†] and Omar Azzaroni*,[ǁ]

Gerencia de Química, CNEA, Centro Atómico Constituyentes, Av. Gral. Paz 1499, San Martín B1650KNA, Argentina, Max-Planck-Institut für Polymerforschung, Ackermannweg 10, 55128 Mainz, Germany, Departamento de Química de Superficies y Recubrimientos, TENARIS, Simini 250, B2804MHA Campana, Argentina, and Instituto de Investigaciones Fisicoquímicas Teóricas y Aplicadas (INIFTA)-CONICET, Universidad Nacional de La Plata, CC 16 Sucursal 4 (1900) La Plata, Argentina

Received April 18, 2009; E-mail: gsoler@cnea.gov.ar; azzaroni@inifta.unlp.edu.ar

In the recent years we have seen remarkable interest in creating new methodologies to achieve active control over the molecular transport in highly confined geometries.[1] This interest originates from the many technological processes relying on controlled transport of molecular species in nanoconfined environments, like molecular separation, dosing, or drug delivery.[2] In particular, the generation of interfaces discriminating the transport of ionic species through which the passage of ions can be triggered or inhibited under the influence of an external stimulus has received increasing attention from the materials science community.[3] The efficiency by which many pore-forming proteins control the ionic transport using pH as a chemical trigger has been a source of inspiration for chemists to mimic such processes using functional hybrid assemblies as a toolbox to create similar synthetic systems. Along these lines, different approaches based on surface-functionalized nanoporous substrates, like silica opals, glass nanoporous electrodes, or mesoporous films, came to light in recent years.[4] In most cases, the selectivity toward anions or cations is controlled by adjusting the environmental pH, which leads, in principle, to the opening and closing of the membrane pores. The conventional strategy is based on using the nanoporous matrix as a scaffold to create robust and shape-persistent nanoscopic channels[5] and dressing the inner walls of the nanoporous cavities with pH-responsive moieties. By changing the solution pH the generation of positive or negative charges can be easily controlled. Then, ionic species with charges matching those confined in the pores will be repelled and prevented from entering the porous matrix. On the contrary, ions of opposite charge will be attracted and transported through the functionalized mesoporous film. When the pores are charged (positive or negative) the membrane operates as an ionic filter. But in the case of being uncharged, the permselectivity vanishes and the transport of both species, anionic and cationic, takes place through the film. This leads to systems in which, depending on the pH, we can shuttle only cations, only anions, or both of them. An ongoing challenge in materials science relies on the construction of fully synthetic hybrid assemblies displaying gating and charge selectivity properties resembling those observed in biological channels. Interesting examples are the acid-sensing ion channels (ASICs) in peripherical sensory neurons and in the neurons of the central nervous system.[6] These are cation-selective, proton-gated biological channels that play an important role in a variety of physiological processes such
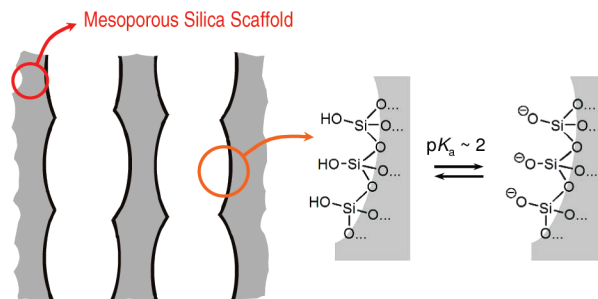

Figure 1. Simplified illustration describing the mesoporous silica film. Also indicated is the chemical equilibrium taking place in the nanopore walls.

as nocireception, mechanosensation, and synaptic plasticity. These biological entities act as gateable ionic filters enabling the selective passage of cations only under determined pH conditions.[7] Biological pores like ASICs pose a challenging situation that still remains elusive in molecular materials science: designing a robust, fully artificial (biomolecule-free) interfacial assembly displaying charge selectivity with proton-activated gating properties. In this context, the quest for new concepts to create novel charge-selective membranes is of critical importance for further expanding the scope of applications of these materials. In this work, we describe the creation of a hybrid organic−inorganic assembly displaying pH-dependent ionic transport properties which until now were not observed in nanoporous permselective membranes. In close resemblance to ASICs, functional hybrids of polyzwitterionic brushes and mesoporous films are able to discriminate and modulate the transport of cations while inhibiting the passage of anions over a wide pH range.

Mesoporous silica thin films were produced via a one-pot sol−gel method by dip-coating of silicon and indium tin oxide (ITO) substrates using protocols described in the literarure. This led to the formation of thin mesoporous films displaying highly organized pore arrays (Figure 1) with a cubic-derived mesostructure (*Im3m*) and pore openings between 6 and 9 nm,[4j] as indicated by transmmision electron microscopy (TEM) and small-angle X-ray scattering with two-dimensional detection (SAXS-2D) (see Supporting Information (SI) for details).

In principle, the presence of surface-confined silanolate groups (Si−O⁻), with $pK_a \approx 2$, would confer permselective properties to the film. The transport of ionic species through the mesoporous silica was electrochemically probed using charged electroactive species diffusing across the film deposited on conductive ITO substrates. Figure 2 displays the cyclic voltammograms of meso-

† CNEA.
‡ Max-Planck-Institut für Polymerforschung.
§ TENARIS.
ǁ Universidad Nacional de La Plata.

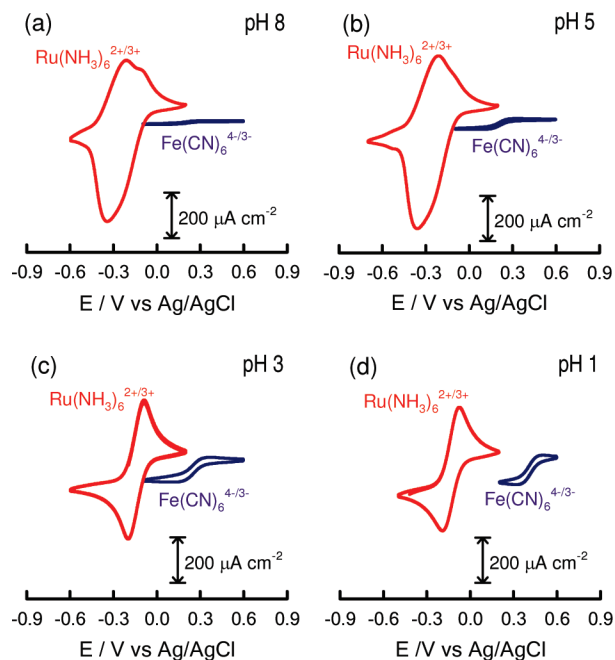**Figure 2.** Cyclic voltammograms corresponding to a mesoporous silica film deposited on an ITO electrode in the presence of 1 mM $Ru(NH_3)_6^{3+}$ (red trace) and 1 mM $Fe(CN)_6^{3-}$, respectively, under different pH conditions: (a) 8, (b) 5, (c) 3, (d) 1.

Figure 3. Cyclic voltammograms corresponding to a polyzwitterionic brush-modified mesoporous silica film deposited on an ITO electrode in the presence of 1 mM $Ru(NH_3)_6^{3+}$ (red trace) and 1 mM $Fe(CN)_6^{3-}$, respectively, under different pH conditions: (a) 8, (b) 5, (c) 3, (d) 1.

porous silica films supported on ITO in the presence of 1 mM $Ru(NH_3)_6^{3+}$ and $Fe(CN)_6^{3-}$ at different pH's. As expected, at pH's significantly above the pK_a of silica, i.e., 8 and 5, a well-defined electrochemical response of $Ru(NH_3)_6^{3+}$ ions is observed whereas that corresponding to the $Fe(CN)_6^{3-}$ species is hardly detectable.

The nanopore walls are negatively charged and permselectively repel the transport of $Fe(CN)_6^{3-}$ while at the same time allowing the diffusion of $Ru(NH_3)_6^{3+}$ to the ITO electrode (Figure 2a,b). Lowering the pH to 3 or 1 is evidenced as a minor decrease in the voltammetric signal of $Ru(NH_3)_6^{3+}$ while the corresponding signal for $Fe(CN)_6^{3-}$ is slightly increased (Figure 2c,d). This can be attributed to the fact that we are in close proximity to the pK_a value of silica, and as a consequence, the loss of surface-confined negative charges affects the permselective properties of the mesoporous film. However, the electrochemical results indicate that the mesoporous silica films exposing SiO^- groups act as permselective barriers precluding the transport of anionic species.[4h,5c]

Then, we proceeded to modify the mesoporous films by growing zwitterionic poly(methacryloyl-L-lysine) (PML) brushes. This was accomplished by surface-initiated radical polymerization[8] of the methacryloyl-L-lysine monomers in the presence of the adequate solvent and initiator (see SI for details).[9] The surface modification of the mesoporous film was corroborated by X-ray photoelectron spectroscopy and diffuse reflectance infrared Fourier transform spectroscopy (see SI for details).

Once the chemical functionalization was corroborated, we proceeded to transport studies using the diffusing redox probes. Figure 3 describes the voltammograms of PML brush-modified mesoporous silica film in contact with electrolyte solutions containing $Fe(CN)_6^{3-}$ and $Ru(NH_3)_6^{3+}$, respectively. It is evident that the presence of the polyzwitterionic brush introduces dramatic changes in the transport properties of the mesoporous film. At pH's 8 and 5 the brush-modified mesoporous film still hinders the transport of anions and enables the diffusion of cations into the film. However, in stark contrast to that observed in silica films, at pH's 3 and 1
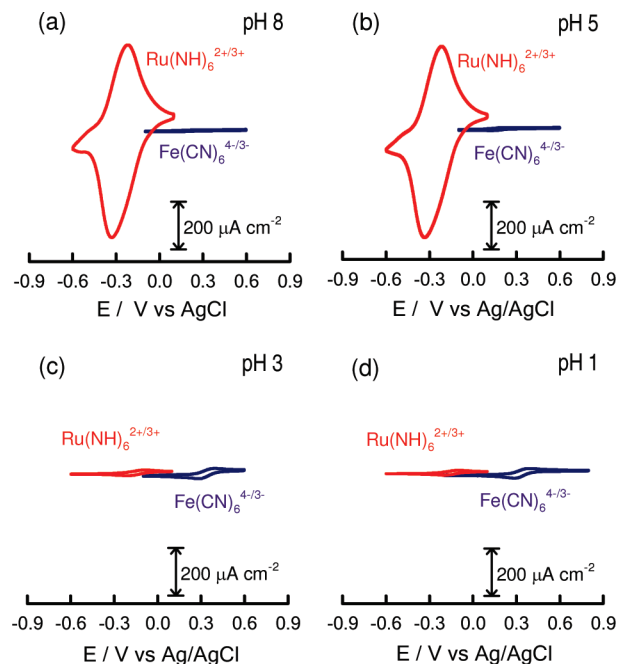
the transport of both cationic and anionic species is completely inhibited (Figure 3c,d).

The isoelectric point (pI) of the zwitterionic brush[9] is ~5, and as such, we should expect that at pH > 5 the nanopore is negatively charged, i.e., cation-permselective, and at pH < 5 the same pore walls are positively charged, i.e, anion-permselective. Recent studies performed on poly(methacryloyl-L-lysine) brush-modified solid-state plastic nanopores, with dimensions comparable to those of the pores used in these studies, strongly support this asseveration. Yameen et al. demonstrated that the permselectivity of PML brushes is easily reversed upon increasing/decreasing the pH above/below the pI.[9] Considering the above arguments and the previous experimental evidence, why is the PML brush-modified mesoporous film acting as an ionic barrier at pH < 5 instead of behaving as an anion-permselective membrane? To understand the physicochemical process giving rise to this unique behavior, we need to describe the actual picture of the nanopore environment. In the pore walls the grafted polyzwitterionic chains coexist with silanol sites, which are negatively charged at pH > 2. At pH's > 5 both the zwitterionic moieties and the SiO^- groups bear negative charges (Figure 4a). As a result, the system shows a remarkable cation-permselective behavior. Then, at pH < 5 the zwitterionic monomers bear positive charges while the silanol groups are still negatively charged (Figure 4b). This situation originates the formation of a zwitterionic, "bipolarly charged" nanopore in the $pI_{brush} > pH > pK_{a_{silica}}$ range. In contrast to the typical Donnan exclusion phenomenon which refers to confined negative charges repelling anions and confined positive charges repelling cations,[10] the confinement of both negative and positive charges leads to a very particular exclusion condition. Initially the anions are attracted to the pore by the positive charges in the "bipolar" wall. However, the negative charges in the "bipolar" wall are very close to the positive ones, and as a result, repulsion of the anions occurs simultaneously. The diffusing cations will have the same electrostatic behavior. This particular Donnan exclusion phenomenon manifested in "bipolar" environments has been previously observed in electrostatic ion chromatography.[11] In these
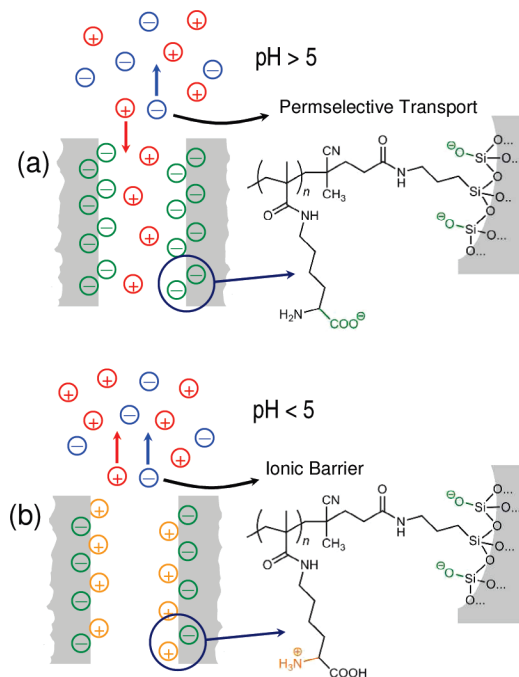
Figure 4. Schematic depiction of the ionic transport processes taking place in the hybrid assembly at different pH's: (a) pH > 5, permselective transport of cations and (b) pH < 5, ionic barrier (exclusion of ionic species). The different chemical entities present in the pore surface after the polymerization are also indicated.

cases, the bipolar exclusion has been exploited to modulate the affinity of ionic species to the stationary phase.

More recently, Advincula and co-workers reported a similar effect in bipolar polyelectrolyte multilayers prepared by layer-by-layer assembly and photocross-linking of benzophenone-modified poly(acrylic acid) and poly(allylamine hydrochloride).[12] These authors observed that, at pH 7, amine and carboxylic groups were ionized and the film excluded both positively and negatively charged redox probes. In our case, this "bipolar" Donnan exclusion phenomenon is responsible for building up, in a reversible manner, a chemically actuated ionic barrier at pH < 5 (see SI for details). More important, this distinctive feature is exclusively due to the *synergy* between the electrostatic characteristics of the brush layer and the silica scaffold. The unique barrier properties of the film could be only observed in the presence of the cooperative interaction between the brush and the mesoporous silica. In other words, the behavior of the whole system significantly differs from the behavior of their parts taken separately. Up to date, nanoporous matrices have been relegated to mere scaffolds to create nanoscopic channels. Here, we described the first example in which the interplay between the intrinsic acid−base properties of a mesoporous scaffold and the pH-responsive characteristics of polymer brushes leads to a functional assembly with ionic transport properties so far believed to be distinctive features of biological (acid-sensing) ion channels. Mesoporous films and polymer brushes, as a whole, represent a new toolbox in which nanoscale topological and chemical aspects can be manipulated at will as a result of the synergism between both the organic and inorganic counterparts. The interplay between the acid−base properties of the scaffold and the brush gave rise to a new proton-gated cation-selective membrane with properties

observed neither in mesoporous films nor in brushes, so far. We consider that these results can lead to a new way of looking at interdisciplinary research in molecular materials science and trigger a cascade of new, refreshing ideas in nanochemistry aimed at the rational design of hyperfunctional assemblies with unprecedented properties.

Supporting Information Available: Detailed experimental procedures and characterization. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Baker, L. A.; Bird, S. P. *Nat. Nanotechnol.* **2008**, *3*, 73–74. (b) Martin, C. R.; Siwy, Z. *Science* **2007**, *317*, 331–332. (c) Sexton, L. T.; Horne, L. P.; Martin, C. R. *Mol. BioSyst.* **2007**, *3*, 667–685. (d) Siwy, Z. *Adv. Funct. Mater.* **2006**, *16*, 735–746. (e) Dekker, C. *Nat. Nanotech.* **2007**, *2*, 209–215. (f) Wanunu, M.; Meller, A. *Nano Lett.* **2007**, *7*, 1580–1585. (g) Karnik, R.; Castelino, K.; Fan, R.; Yang, P.; Majumdar, A. *Nano Lett.* **2005**, *5*, 1638–1642.
(2) (a) Fan, R.; Huh, S.; Yan, R.; Arnold, J.; Yang, P. *Nat. Mater.* **2008**, *7*, 303–307. (b) Jirage, K. B.; Martin, C. R. *Tibtech* **1999**, *197*, 197–200. (c) Kasianowicz, J. J.; Robertson, J. W. F.; Chan, E. R.; Reiner, J. E.; Stanford, V. M. *Annu. Rev. Anal. Chem.* **2008**, *1*, 737–766.
(3) (a) Lee, S. B.; Martin, C. R. *Anal. Chem.* **2001**, *73*, 768–775. (b) Fu, Q.; Rao, G. V. R.; Ista, L. K.; Wu, Y.; Andrzejewski, B. P.; Sklar, L. A.; Ward, T. L.; López, G. P. *Adv. Mater.* **2003**, *15*, 1262. (c) Fu, Q.; Rama Rao, G. V.; Ward, T. L.; Lu, Y.; López, G. P. *Langmuir* **2007**, *23*, 170.
(4) (a) Smith, J. J.; Zharov, I. *Langmuir* **2008**, *24*, 2650. (b) Cichelli, J.; Zharov, I. *J. Mater. Chem.* **2007**, *17*, 1870. (c) Slowing, I. I.; Trewyn, G. G.; Lin, V.S.-Y. *J. Am. Chem. Soc.* **2007**, *127*, 8845. (d) Zhou, Z.; Zhu, S.; Zhang, D. *J. Mater. Chem.* **2007**, *17*, 2428. (e) Wang, G. L.; Zhang, B.; Wayment, J. R.; Harris, J. M.; White, H. S. *J. Am. Chem. Soc.* **2006**, *128*, 7679. (f) Otal, E. H.; Angelomé, P. C.; Bilmes, S. A.; Soler-Illia, G. J. A. A. *Adv. Mater.* **2006**, *18*, 934. (g) Etienne, M.; Quach, A.; Grosso, D.; Nicole, L.; Sanchez, C.; Walcarius, A *Chem. Mater.* **2007**, *19*, 844. (h) Fattakhova-Rohlfing, D.; Wark, M.; Rathousky, J. *Chem. Mater.* **2007**, *19*, 1640. (i) Smith, J. J.; Abbaraju, R. R.; Zharov, I. *J. Mater. Chem.* **2008**, *18*, 5335–5338. (j) Schepelina, O.; Zharov, I. *Langmuir* **2008**, *24*, 14188–14194. (k) Calvo, A.; Angelomé, P. C.; Sánchez, V. M.; Scherlis, D. A.; Williams, F. J.; Soler-Illia, G. J. A. A. *Chem. Mater.* **2008**, *20*, 4661.
(5) (a) Soler-Illia, G. J. A. A.; Innocenzi, P. *Chem.—Eur. J.* **2006**, *12*, 4478. (b) Newton, M. R.; Bohaty, A. K.; White, H. S.; Zharov, I. *J. Am. Chem. Soc.* **2005**, *127*, 7268–7269. (c) Newton, M. R.; Bohaty, A. K.; Zhang, Y.; White, H. S.; Zharov, I. *Langmuir* **2006**, *22*, 4429–4432.
(6) Waldmann, R.; Champigny, G.; Lingueglia, E.; De Weille, J. R.; Heurteux, C.; Lazdunski, M. *Ann. N.Y. Acad. Sci.* **1999**, *868*, 67–76.
(7) Kellenberger, S. In *Sensing with Ion Channels*; Martinac, B., Ed.; Springer-Verlag, Heidelberg, 2008; Chapter 11, pp 225−246.
(8) (a) *Polymer Brushes: Synthesis, Characterization and Applications*; Advincula, R. C., Brittain, W. J., Caster, K. C., Rühe, J., Eds.; Wiley−VCH: Weinheim, 2004. (b) Huang, W.; Skanth, G.; Baker, G. L.; Bruening, M. L. *Langmuir* **2001**, *17*, 1731–1736. (c) Prucker, O.; Rühe, J. *Langmuir* **1998**, *14*, 6893–6898. (d) Azzaroni, O.; Brown, A. A.; Huck, W. T. S. *Angew. Chem., Int. Ed.* **2006**, *45*, 1770–1774. (e) Advincula, R. C. In *Surface-Initiated Polymerization I*; Jordan, R., Ed.; Springer-Verlag: Heidelberg, 2006; p 107.
(9) Yameen, B.; Ali, M.; Neumann, R.; Ensinger, W.; Knoll, W.; Azzaroni, O. *J. Am. Chem. Soc.* **2009**, *131*, 2070–2071.
(10) (a) Ohshima, H.; Kondo, T. *Biophys. Chem.* **1990**, *38*, 117–122. (b) Ohshima, H.; Miyajima, T. *Colloid Polym. Sci.* **1994**, *272*, 803–811. (c) Ohshima, H.; Ohki, S. *Biophys. J.* **1985**, *47*, 673–678.
(11) Hu, W.; Takeuchi, T.; Haraguchi, H. *Anal. Chem.* **1993**, *65*, 2204–2208.
(12) Park, M.-K.; Deng, S.; Advincula, R. C. *J. Am. Chem. Soc.* **2004**, *126*, 13723–13731.

JA9031067