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From polymeric films to nanoreactors

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In recent years much has been learnt about the structure of organic films and interfaces, and techniques to prepare these films in a controlled way have been developed. These have concerned mostly planar systems, but there is no obvious reason why this knowledge could not be transferred to curved interfaces. This is most desirable in order to coat colloids for various reasons:

- One would be able to obtain systems with much specific surface area. This would enable not only many applications requiring surfaces (e.g. chromatography, enzyme technology, separation technology), but also other techniques to study interfaces could be employed. Our motivation resulted from the application of methods typically used for bulk samples: NMR, differential scanning calorimetry and flash spectroscopy.

- Coating colloids in a defined way is also a prerequisite to understanding colloidal solutions, because the interparticle interactions are determined by their interfaces.

Having succeeded in coating colloids there is an obvious next step, to template colloids by dissolving the core and thus obtaining hollow capsules. This route will be proceeded in the following, demonstrating also the interesting properties and possible applications of these capsules.

A technique to prepare polymeric films with nm precision has been introduced by Decher, and is called layer-by-layer adsorption /1/. With this technique a charged surface can be coated by dipping it into a solution of an oppositely charged polyelectrolyte. The latter is adsorbed reversing the surface charge under suitable conditions, and thus a polyelectrolyte with again the opposite charge can be adsorbed. Repeating the process leads to polymeric films of low roughness (<1nm), thickness controllable with nm accuracy by the number of dipping cycles and ionic

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conditions. Functional molecules can also be integrated into the films with a position along the surface normal, and controlled with nm precision. Depending essentially on electrostatic interactions the technique is applicable to many multiply charged systems: synthetic or natural polymers, proteins, colloidal particles, and dyes. It also does not require planar and flat surfaces. Instead the surface can be rough, porous or strongly curved. Consequently we have developed various protocols to coat colloidal particles by this technique /2/ (Fig. 1). These protocols either exist in incubating the colloidal particles in a solution containing more polyelectrolyte than needed for adsorption and then removing excess polyelectrolyte by centrifugation or filtering before adding polyelectrolyte with the opposite charge, or by adding just sufficient polyelectrolyte as needed for saturation coating.

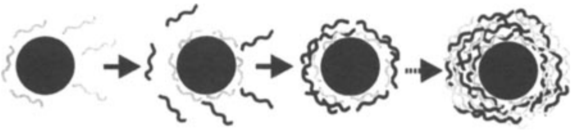

Fig. 1
Scheme of the layer-by-layer adsorption of polyelectrolytes on colloidal particles. The excess polyelectrolyte in the supernatant has to be removed prior to adsorption of the next polyion species.

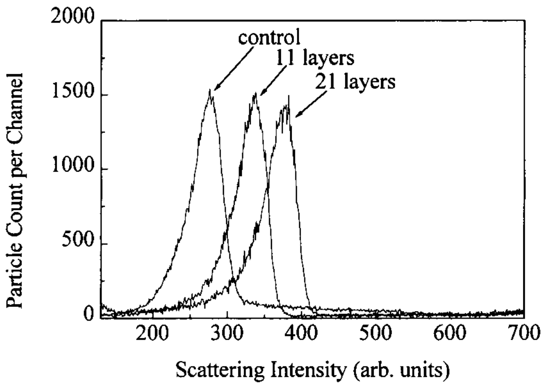

Fig. 2
Single particle light scattering intensity distributions of PSS/PAH coated poly(styrene sulfate) latex particles of 640 nm diameter.

The coating can be followed by single particle light scattering. Fig. 2 shows that the distribution of the scattering intensity per particle shifts to higher values depending on the number of coating processes. This shift can be quantified applying Rayleigh-Debye-Gans or Mie theory knowing the refractive index of the polymer /3/. One thus derives thickness increases of about 1 nm per step which is close to the value determined by X-ray reflectivity for planar surfaces. One also realizes that there is little broadening of the distribution with coating, proving that the deposited thickness is the same for different particles. This does not prove that the coating is uniform. However, if this were not the case one would observe particle aggregation, because there would be Coulomb attraction between oppositely charged areas on different colloids. This is not observed by light scattering. A dimer or higher aggregate would appear at higher intensities, in contrast to our findings.

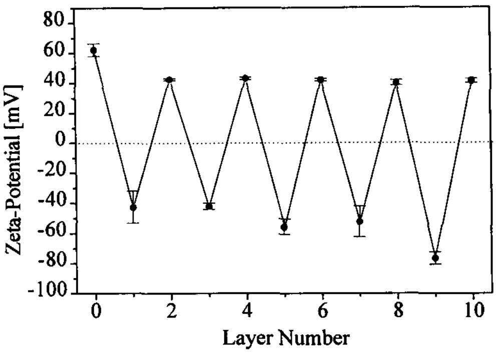

Fig. 3
Zeta potential as a function of layer number of a melamine formaldehyde latex particle (diameter 3.7 μm) coated with chitosan/chitosansulfate layers

The conjecture that each adsorption step leads to reversal of the surface charge is verified by measurements of the electrophoretic mobility. Knowing particle size and solvent viscosity it can be converted into a zeta potential, as given in Fig. 3. We use this value only for qualitative comparisons because of the uncertainty of its interpretation. We realize that coating with extremely different polyelectrolytes (proteins, DNA, synthetic polymers) does not lead to more than a factor of 2 difference in the values. Probably the largest uncertainty is the location of the shear plane separating the volume moved electrophoretically with the particle from that remaining behind in the solvent.

Having successfully coated the particles with a polyelectrolyte film of defined composition, thickness, and inner and outer surface, one can proceed to remove the colloidal core /4/. For this we have used different templates and routes:

(i) Melamine formaldehyde particles of uniform spherical dimensions between 100 nm and 10 μm were prepared. They exhibited a positively charged surface onto which consecutive adsorption according to Fig. 1 could be performed. Reducing the pH below 1.6 or treating by dimethylsulfoxide (DMSO), the colloidal core could be dissolved without destroying the coating. Low molecular weight fragments then permeate through the wall leaving a hollow volume inside. For μm sized particles this process can be visualized by light microscopy and is shown to occur within some 10 seconds. It can also be quantified by single particle light scattering. At this stage, however, there remains the uncertainty that a fraction of some % of the core material may remain undetected inside the capsules.

(ii) An alternative template may be one of biological origin which could exhibit peculiar non-spherical shapes. These templates can be destroyed by deproteinizing (oxidizing) agents. As readily available examples, erythrocytes of echinocyte or discocyte shape were fixed with glutaraldehyde and then coated before destroying the core. Fig. 4 shows an example where an echinocyte with its many spicules was coated with fluorescently labeled polyelectrolyte. The confocal fluorescence micrographs of the coat after core removal reveal that the coat follows each of the original spicules.

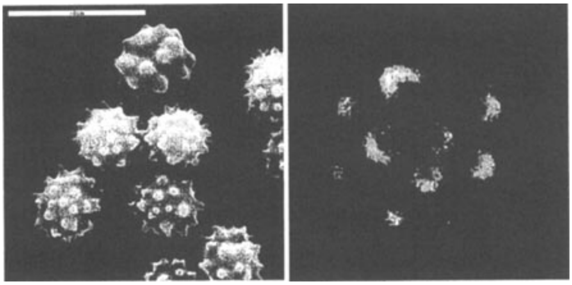

Fig. 4
Confocal micrograph of a polyelectrolyte coat (right) templated on human red blood cells in echinocyte shape (left). The confocal plain is located in the upper part of the capsule. The width of the pictures is 22 and 8 µm, respectively.

Templating could be successfully accomplished due to the fact that the polyelectrolyte shell is reasonably permeable for small molecules. This has been shown previously for planar films where diffusion coefficients between 10^{-12} cm^2/sec and 10^{-15} cm^2/sec were determined for dye molecules like rhodamine B or smaller in size /5/. For larger entities like colloidal particles or proteins, however, the films are impermeable.

Force microscopy and electron microscopy images reveal that the capsules have no holes observable by these techniques, but the issue of permeability requires many more detailed studies, because this is probably one of their key advantages compared with other systems /4/. Controlling the chemistry and the thickness of the walls should allow for selective and switchable permeation, most important for any application as carrier materials. Elegant experiments along this line have been performed using confocal laser scanning fluorescence microscopy. Adding a fluorescently labelled polymer to the outer space of a capsule and measuring the fluorescence out of the interior we find that no polyelectrolyte penetrates the wall within hours /6/ (see Fig. 5). This result was obtained for polystyrene sulfonic acid for all molecular weights investigated (>4000), but it is not clear how it is influenced by size, charge or flexibility of the probe. A similar experiment with the low molecular weight dye 6-carboxyfluorescein demonstrates that these molecules penetrate instantaneously, i.e. in less than a minute. However, it has been possible to slow down penetration by additionally coating the capsule with a phospholipid bilayer.

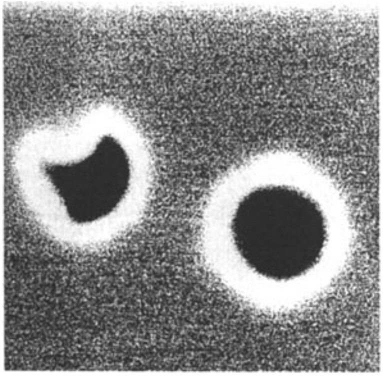

Fig. 5
Confocal microscopy image of hollow polyelectrolyte capsules (diameter 3 μm) consisting of 13 PSS/PAH-FITC layers in the presence of PAH-FITC (70 000 a.m.u.) in the bulk solution

The impermeability for large molecules can be used to create pH gradients across the capsule wall which later can be used to perform specific chemistry inside. This is achieved in the following way: A polymeric acid (polystyrene sulfonic acid) is added to the bulk. It dissociates protons which only partly penetrate into the interior, because negatively charged polymer remains outside. This yields a Donnan equilibrium, and having polymeric pH probes in the inside one can show that a pH difference of 1 unit between outside and inside can be created /6/. Fig. 6 shows the fluorescence intensity of capsules labeled with a pH sensitive dye as a function of pH of the external medium if the probe is inside the capsule or if it is in the outer water phase. One clearly observes the shift indicating that the pH inside and outside differs by about one unit. Since in this experiment the pH was adjusted by adding the proper amount of a polyacid to the external medium it proves again that the wall is impermeable to polymers with molecular weights above 4000 a.m.u.

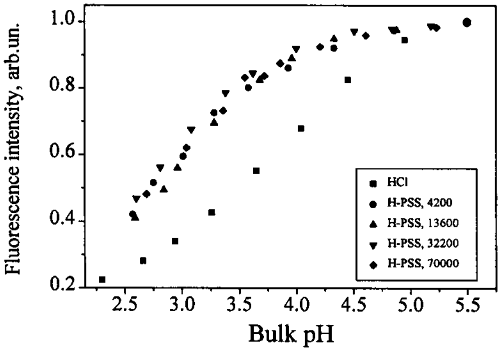

Fig. 6
Fluorescence intensity of a suspension of polyelectrolyte shells (diameter 3 μm) containing 6-carboxyfluorescein as a fluorescent marker vs. the bulk pH titrated by means of H-PSS and HCl. Different symbols as described in the inset refer to either various molecular weights of H-PSS or HCl, respectively.

Meanwhile there have been many ways developed to perform specific chemistry inside the capsules.

The pH difference could be used to form precipitates of small organic molecules inside, an example of loading (Fig. 7).

Since in most cases we observe precipitation to start from the inner capsule walls these may serve as nucleation site. However, the high definition of these walls may also be used to perform specific chemistry.

Since particles are soluble not only in water but also in organic solvents like chloroform or alcohols they could be dispersed also in their mixtures with water. It was then shown that the interior was enriched with one component the external with the other one. Hence also reactants can be preferentially concentrated as was demonstrated optically with dyes.

The impermeability of the walls for entities of above 5 nm dimensions could be used to trap inorganic or biocatalysts. They can be used, e.g. to polymerize monomers in the inside.

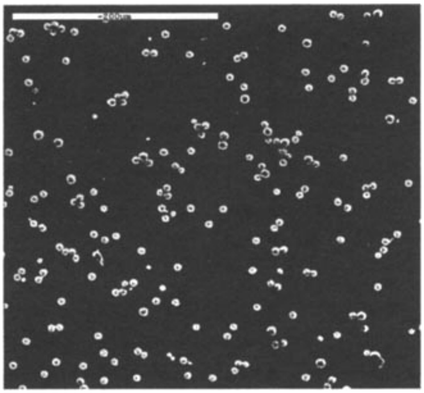

Fig. 7
6-Carboxyfluorescein precipitated into human erythrocyte derived polyelectrolyte shells

Beyond performing chemistry in micro- and nanoreactors another issue is the control of micro-mechanical properties. Besides controlling the polymer parameters like stiffness and crosslinking densities and the wall thickness there is in addition the most important possibility to insert inorganic particles into the wall. It was shown that this can be achieved with a high density for SiO_2, meanwhile also for magnetic particles /7/. Calcination of the organic fraction then may yield stable porous inorganic capsules, the stability apparently coming from sintering processes /8/.

Hence we could show up a route to use the broad knowledge about interfaces to prepare defined colloids and then to obtain a nanoreactor for specific chemistry.

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