VESICLE PHOTONICS

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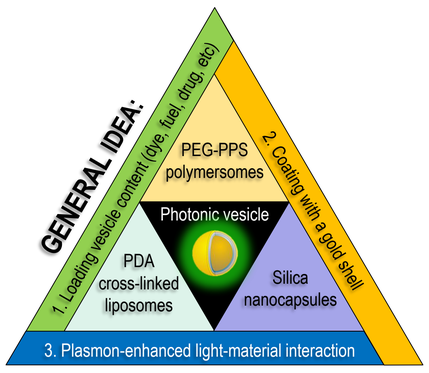
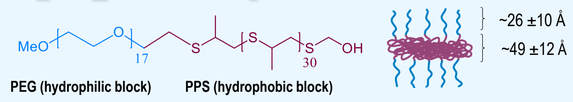


Introduction: Thin molecular membranes, under appropriate boundary conditions, can self-assemble into nanoscale quasi-spherical vesicles that encapsulate and transport liquid / solid state molecular payloads. Vesicles can be artificially synthesized using different materials, e.g., block copolymers [1, 2] or lipids [3], which provide good stability and protection of the vesicle content. Careful tailoring of the membrane surface composition leads to control over its physicochemical features and opens a way towards further surface modifications and synthesis of hybrid nanoparticles, e.g., hollow noble metal nanocontainers [4, 5]. Deposition of the metallic shell not only improves vesicle mechanical properties, but also significantly changes the optical features by the presence of a local surface plasmon field that amplifies the UV-NIR light-material interaction within the subwavelength scale plasmonic cavity volume [6-9].

Herein, we introduce the chemical synthesis of vesicle-based hybrid nanoparticles, as well as mechanisms and applications of their interactions with light. By encapsulating light-sensitive or light-emitting molecules (e.g. photooxidizers or dyes), we show that vesicles can act as imaging agents in addition to cargo carriers. Their interaction with light fields can be employed to directly perturb the stability of vesicle membranes and trigger the delivery of the encapsulated payload. Vesicle gold-coated counterparts, on the other hand, act as subwavelength plasmonic cavities and improve fluorescence photostability of the encapsulated fluorophore molecules against photobleaching, while the vesicle membrane prevents quenching within contact distance with the gold shell [6, 9].

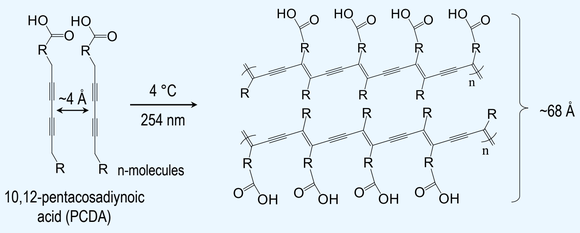
Vesicle membranes:

PEG_{17}-PPS_{30} polymersomes (M_w=750; 28% of PEG) [2, 10]:



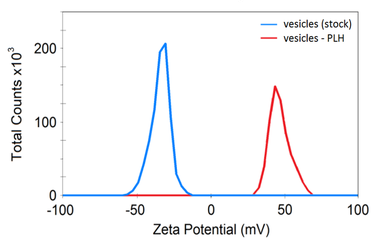
Spontaneously formed vesicle membrane, stabilized by the hydrophobic polypropylene sulfide (PPS) block in water. PEG-PPS vesicles allow:
- efficient size and polydisperssity control via high pressure extrusion;
- efficient loading with hydrophilic molecules (fluorophores, drugs, etc), and prevent leakage of their content;
- doping of the oxidation-sesnitive PEG-PPS membrane with hydrophobic photo-oxidizers (ethyl eosin), and light-controlled rupture of the vesicle membrane and release of its content.

Polydiacetylene (PDA) liposomes [3]:



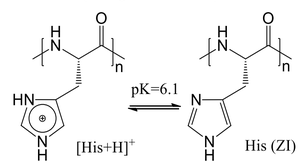
Vesicle membrane assembled by hydration of a thin PCDA film and its ultrasound homogenization; exposure to UV light cross-links the polymer backbone.
PDA vesicles provide:
- pH-, mechanical stress-, and temperature-sensitive colorimetric reversible transition from blue to red [3];
- maintained membrane stability when loaded with low concentrations of some organic solvents (methanole, ethanole, up to 10-15% vol).

Controlled surface charge distribution:

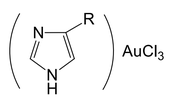


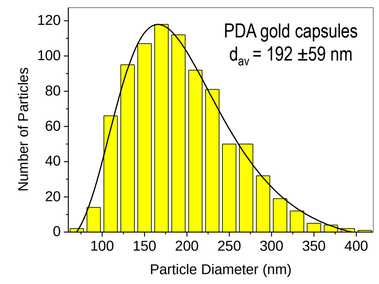
Surface-confined controlled deposition of gold:

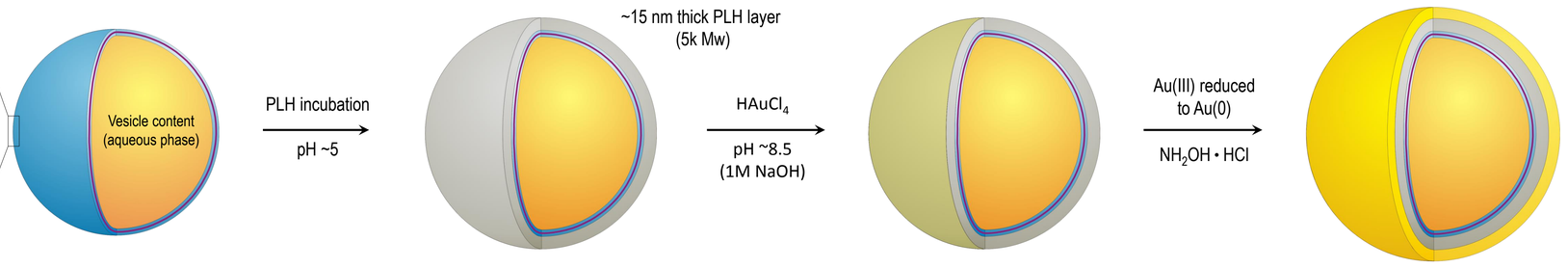
pH - dependent poly-L-histidine adsorption (charge interaction)



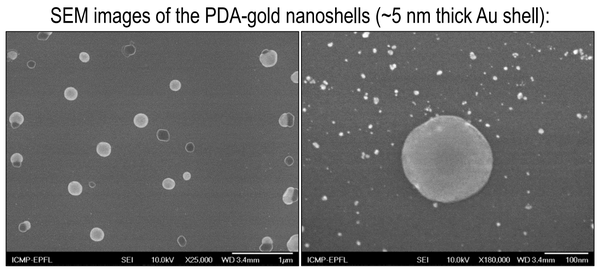
Imidazole – Au(III) complex as an 'anchor' between the membrane and metallic shell



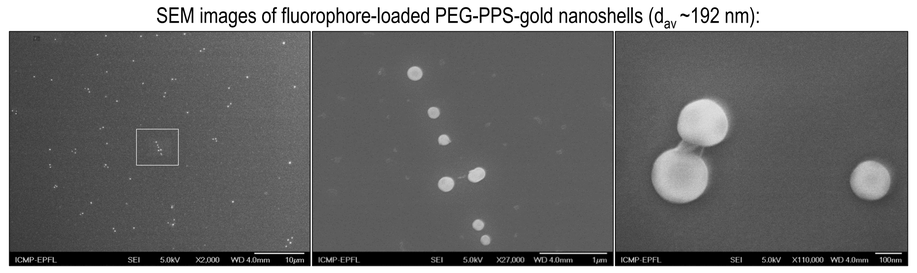




SEM images of the PDA-gold nanoshells (~5 nm thick Au shell):

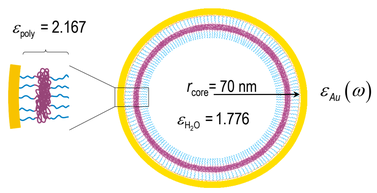


SEM images of fluorophore-loaded PEG-PPS-gold nanoshells (d_{av} ~192 nm):

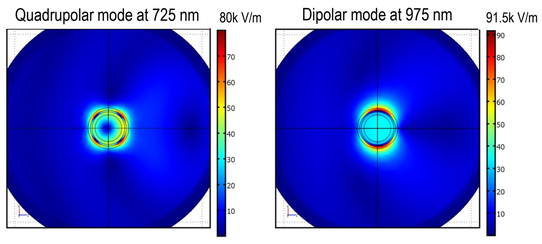


Hollow gold containers – spectral properties:

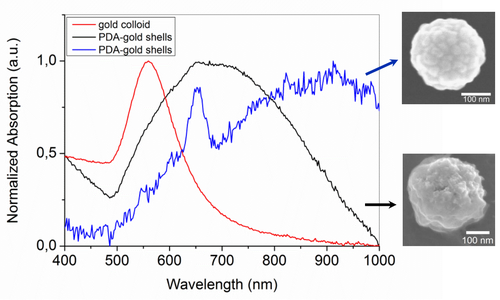
Spectral properties of hollow metallic particles are well explained by the linear Mie scattering theory [11], and strongly depend on the particle geometry as well as material dielectric properties [12].



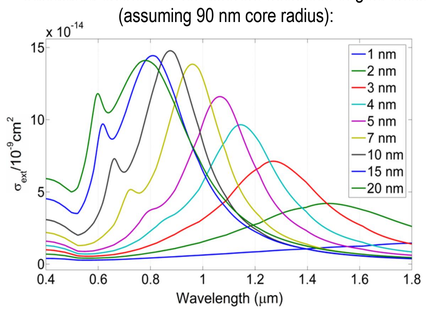
COMSOL simulations of the plasmon field distribution within the particle volume (r_{core}=90 nm, 7 nm thick gold shell)



The plasmon resonance peak and plasmonic cavity *Q*-factor strongly depends on the metal shell thickness and its quality [7, 13].

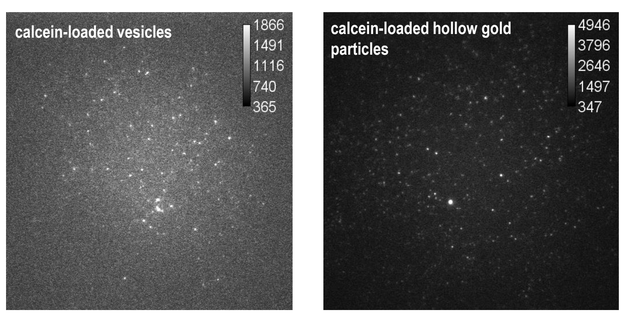


Calculated extinctions for different thickness of gold shells (assuming 90 nm core radius):

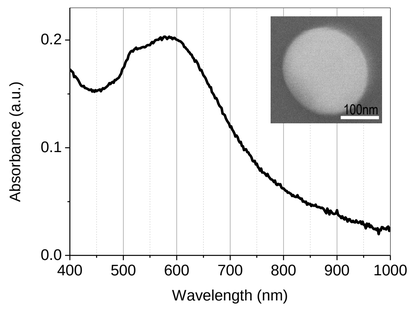


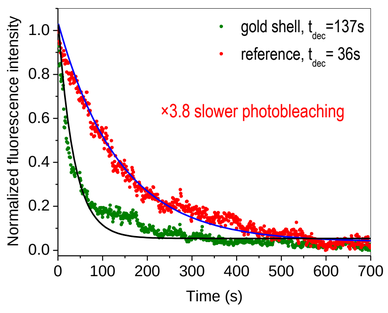
Plasmon-assisted fluorescence enhancement:

Wide field; ×100, NA = 1.4 oil immersion objective; λ_{exc} = 488nm CW; 200mW
(calcein concentration in both cases was 12.5 μM and identical payload volumes)

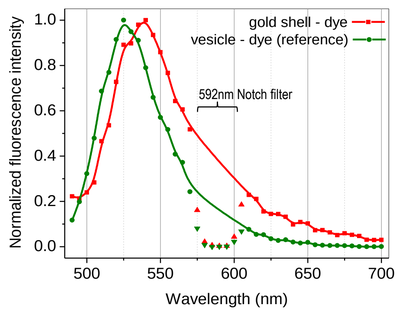


Absorbance spectra of calcein-loaded hollow gold particles (gold templated onto the PEG-PPS vesicle membrane)





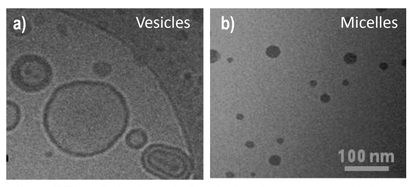
Comparison of fluorescence photoresistance against photobleaching for calcein-loaded vesicles and hollow gold containers (plasmon resonance set at 590 nm).
Particles were exposed to λ_{exc} = 488nm CW; 200mW



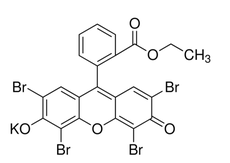
Plasmon field enhancement affects the fluorescence lifetime of a dye [6, 9], resulting here with about 20 nm broader Stock's shift of the fluorescence emission peak of calcein.

Strategy for optofluidic triggered release:

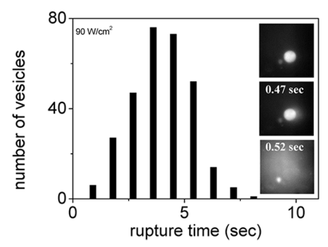
Polymersome membranes can be loaded with hydrophobic photooxidizers, such as ethyl eosin incorporated into the PPS hydrophobic core of the vesicle membrane. Exposure of ethyl eosin-loaded polymersomes to specific light fields results in conversion to micelles and release of the hydrophilic payload [14].

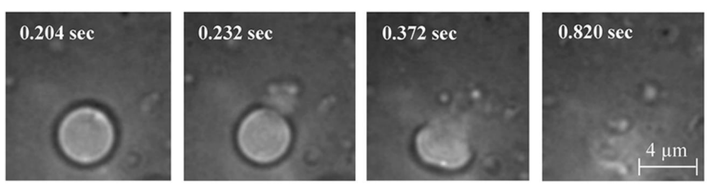


Cryo-TEM of ehtyl eosin-loaded polymersomes before (a) and after (b) exposure to a 488 nm light source



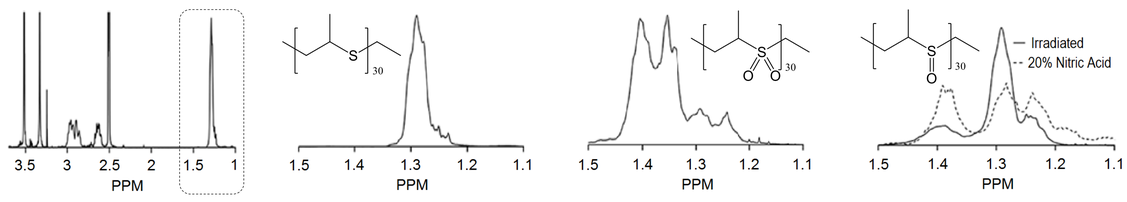
ethyl eosin photooxidizer





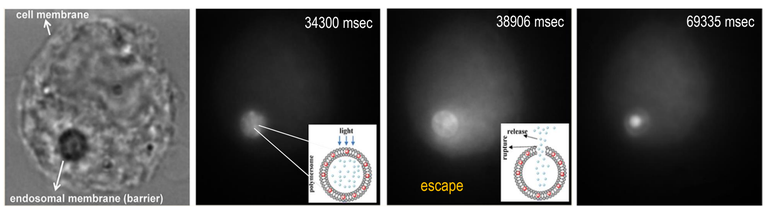
Rupture of a single large polymerosome in a series of video microscopy frames under illumination with a 488 nm laser beam (500 W/cm^2).
Illumination of the whole polymersome surface for longer periods results in a complete destabilization of its membrane [14].

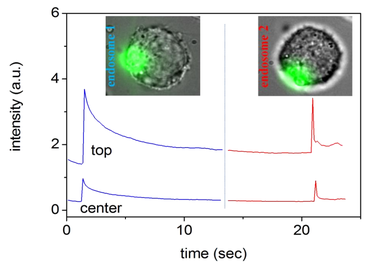
Oxidation of the PEG-PPS block copolymer detected by the ^{1}H NMR spectroscopy [14]:



Optofluidic rupture and precise spatiotemporal control over cytosolic delivery:

Polymersomes within individual endosomes can be ruptured for precise spatiotemporal cytosolic delivery without affecting cell viability. A series of fluorescent microscopy frames (encapsulated calcein, excited at 488nm, CW, 50-80 mW/cm^2) shows polymersomes that have been taken up by RAW macrophage cells rupturing under optical excitation, releasing their contents in the endosome and cytosol over time [14].





Intensity variation at two different locations in a single cell (centre and top) due to the release from two individual endosomes at different time points.

References:

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