Nanoparticle Membrane: A Unique Two-dimensional Material

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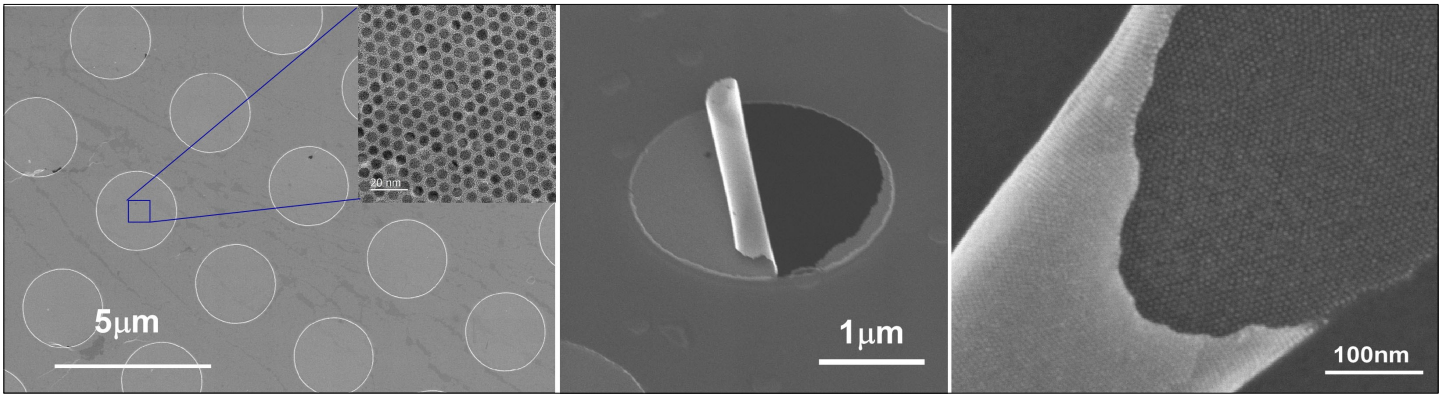

Researchers with the University of Chicago and Argonne National Laboratory created a 2D membrane system that can potentially mimic a cell membrane's complexity. (Image courtesy of Xiao-Min Lin and Heinrich Jaeger).

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The cell membrane serves many important functions in biology as it controls the transport of ions or organic substances in and out of the cell. Synthetic membranes, such as lipid bilayers and graphene membranes, on the other hand, are not as nearly as complex either in terms of structure or functionality. In recent years, through a research collaboration between the University of Chicago and Argonne National Laboratory, we created a two-dimensional (2D) membrane system that can potentially mimic a cell membrane's complexity. Our team shows that tiny colloidal nanoparticles deposited on an air-water interface can self-assemble to form 2D sheets, and drape onto a holey substrate to form free-standing membranes. [1] Inside the membrane, individual nanoparticles are held together through the interdigitation of molecules coating the surface of the nanoparticles. This new type of membrane has the potential to form complex 2D or even 3D structures, because both the inorganic core and organic molecular shell can be exchanged independently with almost unlimited possibilities. [2]

For any practical application, the first parameter to address is the strength of the membrane. Measurements done by atomic force microscopy show that a single sheet of membrane, less than 10nm in thickness, is remarkably strong, with a Young's modulus on the order of Gigapascals (close to the value of Plexiglass). [1,2] We also probed the fracture strength of the membrane by transferring them onto a polydimethylsiloxane (PDMS) substrate, followed by stretching the PDMS substrate. By direct imaging of the fracture patterns with increasing strain, we can obtain the fracture strength, which is on the order of Megapascals. [3] These measurements also show the nanoparticle membranes do not develop channel cracks, like many crystalline materials, but instead show signs of viscoelastic behavior under high strain.

Because nanoparticles membranes are formed at the air-water interface and exposed to a heterogeneous environment, the molecular distribution on the nanoparticle surface could have an asymmetric distribution. Collaborating with our colleagues at Argonne's Advanced Photon Sources, a 6Å difference in molecular layer thickness between the water-facing side and air-facing side of membrane was detected using a grazing incidence small angle x-ray scattering (GISAXS) technique. [4] This tiny and yet significant molecular asymmetry can be amplified under the stress caused by the electron beam irradiation, and induce a unidirectional folding of the membranes into nanoscrolls. Coarse grained molecular dynamics simulations show molecular packing density and mobility strongly affect this molecular distribution asymmetry. Measurements of the stiffness along the nanoparticle scroll allow the bending modulus of the membrane to be extracted, which is two orders of magnitude higher than what the macroscopic continuum theory would predict. [5] From a fundamental scientific point of view, it is still unclear why a sheet less than 10 nanometers in thickness consisting of discrete nanoparticles is mechanically so robust. The answer could lie in the molecular organization and conformation change in a confined space between nanoparticles.

Aside from research into understanding the fundamental physics related to these new materials, our team is actively working towards developing novel applications. Like other macroscopic elastic membranes, these tiny nanometer thick membranes can form mechanical resonators, driven either thermally or by external stimulations. Using a laser interferometry technique, the vibration frequencies and corresponding amplitudes of the nanoparticle

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membranes were mapped out. [6] Because of the ultralow mass and small dimension, the Department of Defense (DoD) would benefit from the portability and sensitivity of this technology as it will allow them to develop ultrasensitive detectors for chemical and biological agents and ammunition. [7]

Another potential application of the membrane lies in the area of water filtration. Nanometer interstitial spaces between membrane nanoparticles could provide size exclusion transport of molecular species. A preliminary measurement of molecular transport through such ultrathin membranes finds the filtration coefficients is two orders of magnitude larger than those observed in polymer-based filters. [8] The rejection coefficient of the solutes depends upon their size and charge. These results open up new possibilities for controlled separation of molecular species by nanoparticle membrane. Nanoparticle based filter has the potential to purify water far more efficiently than other methods. Some nanoparticle based filtration systems already on the market have shown the ability to remove many harmful contaminants from water such as arsenic, lead, bacteria and other viruses. [9] Being able to filtrate clean drinking water offers two major advantages for the DoD. Primarily, the warfighter has the ability to purify their own water and does not have to rely on iodine tablets which can be time consuming and require a makeshift filter such as a T-shirt. Even then, the process for bad cases of water can take over an hour and up to six iodine tablets. [10] Personal water filters can allow the warfighter to be more self-sustaining when a mission requires, reducing the number of supplies held as well as lowering resupply needs for water in areas that clean water is scarce.

Research in the area of nanoparticle membrane is just beginning to show its potentials. With improving fabrication techniques and a clever designing of the membrane composition, new properties and applications are destined to emerge.

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