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The Role of Pore Geometry in Single Particle Detection

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Single pores prepared in thin membranes have demonstrated great potential as platforms for next generation, high-throughput single particle biosensors. The realization of readily accessible solid-state devices applicable to virion-sized particles has yet to come due to an inadequate understanding of particle detection mechanics in pores whose diameters are comparable to their length. Successful detection experiments involving nanoparticles have largely relied on high-aspect-ratio pores prepared in glass or polymers and, most recently, low-aspect-ratio solid-state pores. We present a systematic study of pores bridging the gap between these regimes and evaluating their detection parameters as they relate to pore geometry.

In pore-based detection, a particle occludes current-carrying electrolyte as it translocates the pore. This creates a transient pulse of diminished ionic current which can be characterized by its depth and duration. Integrating recent findings with low-aspect-ratio pores and long-standing high-aspect-ratio pore considerations with our experiments, we formulate an approximation for event depth which, for the first time, depends explicitly on geometric parameters. Further, we develop an approximation for the electric field which allows us to characterize particle zeta potentials with our pores. This approximation is utilized to quantify capture rates in terms of known electric potentials and geometric factors, revealing higher-than-anticipated rates, potentially reducing amount the time an experiment needs to run for successful analysis. Although our results yield refined approximations, these findings represent a step toward realizing practical detection devices.

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Electrochemical Impedance Spectroscopy of Nanopores

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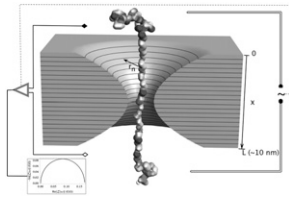
Nanopores have found increasing numbers of applications in basic science research and biotechnological devices. The favorable physical and chemical properties of solid state nanopores makes them attractive for many of these applications. However, the geometry and surface properties of such nanopores is often variable and must be characterized for each experiment. Such characterization typically takes place before or after the experiment. We have developed an approach to characterize the geometry and surface characteristics of nanopores using electrochemical impedance spectroscopy (EIS). We show how EIS can be used to determine the geometry and surface charge density of nanopores and apply the approach to nanocapillaries, focussed ion beam drilled nanopores (~90 nm), and noble gas ion beam sculpted nanopores (~20 nm). The ladder differential equation developed to allow inversion of the EIS to geometry is further adapted to treat the presence of an unfolded protein in the nanopore. We show how the EIS spectrum is expected to shift in response to the local coarse-grain sequence of the unfolded polypeptide chain. The results show that the EIS spectrum is substantially more sensitive to nanopore geometry and local sequence information than traditional DC resistive pulse measurements.



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Enhancing Biopolymer Trapping by Double Electrical Field and Osomotic Flow in a Biological Nanopore

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Nanopore based sensors promise ultrasensitive detection of an array of nucleic acid, peptide, and protein biomarkers. However, the low physiological concentrations of cancer biomarkers can greatly limit their detection in conventional nanopore sensors due to the low trapping rate of these markers. A previous study used a salt gradient in a synthetic nanopore increases the capture rate of double-stranded DNA. In this study, we have demonstrated that the use of salt gradient generates two enhanced electrical filelds (EEFs) by the concentrated the K^+ and Cl^- gradients around the pore at each side, respectively. The K^+ at *cis* side attracts the DNA while the Cl^- at *trans* side expels the DNA. These local EEFs changed the DNA trapping and unzipping profiles in the nanopore. Further, we demonstrated that the EEFs and osmotic flow generated by this salt gradient can lead to dramatic increases in the trapping frequency of multiple biopolymers, such as DNA, peptide, PEG and DNA-protein complex. We then provide evidence that this increase of trapping frequency is directionally and molecularly-dependent, based on the charge and MW of the molecule. Finally, picogram level of liver-specific microRNA was successfully detected in the pore using this salt gradient.

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Nanopore Force Spectroscopy on Nucleic Acid Structures & their Target Complexes using Biological and Synthetic Ion Channels

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Nanopore force spectroscopy (NFS) is a versatile tool for the investigation of single molecule interactions with high throughput and sensitivity. We parallelize this method using a 16-channel chip-based bilayer setup (Nanion-Technologies), making it suitable for screening assays.

In our experiments, we study the binding of the ATP aptamer to its target in terms of complex stability as well as binding affinity. Aptamer-target complexes show a stability that is considerably higher compared to unbound aptamer structures. This allows us to determine the binding affinity of the ATP aptamer to its target molecules by comparing populations in the stability distributions for varying target concentrations. Due to the high force resolution of NFS we observe that the stability of bound aptamer structures splits up into several sub-populations that reveal more detailed information about the binding process.

We extend the use of NFS from DNA to RNA-based molecular structures, which play important roles in biological processes e.g. in the form of aptamers or in gene regulation. In particular RNA hairpin structures are investigated, which are found to display an increased stability compared to their DNA analogues, as their predicted thermodynamic stability suggested. Furthermore, first experiments on RNA aptamers have been performed.

Previous NFS studies were based on naturally occurring membrane channels like α-hemolysin or solid-state nanopores. Tailoring these systems to specific applications remains a challenging task, when altering the channels' geometry or chemical modification becomes necessary. We report on the use of a novel synthetic membrane channel constructed entirely from DNA to perform nanopore-sensing experiments. Scaffolded DNA origami was used to create the channel, allowing for easy modifications in terms of geometry and chemical features. We demonstrate its functionality by studying DNA hairpin unzipping and G-quadruplex unfolding.

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Quantitative Description of Polyethylene Glycol in an Alpha-Hemolysin Pore

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We present a theoretical framework that guides the interpretation of experimental nanopore data with broad applications in single molecule sensing. Polyethylene glycol (PEG) in particular, is important since it can be used as a surrogate for detecting nucleotides when sequencing DNA (2012, Nature Scientific Reports, 2:684). Here, all atom molecular dynamics (MD) simulations are used to refine the model of Reiner et al. (2010, PNAS 107(27):12080) to characterize the interactions of PEG with an alpha hemolysin (αHL) nanopore. The model, in which PEG is represented as a uniformly charged cylinder, yields two key quantities that are compared with experiment: the ratio of ionic current across the pore due to the presence of PEG over the open channel value (blockade depth), and the residence time. The model assumes that these quantities cannot be described by the volume occupied by PEG inside the pore alone, but must also include complexes formed by PEG with cations. MD simulations are

used to test this assumption and refine parameters in the model that are otherwise difficult to measure directly, such as the volume occupied by PEG inside the pore and the local concentration of electrolyte, found to be approximately half the bulk value. MD simulations are also used to test a central hypothesis in the theoretical model that PEG complexes cations to acquire a net positive charge. We confirm that this is indeed the case and that five PEG subunits participate in forming crown-ether like sub-structures with a single cation. The refined theoretical model is then fit to blockade depth and residence time values measured experimentally as a function of PEG size (varying from 1000 g/mol to 2000 g/mol). We find that the theoretical predictions of the model agree quantitatively with experiment thereby validating its assumptions.

2679-Pos Board B698

Integration of Biogenic Nanopore Membranes on Prefabricated Fluidic Support Substrates

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Marine diatoms provide an alternative to machined silica nanopores, avoiding costly and slow throughput fabrication steps, while being able to achieve pore structures with diameters on the order of 40 nm. The hierarchical pore architecture makes these biogenic nanomembranes exceptionally mechanically stable, while maintaining a short pore length and a high porosity. The most prominent issue when replacing machined silica nanopore membranes with biogenic membranes is the initial random placement of the membranes on the solid substrate. This is also problematic when trying to accomplish a permanent fluidic seal around the membrane.

In our study, we demonstrate the ability to localize and immobilize a 200μm-diameter biomineralized nanopore membrane structure from marine algae, Coscinodiscus wailesii, on pre-defined positions on micro-machined silicon substrates. The substrates feature micron-sized through-wafer channels that allow easy access to the nanopore membrane. Localization of the membrane structure is accomplished using patterning of 8 μm thick hydrophobic resin. The addition of poly-L-lysine to the surface before solution-depositing the nanopore membranes results in a strong electrostatic binding force between the oxidized silicon platform and the diatom membranes. Lift-off of the photoresist in acetone removes randomly placed nanopore membranes on the resist-coated area, not affecting diatoms adhering to the silicon surface.

While poly-L-lysine provides an initial fluidic seal, permanent immobilization is accomplished by using UV-curable photoresist SU-8 and proximity photo lithography. Scanning electron micrographs after processing show intact diatoms without the presence of stress cracks. While initial electrochemical measurements indicate that some of the nanopores are clogged by residual epoxy resist after development, subsequent sulfuric-peroxide mixture (SPM) treatment removes the residual resist. Successful translocation experiments using polystyrene beads shows presence of unclogged pores, also indicating that the pore size of the biogenic silica nanomembranes can be modified by chemical treatment.

2680-Pos Board B699

Mixed Company in a Protein Nanopore: Transient Double Occupancy Enables Direct Exchange of Pore Ligand in Nanopore-Based Single Molecule Sensing

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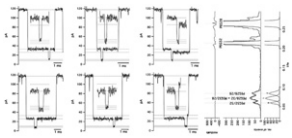
Partitioning of poly(ethylene-glycol) (PEG) into an alpha-hemolysin nanopore gives rise to long-lasting blockades ($\tau \approx 0.1$-10 ms) of ionic current. The depth of blockade shows exquisite sensitivity for polymer length, yielding mass spectra with single monomer resolution in the range between MW ≈ 700-2200 or 15-50 repeat units (r.u.). Unexpectedly, high-resolution recordings of single PEG blocking events using a mixture of two monodisperse species unequivocally identified direct transitions between levels corresponding to 28 and 32 r.u. without an intervening unblocked interval. Closer analysis revealed that these occur by the intermediary of shorter, deeper blocks. Based on statistics and current amplitude distributions, we are able to identify three such deeply blocked states, each corresponding to the simultaneous presence in the pore of two ligands: either 2xPEG-28, 2xPEG-32 or PEG-28+PEG-32 (mixed double occupancy). Direct PEG28->PEG32 transitions (or vice versa) are observed only with an intervening mixed occupancy block, which, however, can also result in return to the first blocked level. We conclude that the alpha-hemolysin pore is capable of accomodating two PEG oligomers, with ligand exchange occurring by displacement and translocation of the first blocker.



2681-Pos Board B700

Nanopores with Fluid Walls for Determining the Shape, Dipole Moment, and Rotational Diffusion Coefficient of Non-Spherical Proteins

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Recording ionic current through electrolyte-filled nanopores during the passage of proteins is an emerging technique for characterizing unmodified proteins in their native, aqueous environment. By measuring the reduction in current, ΔI, during the translocation of single proteins through an electrolyte-filled nanopore, this technique can characterize the size, charge, conformation, assembly and activity of hundreds of unlabeled proteins per second. For non-spherical proteins, however, broad distributions of ΔI values make estimates of protein size unreliable. This work employs lipid-bilayer coated nanopores and describes quantitative procedures for determining the shape and volume of single spherical and non-spherical proteins from distributions of ΔI values. Since the ΔI(t) signal is related to the orientation of non-spherical proteins in the nanopore, individual resistive-pulses can be used to determine the rotational diffusion coefficient and dipole moment of non-spherical proteins while in the nanopore. Moreover, this method has the potential to detect transient changes in the conformation of flexible proteins (e.g. an IgG antibody). This work extends the power of nanopores for characterizing proteins by adding the parameters of shape, volume, rotational diffusion coefficient, and dipole moment of non-spherical proteins to those that can already be determined in a single experiment such as the volume of spherical proteins, charge, and affinity for a ligand.

2682-Pos Board B701

Threading Immobilized DNA through a Solid-State Nanopore with a Tip

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Nanopores have been of interest for scientific research in addition to medical applications since they have the ability to detect and characterize single biomolecules with potentially high throughput and low cost. The Scanning Probe Microscope (SPM) method has sub-nanometer spatial resolution. We have constructed a combined SPM-solid state nanopore apparatus to study the capture and release process of lambda-DNA by a voltage biased solid-state nanopore. By tethering the DNA to an fiber tip in ionic solution, we can control the position of one end of the DNA molecule precisely, allowing us to study the DNA capture and release distance from the nanopore. We also have detected DNA sticking to the nanopore mouth without translocation through, it produced small current blockage, and we can study this process with one DNA molecule repetitively. This tethered DNA nanopore sensing method will provide a means to slow DNA translocation, allowing more detailed features of single DNA molecules to be studied, and potentially can be used with all types of nanopores with single-biomolecule sensitivity at controlled translocation rates.

2683-Pos Board B702

Brownian Dynamics Simulations of DNA Interaction with a Nanoporous Solid State Membrane

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We have developed computational model that allows us to study the influence of a nanoporous solid state membrane on the dynamics of a biomolecule. We apply various electrolyte and membrane biases and monitor the effects on DNA translocation and extension. The translocation of DNA through a nanopore in a single layered doped semiconductor membrane is studied. With our single layered, electrically tunable membranes, the DNA translocation time can be varied by more than one order of magnitude. Nanopore functionalization is also studied by fixing one strand of DNA to the inner surface of the pore. Two different models of DNA molecule are developed. The first model represents each DNA nucleotide as a single bead, while in the second one we consider two beads per nucleotide: one bead representing the phosphate and sugar backbone, and the other being the base. This model is more realistic and allows us to better understand the principles of interaction between the semiconductor membrane and DNA nucleotides.

2684-Pos Board B703

Ligand-Targeted Binding of a Novel Silicone Magnetic Microsphere

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In ligand-targeted drug delivery, a carrier particle conjugated with a ligand binds preferentially to an overexpressed receptor on the membrane of a specific cell type. A therapeutic agent is adsorbed onto or absorbed within the carrier, and its release is often triggered by magnetic stimulation or other means. In