

Supplemental Information : Understanding the nanoscale structure of hexagonal phase lyotropic liquid crystal membranes

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Further details regarding monomer parameterization

We parameterized monomers according to the following procedure:

1. *Create monomer structure file with connectivity* : We drew atomistic structures using MarvinSketch 17.13 [1] with all hydrogen atoms drawn out explicitly. We optimized the 3D geometry of the structure using the 'Clean in 3D' function of MarvinSketch. We saved the structure as a .mol file, then converted it to .pdb format using Open Babel 2.4.1 [2, 3].
2. *Assign GAFF atomtypes using antechamber* : Using the .pdb structure file as input, we ran `antechamber` [4] using the AM1-BCC charge model. The net charge on the monomer is input as -1 since the sodium ion we keep it as a separate residue. We use LEaP [?] and the output of `antechamber` to create Amber topology files. A detailed tutorial can be accessed elsewhere [6].
3. *Create gromacs topologies from Amber output* : The output of LEaP is a .inpcrd and a .prmtop file which are Amber topology files. Using acpype.py [7], we converted the LEaP output into GROMACS .gro and .top files.
4. *Perform a simulated annealing procedure on the monomer* : We created a cubic box around the monomer using the GROMACS command `gmx editconf`. The monomer was centered in the box with edges of the box spaced at least 3 nm from the monomer on all sides. We ran an energy minimization on the system with the steepest descent algorithm. Next we performed an NVT simulated annealing procedure. We linearly decreased the temperature of the system from 1000K to 50K over the course of 10 ns. We randomly chose a monomer configuration from the last 10 % of the trajectory.
5. *Reassign charges with molcharge* : With the monomer configuration taken from the annealed trajectory, we reassigned charges using `molcharge` with the am1bccsym method in order to ensure charges are symmetric. This condition is not guaranteed with `antechamber`. The charges in the GROMACS topology file (.top) were replaced with the new charges calculated by `molcharge`.
6. *Anneal again to get final structure* : We repeated the same simulated annealing procedure using the monomer topology with `molcharge` charges. A random monomer configuration was pulled from the last 10 % of the trajectory and was used to build all assemblies reported (Figure 2).

Calculation of pore-to-pore spacing statistics

We are interested in 5 pore-to-pore distances which should all be equal in a perfect hexagonal array (Figure 5). Only 4 of the 5 distances are independent. We can calculate a trajectory of spacing versus time for each of the 5 distances. We calculated the average pore-to-pore spacing and its uncertainty according to the following procedure:

1. We calculated the time when each of the pore-to-pore distances were equilibrated using `pymbar.timeseries.detectEqui` [?, ?]. We began calculations after the largest of the five values.

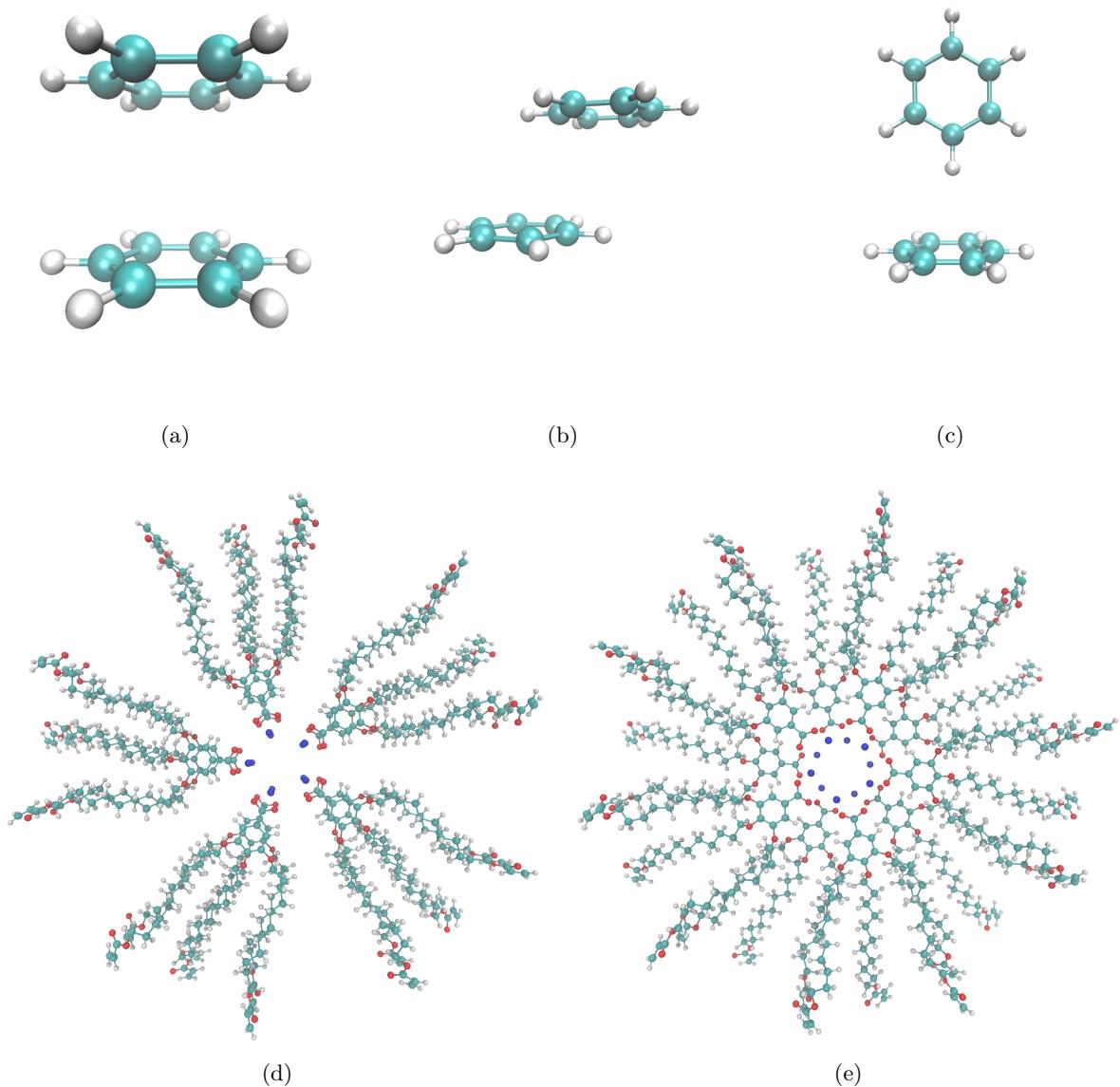


Figure 1: (a) Sandwiched benzene dimers stack 3.8 Å apart. (b) Parallel-Displaced benzene dimers stack 3.4 Å vertically and 1.6 Å horizontally apart. (c) T-shaped benzene dimers stack 5.0 Å apart. (d) Two monomer layers stacked in the sandwiched configuration (e) Two monomer layers stacked in the parallel-displaced configuration

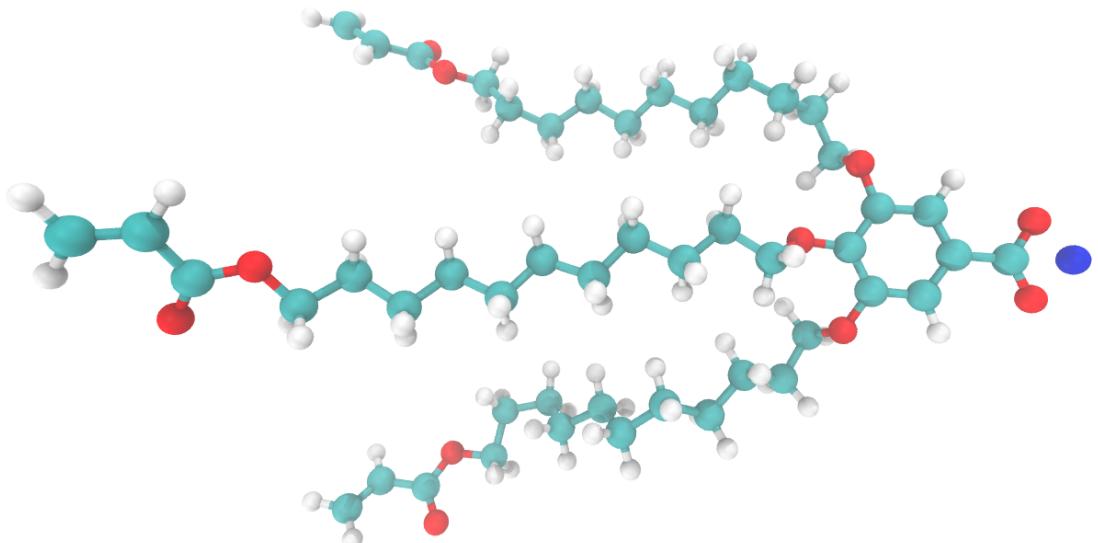


Figure 2: Atomistic representation of the monomer Na-GA3C11. White atoms represent hydrogen, cyan atoms represent carbon, red atoms represent oxygen and the blue atom is sodium.

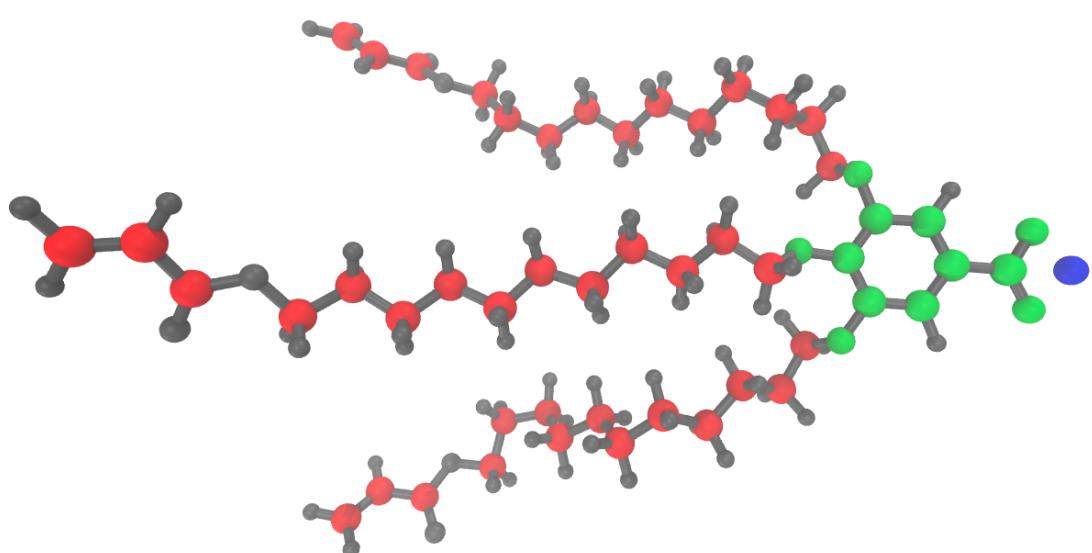


Figure 3: The groups used for $g(z)$ calculations. Red atoms are in the tails group. Green atoms are in the head group region. The blue atom is sodium.

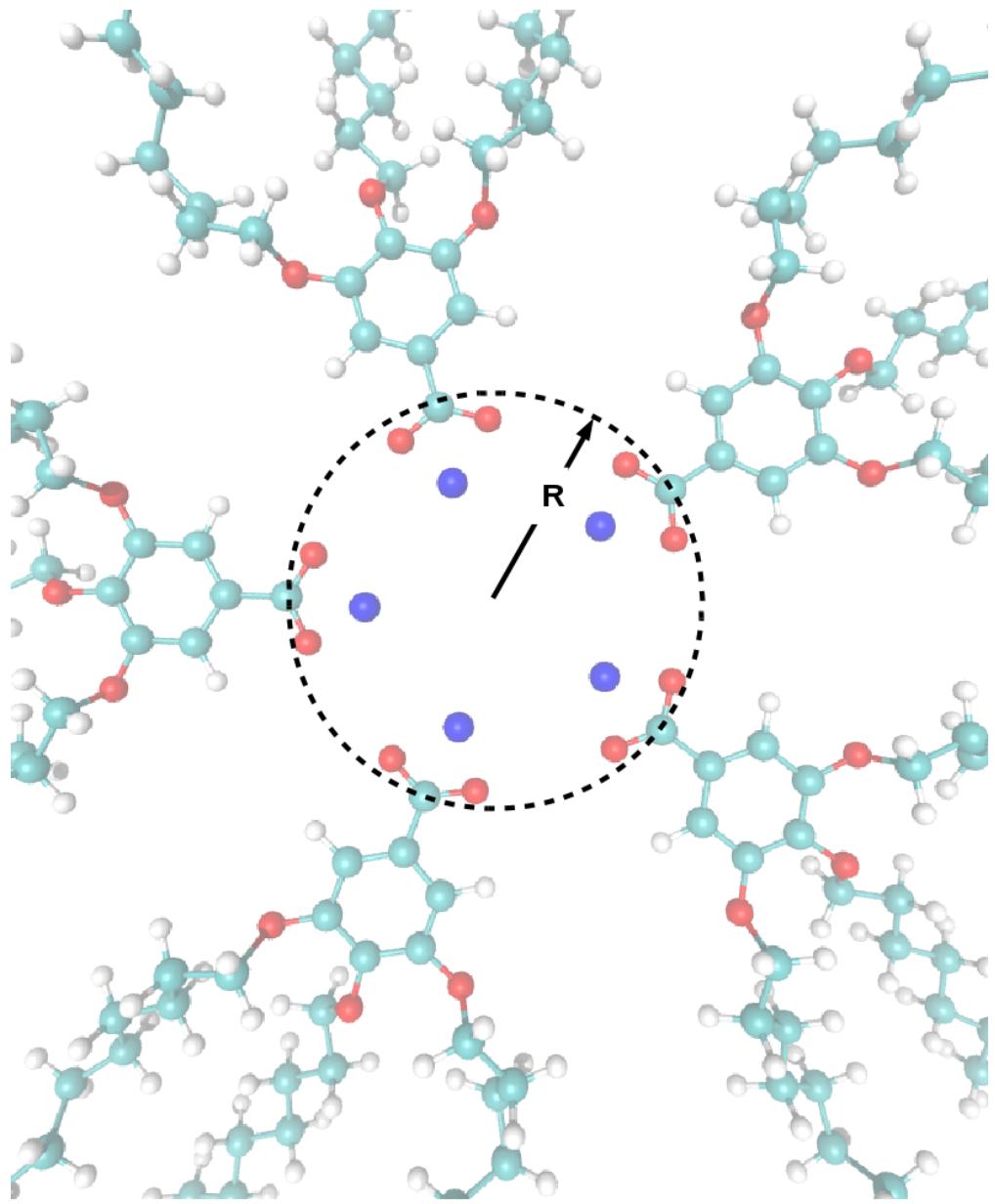


Figure 4: When creating an initial configuration, the pore radius is defined based on the distance of the carbonyl carbon from the pore's central axis

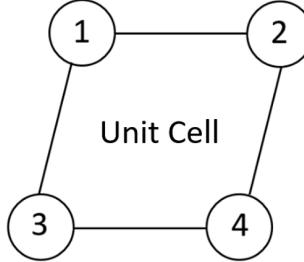


Figure 5: There are five pore-to-pore distances that are equal in a perfect hexagonal. If each number in the diagram represents the center of a pore in a hexagonal unit cell, then the distance from 1 to 2, 2 to 4, 4 to 3, 3 to 1 and 1 to 4 should be equal. Only 4 of the distances are independent. For example, the distance from 1 to 4 is defined by the location of all other pore centers.

2. We calculated how long it takes for the data in each of the 5 trajectories to become uncorrelated using `pymbar.timeseries.integratedAutocorrelationTime()` [?, ?].
3. We broke the full equilibrated trajectory into blocks of length τ , where τ is the maximum of the five autocorrelation times calculated. Each block contains five sub-trajectories of pore-to-pore spacings.
4. We generate statistics using the bootstrapping technique. For each bootstrap trial, we reconstruct an equilibrium trajectory by randomly sampling from the trajectory blocks.
5. The average pore-to-pore distance is the mean of all pore spacings among all bootstrap trials.
6. To calculate the uncertainty in pore-to-pore distance, we calculate the average pore spacing for each pore over all bootstrap trials. Using the 5 average pore-to-pore distances, we calculate the spread with:

$$s = \sqrt{\frac{1}{4} \sum_{i=1}^5 (x_i - \bar{x})^2} \quad (1)$$

where \bar{x} is the average pore-to-pore distance.

Initial Configuration Dependence

We addressed any major dependence on initial configuration in the main text. There we showed that systems are stable when made with 4, 5, 6, 7, and 8 monomers per layer. We also showed that systems are stable when monomer head groups are oriented in the parallel displaced and sandwiched configurations (See Figure 1). Our model best supports a system built with 5 monomers per layer in the sandwiched configuration.

There are three other parameters whose choice may influence the equilibrium structure: initial pore spacing, initial pore radius and initial distance between layers. Here we show the results of a sensitivity analysis performed on the three parameters. To reduce the size of the sensitivity analysis, we only tested systems built with 5 monomers per layer with layers stacked in the parallel displaced configuration. We equilibrated all systems according to the dry equilibration procedure.

Experimental correlation length of $R\pi$

Experimentalists did not measure the correlation length, so we estimated it from the raw data. We took a slice of the 2D WAXS data along the dashed line in Figure 6a. We removed background noise by subtracting the intensity far from the pattern (high q) uniformly. We fit a lorentzian curve to all the data above $q_z = 1.6$ to mitigate interference from R-alkanes. The full width at half maximum (FWHM) is related to the correlation length, L , by the relationship: $L = \frac{\pi}{FWHM}$.

1. Initial pore spacing

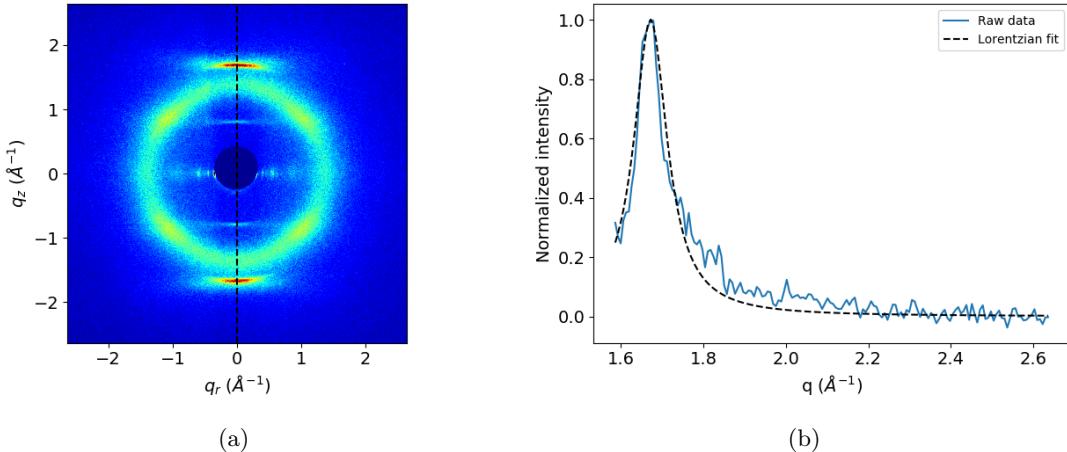


Figure 6

We tested five different initial pore spacings, defined as the distance between the central axis of each pore with all others. To reduce the number of variables, we held the pore radius constant, at 6 Å and the distance between layers at 3.7 Å since those were the values used in our optimal system in the main text. If the initial pore spacing is chosen to be too small, pore columns abruptly repel each other as soon as they are able to overcome the restraining potential present as part of the dry equilibration procedure. We avoided using systems that exhibit this behavior since the behavior increases the chances of a system to become kinetically trapped in an undesired metastable free energy basin.

- (a) 39 Å : We tested a pore spacing of 39 Å in order to have a test system with an intial spacing below the experimental value. As soon as the restraining potential switches to 56 KJ mol⁻¹ nm⁻², the columns are able to separate resulting in a large jump in pore spacing (Figure 7a).
- (b) 41 Å : We chose to test a pore spacing of 41 Å since it closely matches the experimental pore spacing. Again, we observe abrupt repulsion of columns once the restraining potential is switched to 56 KJ mol⁻¹ nm⁻² (Figure 7b).
- (c) 45 Å : A pore spacing of 45 Å is about 10 % larger than the experimental value. We observe relatively stable pore spacing during the restrained portion of the dry equilibration procedure (Figure 7c). We chose to use this value for all our simulations in the main text.
- (d) 50 Å : We tested a pore spacing of 50 Å, about 20 % larger than the experimental value. Once the restraining potential reaches 56 KJ mol⁻¹ nm⁻², the pore spacing begins to decrease linearly (Figure 7d).
- (e) 55 Å : We tested a pore spacing of 55 Å which is at a distance where monomers in each pore no longer intersect adjacent pores. Once the restraining potential reaches 56 KJ mol⁻¹ nm⁻², the pore spacing changes erratically until it begins to settle when the force constants are below 3 KJ mol⁻¹ nm⁻² (Figure 7e). We reccomend avoiding a system such as this where vacuum gaps between pore columns are introduced unnecessarily. The system equilibrates to a pore spacing of 4.27 ± 0.06 nm.

2. Initial pore radius

We tested 3 different pore radii, defined as shown in Figure 4. For each system, we held the initial pore spacing constant at 45 Å and the distance between layers constant at 3.7 Å. Equilibrated values of pore radii are presented in Table 1. The pore radius in each simulation frame is calculated as the average distance of all carbonyl carbons (See Figure 4) from their associated pore center. Statistics for the pore radii reported were generated from the timeseries representing the average pore radius at each

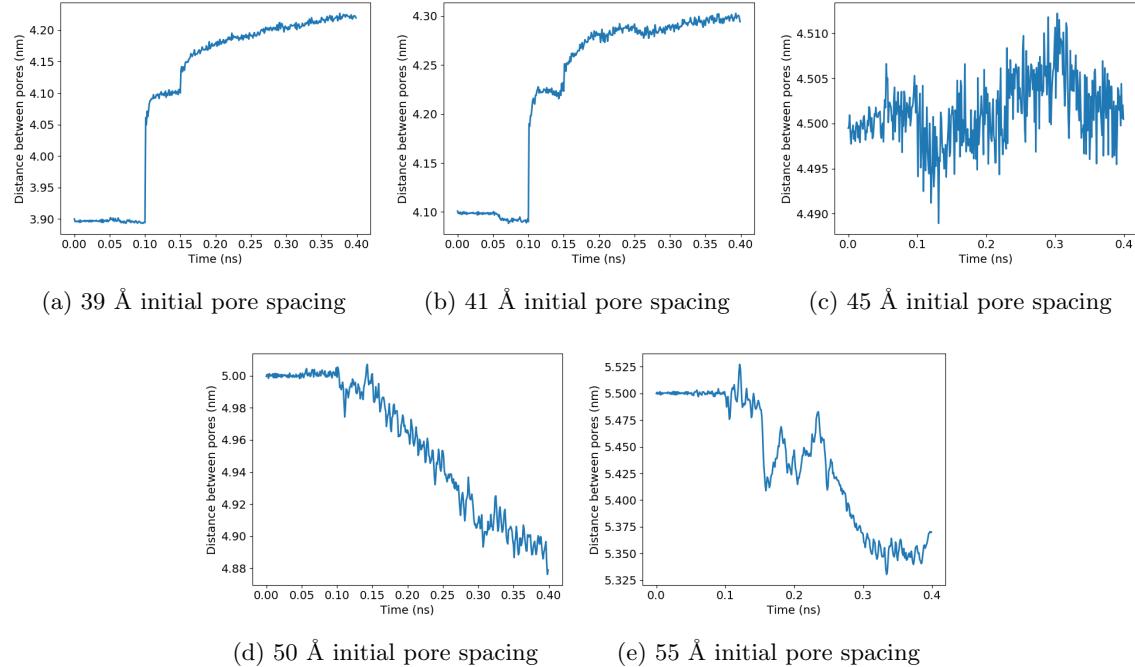


Figure 7: The pore spacing during the restrained portion of the dry equilibration procedure is shown. Every 50 ps (0.05 ns) position restraints are reduced according to the sequence: 1000000, 3162, 56, 8, 3, 2, 1, 0 KJ mol⁻¹ nm⁻². When the initial pore spacing is chosen below the experimental value (a) or at the experimental value (b), there is an abrupt change in pore spacing when the position restraints are reduced to 56 KJ mol⁻¹ nm⁻². When pores are started 45 Å apart (c) the pore spacing remains relatively stable. When pores are spaced 50 Å apart (d), the pore spacing decreases nearly linearly once the restraints are reduced to 56 KJ mol⁻¹ nm⁻². When pores are spaced 55 Å apart (e), so that monomers do not intersect with adjacent pores, and position restraints are reduced to 56 KJ mol⁻¹ nm⁻², the pore spacing changes erratically before stabilizing when force constants are reduced below 3 KJ mol⁻¹ nm⁻².

frame. We detected equilibration using `pymbar.timeseries.detectEquilibration`. We calculated the average and standard deviation of pore radii using only data points collected after equilibration was detected.

- (a) 2.5 Å : The smallest pore radius that we can achieve before energy minimization becomes problematic is 2.5 Å. After being run through the full dry equilibration procedure, the average pore radius is 0.40 ± 0.01 Å.
- (b) 5 Å : We tested a pore radius of 5 Å because it is slightly larger than the equilibrated pore radius of the system simulated with an initial pore radius of 2.5 Å. After being run through the full dry equilibration procedure, the average pore radius is 0.42 ± 0.01 Å, which agrees with the 2.5 Å configuration within error.
- (c) 8 Å : The largest pore radius that can be achieved before energy minimization becomes problematic is 8 Å. One should use caution with such a structure because of the relatively large vacuum space that is created in the pore region of the initial configuration. After being run through the full dry equilibration procedure, we see a combination of cylindrical and slit-like pores (Figure 8). We are wary of such a non-symmetric structure and choose not to use a pore radius of 8 Å for our starting configurations.

Initial Pore Radius	Equilibrated Pore Radius
2.5 Å	0.40 ± 0.01 Å
5 Å	0.42 ± 0.01 Å
8 Å	0.69 ± 0.01 Å

Table 1: The average pore radii of systems built with an initial pore radius of 2.5 Å and 5 Å equilibrate to values that agree within error. If the pore radius is too large, slit pores may form.

3. Initial distance between layers

We tested 3 different initial layer spacings, defined as the distance between the planes of aromatic rings in each layer. Systems built with layers stacked 3.7 Å and 5 Å apart are discussed extensively in the main text. We will focus the discussion here on systems built with layers stacked 10 Å apart.

Figure 9 shows the structure of an assembly built with an initial layer spacing of 10 Å immediately after the restrained portion of the equilibration procedure. Since we used position restraints, the simulations were run in the NVT ensemble. When layer spacing is large, such as this situation, there is a significant amount of vacuum space which the monomer attempts to fill. Even if turning pressure control on allows the system to recover the geometry of the hexagonal phase, we would likely need much longer equilibration times, and it will almost certainly get trapped in a metastable configuration that bears no resemblance to the experimental profile.

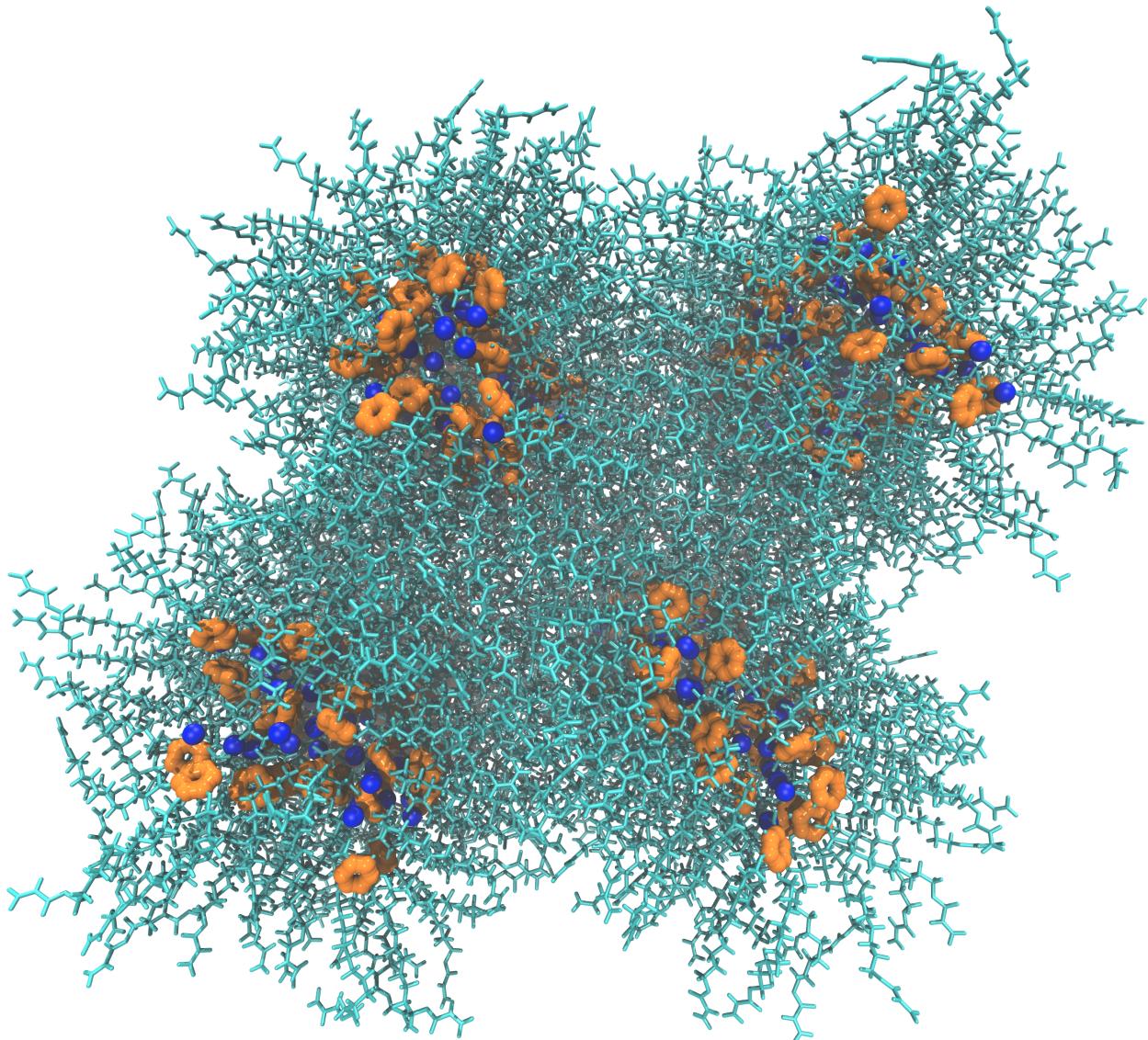


Figure 8: A system that was built with an initial pore radius of 8 Å equilibrates to a structure that exhibits both cylindrical and slit-like pores. As pictured here, sodium ions are colored blue, carbon atoms in the aromatic ring of the head group are colored orange and all else is colored cyan.

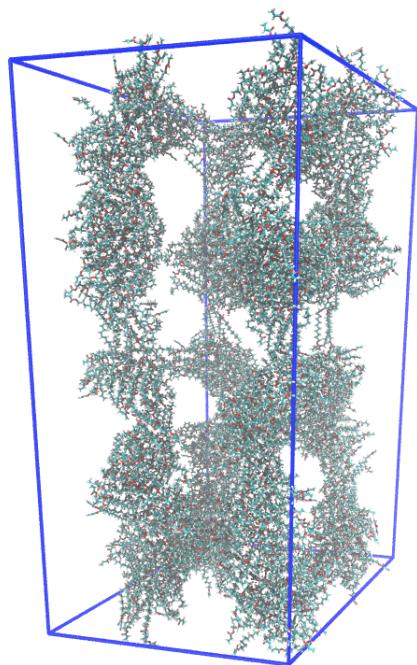


Figure 9: When layers are initially stacked 10 Å apart and the system is equilibrated using the dry equilibration procedure, large vacuum gaps form as the monomers attempt to fill space.

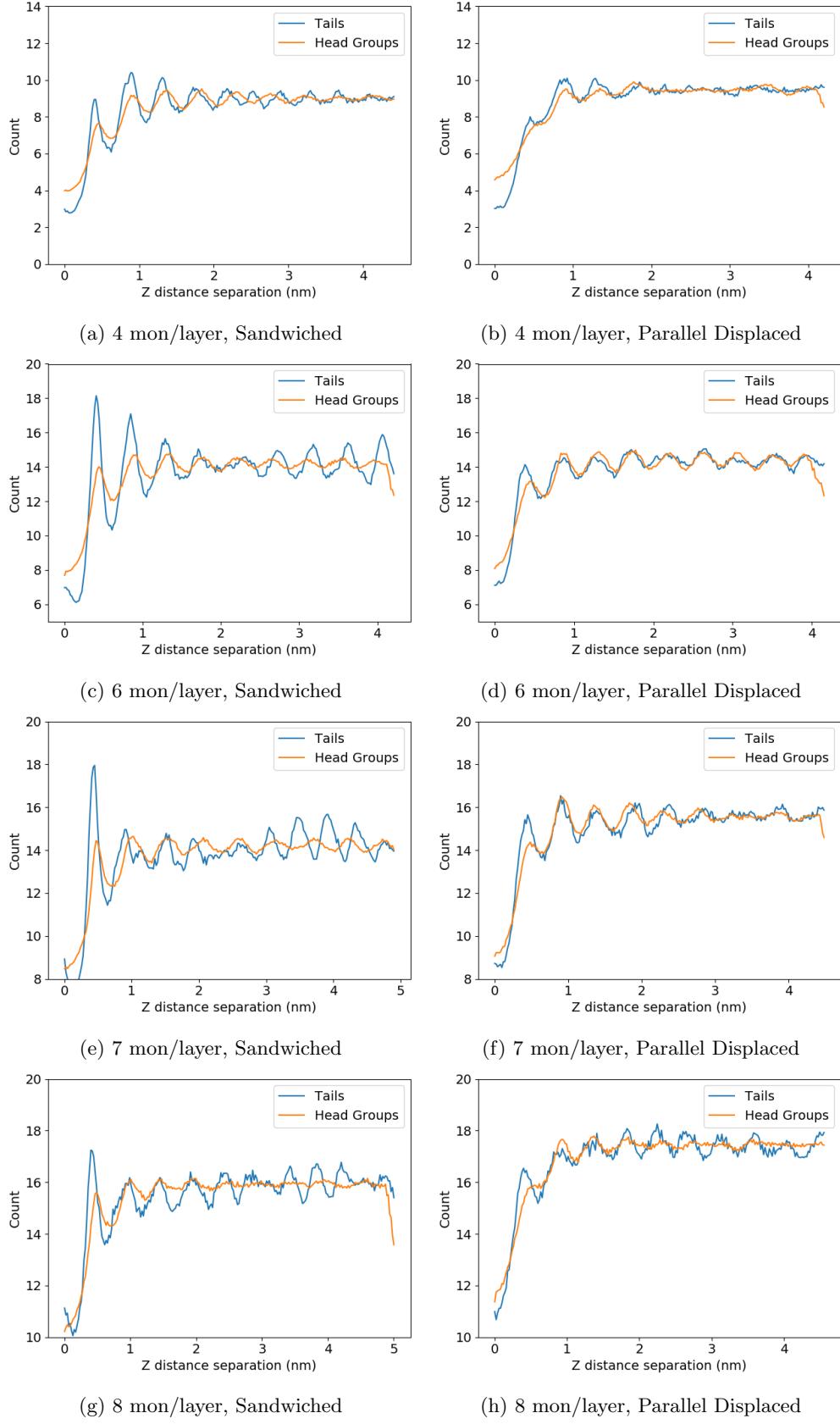


Figure 10: $g(z)$ for all other configurations built with layers stacked 3.7 Å apart

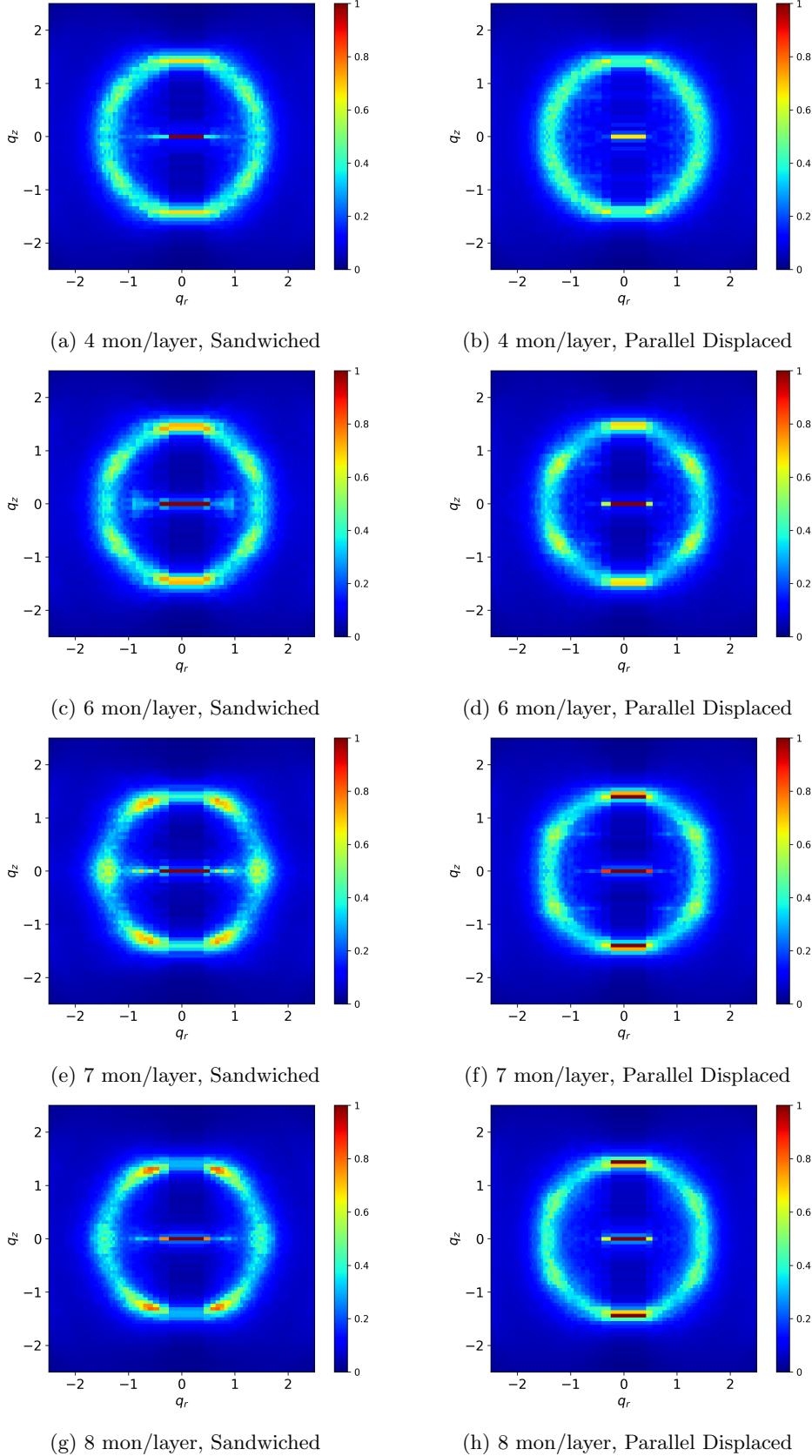


Figure 11: Simulated XRD patterns for all other configurations built with layers stacked 3.7 Å apart

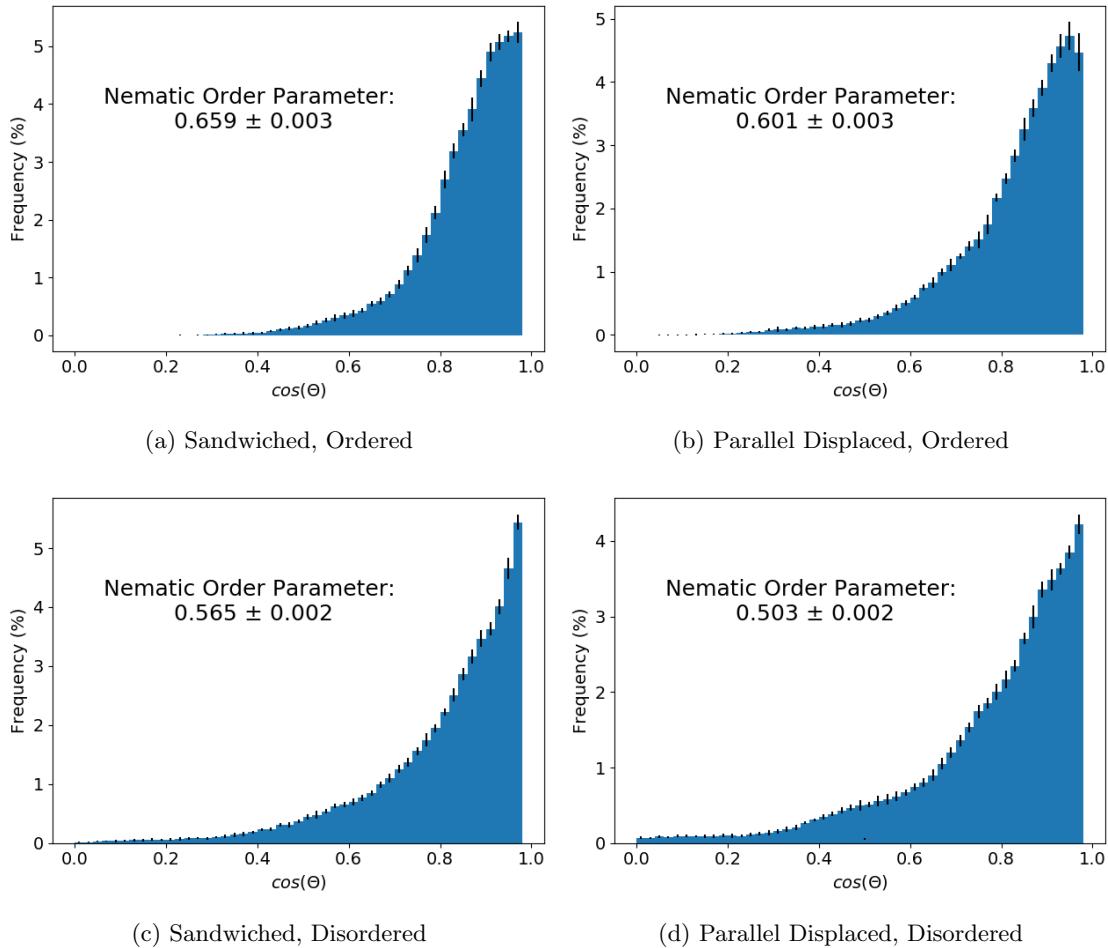


Figure 12

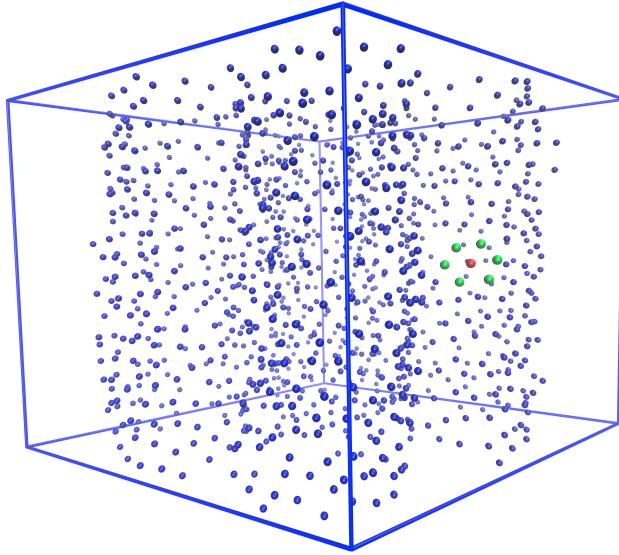


Figure 13: Monomer tails pack together hexagonally. The centroid of each tail is visualized as a blue sphere. The centroids are calculated based on the red atoms in Figure 3. The red sphere highlights an example of an alkane tail centroid with its nearest neighbors (green spheres) surrounding it in a hexagonal pattern.

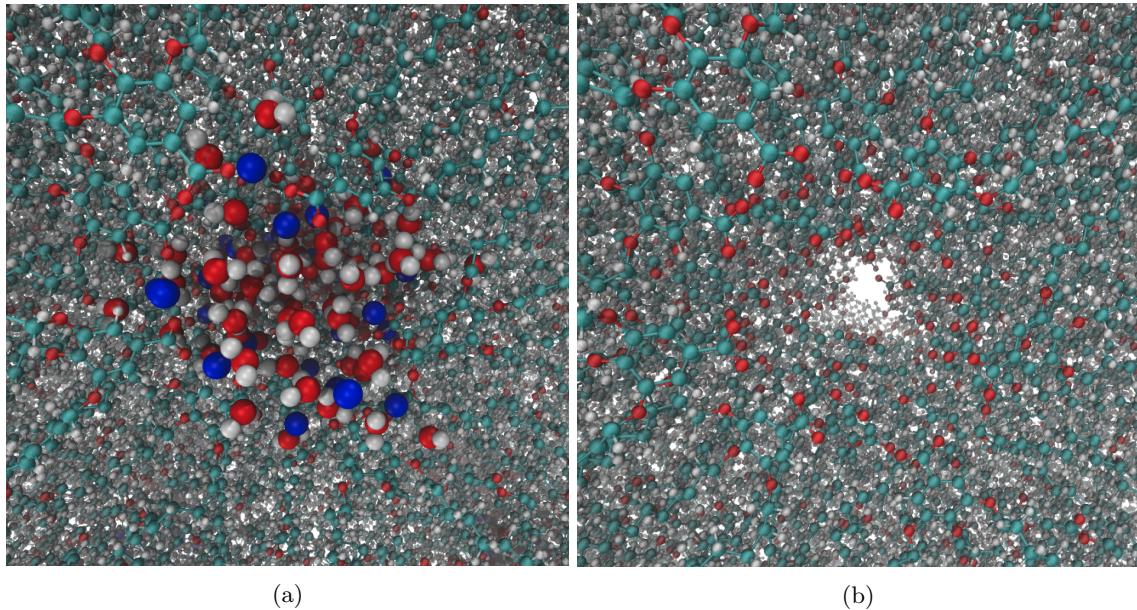


Figure 14: (a) Pores built in the parallel displaced configuration with 5 monomers per layer are filled with 5 wt% water. (b) The same system is visualized with water molecules and sodium ions removed. Head groups vacate the pore region leaving an aqueous solution of water and sodium ions.

References

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