Polymorphism and polyamorphism in bilayer water confined to slit nanopore under high pressure

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A distinctive physical property of bulk water is its rich solid-state phase behavior, which includes 15 crystalline (ice I–ice XIV) and at least 3 glassy forms of water, namely, low-density amorphous, high-density amorphous, and very-high-density amorphous (VHDA). Nanoscale confinement adds a new physical variable that can result in a wealth of new quasi-2D phases of ice and amorphous ice. Previous computer simulations have revealed that when water is confined between two flat hydrophobic plates about 7–9 Å apart, numerous bilayer (BL) ices (or polymorphs) can arise (e.g., BL-hexagonal ice (BL-ice I)). Indeed, growth of the BL-ice I through vapor deposition on graphene/Pt(111) substrate has been achieved experimentally. Herein, we report computer simulation evidence of pressure-induced amorphization from BL-ice I to BL-amorphous and then to BL-VHDA at 250 K. In particular, BL-VHDA can transform into BL-VHDA, via decompression from 3 to 1.5 GPa at 250 K. This phenomenon of 2D polyamorphic transition is akin to the pressure-induced amorphization in 3D ice (e.g., from hexagonal ice to HDA and then to VHDA via isobaric annealing). Moreover, when the BL-ice I is compressed instantly to 6 GPa, a new very-high-density BL ice is formed. This new phase of BL ice can be viewed as an array of square ice nanotubes. Insights obtained from pressure-induced amorphization and crystallization of confined water offer a guide with which to seek a thermodynamic path to grow a new form of methane clathrate whose BL ice framework exhibits the Archimedean 48² (square-octagon) pattern. Bilayer water and ice | molecular dynamics simulation | bilayer methane hydrate | amorphous-to-amorphous transition

The special character of confined water stems not only from unique properties of a hydrogen-bonding network, such as its ability to expand when cooled below the freezing point or to form rich structures of polymorphs under strong compressions, but from its spatial inhomogeneity, particularly in the nanoscale spaces. Forced to pack into the nanoscale spaces severely constricted by confining surfaces, water molecules in the vicinity of a flat surface tend to arrange themselves in layers parallel to the surface. The resulting oscillations in local density are reflected in properties of the confined water that can differ drastically from those of the bulk water. Not only are intriguing properties of confined water of fundamental interest, but they have implications for diverse practical phenomena at the intersection between chemistry, biological sciences, engineering, and physics: boundary lubrication in nano-fluidic and laboratory-on-a-chip devices; frost heaving in soil; synthesis of antifreeze proteins for ice-growth inhibition; rapid cooling of biological suspensions or quenching emulsified water under high pressure; storage of gas hydrates; and hydrogen fuel cells that generate electricity by passing hydrogen ions across a membrane, where water is confined in nanoscale channels. Hence, an improved understanding of the behavior of confined water could have practical benefits in addition to advancing basic science, such as better understanding of polymorphic transition at low dimension.

Polymorphism and polyamorphism refer to the existence of multiple crystalline and (metastable) amorphous states for homogeneous solid material, such as bulk ice (1–11). Mishima et al. (3) were the first to demonstrate that the high-density amorphous (HDA) ice can be achieved through pressure-induced amorphization of either hexagonal ice, Ih, or low-density amorphous (LDA) ice at 77 K and 1 or 0.6 GPa. Later, Loerting et al. (6) uncovered a very-high-density amorphous (VHDA) ice, produced via isobaric heating of HDA from 77 to 165 (or 177) K at a pressure of 1.1 (or 1.9) GPa. More recently, Loerting et al. (9) observed a sequence of polyamorphic transitions (i.e., LDA → HDA → VHDA) at 125 K, starting from an LDA sample that is subjected to stepwise increasing pressure from 0.25 to 1.5 GPa. This was the first report of stepwise amorphous-to-amorphous-to-amorphous transitions. As elucidated by Debenedetti (11), a deeper insight into polyamorphic transitions of ice is required not only “for understanding phase behavior of water, but for the physics of disordered systems in general.”

A question that arises is the following: Can the polyamorphic transition occur in confined water/ice systems? For water confined to cylindrical pores (quasi-1D confinement), two recent experiments have demonstrated the existence of the low-density liquid (LDL) and prominent density hysteresis phenomenon, suggesting the possible existence of a first-order liquid–liquid phase transition in supercooled water (12, 13). Evidence of amorphous-to-amorphous transition in quasi-1D pores, however, has not been observed either from experiments or simulations. For water confined to quasi-2D slit pores with smooth walls and a width <6 Å, two distinctive crystalline forms of monolayer (ML) ice have been reported based on computer simulations, namely, the Archimedean 48² monolayer low-density ice (ML-LDI) and the puckered square monolayer high-density ice (ML-HDI) (14, 15). Such ML-LDI has also been found as a stable structure on a hydroxylated silica surface, but it is not free-standing due to strong interaction between water and the hydrophilic surface (16). However, no evidence of ML amorphous ice has been reported in the literature, suggesting that the glassy forms of ML water are unlikely to occur. In stark contrast to ML water, previous computer simulations have shown that numerous bilayer (BL) ices (or polymorphs) can be formed when a BL water is confined between two flat hydrophobic plates about 7–9 Å apart; for example, the BL-hexagonal ice (17–21), BL-Cairo pentagonal ice (22), BL-mixed pentagon hexagonal ice (22), BL-quasicrystal ice with 12-fold symmetry (22), BL-amorphous (BL-A) (21), and BL-VHDA (23). In particular, a BL water can easily be turned into a BL-A ice within 200–270 K when the width of slit pore is fixed (in a range of 7–9 Å), as shown from previous computer simulations (21–24). Depending on the width of the slit pore and the magnitude of the lateral pressure, the density of the BL-A can be either lower or higher than that of BL liquid water. Note that the BL-A ice is a metastable phase, whereas the BL hexagonal ice (or BL-ice I) (17–25) is the thermodynamically stable phase in the slit pore when the lateral...
pressure is less than 1 GPa. This is because BL-ice I can be obtained by annealing the BL-A through repeated cycles of cooling and heating (24).

**Results and Discussion**

We first demonstrate a polymorphic transition from the BL-ice I to a new VHDA at 250 K (akin to the pressure-induced bulk ice Ih to HDA transition). At 0 GPa lateral pressure and 250 K, a BL liquid water can freeze spontaneously into the BL-A (21, 24). Subsequent annealing of the BL-A for 20 ns yields the hexagonal BL-ice I, indicating BL-A is metastable with respect to BL-ice I. Next, we increase the lateral pressure from 0 to 4 GPa in several steps onto the BL-ice I. A sharp transition is observed at 2.9 GPa (Fig. 1A), and the new high-pressure phase is the BL-VHDA2 whose structure can be viewed as antistacked parallelograms (Fig. 1B and Fig. S1B and D). Moreover, if the VHDA2 is decompressed stepwise from 3 to 0.5 GPa at 250 K, it turns into BL-A below 1 GPa. Contrary to the BL-A ↔ VHDA2 transition, which appears to be strongly first order due to the large hysteresis, the bulk LDA ↔ HDA transition has been viewed as “apparently first-order” (3), whereas the bulk HDA ↔ VHDA transition may be viewed either as a first-order or kinetic densification (7), because the true nature of the first-order transition between bulk LDA, HDA, and VHDA is still under debate (9). Note also that unlike the BL-A, which satisfies the ice rule (i.e., every water molecule is hydrogen-bonded to exactly four nearest neighbor water molecules) (21), a hallmark for the BL-VHDA icy, such as BL-VHDA1 reported previously (23) or BL-VHDA2 as observed here, is that the ice rule is not satisfied (Fig. 1B). Also, importantly, if the BL-VHDA2 is decompressed instantly from 3 to 1.5 GPa at 250 K, it turns into BL-VHDA1 spontaneously, as shown in Fig. 1C (Movie S1). Unlike VHDA2, which exhibits a structure of antistacked parallelograms, VHDA1 exhibits a pentagon-based structure (23) (Fig. S1C and E). At 250 K and 1.5 GPa, not only is the potential energy of VHDA2 lower than that of VHDA1 (Fig. 1C), but the spontaneous transformation of VHDA2 → VHDA1 suggests VHDA1 is thermodynamically more stable than VHDA2. Moreover, if VHDA1 is compressed instantly from 1.5 to 3.0 or 6.0 GPa, it still maintains the pentagon-based structure, at least within 80 ns of simulation. Note that the computed diffusion constant for VHDA1 and VHDA2.

![Fig. 1.](image-url)

(A) Isotherms (250 K) of BL water confined to a hydrophobic slit pore (with width $h = 8$ Å). Lines with open or filled symbols refer to the compression or decompression process in the lateral direction. (B) Top view of the BL-VHDA1. (C) Time-dependent potential energy of the VHDA systems under instant decompression from 3.0 to 1.5 GPa at 250 K. (Insets) VHDA2 and VHDA1. The latter is composed of pentagons (Fig. S1C). (D) Side (Upper) and top (Lower) views of BL-VHDA1. Color code: O, red; H, white; hydrogen bond, blue dotted line. (E) Red lines refer to time-dependent energy and show a phase transition from BL-ice I to BL-VHDA via compressing BL-ice I instantly from 0 to 6 GPa at 250 K; green lines (compression from 0 to 2.9 GPa in 100-MPa step at 250 K) and blue lines (compression from 0 to 2.8 GPa in 100-MPa step at 270 K) refer to time-dependent energy during the phase transition from BL-ice I to VHDA2 via stepwise compression.
is \( \sim 8 \times 10^{-9} \text{ cm}^2/\text{s} \) and \( 5 \times 10^{-9} \text{ cm}^2/\text{s} \) (at 250 K and 2 GPa), respectively, whereas the computed diffusion constant of BL water is \( \sim 6 \times 10^{-9} \text{ cm}^2/\text{s} \) (at 280 K and 0.5 GPa), about three orders of magnitude larger.

In addition to the VHDA\(_2\), a new very-high-density crystalline ice (VHDI) is obtained through an instant lateral compression from 0 to 6 GPa on the BL-ice I at 250 K. As shown in Fig. 1D, the structure of the VHDI can be viewed as an array of square ice nanotubes. Within each square ice nanotube, the ice rule is satisfied, as is the case for all BL crystalline ices reported thus far. The computed diffusion constant for VHDI is \( \sim 3 \times 10^{-10} \text{ cm}^2/\text{s} \) (at 250 K and 2 GPa), which is slightly smaller than that of VHDA\(_2\) and VHDA\(_3\). The brown isotherm in Fig. 1E demonstrates the inverse polymorphic transition from VHDI to BL-A at 0.3 GPa under a lateral decompression at 250 K. Here, the large hysteresis indicates that the BL-VHDI can be (meta)stable over a wide range of pressure (0.3 to 6 GPa). Note that the transition from the BL-ice I to VHDI or to VHDA\(_2\) exhibits the Oswald staging phenomenon; namely, an intermediate liquid state arises during the solid-to-solid transition (Fig. 1E and Movies S2 and S3). In the middle Oswald stage, the diffusion constant of water increases up to \( 8 \times 10^{-9} \text{ cm}^2/\text{s} \) and stays above \( 10^{-10} \text{ cm}^2/\text{s} \) for 0.5–1.5 ns. Thereafter, the diffusion constant decreases gradually toward that of solid phases on freezing. The Oswald staging phenomenon was previously observed in the transition from the ML-LDI to ML-HDI (24).

To gain more insight into the structural features of the VHDA\(_s\) and VHDI site-site radial distribution functions (RDFs) are plotted (see Fig. 2). Owing to the long-range order, all RDFs of the VHDI show features of sharp peaks. In particular, the oxygen (O)–hydrogen (H) RDF of the VHDI can be used to understand hydrogen-bond ordering and violation of the ice rule (Fig. 2C). The arrow in Fig. 2C refers to the cutoff distance (2.2 Å) to define intrasquare ice nanotube hydrogen bonds. All sharp peaks located left of the arrow correspond to the hydrogen bonds within each square ice nanotube, which satisfies the ice rule. Major peaks located between 2.3 and 2.5 Å correspond to the intersquare nanotube hydrogen bonds, whose length is typically between 2.3 and 2.5 Å (Fig. S1A). These intertube hydrogen bonds are weaker compared with intratube hydrogen bonds whose length is < 2.2 Å. The hydrogen-bond arrangement in VHDI suggests that the ice rule still plays an important role in the formation of ice structures under very high pressure. The O-O RDFs of VHDA\(_2\) (both inherent structure and structure at 250 K) indicate strong short-range order, but the long-range order disappears as the radial distance increases. This is very similar to the O-O RDFs of VHDA\(_1\) reported by Han et al. (23) (Fig. 2). The O-H RDFs indicate that the hydrogen-bond lengths in VHDA\(_s\) are typically less than 2 Å and the distribution of O-H RDF distances of VHDA\(_2\) and VHDA\(_3\) are quite similar to one another (Fig. 2C). Overall, the O-O RDFs confirm that VHDA structures indeed lack the long-range order, and the transition from BL-ice I to VHDA\(_2\) is a strong first-order polymorphic transition, whereas the transition from BL-ice I to VHDI is a strong first-order polymorphic transition.

To achieve better understanding of the polymorphic transition of BL water, isotherms (290 and 300 K) are displayed as a function of lateral pressure in Fig. 3A. Here, the green-square line shows a smooth transition from a BL liquid to VHDA\(_2\) at \( \sim 3.1 \text{ GPa} \) at 300 K. At relatively low pressures (< 0.5 GPa), the densities of a BL liquid are increased at a faster rate during the compression, whereas in the region of 0.5–3 GPa, the densities increase more slowly. Near 3.1 GPa, the number densities of liquid and VHDA\(_2\) are very close to each other. Beyond 3.1 GPa, the densities of VHDA\(_2\) follow the green-square line up to 4 GPa. Hence, the VHDA\(_2\) appears to be a continuous densification of liquid on compression at 300 K. The orange-triangle line in Fig. 3 shows a sharp phase transition from the BL-ice I to a BL liquid at \( \sim 1.1 \text{ GPa} \) and 300 K. Like bulk ice \( I_\beta \), which has a lower density than bulk water, the BL-ice I also has an area density much lower than that of BL liquid under high lateral pressure. Overall, the three 300-K isotherms in Fig. 3 exhibit a sequence of crystal-to-liquid-to-amorphous transition. The blue-diamond line in Fig. 3 shows a sharp phase transition at \( \sim 2.2 \text{ GPa} \) and 290 K from the VHDA\(_2\) to a BL liquid under stepwise decompression. Subsequent to the phase transition, the liquid density decreases continuously under further decompression, following exactly an inverse path of the green-square line. Evidence of the first-order liquid-to-liquid (or BL-HDL to BL-LDL) transition is not observed for the BL water (26). The purple-diamond line in Fig. 3 represents decompression of the VHDI at 300 K, which leads to the melting of VHDI at \( \sim 1 \text{ GPa} \). Fig. 3B displays a schematic phase diagram of three stable phases, BL-ice I, VHDI, and BL liquid, constructed based on Figs. 1A and 3A and complementary

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Fig. 2. RDFs of compressed BL-VHDI, BL-VHDA\(_1\), and BL-VHDA\(_2\). Projected O-O RDFs (inherent structures) (A), projected O-O RDFs of the BL structures at 2 GPa and 250 K (B), short-range O-H RDFs (inherent structures) (C), and O-O RDFs (inherent structures) (D). The arrow in C denotes the cutoff distance; the peaks on the left of the green arrow correspond to hydrogen bonds within each square ice nanotube, which satisfy the ice rule. (Inherent structures have a density corresponding to 2 GPa at 250 K.)
Fig. 3. (A) Isotherms of BL liquid water and BL-ice I confined to a hydrophobic slit pore (with width h = 8 Å). The purple-diamond, green-square, and orange-triangle lines refer to those of 300 K, and the blue-diamond lines refer to those of 290 K. Lines with open or filled symbols refer to the compression or decompression process, respectively, in the lateral direction. (B) Schematic lateral pressure-temperature phase diagram shows the location of three stable phases (BL-ice I, BL-VHDI, and BL liquid water). The red dotted-dashed line and blue solid line refer to stability lines of BL-ice I and BL-VHDI, respectively. The brown and blue dashed lines, and red-dotted line refer to metastability lines (or limits of metastability) of VHDA1, VHDA2, and BL-A, respectively. The green lines refer to the stability line of BL liquid water. The purple line refers to the metastability line of the BL-DI with the Archimedean 4\textsuperscript{8}√2\textsuperscript{8} pattern (Fig. S2). The orange shade region left to the red-dotted line, an amorphous-to-amorphous transition from BL-A to VHDA1 is observed when the BL-A is under an instant compression to 1.6 GPa.

Simulations. The stability lines of the stable phases and metastability lines of metastable amorphous phases are also estimated from the molecular dynamics (MD) simulation (15, 27) and shown schematically in Fig. 3B. The orange region between the two stable crystalline phases of BL-ice I and VHDI in Fig. 3B refers to the possible existence of multiple metastable phases. Here, the polymorphism is plausible because the metastable phase is strongly path-dependent; namely, the final structure depends on the initial structure. In stark contrast, no such metastable phase region was found between the ML-LDI and ML-HDI phases for ML water (15).

Having demonstrated the formation of BL-VHDI and BL-VHDAs, as well as polymorphic and polyamorphic transitions in the slit nanopore, we attempt to simulate spontaneous formation of methane clathrate (MeC) (28–32) in the slit nanopore with guest methane molecules entrapped in octagons. A motivation of this specific simulation stems from our previous study of ML-MeC (15), for which we find that the guest-free ML ice clathrate is actually a low-density stable phase of ML ice (namely, ML-LDI). One may ask whether the guest-free BL ice clathrate would be a stable bilayer low-density ice (BL-LDI). To address this question, we first examine the stability of BL-MeC without any guest molecules. To this end, we construct a new BL ice by stacking two ML-LDIs (with the Archimedean 4\textsuperscript{8}√2\textsuperscript{8} pattern) on top of each other in registry. This BL ice has a lower density than the BL-ice I, and thus is a BL-LDI (Fig. S2A and E). The BL-LDI is optimized at zero temperature with a fixed volume in the slit nanopore. Subsequent to the structural optimization, an MD simulation in the canonical (NVT) ensemble is performed at several different temperatures. It turns out that the BL-LDI whose hydrogen-bonding network satisfies the ice rule is metastable up to 200 K (Fig. S2). When the temperature is in the range of 220–240 K, polymers other than square and octagon arise, and the BL-LDI is changed eventually to a solid structure consisting of domains of BL-ice I and cavities (Fig. S2D). The formation of cavities in the BL-ice I is largely due to the fixed-volume simulation wherein the BL-LDI cannot be converted to a perfect BL-ice I without changing the area of the simulation cell. We also perform the constant particle number, lateral pressure, constant slit width, and temperature (NPT, hT) simulation, with the lateral pressure being zero. As expected, the area of the simulation cell is reduced when octagons are converted to hexagons and no cavities are formed (Fig. S2F).

Because the BL-LDI is thermodynamically unstable above 200 K, can the BL-LDI be stabilized by methane molecules? To pursue this possibility, we examine direct temperature quenching of BL liquid water/methane mixtures. As shown in Fig. S3, several different ratios of methane/water molecule (ranging from 0% to 12.5%) are considered. The mixtures are equilibrated at 1,000 K and 0.5 GPa and are then quenched instantly to 250 K at the same lateral pressure. As shown in Fig. S3F, the pure BL ice without methane is very similar to BL-ice I, confirming that the BL-LDI is unlikely to form at 250 K. For the mixture with 1.25% composition of methane (CH\textsubscript{4}), water octagons are formed, each containing a CH\textsubscript{4} molecule (Fig. S3E), and the nucleation of octagons promotes further formation of empty water octagons. As the composition of CH\textsubscript{4} increases to 5% (Fig. 3C), more CH\textsubscript{4}-containing octagons are formed. When the composition of CH\textsubscript{4} is increased to 6.25%, interestingly, the number of water BL-pentagons becomes comparable to that of water BL-hexagons in the system. This trend suggests that adding a small fraction of CH\textsubscript{4} in a BL liquid promotes the formation of BL-LDA ice that contains small and random domains of water octagon-square structure, wherein a CH\textsubscript{4} molecule is trapped in the octagon. This mechanism is very similar to that of making hyperquenched glassy water via spraying water droplets onto an ultracold liquid, such as liquid propane at ∼80 K.

With the largest composition (12.5%) of CH\textsubscript{4} considered (Fig. 3C), methane is supersaturated; thus, domains of liquid CH\textsubscript{4} can be observed during the quenching simulation for 40 ns (Movie S4). Nevertheless, there are still small and random domains of BL-LDI formed in the system, a sign of nucleation of BL-LDI.
Nevertheless, the emergence of the aforementioned water BL-pentagons offers a clue to finding a simulation procedure to produce near-perfect BL-MeC. The key is to remove BL-pentagons that favor amorphous rather than crystalline structure. Note that the BL-pentagon water cluster is energetically more stable than any other BL-polygonal water cluster. As shown in Fig. 4, we use a four-step simulation procedure, including cyclical heating/annealing, stepwise compression, and long-term incubation, which can remove most BL-polygon defects, BL-pentagons in particular, concomitant with the growth of octagon-square domains. To gain more insight into the strenuous simulation process required to grow a perfect BL-MeC, we perform a test NPxyT simulation at 300 K and 1 GPa for 160 ns as illustrated in Fig. S4A and B and Movie S10. Here, the simulation starts from an initial configuration of a phase-separated liquid water and CH$_4$ gas at 300 K and 10 MPa (Fig. S4A). When the lateral pressure is increased instantly to 1.0 GPa (Fig. S4B), nucleation of CH$_4$-containing octagon can be observed even at a very early stage. However, the formed octagons can easily collapse until a nucleus of a critical size (consisting of at least four octagons) forms. As more CH$_4$ molecules are dissolved in the solid solution (becoming MeC), numerous pentagons start to form to connect the octagons. The formation of nexus BL-pentagons is responsible for obstruction of the growth of BL-MeC.

To some extent, the kinetic process required to grow a perfect BL-MeC illustrated above has some similarity to that involved in the computer simulation of the growth of bulk MeC (31). For the latter, the ice/CH$_4$ mixture is compressed instantly from 0 to 22 MPa at 250 K, and the temperature and pressure are then increased up to 27.2 MPa and 272 K, respectively. Thereafter, the temperature and pressure of the mixture are increased along the nonlinear $P$-$T$ curve, which includes a decompression process, above the ice-melting temperature and below the MeC dissociation temperature. Likewise, the present simulation shows evidence of solid-state deformation and superheating of BL-ice I during the formation of BL-MeC. Despite the differences in the phase boundary of bulk ice (I$_s$ and III) and BL-ice (BL-ice I and BL-MeC), the kinetic processes of bulk and BL-MeC formation show a similar trend. For example, the previous simulation study (32) reveals an unknown cage formed during the growth of bulk MeC, which is different from a known nexus cage. The unknown cages can cause adverse effects on the growth of MeC. A similar behavior exists in the growth of BL-MeC. Here, the highly stable BL-pentagons tend to fill the space between BL-octagons to hinder the formation of BL-MeC. The BL-pentagons are smaller than BL-hexagons but larger than BL-tetragons. Like BL-tetragons, the BL-pentagons can maintain their structural integrity together with BL-octagons. The incubation at 320 K can remove the unwelcome BL-pentagons. Once they are removed, the BL-squares become the nexus cages to grow BL-MeC. Likewise, a certain strategy needs to be developed to remove the unknown nexus cage during the growth of bulk MeC.

The BL-MeC crystal is stable up to 330 K at zero pressure (i.e., the stability limit under heating), and it transforms into methane gas and liquid water at 340 K. To determine the melting temperature of the BL-MeC crystal [(H$_2$O)$_8$CH$_4$] at zero pressure more accurately, we use the two-phase coexistence simulation method with the constant particle number, lateral pressure, constant slit width, and enthalpy (NP$^z$H ensemble) (33). As shown in Fig. S5A, the simulated melting temperature of BL-MeC is about 285 K. For comparison, the computed melting temperature of the BL-ice I is about 293 K (Fig. S5B).

Density profiles of oxygen and CH$_4$ in the $z$-direction (normal to the wall surface) are plotted in Fig. S4E and F. The distribution function of oxygen in the BL-MeC exhibits sharp peaks, a manifestation of solid state, whereas the distribution of oxygen atoms in the phase-separated liquid is broad. In contrast, the distribution function of methane in the BL-MeC is also broad but differs from that in the phase-separated liquid (Fig. S4F). The distribution function of methane at several different temperatures (Fig. S4F) indicates that methane molecules become less mobile in the $z$-direction as the temperature is lowered, but they are still not confined between two MLs until the temperature is below 50 K.

In conclusion, several stable and metastable BL ices and amorphous ices are found within a slit nanopore. Structural transitions among them provide clear simulation evidence of polymorphism and polyamorphism in BL water. Moreover, the BL-square water clusters are not only building blocks of VHDI at high pressure but become the nexus “cages” for connecting methane-containing BL-octagons to form the BL-MeC. Due to high stability of BL-pentagon water clusters, which tend to hinder the growth of BL-MeC, a strenuous simulation procedure is required to remove the BL-pentagons and to grow near-perfect BL-MeC. Finally, we remark that the network structure of BL-MeC can be viewed as a projection of the network structure of bulk methane hydrate.

**Fig. 4.** Thermodynamic path designed in an MD simulation to grow the BL-MeC spontaneously. Specifically, starting from an ice/CH$_4$ mixture structure as shown in Fig. S3A (obtained at 250 K and 0.5 GPa; Movie S4), the structure is heated instantly to 270 K and then goes through incremental step annealing and reheating cycles (270 → 265 → 260 → 255 → 250 → 245 → 240 → 235 → 230 → 225 K) for total 40 ns, for which each incremental step takes 1 ns. As a result, the water octagon-square domain grows gradually. At certain stage, the growth process stops due to high stability of BL-polygons (defects) in the structure. Next, the temperature and pressure of the system are raised instantly to 300 K and 1.0 GPa for 10 ns (Movie S5). (A) Top view of a snapshot of the methane-water mixture at 300 K. The temperature and pressure of the system are then raised instantly to 310 K and 1.5 GPa, respectively, for 10 ns (Movie S6), followed by a rise of temperature to 320 K for 20 ns (Movie S7) and to 325 K for 20 ns (Movie S8). (B) Top view of the final snapshot of the methane-water mixture is shown. Lastly, a long simulation (65 ns) is performed at 1.0 GPa and 325 K to achieve a perfect BL-MeC (Movie S9). (C) Top view of the inherent structure of the BL-MeC at 325 K and 1.0 GPa is shown. The slit pore width $h = 8$ Å in all simulations.
phase III (MH-III) along the direction normal to the octagon cages. It is known that MH-III is stable only at high pressures beyond 1.8 GPa (34). On the other hand, the BL-ice I can be viewed as a projection of bulk ice I$_h$ in the direction normal to the puckered hexagons. Such a geometric connection between BL-ices (ice clathrate) and their 3D counterparts suggests more qualitative connections in polymeric and polymorphic transitions for BL and bulk ices (clathrates) may exist, despite the strong effect of confinement with the BL water.

**Materials and Methods**

**MD Simulation.** The slit nanopore consists of two rigid and smooth hydrophobic walls. The wall-wall separation (width $h$) is set to be 8 Å, which can accommodate two MLs of water. The transferable-intermolecular-potentials 5-point-charge (TIP5P) water model is adopted (35). The 9-3 Lennard-Jones (LJ) potential is used to describe the water-hydrophobic wall interaction (15, 17, 21, 24). The MD simulations are performed using the NPT, $h$ ensemble. The periodic boundary conditions are applied in the lateral direction ($x$ and $y$) in parallel with the two walls. The simulation supercell contains 400 water molecules with or without methane. A test simulation of the compression of BL-ice I is also performed with 800 water molecules at 250 K and 6 GPa. Spontaneous formation of BL-VHDI is observed, as in the case of using 400 molecules. No apparent size effect is detected.

The methane molecule is modeled by a united-atoms model whose LJ parameters are $\sigma_{methane} = 3.758$ Å and $\epsilon_{methane} = 0.2959$ kcal/mol (15). The cross-interaction parameters between methane and TIP5P water are given according to the Lorentz-Berthelot rule. The methane–wall interaction is described by the 9-3 LJ potential function, $U(r) = \epsilon \left( \frac{1}{r^9} - \frac{1}{r^3} \right)$, where the LJ parameters are $\sigma_{methane-w} = 2.5581$ Å and $\epsilon_{methane-w} = 3.84237$ kcal/mol.

The oxygen–wall interaction is also described by the 9-3 LJ potential with LJ parameters $\sigma_{O-w} = 2.4737$ Å and $\epsilon_{O-w} = 1.2024$ kcal/mol. All intermolecular interactions, including the long-range charge–charge interaction and the LJ interaction between oxygen atoms, are truncated at 8.75 Å by using a switching function (17, 21). This cutoff distance has been used by us (15, 17) and is very close to the 9 Å used by Stanley and coworkers (23, 36). Other groups have used the Ewald sum method to treat the long-range charge–charge interaction (20, 37). Previously, we have shown that when computing the melting point of bulk ice $I_h$, e.g., based on the TIP5P model with the two-phase coexistence method, the Ewald sum method tends to give a lower melting point compared with the simple truncation method (33).

**Structural Analysis.** Instantaneous configurations (snapshots) generated in the MD simulations are mapped onto corresponding potential energy local minimum configurations (inherent structures at constant volume) using a steepest descent method.

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