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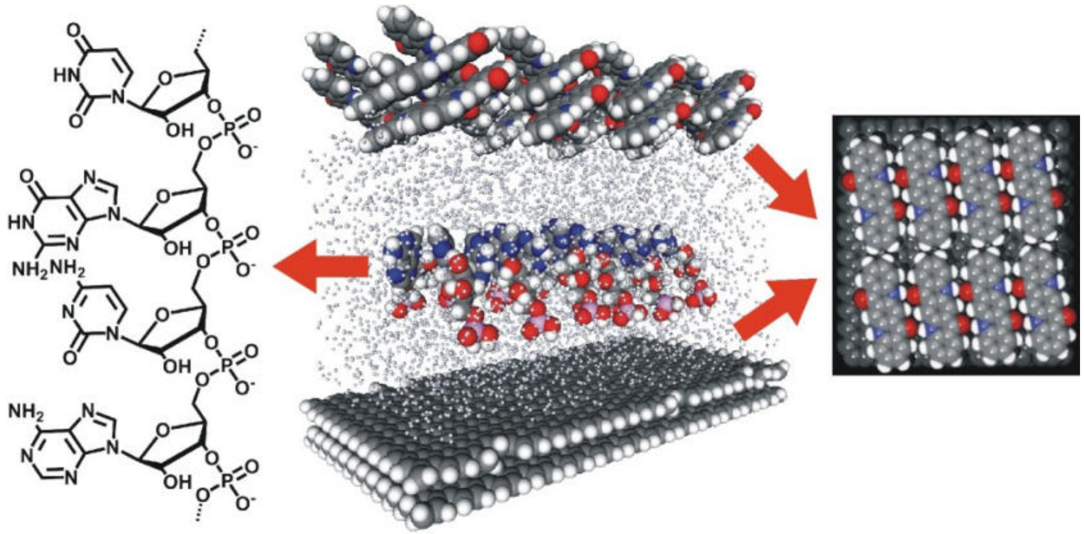
Natural Nanofluidic Environments as Prebiotic Reaction Vessels

Abiotic RNA formation in temporal nanoconfined water



Background

The water paradox in prebiotic chemistry:

Water is essential to biochemical reactions,

but also inhibitive to key prebiotic chemical reactions such as RNA synthesis

Aim of this talk

Showing experimental evidence for
spontaneous, abiotic RNA synthesis in water
enabled by temporal nanoconfinements
in environments of geological ubiquity

↓

Revealing the role of
anomalous properties of confined water
in such nanofluidic environments
for allowing condensation reactions in water

↓

Introducing a model to solve the water paradox
based on the discussed observations
in line with **evolutionary conservatism**

Outline

Introduction: the water paradox

Can RNA form in water anyway?

What determines our observed polymerization?

What has computational chemistry and thermodynamics to say about this?

What are the implications of our findings?

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The water paradox

water is essential to life

water causes unfavourable reactions with key biomolecules

The water paradox

Water:

- **crucial component for running biochemistry**
- **highly destructive compound in prebiotic chemistry**

e.g. nucleic acid synthesis:
phosphodiester bonds form in a condensation-dehydration reaction
→ releases water

A product of a reaction is difficult to form when being at the same time the solvent:
condensation-dehydration reactions are highly unfavourable in water!

→ **spontaneous formation of nucleic acids is prohibited by water.**

The water paradox

Some approaches to overcome the water paradox:

- Using alternative solvents (e.g. formamide)
- get rid of the water via evaporation (wet/dry cycles)
- adding condensing agents (e.g. cyanamide)
- high temperatures (~ 160°C)

The water paradox

Prebiotic plausible?

→ life manages the water problem within a stable environment full of water at physiological temperatures/ pressures

→ evolution builds on existing pathways

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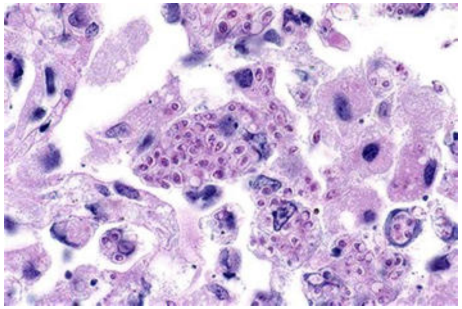
Can RNA form in water abiotically?

Preliminary considerations

Living cells:

→ contain intracellular aqueous fluid,
crowded with large, complex biomolecules



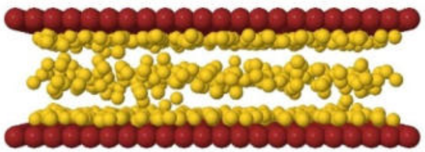
→ **water exists mostly as interfacial/ nanoconfined water**

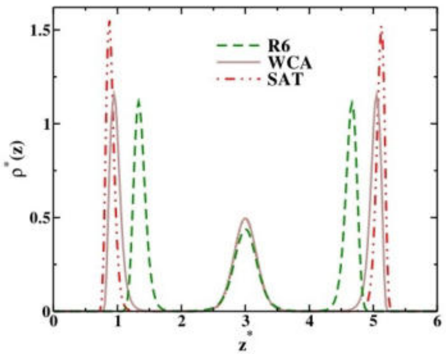
Can RNA form in water abiotically?

Preliminary considerations

nanoconfined water → different properties compared to bulk state:

- activity
- H-bonding network dynamics
- density
- reactivity
- dielectric constant
- phase diagram of water shifted to gas-like
- quantum state of the protons
- ...





Krott et al., Phys. Rev. E 89, 012110

↓

anomalous behaviour of nanoconfined water

Can RNA form in water abiotically?

Preliminary considerations

anomalous behaviour of water when being nanoconfined

results from a complex interplay of various

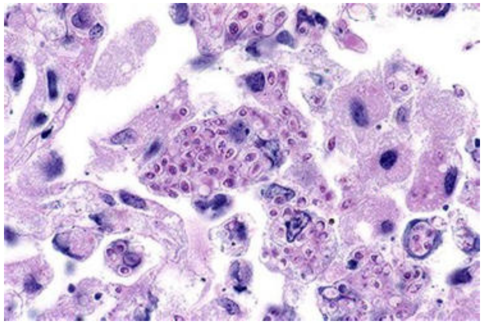
nanofluidic phenomena/ forces

related to e.g.

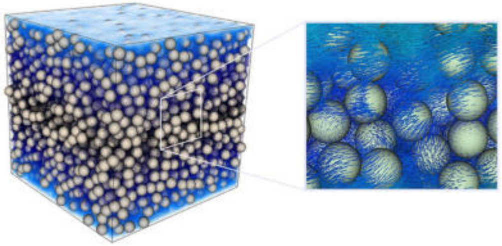
- surface energy and size of the confining boundaries
- shear
- molecular structure
- electrical double layer
- fluctuations of general order parameter (thermal Casimir effect etc.)
- ...

Can RNA form in water abiotically?

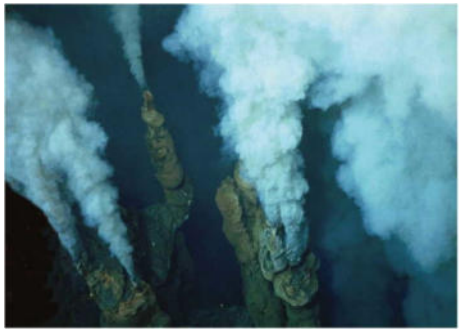
<u>Preliminary considerations</u>



Living cell
= intracellular fluid crowded with large biomolecules



Materials science
aqueous suspension of concentrated nanoparticles
generates **nanofluidic effects on water**



Nanogeochemical environments
= sediments with pore water;
= hydrothermal vent fluids with precipitated particles;
= particle aggregates in water-filled cracks in earths crust

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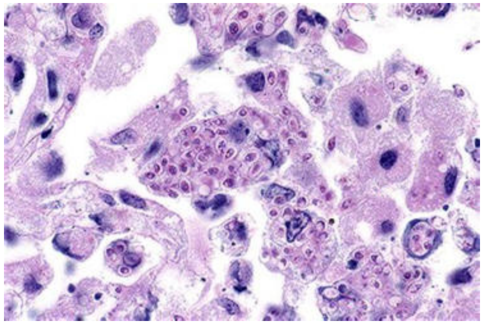

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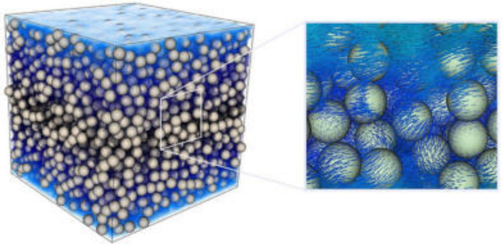

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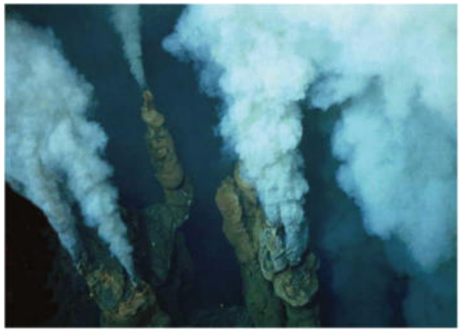

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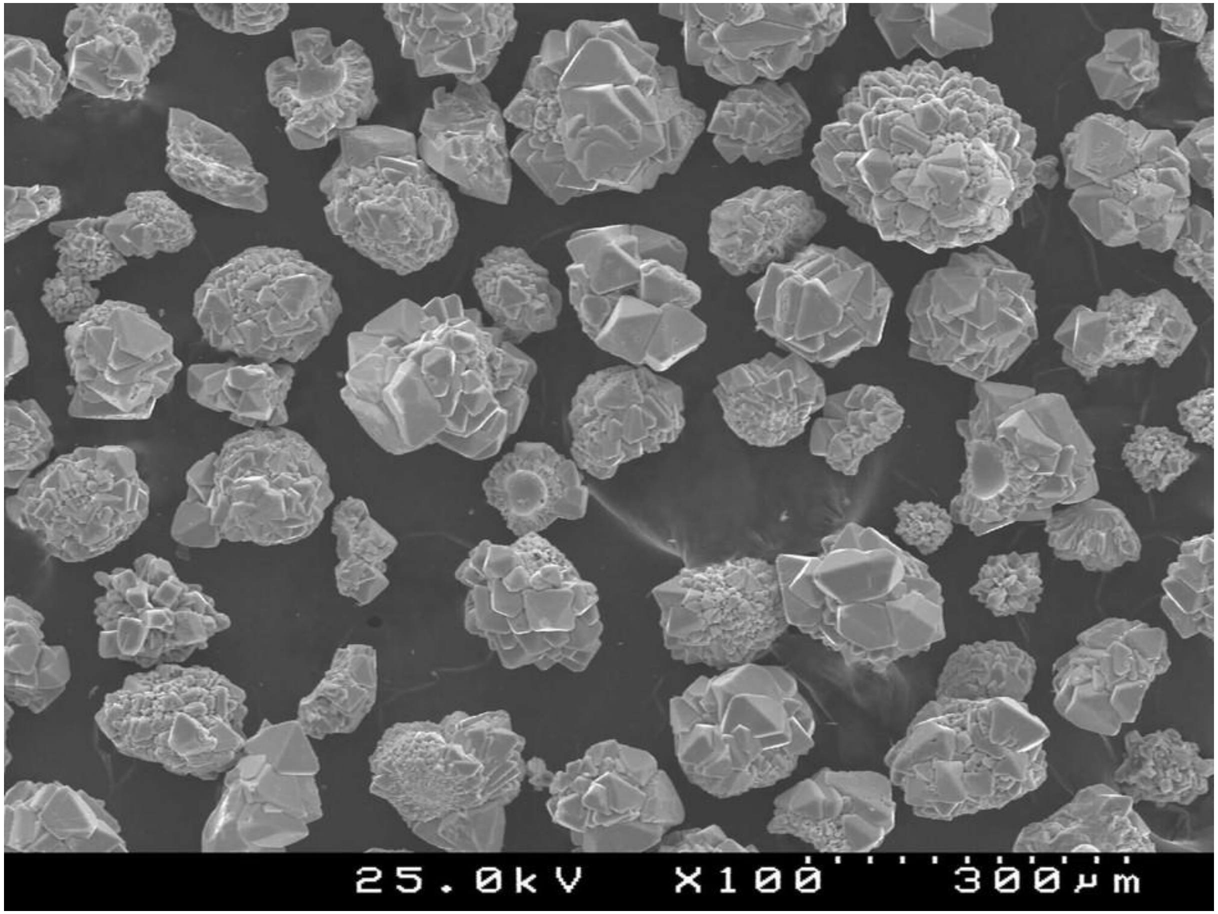


Yang et al RSC Adv., 2014,7818

Can RNA form in water abiotically?

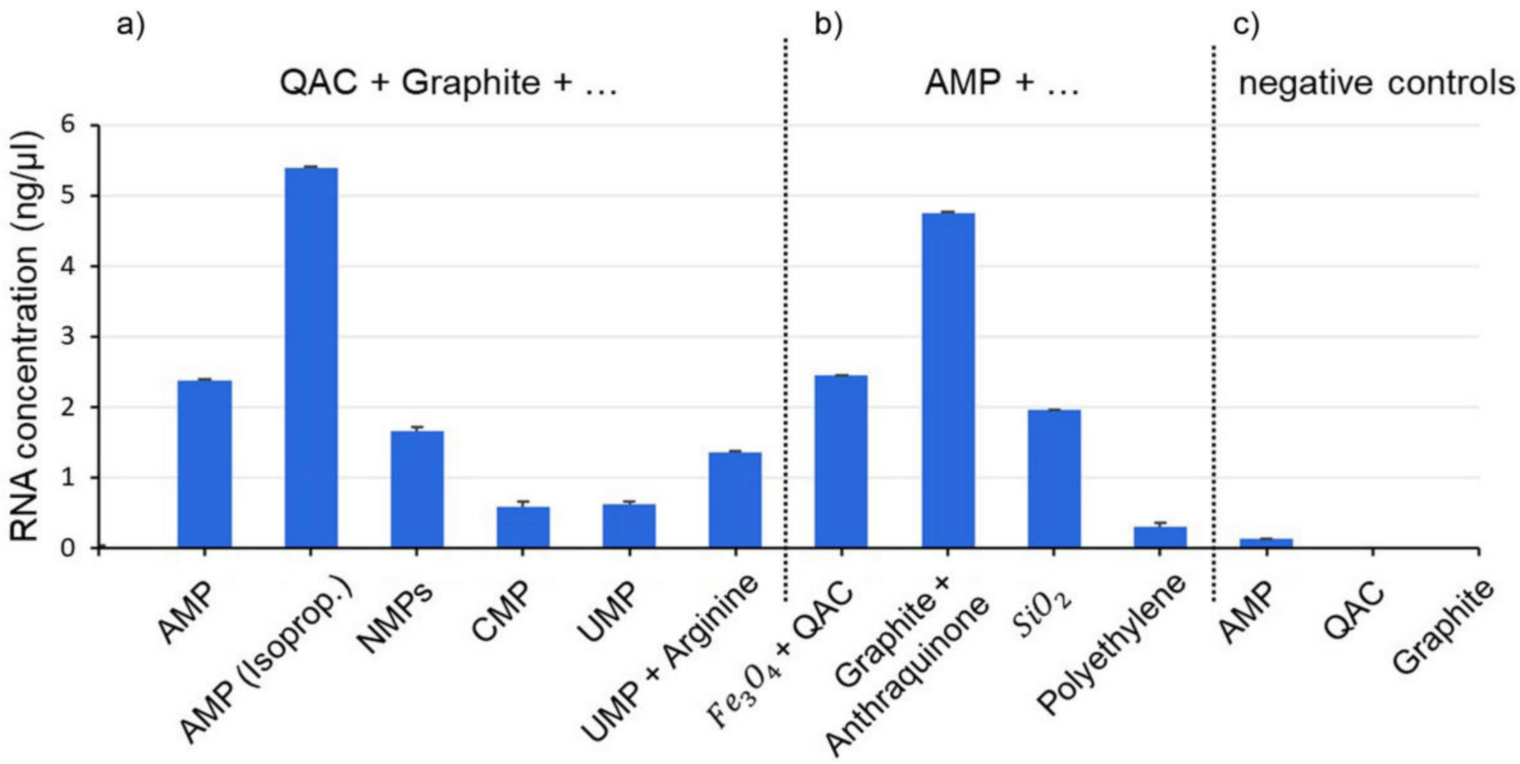
Do abiotic nanofluidic environments within aqueous suspension have the potential of inducing key biochemical reactions?

Example reaction:
Polymerization of nucleotides into RNA
→ abiotic synthesis of RNA in water: common goal of prebiotic chemistry

Example system:
Suspension of a mixture of polyaromatic heterocyclic crystal particles (quinacridone) and inorganic particles (graphite)
→ well characterized system in terms of inducing nanofluidic phenomena in aqueous suspensions (A. Eberle, T. Markert, F. Trixler: *JACS* **140**, 1327 (2018)).

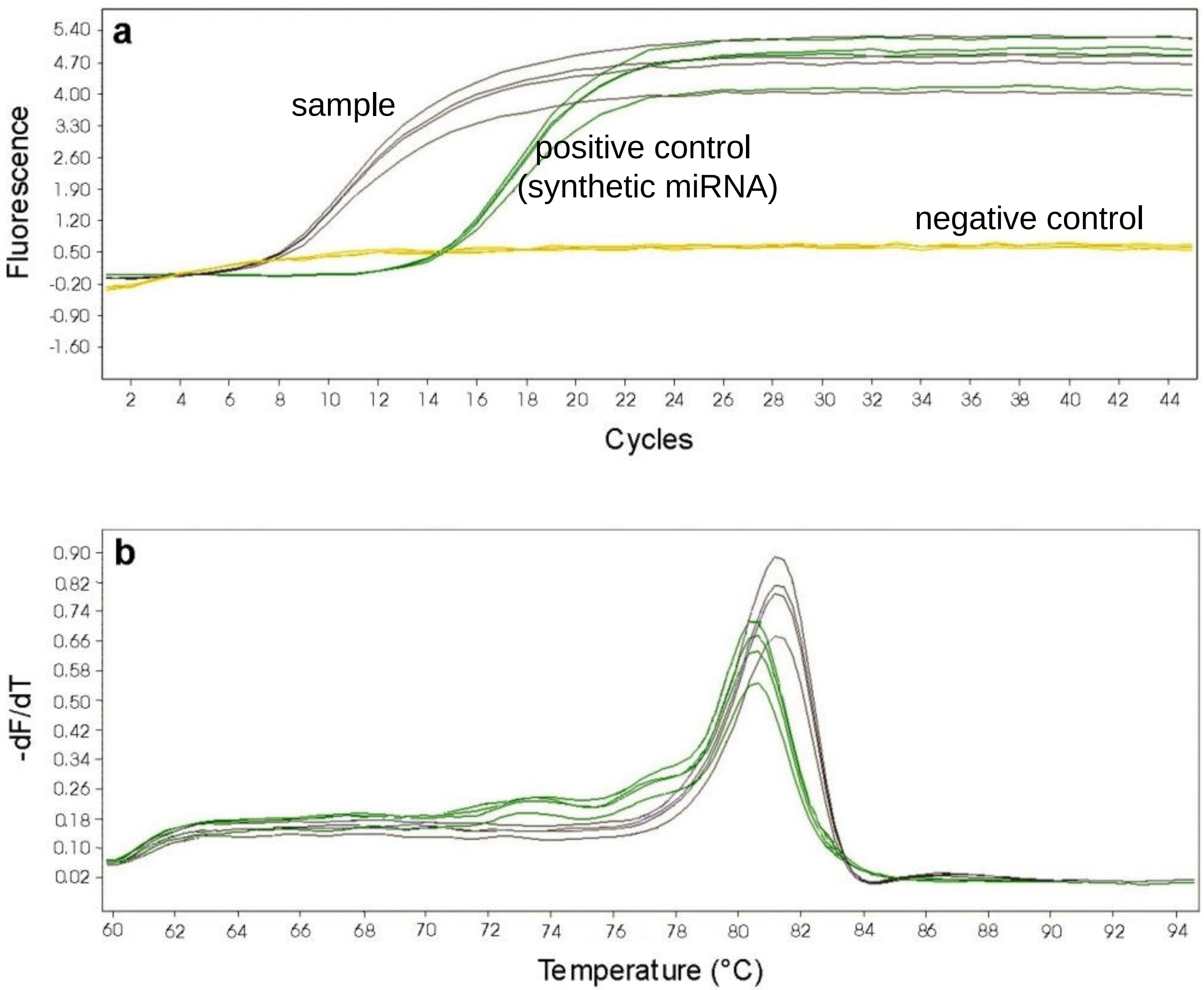
Can RNA form in water abiotically?

Fluorometric poly-A-RNA concentrations



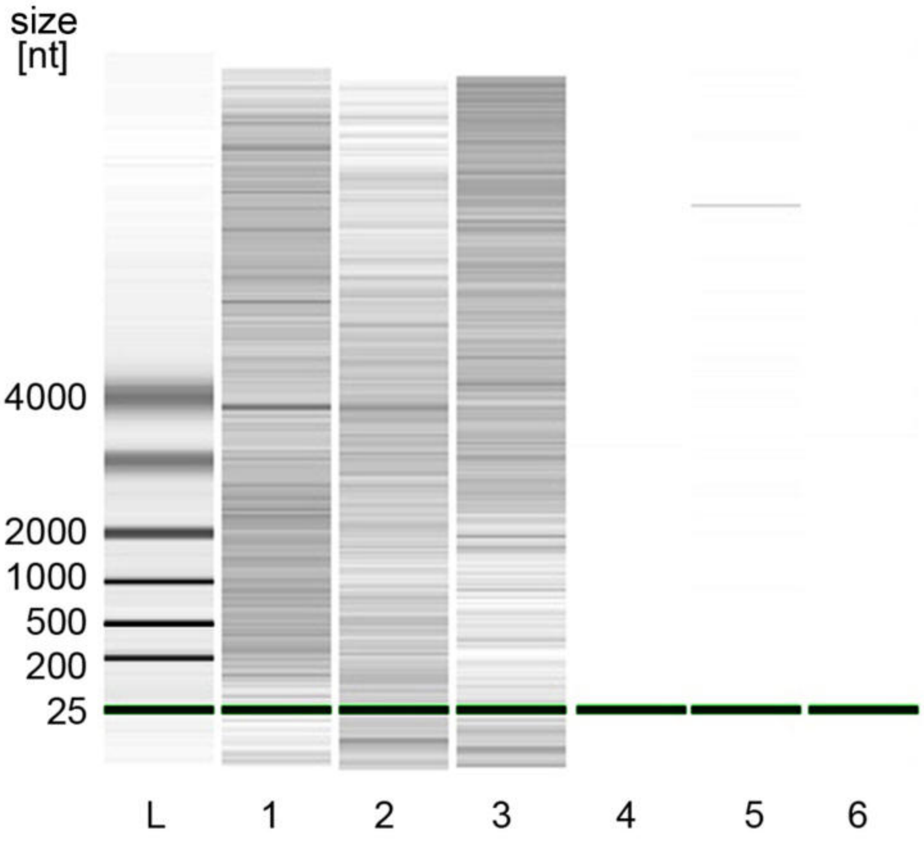
Can RNA form in water abiotically?

Quantitative PCR after reverse transcription



Can RNA form in water abiotically?

Gel Electrophoresis



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related to e.g.

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- **shear**
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- **electrical double layer**
- **fluctuations of general order parameter (thermal Casimir effect etc.)**
- **...**

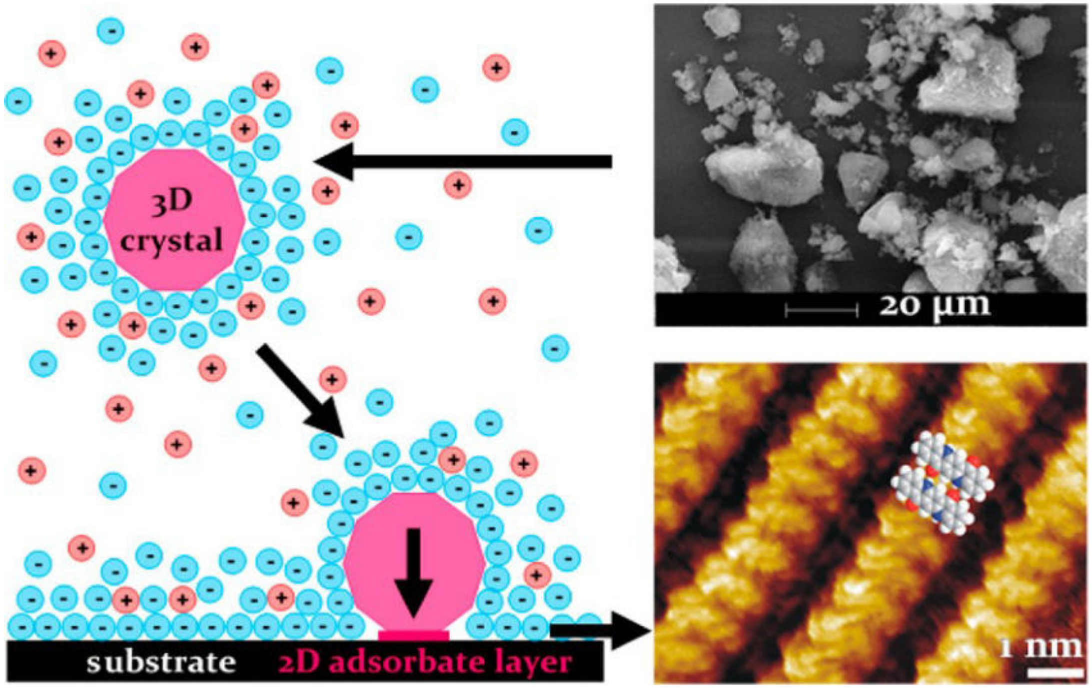
What determines the polymerisation?

Organic Solid/Solid Wetting Deposition (OSWD)

→ Correlation between OSWD and RNA formation?

What determines the polymerisation?

Organic solid/solid wetting



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Organic solid/solid wetting

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Article

Cite This: *J. Am. Chem. Soc.* 2018, 140, 1327–1336

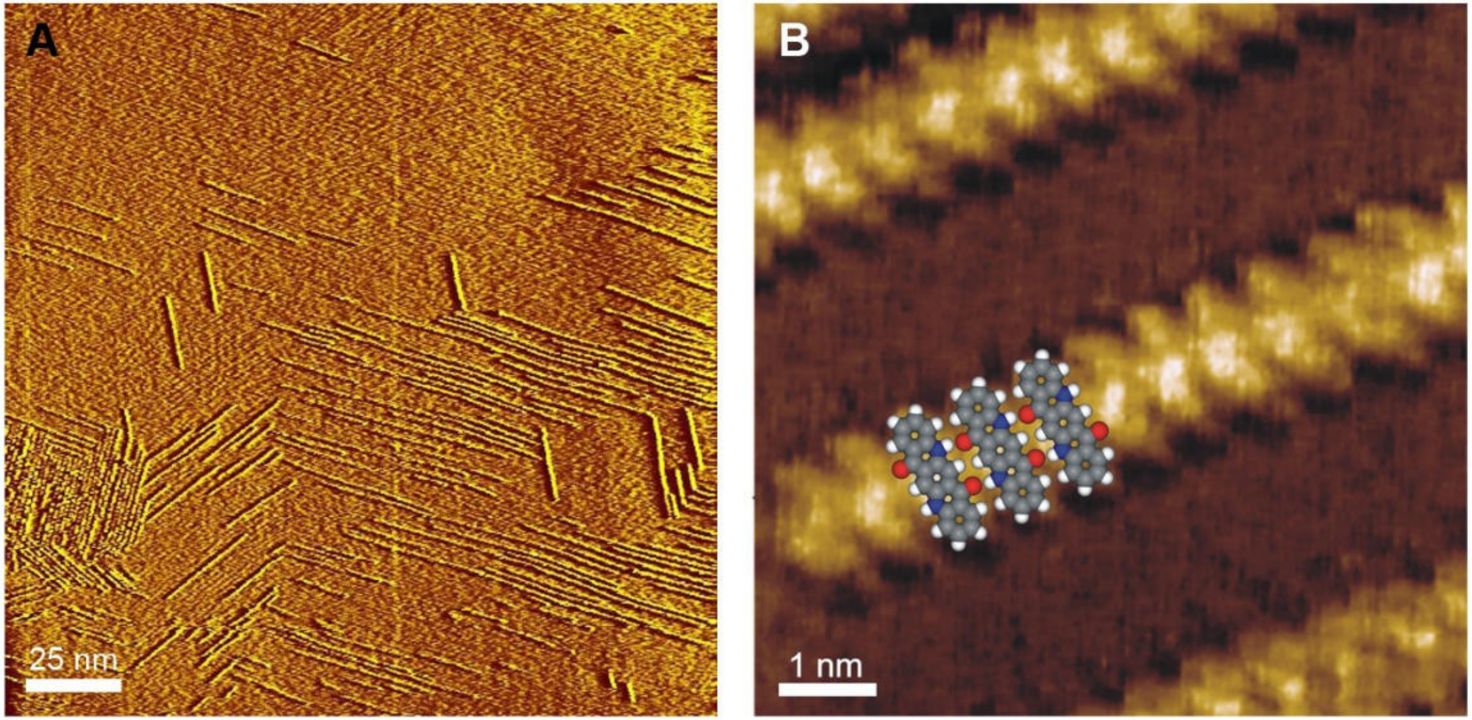
pubs.acs.org/JACS

Revealing the Physicochemical Basis of Organic Solid–Solid Wetting Deposition: Casimir-like Forces, Hydrophobic Collapse, and the Role of the Zeta Potential

Alexander Eberle,[†,‡] Thomas Markert,[§] and Frank Trixler*[†,∥]

What determines the polymerisation?

Organic solid/solid wetting as a probe



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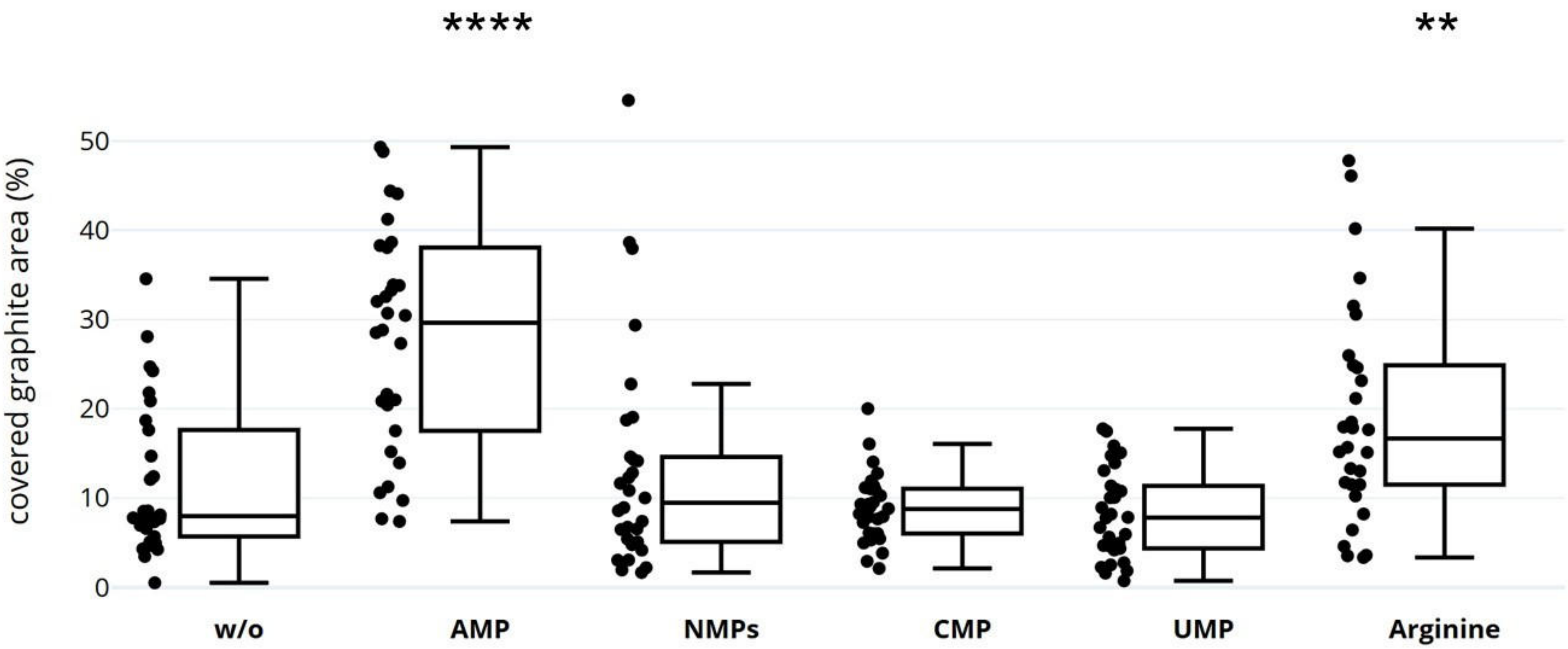
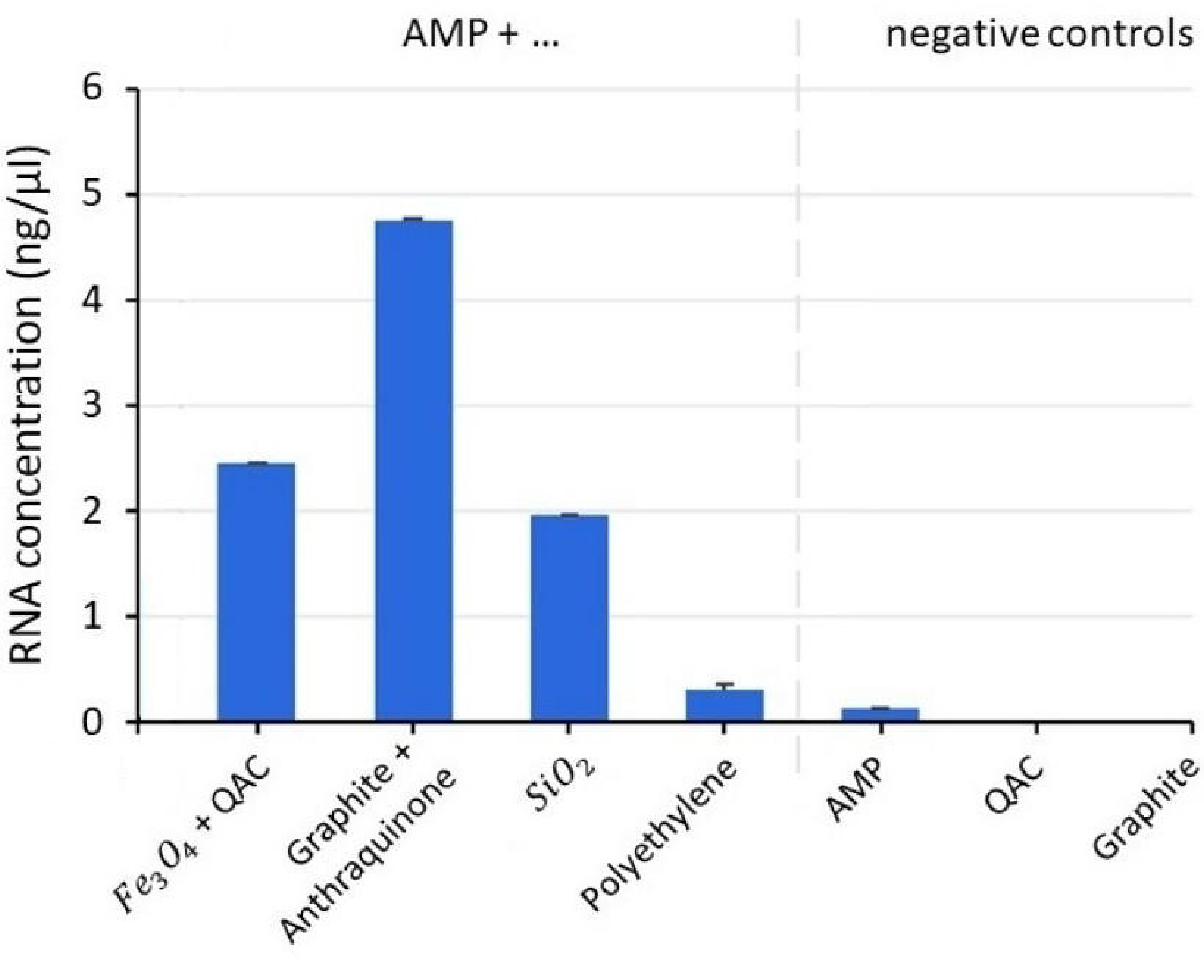


OSSW efficiency as a function of biomolecular species added to aqueous suspension

What determines the polymerisation?

Fluorometric poly-A-RNA concentrations



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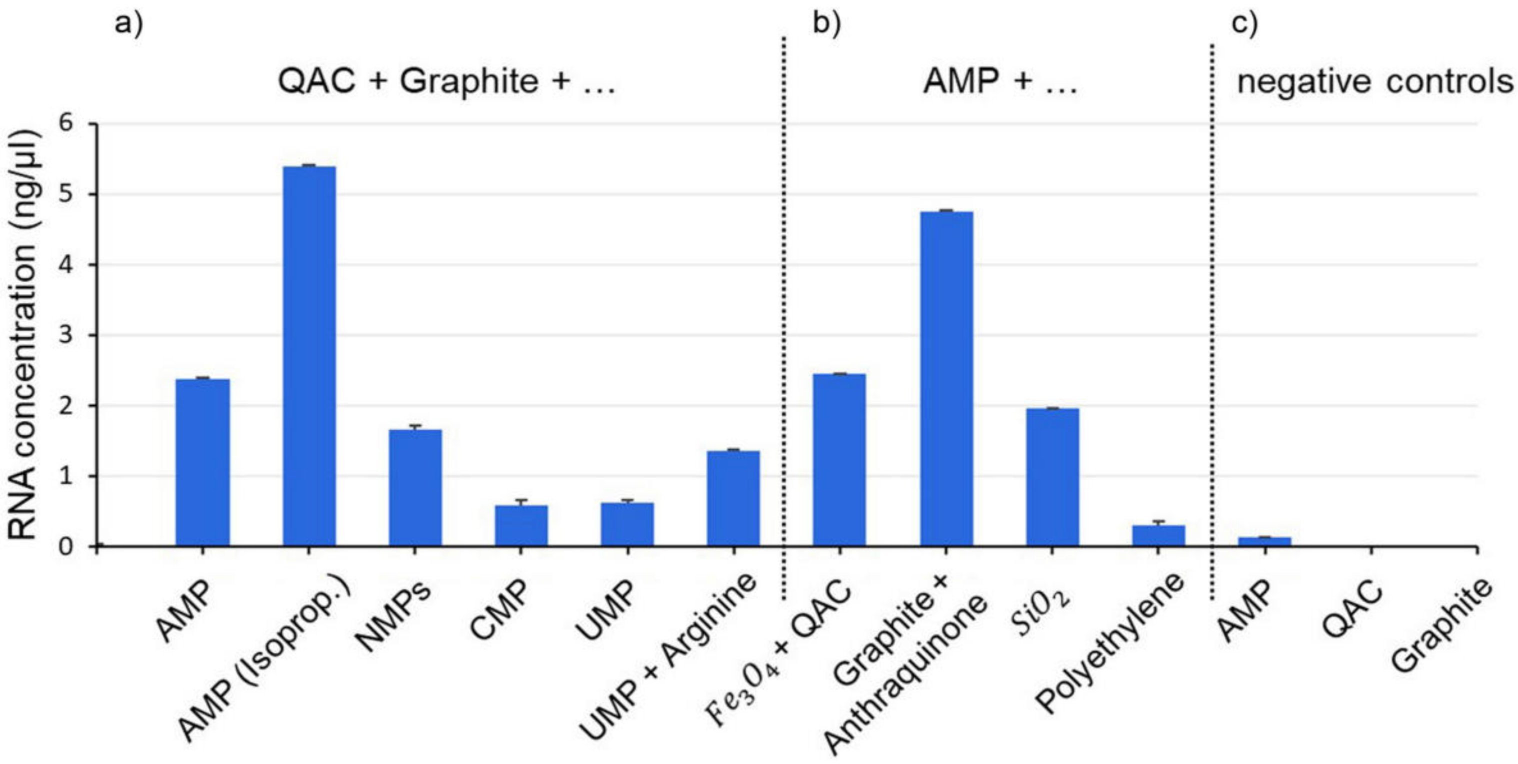

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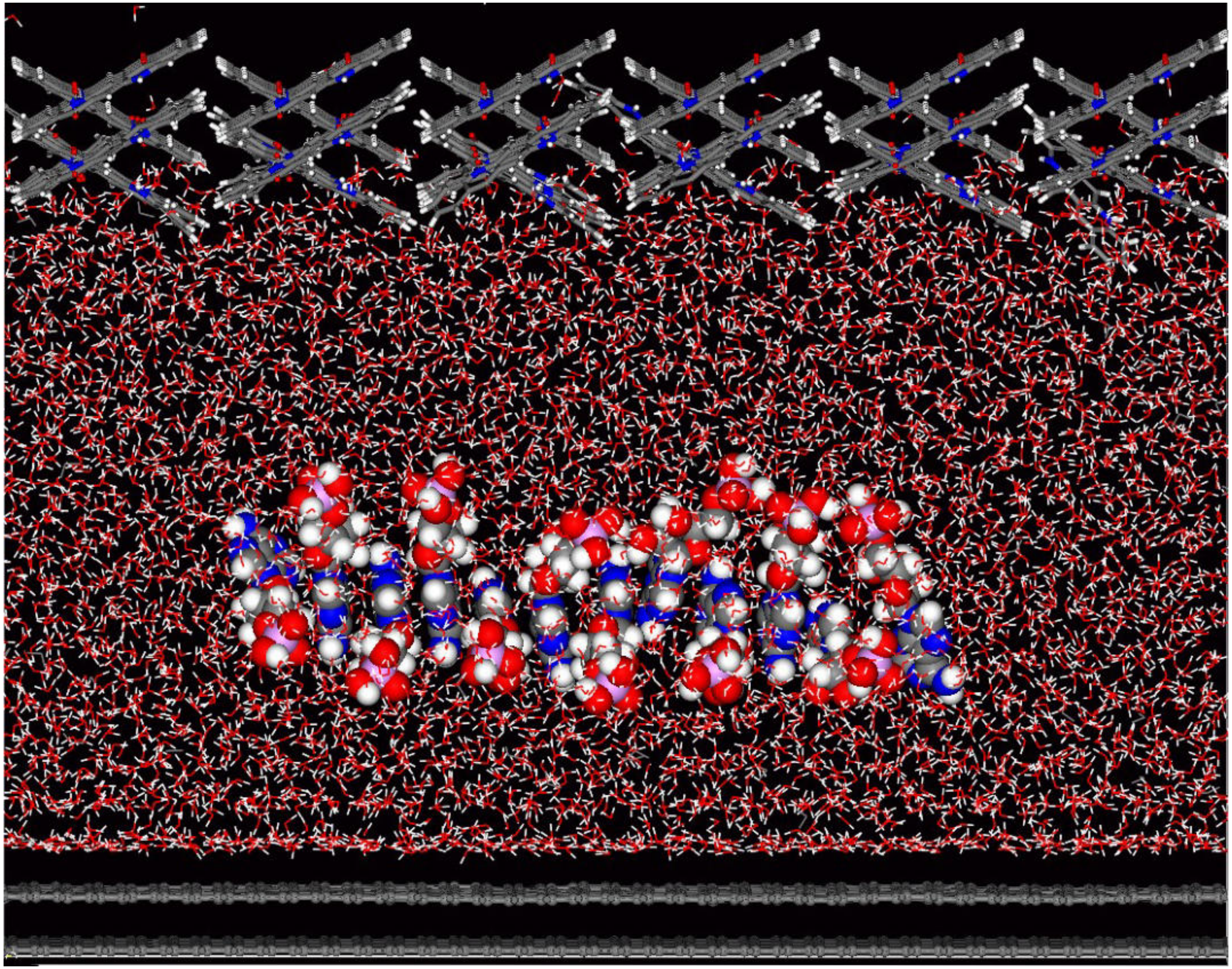

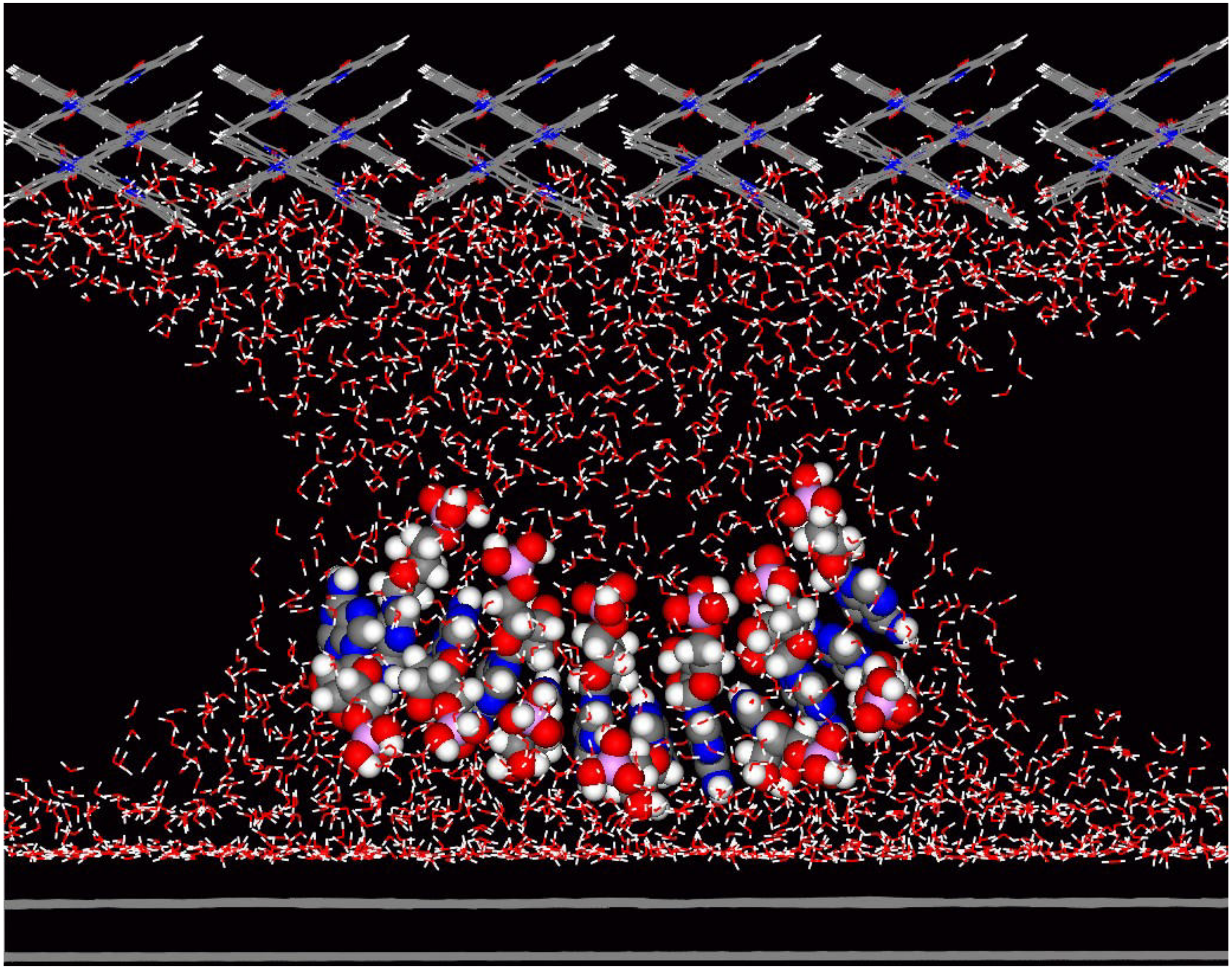

Discussion

Gibbs free energy change: $\Delta G = \Delta H - T\Delta S$

Nucleotide polymerization release water
→ TD barrier: ($\Delta G > 0$)

=> uphill reaction → extremely inefficient to occur spontaneously
under ambient conditions

If water activity is very low:
→ ($\Delta S >> 0$) → ($\Delta G < 0$) (exergonic)

=> by reducing water activity: thermodynamic barrier can be overcome

Temporal nanoconfined water:
changes vapour pressure and H-Bond network dynamics:
→ reduces water activity (gap size, characteristics of confining walls)

Discussion

Exergonic impact of nanoconfinement effects on nucleotide polymerization/ stabilization

→ relevant for prebiotic plausibility:

- no non-physiological conditions
  (drying, alternative solvents, high temperature)

- In line with evolutionary conservatism:
  nanofluidics both in nanogeochemical
  and intracellular environments.

Discussion

communications chemistry

ARTICLE

Check for updates

https://doi.org/10.1038/s42004-023-00872-y

OPEN

Temporal nanofluid environments induce prebiotic condensation in water

Andrea Greiner de Herrera[1,2,3], Thomas Markert[4] & Frank Trixler[1,3,5]

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Implications

Abiotic, temporal nanofluidic confinements…

- allow prebiotic condensation reaction pathways in water under stable, moderate conditions
- emerge in aqueous particle suspensions as geologically ubiquitous and thus prebiotic plausible environments
- are consistent with the principle that evolution builds on existing pathways as living cells also work with temporal nanoconfined water

Acknowledgements

- Center for Neuropathology and Prion Research, Faculty of Medicine,
  LMU Munich, Germany
  → molecular biology experiments (Fluorometry, PCR) (A. Greiner de Herrera)

- Institute of Theoretical Chemistry, Ulm University, Germany
  → dynamic force field calculations (T. Markert)

Summary

Don‘t combat water (cooking, replacing, drying) in aiming to solve the water paradox; dive to the bottom of the nanoscopic waterworld.