



Since 1959

Water, Droplets and Ice

Examples of Science for Sustainability

Thalappil Pradeep

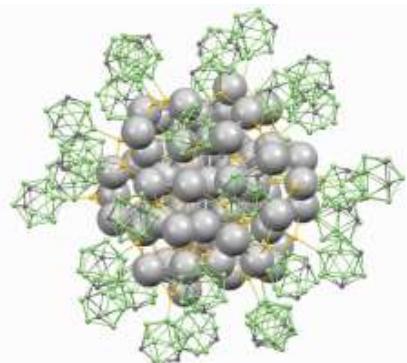
Institute Professor, IIT Madras

pradeep@iitm.ac.in

<https://pradeepresearch.org>

Co-founder

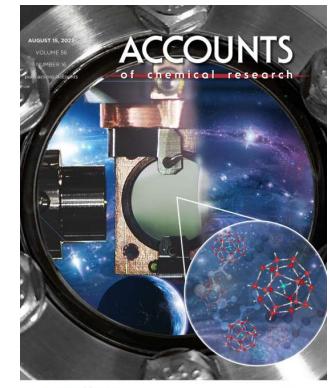
InnoNano Research Pvt. Ltd.
InnoDI Water Technologies Pvt. Ltd.
VayuJAL Technologies Pvt. Ltd.
Aqueasy Innovations Pvt. Ltd.
Hydromaterials Pvt. Ltd.
EyeNetAqua Solutions Pvt. Ltd.
DeepSpectrum Innovations Pvt. Ltd.



Professor-in-charge



International Centre for Clean Water



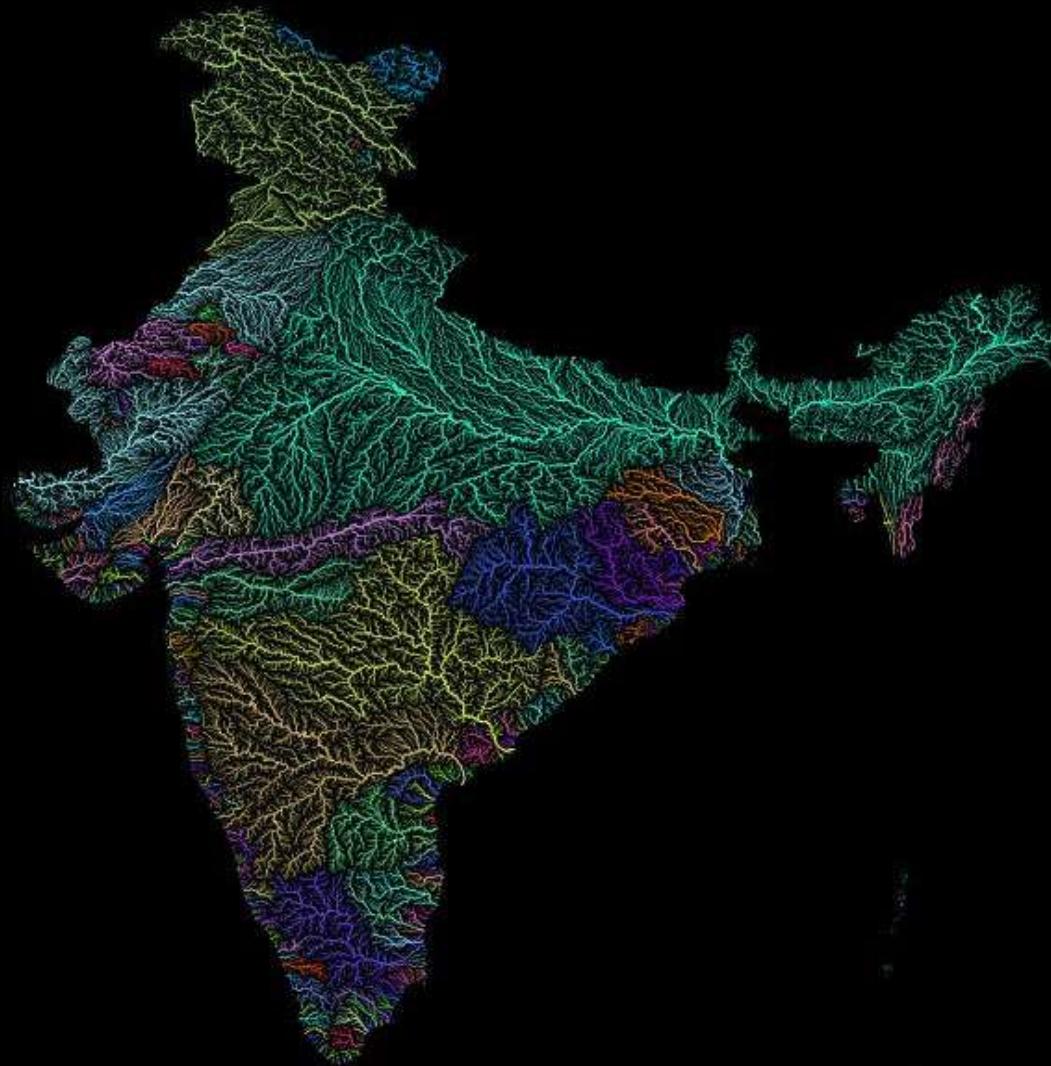
Associate Editor

3rd International Conference on Energy, Functional
Molecules/Materials and Nanotechnology, Kumaun University
Nainital, Uttarakhand, March 20-22, 2025





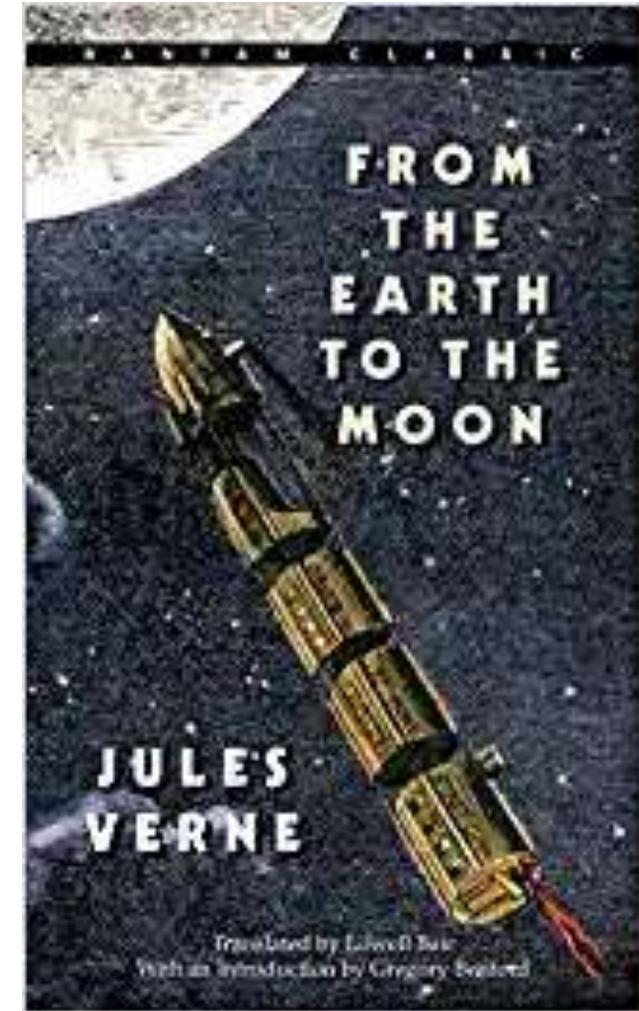
“Pale blue dot” Voyager 1 Feb. 14, 1990
Water is the most important inheritance of our planet



From S. Vishwanath

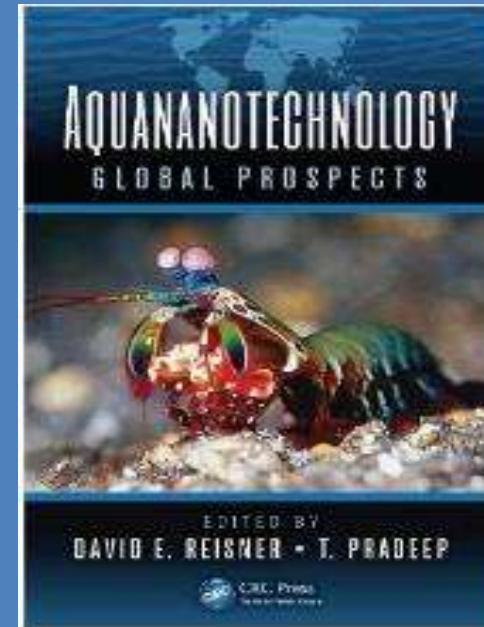
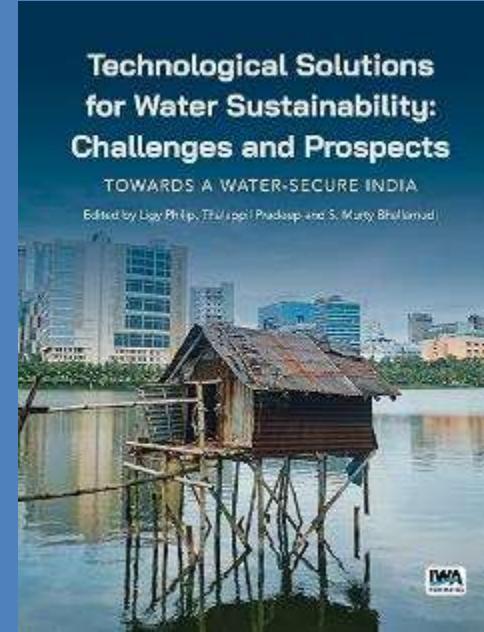
© Robert Szucs/Grasshopper Geography

Our dreams become reality
with materials



Affordable clean water is a problem of advanced materials

- New adsorbents
- New sensors
- New catalysts
- Novel phenomena
- New devices

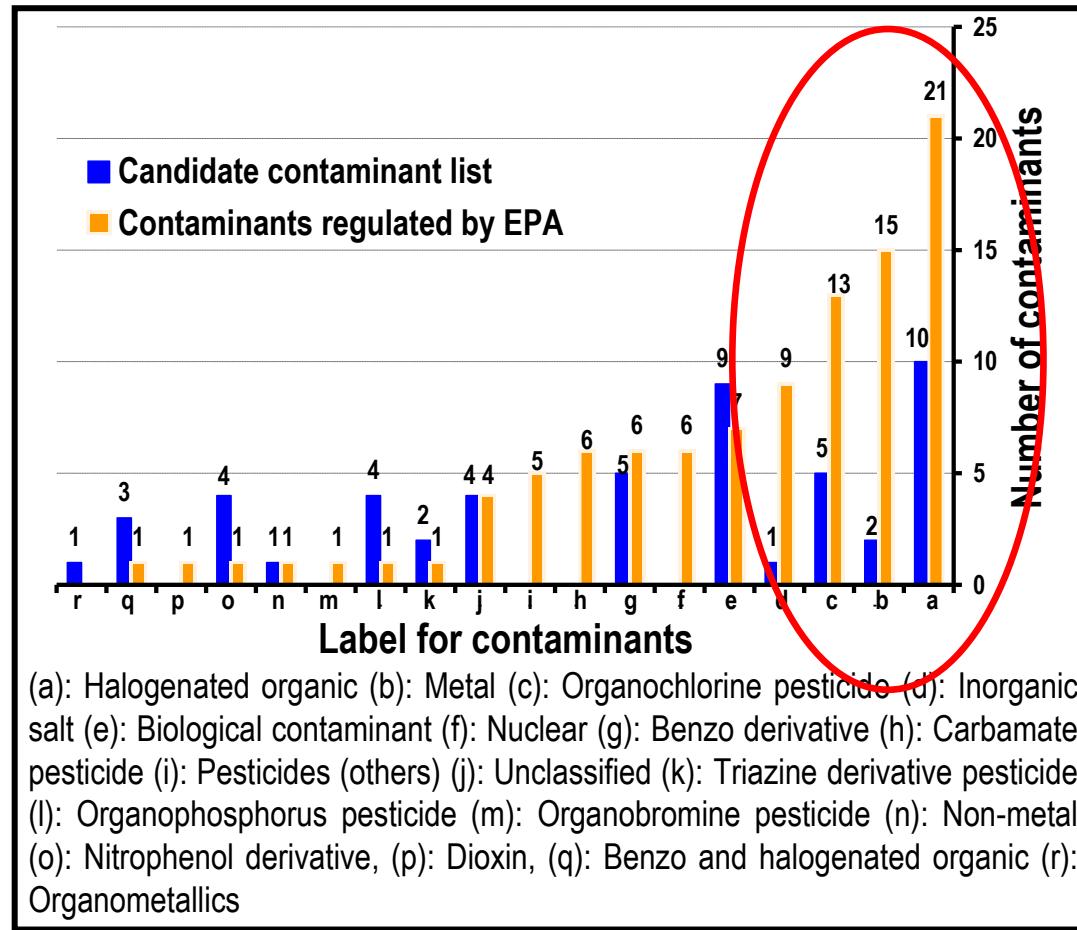


Water purification, history

Important milestones in the history of water purification (1800–2007) from the perspective of noble metal nanoparticles in water treatment (compiled from multiple sources on the World Wide Web).

Year	Milestone
1804	Setup of world's first city-wide municipal water treatment plant (Scotland, sand-filter technology)
1810	Discovery of chlorine as a disinfectant (H. Davy)
1852	Formulation of Metropolis Water Act (England)
1879	Formulation of Germ Theory (L. Pasteur)
1902	Use of chlorine as a disinfectant in drinking water supply (calcium hypochlorite, Belgium)
1906	Use of ozone as a disinfectant (France)
1908	Use of chlorine as a disinfectant in municipal supply, New Jersey
1914	Federal regulation of drinking water quality (USPHS)
1916	Use of UV treatment in municipal supplies
1935	Discovery of synthetic ion exchange resin (B. A. Adams, E. L. Holmes)
1948	Nobel Prize to Paul Hermann Muller (insecticidal properties of DDT)
1959	Discovery of synthetic reverse osmosis membrane (S. Yuster, S. Loeb, S. Sourirajan)
1962	<i>Silent Spring</i> published, first report on harmful effects of DDT (R. Carson)
1965	World's first commercial RO plant launched
1974	Reports on carcinogenic by-products of disinfection with chlorine Formulation of Safe Drinking Water Act (USEPA)
1975	Development of carbon block for drinking water purification
1994	Report on use of zerovalent iron for degradation of halogenated organics (R. W. Gillham, S. F. O'Hannesin)
1997	Report on use of zerovalent iron nanoparticles for degradation of halogenated organics (C-B. Wang, W.-X. Zhang)
1998	Drinking Water Directive applied in EU
2000	Adoption of Millennium Declaration during the UN Millennium Summit (UN Millennium Development Goals)
2003	Report on use of noble metal nanoparticles for the degradation of pesticides (A.S. Nair, R. T. Tom, T. Pradeep)
2004	Stockholm Convention, banning the use of persistent organic pollutants
2007	Launch of noble metal nanoparticle-based domestic water purifier (T. Pradeep, A. S. Nair, Eureka Forbes Limited)

Future of water purification: An enigma with some pointers



Category-wise distribution of contaminants regulated by USEPA and future contaminants

World's first nanochemistry-based water purifier

RSC Advancing the
Chemical Sciences
Chemistry World

Pesticide filter debuts in India

20 April 2007

Kilugudi Jayaraman/Bangalore, India

A domestic water filter that uses metal nanoparticles to remove dissolved pesticide residues is about to enter the Indian market. Its developers at the Indian Institute of Technology (IIT) in Chennai (formerly Madras) believe it is the first product of its kind in the world to be commercialised.

Mumbai-based Eureka Forbes Limited, a company that sells water purification systems, is collaborating with IIT and has tested the device in the field for over six months. Jayachandra Reddy, a technical consultant to the company, expects the first 1000 units to be sold door-to-door from late May.

'Our pesticide filter is an offshoot of basic research on the chemistry of nanoparticles,' Thalappil Pradeep, who led the team at IIT Chemical and Chemistry World. He and his student Sreekumaran Nair discovered in 2003 that hexacarbons such as carbon hexachloride (CCl₆) completely break down into metal halides and amorphous carbon upon reaction with gold and silver nanoparticles.¹

Pradeep said this prompted them to extend their study to include organochlorine and organophosphorous pesticides, whose presence in water is posing a health risk in rural India. In research funded by the Department of Science and

Technology in New Delhi, he has found^{2,3} that gold and silver nanoparticles loaded on alumina were indeed able to completely remove endosulfan, malathion and chlorpyrifos - three pesticides that have been found in Indian drinking water supplies.

Use and recycle

The results of this research have been published in the journal *Environmental Science and Technology*.

Pradeep's team has now developed a water filter that uses silver and gold nanoparticles to remove pesticides from drinking water.

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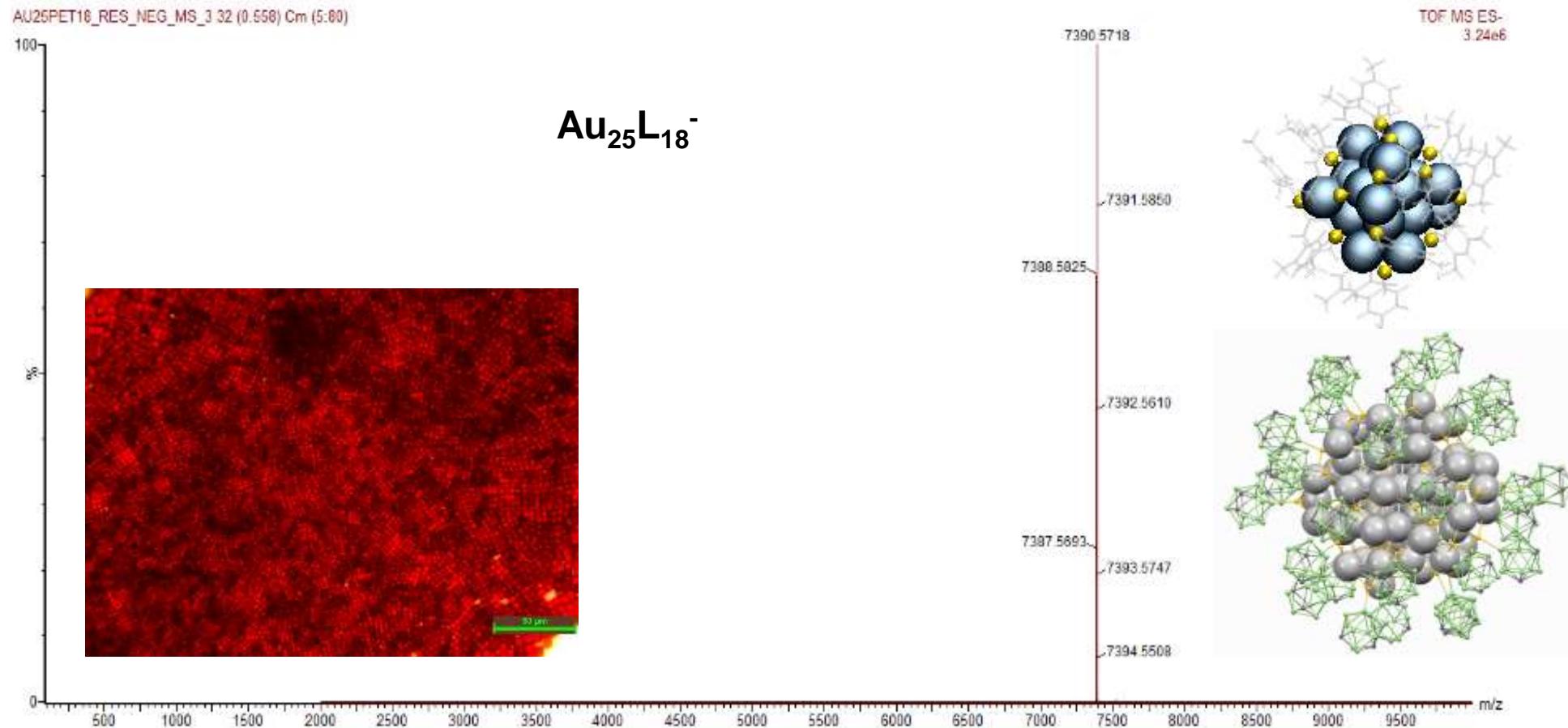
Chemistry world
First ever
nanotechnology
product for clean
water



A plant to make supported nanomaterials for water purification; with capacity of 4.5 tons per month, 2007

1. Patents: A method of preparing purified water from water containing pesticides, **Indian patent 200767**
2. Extraction of malathion and chlorpyrifos from drinking water by nanoparticles , **US 7,968,493** A method for decontaminating water containing pesticides, **EP 17,15,947**
Product is marketed now by a Eureka Forbes Ltd.
Several new technologies are now available

Nanomaterials are now atomically precise



T. Pradeep et. al. *Acc. Chem. Res.* 2018; 2019.

Clean water for everyone



ACS Sustainable Chemistry & Engineering Editorial,
December 2016

Water positive materials

PNAS

Biopolymer-reinforced synthetic granular nanocomposites for affordable water purification

Mohan Udhaya Sankar¹, Sahaja Algal², Kamalesh Chaudhari, and Thalappil P.

Unit of Nanoscience and Thematic Unit of Excell

Edited by Eric Hoek, University of California, Los

Creation of affordable materials for constant water is one of the most promising ways to drinking water for all. Combining the cap composites to scavenge toxic species such other contaminants along with the above affordable, all-inclusive drinking water pu without electricity. The critical problem i synthesis of stable materials that can reliously in the presence of complex spe drinking water that deposit and cause si surfaces. Here we show that such consta be synthesized in a simple and effective fast out the use of electrical power. The nano sand-like properties, such as higher shear forms. These materials have been used to water purifier to deliver clean drinking wat. The ability to prepare nanostructures ambient temperature has wide relevance water purification.



Anil Kumar,

6, India

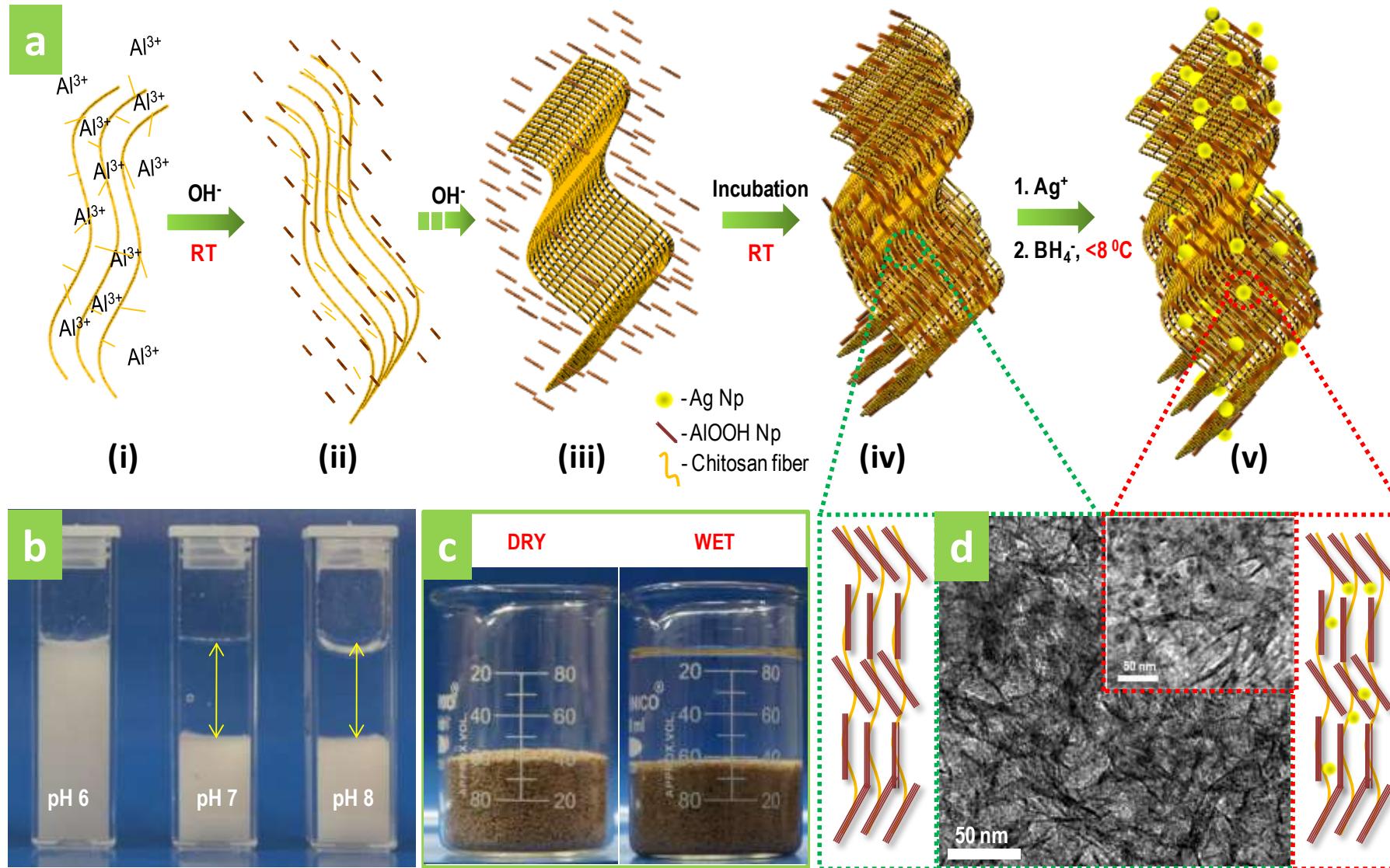
ember 21, 2012)

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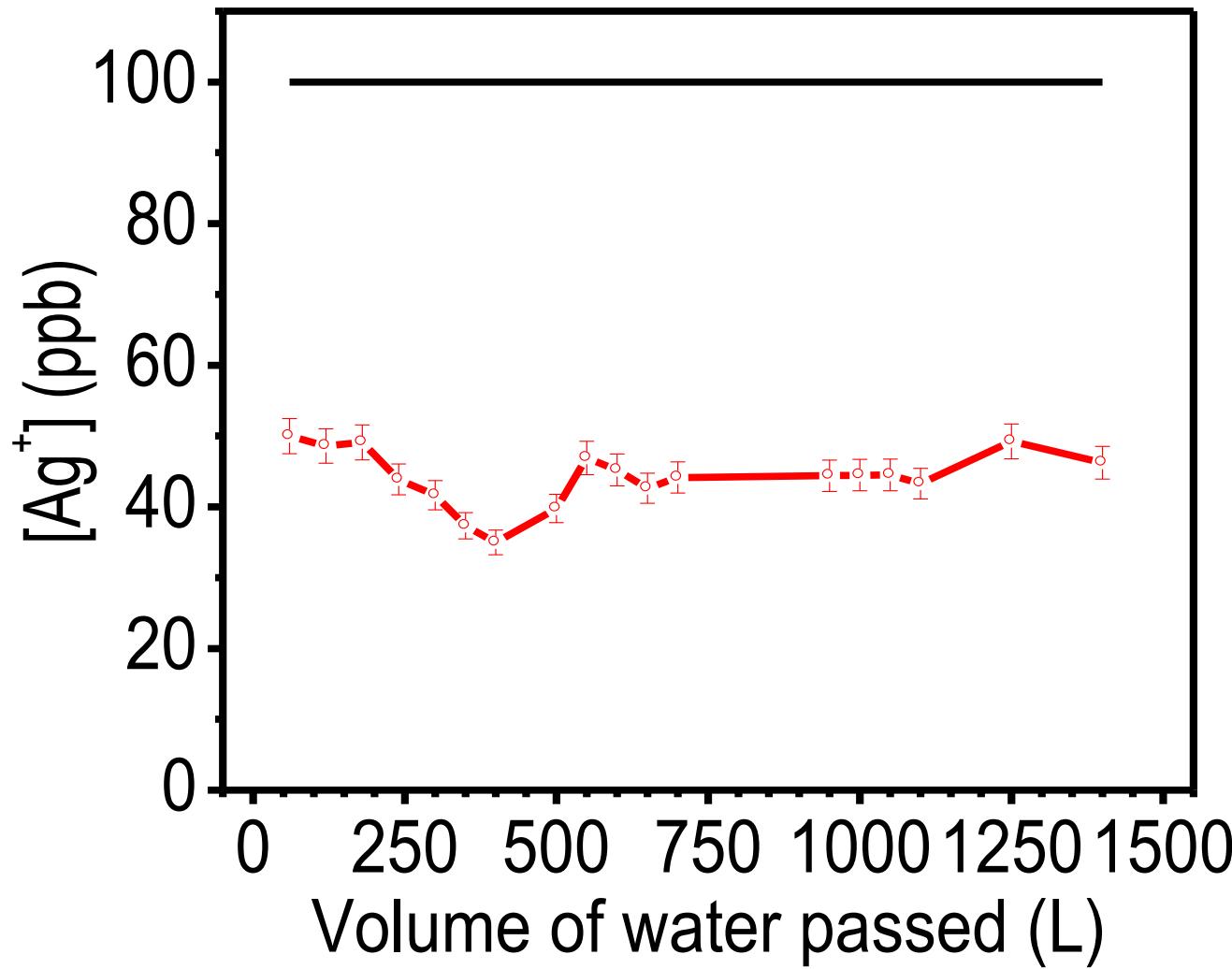
f nanocrystalline : materials pre- eous route. The i to abundant -O- help in the cry- : strong covalent ix. X-ray photo- mposition is rich ral imaging, the was confirmed. er nanoparticle vity in drinking eloped that can nstitute an af- i composites de- rials in India, as the waterborne

hybrid | green | appropriate technology | frugal science | developing world

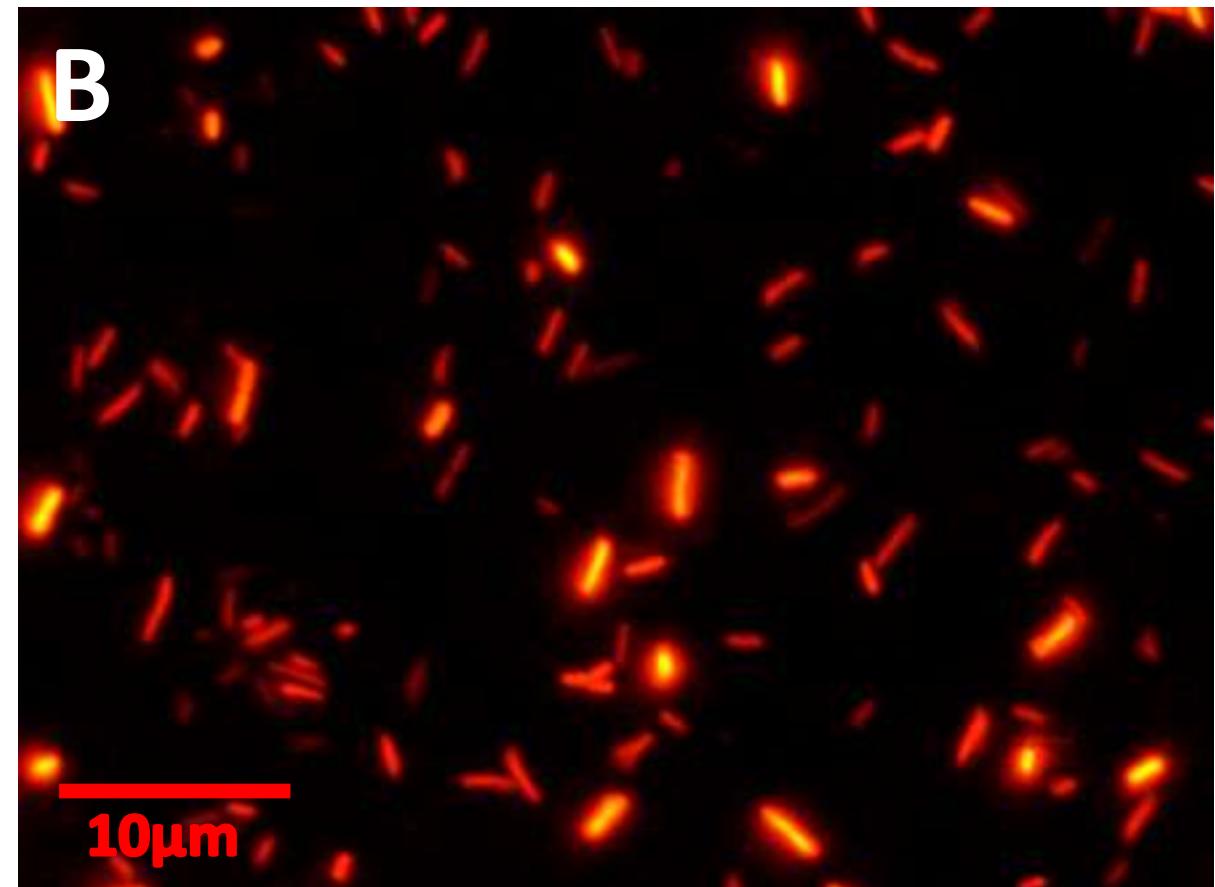
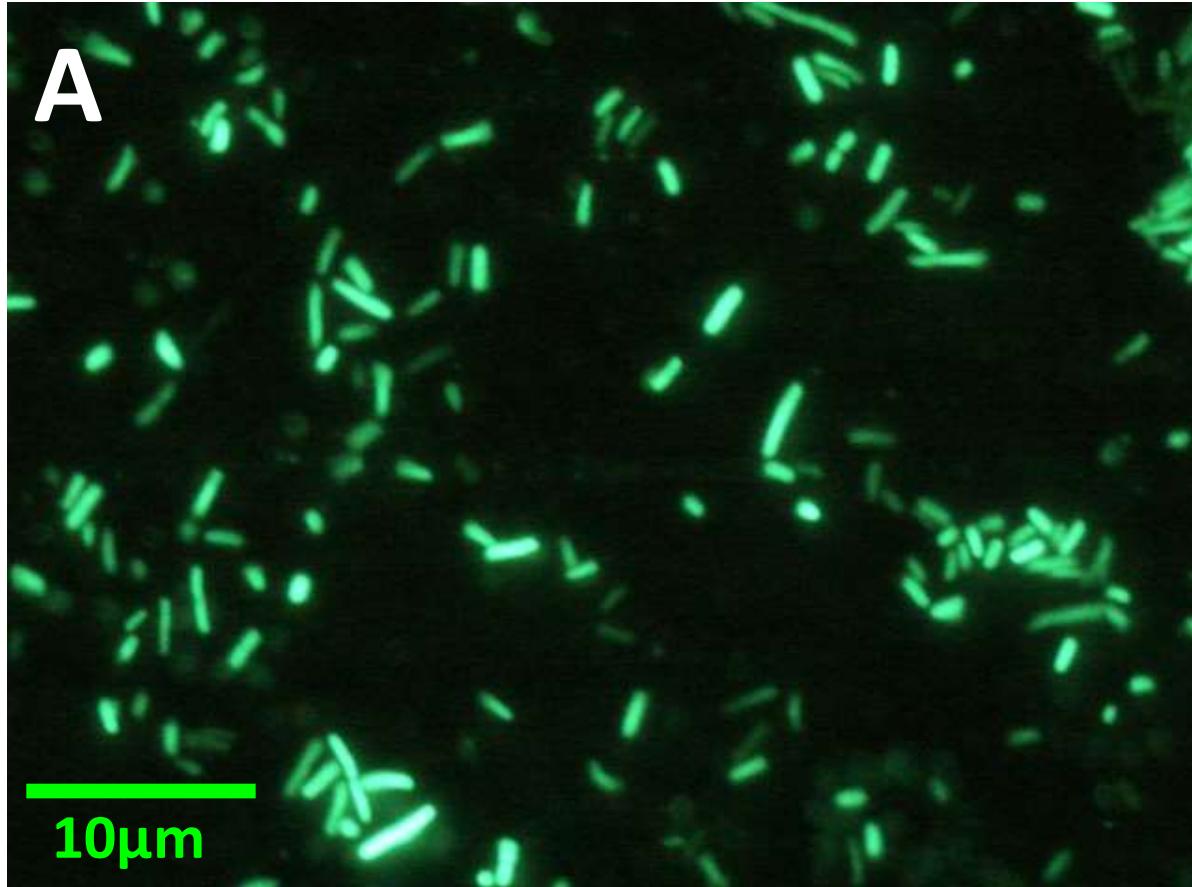
How to make?



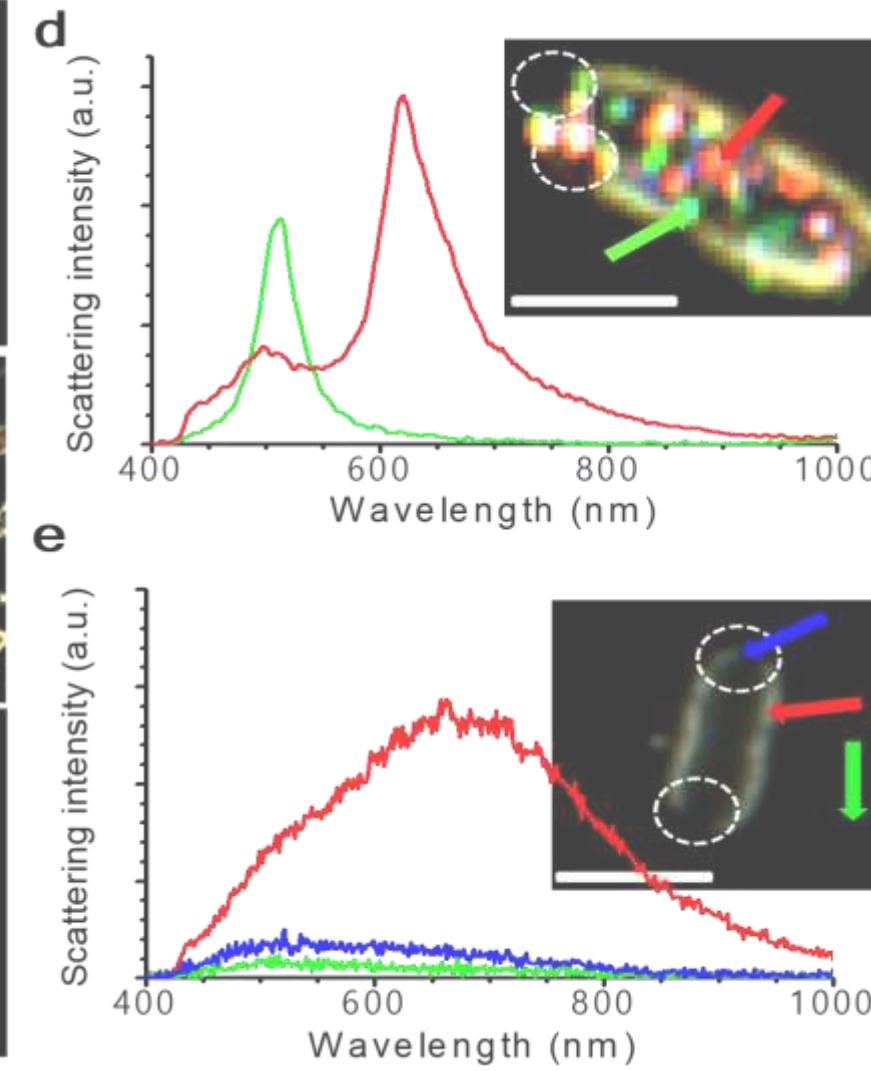
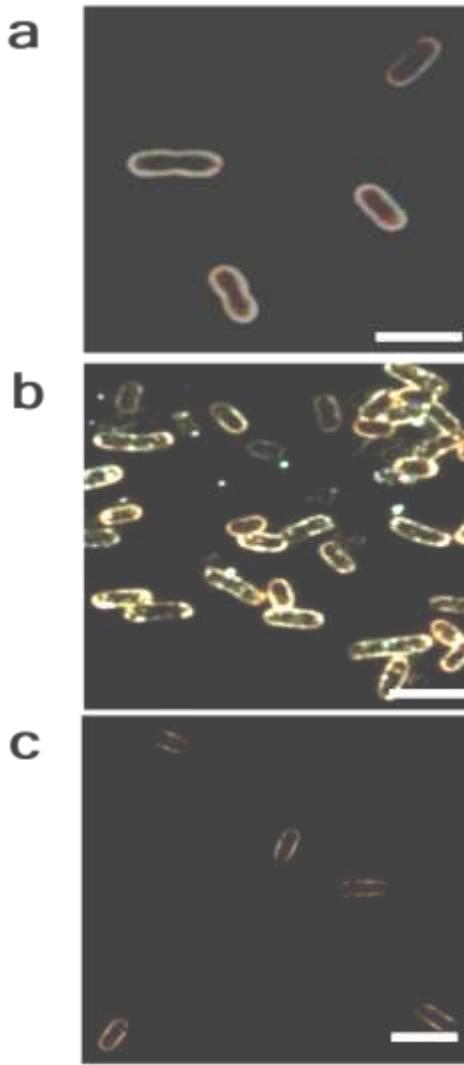
What is special?



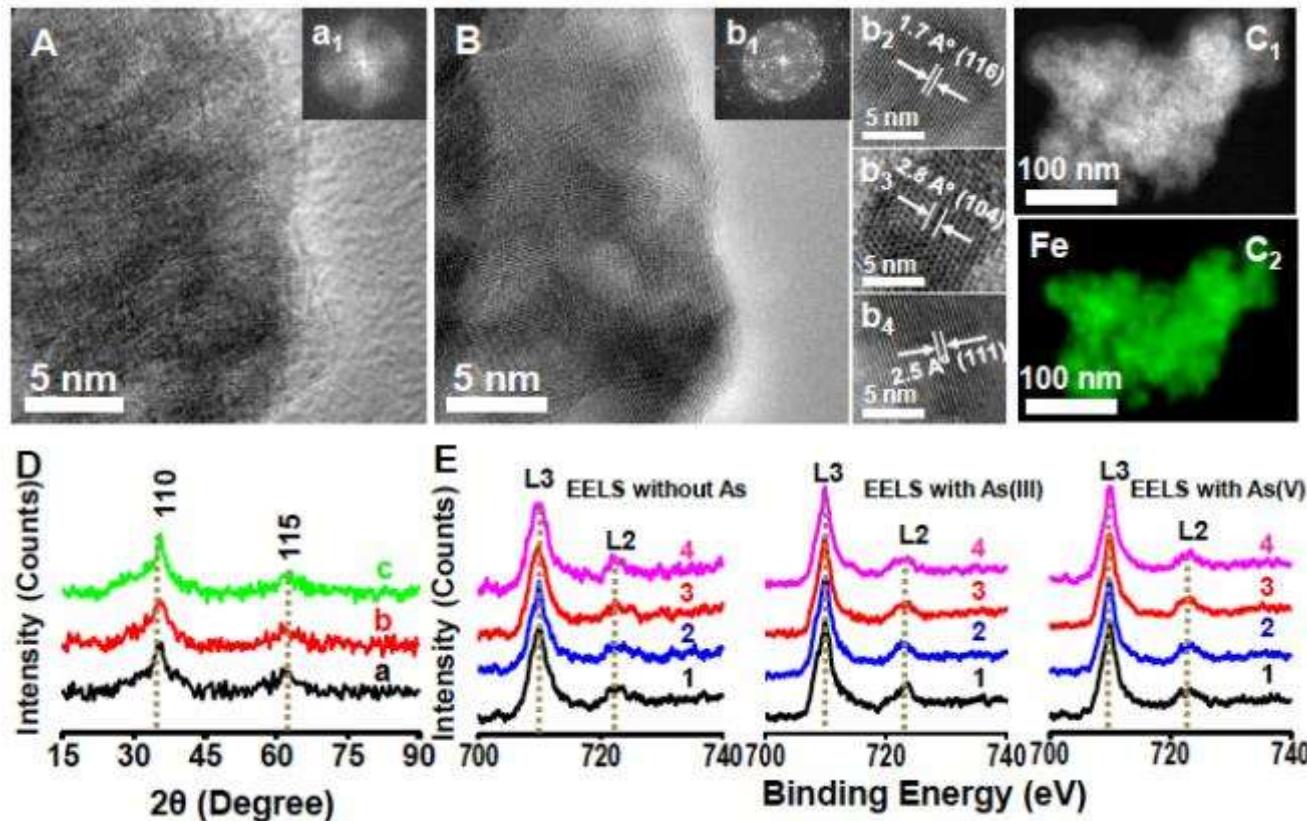
Live/dead staining experiments



No nanotoxicity



Variety of materials



www.advmat.de

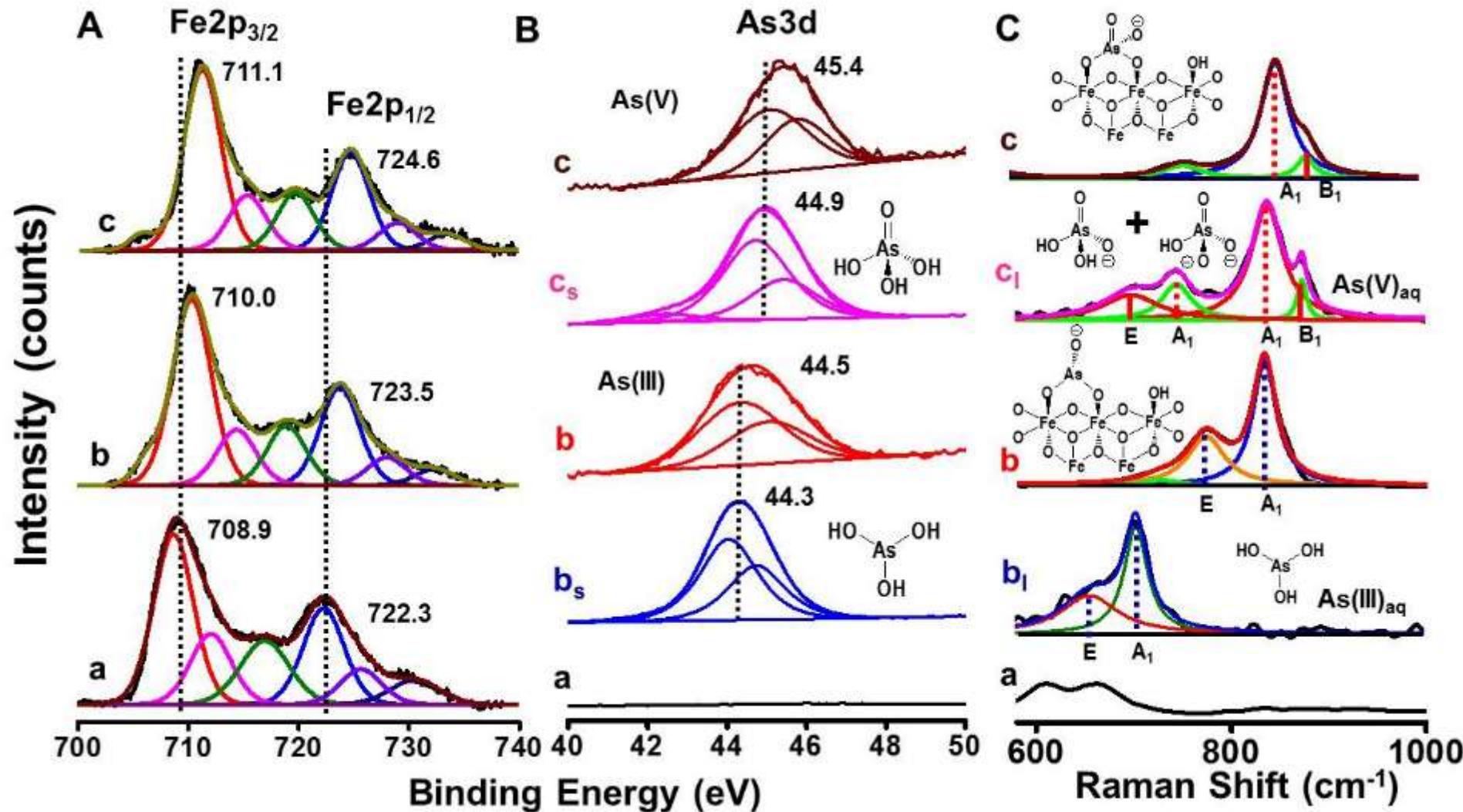
Author Pradeep
ADVANCED MATERIALS

Confined Metastable 2-Line Ferrihydrite for Affordable
Point-of-Use Arsenic Free Drinking Water

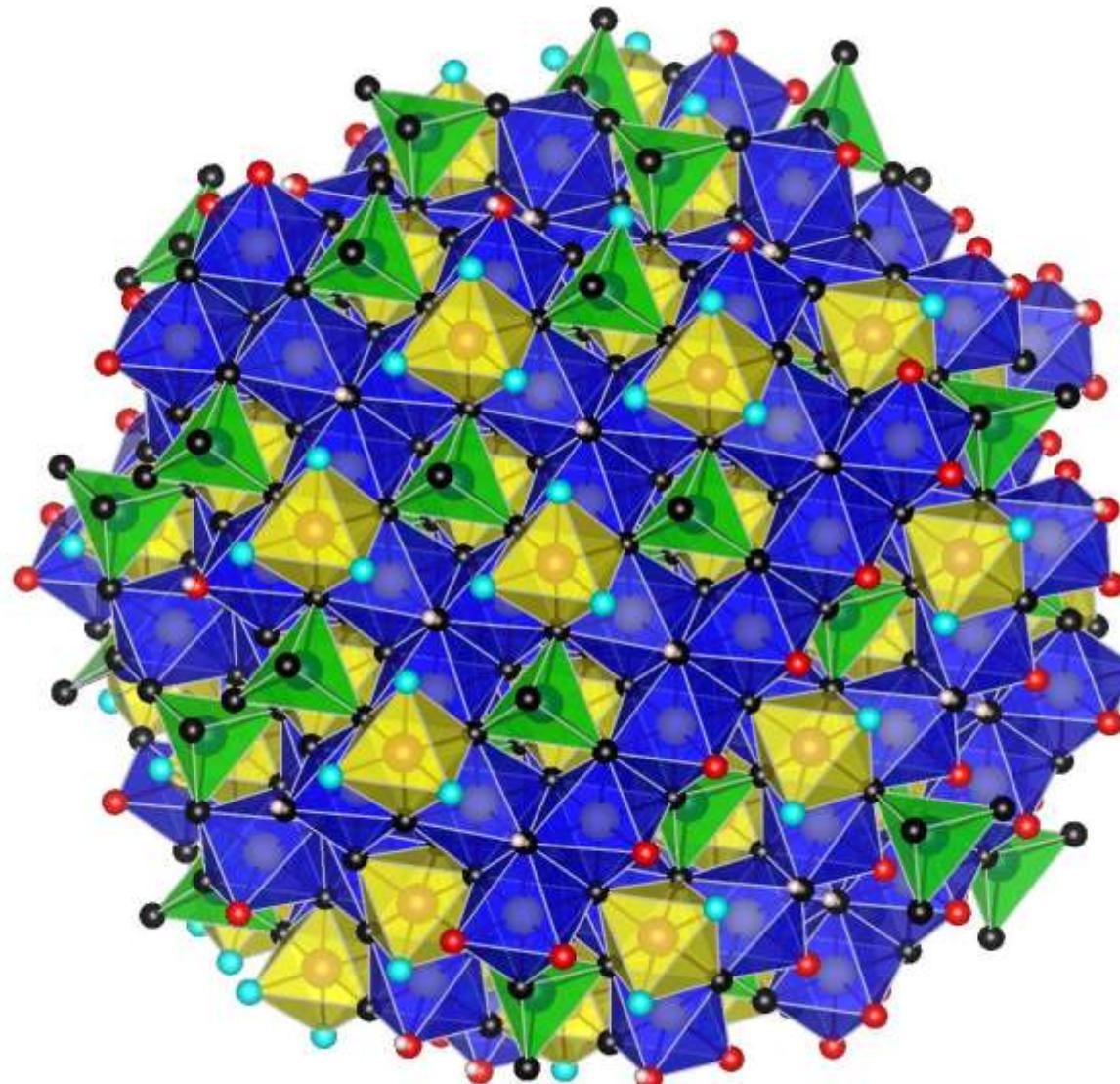
By Avula Anil Kumar, Anirban Som, Paolo Longo, Chennu Sudhakar,
Radha Gobinda Bhui, Soujat Sen Gupta, Anshup, Mohan Udhaya Sankar,
Amrita Chaudhary, Ramesh Kumar, and T. Pradeep*

Communication

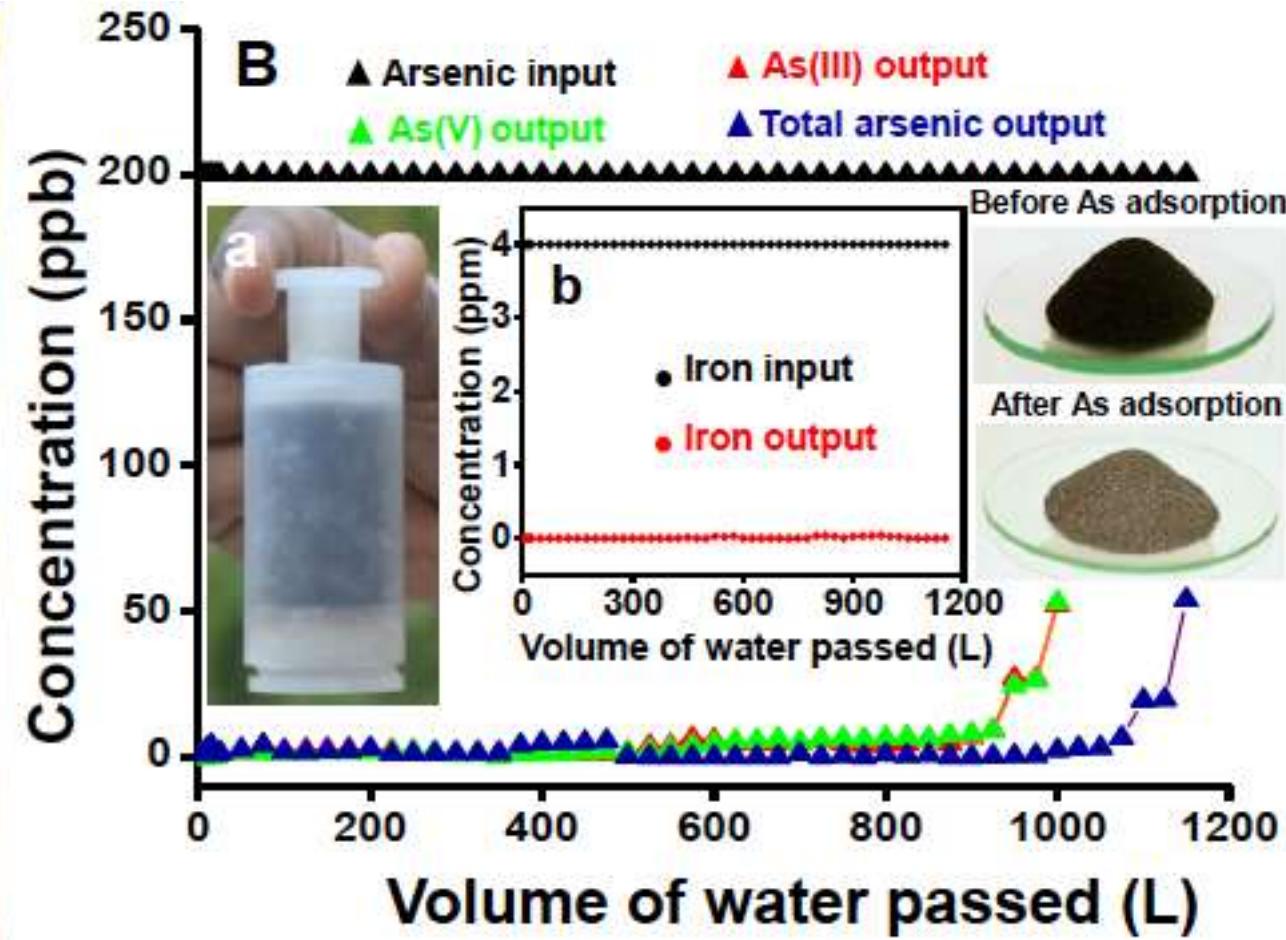
Mechanism – molecular tools



Modeling surfaces



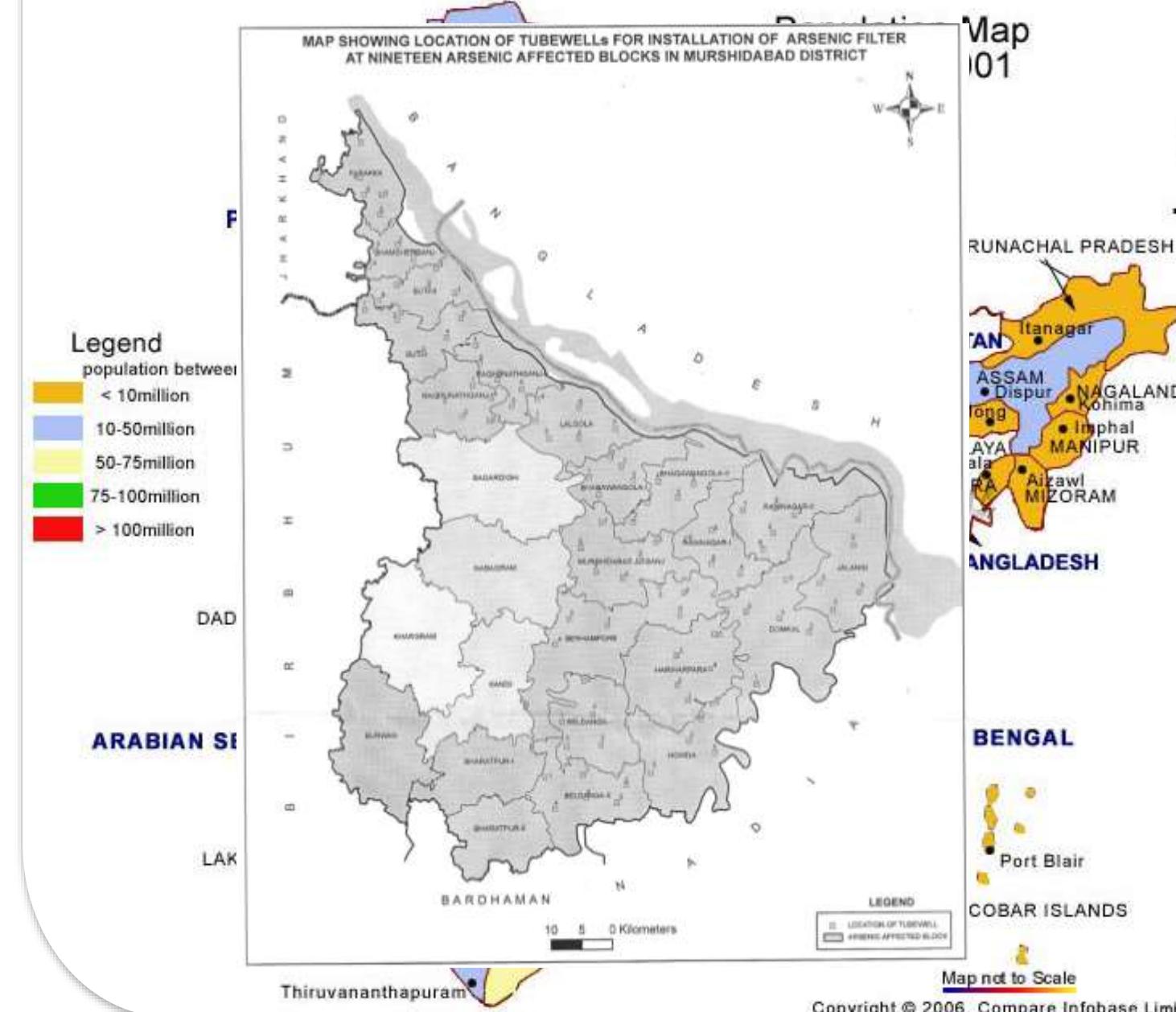
Lab studies



Initial pilot studies



Larger pilot studies



Changing the dynamics in the field



- Existing unit for iron and arsenic removal – 20 m³/h
- Uses activated alumina and iron oxide (old generation of adsorbents)

- Existing unit for iron and arsenic removal – 18 m³/h
- Uses iron oxyhydroxide (new generation of adsorbents)
- Input arsenic concentration: 168 ppb
- Output arsenic concentration: 2 ppb

Completed 3 years maintenance (stipulated: 2 years)
for 330 bamboo unit project in Nadia, WB



Minimum uptime: 91%, Maximum: 98%
Only 4/330 have reported arsenic above 10 ppb
Benefiting over 100,000 children and villagers

Glimpse of Installed units (330 nos)

Implementation - From 25 KLD to 1 MLD



Large water supply schemes
Capacity: above 1 MLD

5 schemes in use across India



Retrofitted Water Purification Plant
Capacity: 0.1-1 MLD

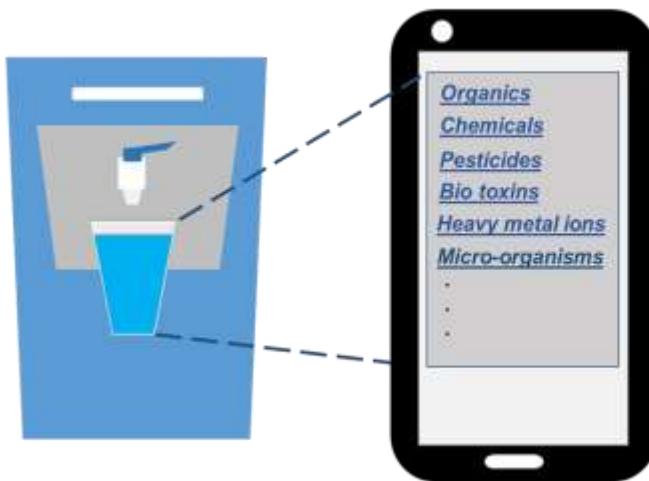
Over 180 units in use across India

Clean water at 2.1 paise per litre!

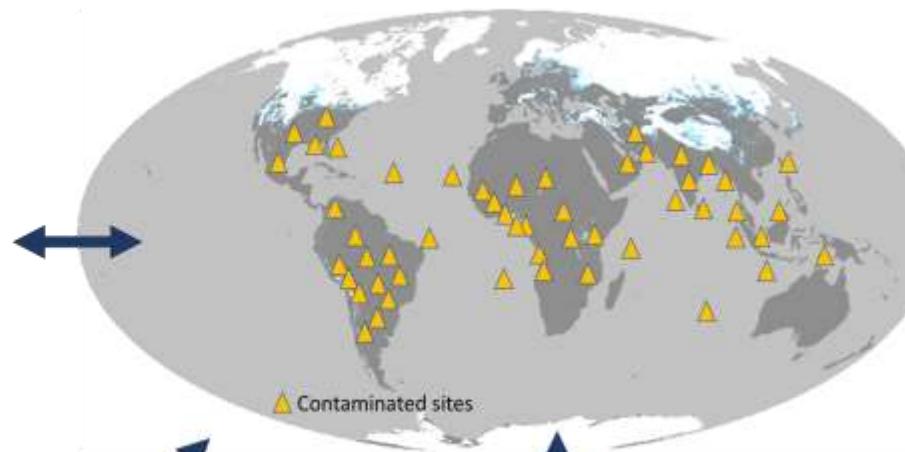
Calculation for the Tariff to be collected for treated water (Revision if Required)			
	Design population	1,071	Plant capacity/70 LPCD
Sr.No.	Item/Description	Cost / Quantity	Remarks
1	Cost of Replacement of Iron removal media	56400	After minimum two years if Iron concentration is more than 5 ppm. But iron concentration is more than 5 ppm at only two to three places. Therefore media may work for 3 years also.
2	Cost of Replacement of Arsenic removal media	978660	After minimum two years if Arsenic concentration is more than 100 ppb. But arsenic concentration is more than 100 ppb at only two to three places. Therefore media may work for 3 years also.
3	Cost of replacement of Activated Carbon	28560	
4	Total cost of Replacement of media	1063620	After minimum two years.
5	Total cost of Replacement of media for one year	531810	
6	Plant capacity	75000	ltr per day
7	Design population	1,071	Plant capacity/70 LPCD
8	Cost per ltr of water	2.1 Paise per ltr	0.025 cents
9	Cost of replacement of media	1.36	Rs. per head per day =Media replacement cost per year/365/Design population
		40.80	per head per month for 70 LPCD water

Smart water purifiers and big data

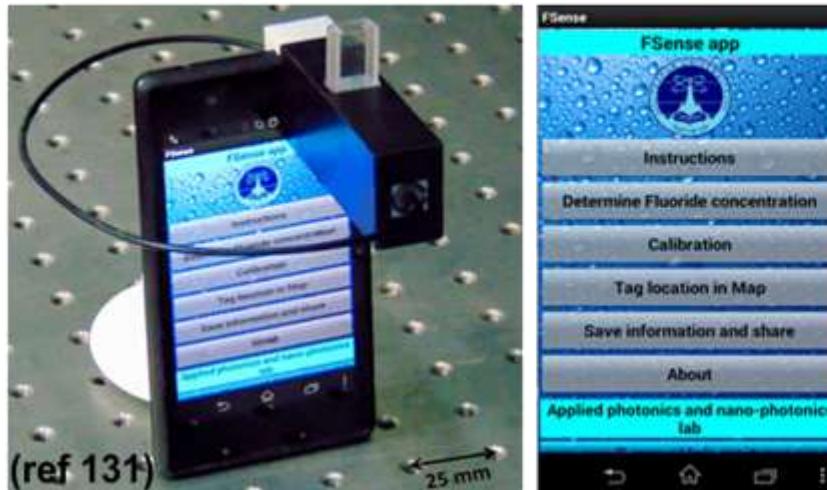
Smart Water Purifiers linked to IoT



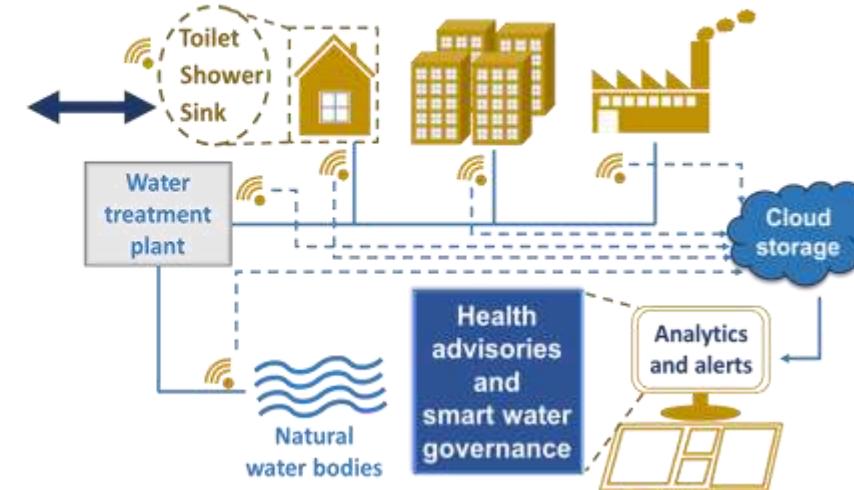
Global Map of Water Health



Cost-effective sensor accessory for point-of-use applications



IoT-enabled sensing for households and distribution networks



Waste management

- Adsorbents conform to toxicity characteristic leaching procedure
- Elemental waste goes back to local environment
- Safe disposal of arsenic (or any other) laden waste
- Additional protection could be considered, if necessary
- Exploring viable uses

Now they are across the country



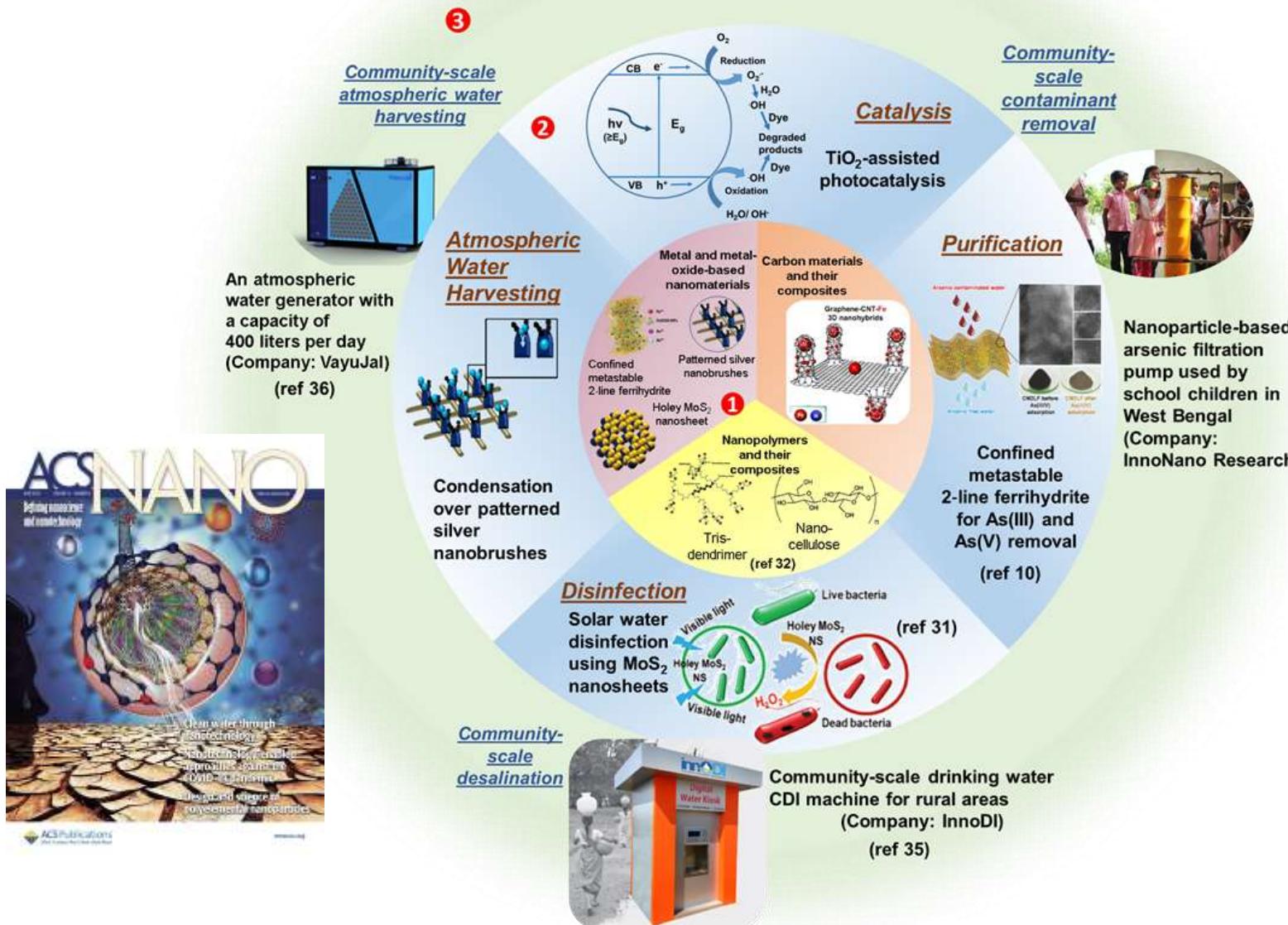
Components of IoT architecture implemented by DWSS, GoP



Typical IoT architecture comprises various sensors and meters, communication gateway, Cloud Server, SMS gateway, Webservices and mobile phone application for operator



Evolution of materials to products



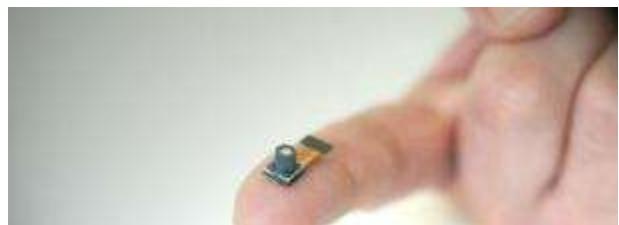
Sensors and new opportunities



Analog/Grating
Equipment
\$ 5~6 Billion (2017)
a few 100k units (2017)



**Ultra compact Low Cost
Spectral Sensor Module
~ Billions units (? 2027)**

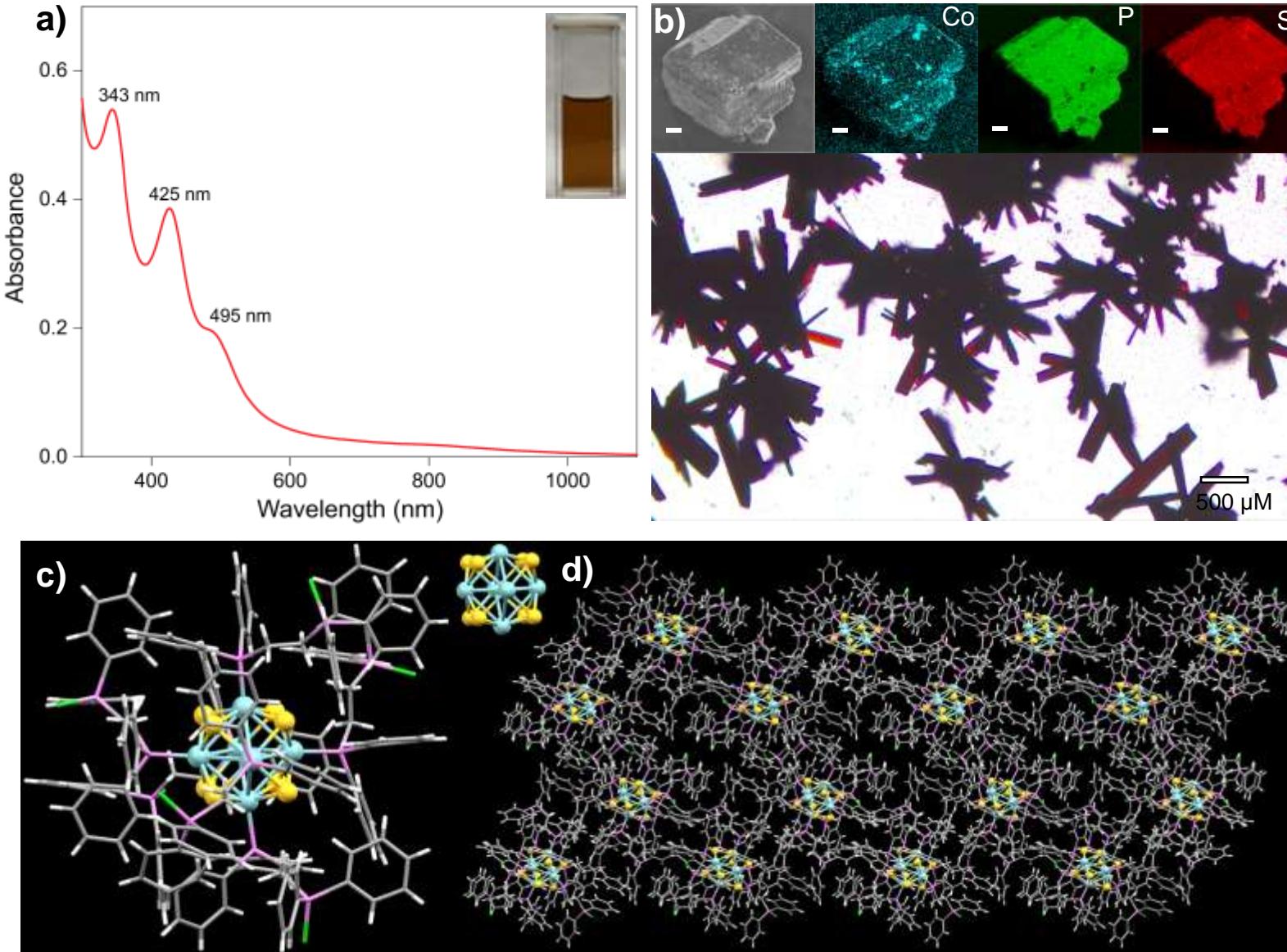


Water quality measurement – In the pipeline

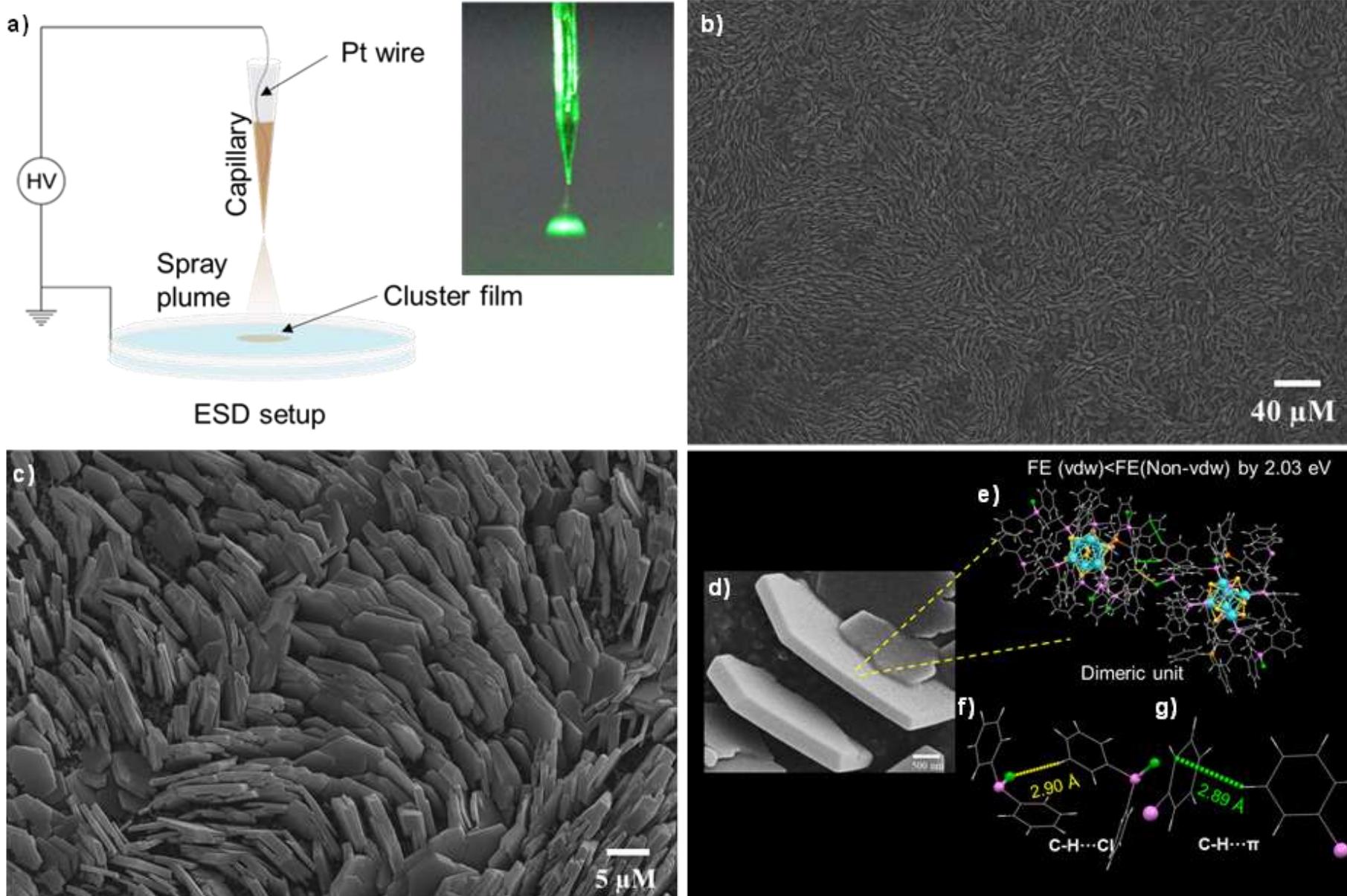
nanoλ

New electrodes - Aligned nanoplates of Co_6S_8

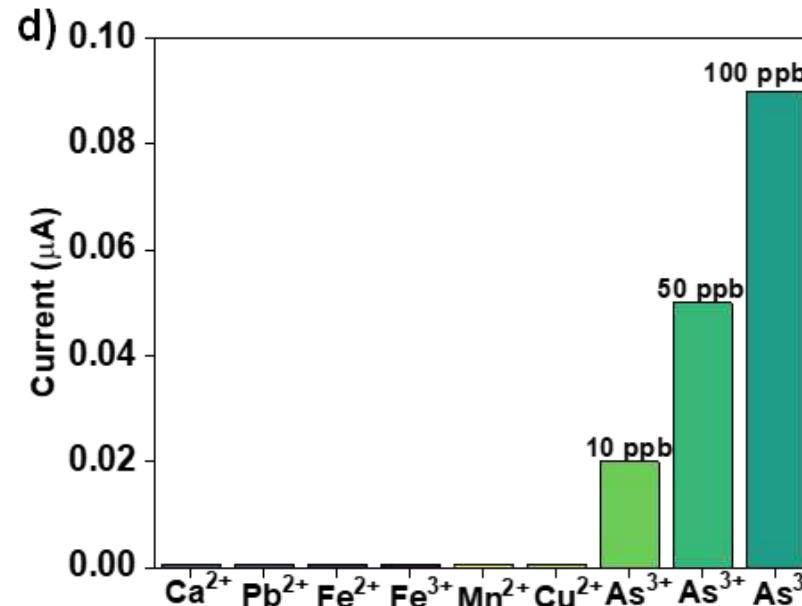
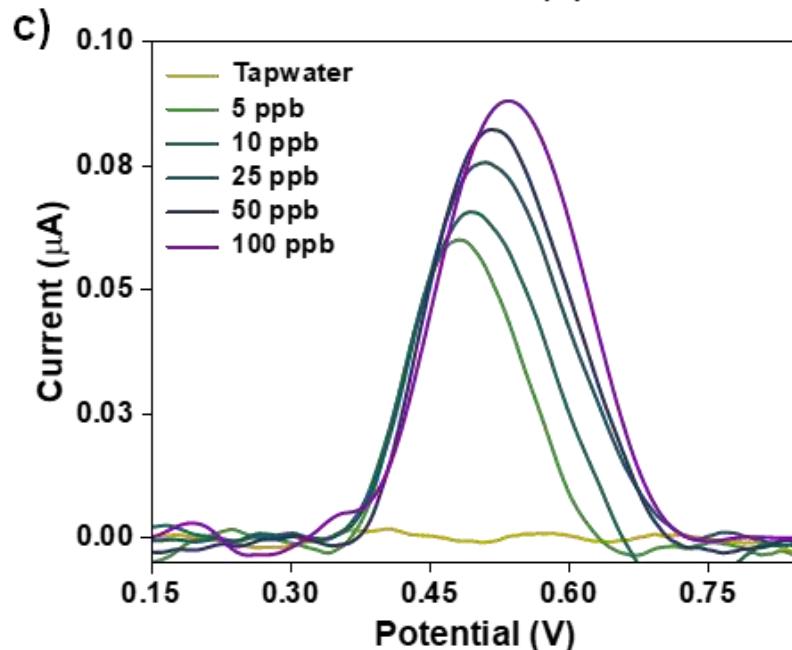
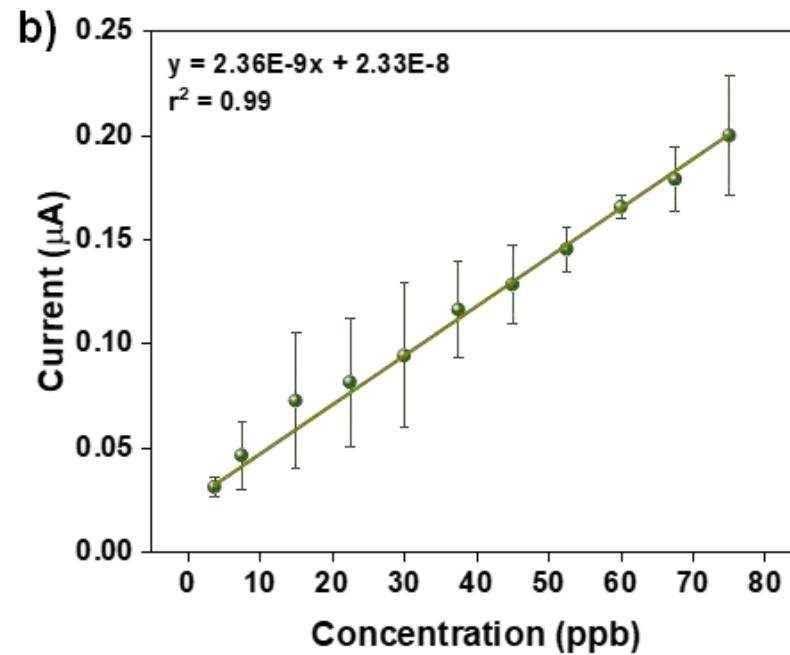
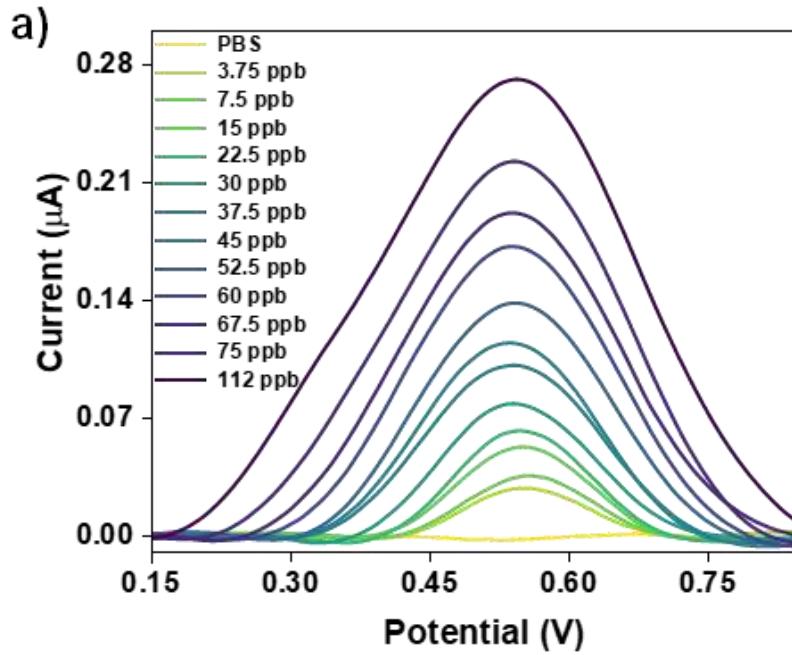
1,2-bis(diphenylphosphino)ethane (DPPE)



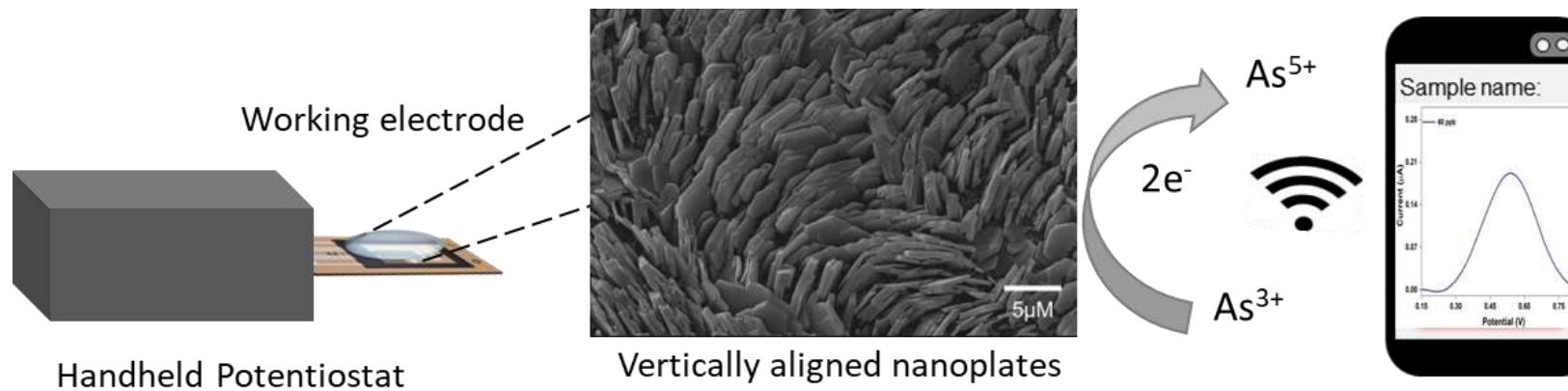
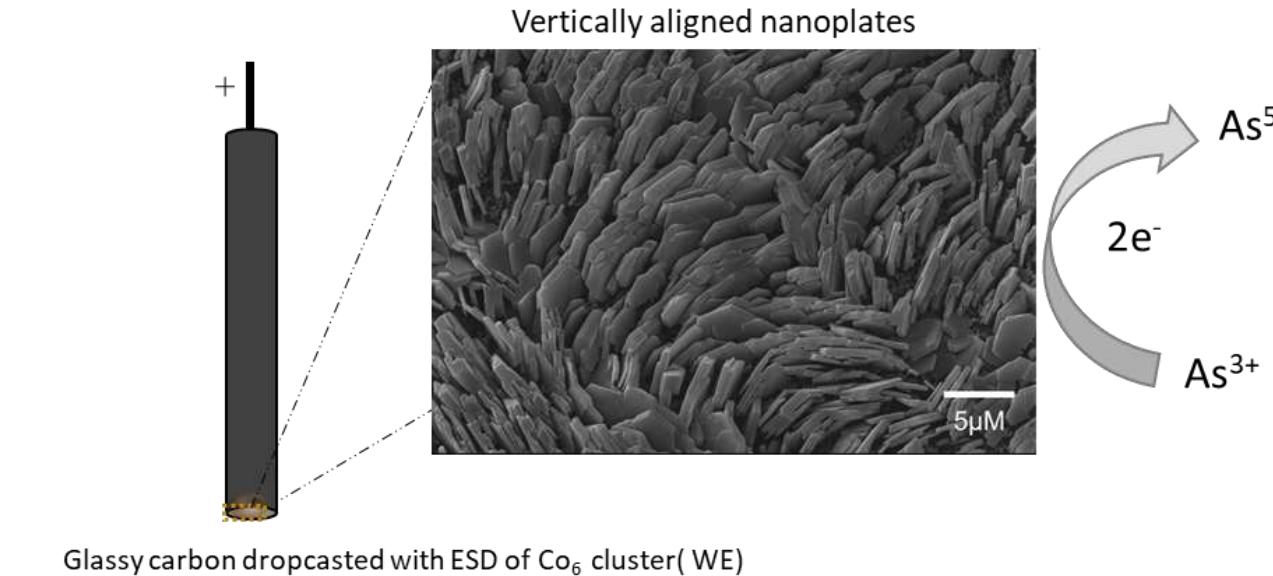
Electrospray deposition



Sensing



Working electrode

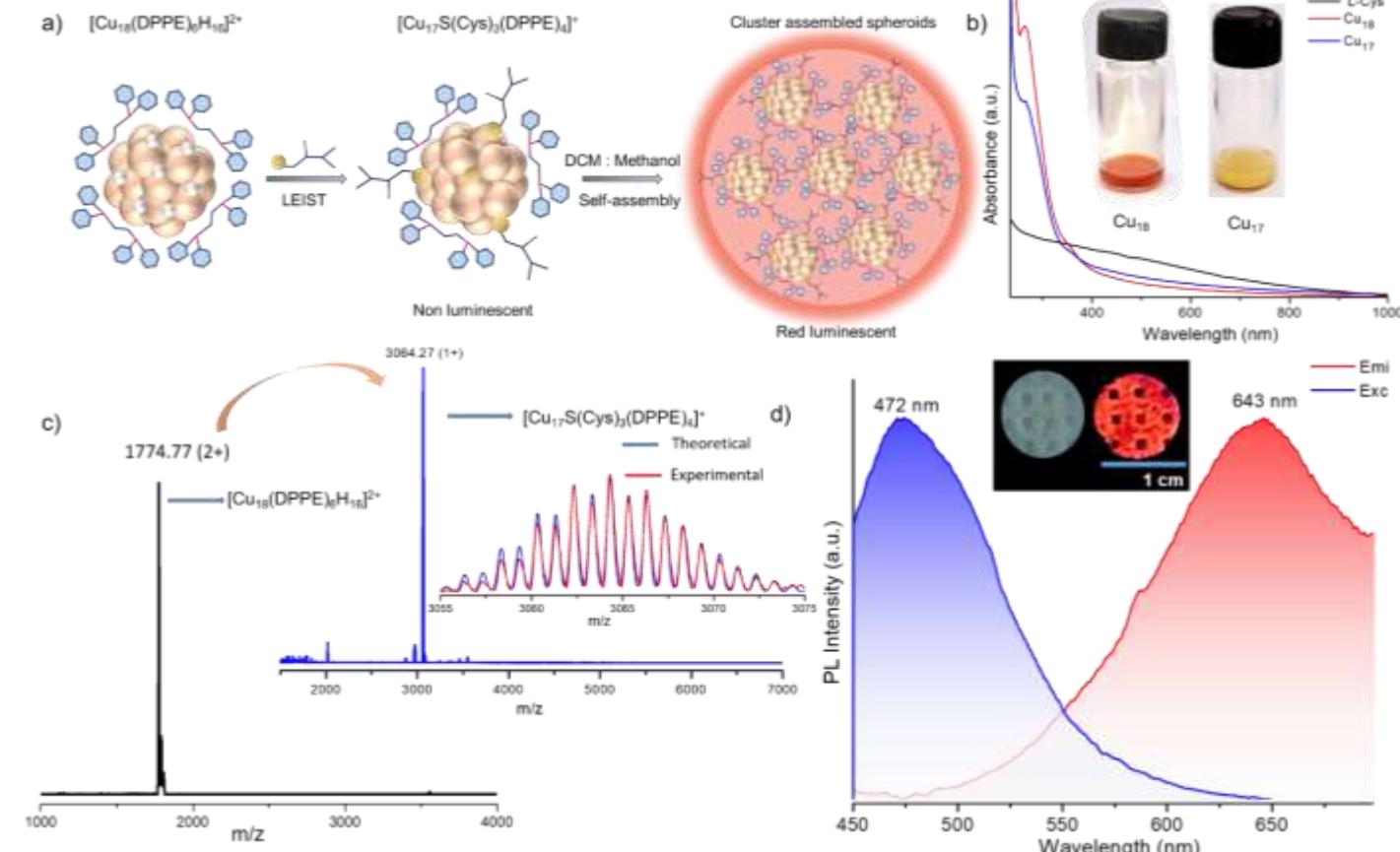
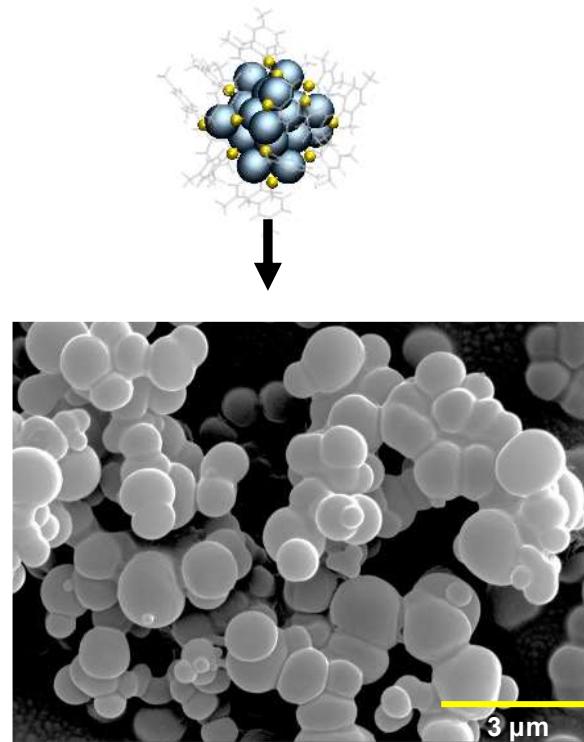


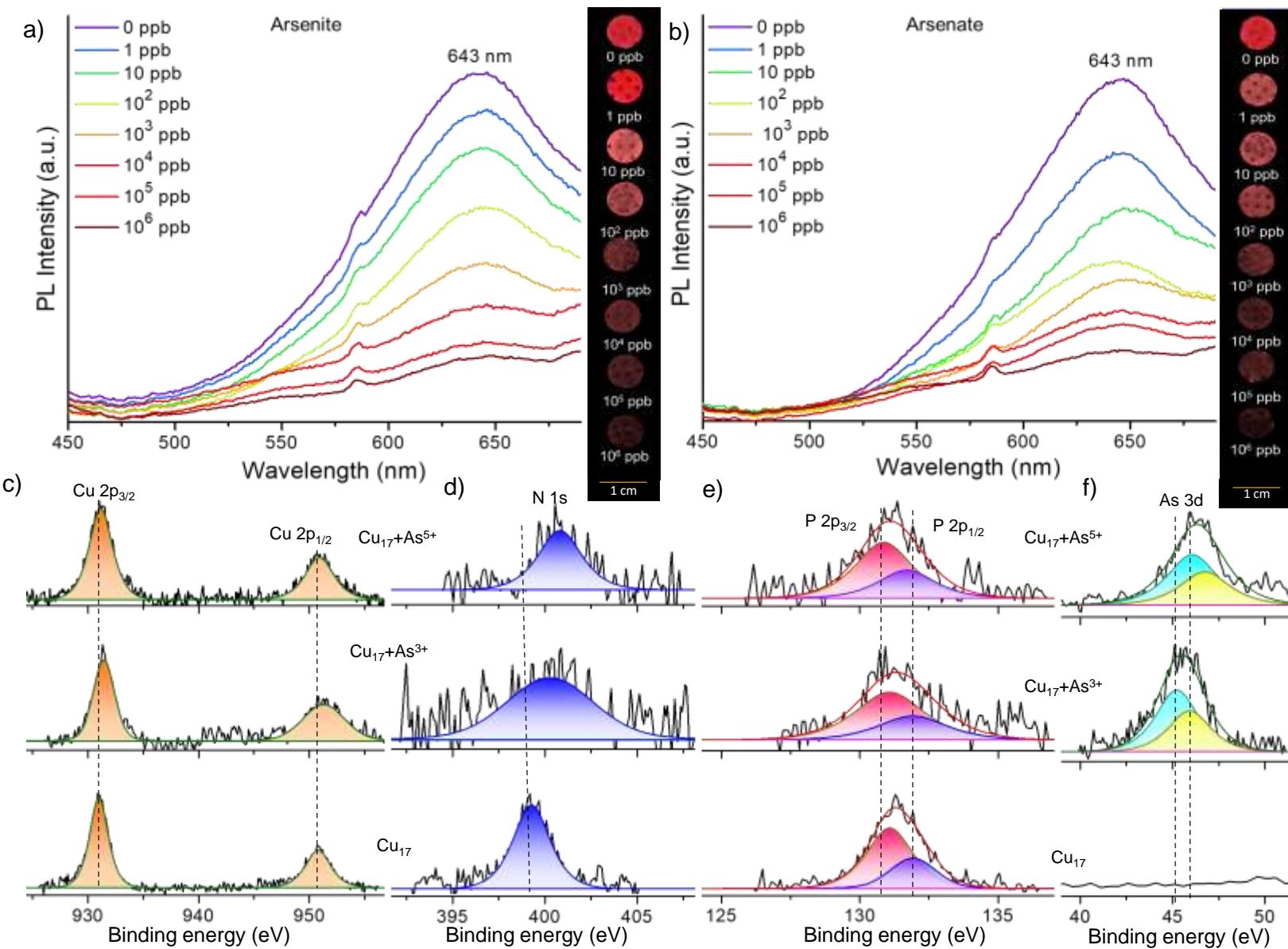
Cysteine-Protected Antibacterial Spheroids of Atomically Precise Copper Clusters for Direct and Affordable Arsenic Detection from Drinking Water

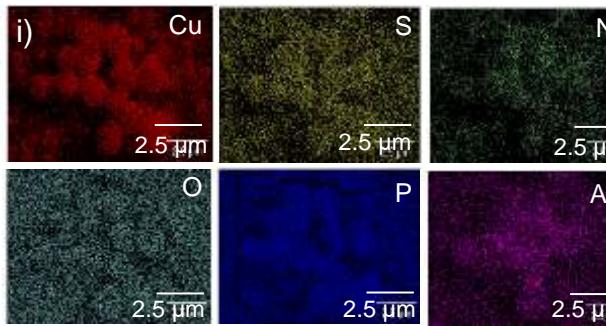
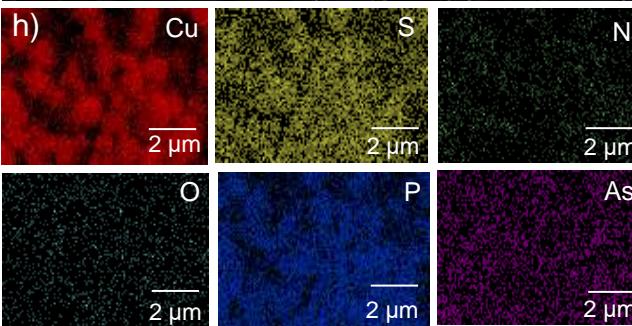
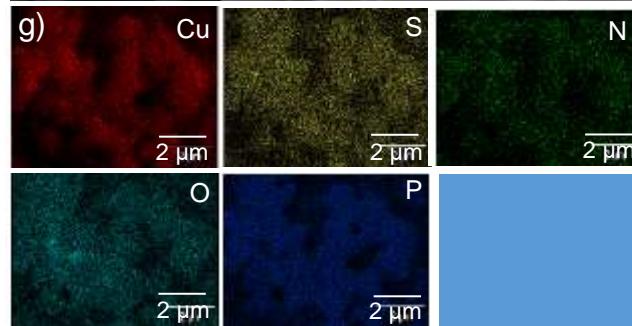
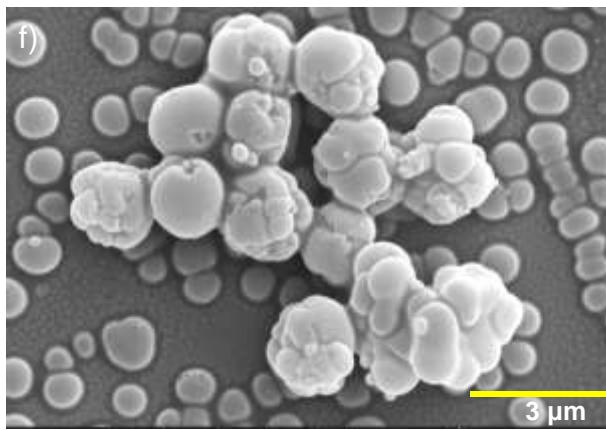
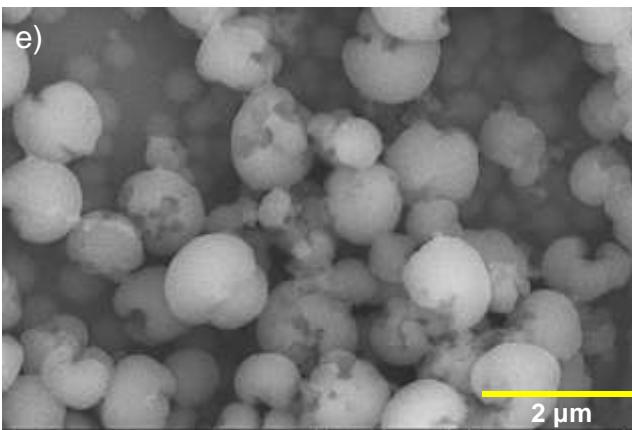
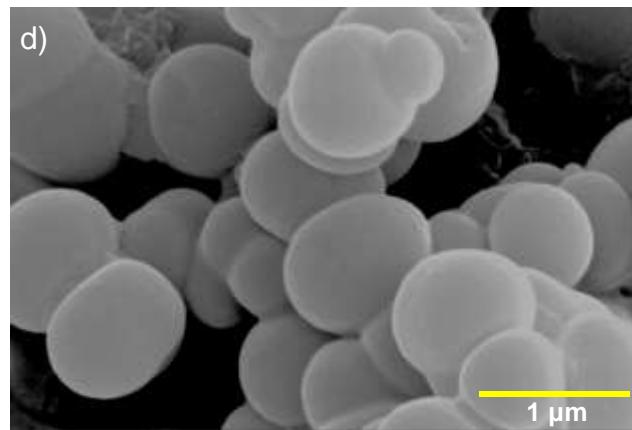
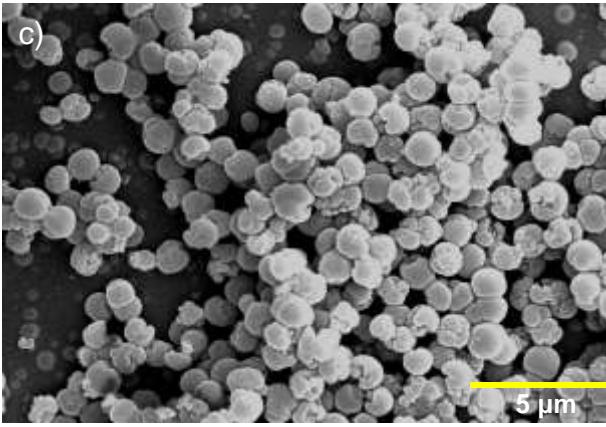
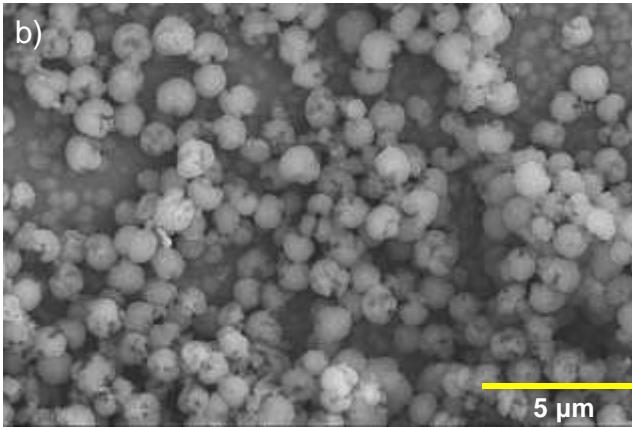
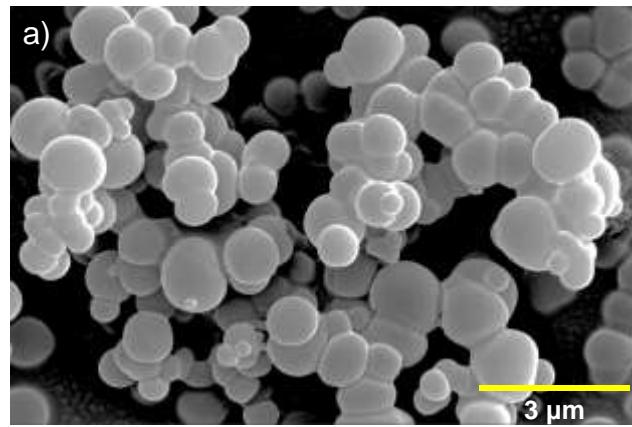
Jenifer Shantha Kumar, Arijit Jana, Jayathraa Raman, Hema Madhuri Veera, Amoghavarsha Ramachandra Kini, Jayoti Roy, Saurav Kanti Jana, Tiju Thomas, and Thalappil Pradeep*

Cite This: <https://doi.org/10.1021/acs.estlett.4c00264>

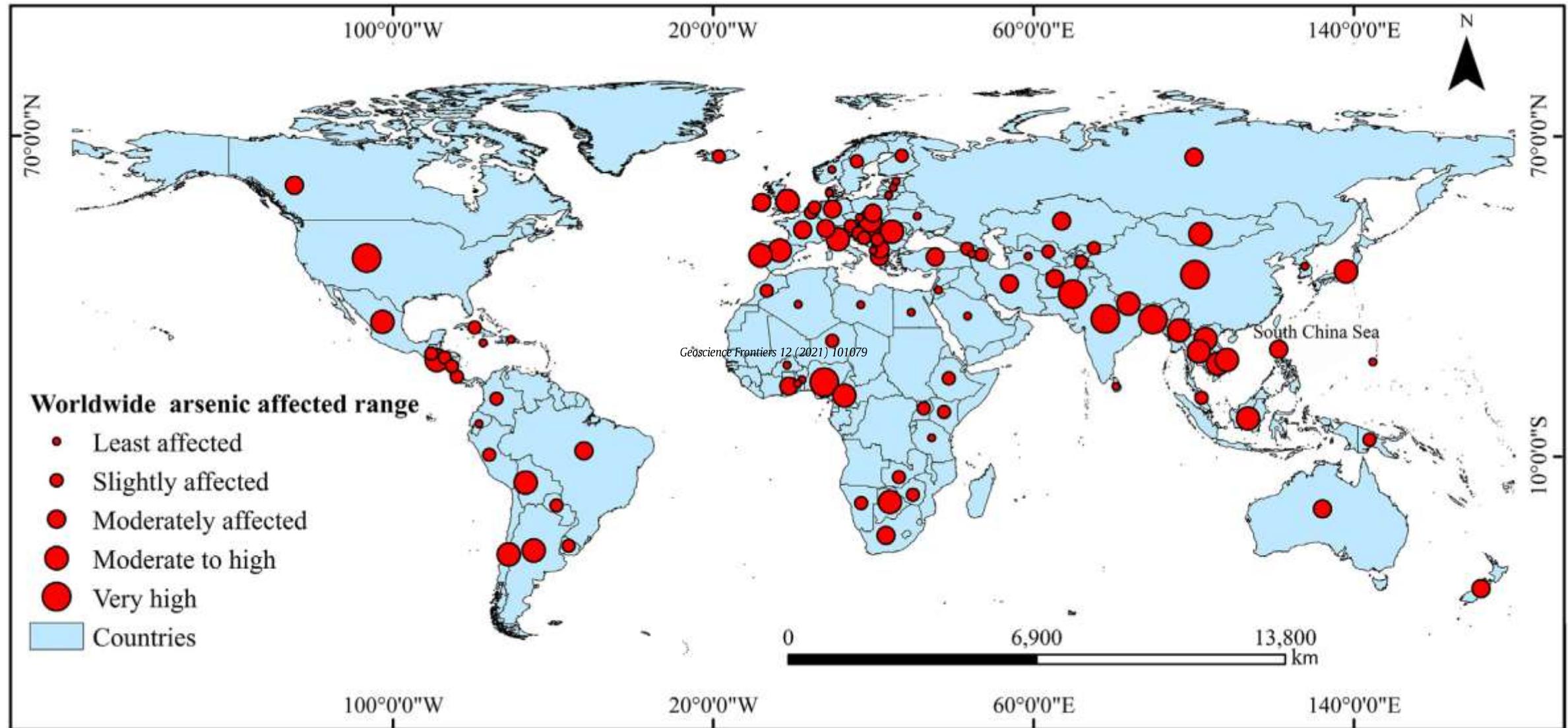
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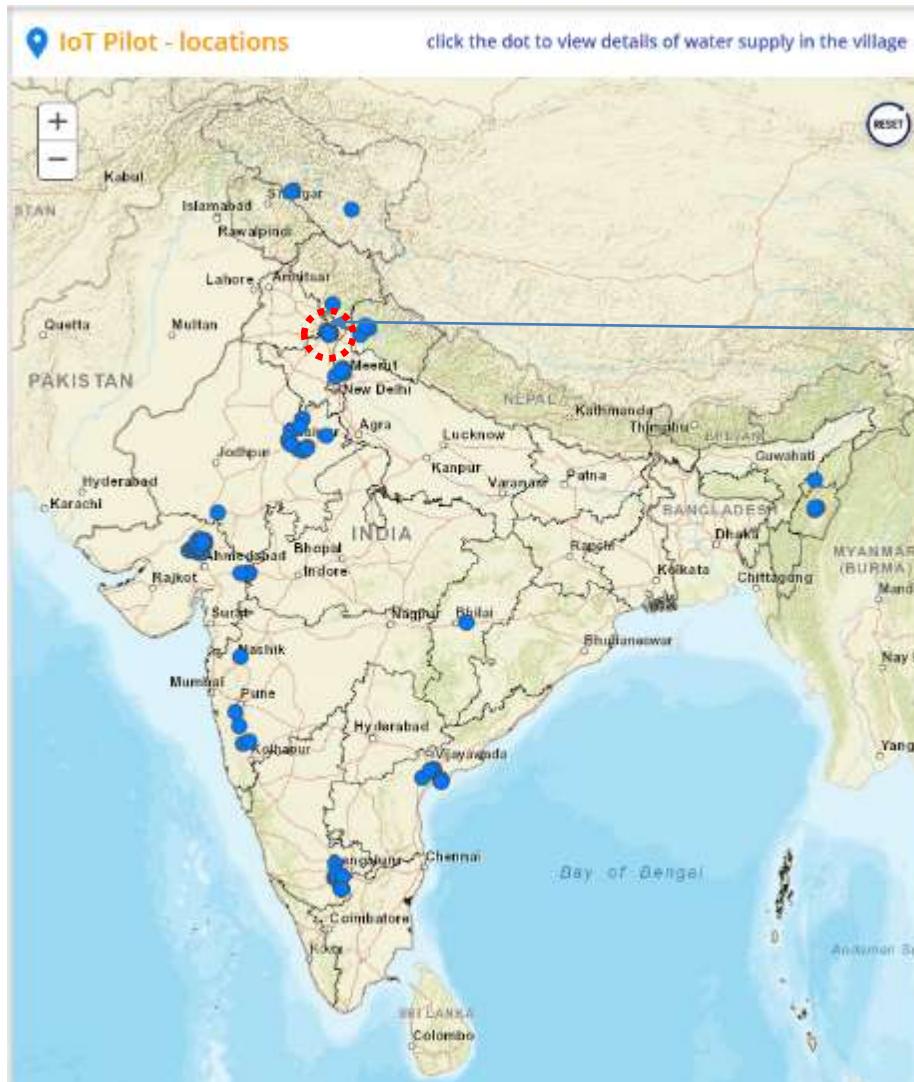


Arsenic poisoning across the world



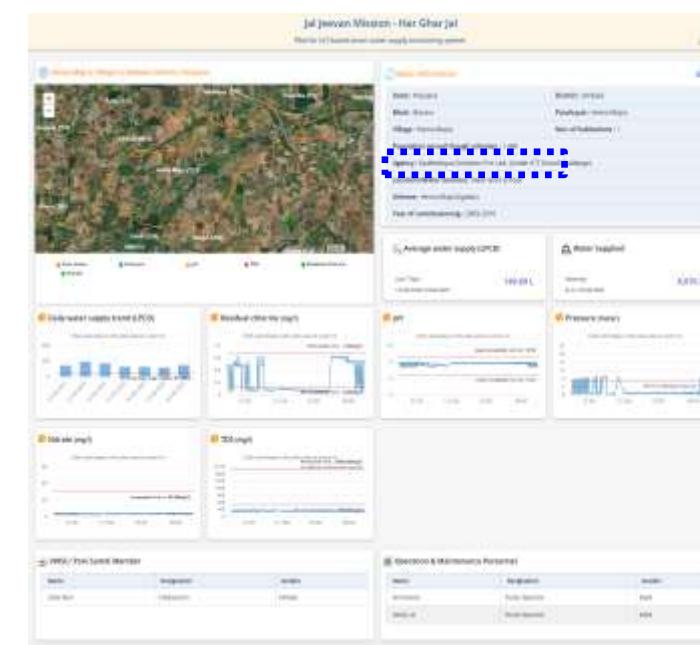


India's water is being monitored



IITM/IISc

Installations made by four companies





Can Water Microdroplets Make Soil?

A path to sustainable nanotechnology

Science



RESCUE-01

NANOPARTICLES

Sporadic weathering of natural minerals in
charged water microdroplets forms nanomaterials

✉ E. K. Sponholz¹, Mayankita Lahiri², Pratibh Ghosh¹ Arindra Nageswaran³, V. Venkateswaran², Thejaswi Pratap^{1,3*}

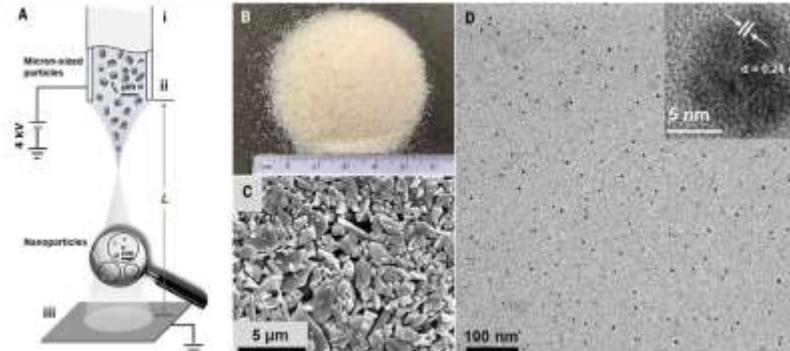
In this work, we show that particles of common minerals break down spontaneously to form nanoparticles (shape-preserved microspheres) within milliseconds. We find nano-crystalline mineral fragments transform into 5-15-nanometer particles when exposed to aqueous microdroplet potential via electrospray. We designed the droplet as a substrate, which allows nanoparticle chain formation. We determined through simulations that quartz undergoes preferential cleavage, especially when natural and exposed to an electric field. This leads to particle co-solutes and the formation of acidic fragments, which are confirmed via mass spectrometry. This rapid weathering process may be important for soil formation, given the prevalence of charged minerals in the landscape.

NATIONALISTS of various sorts have sprung up in the 1970s, and state-of-the-art state-nationalists are no exception [1]. In this article, I shall look at one such state-nationalist, the Tamil Nationalist Party (TNP), and examine its political philosophy, its political activities, and its political influence.

For our experiments, we prepared stable-atomized oil-in-water emulsion (EW1) and using $(\text{Co}-\text{ammonium})_2\text{P}_2\text{O}_7$ for stable emulsion-catalyzed emulsion (EW2, *i.e.*, emulsified oil-in-water emulsion) (Fig. 1, *i.e.*, B). Prepared emulsion is stable-atomized emulsion for industrial oil-in-water emulsion.

Another study provided similar results using *Escherichia coli* as the indicator. When *Escherichia coli* and *Escherichia coli* O157 were added to 10 g of soil, the *Escherichia coli* O157 was reduced to 5 x 10³ cfu/g after 10 min of soil treatment. However, for *Escherichia coli* O157, 10% of the *Escherichia coli* O157 was reduced after 10 min of soil treatment. When *Escherichia coli* O157 was added to 10 g of soil, the *Escherichia coli* O157 was reduced to 5 x 10³ cfu/g after 10 min. This study differing from the previous study, probably because the *Escherichia coli* O157 used in this study was a different strain of *Escherichia coli* O157.

The determined Cr^{2+} MMT intercalation products firmly intercalated with the galleries, were potassium and ammonium salts. Single layered MnO_2 nanosheets were obtained by the same route of the synthesis. The intercalated 1 nm of the intercalated MnO_2 nanosheets were obtained. The MnO_2 1 nm intercalated MnO_2 nanosheets were obtained by the same route of the synthesis. The intercalated 1 nm of the intercalated MnO_2 nanosheets were obtained.



Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India; Theoretical Sciences Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560064, India; International Centre for Green Value, IIT Madras Research Park, Chennai 600113, India

A scale of 1000

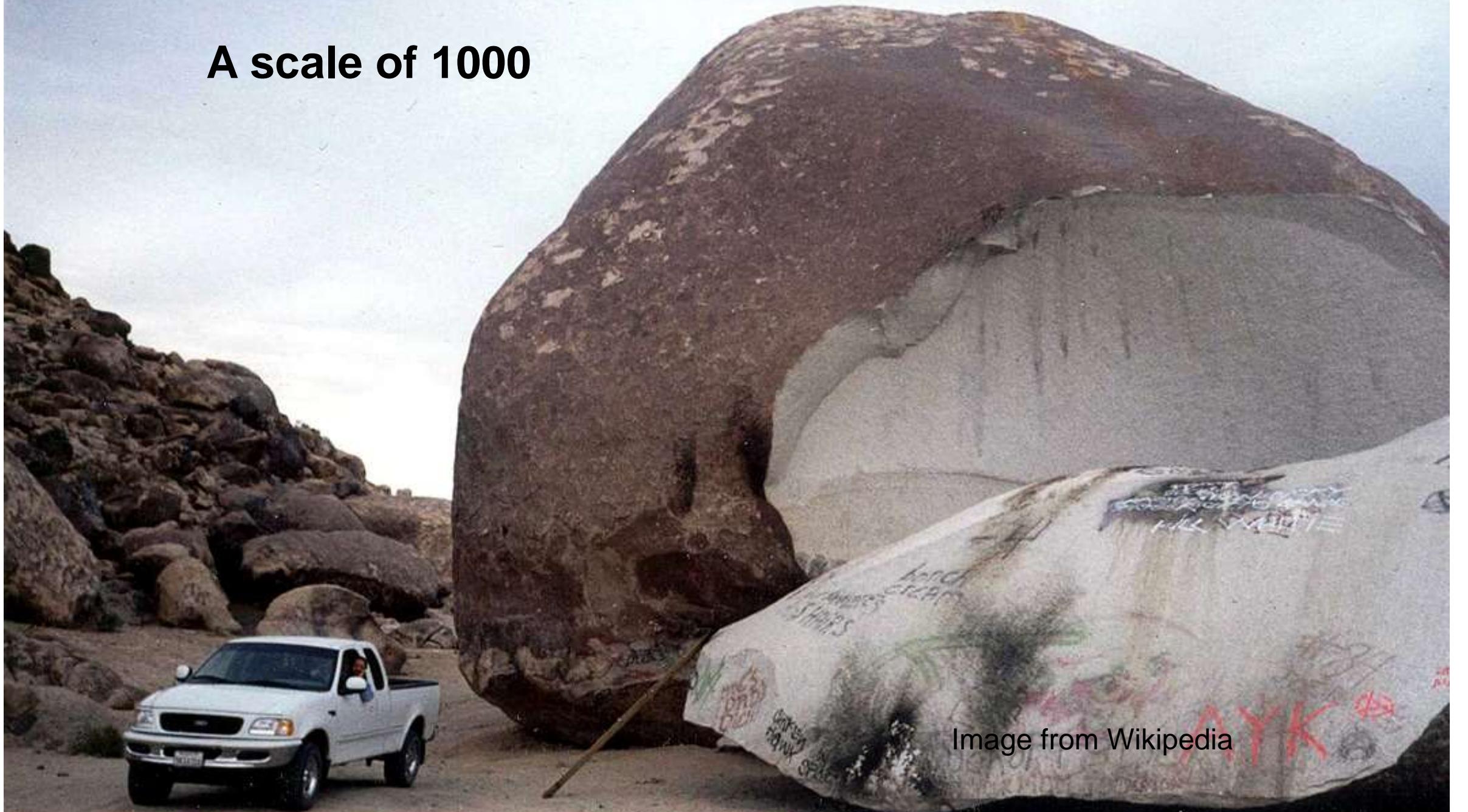
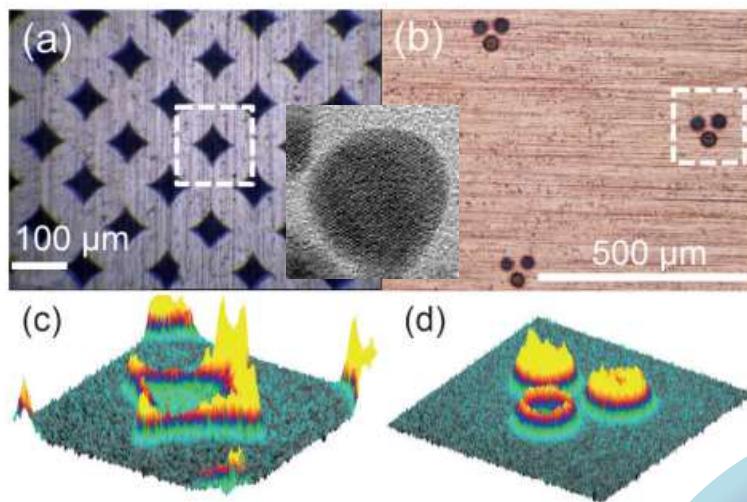
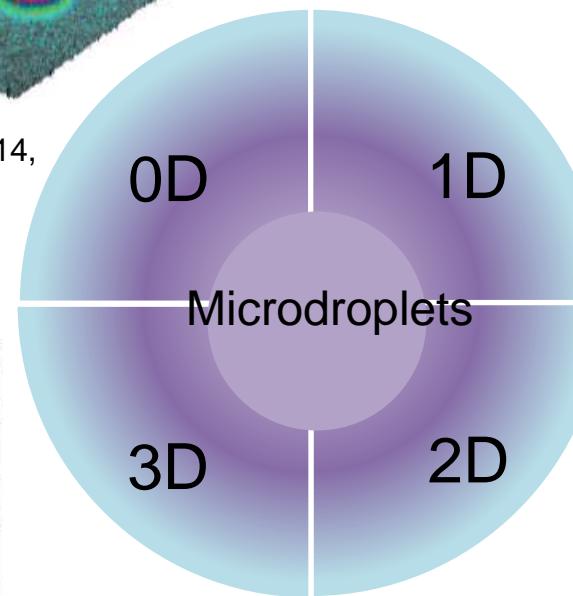
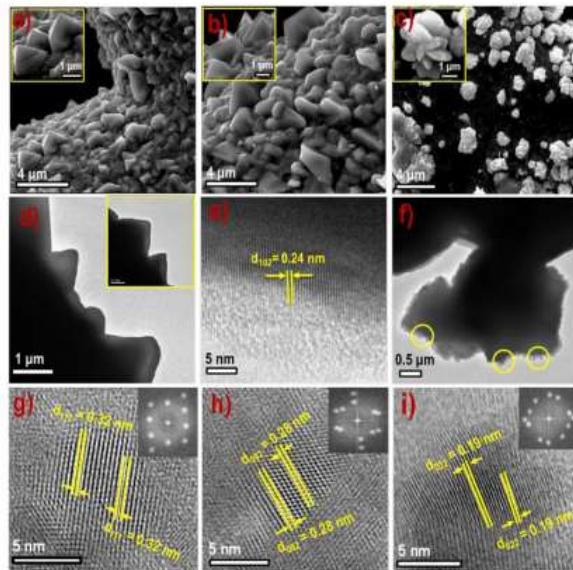


Image from Wikipedia

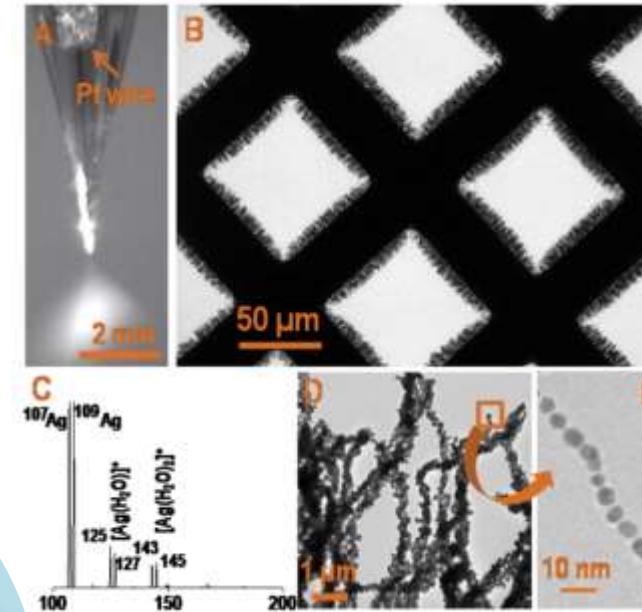
Functional Nanomaterials



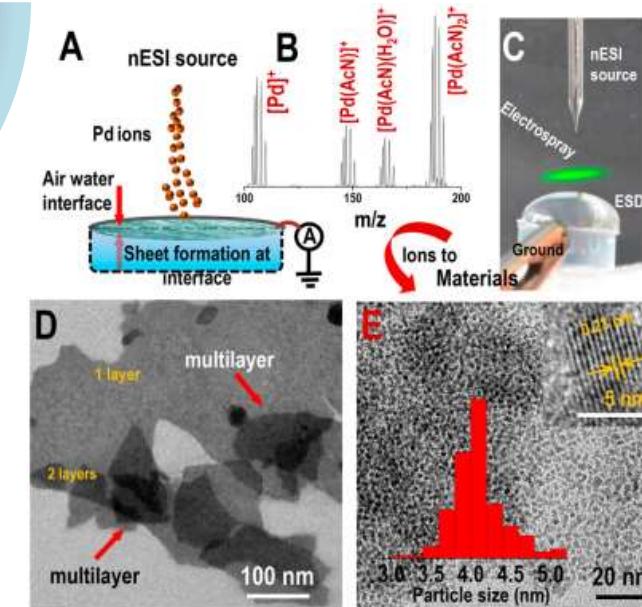
Anyin Li, et. al., *Angew. Chem. Int. Ed.* 2014, 53, 12528 –12531.



Arijit Jana et. al., *J. Mater. Chem. A*, 2019, 7, 6387–6394.



Depanjan Sarkar et. al., *Adv. Mater.* 2016, 28, 2223–2228.



Depanjan Sarkar, et. al., *J. Phys. Chem. C* 2018, 122, 17777–17783.



Chemical Science

rsc.li/chemical-science

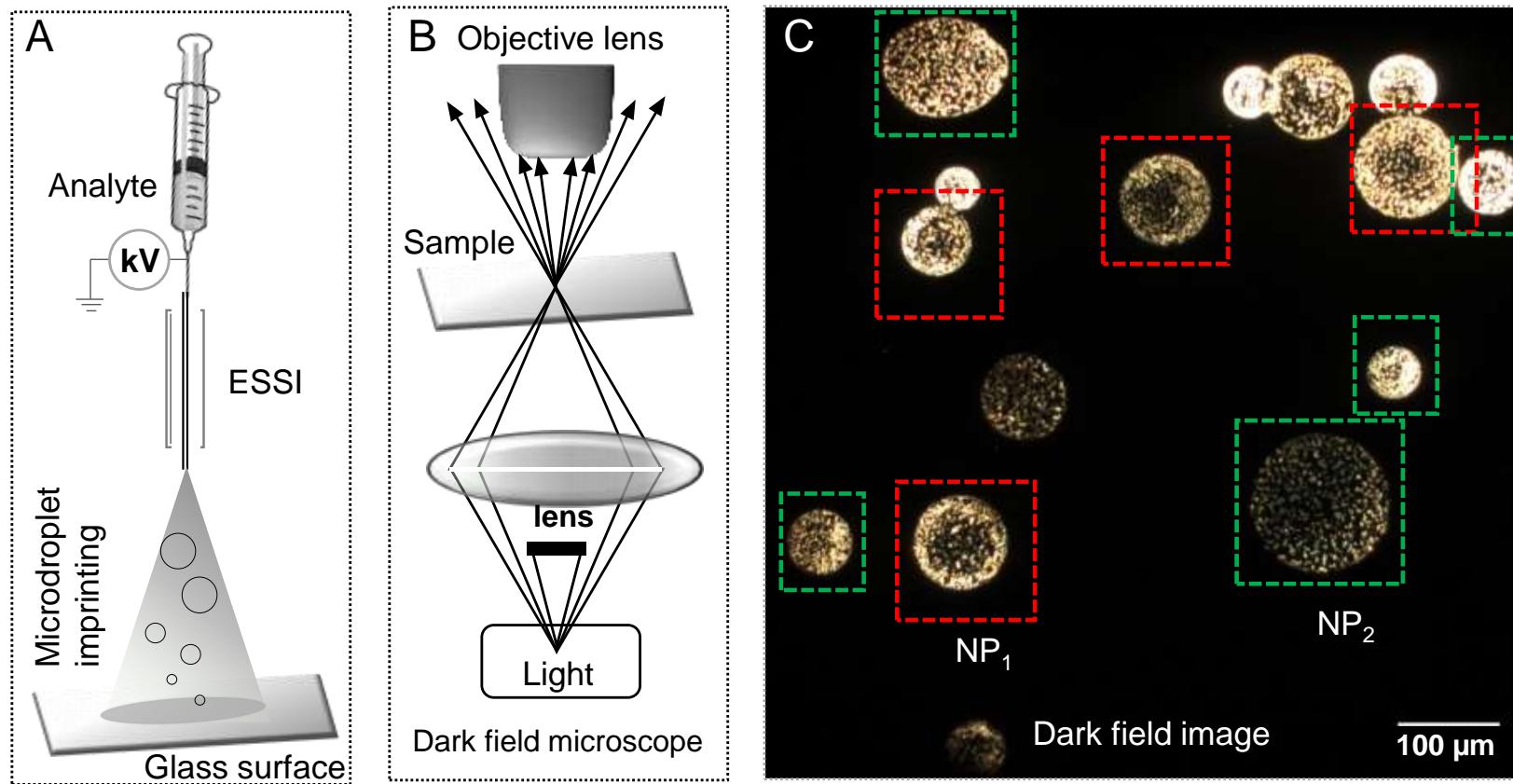


ISSN 2041-6539

EDGE ARTICLE

Thalappil Pradeep *et al.*
Spatial reorganization of analytes in charged aqueous
microdroplets

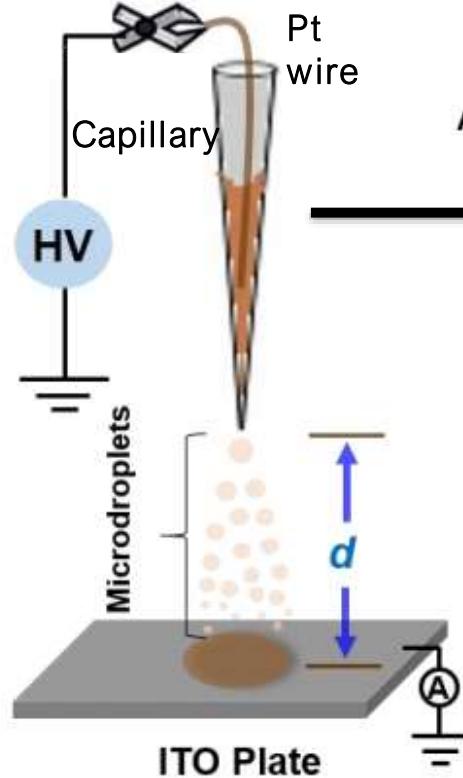
Understanding Microdroplets



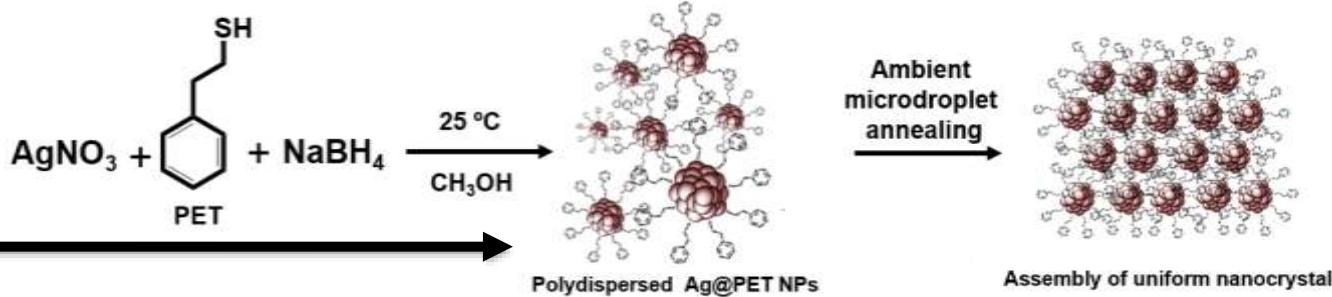
Transformation of Materials in Microdroplets

Ambient Microdroplet Annealing of Nanoparticles

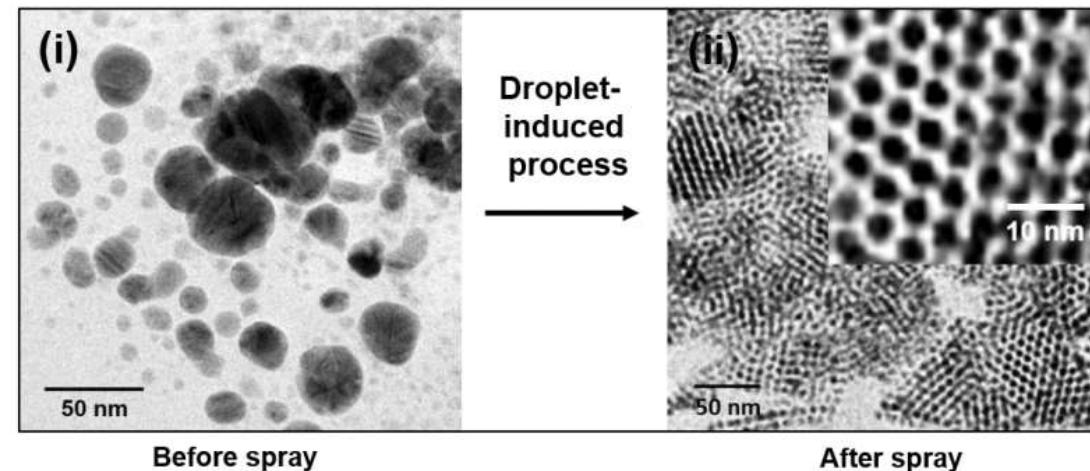
Experimental set-up



Synthesis of polydisperse NPs



Transformation process





Thanks to ChatGPT

Weathering in Nature

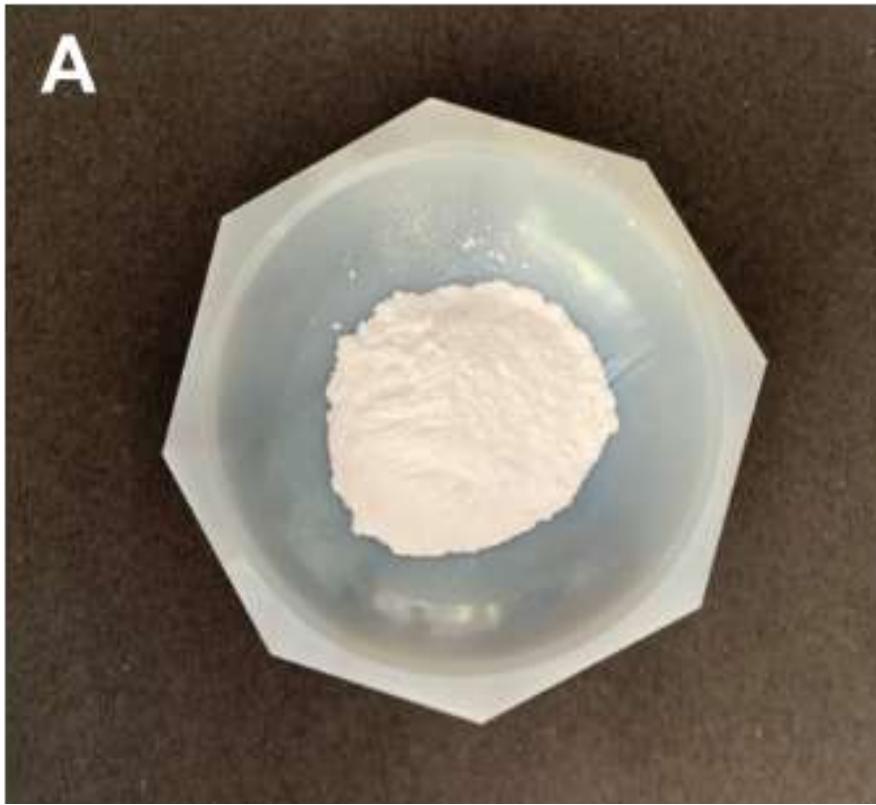


Sand, the Ubiquitous Material

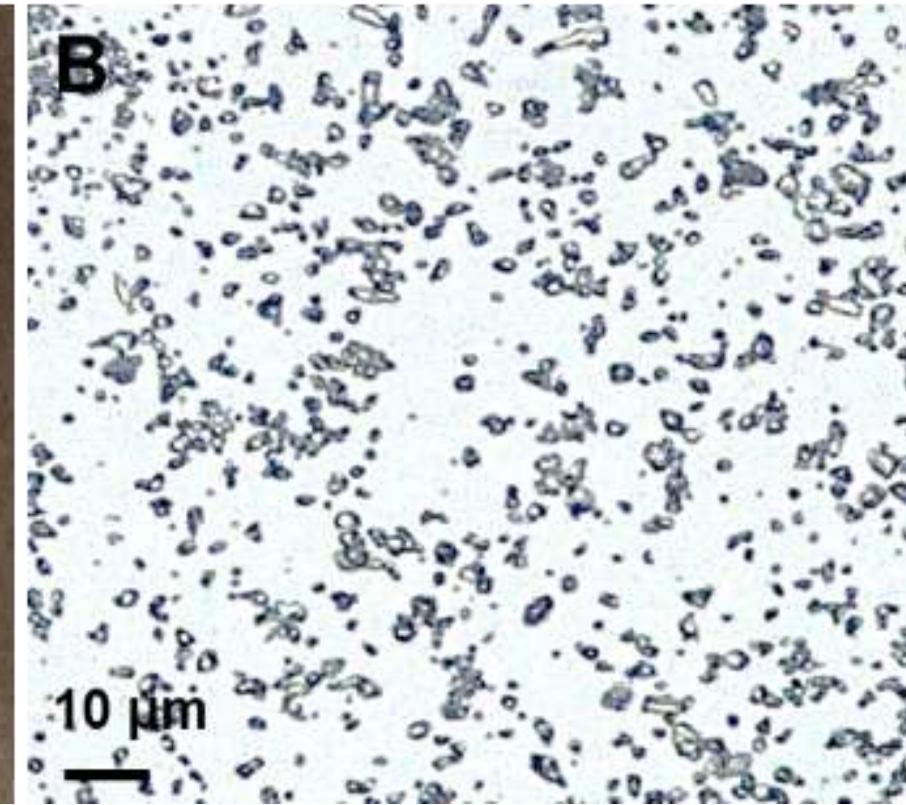


Images from Wikipedia



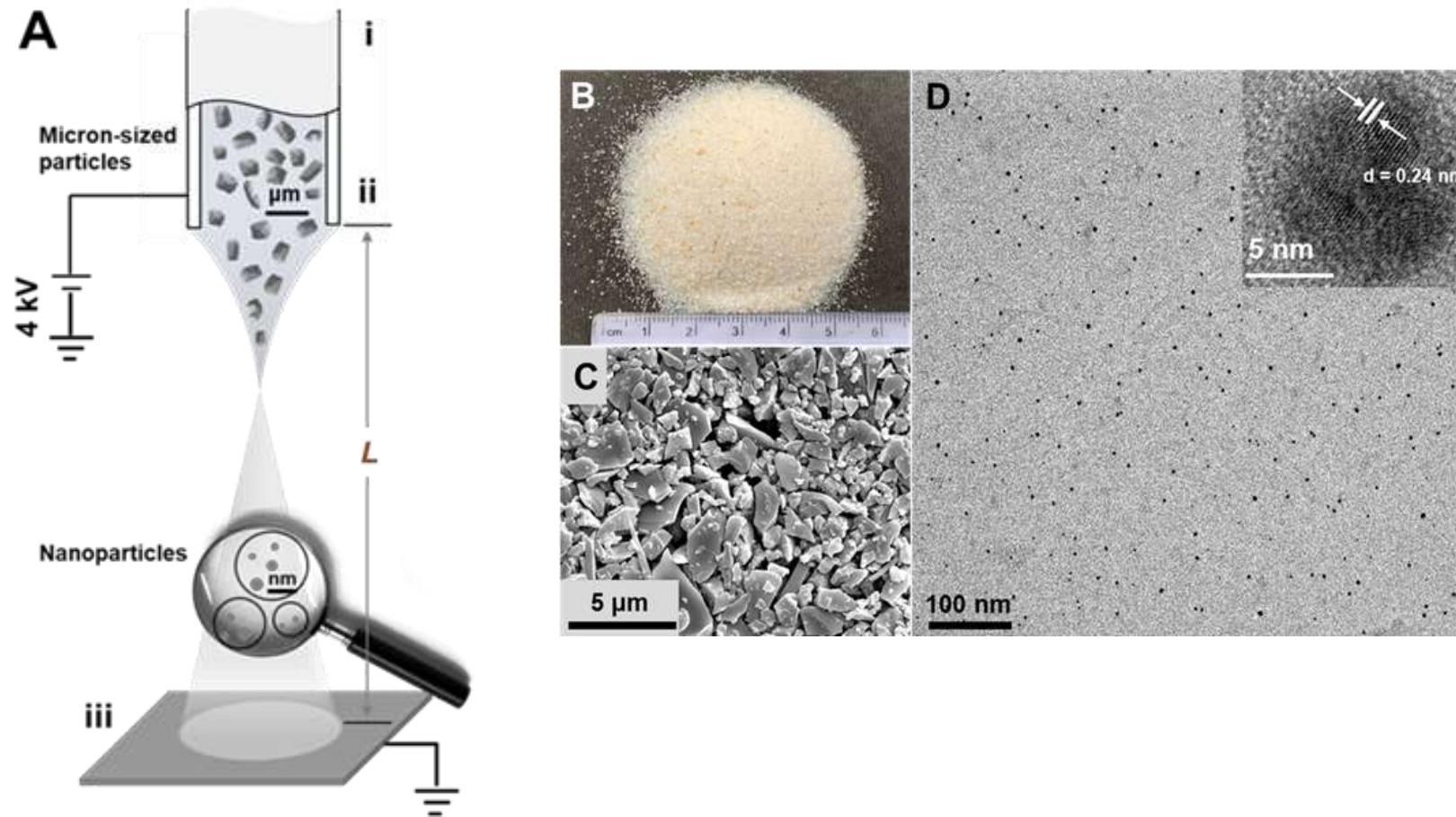


Ground silica

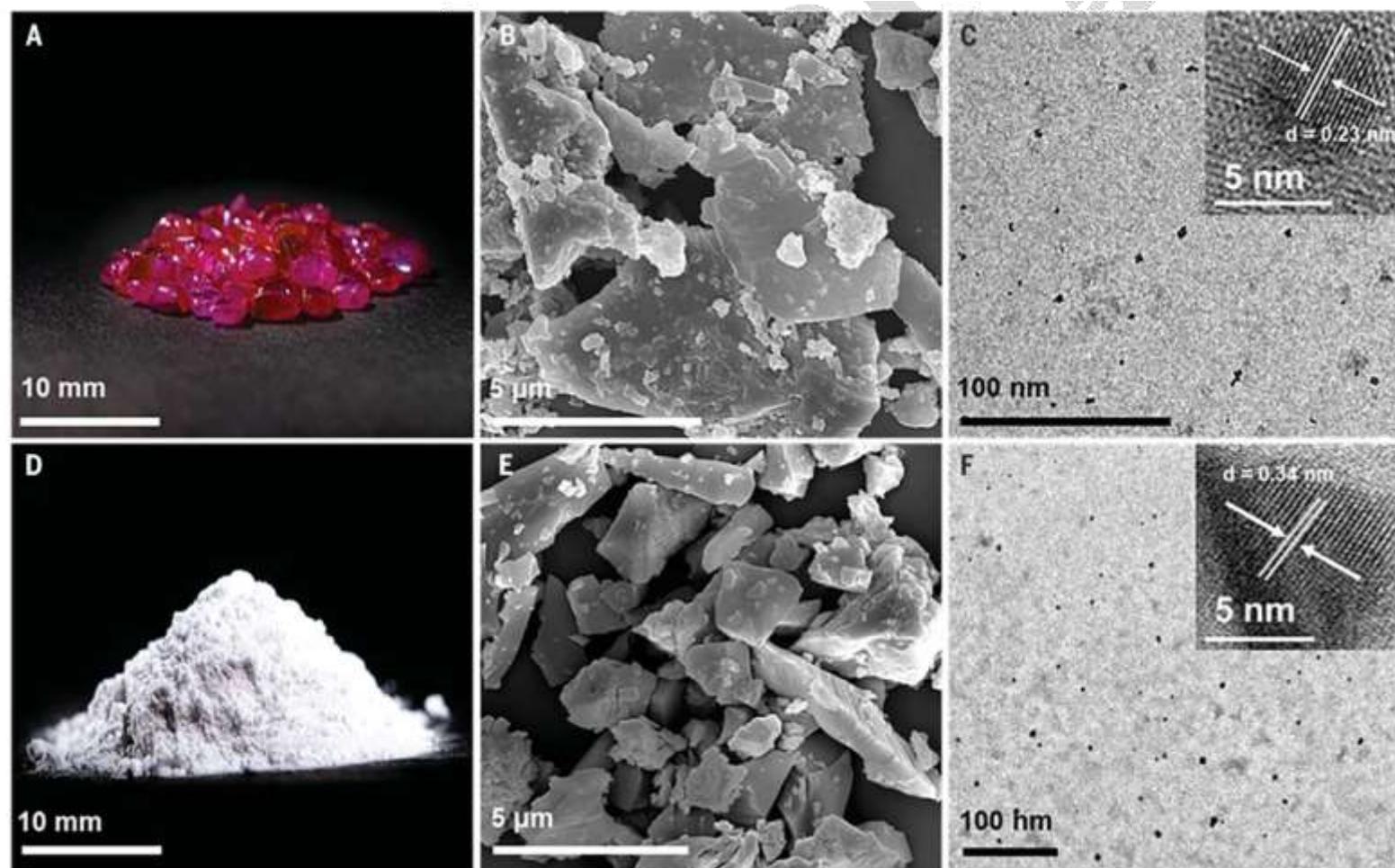


Optical image of silica

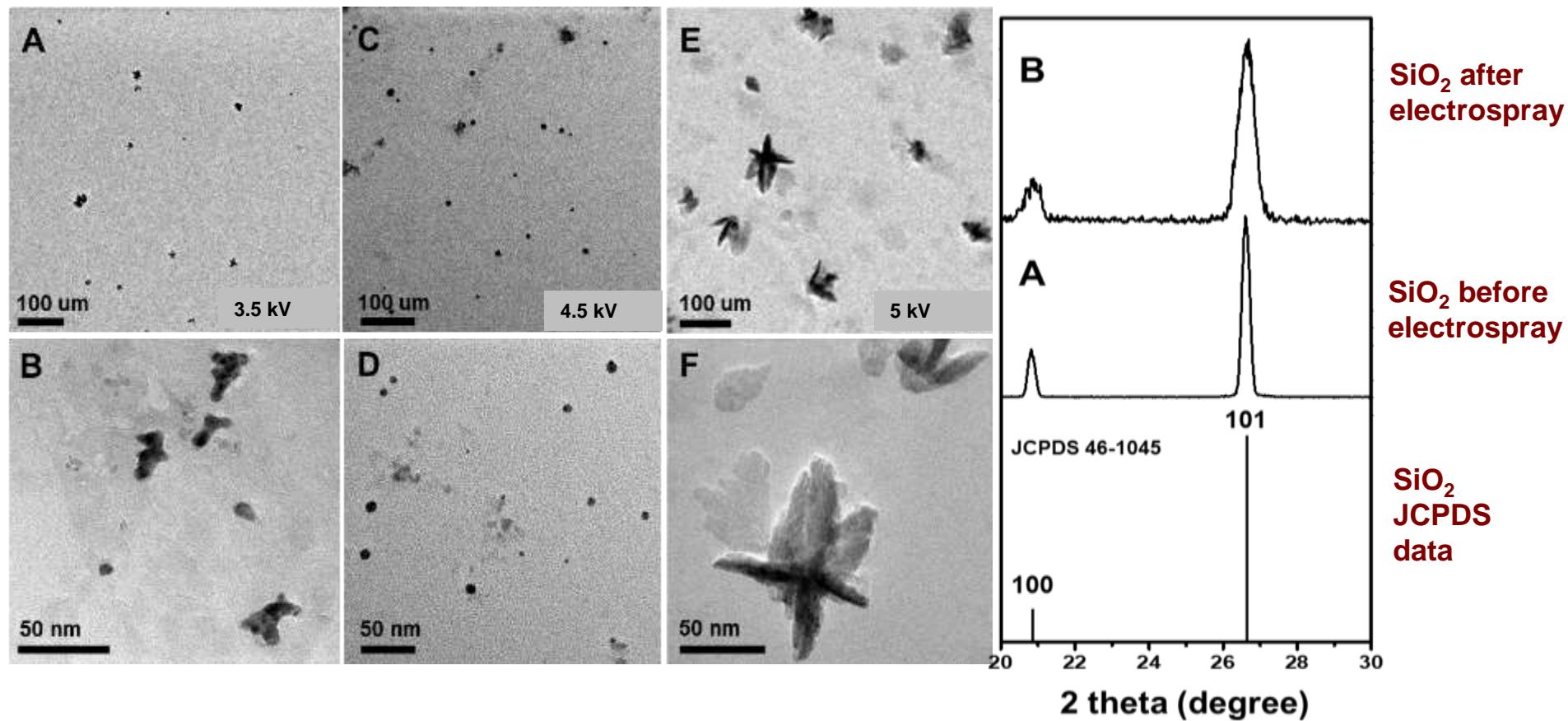
Weathering of Minerals in Microdroplets



Ruby, Fused Alumina

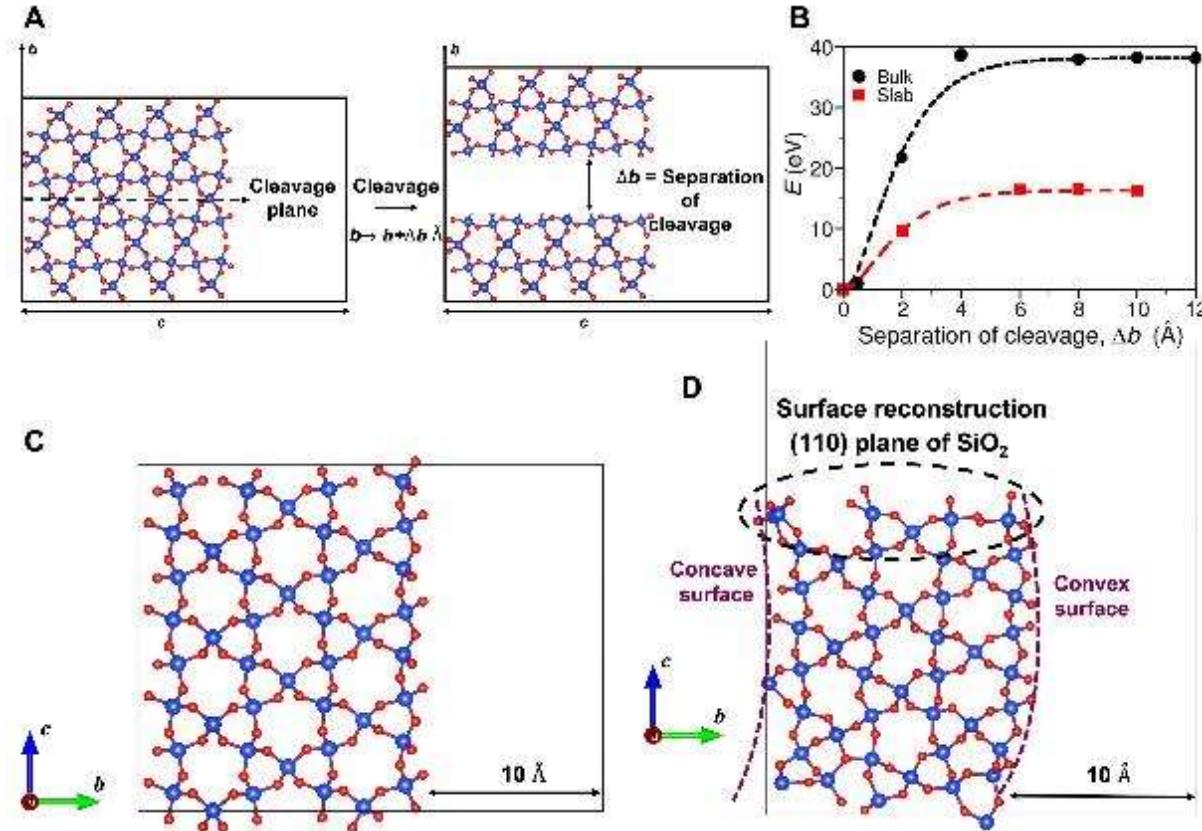
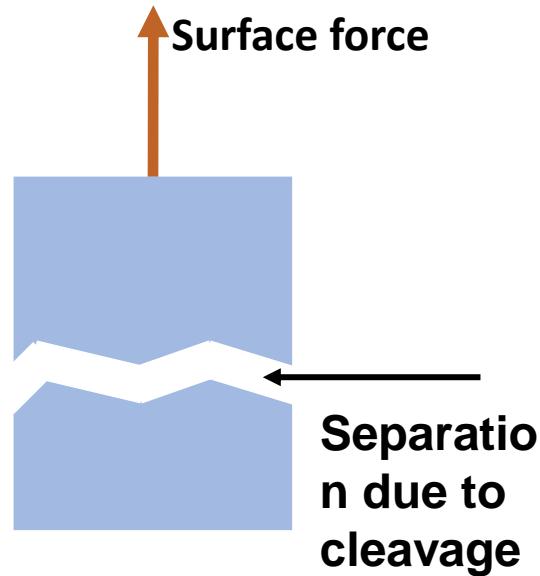


Fragmentation of Silica – Varying Conditions

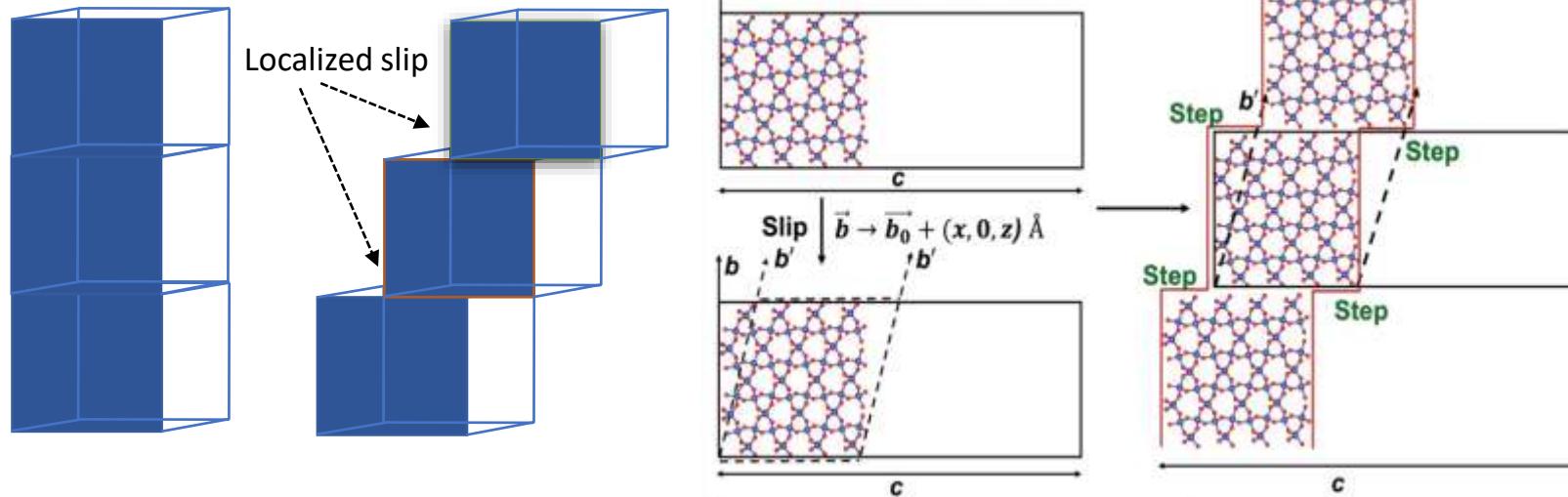


Mechanism: Cleavage

The process of cleavage and surface reconstruction visualized with first-principles simulations



Mechanism: Slip



This instability leads to the formation of a stacking fault on the (010) plane, achieved with slip localized at (010) plane

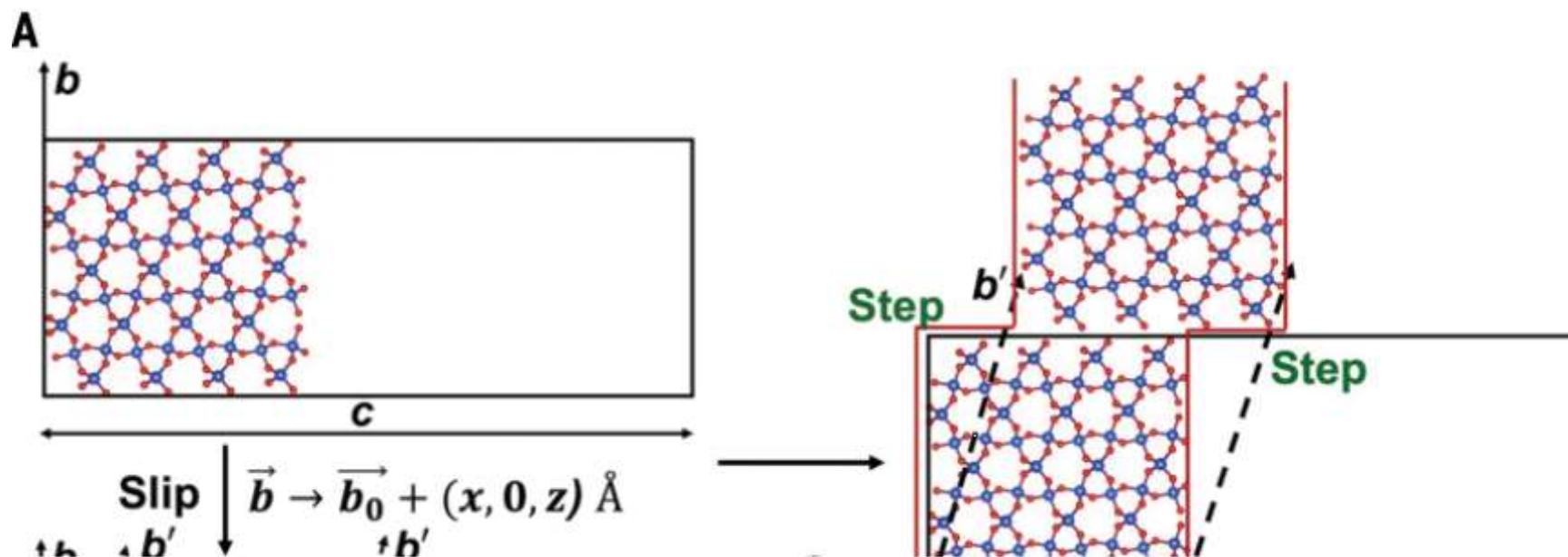
Stacking fault

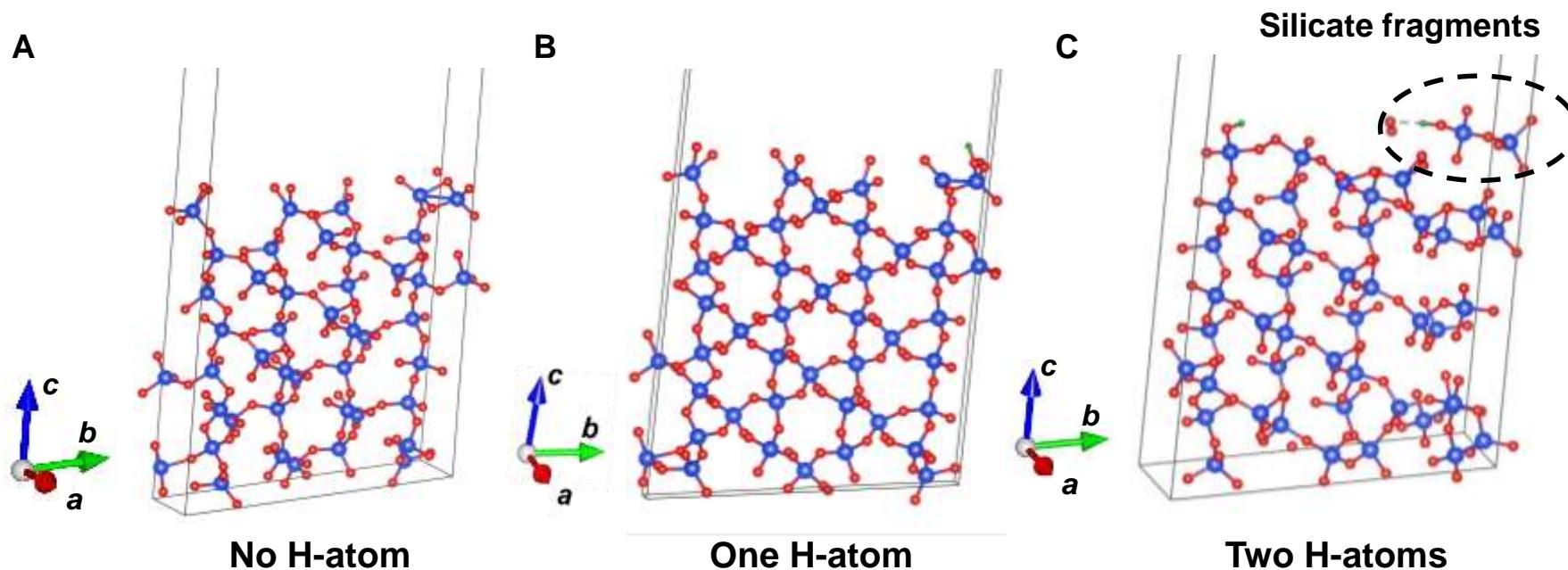
$$\vec{b} \rightarrow \vec{b}_0 + (x, 0, z),$$

$(x, z \in [0,1])$ - fractional coordinates

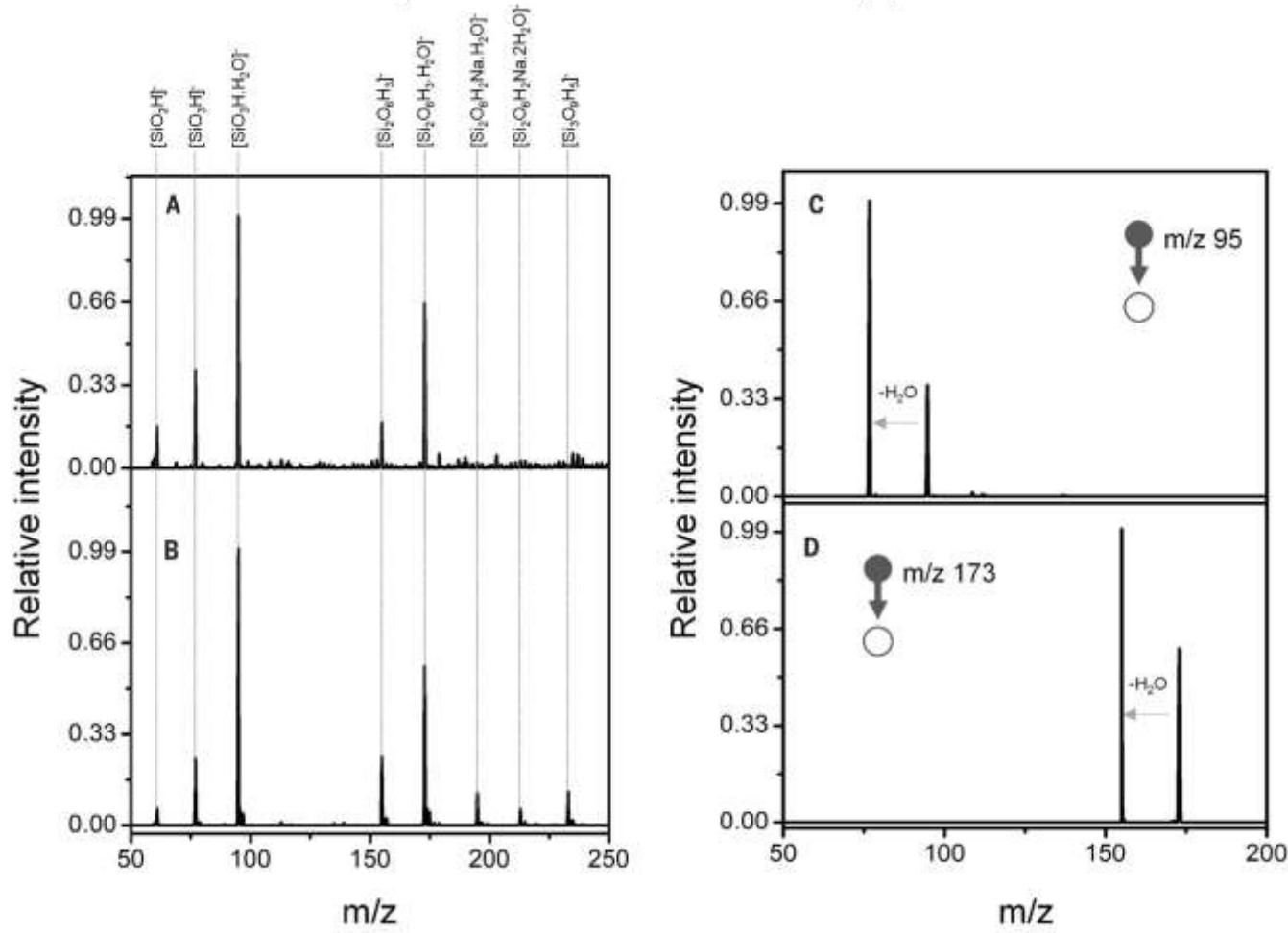
SFEs of (010) direction with (0, 0), (0, 0.5), (0.5, 0) and (0.5, 0.5) slip configurations on the (110) plane of SiO_2

SFE (J/m^2)	Slab					
	x	z	w/o H-atom	1 H-atom	2 H-atoms	E
0.0	0.0	0.0	0	0	0	0
0.5	0.5		-1.21	-0.93	-0.88	-1.20
0.5	0.0	0.0	1.20	1.18	0.90	1.12
0.0	0.5		-0.07	0.89	-0.83	-0.09

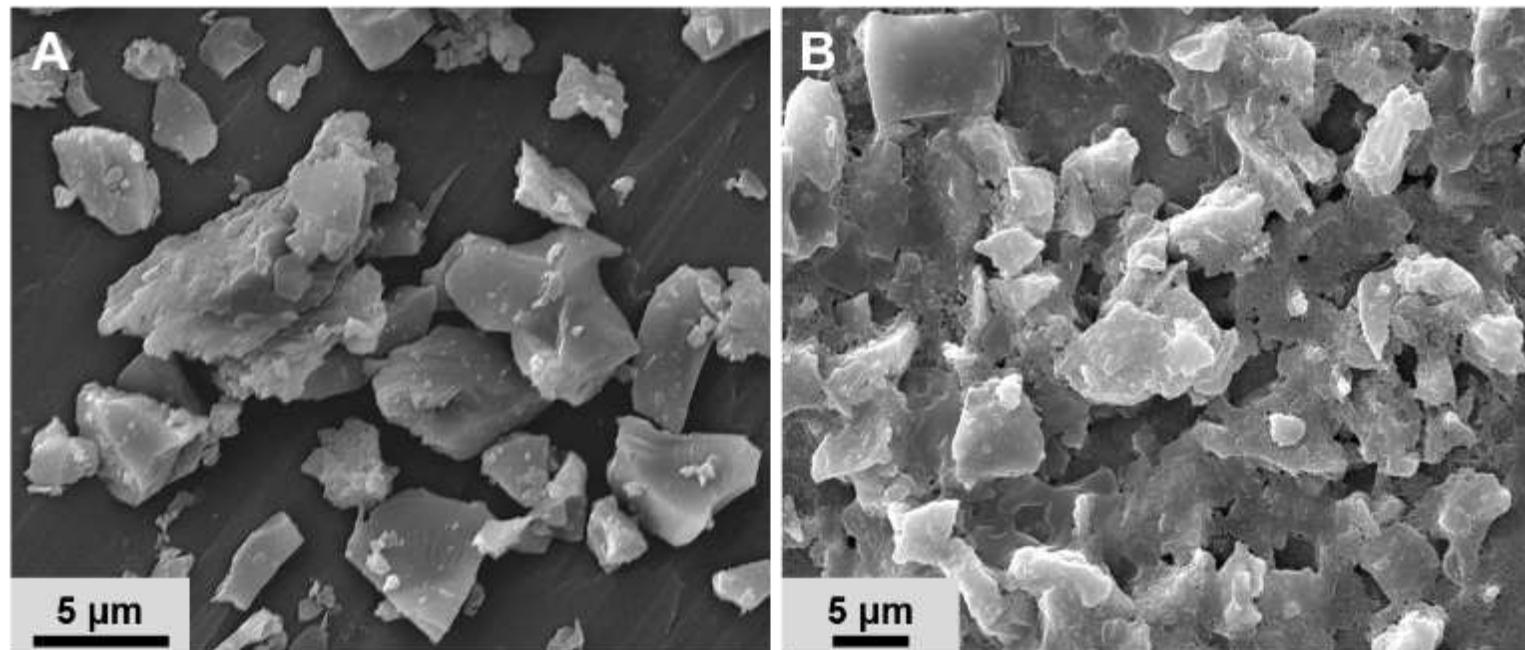




Mass Spectrometry of the Fragments

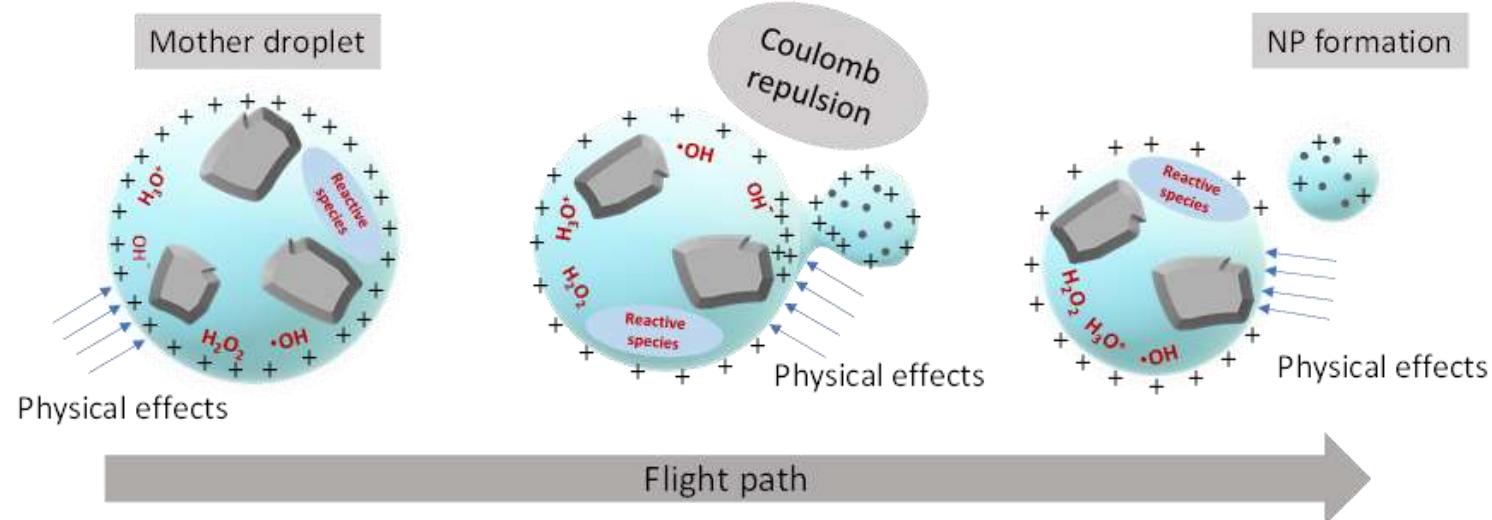


Effect of charged microdroplets on quartz



Increased surface roughness after the spray

Mechanism of nanoparticle formation



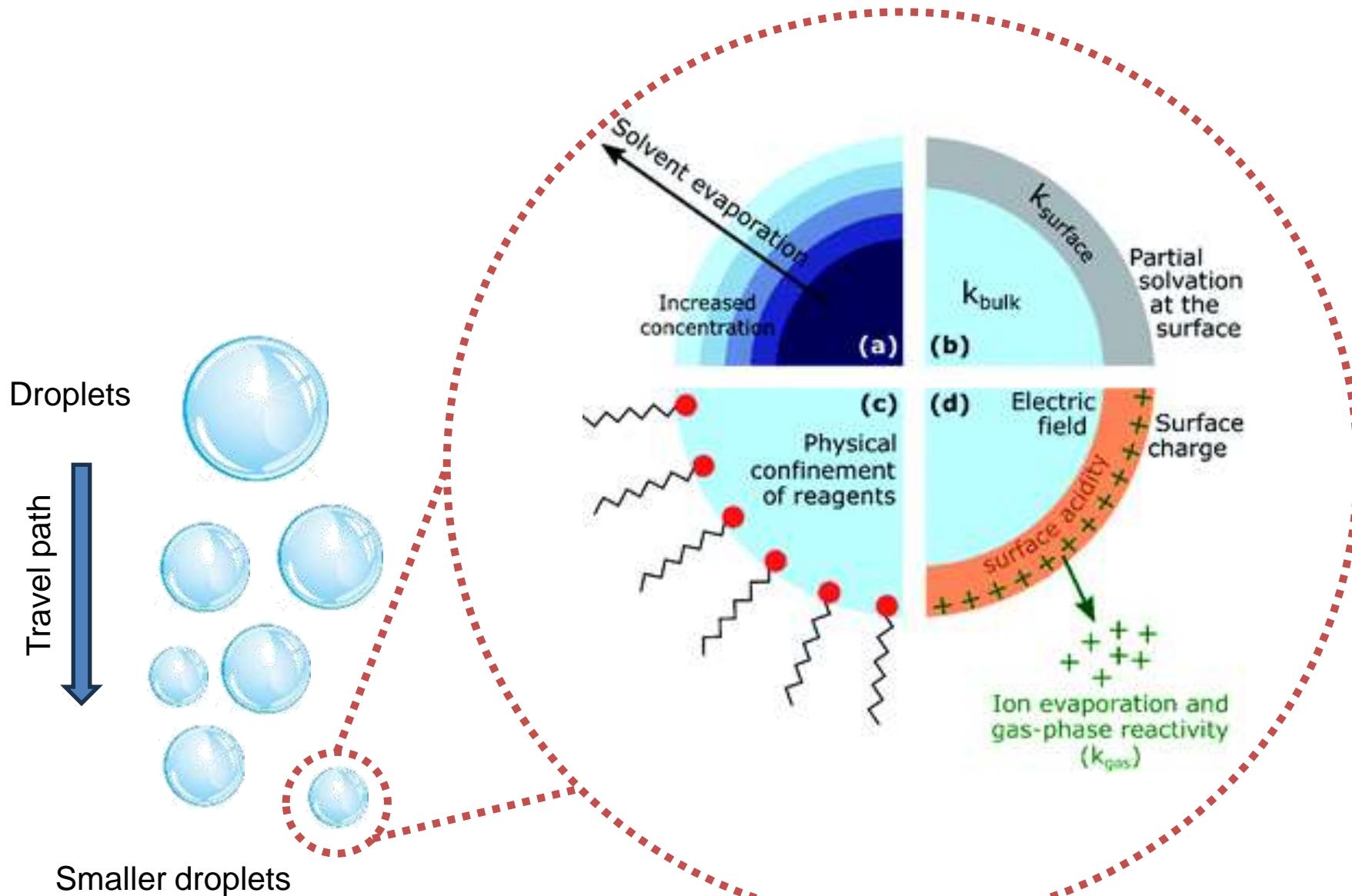
Rayleigh, On the
equilibrium of liquid
conducting masses
charged with electricity,
Philosophical Magazine,
1882

$$Q = 8\pi (\epsilon_0 \gamma R^3)^{1/2}$$



Image from Wikipedia

Understanding Microdroplets



Breaking down microdroplet chemistry

Charged microdroplets accelerate mineral disintegration

By R. Graham Cooks and Dylan T. Holden

Charged microdroplets are commonly observed in clouds, sea spray, and other natural aerosols. The chemistry that occurs at the air-water interface of these droplets is often distinct from that observed in bulk solution, which is of considerable interest because chemical reactions can be accelerated at this boundary (1, 2). This may have implications for environmental processes such as the weathering of rocks, which contributes to soil formation. On page 1012 of this issue, Spoorthi *et al.* (3) report that micrometer-scale mineral particles can rapidly break down into nanoparticles when in charged aqueous microdroplets (see the figure). This points to a potential role for atmospheric water droplets in the natural disintegration of minerals.

To examine material degradation, Spoorthi *et al.* borrowed methodology used to accelerate bond-forming chemical reactions. By spraying an aqueous suspension of microparticles of natural minerals, the authors produced nanoparticles of minerals in high yield. Specifically, Spoorthi *et al.* used an electrospray device to emit a jet of liquid droplets (by applying high voltage) containing mineral particles of natural quartz, ruby, or synthetic alumina that ranged in size from 1 to 5 μm in diameter. The authors observed the production of nanoparticles that were 5 to 10 nm in diameter. Moreover, the fragmentation occurred in approximately 10 ms.

Such material degradation and chemical synthesis experiments are united by the extremes of chemical reactivity that occur at the air-water interface, where reagents are partially solvated (4). Whether formed through nebulization, splashing from a surface, or other means, microdroplet populations will include droplets with nonzero net charges. The small radius of curvature in a microdroplet produces a very strong electric field (5) that can support a double layer of electric charge at the air-water interface. The change in geometry (radius of curvature)

converts a two-dimensional air-water interface with limited electric field into a sphere with an electric field of a strength approaching the order of chemical bond energies (3 to 4.5 eV/A). Coulombic fission (the splitting of charged microdroplets due to excess charge overcoming the surface tension) and evaporative processes further increase the surface area, reduce the radius of curvature, and augment the surface electric field of the droplet.

The unusual chemical nature of the air-water interface results in much remarkable chemistry. For example, amino acids in water undergo dehydration to form peptides in this environment (6), whereas bulk water simply solvates amino acids. The superacidic interface activates amino acids and removes water to yield peptides. In addition to such acid-base reactions, redox chemistry results from the formation of strong oxidants and reductants from water at the interface. For example, a high hydronium ion (H_3O^+) concentration at the interface derived from fleetingly charged surface water molecules ($\text{H}_2\text{O}^+/\text{H}_3\text{O}^+$) coexists with oxidative species such as hydrogen peroxide (H_2O_2) and OH^+ . These redox species enable a variety of spontaneous chemical trans-

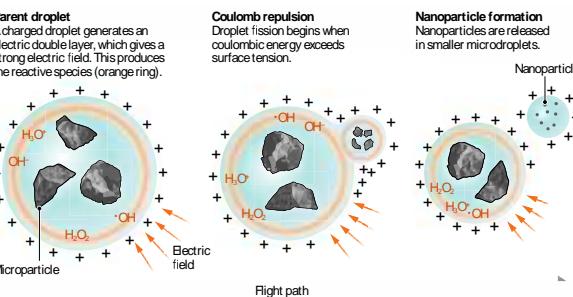
formations, including carbon-oxygen (O) bond cleavage in phosphonates, which yields the corresponding phosphonic acid (7), and in the Baeyer-Villiger oxidation of aryl ketones to give esters (8). These considerations thereby enable simultaneous acid-base and oxidation-reduction chemistry in a single population of droplets (7).

Through their study, Spoorthi *et al.* have added natural weathering to a list of processes in which accelerated interfacial microdroplet reactions play an important role. Other processes include those in the atmosphere, both natural and anthropogenic, the latter typified by pollution that involves nitrate photochemistry (9). A substantial number of accelerated catalyst-free microdroplet reactions form the basis for chemical syntheses that generate a variety of small molecules (10), including the facile and high-throughput functionalization of drugs. This latter approach can be scaled up so that microdroplet reactions produce substantial small-molecule products. Prebiotic chemistry, including peptide and nucleotide formation, is another process that is accelerated at the microdroplet air-water interface (11).

The millisecond timescale of quartz degradation reported by Spoorthi *et al.* matches the known microsecond-to-millisecond timescale for accelerated bond-formation and bond-cleavage chemical reactions in microdroplets (1). This reinforces the conclusion that the chemical basis for accelerated weathering lies in the powerful acidic and hydrolytic nature of the air-water interface. The authors further suggest a role for the superacid interface in inducing slippage at crystal plane boundaries in quartz and ruby fragmentation. Their simulations show that individual protons inserted into the slip configuration mineral

Micro-to-nano transitions in minerals at the air-water interface

Reactions that promote mineral disintegration are accelerated at the air-water interface of microdroplets. Key reactive species are the result of the effects of a high electric field at the surface of the water droplets.



GRAPHIC: K. HOLDEN/SCIENCE

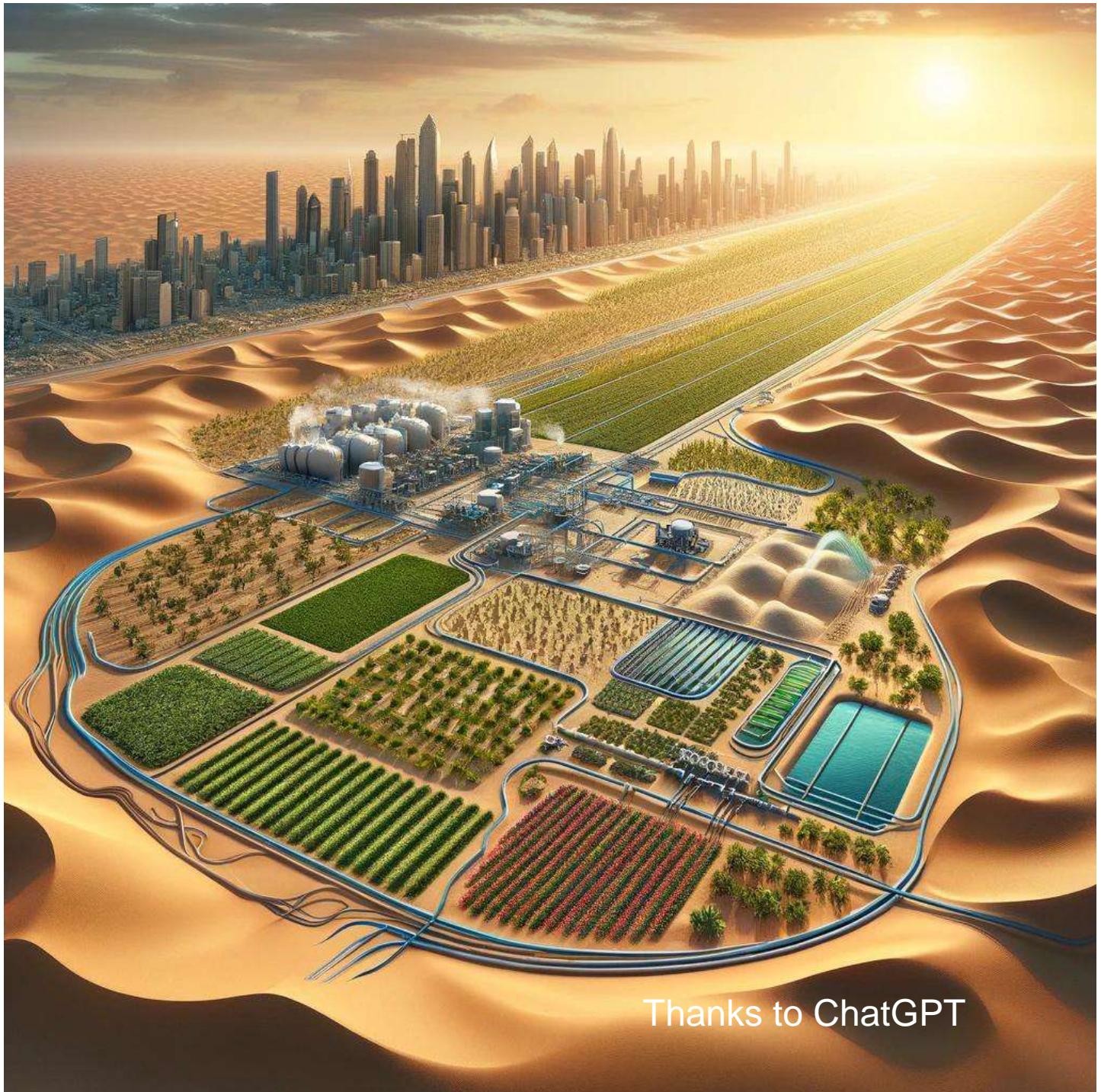
Department of Chemistry, Purdue University, West Lafayette, IN, USA. Email: cooks@purdue.edu



Thanks to ChatGPT

Vision

Make soil using
processed wastewater
and make deserts
bloom.

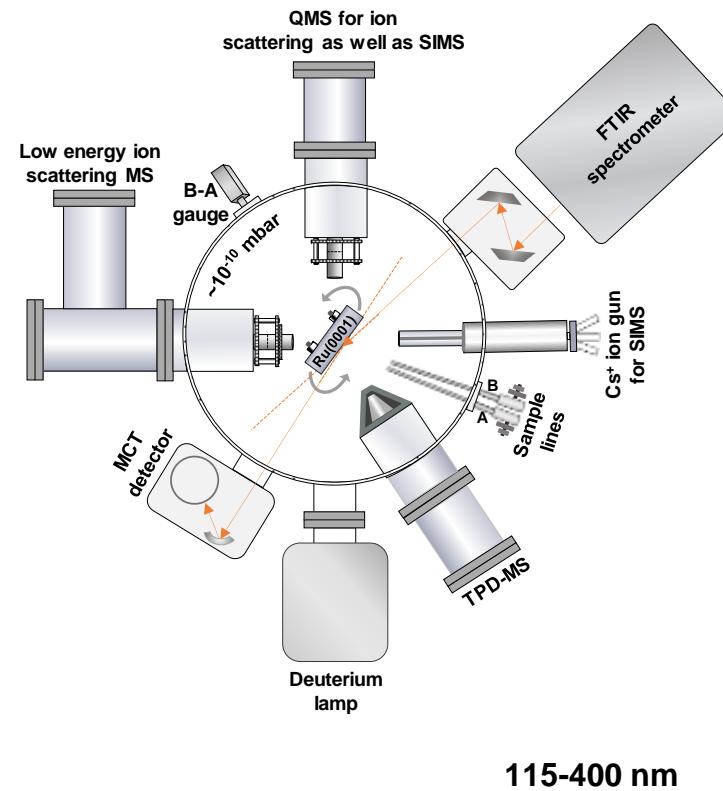
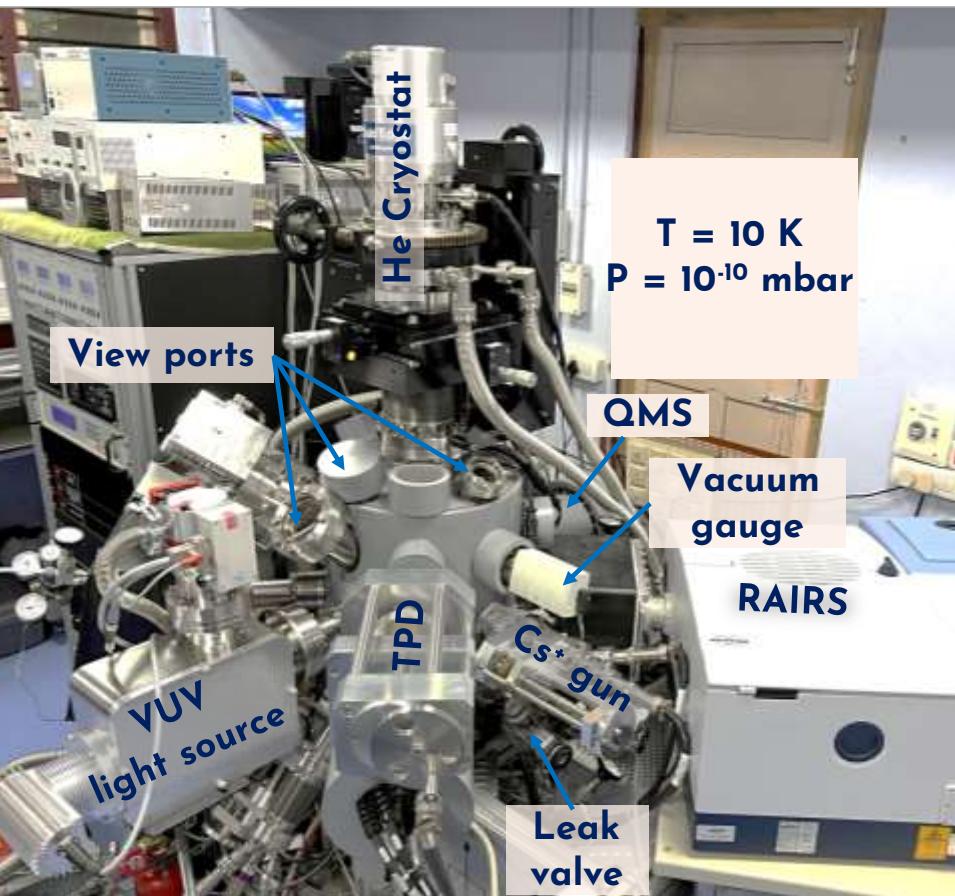


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Can Clathrate Hydrates Exist in Space?

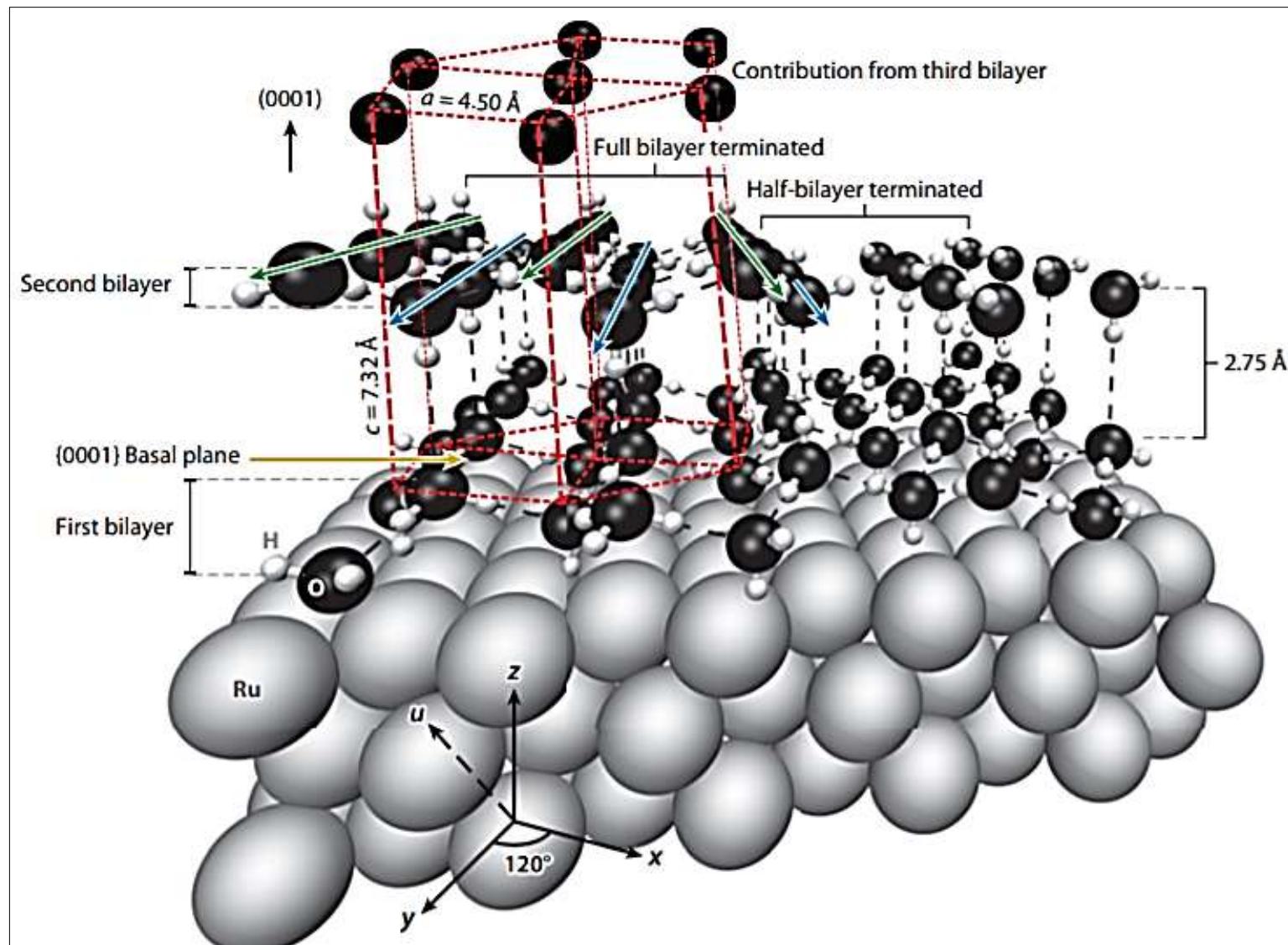
Exploring astrobiology

Instrumentation



Bag, S. et al., *Rev. Sci. Instrum.* **2014**, *85*, 014103/1-014103/7

Viswakarma, G. et al., *J. Phys. Chem. Lett.*, **2023**, *14*, 2823–2829



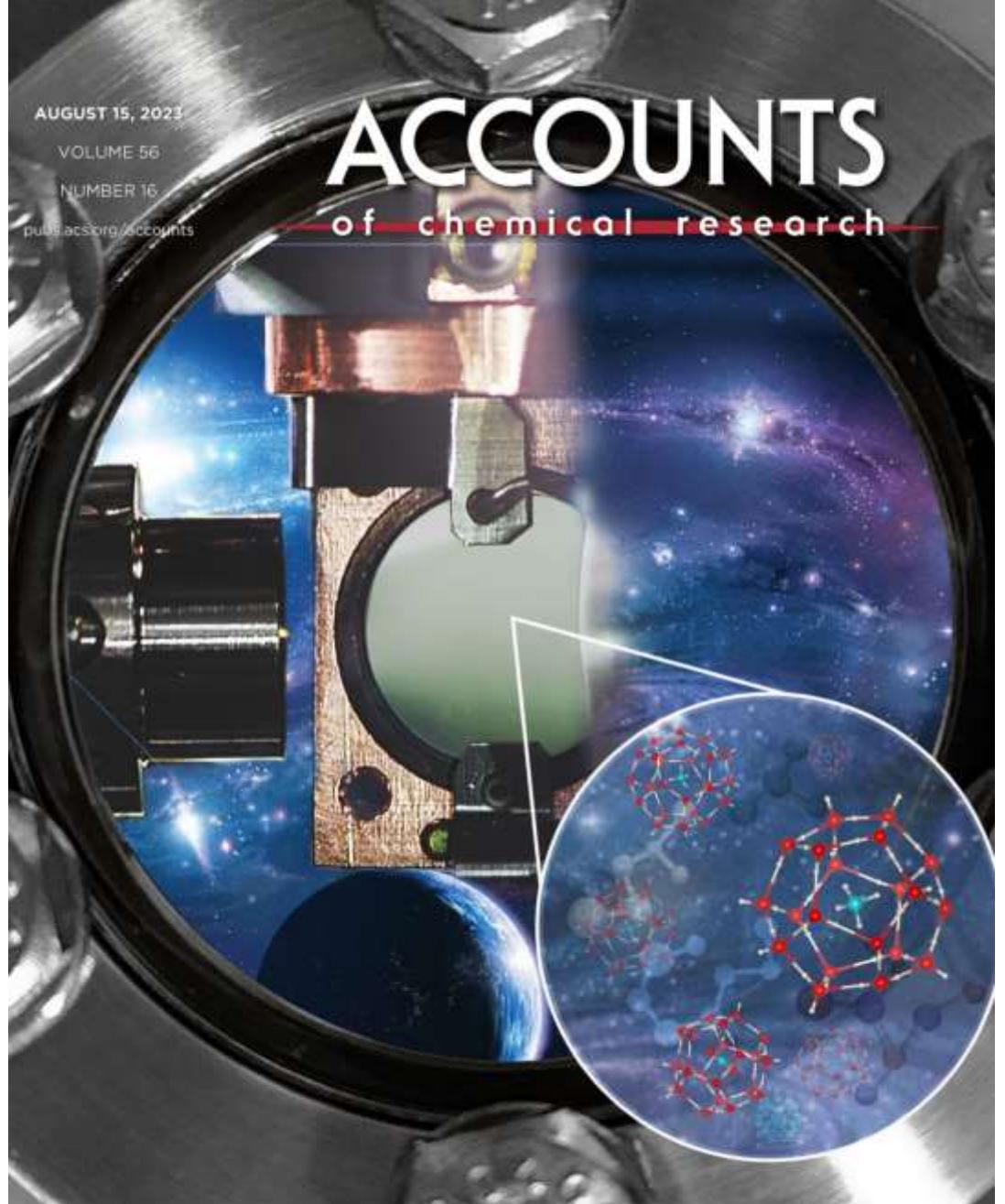
Formation and Transformation of Clathrate Hydrates under Interstellar Conditions

Jyotirmoy Ghosh, Gaurav Vishwakarma, Rajnish Kumar,* and Thalappil Pradeep*

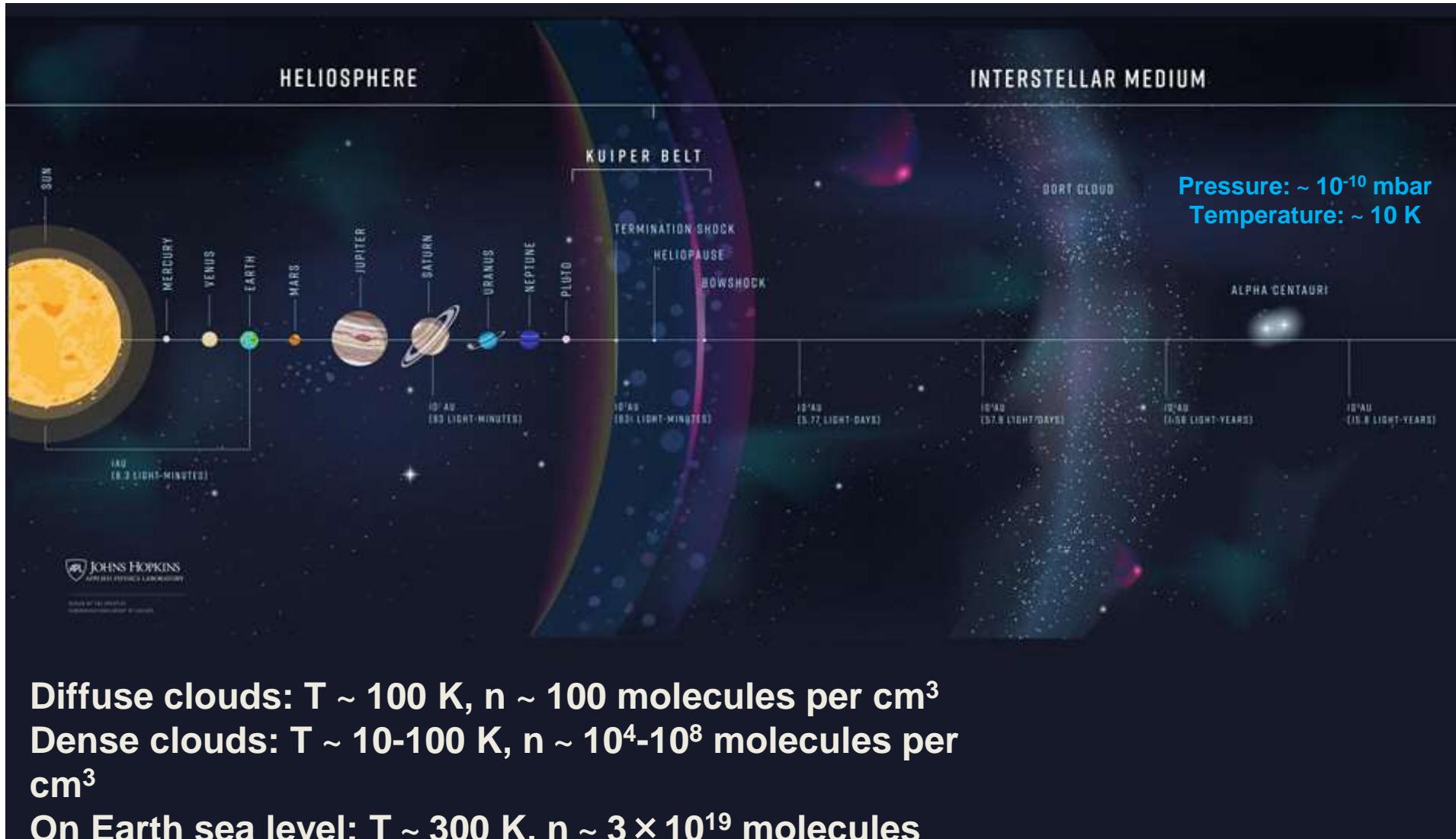
 Cite This: <https://doi.org/10.1021/acs.accounts.3c00317>

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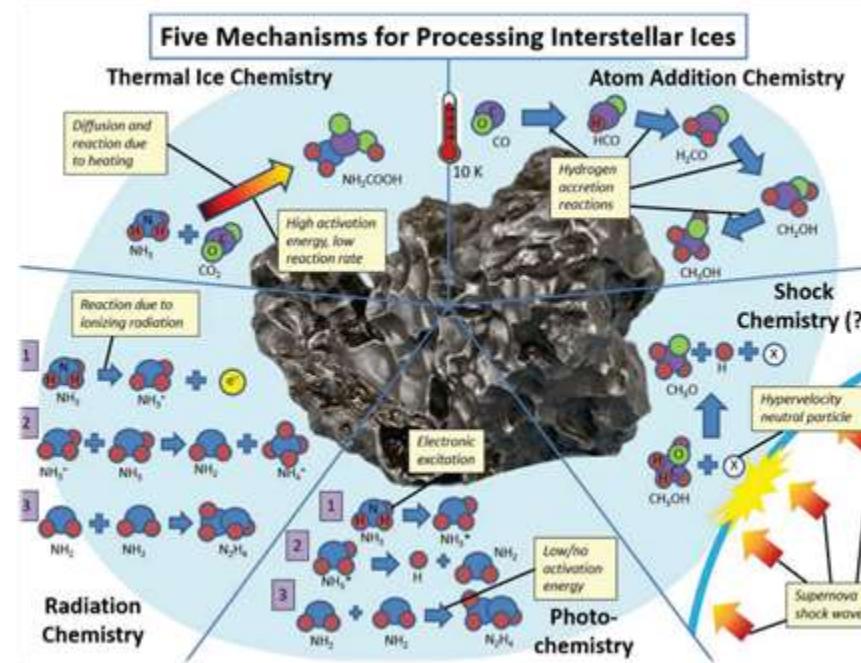
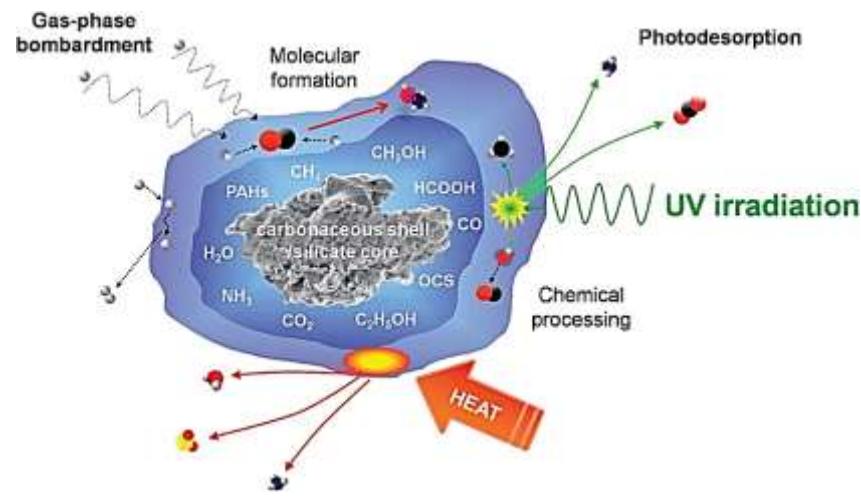
AUGUST 15, 2023
VOLUME 56
NUMBER 16
pubs.acs.org/accounts



Interstellar medium



Interstellar ices

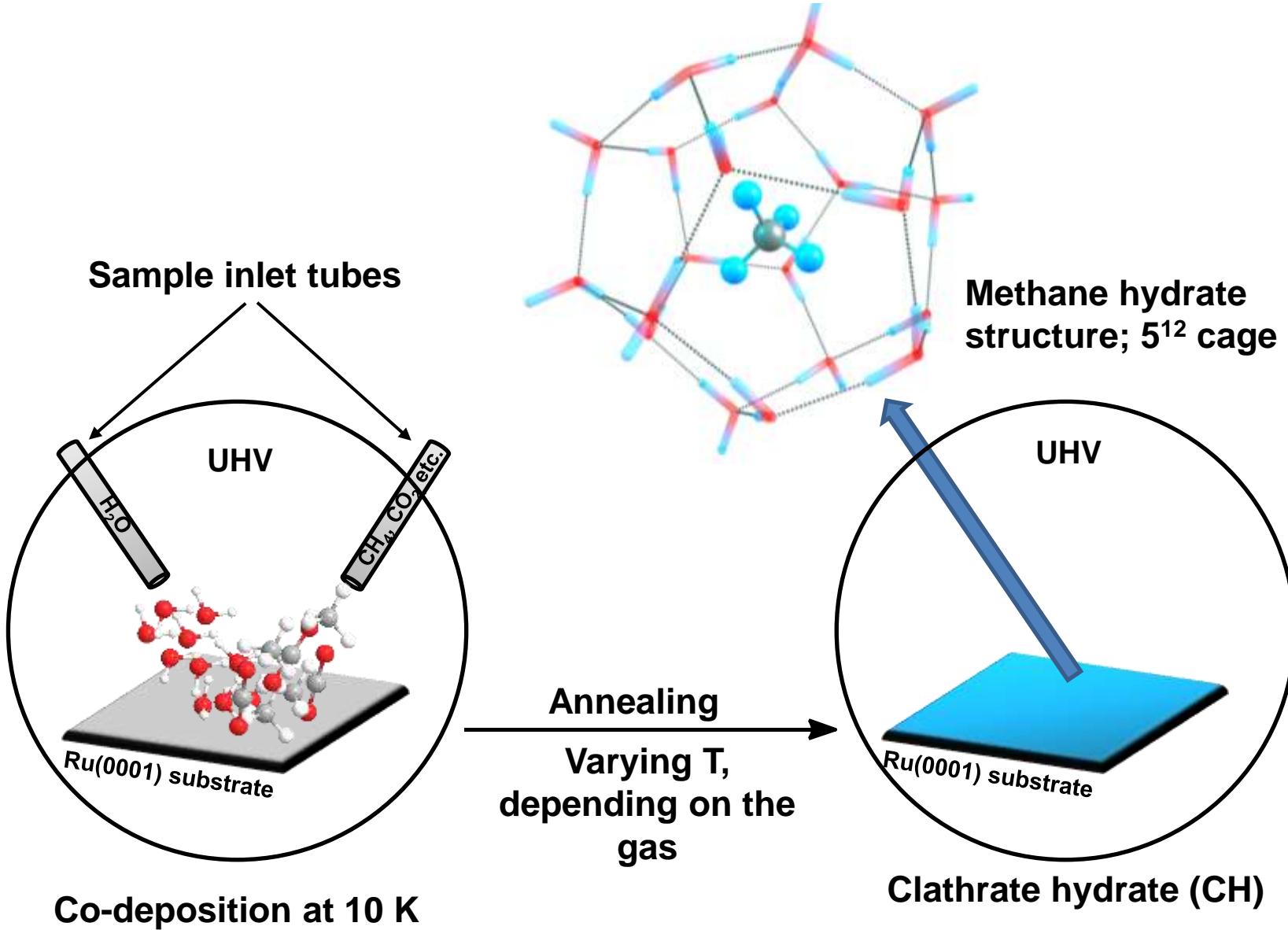


Silicates and carbonaceous material – 0.01-0.5 μm

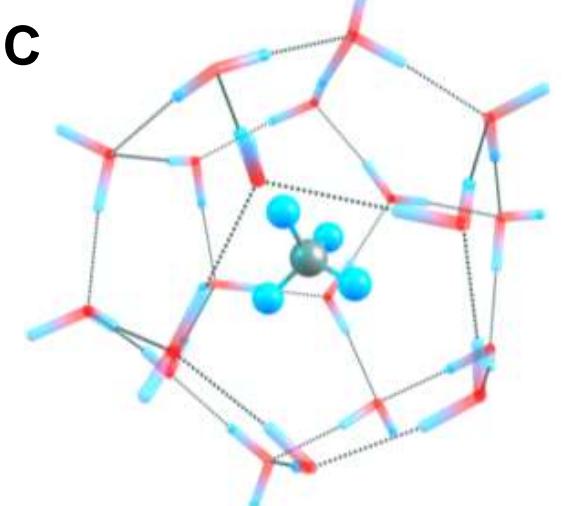
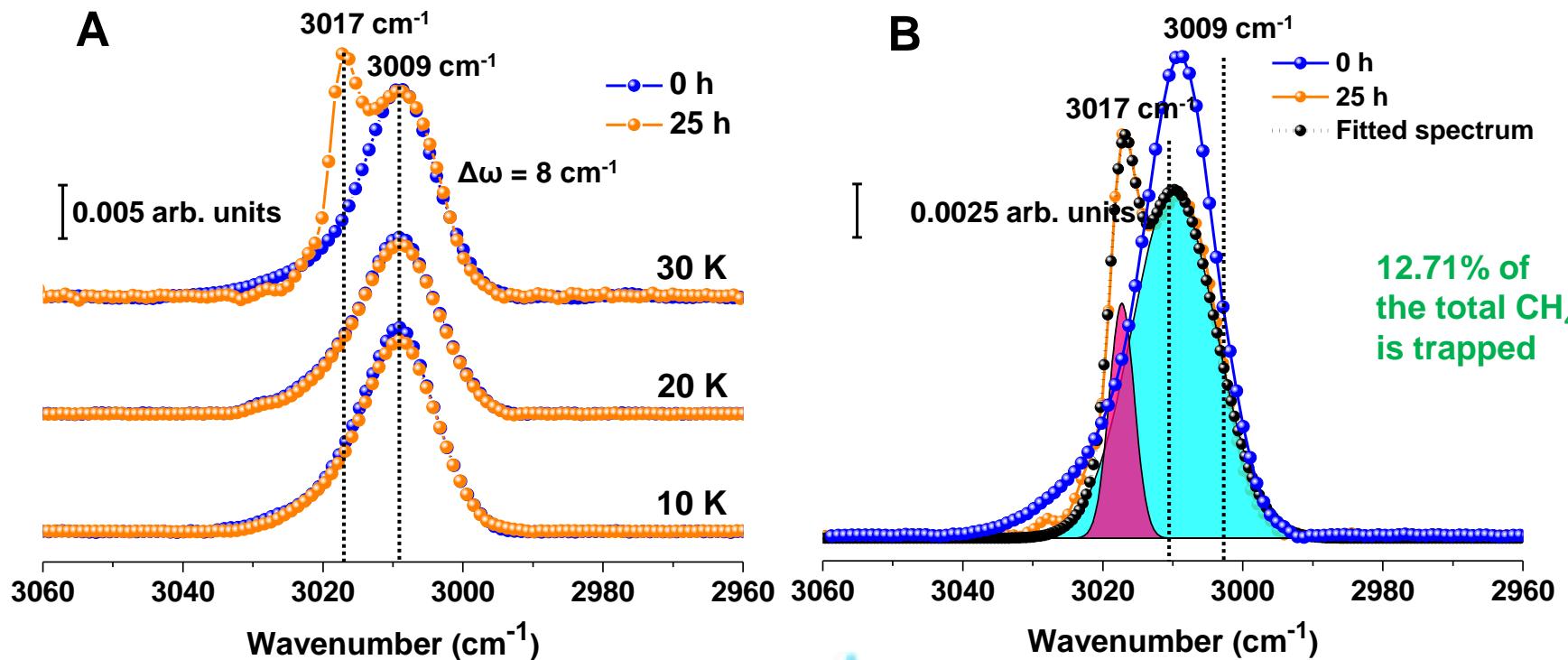
Clathrate hydrates in interstellar environment

Ghosh, J. et al., *Proc. Natl. Acad. Sci. U.S.A.*, **2019**, 116, 1526-1531

Experimental method



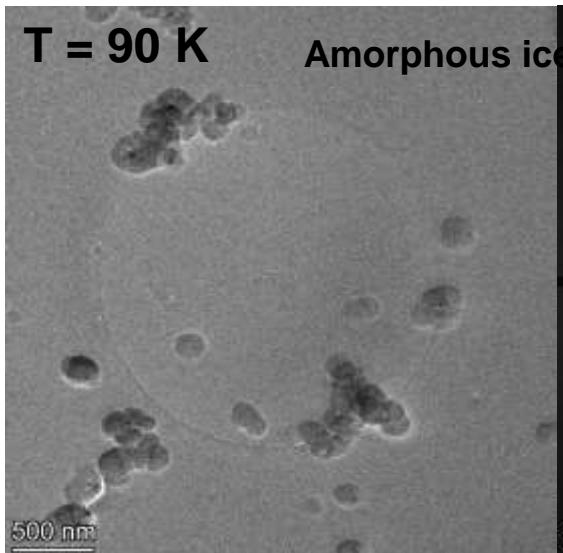
Clathrate hydrates in interstellar environment



5¹² cage of CH_4 hydrate

Observing growth of crystalline ice from amorphous ice

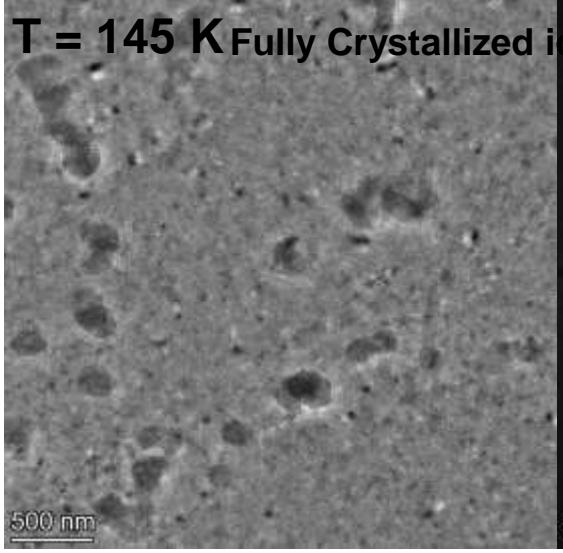
(a) $T = 90\text{ K}$



Amorphous ice

Amorphous ice

2 nm^{-1}



$T = 145\text{ K}$ Fully Crystallized ice

Ice Ic

2 nm^{-1}

(b)

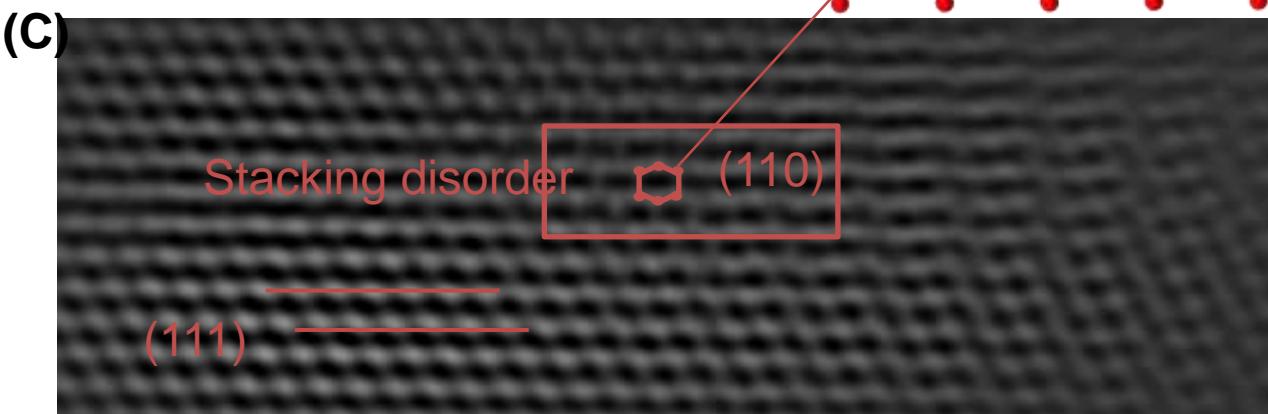
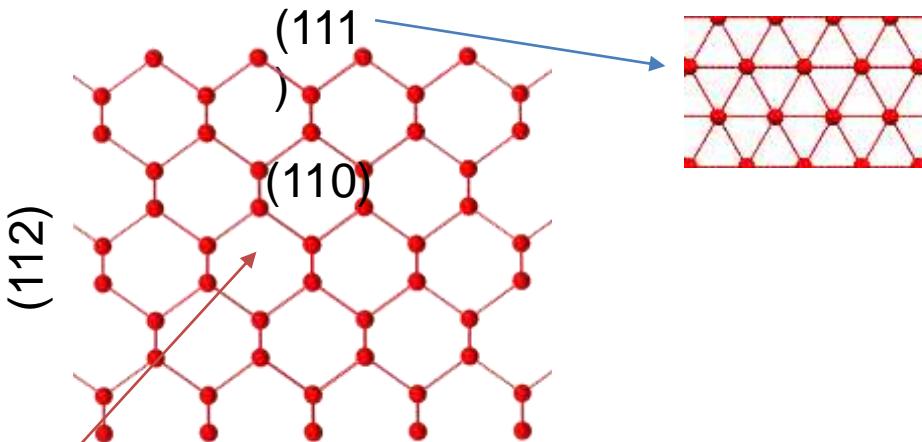
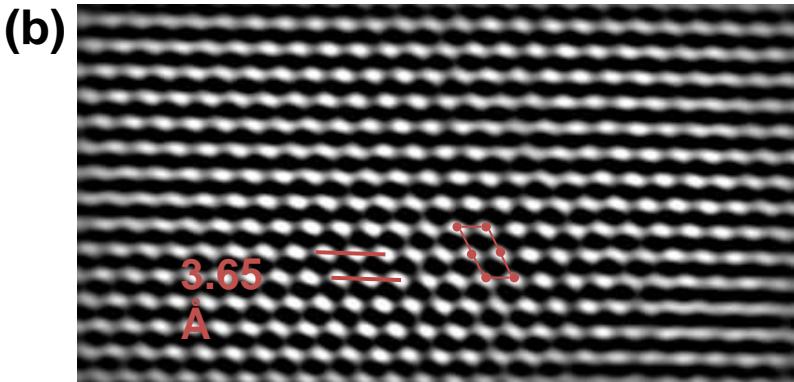
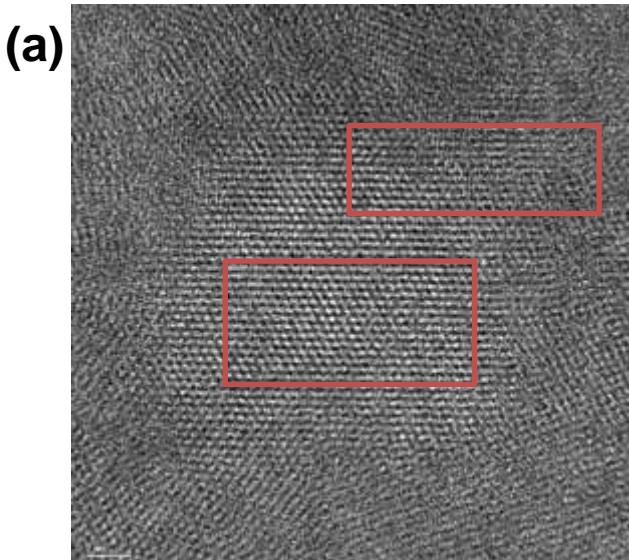
Ice at molecular resolution

2 nm

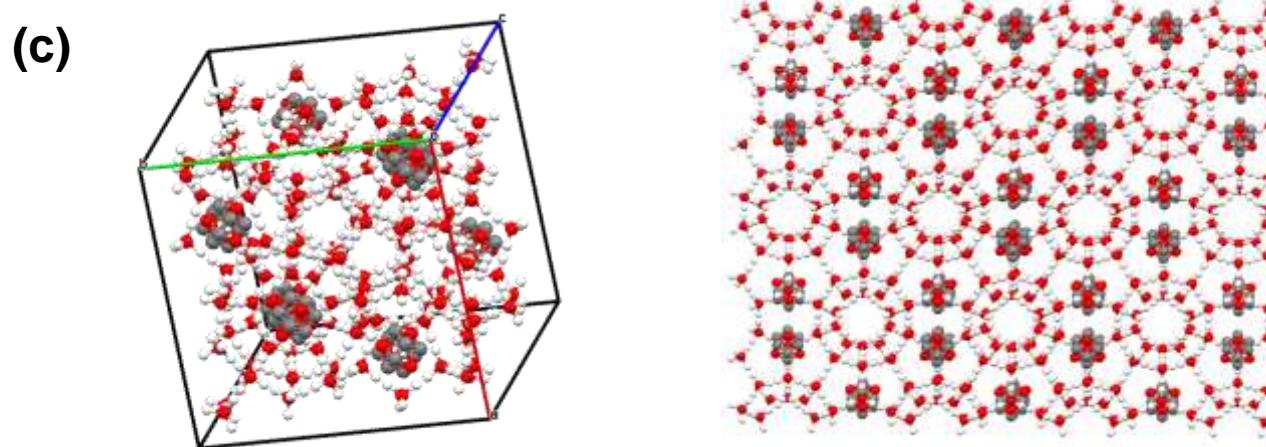
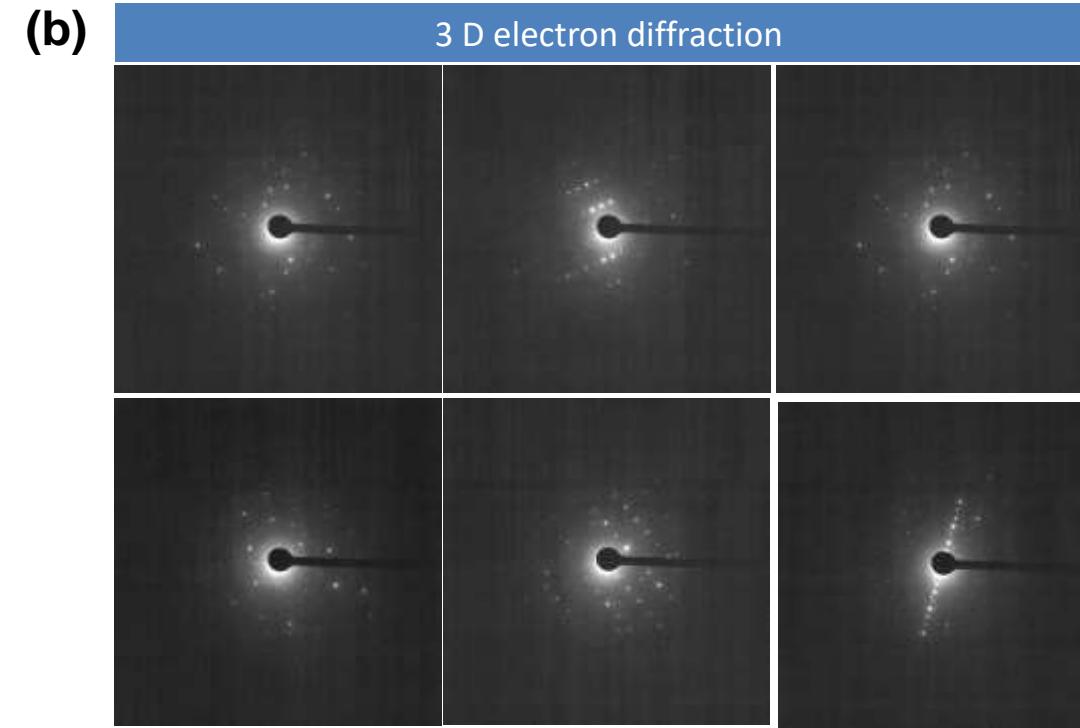
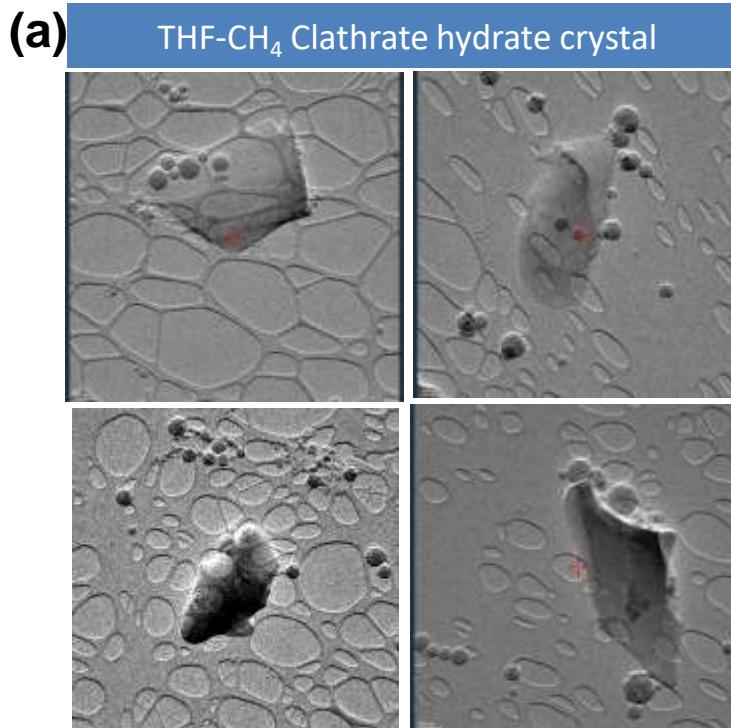
IFFT

2 nm

Imaging cubic ice at molecular resolution



Electron diffraction of nanometer-scale crystals of clathrate hydrate



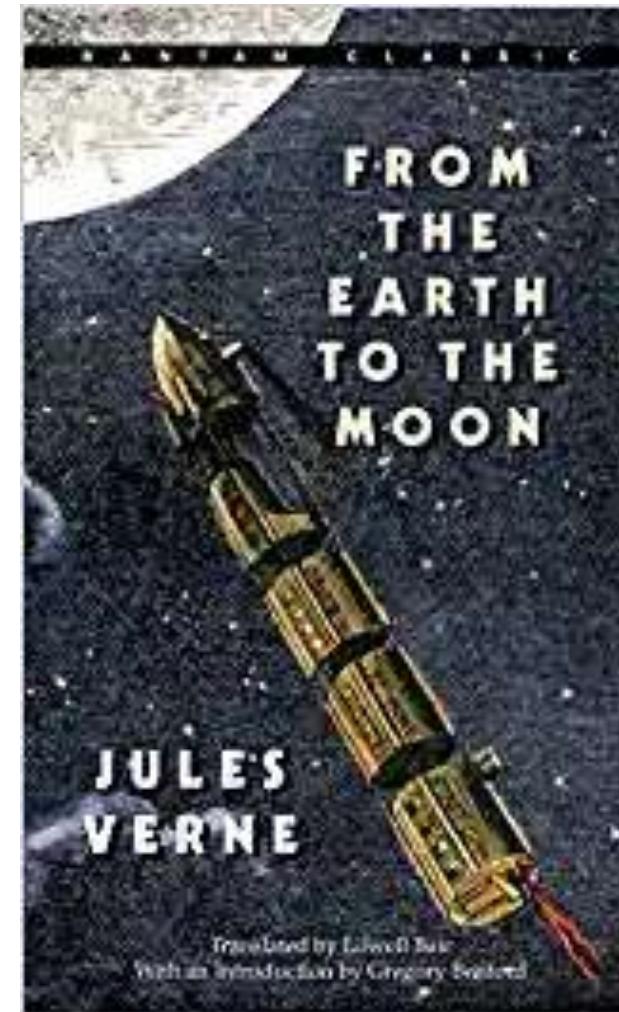
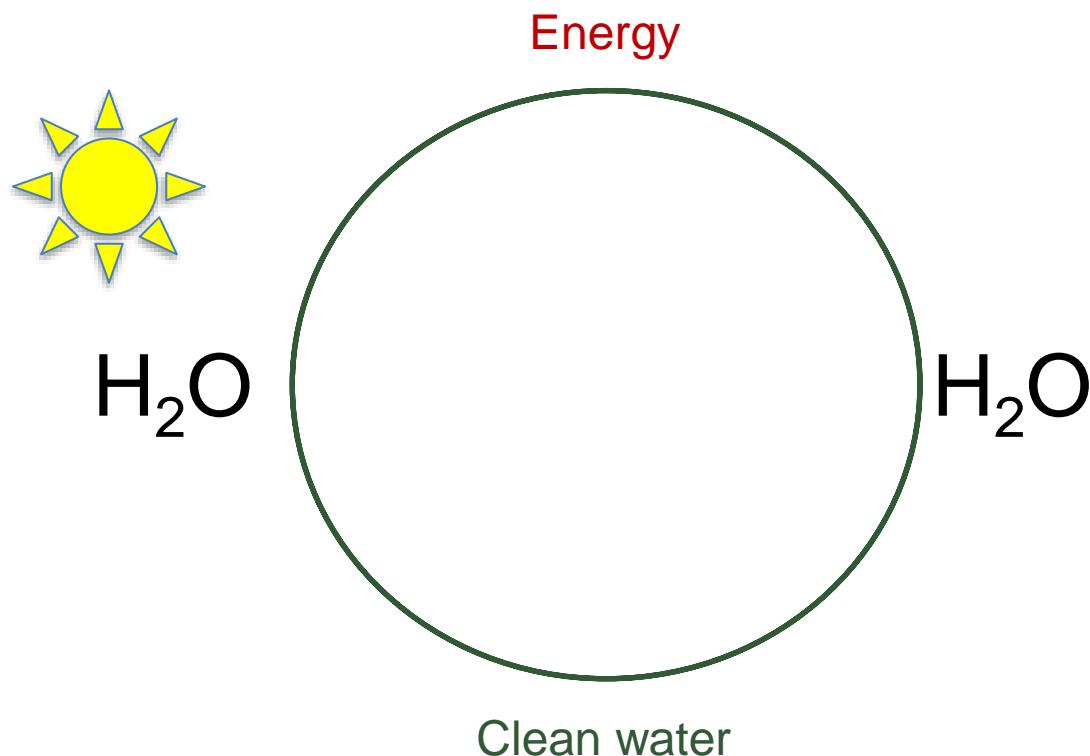
Crystal structure





International Centre for Clean Water

Our dreams become reality with materials





<https://www.youtube.com/watch?v=fiJyptbXBtM>

An ocean of opportunities

Water presents a unique opportunity to find a purpose in life.



Earthrise, taken on December 24, 1968, by Apollo astronaut William Anders.
From Wikipedia

Conclusions

Affordable clean water with advanced materials is demonstrated at scale.

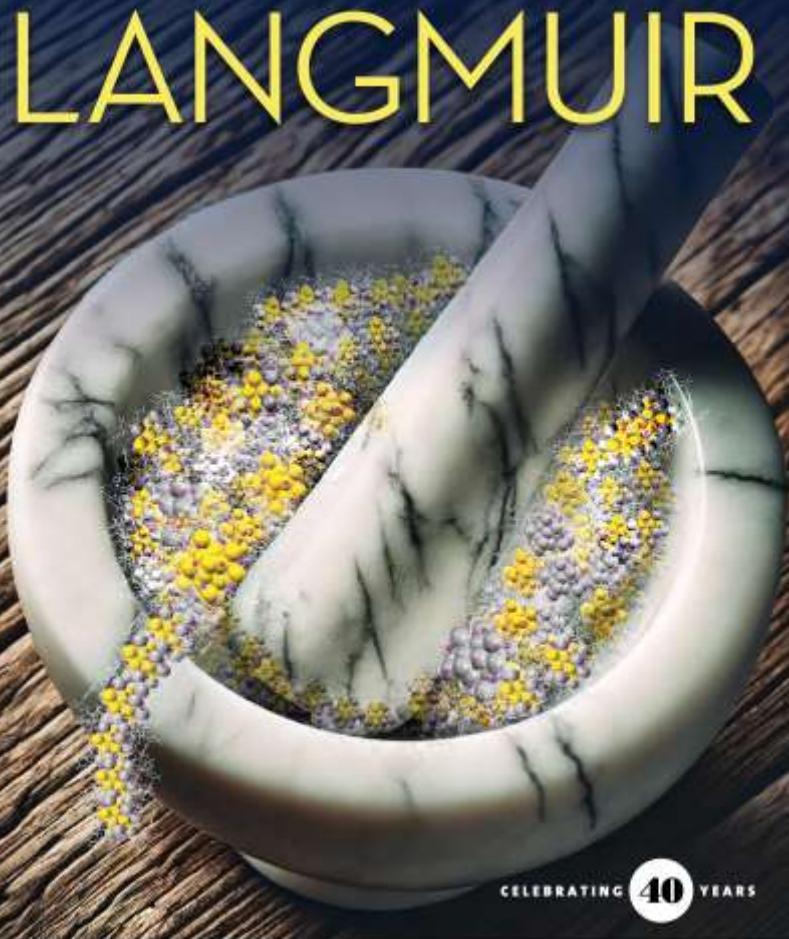
Natural minerals break spontaneously in charged water microdroplets.

Clathrate hydrates exist in ultrahigh vacuum.

Implications of all these are profound.

New research is needed in these areas.

Affordable, inclusive, sustainable and contextual excellence



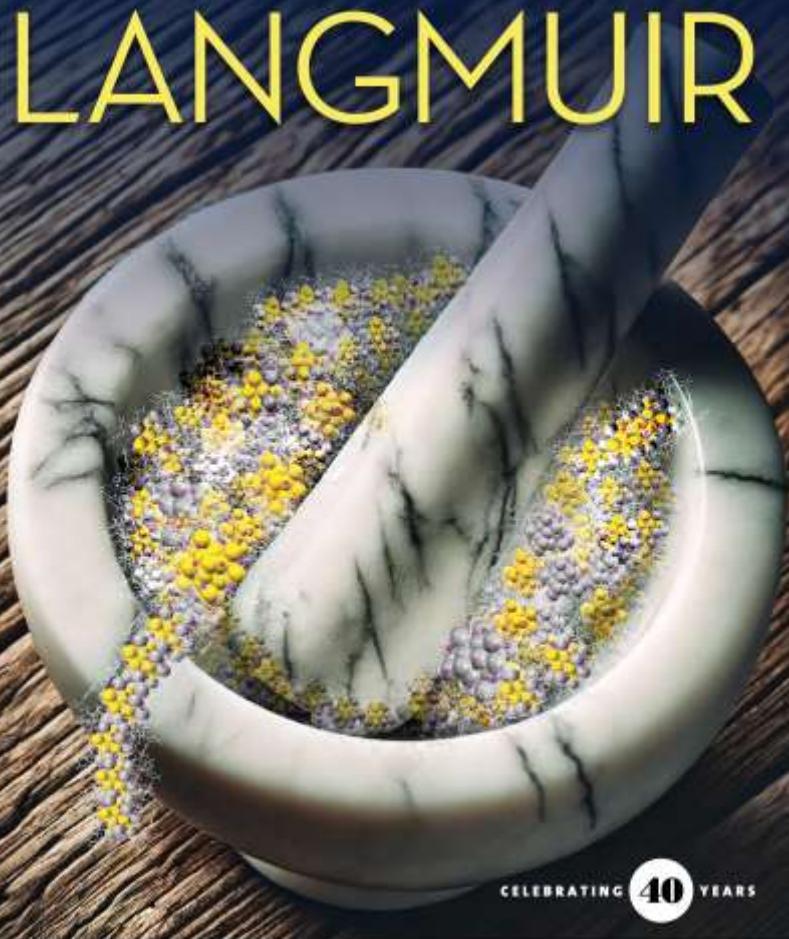
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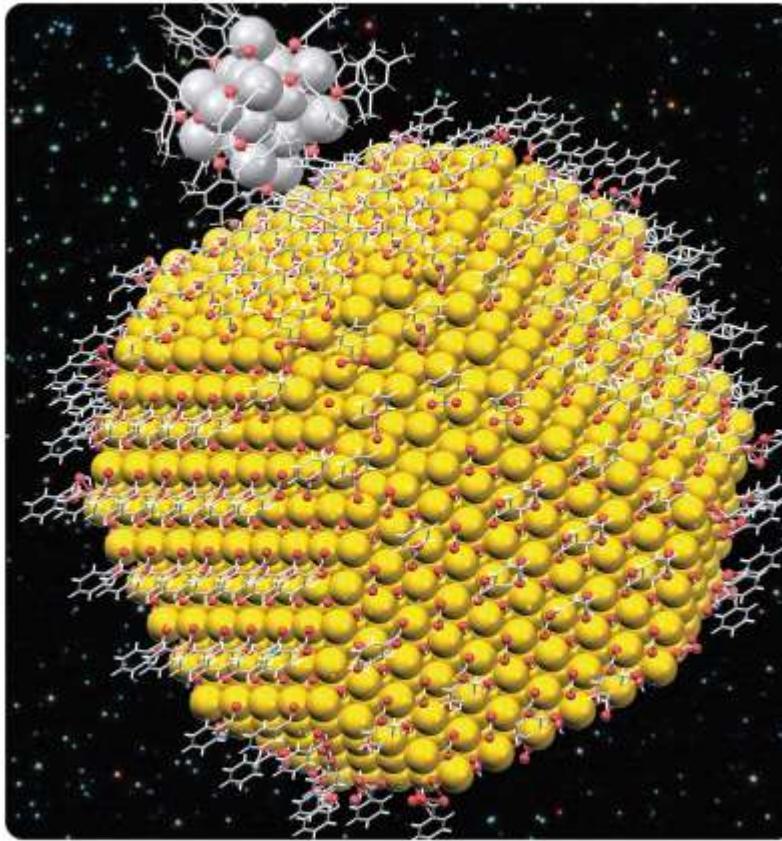
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OF CHEMISTRY

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"Selaipal, Prakash, et al."
A series guide to the synthesis, structure, and properties of noble metal nanoclusters.

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Department of Science and Technology
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Many Outstanding Individuals



The AMRIT Team, 2013





Water team at IIT: A. Sreekumaran Nair, Anshup, M. Udhaya Sankar, Amrita Chaudhary, Renjis T. Tom, T. S. Sreeprasad, Udayabhaskararao Thumu, M. S. Bootharaju, K. R. Krishnadas, Kalamesh Chaudhari, Soujit Sengupta, Depanjan Sarkar, Avijit Baidya, Swathy Jakka Ravindran, Abhijit Nag, S. Vidhya, Biswajit Mondal, Krishnan Swaminathan, Azhardin Gnayee, Sudhakar Chennu, A. Suganya, Rabiul Islam, Sritama Mukherjee, Tanvi Gupte, Jenifer Shantha Kumar, A. Anil Kumar, Ankit Nagar, Ramesh Kumar Soni, Tanmayaa Nayak, Sonali Seth, Shihabudheen M. Maliyekkal, G. Velmurugan, Wakeel Ahmed Dar, Ganapati Natarajan, N. Pugazhenthiran, A. Leelavathi, Sahaja Aigal, S. Gayathri, Bibhuti Bhushan Rath, Ananthu Mahendranath, Harsh Dave, Erik Mobegi, Egor Moses, Hemanta R. Naik, Sourav Kanti Jana, Tanmayaa Nayak, Sonali Seth...

Avula Anil Kumar, Chennu Sudhakar, Sritama Mukherjee, Anshup, and Mohan Udhaya Sankar

Funding: Department of Science and Technology, Government of India

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MS Theses: Ananthu Mahedranath, Ramesh Kumar Soni

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Manswita Mandal for help with the slides