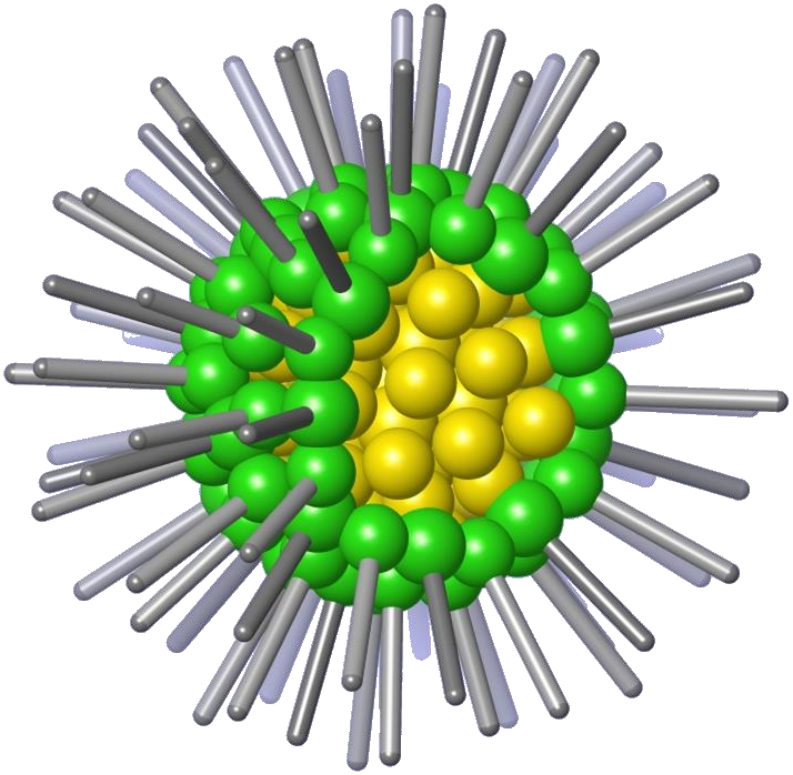
Affordable point-of-use drinking water purification using nanomaterials



T. Pradeep

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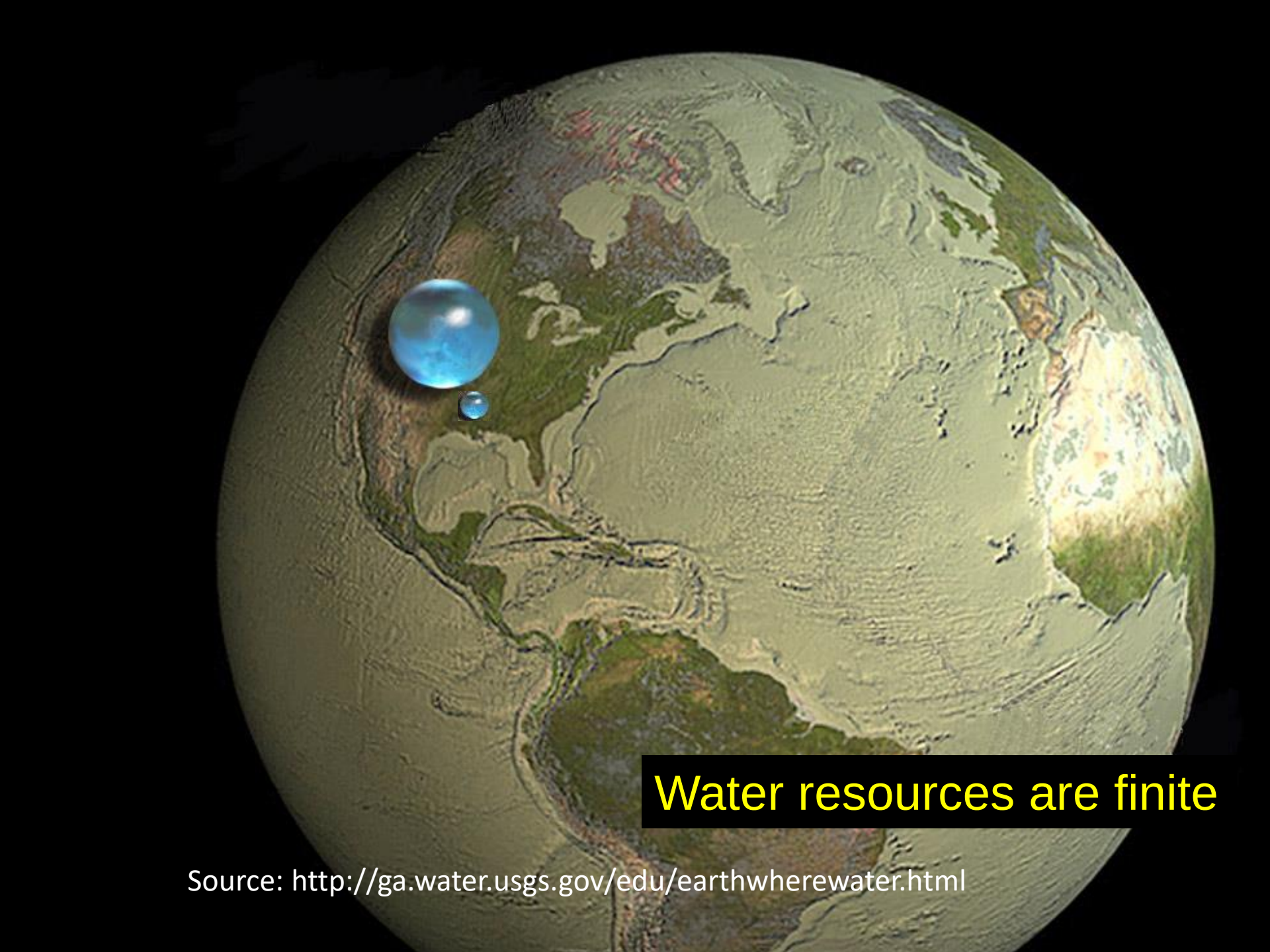
Chennai 600 036, India

AsiaNANO 2014, October 26-28, 2014

Indian Institute of Technology Madras

Bhaskar Ramamurthi
Director


Raj Bhavan
Guindy National Park
Academic zone
Residential zone
IIT Madras, Chennai, Tamil Nadu India
Research Park
Hostel zone
Image © 2007 DigitalGlobe



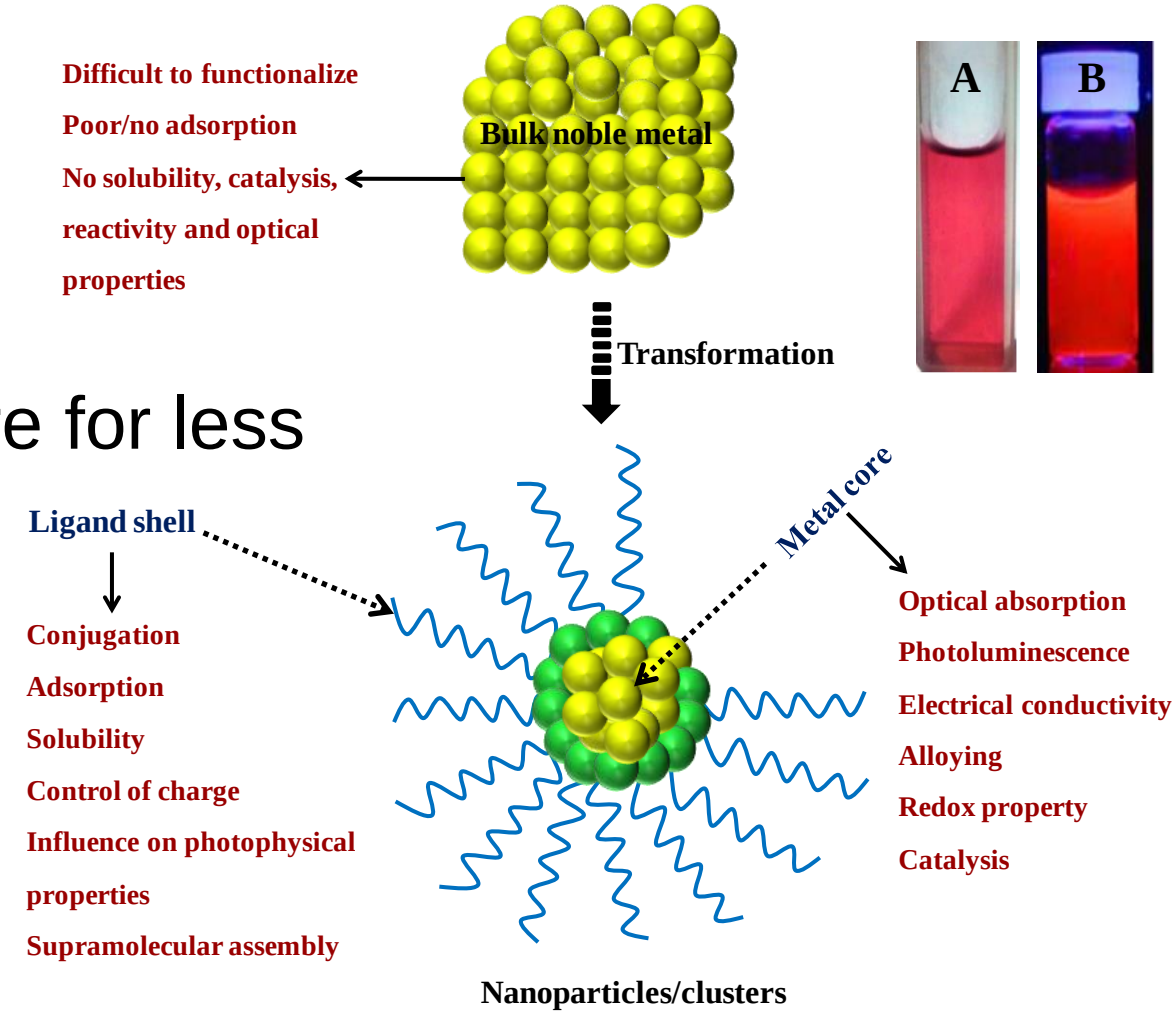
Source: http://ga.water.usgs.gov/edu/earthwherewater.html

Why nanotechnology?

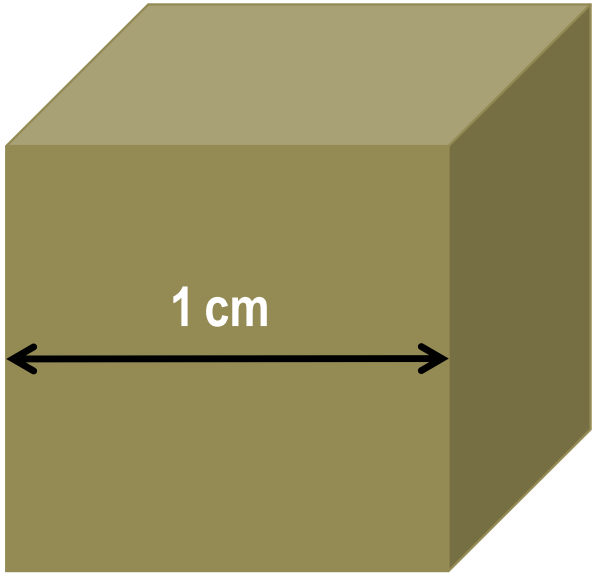
10^{-9}

T. Pradeep, Env. Sci. Technol. 2014, Feature

1. More for less



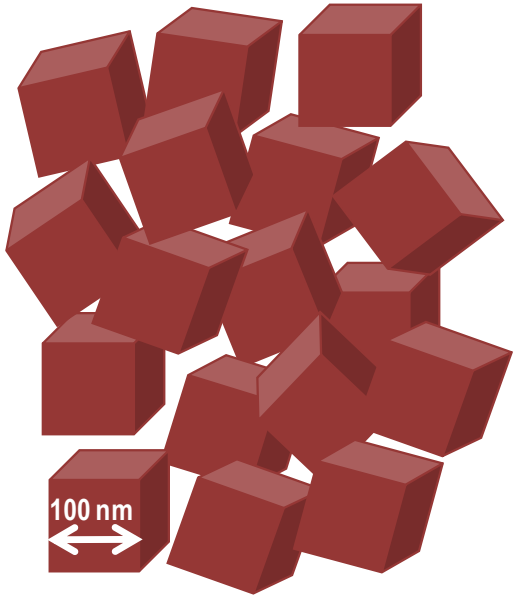
Variation in properties originating from ligand shell and metal core as bulk noble metals transform to nanoparticles/clusters. Sizes are not to scale. New properties such as color and photoluminescence arise in such size regime. Photographs of Au@citrate nanoparticles (inset A) showing intense absorption of visible light and Au@SG (SG corresponds to glutathione thiolate) clusters (inset B) showing intense photoluminescence upon ultraviolet irradiation (from the author's work).



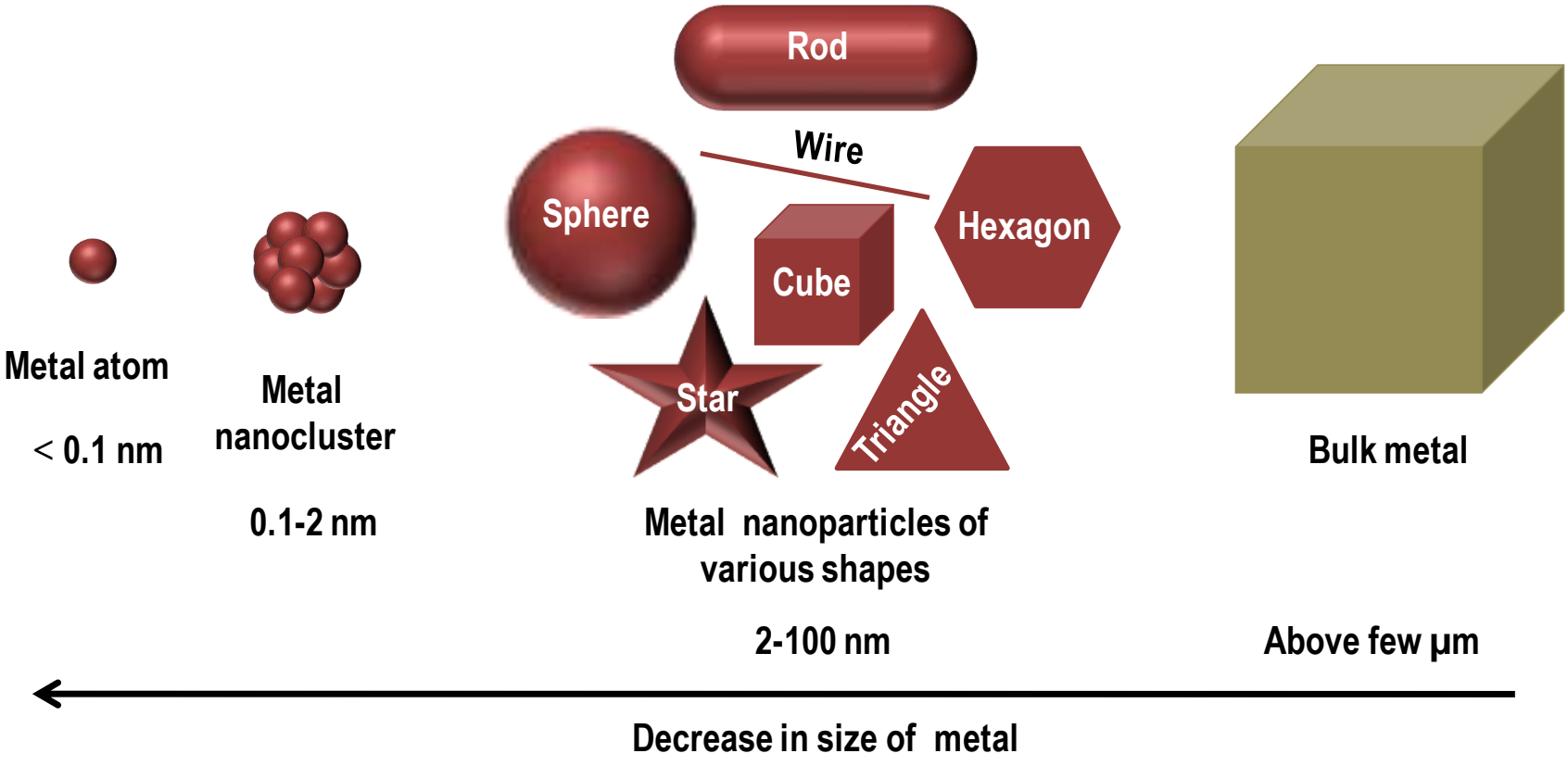
Bulk noble metal

Reduction of size

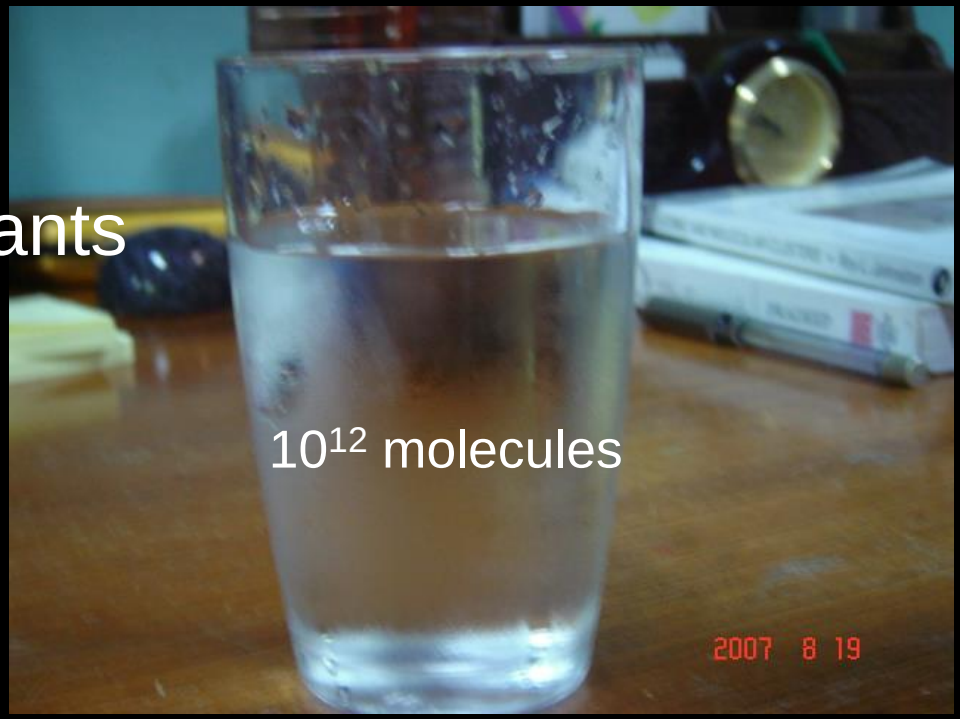
Surface area increases by 10^5

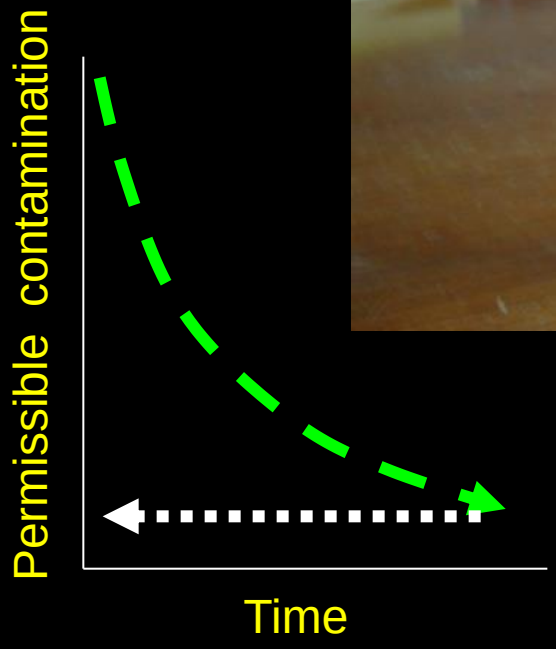


Noble metal of smaller size

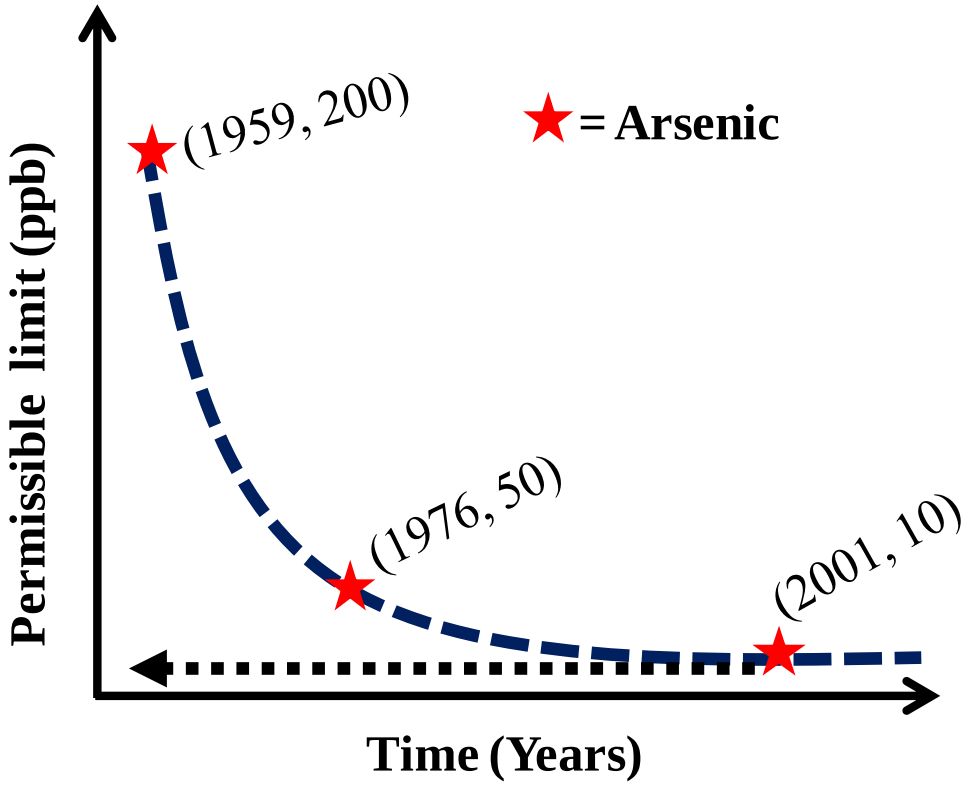

Rod
Wire
Sphere
Hexagon
Cube
Star
Triangle
Metal atom
< 0.1 nm
Metal nanocluster
0.1-2 nm
Metal nanoparticles of various shapes
2-100 nm
Bulk metal
Above few µm
Decrease in size of metal

2. Limits of contaminants



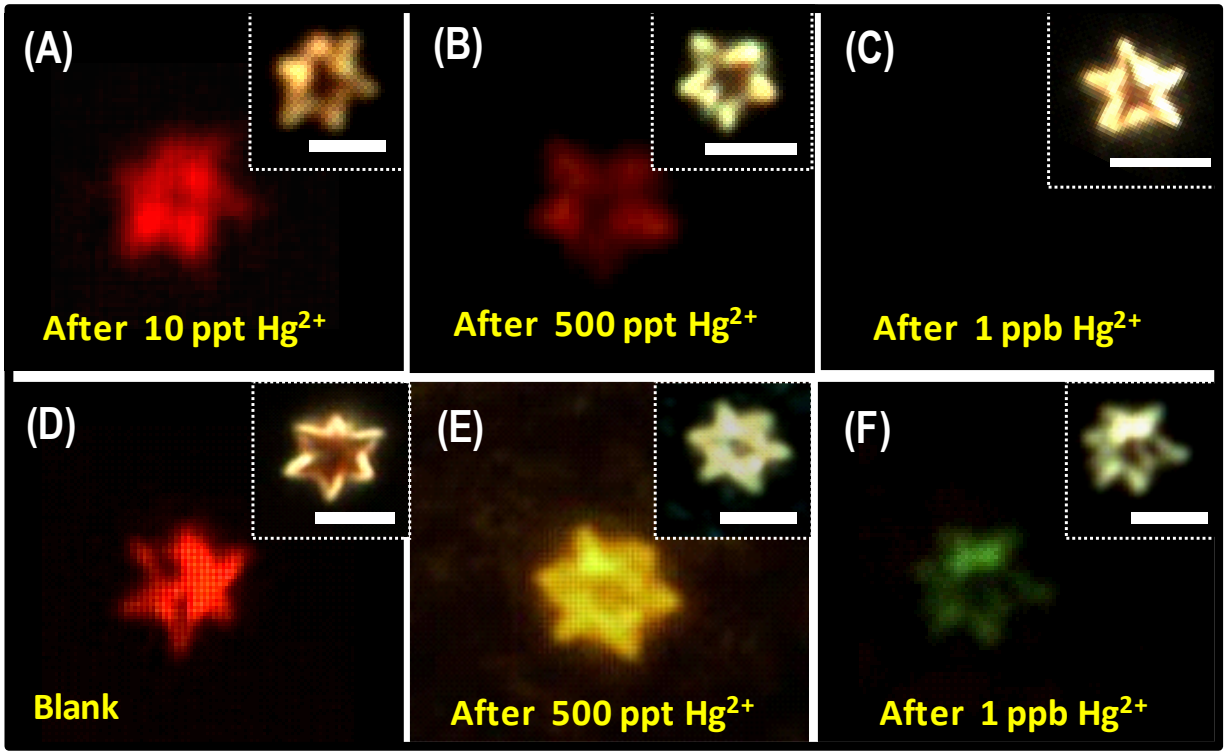


Permissible contamination reaches limits of detection



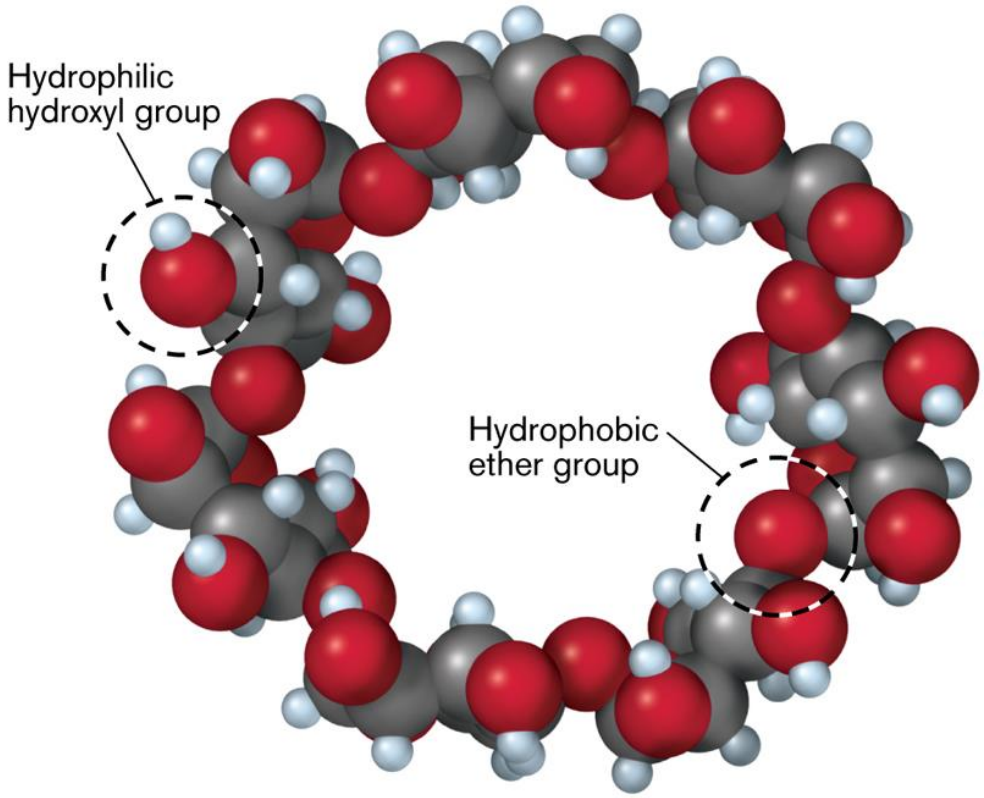
Decrease in the permissible limit of arsenic in drinking water, according to US EPA, with time. The graph indicates a general trend.

3. Can we reach limits?

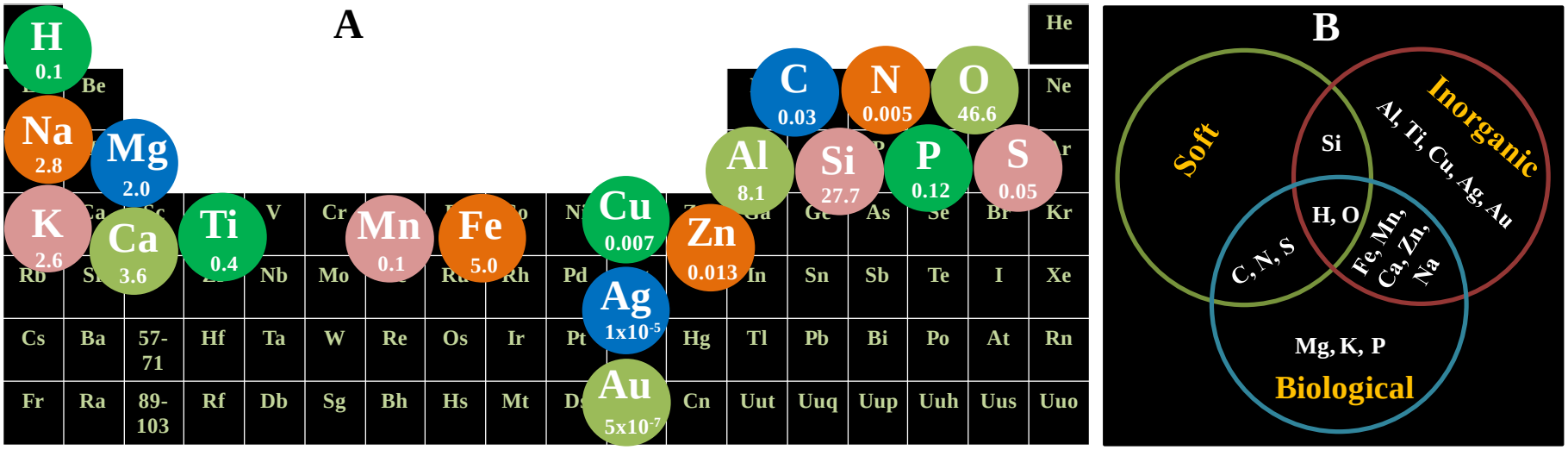


(A)–(C) Dark field fluorescence images of $Au@SiO_2@Ag_{15}$ MFs showing the gradual disappearance of luminescence with increasing Hg^{2+}. (D)–(F) Fluorescence images showing variation in color during the addition of Hg^{2+} of different concentrations to $Au@SiO_2$-FITC$@Ag_{15}$ MFs. Insets in all images show the corresponding optical images of the MFs; scale bars are 3 μm.

Cavities, channels, imprints, assemblies, fibres, ……

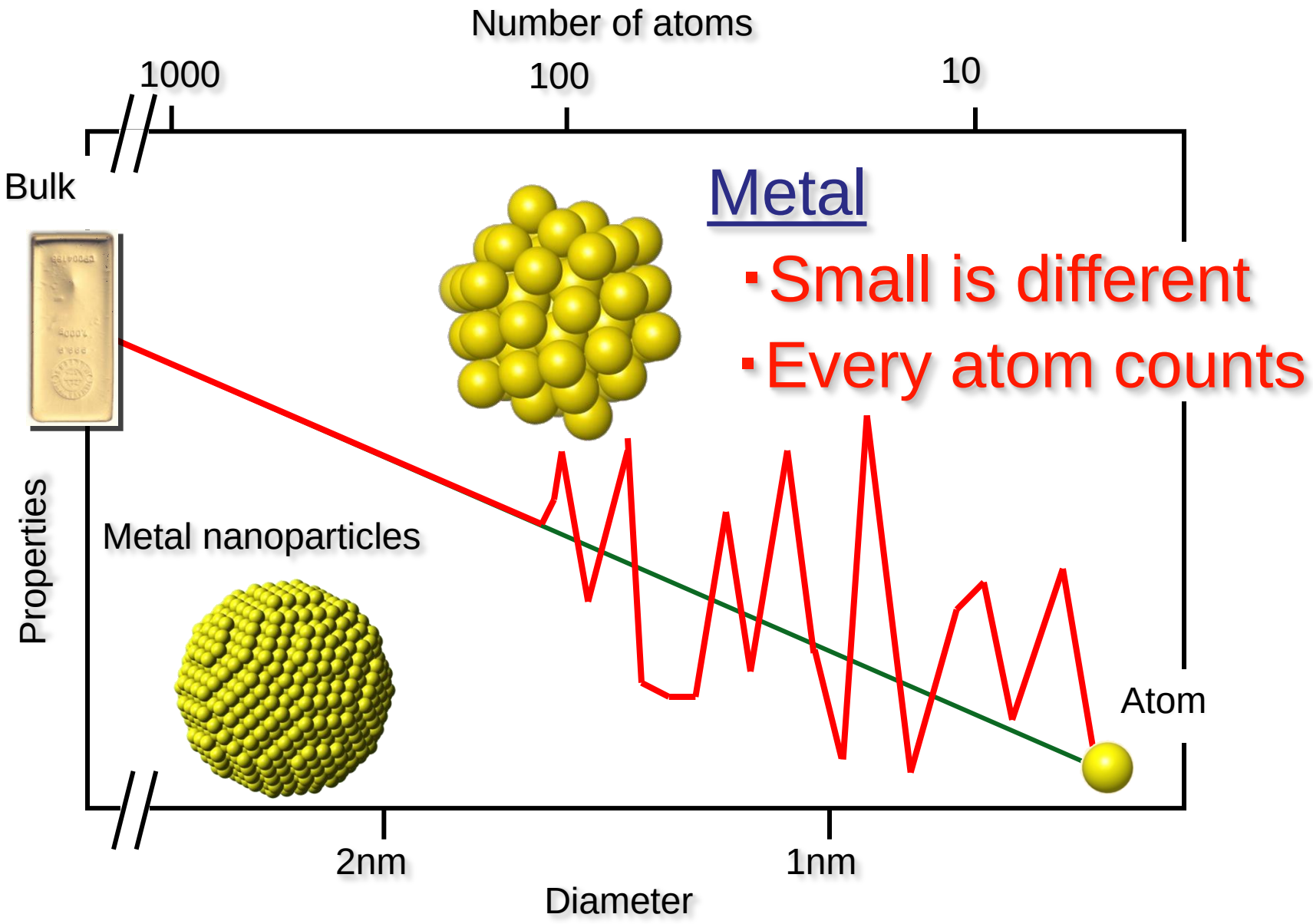


Materials in water – A simple view

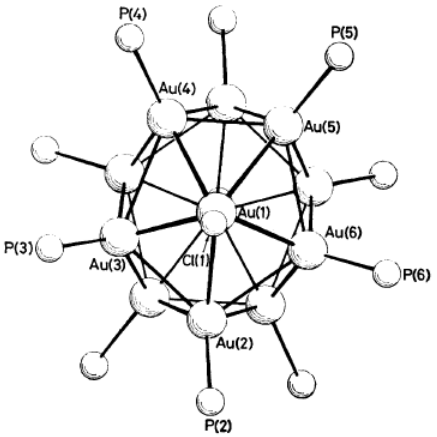


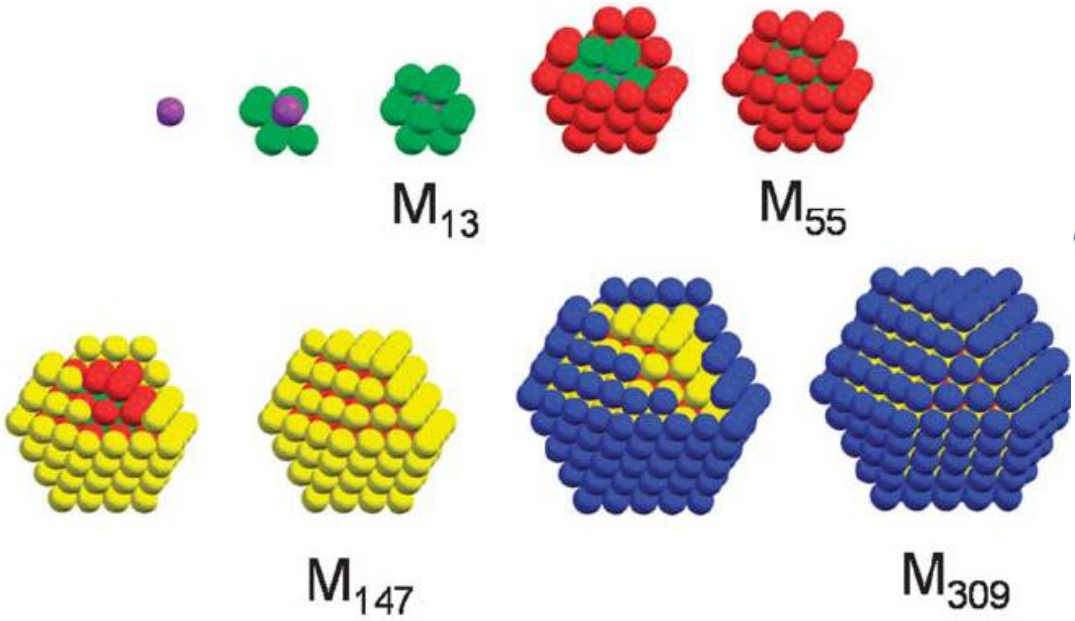
(A) Periodic table of elements and those used for water purification (highlighted). Abundances (in wt %)[2] of the highlighted elements in earth's crust are also mentioned. Note: The highlighted elements are not exactly in their original positions of the periodic table for clarity. (B) Elements that can be grouped to create diverse materials used for water purification.

Metal Clusters



Magic clusters





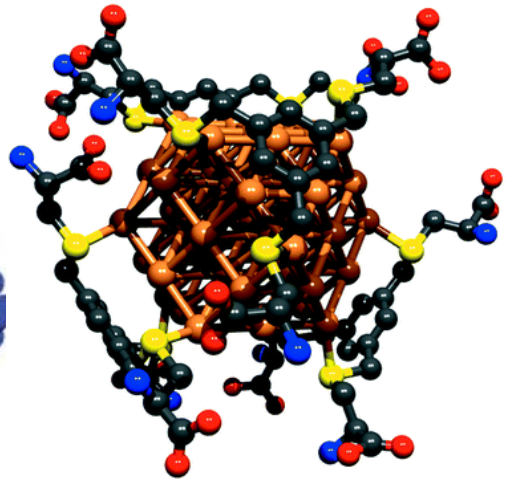
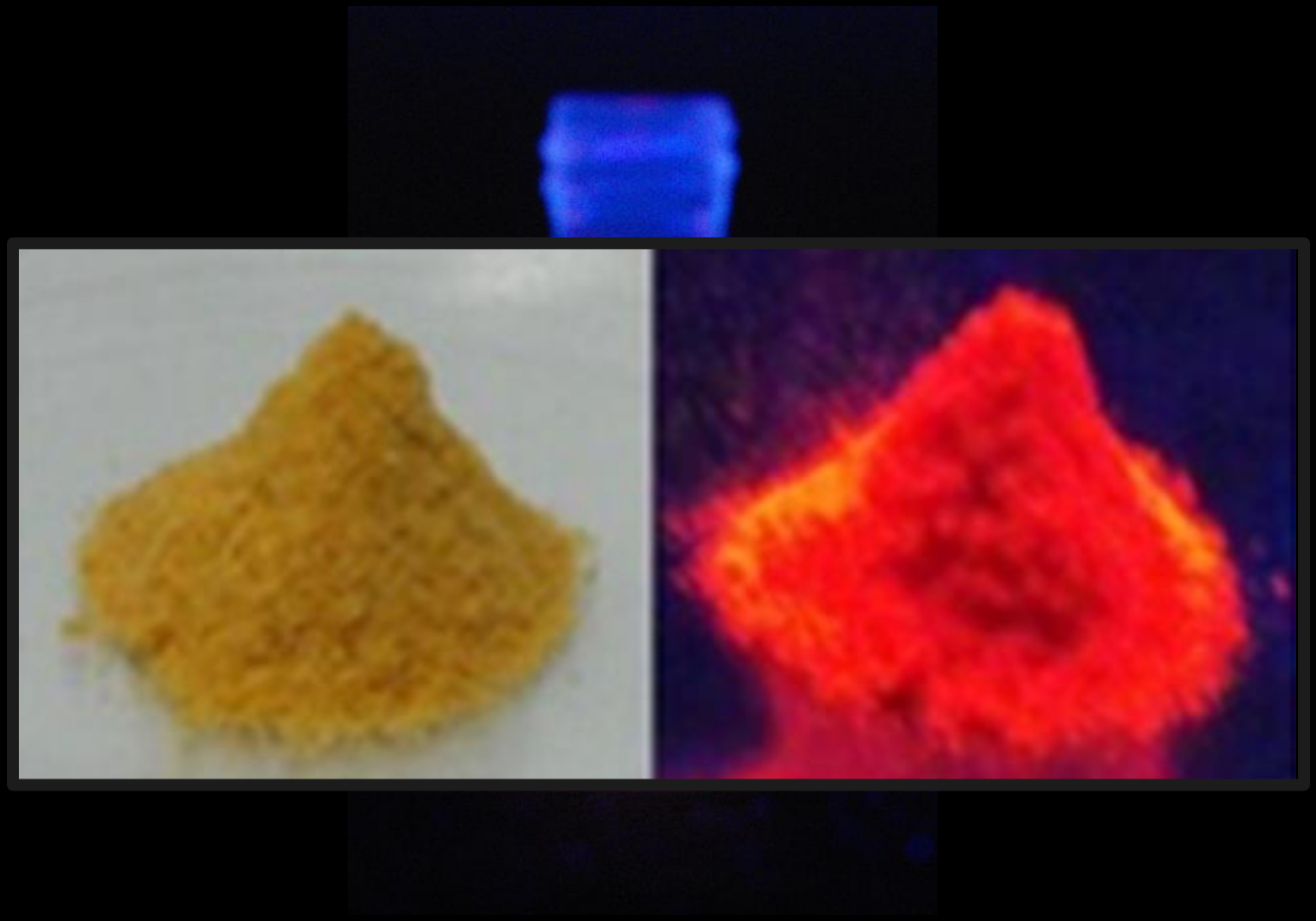
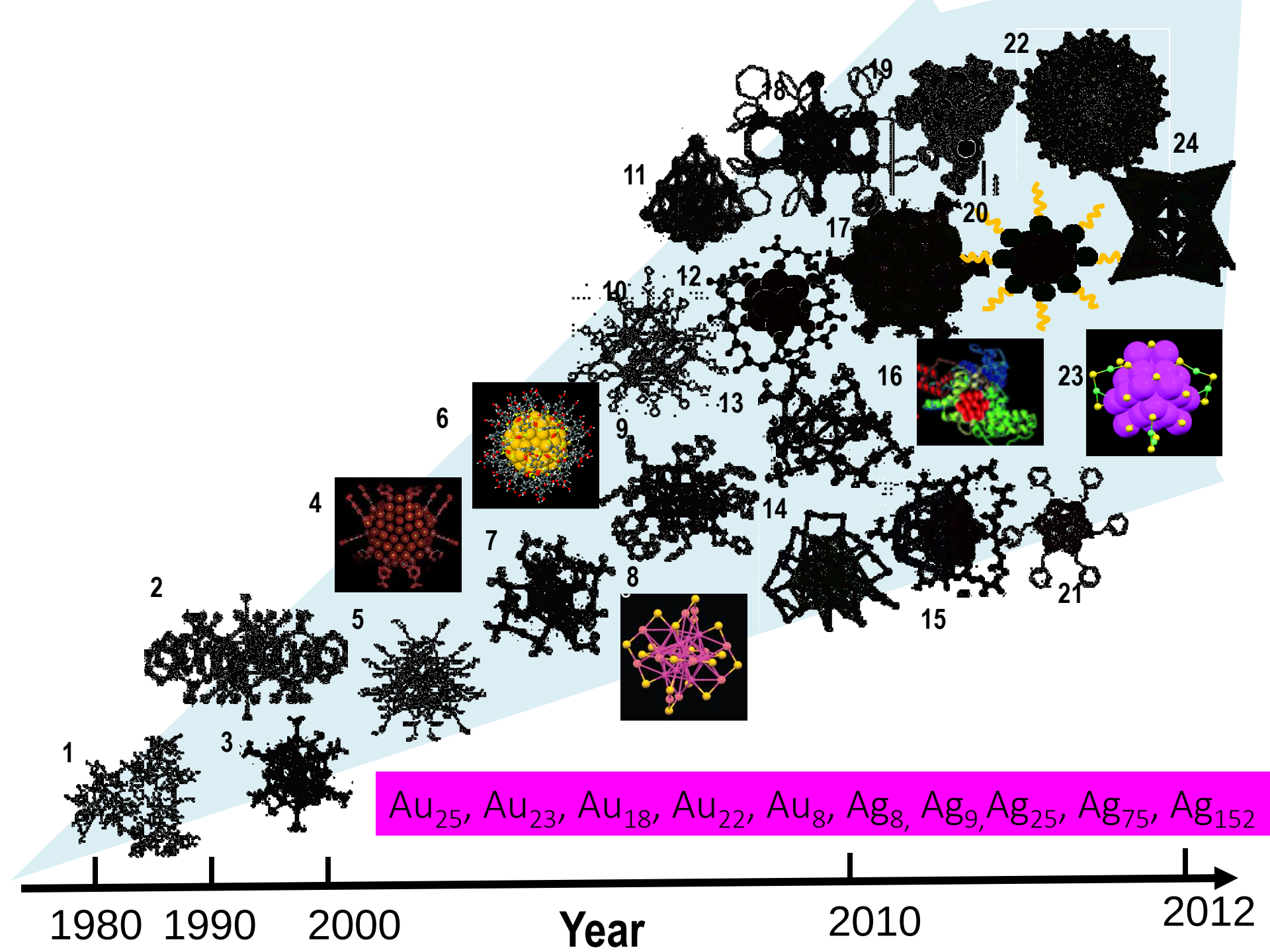


Fig. 1 Organization of full-shell clusters: a first single atom (purple) is surrounded by 12 others (green) to give a one-shell cluster M_{13}. 42 atoms (red) can be densely packed on the 12 green atoms ending with the M_{55} two-shell cluster, followed by 92 atoms (yellow) and 162 atoms (blue) to give M_{147} and M_{309}, respectively.

From Gunter Schmidt, *Chem. Soc. Rev.* **2008**, *37*, 1909–1930



Shibhu, Habeeb, Uday, Kamalesh, Lourdu, Ammu, Ananya, Indranath, Atanu,….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Au_{25}, Au_{23}, Au_{18}, Au_{22}, Au_{8}, $Ag_{8,}$ $Ag_{9,}$$Ag_{25}$, Ag_{75}, Ag_{152}
1980
1990
2000
Year
2010
2012

THE JOURNAL OF PHYSICAL CHEMISTRY Letters

Perspective

pubs.acs.org/JPCL

New Protocols for the Synthesis of Stable Ag and Au Nanocluster Molecules

T. Udayabhaskararao and T. Pradeep*

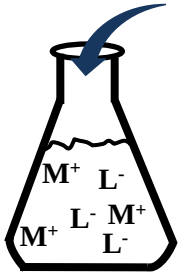
DST Unit of Nanoscience (DST UNS), Thematic Unit of Excellence (TUE), Department of Chemistry, Indian Institute of Technology Madras, Chennai 600 036, India

ABSTRACT: "Catching" metals in the nonmetallic form in solution, as they grow to bulk, is one of the most exciting areas of contemporary materials research. A new kind of stabilization to catch the nonmetallic form of noble metals with small thiols has evolved as an exciting area of synthesis during the past decade. Gold clusters stay in the frontline of this research, yielding new "molecules" composed of a few to several hundreds of atoms. By taking guidelines from gold cluster research, various new protocols for silver nanoclusters were developed. In this Perspective, we highlight the recent advances on the synthesis of atomically precise silver, gold, and their alloy clusters with a special emphasis on silver. As a result of intense efforts of the recent past, clusters such as $Ag_{7,8}(SR)_{7,8}$, $Ag_7(-S-R-S-)_4$, $Ag_9(SR)_7$, $Ag_{32}(SR)_{19}$, $Ag_{44}(SR)_{30}$, $Ag_{140}(SR)_{53}$, $Ag_{280}(SR)_{140}$, and $Ag_{152}(SR)_{60}$ (SR and S−R−S refer to thiolate and dithiolate ligands, respectively) were added to the literature. Moreover, "silver-covered" and "gold-covered" alloy clusters have also been synthesized. Early reports of the crystallization of such clusters are available. Several of these clusters are shown to act as sensors, catalysts, and pesticide degradation agents, which suggests that these materials may find applications in daily life in the foreseeable future.

Ghosh et al. J. Phys. Chem. Lett. **2012**, 3, 1997

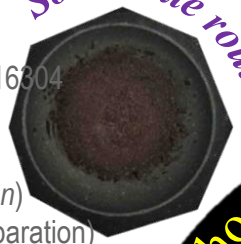
Diverse methods of synthesis

Slow reduction



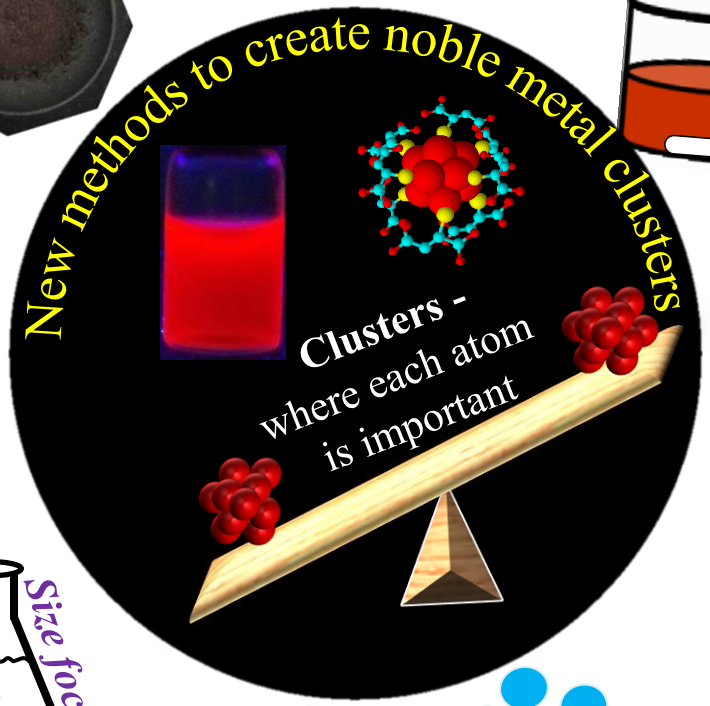
Habeeb *et al. Chem. Eur. J.* **2009**, *15*, 10110
Udayabhaskararao et. al. Angew. Chem. Int. Ed. **2010**, *49*, 392
Mrudula *et al. J. Mater. Chem.* **2009**, *19*, 4335

Solid state route



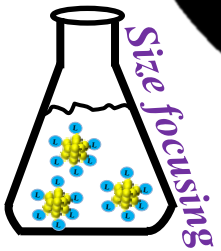
Udayabhaskararao et al. J. Am. Chem. Soc..**2010**, *132*, 16304
Indranath *et al. Nano Lett.* **2012,** *12,* 5861
Anindya *et al. J. Nanoparticle Res.* (In Press)
Udayabhaskararao et al. J. Phys. Chem. C **2012** (*Revison*)
Udayabhaskararao et al. J. Nanoparticle Res. **2013** (Peparation)

Interfacial etching



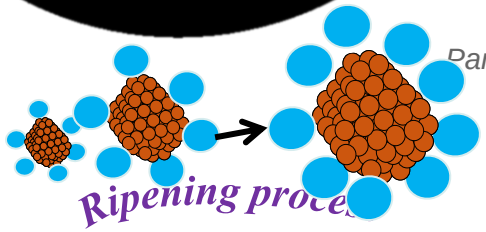
Indranath *et al. J. Haz. Mater.* **2012**, *211-212*, 396
Aditi and T. Pradeep *J. Phys. Chem. C* **2012,** *116*,14057
Remya et al. J. Phys. Chem. C, **2012**, *116*, 26019

Inside gels



Size focusing

Indranath *et al. Chem. Commun.***2012**, *48*, 859
Dhanalakshmi *et al. Chem. Commun.* **2012**, 48, *6788*
Shibu and T. Pradeep, *Chem. Mater.* 2011, 23, 989
Shibu *et al.* J. Phys. Chem C **2008** 112, 12168
Shibu *et al. ACS Appl. Mater. Interfaces*, 2009, 1, 2199
Habeeb *et al.* Nano Res. **2008**, 1, 333



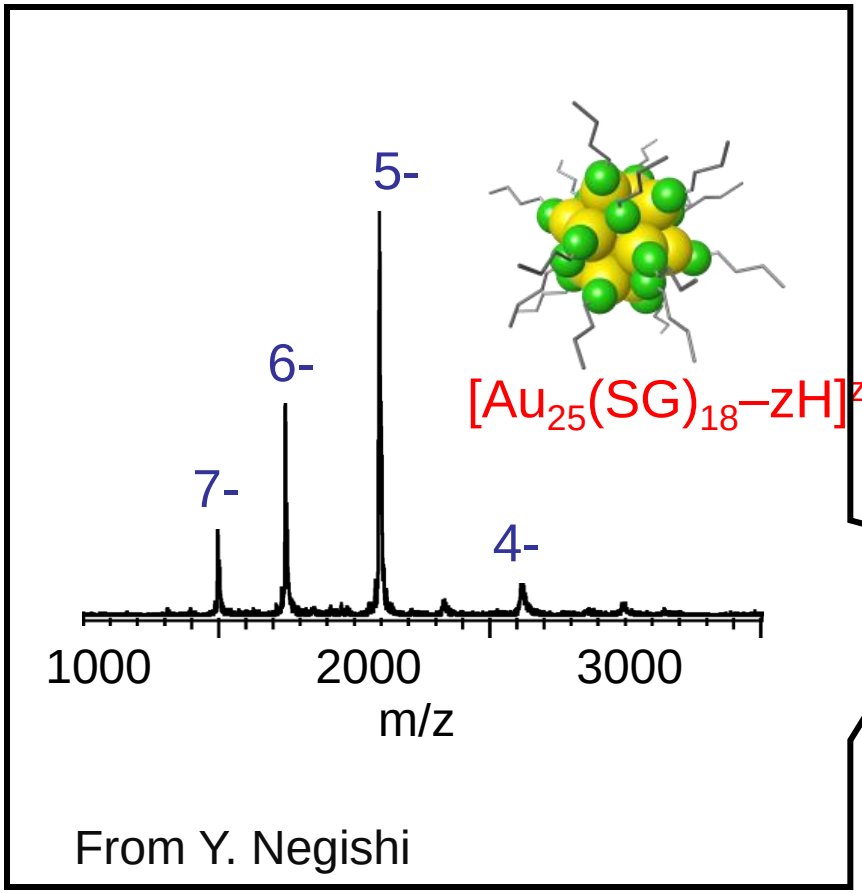
Ripening proce

Part. Part. Syst. Char. (*2013*)

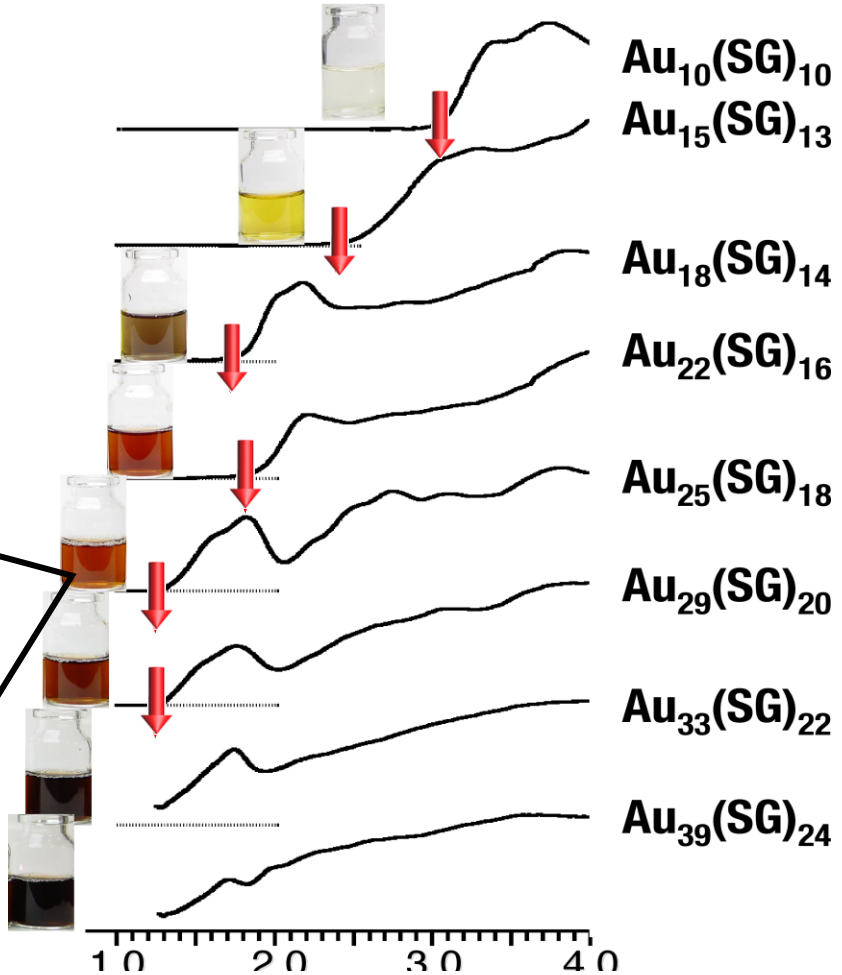
T. Udayabhaskararao and T. Pradeep, J. Phys. Chem. Lett. 4 (2013) 1553–1564

Systematic Isolation of Glutathione-Protected Gold clusters

Negative ESI mass spectrum



UV-vis absorption spectra

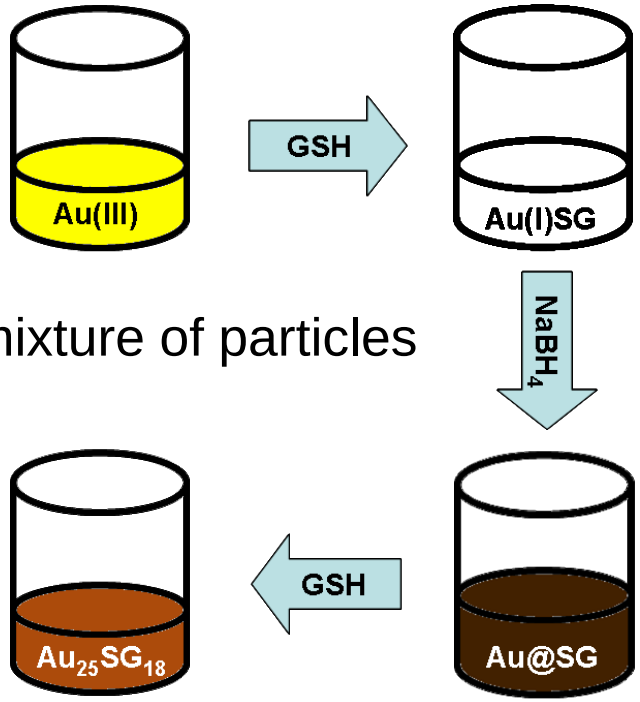


Negishi, Y.; Nobusada, K.; and Tsukuda, T.
J. Am. Chem. Soc. **2005**, *127*, 5261-70.

$Au_{25}SG_{18}$

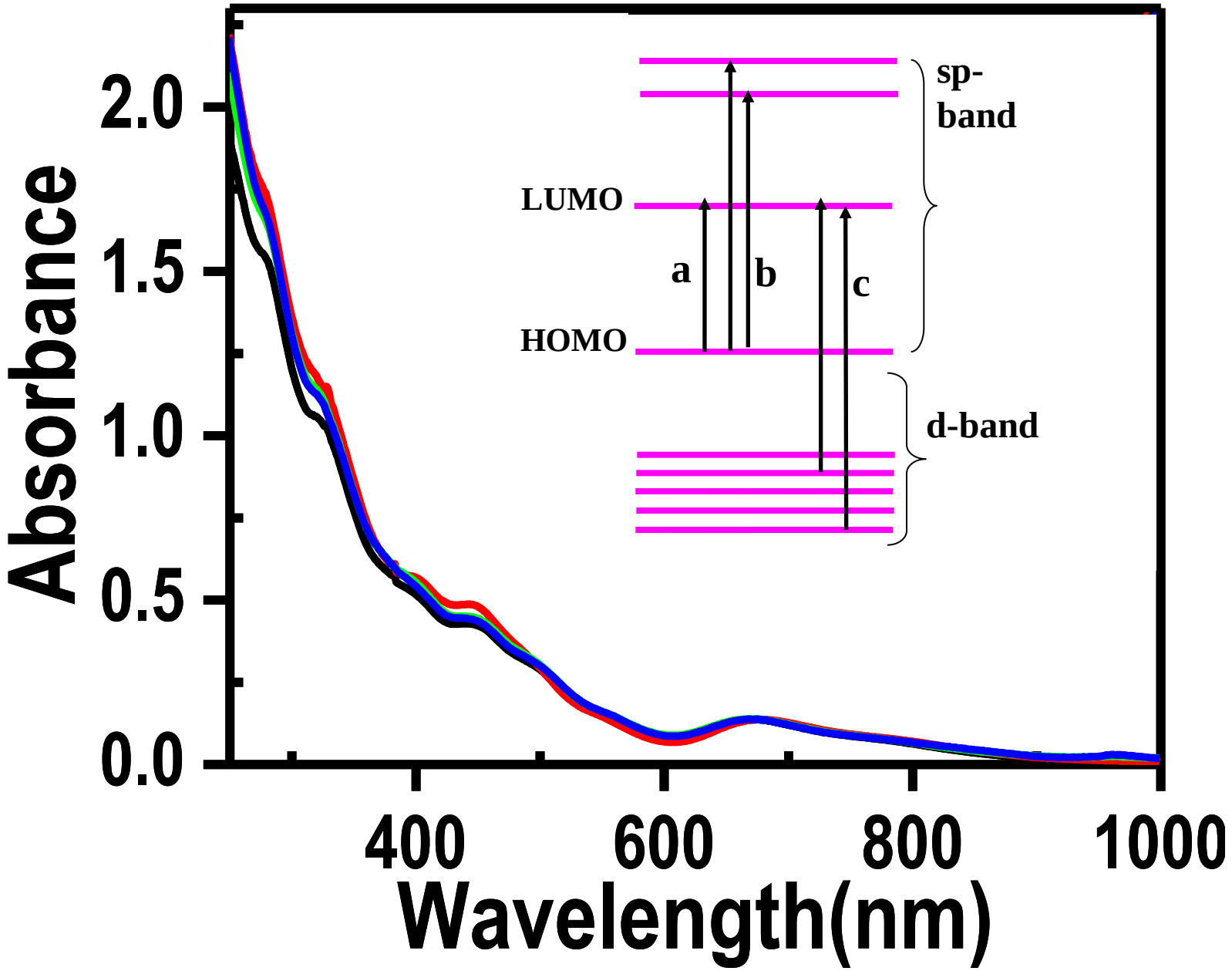
Synthesis: Au_{25} clusters can be preferentially populated by dissociative excitation of larger precursors

Direct synthesis from mixture of particles

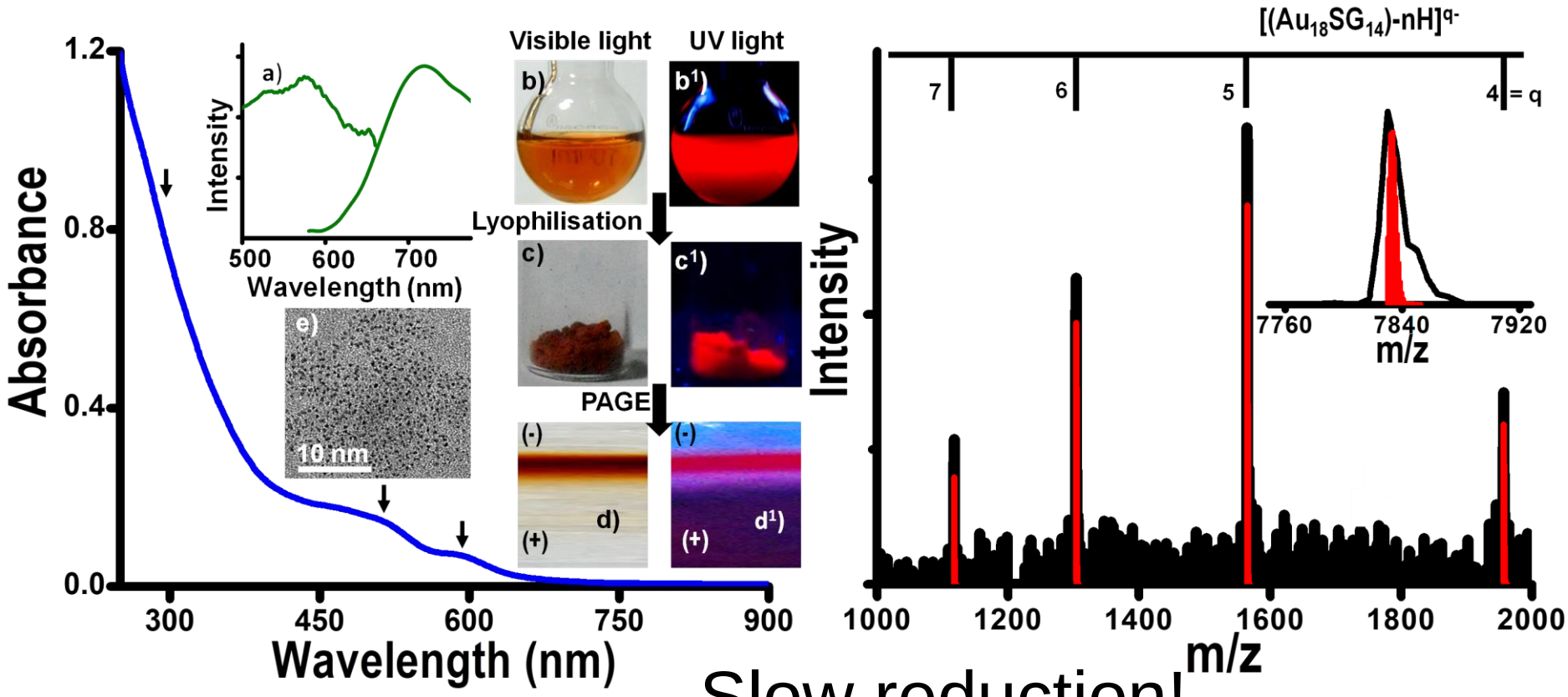


Scheme showing the synthesis of $Au_{25}SG_{18}$ clusters

E. S. Shibu et al. J. Phys. Chem. C. 2008


Absorbance
2.0
1.5
1.0
0.5
0.0
400
600
800
1000
Wavelength(nm)
sp-
band
LUMO
a
b
c
HOMO
d-band

One step methods - $Au_{18}SG_{14}$



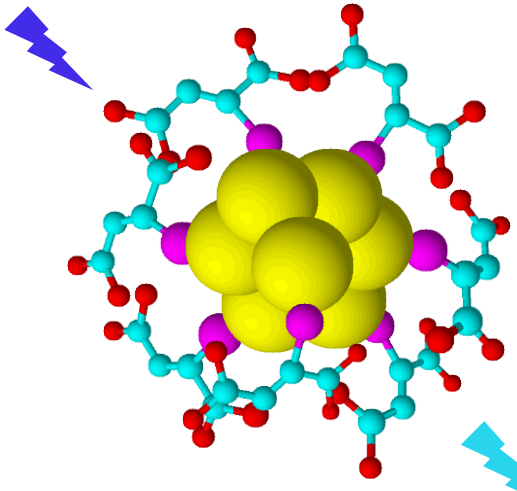
Slow reduction!

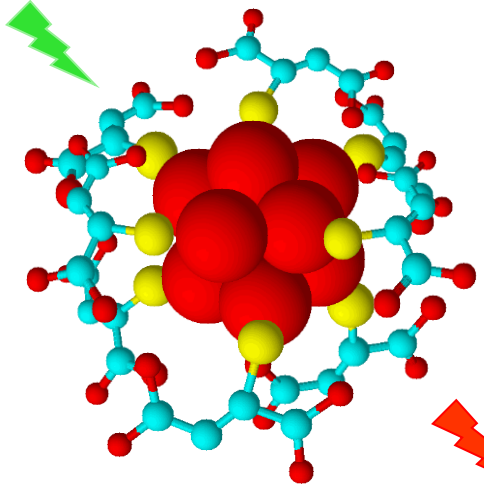
Atanu Ghosh, T. Udaya Bhaskara Rao and T. Pradeep, J. Phys. Chem. Lett., 3 (2012) 1997-2002

Silver clusters - interfacial etching

350 nm

550 nm



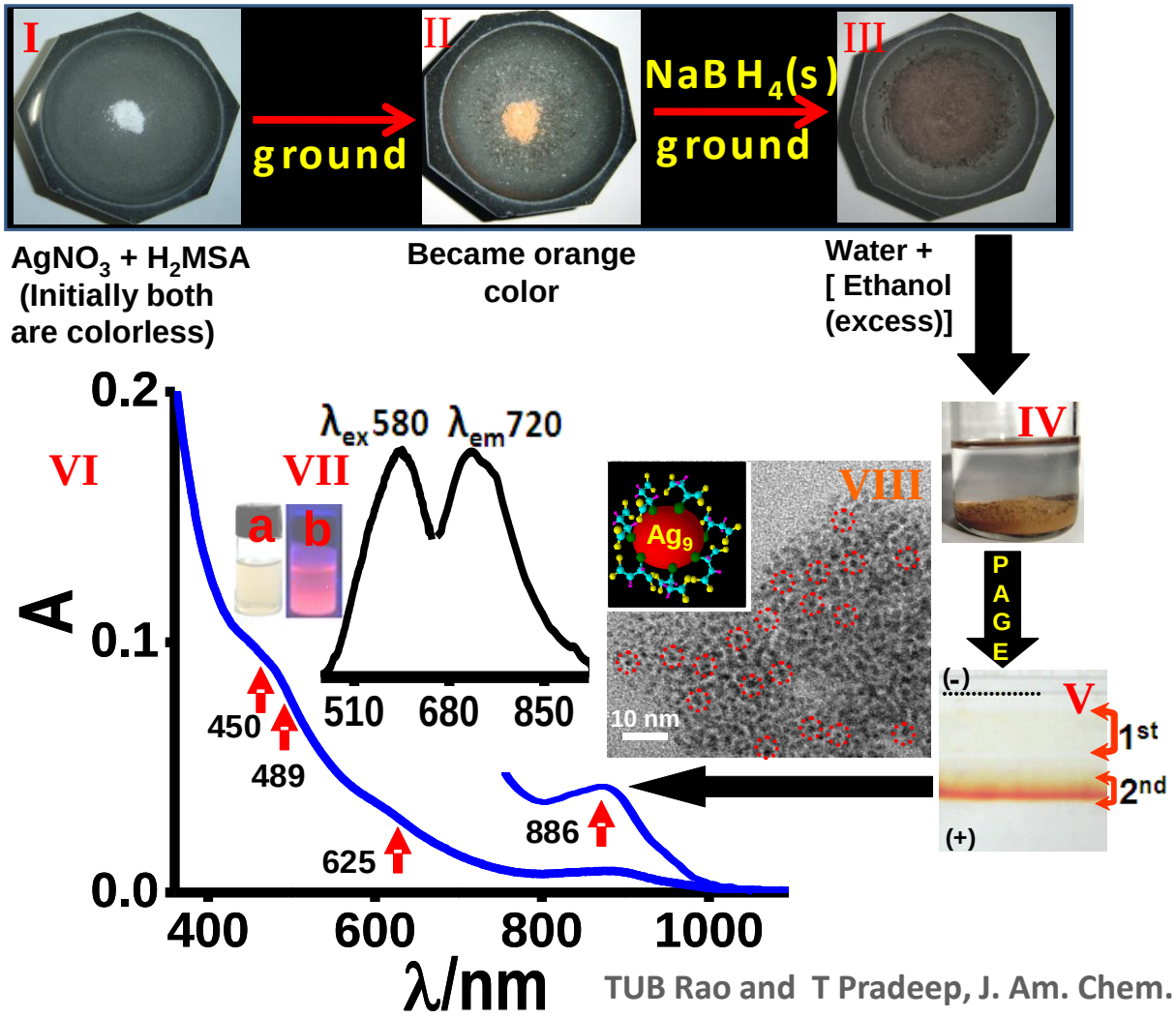


550 nm

640 nm

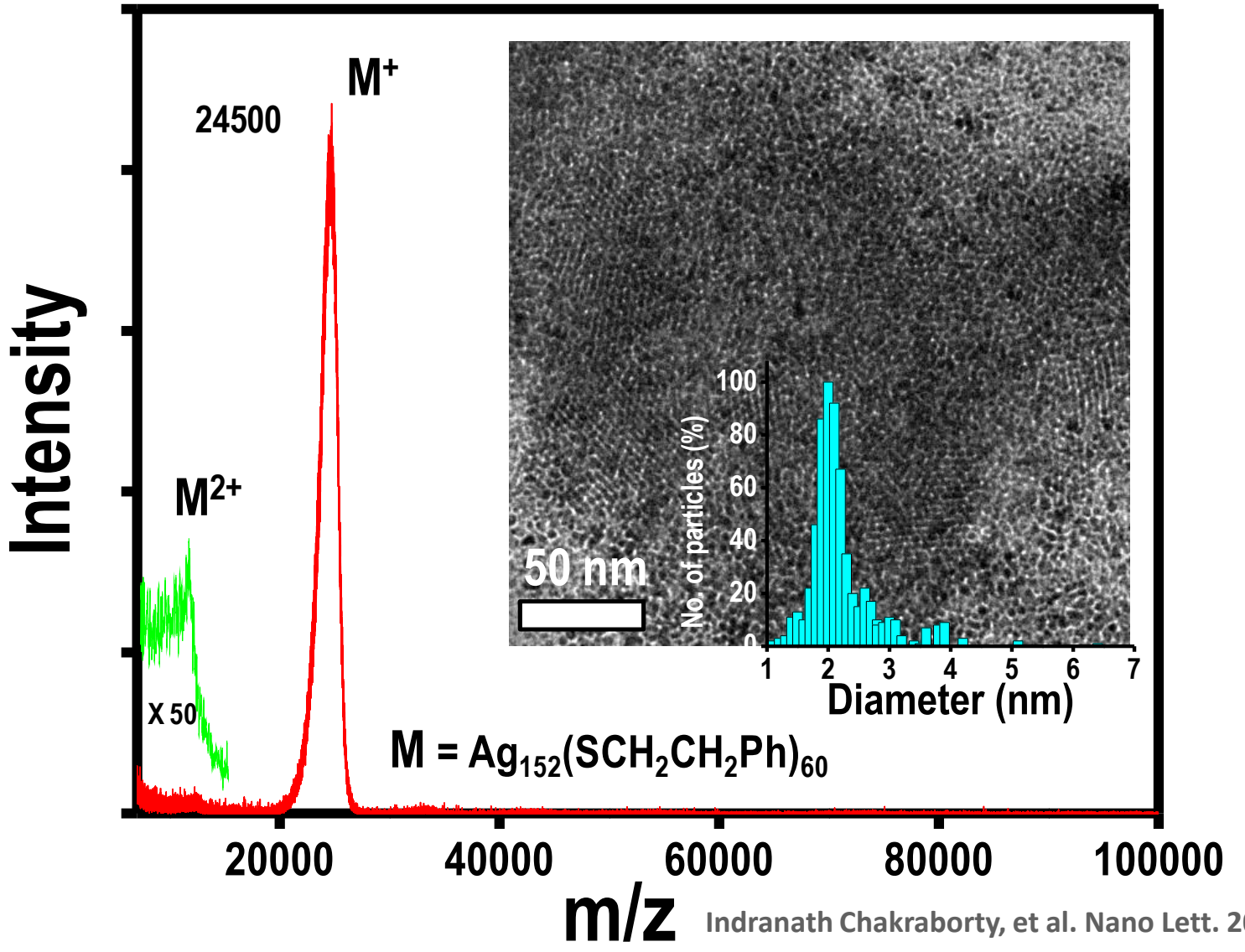
TUB Rao and T Pradeep, Angew. Chem. Int. Ed. 49 (2010) 3925-3929(2010).

Ag_9MSA_7 - solid state synthesis

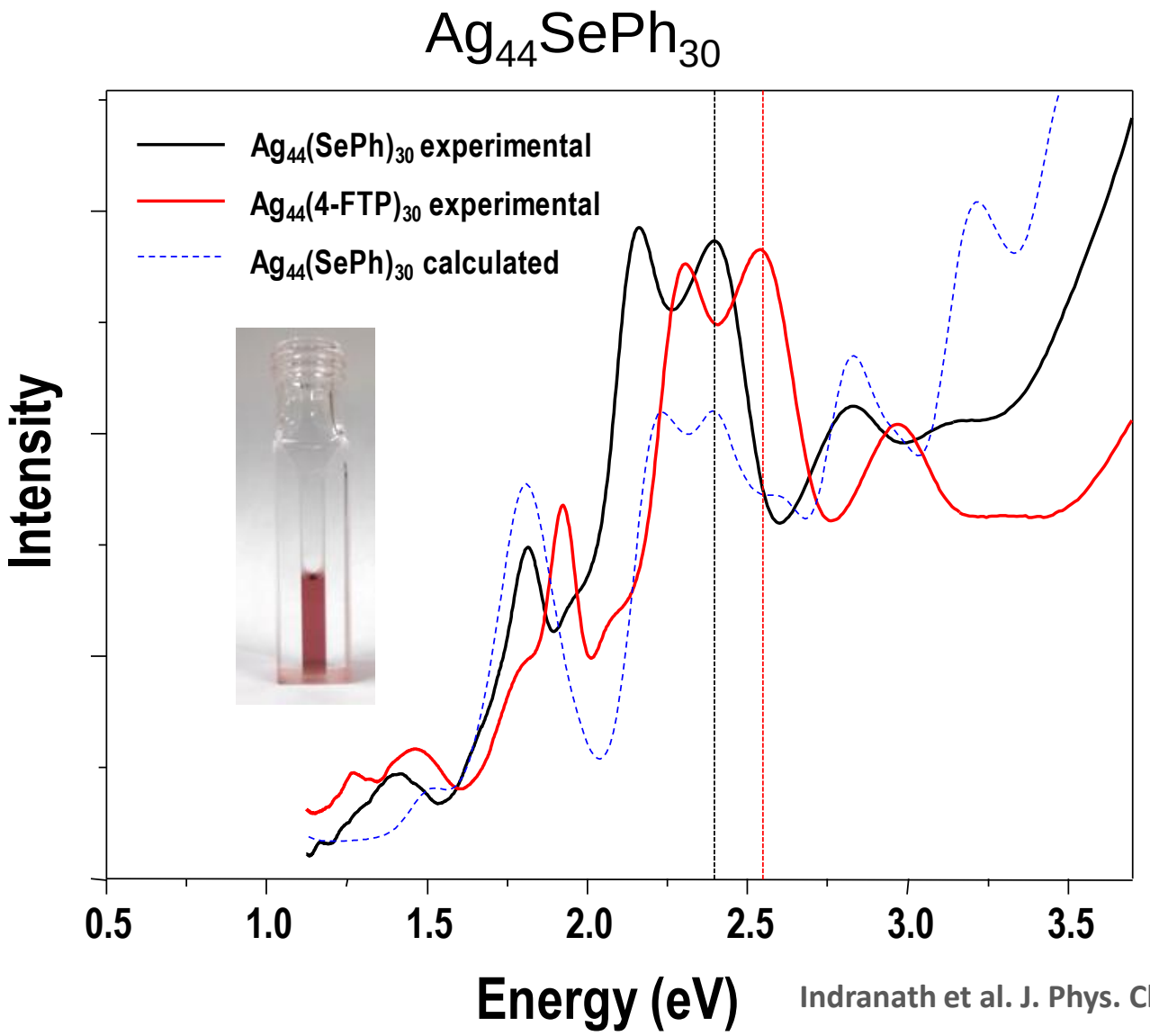


TUB Rao and T Pradeep, J. Am. Chem. Soc. 132 (2010) 16304-16307.

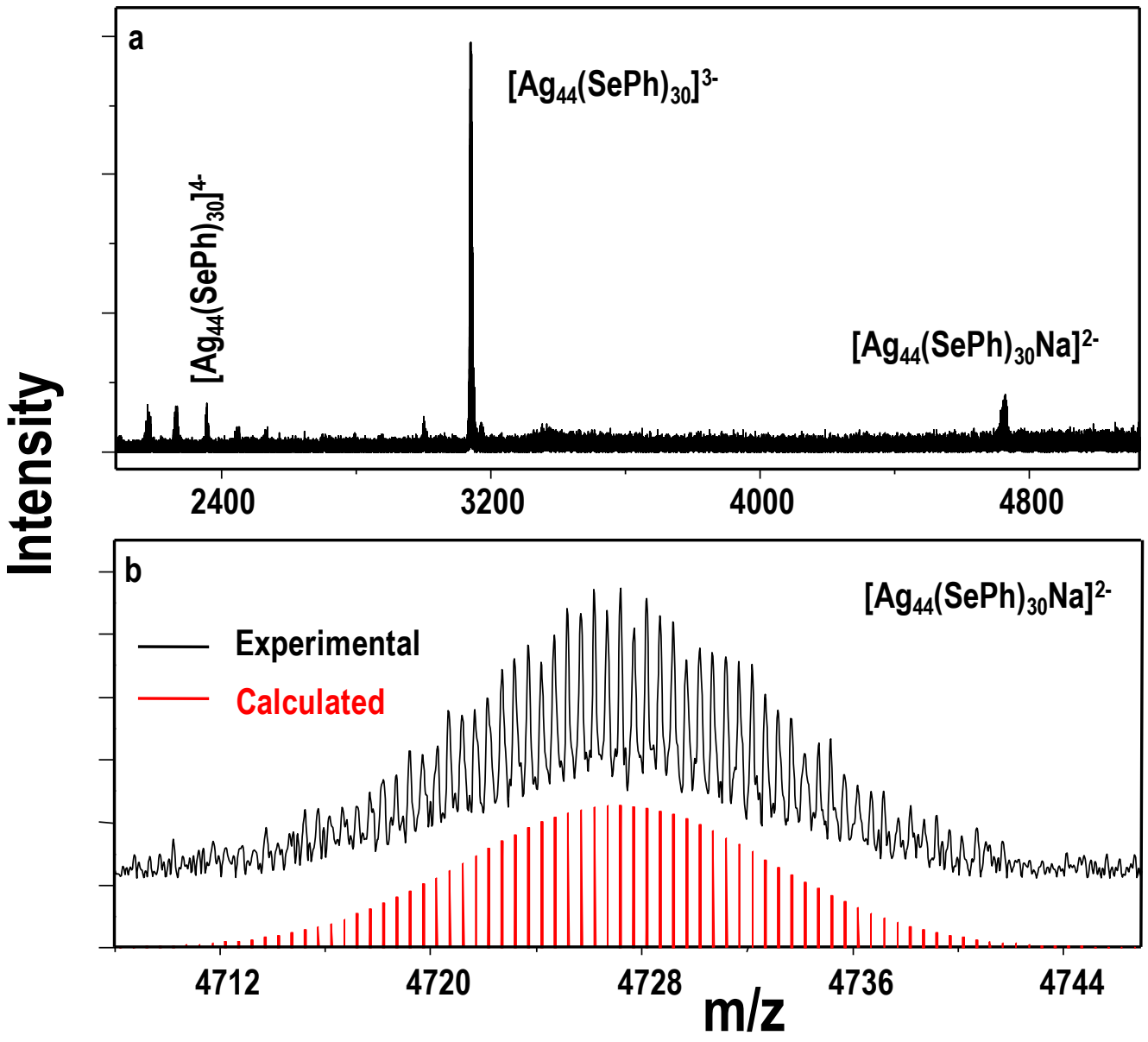
$Ag_{152}PET_{60}$



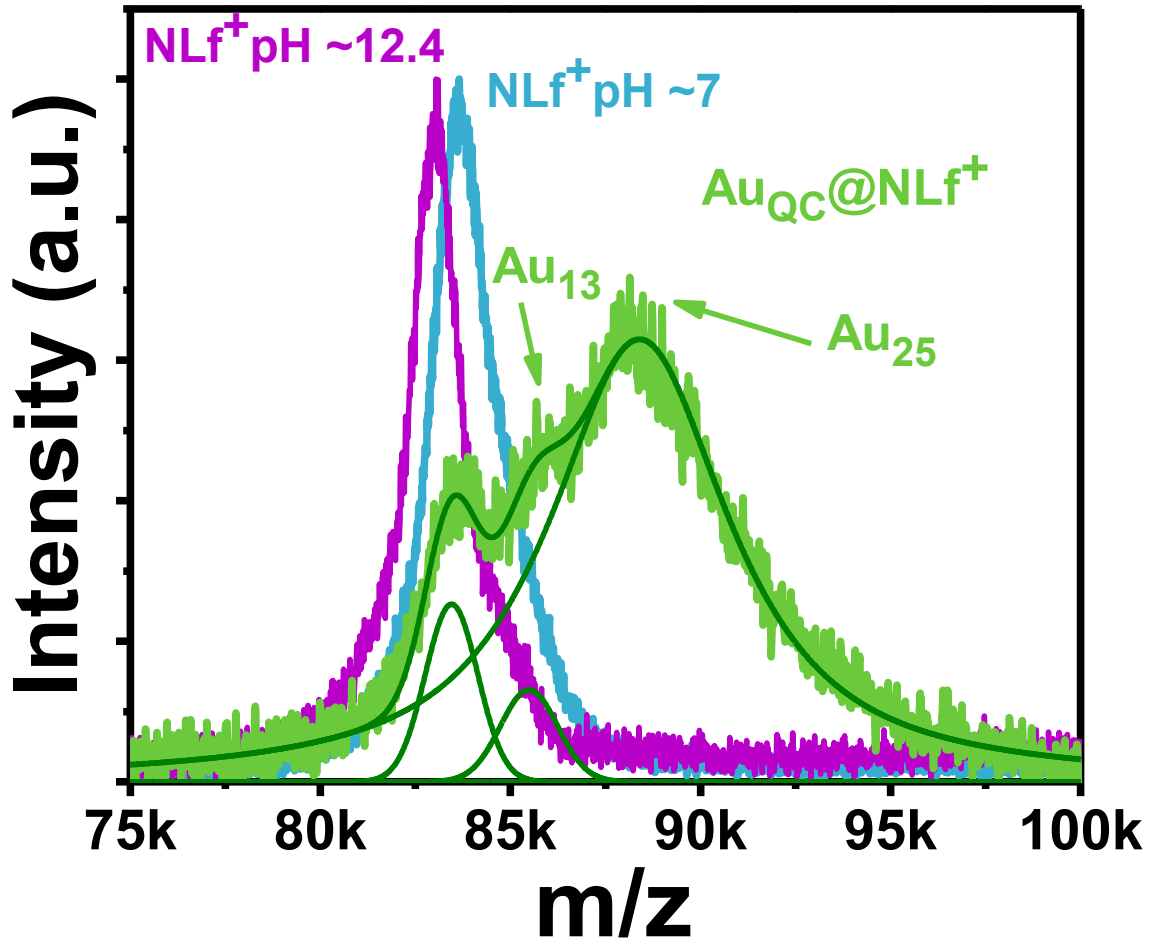
Indranath Chakraborty, et al. Nano Lett. 2012 With Uzi Landm



Indranath et al. J. Phys. Chem. Lett. 2013


a
$[Ag_{44}(SePh)_{30}]^{3-}$
$[Ag_{44}(SePh)_{30}]^{4-}$
$[Ag_{44}(SePh)_{30}Na]^{2-}$
2400
3200
4000
4800
Intensity
b
$[Ag_{44}(SePh)_{30}Na]^{2-}$
Experimental
Calculated
4712
4720
4728
4736
4744
m/z

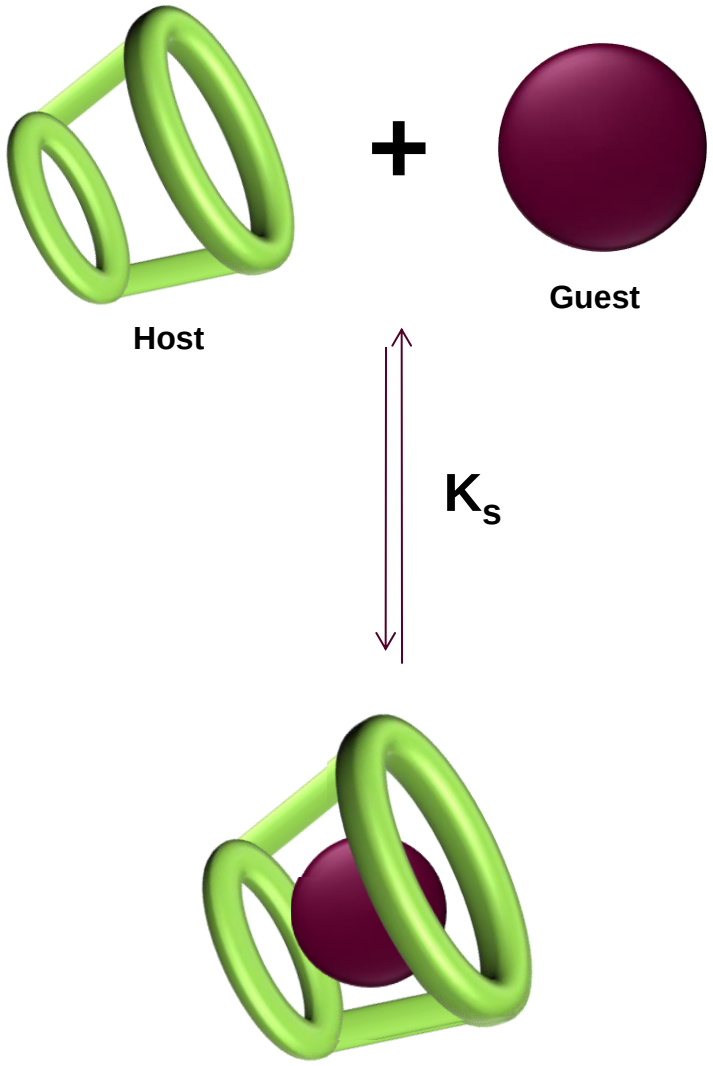
Cluster nucleation in proteins

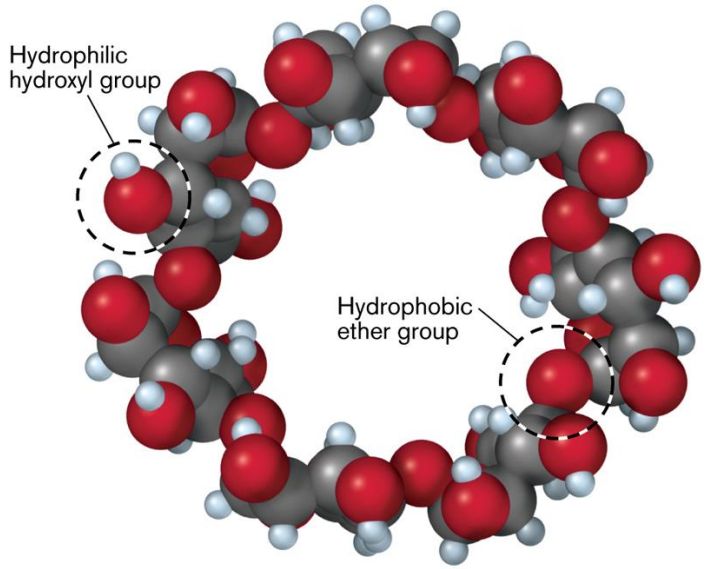


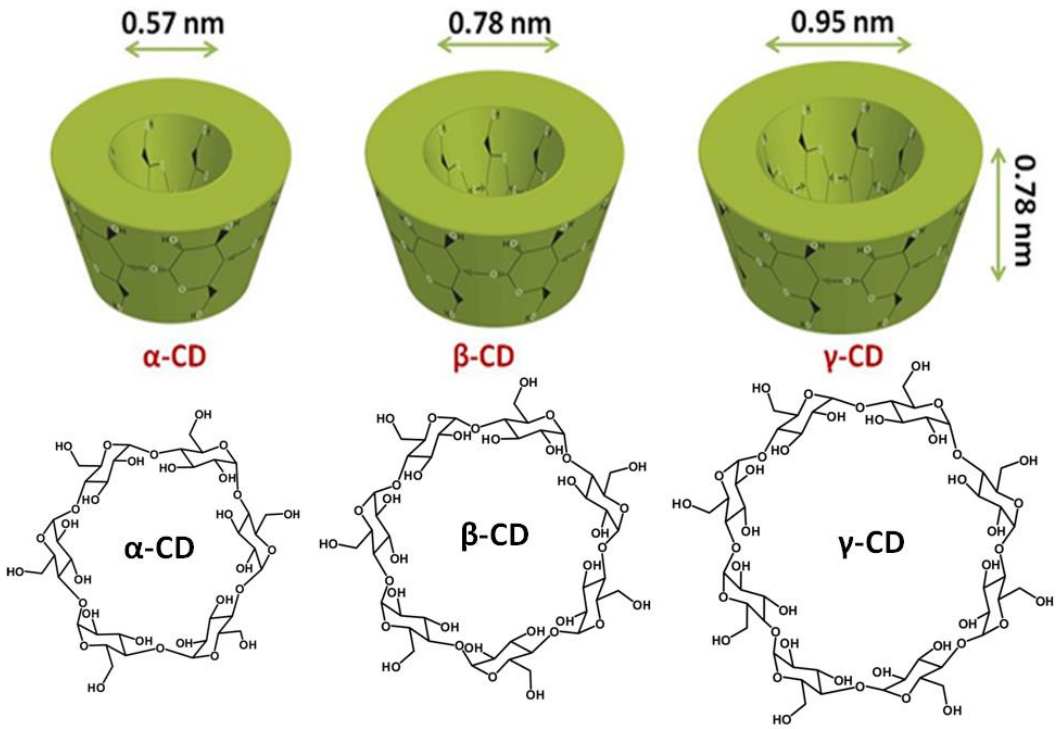
Kamalesh Choudhari et al. ACS Nano (2011)

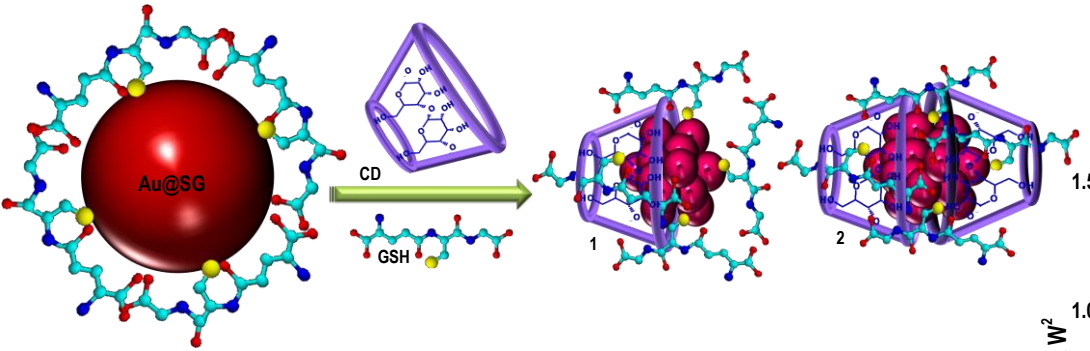
Clusters in cavities

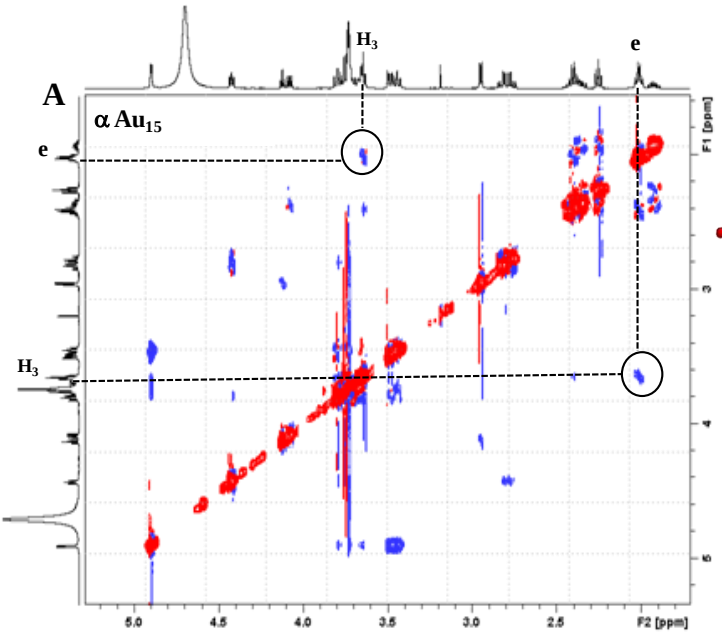
Cluster assemblies and host-guest complexes

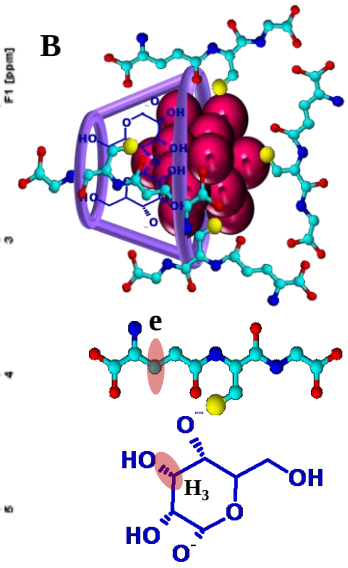


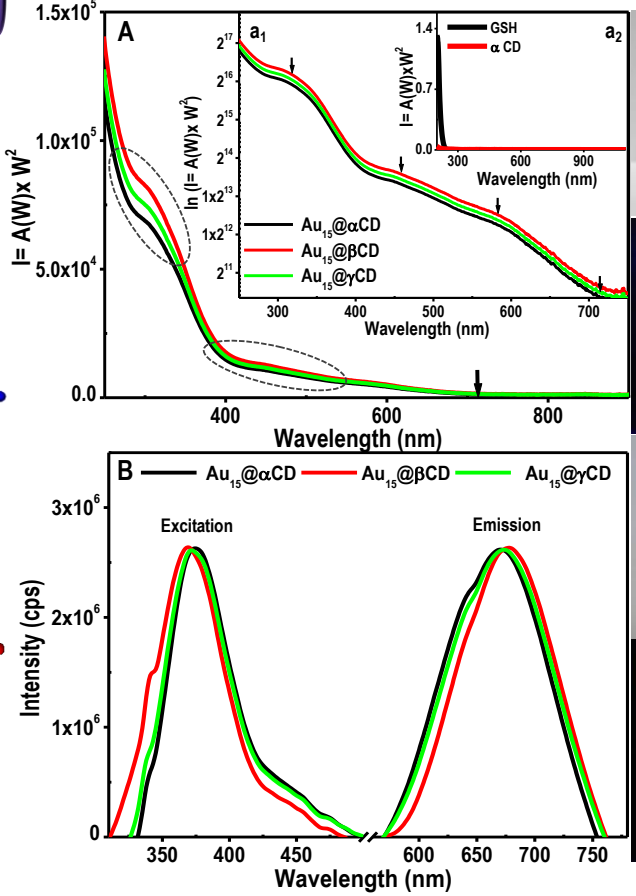


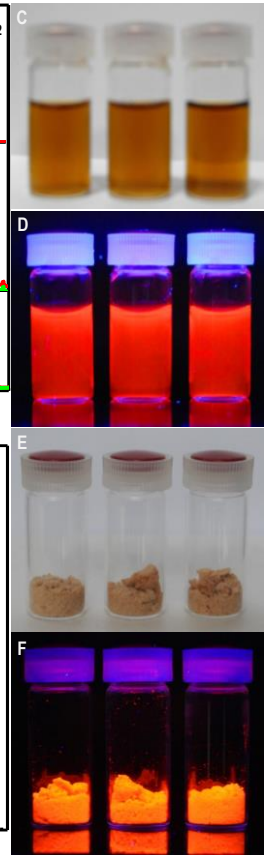








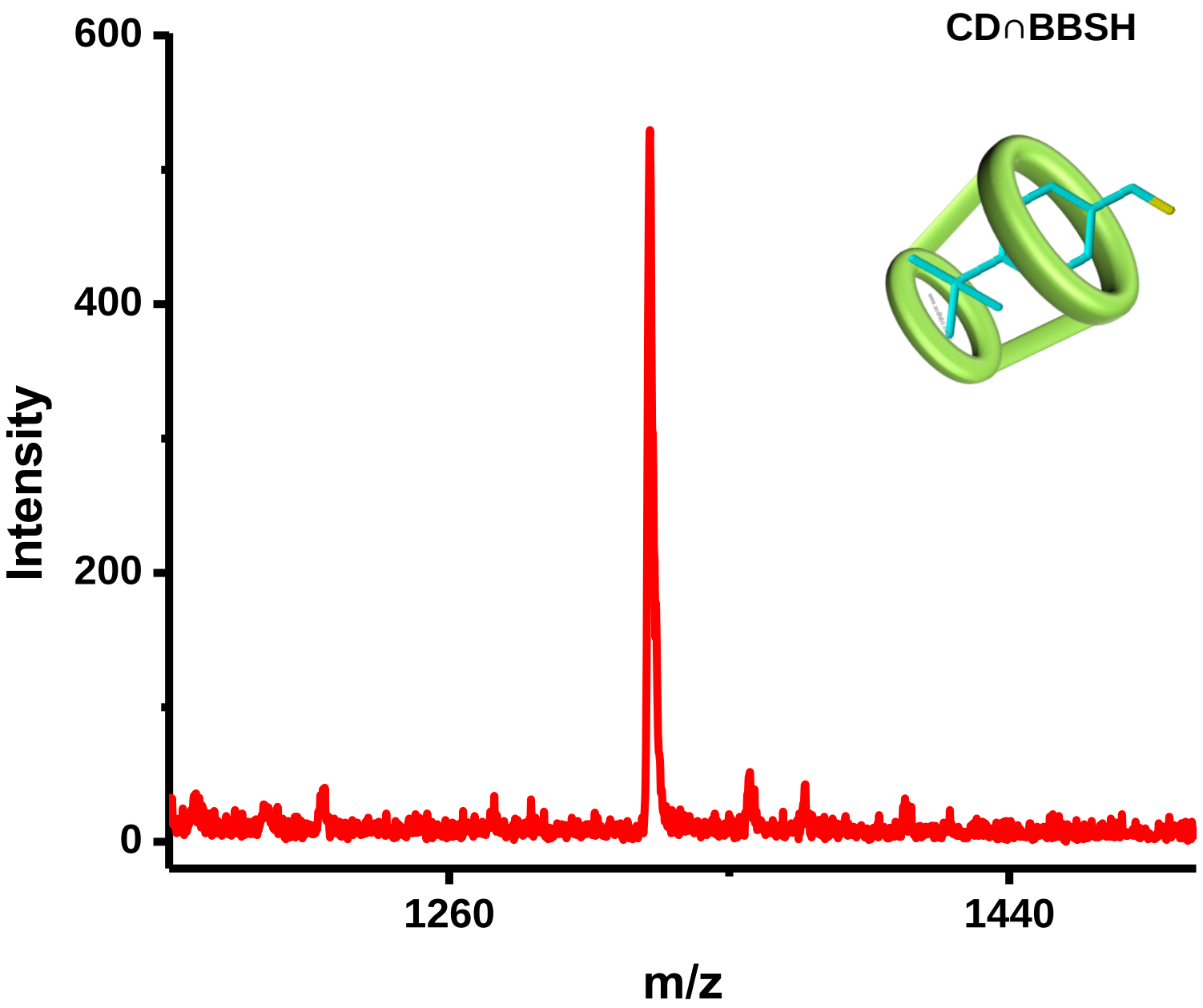




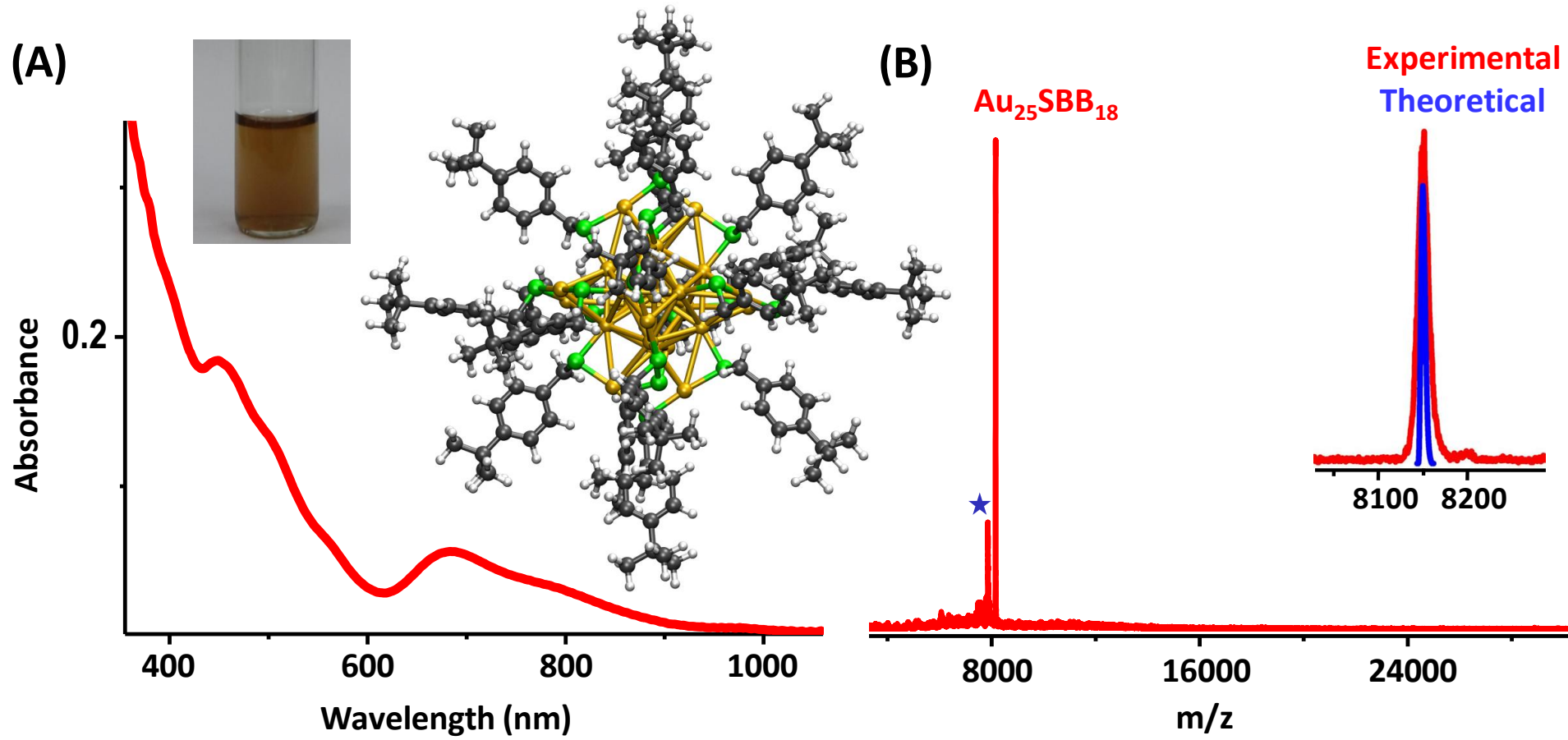
Indian patent, 4036/CHE/2010, filed on December 30, 2010.

E. S. Shibu and T. Pradeep, Chem. Mater. 23 (2011) 989–999.

Positive mode MALDI of BBSH∩CD complex

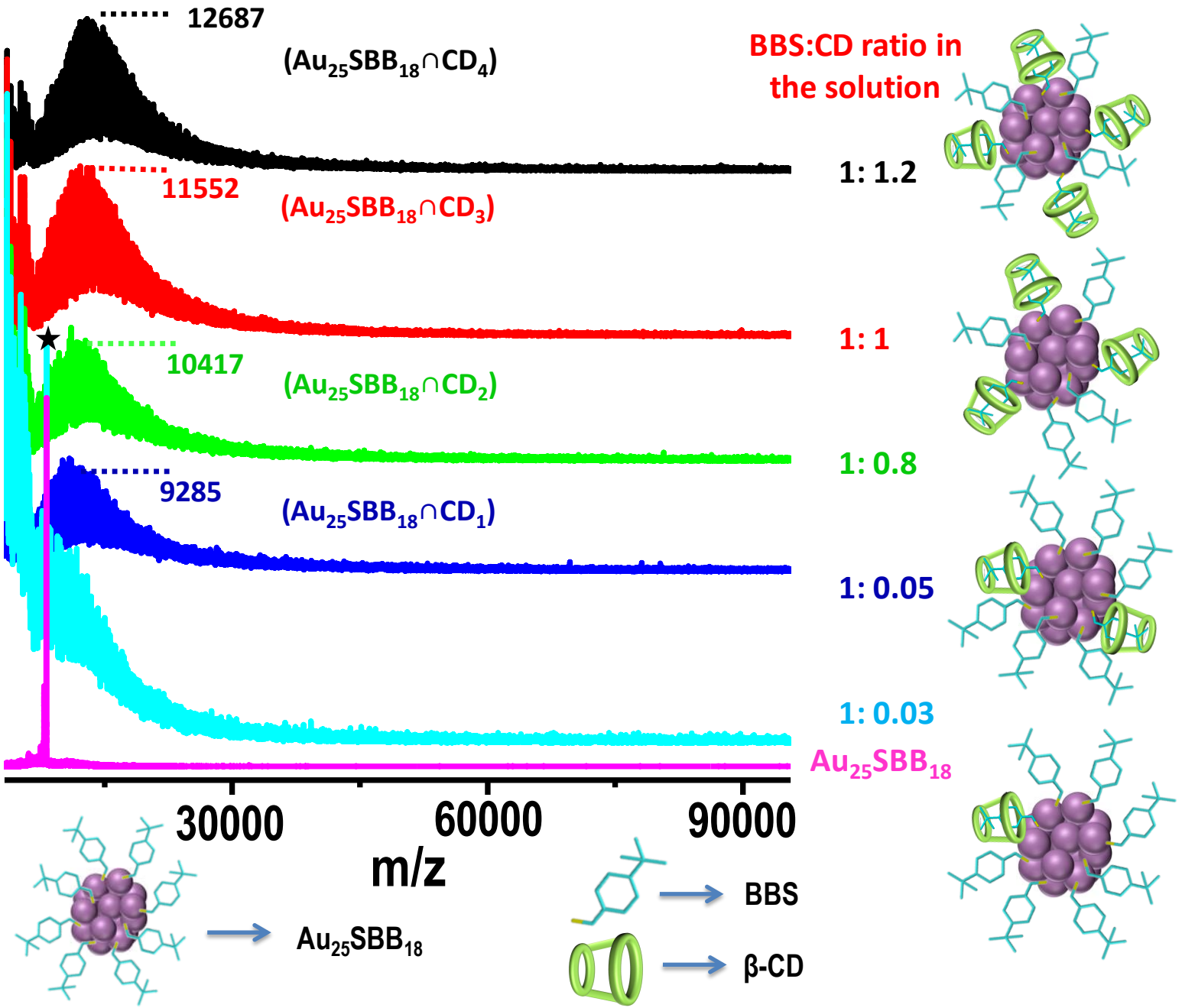


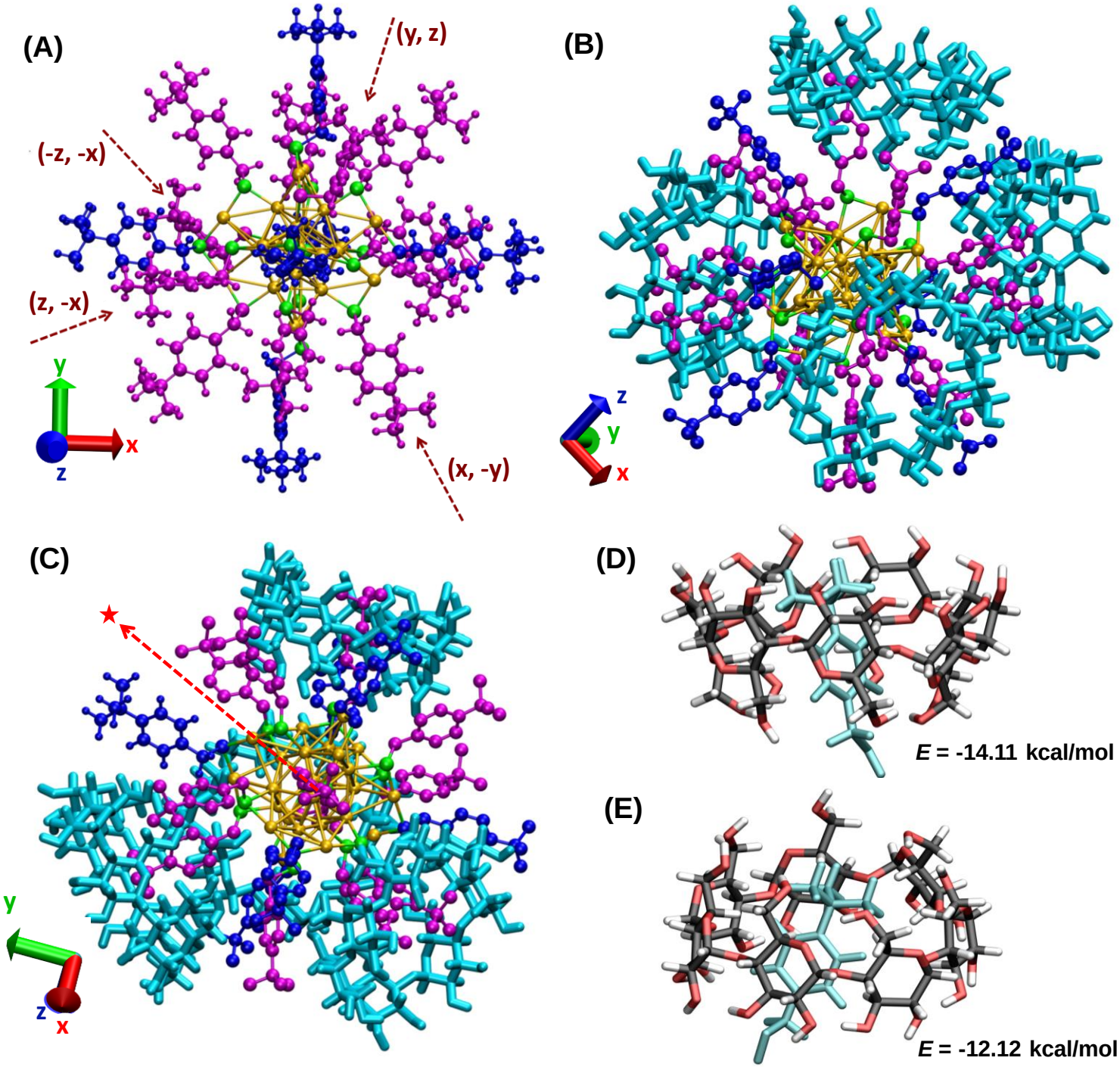
$Au_{25}SBB_{18}$

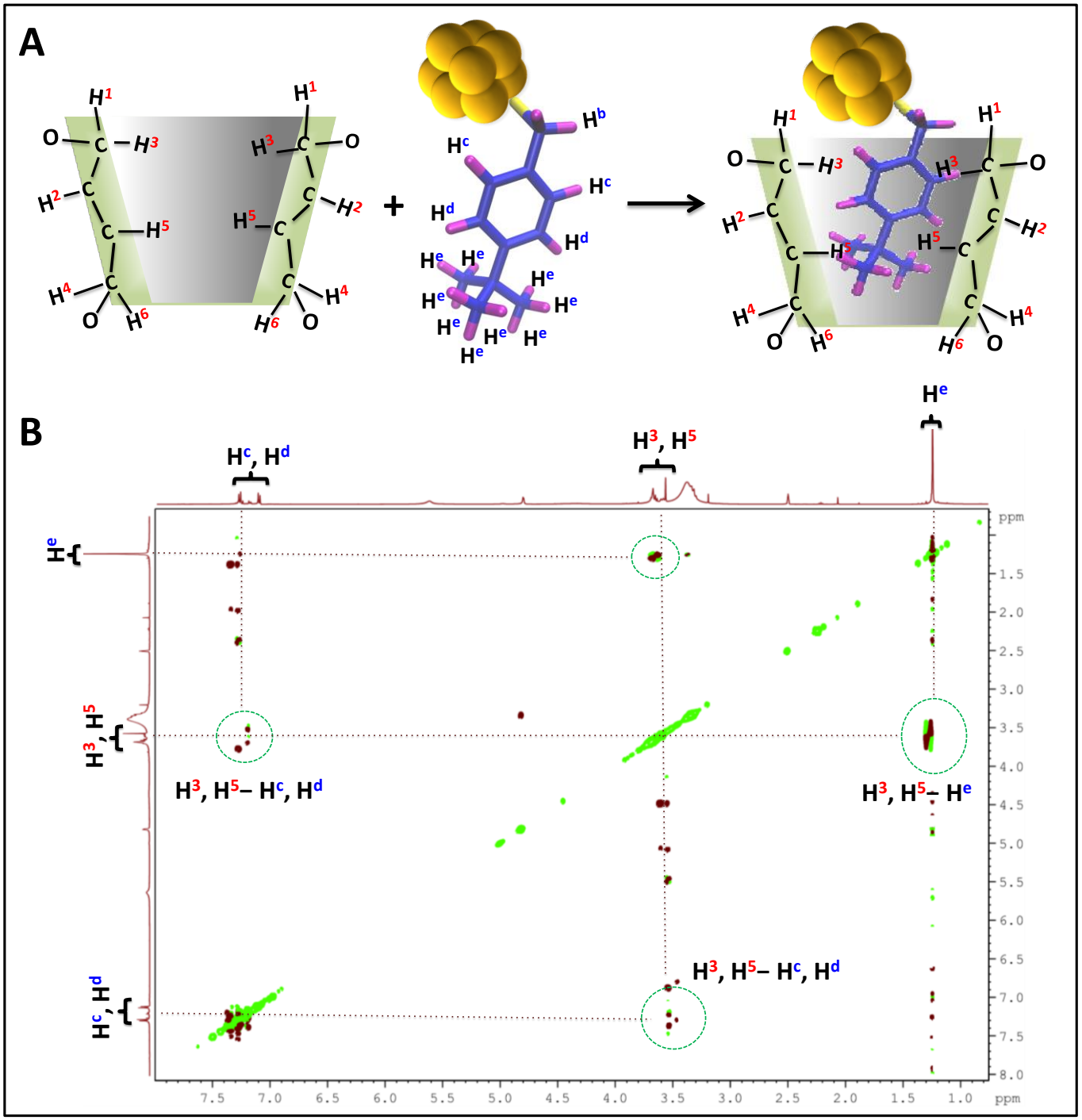


Ammu Mathew et al. ACS Nano 2014.

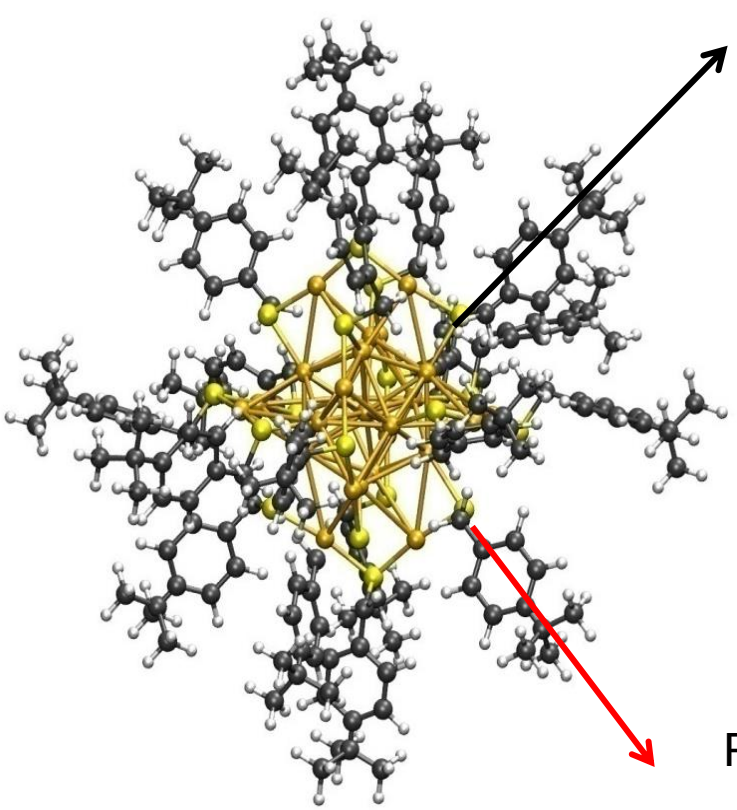
$Au_{25}BBS_{18}\cap CD$




(A)
(y, z)
(-z, -x)
(z, -x)
(x, -y)
y
x
z
(B)
z
y
x
(C)
y
z
x
(D)
E = -14.11 kcal/mol
(E)
E = -12.12 kcal/mol


A
B
H1
H2
H3
H4
H5
H6
O
C
Hb
Hc
Hd
He
Hc, Hd
H3, H5
He
H3, H5
He
H3, H5– Hc, Hd
H3, H5– He
Hc, Hd
H3, H5– Hc, Hd
ppm
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
8.0

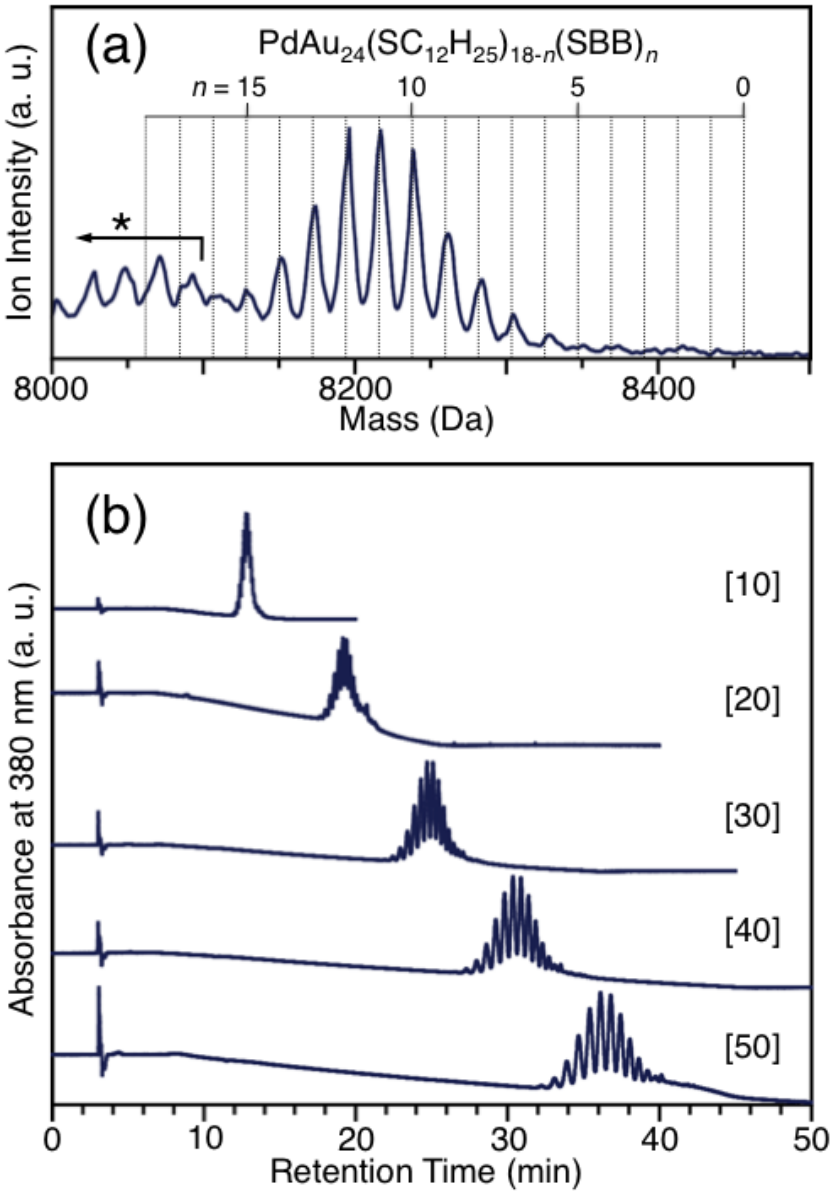
Substitution chemistry of clusters



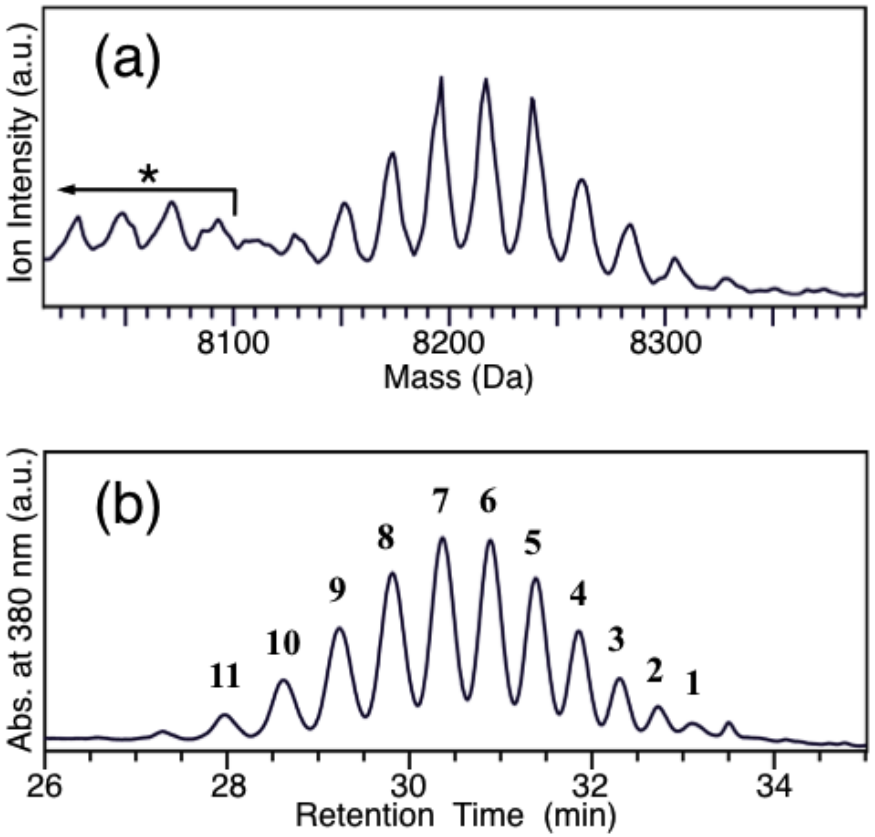
Mixed functionalised clusters

Yoshiki Niihori, Miku Matsuzaki, T. Pradeep and Yuichi Negishi, J. Am. Chem. Soc., 135 (2013) 4946-4949

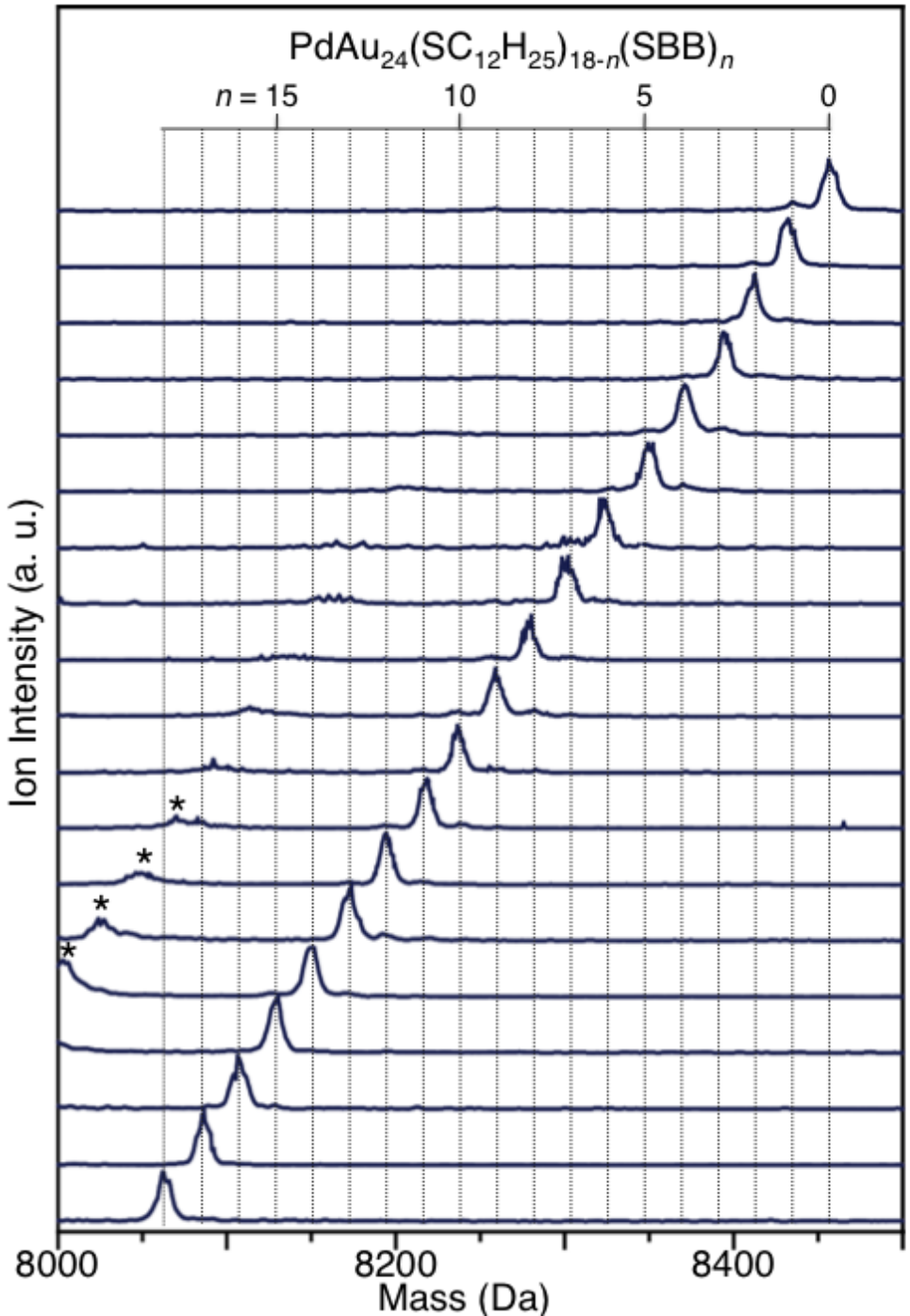
Separation of precise compositions of noble metal clusters protected with mixed ligands

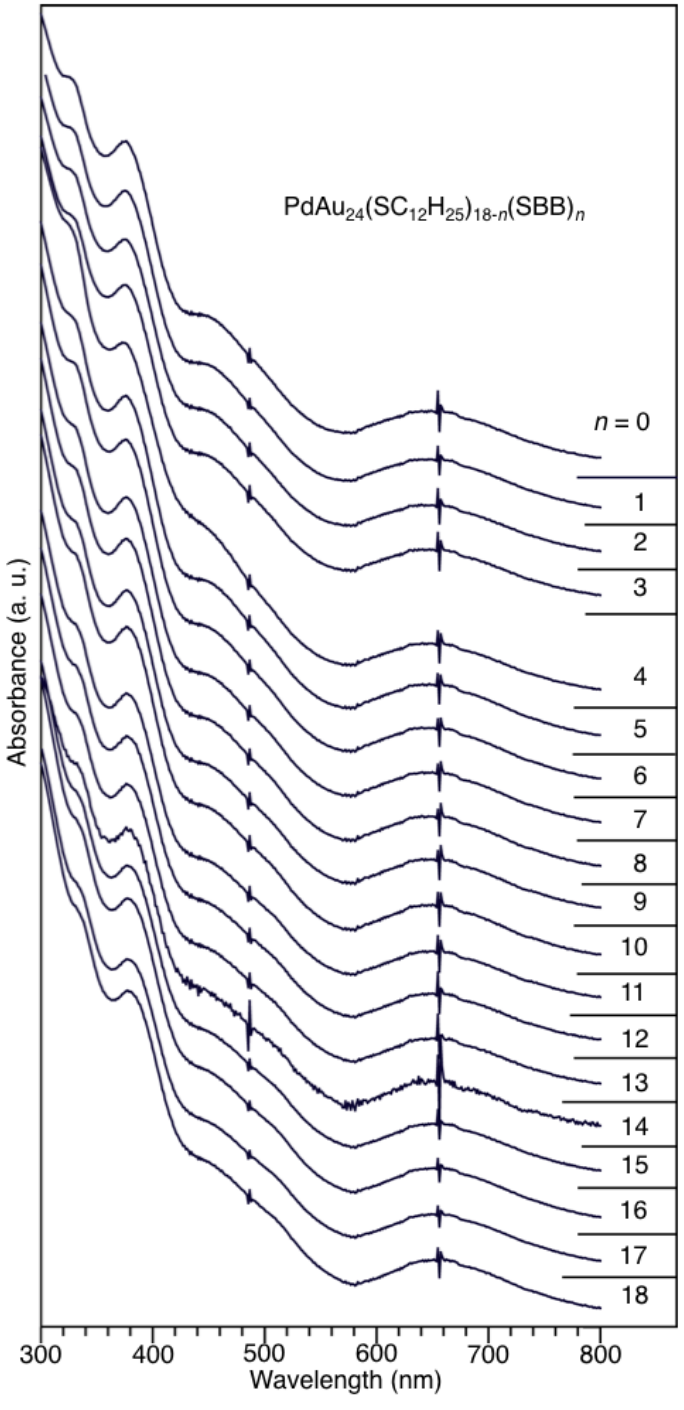


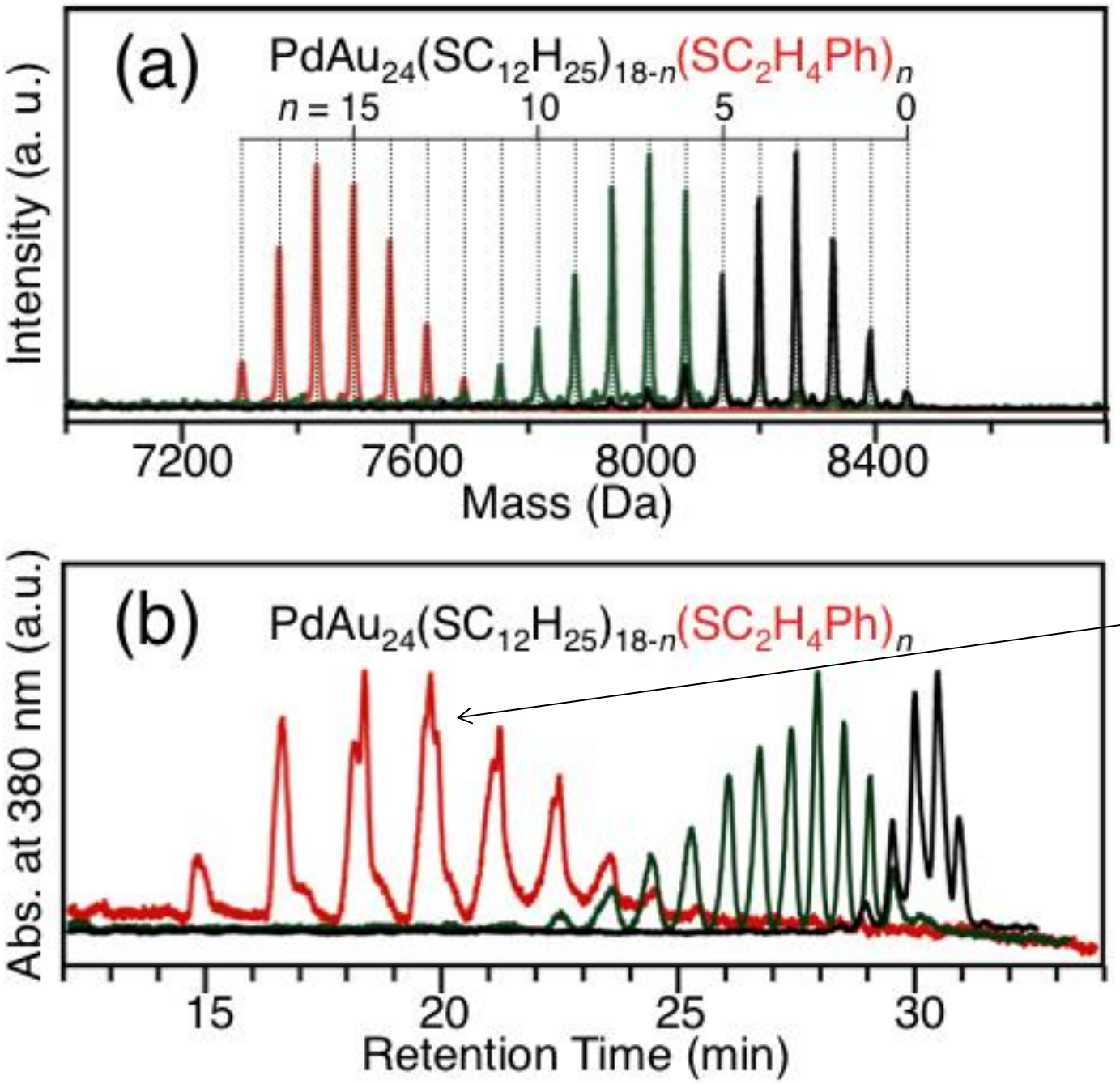
Ligand exchange chemistry – Substitution chemistry



With Niihori and Negishi, Tokyo University of Science

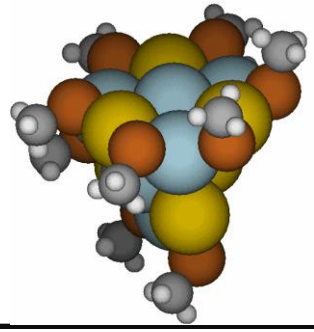

PdAu24(SC12H25)18-n(SBB)n
n = 15
10
5
0
Ion Intensity (a. u.)
*
8000
8200
8400
Mass (Da)

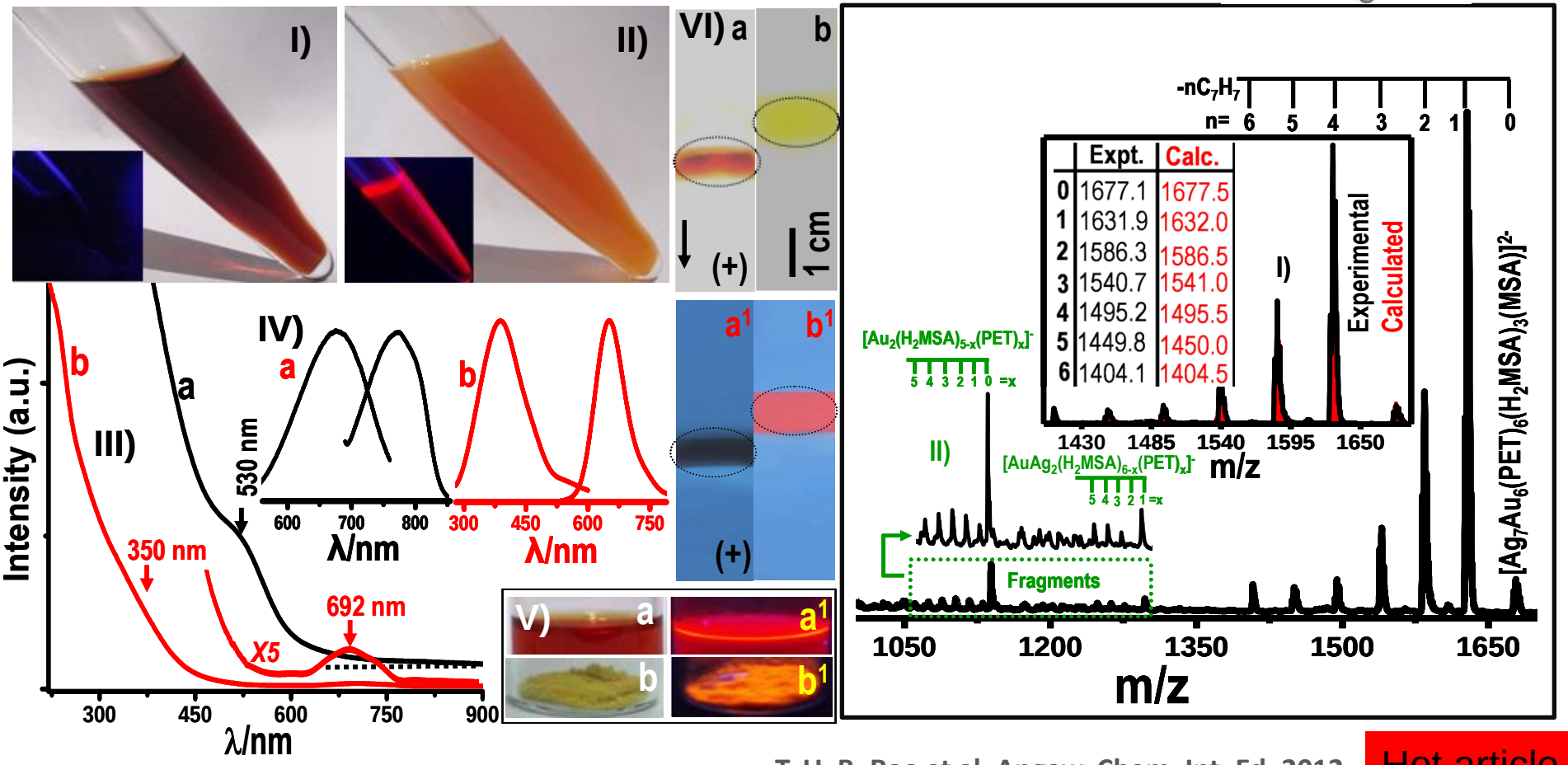

PdAu24(SC12H25)18-n(SBB)n
Absorbance (a. u.)
n = 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
300
400
500
600
700
800
Wavelength (nm)


(a)
PdAu24(SC12H25)18-n(SC2H4Ph)n
n = 15
10
5
0
Intensity (a. u.)
7200
7600
8000
8400
Mass (Da)
(b)
PdAu24(SC12H25)18-n(SC2H4Ph)n
Abs. at 380 nm (a.u.)
15
20
25
30
Retention Time (min)
Cluster isomer

Cluster alloys

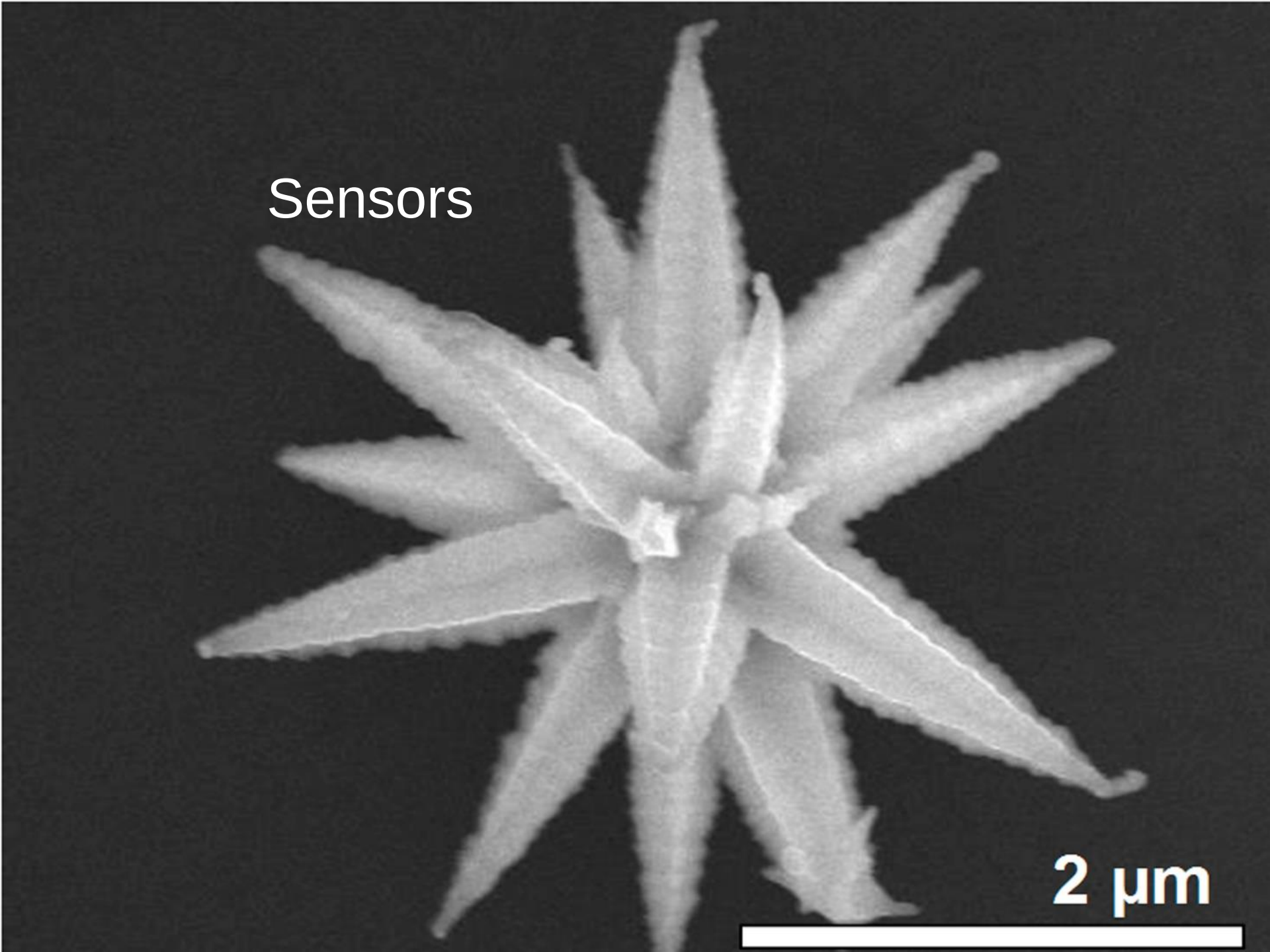
Ag_7Au_6 – 13 atom alloy cluster





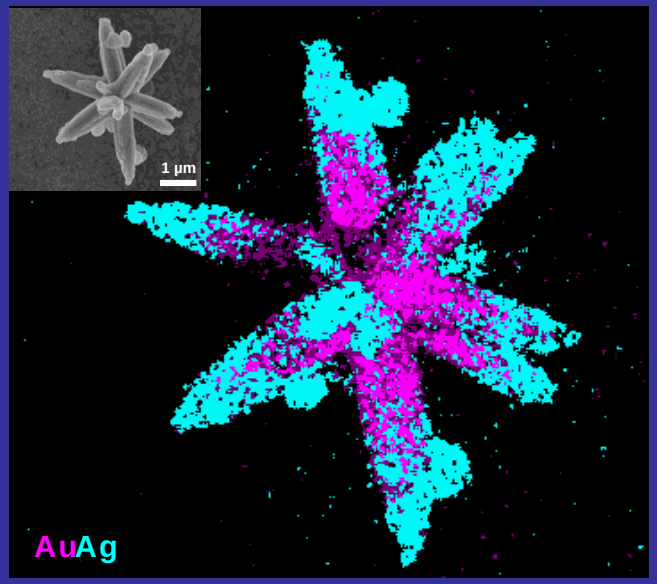
T. U. B. Rao et al. Angew. Chem. Int. Ed. 2012

Hot article

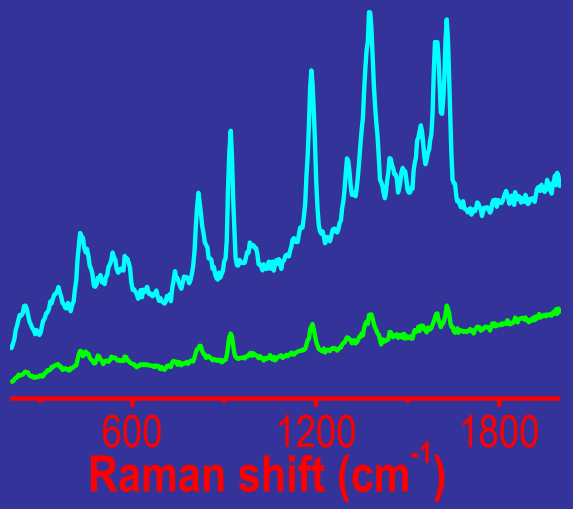

Sensors
2 µm

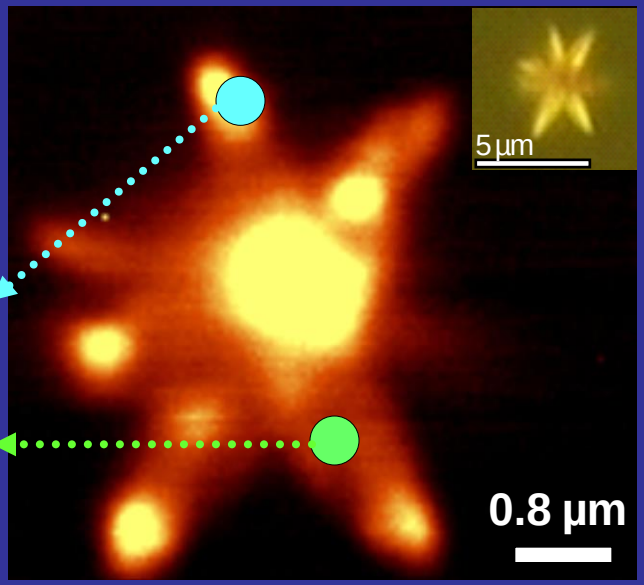
Region-specific SERS activity

Decreasing order of SERS activity → Au/Ag MFs> Au MFs> Au/Pt MFs



EDAX image of Au/Ag MF





Raman image of Au/Ag MF

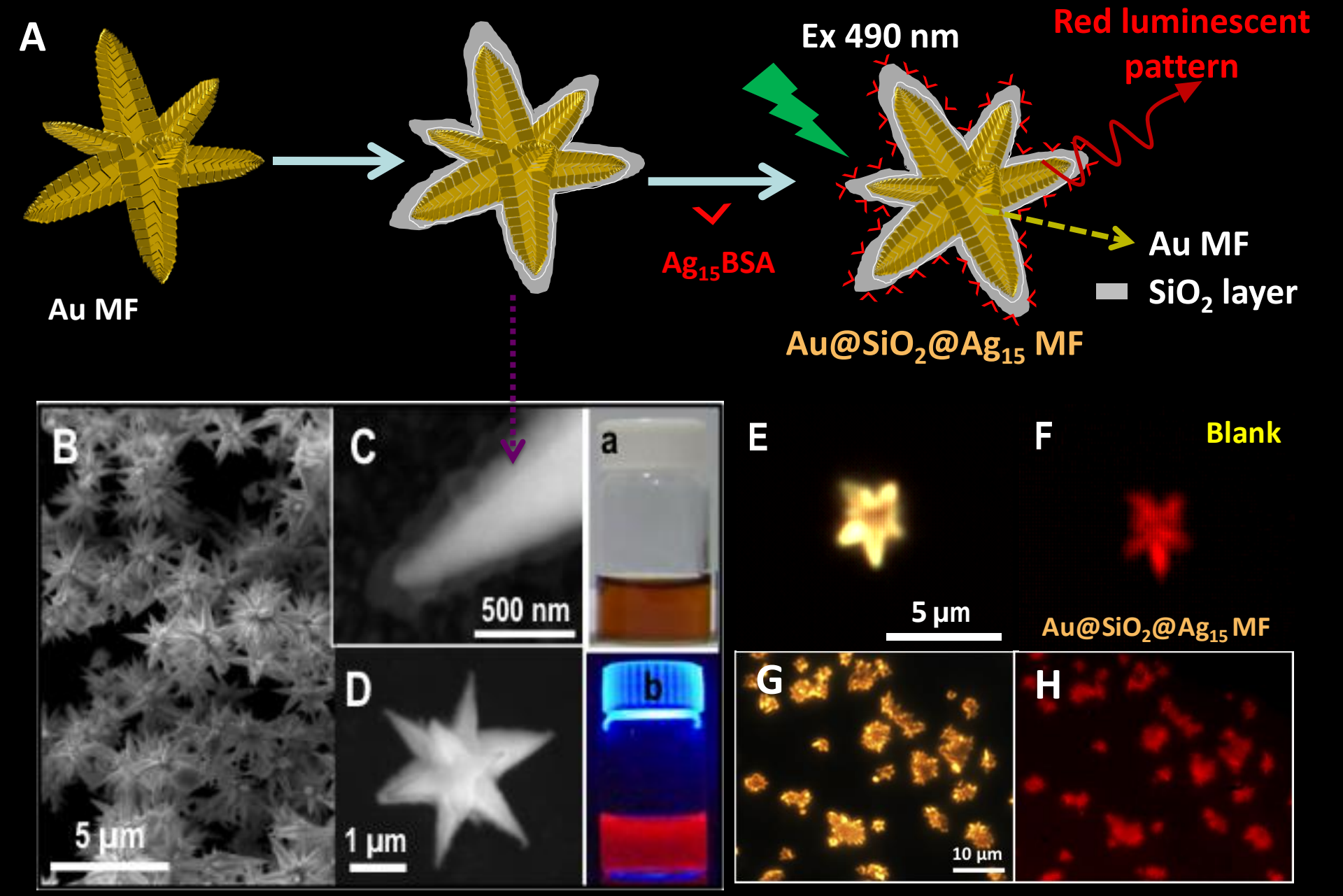
SERS intensity is higher at the tip compared to the body of the stem.

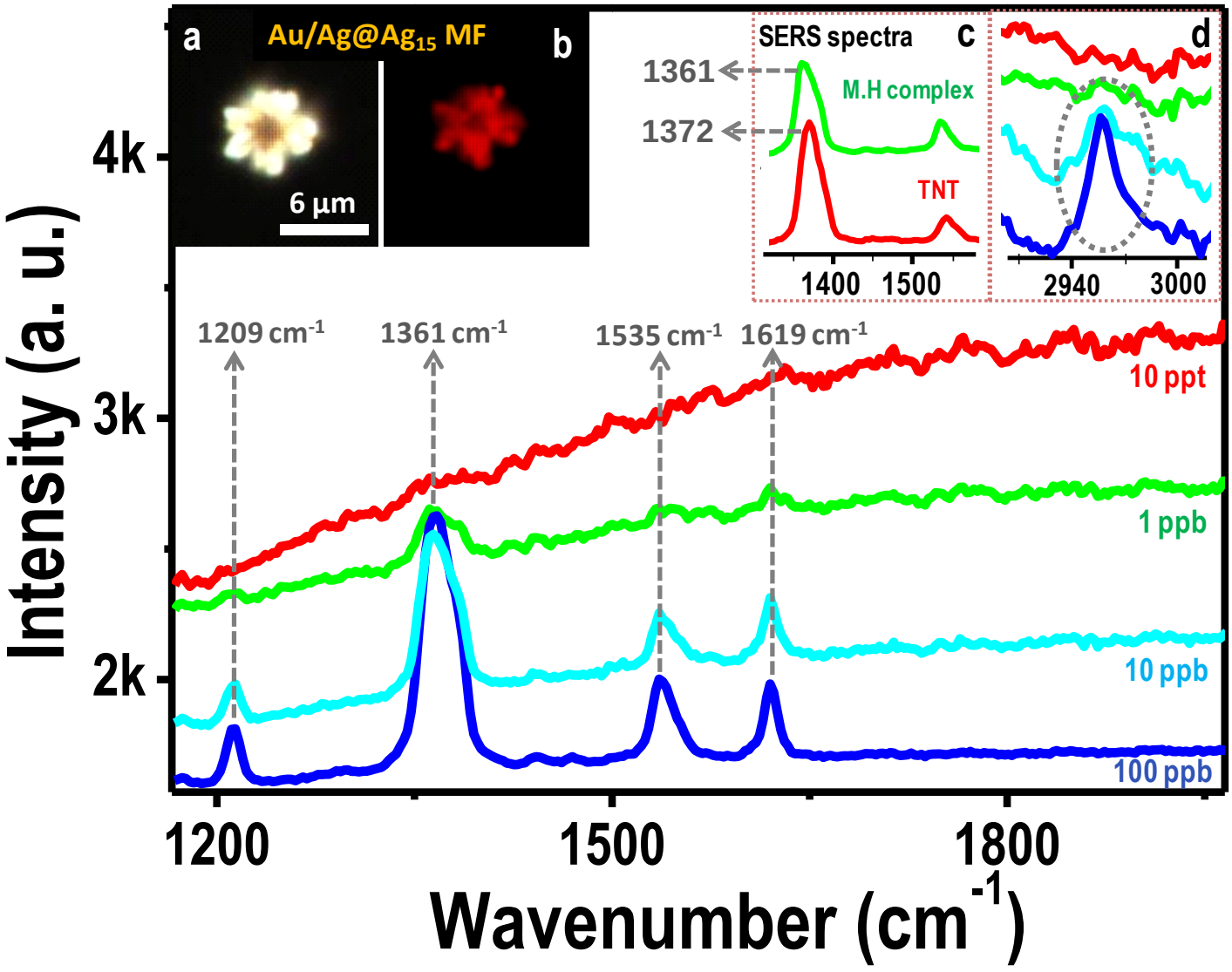
Au/Ag mesoflowers

- **show high SERS activity than Au mesoflowers.**
- **show ten-fold increase in the SERS enhancement factor than Au mesoflowers.**
- **capable of detecting biomolecules and explosives at very low concentrations.**

P. R. Sajanlal and T. Pradeep, *Langmuir*, 26 (2010) 8901- 8907.

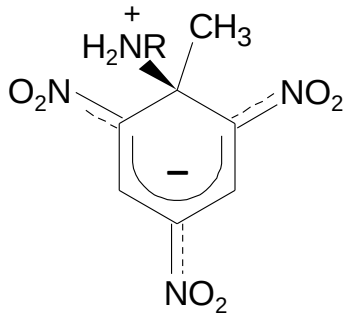
Designing a sensor





Meisenheimer complex

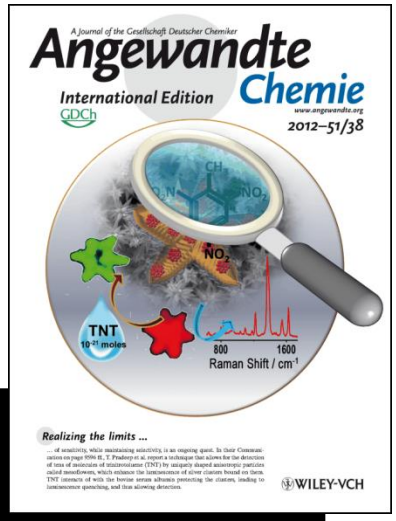
TNT

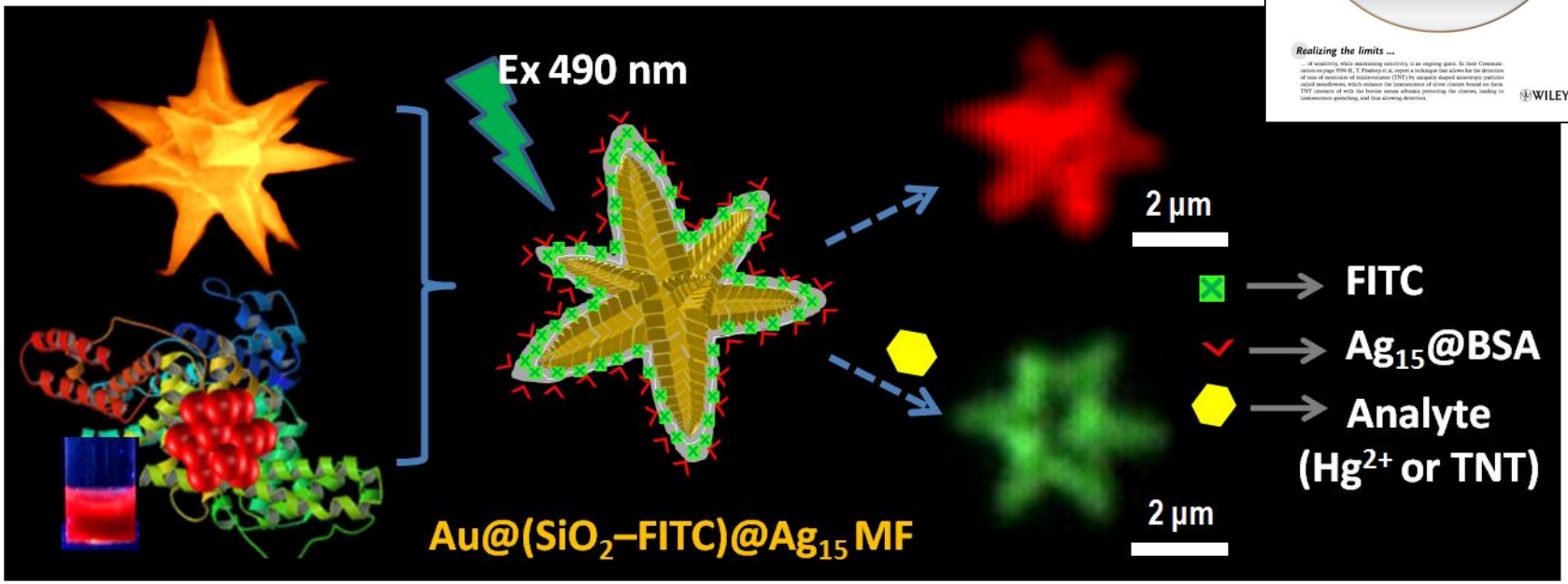


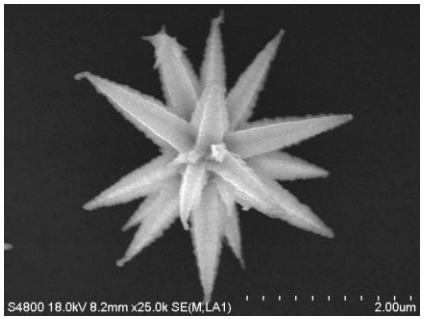
Meisenheimer complex is formed easily due to charge delocalization

Raman spectra showing the gradual evolution of TNT features as the concentration of TNT added to Au/Ag@Ag15 MFs (a and b) increases. (c) Comparison of the symmetric and asymmetric NO2 stretching bands in the SERS spectra of TNT before (black) and after Meisenheimer complex formation (gray). (d) The gradual appearance of a Raman band at 2960 cm^{-1}.

Sub-zeptomolar detection



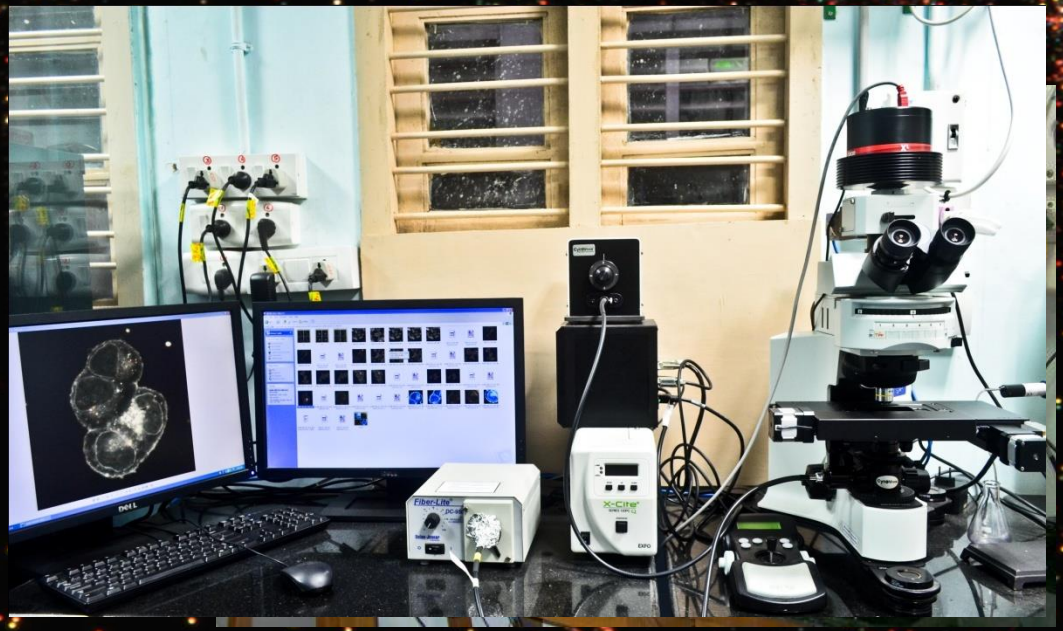




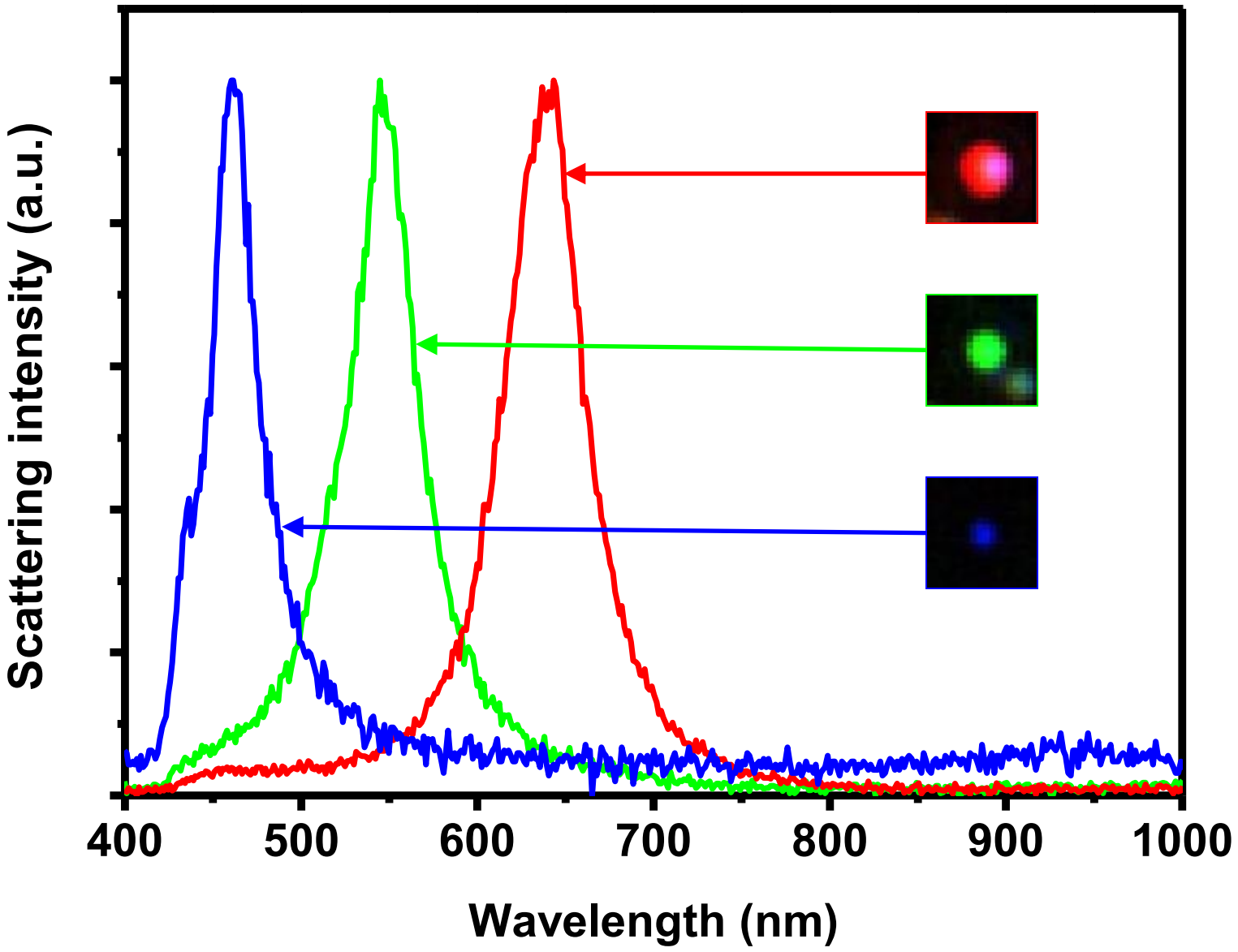
Featured in:
The Hindu, Telegraph, Times of India, etc.
C&E News
and many others

Ammu Mathew, et al. Angew. Chem. Int. Ed. 2012

Observing nanochemistry in real time

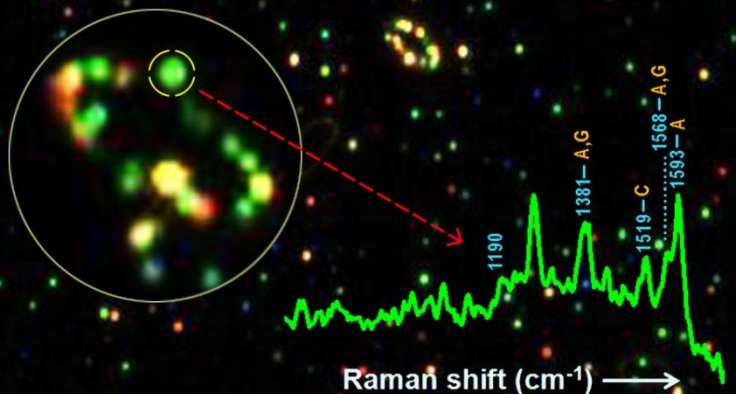


Mechanism of action


Scattering intensity (a.u.)
400
500
600
700
800
900
1000
Wavelength (nm)

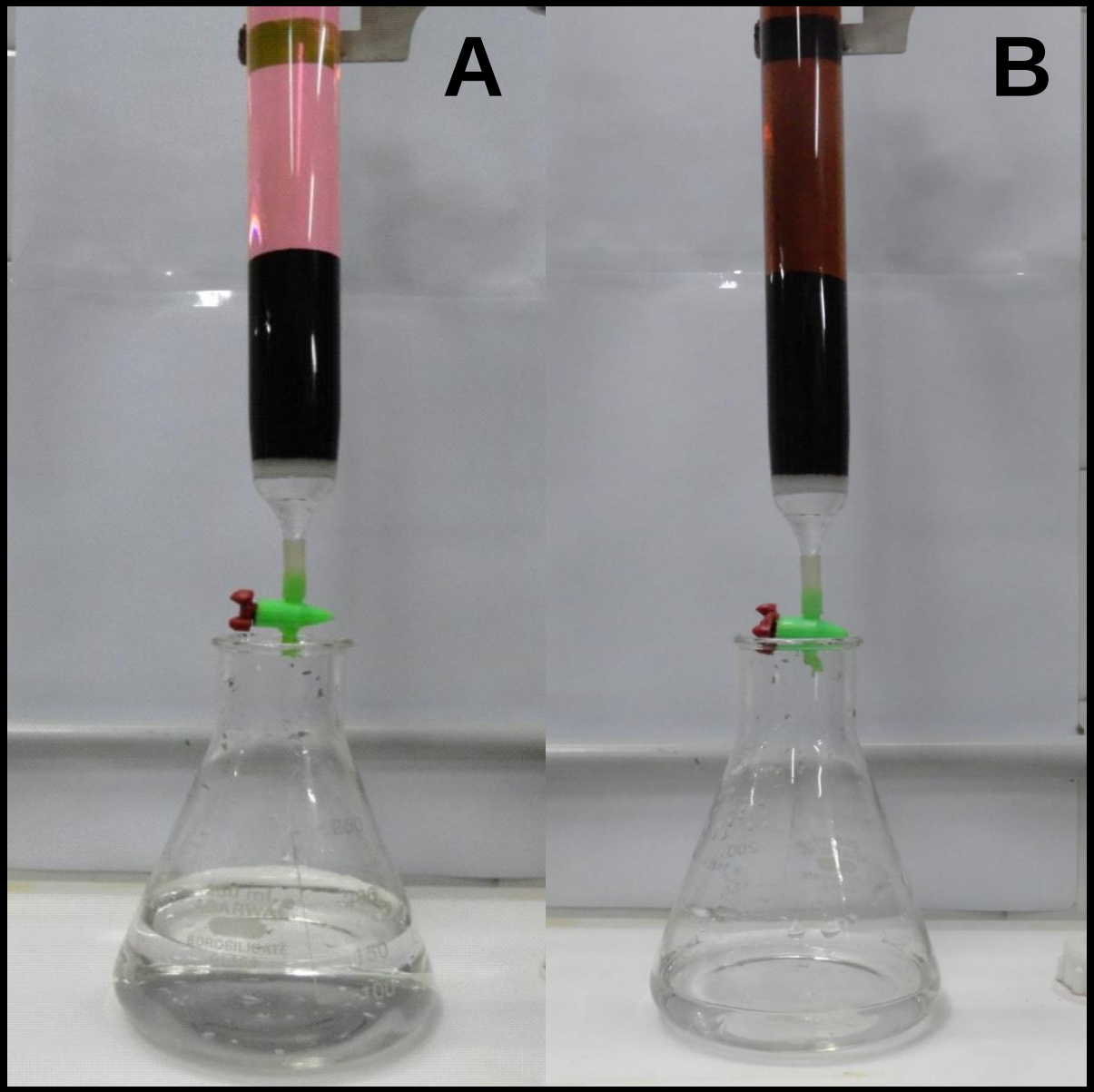
Probing the mechanism of antibacterial activity of AgNPs

Particle & Particle Systems Characterization

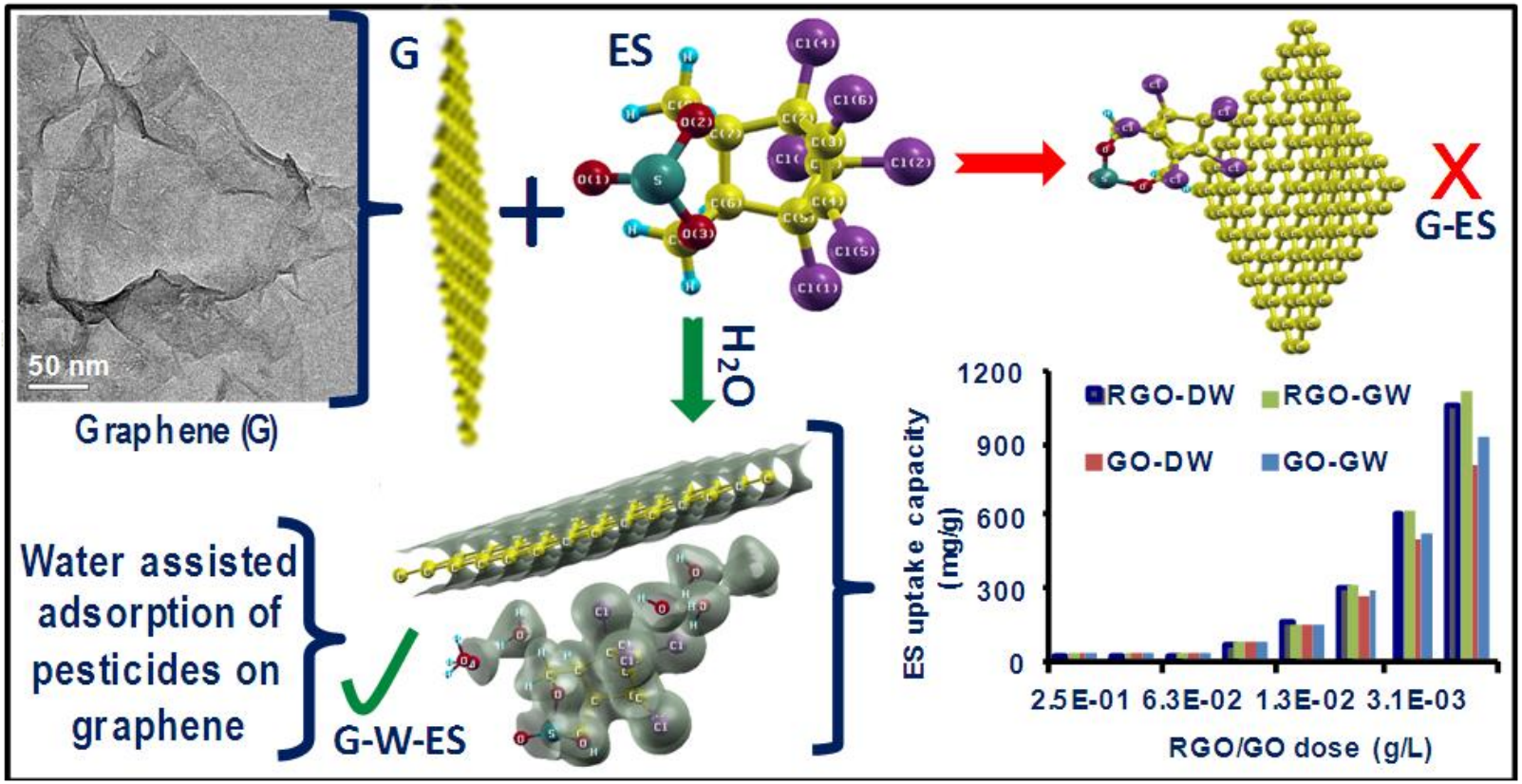


www.particle-journal.com

WILEY-VCH



Soujit Sen Gupta et al. *ACS Appl. Mater. Interfaces* 2012



Graphene adsorbs pesticides more than its self weight!

S. M. Maliyekkal et al *Small* 2012

PNAS PNAS PNAS

Biopolymer-r
nanocomposi
water purific

Mohan Udhaya Sankar[1], Sah
Kamalesh Chaudhari, and Th

Unit of Nanoscience and Thematic Ur

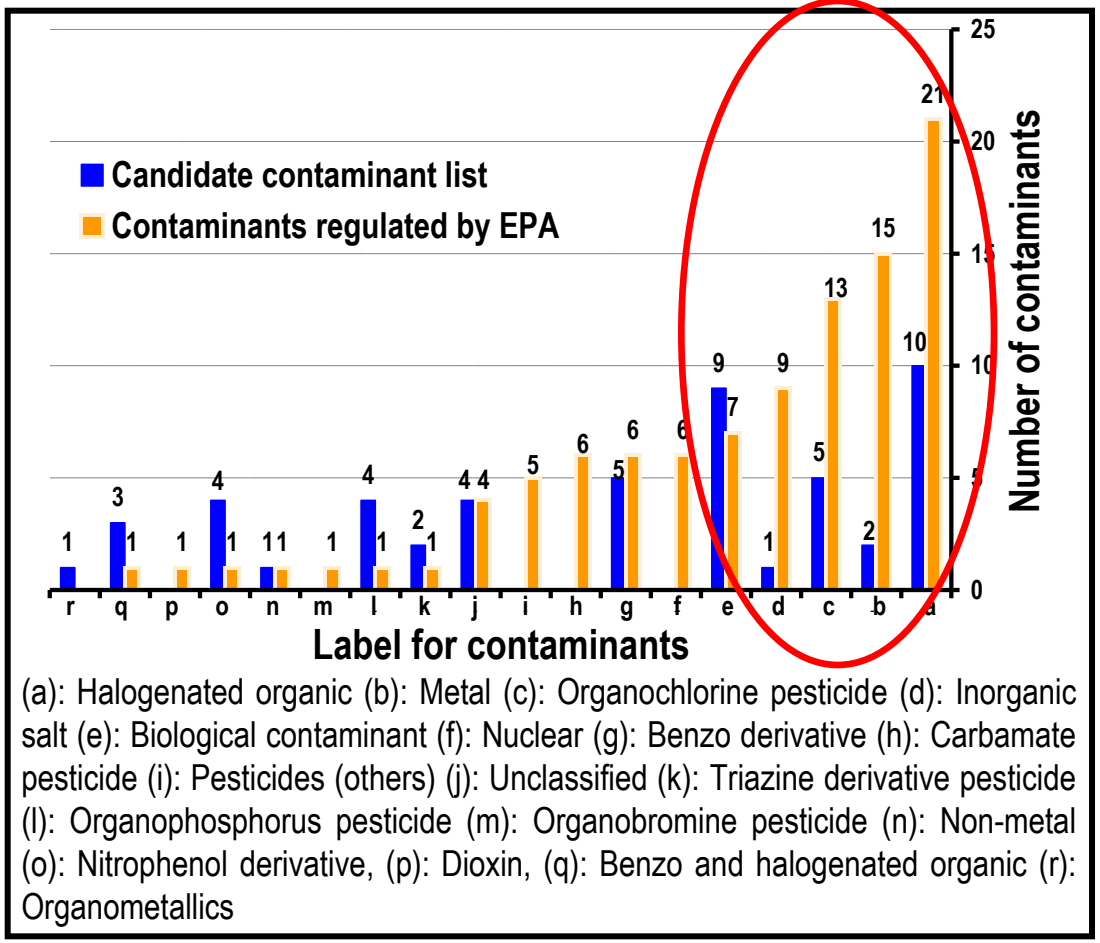
Edited by Eric Hoek, University of Cal

**Creation of affordable materials f
water is one of the most promisin
drinking water for all. Combini
composites to scavenge toxic s
other contaminants along with
affordable, all-inclusive drinking
without electricity. The critical
synthesis of stable materials th
uously in the presence of com
drinking water that deposit an
surfaces. Here we show that su
be synthesized in a simple and eff
out the use of electrical power.
sand-like properties, such as high
forms. These materials have bee
water purifier to deliver clean dri
ily. The ability to prepare nano
ambient temperature has wide
water purification.**

hybrid | green | appropriate technolo

Featured in:
The Guardian, UK
The Hindu, Telegraph, Times of India, etc.
Scientific American
New Scientist
and many others

Future of water purification: An enigma with some pointers



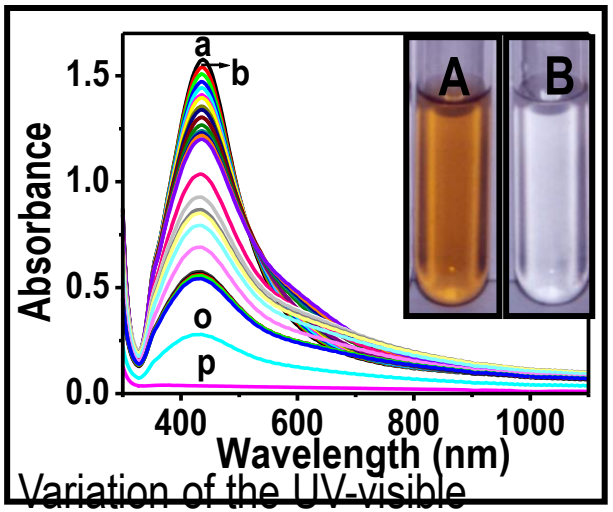
(a): Halogenated organic (b): Metal (c): Organochlorine pesticide (d): Inorganic salt (e): Biological contaminant (f): Nuclear (g): Benzo derivative (h): Carbamate pesticide (i): Pesticides (others) (j): Unclassified (k): Triazine derivative pesticide (l): Organophosphorus pesticide (m): Organobromine pesticide (n): Non-metal (o): Nitrophenol derivative, (p): Dioxin, (q): Benzo and halogenated organic (r): Organometallics

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

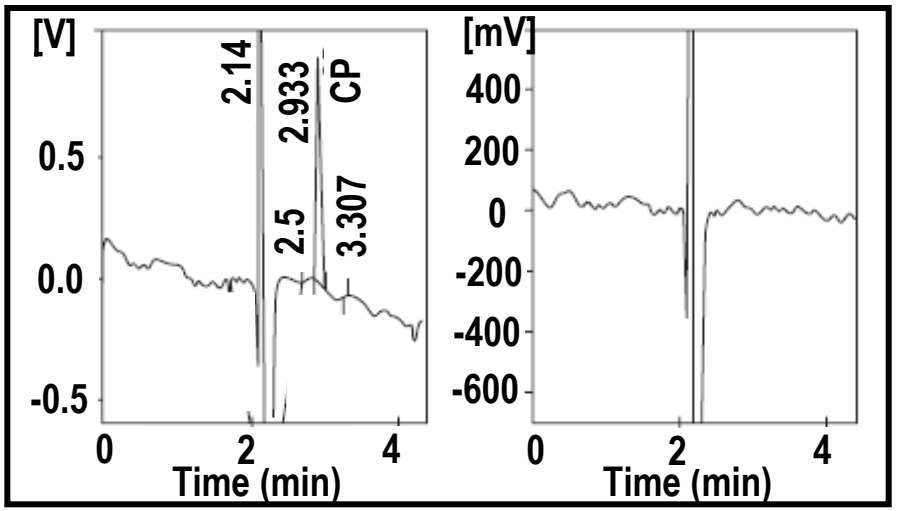
Noble metal nanoparticles for water purification: A critical review, T. Pradeep and Anshup, Invited critical review, Thin Solid Films, 517 (2009) 6441-6478 (DOI: 10.1016/j.tsf.2009.03.195).

Noble metal nanoparticles: removal of pesticides from water

A.S. Nair, T. Pradeep, Curr. Sci. 84 (2003) 1560



Variation of the UV-visible absorption spectrum of silver nanoparticles upon the addition of CCl_4



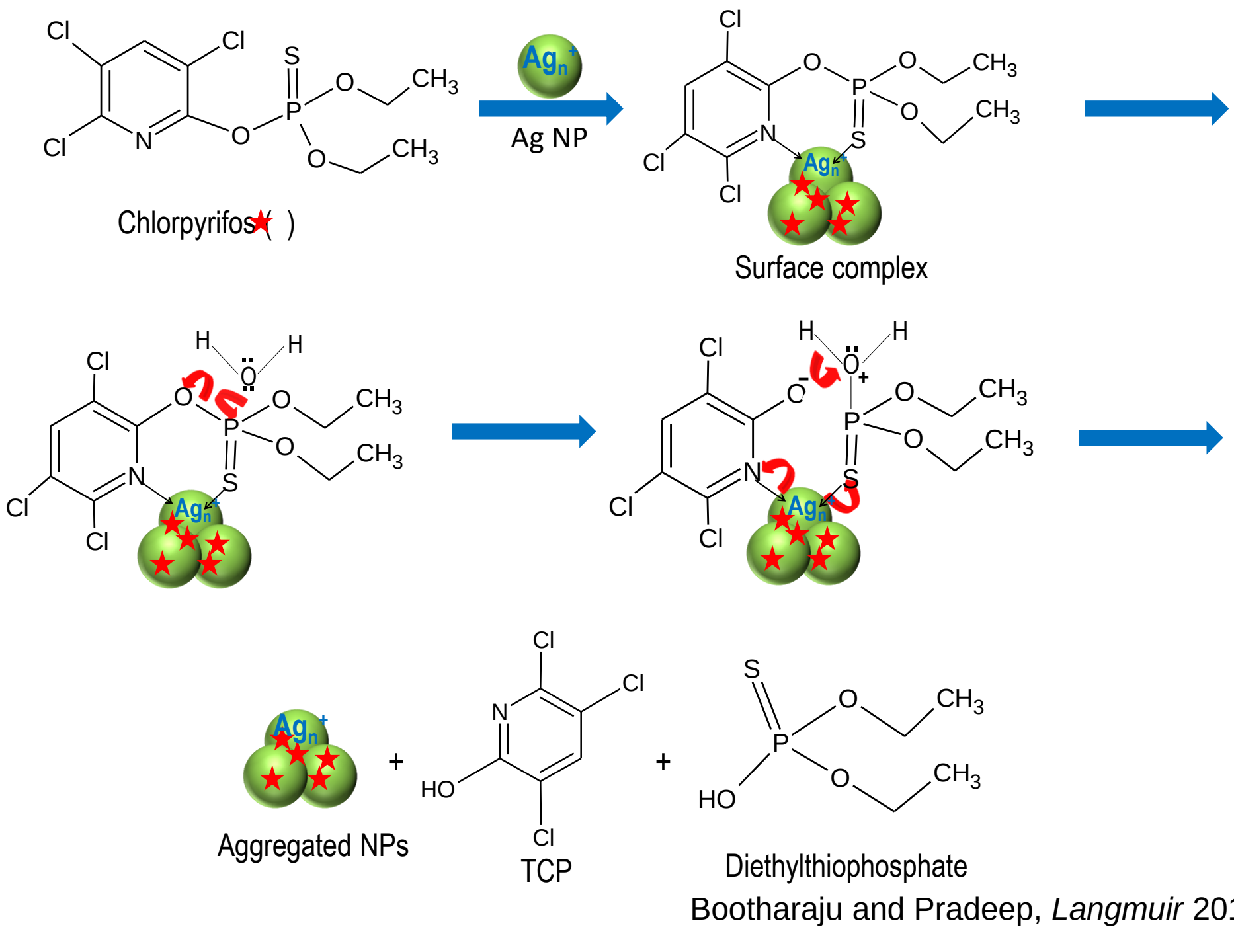
Gas chromatogram of chlorpyrifos solution (L) and after treatment with silver nanoparticles (R)

A.S. Nair, R.T. Tom, V.R. Rajeev Kumar, C. Subramaniam, T. Pradeep, Cosmos 3, (2007) 103

Indian patent 2006
PCT 2011 – US, Europe, Asia

June 2007

(L) Silver nanoparticles coated on activated alumina (R) Photograph of a pesticide filter device using supported nanoparticles (WQA certified)



Bootharaju and Pradeep, *Langmuir* 2012

World's first nanochemistry-based water purifier

RSC | Advancing the Chemical Sciences

Chemistry World

Pesticide filter debuts in India

20 April 2007

Killugudi 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 Chennai told *Chemistry World*. He and his student Sreekumaran Nair discovered in 2003 that halocarbons such as carbon tetrachloride (CCl4) 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, his team 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 at elevated levels in Indian water supplies.

Use and recycle

The mechanism of removal [illegible] Pradeep explained [illegible] environment[illegible] filter ar[illegible] pe[illegible]

[illegible] nanot[illegible] novel,' Sa[illegible]

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 malatheon and chlorpiryhphos 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

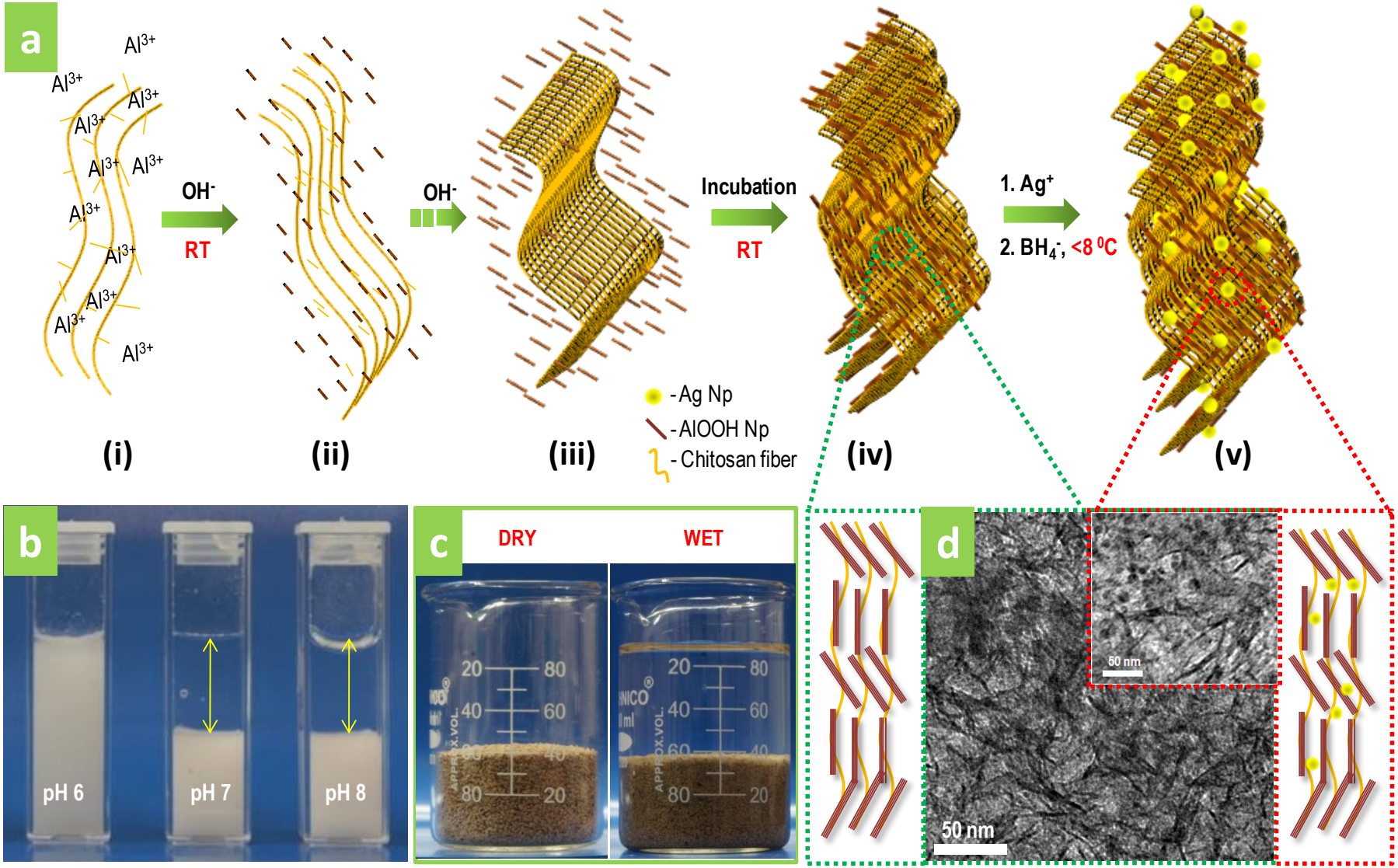
Affordable materials for water purification - Bioinspired

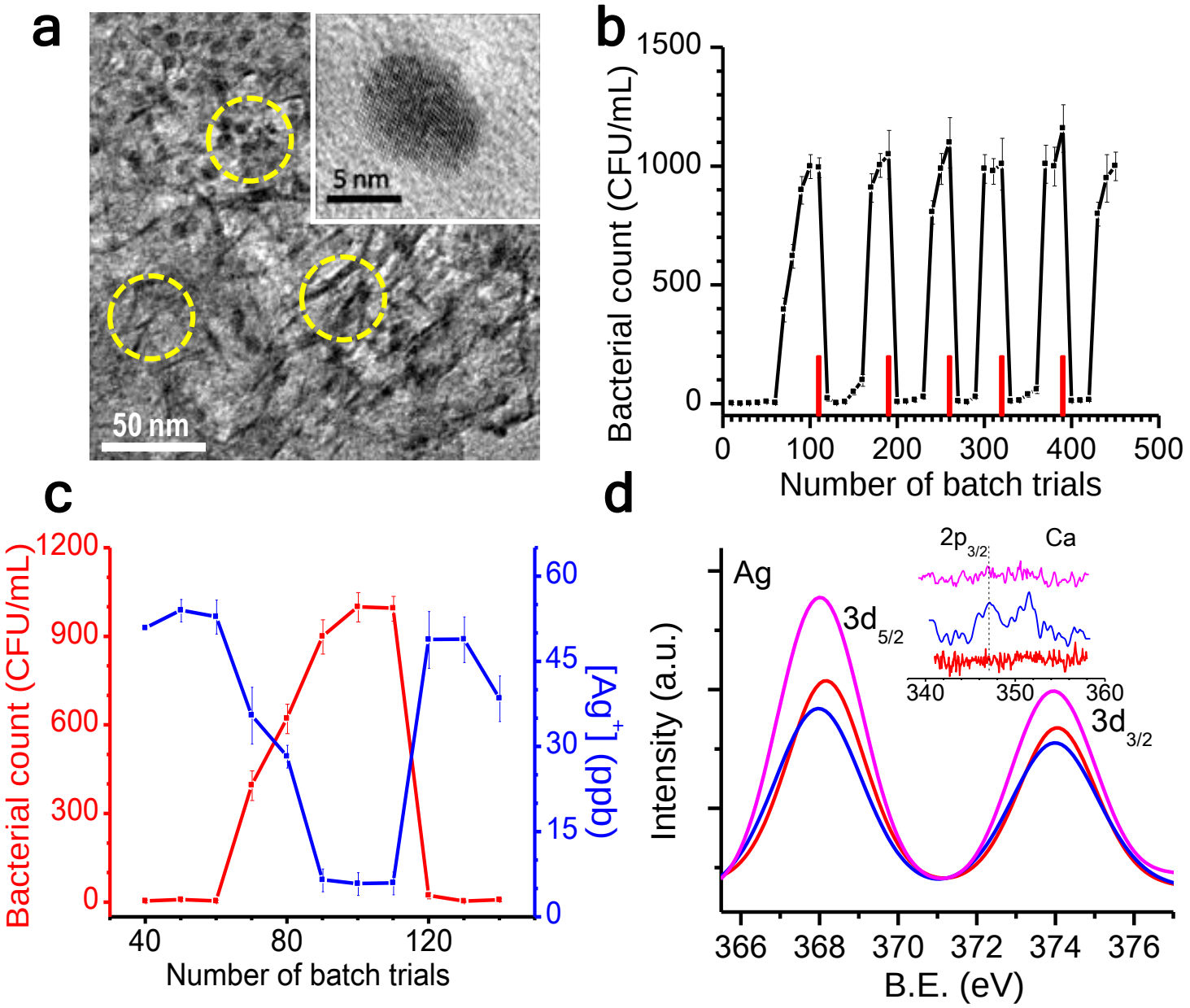
Water positive

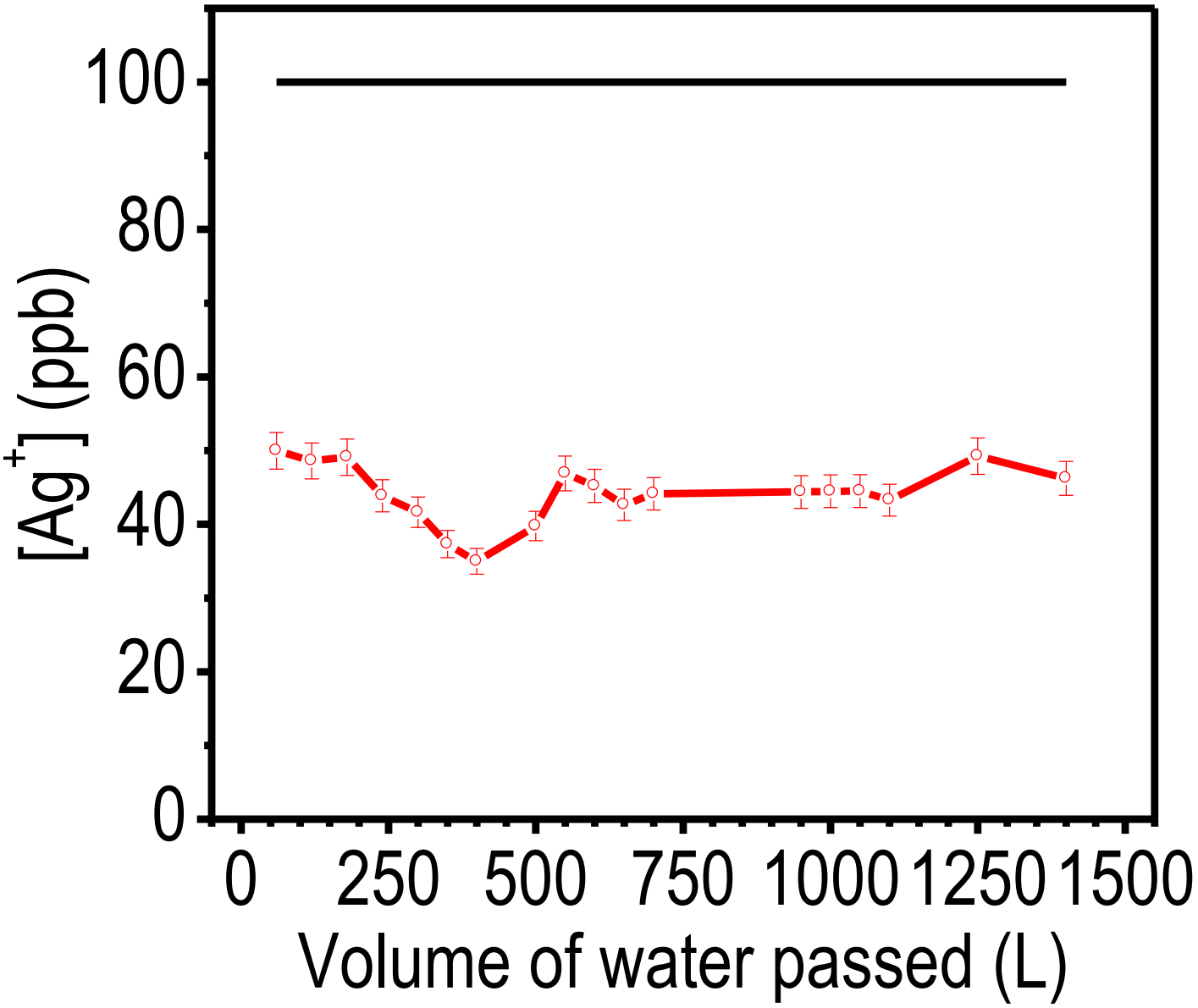
Water-based, room temperature, water stable

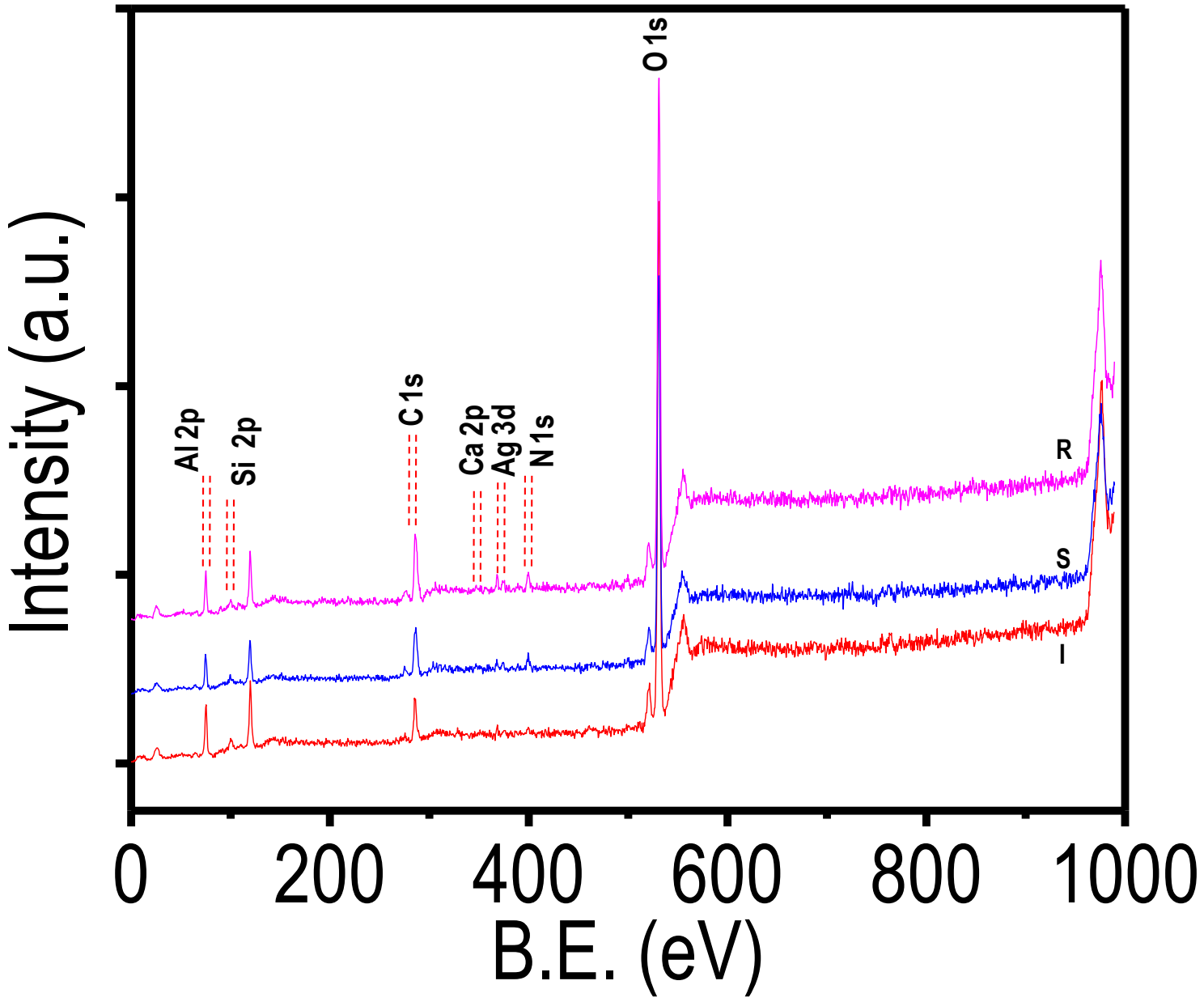
Green

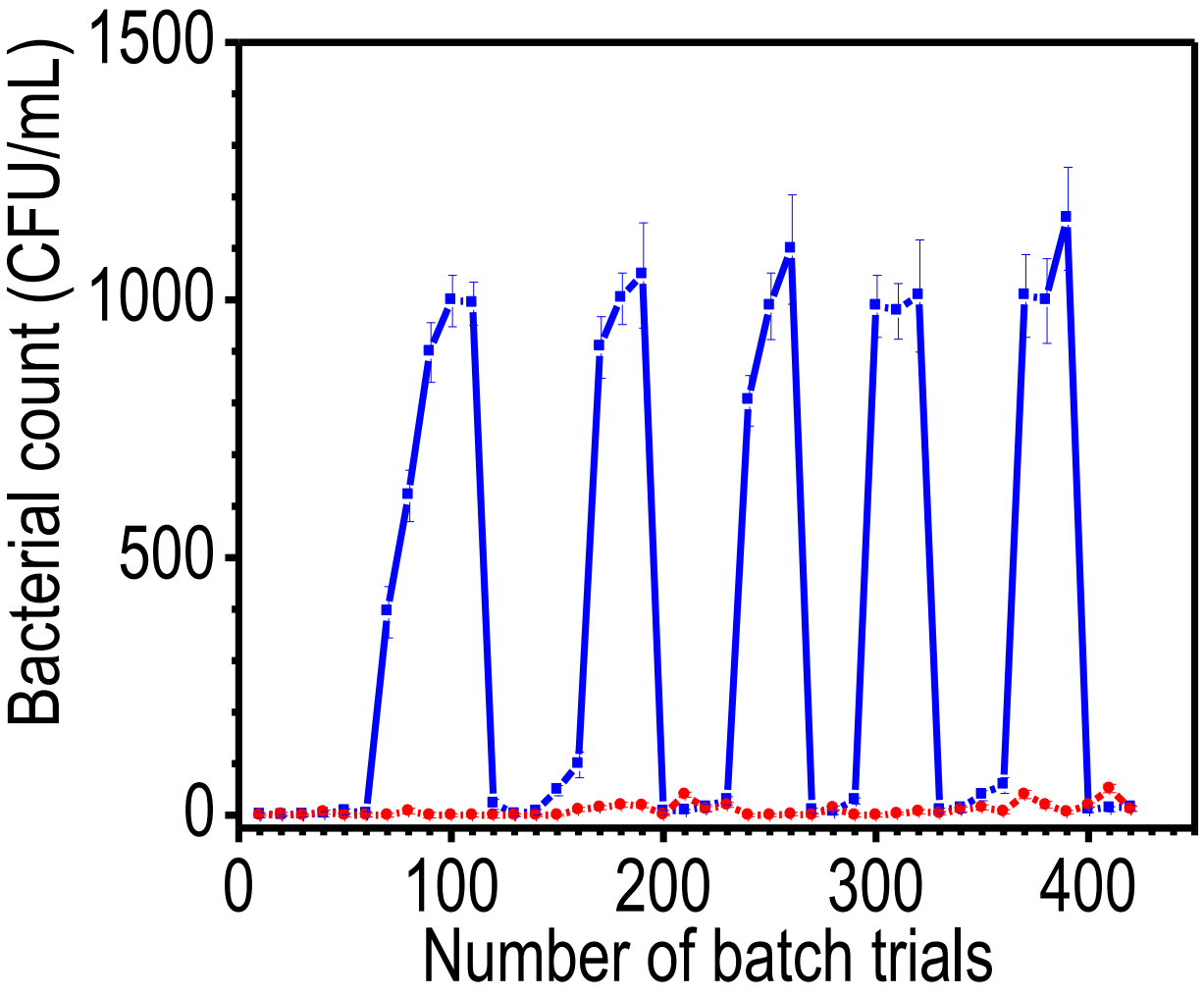
M. U. Sankar et al, PNAS 2013

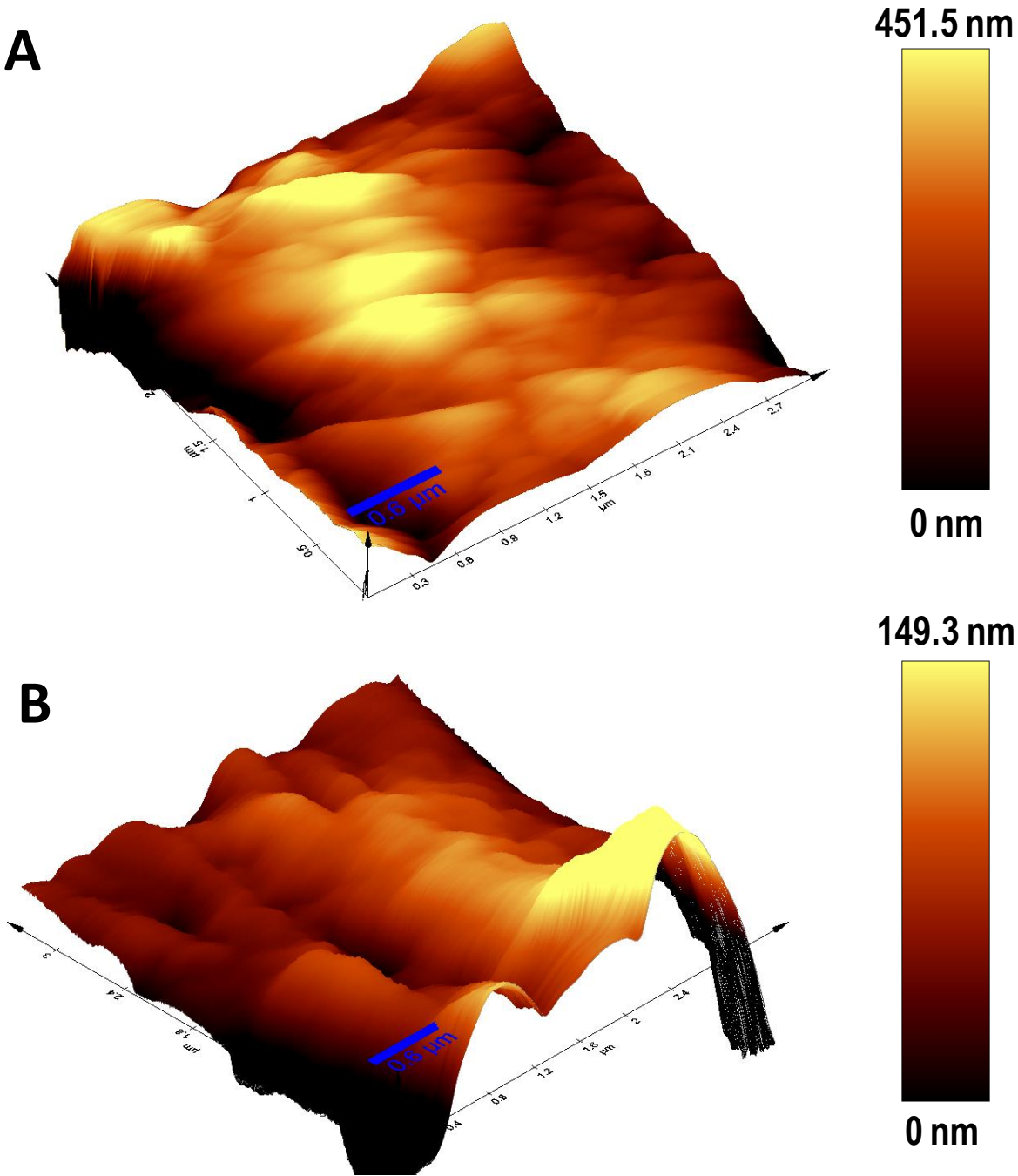

a
Al3+
OH-
RT
OH-
Incubation
RT
1. Ag+
2. BH4-, <8 0C
(i)
(ii)
(iii)
(iv)
(v)
- Ag Np
- AlOOH Np
- Chitosan fiber
b
pH 6
pH 7
pH 8
c
DRY
WET
d
50 nm
50 nm

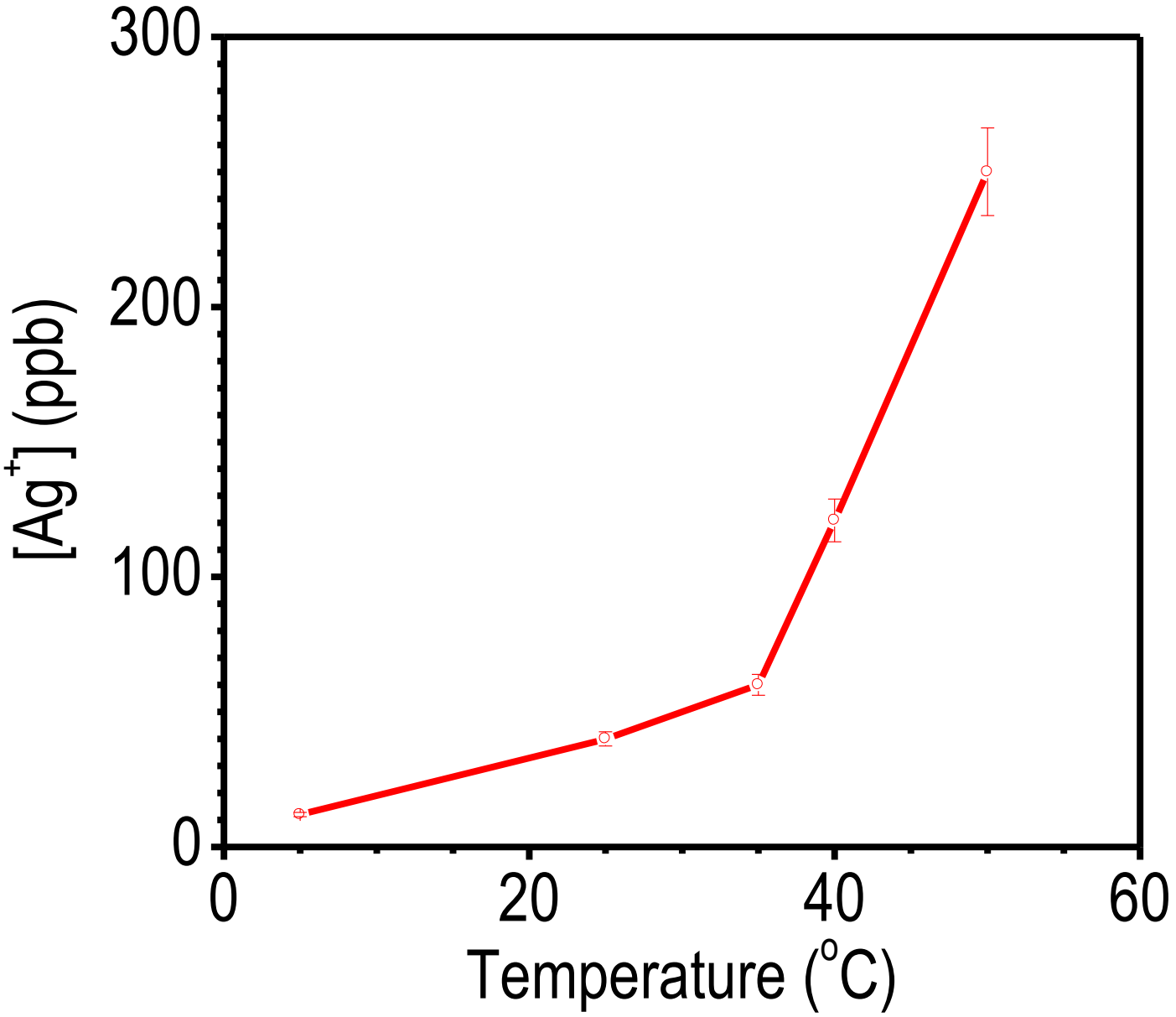

a
5 nm
50 nm
b
Bacterial count (CFU/mL)
1500
1000
500
0
0
100
200
300
400
500
Number of batch trials
c
Bacterial count (CFU/mL)
1200
900
600
300
0
60
45
30
15
0
[Ag+] (ppb)
40
80
120
Number of batch trials
d
Ag
3d5/2
3d3/2
2p3/2
Ca
340
350
360
Intensity (a.u.)
366
368
370
372
374
376
B.E. (eV)

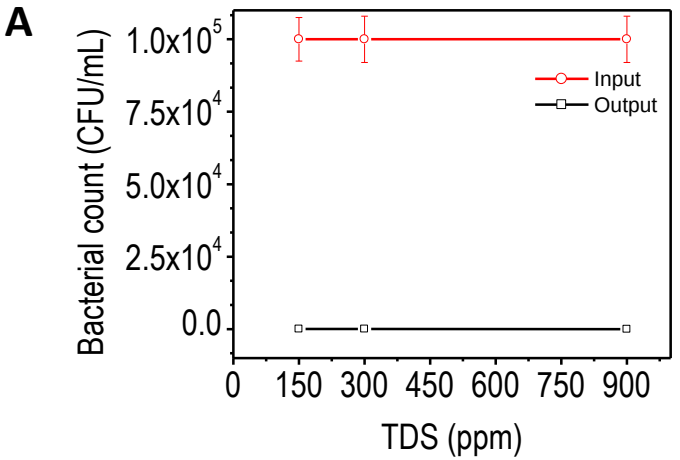

100
80
60
40
20
0
[Ag+] (ppb)
0
250
500
750
1000
1250
1500
Volume of water passed (L)


Intensity (a.u.)
O 1s
Al 2p
Si 2p
C 1s
Ca 2p
Ag 3d
N 1s
R
S
I
0
200
400
600
800
1000
B.E. (eV)

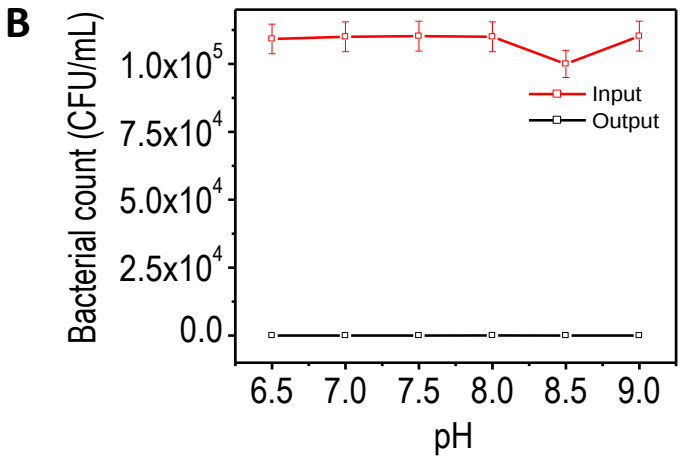

Bacterial count (CFU/mL)
1500
1000
500
0
0
100
200
300
400
Number of batch trials


A
451.5 nm
0 nm
0.5 µm
B
149.3 nm
0 nm
0.5 µm


300
200
100
0
[Ag+] (ppb)
0
20
40
60
Temperature (°C)

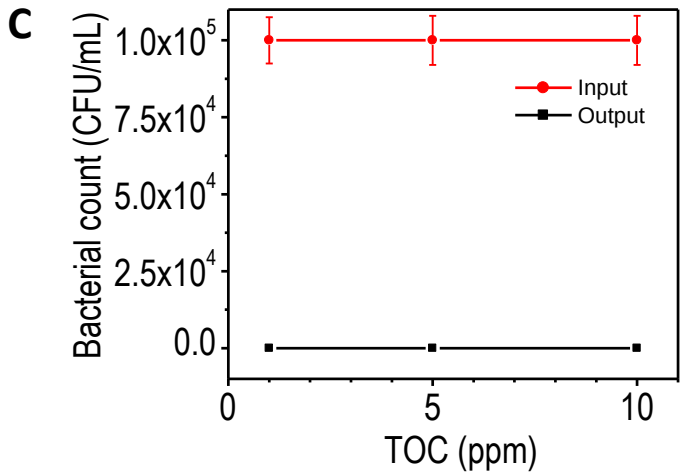


TDS



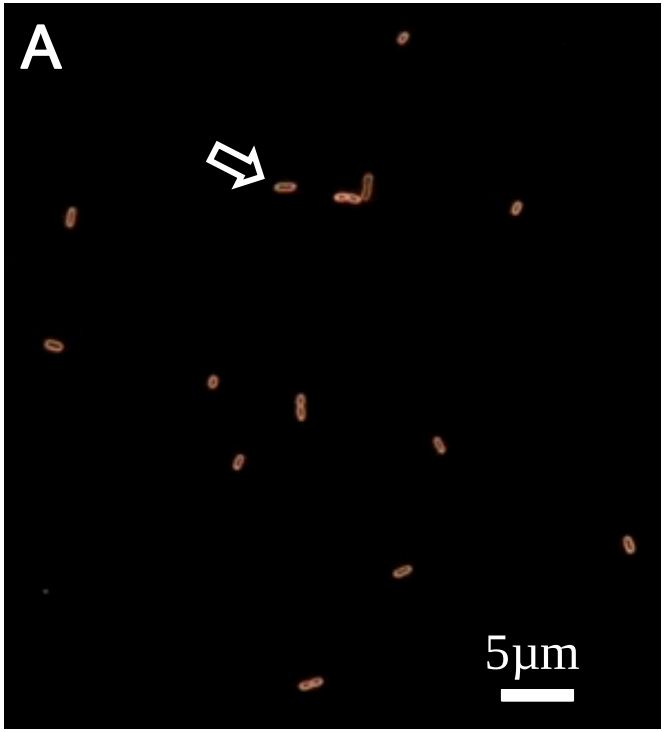
pH

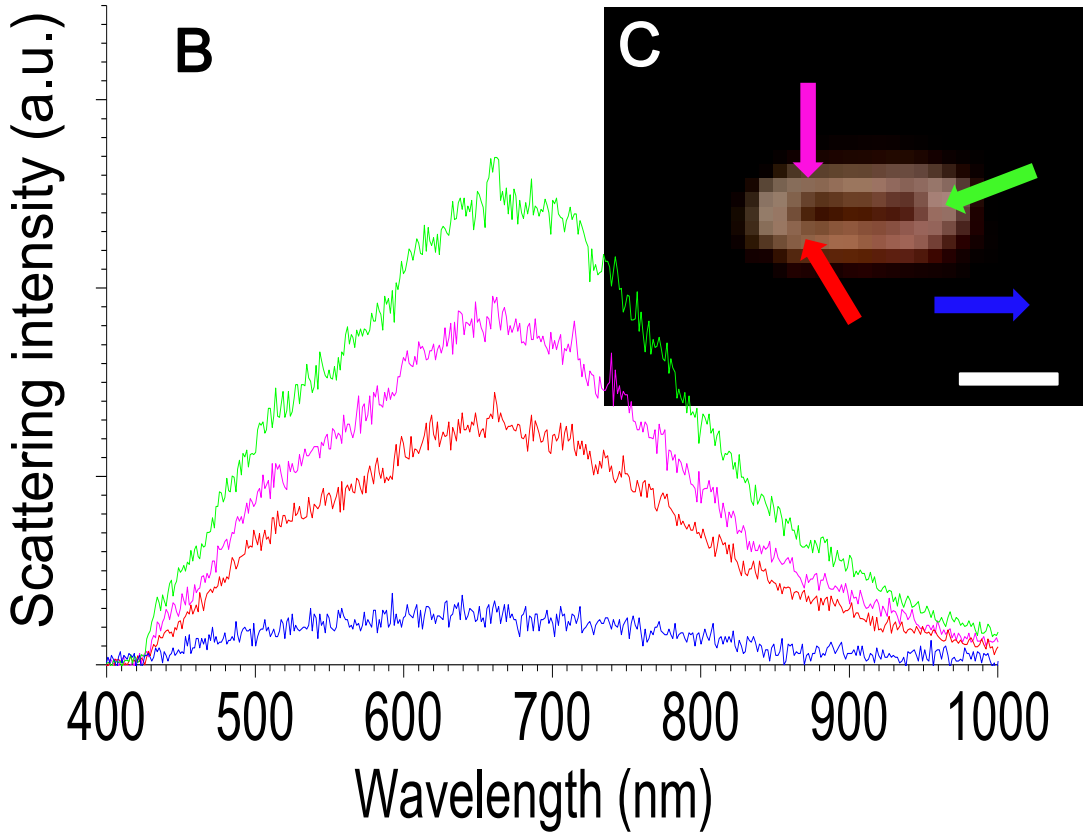
Real water experiments

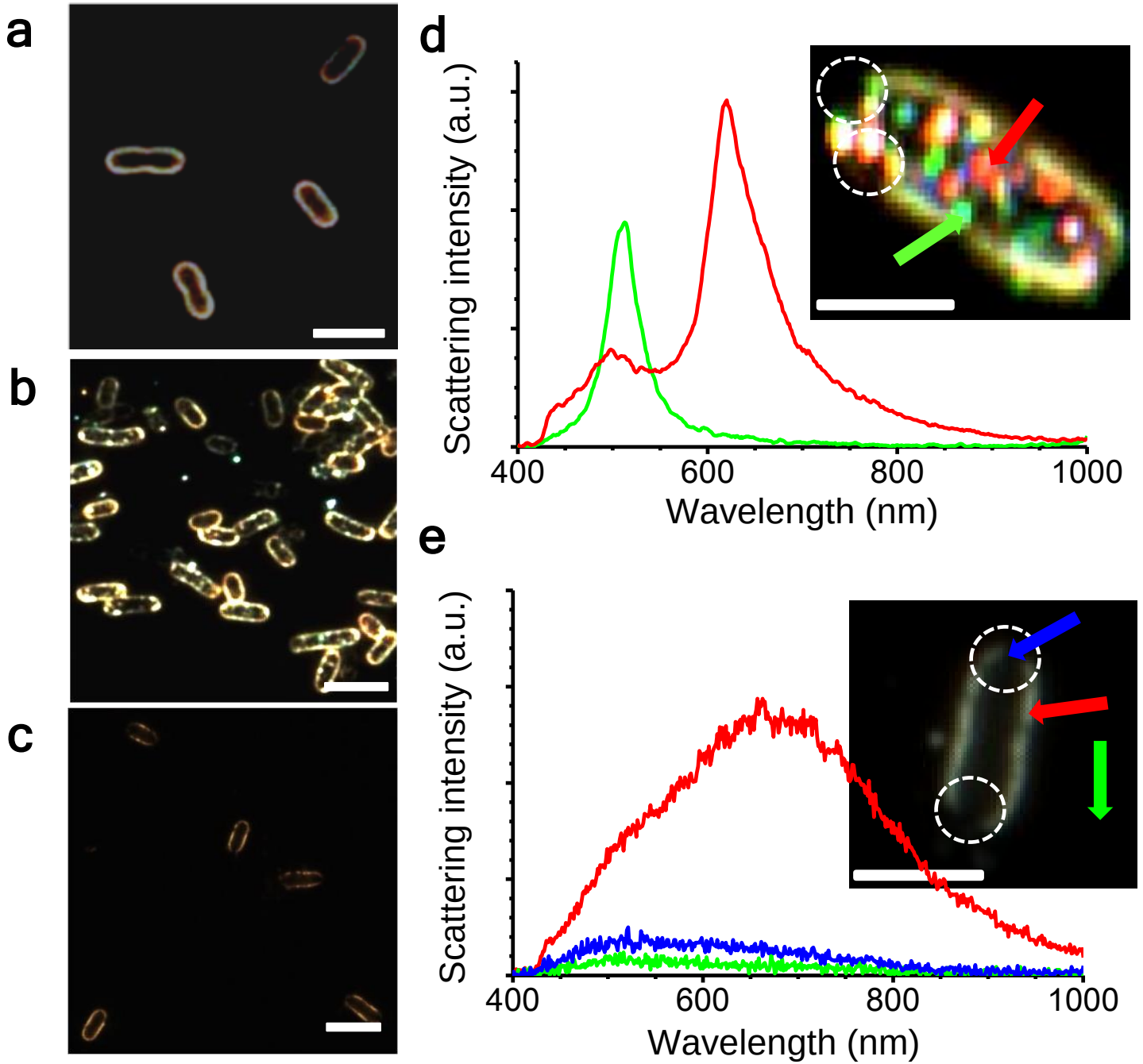


TOC – Humic acid

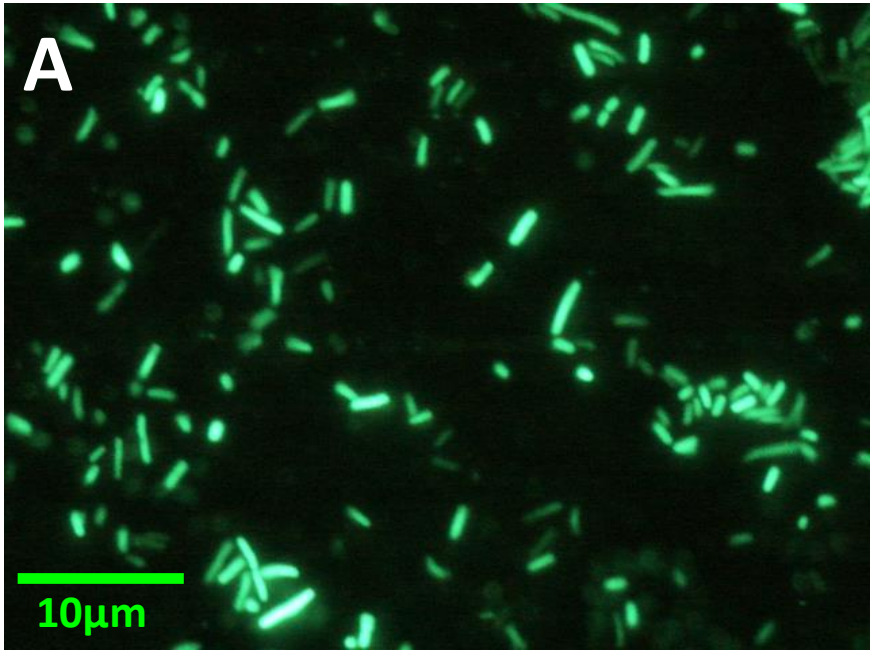
Nanotoxicity?

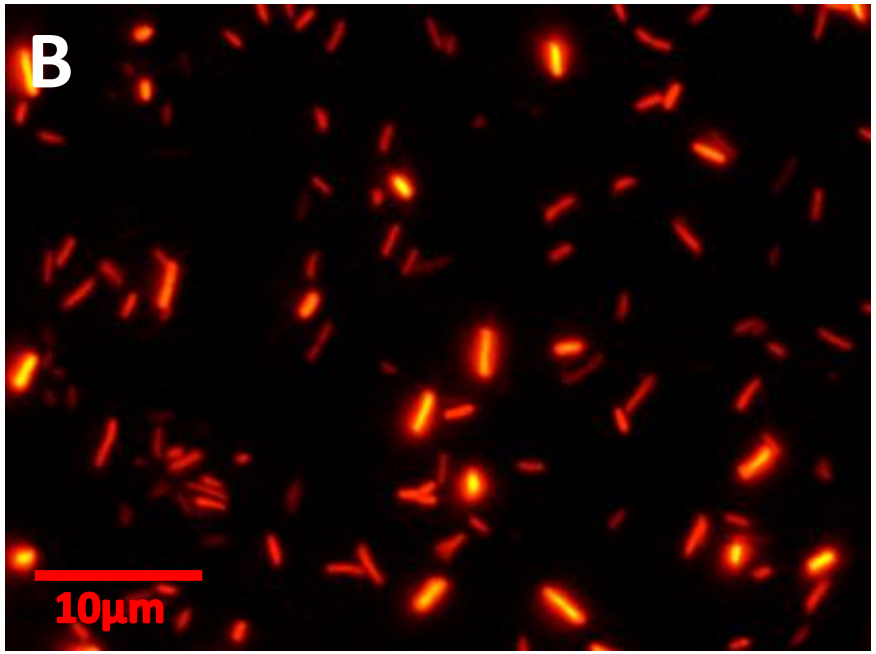


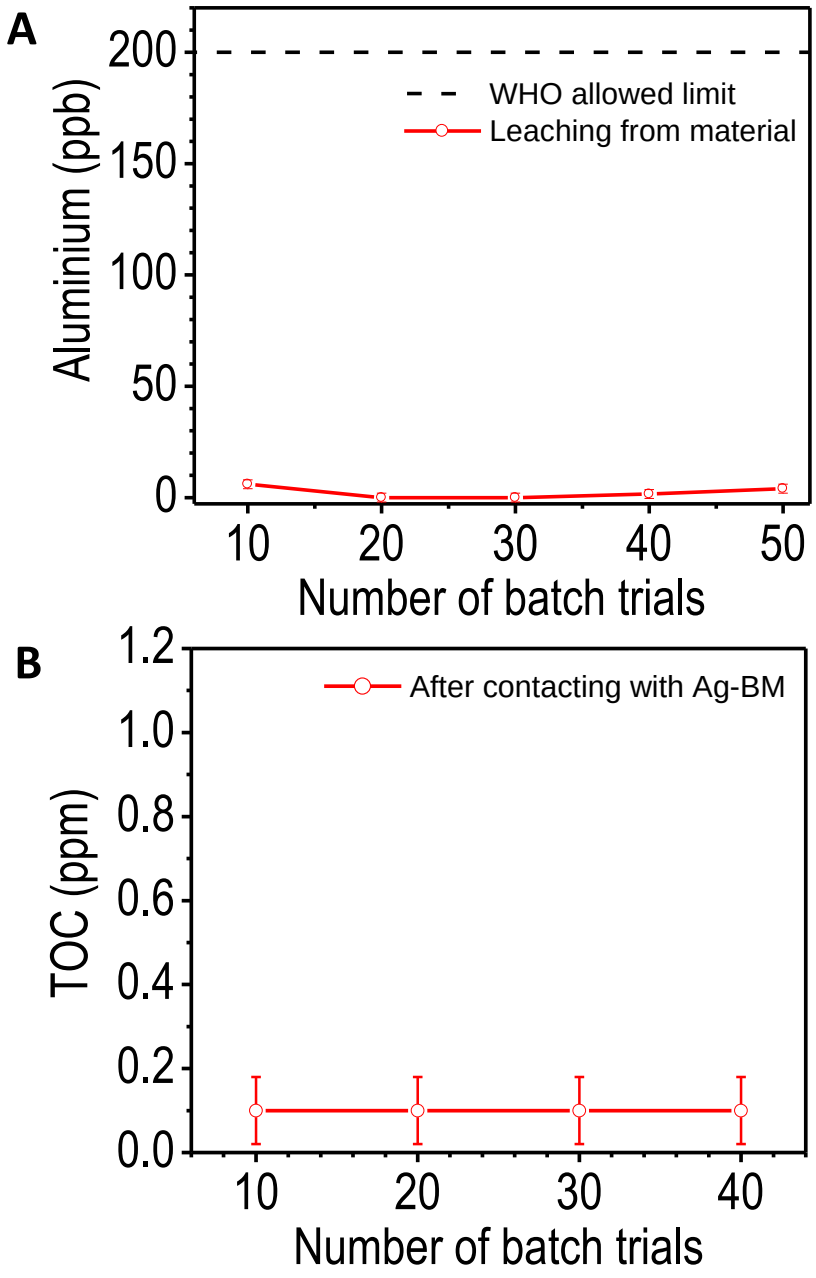



a
b
c
d
e
Scattering intensity (a.u.)
400
600
800
1000
Wavelength (nm)
Scattering intensity (a.u.)
400
600
800
1000
Wavelength (nm)

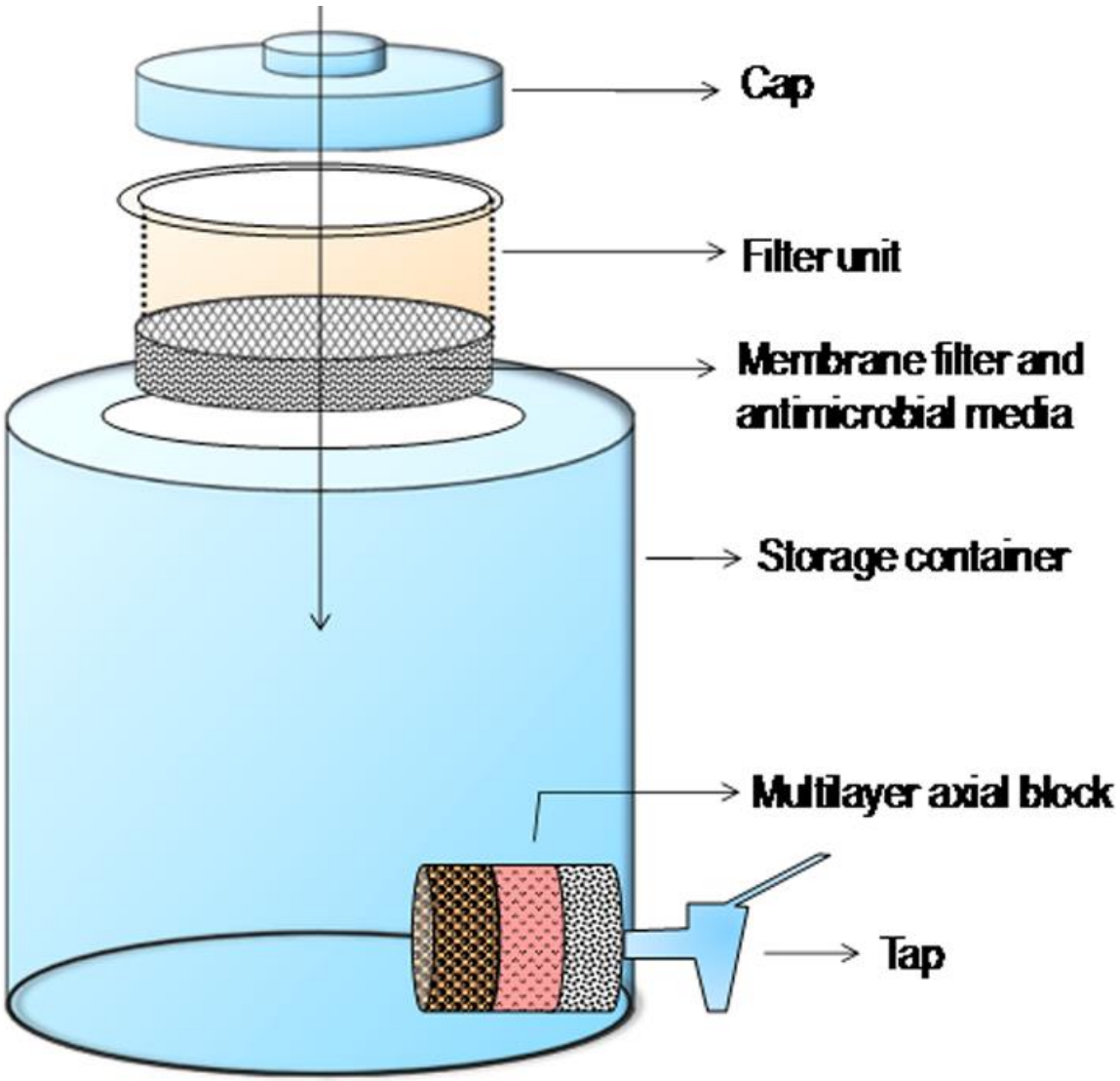
Live/dead staining experiments







Leaching experiments


Cap
Filter unit
Membrane filter and antimicrobial media
Storage container
Multilayer axial block
Tap

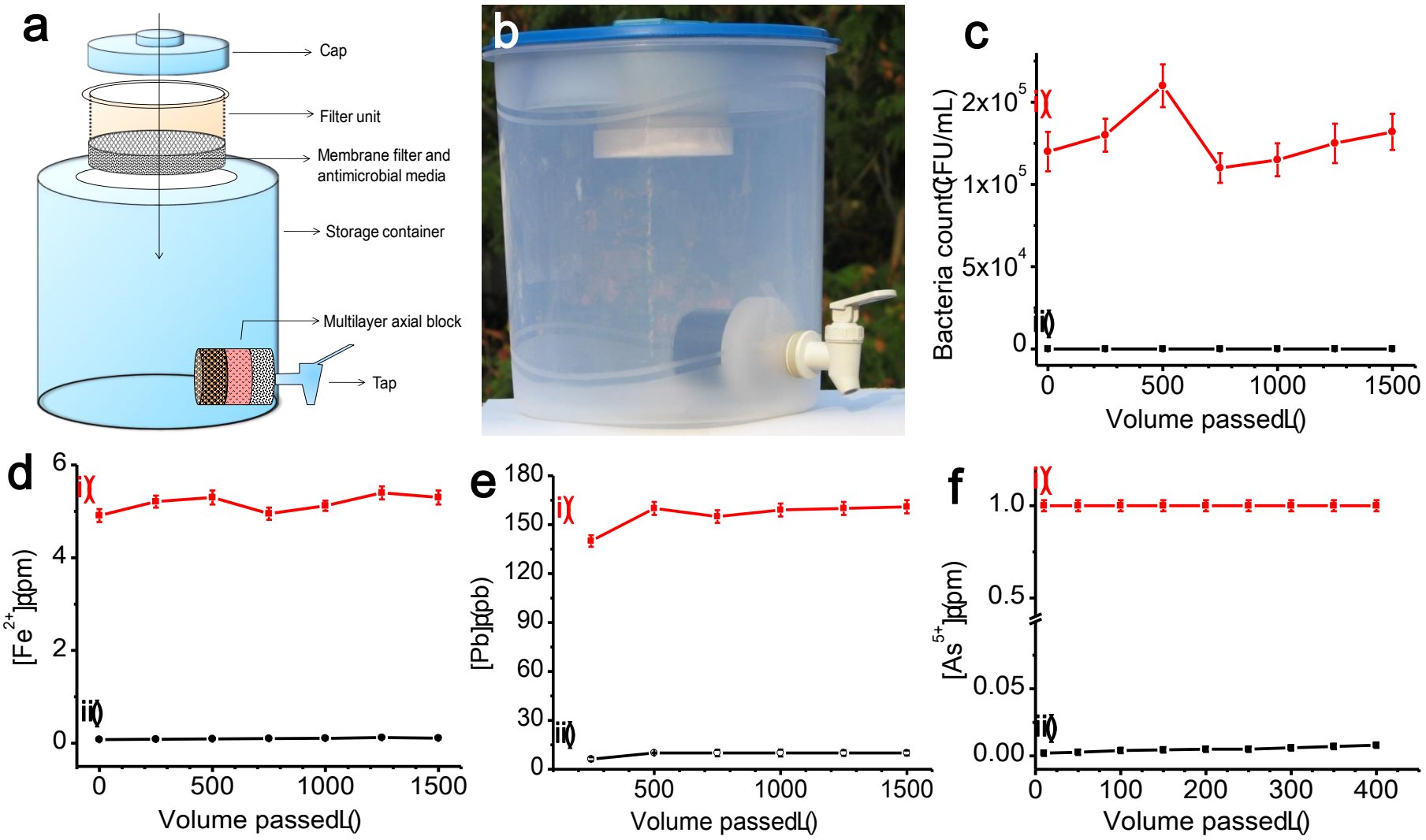
Physicochemical characteristics of influent natural drinking water

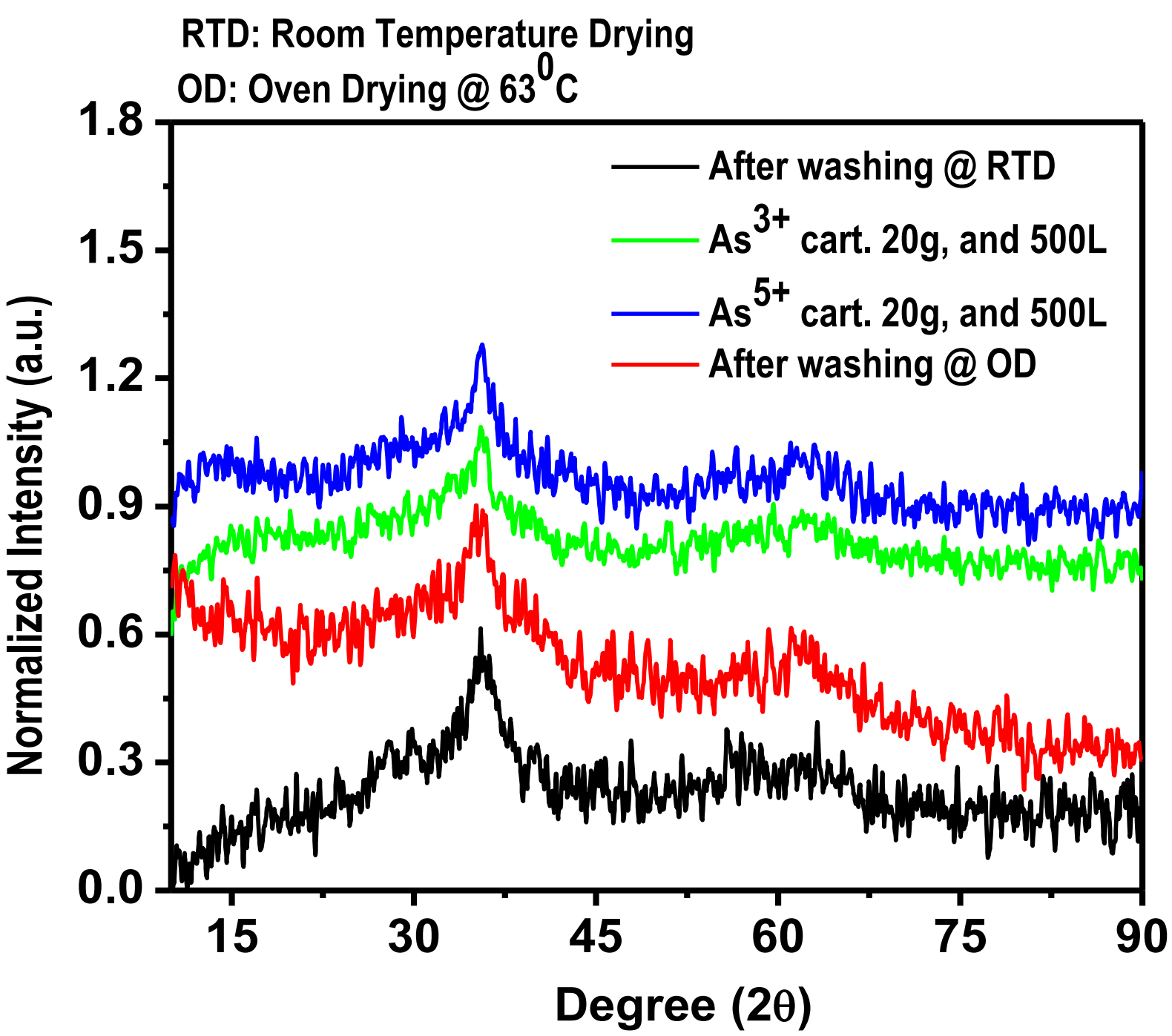
(Note: All parameters are expressed in mg L^{-1}, except for pH and conductivity)

ND-not detected

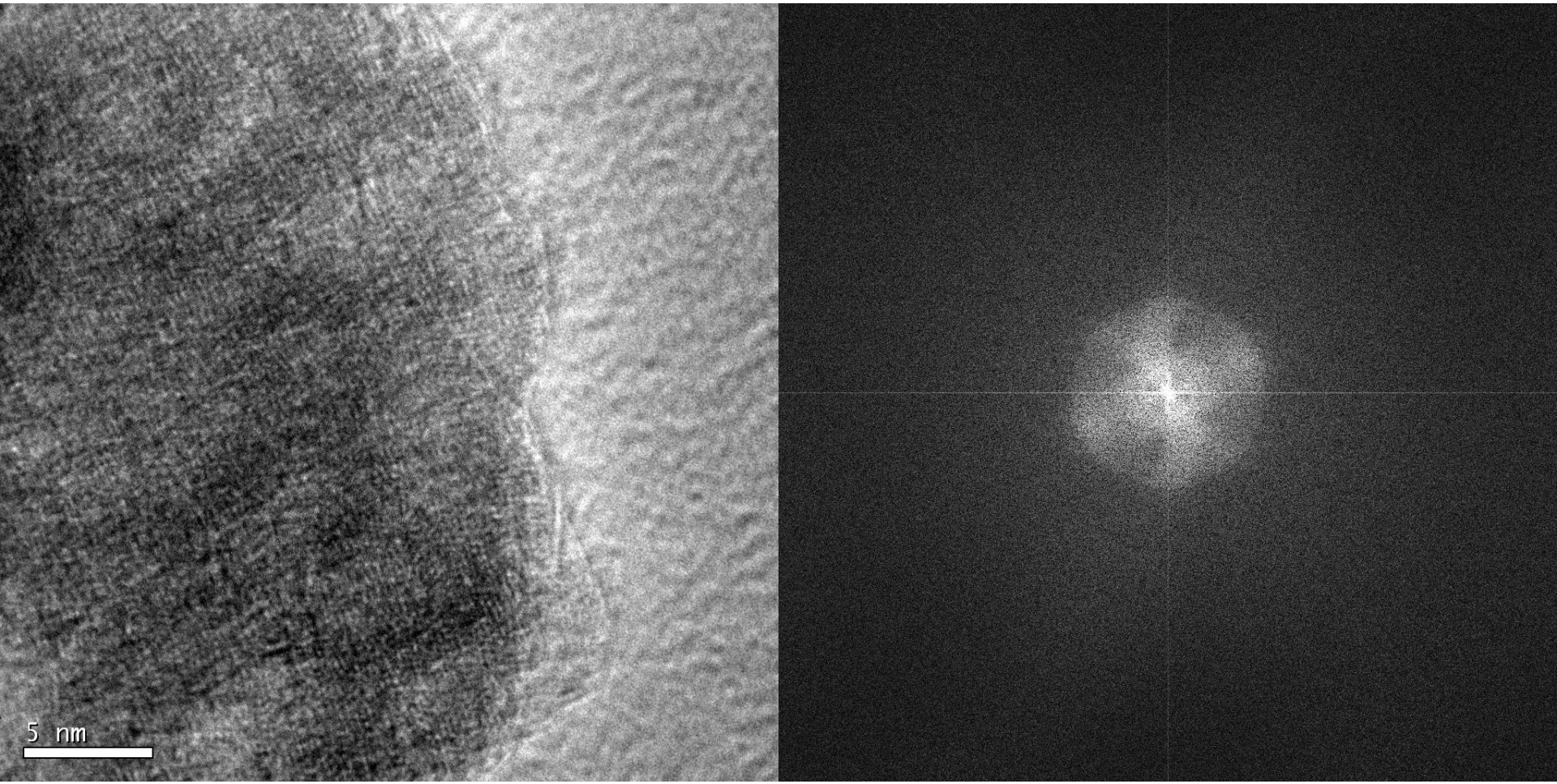
Natural drinking water (without treatment so that there is a residual bacterial count in it) was used for testing to ensure that that the material functions in the field.

Parameters	Value
Total coliforms (CFU/mL)	1-2 x 10^3
p H @25°C	7.8
Conductivity (µS/cm)	640.000
Fluoride	0.573
Chloride	86.340
Nitrate	1.837
Sulphate	32.410
Silicate	15.870
Lithium	ND
Sodium	53.740
Ammonium	ND
Potassium	2.330
Magnesium	14.340
Calcium	28.720

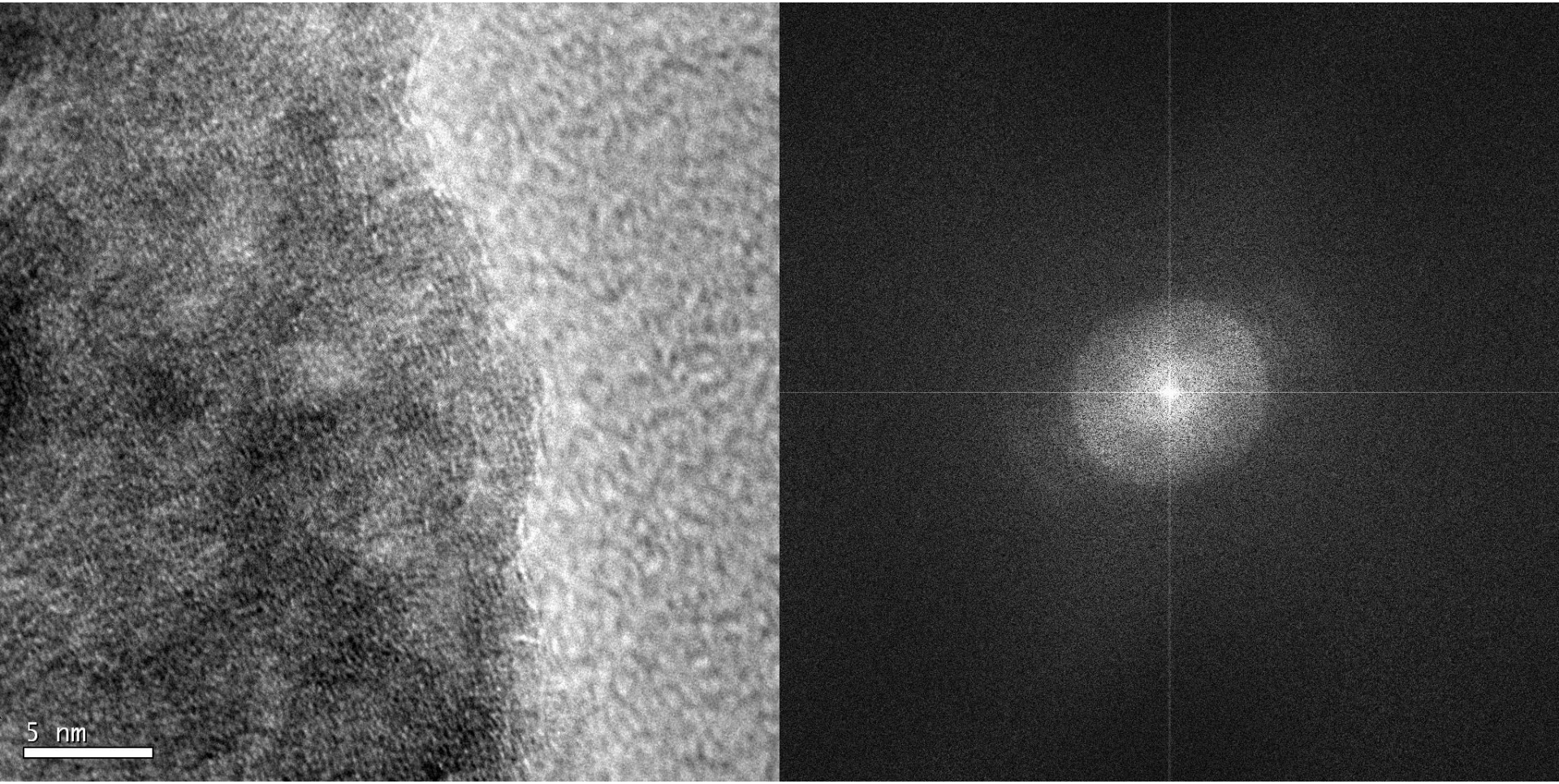

a
Cap
Filter unit
Membrane filter and antimicrobial media
Storage container
Multilayer axial block
Tap
b
c
Bacteria count(CFU/mL)
2x10^5
1x10^5
5x10^4
0
i)
ii)
0
500
1000
1500
Volume passedL()
d
[Fe^2+]p(pm)
6
4
2
0
i)
ii)
0
500
1000
1500
Volume passedL()
e
[Pb]p(pb)
180
150
120
90
60
30
0
i)
ii)
500
1000
1500
Volume passedL()
f
[As^5+]p(pm)
1.0
0.5
0.05
0.00
i)
ii)
0
100
200
300
400
Volume passedL()

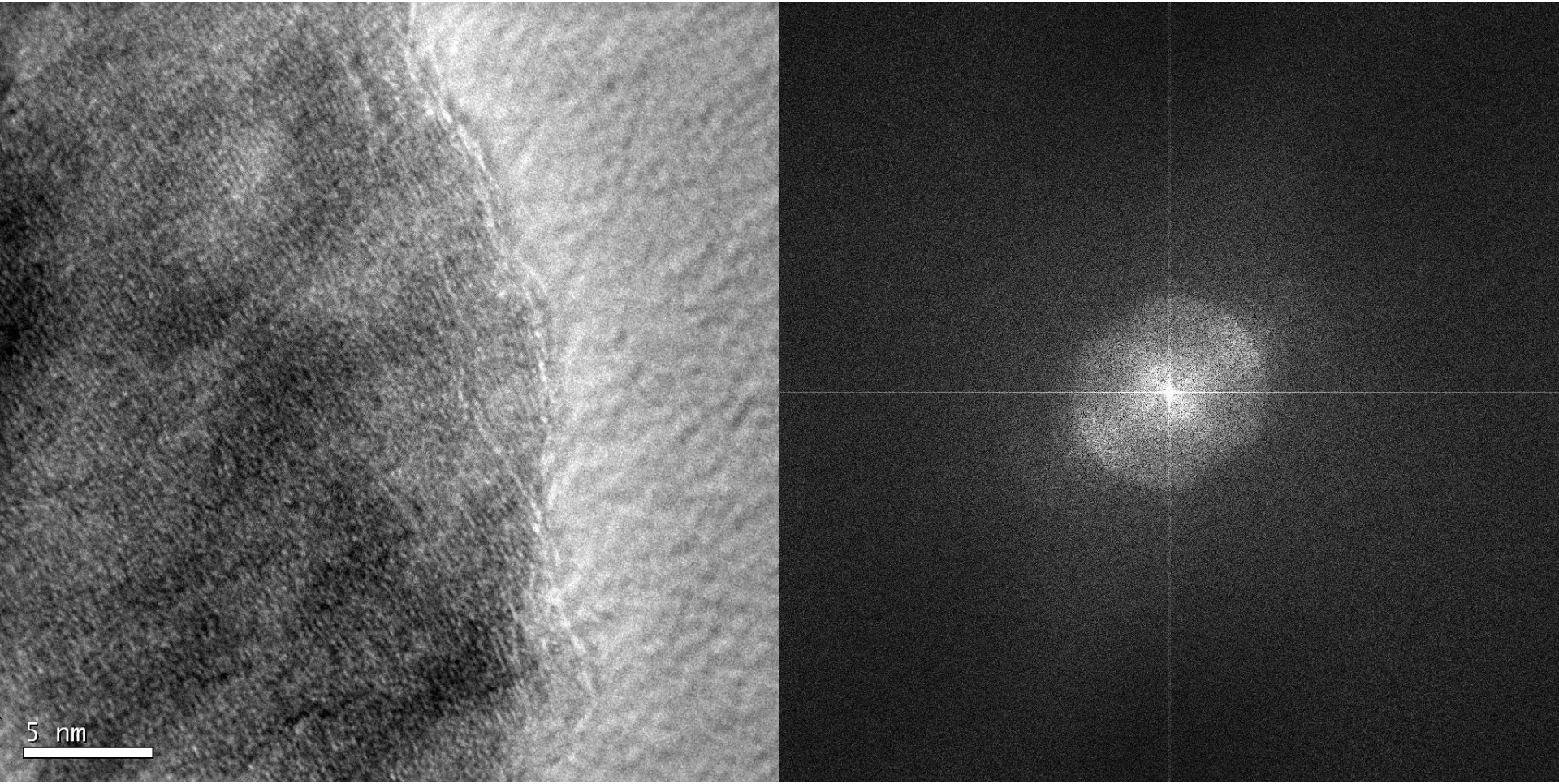

RTD: Room Temperature Drying
OD: Oven Drying @ 63^{0}C
After washing @ RTD
As^{3+} cart. 20g, and 500L
As^{5+} cart. 20g, and 500L
After washing @ OD
Normalized Intensity (a.u.)
Degree (2θ)
0.0
0.3
0.6
0.9
1.2
1.5
1.8
15
30
45
60
75
90

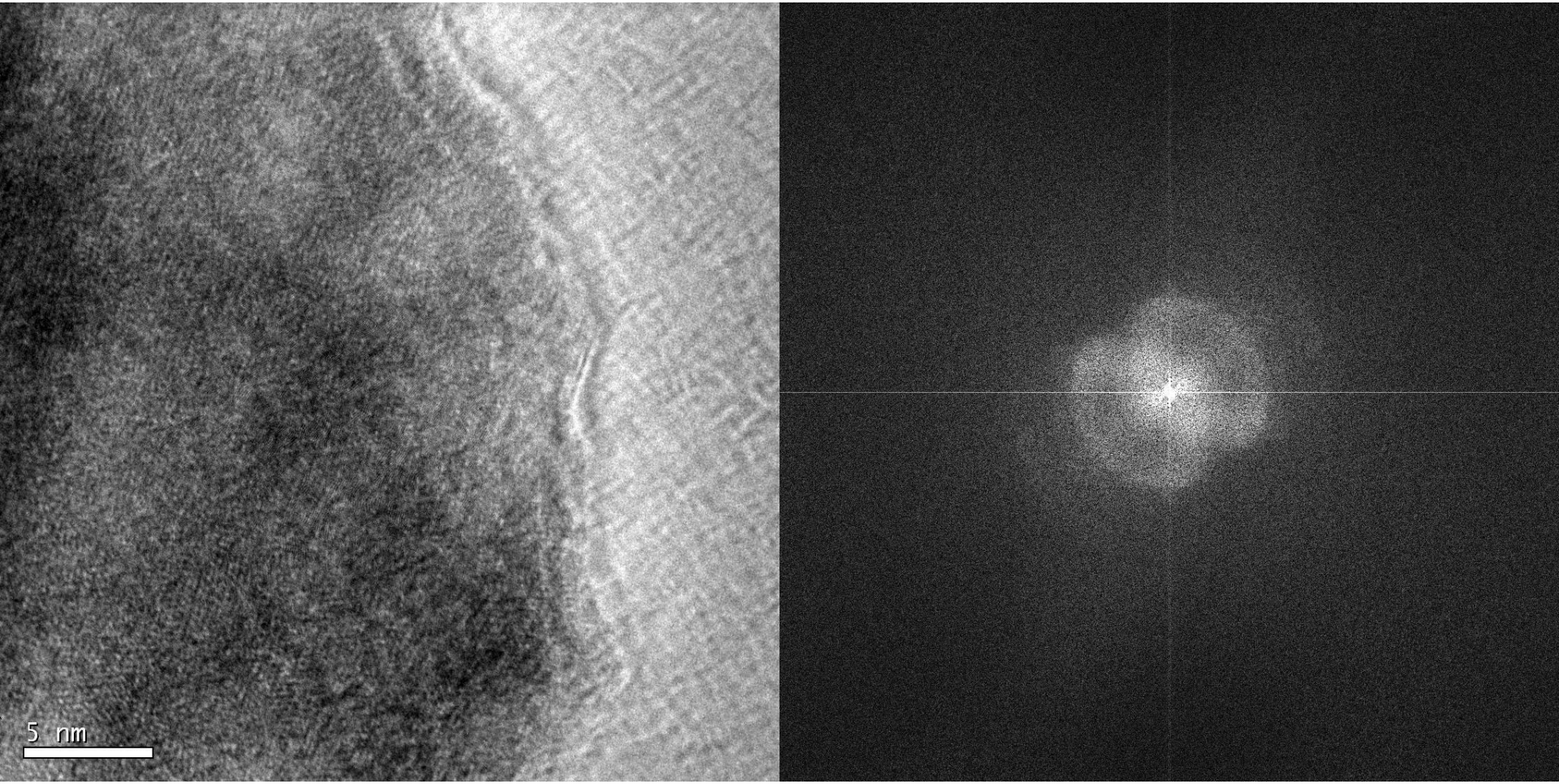
Metastable phase

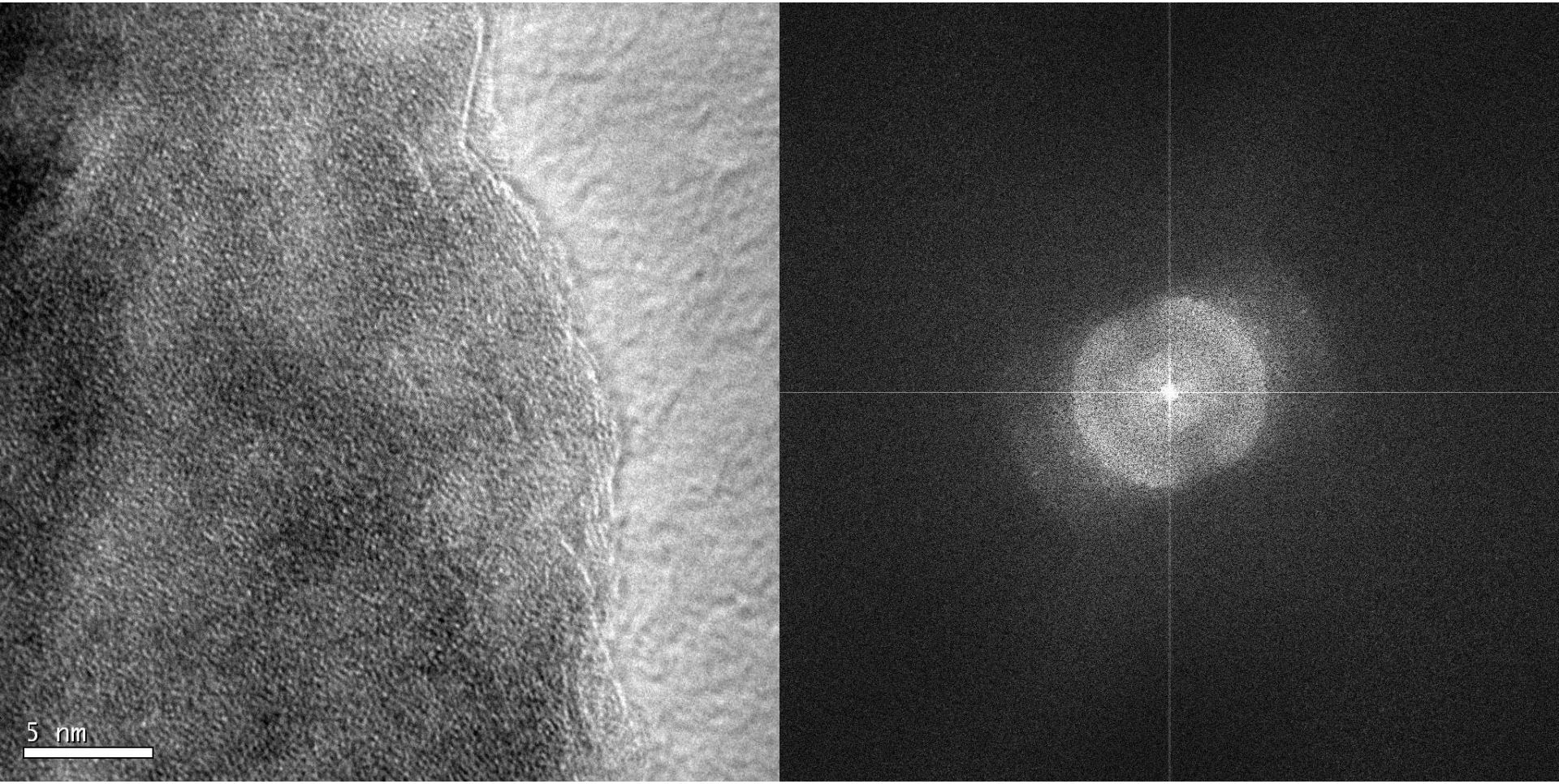


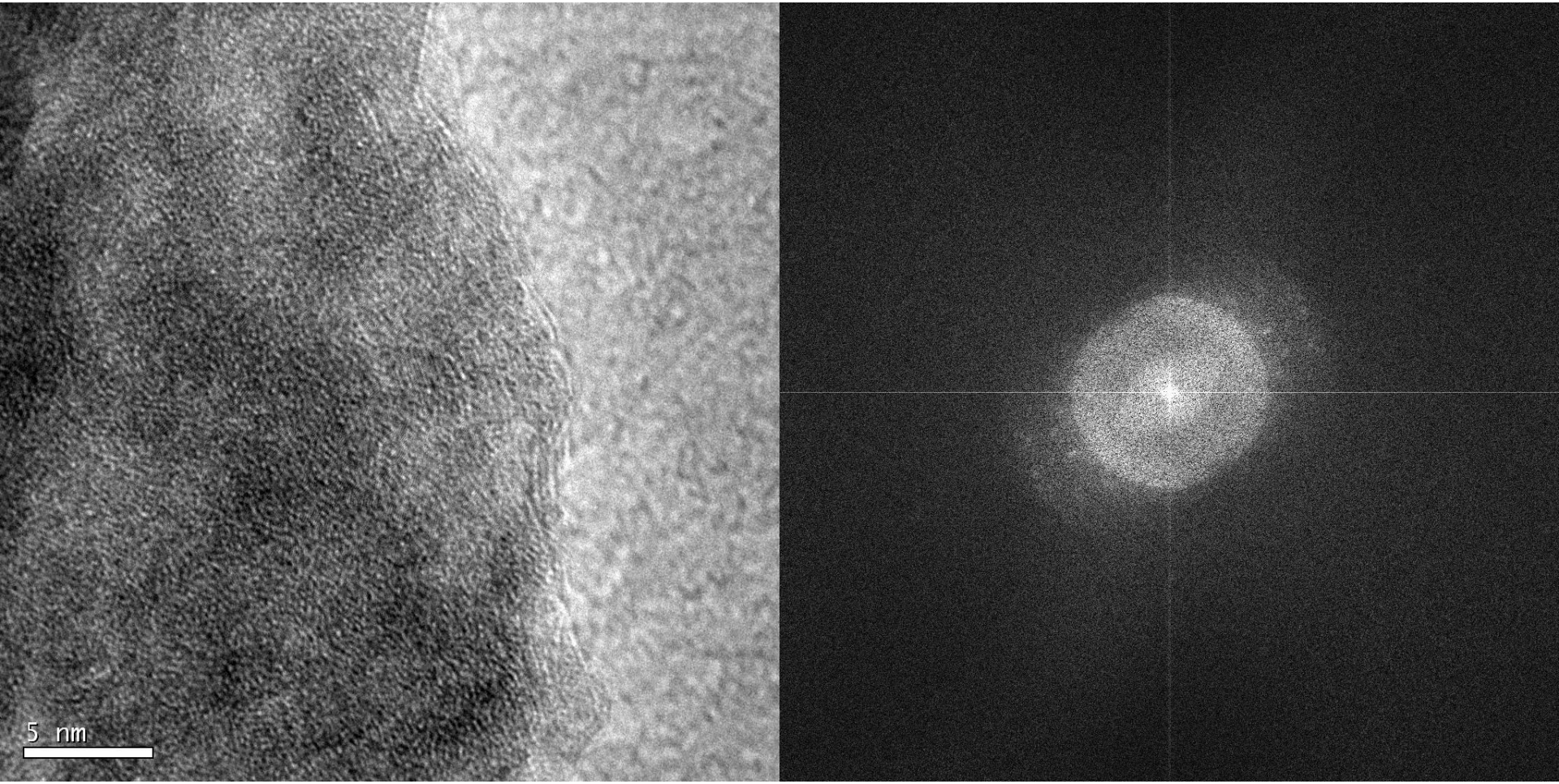
Time dependent TEM

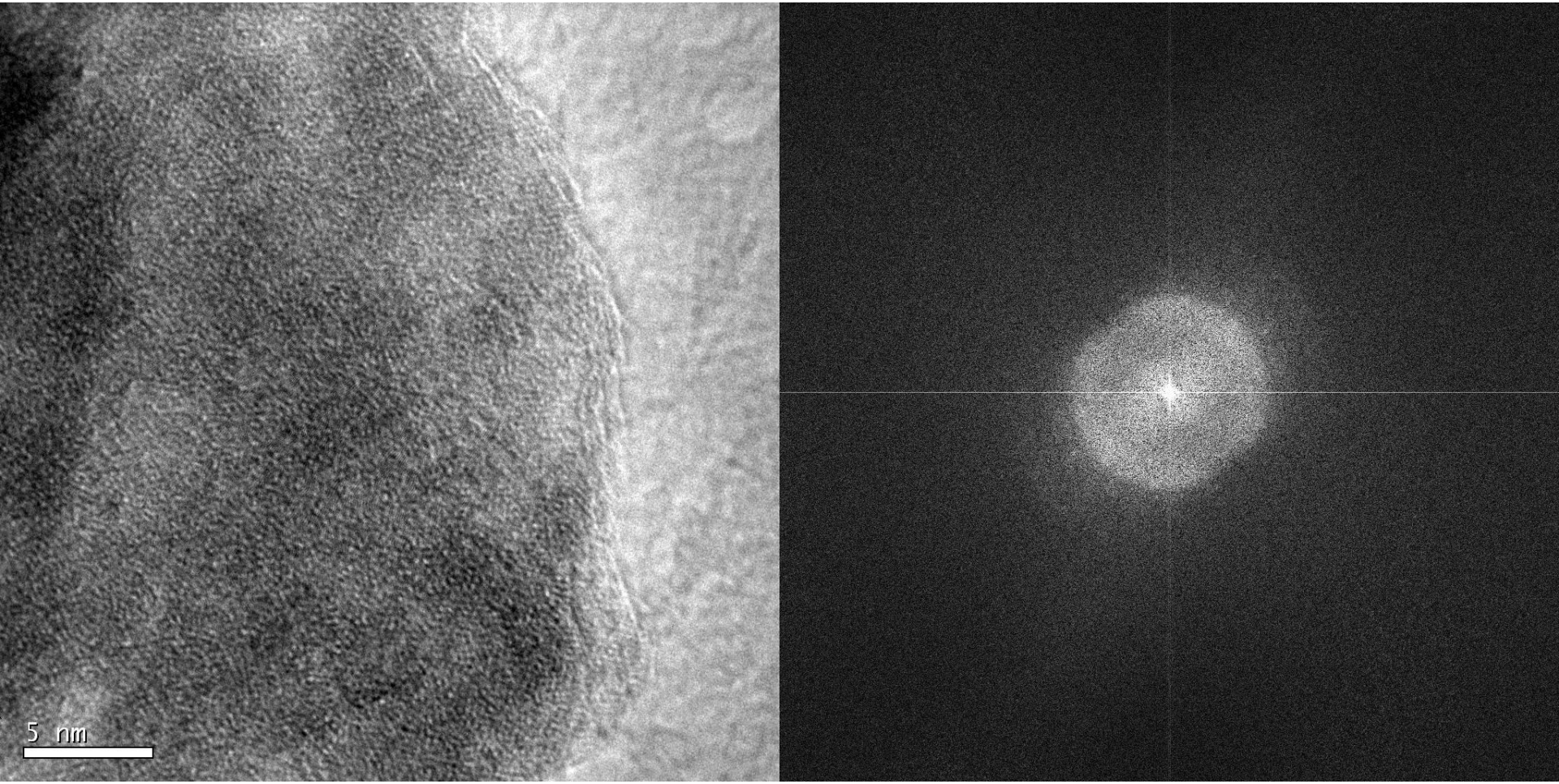

5 nm

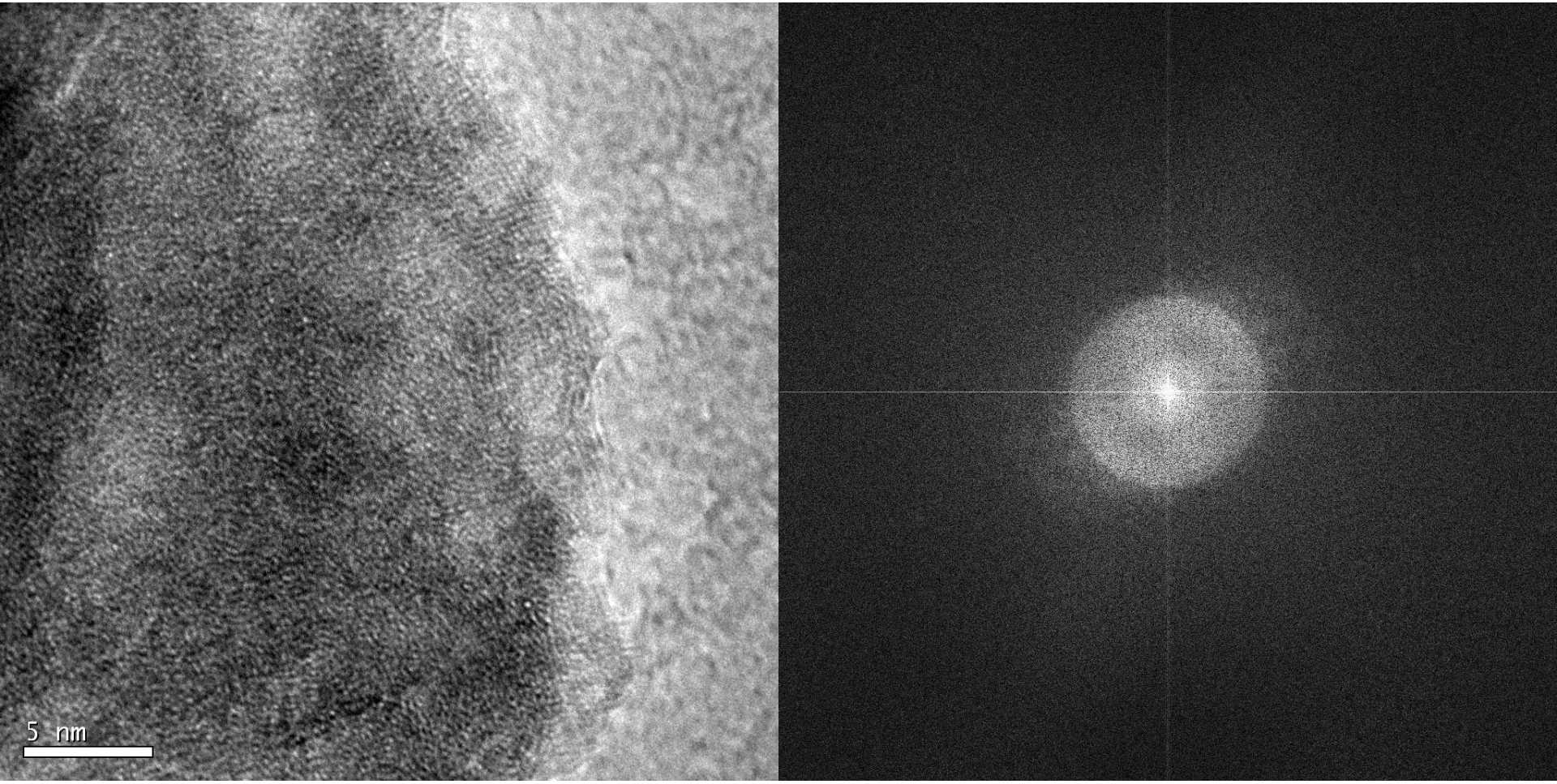

5 nm

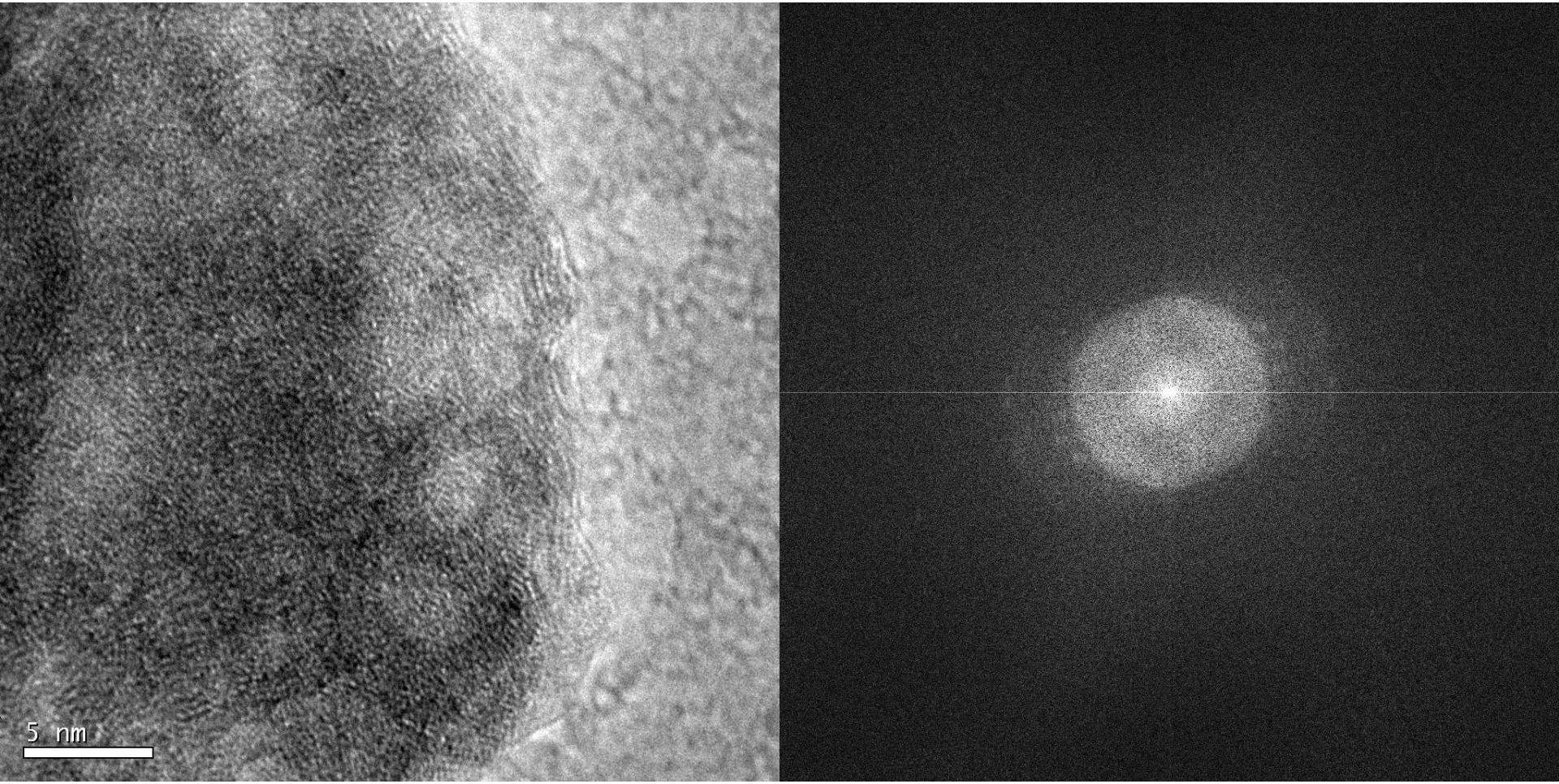

5 nm

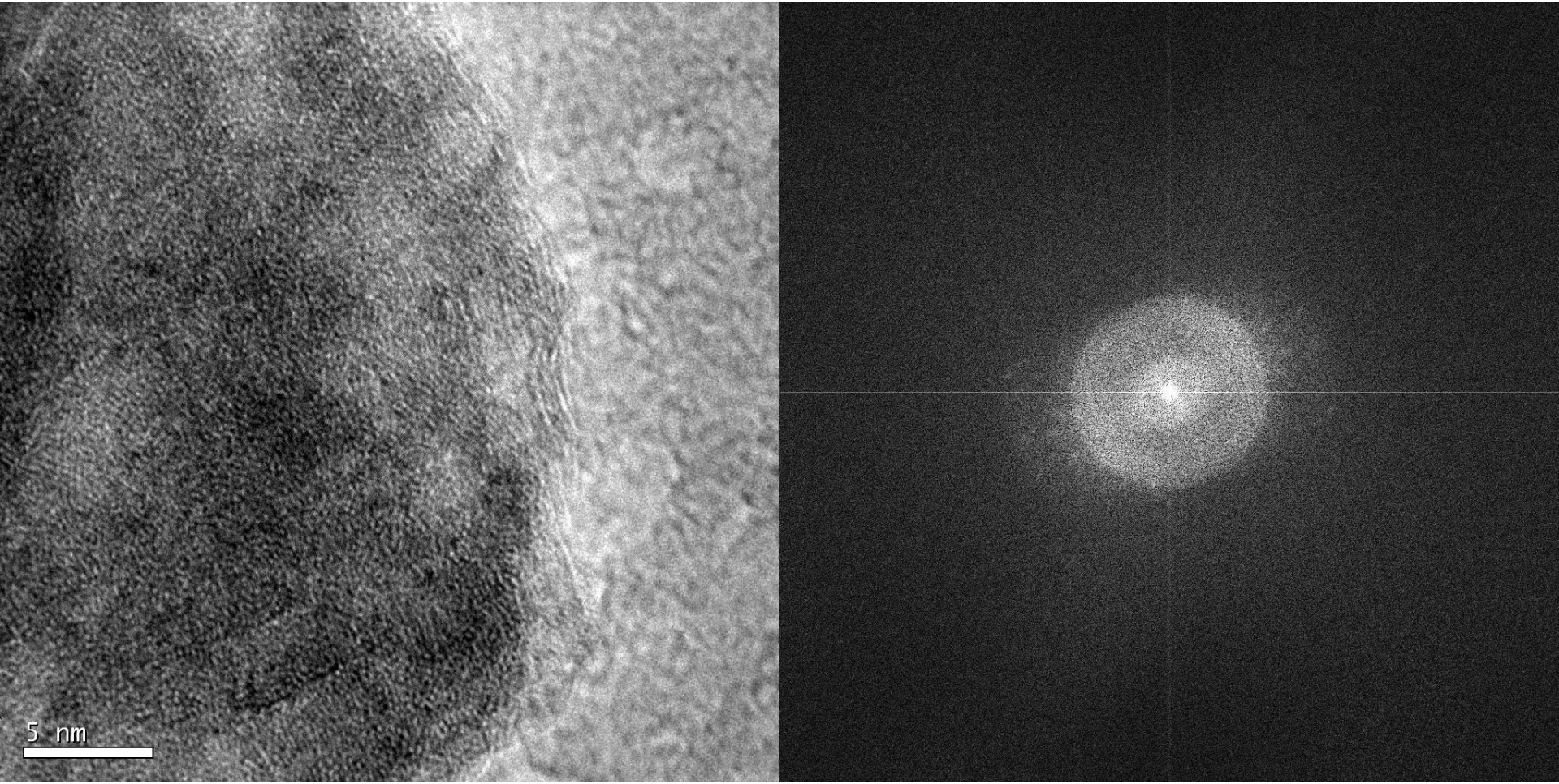

5 nm

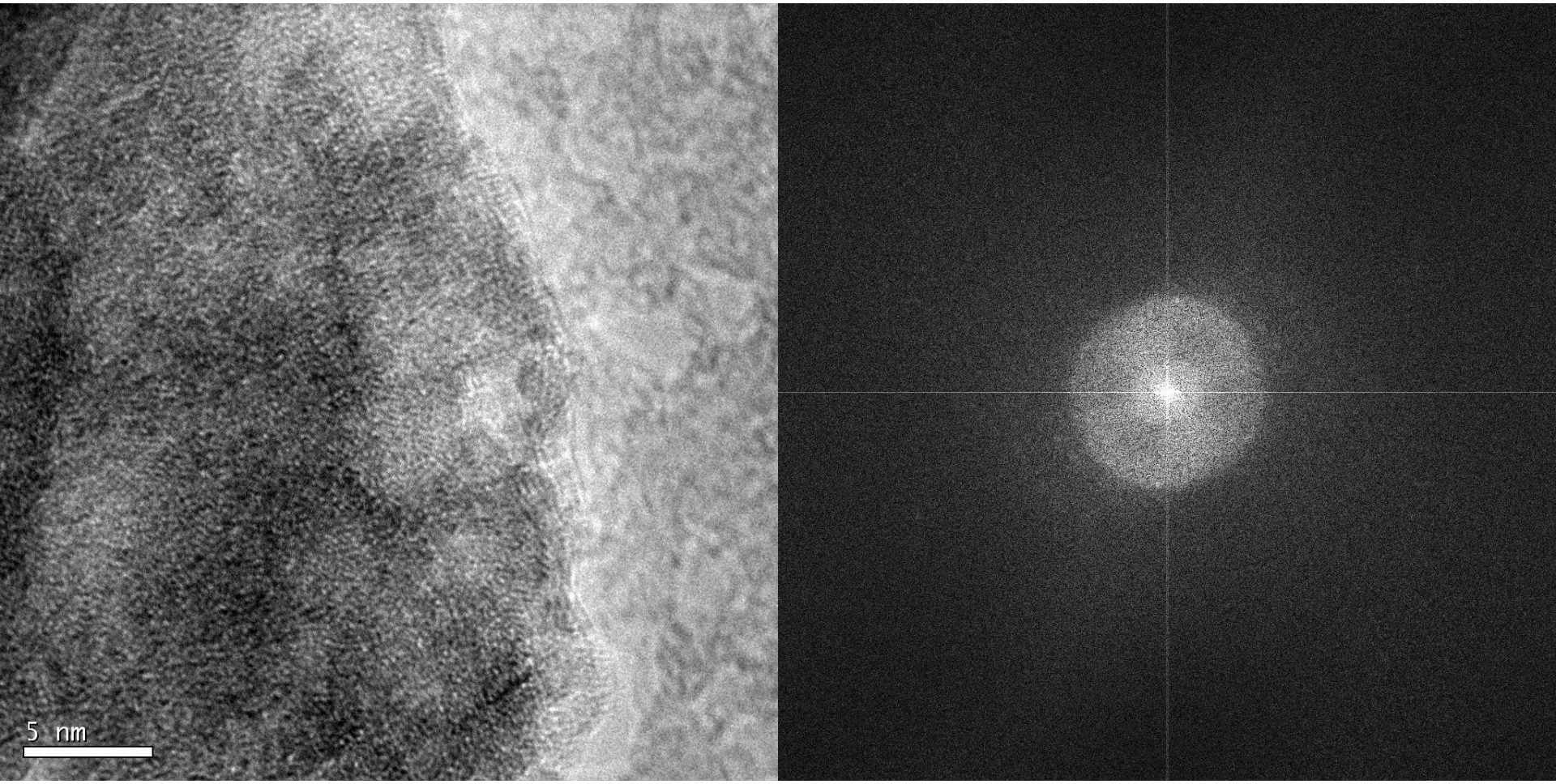

5 nm

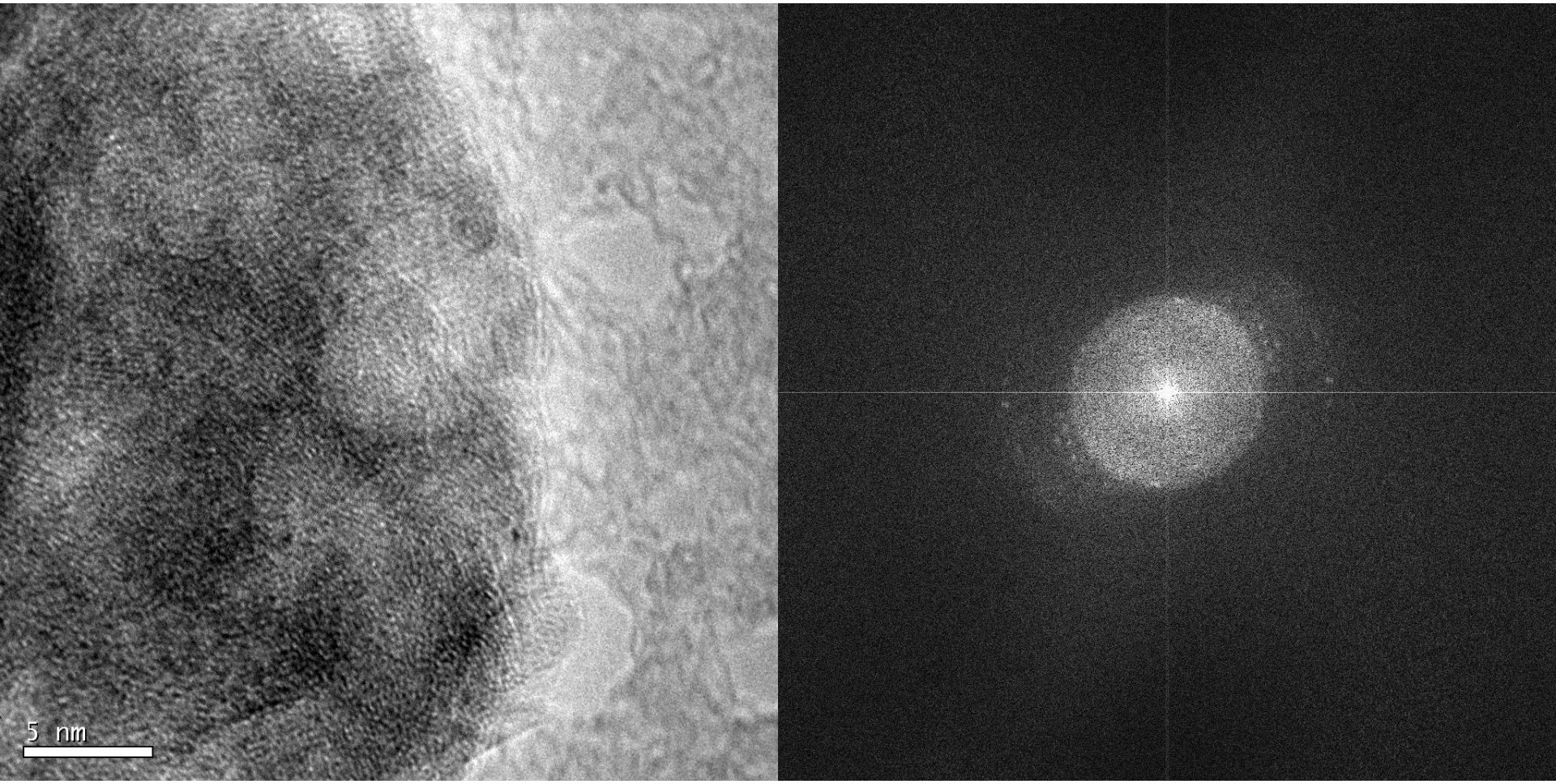

5 nm

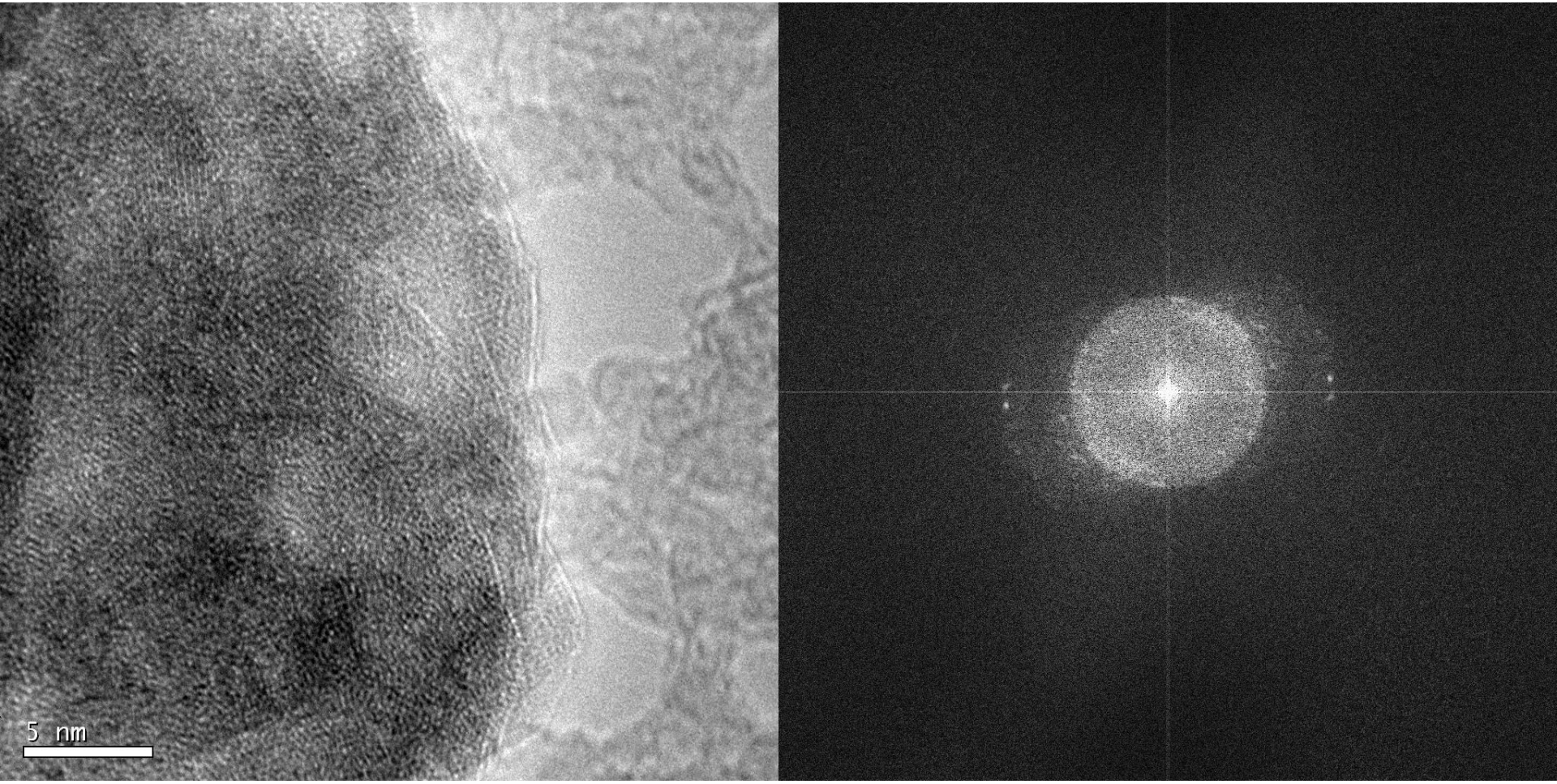

5 nm

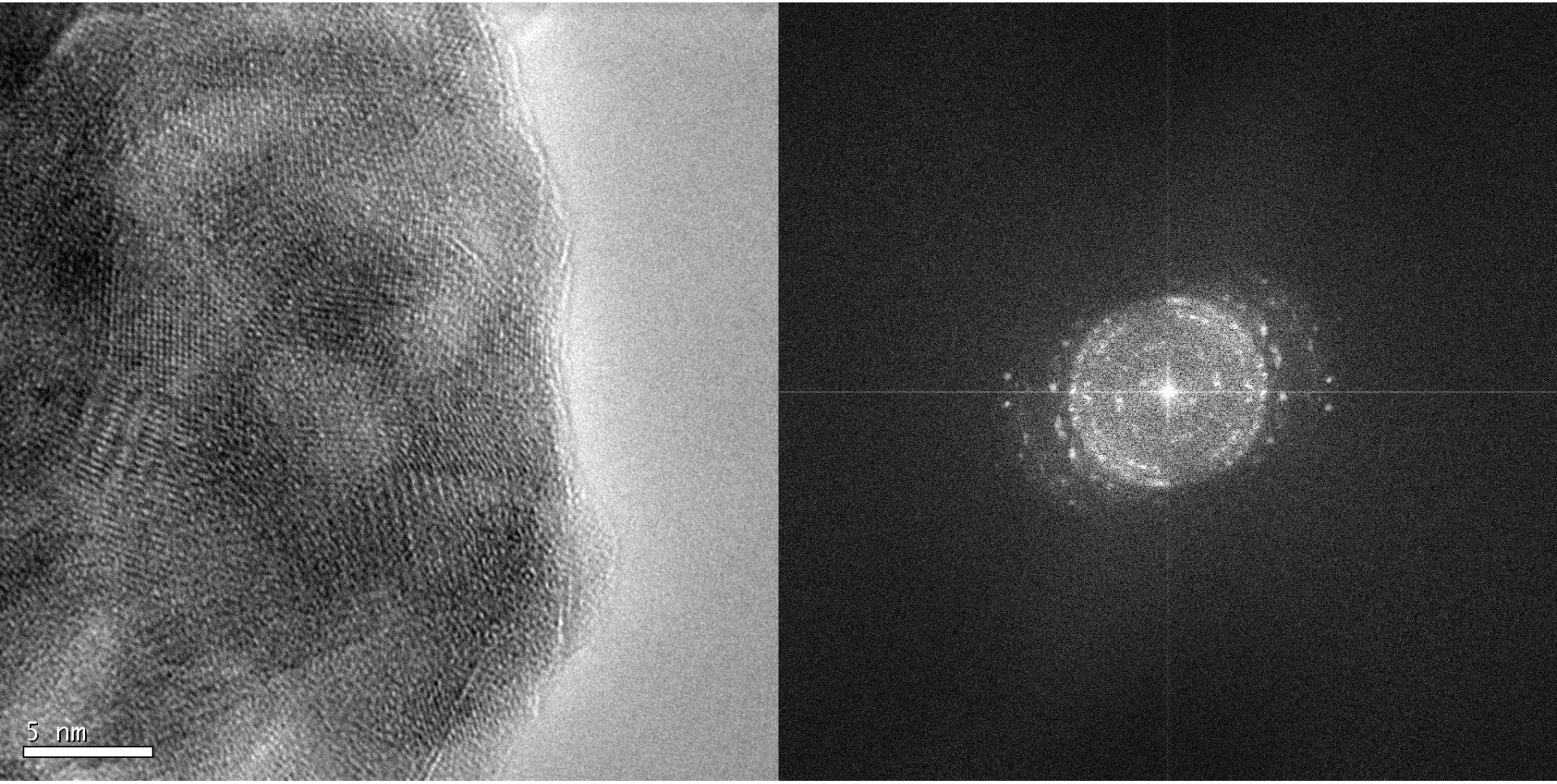

5 nm

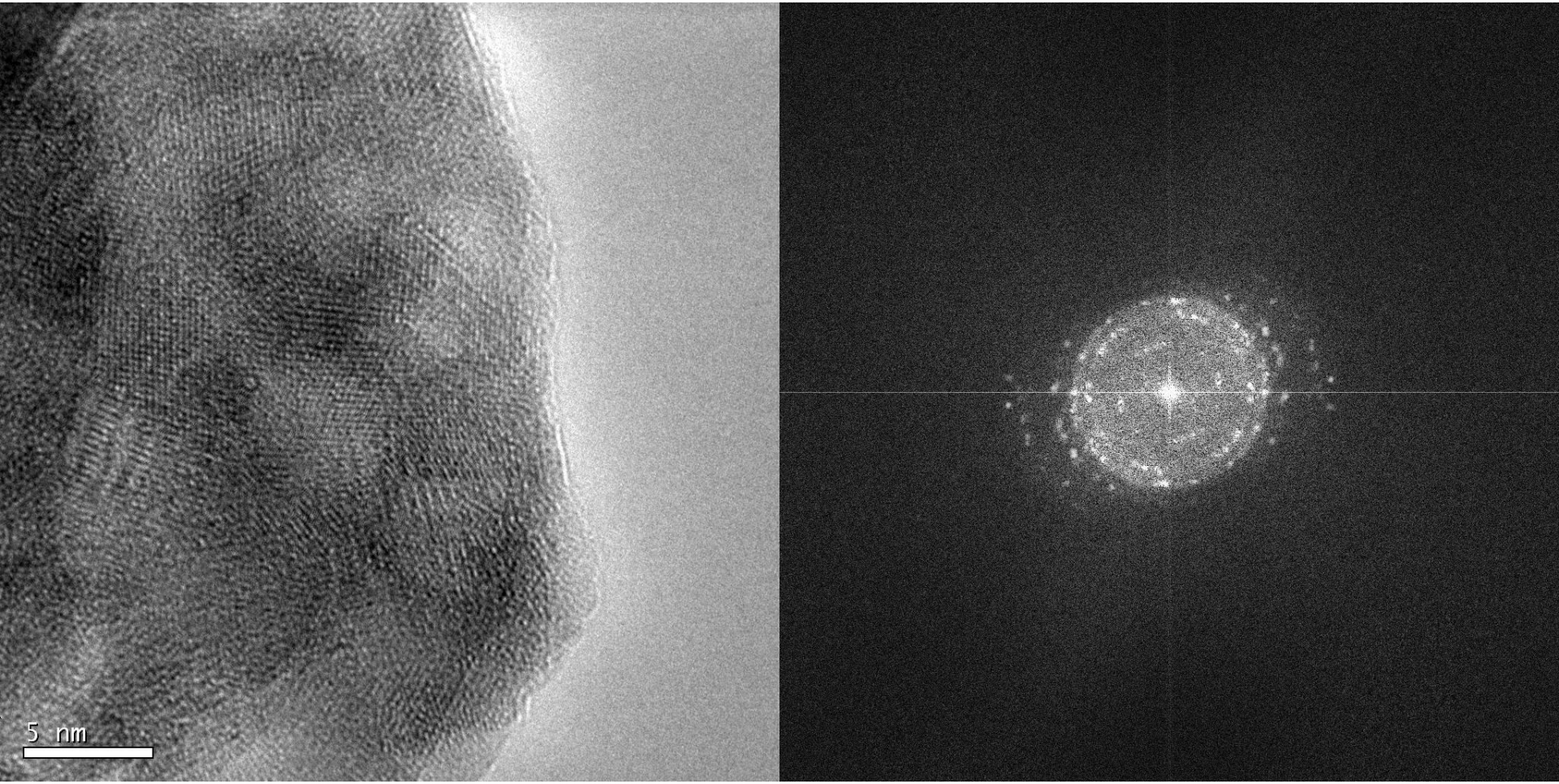

5 nm

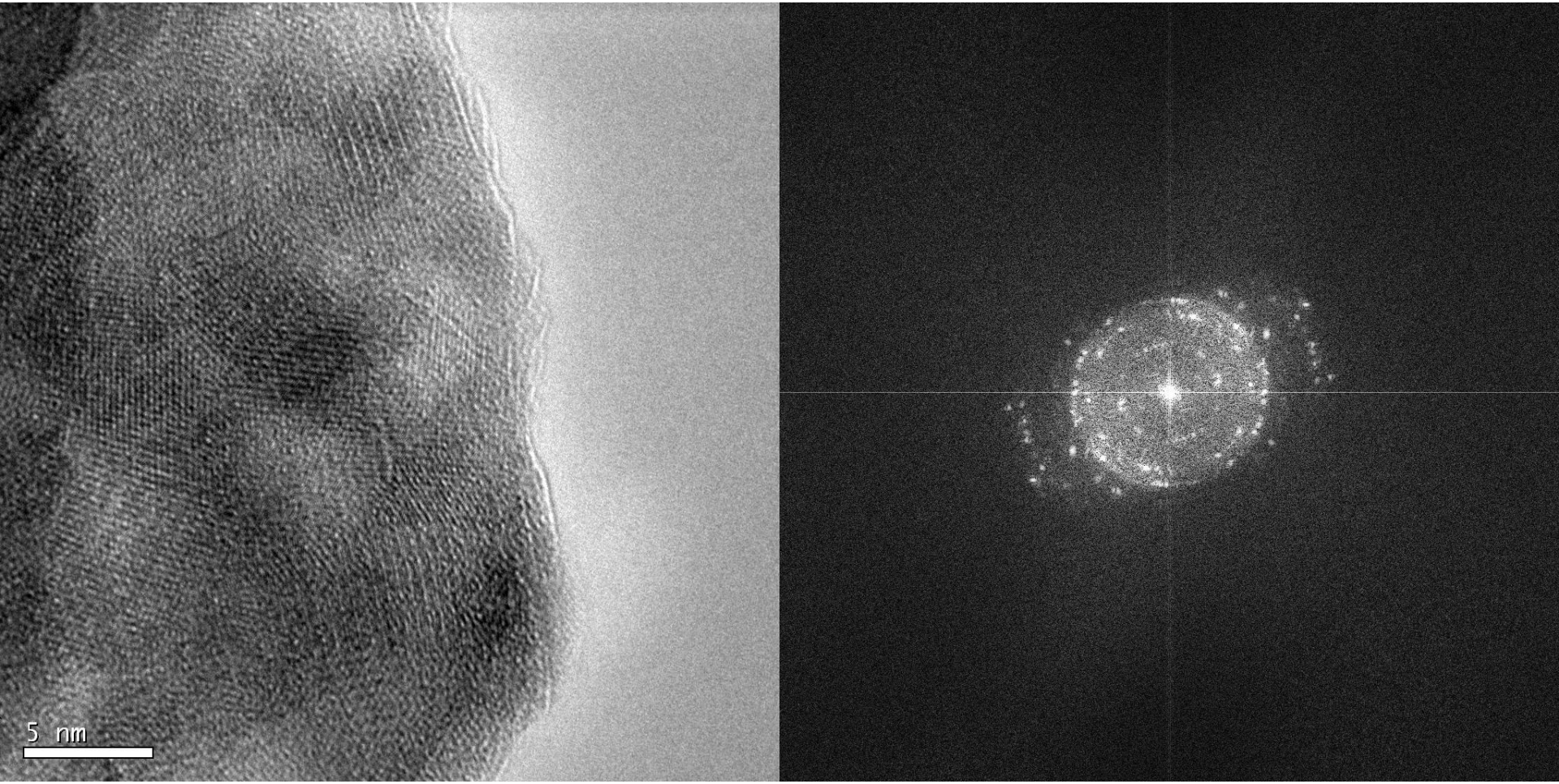

5 nm

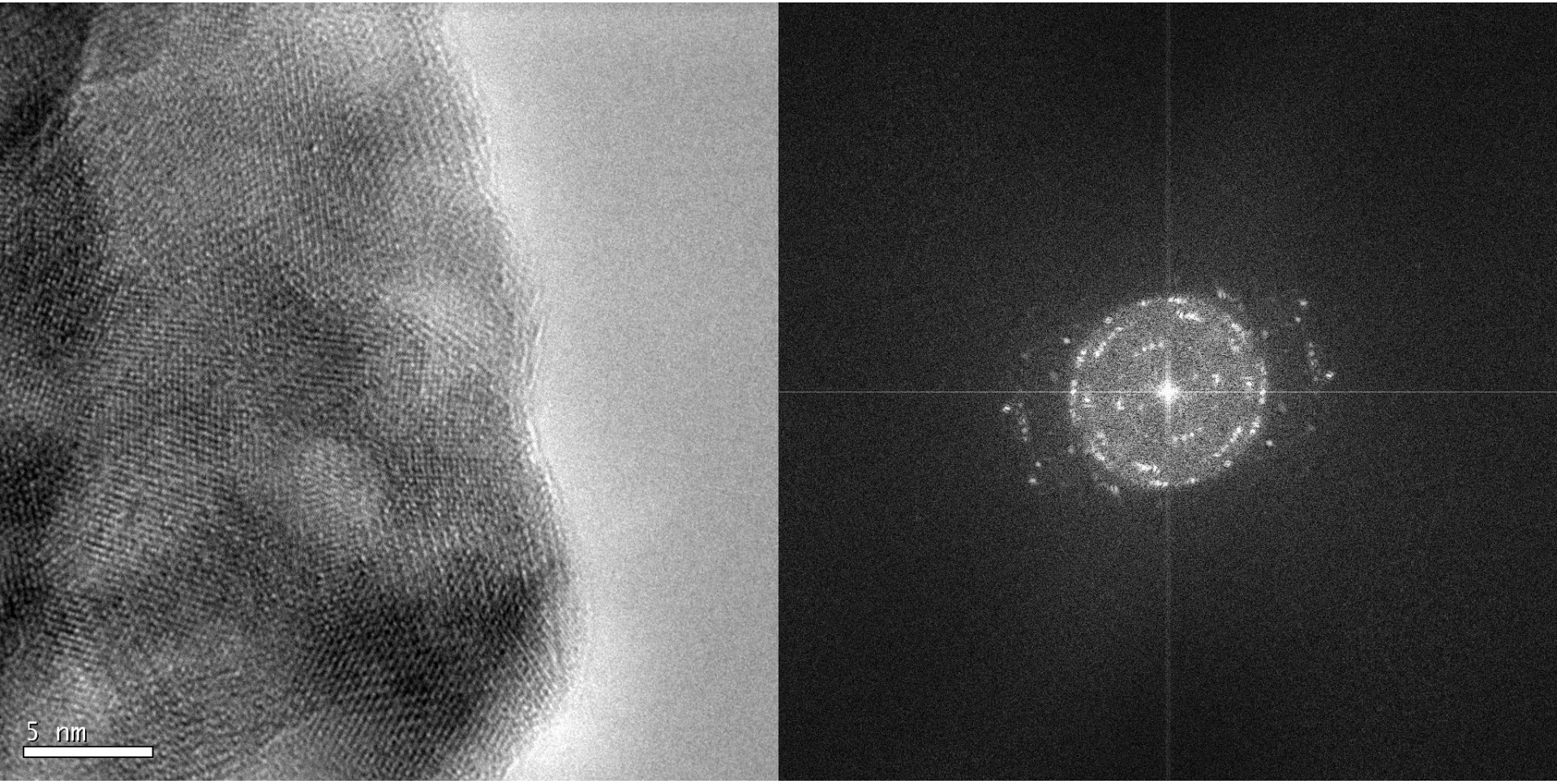

5 nm

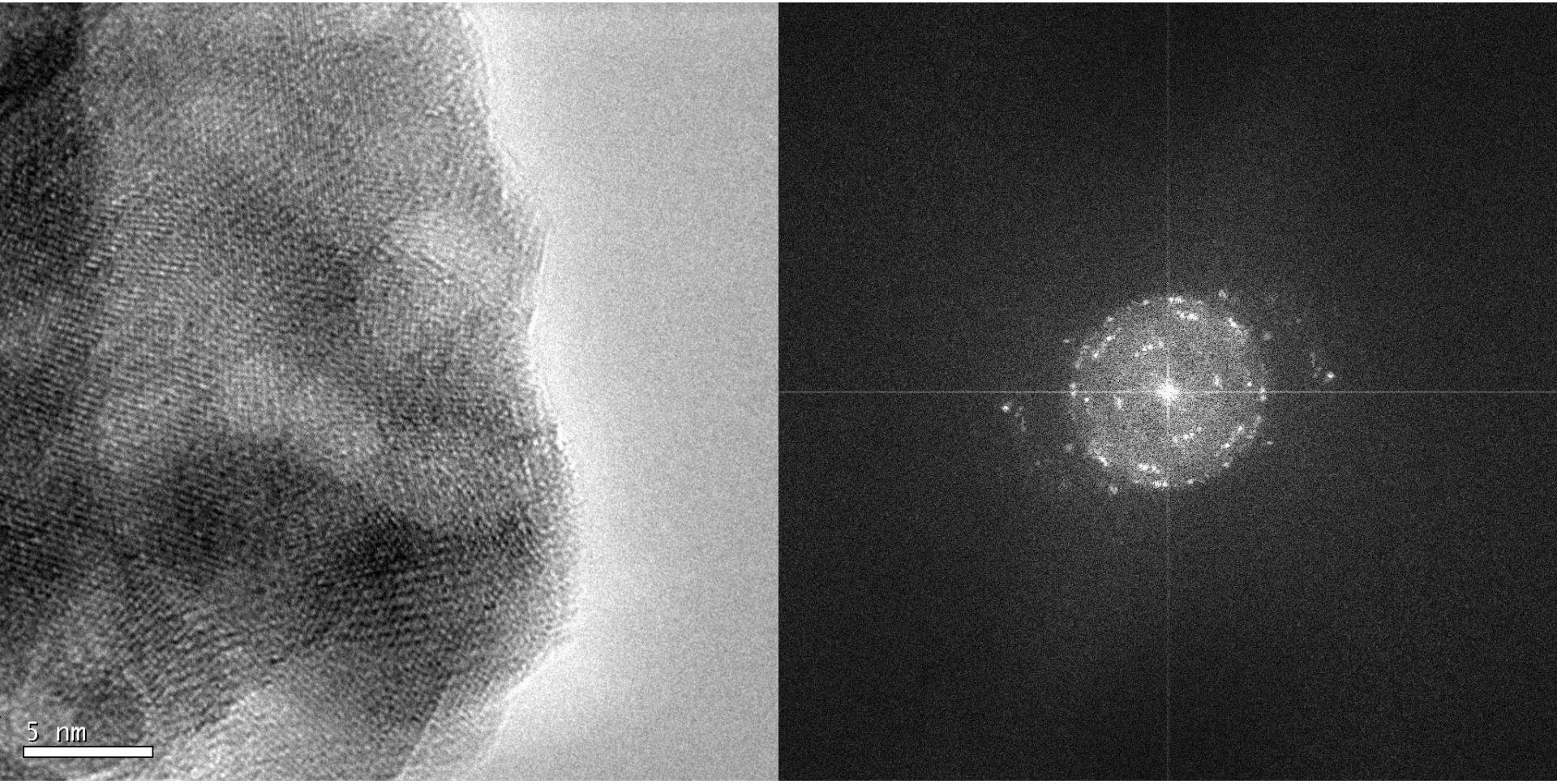

5 nm

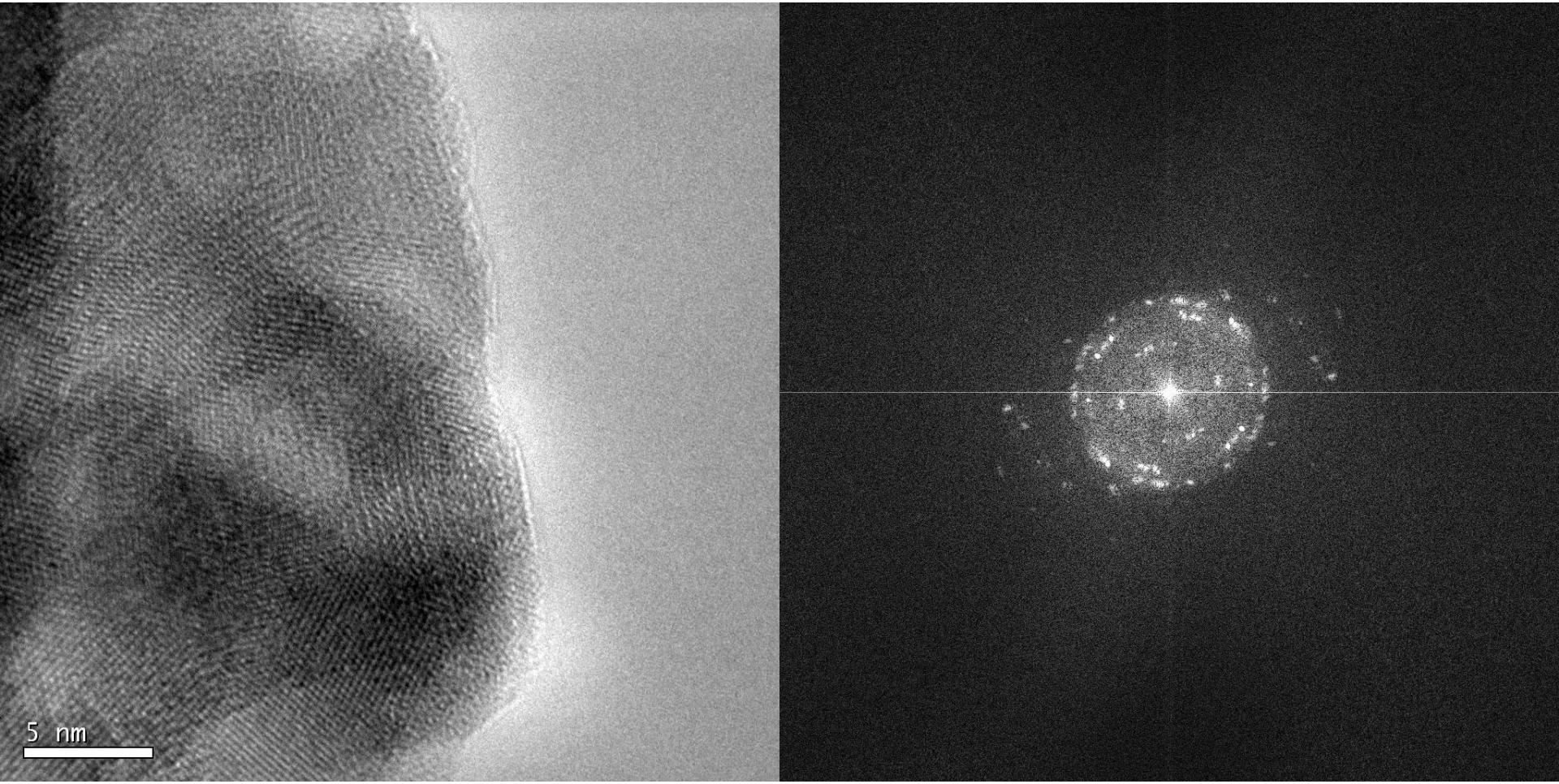

5 nm

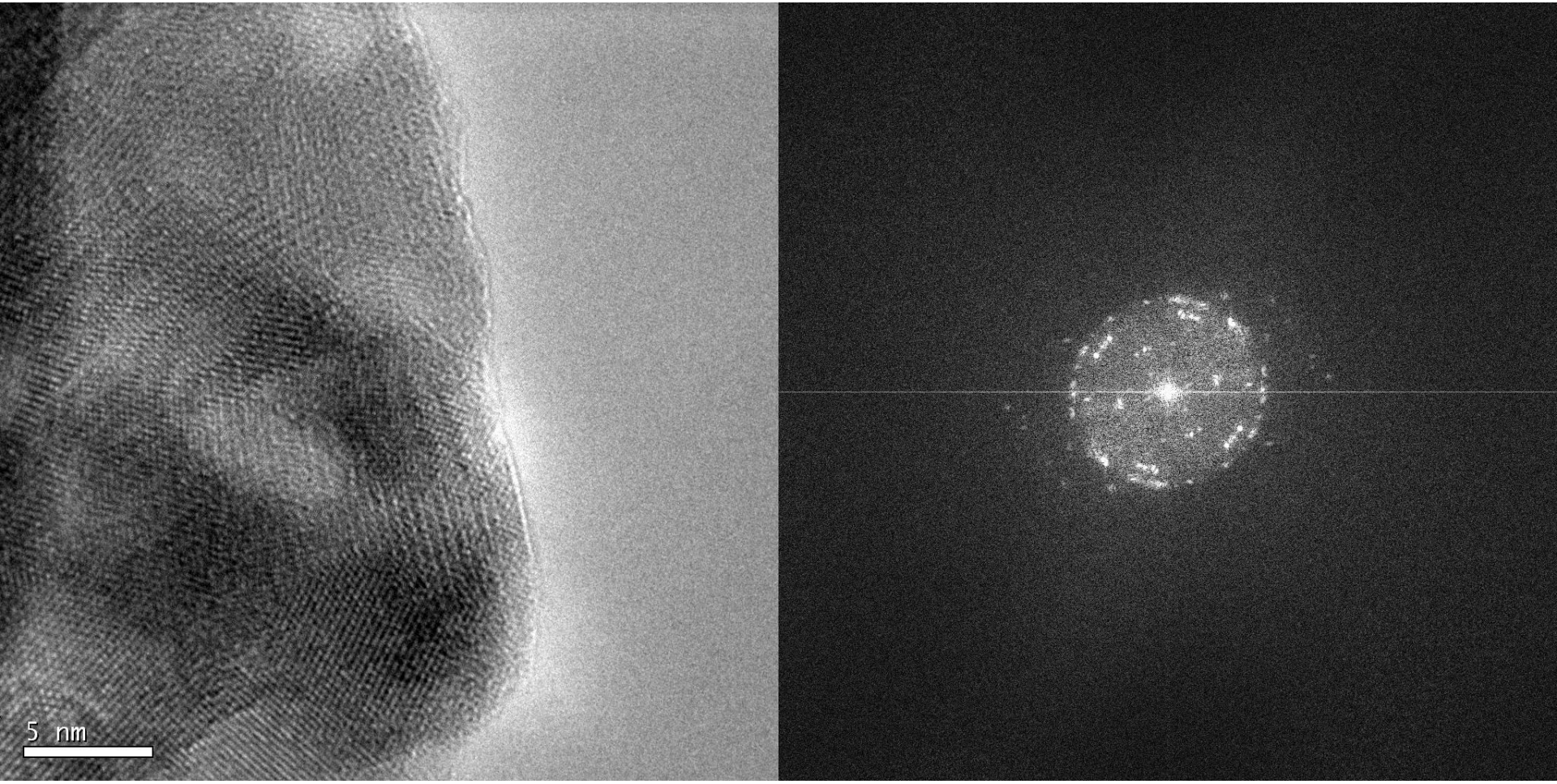

5 nm


5 nm


5 nm


5 nm


5 nm


5 nm

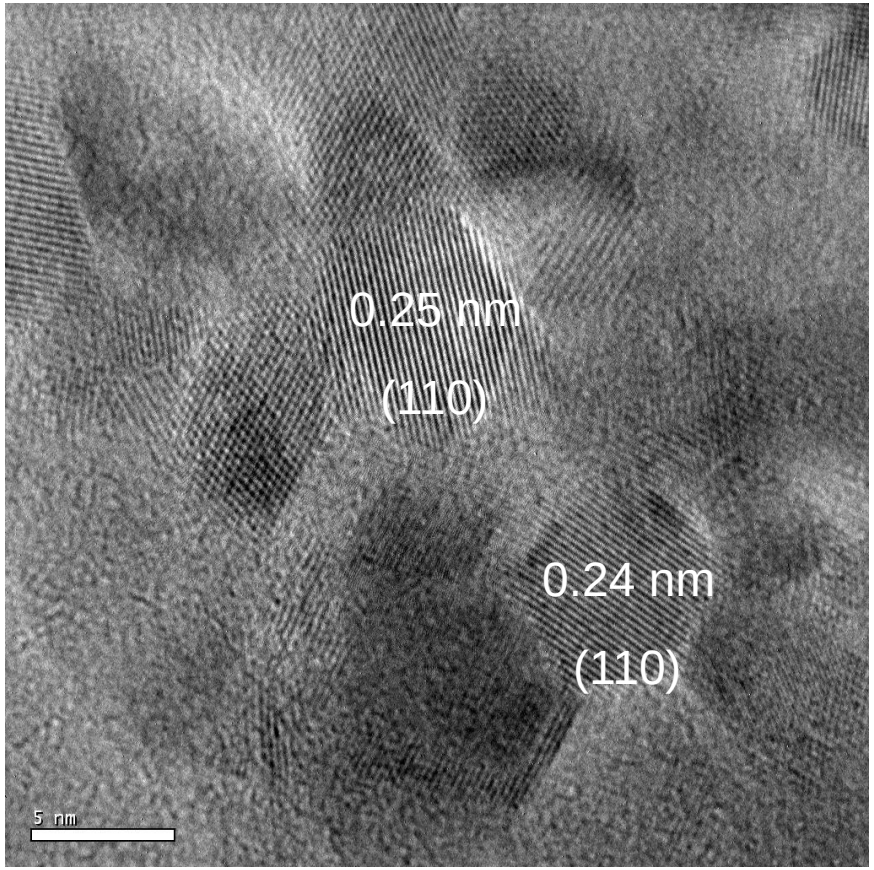
Ferrihydrite: 0.22 nm, 0.25 nm

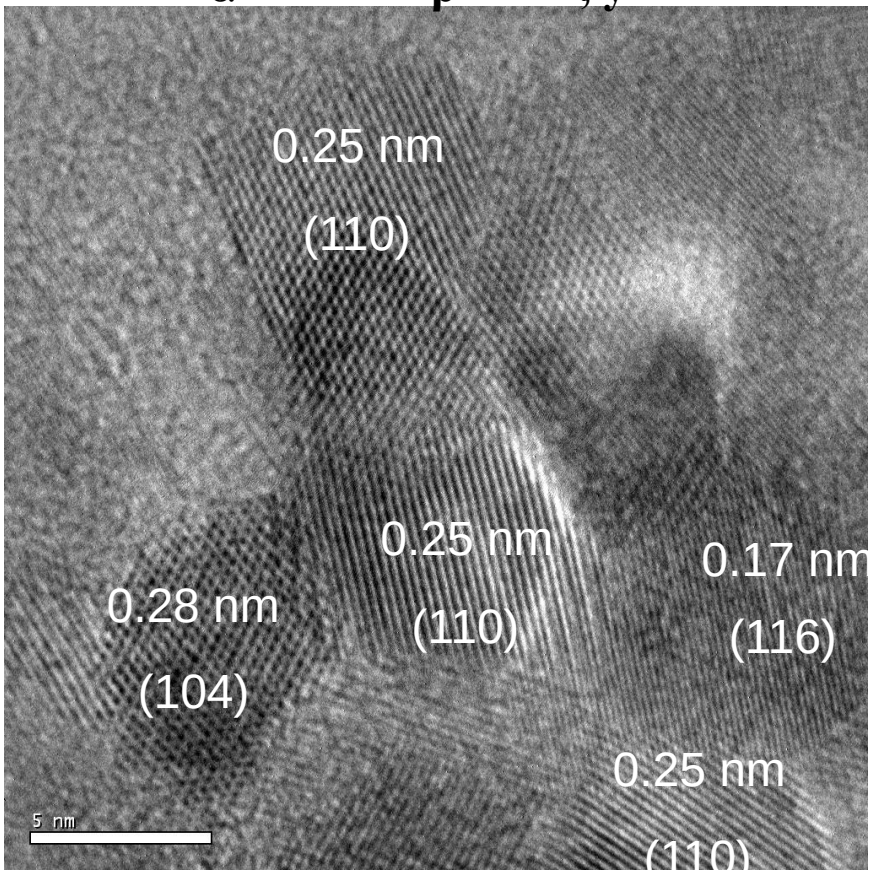
HRTEM images of initial material

PCPDF No. **29-0712 (Hexagonal)**

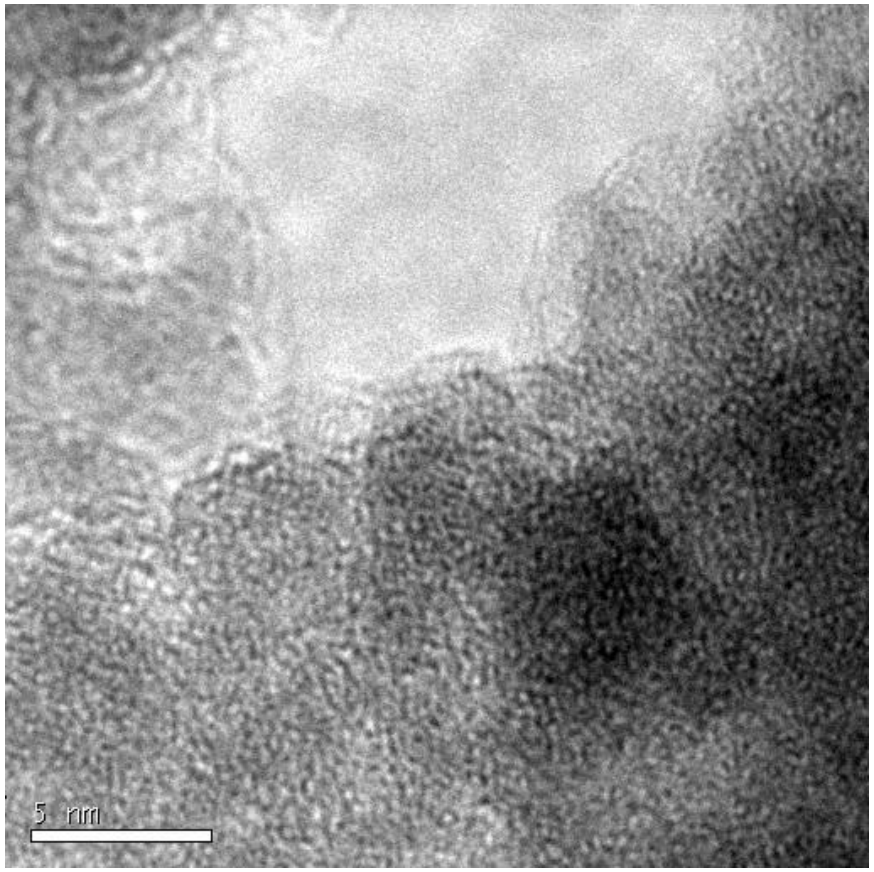
a = 5.08, b = , c = 9.4

α = β = , γ=

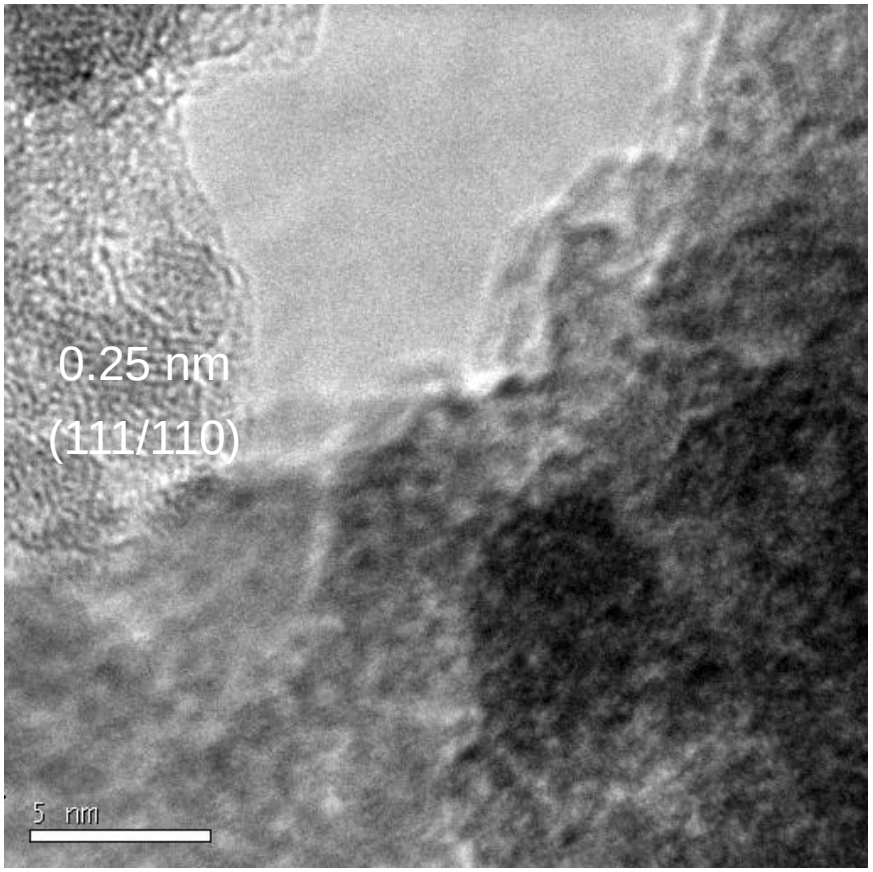




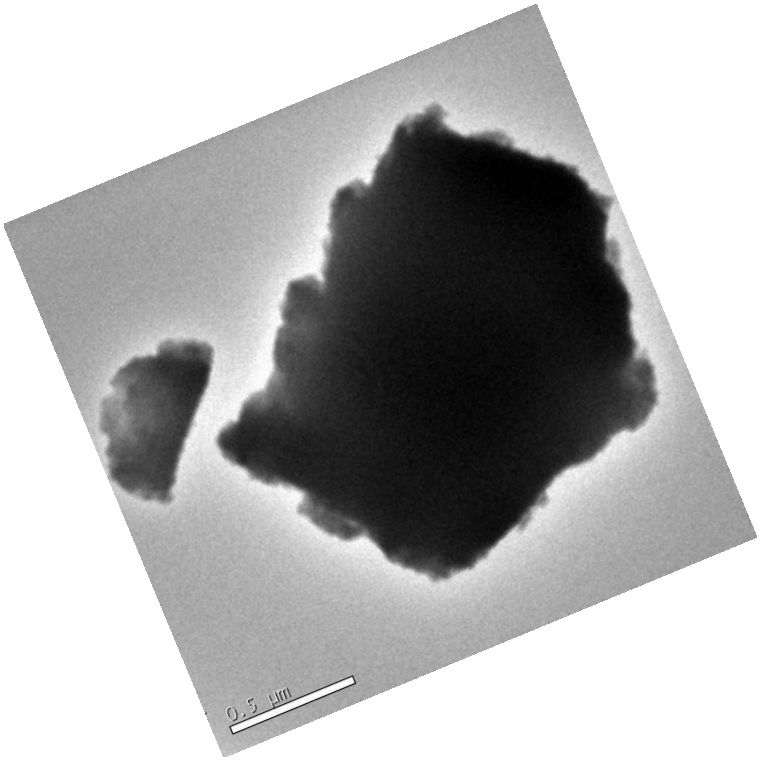
HRTEM images of As(V) adsorbed (or reacted) material [image from the same area at different depth of focus]



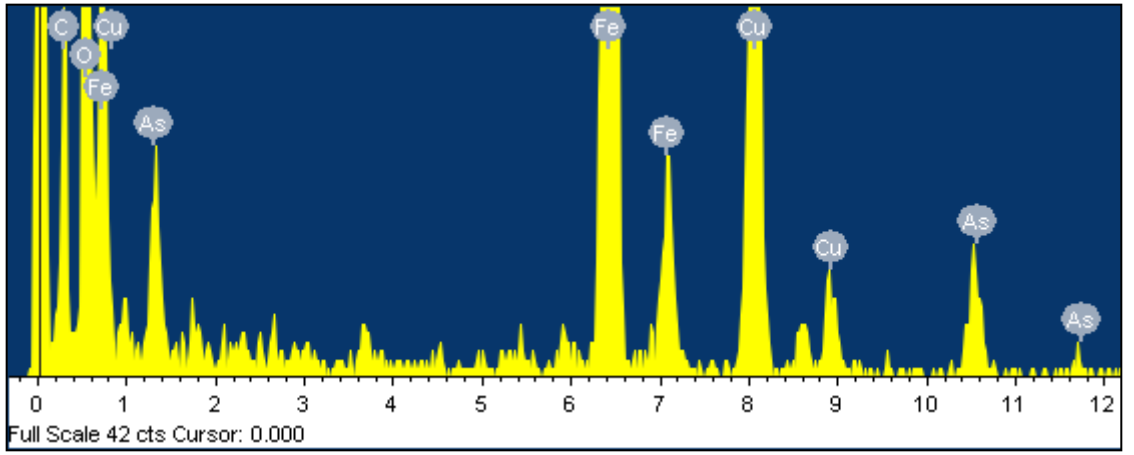
Goethite: α **–FeOOH (0.25 nm)**
PCPDF No. **81-0464 (Orthorhombic)**
a = 4.604, b = 9.959 , c = 3.023
α = β = , γ =

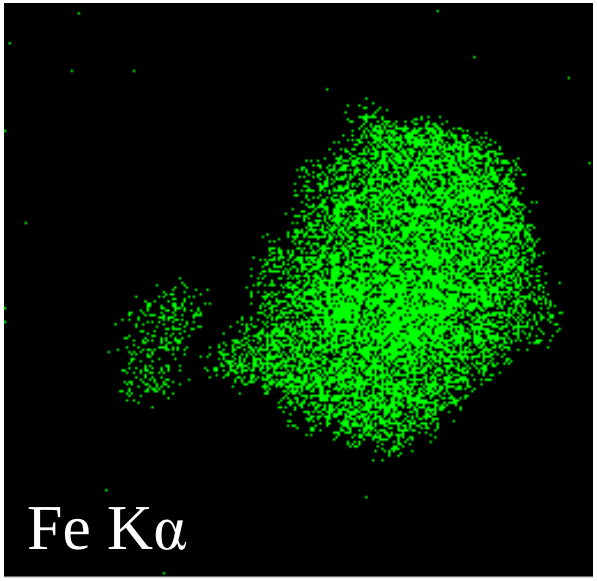


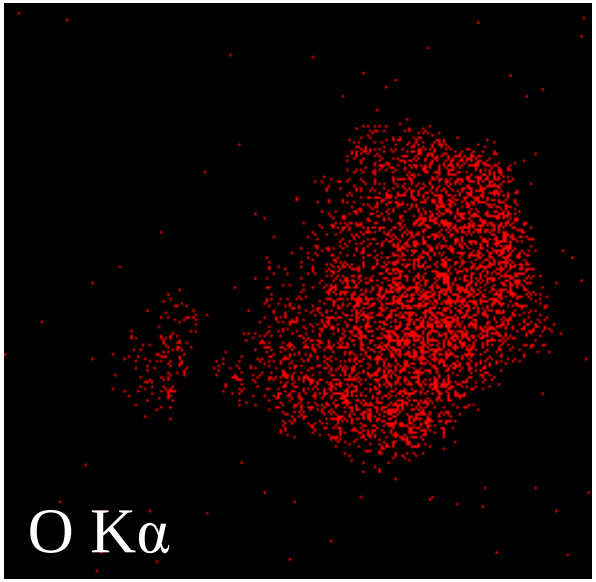
Ferrihydrite: 0.22 nm, 0.25 nm
PCPDF No. **29-0712 (Hexagonal)**
a = 5.08, b = , c = 9.4
α = β = , γ =

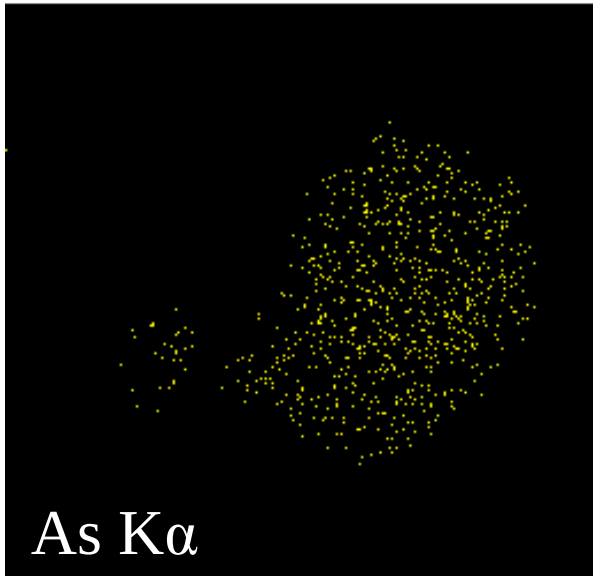


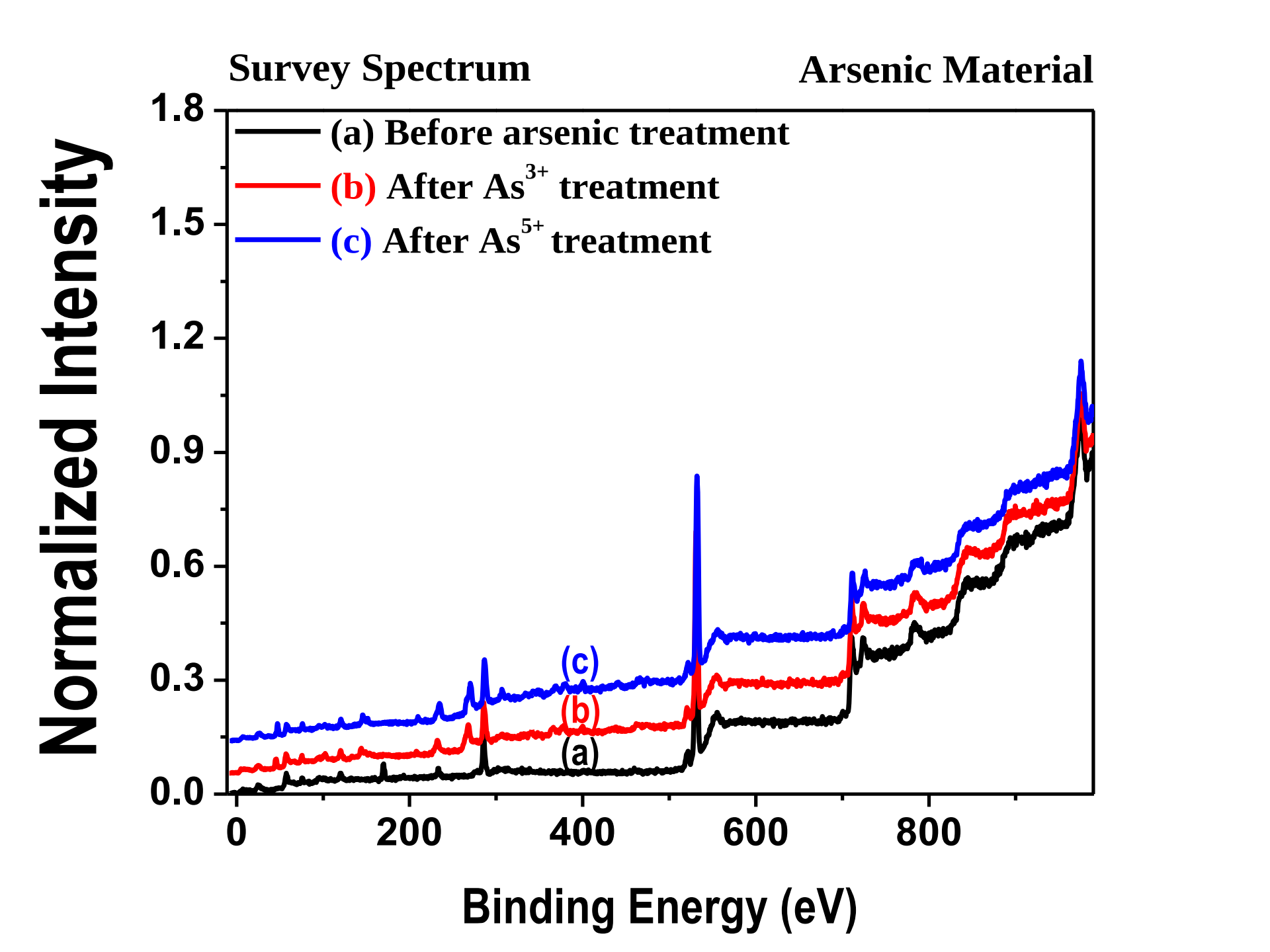
Element	Weight%	Atomic%
O K	32.84	63.62
Fe K	60.89	33.79
As K	6.27	2.59
Totals	100.00	100.00



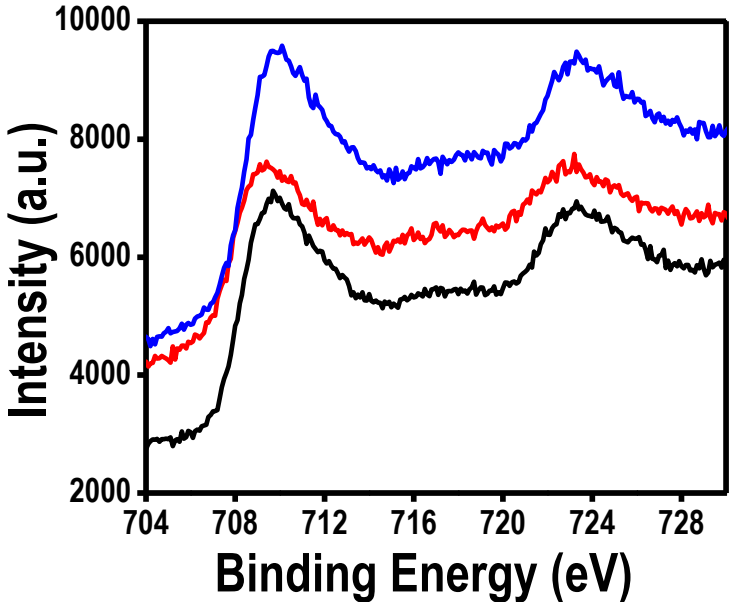


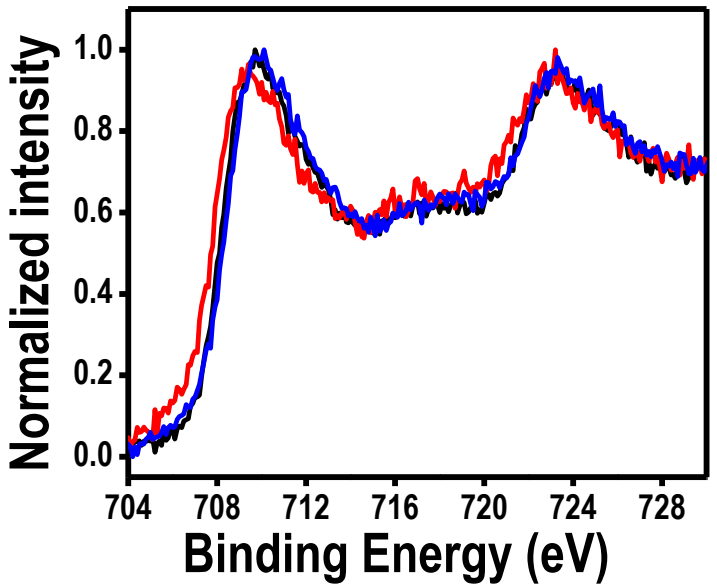




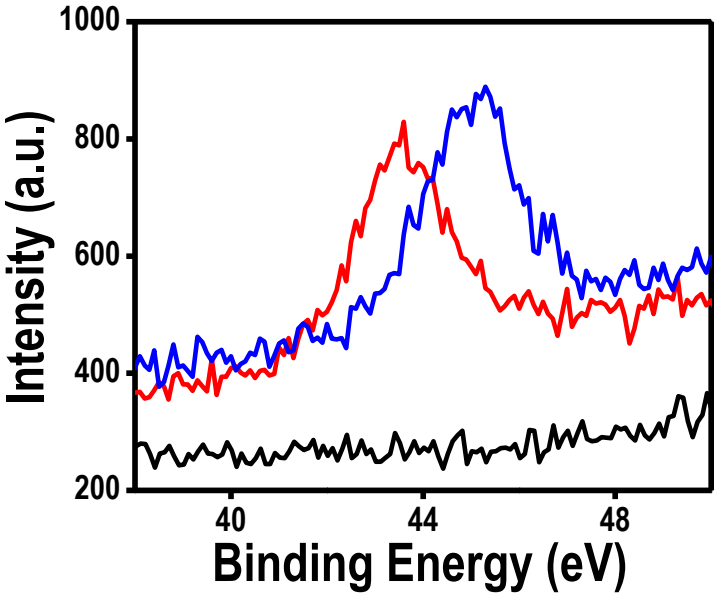

Survey Spectrum
Arsenic Material
(a) Before arsenic treatment
(b) After As3+ treatment
(c) After As5+ treatment
Normalized Intensity
Binding Energy (eV)
1.8
1.5
1.2
0.9
0.6
0.3
0.0
0
200
400
600
800
(c)
(b)
(a)

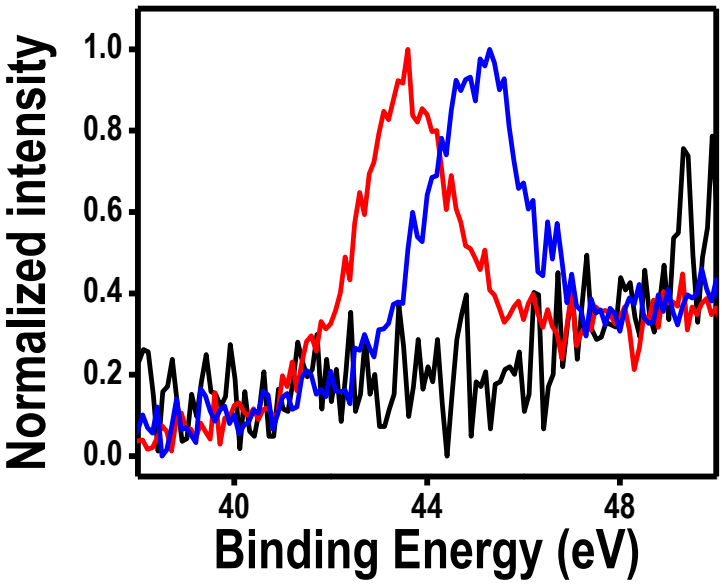
Iron 2p

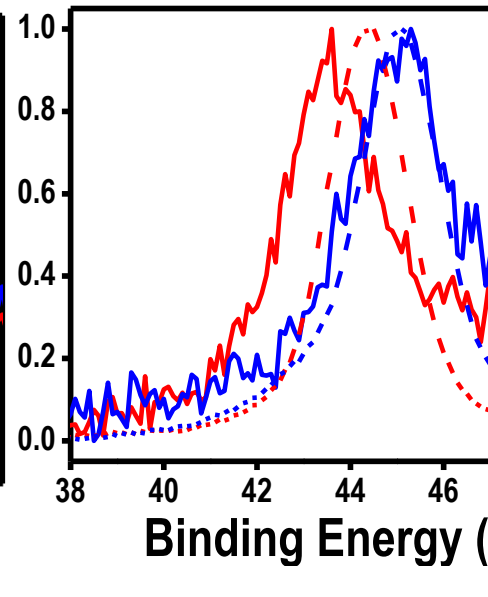




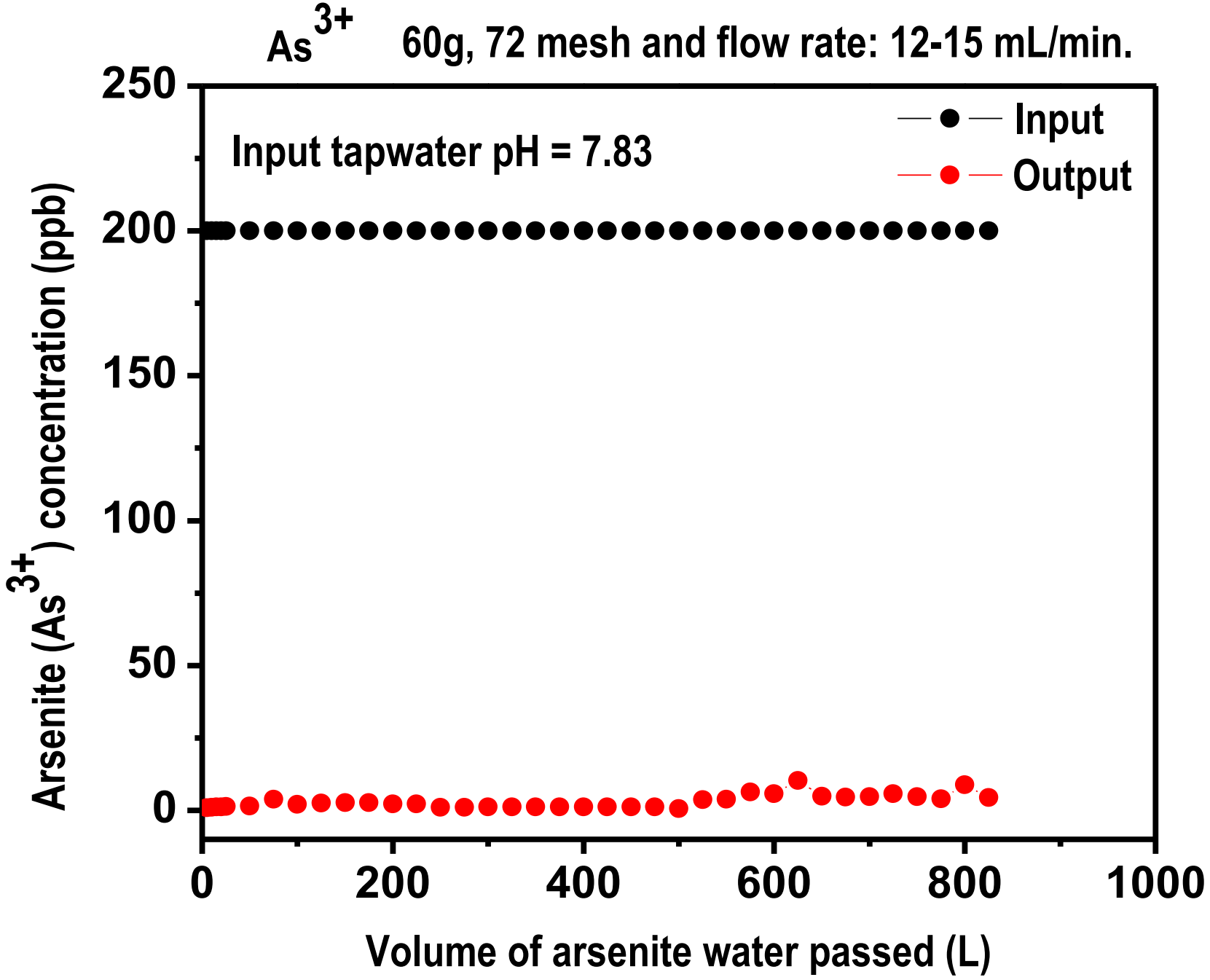
Arsenic $3d_{5/2}$



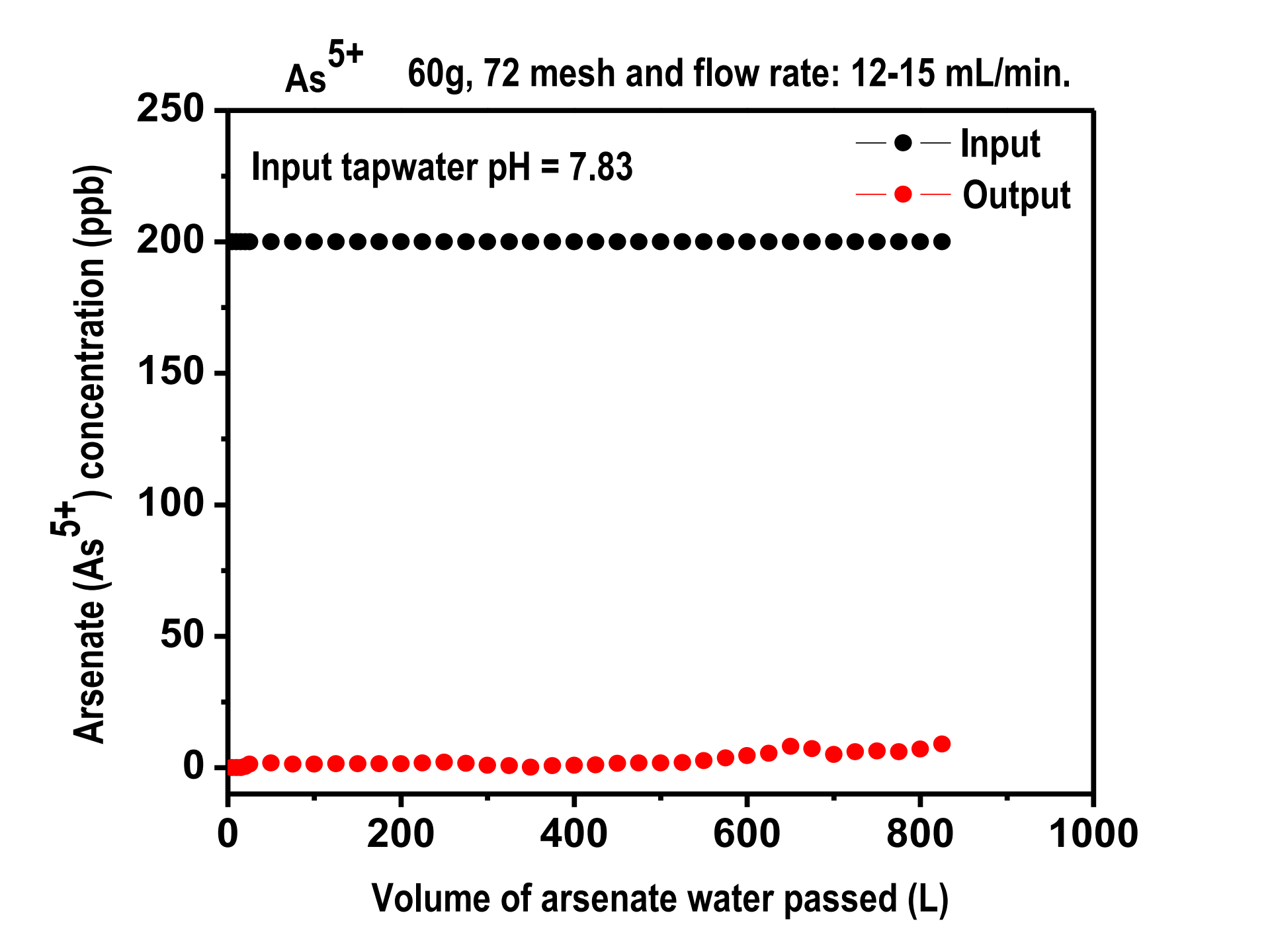




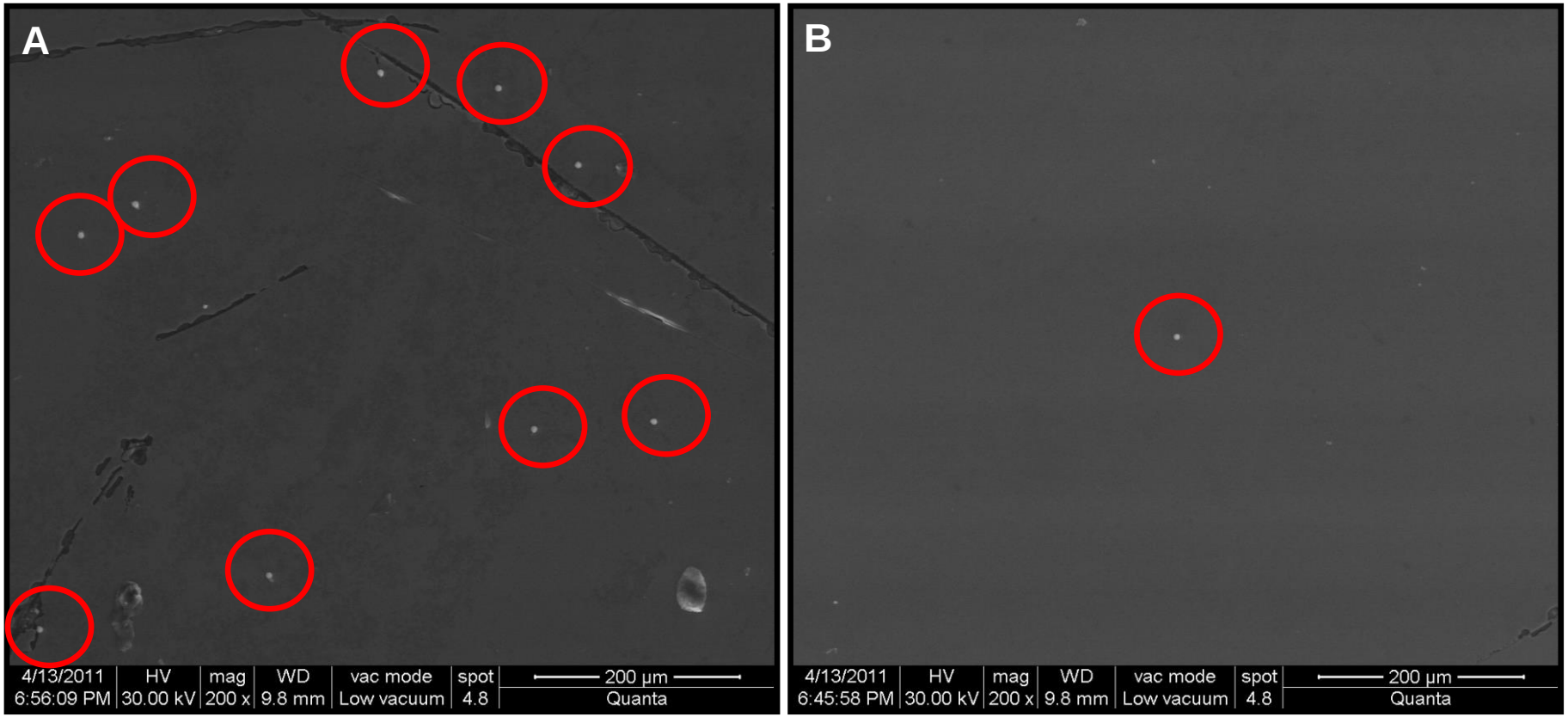
As^{3+}


As3+ 60g, 72 mesh and flow rate: 12-15 mL/min.
Input tapwater pH = 7.83
Input
Output
Arsenite (As3+) concentration (ppb)
250
200
150
100
50
0
0
200
400
600
800
1000
Volume of arsenite water passed (L)

$$As^{5+}$$


As5+ 60g, 72 mesh and flow rate: 12-15 mL/min.
Input tapwater pH = 7.83
Input
Output
Arsenate (As5+) concentration (ppb)
Volume of arsenate water passed (L)
250
200
150
100
50
0
0
200
400
600
800
1000

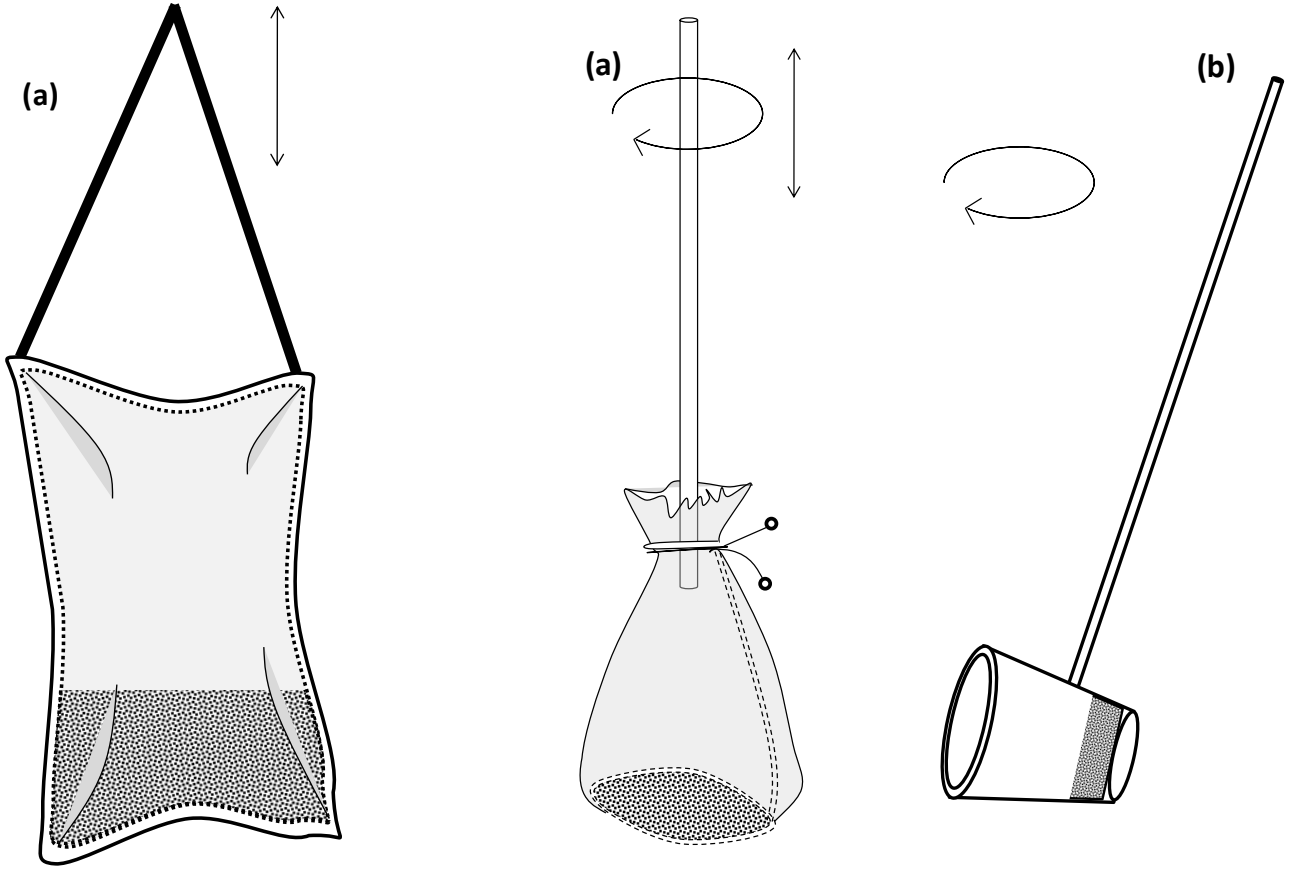
Cyst removal



Performance summary

		NSF norms	NSF Standard	InnoNano's Product
Functional Parameters	Sand & Sediment	Turbidity: 11 NTU to <0.5 NT	NSF/ANSI 53	√
	Chlorine	2 ppm to <0.5 ppm	NSF/ANSI 42	√
	Bacteria	105 CFU/ml to absent	NSF/ANSI 55	√
	Virus	103 PFU/ml to absent	NSF/ANSI 55	√
	Cyst	50000/ml to <2/ml	NSF/ANSI 53	√
	Pesticides	Chloroform: 300 ppb to <15	NSF/ANSI 53	√
	Iron	2 ppm to <0.2 ppm		√
	Lead	150 ppb to 10 ppb	NSF/ANSI 53	√
	Arsenic	300 ppb to 10 ppb	NSF/ANSI 53	√
	Mercury	6 ppb to 2 ppb	NSF/ANSI 53	√
	TDS	Not applicable		X
	Nitrate	Not applicable		X

Implementing technologies

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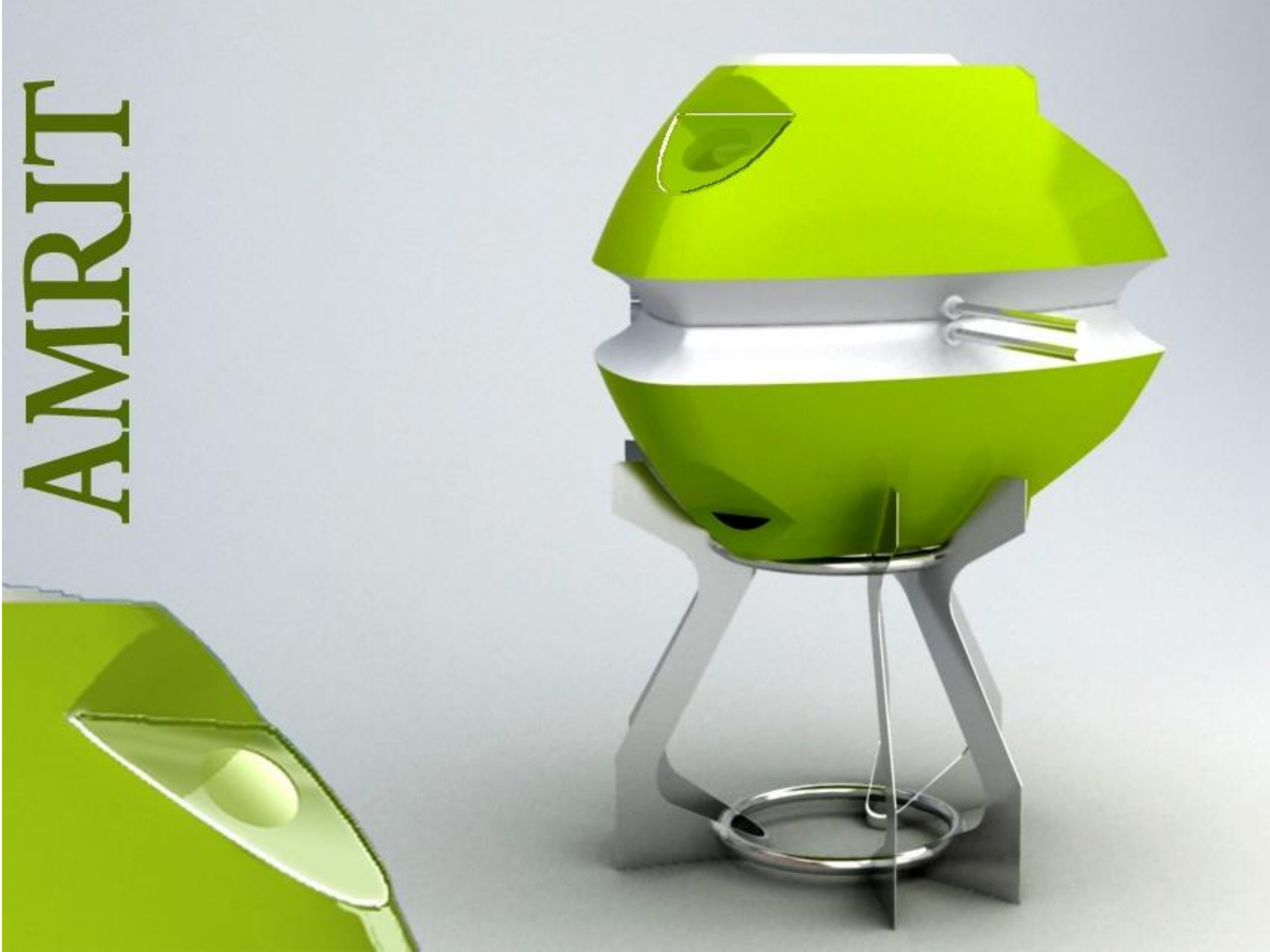
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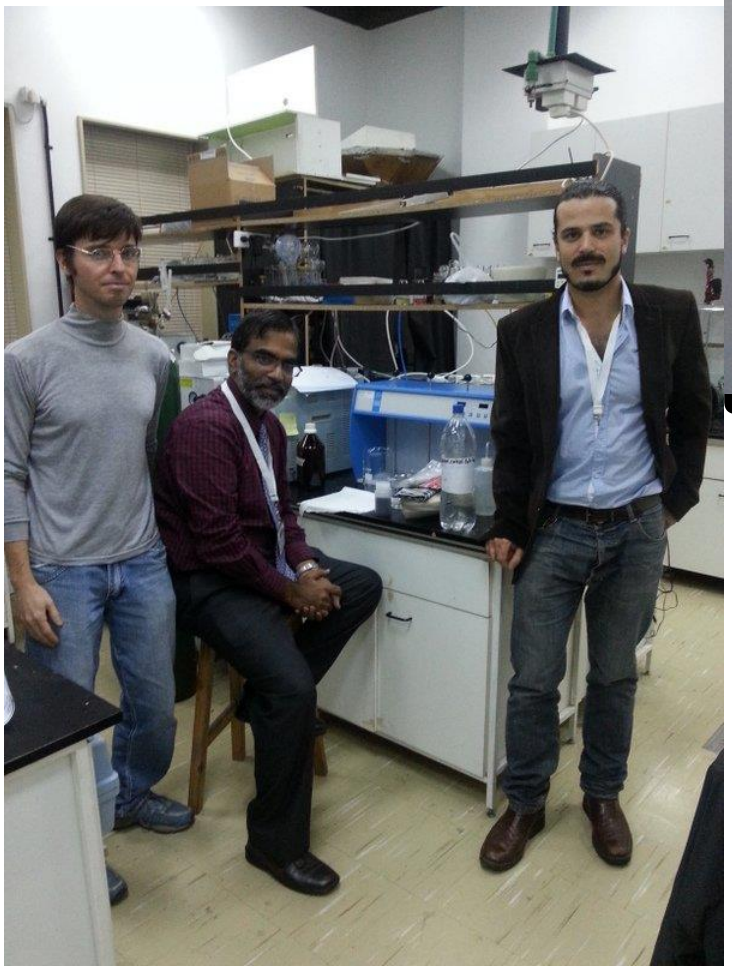

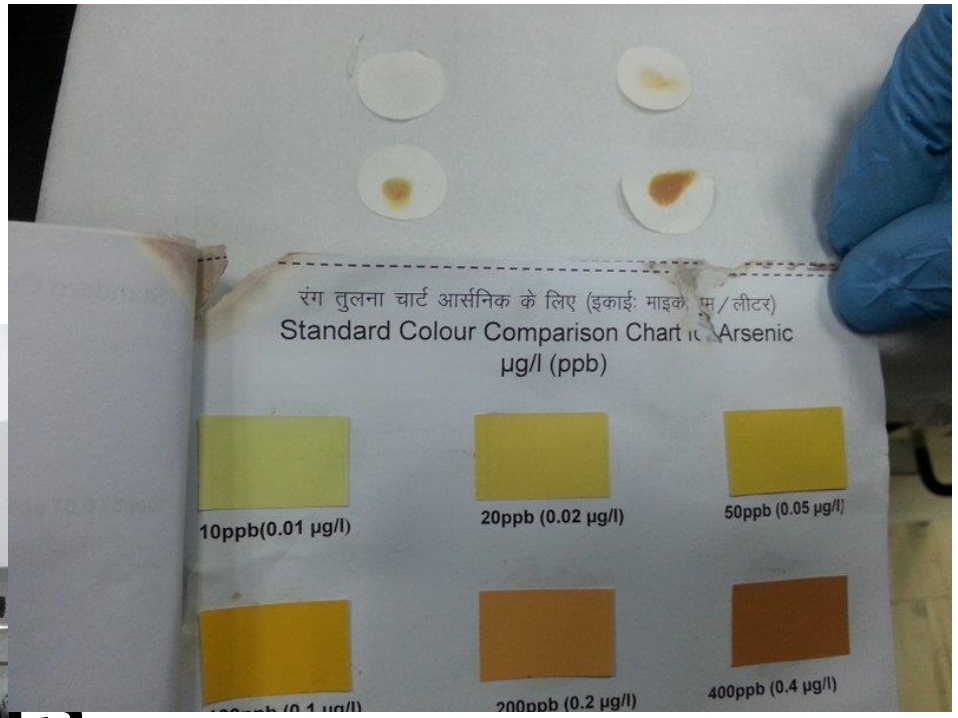
रंग तुलना चार्ट आर्सनिक के लिए (इकाईः माइक्रो ग्राम / लीटर)
Standard Colour Comparison Chart for Arsenic
µg/l (ppb)
10ppb(0.01 µg/l)
20ppb (0.02 µg/l)
50ppb (0.05 µg/l)
200ppb (0.2 µg/l)
400ppb (0.4 µg/l)

DST Nano Mission


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On water, let us unite!

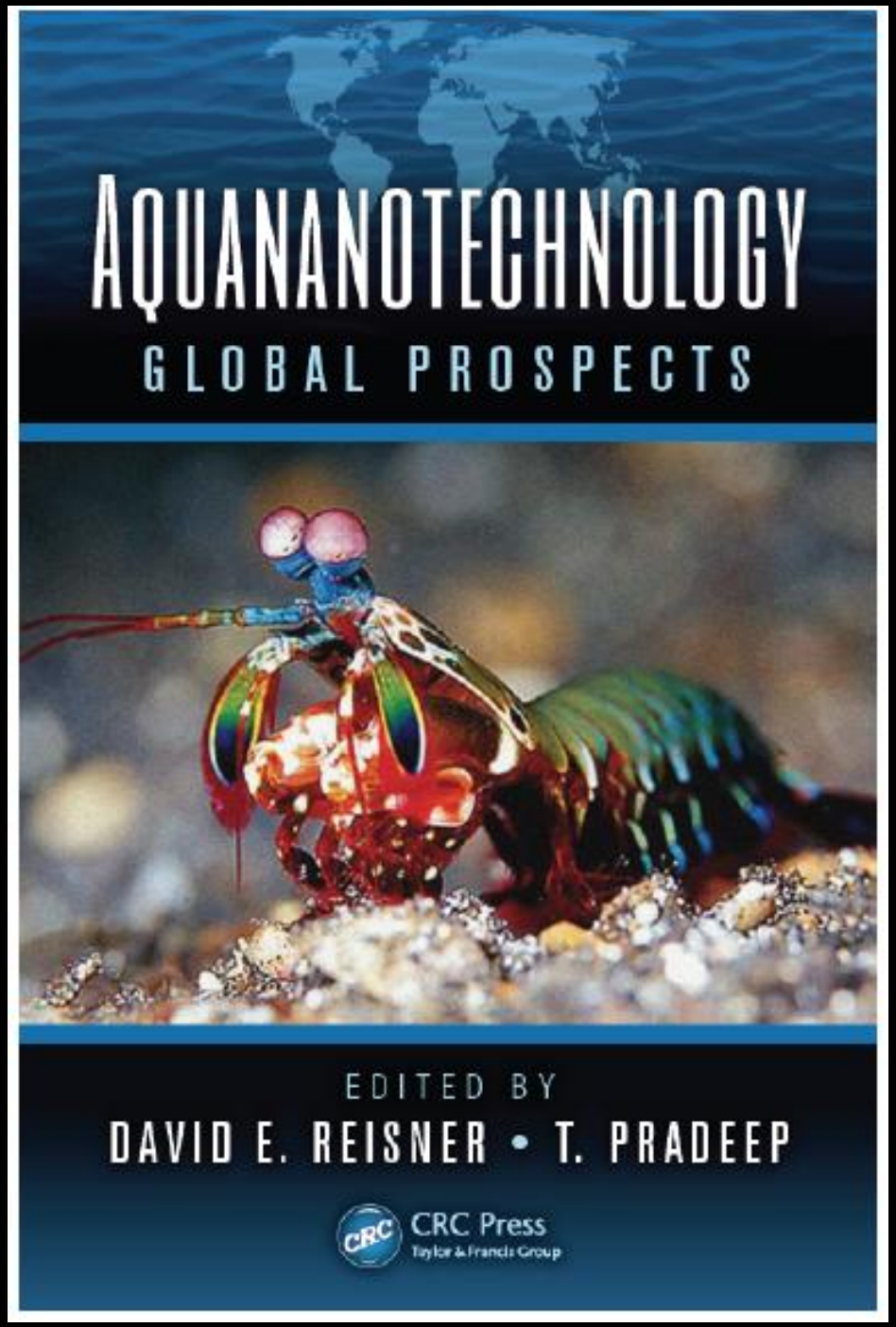
Aquananotechnology CRC Press - 2014

Samir Pal, Uzi Landman, Rob Whetten, Y. Negishi, Hannu Hakkinen, Robin Ras,...

Thank you

Department of Science and Technology

New Book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