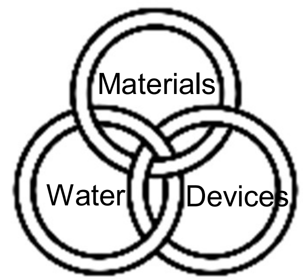
Since 1959

Beyond dimensions: Reactions between clusters, nanoparticles and bulk matter

T. Pradeep
Institute Professor, IIT Madras
https://pradeepresearch.org/
pradeep@iitm.ac.in



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Reaction between Au(PET) and Ag(DMBT)
5400
5850
6300
6750
m/z
5400
5850
6300
6750
m/z

CHEMICAL REVIEWS

Review

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Atomically Precise Clusters of Noble Metals: Emerging Link between Atoms and Nanoparticles

Indranath Chakraborty[†] and Thalappil Pradeep*

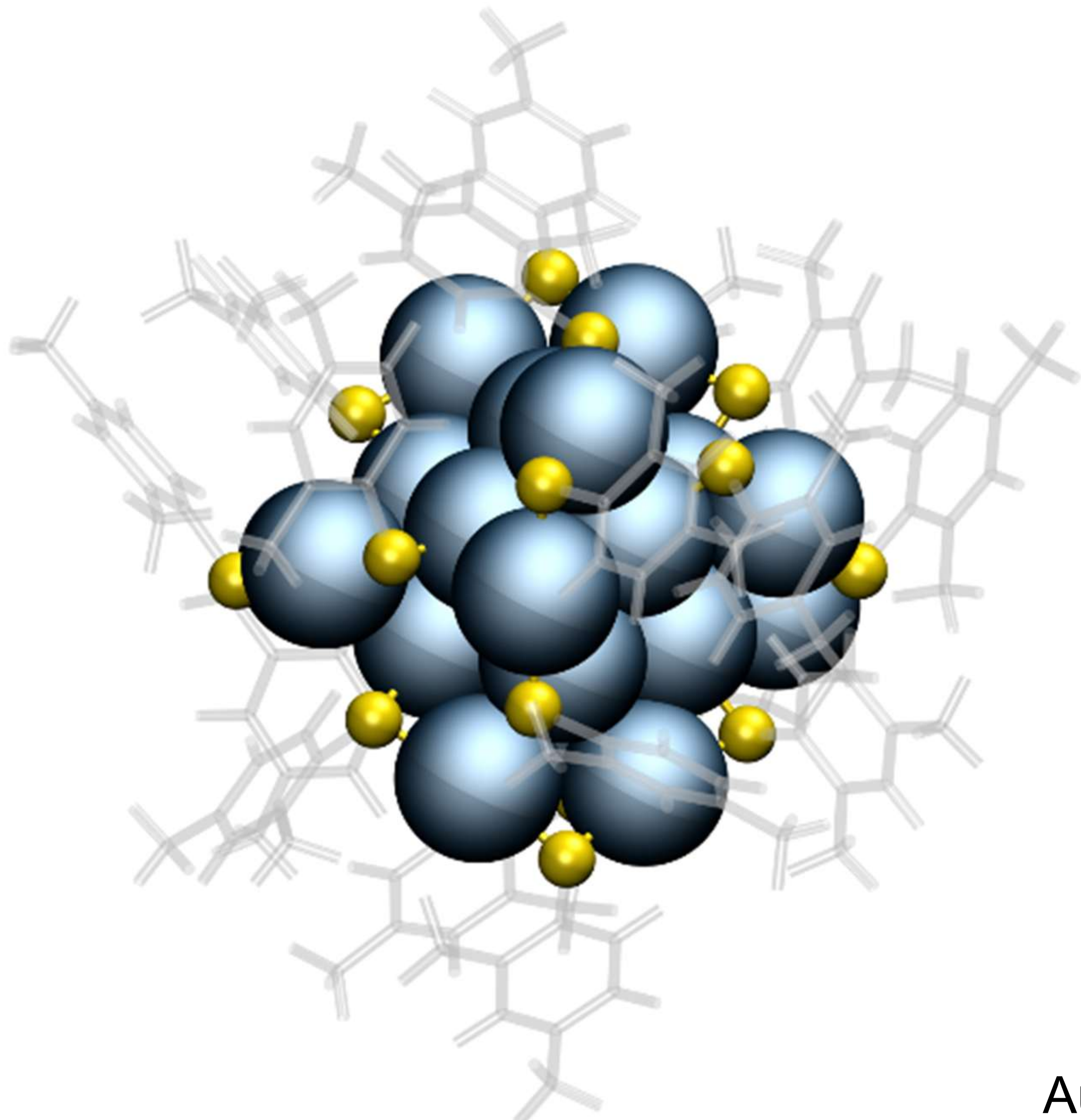
DST Unit of Nanoscience (DST UNS) and Thematic Unit of Excellence, Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India

Supporting Information

Citations: >1100

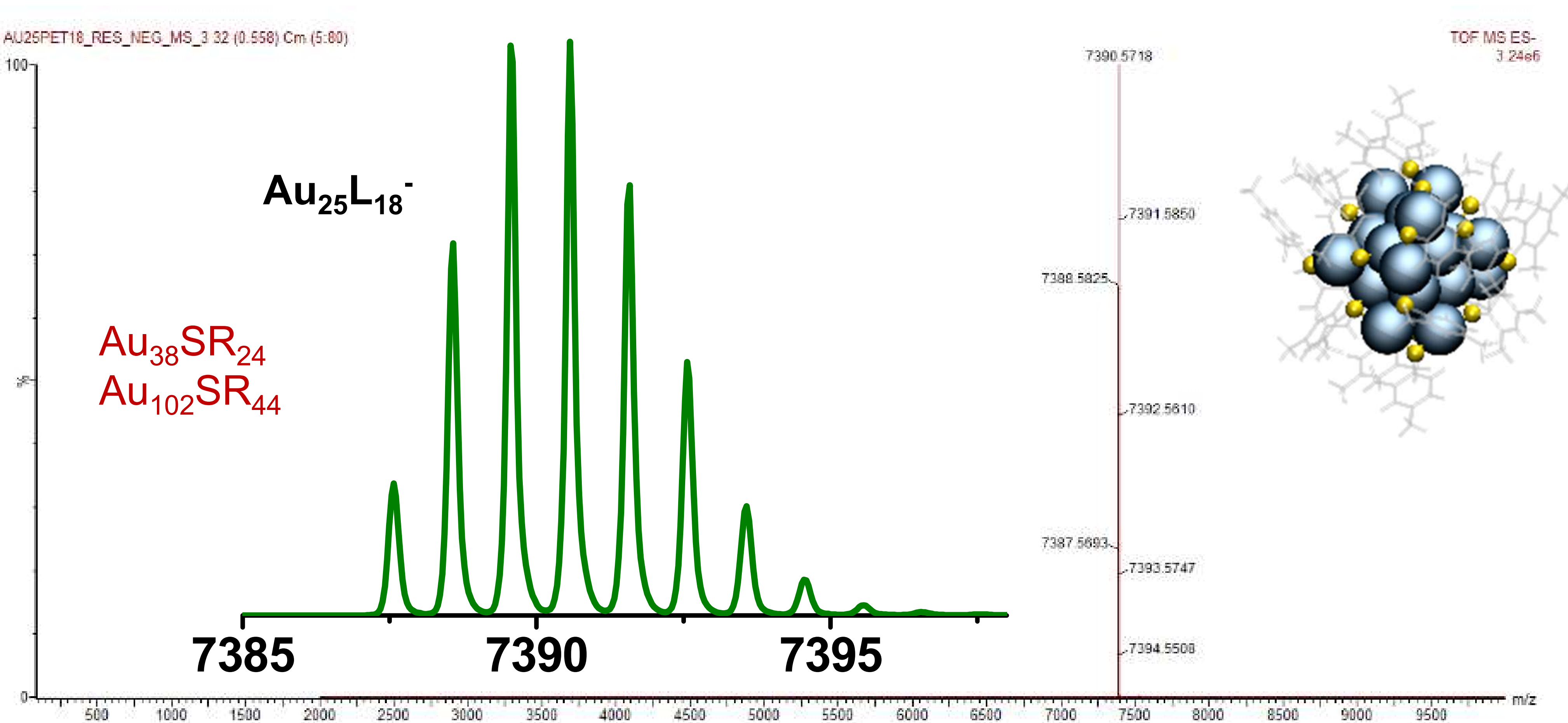
ABSTRACT: Atomically precise pieces of matter of nanometer dimensions composed of noble metals are new categories of materials with many unusual properties. Over 100 molecules of this kind with formulas such as $Au_{25}(SR)_{18}$, $Au_{38}(SR)_{24}$, and $Au_{102}(SR)_{44}$ as well as $Ag_{25}(SR)_{18}$, $Ag_{29}(S_2R)_{12}$, and $Ag_{44}(SR)_{30}$ (often with a few counterions to compensate charges) are known now. They can be made reproducibly with robust synthetic protocols, resulting in colored solutions, yielding powders or diffractable crystals. They are distinctly different from nanoparticles in their spectroscopic properties such as optical absorption and emission, showing well-defined features, just like molecules. They show isotopically resolved molecular ion peaks in mass spectra and provide diverse information when examined through multiple instrumental methods. Most important of these properties is luminescence, often in the visible−near-infrared window, useful in biological applications. Luminescence in the visible region, especially by clusters protected with proteins, with a large Stokes shift, has been used for various sensing applications, down to a few tens of molecules/ions, in air and water. Catalytic properties of clusters, especially oxidation of organic substrates, have been examined. Materials science of these systems presents numerous possibilities and is fast evolving. Computational insights have given reasons for their stability and unusual properties. The molecular nature of these materials is unequivocally manifested in a few recent studies such as intercluster reactions forming precise clusters. These systems manifest properties of the core, of the ligand shell, as well as that of the integrated system. They are better described as protected molecules or *aspicules*, where *aspis* means shield and *cules* refers to molecules, implying that they are "shielded molecules". In order to understand their diverse properties, a nomenclature has been introduced with which it is possible to draw their structures with positional labels on paper, with some training. Research in this area is captured here, based on the publications available up to December 2016.

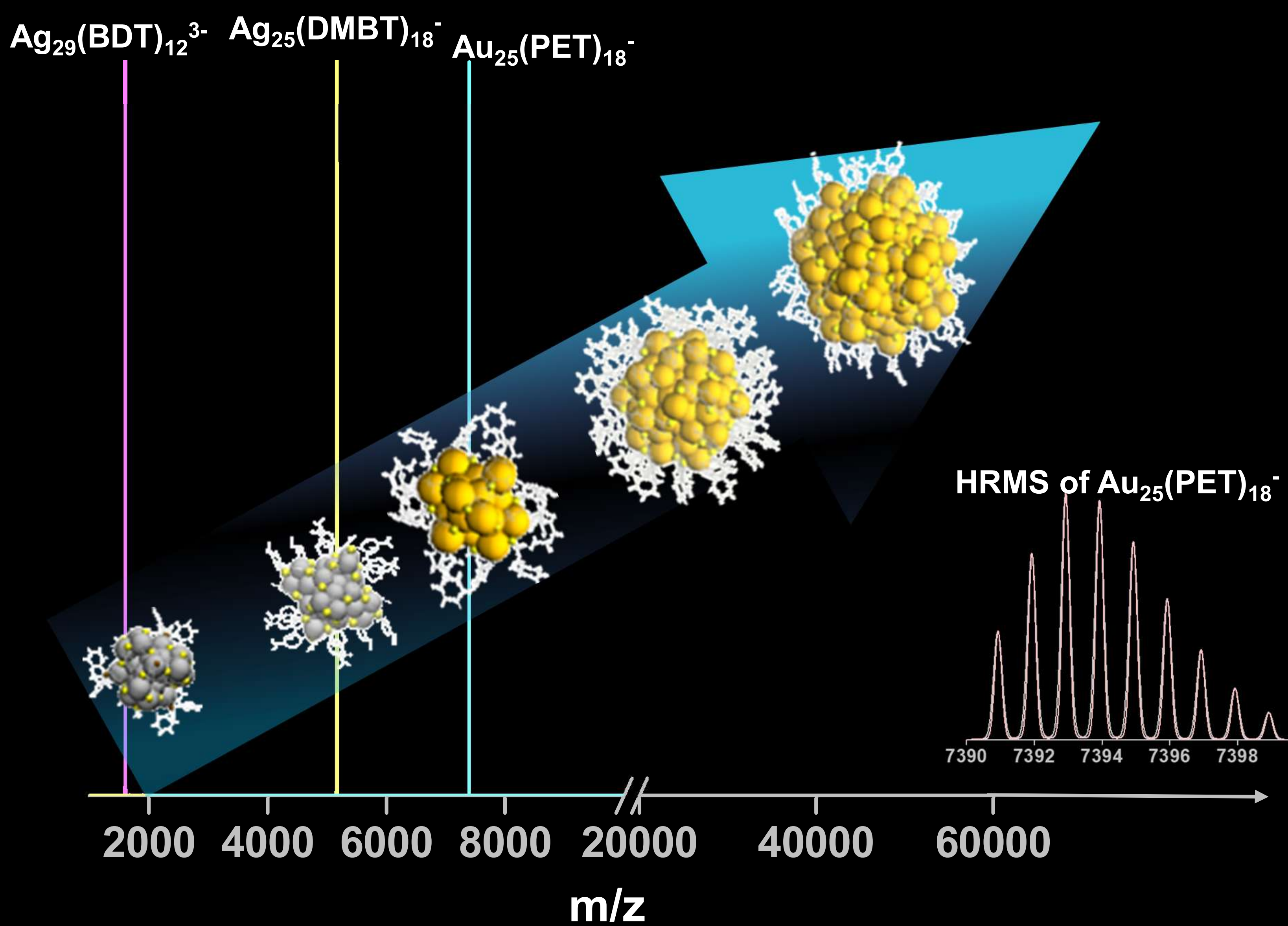
Also the pioneering work of R. W. Murray, Robert L. Whetten, Uzi Landman, Tatuya Tsukuda, Yuichi Negishi, Hannu Hakkinen, Rongchao Jin, Nanfeng Zheng, Terry Bigioni, Osman Bakr, Kornberg, Jianping Xie, C. M. Aikens, Thomas Buergi, Amala Dass, Ackerson, De-en Jiang, …. A. W. Castleman Jr., H. Schmidbauer, …. Robin Ras, Olli Ikkala …Manfred Kappes, Horst Hahn



Au_{25}, Ag_{25}, Ag_{29}

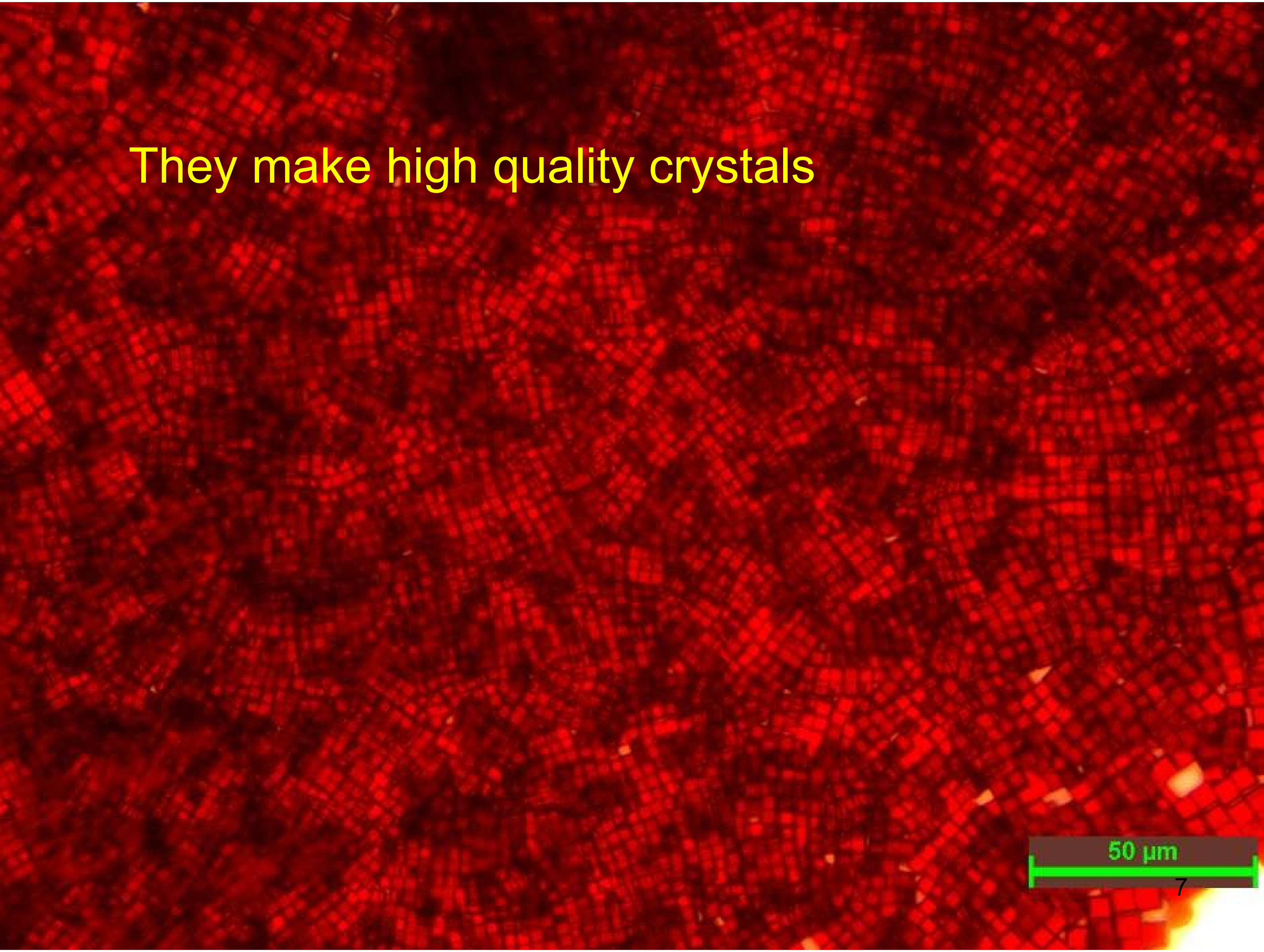
Molecular formula, Molecular weight



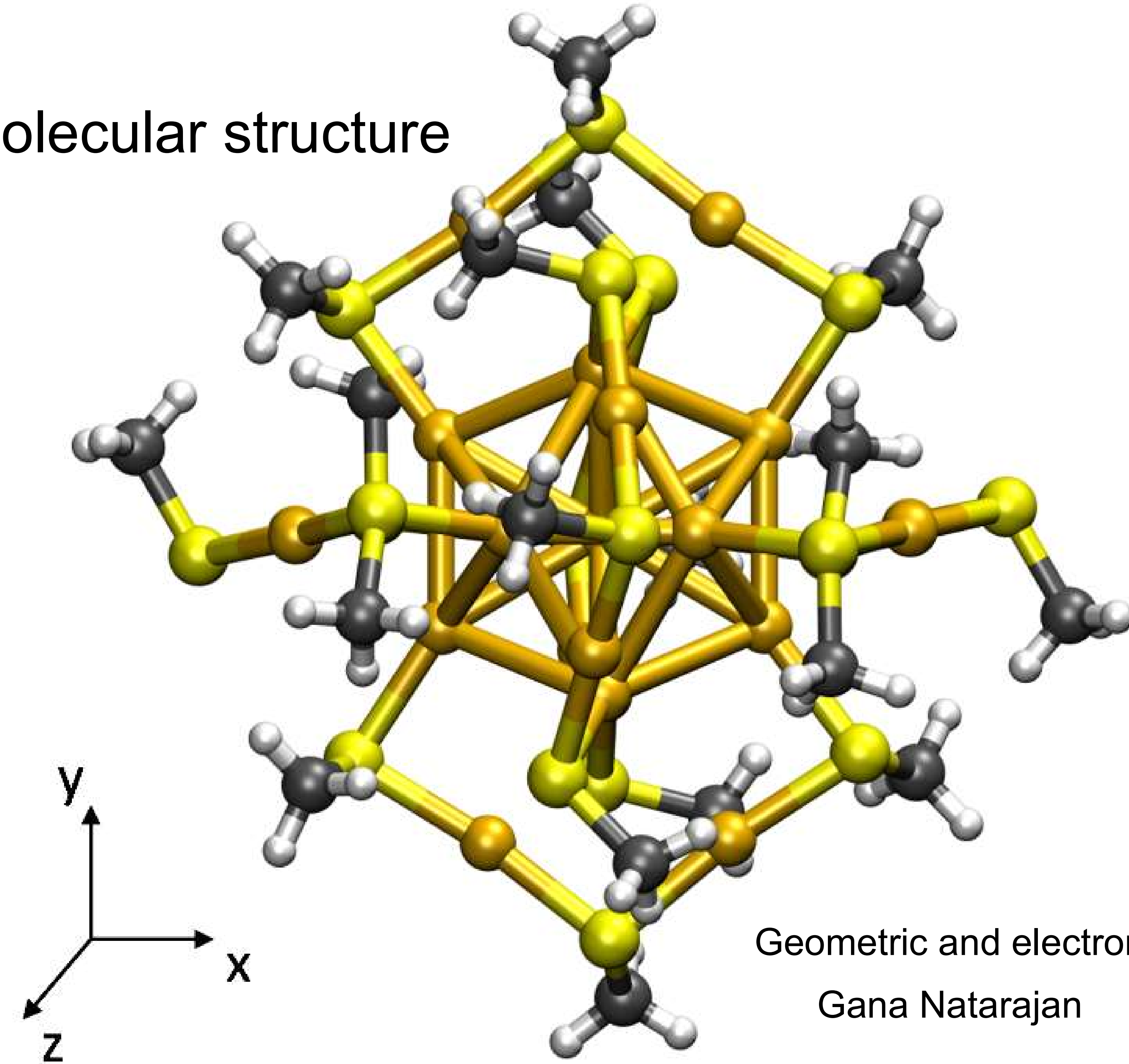


Ag29(BDT)12 3-
Ag25(DMBT)18 -
Au25(PET)18 -
HRMS of Au25(PET)18 -
7390 7392 7394 7396 7398
2000 4000 6000 8000 20000 40000 60000
m/z

They make high quality crystals

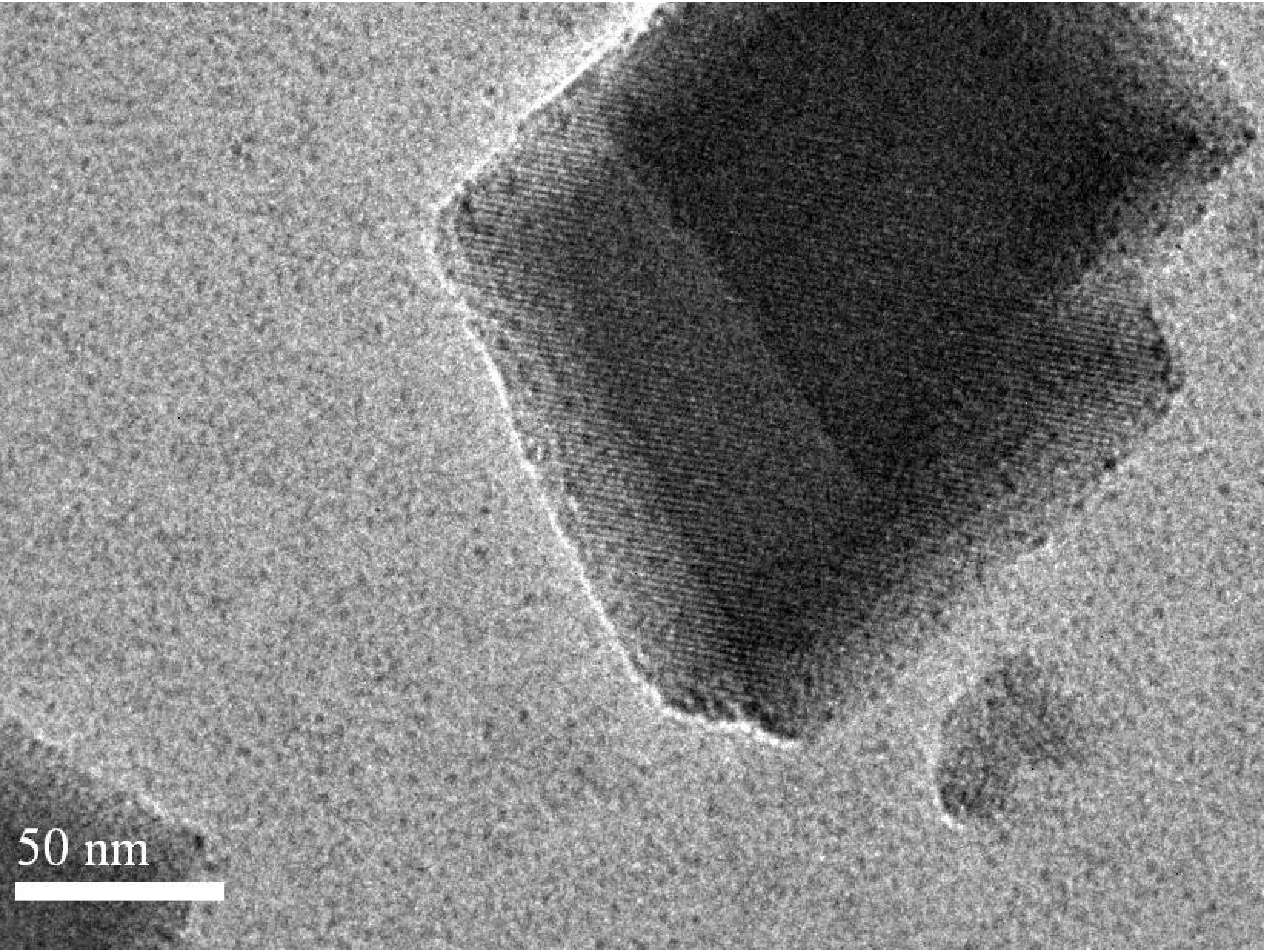


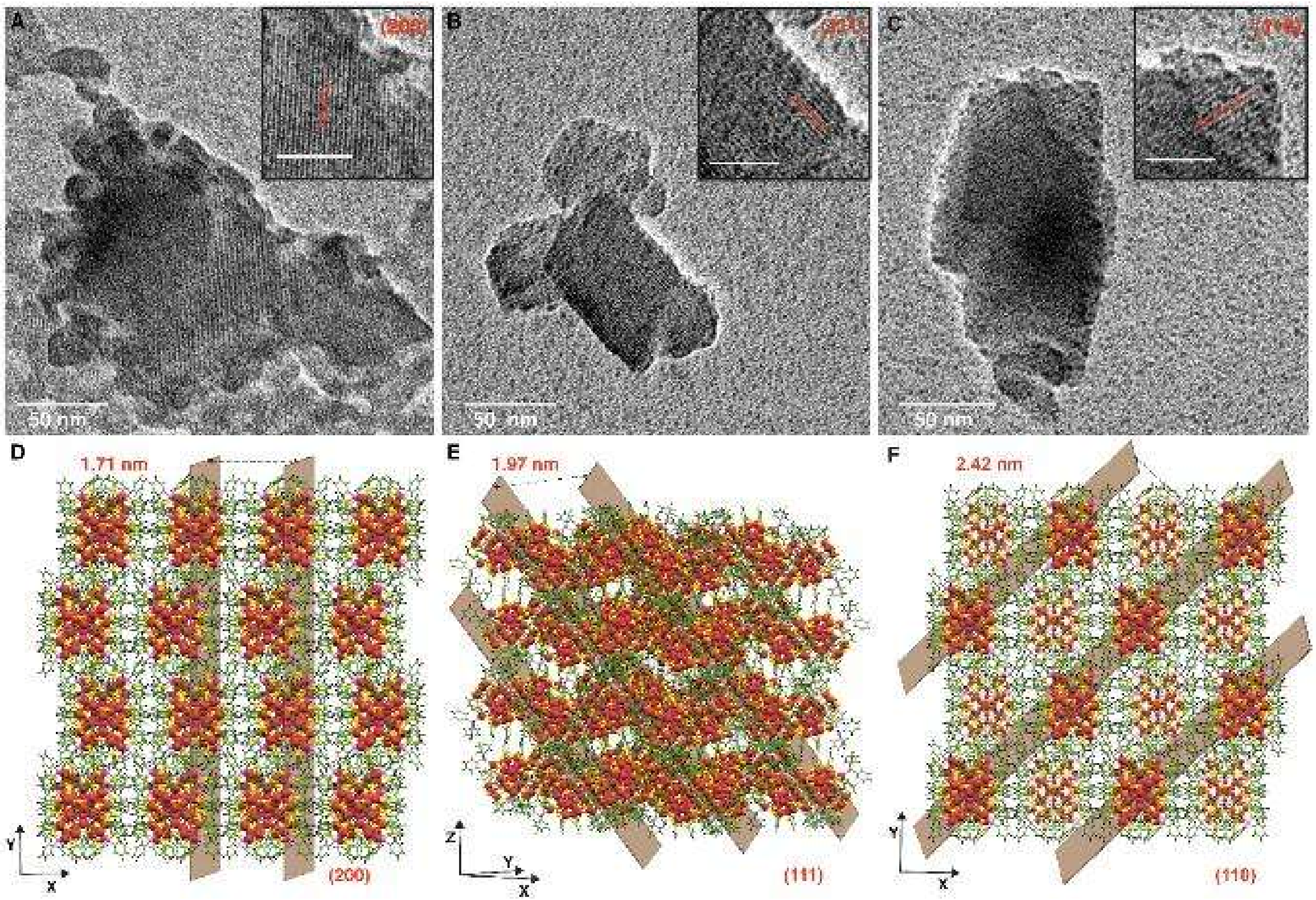
Molecular structure



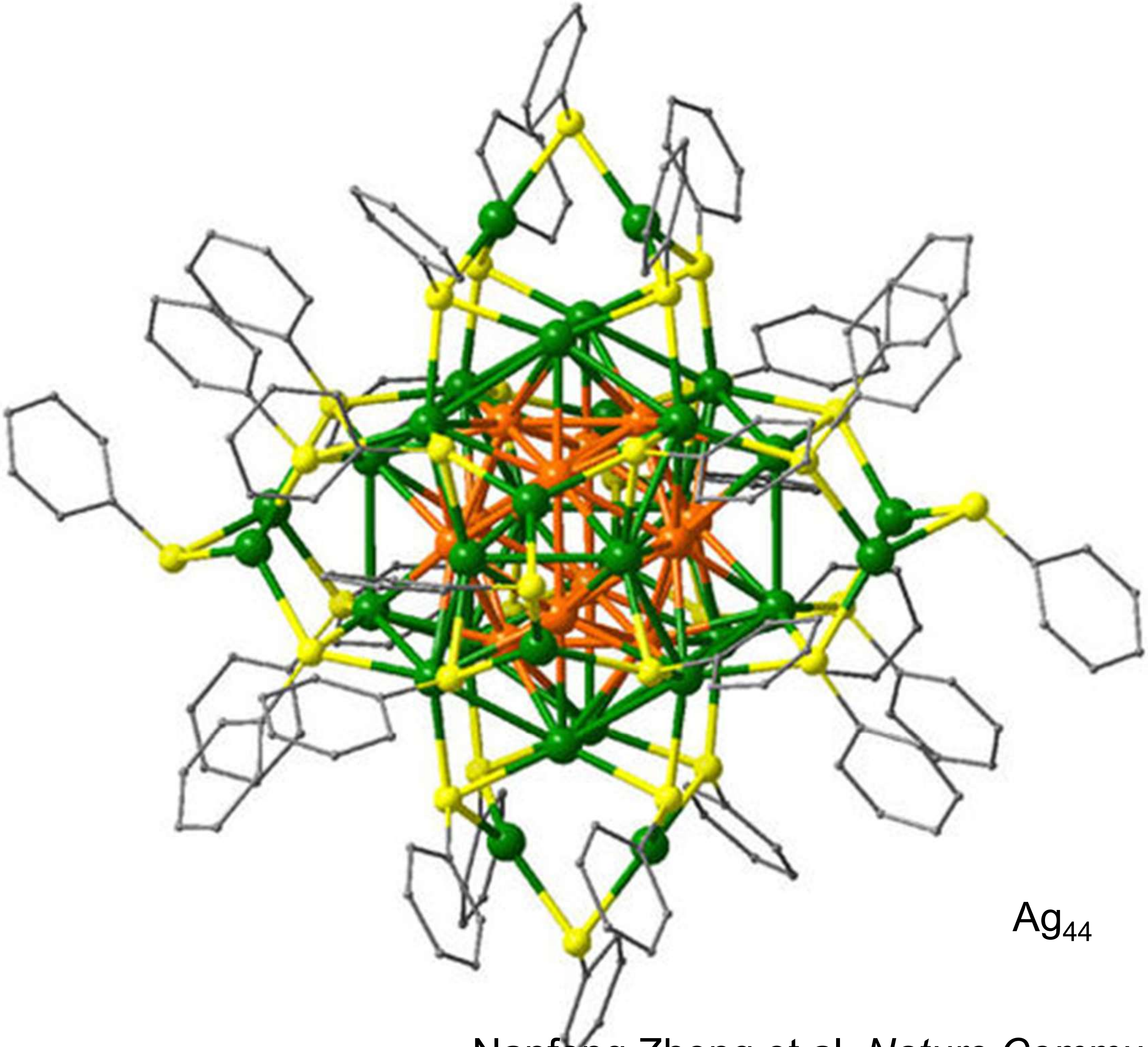
Molecules and their properties

Chemical formula	H_2O
Molecular weight	18.0148
Critical temperature	373.91°C
Critical pressure	22.05 MPa
Critical density	315.0 kg/m^3
Triple point temperature	0.01°C
Triple point pressure	615.066 Pa
Normal boiling point	100.0°C
Normal freezing point	0.0°C
Density of ice at normal melting point	918.0 kg/m^3
Maximum density, 3.98°C	999.973 kg/m^3
Viscosity, 25°C	0.889 mN s/m^2
Surface tension, 25°C	72 mN/m
Heat Capacity, 25°C	4.1796 kJ/kg.K
Enthalpy of vaporisation, 100°C	2,257.7 kJ/kg
Enthalpy of fusion, 0°C	333.8 kJ/kg
Velocity of sound, 0°C	1.403 km/s
Dielectric constant, 25°C	78.40
Electrical conductivity, 25°C	8 μS/m
Refractive index, 25°C	1.333
Liquid compressibility, 10°C	$480. \times 10^{-12} m^2/N$
Coefficient of thermal expansion, 25°C	$256.32 \times 10^{-6}\ K^{-1}$
Thermal Conductivity, 25°C	0.608 W/m.K


50 nm



Ananthu Mahendranath et al. Chem.Comm.2021



Ag_{44}

Nanfeng Zheng et al. *Nature Communications* 2013
Terry Bigioni et al. *Nature* 2013

Molecular reactions

Reactions on clusters

Reactions <u>between</u> clusters

Inter-cluster reactions

JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Article
pubs.acs.org/JACS

Intercluster Reactions between $Au_{25}(SR)_{18}$ and $Ag_{44}(SR)_{30}$

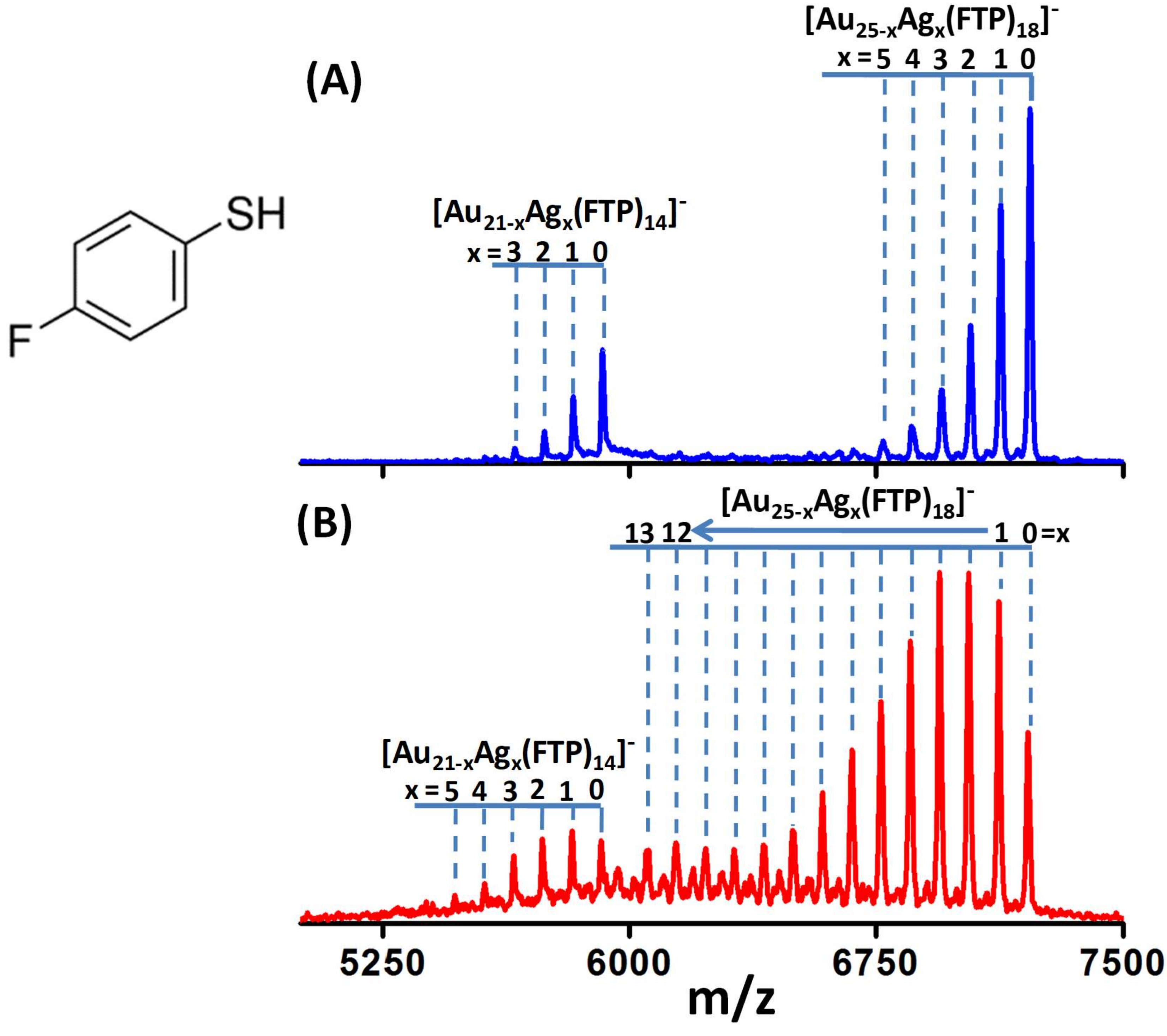
K. R. Krishnadas, Atanu Ghosh, Ananya Baksi, Indranath Chakraborty,[†] Ganapati Natarajan, and Thalappil Pradeep*

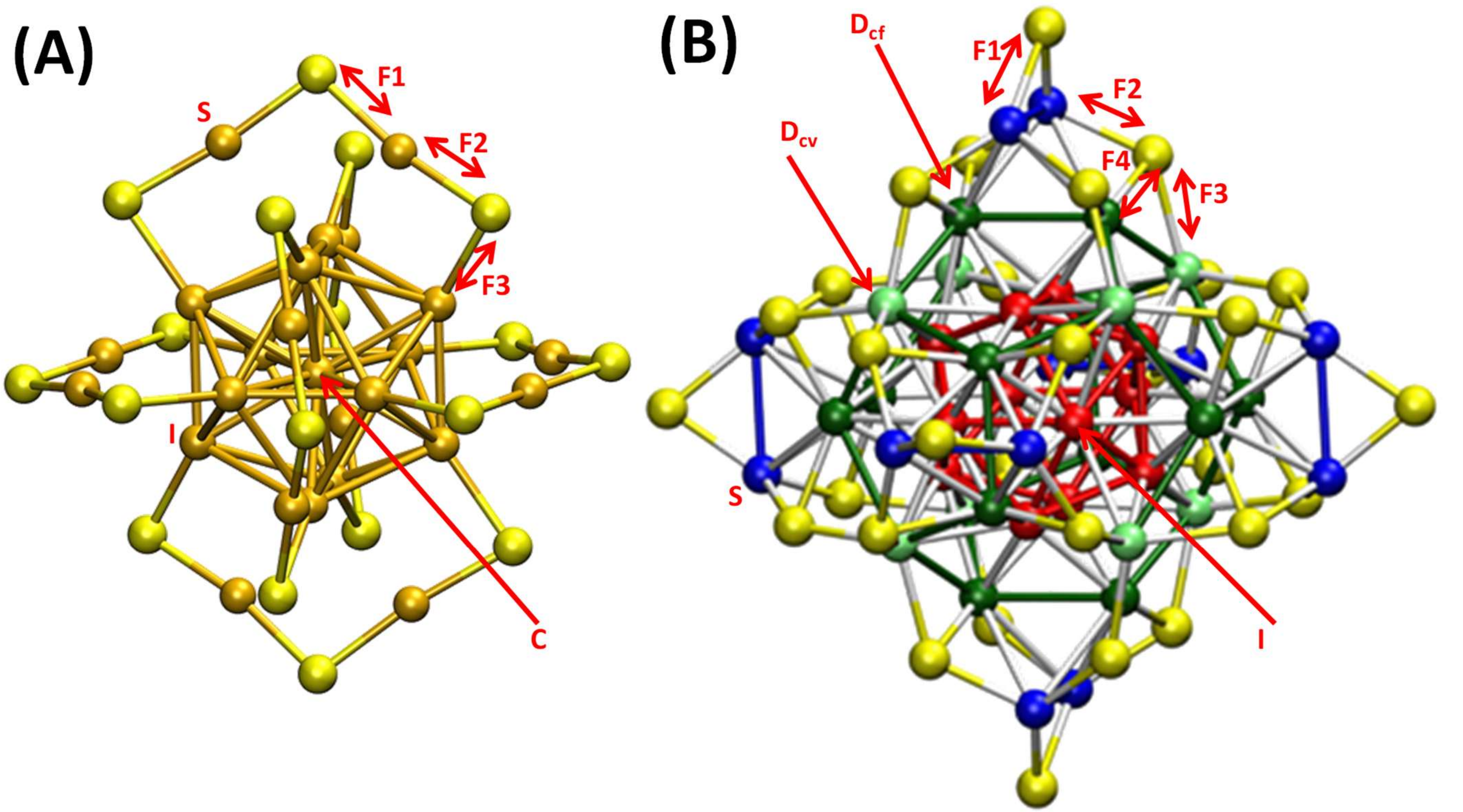
DST Unit of Nanoscience (DST UNS) and Thematic Unit of Excellence, Department of Chemistry, Indian Institute of Technology Madras, Chennai, 600 036, India

S Supporting Information

$$A + B \rightarrow C + D$$

$Au_{25}(FTP)_{18} + Ag_{44}(FTP)_{30} \rightarrow Au_{25-x}Ag_x(FTP)_{18}$




(A)
S
F1
F2
F3
I
C
(B)
D_{cf}
D_{cv}
F1
F2
F4
F3
S
I

Energies for the substitution reaction of (A) Au in $Ag_{44}(SR)_{30}$, (B) Ag in $Au_{25}(SR)_{18}$ and (C) the overall reaction energies (in eV) as a function of their positions in product clusters, $Au_xAg_{44-x}(SR)_{30}$ and $Au_{25-x}Ag_x(SR)_{18}$ for x=1

(A)

Location of Au in $Au_xAg_{44-x}(SR)_{30}$	ΔE/eV
Icosahedron (I)	-0.72
Dodecahedron: cube vertex (D_{cv})	-0.14
Dodecahedron: cube face (D_{cf})	-0.32
Staples (S)	-0.48

(B)

Location of Ag in $Au_{25-x}Ag_x(SR)_{18}$	ΔE/eV
Central atom (C)	+0.71
Icosahedron (I)	+0.23
Staples (S)	+0.44

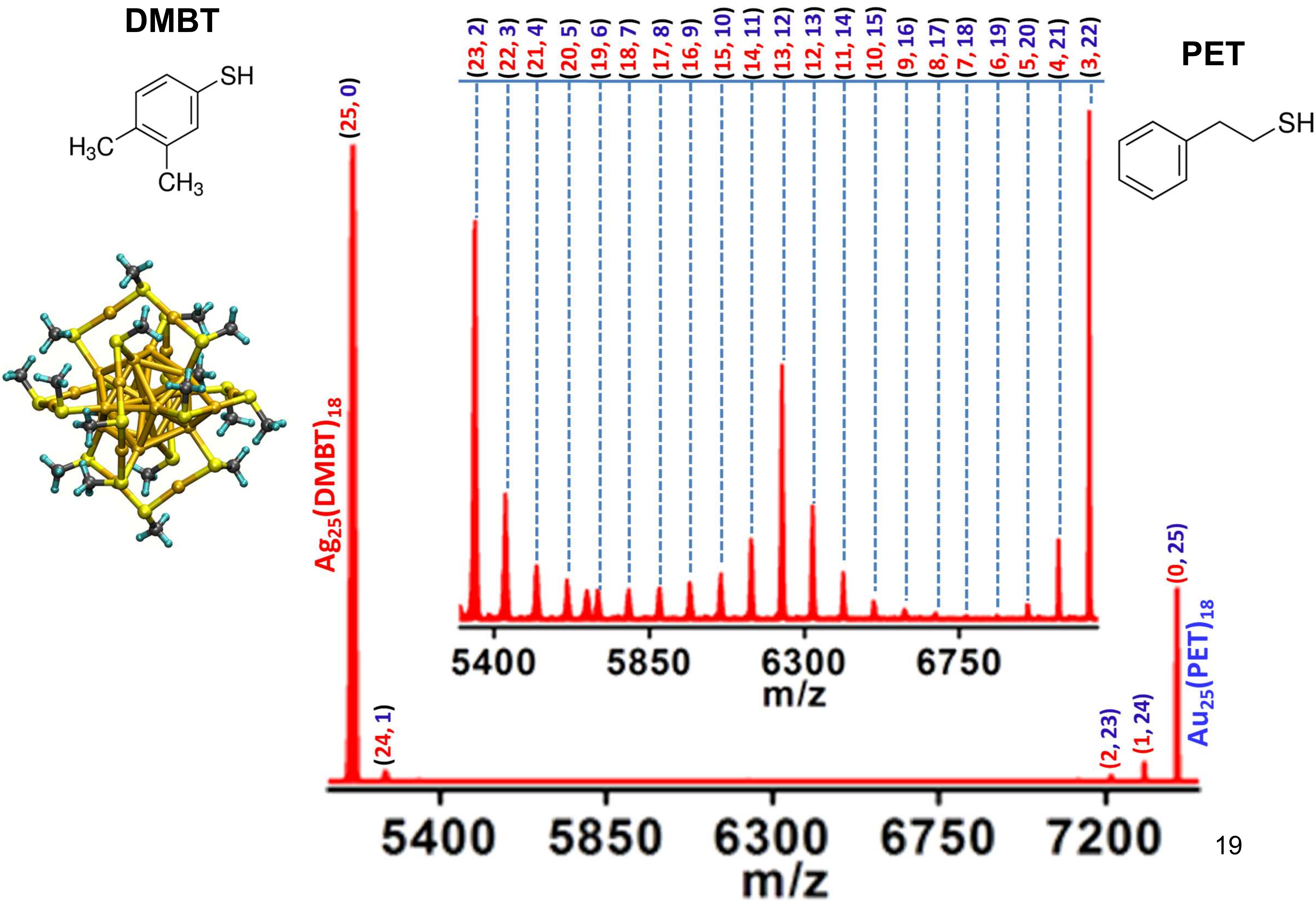
(C)

Location of Ag in $Au_{25-x}Ag_x(SR)_{18}$	Locations of Au in $Au_xAg_{44-x}(SR)_{30}$: I	D_{cv}	D_{cf}	S
C	-0.015	+0.564	+0.388	+0.226
I	-0.486	+0.093	-0.083	-0.245
S	-0.276	+0.303	+0.127	-0.035

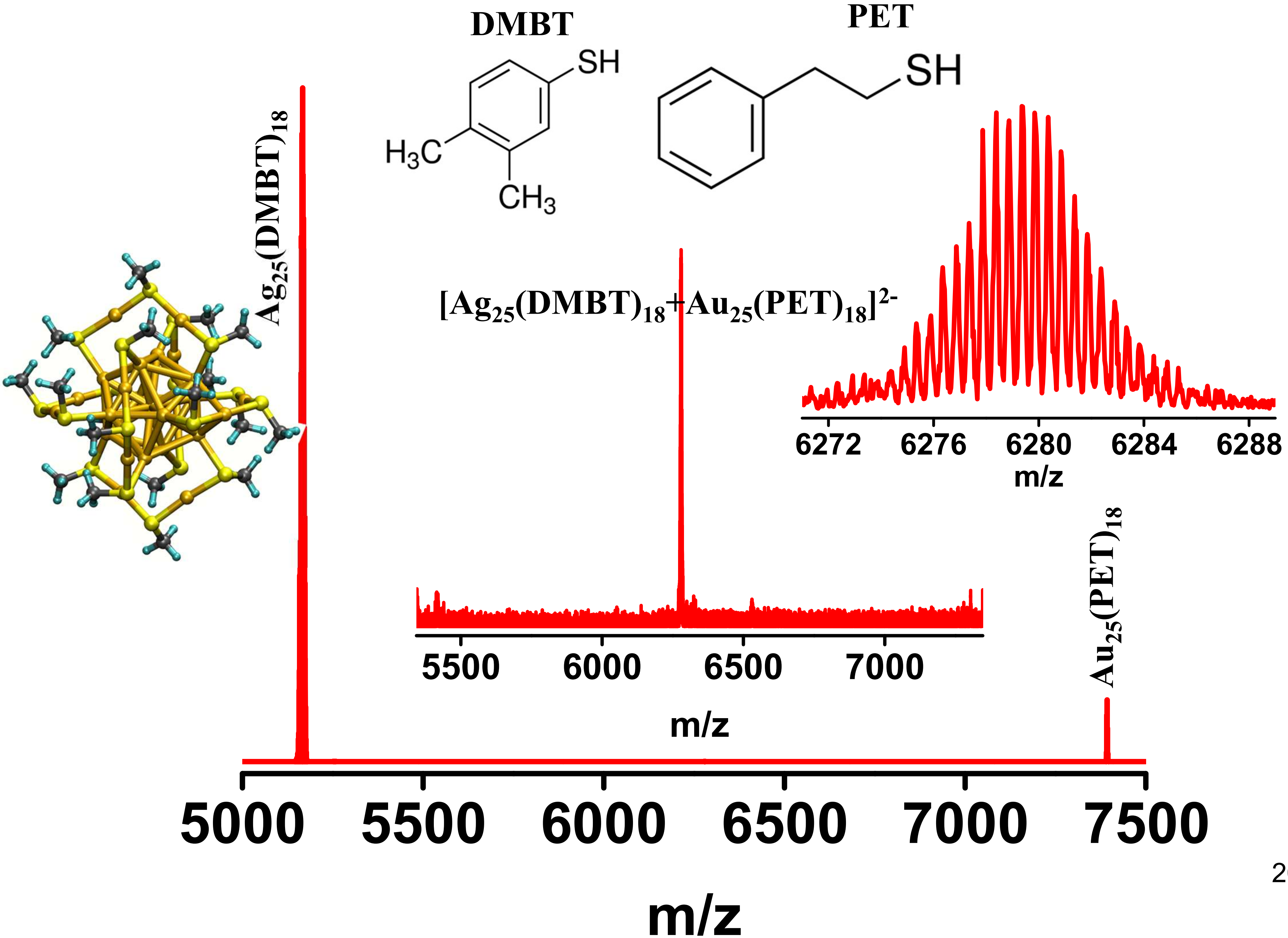
Ag_{25}-Au_{25} experiments

K. R. Krishnadas et al. *Nature Commun.* 2016

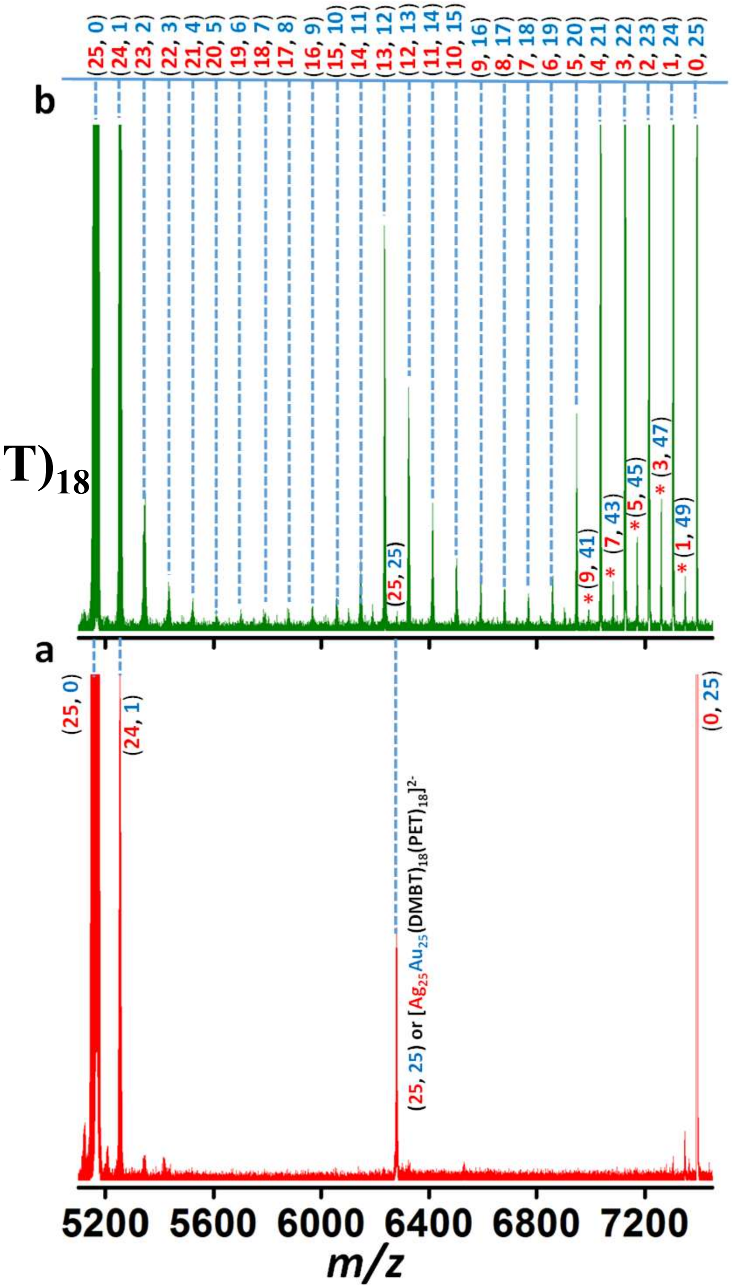
Reaction between $Au_{25}(PET)_{18}$ and $Ag_{25}(DMBT)_{18}$



$[Ag_{25}(DMBT)_{18}+Au_{25}(PET)_{18}]^{2-}$



Evolution of alloy clusters from the dianionic adduct, $[Ag_{25}Au_{25}(DMBT)_{18}(PET)_{18}]^{2-}$

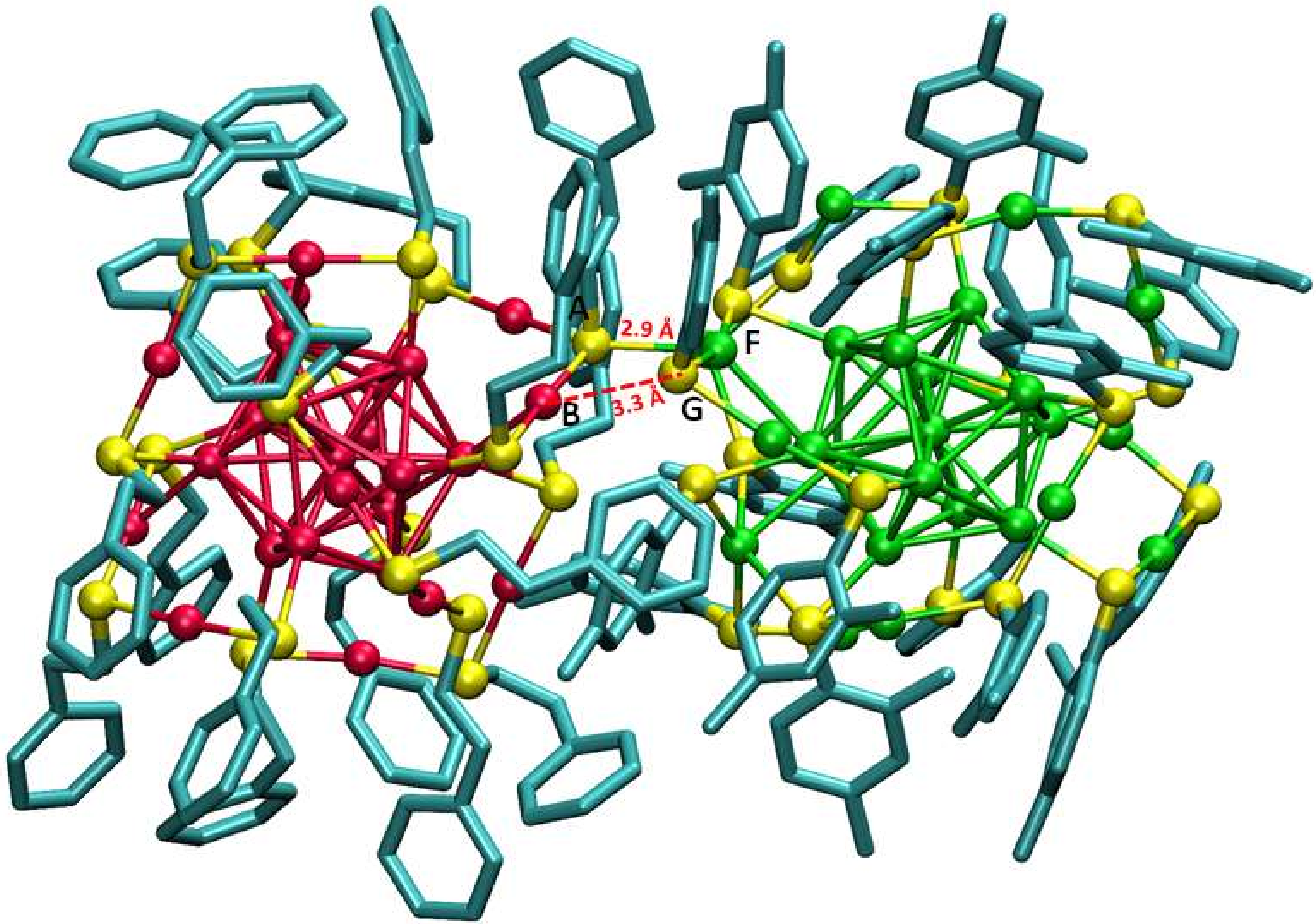


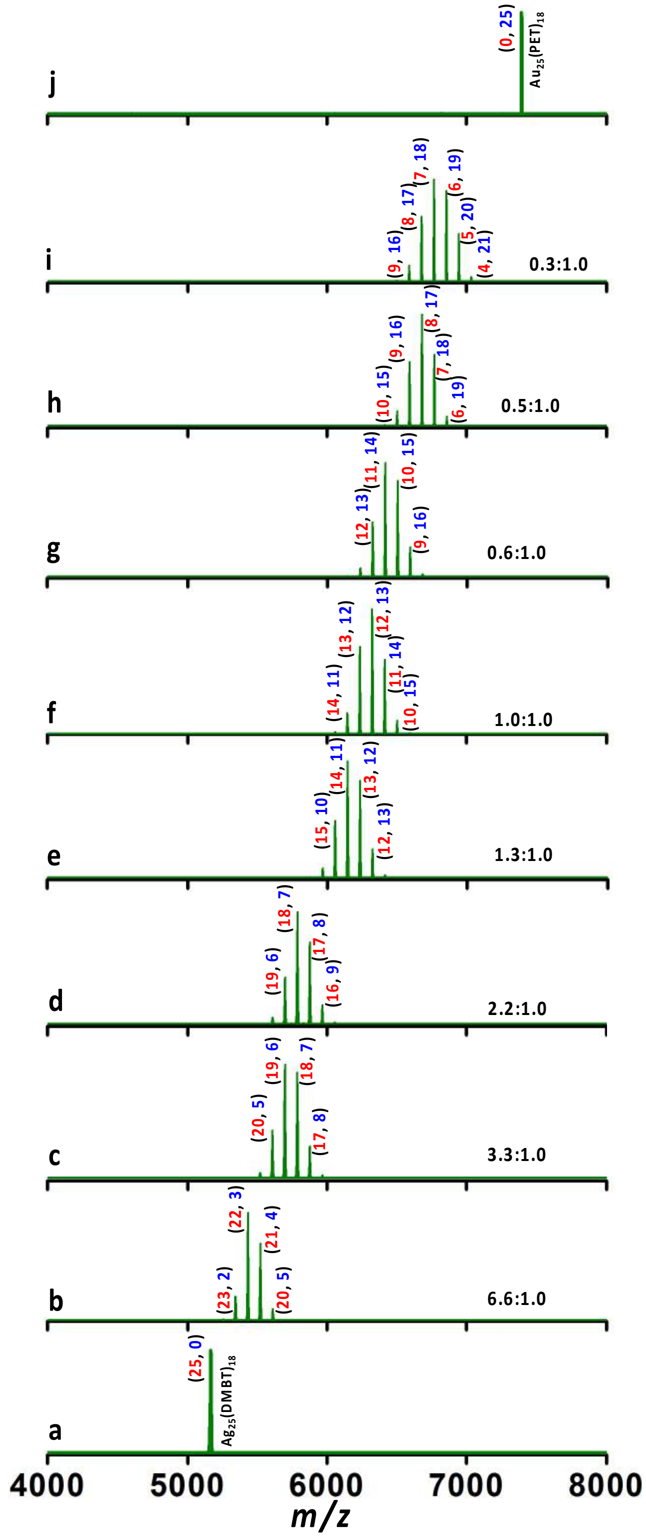
within 5 min

$Ag_{25}(DMBT)_{18}$:$Au_{25}(PET)_{18}$
0.3:1.0

within 2 min

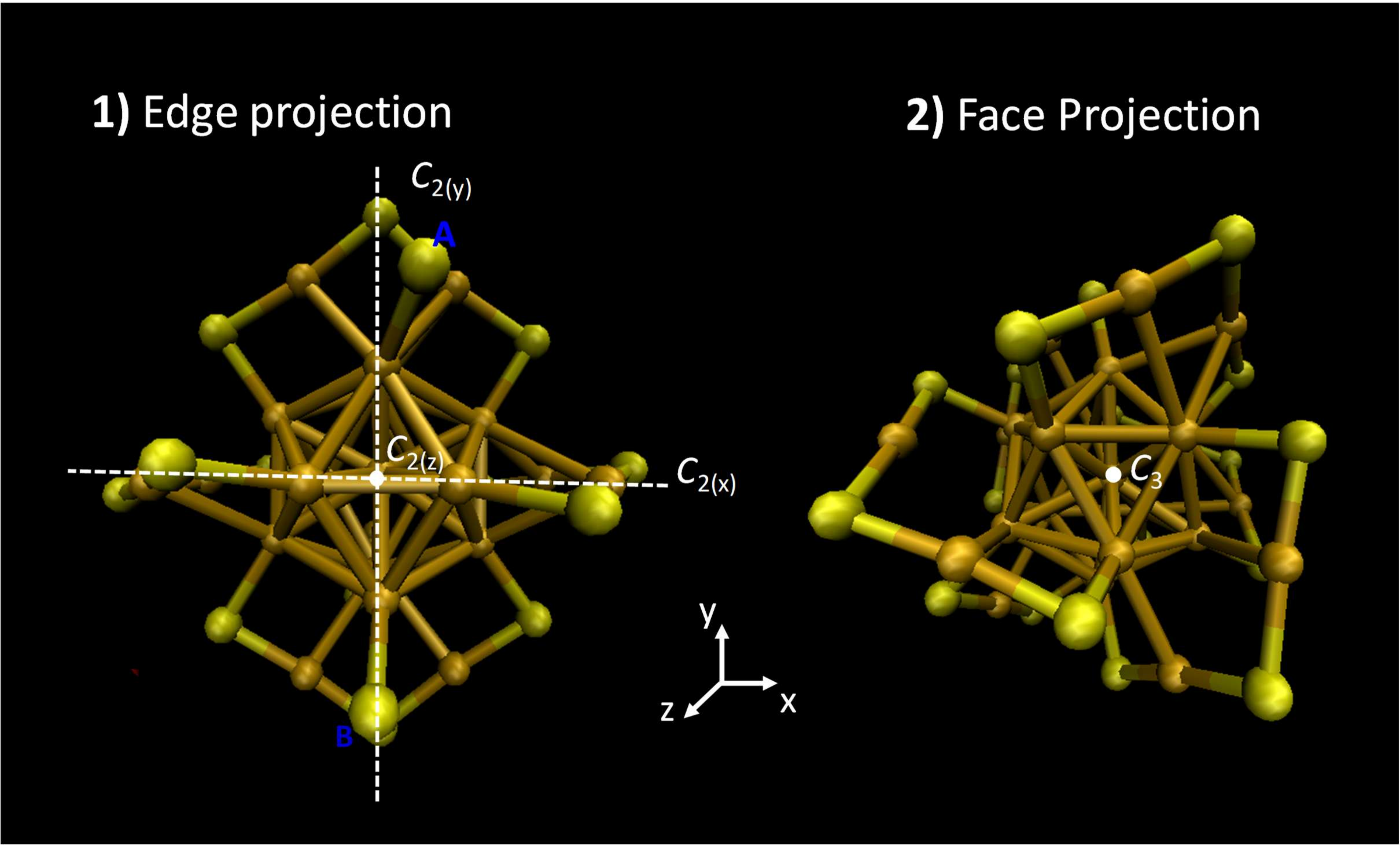
Optimized structure of $[Ag_{25}Au_{25}(DMBT)_{18}(PET)_{18}]^{2-}$

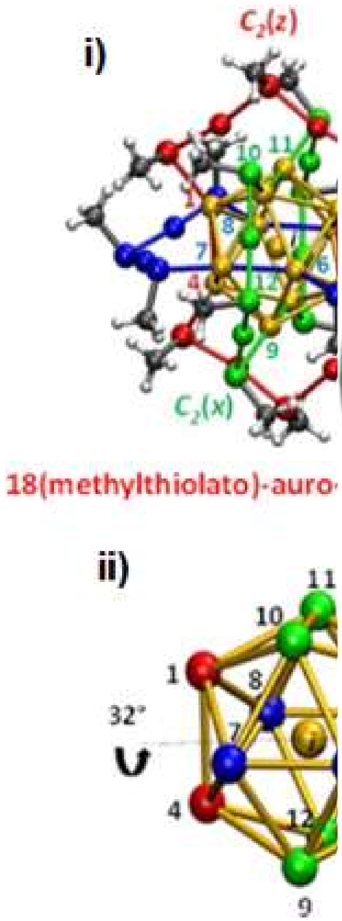


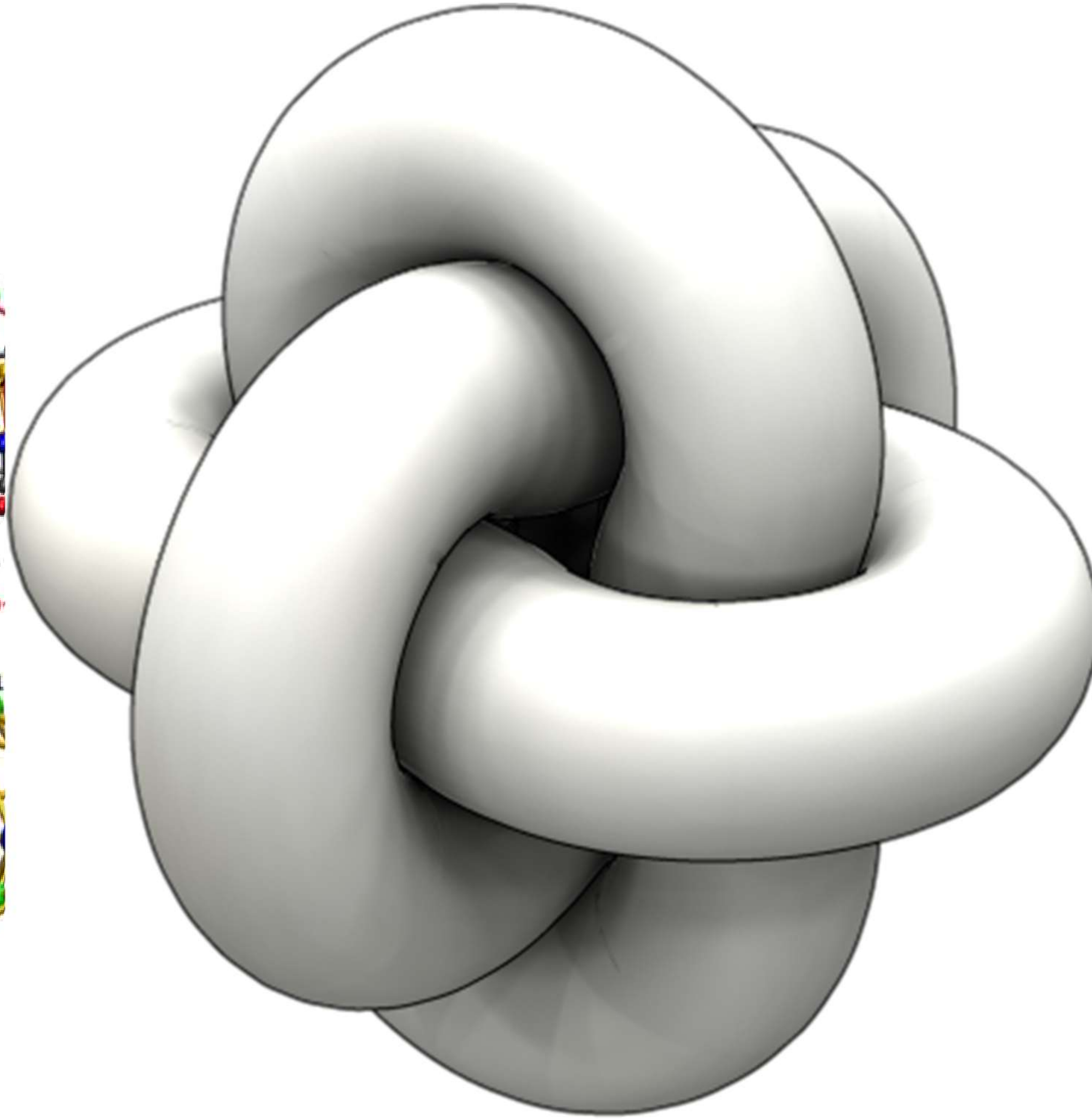


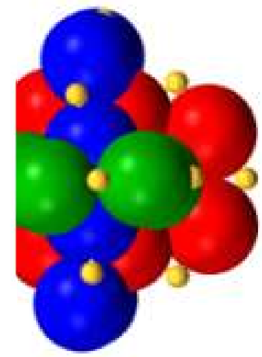
j
(0, 25)
$Au_{25}(PET)_{18}$
i
(9, 16)
(8, 17)
(7, 18)
(6, 19)
(5, 20)
(4, 21)
0.3:1.0
h
(10, 15)
(9, 16)
(8, 17)
(7, 18)
(6, 19)
0.5:1.0
g
(12, 13)
(11, 14)
(10, 15)
(9, 16)
0.6:1.0
f
(14, 11)
(13, 12)
(12, 13)
(11, 14)
(10, 15)
1.0:1.0
e
(15, 10)
(14, 11)
(13, 12)
(12, 13)
1.3:1.0
d
(19, 6)
(18, 7)
(17, 8)
(16, 9)
2.2:1.0
c
(20, 5)
(19, 6)
(18, 7)
(17, 8)
3.3:1.0
b
(23, 2)
(22, 3)
(21, 4)
(20, 5)
6.6:1.0
a
(25, 0)
$Ag_{25}(DMBT)_{18}$
4000
5000
6000
7000
8000
m/z

How do we comprehend this?


1) Edge projection
$C_{2(y)}$
A
$C_{2(z)}$
$C_{2(x)}$
B
y
x
z
2) Face Projection
C_3







Gana Natarajan et. al. *JPC C* 2015

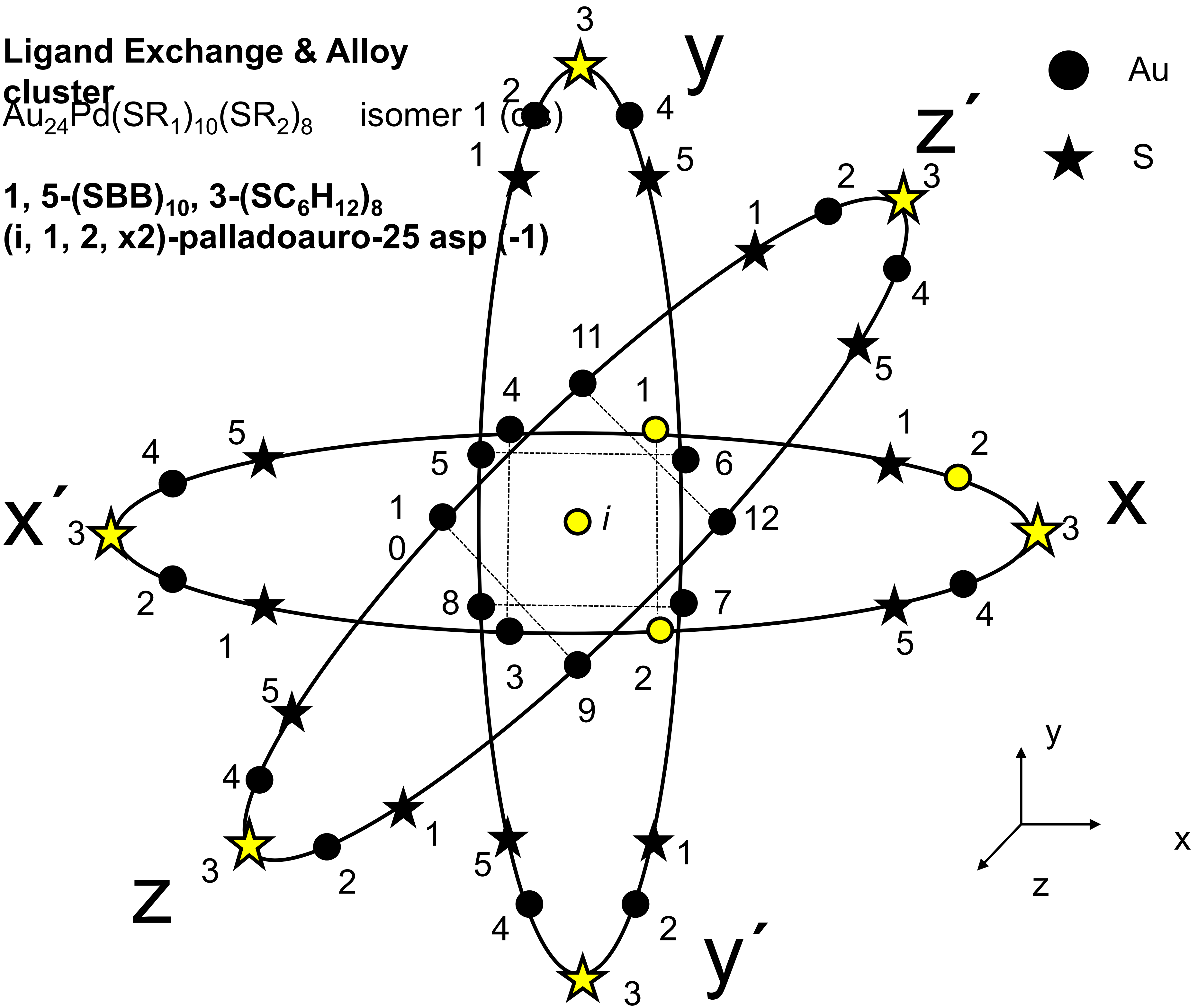
Aspicules

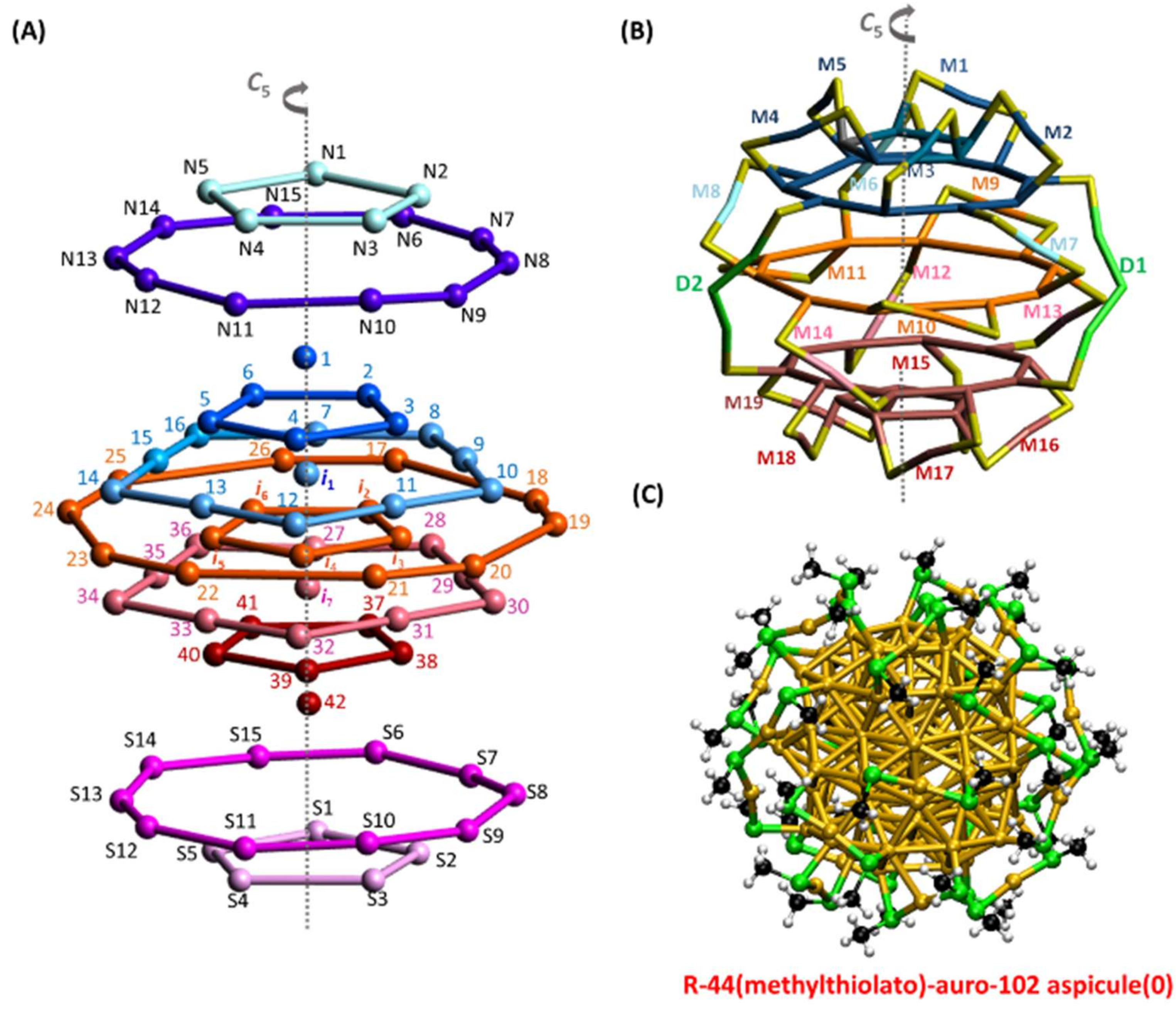
(D1-3,D2-3)-di(2-phenylethylthiolato),16(methylthiolato)-auro-25 aspicule(1-)
(D1-3,D2-3)-$(PET)_2$,$(SMe)_{16}$-auro-25 aspicule(1-)

Ligand Exchange & Alloy cluster

$Au_{24}Pd(SR_1)_{10}(SR_2)_8$ isomer 1 (cis)

1, 5-$(SBB)_{10}$, 3-$(SC_6H_{12})_8$
(i, 1, 2, x2)-palladoauro-25 asp (-1)





R-$(SMe)_{44}$-auro-102 aspicule**(**0**)** and L-$(SMe)_{44}$-auro-102 aspicule**(0)** [30]

ACCOUNTS of chemical research

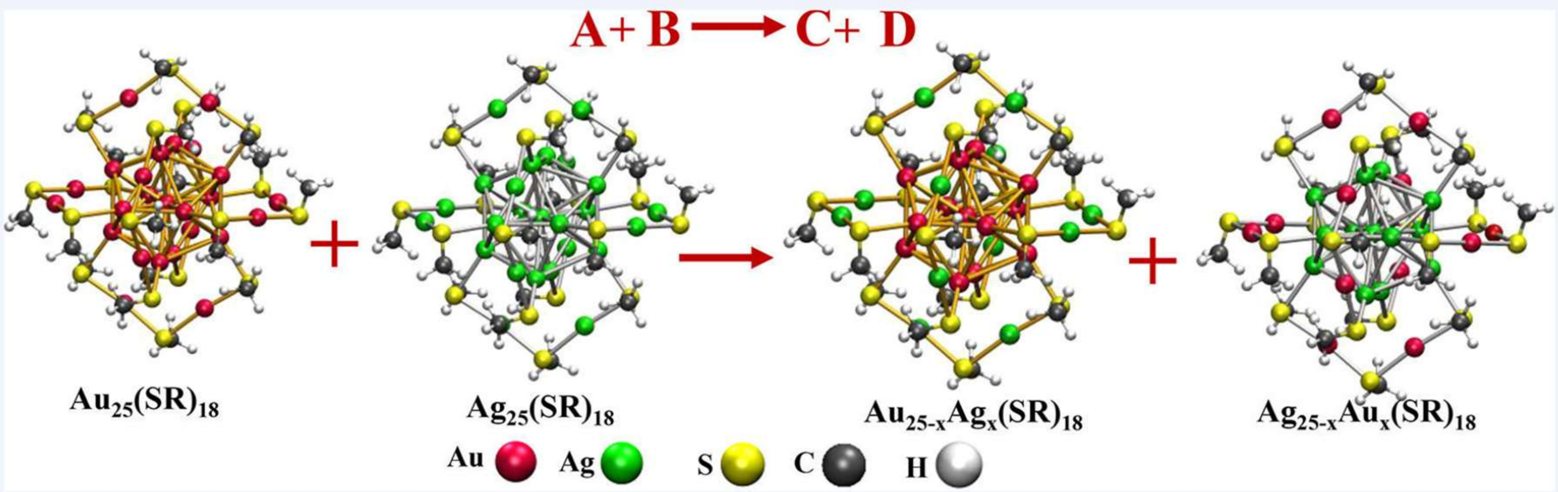
Article

pubs.acs.org/accounts

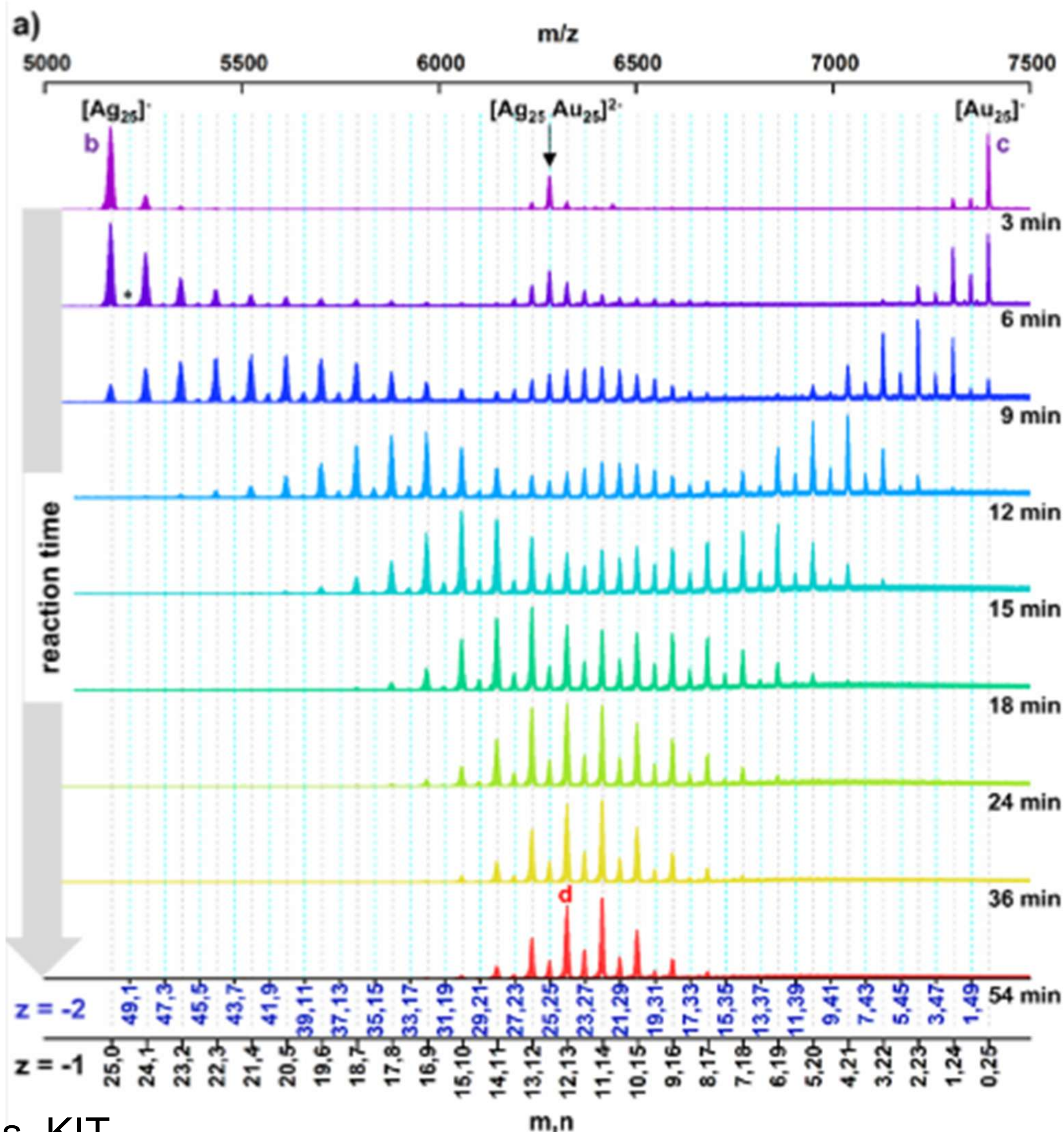
Interparticle Reactions: An Emerging Direction in Nanomaterials Chemistry

K. R. Krishnadas, Ananya Baksi,[†] Atanu Ghosh, Ganapati Natarajan, Anirban Som, and Thalappil Pradeep*

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

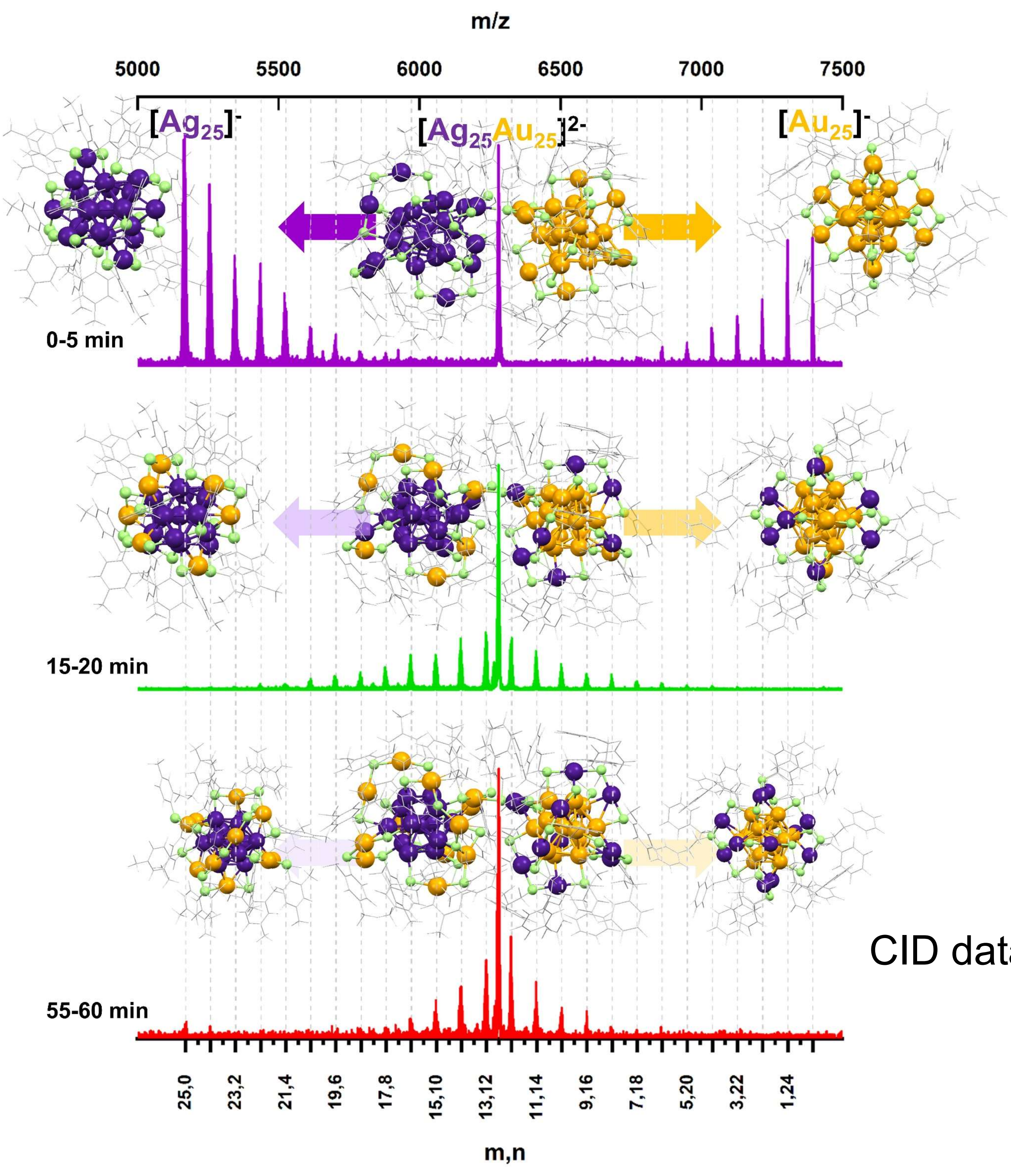


CONSPECTUS: Nanoparticles exhibit a rich variety in terms of structure, composition, and properties. However, reactions between them remain largely unexplored. In this *Account*, we discuss an emerging aspect of nanomaterials chemistry, namely, interparticle reactions in solution phase, similar to reactions between molecules, involving atomically precise noble metal clusters.



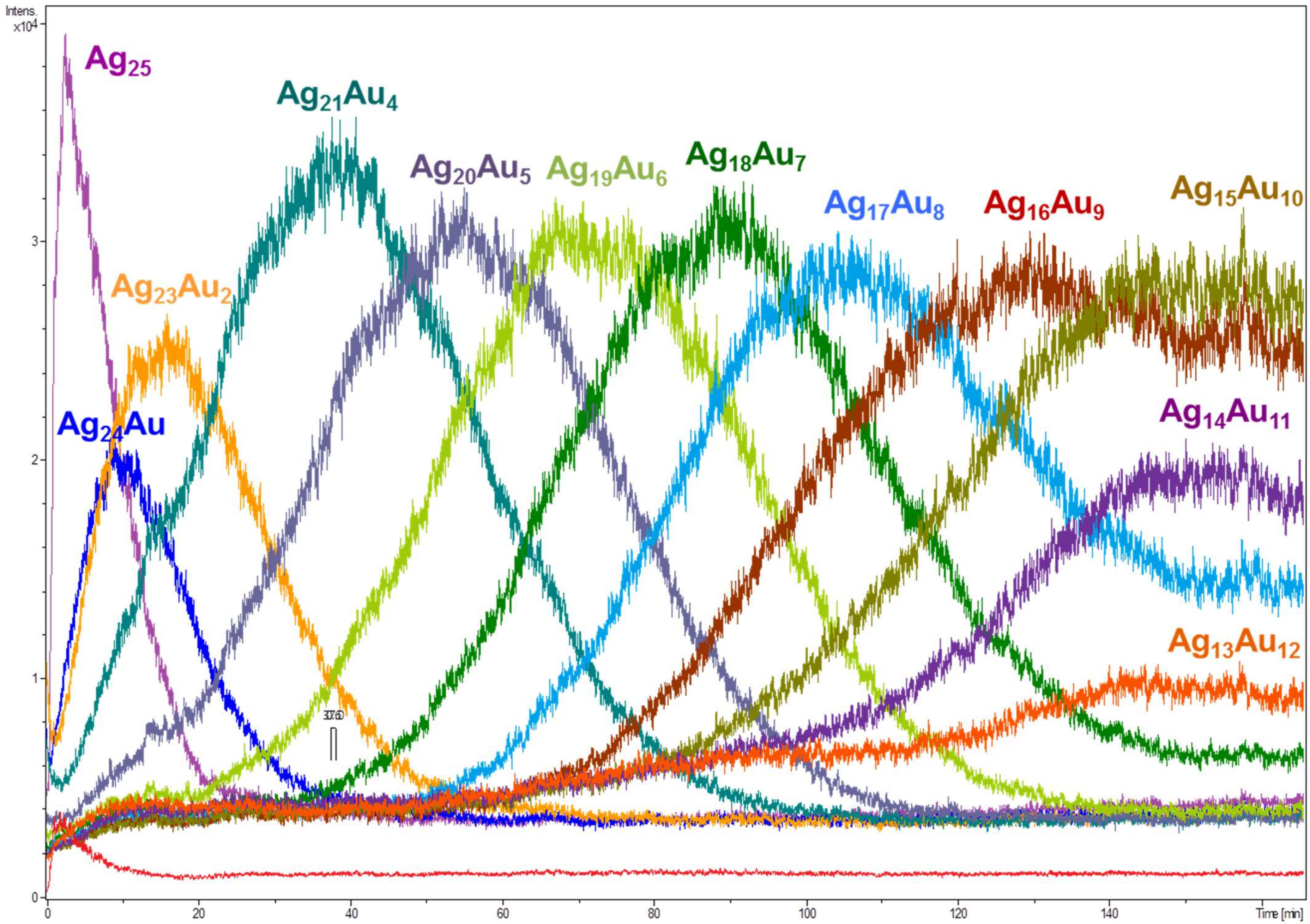
Manfred Kappes, KIT

M. Neumaier, A. Baksi, et. al., *JACS* 2021



CID data of $[Au25Ag25]^{2-}$

Kinetics of the exchange (monitored on the Ag_{25} side)



Expanding reactions

CHEMISTRY OF MATERIALS

Article

Cite This: Chem. Mater. 2020, 32, 611−619

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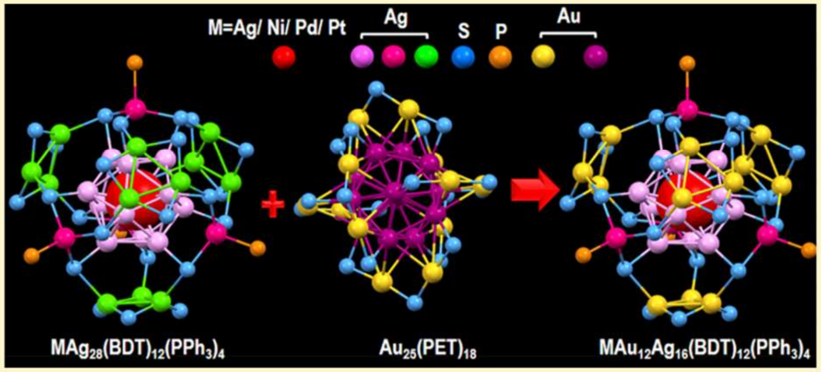
Intercluster Reactions Resulting in Silver-Rich Trimetallic Nanoclusters

Esma Khatun, Papri Chakraborty, Betsy Rachel Jacob, Ganesan Paramasivam, Mohammad Bodiuzzaman, Wakeel Ahmed Dar, and Thalappil Pradeep*

Department of Chemistry, DST Unit of Nanoscience (DST UNS) and Thematic Unit of Excellence (TUE), Indian Institute of Technology Madras, Chennai 600036, India

Supporting Information

ABSTRACT: Herein, we present an intercluster reaction leading to new trimetallic nanoclusters (NCs) using bimetallic and monometallic NCs as reactants. Dithiol protected bimetallic $MAg_{28}(BDT)_{12}(PPh_3)_4$ (BDT = 1,3-benzenedithiol and M = Ni, Pd, or Pt) and monothiol protected $Au_{25}(PET)_{18}$ (PET = 2-phenylethanethiol) were used as model NCs. A mixture of trimetallic $MAu_xAg_{28-x}(BDT)_{12}(PPh_3)_4$ (x = 1−12) and bimetallic $Ag_xAu_{25-x}(PET)_{18}$ (x = 1−7) NCs were formed during the reaction as understood from time-dependent electrospray ionization mass spectrometry (ESI MS). Detailed studies of intercluster reaction between



$Ag_{29}(BDT)_{12}(PPh_3)_4$ and $Au_{25}(PET)_{18}$ were also performed. Although both $MAg_{28}(BDT)_{12}(PPh_3)_4$ (M = Ag, Ni, Pd, or Pt) and $Au_{25}(PET)_{18}$ contain 13 atoms icosahedral core, only a maximum of 12 Au doped NCs were formed for the former as a major product and not the 13 Au doped one, unlike the previous reports of intercluster reaction. The transfer of Ni, Pd, or Pt atom from the center of icosahedron of $MAg_{28}(BDT)_{12}(PPh_3)_4$ to $Au_{25}(PET)_{18}$ was not observed, which suggests that the

Interparticle reactions forming product co-crystals

ACS NANO
Cite This: *ACS Nano* 2019, 13, 13365−13373
www.acsnano.org
ARTICLE

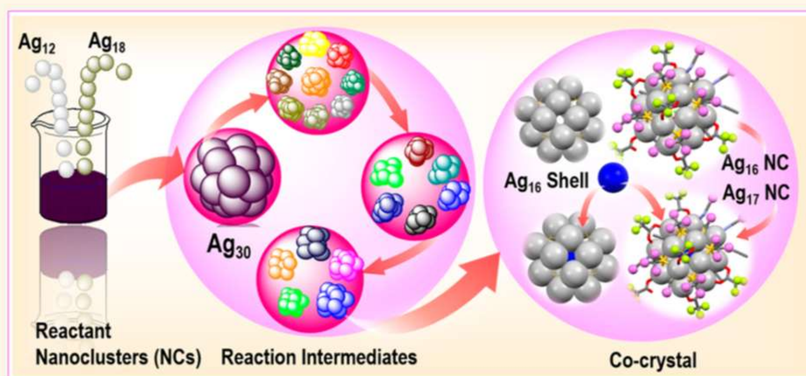
Interparticle Reactions between Silver Nanoclusters Leading to Product Cocrystals by Selective Cocrystallization

Wakeel Ahmed Dar,[†] Mohammad Bodiuzzaman,[†] Debasmita Ghosh, Ganesan Paramasivam, Esma Khatun, Korath Shivan Sugi, and Thalappil Pradeep*

Department of Chemistry, DST Unit of Nanoscience and Thematic Unit of Excellence, Indian Institute of Technology Madras, Chennai 600036, India

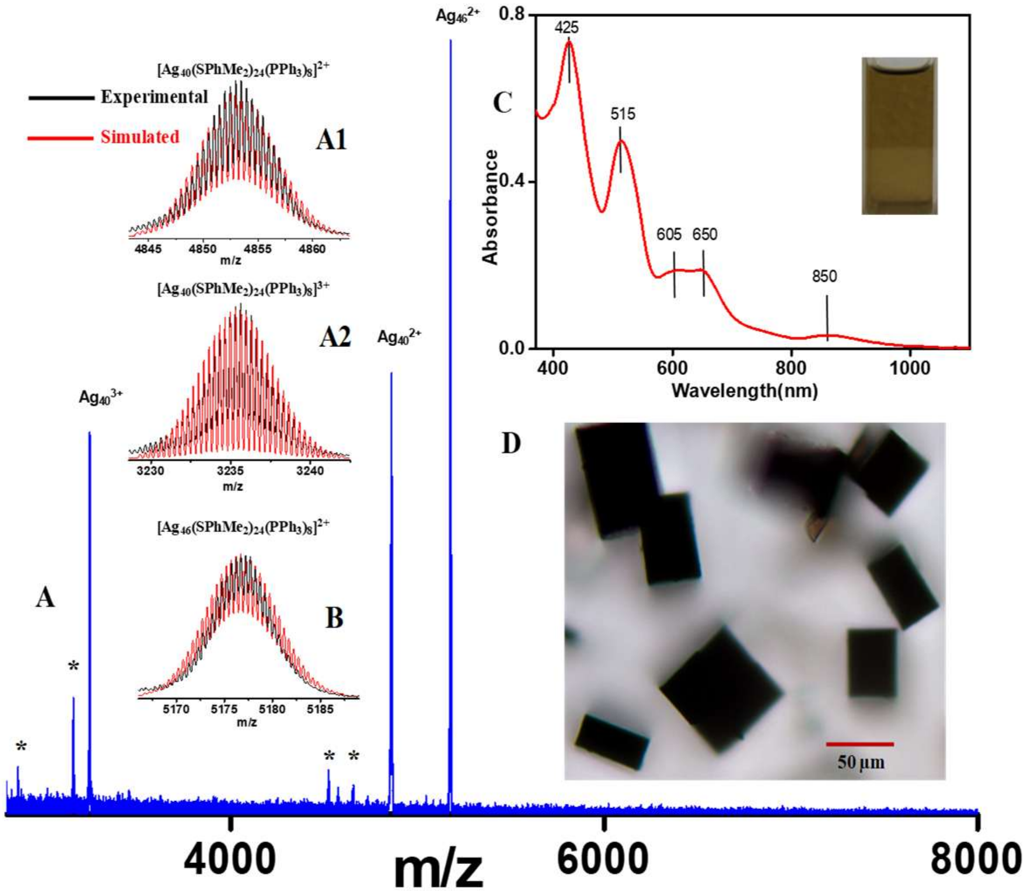
Supporting Information

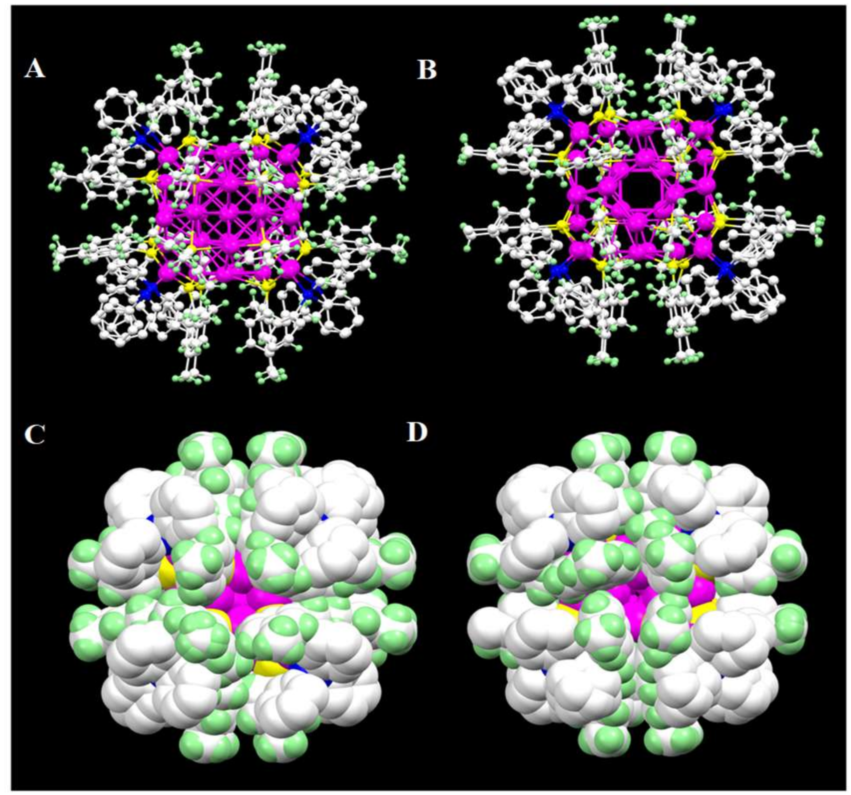
ABSTRACT: We present an example of an interparticle reaction between atomically precise nanoclusters (NCs) of the *same* metal, resulting in entirely different clusters. In detail, the clusters $[Ag_{12}(TBT)_8(TFA)_5(CH_3CN)]^+$ (TBT = *tert*-butylthiolate, TFA = trifluoroacetate, CH_3CN = acetonitrile) and $[Ag_{18}(TPP)_{10}H_{16}]^{2+}$ (TPP = triphenylphosphine) abbreviated as Ag_{12} and Ag_{18}, respectively, react leading to $[Ag_{16}(TBT)_8(TFA)_7(CH_3CN)_3Cl]^+$ and $[Ag_{17}(TBT)_8(TFA)_7(CH_3CN)_3Cl]^+$, abbreviated as Ag_{16} and Ag_{17}, respectively. The two product NCs crystallize together as both possess the same metal chalcogenolate



Co-crystals

Ag_{40} and Ag_{46} with the same shell





M. Bodiuzzaman, et. al. *Angew. Chem. Int. Ed.* **2018**

Atom transfer dynamics

They are indeed molecules!

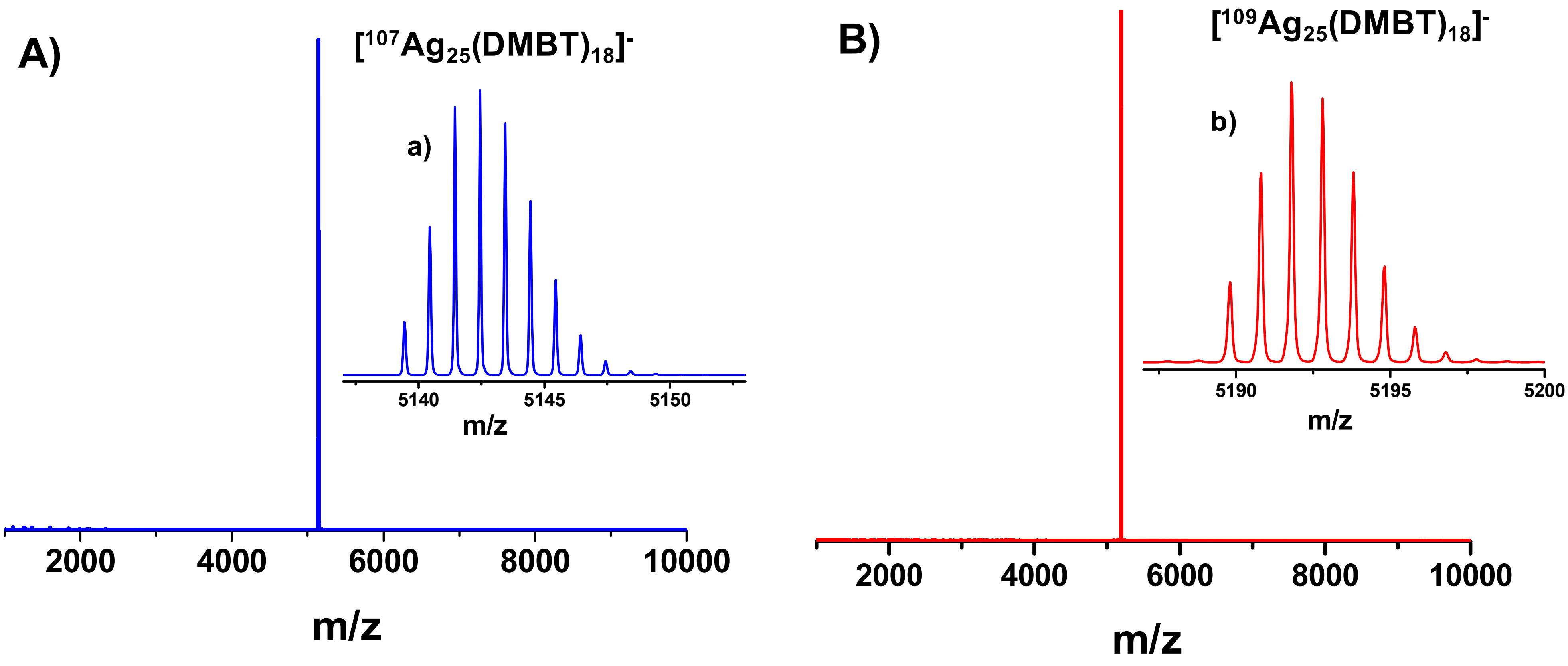
SCIENCE ADVANCES | RESEARCH ARTICLE

CONDENSED MATTER PHYSICS

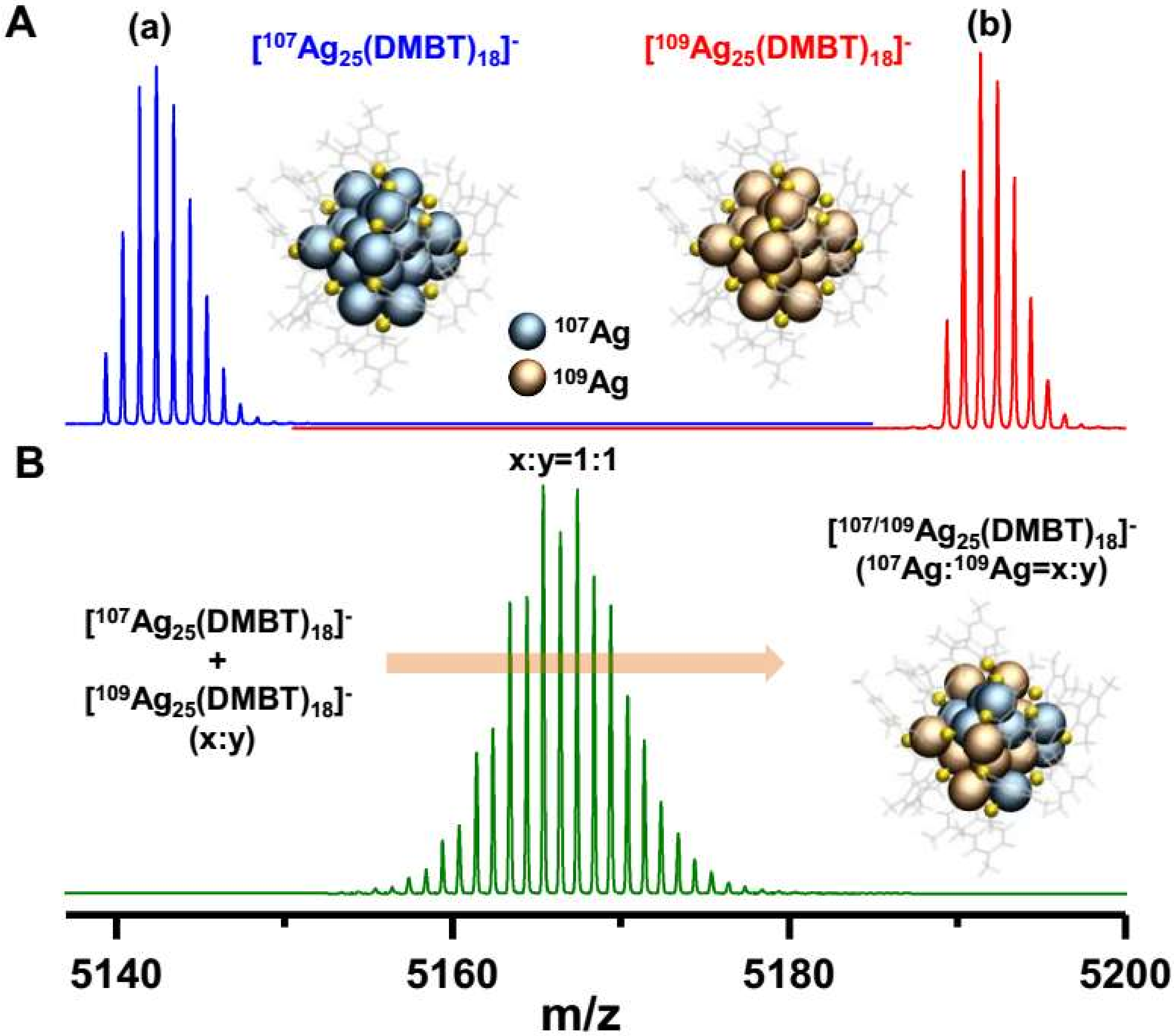
Rapid isotopic exchange in nanoparticles

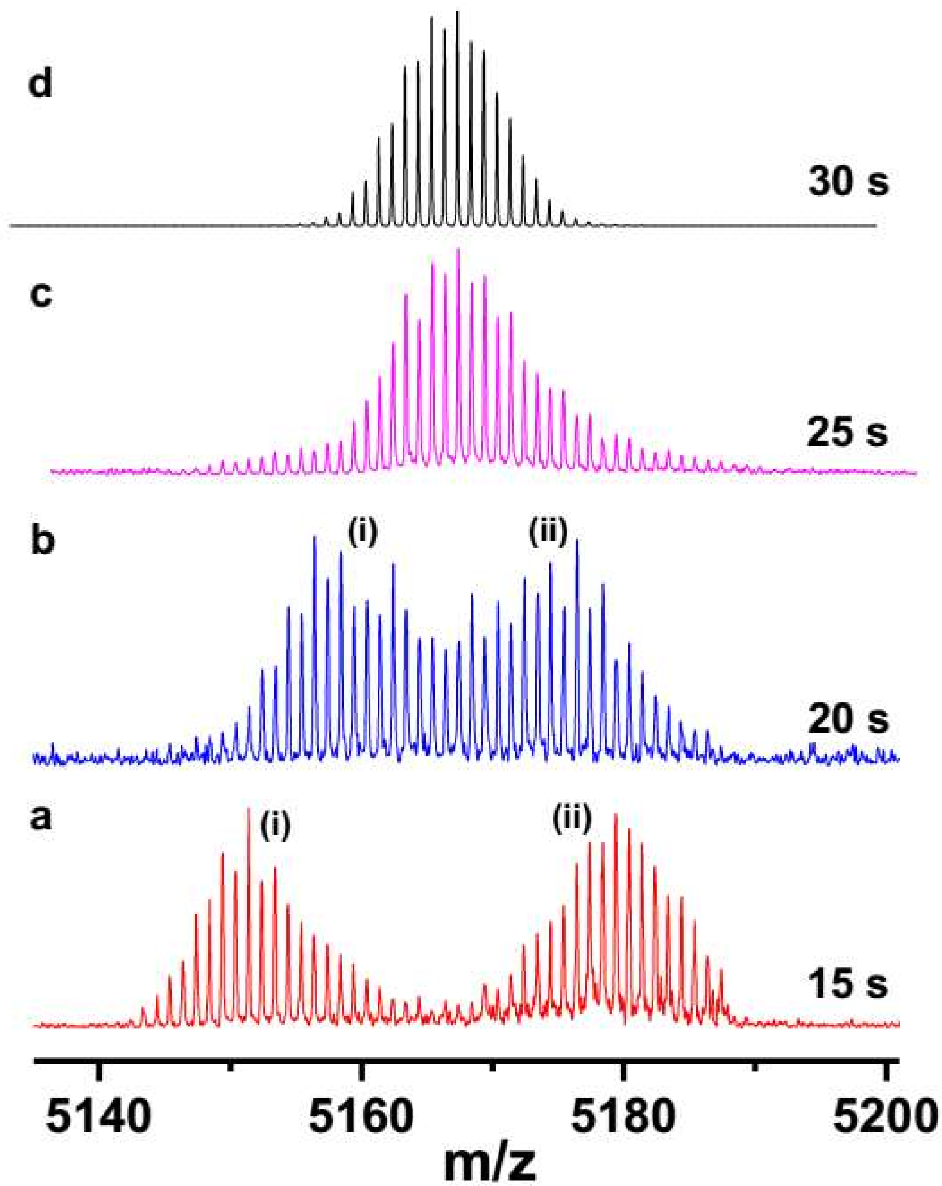
Papri Chakraborty[1], Abhijit Nag[1], Ganapati Natarajan[1], Nayanika Bandyopadhyay[1], Ganesan Paramasivam[1], Manoj Kumar Panwar[1], Jaydeb Chakrabarti[2], Thalappil Pradeep[1]*

Rapid solution-state exchange dynamics in nanoscale pieces of matter is revealed, taking isotopically pure atomically precise clusters as examples. As two isotopically pure silver clusters made of ^{107}Ag and ^{109}Ag are mixed, an isotopically mixed cluster of the same entity results, similar to the formation of HDO, from H_2O and D_2O. This spontaneous process is driven by the entropy of mixing and involves events at multiple time scales.

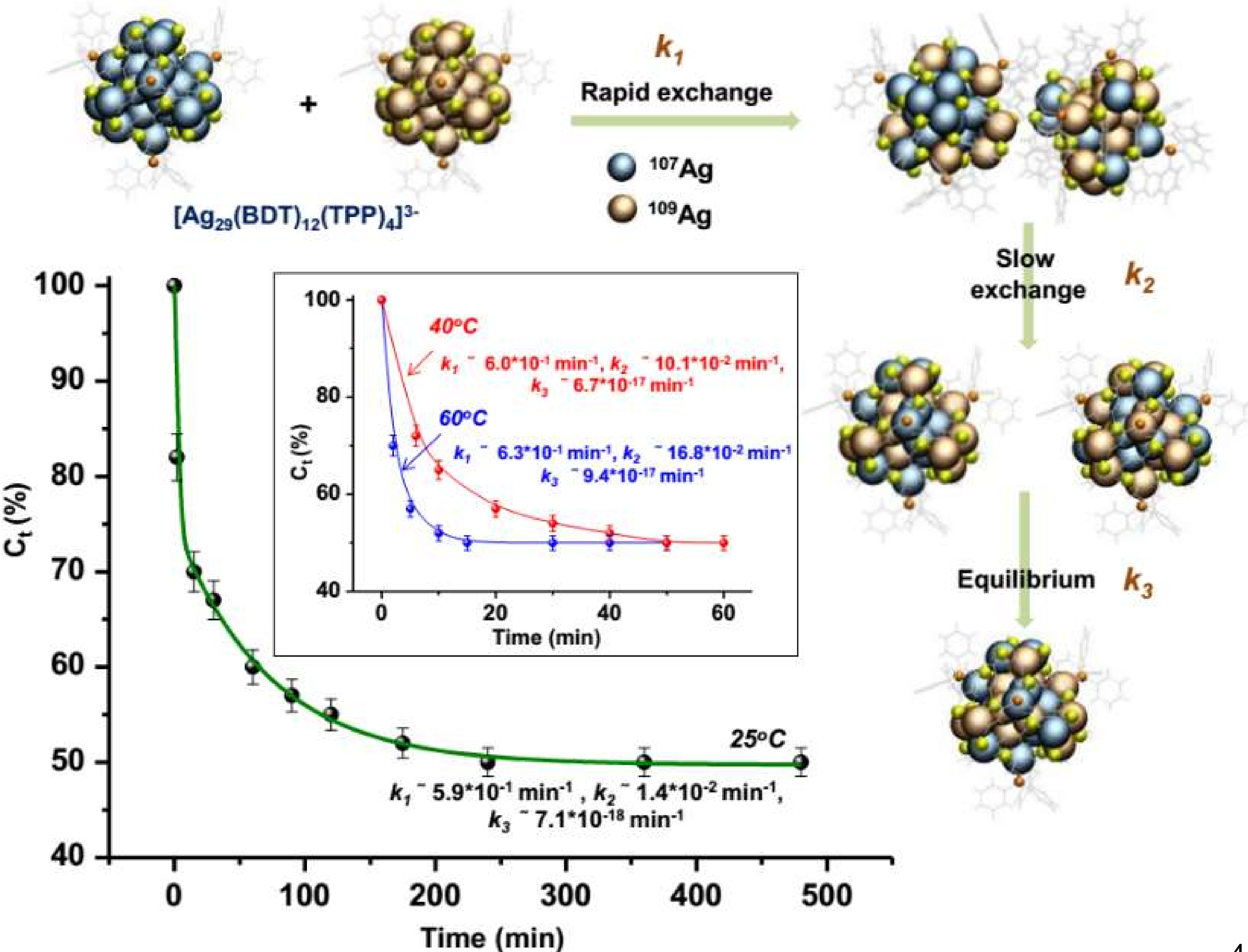


ESI MS of **A)** $^{107}Ag_{25}(DMBT)_{18}$ and **B)**$^{109}Ag_{25}(DMBT)_{18}$. Insets shows the respective isotope patterns.


A
(a)
[$^{107}Ag_{25}(DMBT)_{18}$]$^-$
[$^{109}Ag_{25}(DMBT)_{18}$]$^-$
(b)
^{107}Ag
^{109}Ag
B
x:y=1:1
[$^{107/109}Ag_{25}(DMBT)_{18}$]$^-$
(^{107}Ag:^{109}Ag=x:y)
[$^{107}Ag_{25}(DMBT)_{18}$]$^-$
+
[$^{109}Ag_{25}(DMBT)_{18}$]$^-$
(x:y)
5140
5160
5180
5200
m/z

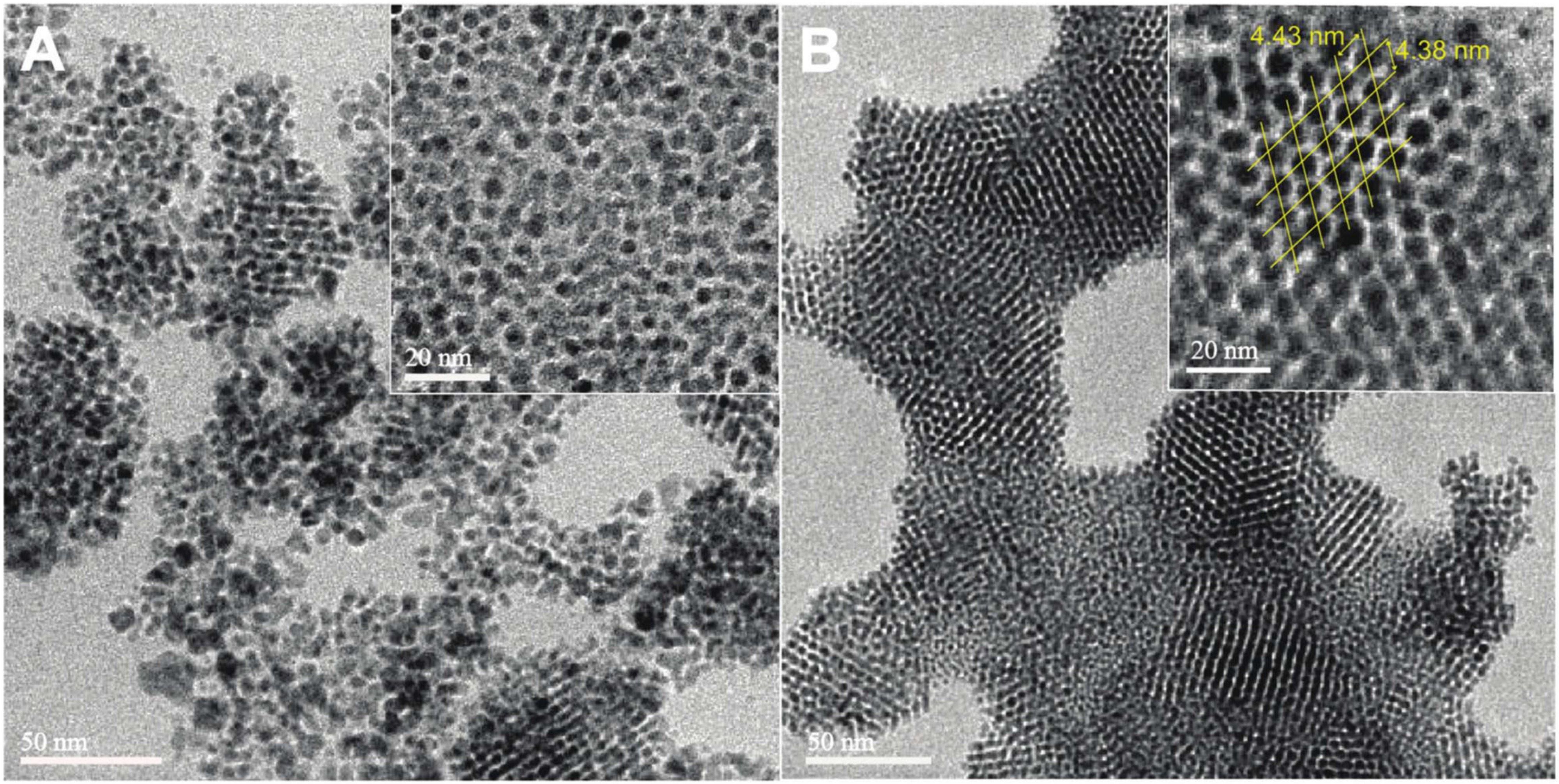


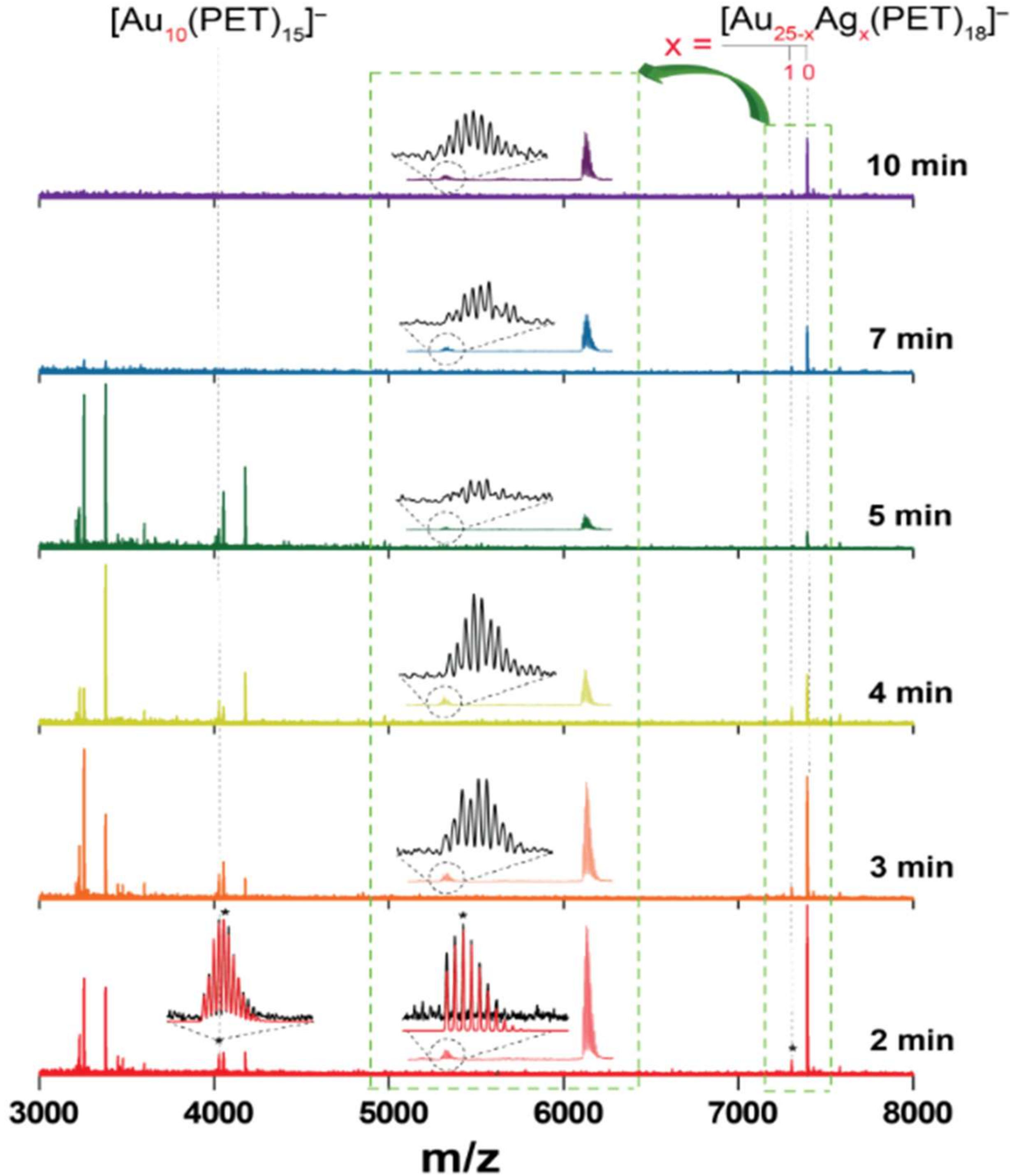
Papri Chakraborty, et. al. *Science Advances* 2019



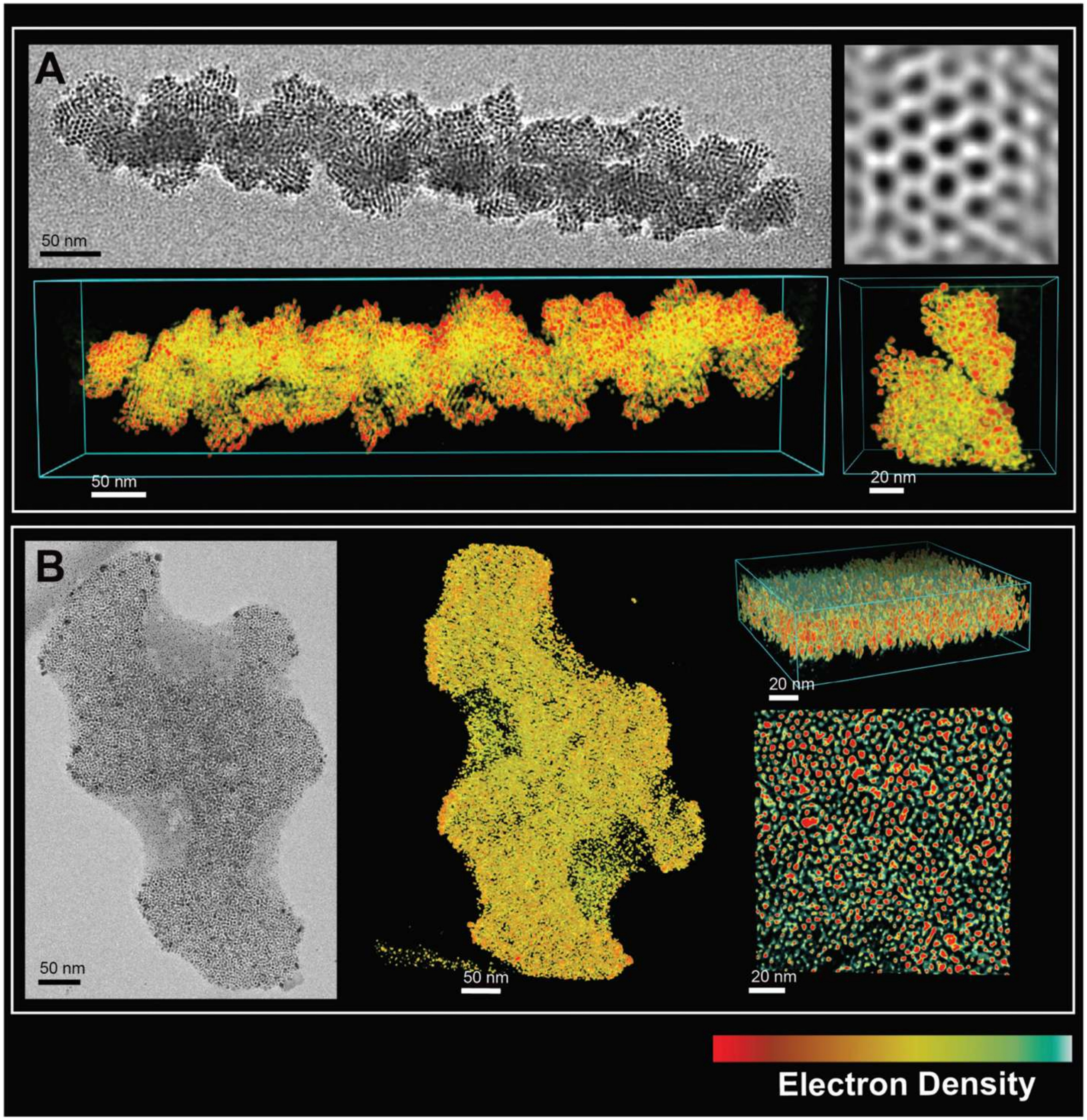
k1
Rapid exchange
107Ag
109Ag
[Ag29(BDT)12(TPP)4]3-
Slow exchange
k2
Equilibrium
k3
40°C
k1 ~ 6.0*10-1 min-1, k2 ~ 10.1*10-2 min-1, k3 ~ 6.7*10-17 min-1
60°C
k1 ~ 6.3*10-1 min-1, k2 ~ 16.8*10-2 min-1 k3 ~ 9.4*10-17 min-1
Ct (%)
Time (min)
25°C
k1 ~ 5.9*10-1 min-1 , k2 ~ 1.4*10-2 min-1, k3 ~ 7.1*10-18 min-1

Can clusters react with nanoparticles?


A
20 nm
50 nm
B
4.43 nm
4.38 nm
20 nm
50 nm

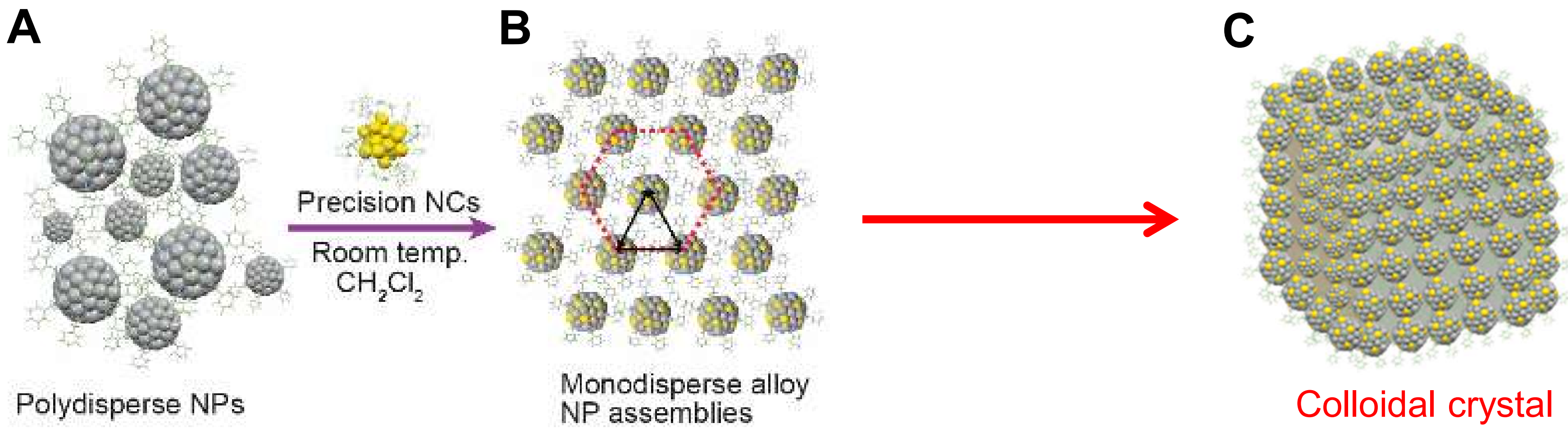


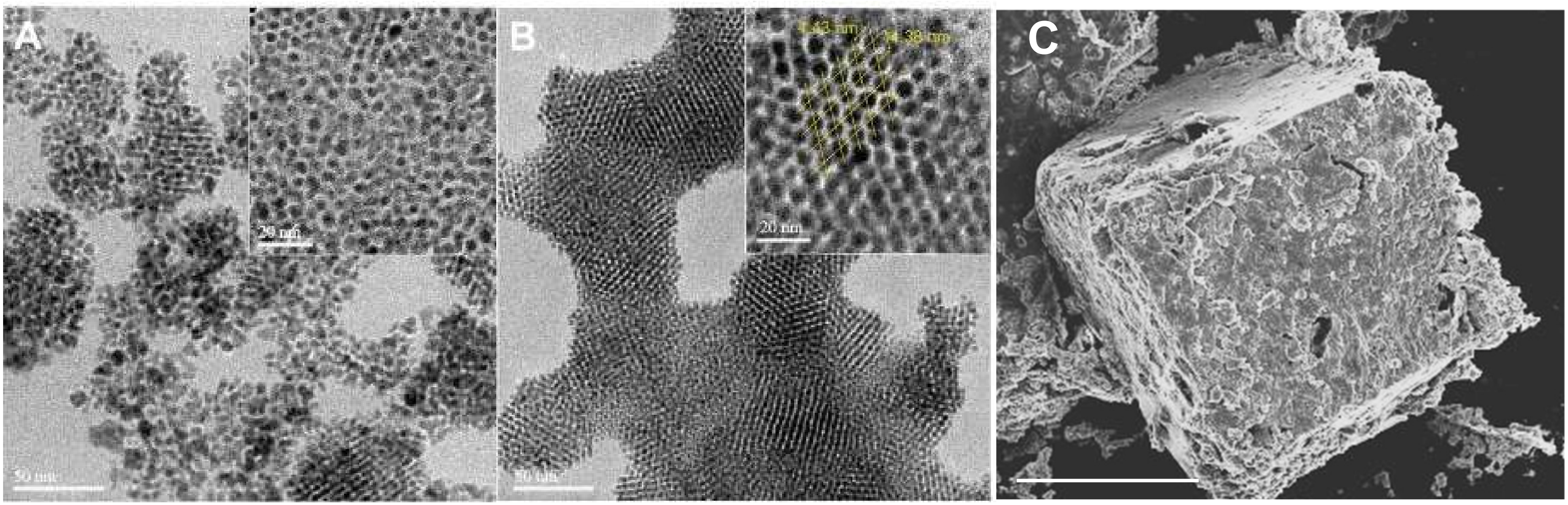
[Au10(PET)15]⁻
[Au25-xAgx(PET)18]⁻
x =
1
0
10 min
7 min
5 min
4 min
3 min
2 min
3000
4000
5000
6000
7000
8000
m/z



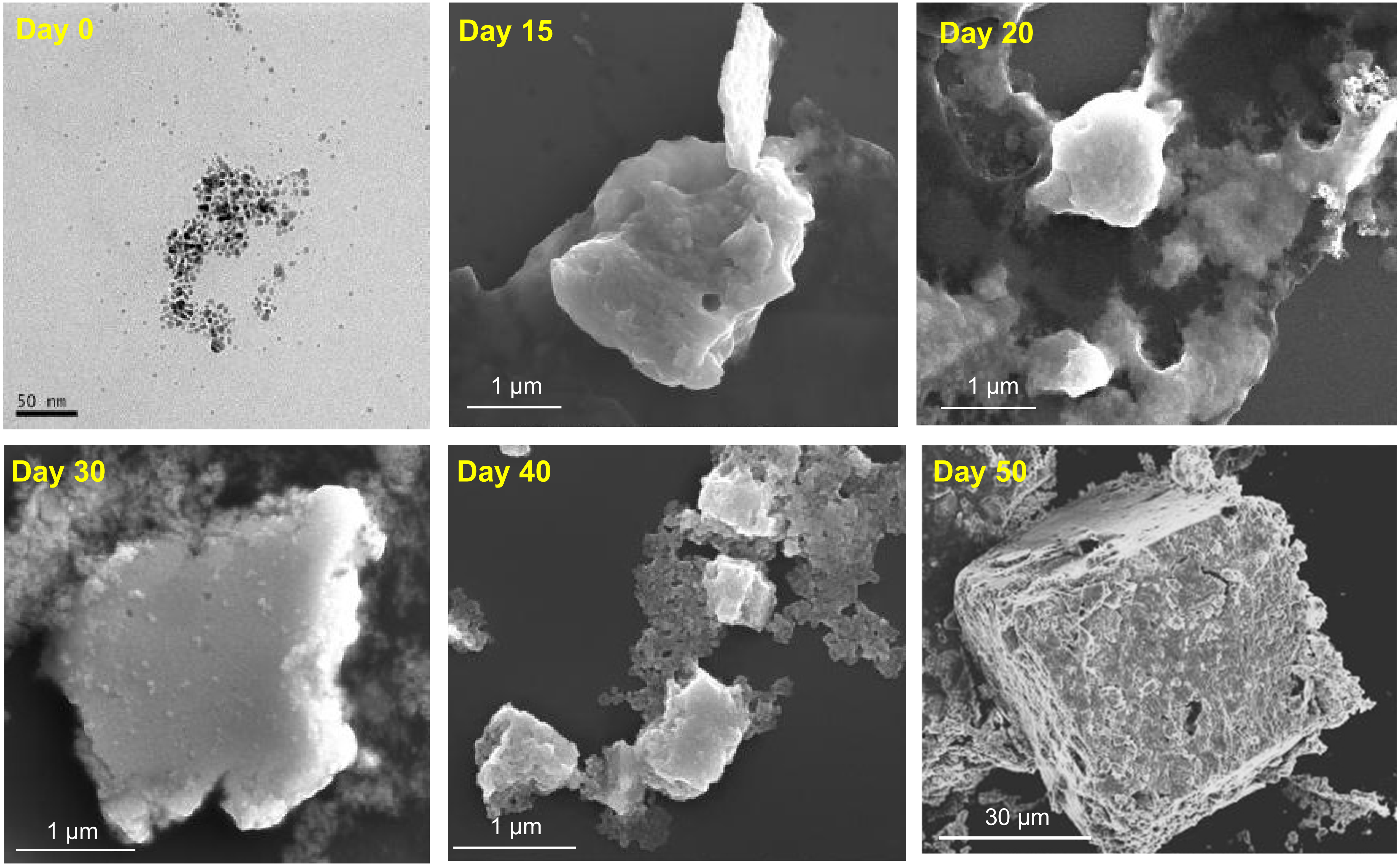
A
50 nm
50 nm
20 nm
B
50 nm
50 nm
20 nm
20 nm
Electron Density

Crystallization of AgAu NP

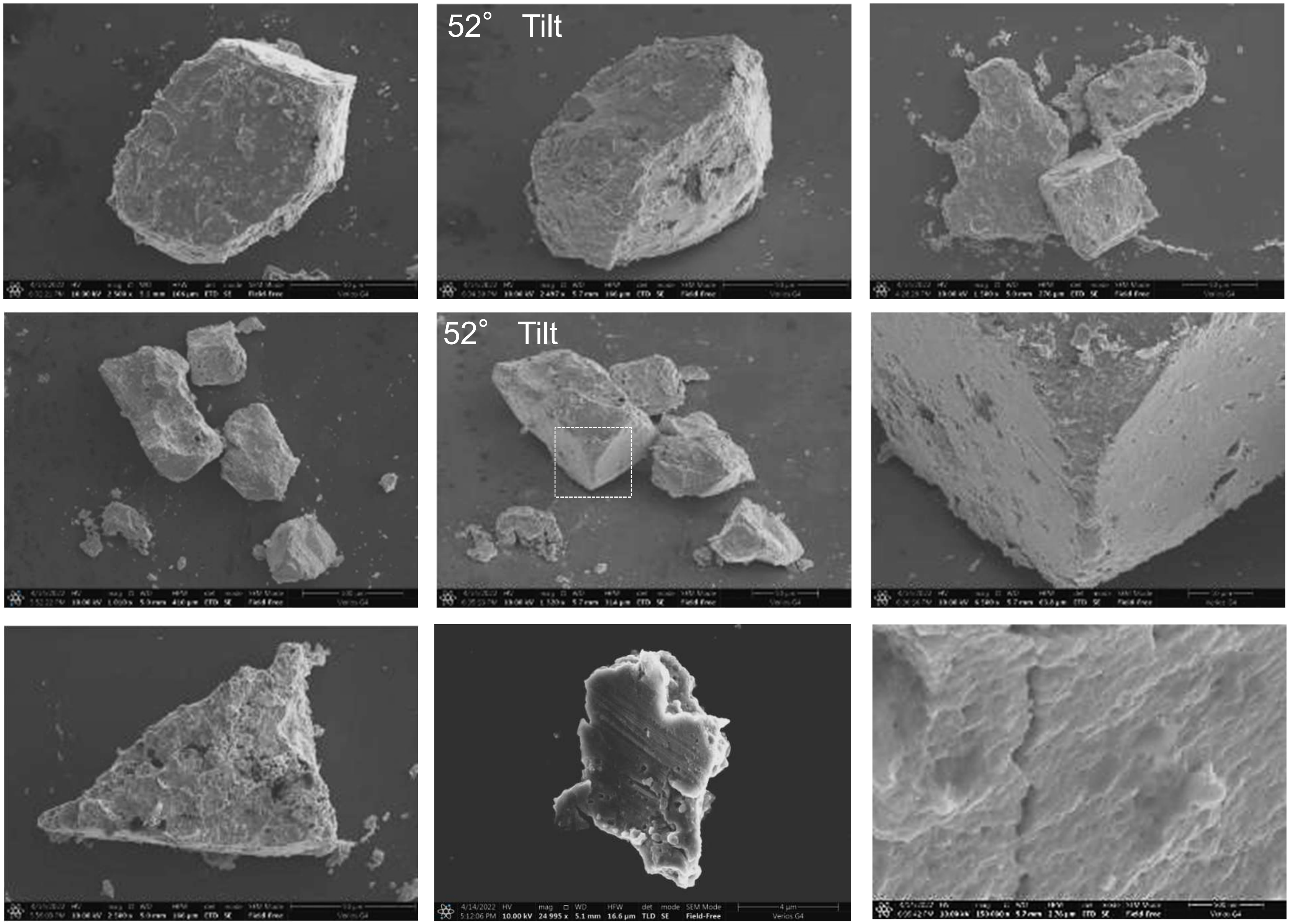




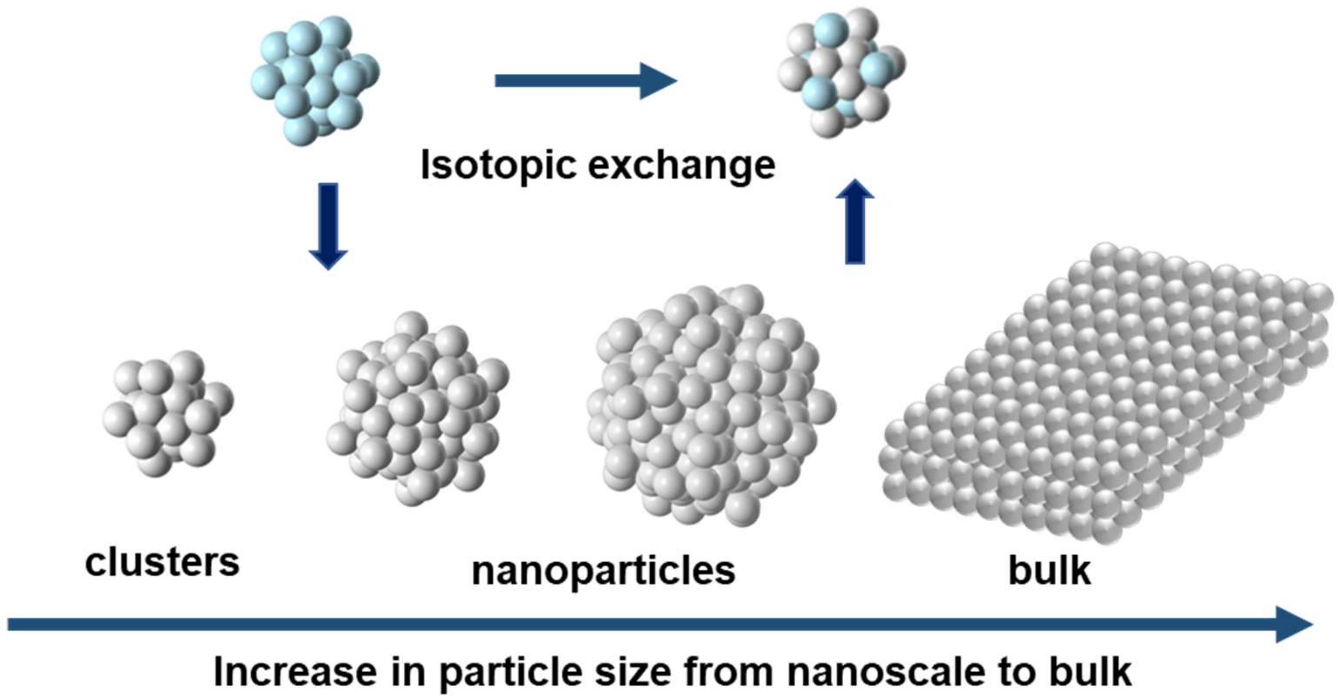
Transformation of colloidal particles in solution



Crystals imaged after 50 days

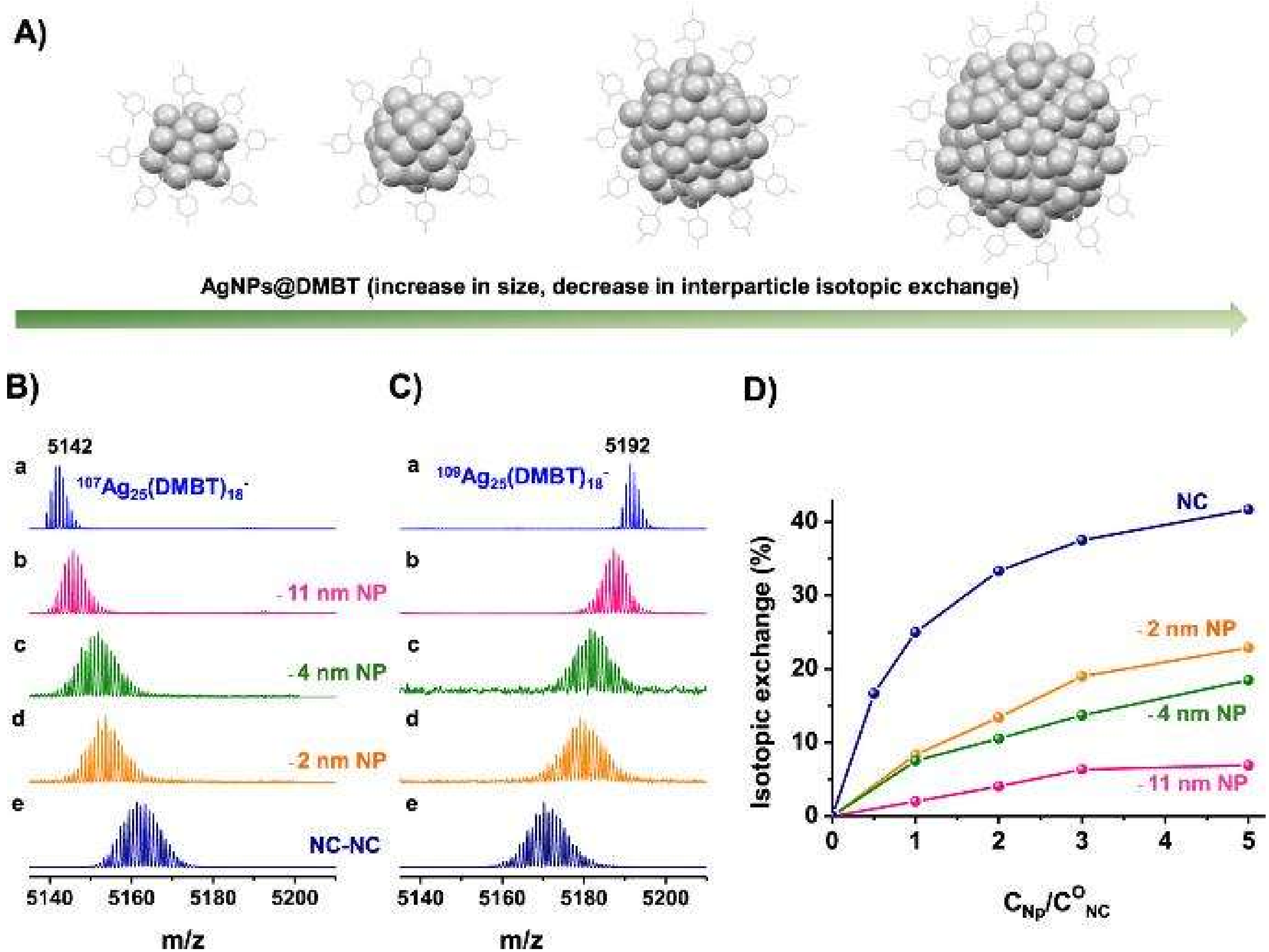


Isotopic exchange of atomically precise nanoclusters with materials of varying dimensions: from nanoscale to bulk



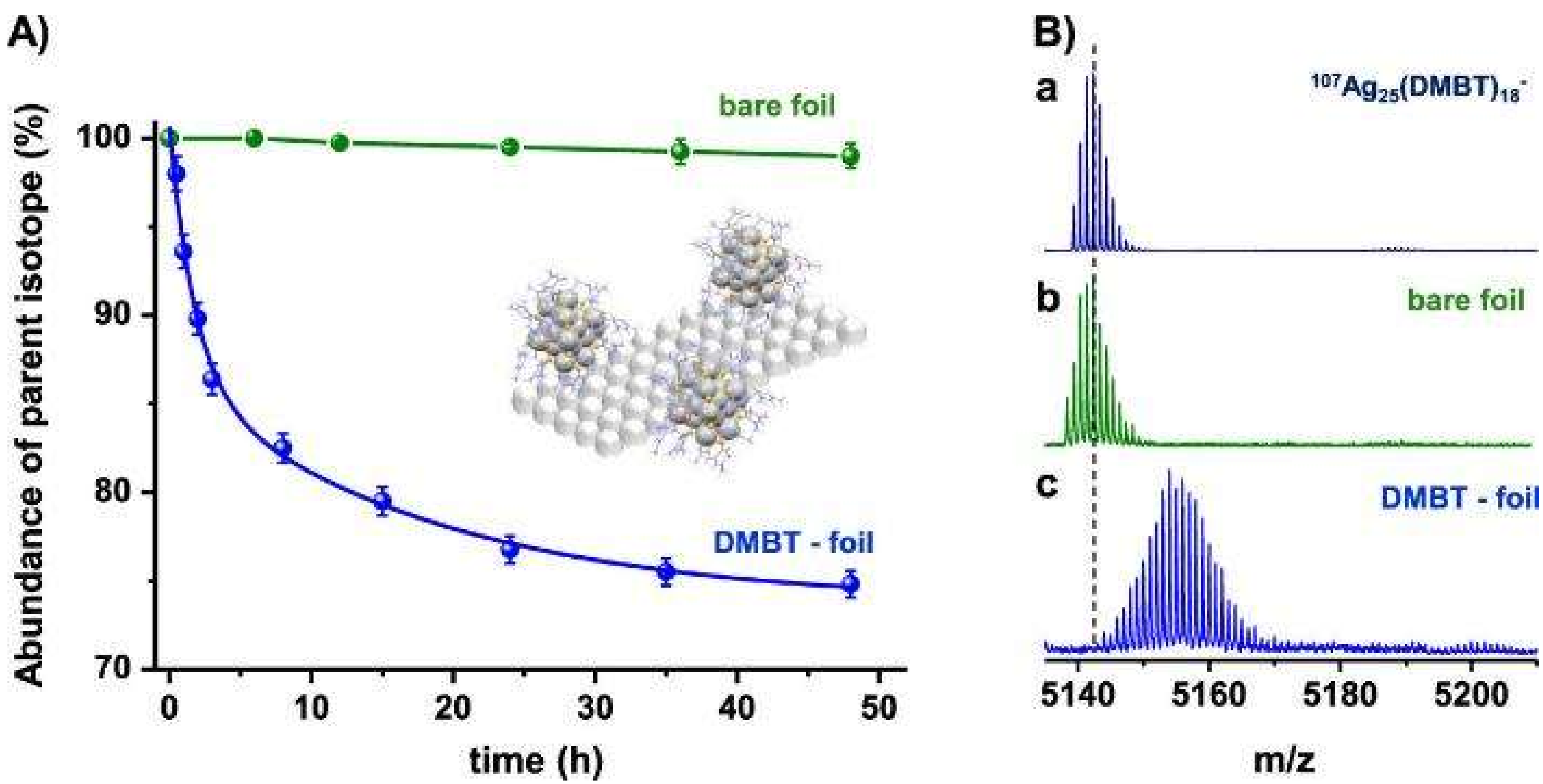
Chakraborty et al., *J. Phys. Chem. C* 2021, 125, 29, 16110–16117

Isotopic exchange with Ag nanoparticles



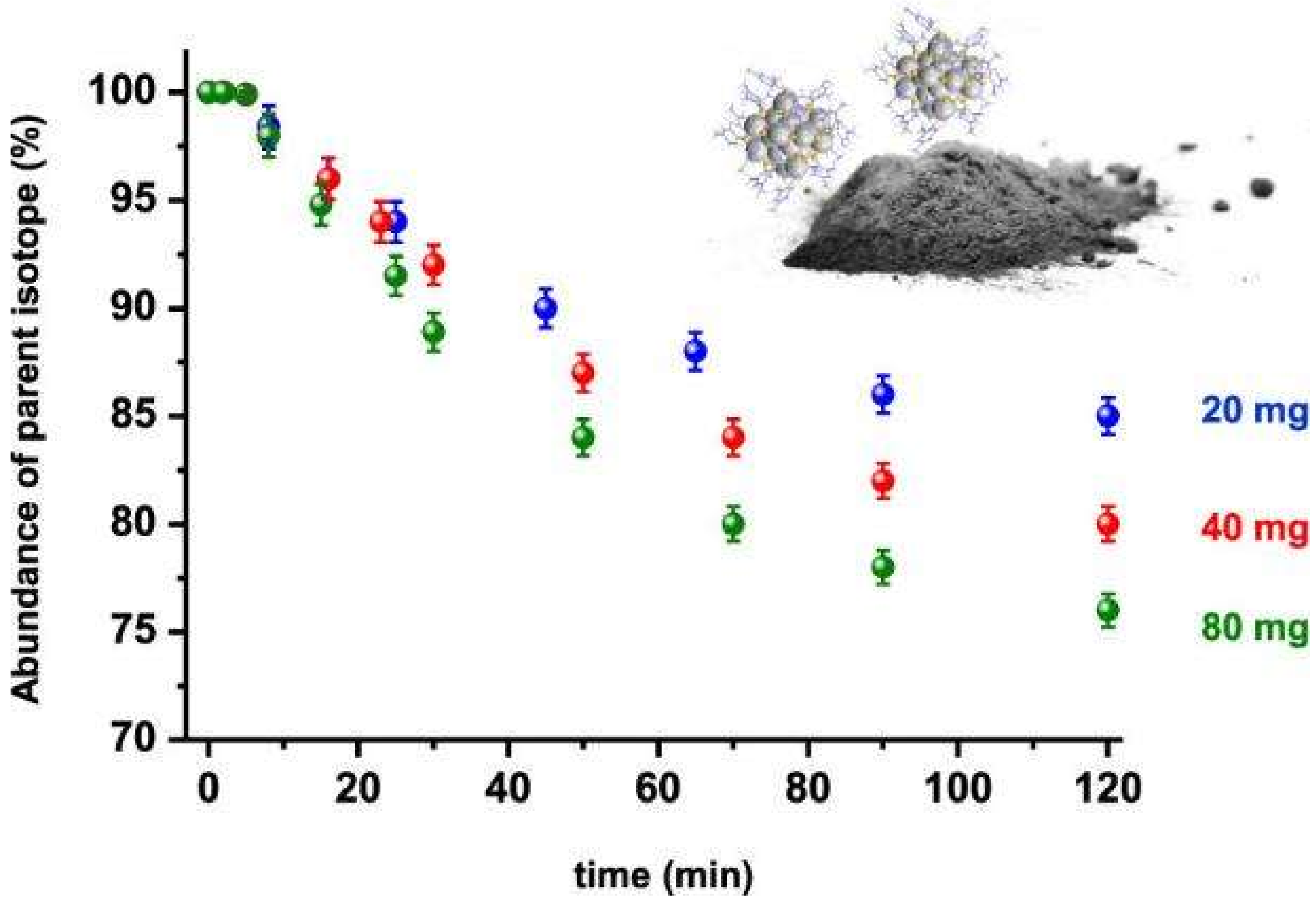
(A) Schematic showing NPs of increasing sizes, (B,C) ESI MS of (a) parent isotopic NCs, $^{107}Ag_{25}(DMBT)_{18}^-$ and $^{109}Ag_{25}(DMBT)_{18}^-$, respectively, and products formed by the reaction of the isotopic NCs with (b) ~11, (c) ~4, (d) ~2 nm AgNPs, and (e) NC (made from naturally abundant Ag) at 1:5 molar ratio in each case. (D) Plot showing the extent of isotopic exchange (%) as a function of the ratio of the concentration of NPs (C_{NP}) and concentration of isotopic NCs (C_{NC}^{o}) used in the NC–NP and NC–NC reactions.

Isotopic exchange with Ag foil



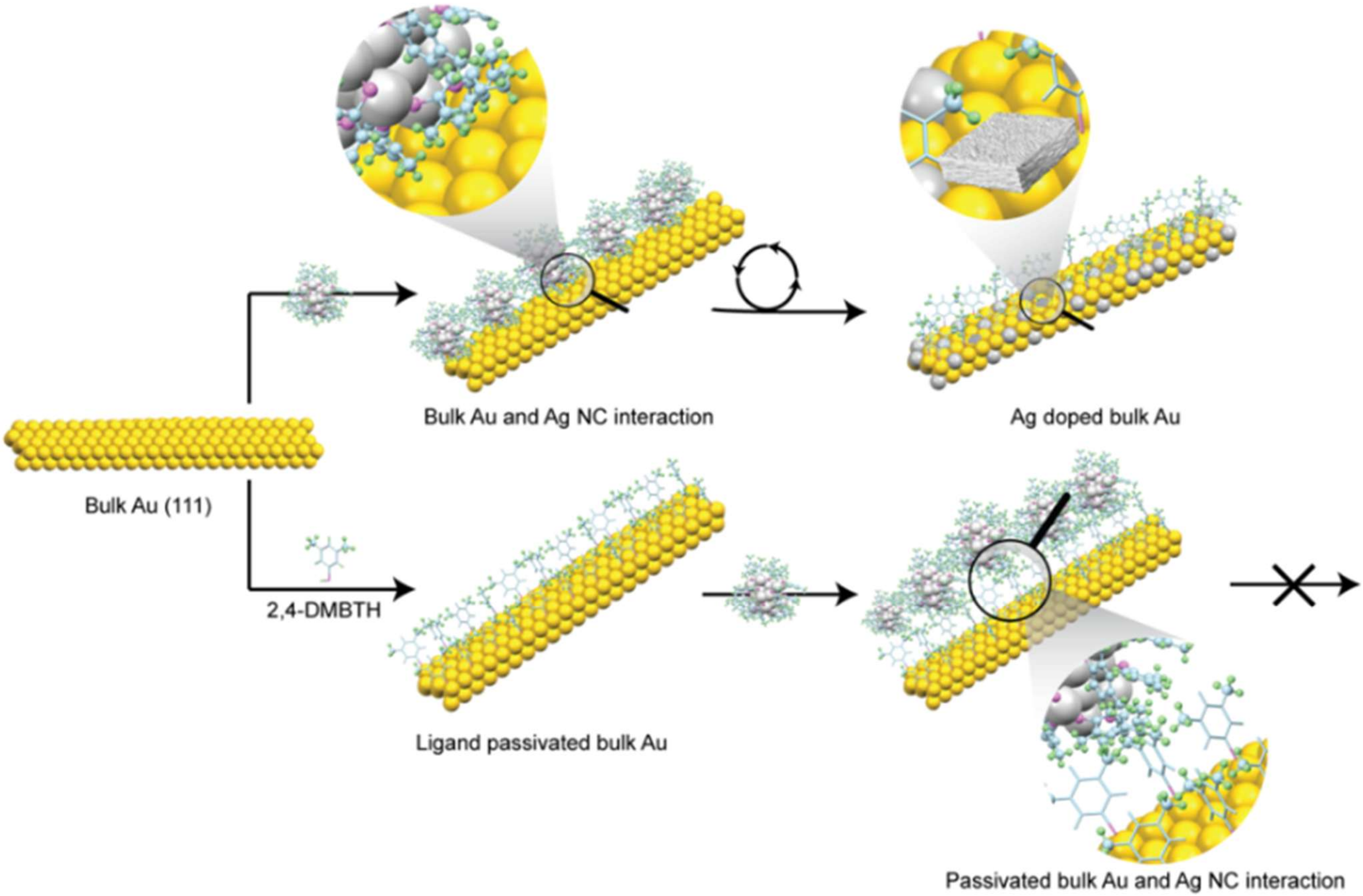
(A) Abundance of the parent isotope (%) in the NC as a function of reaction time (h) during the reaction with bare and monolayer-protected Ag foils. A schematic showing the reaction of the NCs with a foil is presented as an inset. (B) ESI MS of (a) $^{107}Ag_{25}(DMBT)_{18}^{-}$ and product taken after 48 h of the reaction of $^{107}Ag_{25}(DMBT)_{18}^{-}$ with (b) bare and (c) DMBT-protected Ag foils.

Isotopic exchange with Ag powder

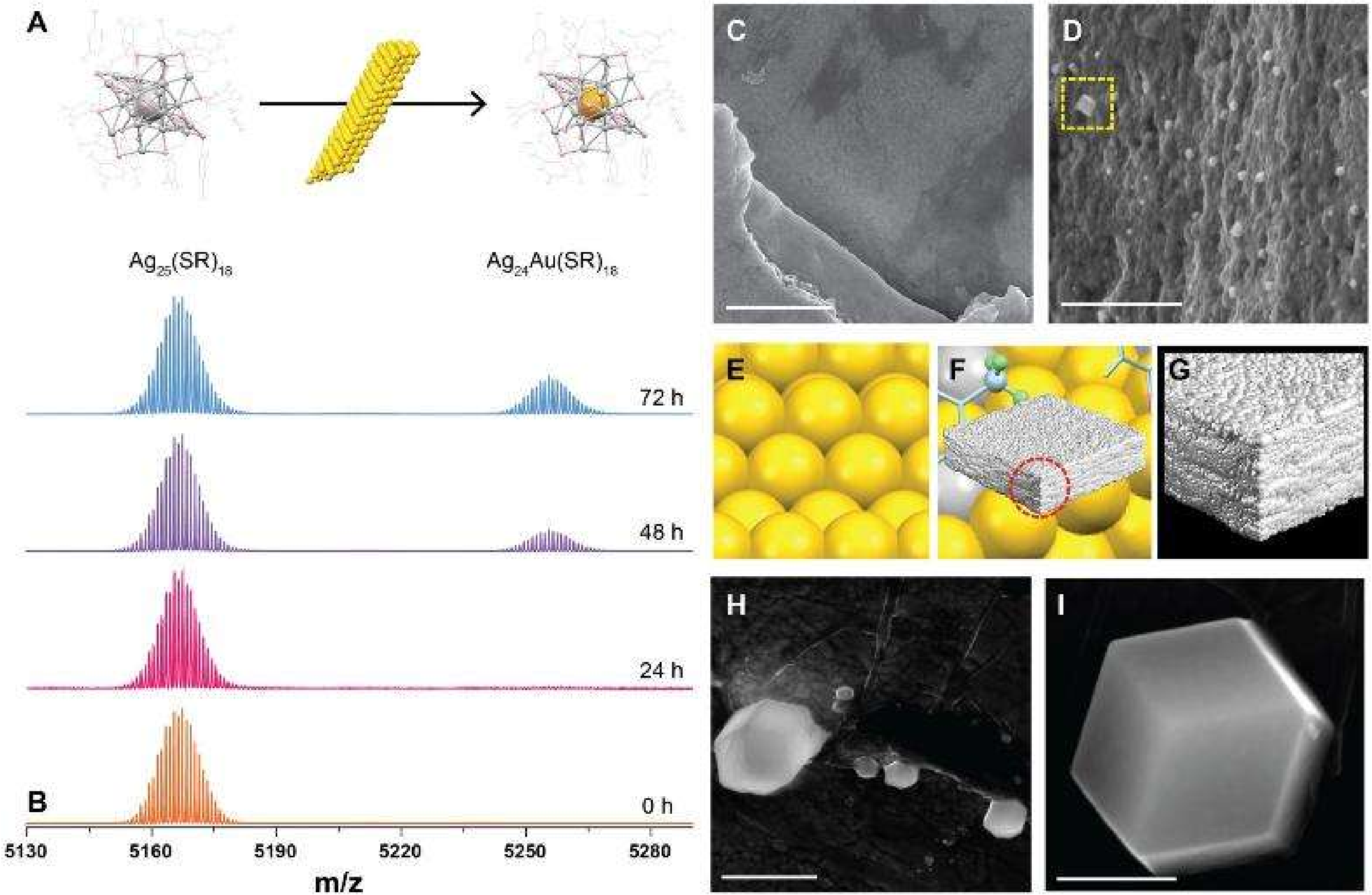


Abundance of parent isotope (%) of the isotopic NC as a function of time (min) during the reaction with various quantities of Ag powder, with a fixed quantity of the NC. A scheme of this reaction is presented as an inset.

Bulk Au— Ag NC reaction



Characterization of reaction products



Expanding chemistry

Supramolecular chemistry

Papri Chakraborty, et,. al. *ACS Nano* 2018

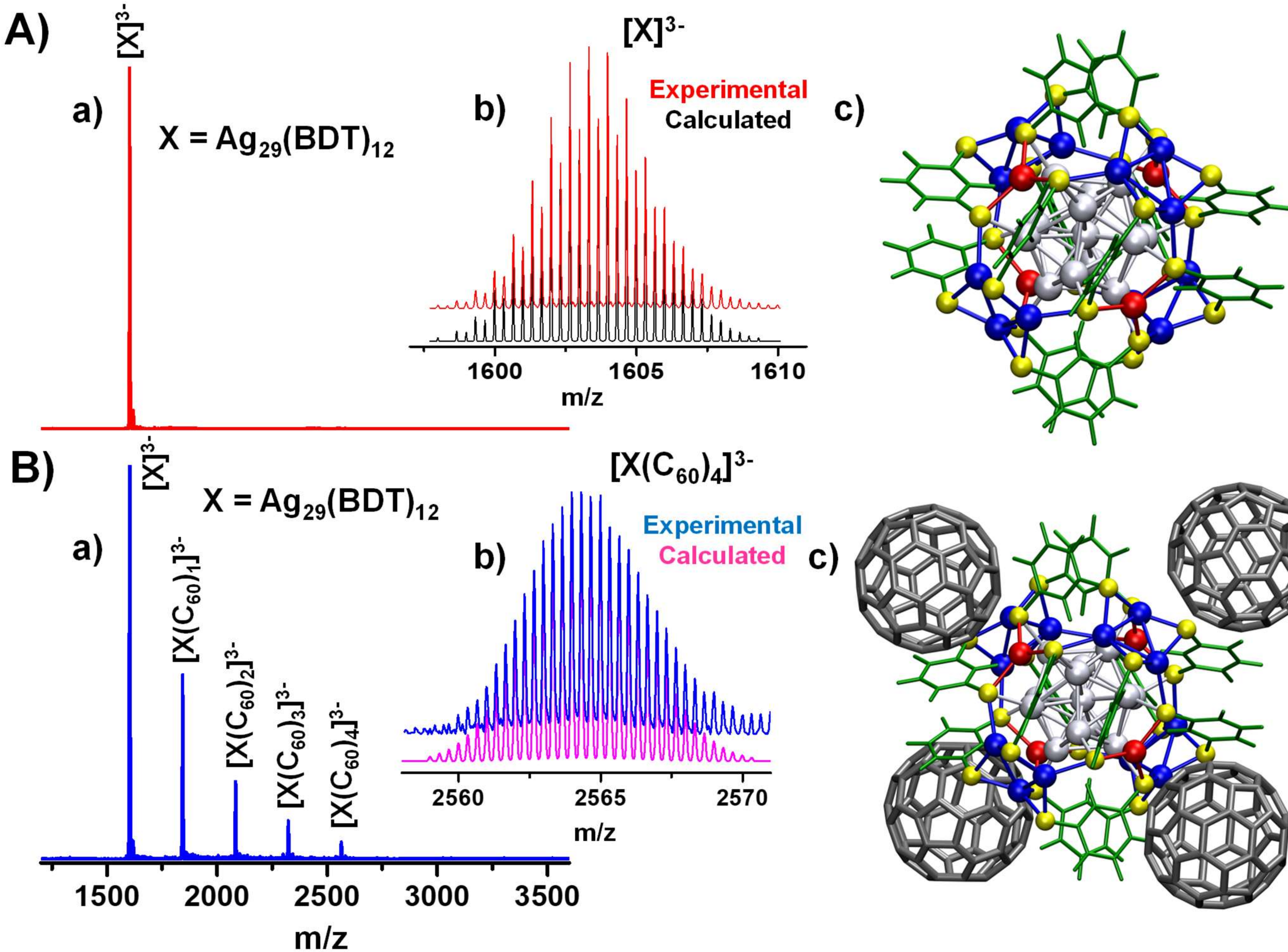
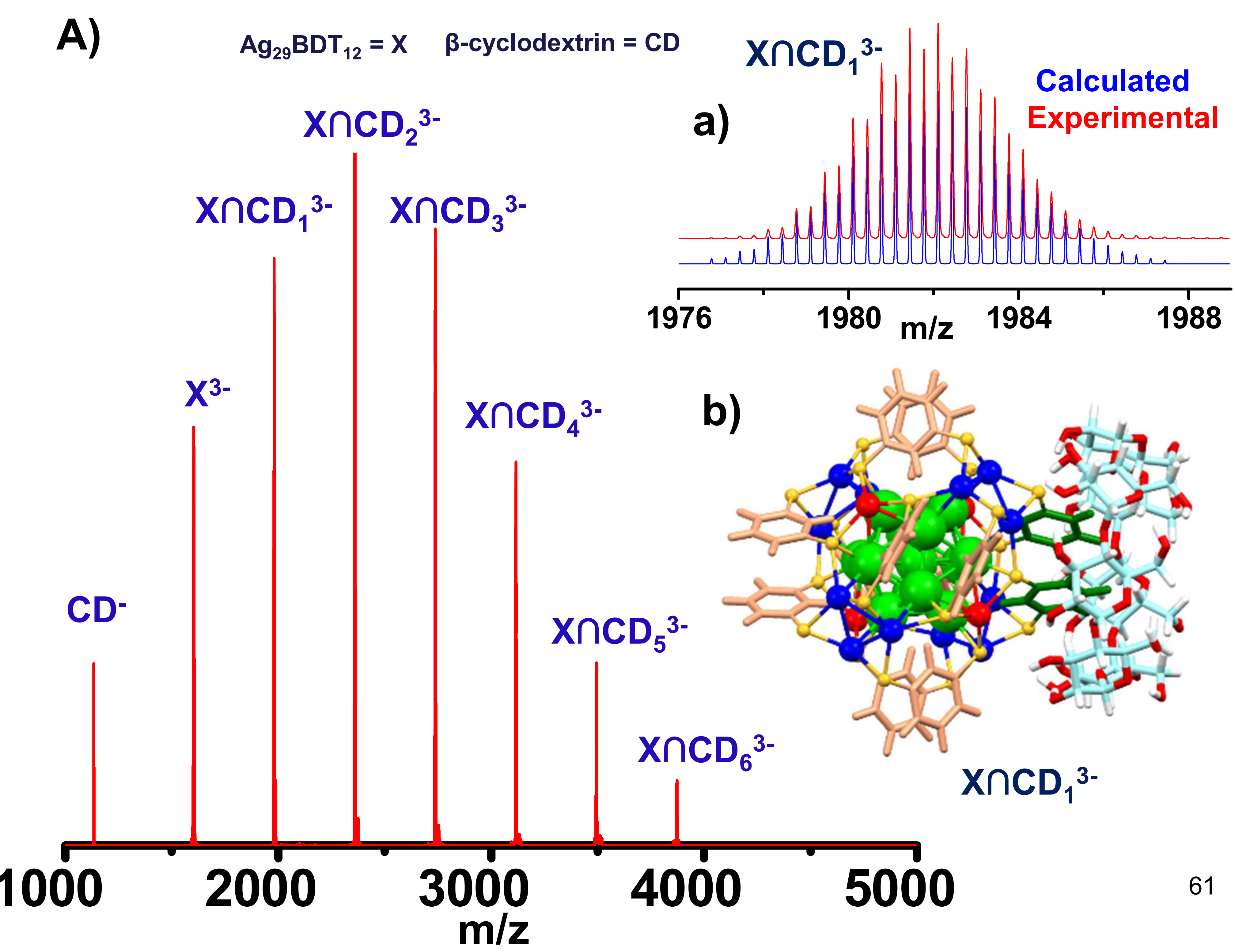


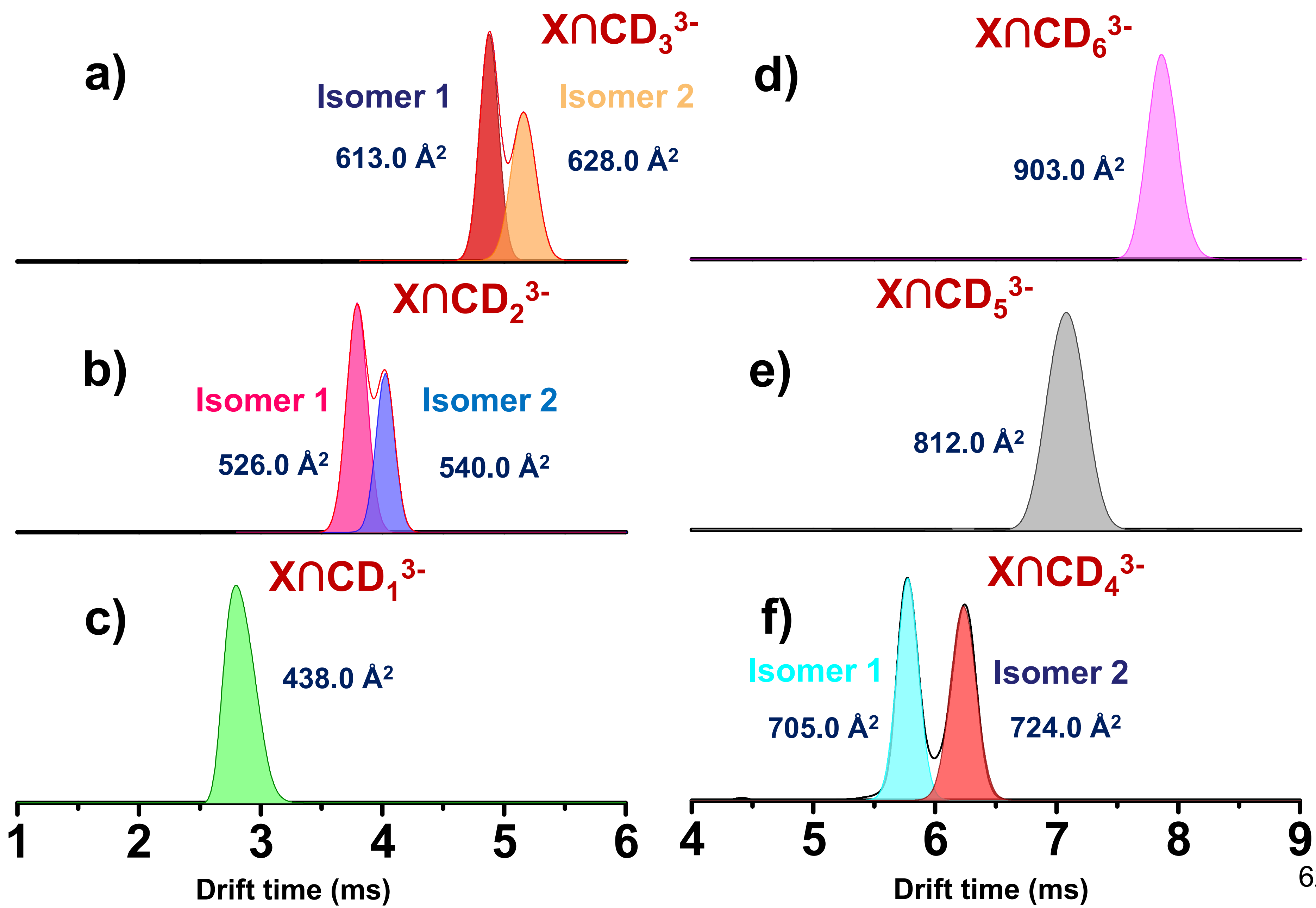
Figure 1. A) (a) Full range ESI MS, **(b)** experimental and calculated isotope patterns and **(c)** DFT optimized structure of $[Ag_{29}(BDT)_{12}]^{3-}$ cluster. **B) (a)** ESI MS of $[Ag_{29}(BDT)_{12}(C_{60})_n]^{3-}$ (n=1-4) complexes, **(b)** experimental and calculated isotope patterns of $[Ag_{29}(BDT)_{12}(C_{60})_4]^{3-}$ and **(c)** schematic of the possible structure of $[Ag_{29}(BDT)_{12}(C_{60})_4]^{3-}$.

Isomerism in supramolcular adducts

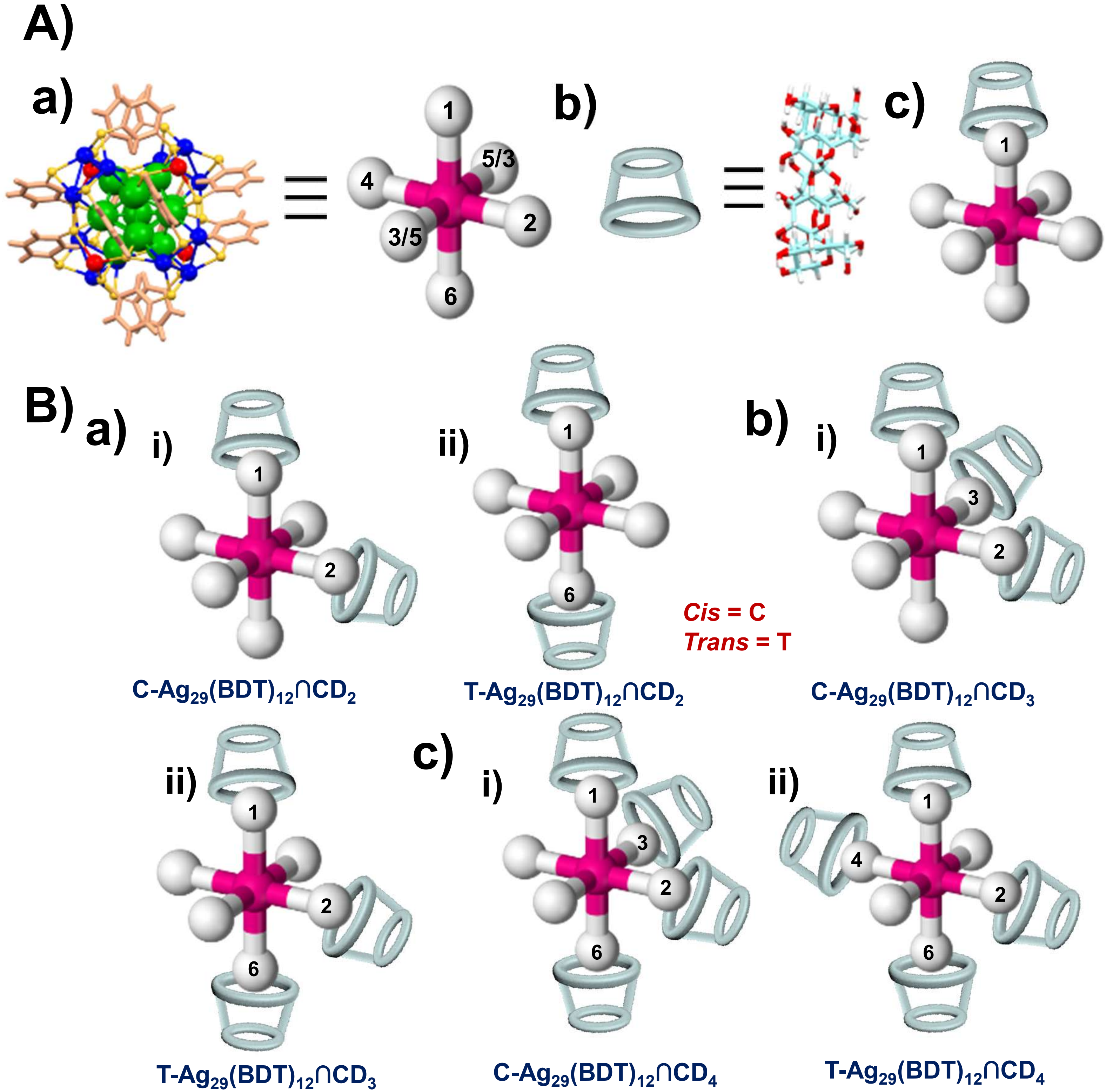
Abhijit Nag, et al. *JACS* 2018



A)
Ag29BDT12 = X β-cyclodextrin = CD
CD-
X3-
X∩CD1 3-
X∩CD2 3-
X∩CD3 3-
X∩CD4 3-
X∩CD5 3-
X∩CD6 3-
1000
2000
3000
4000
5000
m/z
a)
X∩CD1 3-
Calculated
Experimental
1976
1980
1984
1988
m/z
b)
X∩CD1 3-

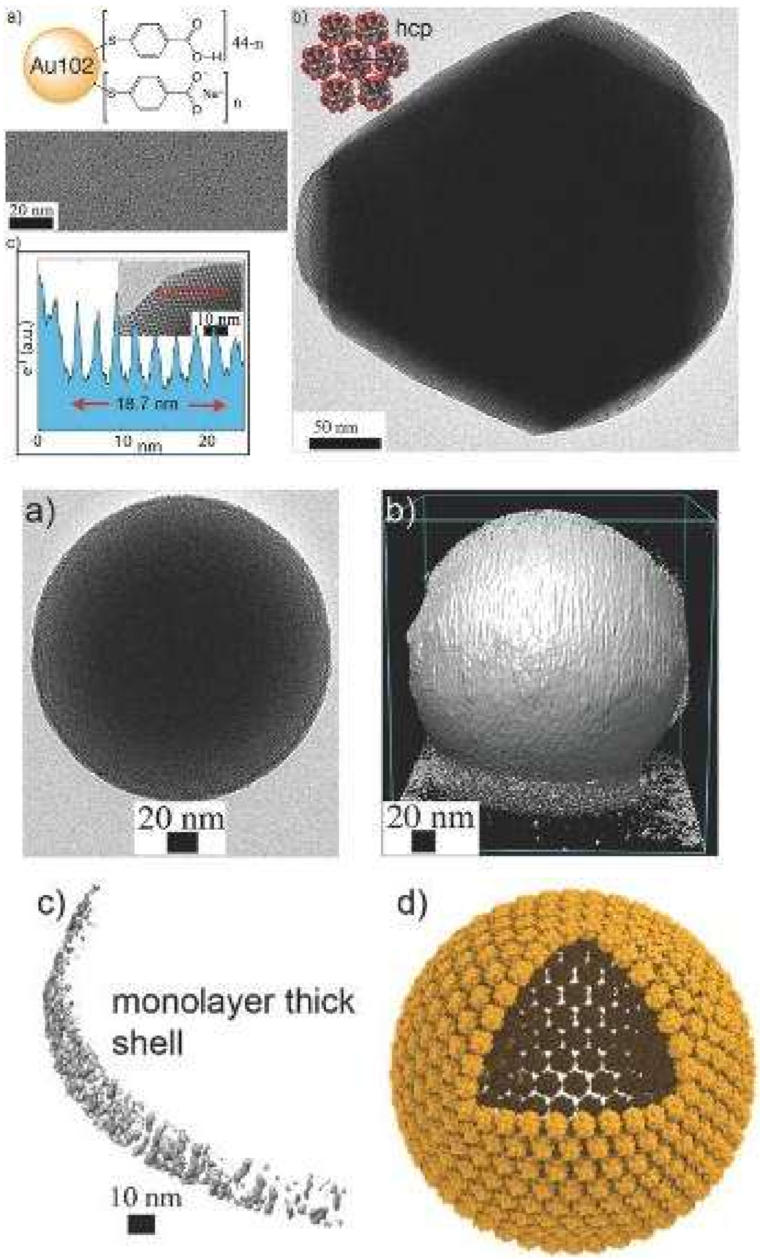


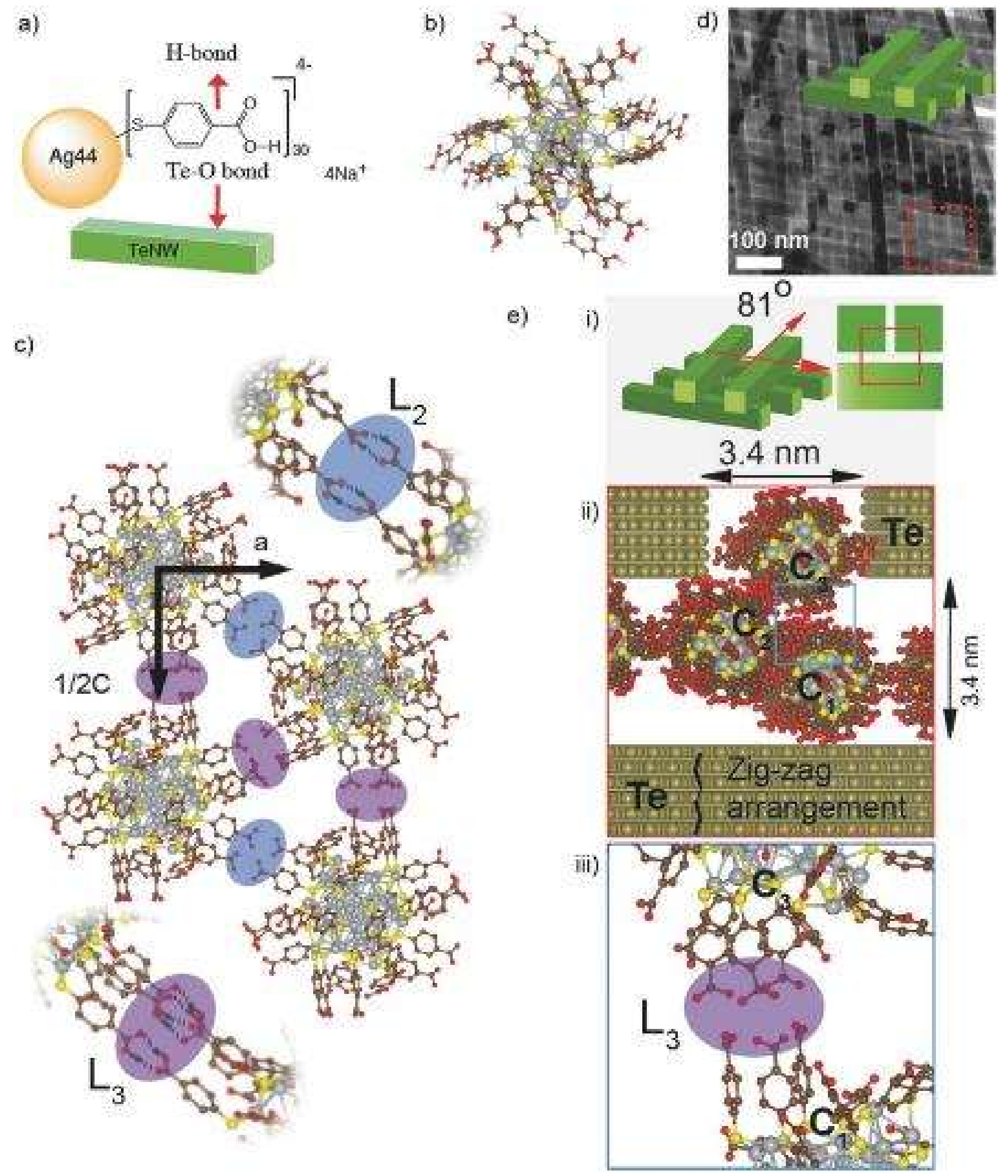
a)
X∩CD$_3^{3-}$
Isomer 1
613.0 Å^2
Isomer 2
628.0 Å^2
b)
X∩CD$_2^{3-}$
Isomer 1
526.0 Å^2
Isomer 2
540.0 Å^2
c)
X∩CD$_1^{3-}$
438.0 Å^2
1 2 3 4 5 6
Drift time (ms)
d)
X∩CD$_6^{3-}$
903.0 Å^2
e)
X∩CD$_5^{3-}$
812.0 Å^2
f)
X∩CD$_4^{3-}$
Isomer 1
705.0 Å^2
Isomer 2
724.0 Å^2
4 5 6 7 8 9
Drift time (ms)


A)
a)
1
5/3
4
2
3/5
6
b)
c)
1
B)
a)
i)
1
2
C-Ag29(BDT)12∩CD2
ii)
1
6
T-Ag29(BDT)12∩CD2
Cis = C
Trans = T
b)
i)
1
3
2
C-Ag29(BDT)12∩CD3
ii)
1
2
6
T-Ag29(BDT)12∩CD3
c)
i)
1
3
2
6
C-Ag29(BDT)12∩CD4
ii)
1
4
2
6
T-Ag29(BDT)12∩CD4

Assemblies and superstructures

Nanoclusters in colloidal assemblies

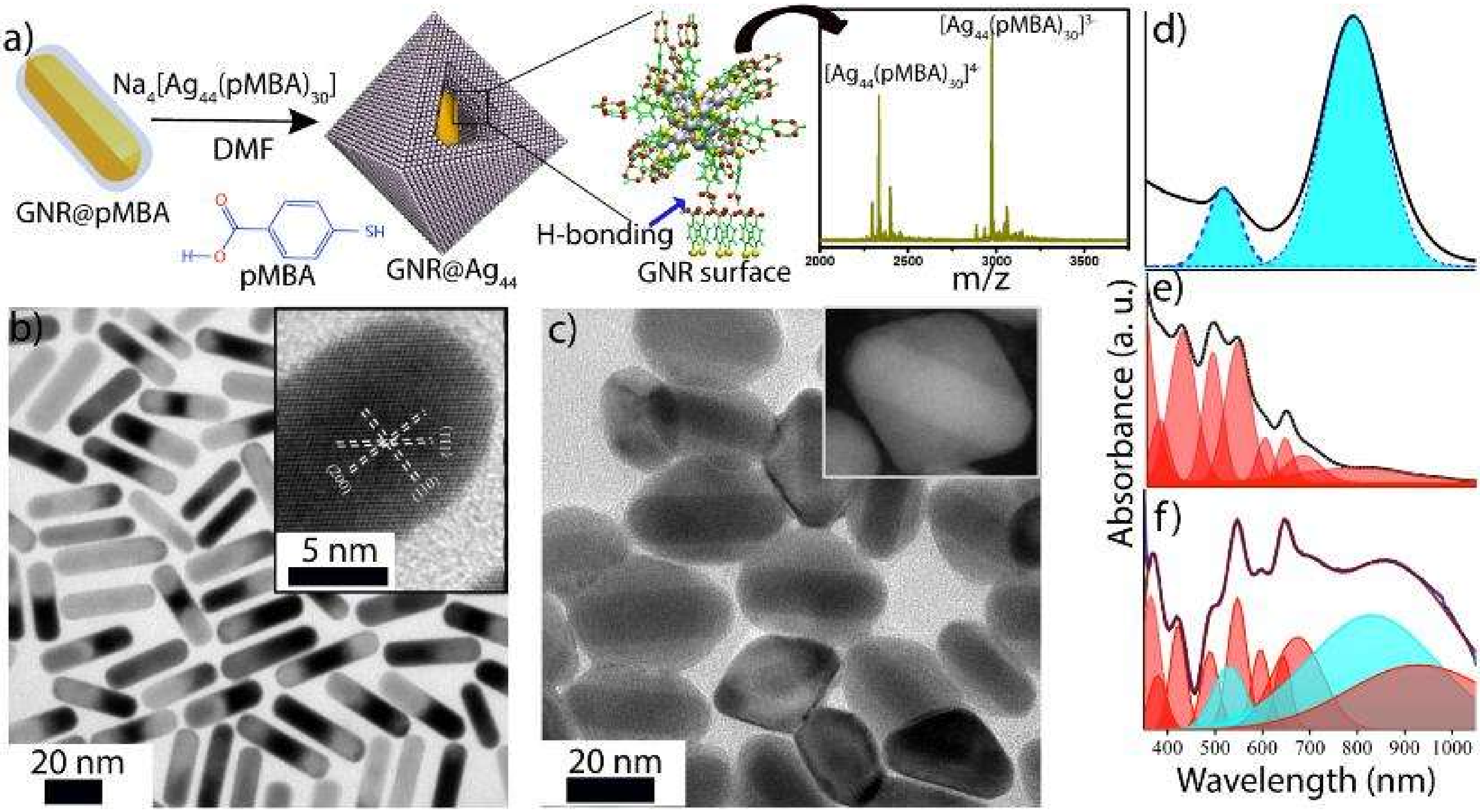




Som, A. et al., *Adv. Mater.* **2016**, *28*, 2827–2833

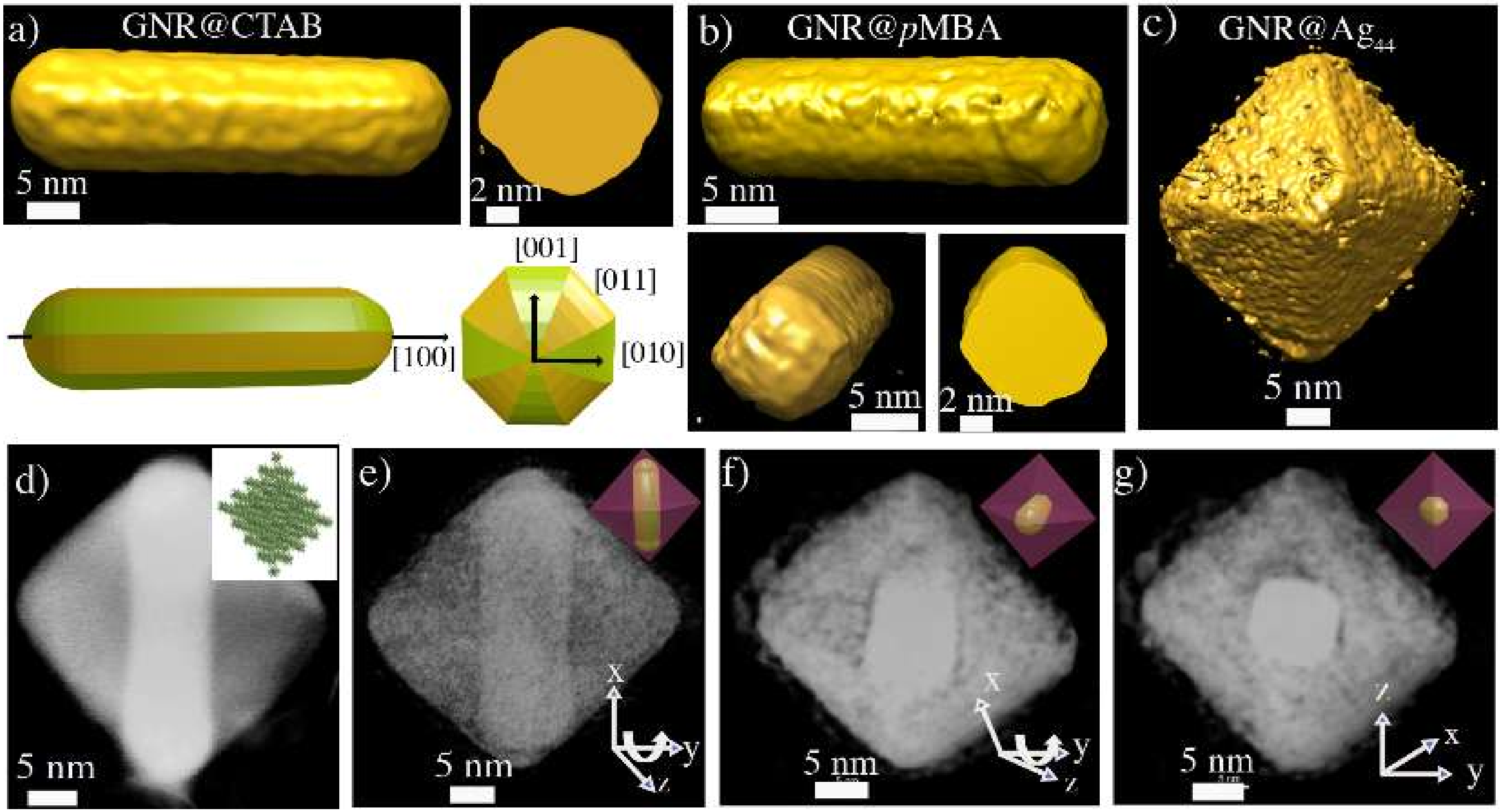
Nonappa et al., *Angew. Chem. Int. Ed.* **2016**, *55*, 16035–16038.

Atomically precise nanocluster assemblies encapsulating plasmonic gold nanorods

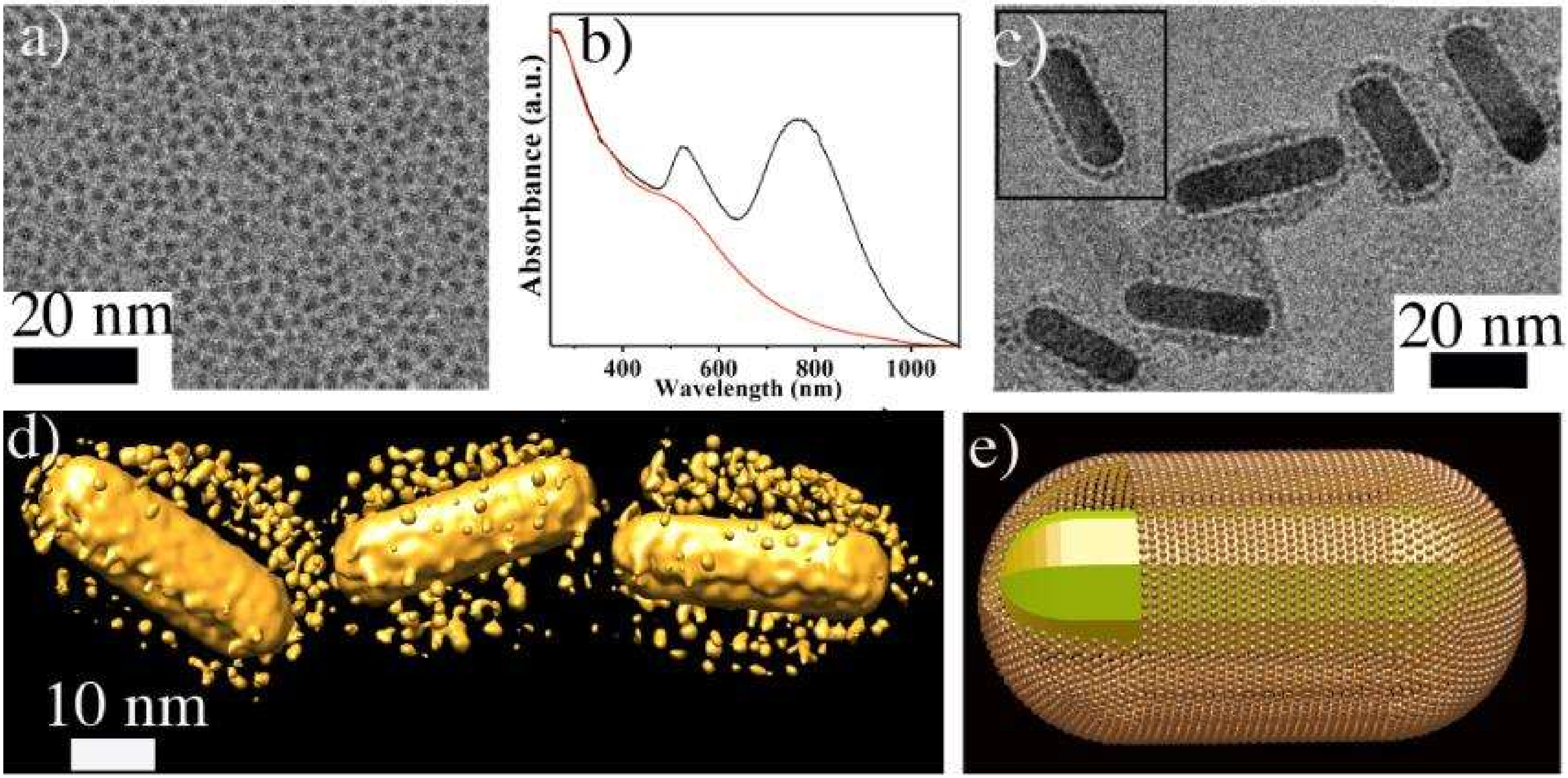


Chakraborty, A. et al., *Angew. Chem. Int. Ed.* **2018,** *57*, 6522–6526.

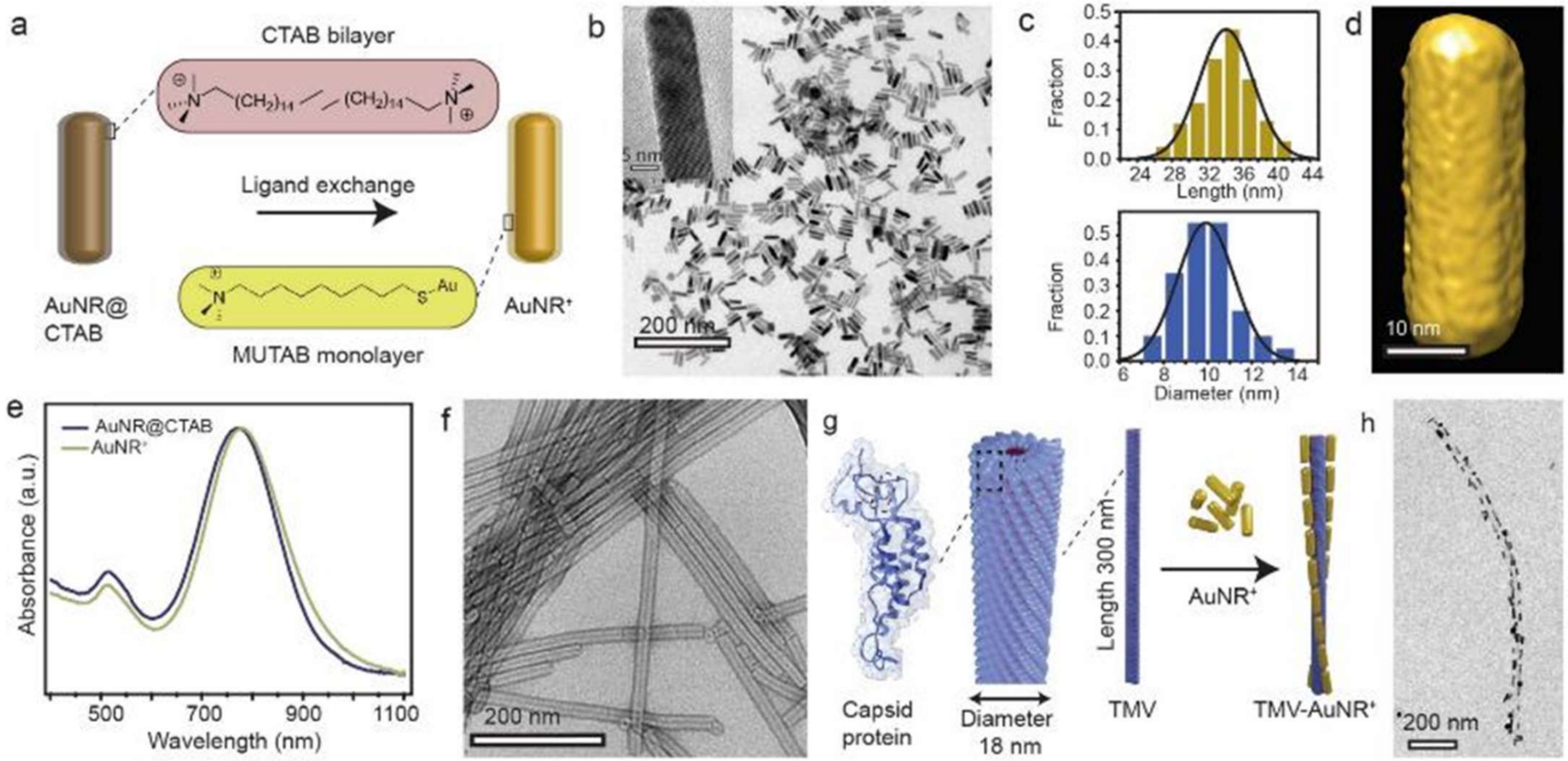
3D morphological analysis



Works for $Au_{250}(p\mathrm{MBA})_n$ and aqueous solvent



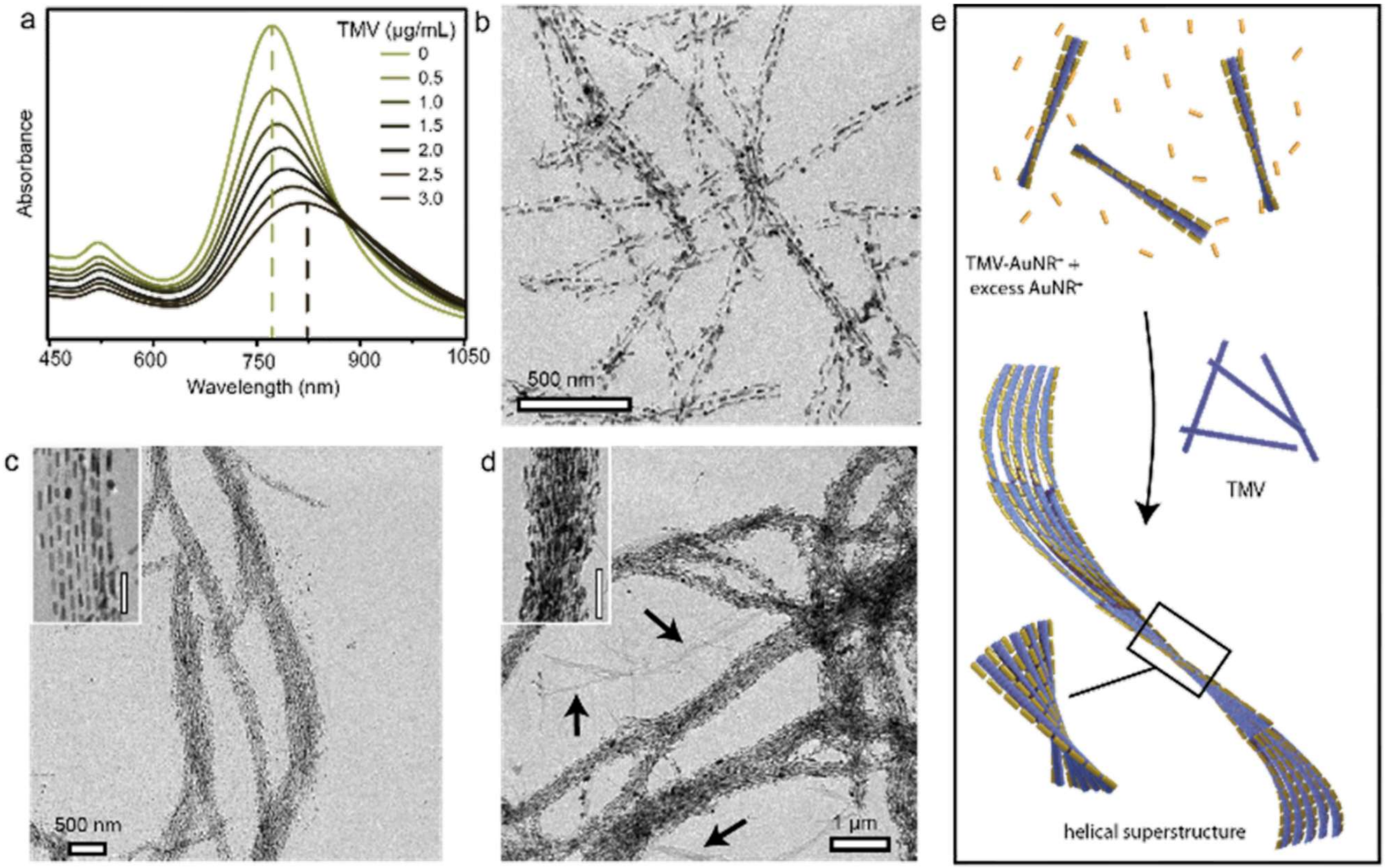
Near-infrared chiral plasmonic microwires through precision assembly of gold nanorods on soft biotemplates



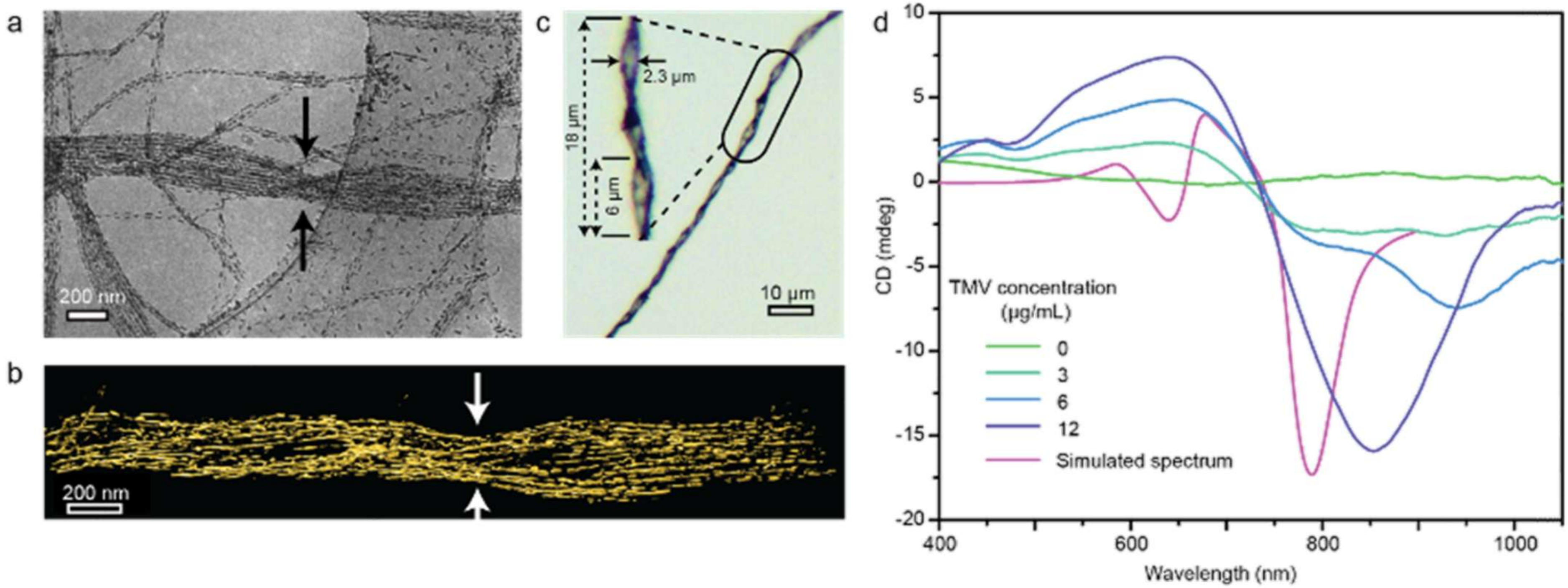
Chakraborty, A. et al., *J. Phys. Chem. C* **2021,** *125*, 3256−3267.

With Nonappa, Mauri A. Kostiainen and Robin H. A. Ras

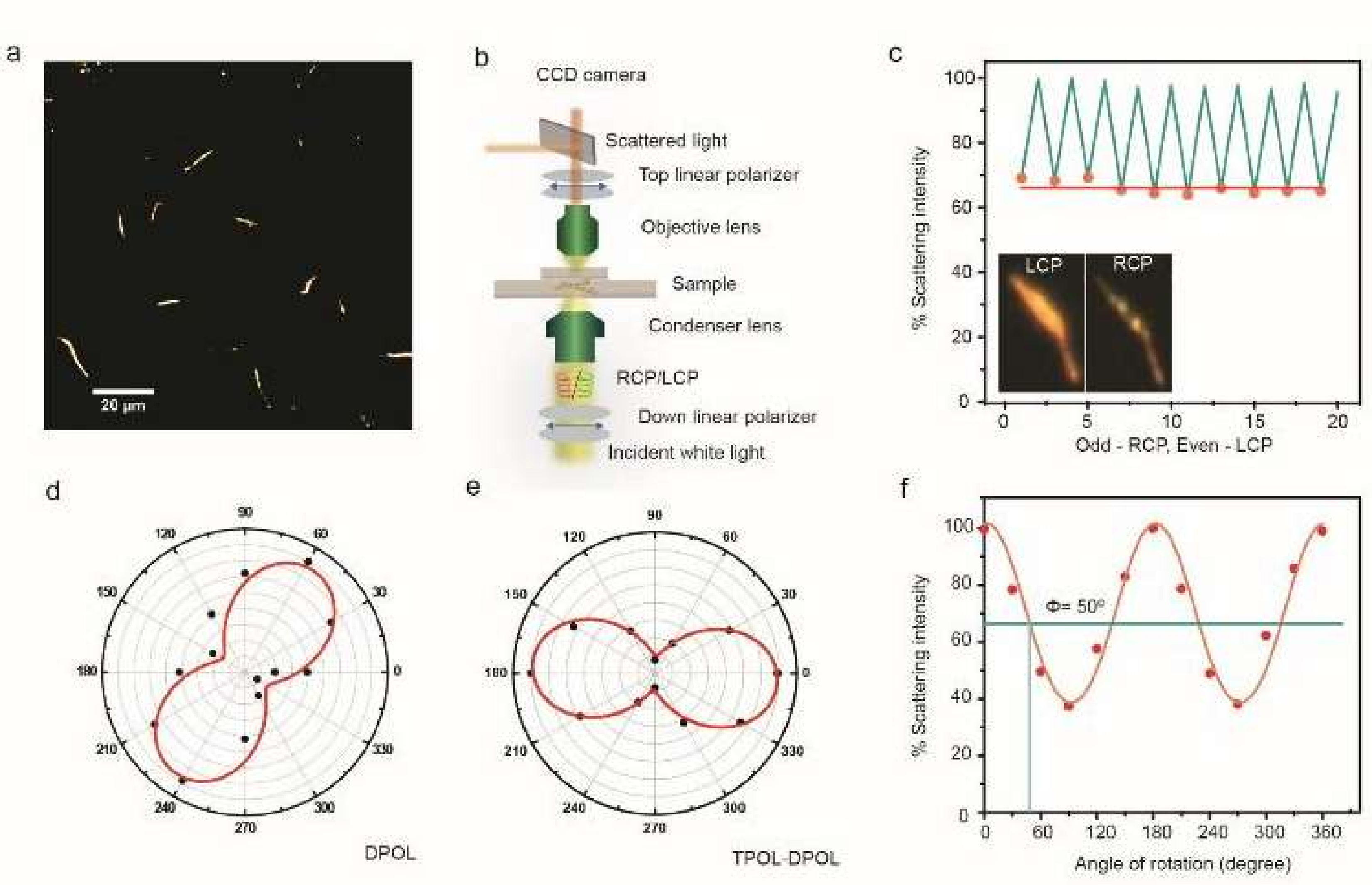
Long-range assembly



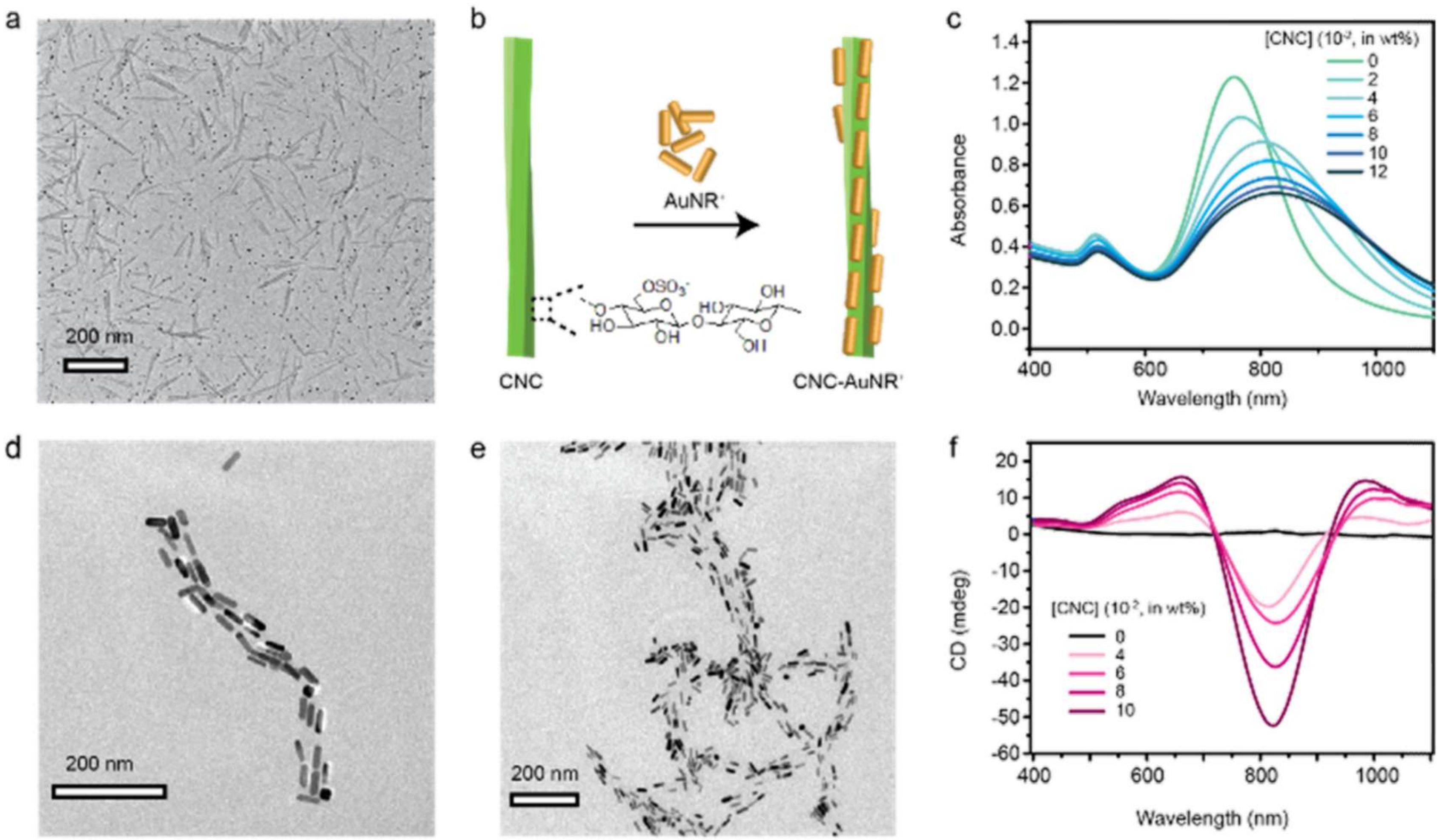
NIR chirality



Single particle chirality measurement



With cellulose nanocrystals



Outlook

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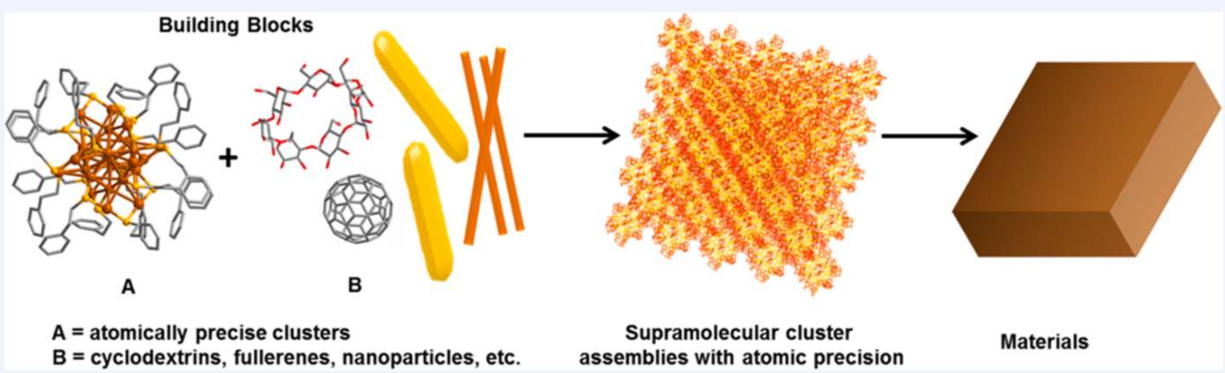
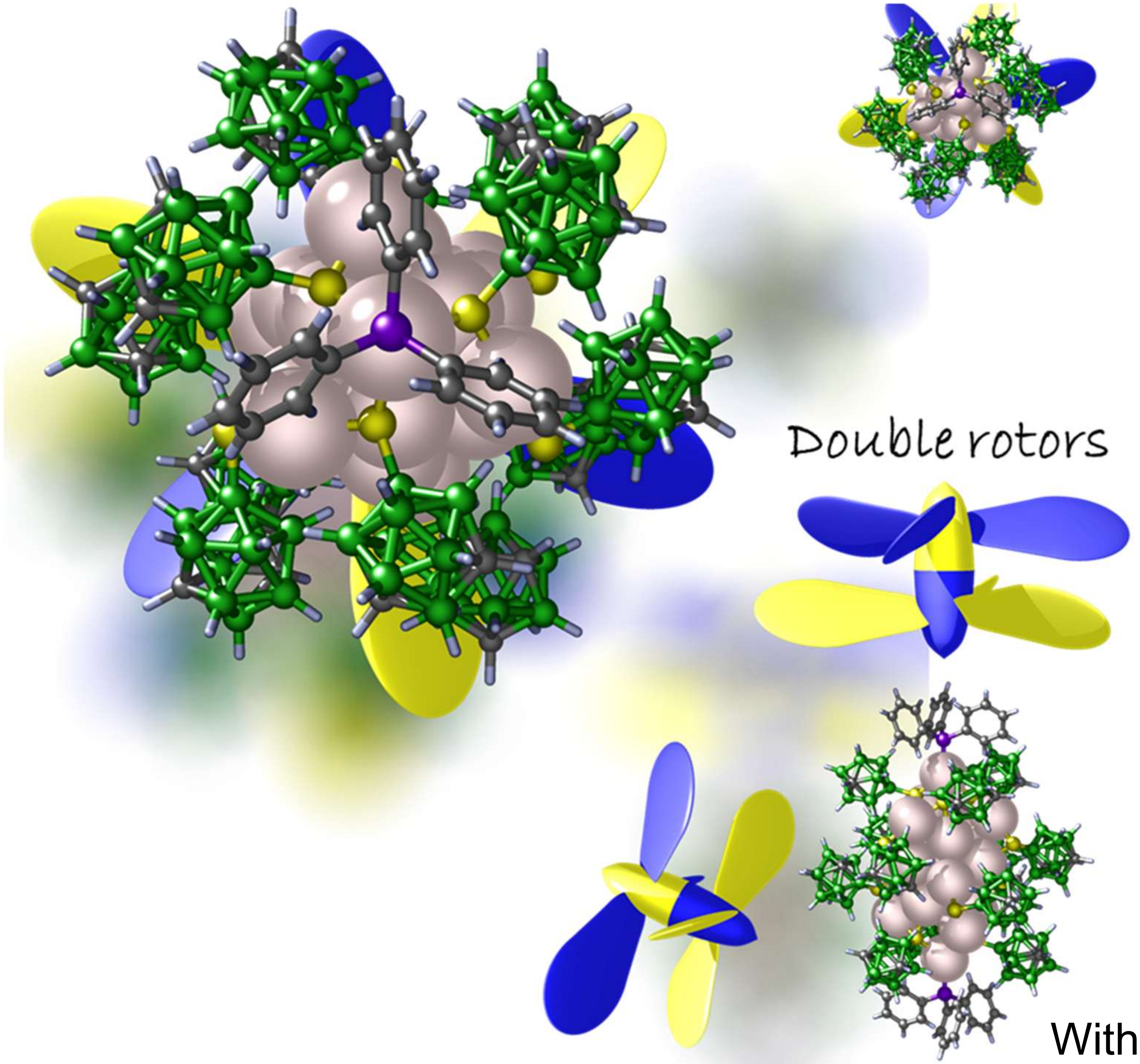
Approaching Materials with Atomic Precision Using Supramolecular Cluster Assemblies

Papri Chakraborty, Abhijit Nag, Amrita Chakraborty, and Thalappil Pradeep*

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



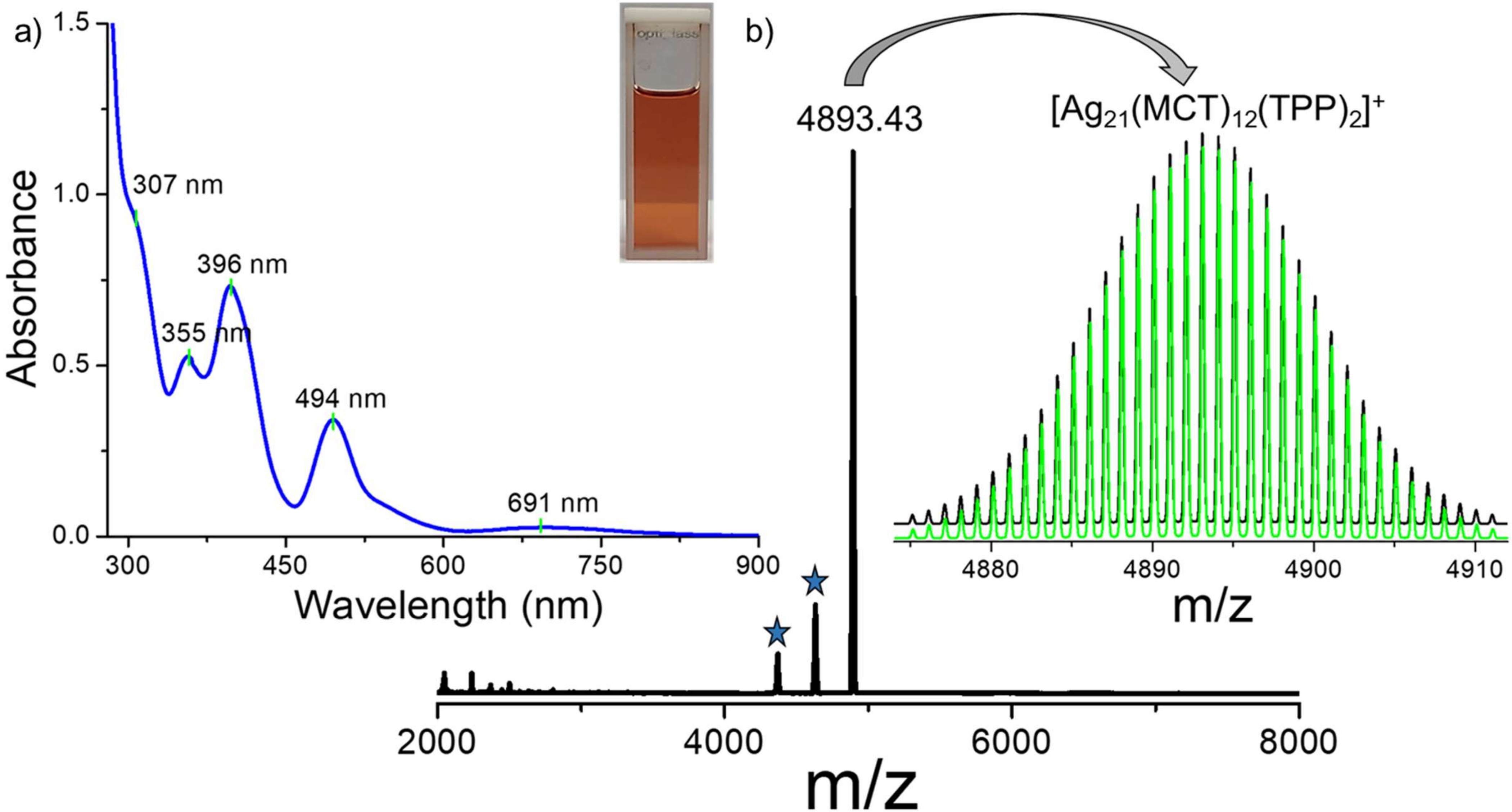
Carborane-thiol protected propeller-shaped photoresponsive silver nanomolecule



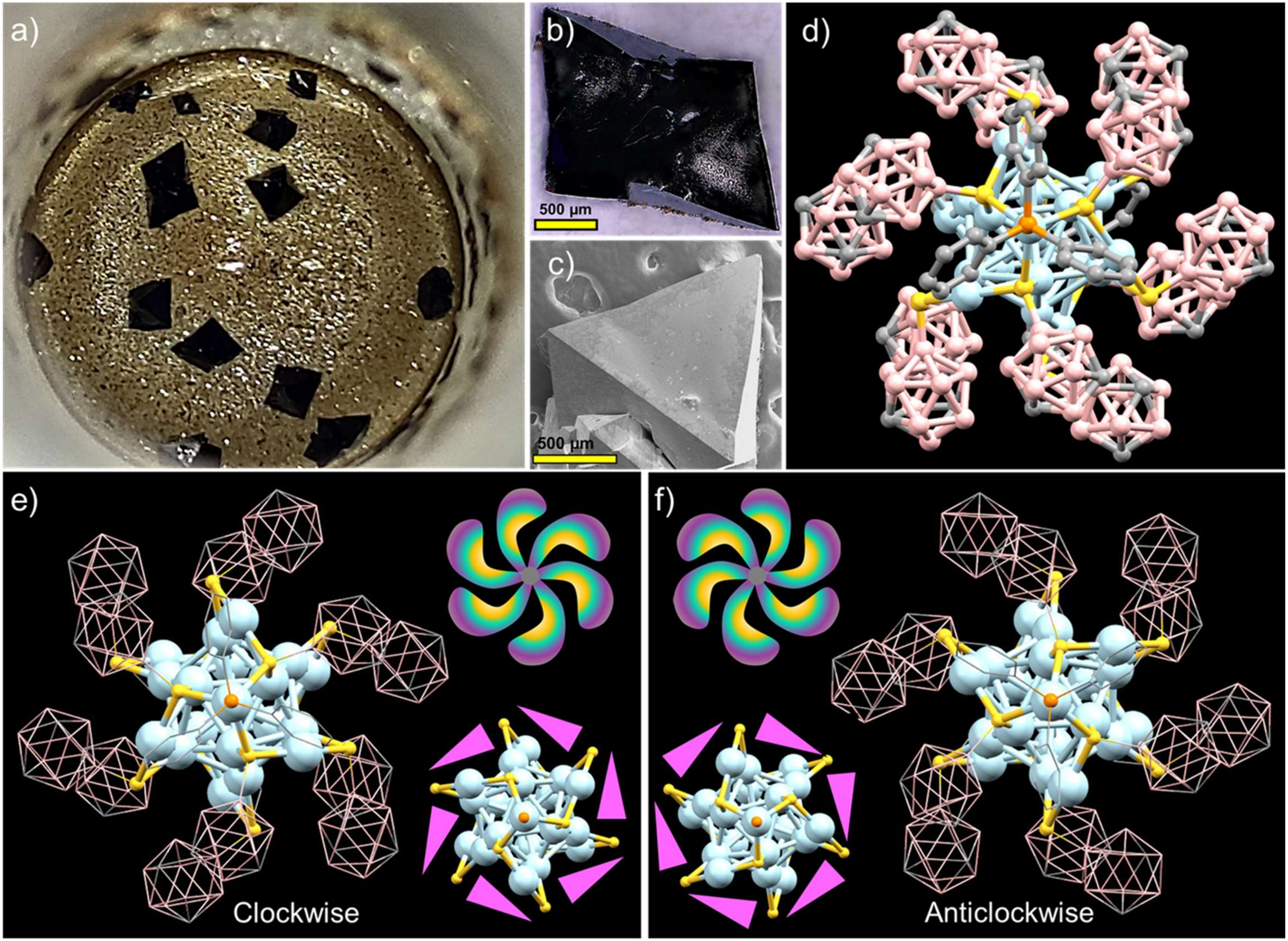
With Tomas Base

Jana *et. al*, Inorganic Chemistry (just accepted)

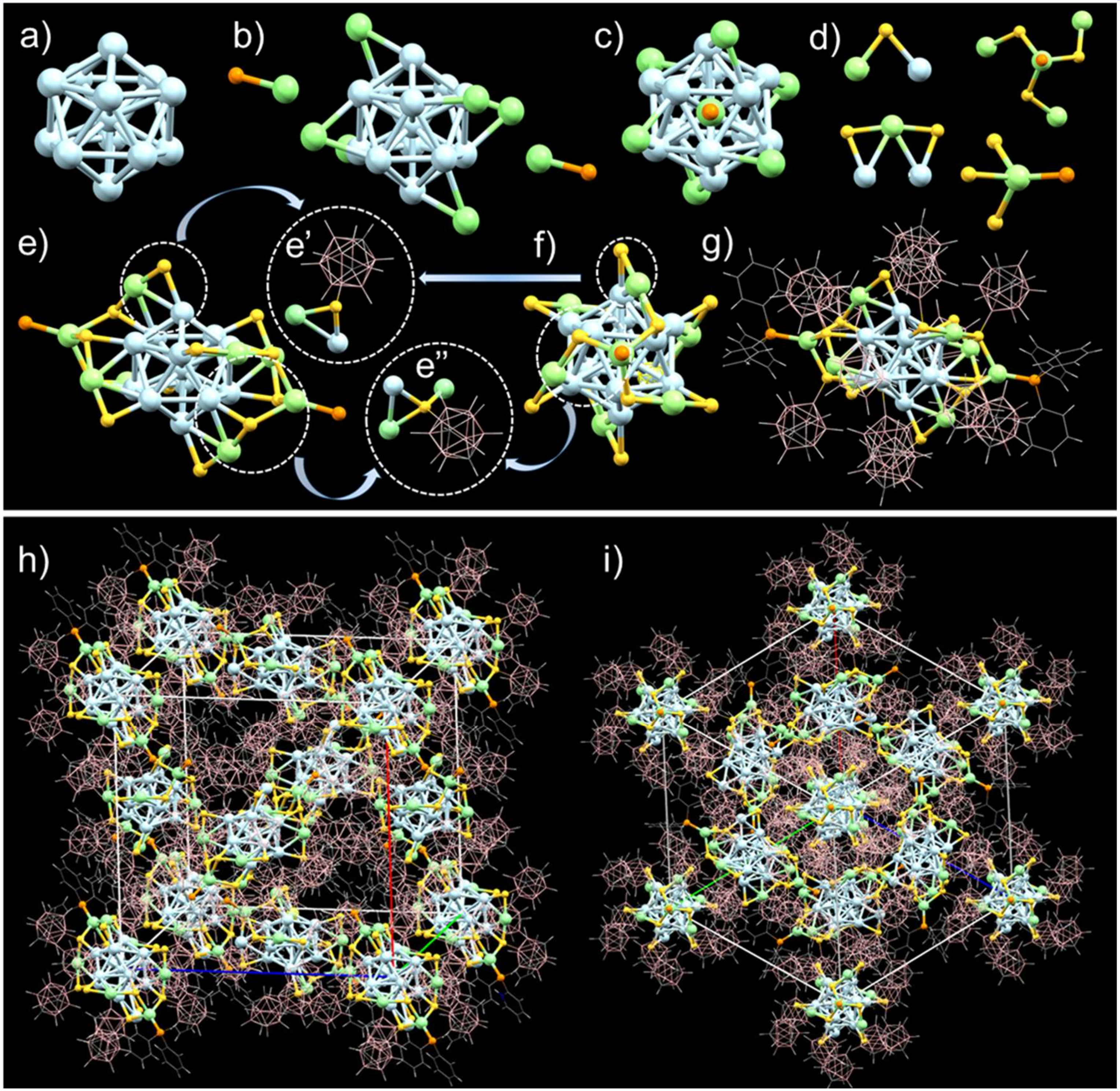
Characterization of Ag_{21}



Structural details of Ag_{21}



Structural details of Ag_{21}



Molecules and their properties

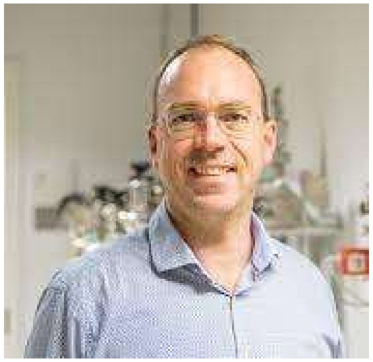
Chemical formula	H_2O
Molecular weight	18.0148
Critical temperature	373.91°C
Critical pressure	22.05 MPa
Critical density	315.0 kg/m^3
Triple point temperature	0.01°C
Triple point pressure	615.066 Pa
Normal boiling point	100.0°C
Normal freezing point	0.0°C
Density of ice at normal melting point	918.0 kg/m^3
Maximum density, 3.98°C	999.973 kg/m^3
Viscosity, 25°C	0.889 mN s/m^2
Surface tension, 25°C	72 mN/m
Heat Capacity, 25°C	4.1796 kJ/kg.K
Enthalpy of vaporisation, 100°C	2,257.7 kJ/kg
Enthalpy of fusion, 0°C	333.8 kJ/kg
Velocity of sound, 0°C	1.403 km/s
Dielectric constant, 25°C	78.40
Electrical conductivity, 25°C	8 μS/m
Refractive index, 25°C	1.333
Liquid compressibility, 10°C	$480. \times 10^{-12}$ m^2/N
Coefficient of thermal expansion, 25°C	256.32×10^{-6} K^{-1}
Thermal Conductivity, 25°C	0.608 W/m.K

Molecular formula
Molecular weight
Molecular structure
Molecular absorption and emission
Molecular reactions
Molecular assembly
Molecular co-crystals

Phases - phase transitions
Physical properties
Electrical, magnetic
Mechanical properties
Electrochemical properties

Future?

Collaborators



Robin Ras

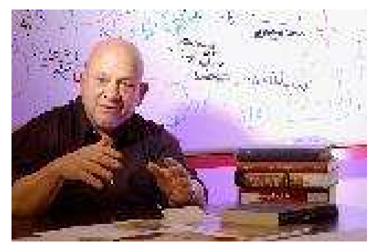
Nonappa

Mauri Kostiainen

Manfred Kappes

Olli Ikkala

Horst Hahn



Tatsuya Tsukuda, Keisaku Kimura, Yuichi Negishi, Uzi Landman, Hannu Hakkinen, Rob Whetten, Tomas Base

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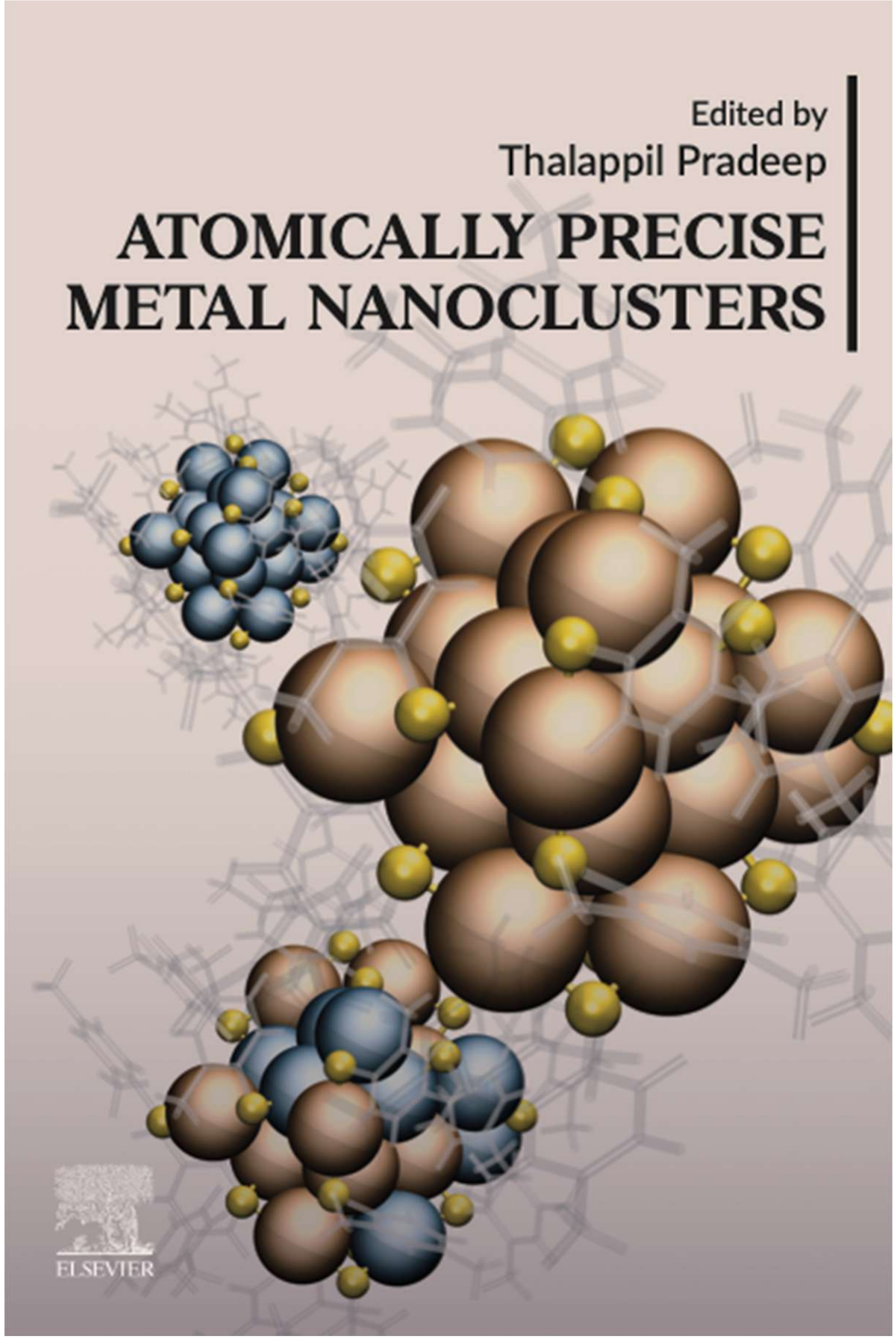
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Thank you all