Luminescent gold molecules

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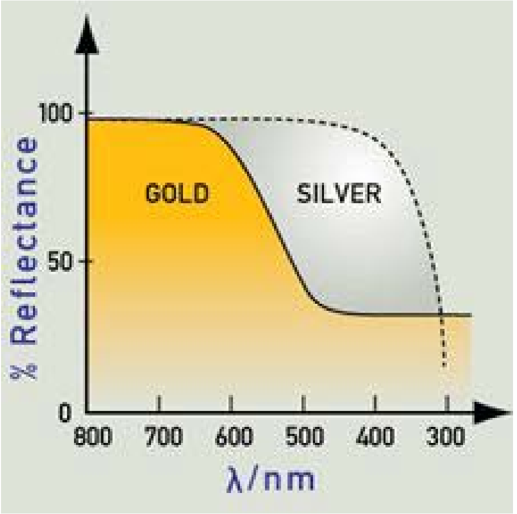
Au_{25}, Au_{23}, Au_{22}, Au_8 and Ag_8

IIT Delhi February 9, 2010



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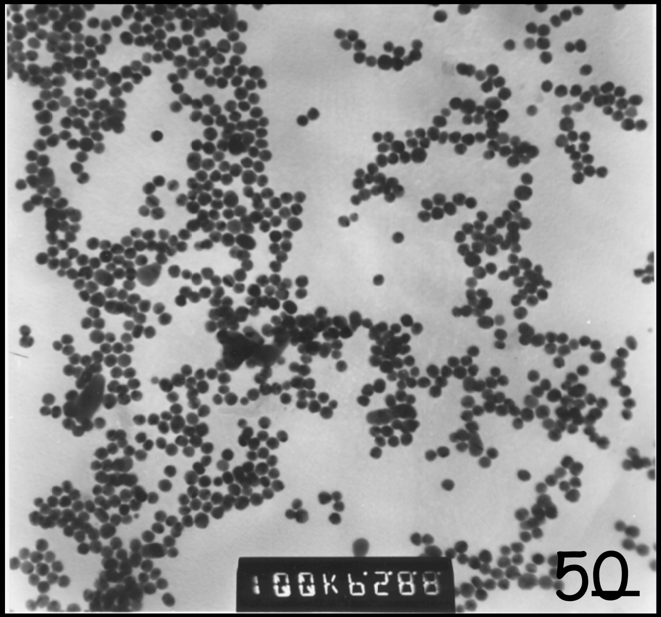
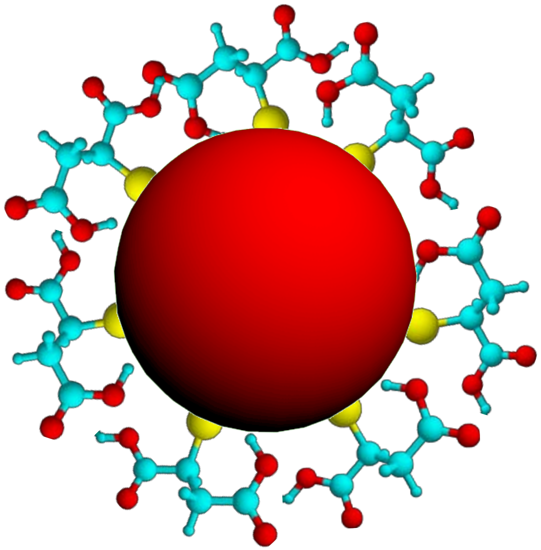
Nano Mission, Department of Science and Technology



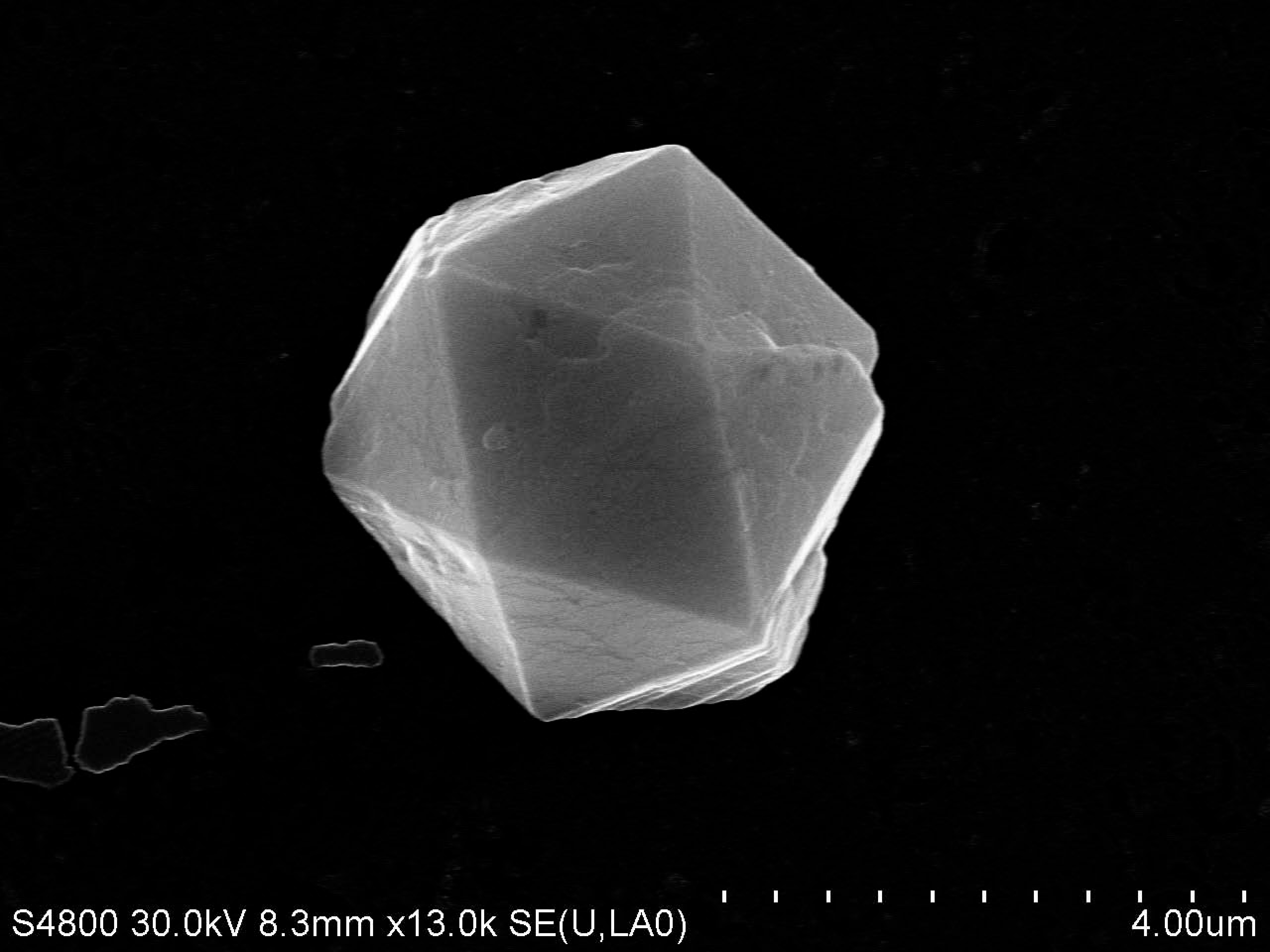
Faraday’s gold preserved in Royal Institution. From the site,
http://www.rigb.org/rimain/heritage/faradaypage.jsp

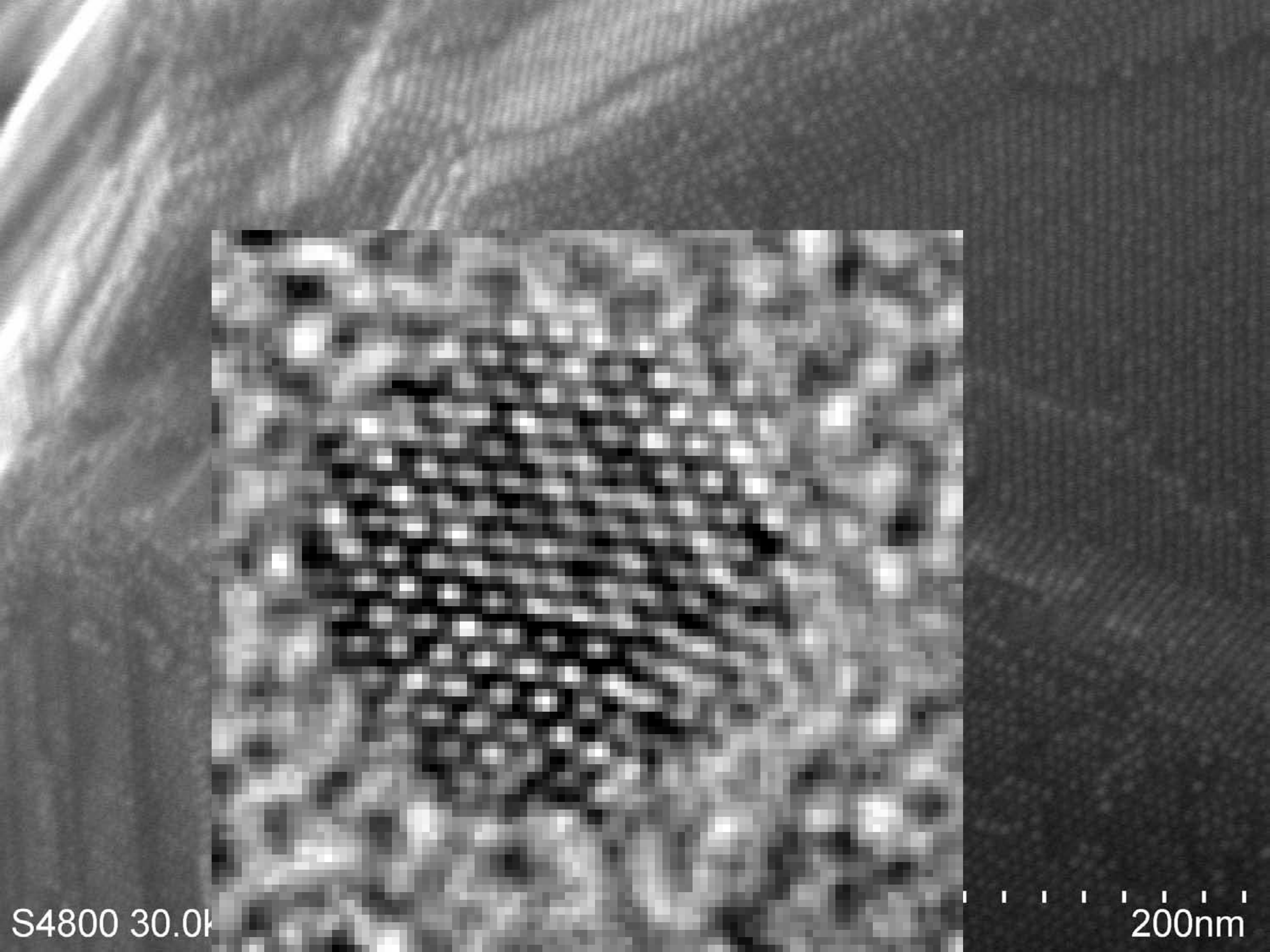
Monolayer Protected Metal Nanoparticles

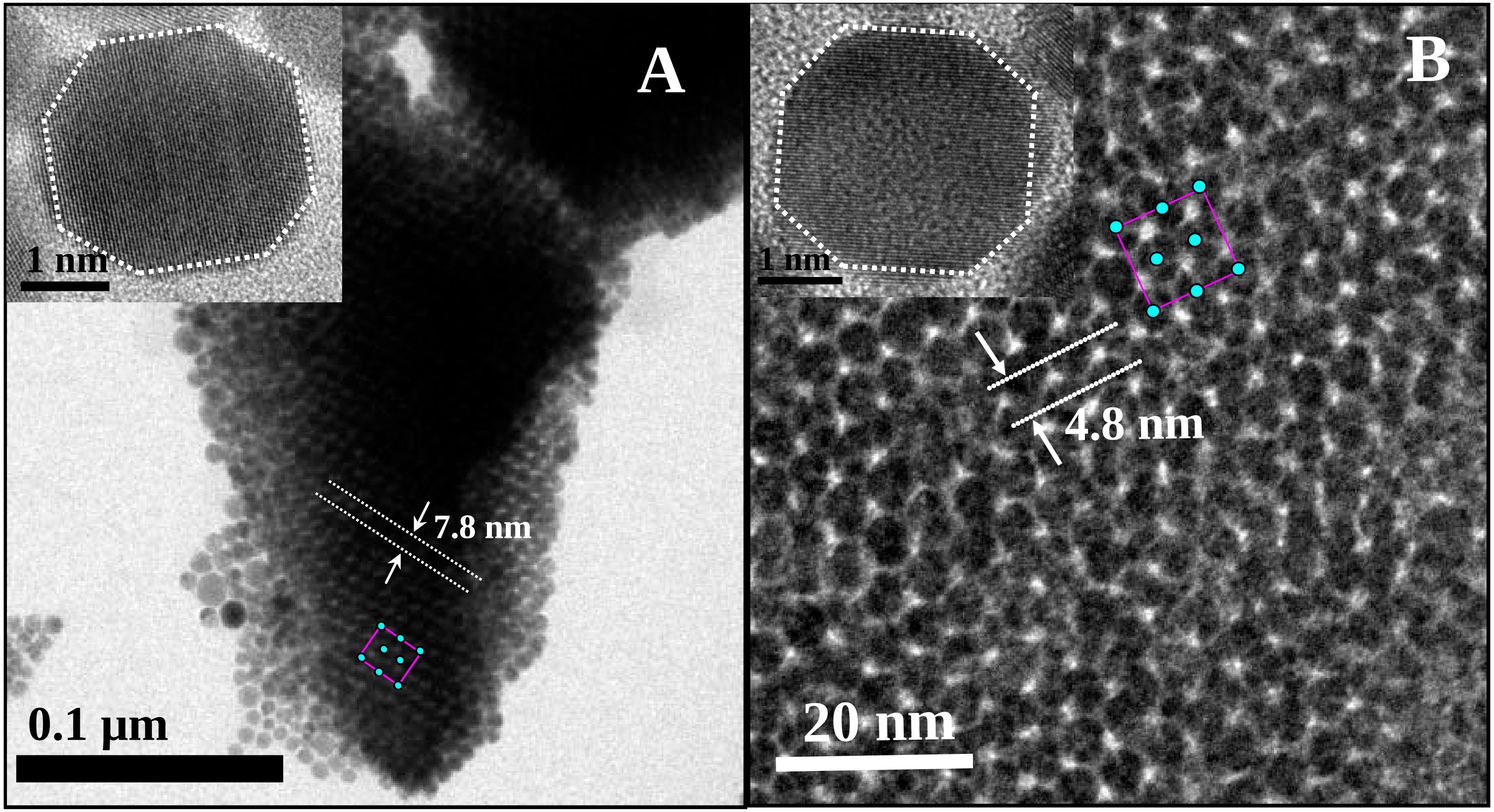
Monolayer Protected Clusters (MPCs)



Synthesis of thiol-derivatised gold nanoparticles in a two-phase Liquid–Liquid system, Brust, M.; Walker, M.; Bethell, D.; Schiffrin, D. J.; Whyman, R. *Chem. Commun.* **1994**, 801.

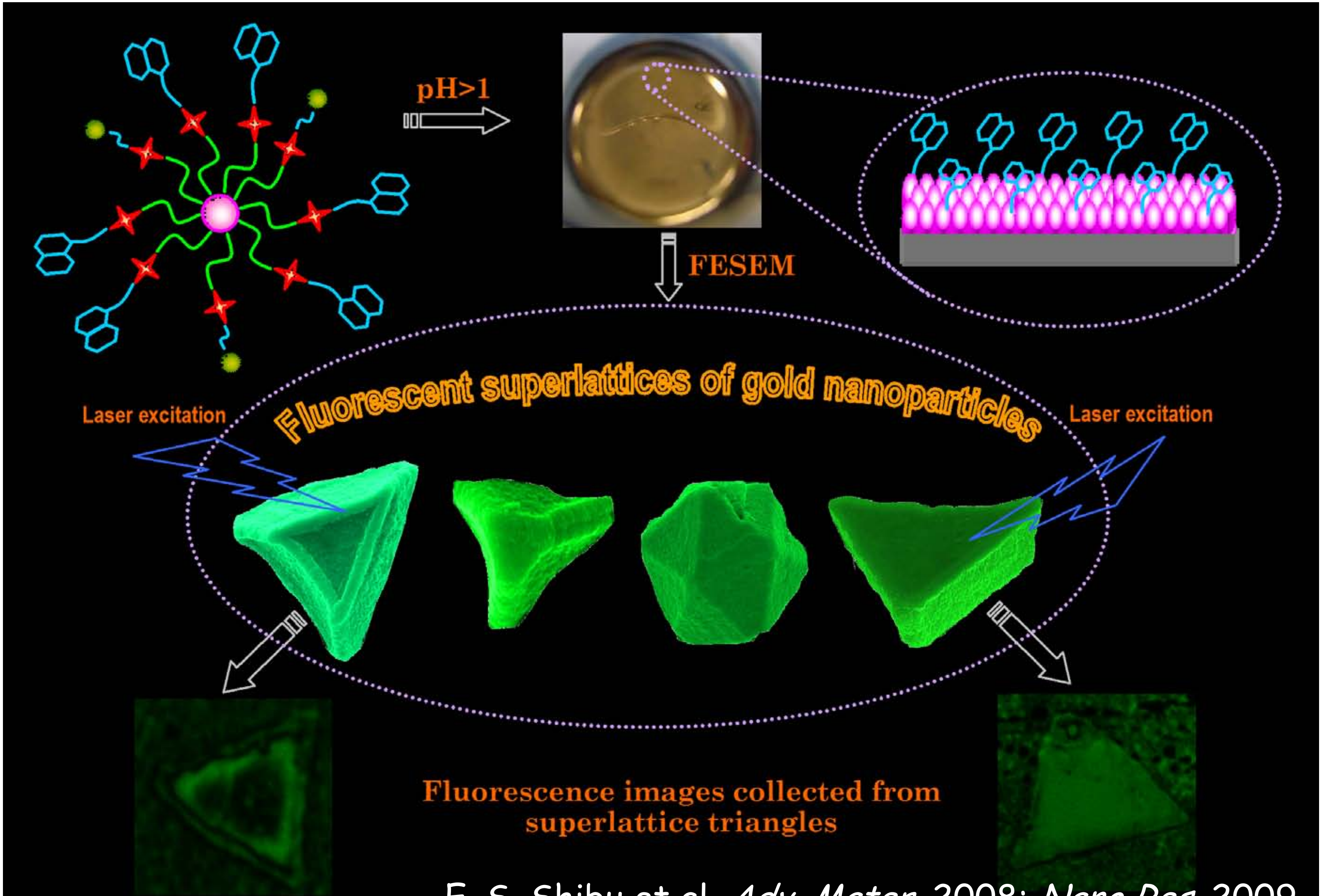

S4800 30.0kV 8.3mm x13.0k SE(U,LA0)
4.00um


S4800 30.0k
200nm



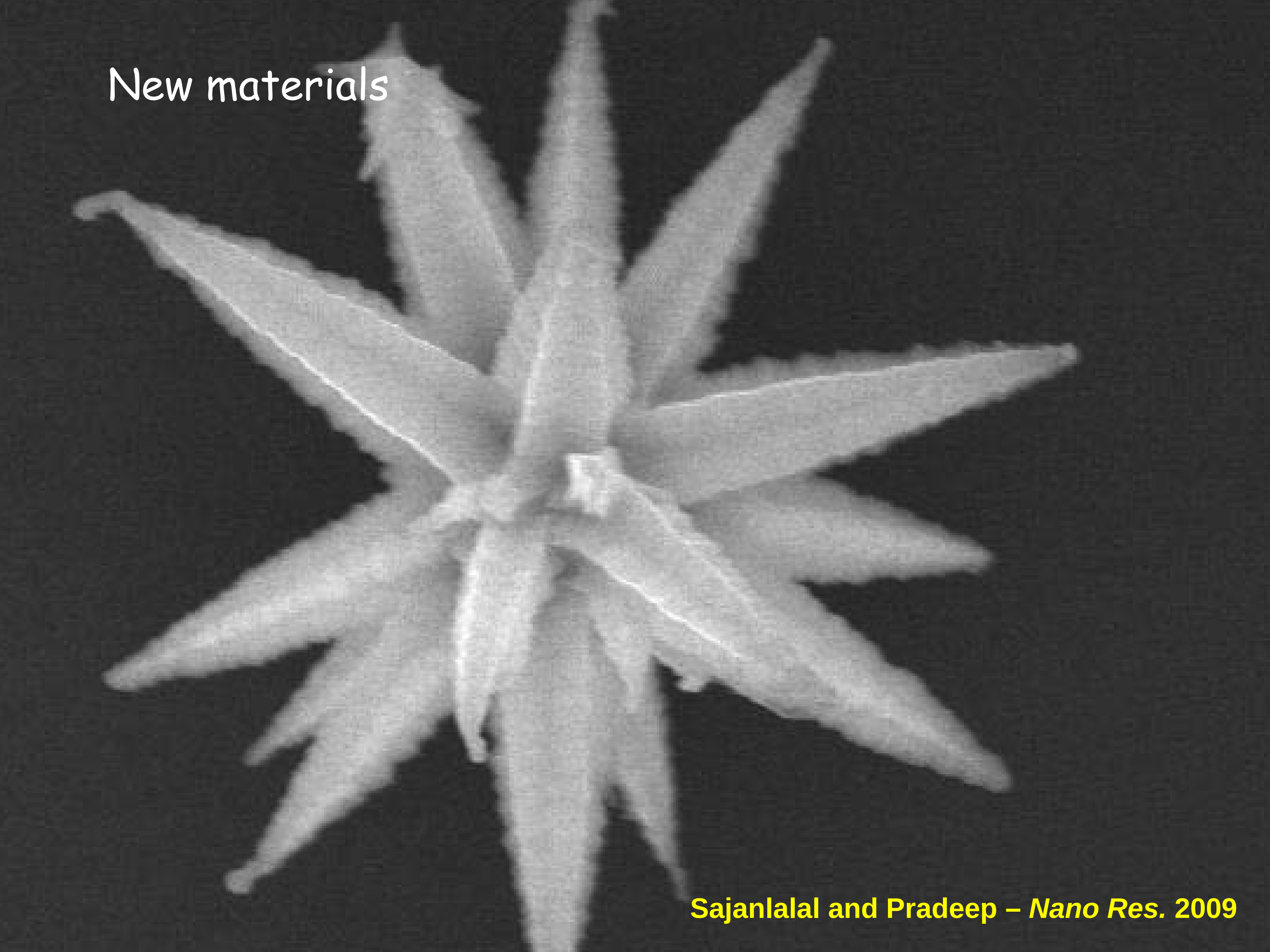
E. S. Shibu, e .al. *Chem. Mater.* 2009

Fluorescent superlattices

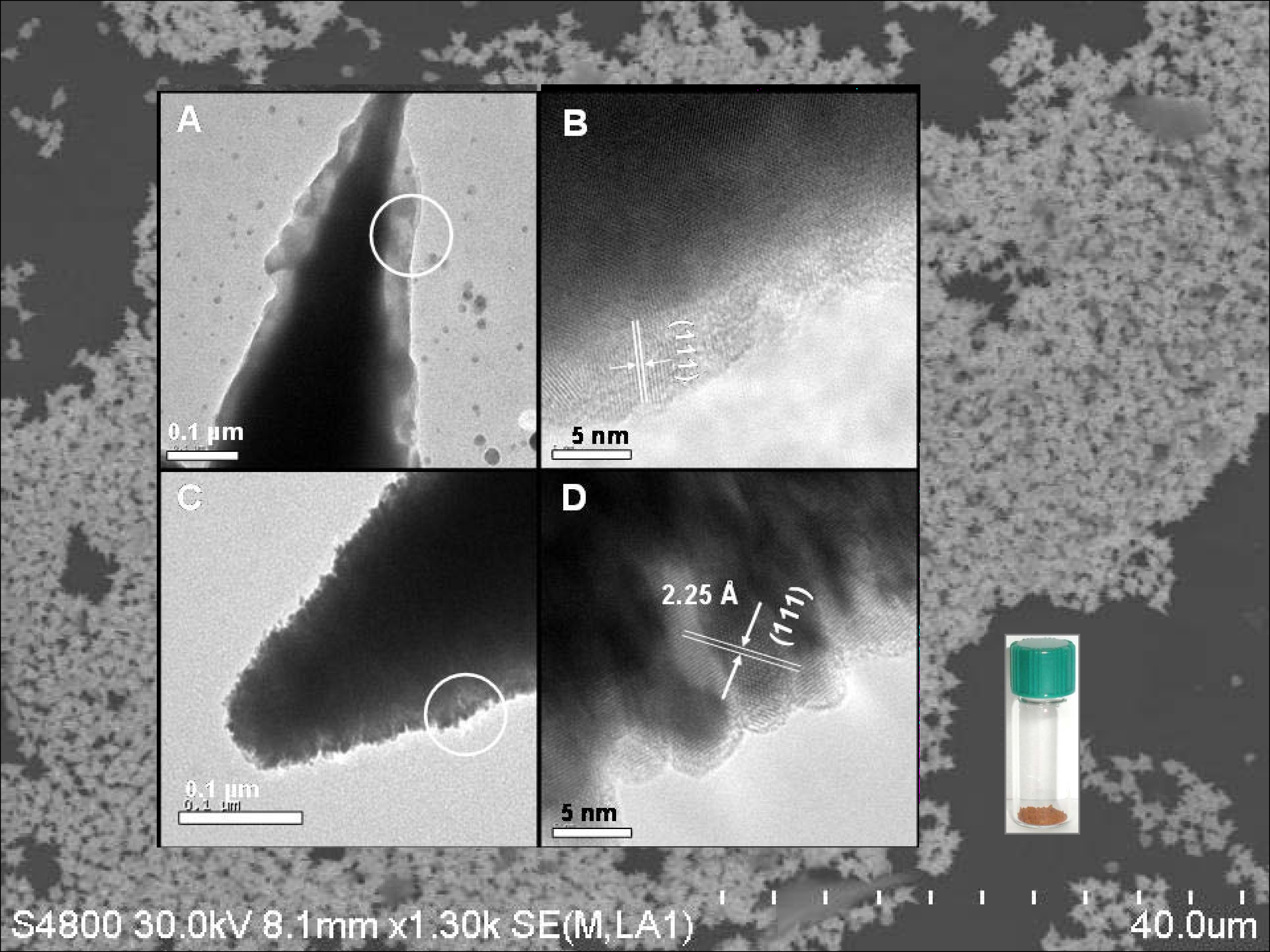


E. S. Shibu et al. *Adv. Mater.* 2008; *Nano Res.* 2009

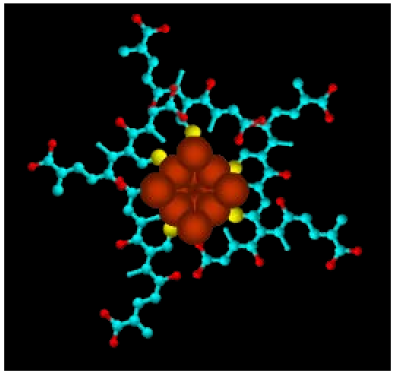
New materials

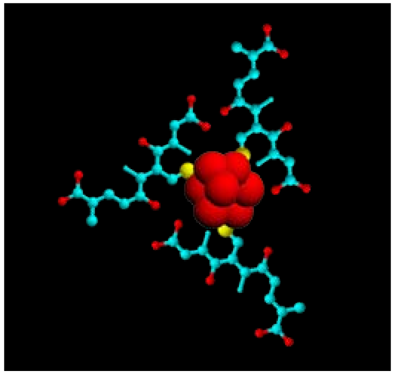


Sajanlalal and Pradeep – *Nano Res.* 2009


A
0.1 μm
B
(111)
5 nm
C
0.1 μm
D
2.25 Å
(111)
5 nm
S4800 30.0kV 8.1mm x1.30k SE(M,LA1)
40.0um

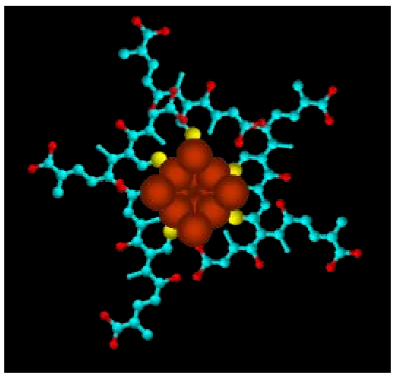
Molecular Clusters

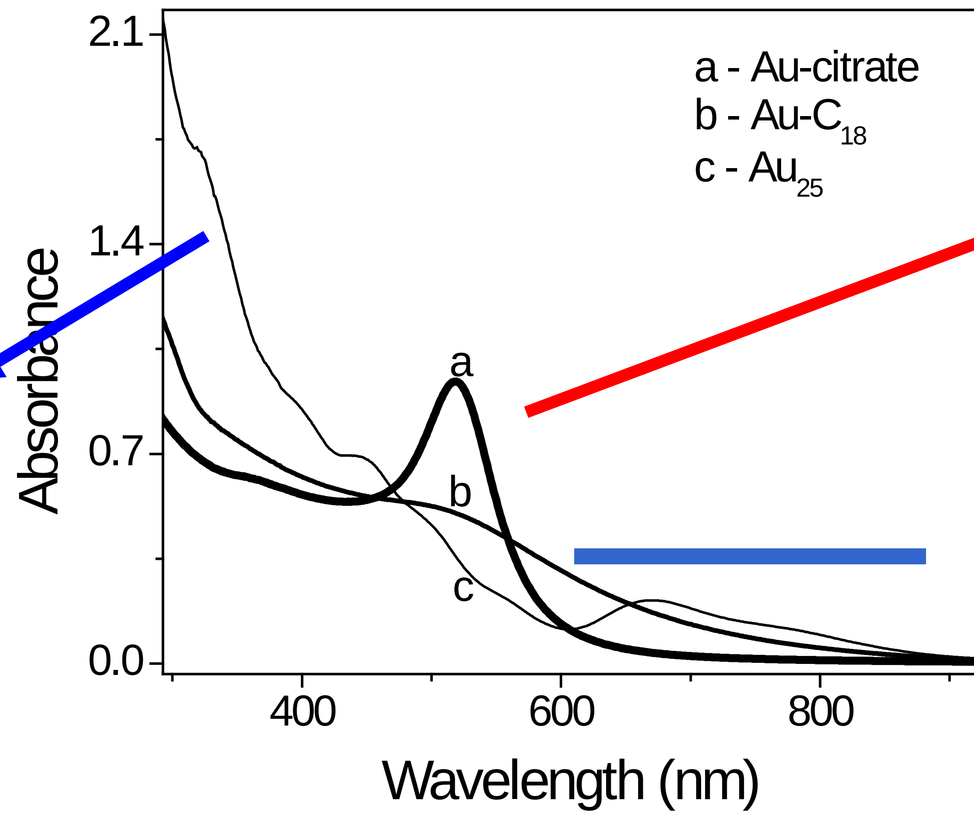


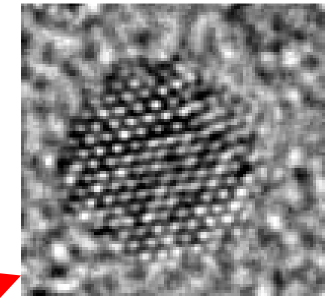


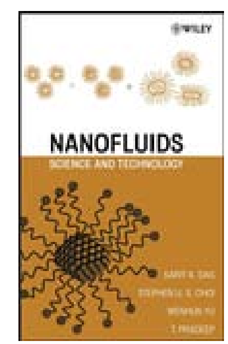
- **28 kDa Alkanethiolate-Protected Au Clusters Give Analogous Solution Electrochemistry and STM Coulomb Staircases,** Ingram, R. S.; Hostetler, M. J.; Murray, R. W.; Schaaff, T. G.; Khoury, J.; Whetten, R. L.; Bigioni, T. P.; Guthrie, D. K.; First, P. N. *J. Am. Chem. Soc.* **1997**, *119*, 9279.
- **Isolation of Smaller Nanocrystal Au Molecules: Robust Quantum Effects in Optical Spectra**, Schaaff, T. G.; Shafigullin, M. N.; Khoury, J. T.; Vezmar, I.; Whetten, R. L.; Cullen, W. G.; First, P. N.; Gutierrez-Wing, C.; Ascensio, J.; Jose-Yacaman, M. J. *J. Phys. Chem. B* **1997**, *101*, 7885.
- **Optical Absorption Spectra of Nanocrystal Gold Molecules**, Alvarez, M. M.; Khoury, J. T.; Schaaff, T. G.; Shafigullin, M. N.; Vezmar, I.; Whetten, R. L. *J. Phys. Chem. B* **1997**, *101*, 3706.

- **Isolation and Selected Properties of a 10.4 kDa Gold:Glutathione Cluster Compound**, Schaaff, T. G.; Knight, G.; Shafigullin, M. N.; Borkman, R. F.; Whetten, R. L. *J. Phys. Chem. B* **1998**, *102*, 10643.
- **Controlled Etching of Au:SR Cluster Compounds,** Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **1999**, *103*, 9394.
- **Giant Gold-Glutathione Cluster Compounds: Intense Optical Activity in Metal-BasedTransitions**, Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **2000**, *104*, 2630.
- **Near-Infrared Luminescence from Small Gold Nanocrystals**, Bigioni, T. P.; Whetten, R. L.; Dag, O. *J. Phys. Chem. B* **2000**, *104*, 6983.
- **Properties of a Ubiquitous 29 kDa Au:SR Cluster Compound.** Schaaff, T. G.; Shafigullin, M. N.; Khoury, J. T.; Vezmar, I.; Whetten, R. L. *J. Phys. Chem. B* **2001**, *105*, 8785.
- **Visible to Infrared Luminescence from a 28-Atom Gold Cluster**, Link, S.; Beeby, A.; FitzGerald, S.; El-Sayed, M. A.; Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **2002**, *106*, 3410.
- **All-Aromatic, Nanometer-Scale, Gold-Cluster Thiolate Complexes,** Price, R. C.; Whetten, R. L. *J. Am. Chem. Soc*. **2005**, *127*, 13750.



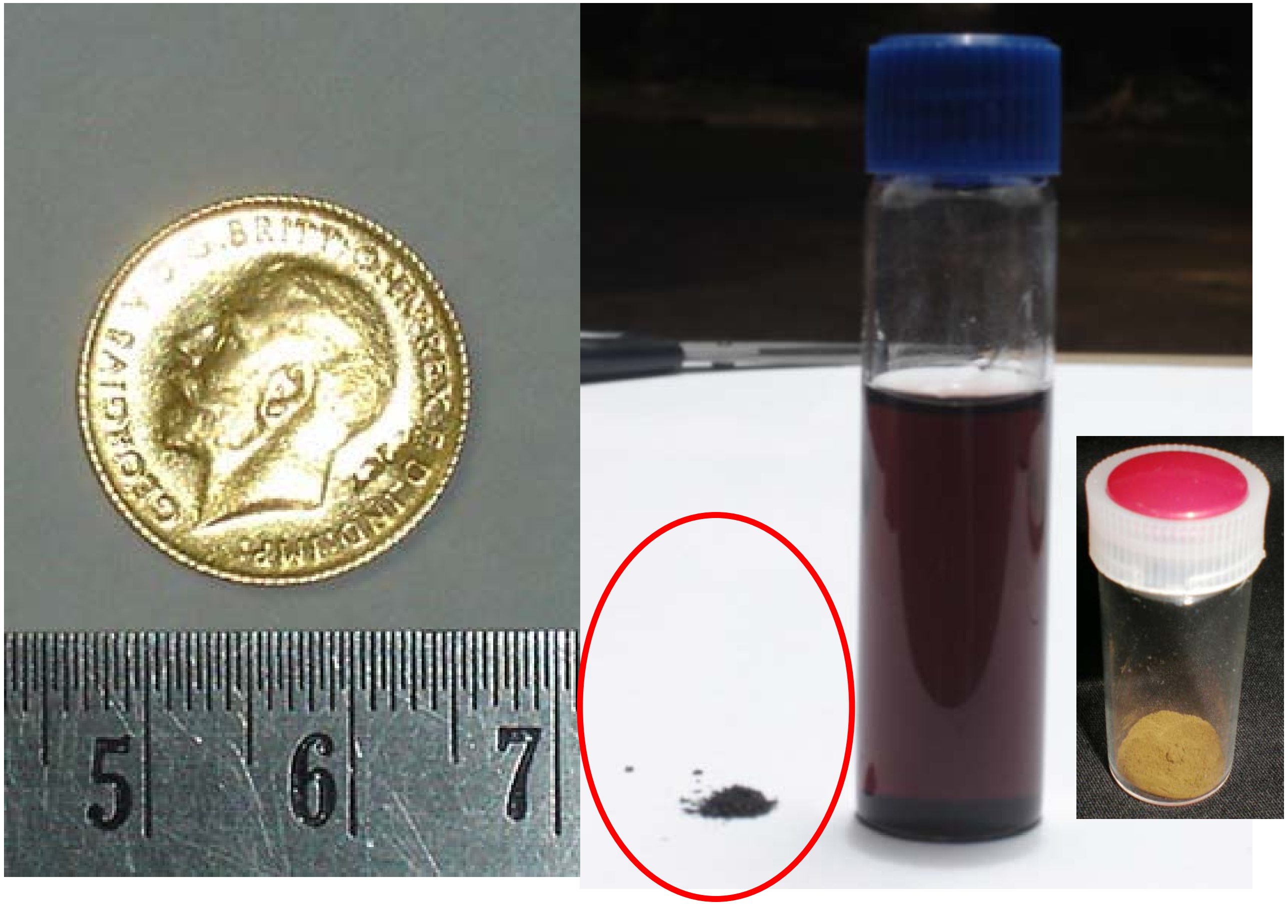




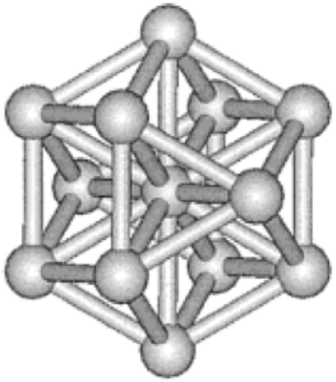


Optical absorption (extinction) spectrum of (a) 15 nm gold particles in aqueous solution (labeled Au@citrate). The spectrum of (b) 3 nm particles in toluene is also shown. See the broadening of the plasmon feature. The spectrum of (c) Au_{25} in water. In this, there is no plasmon excitation and all the features are due to molecular absorptions of the cluster.

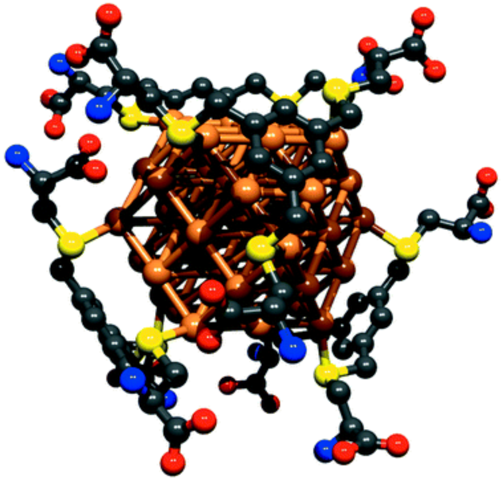
Das, Choi, Yu and Pradeep, *Nanofluids*, John Wiley, New York, 2008


5
6
7

Phosphine Capped Gold Clusters



Au_{13}

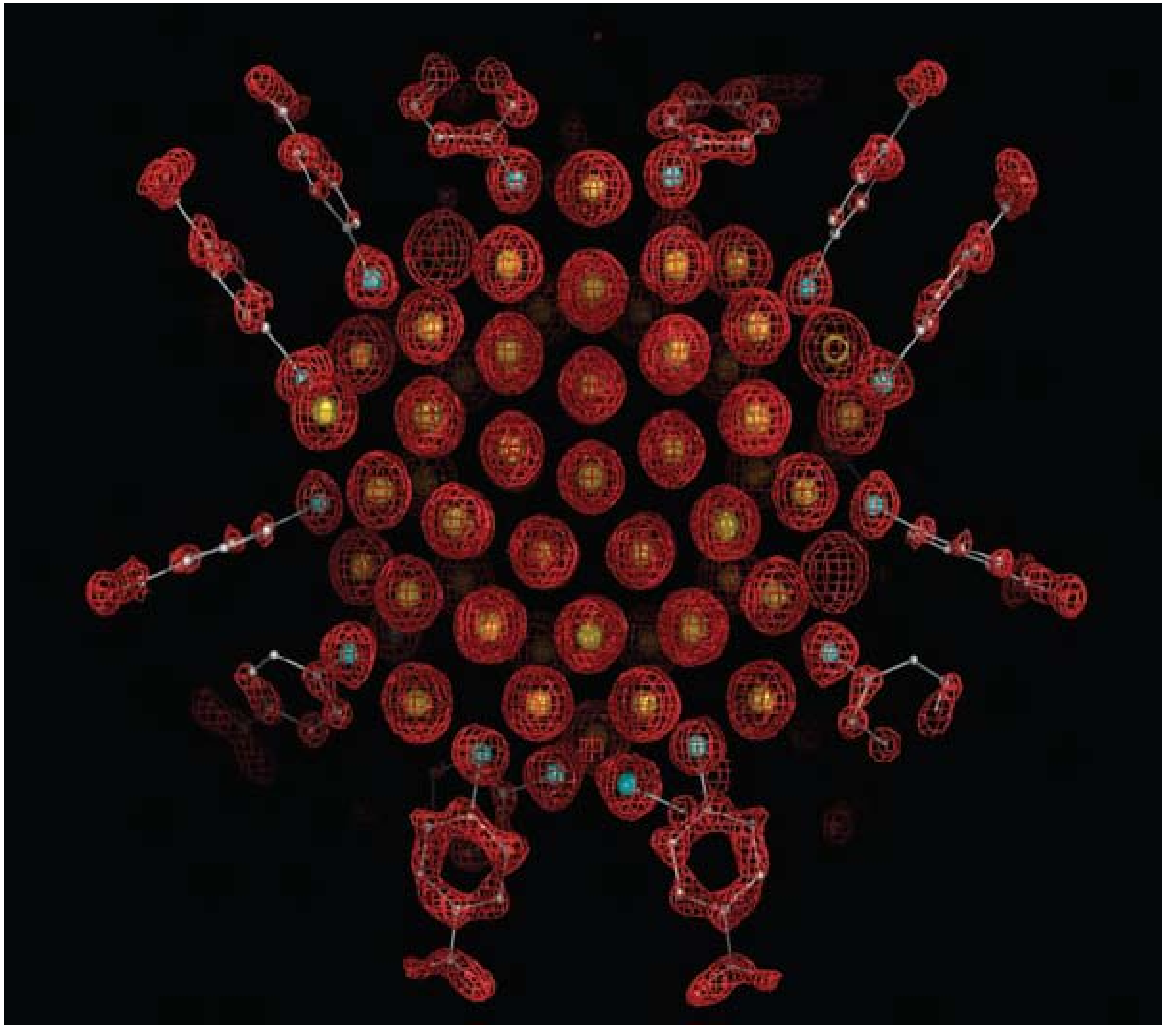


Au_{55}

- **Au_{55} [$P(C_6H_5)_3]_{12}Cl_6$ - a gold cluster of unusual size,** Schmid, G.; Pfeil, R.; Boese, R.; Brandermann, F.; Meyer, S.; Calis, G. H. M.; Van der Velden.; Jan W. A. *Chemische Berichte* **1981**, *114*, 3634.
- **Synthesis and x-ray structural characterization of the centered icosahedral gold cluster compound [Au_{13} $(PMe_2Ph)_{10}Cl_2](PF_6)_3$; the realization of a theoretical prediction,** Briant, C. E.; Theobald, B. R. C.; White, J. W.; Bell, L. K.; Mingos, D. M. P.; Welch, A. J. *Chem. Commun.* **1981**, *5*, 201.
- **Synthesis of water-soluble undecagold cluster compounds of potential importance in electron microscopic and other studies in biological systems**, Bartlett, P. A.; Bauer, B.; Singer, S. *J. Am. Chem. Soc.* **1978**, *100*, 5085.

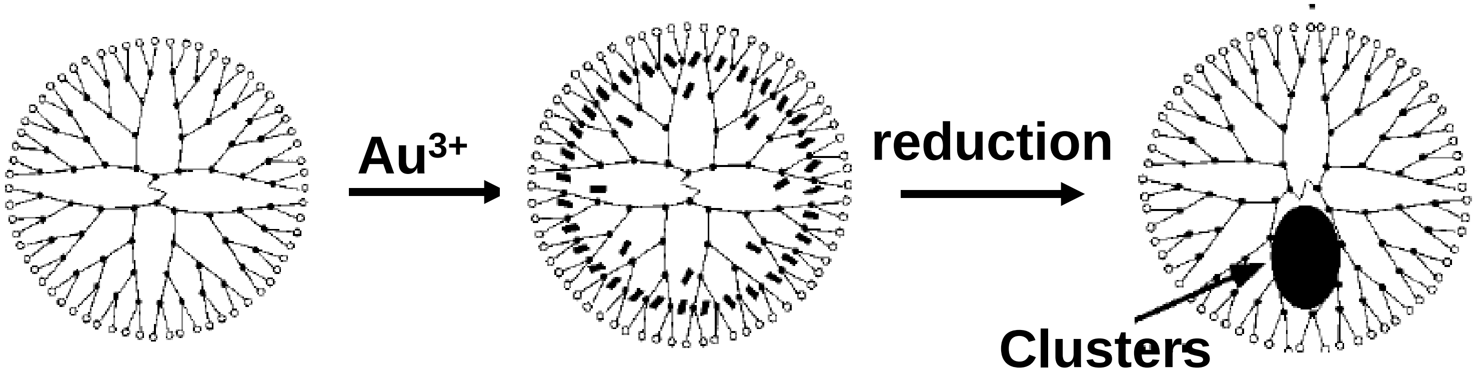
Au_{102}

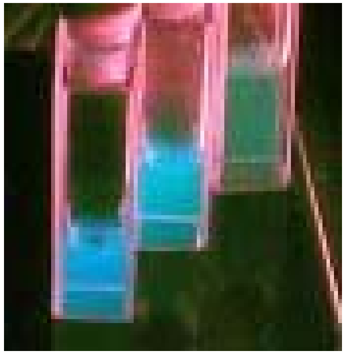
$Au_{102}(p\text{-}MBA)_{44}$



Jadzinsky, P. D.; Calero, G.; Ackerson, C. J.; Bushnell, D. A.; Kornberg, R. D. Structure of a Thiol Monolayer–Protected Gold Nanoparticle at 1.1 Å Resolution *Science* **2007**, *318*, 430.

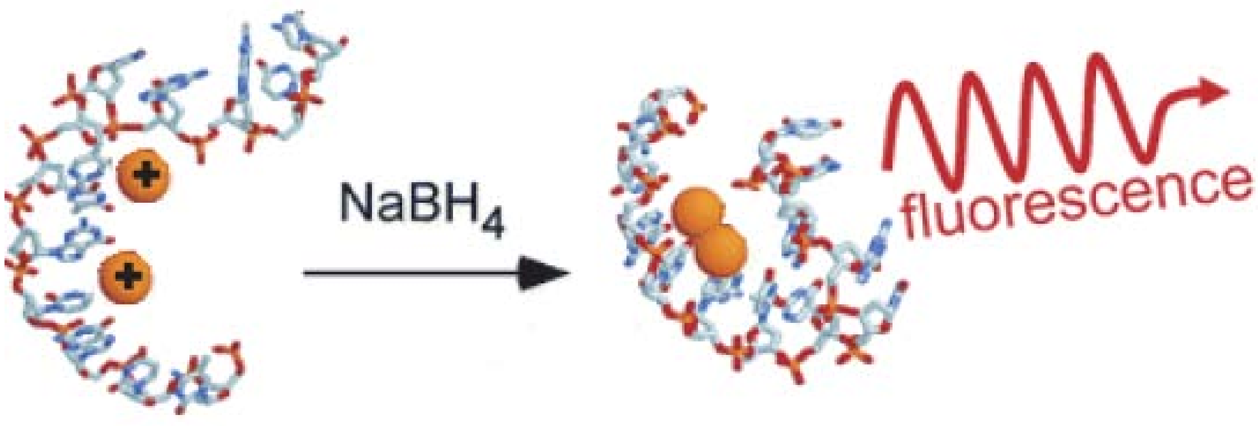
Dendrimer Encapsulated Clusters



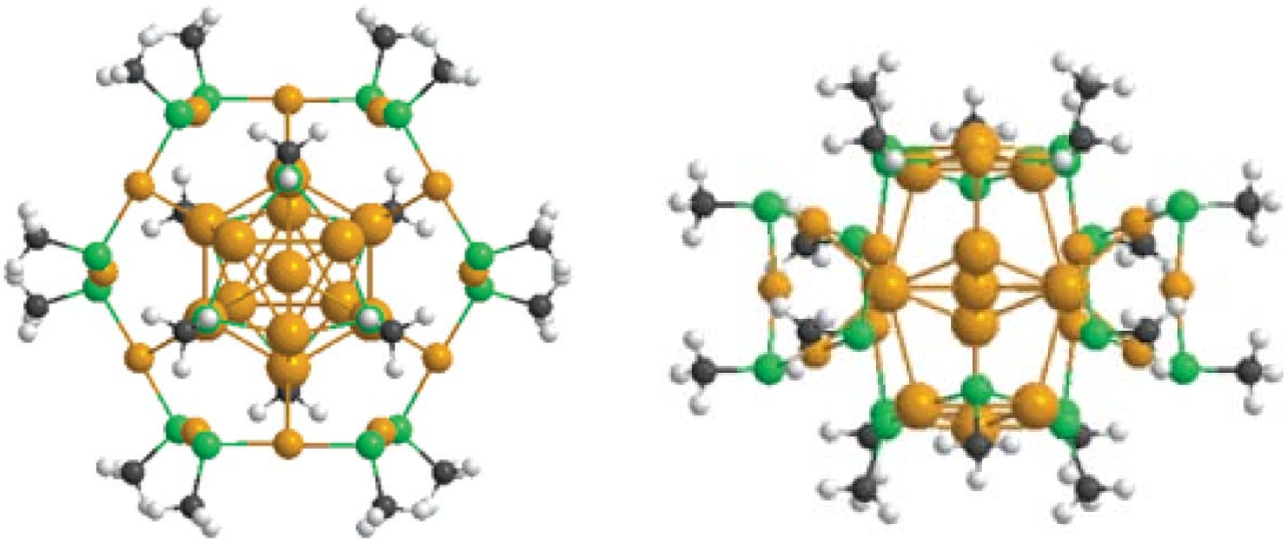


- **High quantum yield blue emission from water-soluble Au_8 nanodots**, Zheng, J.; Petty, J. T.; Dickson, R. M. *J. Am. Chem. Soc*. **2003**, *125*, 7780.
- **Highly fluorescent, water-soluble, size-tunable gold quantum dots,** Zheng, J.; Zhang, C. W.; Dickson, R. M. *Phys. Rev. Lett*. **2004**, *93*, 077402.
- **Highly fluorescent noble-metal quantum dots**, Zheng, J.; Nicovich, P. R.; Dickson, R. M. *Annu. Rev. Phys. Chem.* **2007**, *58*, 409.
- **Etching colloidal gold nanocrystals with hyperbranched and multivalent polymers: A new route to fluorescent and water-soluble atomic clusters**, Duan, H.; Nie, S. *J. Am. Chem. Soc*. **2007**, *129*, 2412.

DNA Encapsulated Clusters



DNA-Templated Ag Nanocluster Formation, Petty, J. T.; Zheng, J.; Hud, N. V.; Dickson, R. M. *J. Am. Chem. Soc*. **2004**, *126*, 5207.

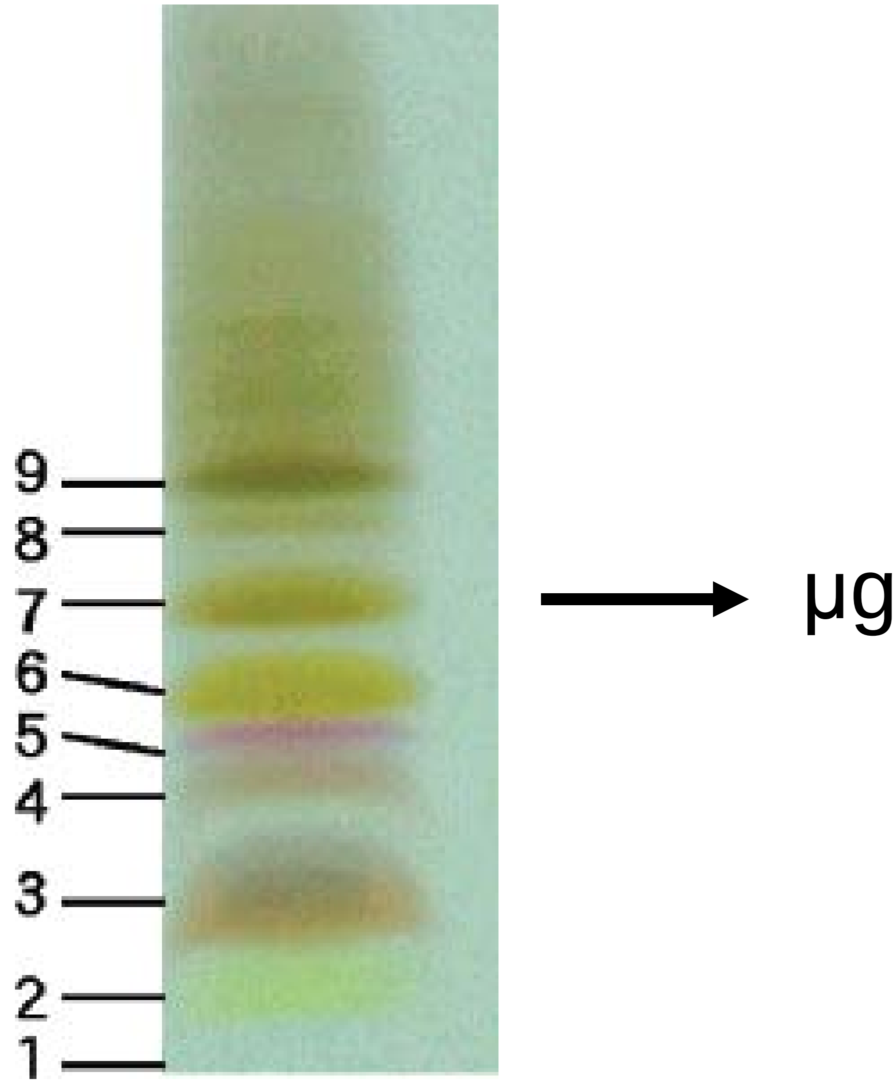


Top and side view of $[Au_{25}(SCH_3)_{18}]^+$

Theoretical Investigation of Optimized Structures of Thiolated Gold Cluster $[Au_{25}(SCH_3)_{18}]^+$, Iwasa, T.; Nobusada, K. *J. Phys. Chem. C* **2007**, *111*, 45.

How to make them?

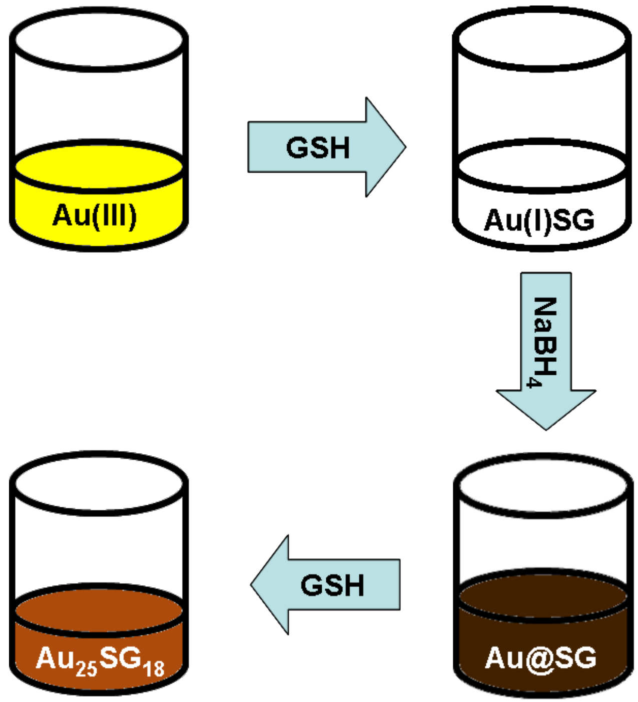
Polyacrylamide gel electrophoresis (PAGE)



Negishi, Y.; Nobusada, K.; and Tsukuda, T. Glutathione-Protected Gold Clusters Revisited: Bridging the Gap between Gold(I)-Thiolate Complexes and Thiolate-Protected Gold Nanocrystals. *J. Am. Chem. Soc*. 2005, *127*, 5261-70.

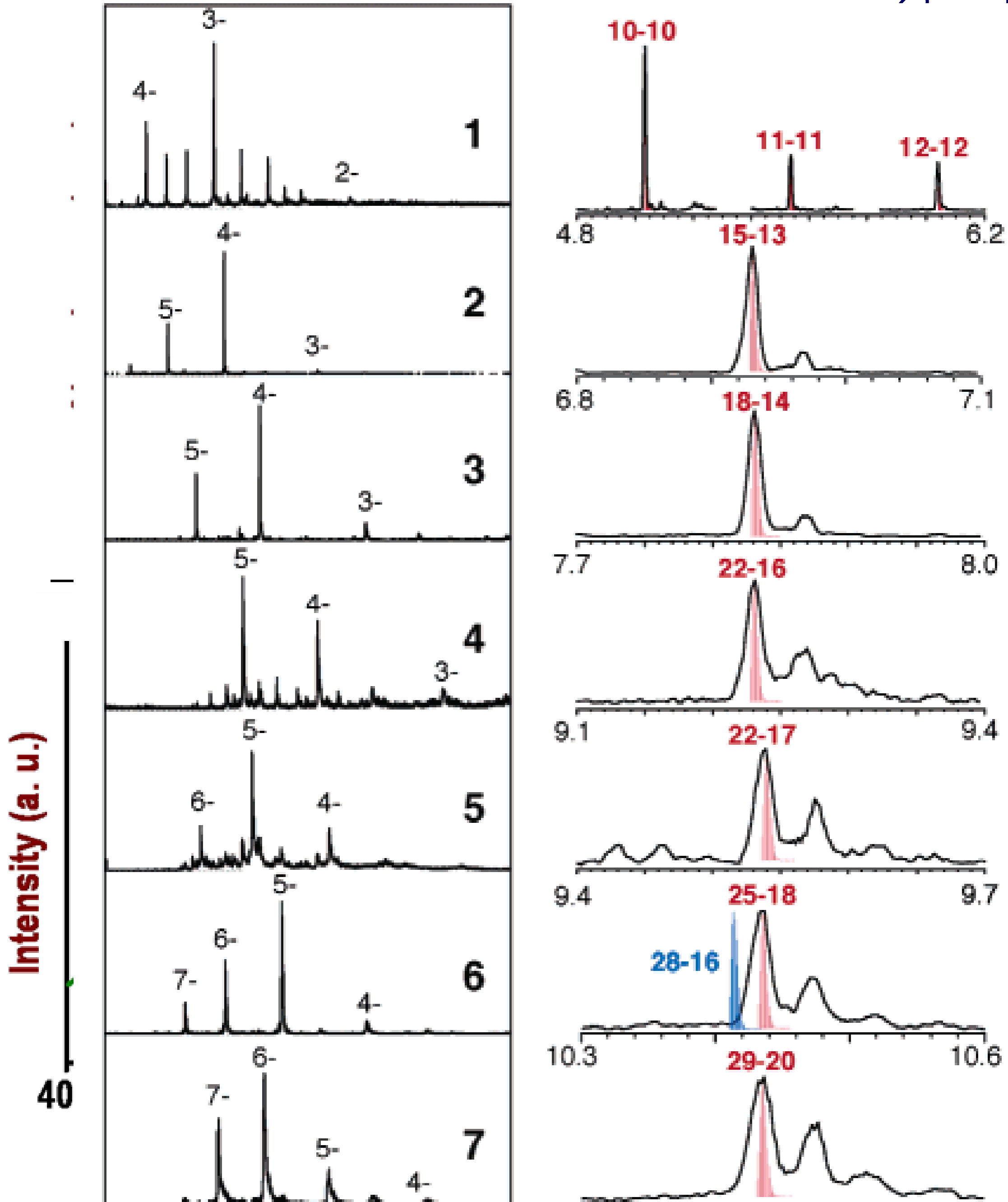
$Au_{25}SG_{18}$

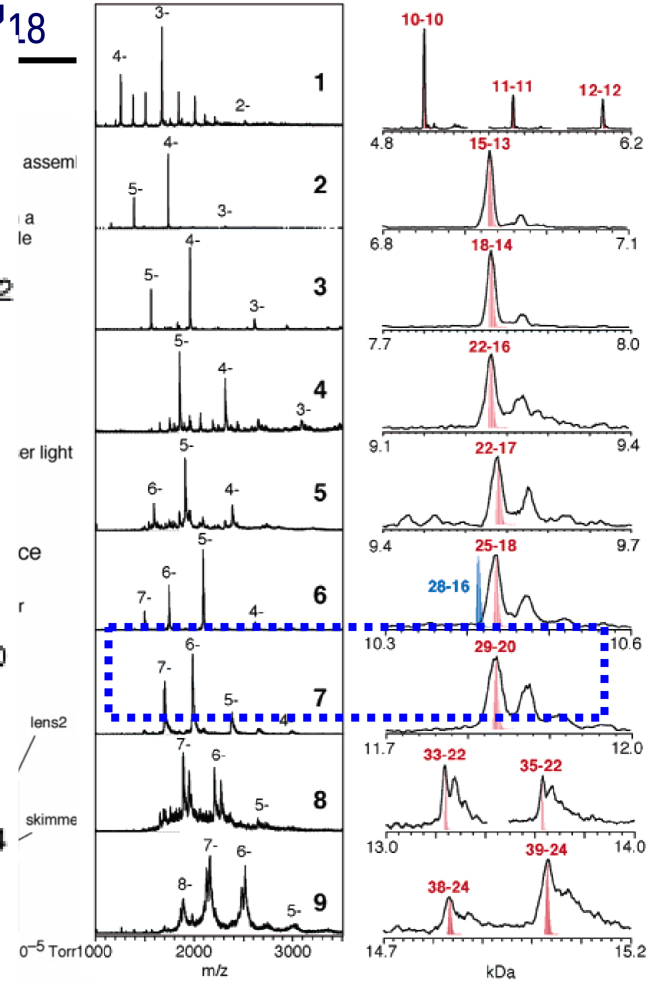
Synthesis: Au_{25} clusters can be preferentially populated by dissociative excitation of larger precursors



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

Characterization of $Au_{25}SG_{18}$

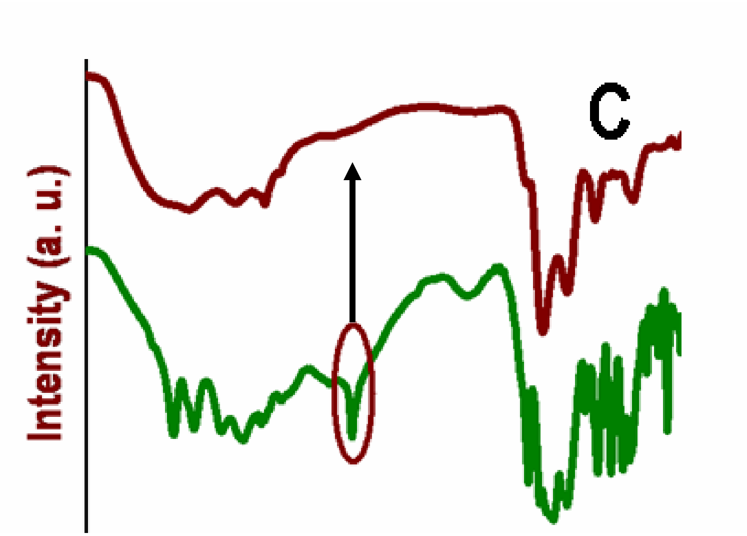


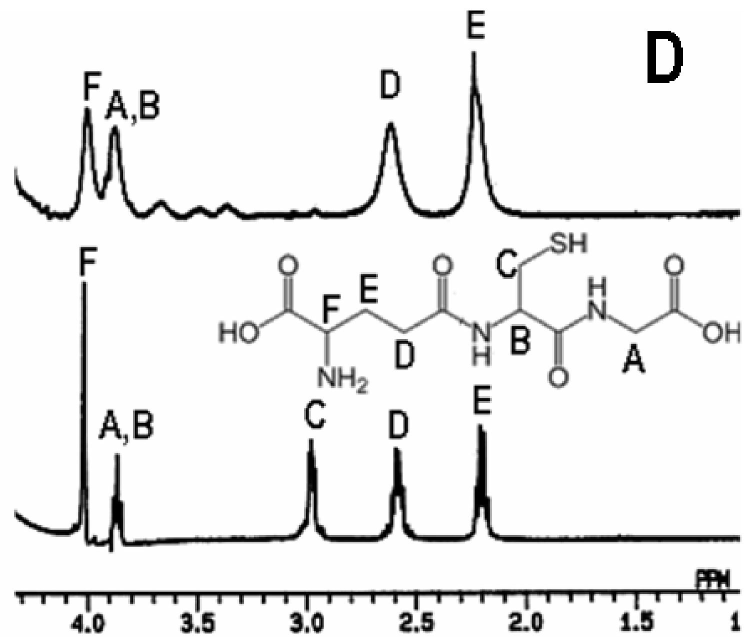


Tsukuda et. al. JACS 2005

profile with excitation

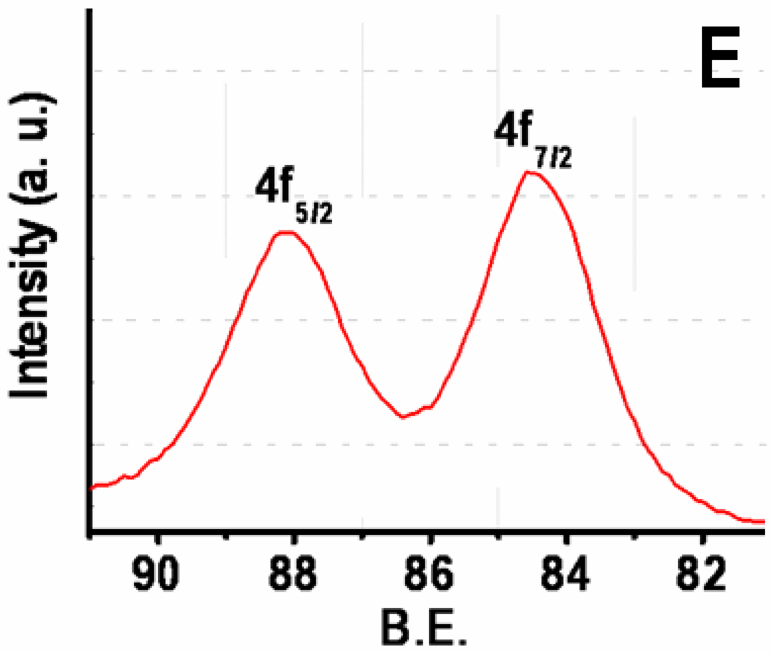
a at 535 and 700 nm,



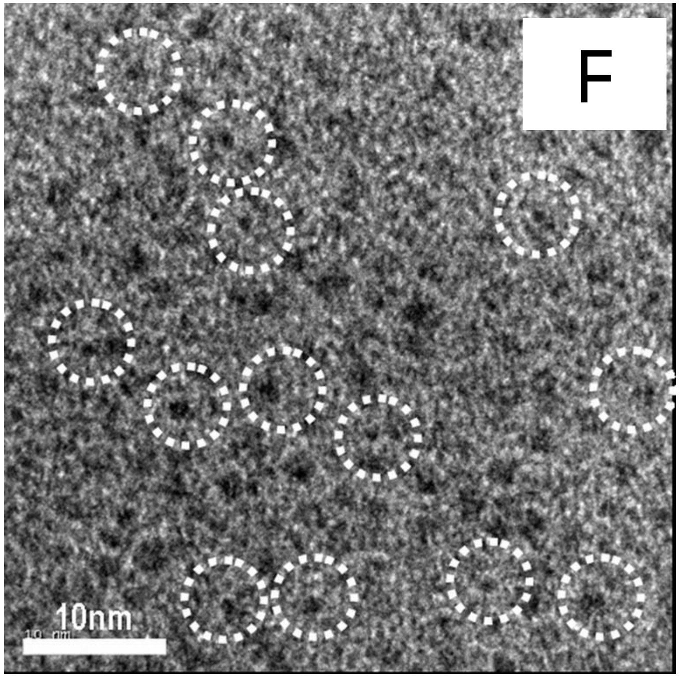


FTIR spectrum: The peak at 2526 cm^{-1} of glutathione due to –SH stretching frequency is absent in IR spectrum of Au_{25} suggesting the ligand binding on cluster surface.

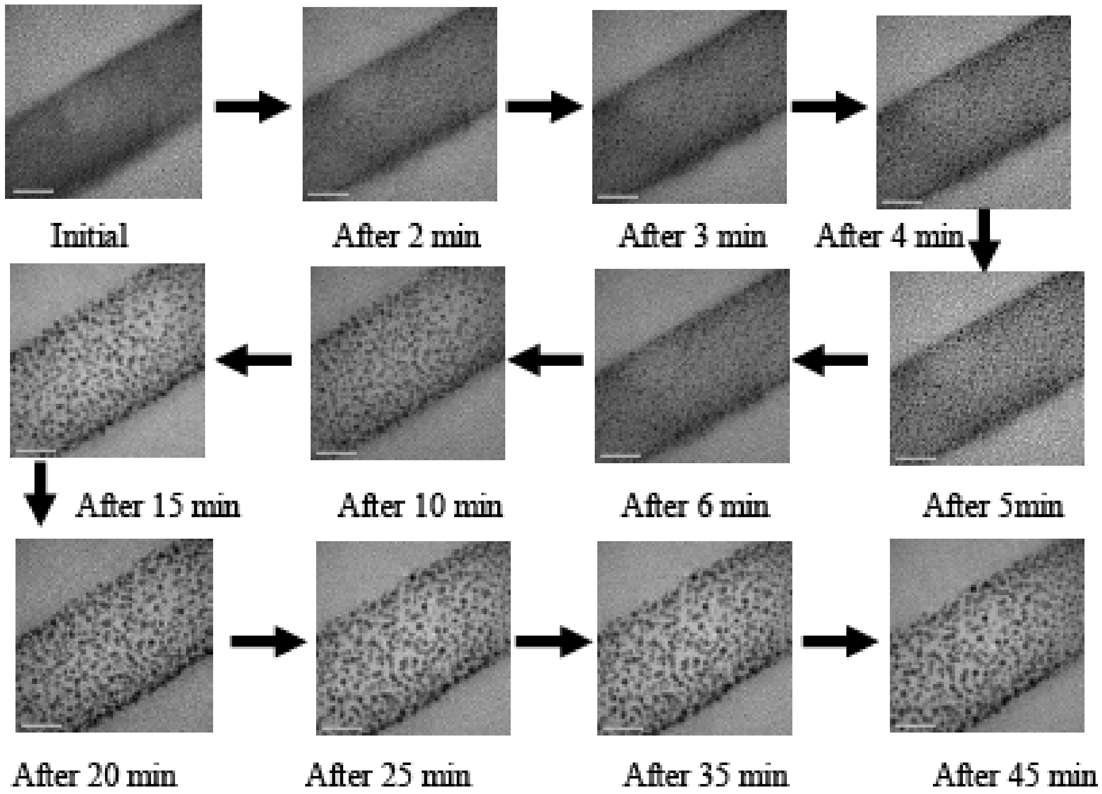
1H NMR spectrum: There is one-to-one correspondence between the two spectra, except that the **β**CH_2 resonance (labeled as C) disappears completely in the cluster which is expected as it is close to the cluster surface. All the observed resonances have been broadened in view of their faster relaxation and non-uniform distribution of ligands.

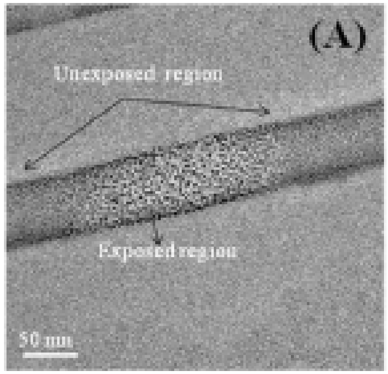


XPS spectrum



TEM image: The clusters are seen only faintly since the size is ~1 nm. Some of the individual clusters are shown by circles. There are also cluster aggregates which upon extended electron beam irradiation fuse to form bigger particles

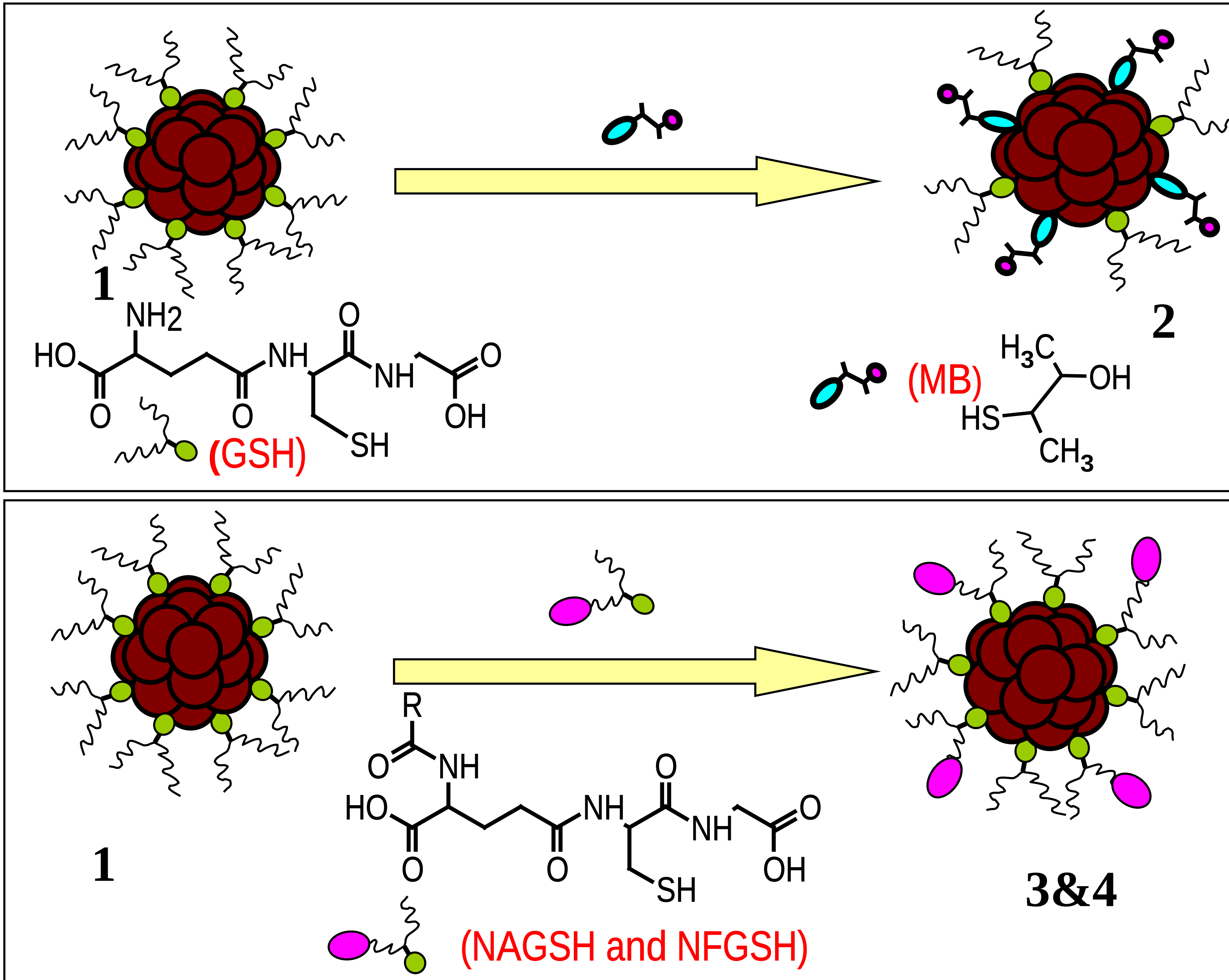


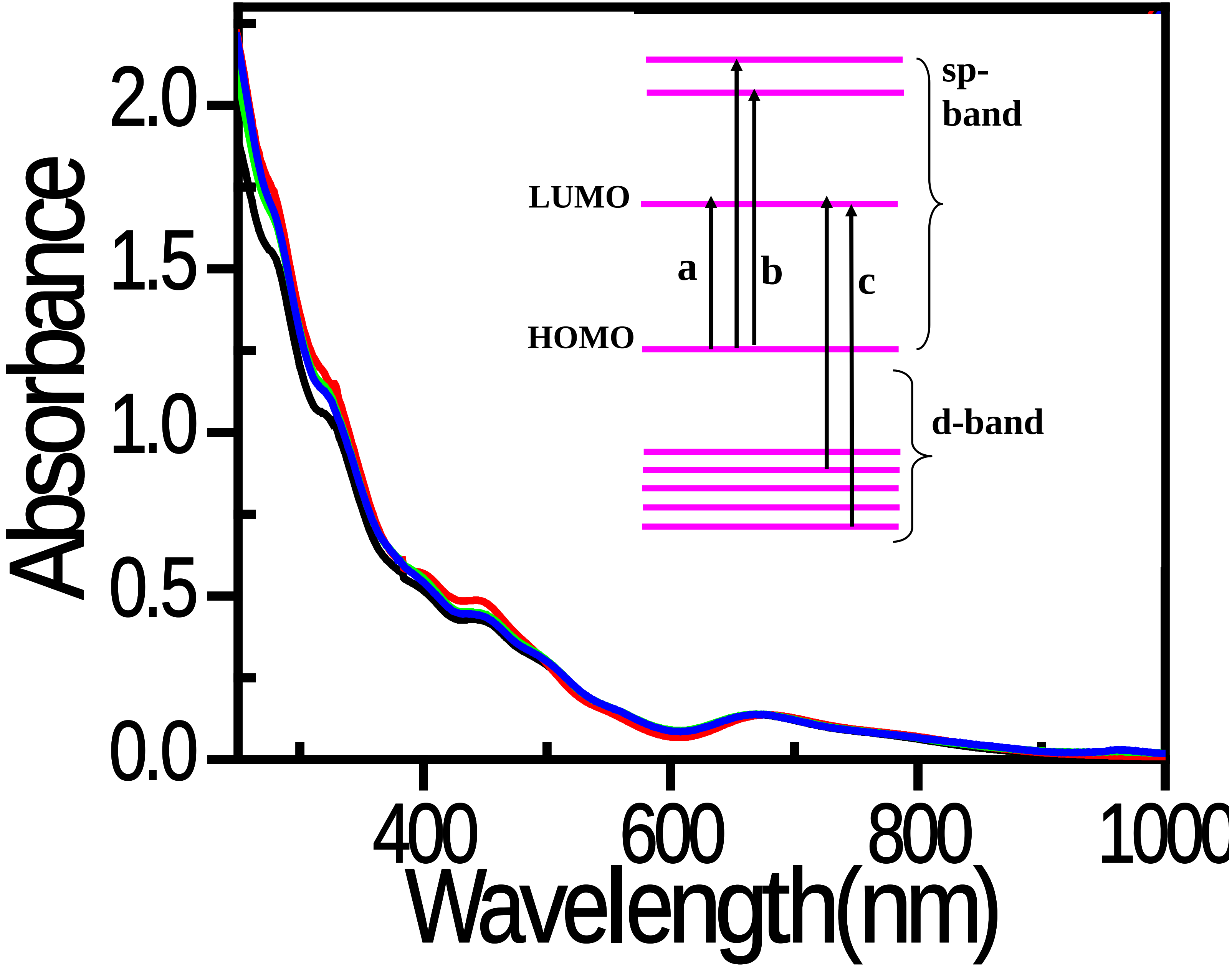


Perumal Ramasamy *et al. J. Mater. Chem.*, **2009**, *19*, 8456.

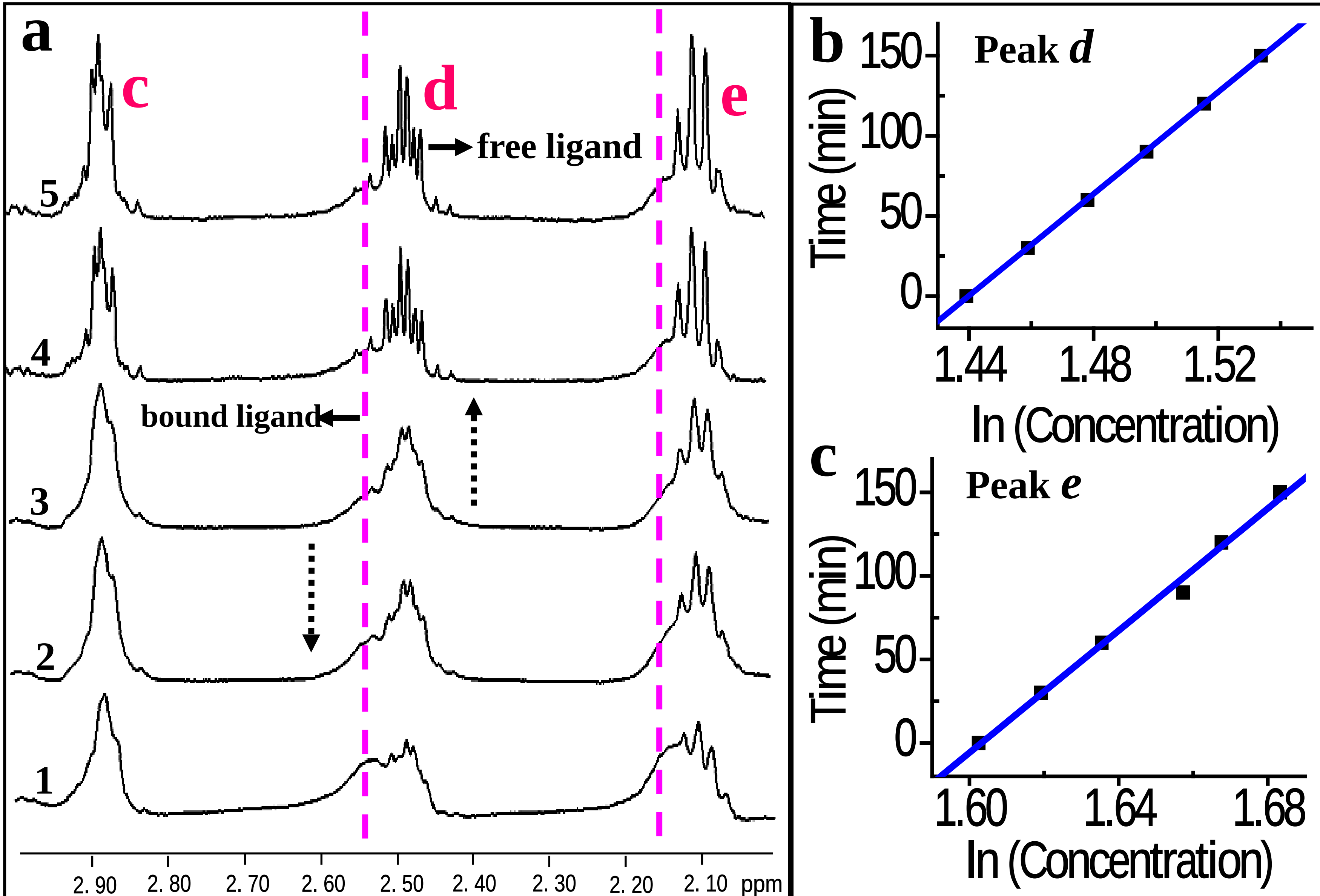
With Arindam Banerjee

Ligand Exchange of Au_{25}

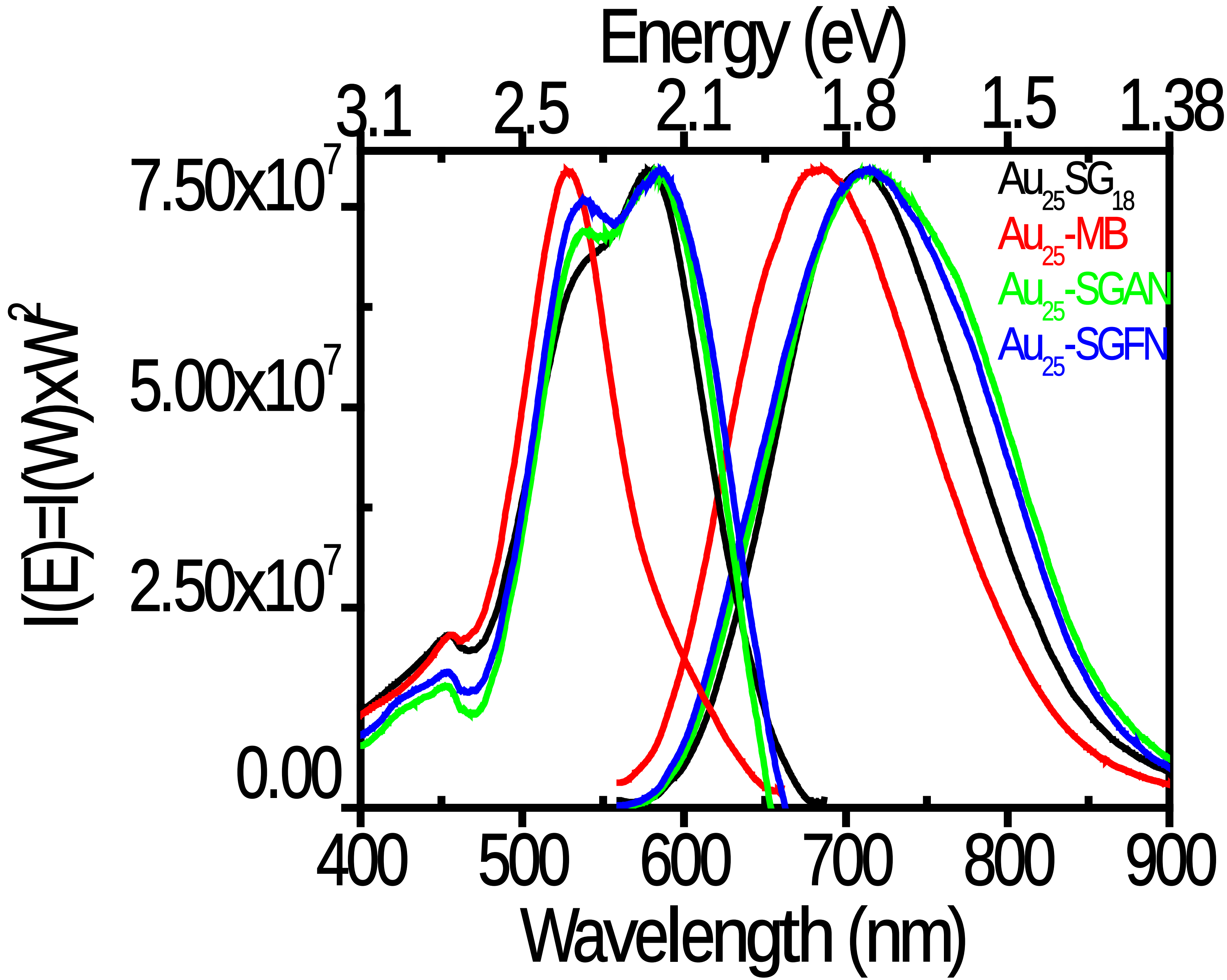




Shibu et al. *J. Phys. Chem. C* 2008

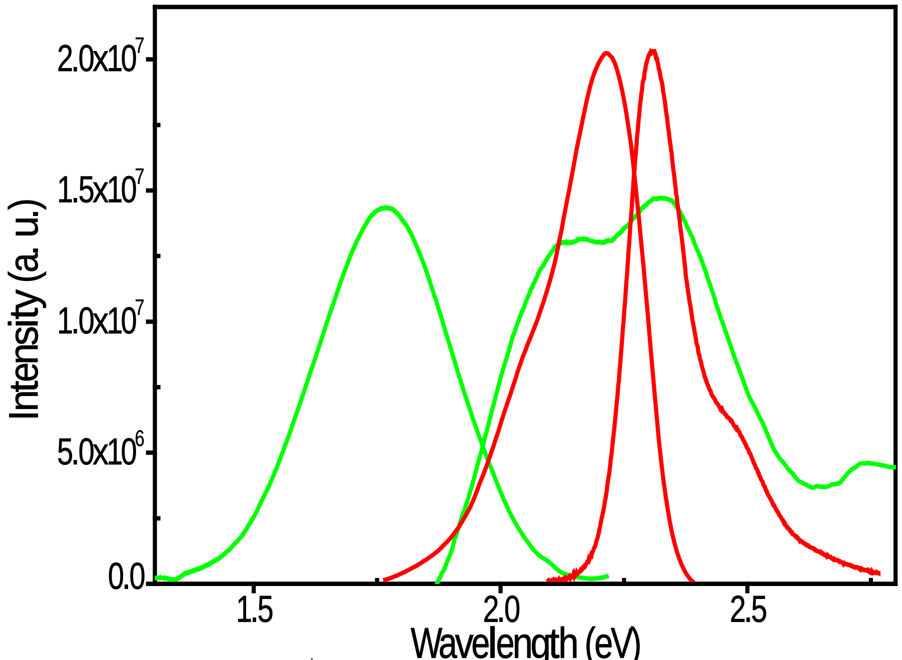


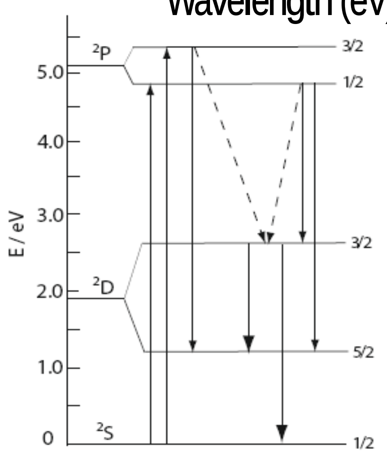
a
c
d
e
free ligand
bound ligand
5
4
3
2
1
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
ppm
b
Peak d
Time (min)
150
100
50
0
1.44
1.48
1.52
ln (Concentration)
c
Peak e
Time (min)
150
100
50
0
1.60
1.64
1.68
ln (Concentration)

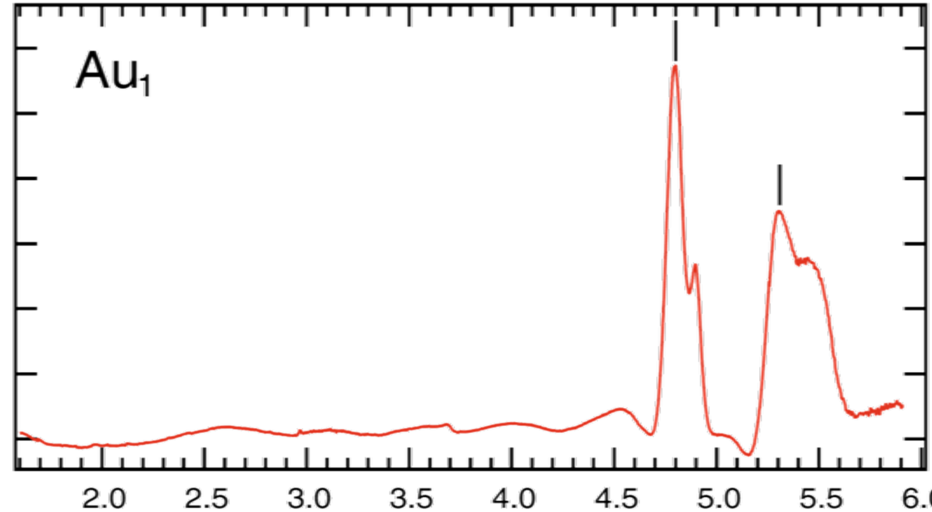


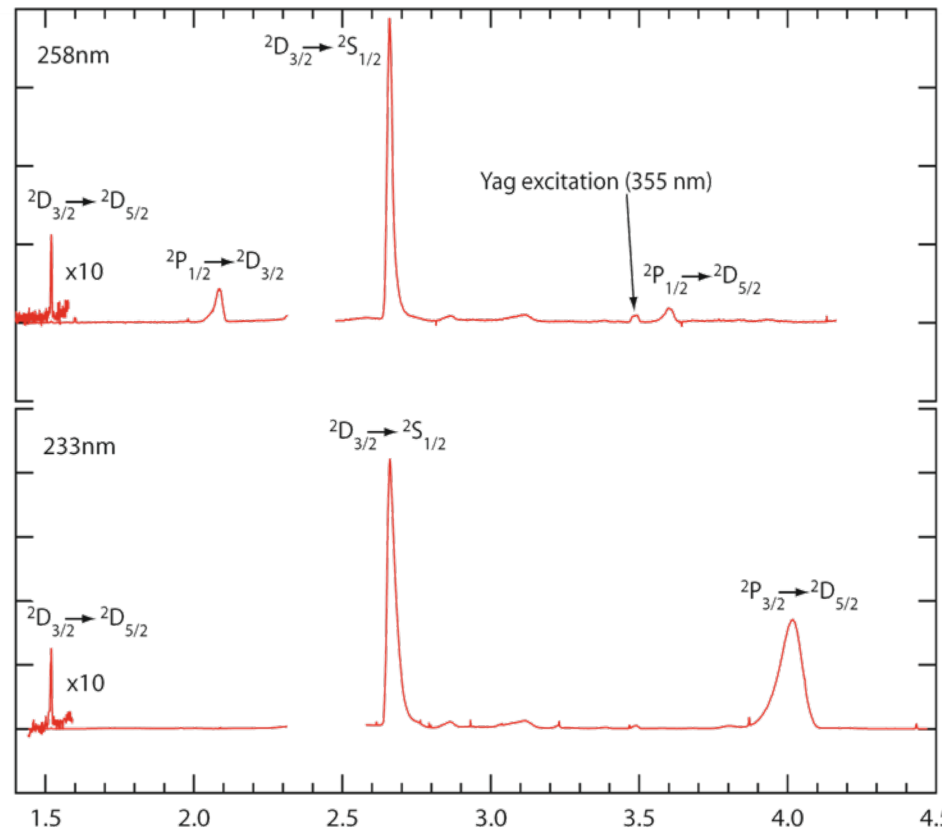
Energy (eV)
3.1
2.5
2.1
1.8
1.5
1.38
$7.50x10^7$
$5.00x10^7$
$2.50x10^7$
0.00
$I(E)=I(W)xW^2$
$Au_{25}SG_{18}$
Au_{25}-MB
Au_{25}-SGAN
Au_{25}-SGFN
400
500
600
700
800
900
Wavelength (nm)

Fluorescence : A comprehensive study between organic dye, gold atoms and molecular clusters of gold









Lecoultrea, S.; Rydlo, A.; F elixb, C.; Harbich, W. *Eur. Phys. J. D*, **2009** DOI: 10.1140/epjd/e2008-00290-0

Cluster	Q.Yield
$Au_{10}(SG)_{10}$ $Au_{11}(SG)_{11}$ $Au_{11}(SG)_{11}$	$1*10^{-4}$
$Au_{15}(SG)_{13}$	$2*10^{-4}$
$Au_{18}(SG)_{14}$	$4*10^{-3}$
$Au_{22}(SG)_{16}$	$4*10^{-3}$
$Au_{22}(SG)_{17}$	$2*10^{-3}$
$Au_{25}(SG)_{18}$	$1.9*10^{-3}$
$Au_{29}(SG)_{20}$	$3*10^{-3}$
$Au_{33}(SG)_{22}$ $Au_{35}(SG)_{22}$	$2*10^{-3}$
$Au_{38}(SG)_{24}$, $Au_{39}(SG)_{24}$	$2*10^{-3}$
Gold nanoparticles	$1*10^{-10}$

Recently developed clusters using Au_{25} as precursor

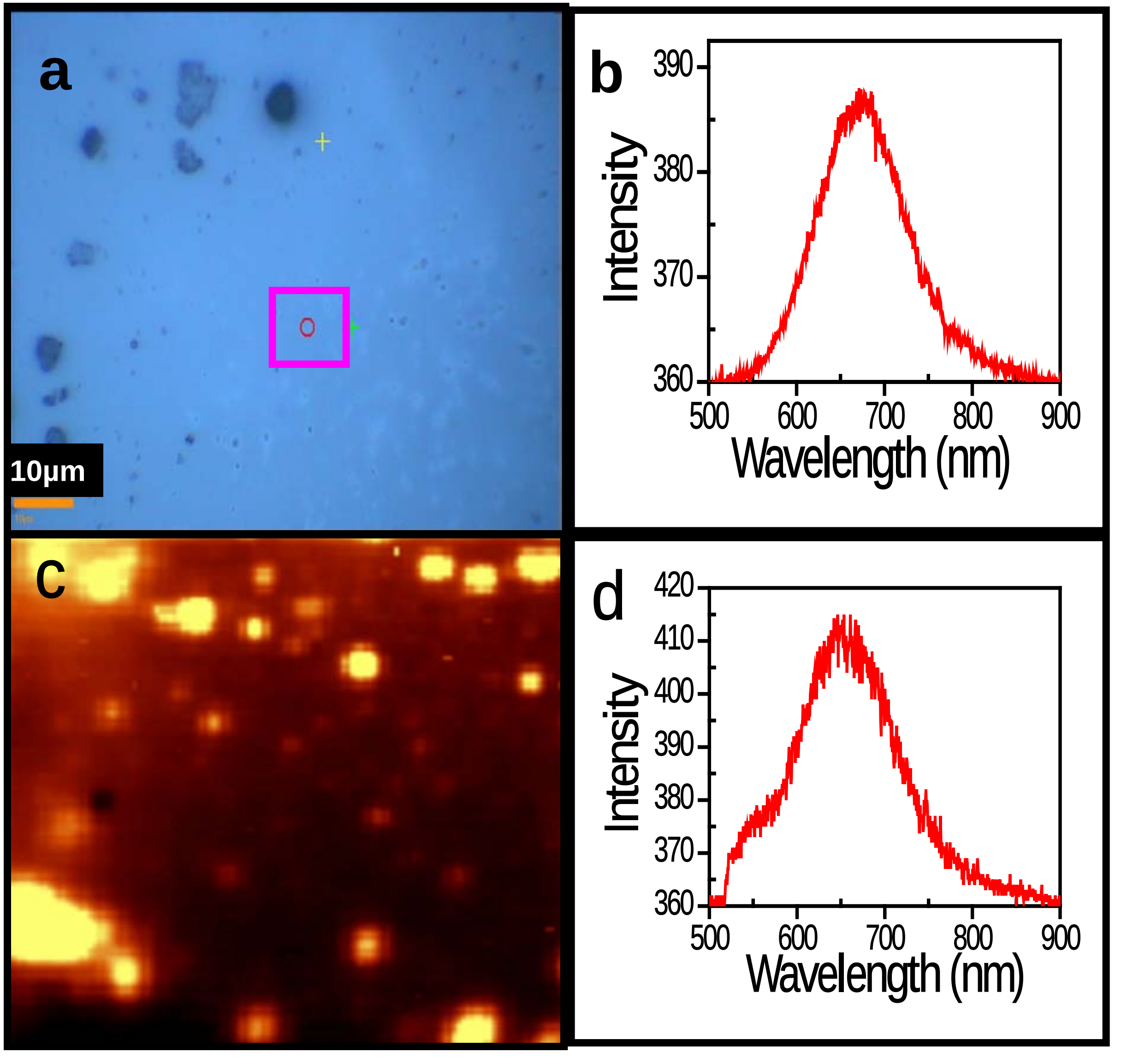
Precursor

Using other ligands

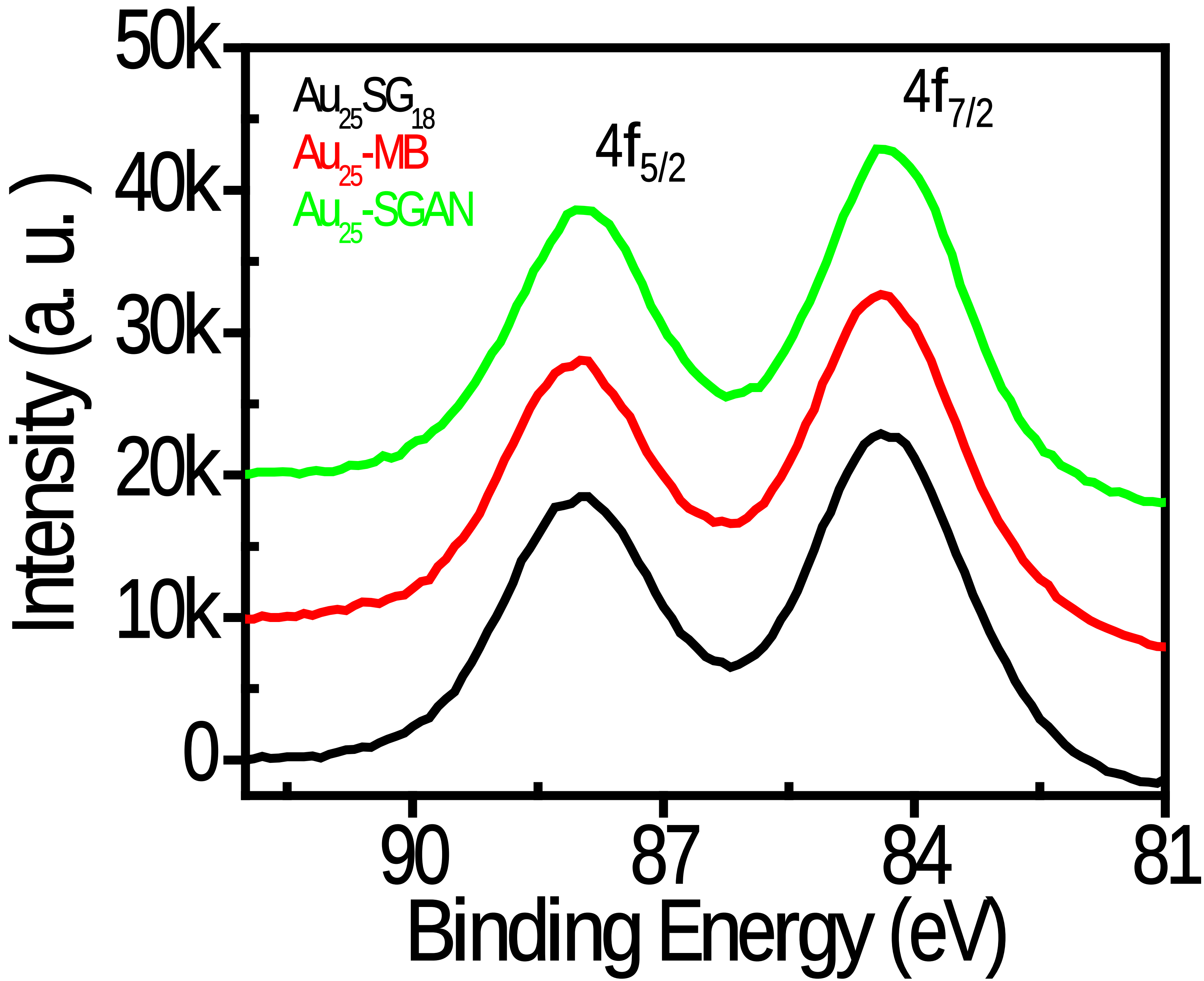
Cluster	Q. Yield
Au_{22}	$4.0*10^{-2}$
Au_{23}	$1.3*10^{-2}$
Au_{31}	$1.0*10^{-2}$
$Au_8(SG)_8$	$1.5*10^{-1}$

1. Nano Res., 1(2008) 333-340.
2. Chemistry A European Journal. (In Press).
3. ACS Applied Materials and Interfaces (in press)

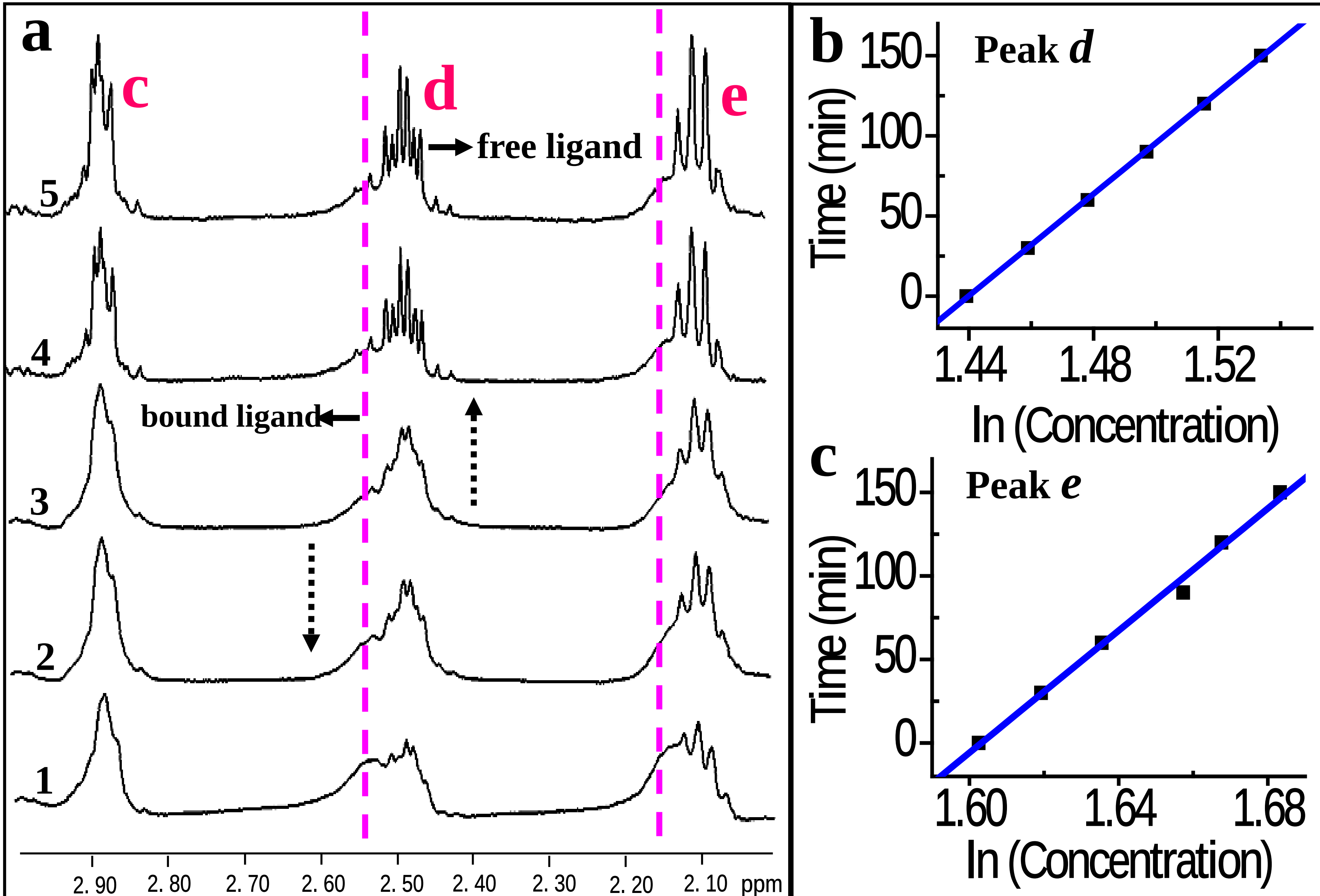
Negishi, Y.; Nobusada, K.; Tsukuda, T. *J. Am. Chem. Soc.* **2005**, *127*, 5261.



a
10μm
b
Intensity
390
380
370
360
500
600
700
800
900
Wavelength (nm)
c
d
Intensity
420
410
400
390
380
370
360
500
600
700
800
900
Wavelength (nm)

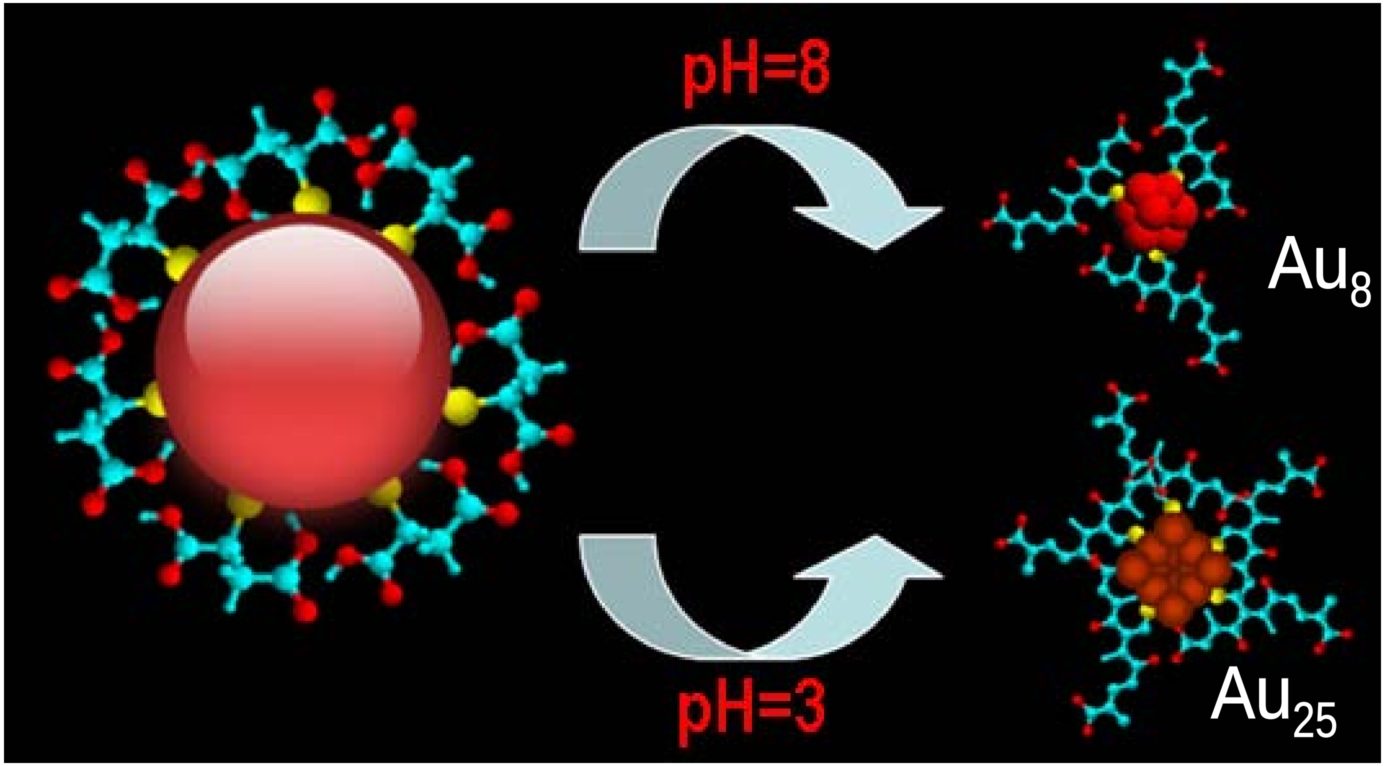


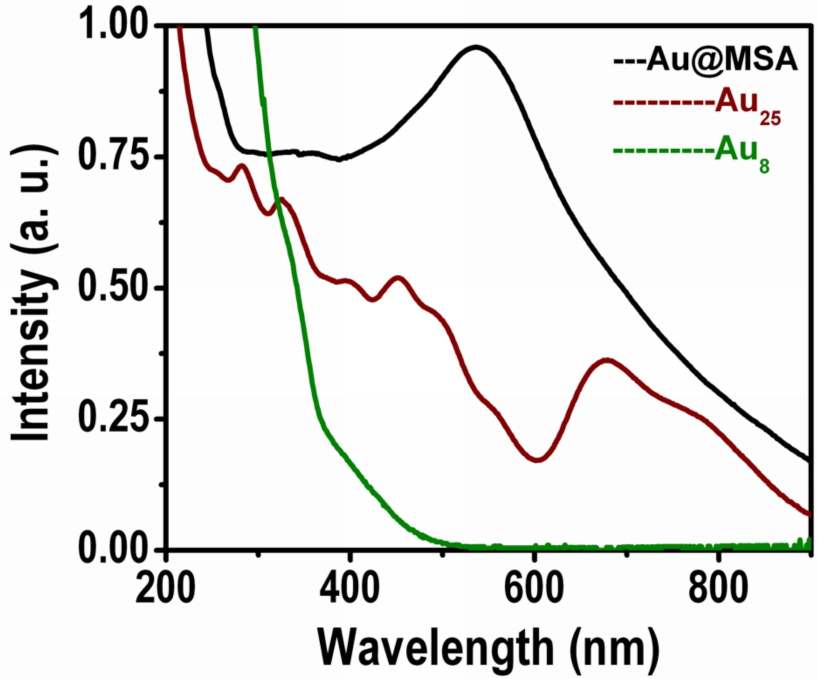
Au25SG18
Au25-MB
Au25-SGAN
4f5/2
4f7/2
50k
40k
30k
20k
10k
0
90
87
84
81
Intensity (a. u.)
Binding Energy (eV)



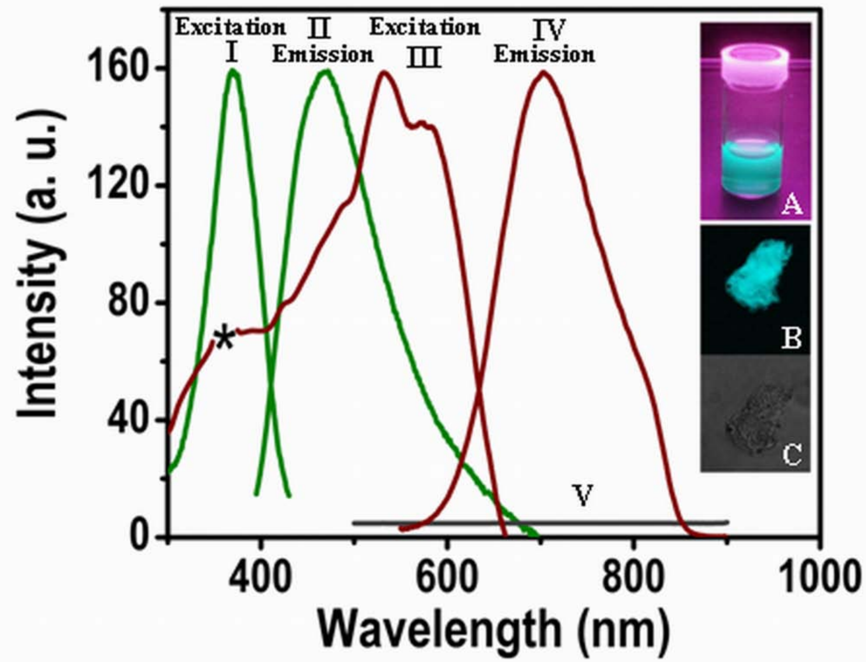
a
c
d
e
free ligand
bound ligand
5
4
3
2
1
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
ppm
b
Peak *d*
Time (min)
150
100
50
0
1.44
1.48
1.52
ln (Concentration)
c
Peak *e*
Time (min)
150
100
50
0
1.60
1.64
1.68
ln (Concentration)

Au_8SG_8



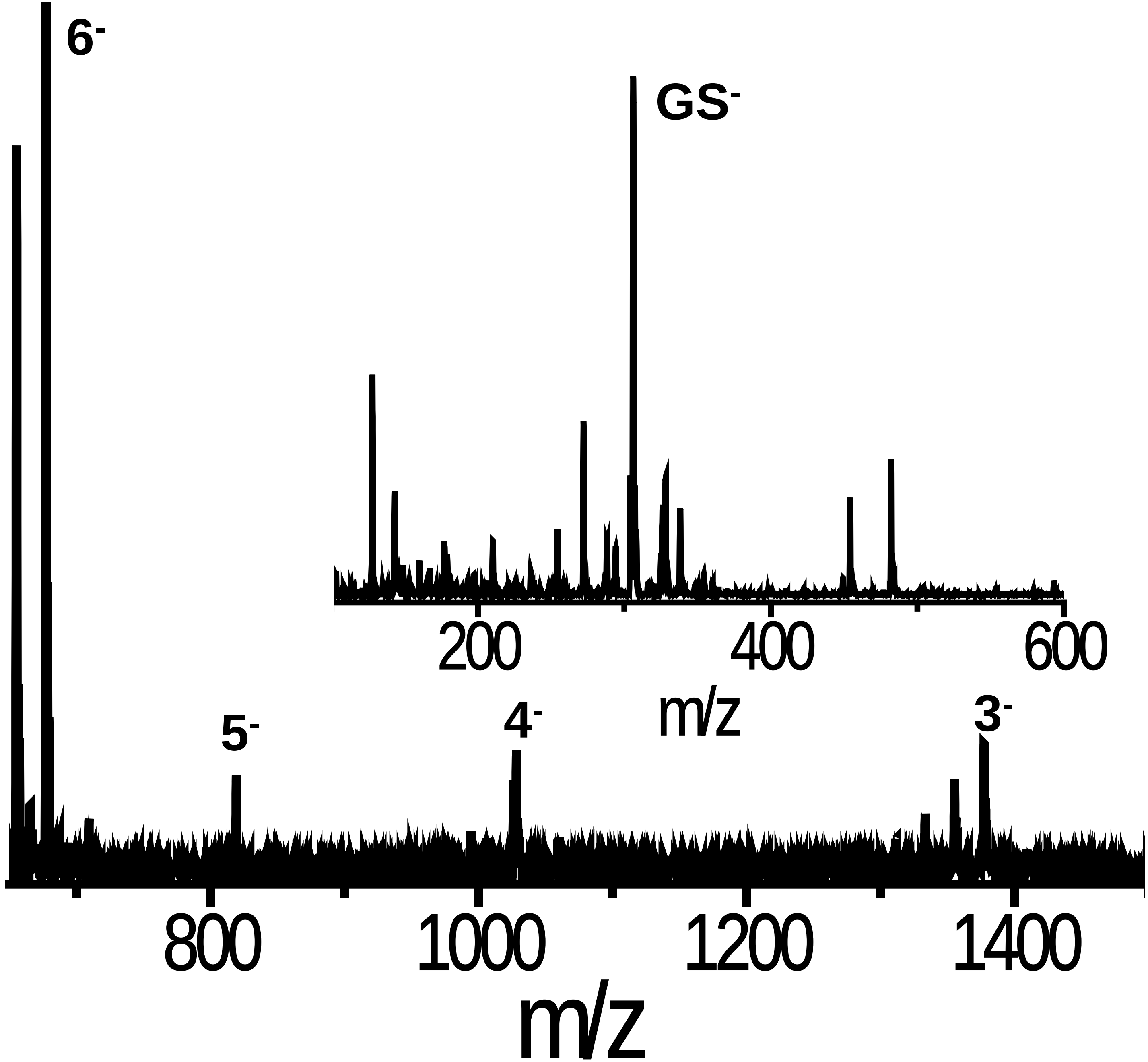


Comparison of the optical absorption profiles of Au@MSA, Au_{25} and Au_8.

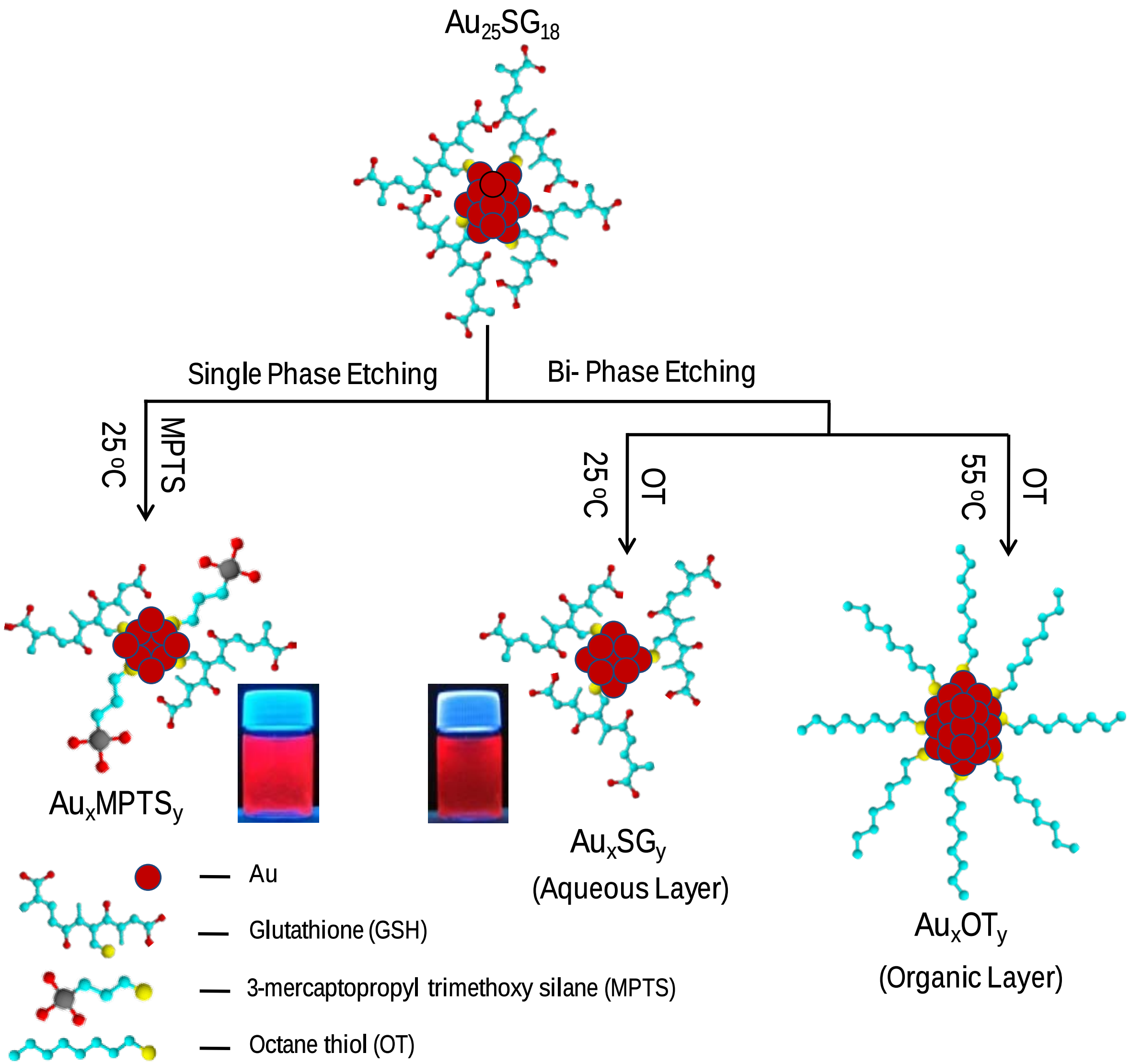


Comparison of the photoluminescence profiles of the clusters with Au@MSA. Traces I and II are the excitation and emission spectra of Au_8, respectively. Traces III and IV are the excitation and emission spectra of Au_{25}, respectively and trace V is the emission spectrum of Au@MSA.

Habeeb Muhammed *et al. Nano Res.* **2008**, *1*, 333.

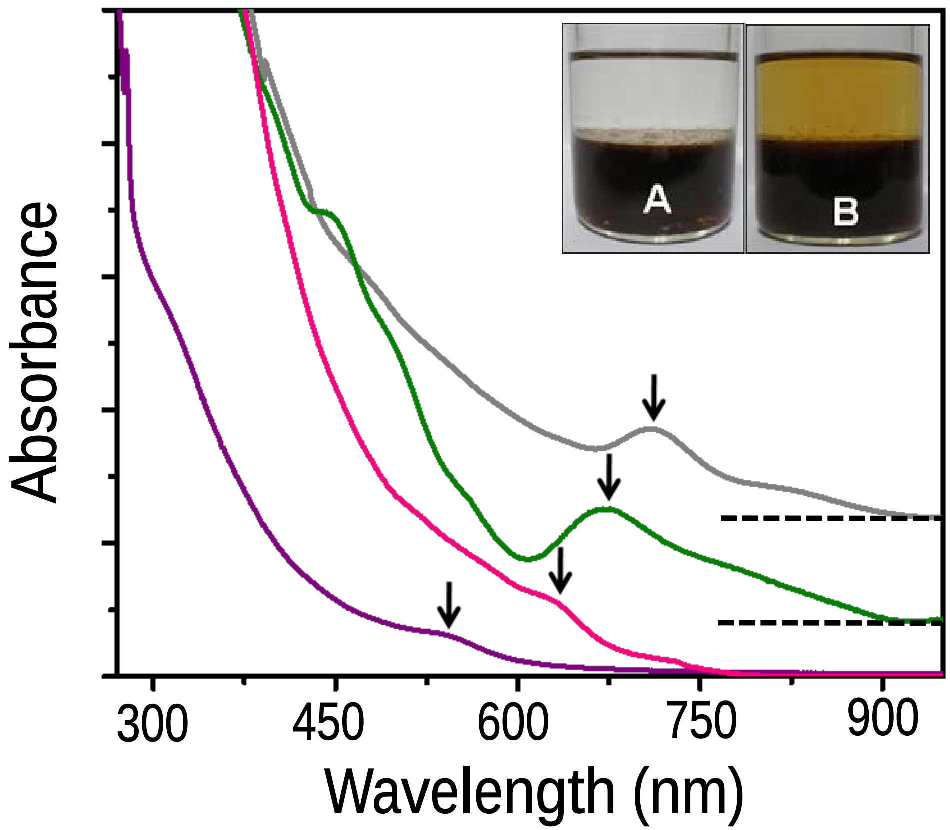


Habeeb Muhammed *et al*. Unpublished



Scheme 1. Formation of the three sub-nanoclusters from $Au_{25}SG_{18}$ by core etching by two routes. Photographs of the cluster aqueous solutions under UV light are also given.

Habeeb Muhammed *et al. Chem. Euro. J.* **2009**, *15*, 10110.



Comparison of the optical absorption features of $Au_{25}SG_{18}$ (green trace) with Au_xOT_y (grey trace), Au_xSG_y (pink trace) and Au_xMPTS_y (purple trace). The arrows show the absorption peaks of the clusters due to intra band transitions. The spectra are shifted vertically for clarity. Dotted lines indicate the threshold of absorption. Inset shows the photographs (under white light) of the water-toluene bi-phasic mixture before (A) and after (B) reaction at 55 ºC (interfacial etching) for 1 h.

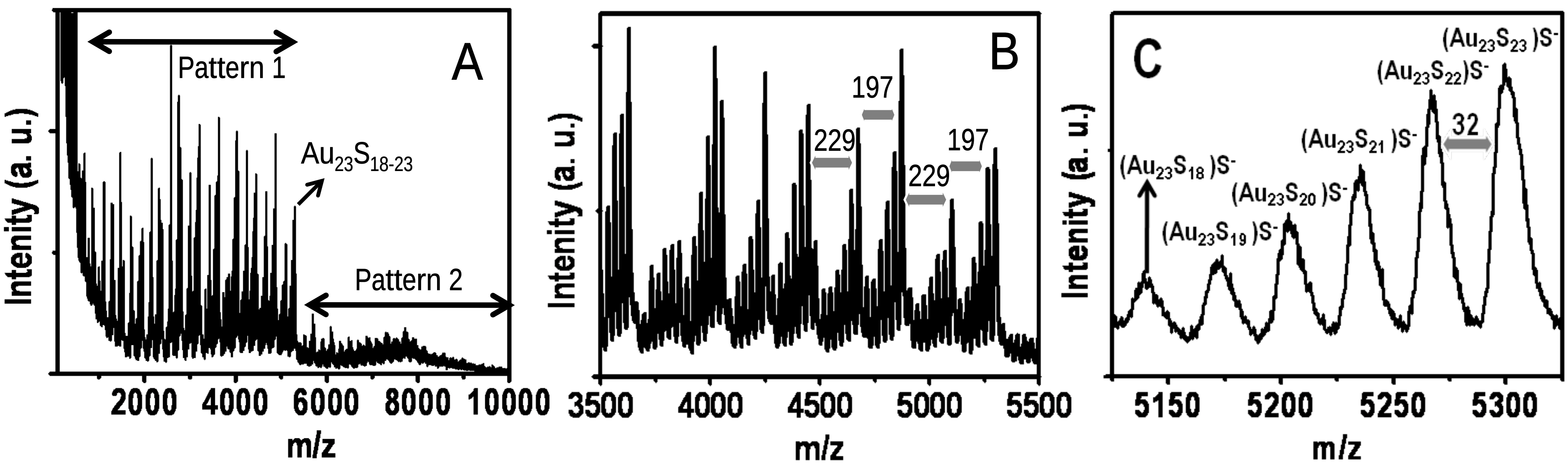
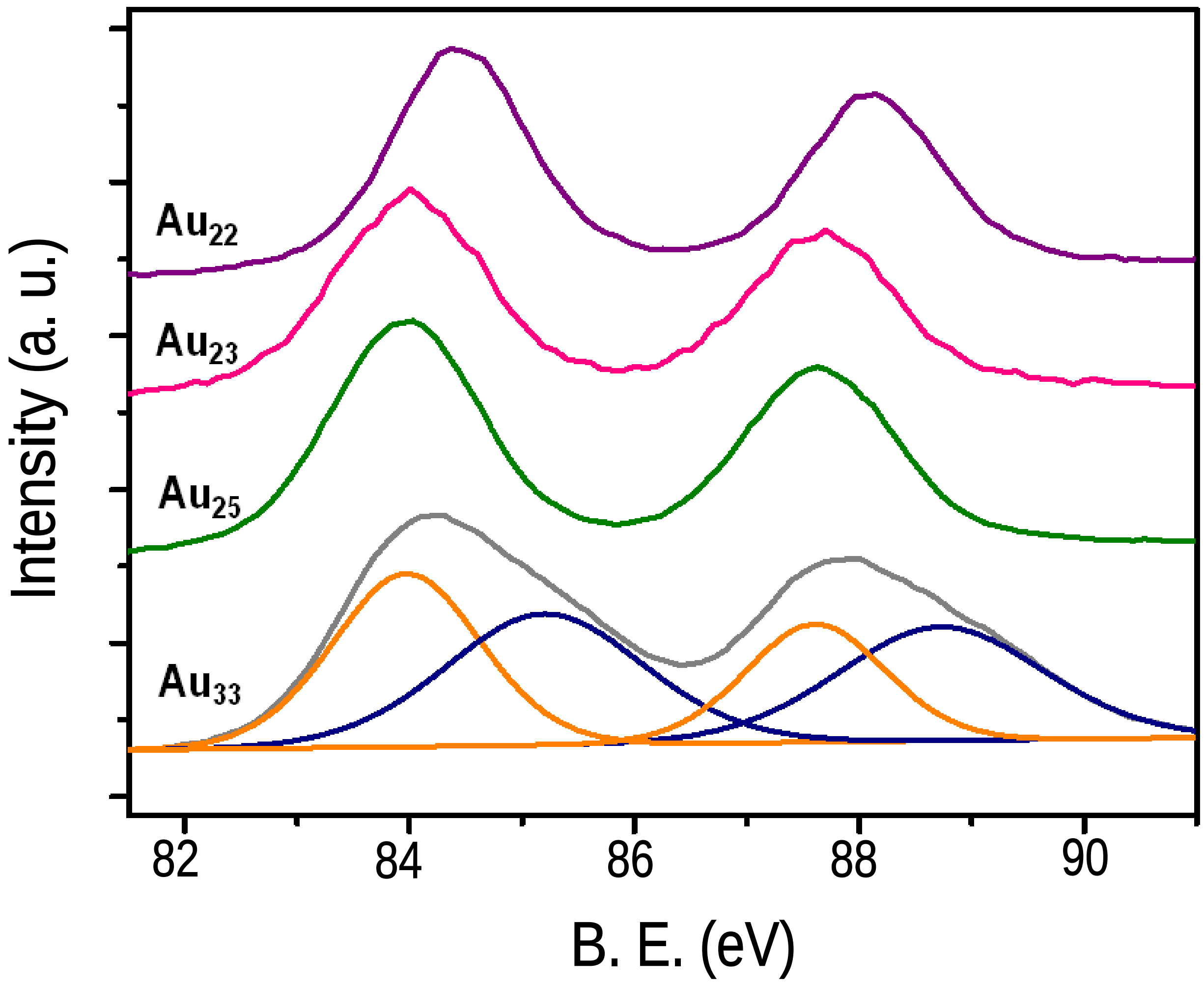
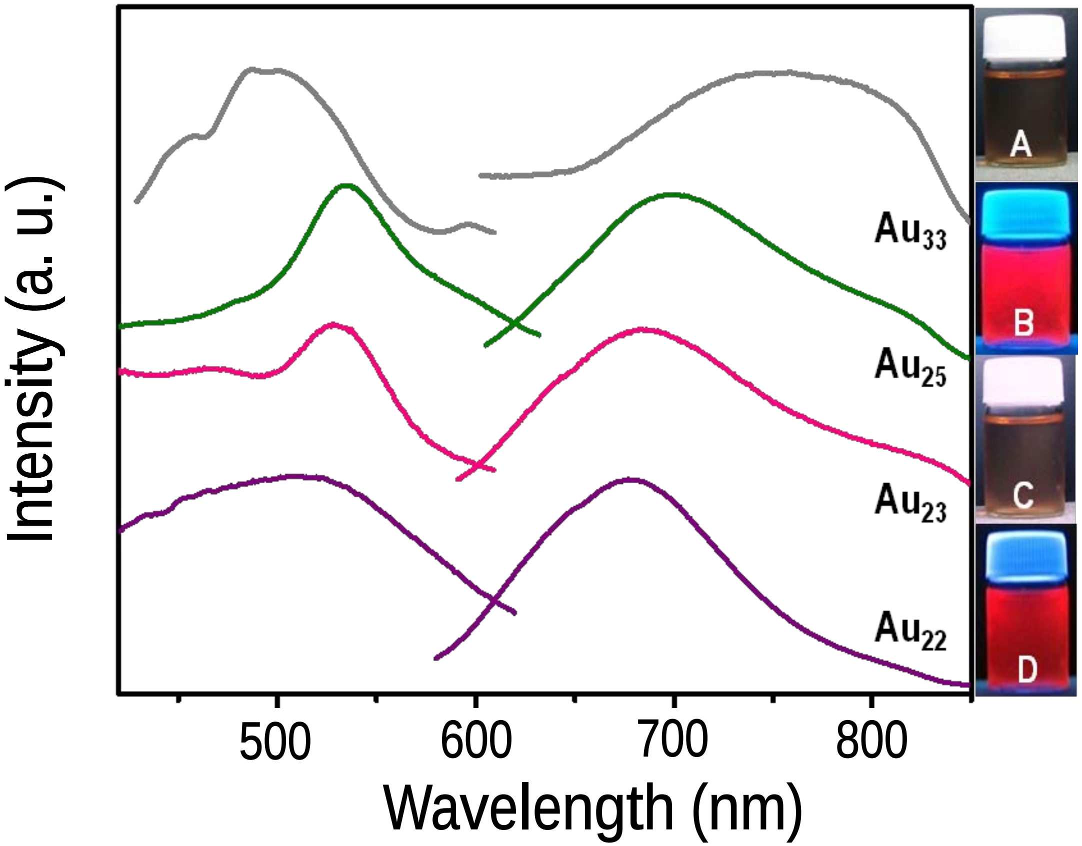


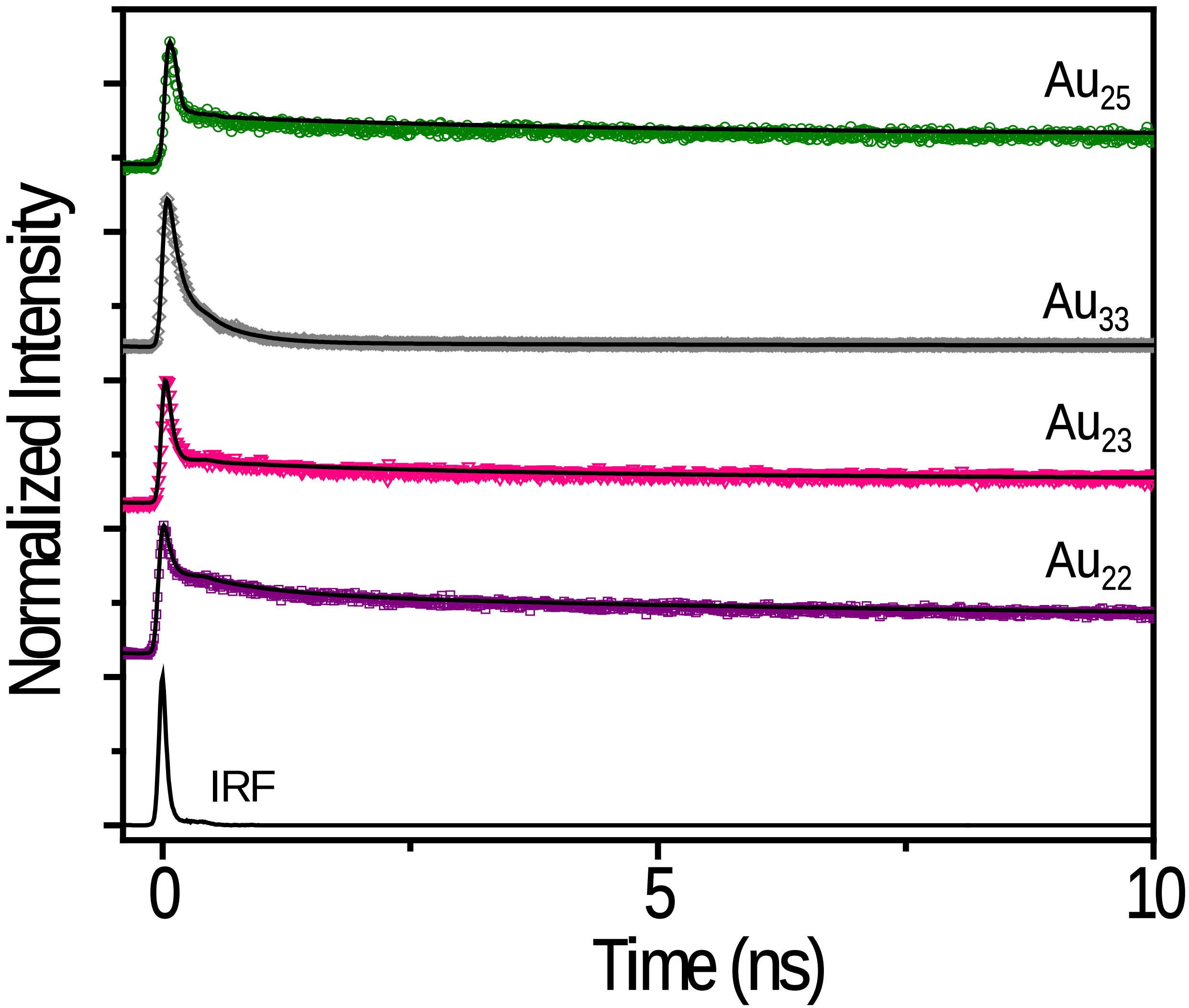
Figure 2. A) MALDI-MS of Au_xSG_y which shows bunch of peaks due to Au_mS_n clusters. B) A group of peaks with m/z spacing of 197 or 229 between the major peaks of the adjacent group of peaks. C) Expanded view of peaks due to $Au_{23}S_{18-23}$.



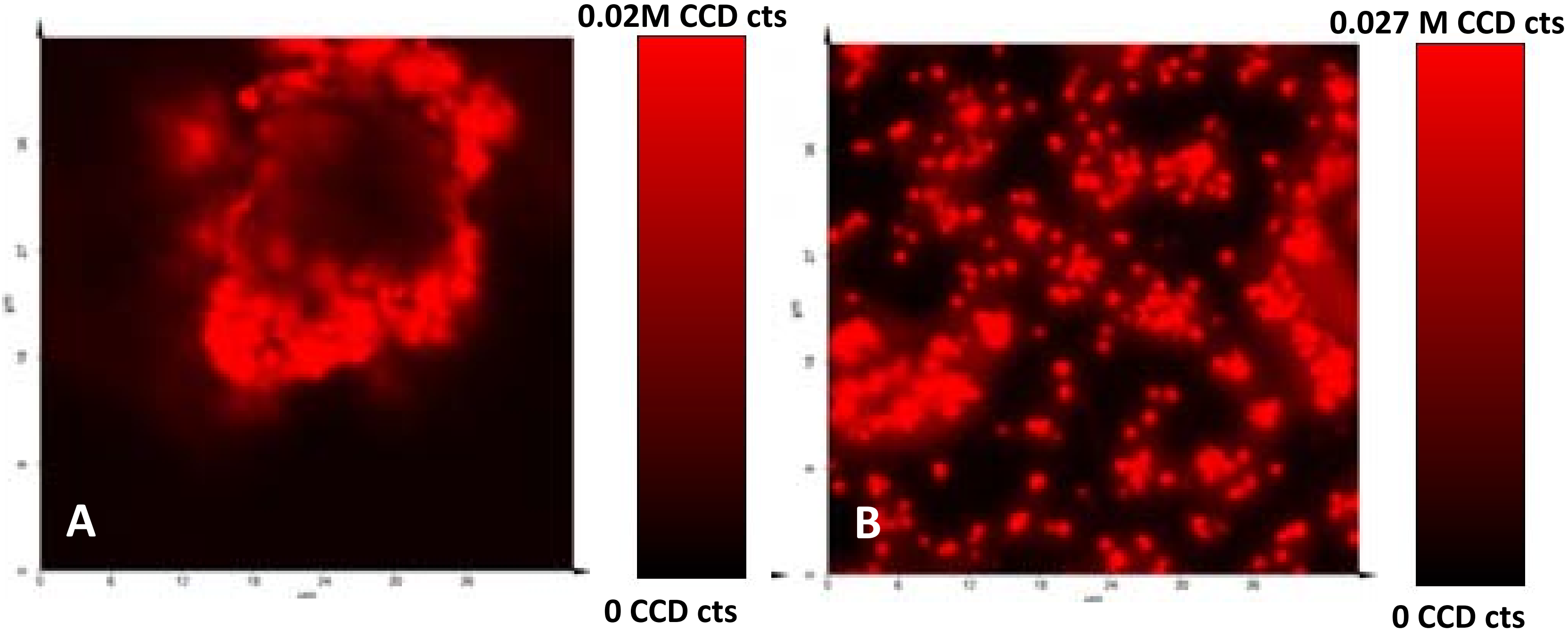
Comparison of the Au(4f) XPS spectra of Au_{22}, Au_{23} and Au_{33} along with parent Au_{25}.



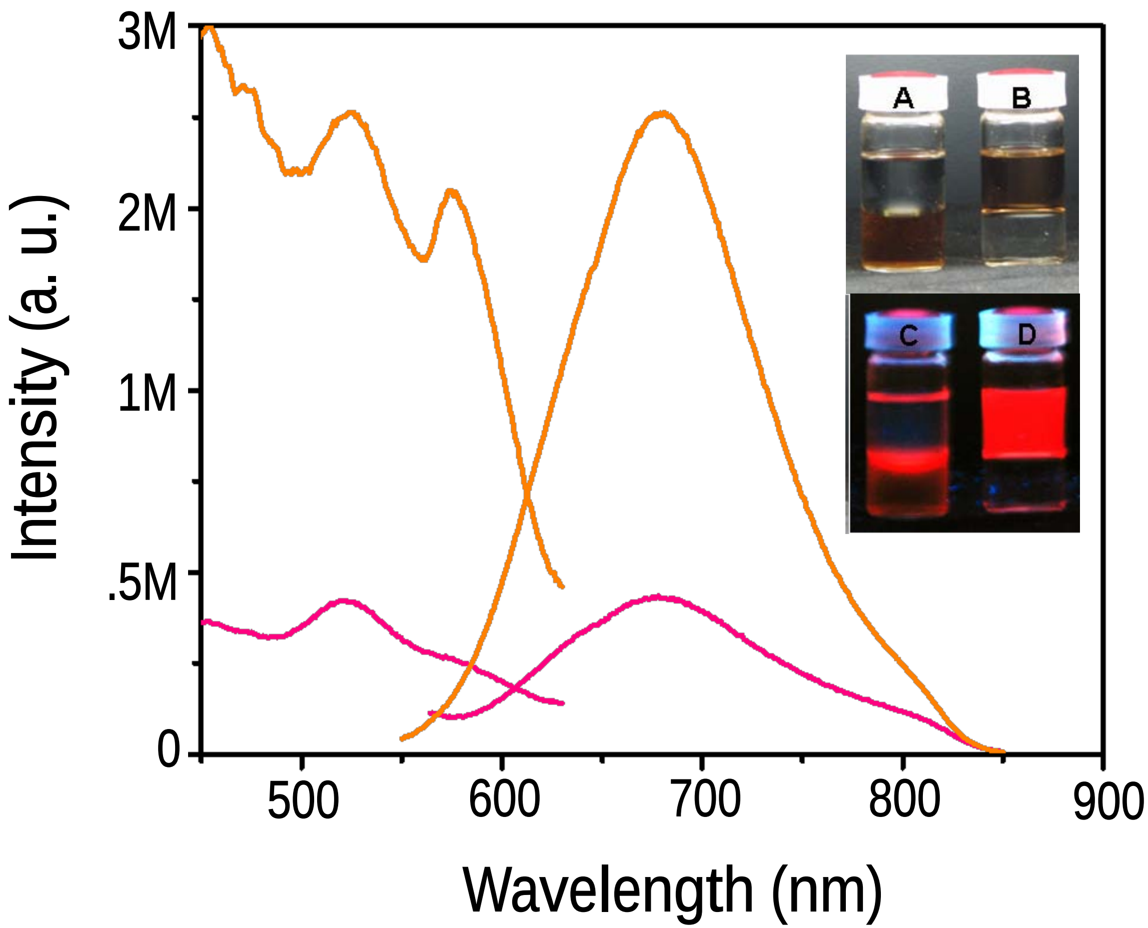
Comparison of the photoluminescence profiles of Au_{22}, Au_{23} and Au_{33} along with parent Au_{25}. Photographs of the aqueous solutions of Au_{22} and Au_{23} under white light (A and C, respectively) and UV light (B and D, respectively) are also given.



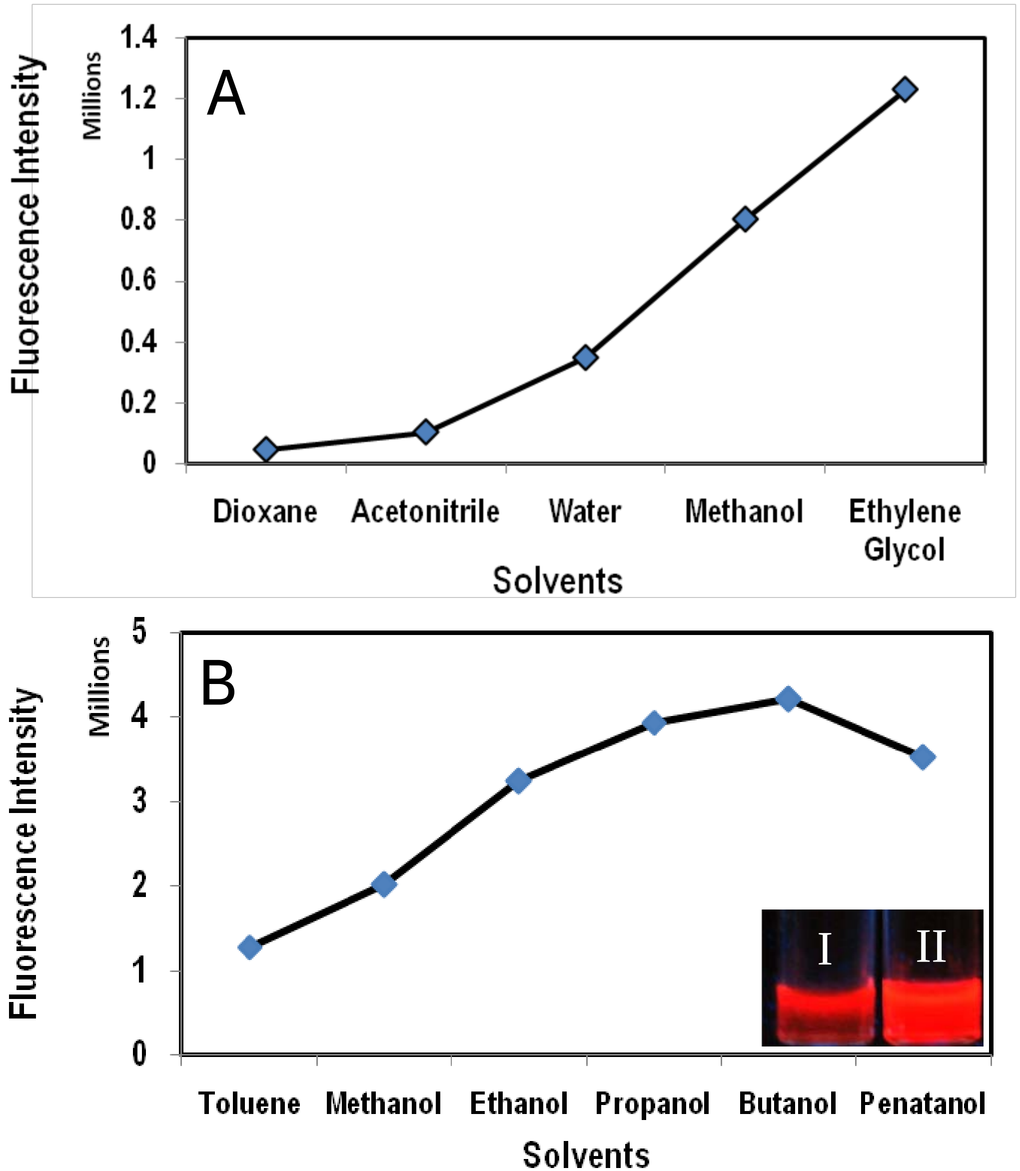
Fluorescence decay pattern of Au_{25}, Au_{33}, Au_{23}, and Au_{22} collected at 630 nm.



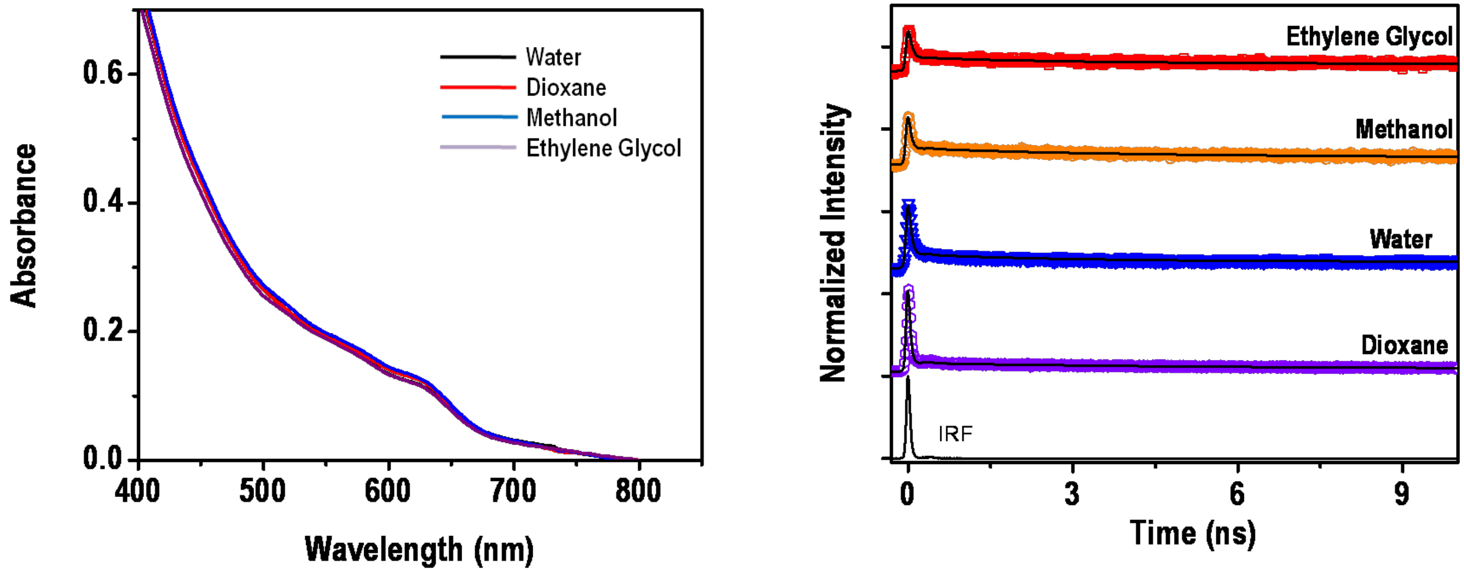
Inherent fluorescence image of Au_{22} (A) and Au_{23} (B) collected by the spectroscopic mapping at an excitation wavelength of 532 nm. Regions coded red represents the pixels where the signal (used for mapping) is a maximum, the minima being represented with black colors. The scan area was 40 µM x 40 µM.



Photoluminescene profile of Au_{23} cluster before (pink trace) and after (orange trace) phase transfer. Emission of the cluster enhances considerably after the phase transfer. Photographs of the aqueous-toluene mixture containing the cluster before and after phase transfer under white light (A and B, respectively) and UV light (C and D, respectively). In C, only the interface is illuminated as the UV is attenuated as the sample was irradiated from the top

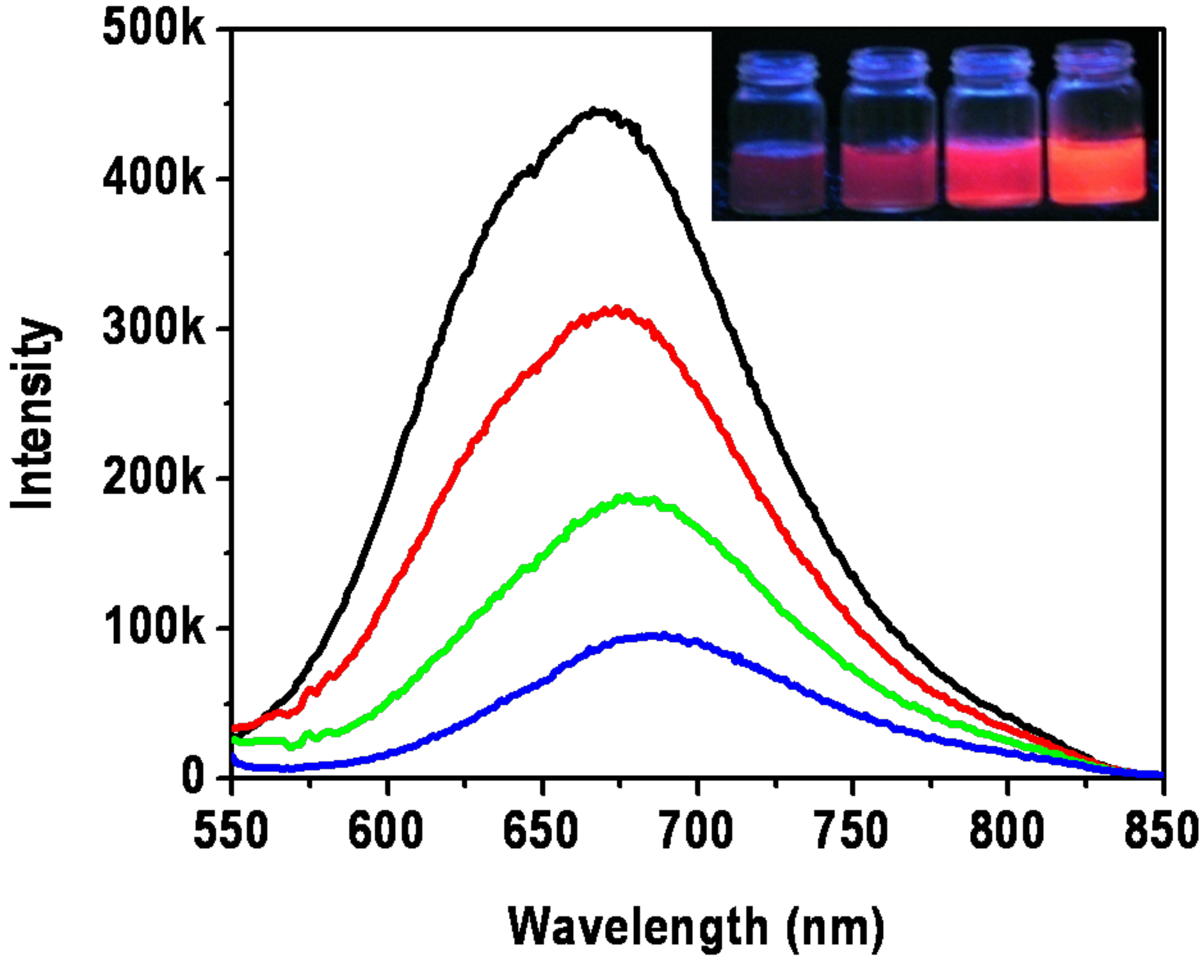


A) Solvent dependent fluorescence of 50 μM Au_{23} in ethylene glycol, methanol, water, acetonitrile and dioxane before phase transfer. B) Solvent dependent fluorescence of Au_{23} in methanol, ethanol, propanol, butanol and pentanol after phase transfer. Inset of B shows the photograph of phase transferred Au_{23} in toluene (I) and butanol (II) under UV light irradiation

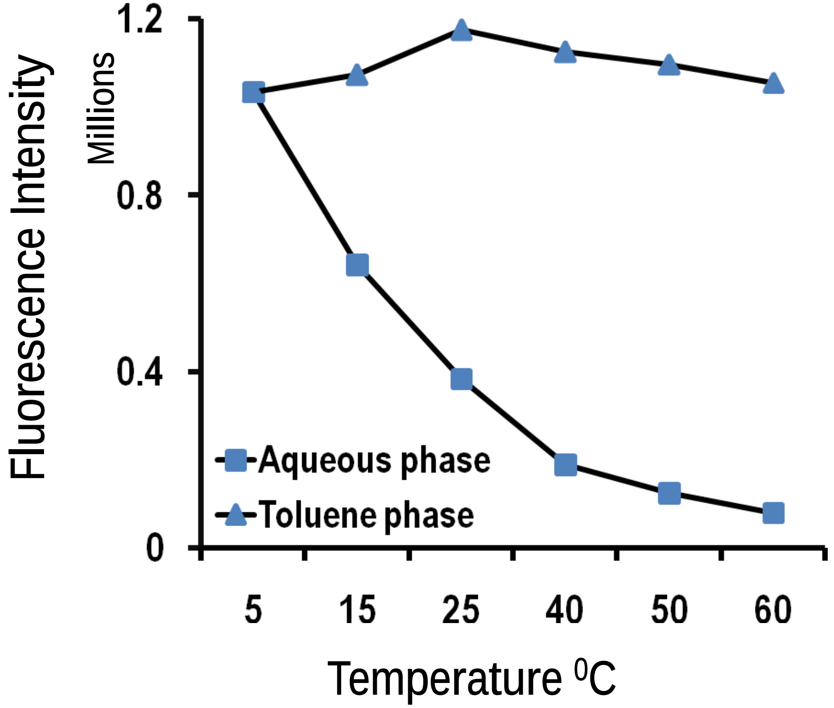


Solvent	τ_1 (ps)	%	τ_2 (ns)	%	τ_3 (ns)	%
Ethylene Glycol	47	86.5	2.67	5.5	70.06	7.9
Methanol	36	87.6	3.27	5.8	62.91	6.6
Water	39	92.4	2.41	3.6	68.55	3.9
Dioxane	16	98.0	5.07	1.1	31.63	0.9

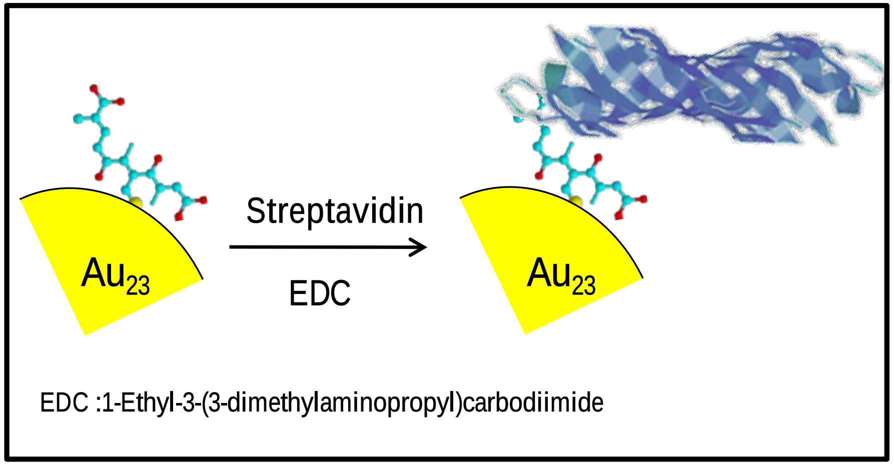
A) Optical absorption spectra of Au_{23} in dioxane, water, methanol and ethylene glycol. B) Fluorescence decay of Au collected at 630 nm in various solvents. Table tabulates the life time of the cluster in various solvents.



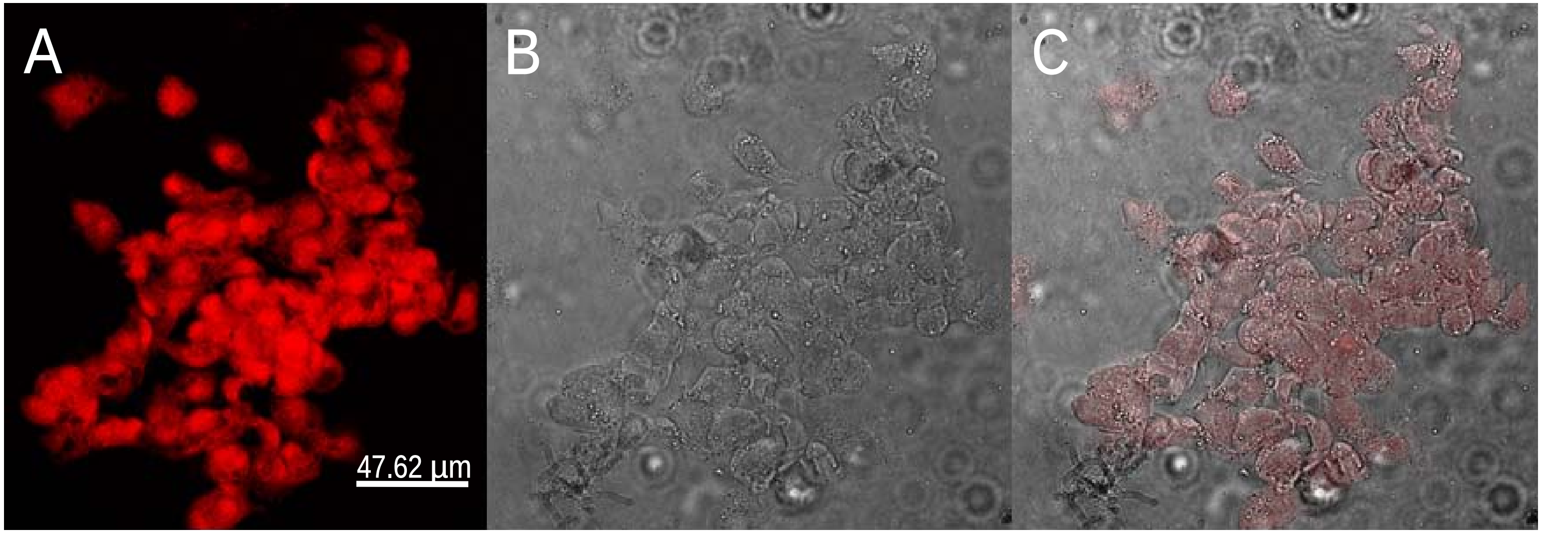
Plot of fluorescence intensity of Au_{23} cluster in water-DMSO mixture starting from pure water (blue line) to 1:1 (green line), 1:2 (red line) and 1:3 (black trace) water-DMSO mixtures. Inset shows the photographs of the corresponding solutions under UV light irradiation



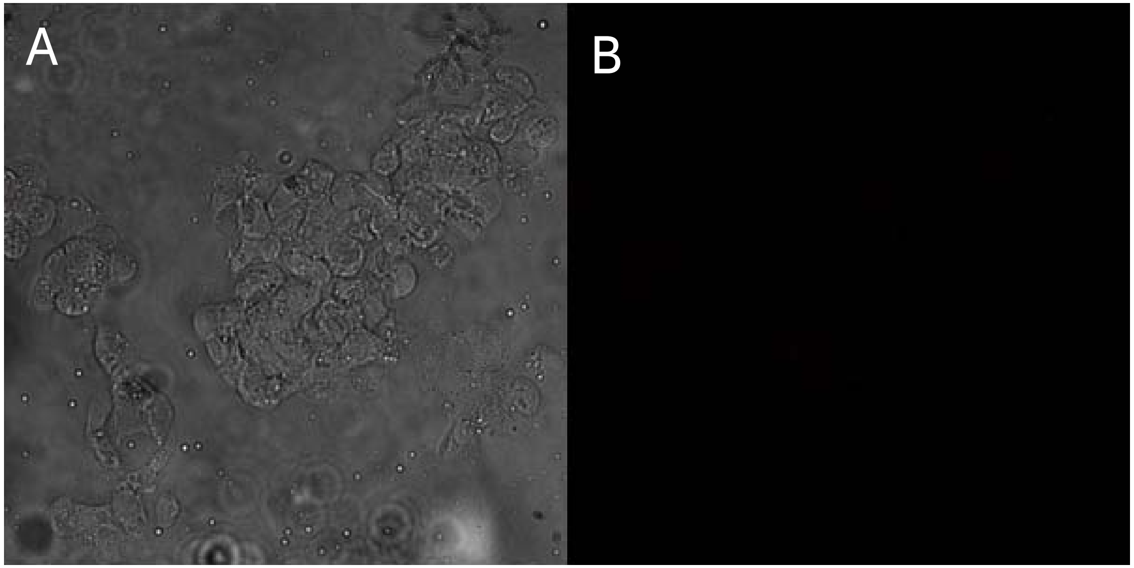
Plot of temperature *vs* fluorescence intensity of the cluster in the aqueous and toluene layers. While the intensity of emission of aqueous solution of Au_{23} decreases with increase in temperature, the emission intensity remains unaltered for phase transferred Au_{23}.



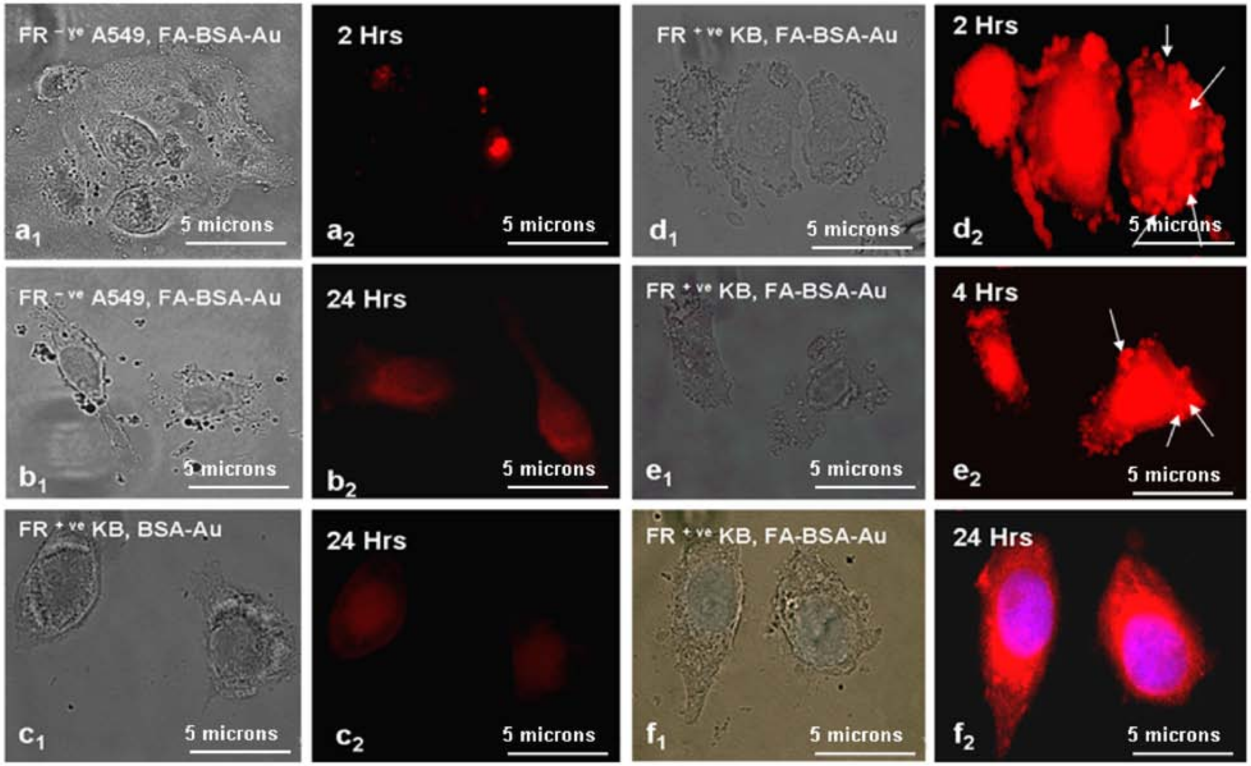
Schematic representation of the conjugation of streptavidin on $Au_{23}SG_{18}$ by EDC coupling.



Fluorescence (A), bright field (B) and overlay of fluorescent and bright field images (C) of human hepatoma (HepG2) cells stained with streptavidin conjugated Au_{23}.



Bright field (A) and fluorescence (B) images of HepG2 cells stained with unconjugated Au_{23} clusters. No fluorescence was observed from the cells after washing



Fluorescent microscopic images showing interaction of Au-BSA-FA NCs with different types of cell lines: a1-a2) FR-ve lung carcinoma A549 after 2 hours of incubation, b1-b2) FR-ve lung carcinoma A549 after 24 hours of incubation, c1-c2) FR+ve KB cells with unconjugated Au clusters, d1-d2) FR+ve KB cells with FA conjugated Au clusters at 2 hrs, e1-e2) 4 hrs and f1-f 2) 24 hrs of incubation [Archana R, Sonali S, Deepthy M et al (2009) Molecular Receptor Specific, Non-toxic, Near-infrared Emitting Au Cluster-Protein Nanoconjugates for Targeted Cancer Imaging. Nanotechnology (in press)]

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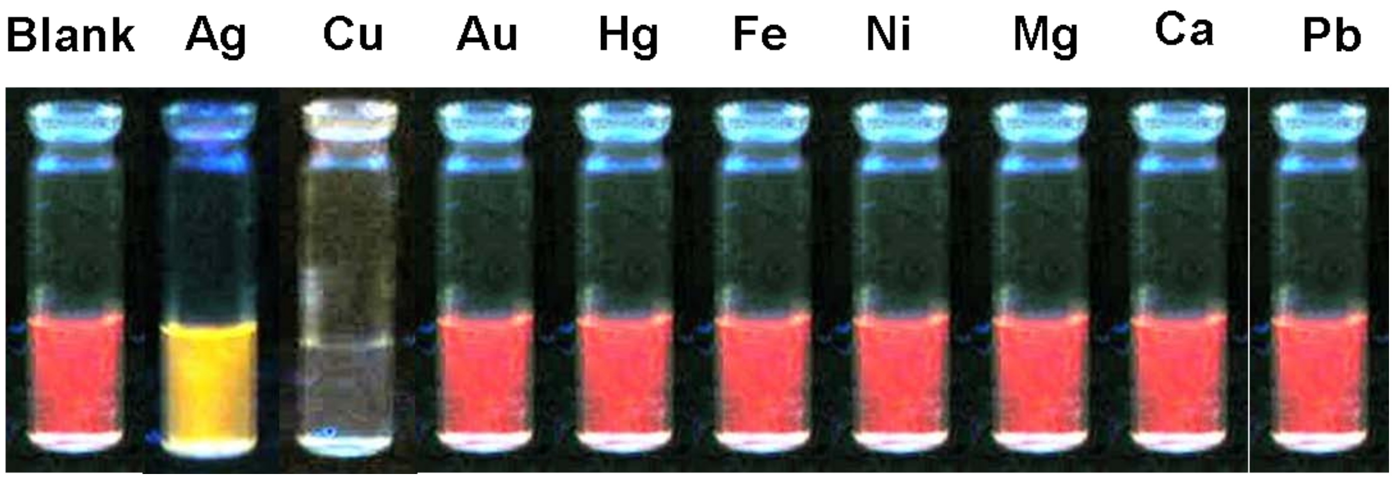
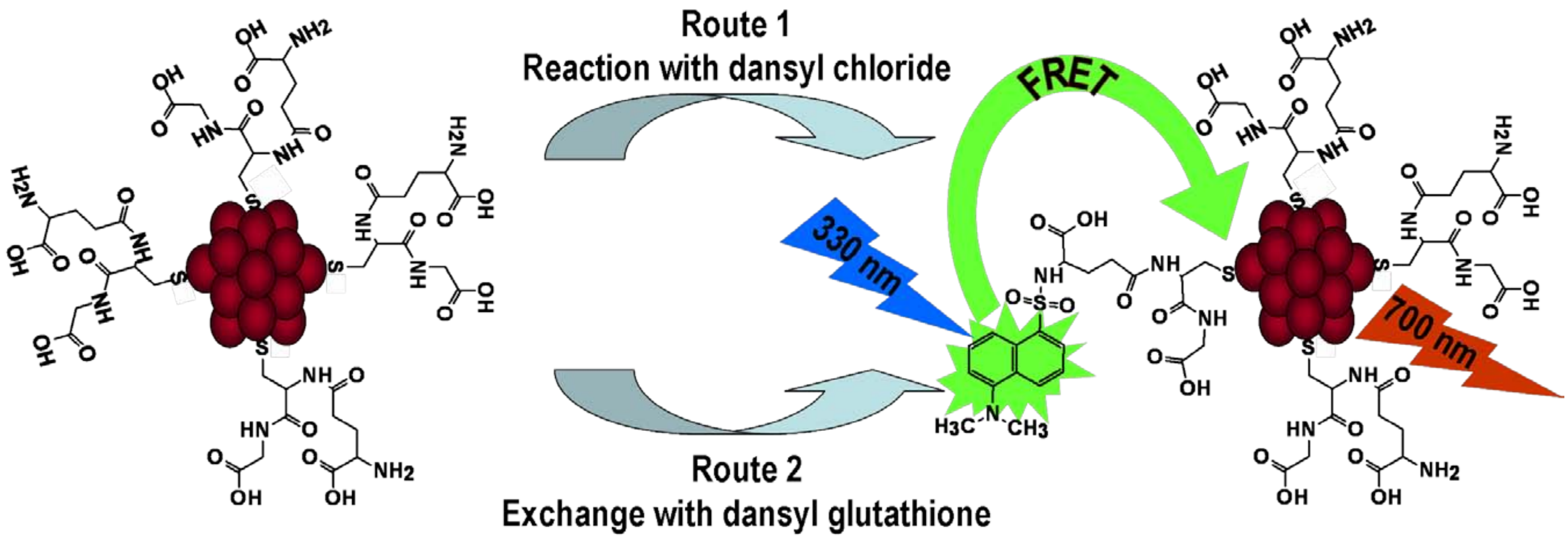
Clusters for metal ion detection



Water soluble red emitting clusters where treated with various metal ions with a final Concentration of 25 ppm. The emission was shifted to lower wavelength in case of silver ions and quenched completely in case of copper ions. The emission was an altered in case of other ions.

Habeeb Muhammed *et al. Chem. Euro. J.* **2009**, *15*, 10110.

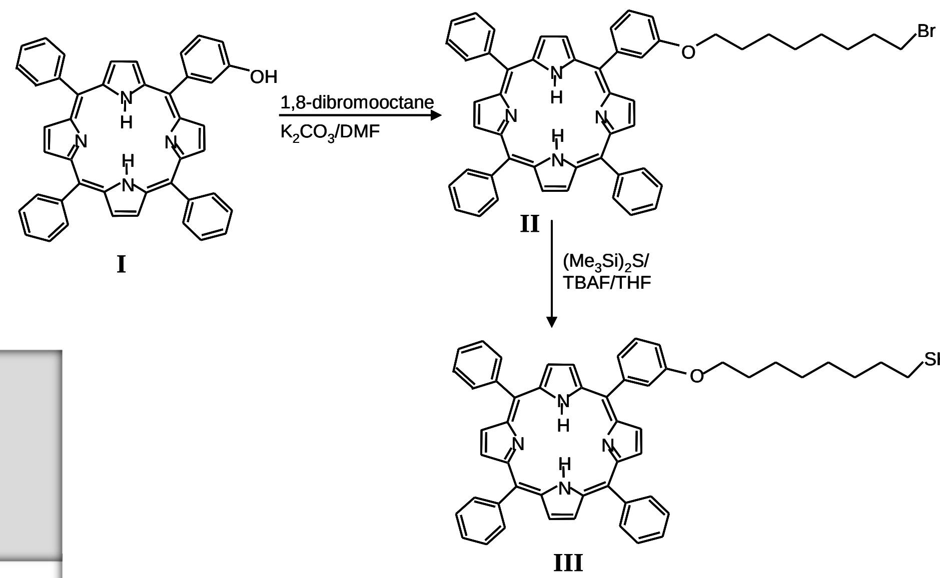
FRET between Au_{25} and Dansyl Chromophore

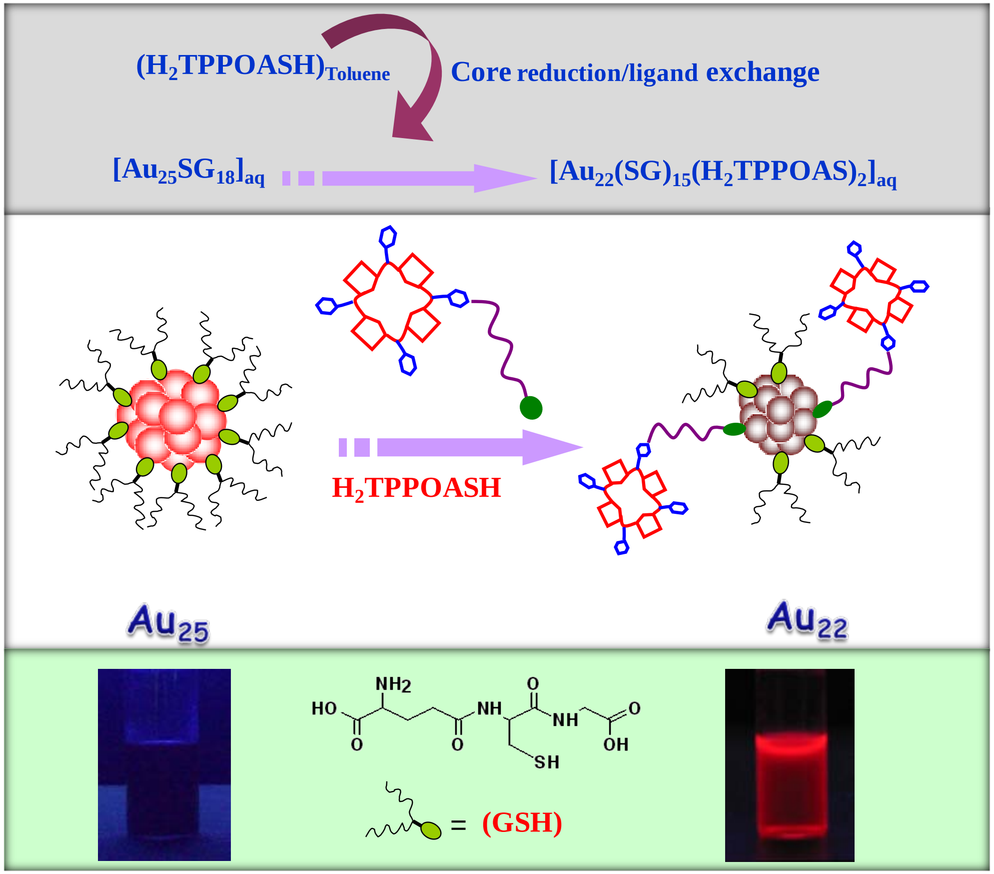


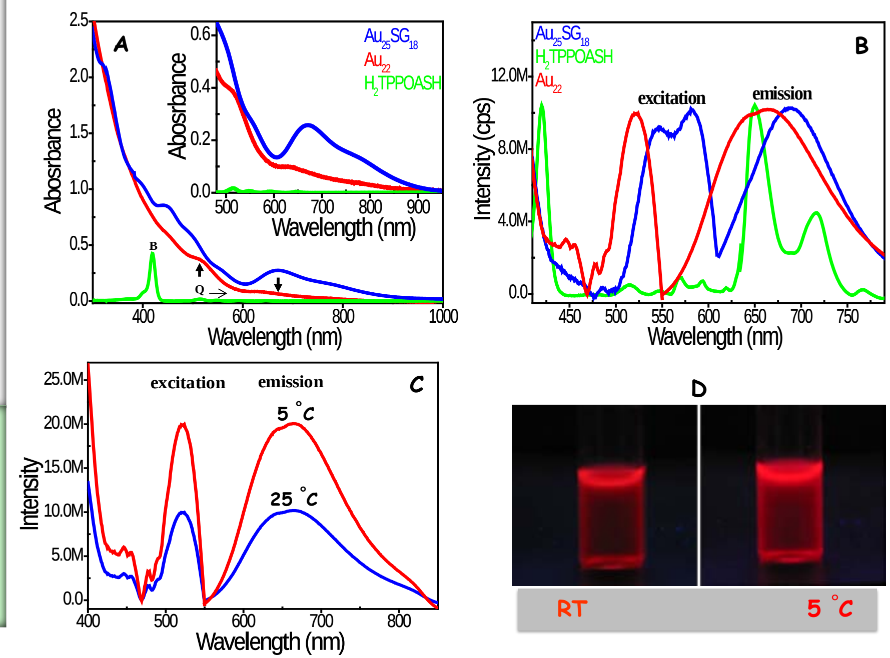
Approaches Used for the Functionalization of Dansyl Chromophore on the Au_{25} Cluster.

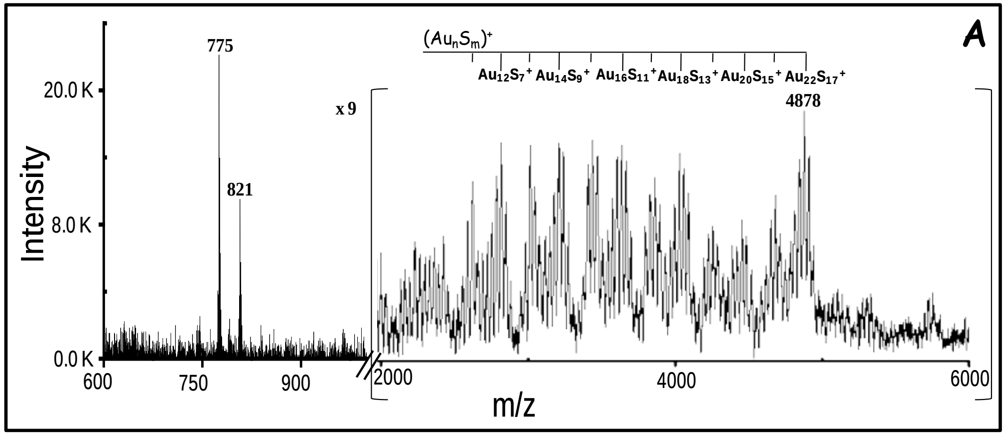
Habeeb Muhammmed *et al. J. Phys. Chem. C* **2008**, *112*, 14324.

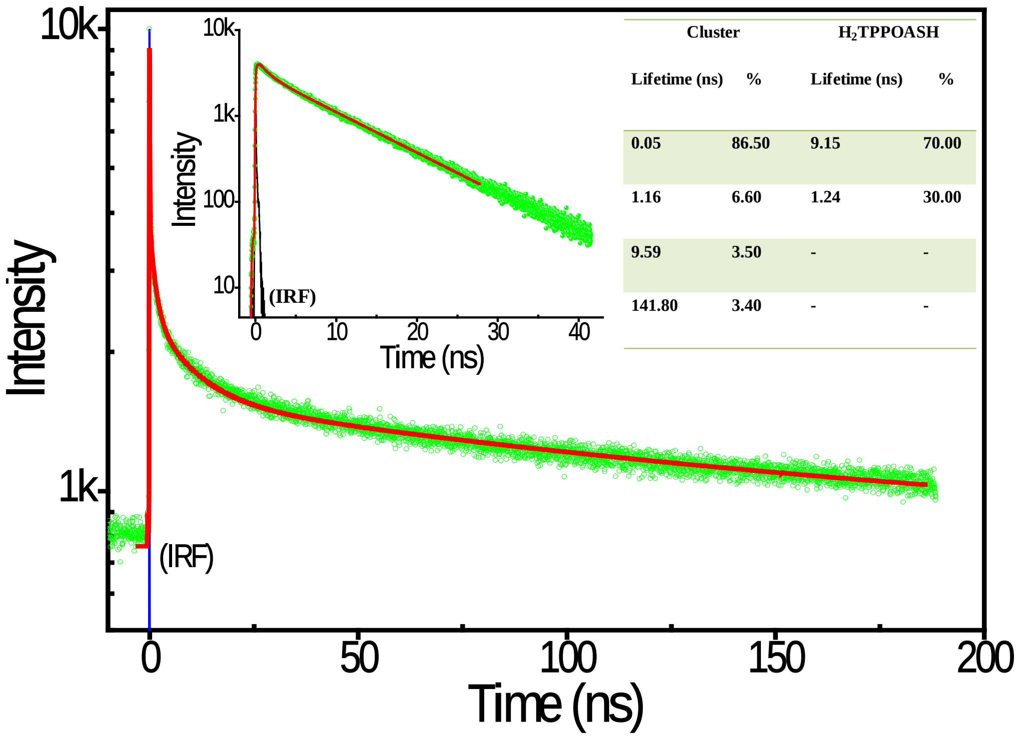
Cluster based patterns



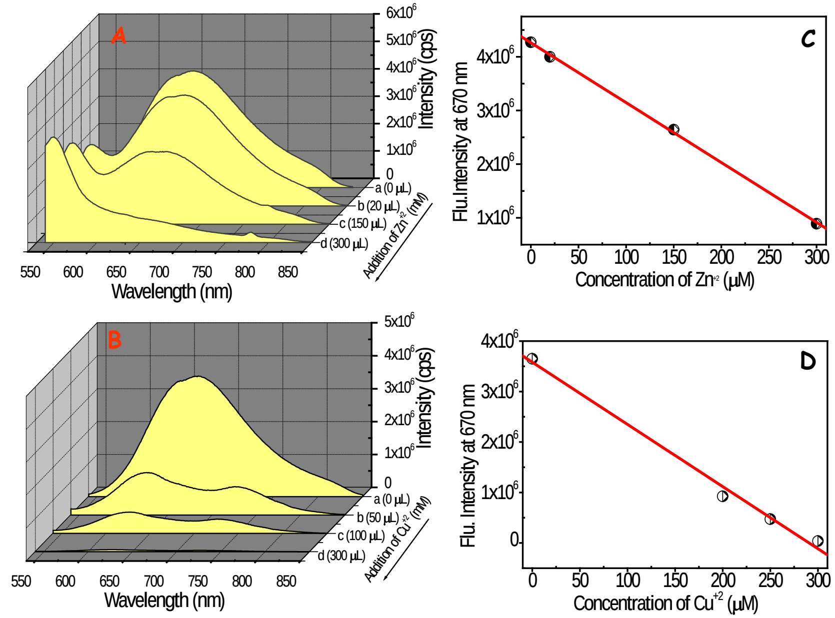




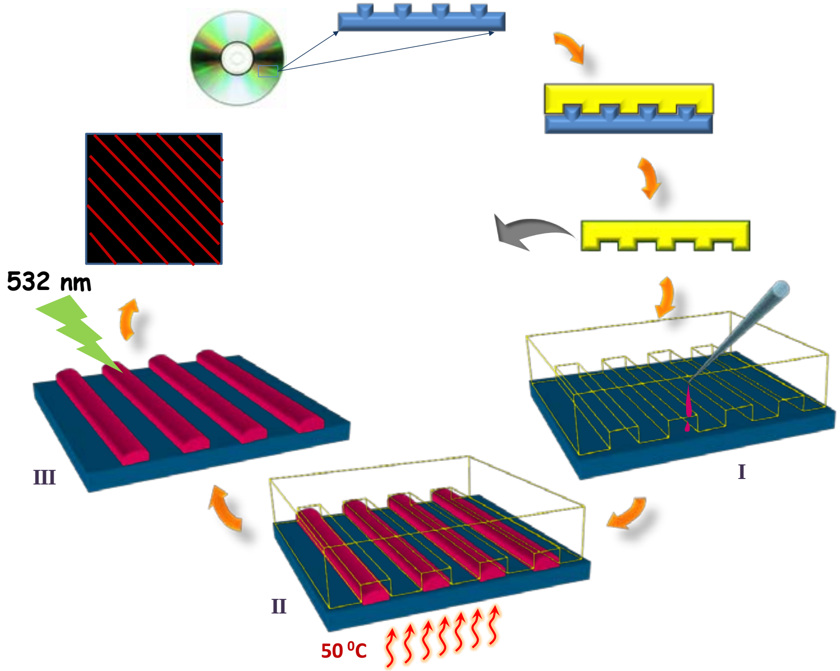


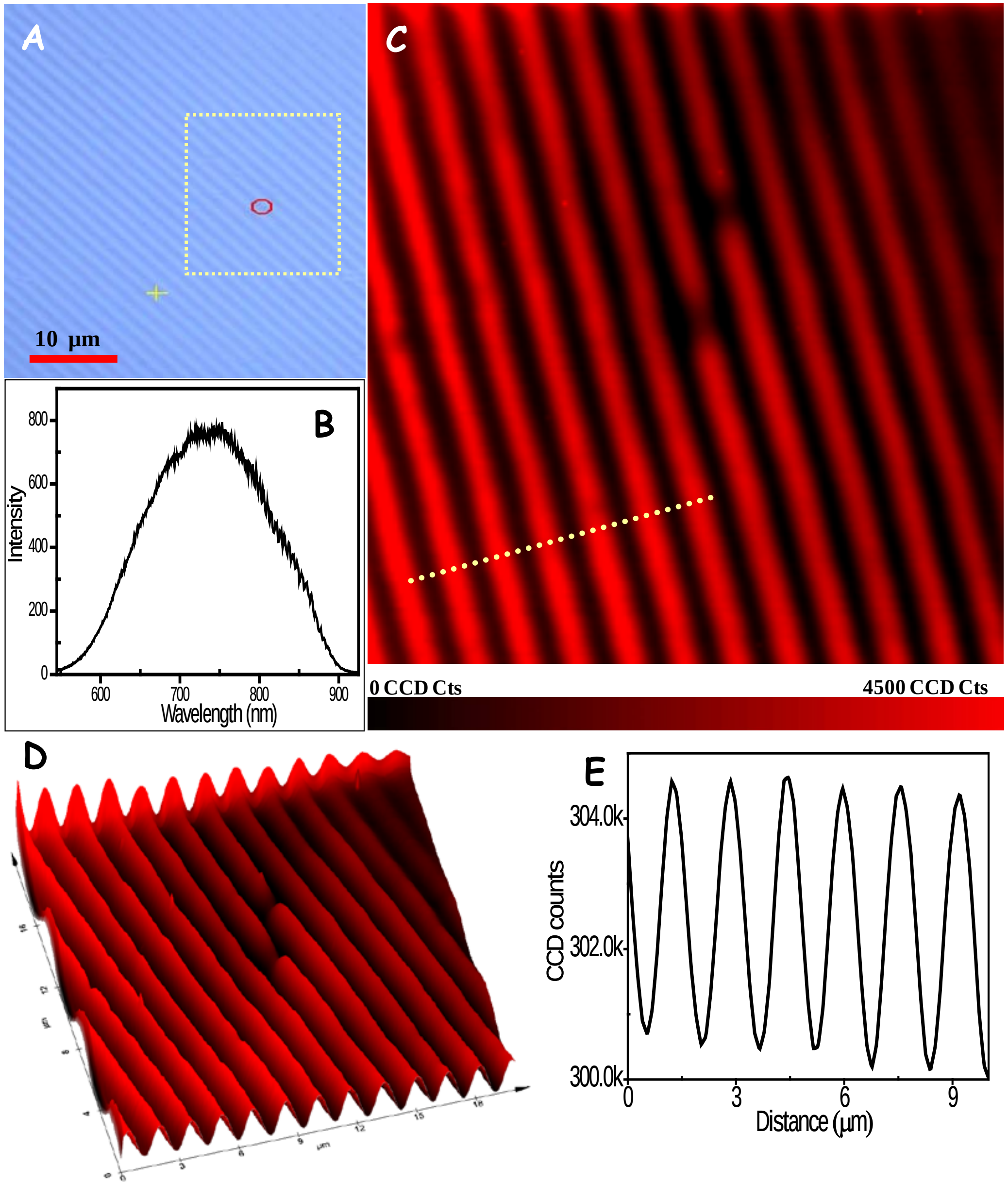


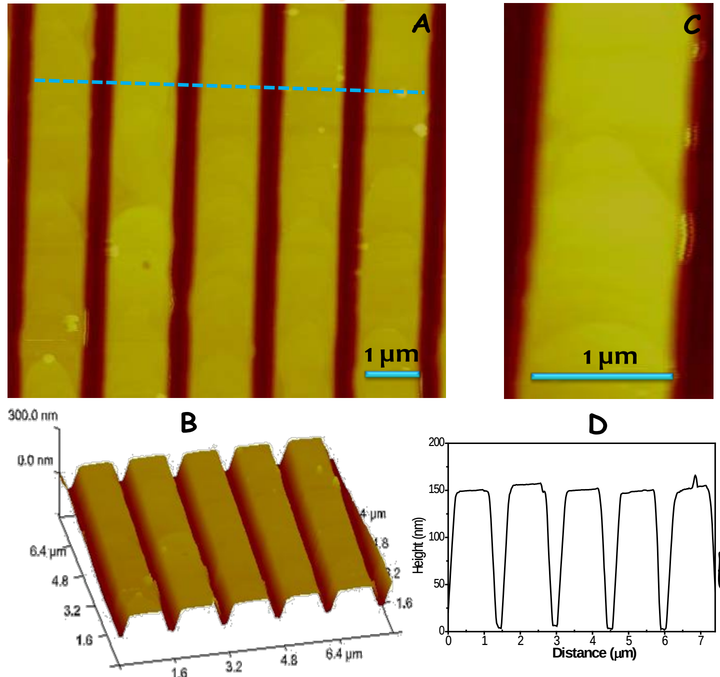
Cluster		$H_2TPPOASH$	
Lifetime (ns)	%	Lifetime (ns)	%
0.05	86.50	9.15	70.00
1.16	6.60	1.24	30.00
9.59	3.50	-	-
141.80	3.40	-	-



With G. U. Kulkarni

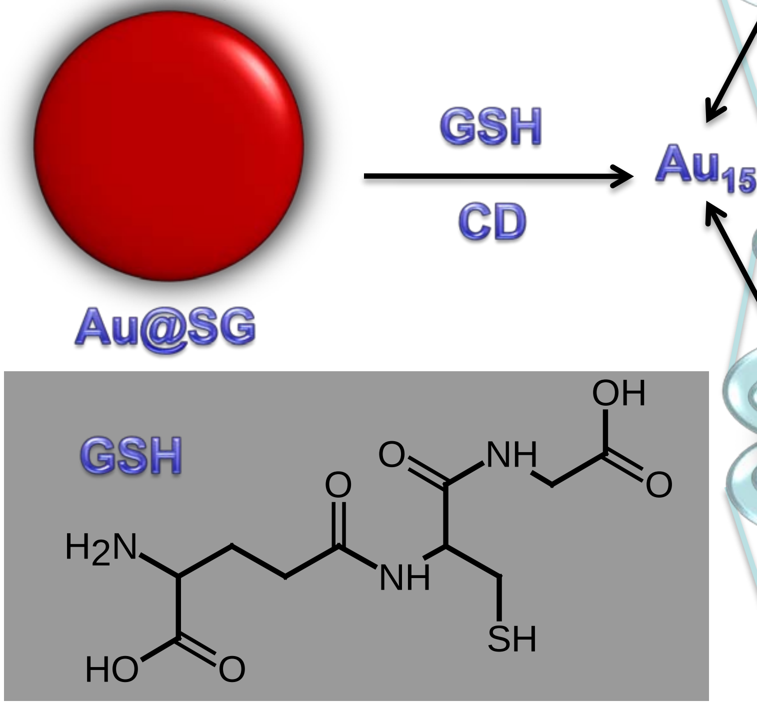


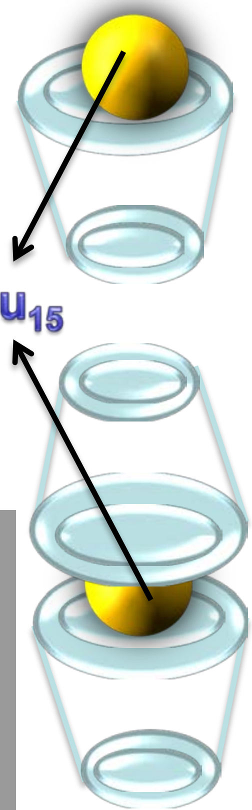


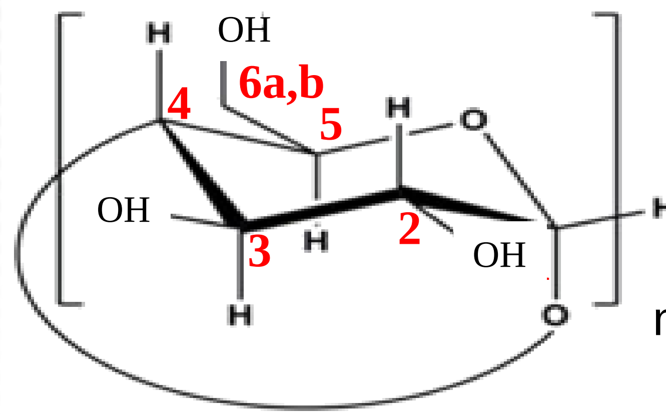


E. S. Shibu *et al. ACS Appl. Mater.* **2009**, *1*, 2199.

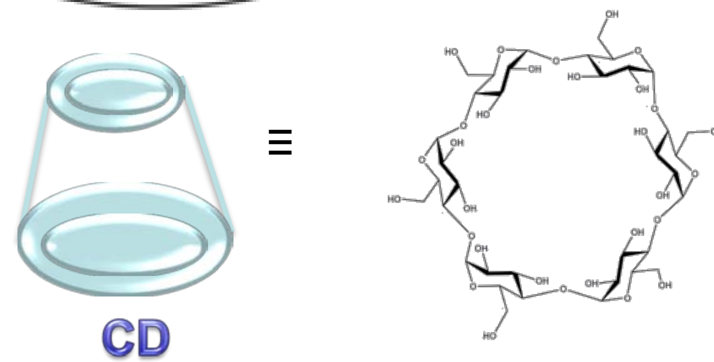
Au@SG – glutathione (GSH) protected gold nanoparticle



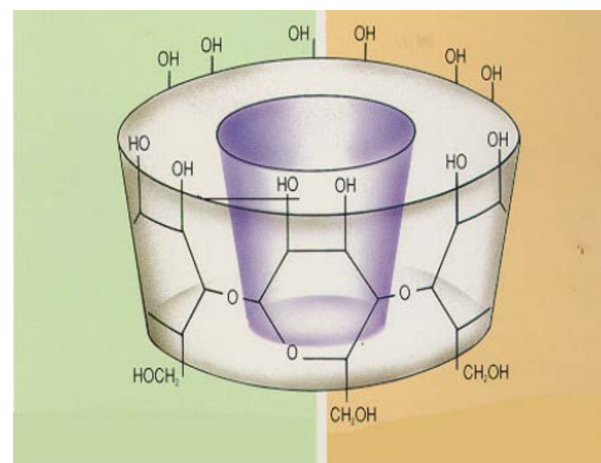




n= 6, 7, 8
6---alpha CD
7---beta CD
8---gamma CD



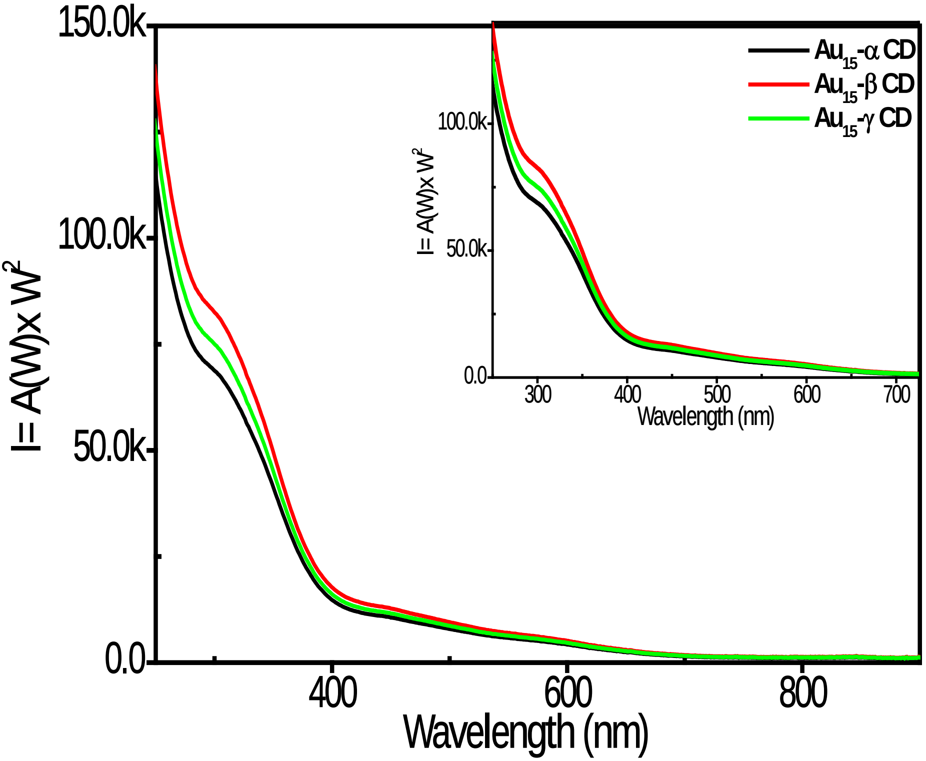
Basic unit of CD is 6 membered glucose

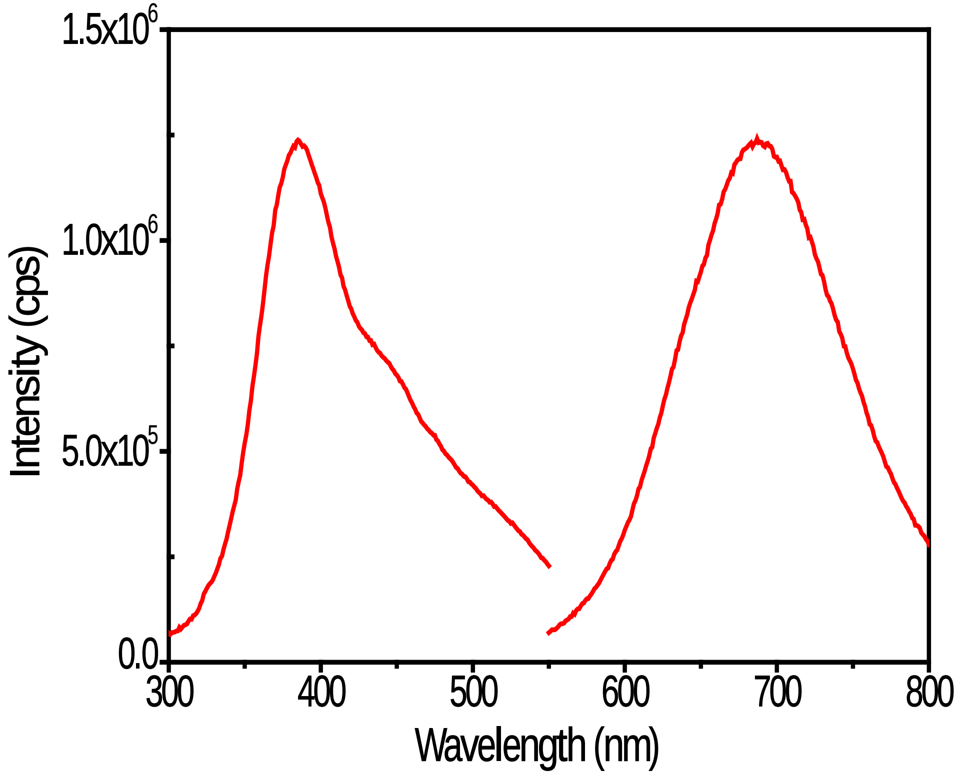


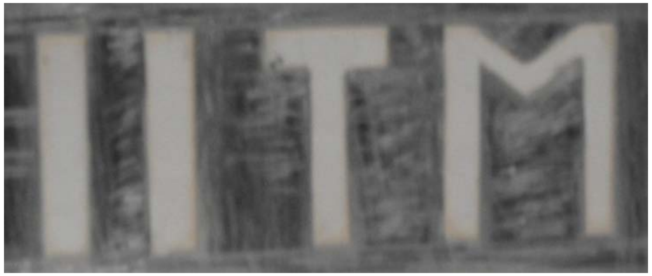
3D image of CD showing the nanometer cavity

Scheme: Au_{15} was synthesized inside the cyclodextrin (CD) cavity (*in situ*). Note: CD and GSH are the abbreviations of cyclodextrin and glutathione, respectively. For our synthesis we have used all 3 CDs (alpha, beta and gamma)

E. S. Shibu and T. Pradeep. Unpublished

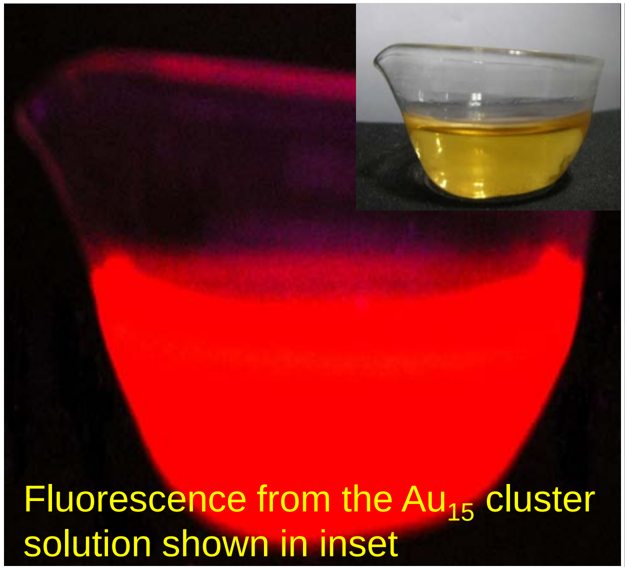




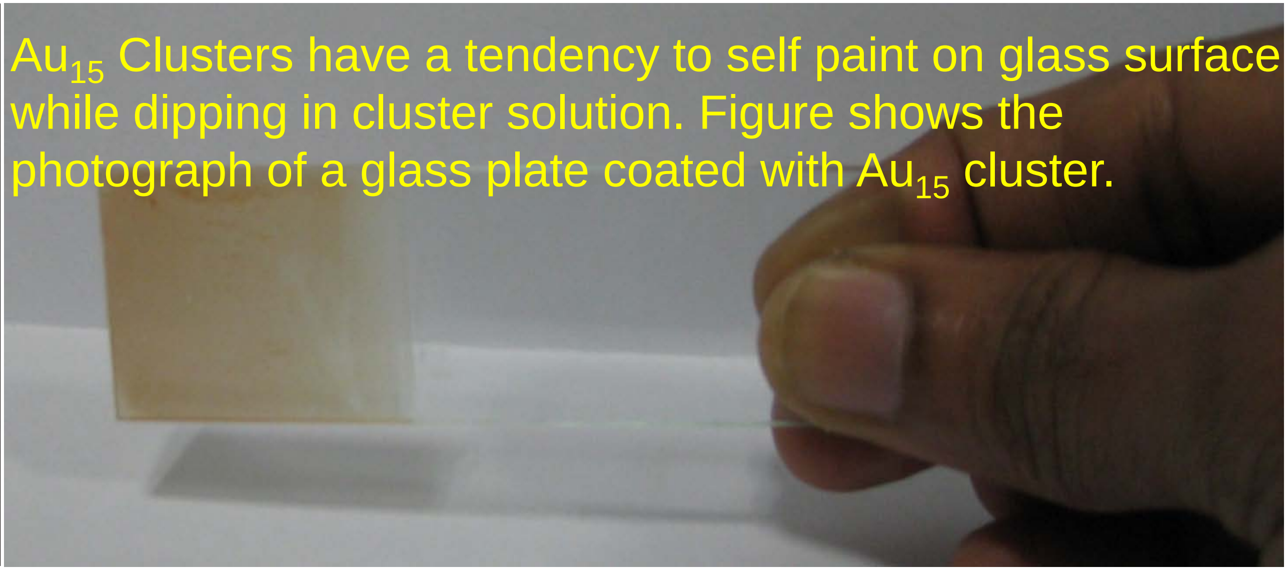


E. S. Shibu and T. Pradeep. Unpublished

Glass coating and fluorescence

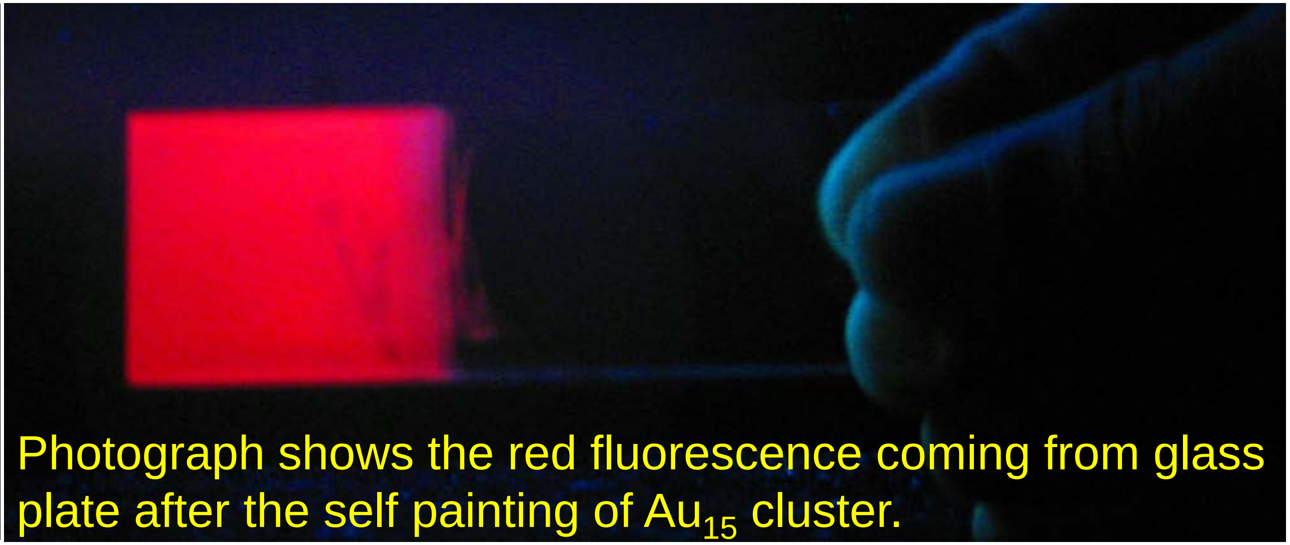


Fluorescence from the Au_{15} cluster solution shown in inset



Au_{15} Clusters have a tendency to self paint on glass surface while dipping in cluster solution. Figure shows the photograph of a glass plate coated with Au_{15} cluster.

The red fluorescence coming from glass after decanting the cluster solution



Photograph shows the red fluorescence coming from glass plate after the self painting of Au_{15} cluster.

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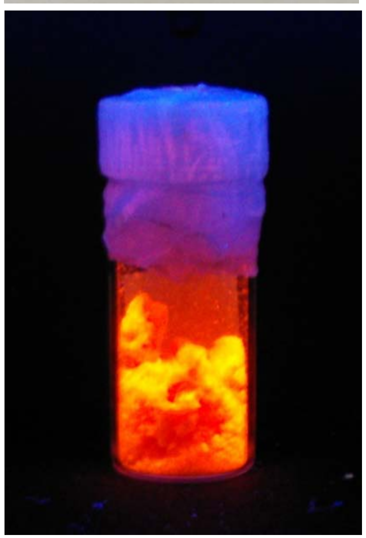
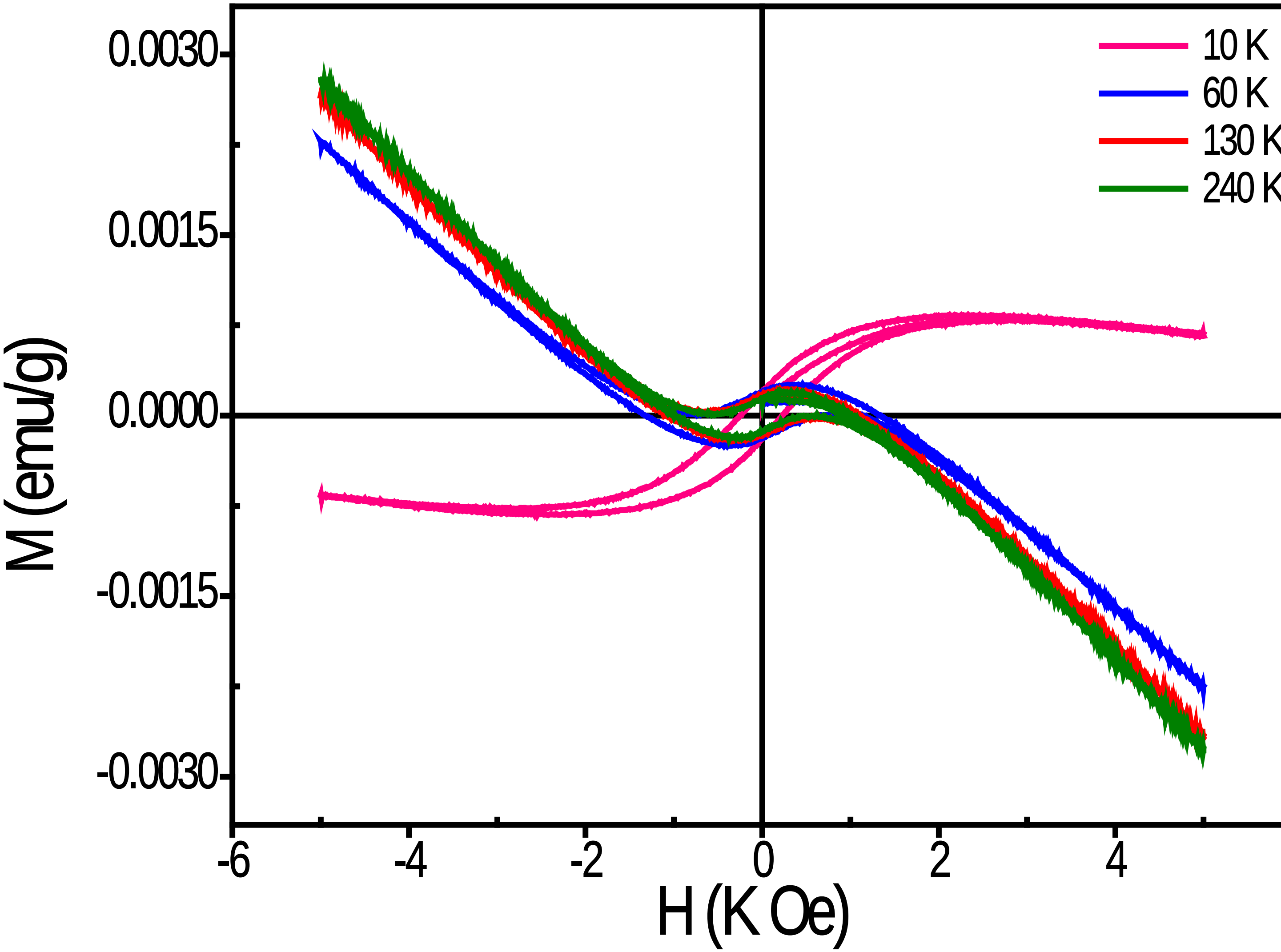
[redacted]

Magnetism in Au_{15} cluster





E. S. Shibu and T. Pradeep. Unpublished

Size selected metal clusters

- The Optical Absorption Spectra of Small Silver Clusters (5-11) Embedded in Argon Matrices. Harbich, W.; Fedrigo, S.; Buttet, J. *Chem. Phys. Lett.* **1992,** *195,* 613

- Soft Landing and Fragmentation of Small Clusters Deposited in Noble-Gas Films. Harbich, W.; Fedrigo, S.; Buttet, J. *Phys. Rev. B* **1998,** *58*, 7428

- CO combustion on supported gold clusters. Arenz M, Landman U, Heiz U. *Chemphyschem* **2006,** *7*, 1871.

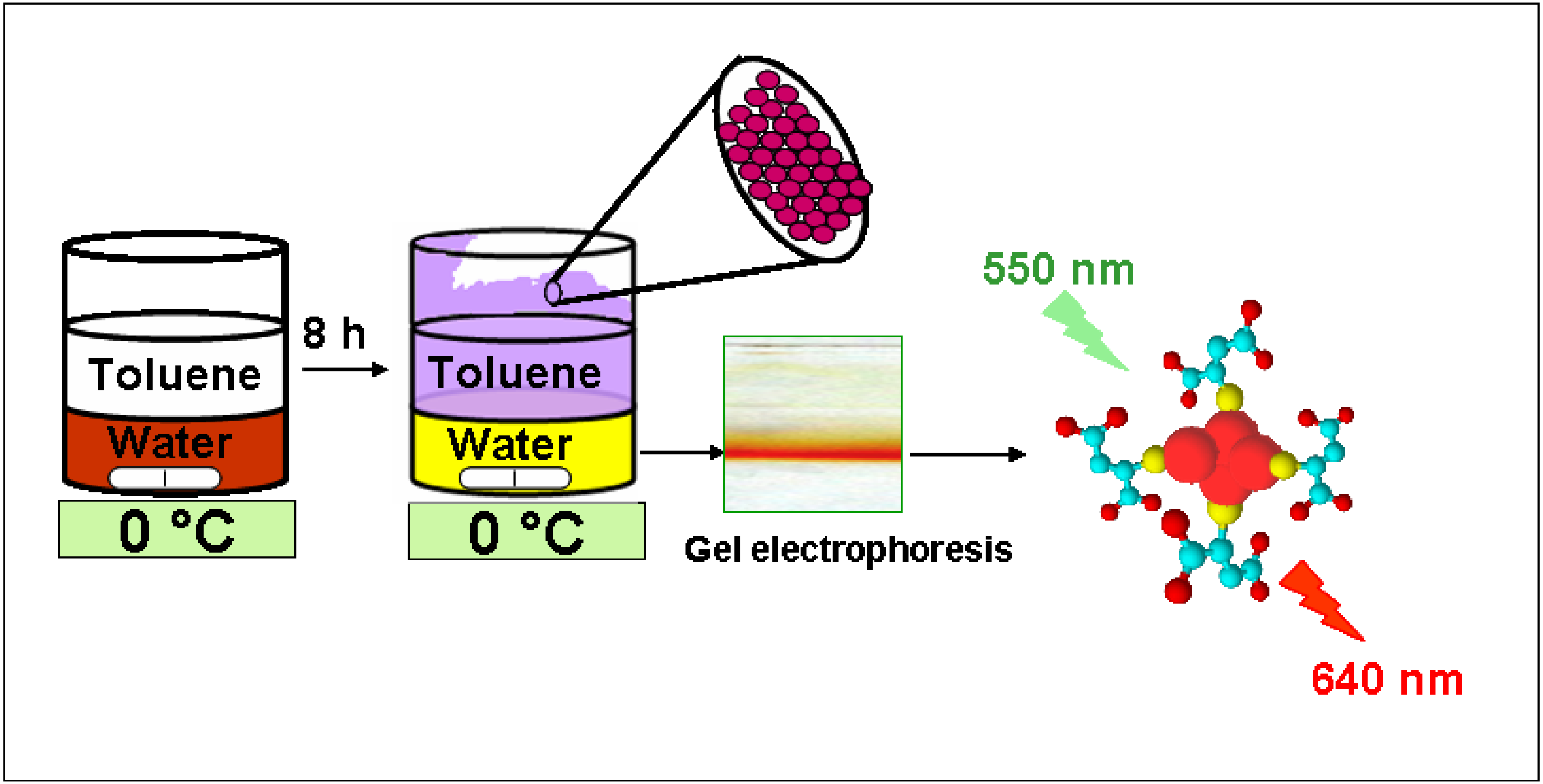
- Low-temperature cluster catalysis. Judai, K.; Abbet, S.; Worz, A. S.; Heiz U.; Henry, C. R. *J Am. Chem. Soc.* **2004,** *126*, 2732.

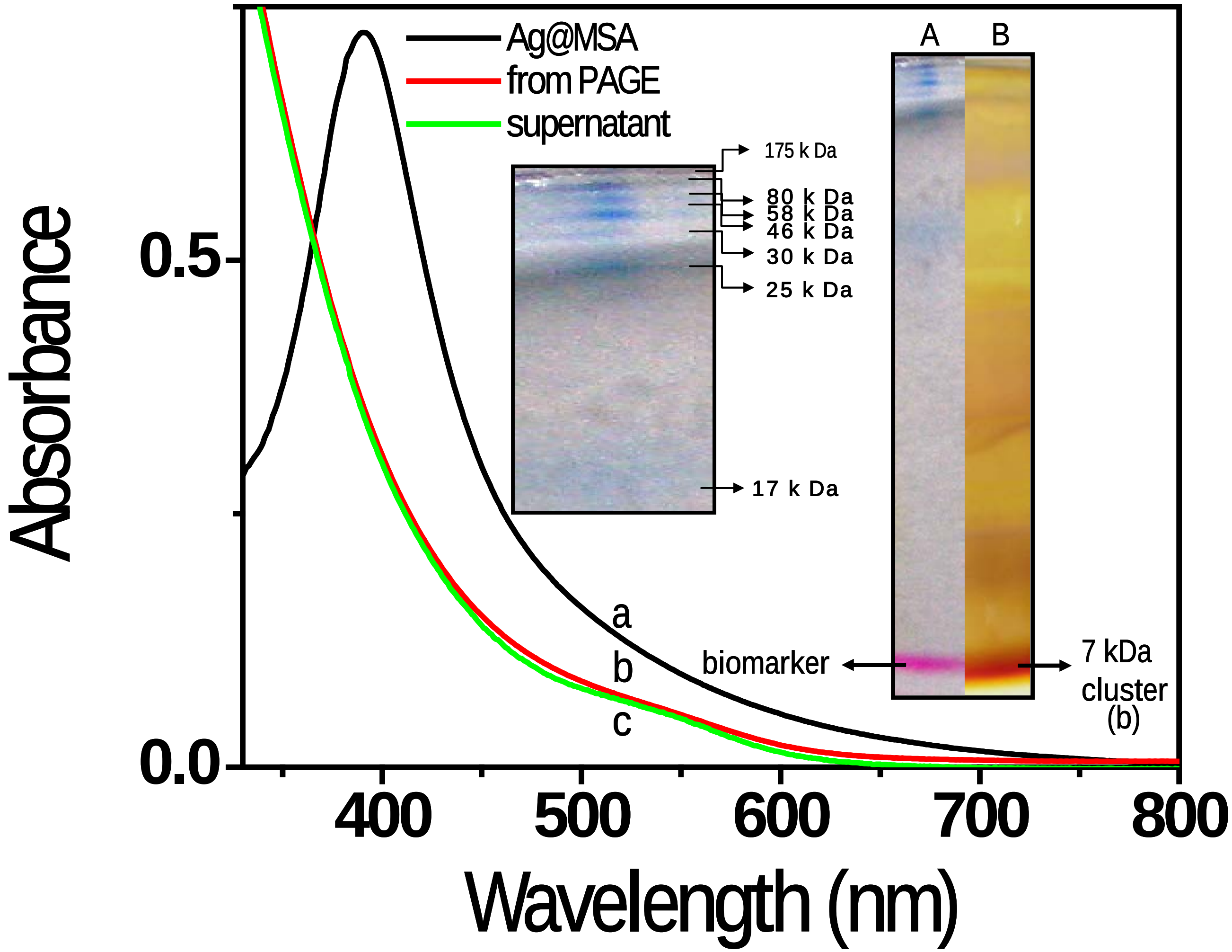
- The Reactivity of Gold and Platinum metals in their cluster phase. Heiz, U.; Sanchez,A.; Abbet, S. *Eur. Phys. J. D* **1999,** *9*,35.

- When gold is not noble: Nanoscale gold catalysts. Sanchez A, Abbet S, Heiz U *J. Phys. Chem.* A. **1999,** *103*, 9573.

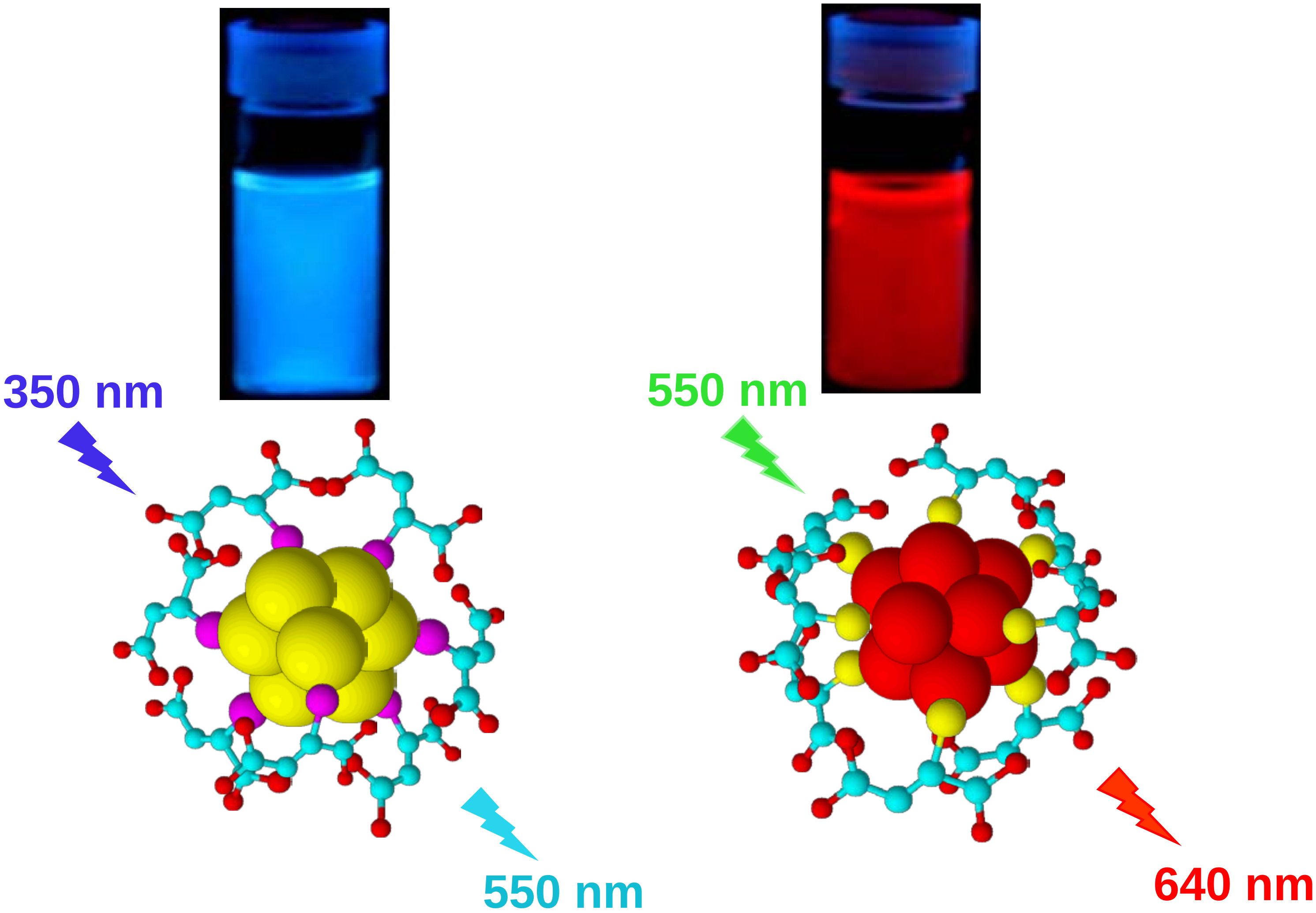
Silver clusters

Interfacial etching

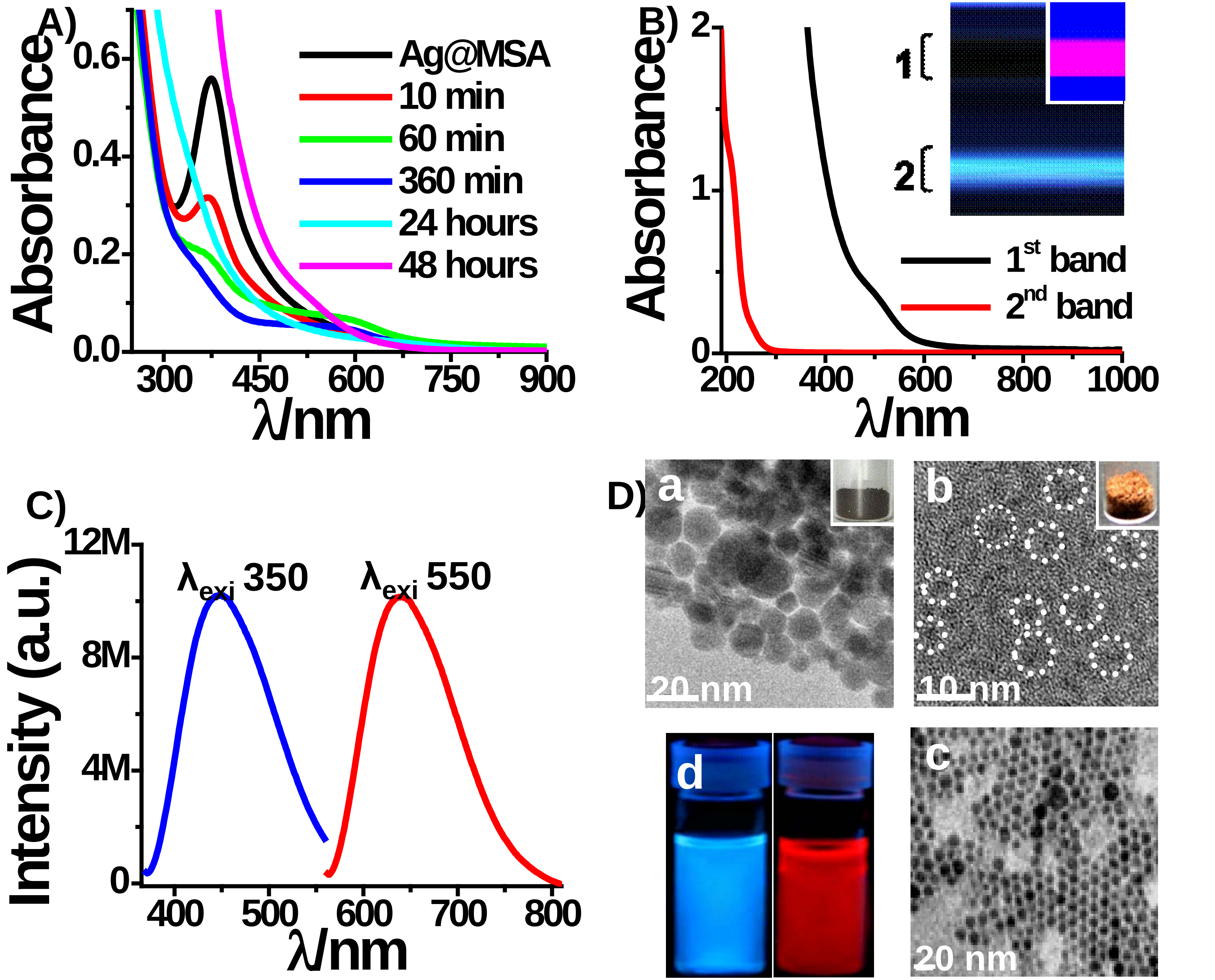




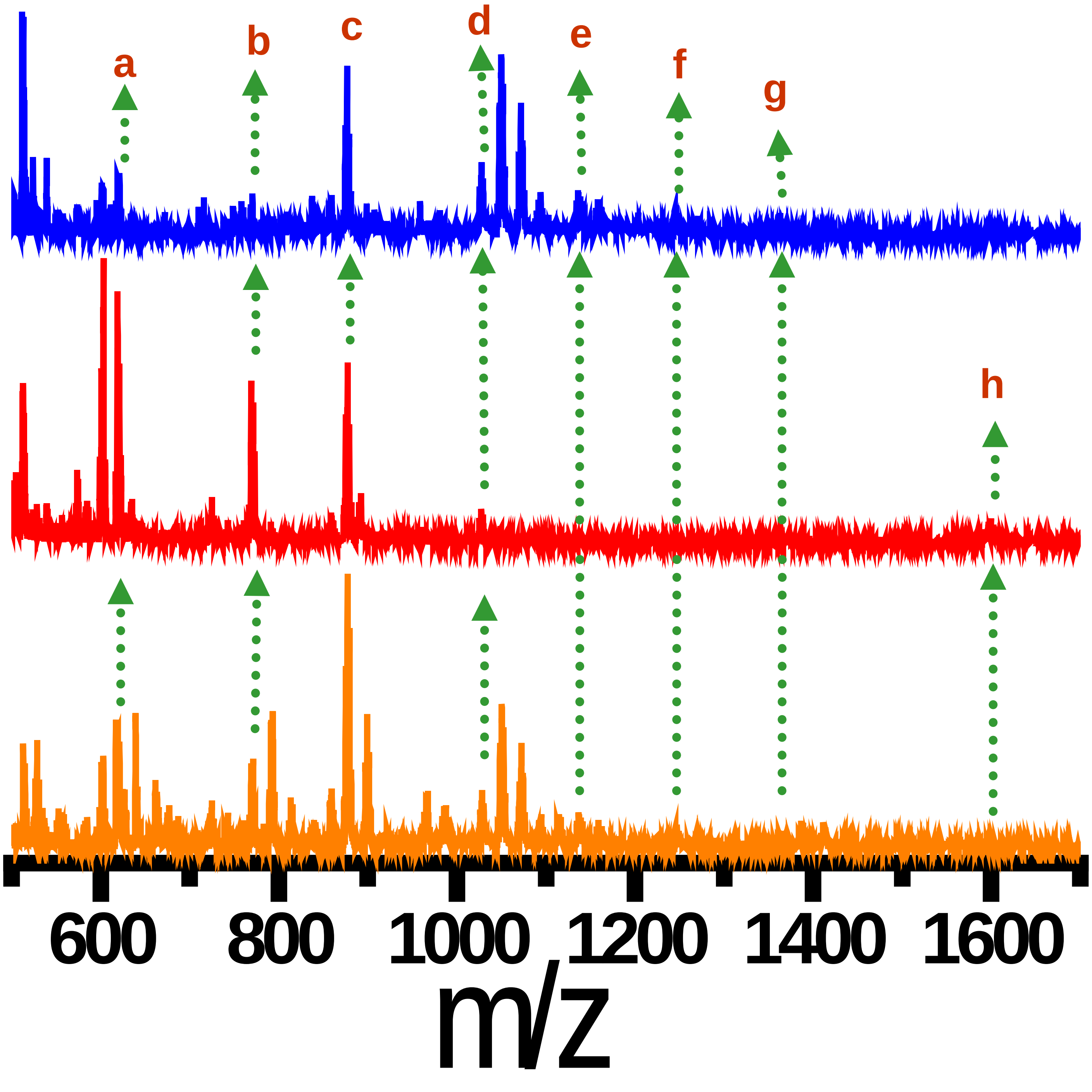
K.V. Mrulula et al. *J. Mater. Chem. 2009 CNR Rao Special Issue*

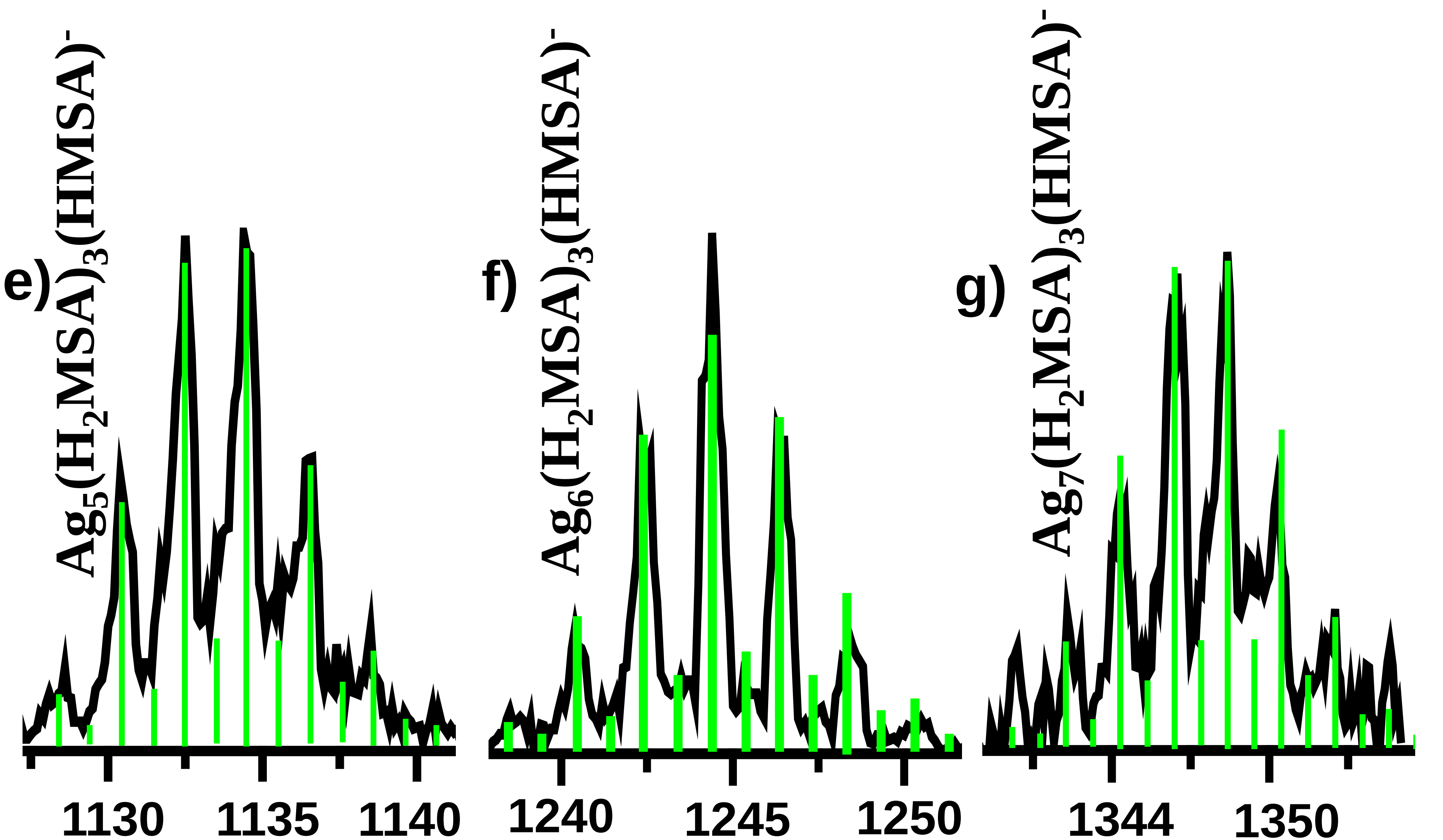


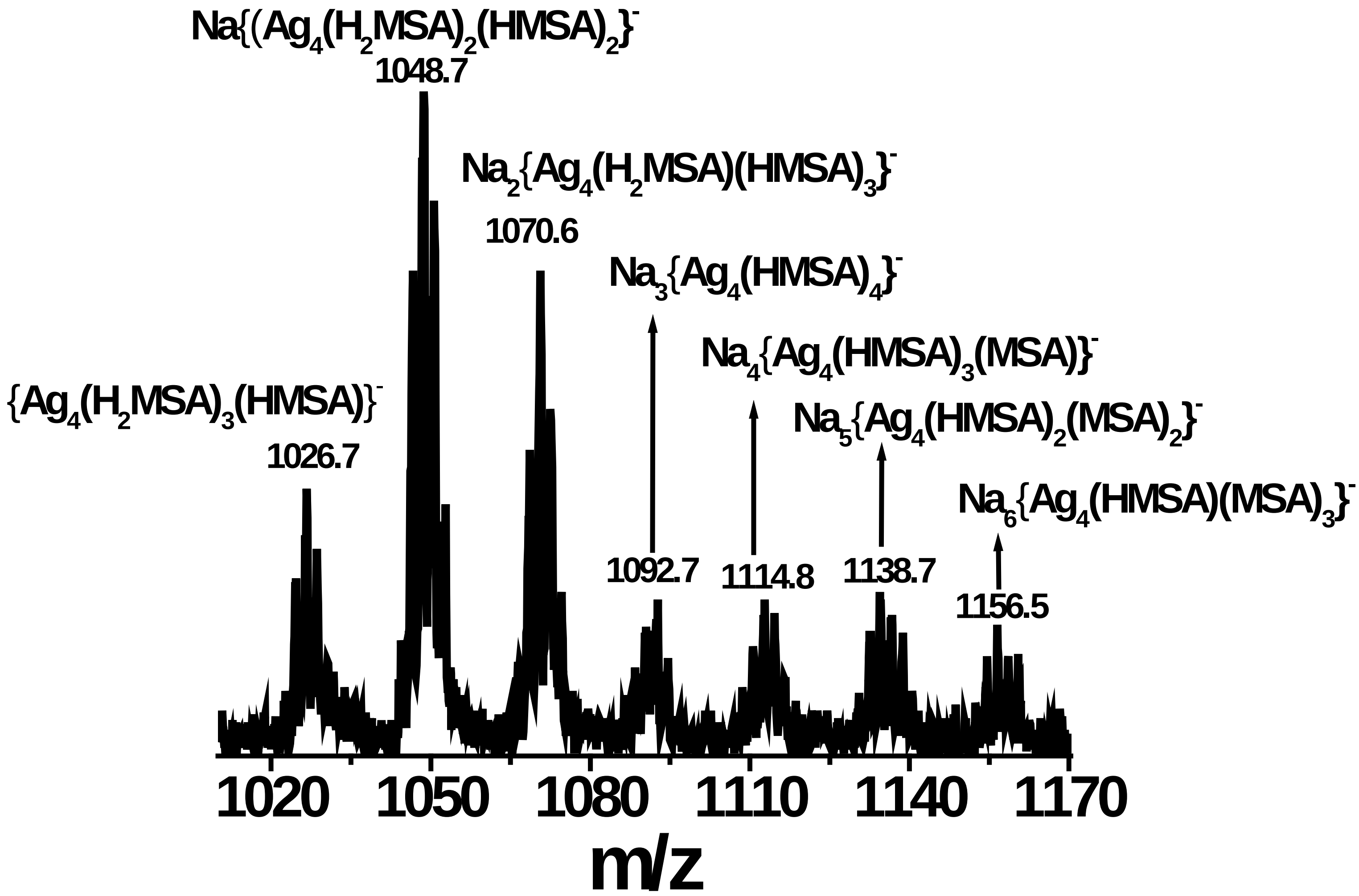
350 nm
550 nm
550 nm
640 nm

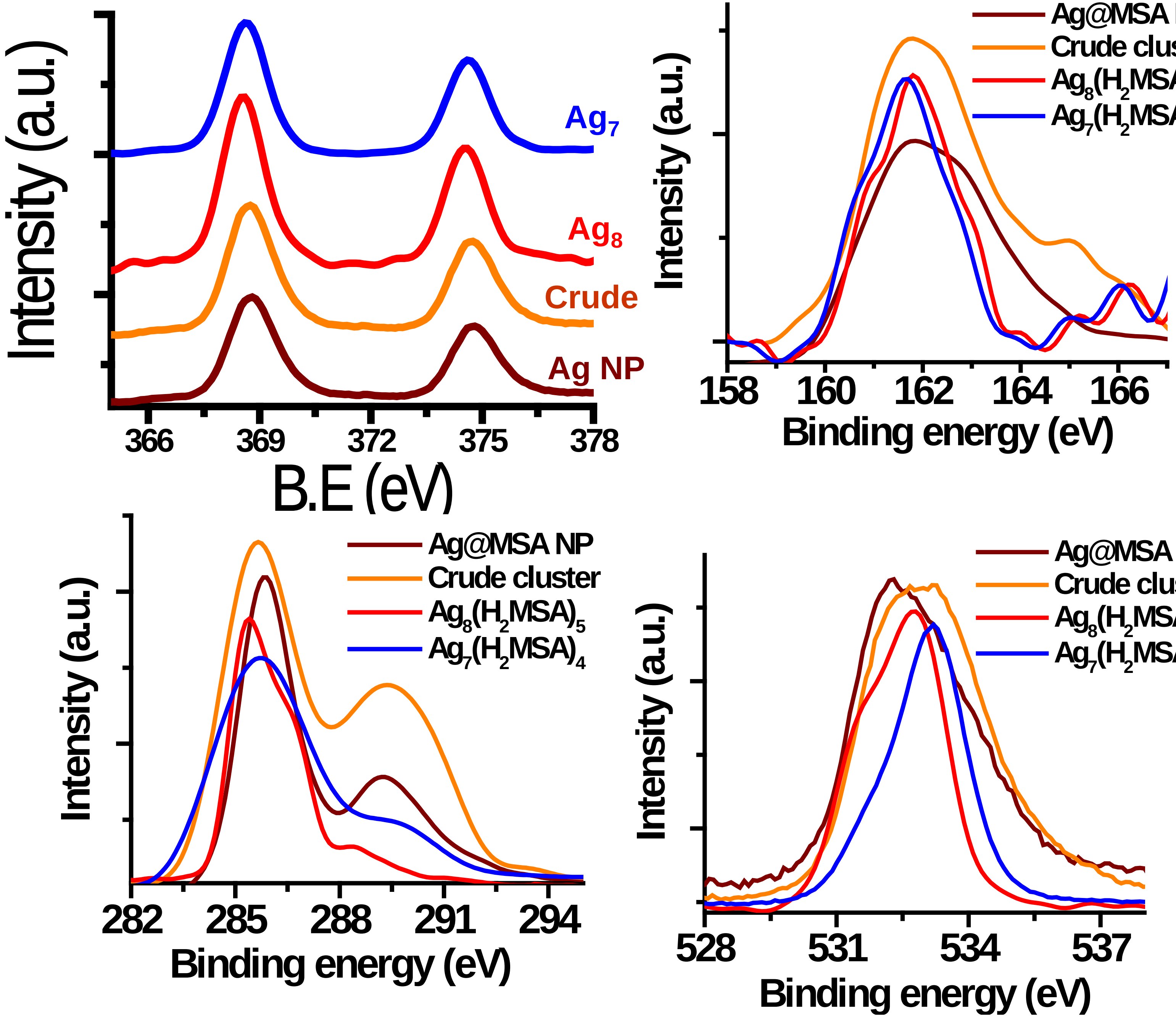


Udaybhaskar Rao and Pradeep, Submitted

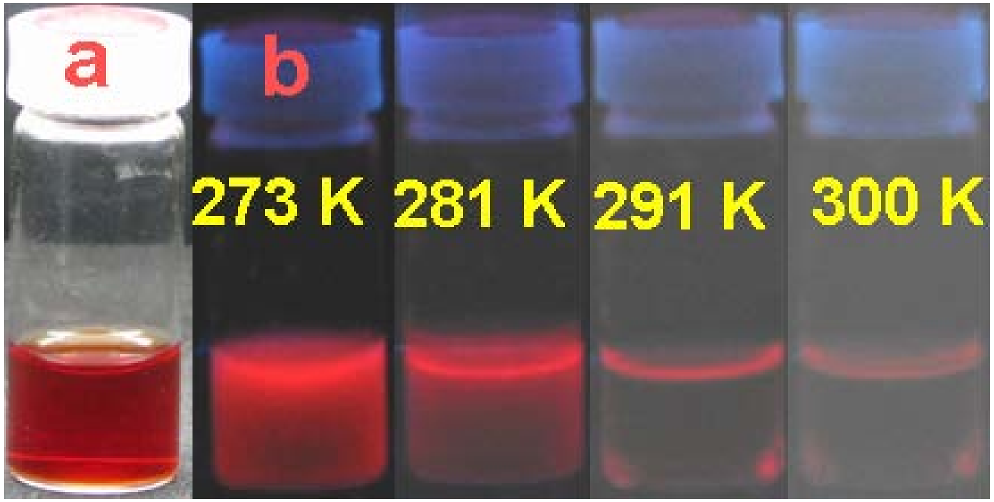

a
b
c
d
e
f
g
h
600
800
1000
1200
1400
1600
m/z


e)
$Ag_5(H_2MSA)_3(HMSA)^-$
1130
1135
1140
f)
$Ag_6(H_2MSA)_3(HMSA)^-$
1240
1245
1250
g)
$Ag_7(H_2MSA)_3(HMSA)^-$
1344
1350


Na{(Ag4(H2MSA)2(HMSA)2}-
1048.7
Na2{Ag4(H2MSA)(HMSA)3}-
1070.6
Na3{Ag4(HMSA)4}-
Na4{Ag4(HMSA)3(MSA)}-
{Ag4(H2MSA)3(HMSA)}-
1026.7
Na5{Ag4(HMSA)2(MSA)2}-
Na6{Ag4(HMSA)(MSA)3}-
1092.7
1114.8
1138.7
1156.5
1020
1050
1080
1110
1140
1170
m/z



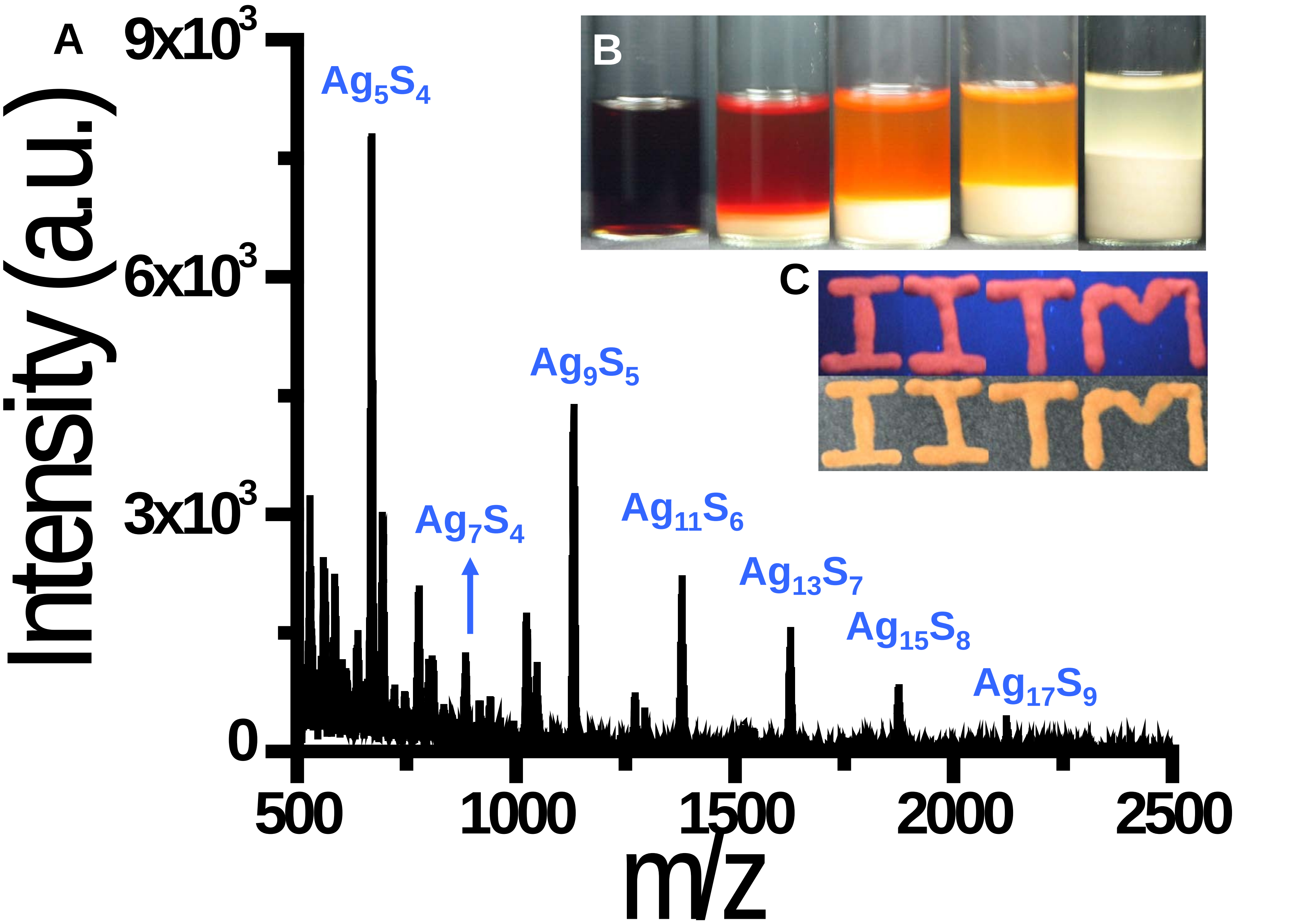
Intensity (a.u.)
Ag7
Ag8
Crude
Ag NP
366
369
372
375
378
B.E (eV)
Ag@MSA NP
Crude cluster
Ag8(H2MSA)5
Ag7(H2MSA)4
Intensity (a.u.)
158
160
162
164
166
Binding energy (eV)
Ag@MSA NP
Crude cluster
Ag8(H2MSA)5
Ag7(H2MSA)4
Intensity (a.u.)
282
285
288
291
294
Binding energy (eV)
Ag@MSA NP
Crude cluster
Ag8(H2MSA)5
Ag7(H2MSA)4
Intensity (a.u.)
528
531
534
537
Binding energy (eV)

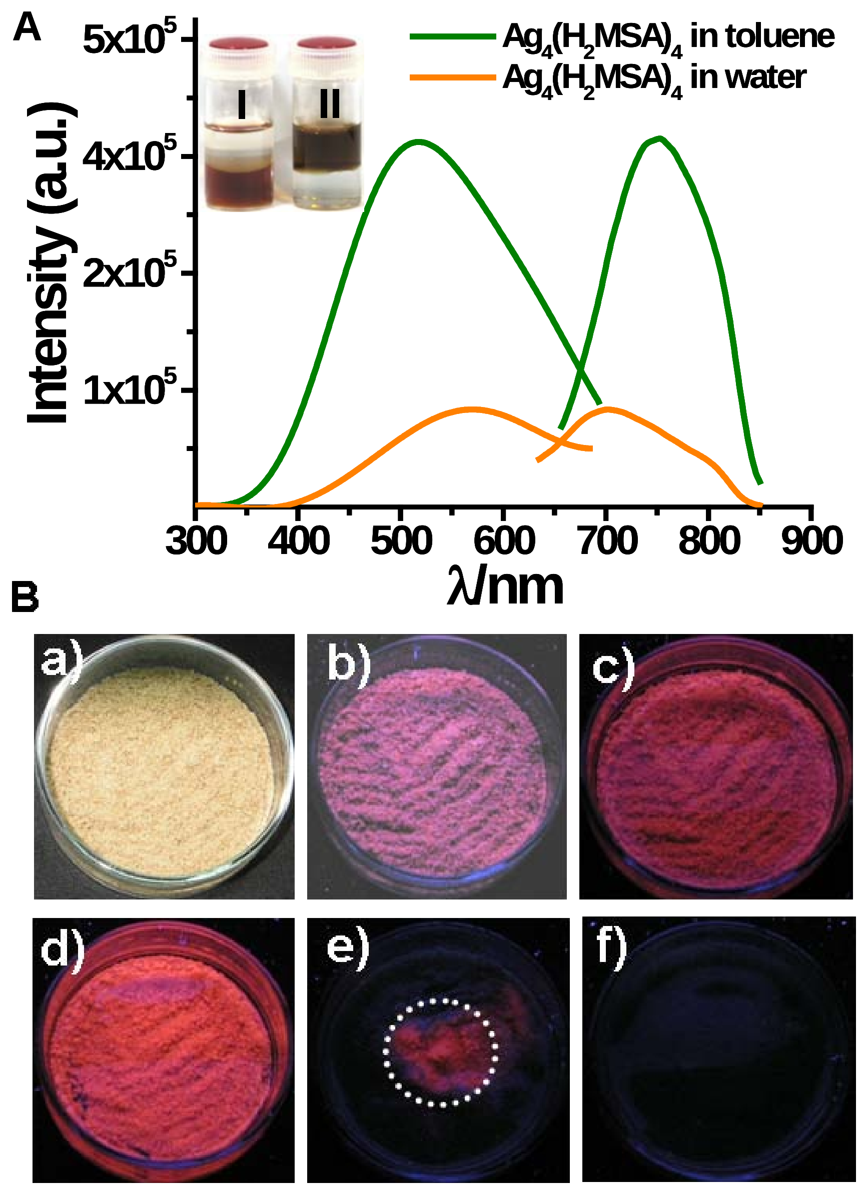


White light
RT

UV light

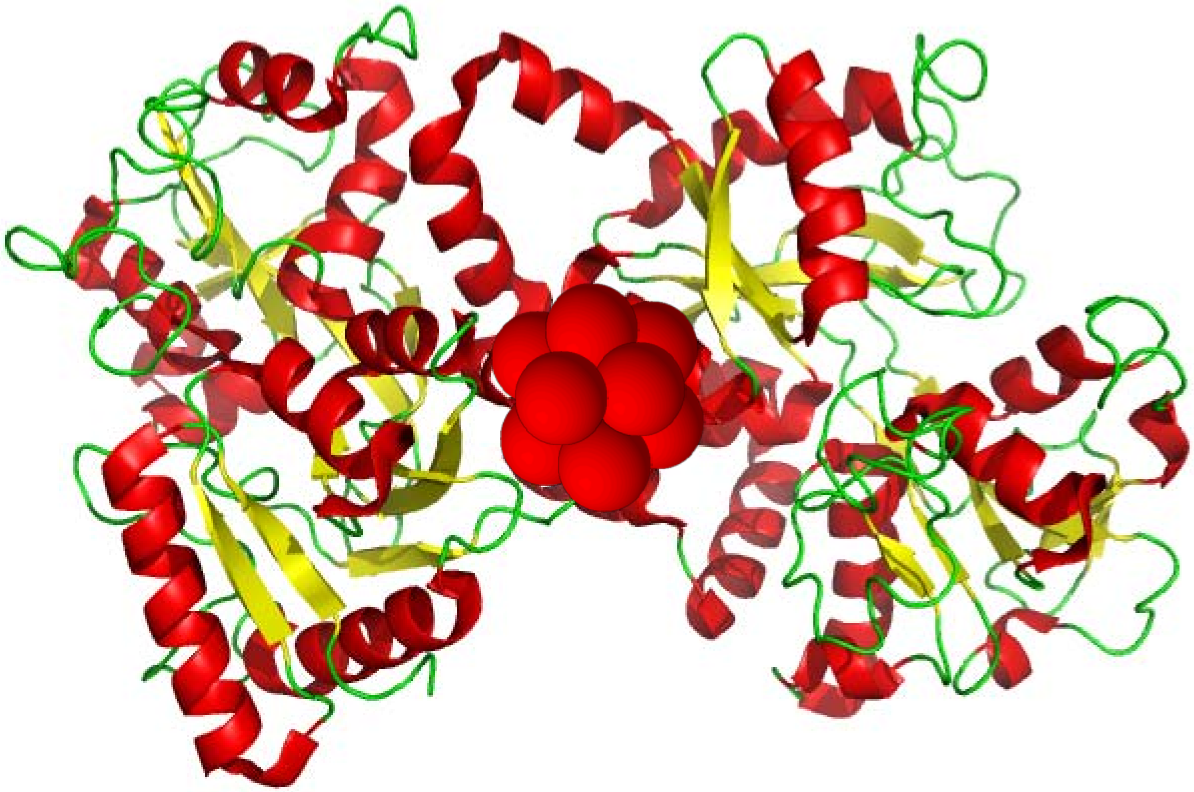
T →


A
B
C
Intensity (a.u.)
9x10^3
6x10^3
3x10^3
0
500
1000
1500
2000
2500
m/z
Ag_5S_4
Ag_7S_4
Ag_9S_5
$Ag_{11}S_6$
$Ag_{13}S_7$
$Ag_{15}S_8$
$Ag_{17}S_9$
IITM
IITM

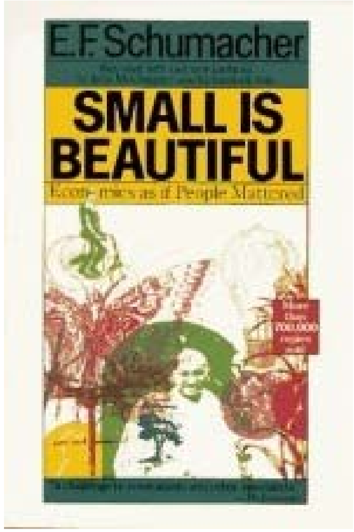


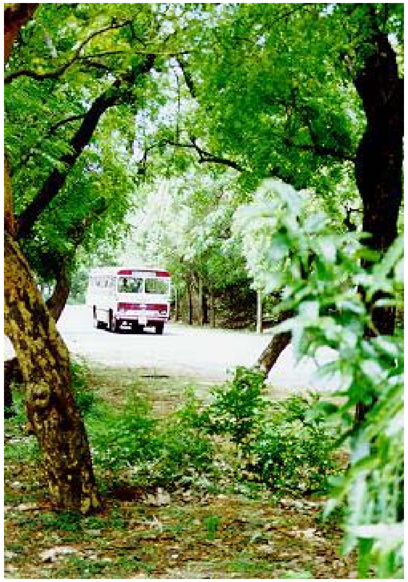
A
Ag4(H2MSA)4 in toluene
Ag4(H2MSA)4 in water
I
II
5x10^5
4x10^5
2x10^5
1x10^5
Intensity (a.u.)
300
400
500
600
700
800
900
λ/nm
B
a)
b)
c)
d)
e)
f)

Clusters in proteins



Lourdu Xavier, Kamalesh Choudhari


E.F. Schumacher
SMALL IS
BEAUTIFUL



Nano Mission, Department of Science and Technology

IIT Madras

Thanks!