Introduction to physical basis of nanotechnology and nanoparticles research

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Outline

- What does it mean nano- ?
- Why everybody talk about nano?
- History:
  "prehistoric times"
  predictions by Richard Feynman (1959)
  the real start (1985/1986)
- Current state of nanotechnology development (Do hopes come real?)
- Physical basis of nanotechnology
- Possible problems
- What are we working on?
- Questions without answers

What does it mean nano- ?

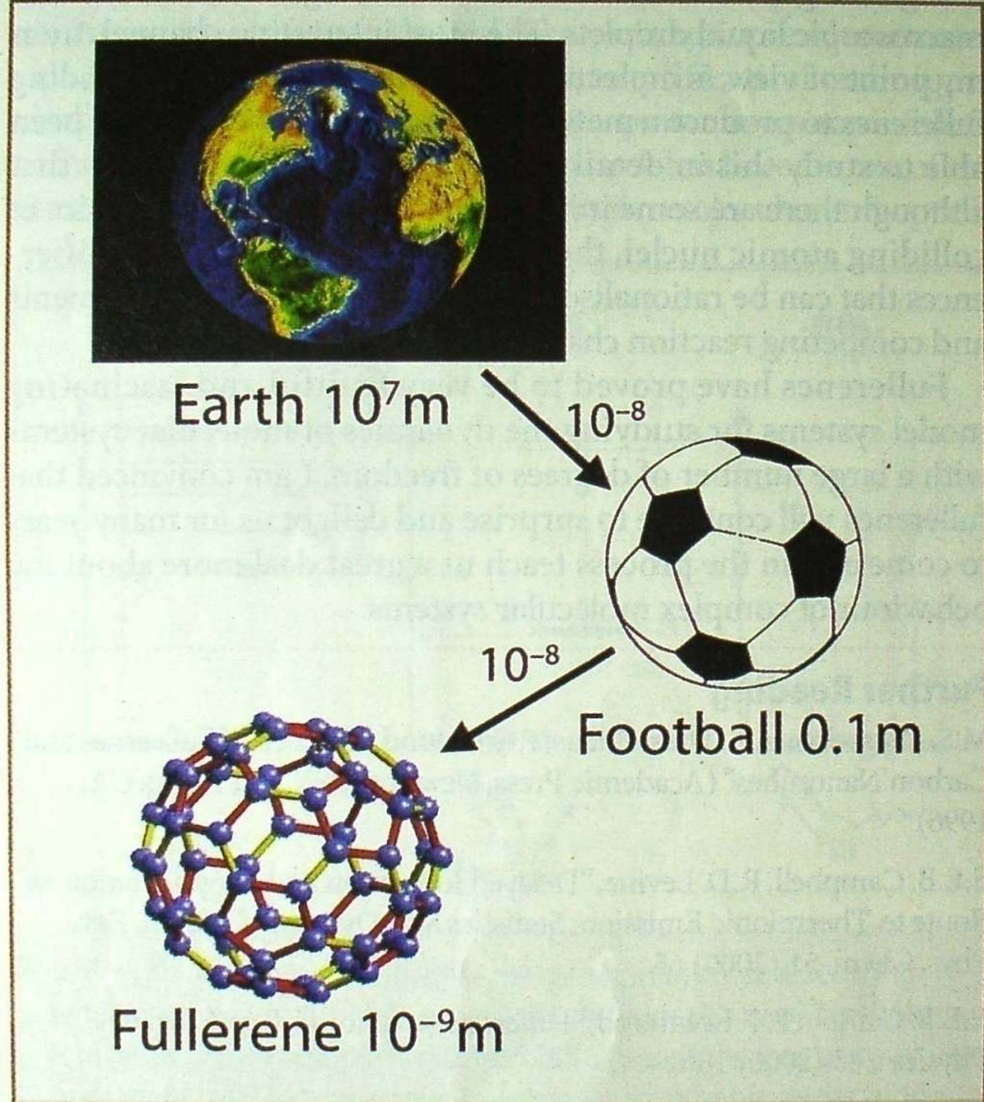
νάνος - dwarf

nano - 10^{-9}

nanoscience, nanotechnology

Size range

0.1-100 nm



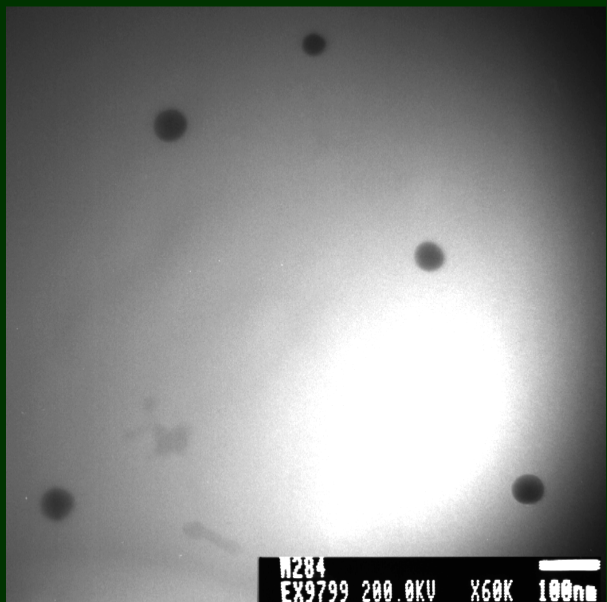
▲ **Fig. 1:** A fullerene bears the same relation in size to a European football as the football does to the size of the Earth.

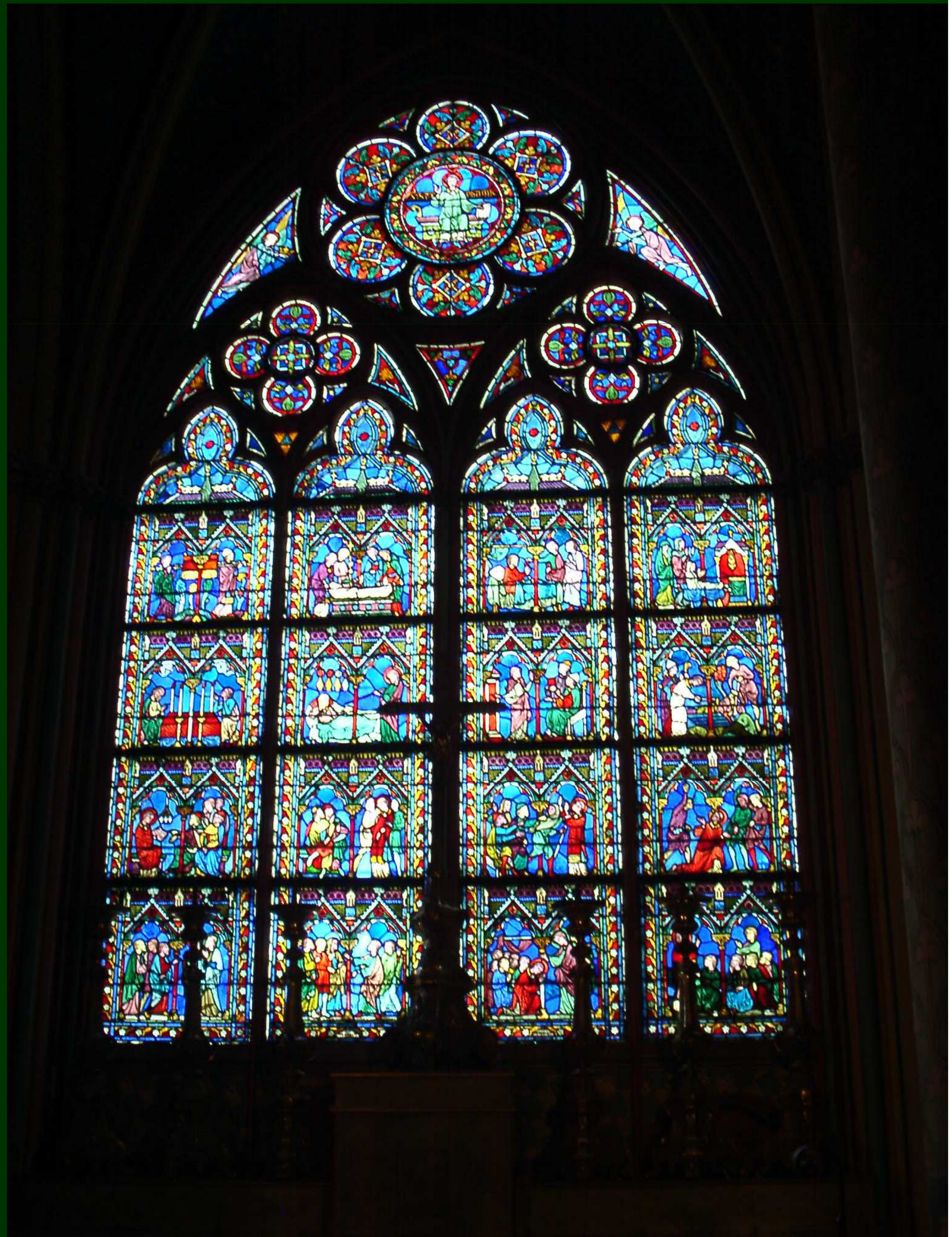
europhysics news NOVEMBER/DECEMBER 2002

History

Lycurgus cup, Rome, 4th century

History





Nanomaterials in nature

Predictions

There's Plenty of Room at the Bottom

An Invitation to Enter a New Field of Physics

by Richard P. Feynman

This transcript of the classic talk that Richard Feynman gave on December 29th 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) was first published in the February 1960 issue of Caltech's *Engineering and Science*, which owns the copyright. It has been made available on the web at http://www.zyvex.com/nanotech/feynman.html with their kind permission.

Predictions

- Can I record the whole British Encyclopedia on the head of the pin ?

- Yes, with a decrease of 25,000 times.

- Is it possible to record all the printed information, which was available at that time (approximately 10^{15} bits) in the volume of the grain of sand?

- Fundamentally, yes. That is a density of recording information in biological systems.

- How to make nanomachines?
- Contact synthesis.

The real start

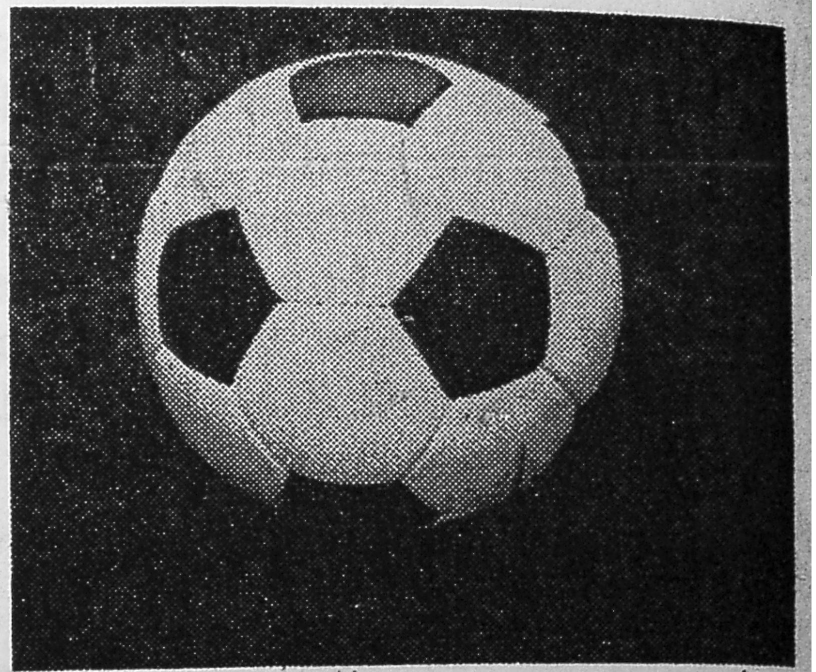
C_{60}: Buckminsterfullerene

H. W. Kroto*, J. R. Heath, S. C. O'Brien, R. F. Curl & R. E. Smalley

Rice Quantum Institute and Departments of Chemistry and Electrical Engineering, Rice University, Houston, Texas 77251, USA

During experiments aimed at
which long-chain carbon molecu
and circumstellar shells[1], gra
irradiation, producing a remar
60 carbon atoms. Concerning
carbon atom structure might g
suggest a truncated icosahedr
32 faces, 12 of which are pentag
is commonly encountered as th
molecule which results when a c

Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.

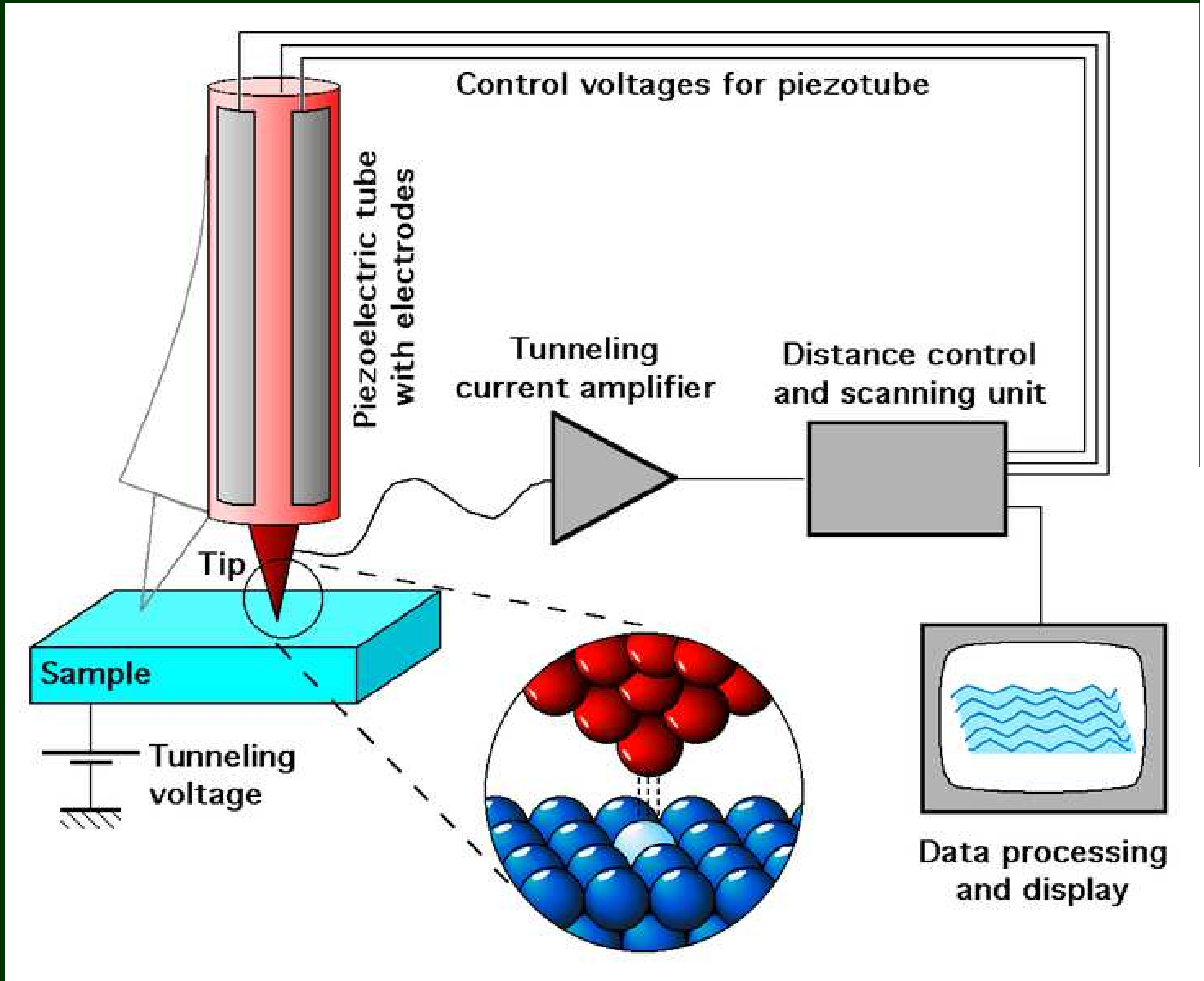


Scanning tunnelling microscopy

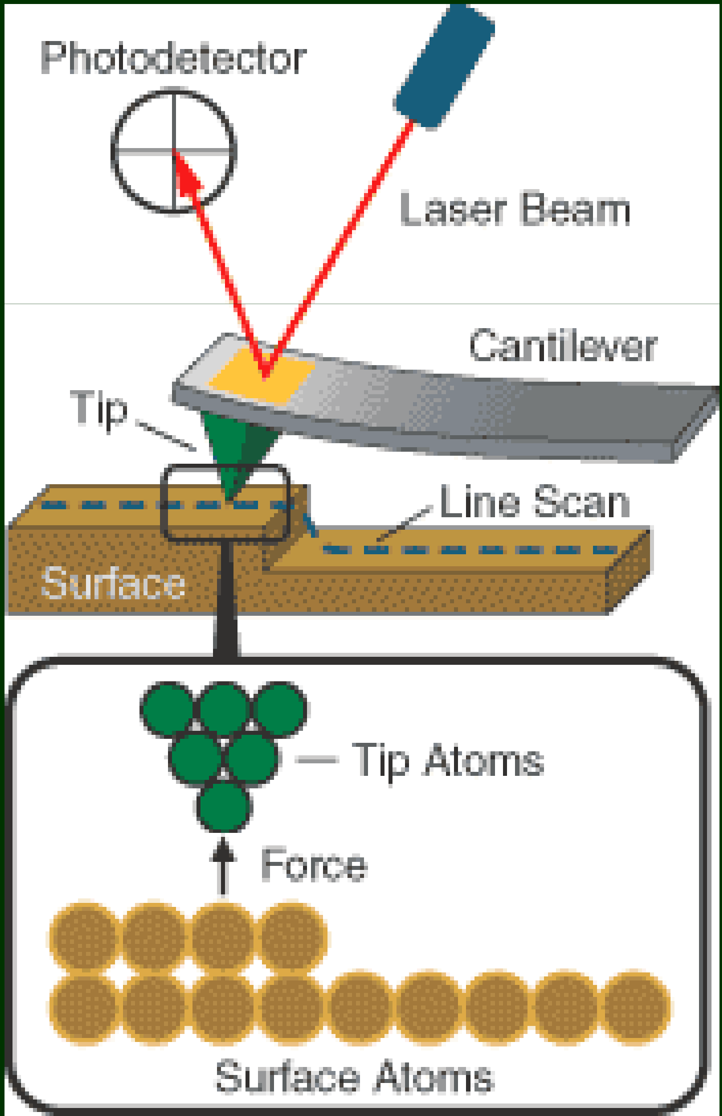
The Nobel Prize in Physics 1986

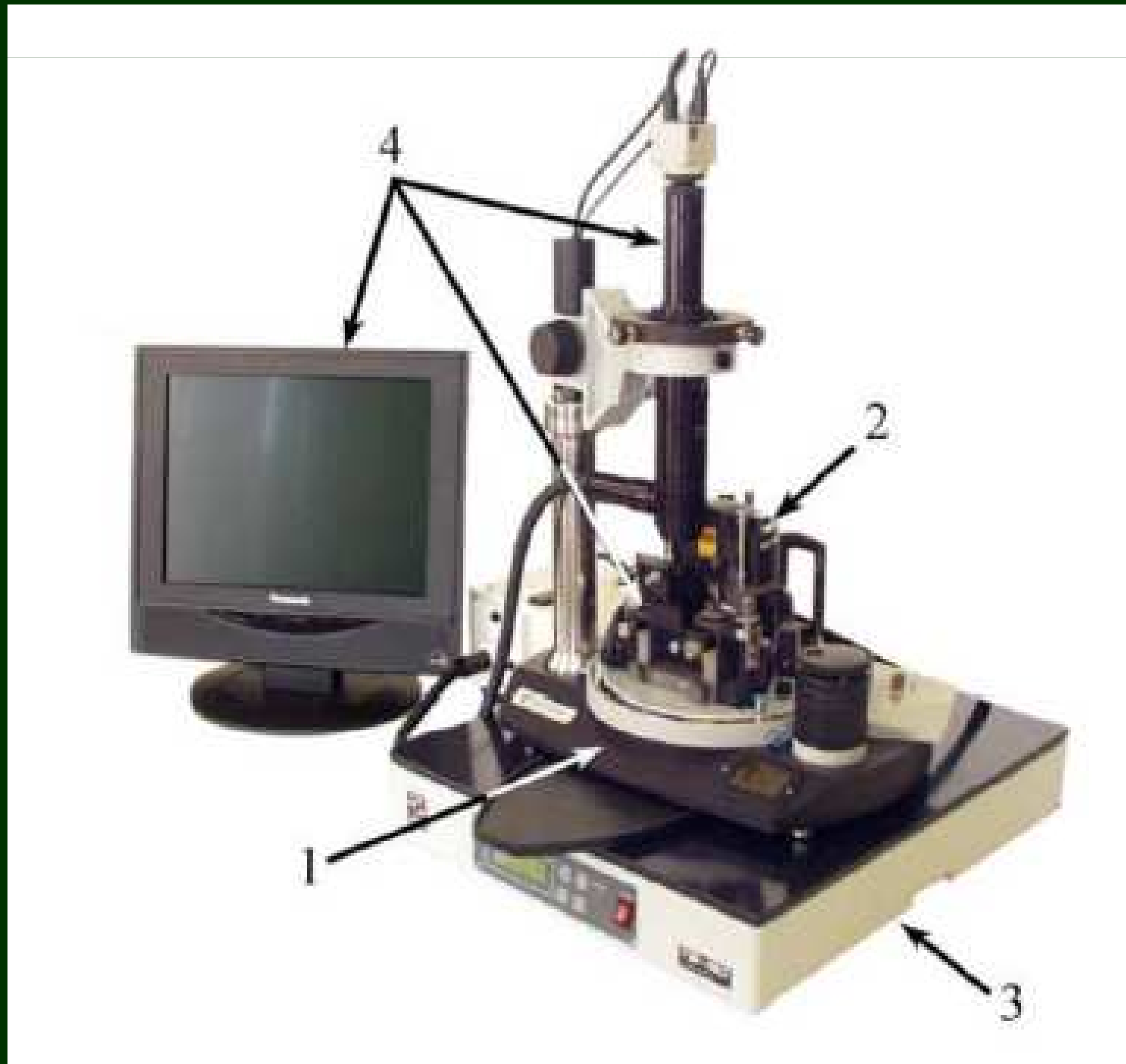
Gerd Binnig

Heinrich Rohrer

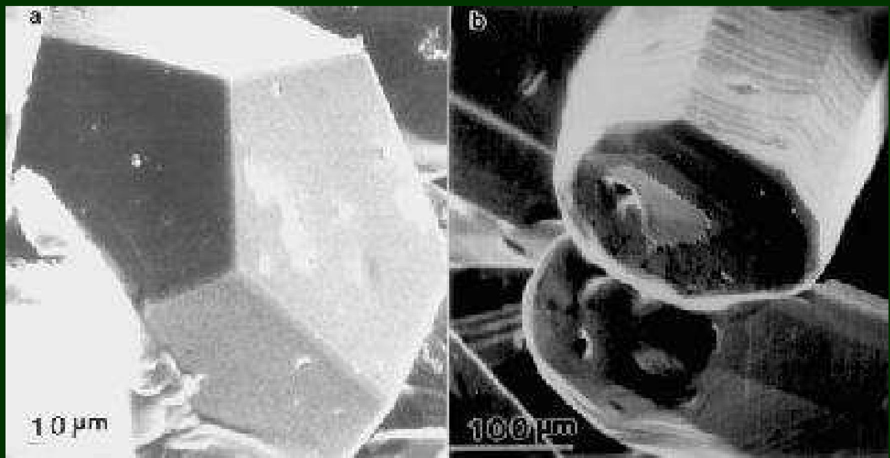


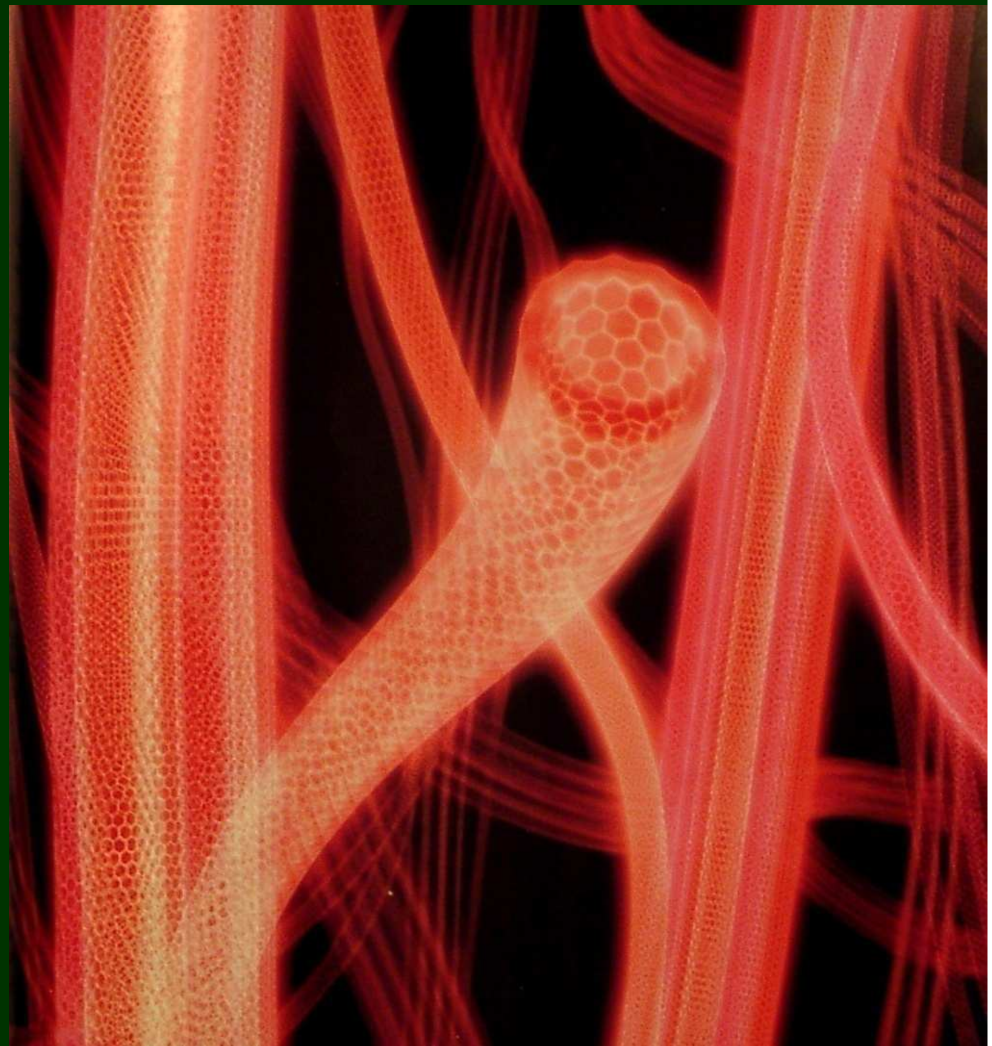
Atomic force microscopy



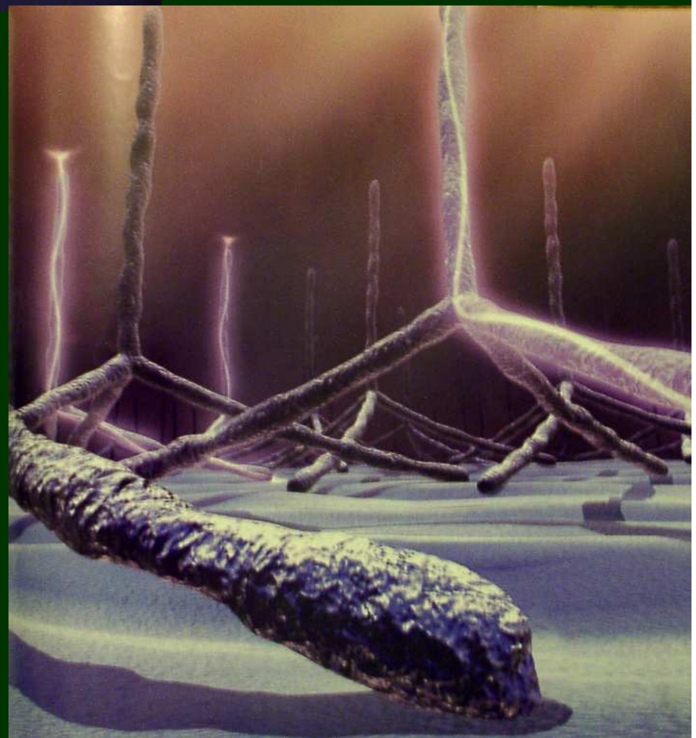


New materials

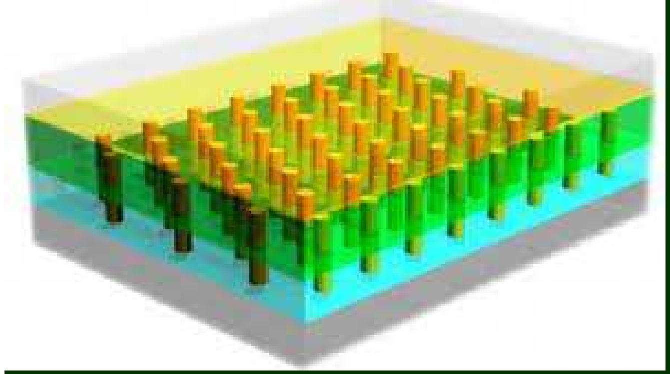


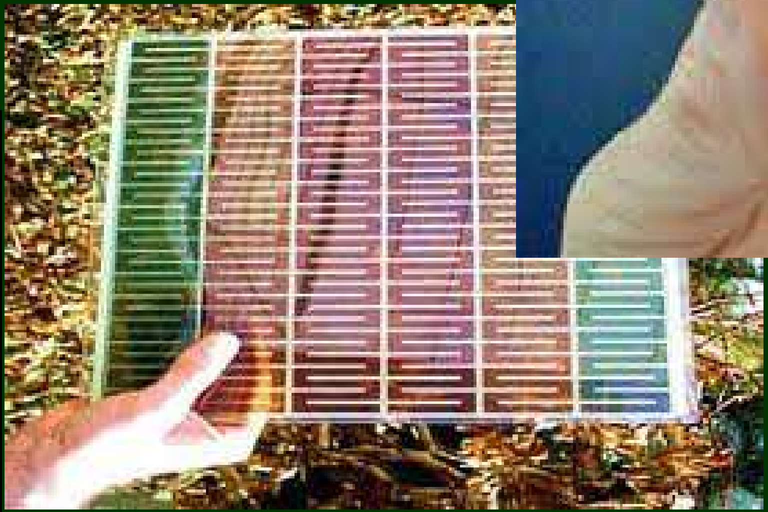


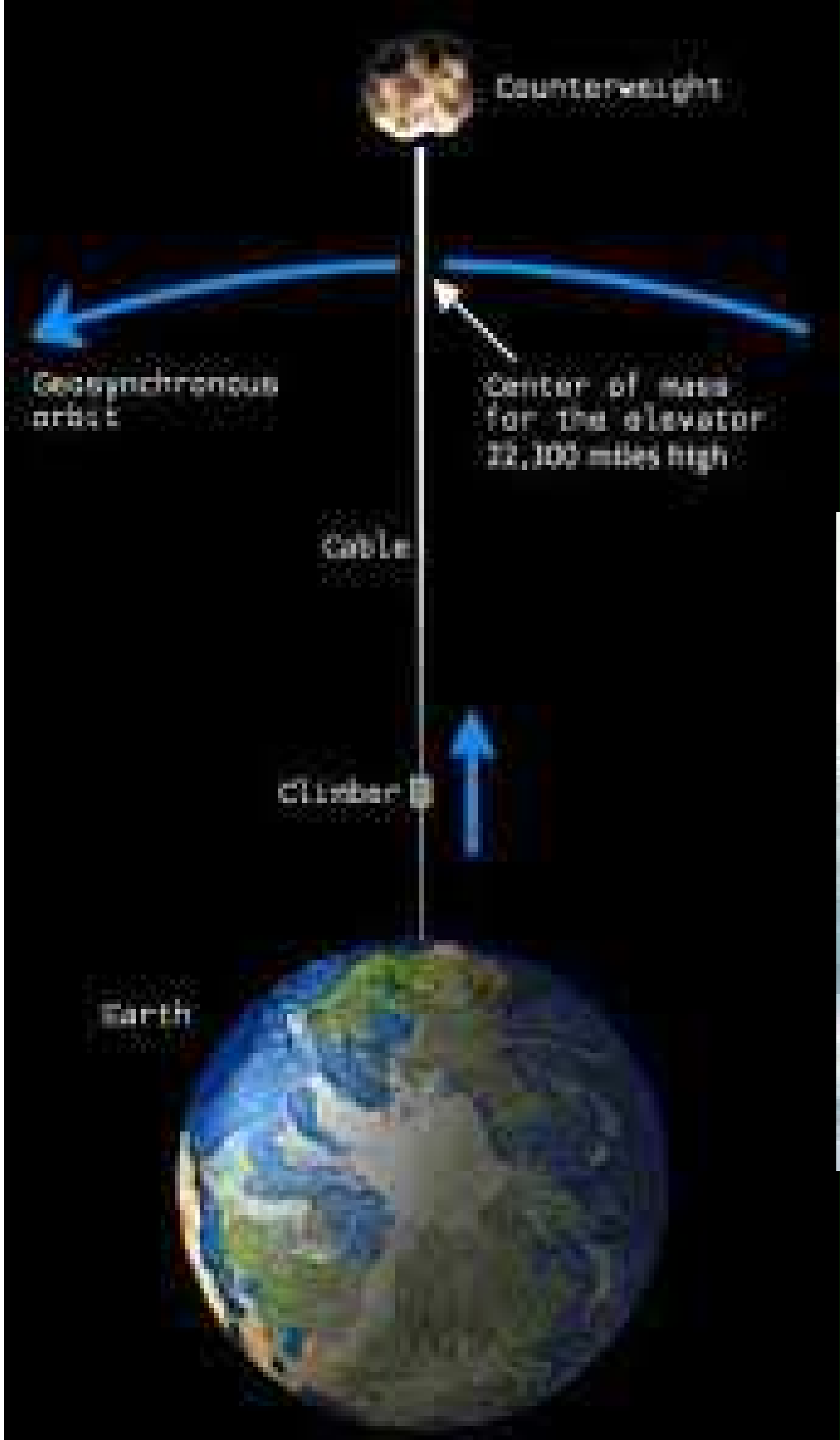
New materials



New materials







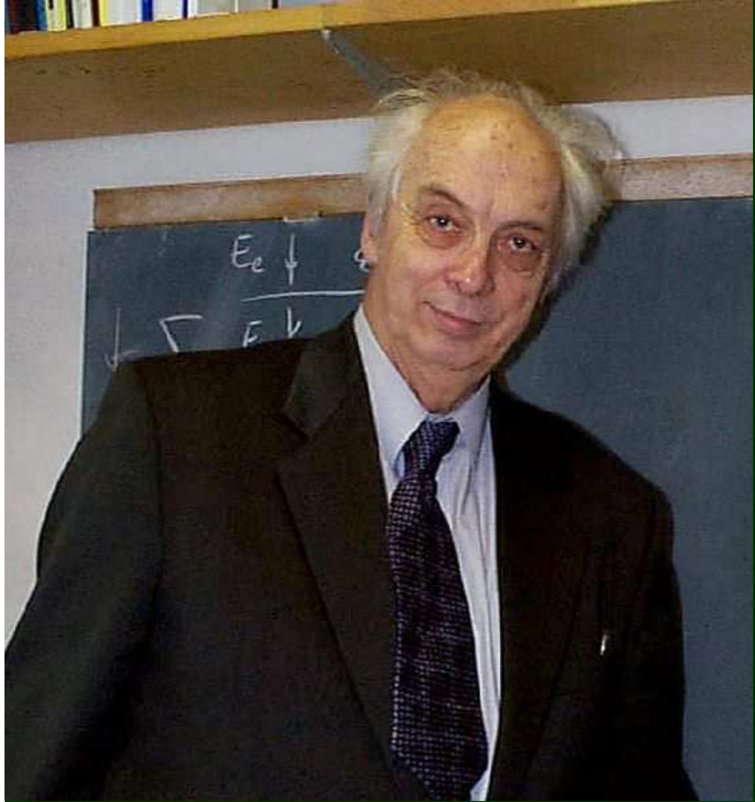
New materials, which give an opportunity to look at the old idea in a new way

Space elevator

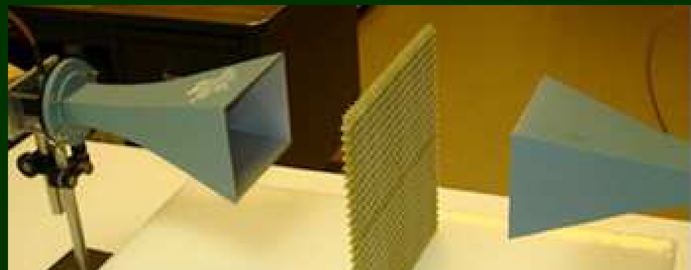
New materials, which give an opportunity to look at the old idea in a new way

Students competition

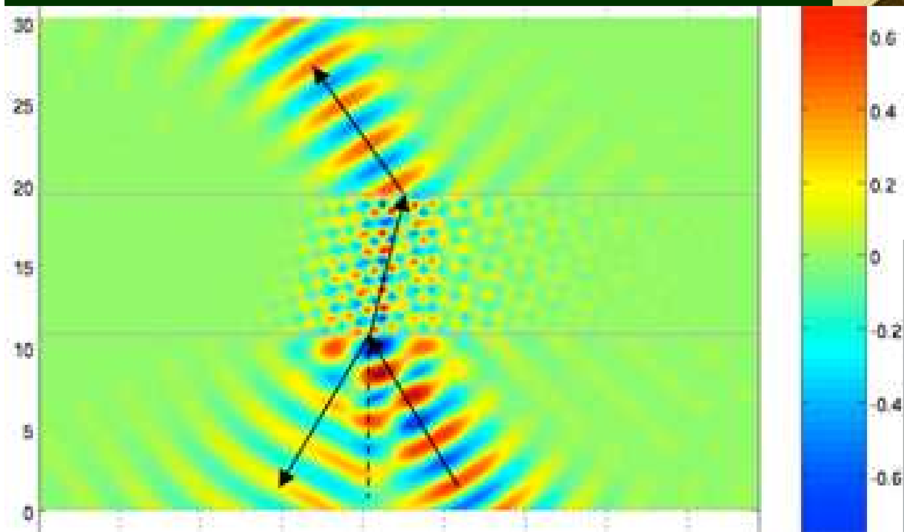
Metamaterials



Uniaxial chiral metamaterials based on chiral SRR and a perfect absorber based on this metamaterial design.



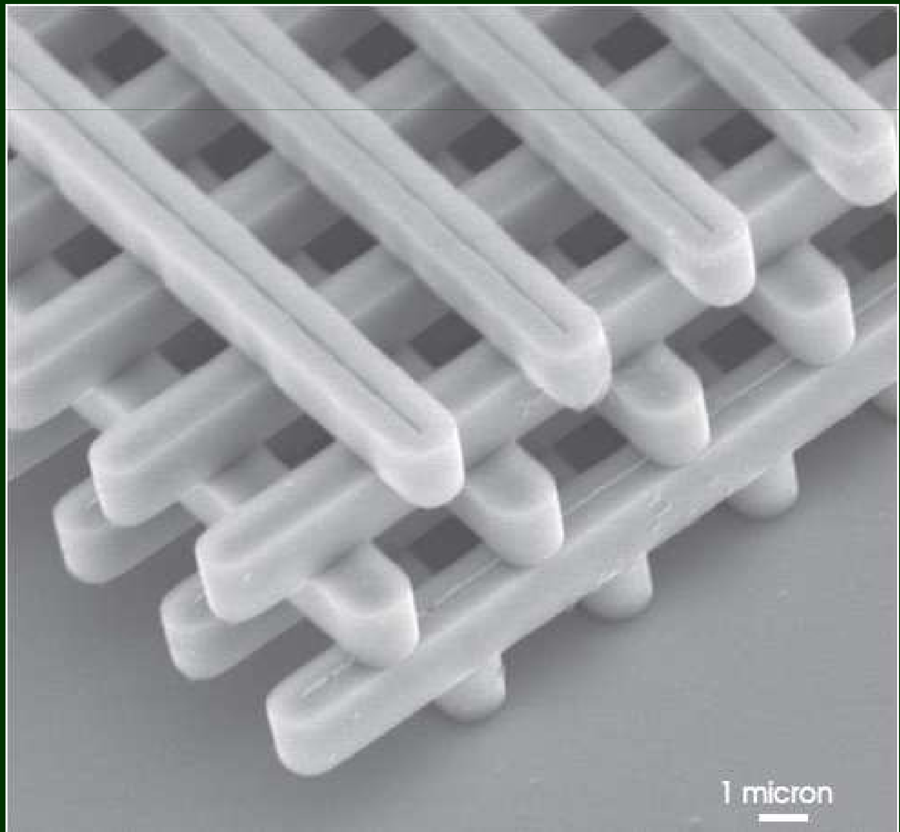
Measurement of negative index chiral metamaterial slab operating at microwave frequencies.



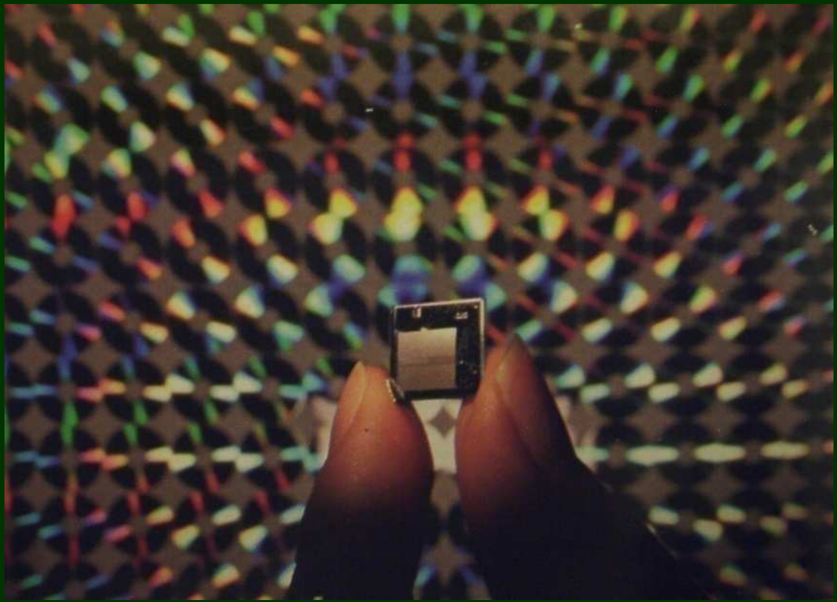
Simulation of negative refraction in a photonic crystal: The incident beam is refracted to the "wrong"

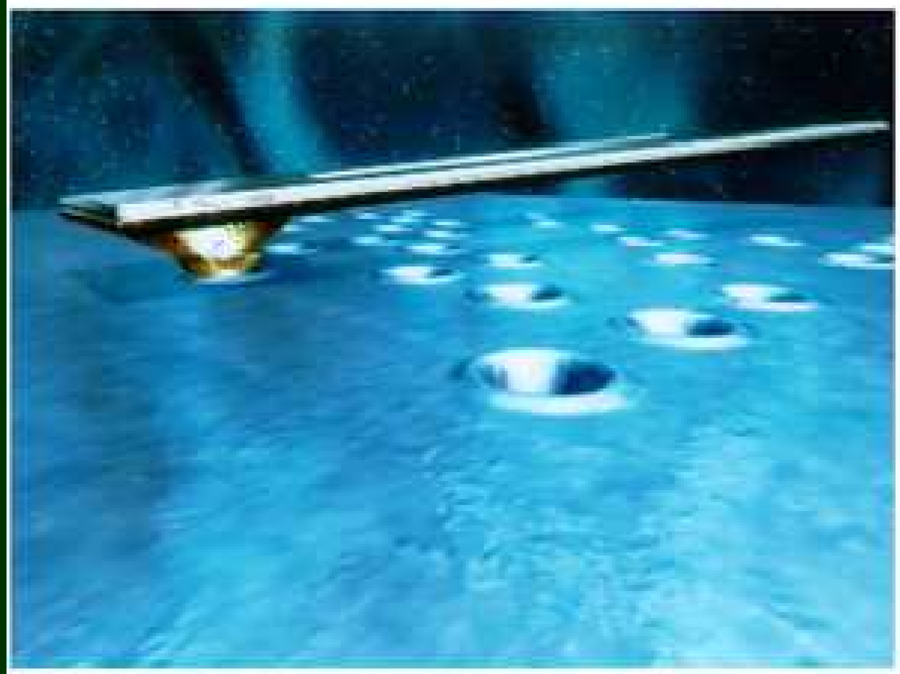
(a) (b) (c)

“Photonic crystals”

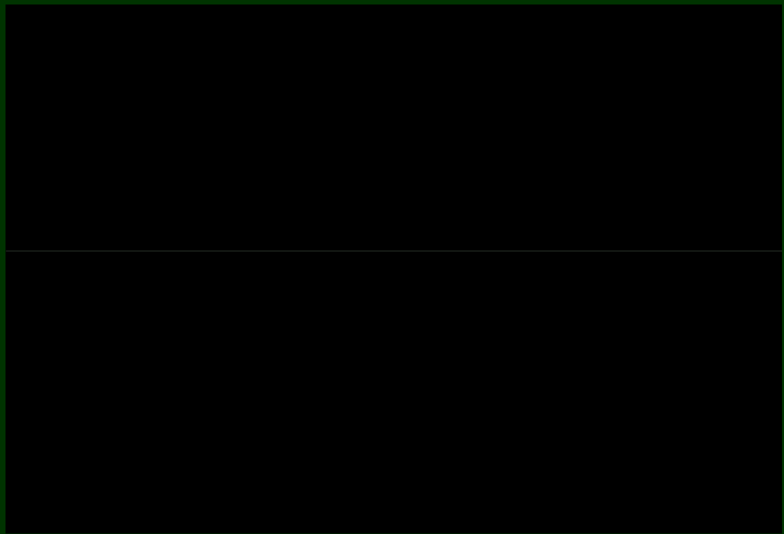


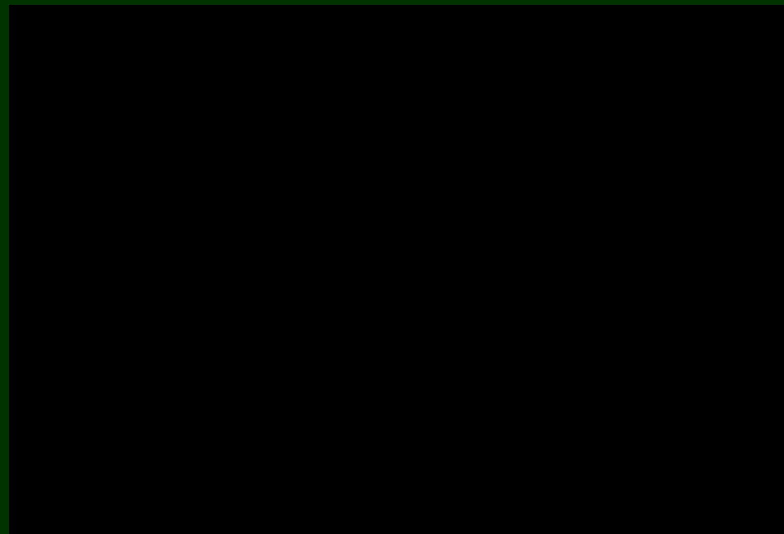
New methods of information recording

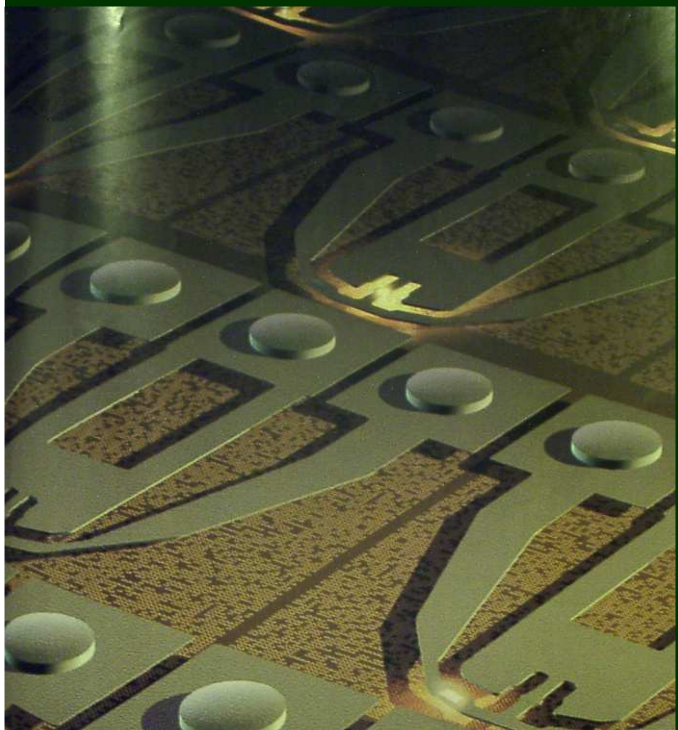




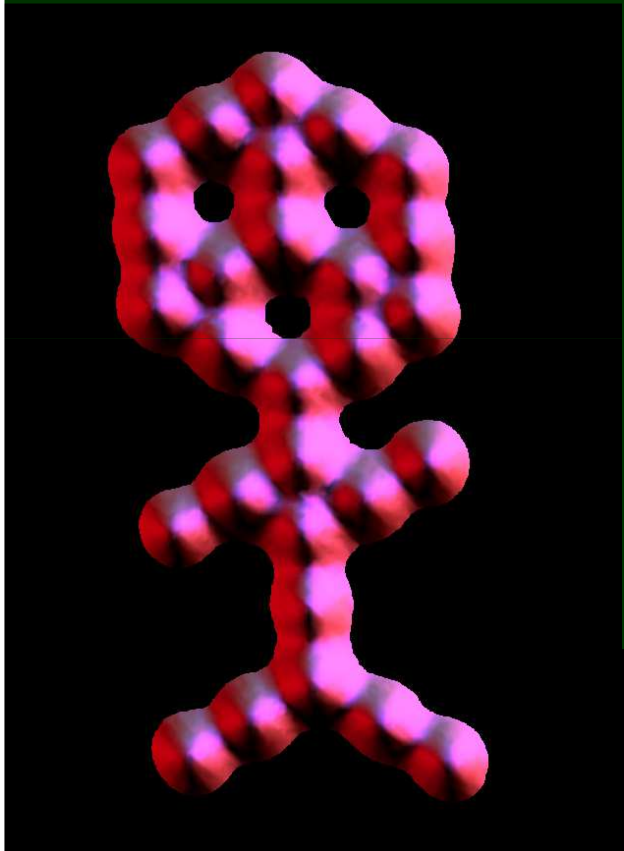
New methods of information recording

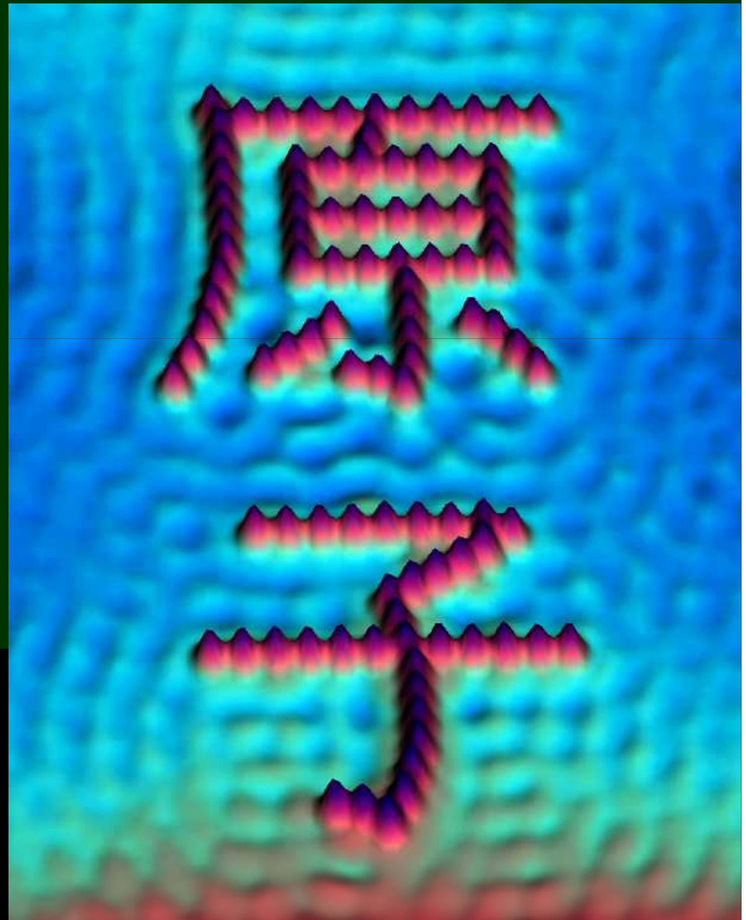


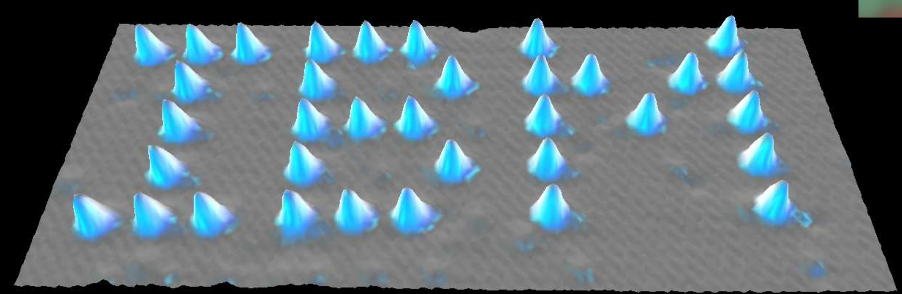




Atomic information recording

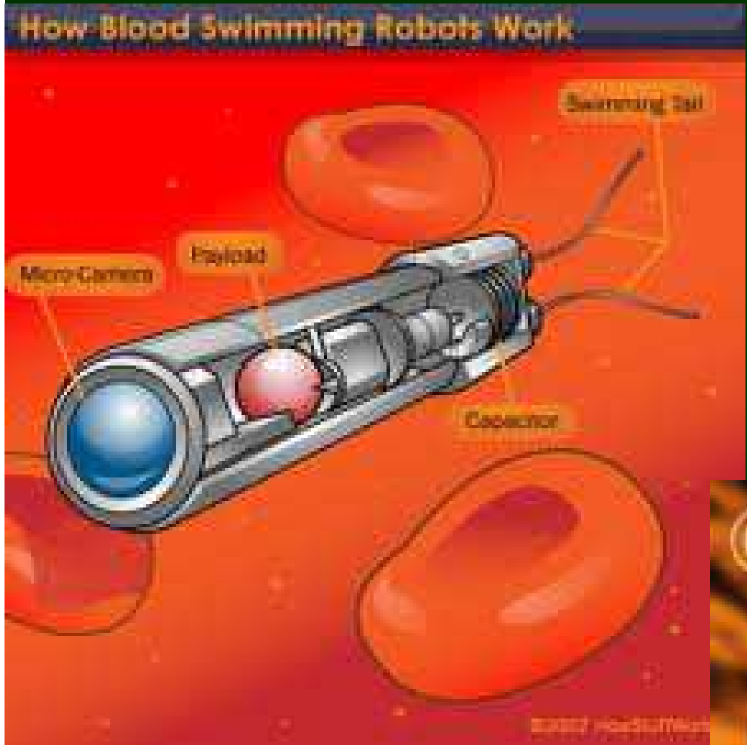


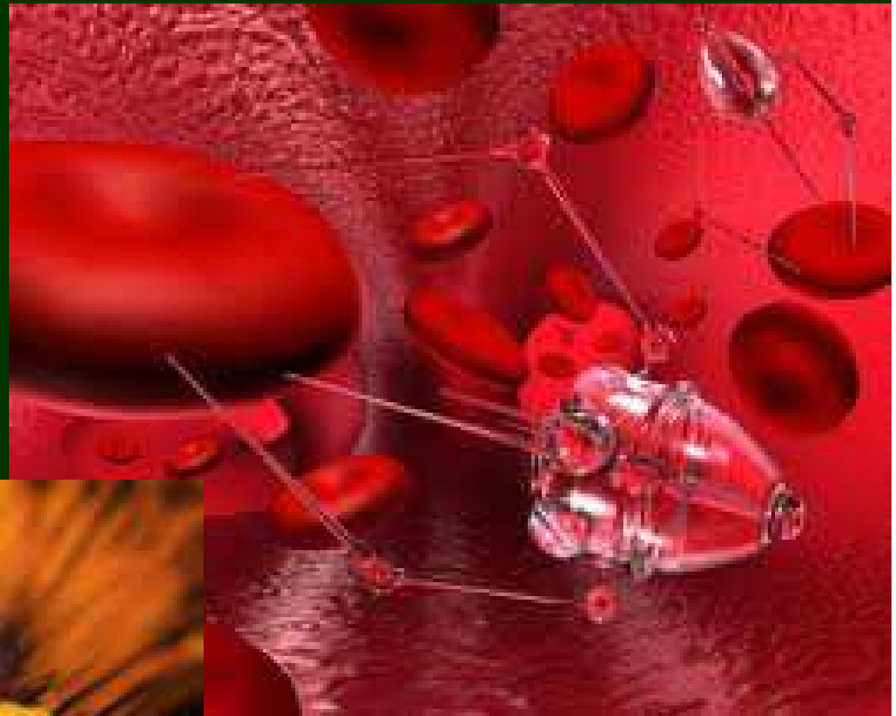


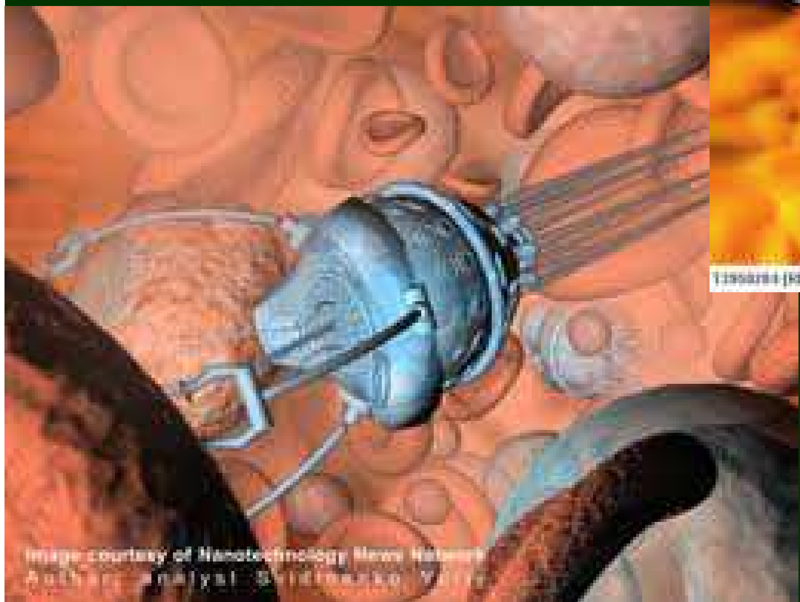


Nanomashines

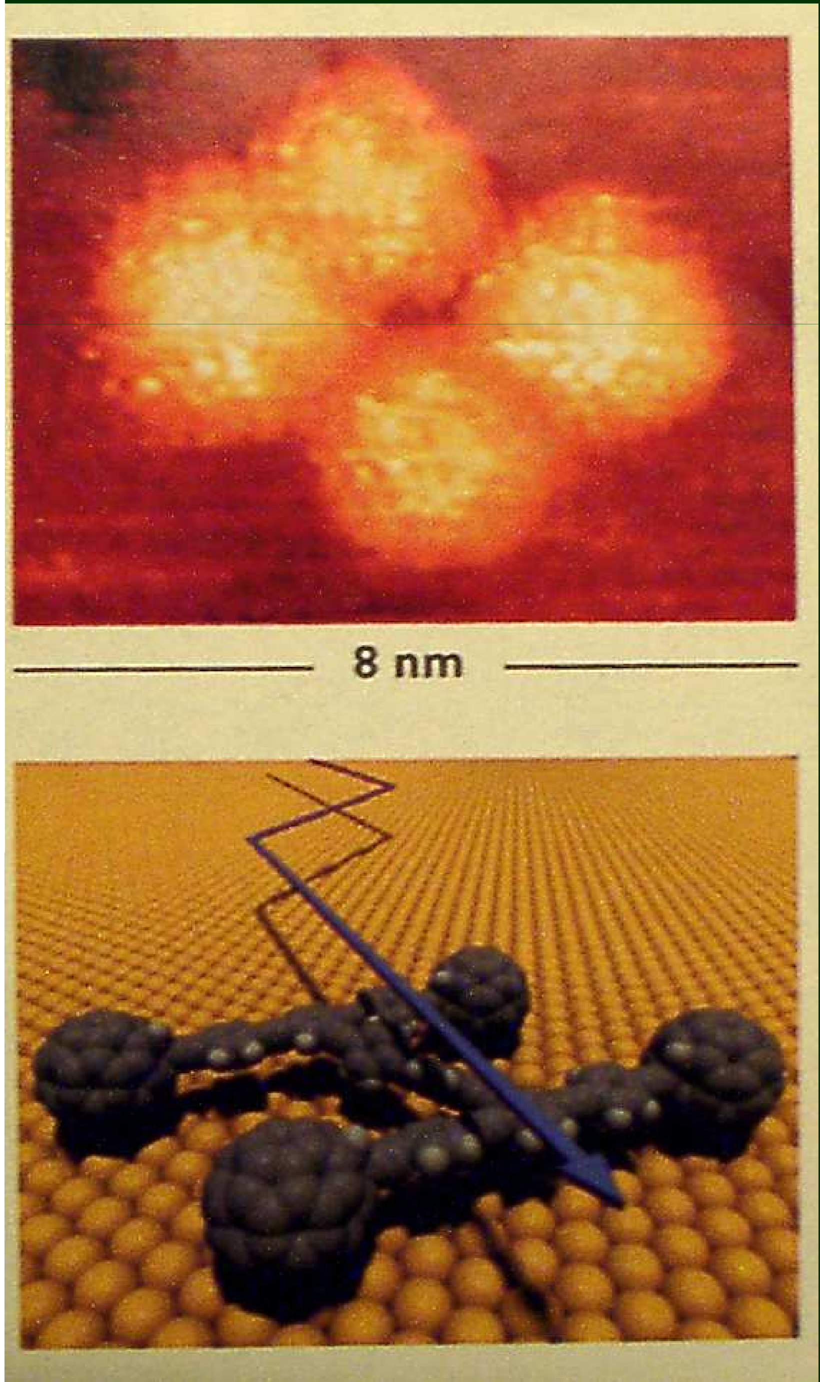
Nanomashines

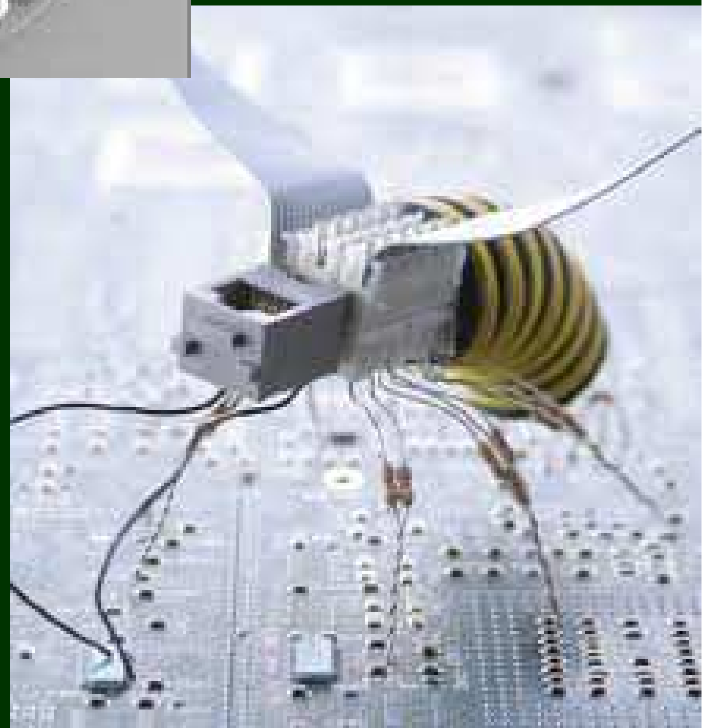




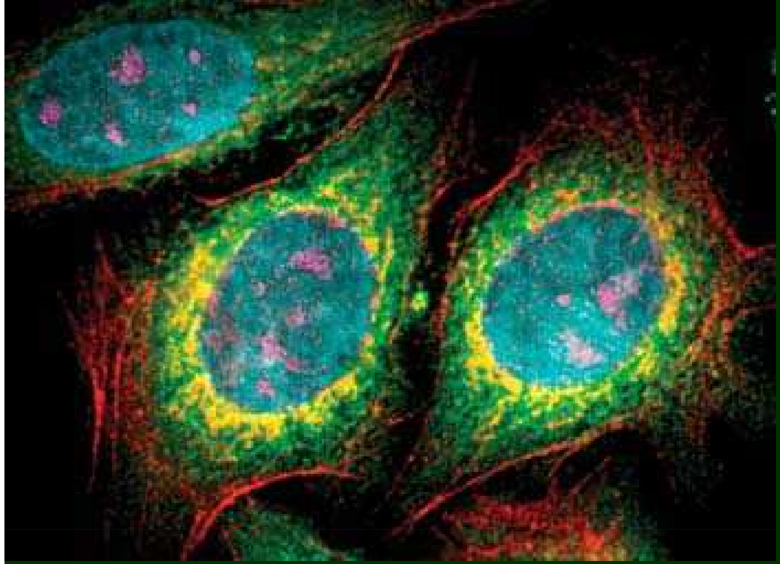


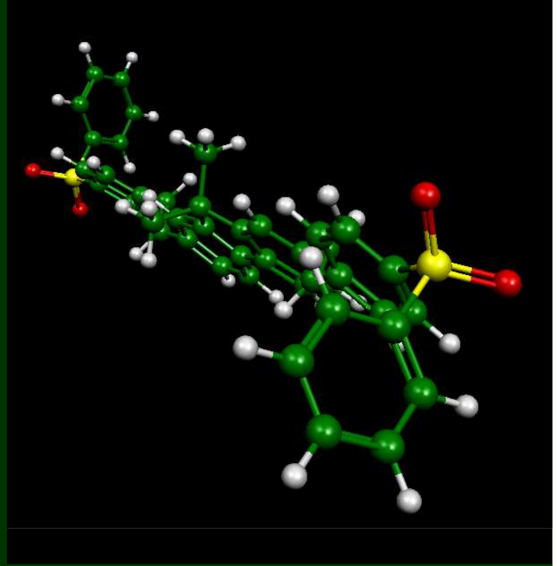
Nanomashines

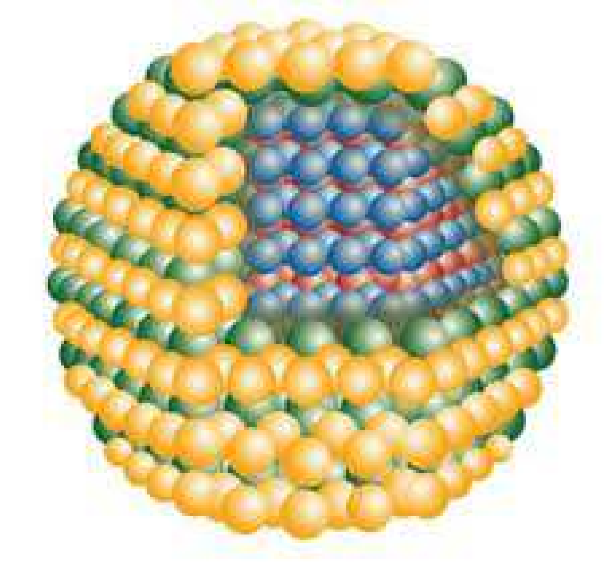


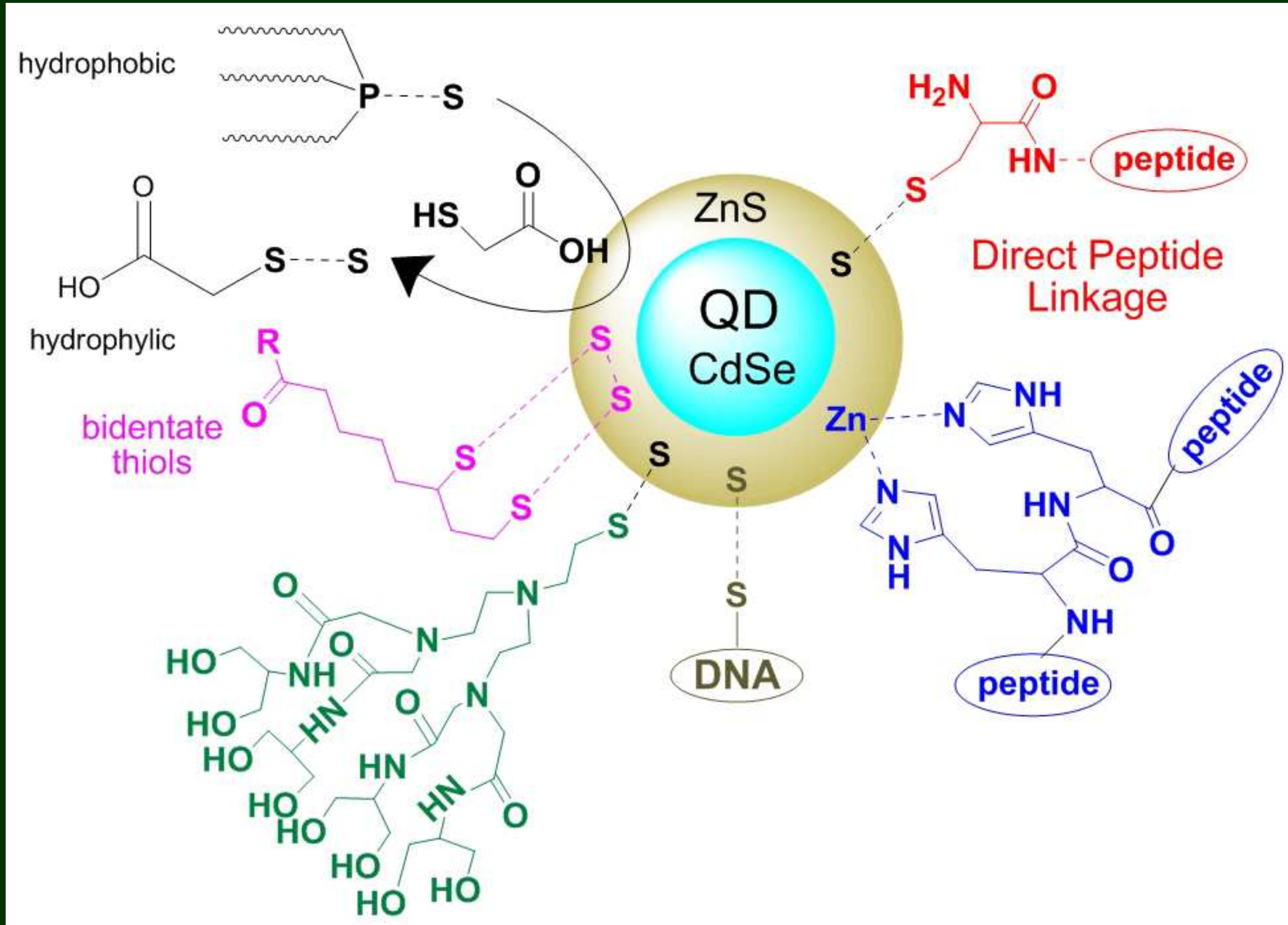


Biological labels

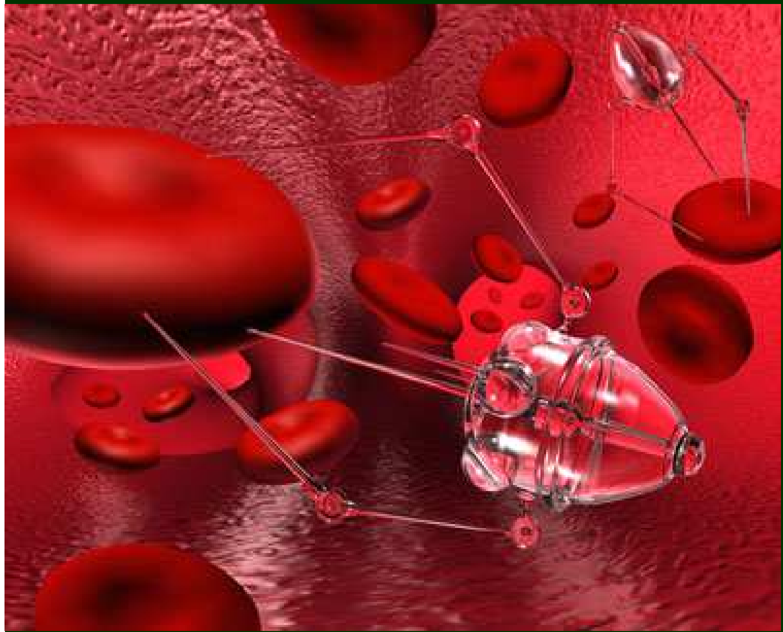


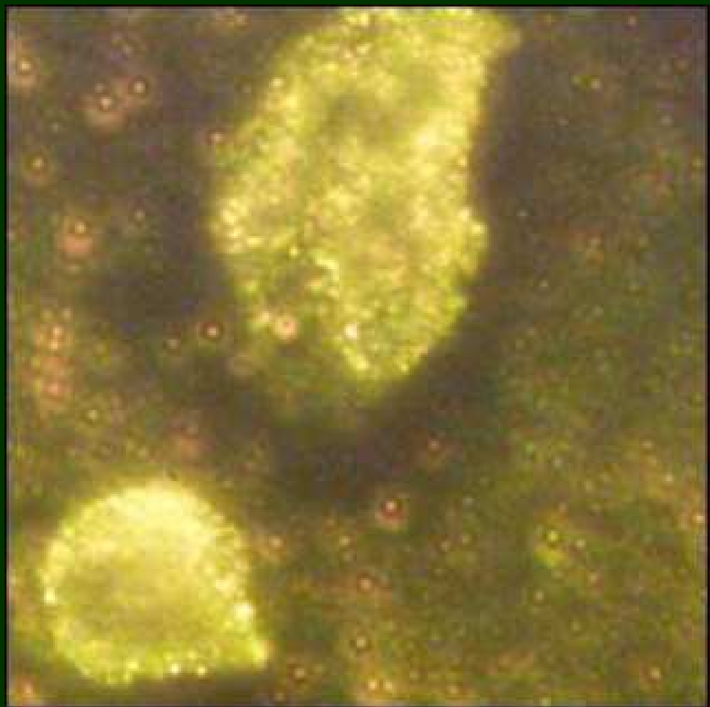


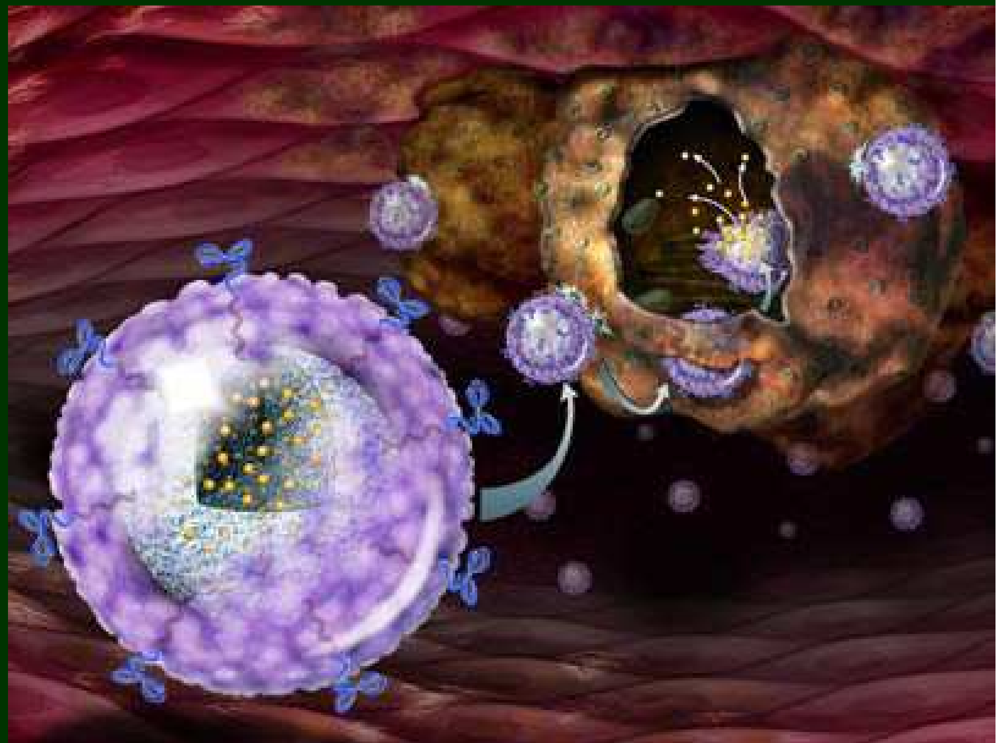




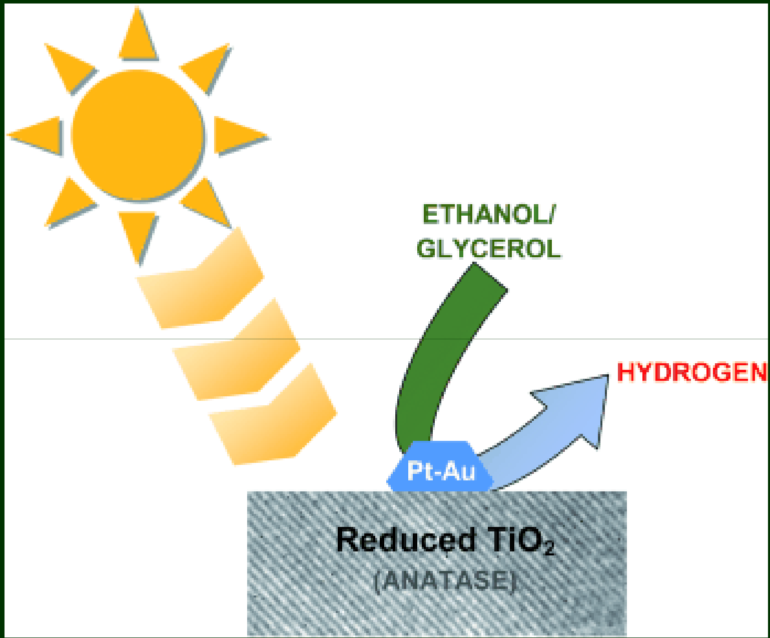
Nanotechnology in medicine

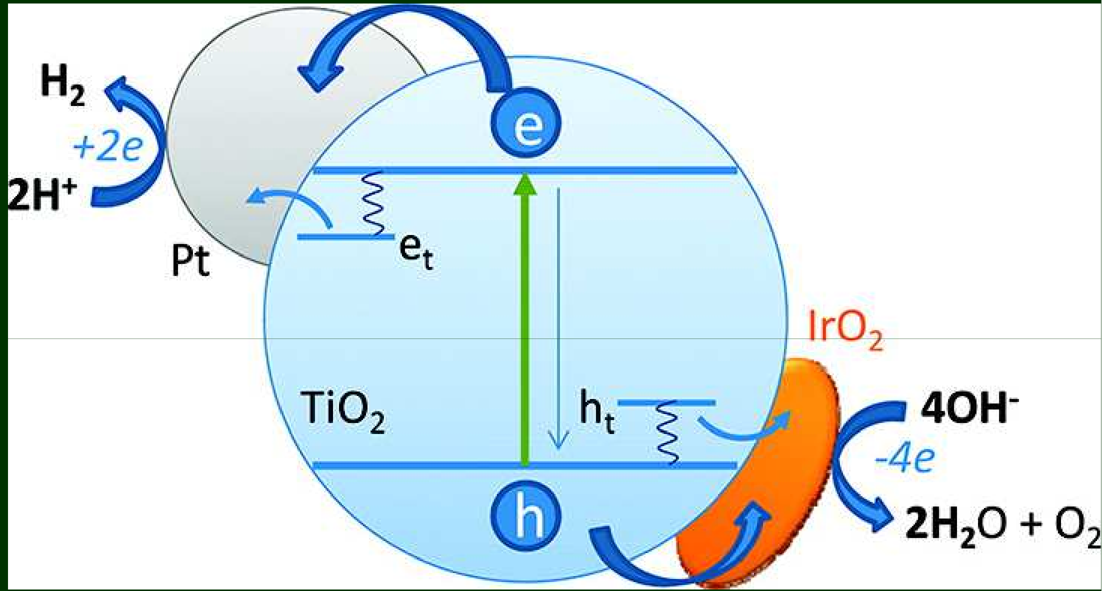






Nanoparticles for photocatalysis





Main ideas in the basis of nanotechnology

- Small devices, high density of information storage, etc.

- Saving materials

- Large surface-to-volume ratio

- New physical properties of the same substances

Quantum size effect (dependence of physical properties on size)

Quantum size effect on electrons, on holes, on phonons, on excitons, etc. is based on Heisenberg's uncertainty principle

$$\Delta x \cdot \Delta p_x \geq h$$

$$\Delta x \Delta p_x \geq h$$

confinement in a box with size a

results in

minimal value of momentum $p_x = h/a$

Thus, minimal kinetic energy of the particle

$$E_x = p_x^2/2m = h^2/2ma^2$$

For 3D confinement

$$\Delta E = E_x + E_y + E_z = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + \frac{p_z^2}{2m} = \frac{h^2}{2m}\left(\frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2}\right).$$

More precise for particle in a spherical quantum well

$$E_{\min} = E_1 = \frac{\pi^2 \hbar^2}{2ma^2}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial R(r)}{\partial r}\right)+\frac{2m}{\hbar^2}\left[E_R-U_0(r)\right]R(r)=-\frac{2m}{\hbar^2}l(l+1)R(r)$$

$$\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)+\frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\varphi^2}\right]Y(\theta,\varphi)=l(l+1)Y(\theta,\varphi)$$

1) $$\frac{\partial^2 R}{\partial r^2}+\frac{2}{r}\frac{\partial R}{\partial r}+\frac{2mE}{\hbar^2}R=0 \qquad r<a,$$

2) $$\frac{\partial^2 R}{\partial r^2}+\frac{2}{r}\frac{\partial R}{\partial r}-\frac{2m(U_0-E)}{\hbar^2}R=0 \qquad r\ge a$$

$$\frac{2mE}{\hbar^2}=k^2,$$

$$\frac{2m(U_0-E)}{\hbar^2}=\chi^2$$

$$R(r)=\rho(r)/r$$

1) $$\frac{\partial^2\rho_1}{\partial r^2}+k^2\rho_1=0$$

2) $$\frac{\partial^2\rho_2}{\partial r^2}-\chi^2\rho_2=0$$

$$\rho_1(r) = A\sin(kr) + B\cos(kr), \; R_1(r) = \frac{A\sin(kr)}{r} + \frac{B\cos(kr)}{r}$$

$$\rho_2(r) = Ce^{-\chi r} + De^{\chi r}, \; R_2(r) = \frac{Ce^{-\chi r}}{r} + \frac{De^{\chi r}}{r}.$$

B=0, D=0

$$R_1(a) = R_2(a), \left.\frac{dR_1}{dr}\right|_a = \left.\frac{dR_2}{dr}\right|_a$$

$$A\sin(ka) = Ce^{-\chi a},$$

$$A\left(ka\cos(ka) - \sin(ka)\right) = C\left(-\chi a e^{-\chi a} - e^{-\chi a}\right)$$

$$ctg(ka) = -\frac{\chi}{k} \qquad ctg(ka) < 0$$

$$k = \sqrt{\frac{2m}{\hbar} E} \qquad \chi = \sqrt{\frac{2m}{\hbar}(U_0 - E)}$$

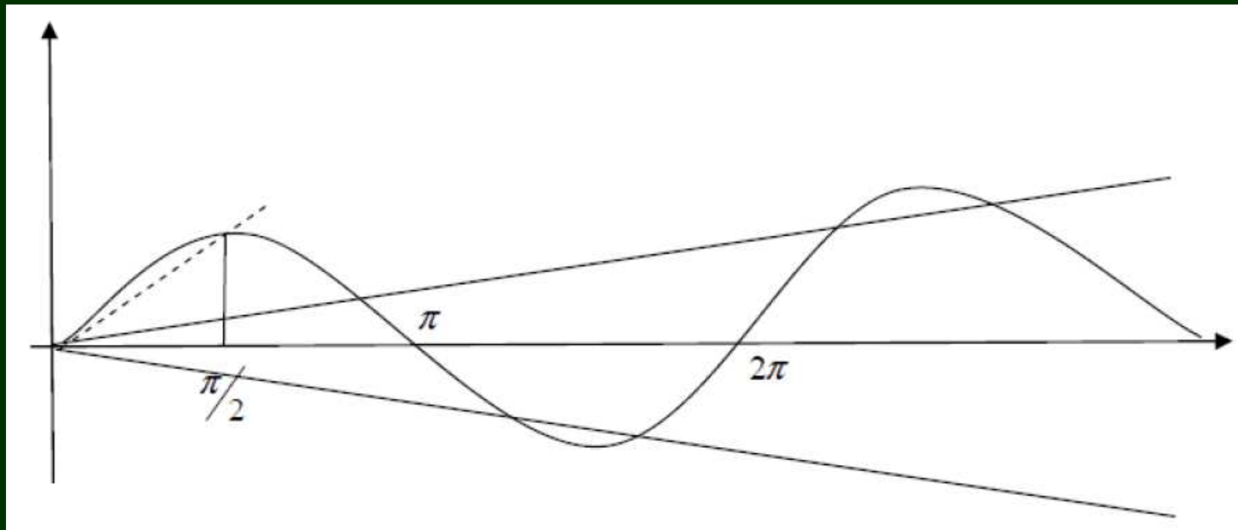
$$ctg^2(ka) = \frac{U_0}{E} - 1$$

$$\sin(ka) = \pm\sqrt{\frac{E}{U_0}} = \pm\sqrt{\frac{\hbar^2 k^2}{2mU_0}} = \pm\sqrt{\frac{\hbar^2}{2ma^2U_0}}ka$$

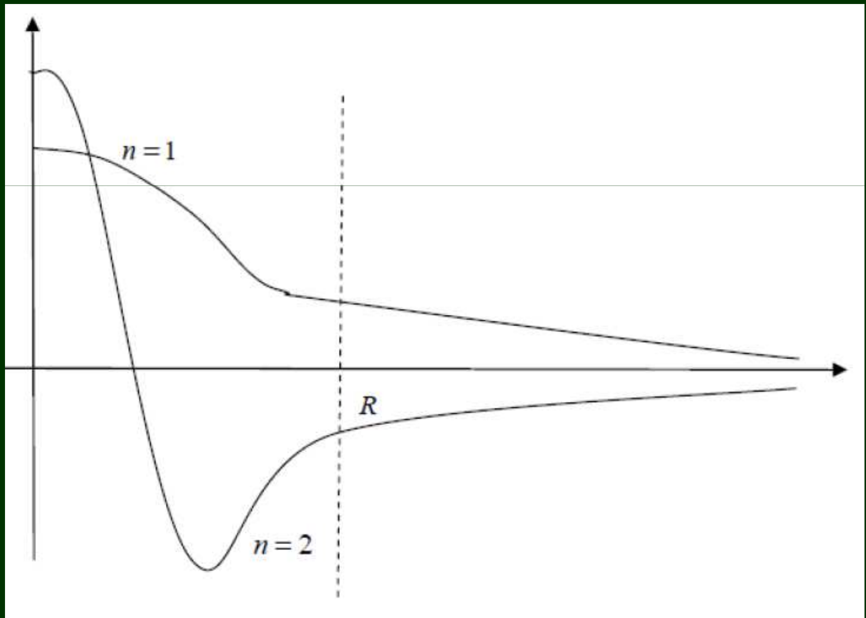
$$\sin^2(ka) = \frac{E}{U_0}$$

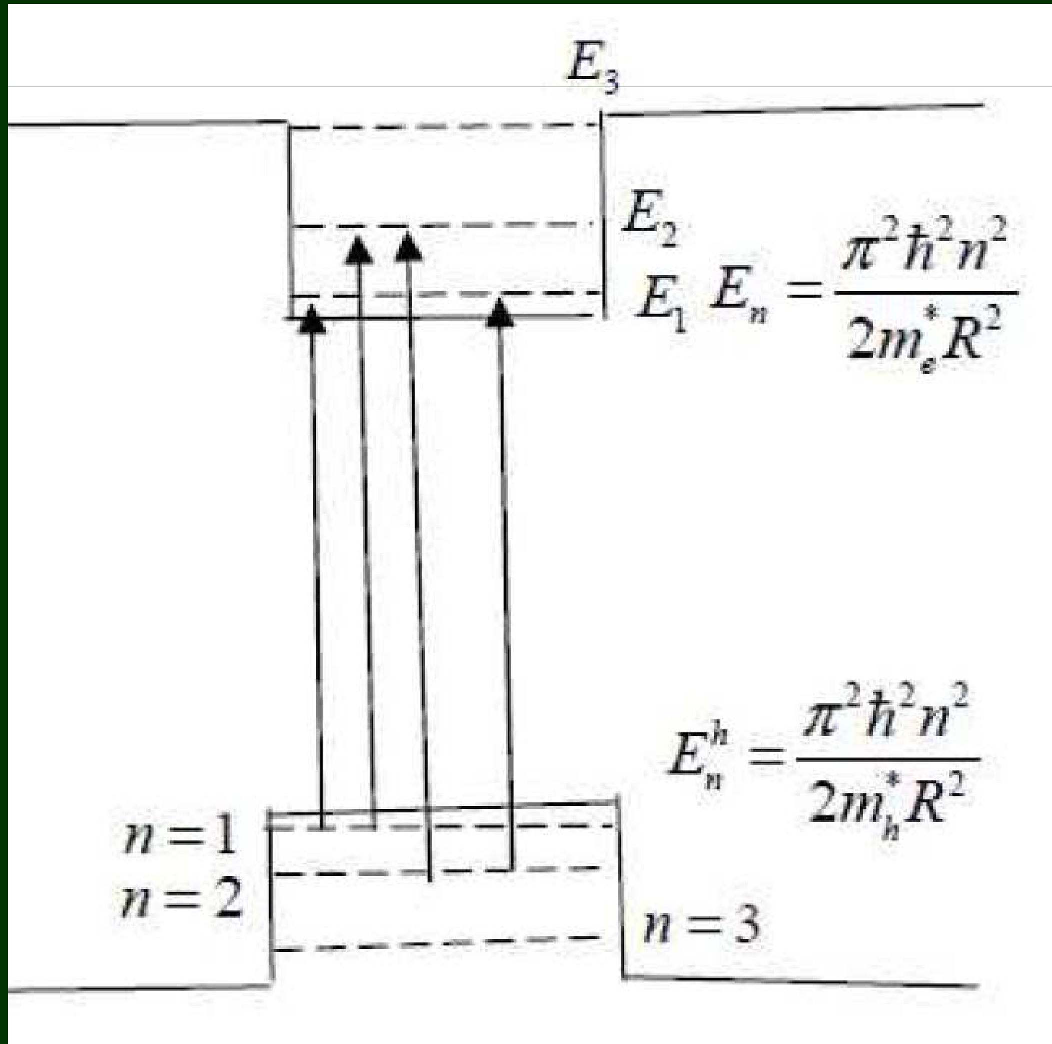
$$b = \sqrt{\frac{\hbar^2}{2ma^2U_0}}, \; ka = x$$

$$\sin x = \pm bx$$

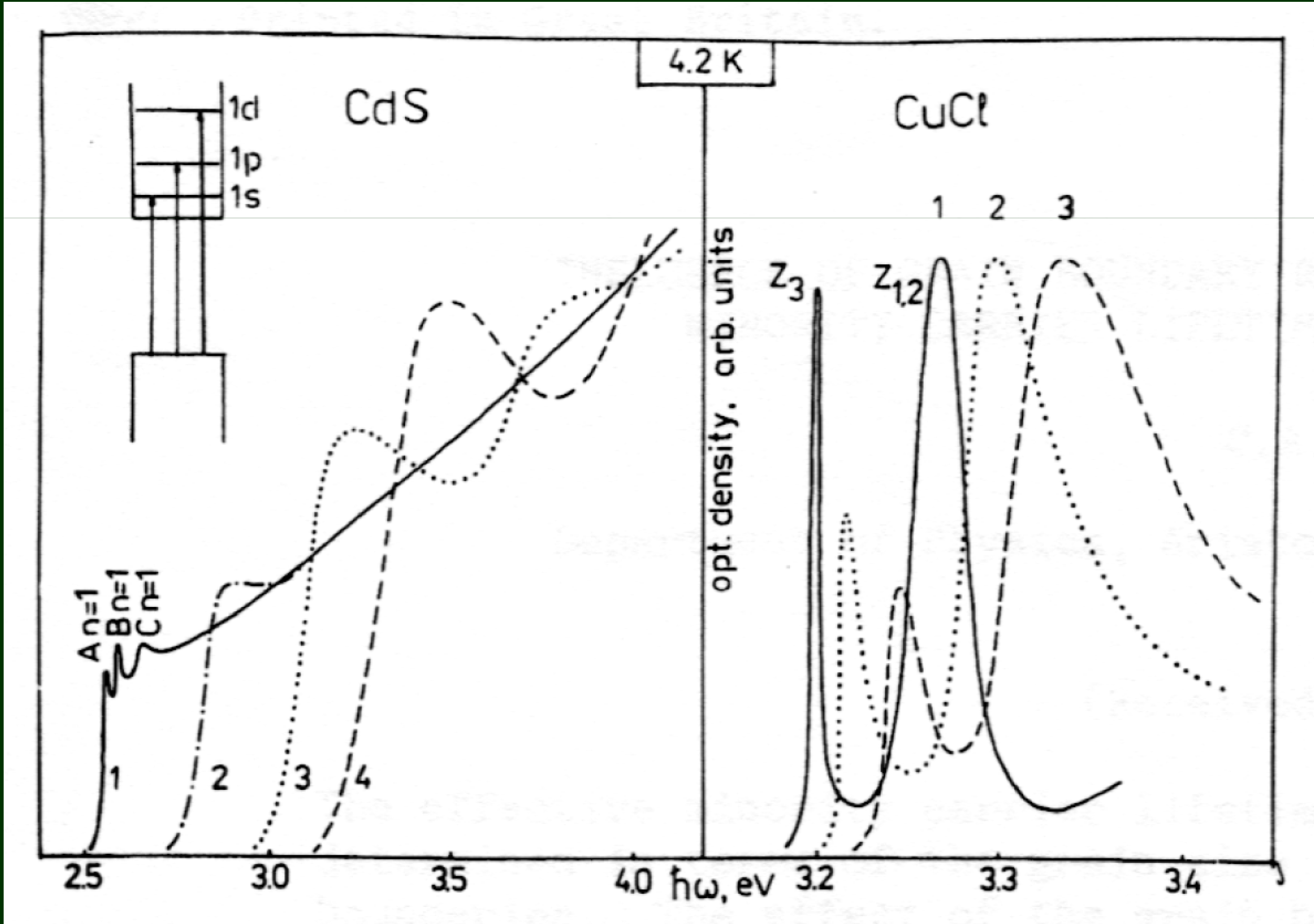


$U_0 \to \infty$ $x = n\pi$ $E = \frac{\pi^2 \hbar^2 n^2}{2ma^2}$

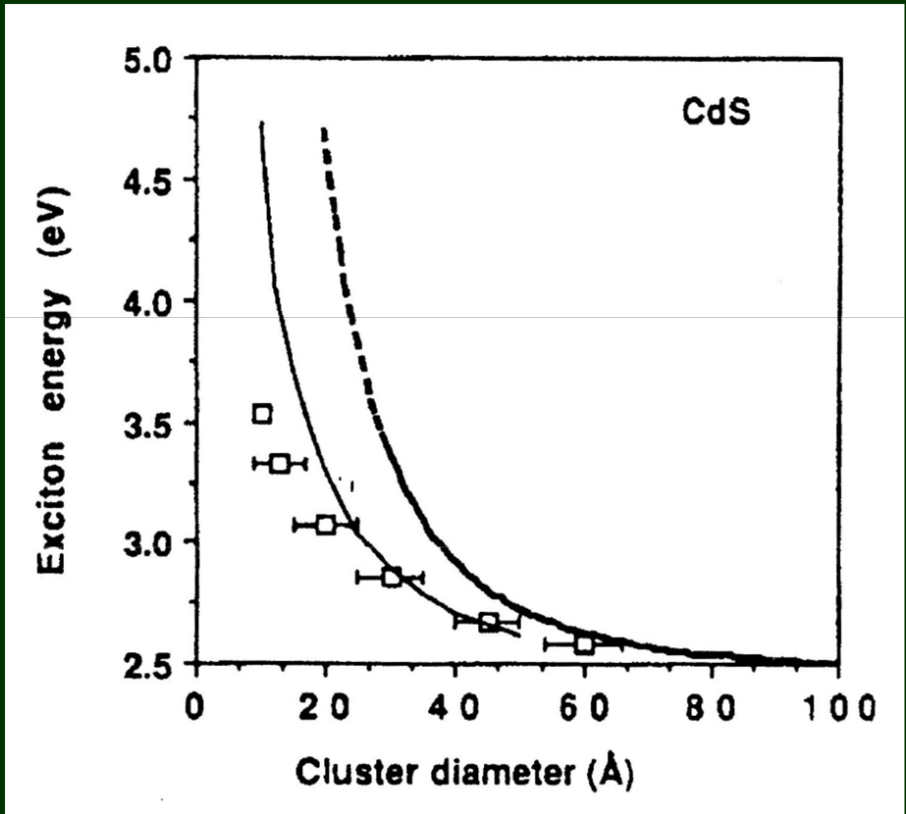


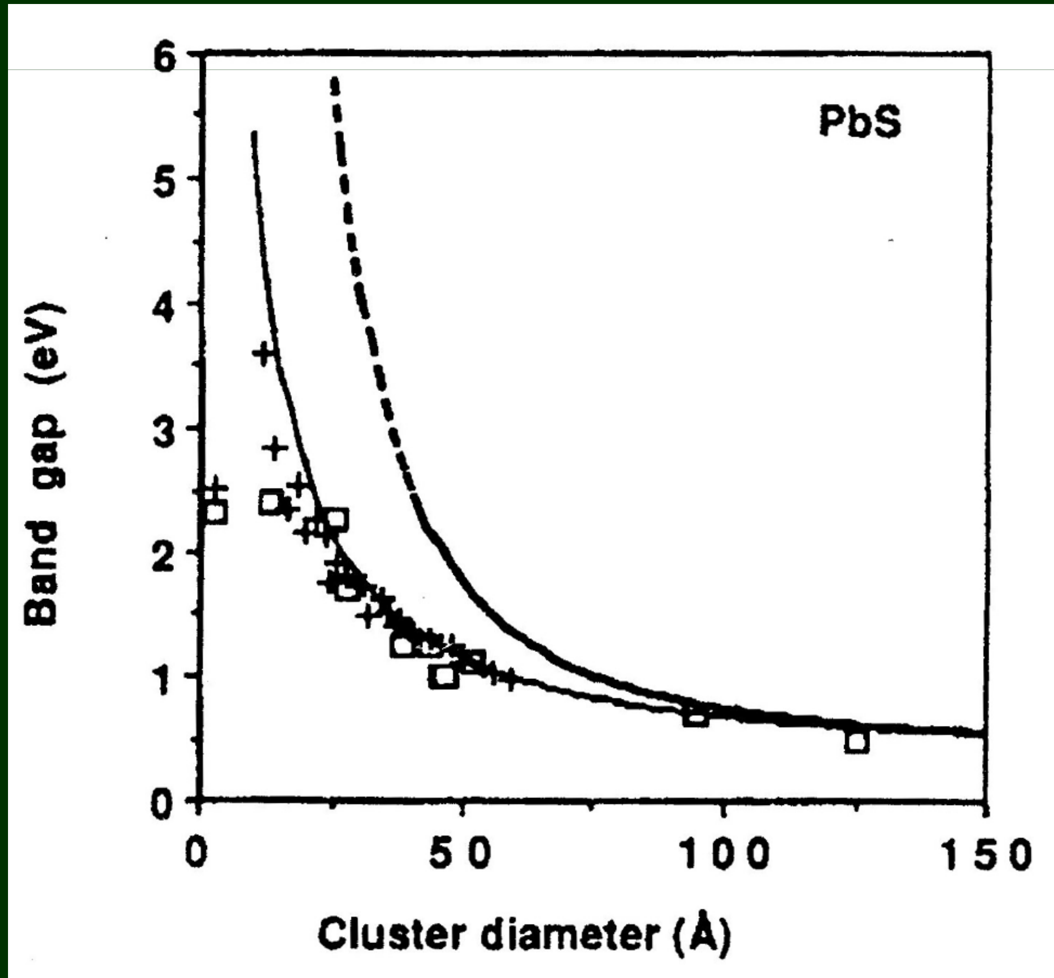


Comparison with experiment

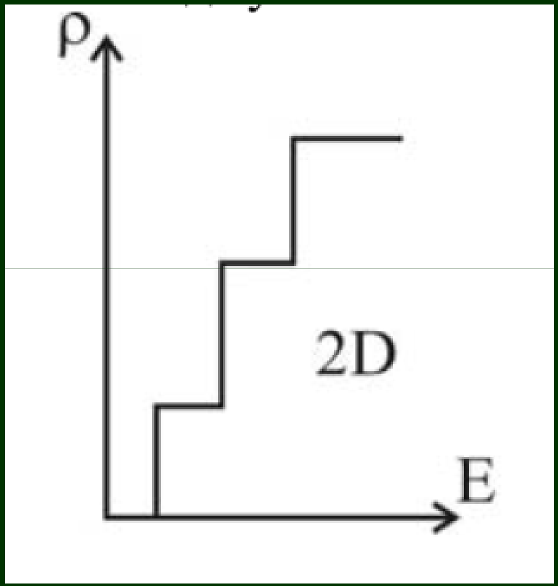


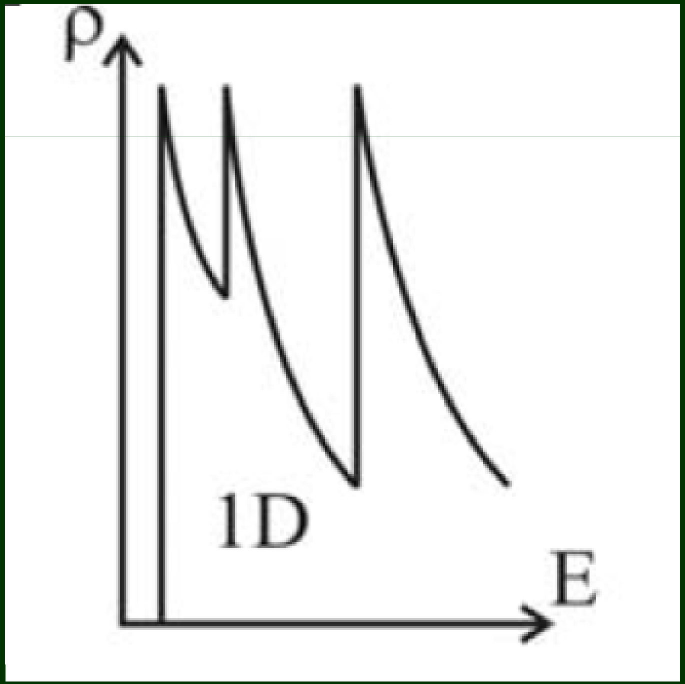
Comparison with experiment

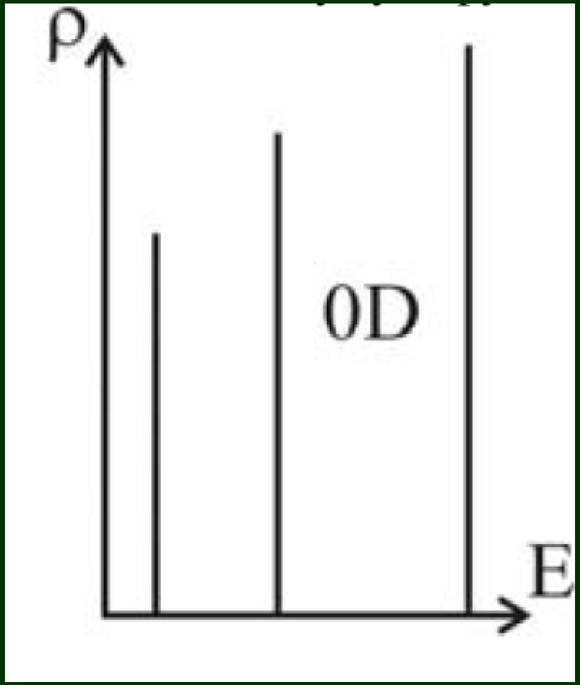




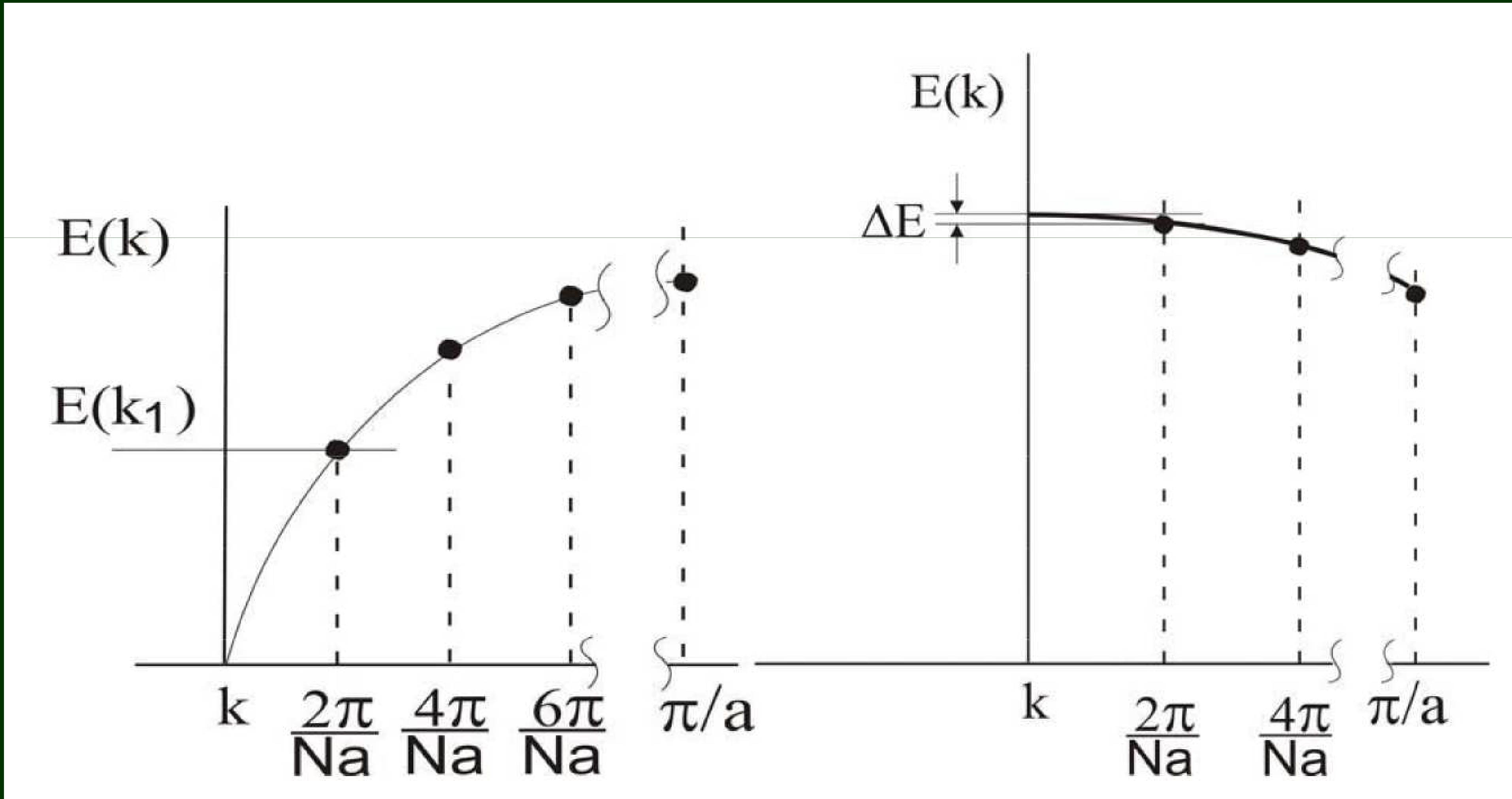
Density of states



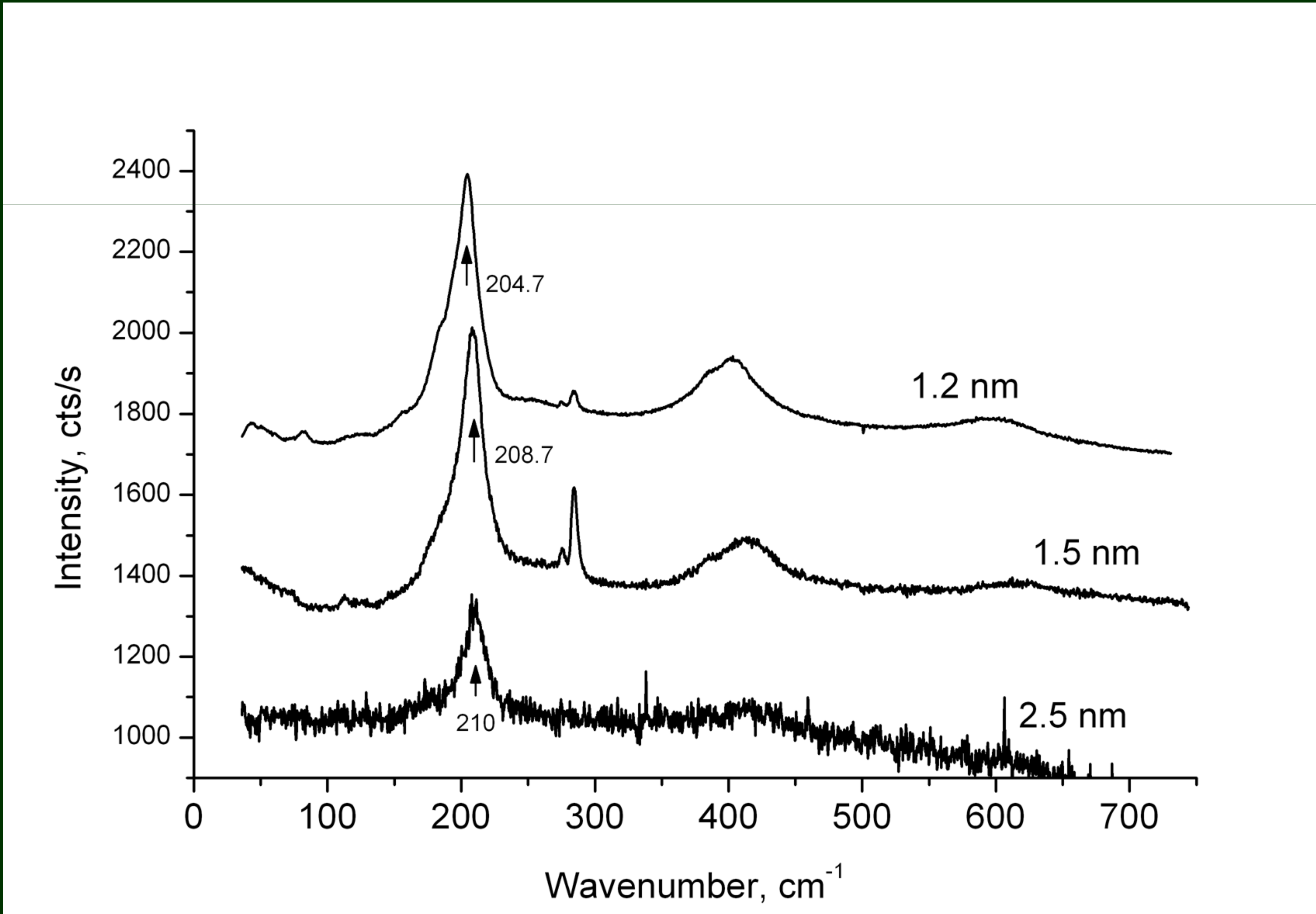




For phonons the story is different

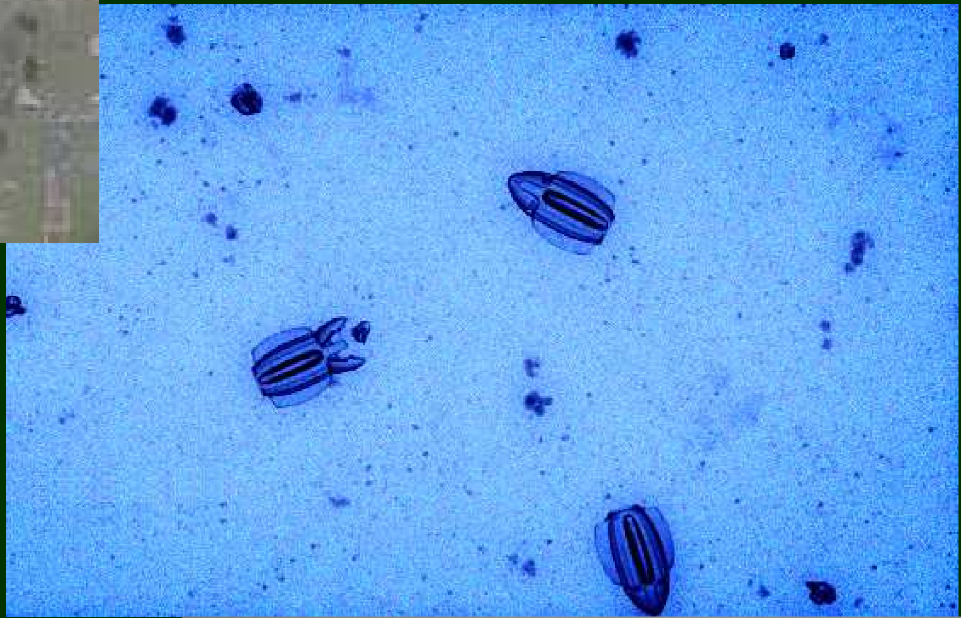


Raman spectra of nanocrystals



Possible problems (real and fantastic)

- toxicity
- grey goo



Possible problems

• New properties of substances and physical phenomena at nanoscale (e.g. Casimir forces)

• Toxicity of nanoproducts

•Ethics of nanoresearch (or “nanoethics”)

What are we working on?

LETTERS

Ultra-stable nanoparticles of CdSe revealed from mass spectrometry

ATSUO KASUYA*[1], RAJARATNAM SIVAMOHAN[1], YURII A. BARNAKOV[1], IGOR M. DMITRUK[1], TAKASHI NIRASAWA[2,3], VOLODYMYR R. ROMANYUK[1], VIJAY KUMAR[1,4,5], SERGIY V. MAMYKIN[1], KAZUYUKI TOHJI[2], BALACHANDRAN JEYADEVAN[2], KOZO SHINODA[2], TOSHIJI KUDO[3], OSAMU TERASAKI[6], ZHENG LIU[6], RODION V. BELOSLUDOV[4], VIJAYARAGHAVAN SUNDARARAJAN[1,7] AND YOSHIYUKI KAWAZOE[4]

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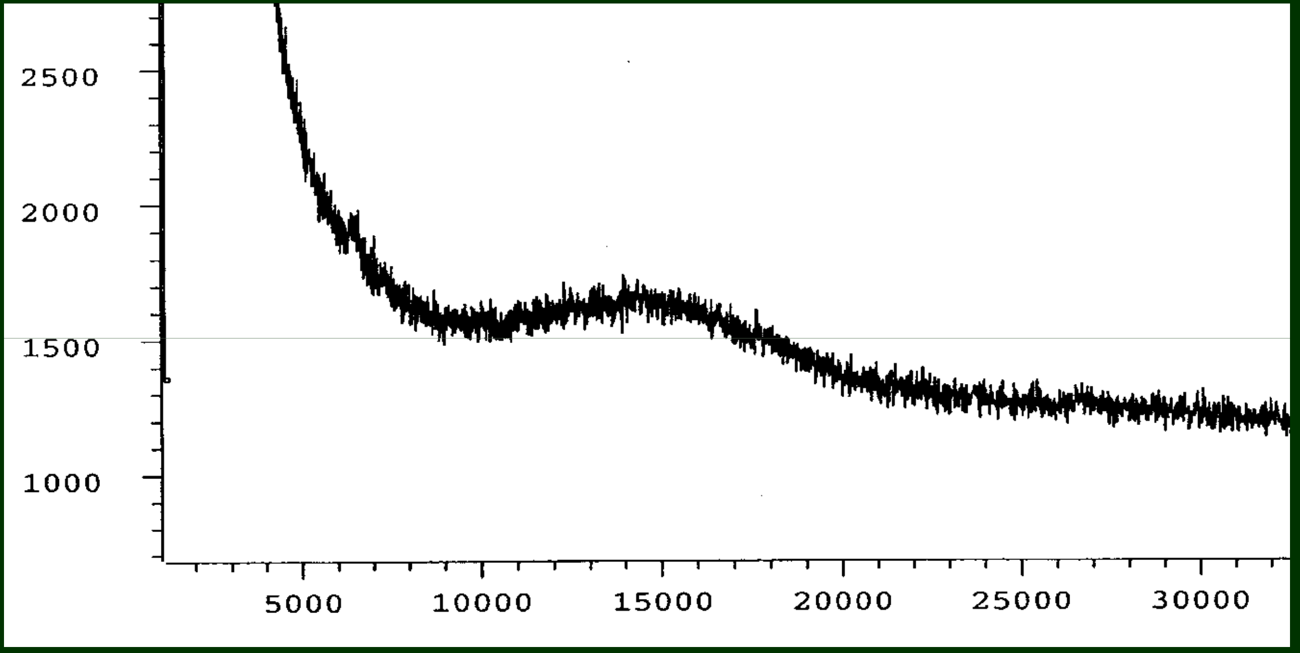
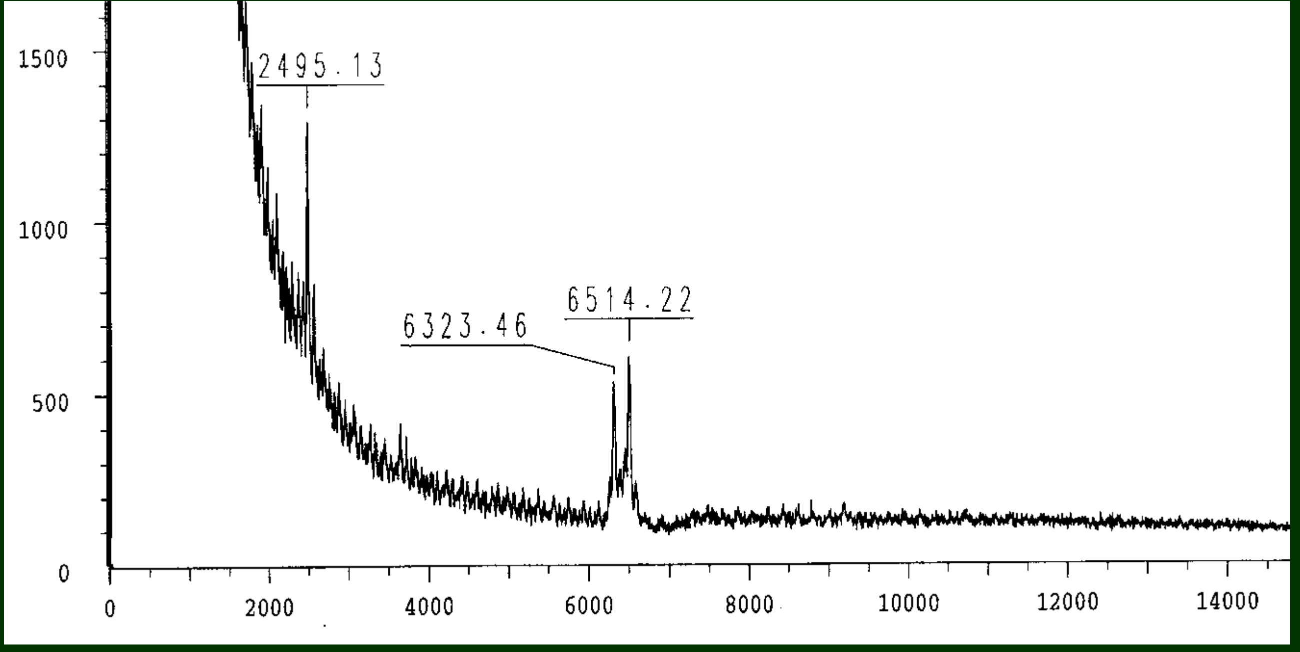
Nanoparticles under a few nanometres in size have structures and material functions that differ from the bulk because of their distinct geometrical shapes and strong quantum confinement. These qualities could lead to unique device

of mass-selected $(CdSe)_{33}$ and $(CdSe)_{34}$ nanoparticles in solution. These constitute the first compound nanoparticles that are stable and macroscopically produced at precisely specified numbers of constituent atoms with their stoichiometric composition identical to the bulk solids.

Bruker Reflex III-T time-of-flight mass spectrometer

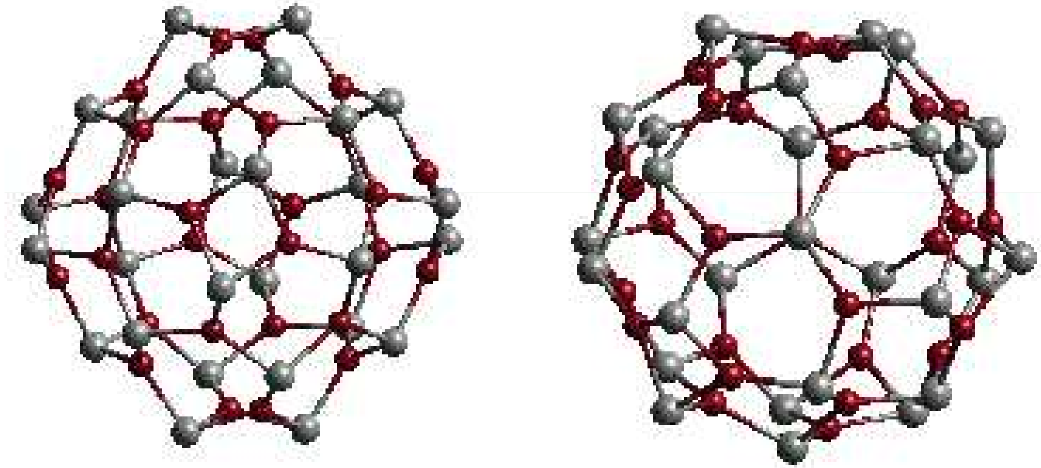
“Magic” CdSe nanoclusters



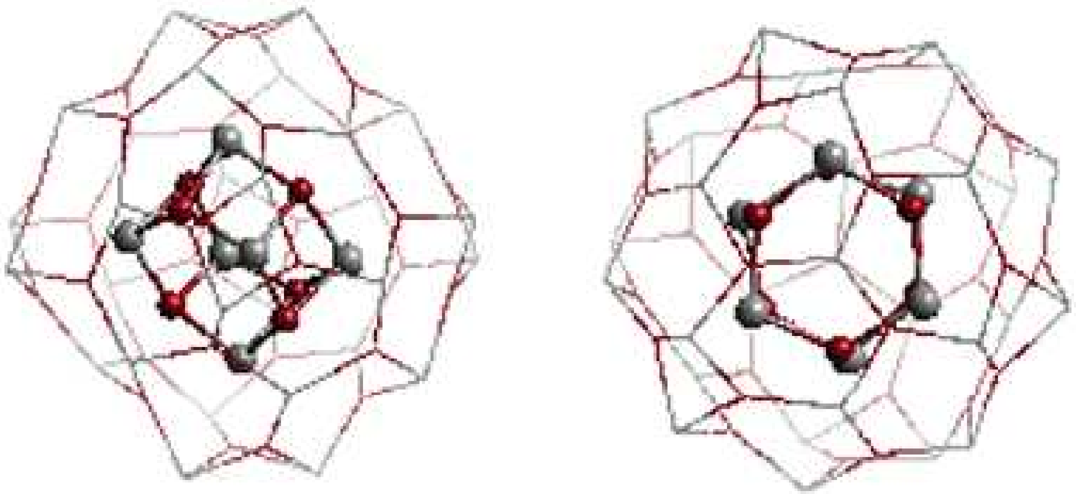


Structure

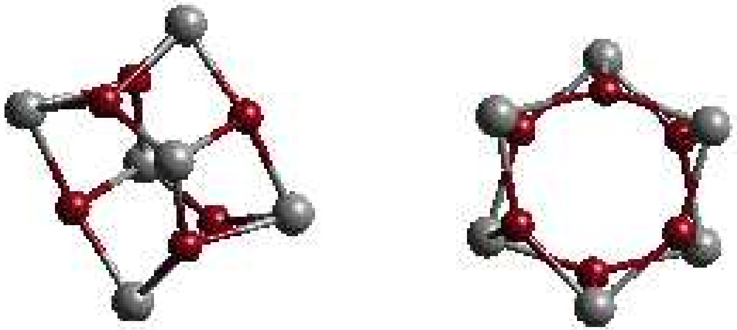
$Cd_{28}Se_{28}$



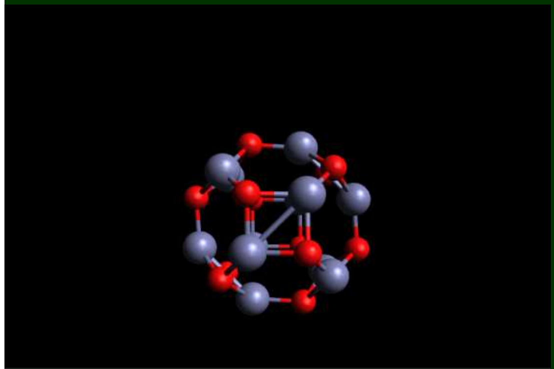
$Cd_{34}Se_{34}$

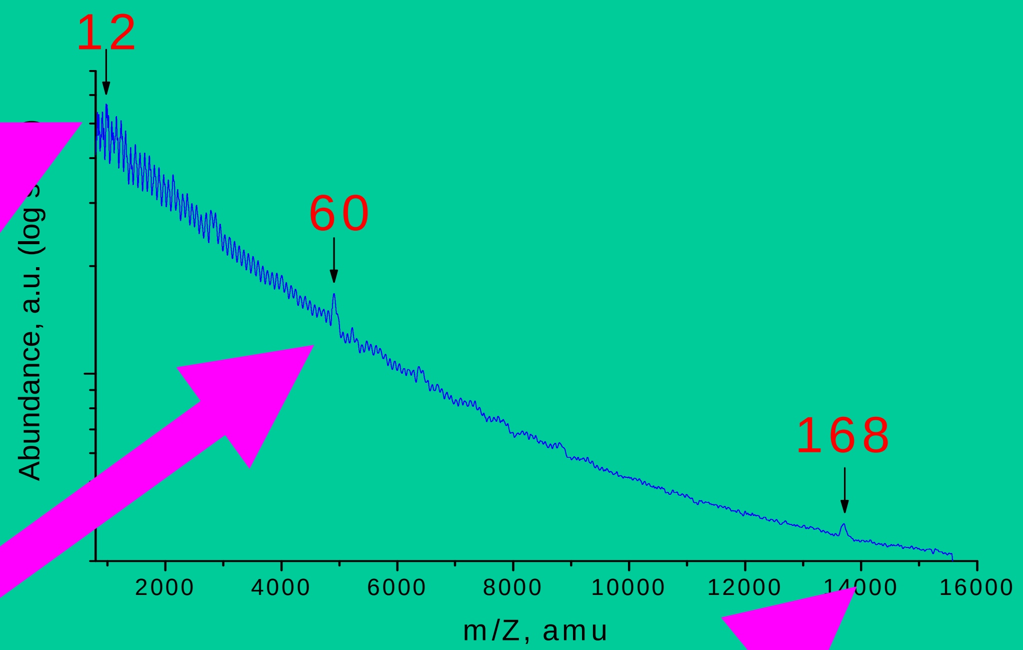


$Cd_{6}Se_{6}$



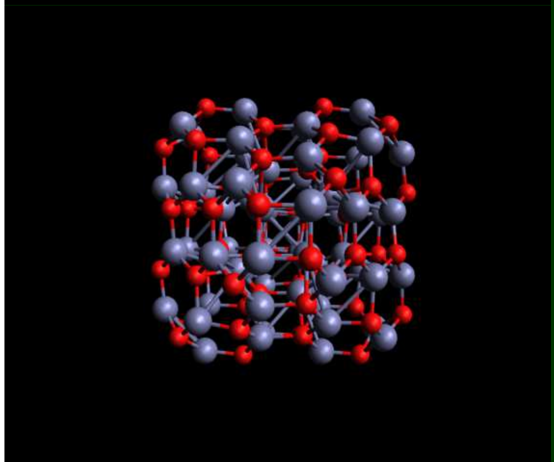
$(ZnO)_{12}$ @ $(ZnO)_{48}$ @ … @ $(ZnO)_{12m^2}$ series:





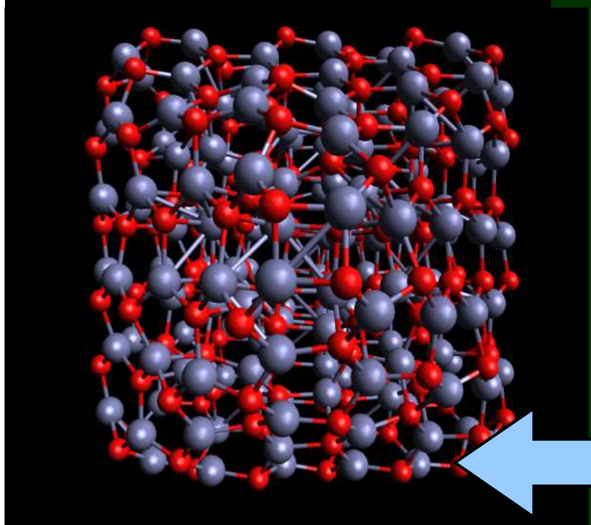
•m=1:

•$(ZnO)_{12}$



•m=2:

•$(ZnO)_{60}$ = $(ZnO)_{12}$ @ $(ZnO)_{48}$

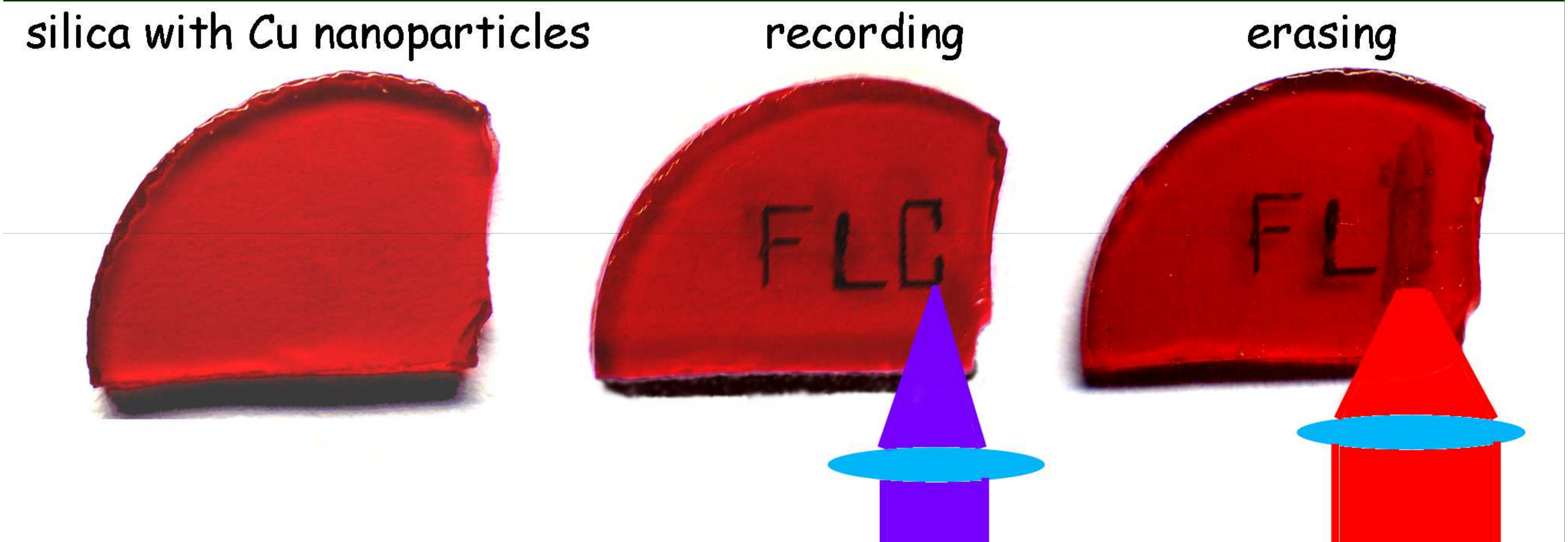


•m=3:

•$(ZnO)_{168}$ = $(ZnO)_{12}$ @ $(ZnO)_{48}$ @ $(ZnO)_{108}$

Optimized structure (B3LYP/6-31G)

Application Optical recording and erasing

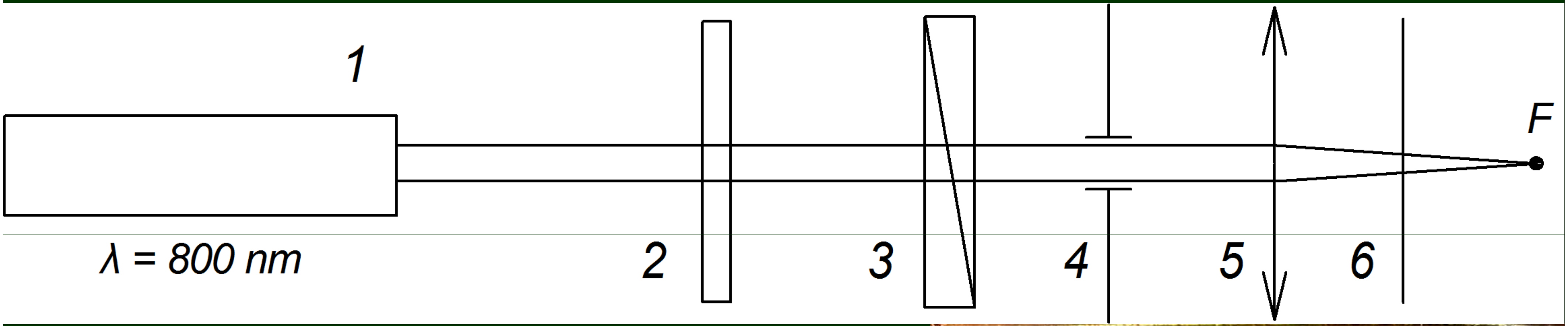


Initial

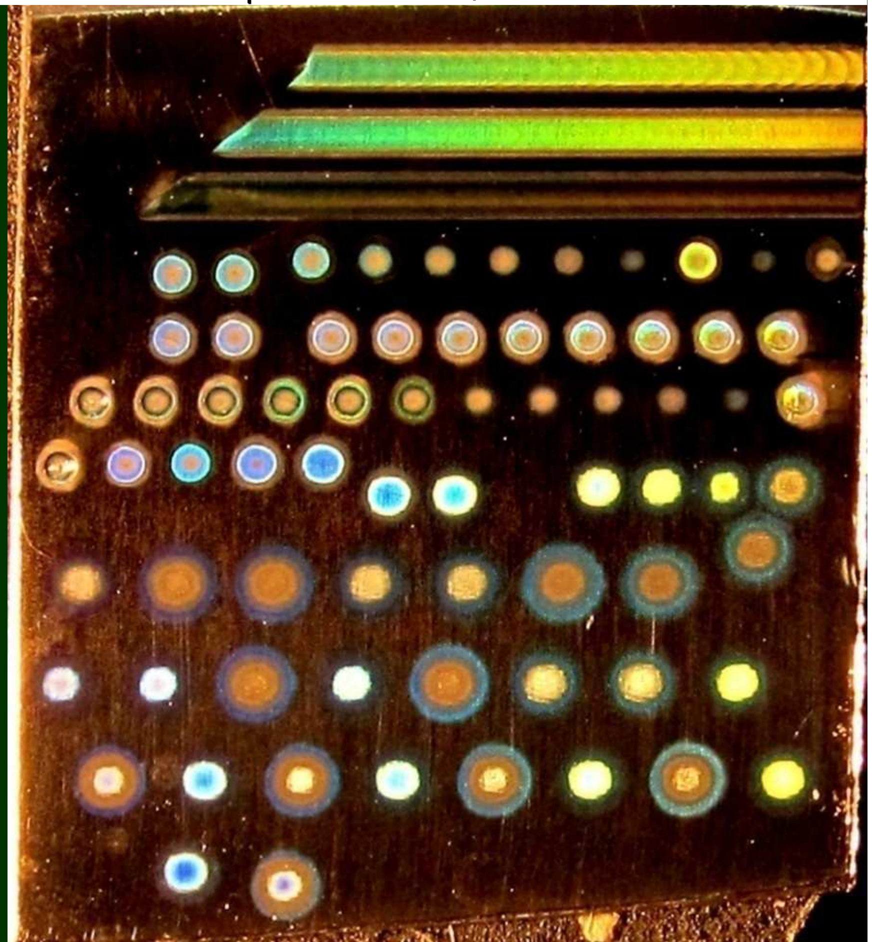
Recording (400 nm)

Erasing (800 nm)

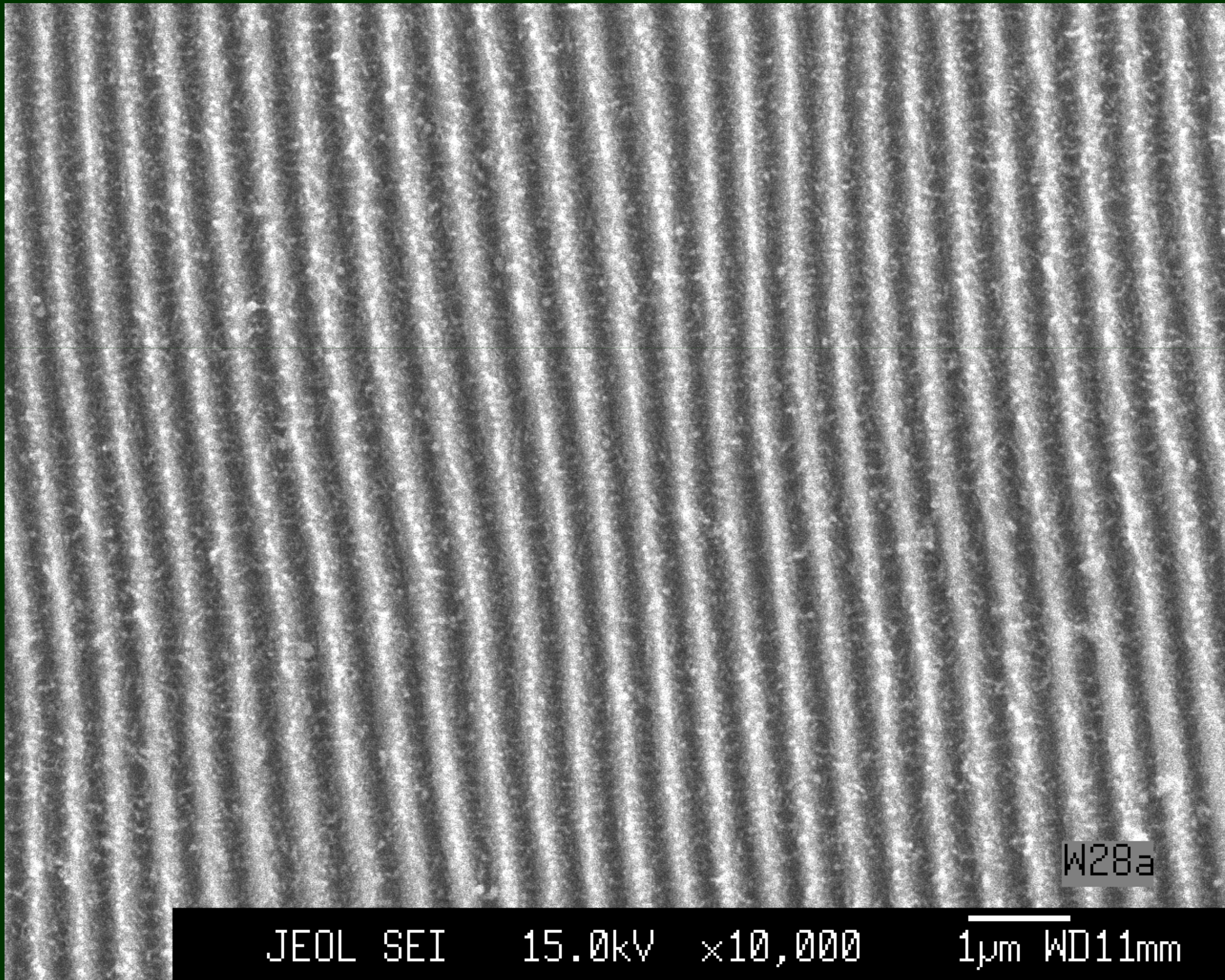
Laser-induced surface structures



- 1 – laser system
- 2 – half-wave plate
- 3 – polarizer
- 4 – diaphragm
- 5 – lens
- 6 - sample



Formation of laser-induced periodic structures



SEM image of the stripes on the surface of tungsten irradiated with 10^{12} W/cm^2 femtosecond laser pulses

Questions that are not answered yet

- Is it real mass production of nanodevices?
- When will nanotechnology come out of laboratories?
- Are the costs justified?
- Real and fantastic dangers of nanotechnology (toxicity of fullerenes and "gray goo").