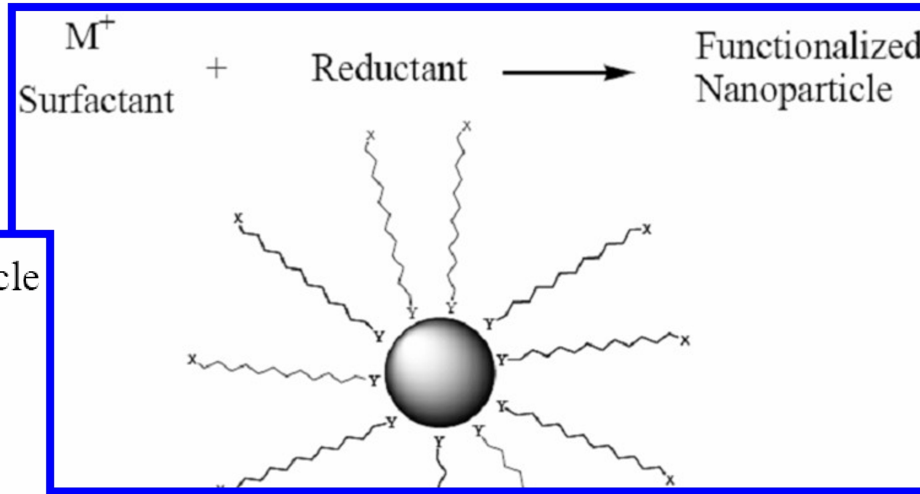
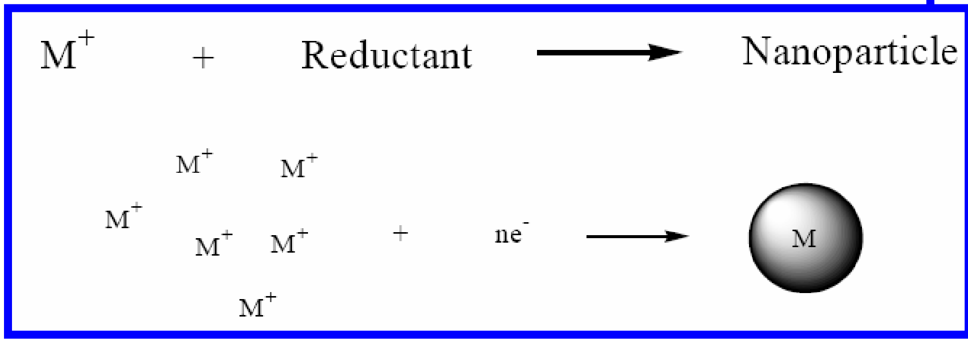
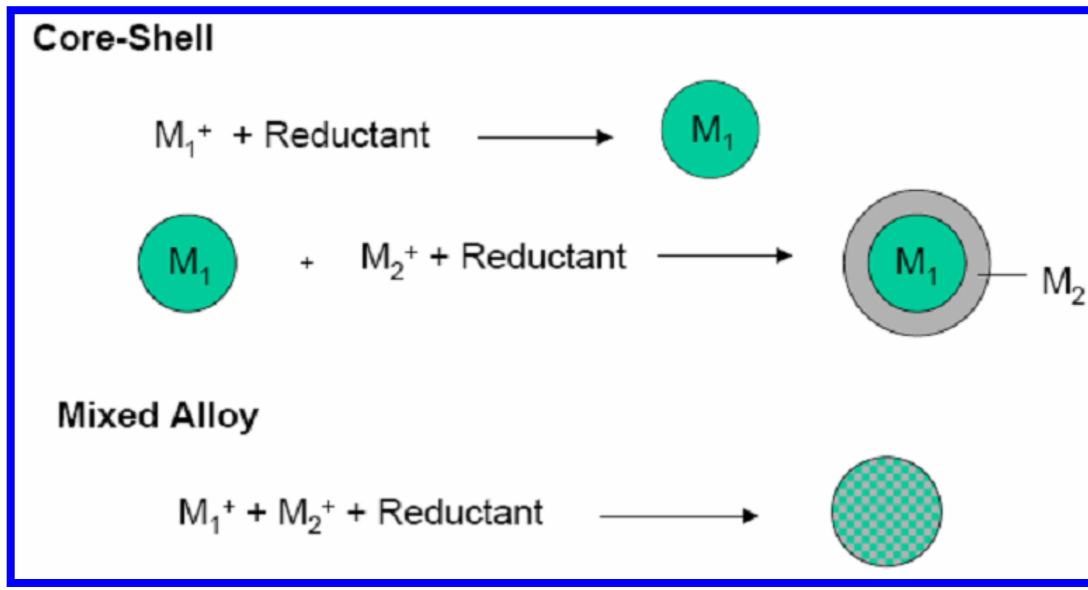
Metal-based nanomaterials

Type of metal NPs





- **functionalization:**
  - anions, polymers, proteins, …

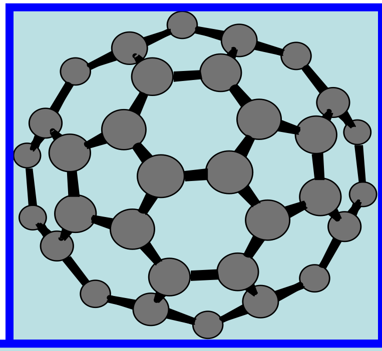


Synthesis of metallic nanoparticles

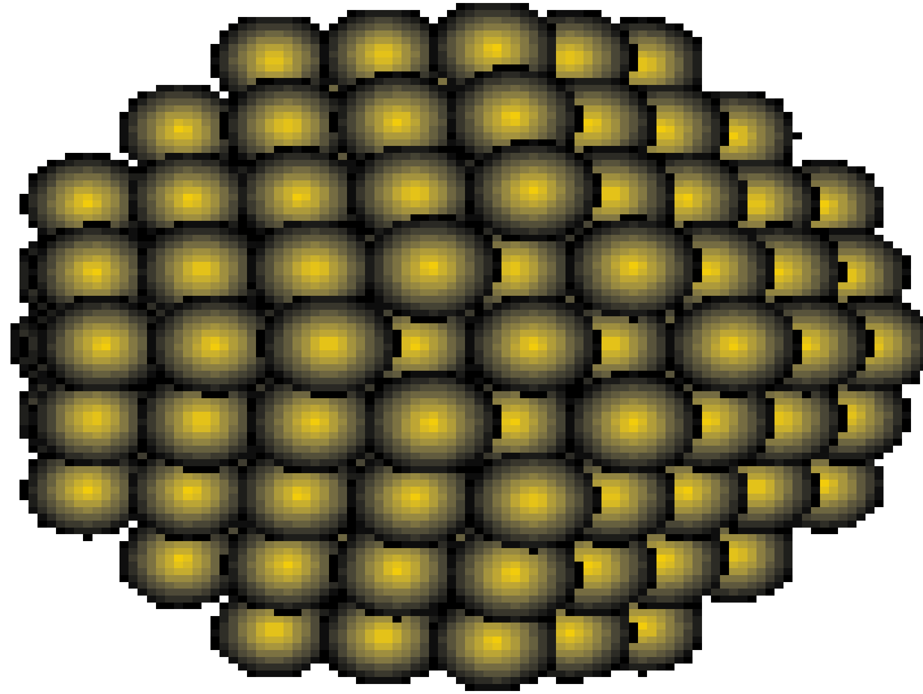
- **diffusion controlled proces**
  - achieved by low concentration of solute
  - or polymeric monolayer adhered onto the growing surface
- **precursor: elemental metals, inorganic salts and metal complexes**
  - anodes from Pd / Ni / Co
  - $PdCl_2$, H_2PtCl_6, K_2PtCl_4, $HAuCl_4$, $AgNO_3$, $RhCl_3$
- **reduction agent**
  - citrate / citric acid, H_2O_2, hydroxylamine, H_2, CO, P (in ether), methanol, formaldehyde, $NaBH_4$, NaOH, NH_4^+, Na_2CO_3
- **polymeric stabilizer**
  - polyvinyl alcohol (PVA), polyvinyl pyrrolidone (PVP), polyethylene imine (PEI), polyphosphate, polyacrylate, tetraalkylammonium halogenides

Gold nanoparticles (AuNP)

1 nm   2 nm



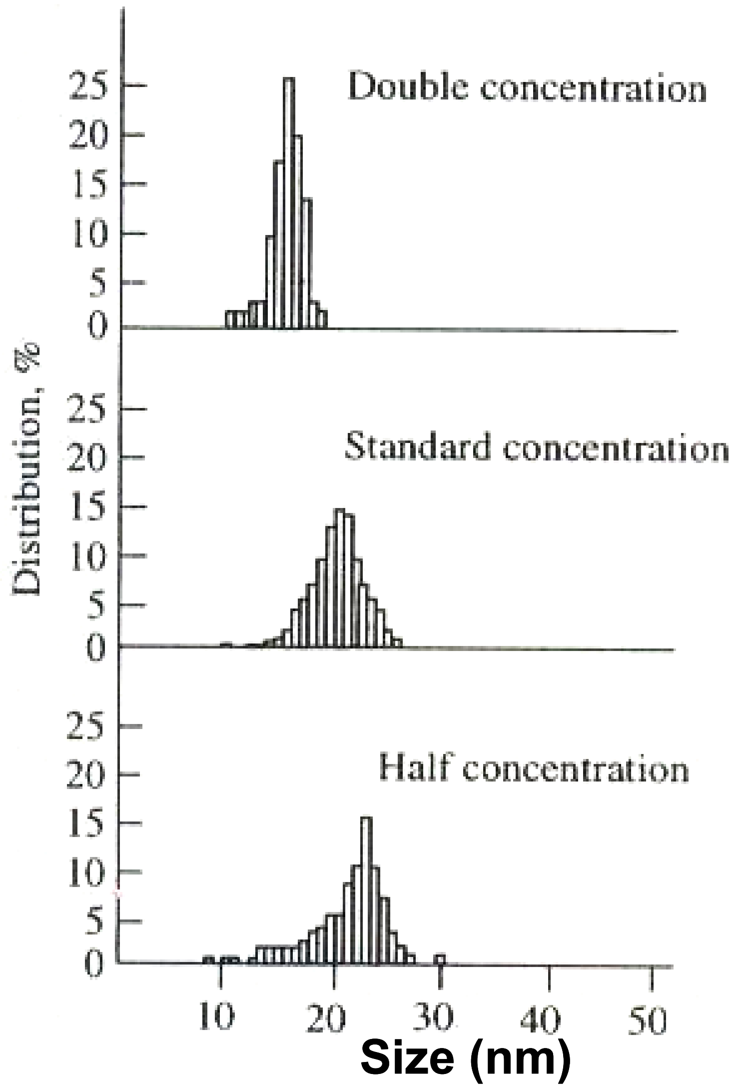
C_{60} – Buckminsterfullerene

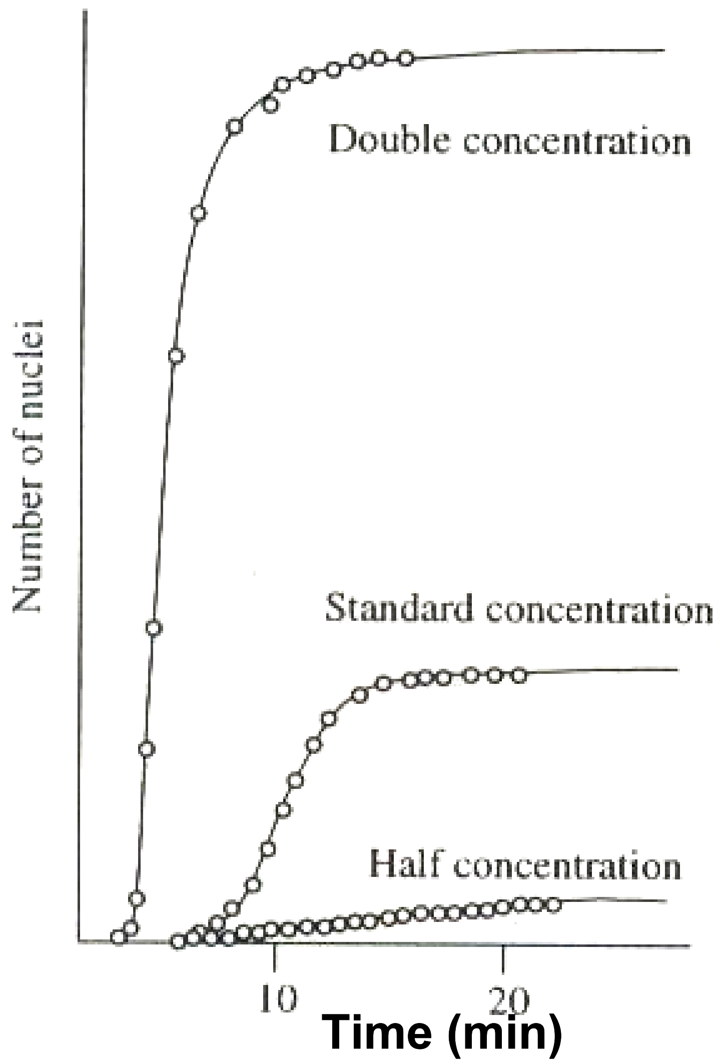


gold nanoparticle: ~ 300 Au atoms

- **preparation - classic:**
  - chlorauric acid dissolves into water to make 20 ml very dilute solution of 250 uM
  - then 1 ml 0.5% sodium citrate is added into the boiling solution
  - the mixture is kept at 100^{o}C till color changes, while maintaining the overall volume of the solution by adding water
- **… Turkevich, J. Discuss. Faraday Soc., 1951**

Effect of concentration



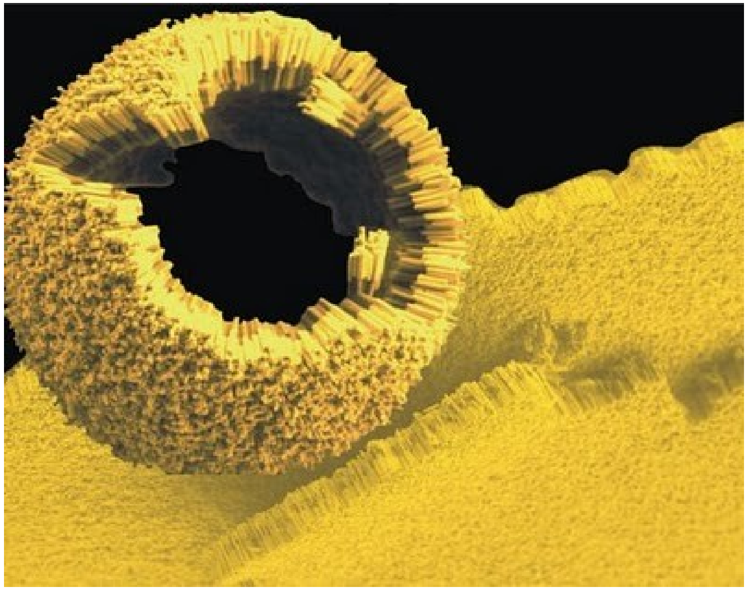


Colloid gold

- **stable suspension of dispersed metal particles, 5 to some 150 nm**
  - in solution looks intensively colored (**red**, corresponding to the size) after eventual coagulation turns dark (**blue**)
- **conjugation with proteins – variable, according to:**
  - type of interaction responsible for binding with the NP (negatively charged)
  - hydrophobic interaction can be involved, too
  - for Au NP (or other noble metal NPs), the strong **binding of thiols** is convenient (SAM, self assembled monolayer is formed)
- **the adsorbed proteins generally stabilize the colloid gold and prevent coagulation**
  - binding of proteins should occur near the isoelectric point (small charge …)
  - the process can be followed photometrically (at 580 nm for Au NPs)
- **coagulation can be initiated by e.g. addition of sodium chloride – change of ionic strength**

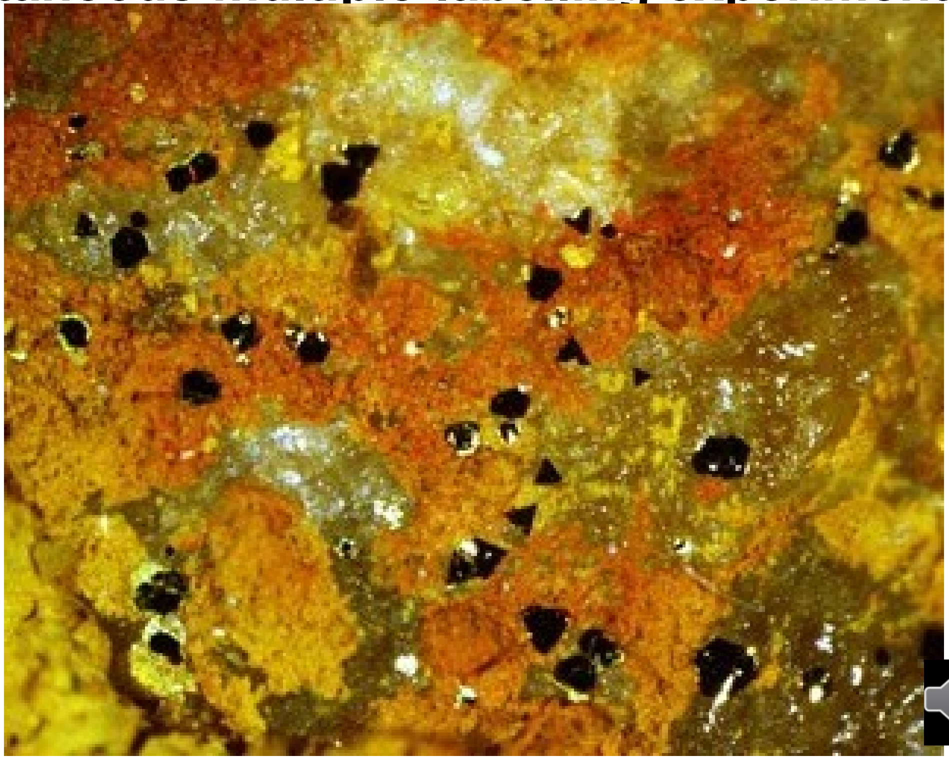
Nanogold (colloidal gold)

- a suspension / colloid of gold in a fluid
- 10 nm particles absorb green light and thus appear red
- the size goes down, the melting temperature decreases
- gold ceases to be noble
- turn into insulators
- shape: icosahedral symmetry, or hollow or planar, depending on size



Usage of nanogold

- colloidal gold is widely-used contrast agent for biological electron microscopy
- Au NPs can be attached to many traditional biological probes such as antibodies, lectins, superantigens, glycans, nucleic acids, and receptors
- "immunogold" - antibody labeled with AuNPs, is used since 1970
- particles of different sizes are easily distinguishable in electron micrographs, allowing simultaneous multiple-labelling experiments

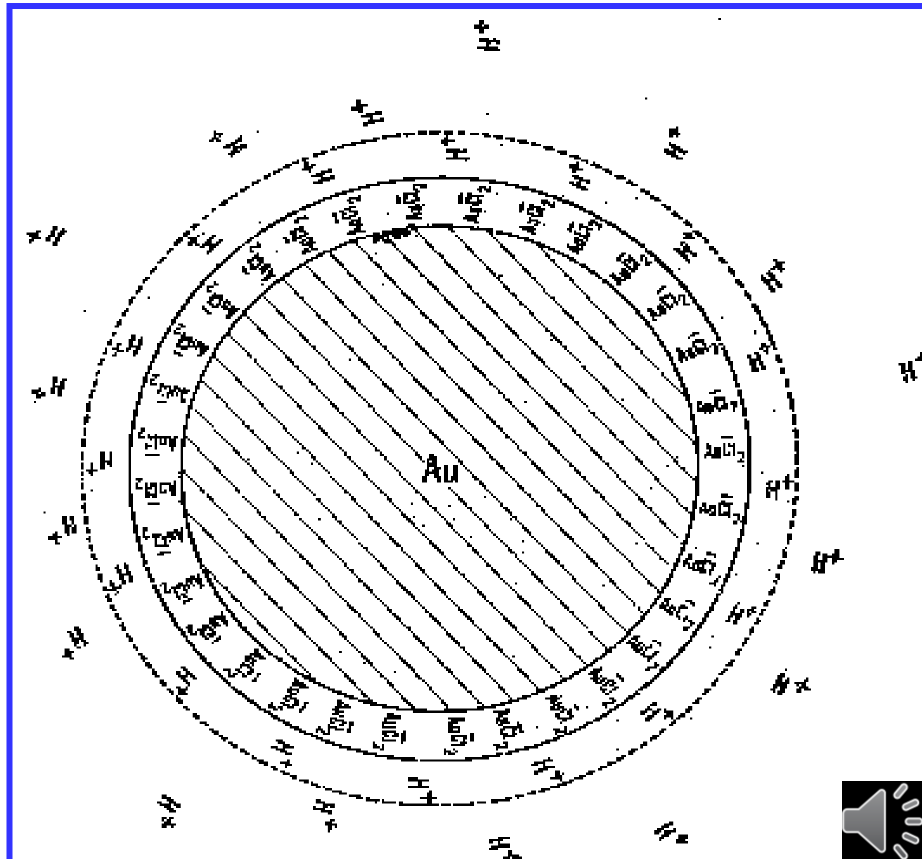


Nanogold / medical apps

- colloidal gold has been successfully used as a therapy for rheumatoid arthritis in rats; implantation of gold beads near arthritic hip joints in dogs has been found to relieve pain
- combination of microwave radiation and colloidal gold can destroy the beta-amyloid fibrils and plaque which are associated with Alzheimer's disease
- possibilities for numerous similar radiative applications are also currently explored
- AuNPs are being investigated as carriers for drugs such as Paclitaxel
- nanosized particles are particularly efficient in evading the reticuloendothelial system
- in cancer research, colloidal gold can be used to target tumors

Preparation

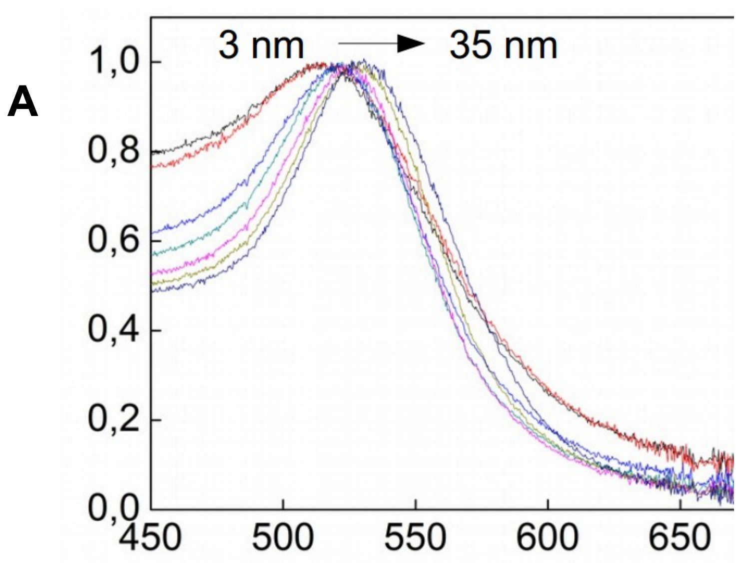
- monodispersed NPs are more useful for practical use
- reduction of tetrachloroauric acid $HAuCl_4$ using different reagents:
- sodium citrate - 15 to 150 nm large NPs, according to concentrations
- sodium ascorbate - moderate 6 to 15 nm NPs
- smallest NPs < 5 nm – using white phosphorus
- sodium borohydride ~ 2 nm

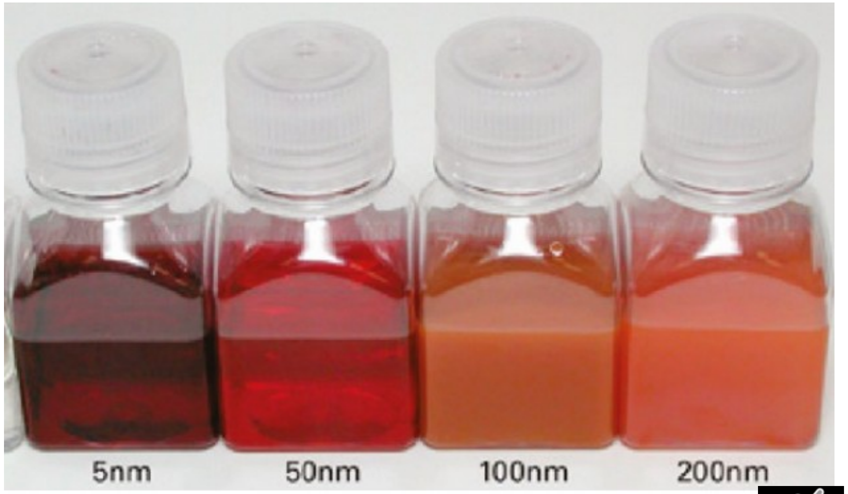


- structure of the coloid Au NP coated with negative $[AuCl_2]^-$
- prevents coagulation

Reduction and size of NPs

- for transition metals - the stronger the reduction reagent, the smaller the produced nanoparticles
- stronger reduction reagent would generate an abrupt surge of the concentration of growth species
- resulting in a very high supersaturation
- and a large number of the formed initial nuclei
- for a given concentration of metal precursor, the formation of a large number of initial nuclei would result in a smaller size of the grown NPs





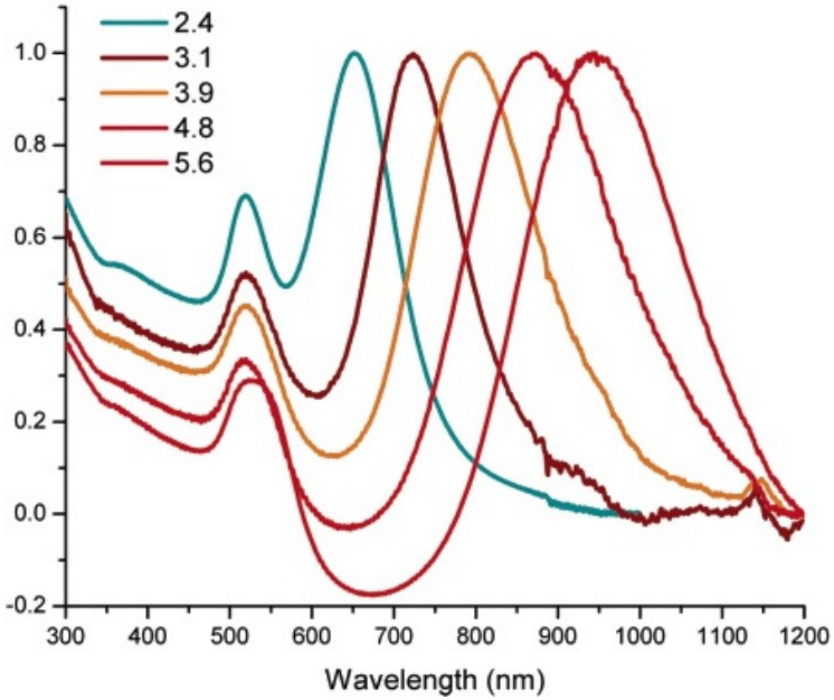
Effect of polymers

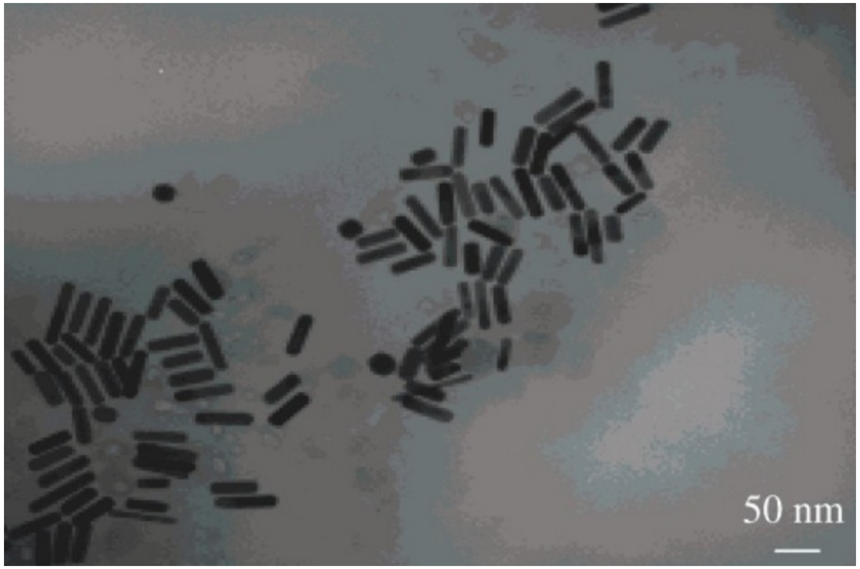
- strong absorption of polymer would occupy the growth sites and reduce the growth rate of nanoparticles
- full coverage of polymer can hinder the diffusion of growth species from the surrounding solution to the surface of the particles
- in addition, polymer may interact with solute, catalyst, or solvent and affect reaction

Effect of the shape of NPs

- absorption spectra reflect also the shape of NPs
- for Au nanorods, another resonance maximum appears
- position depends on the length / diameter ratio

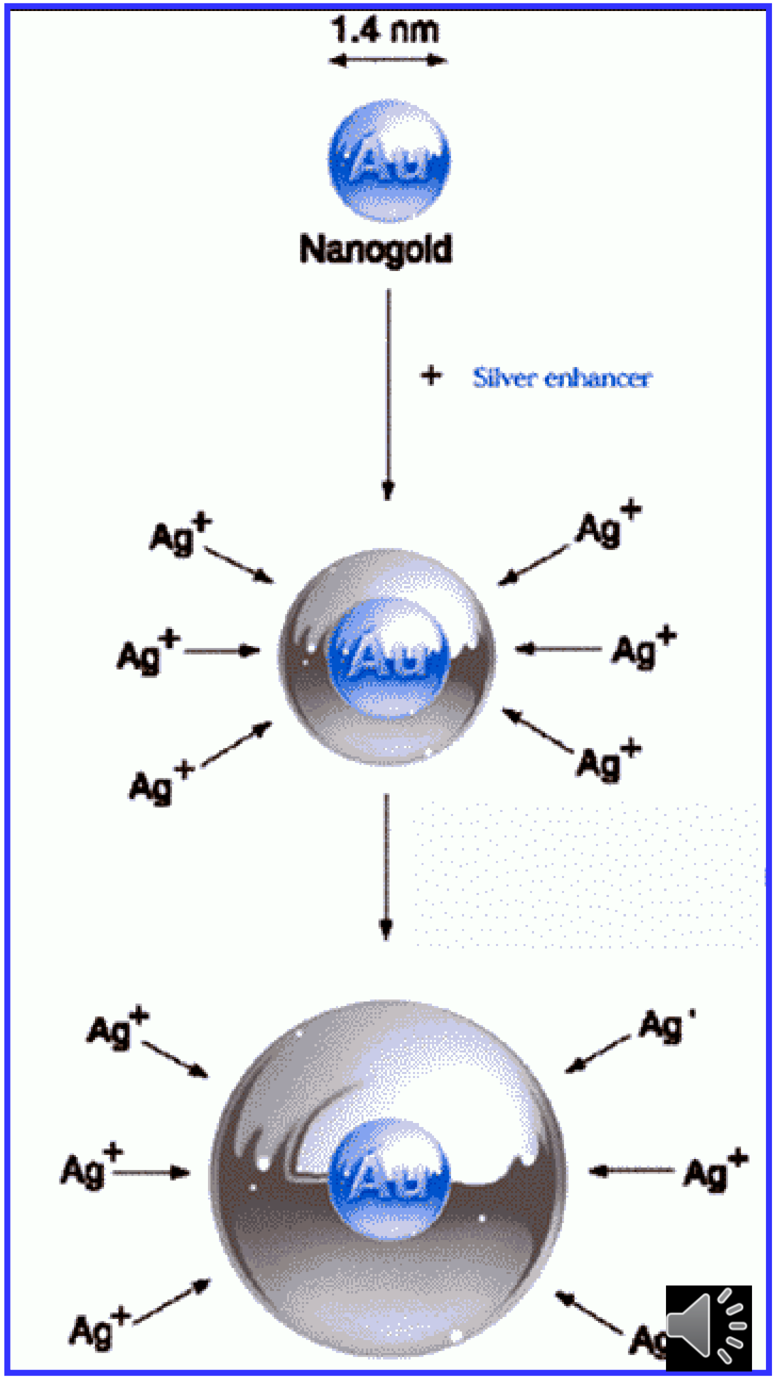
A





Enhanced sensitivity

- **for assays / imaging applications, a higher sensitivity is achieved by increasing the size of NPs**
- **catalytic deposition of silver**
  - increased size of NPs in the course of the assay
  - specifically bound Au NPs function as nucleation sites for further growth of crystals in the presence of Ag^+ salts

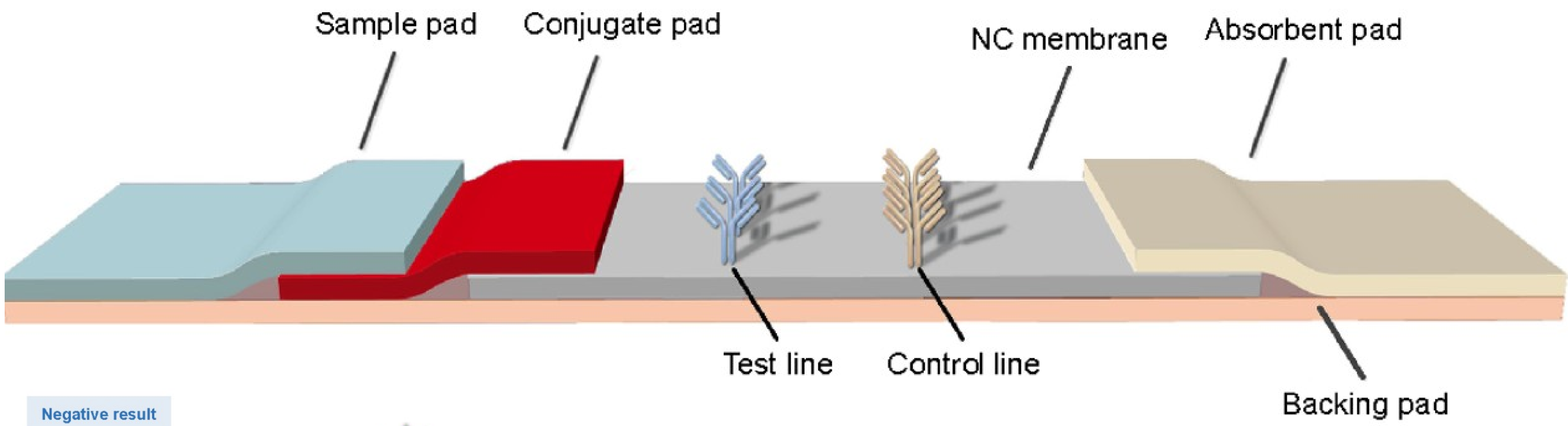


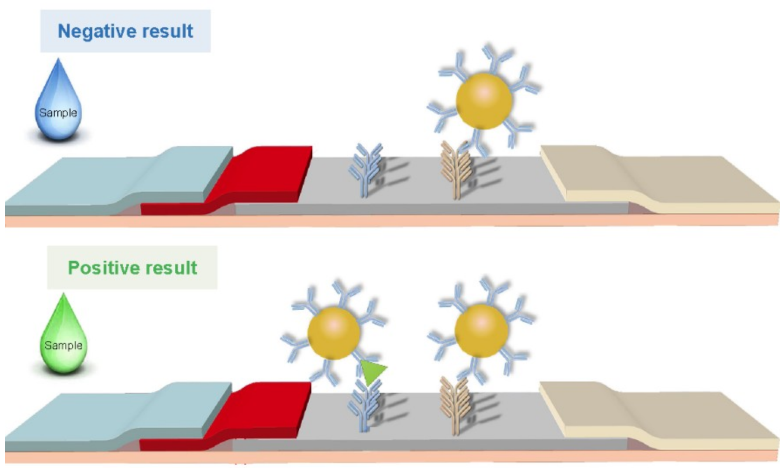
Adsorption of protein s

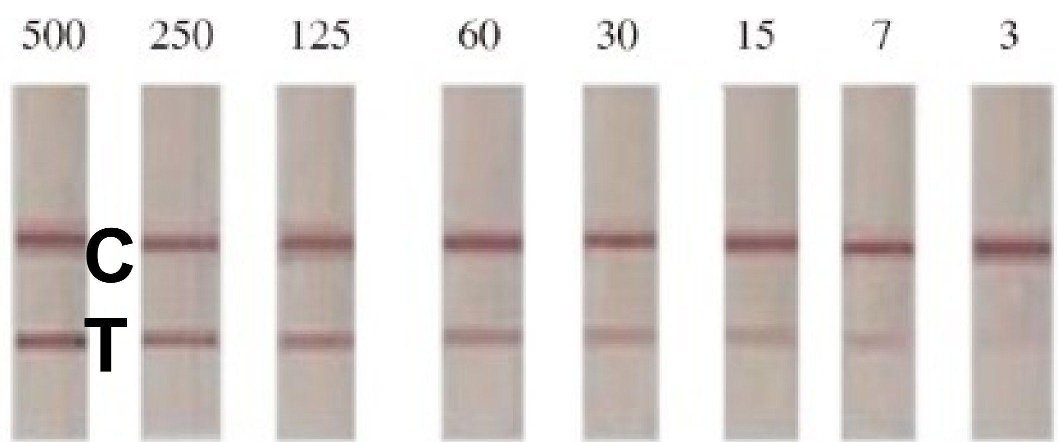
- **incubation with protein, centrifugation, resuspension**
- **Au NPs with protein A (G, L) – universal labeling of immunocomplexes**
  - adsorption at pH 6.9 with stabilizer (PEG 20 kDa, 0,025%)
  - conjugate kept in 10 mM phosphate buffer pH 7.4 containing 1% PEG
- **adsorption of antibodies**
  - pH 8 až 9, PEG can be substituted with albumin (0.25%)
- **other useful conjugates**
  - lectins – detection of saccharides decorating cellular surfaces
  - avidine / streptavidine – universal use
- **rapid visual immunotests (strips)**
  - red colours is easy to detect, high sensitivity
  - stability of NPs – no degradation, an advantage compared to biolabels (enzymes, …), zero toxicity

Au NPs for immunostrips

- rapid visual evaluation (or scanner, smartphone)

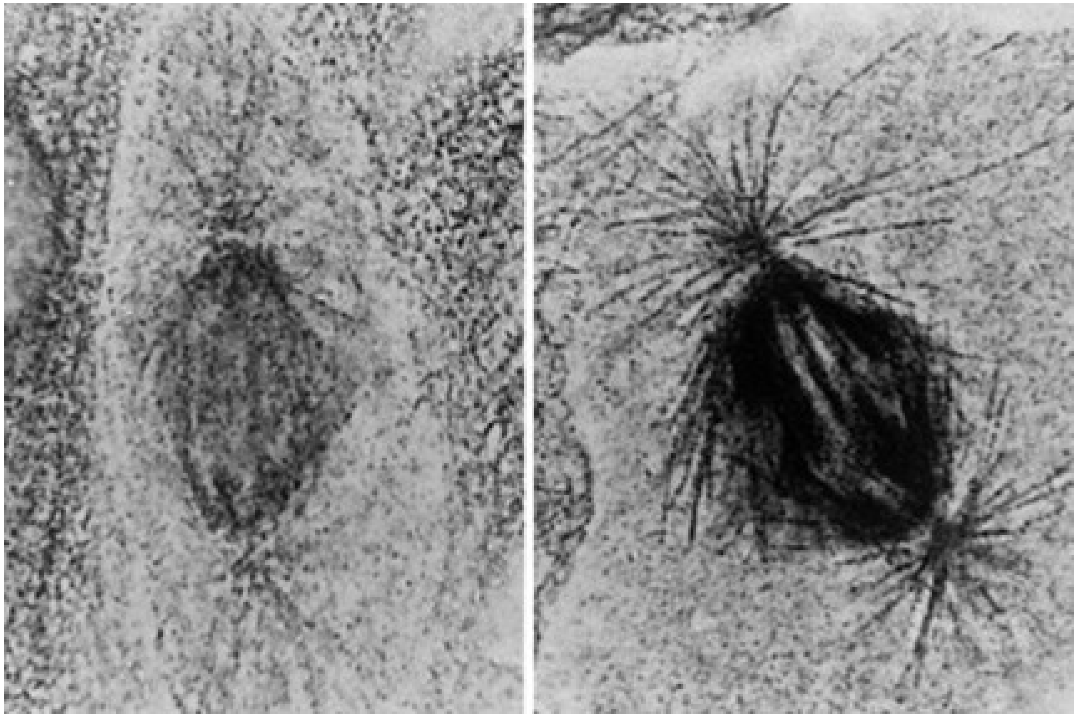


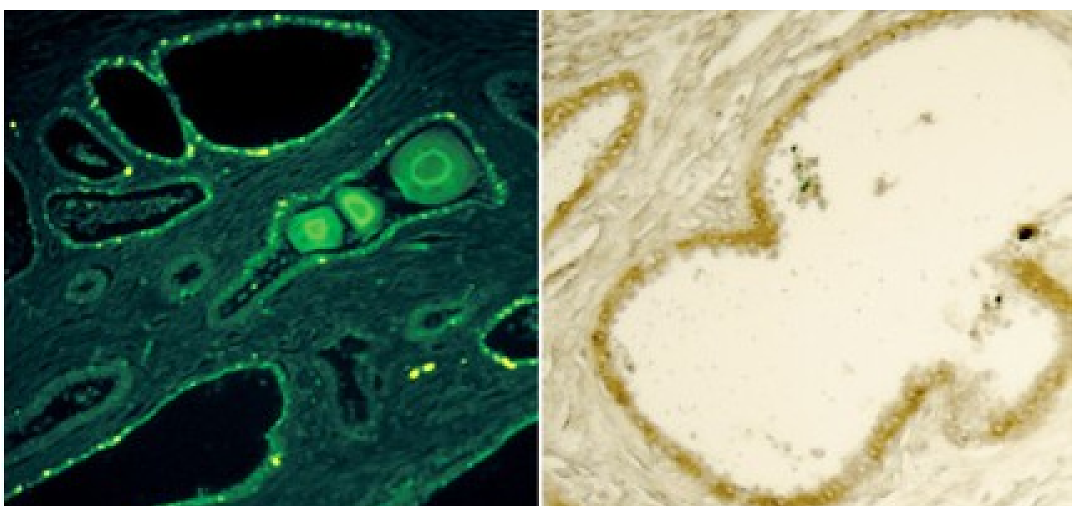




- sandwich immunocomplex formed in the test zone
- Ab-Au NP conjugate binds also in the control zone

Au NPs for microscopy

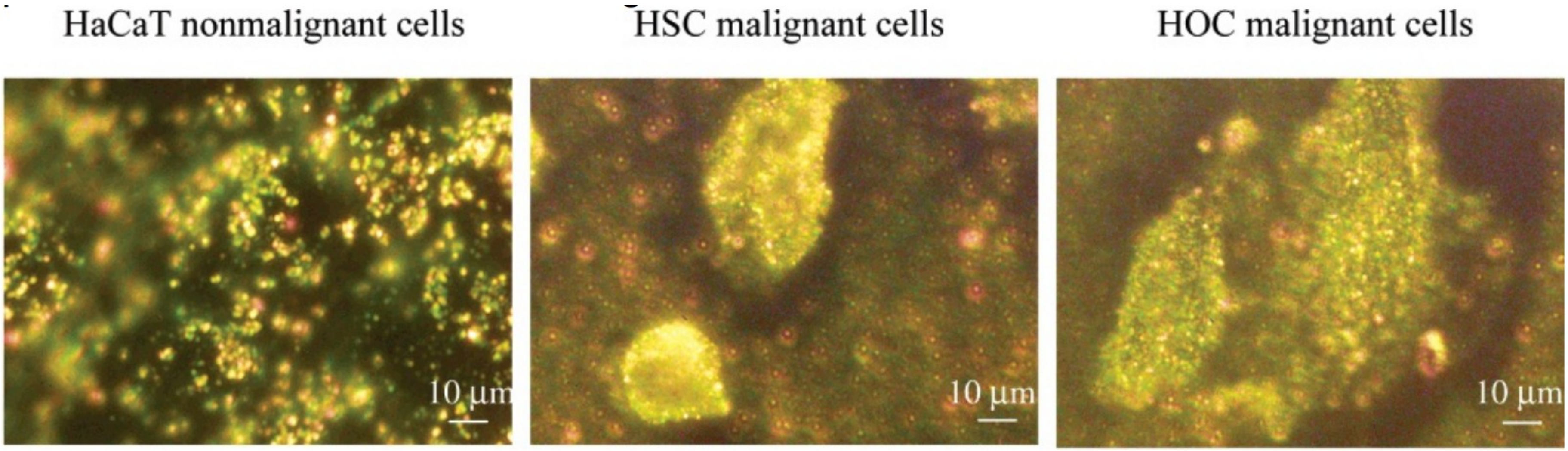




- **microtubules**
  - anti-tubuline Ab, then goat Ab anti mouse IgG with coloid gold (left) and NANOGOLD (right)
  - magnified 1300x
- **contrast enhancing agent**
- **prostate adenocarcinom**
  - Ab anti cytokeratine antibody, conjugate Alexa Fluor 488 FluoroNanogold with the Fab' fragment of goat Ab anti mouse IgG
  - left, fluorescence
  - right, localized Au after enhancement with Ag^+

Imaging of cells

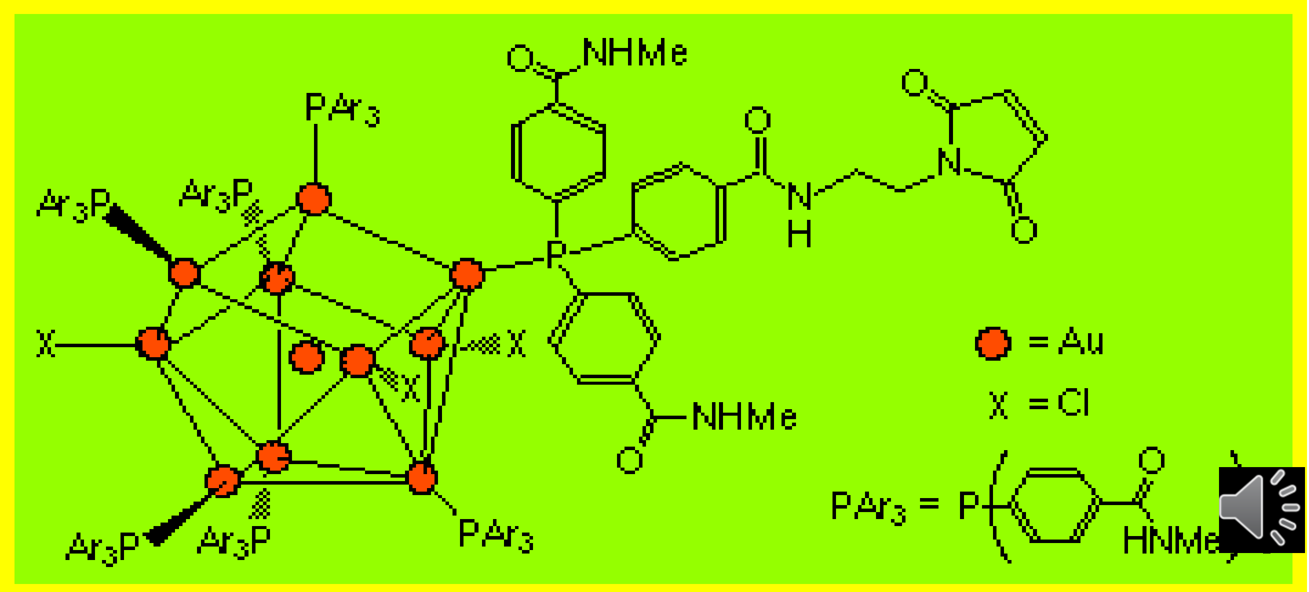
- **different binding of Au NPs depending on the state of cells**



Nanoclasters of gold

- **in fact, these are coordination complexes**
- **central atoms Au are in the given configuration, at the surface are Au atoms coordinated with a suitable ligang – Au valency becomes saturated and thus stabilised**
- **products as Undecagold and Nanogold**
  - tris(aryl) phosphine
  - halid anionts
- **smaller clasters as Hexagold (6 Au) and Octagold (8 Au) can be charged**

- **surface ligands adapted for simple bioconjugation**
- **maleimide – for coupling with sulfhydryl groups (-SH)**



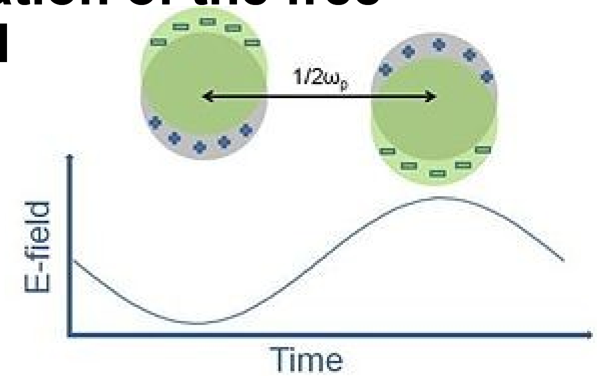
Optical properties of Au NPs

- metal NPs were used for glass staining from the ancient times
- late 17th century - combining aqua regia solution of gold and tin produces a precipitate with deep and vibrant red color
- "purple of Cassius", the colorant became one of the most successful red pigments used in the production of glass and ceramics
- "ruby glass" - essentially glass containing gold nanoparticles
- a classic example of an ancient piece of art gaining its appeal from the color produced by metal nanoparticles is the late Roman "Lycurgus Cup" - extraordinary dichroic behavior exhibiting red color in transmission and green color in reflection
- due to absorption and scattering of Au and Ag NPs in the glass

- surface plasmons

Surface plasmon resonance (SPR)

- **… prominent spectroscopic feature of noble metal NPs**
- **gives rise to a sharp and intense absorption band in visible range**
- **physical origin is a collective resonant oscillation of the free electrons of the conduction band of the metal**



- **surface plasmon oscillations induced by an oscillating electric field in a metal sphere. The displacement of the conduction electrons (green) relative to the nuclei (gray) is shown. The frequency of SPR is denoted omega**

- **for NPs << wavelength of the incident light**
  - response to the oscillating electric field can be described by dipole approximation of the Mie theory
- **the wavelength-dependent extinction cross section of a single particle, *$C_ext(\lambda)$*, defines the energy losses in the direction of propagation of the incident light due to both scattering and absorption by the particle described in terms of the dielectric function of metal, ε(λ) = ε'(λ) + iε''*(λ),* and the dielectric constant of the medium, ε_m**

$$C_ext(\lambda) = \frac{24\pi^2 R^3 \varepsilon_m^{3/2}}{\lambda} \frac{\varepsilon''(\lambda)}{(\varepsilon'(\lambda) + 2\varepsilon_m) + \varepsilon''(\lambda)^2}$$

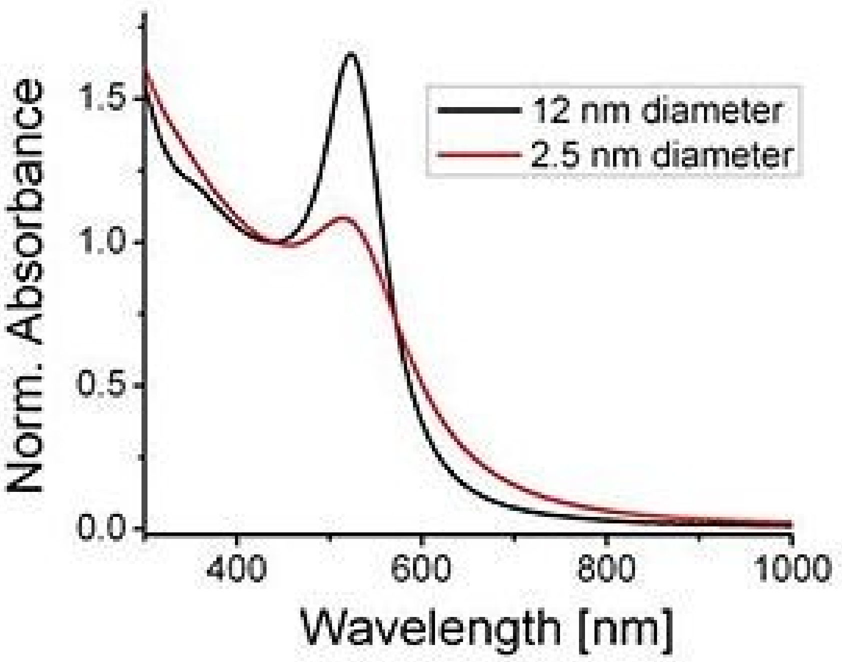
SPR of NPs cont.

- *C_ext* depends on the dielectric function of the metal of which the particle is composed - different absorption and scattering characteristics for different metal NPs
- maximum of $C_ext(\lambda)$ - the resonance condition, will take place when the denominator of the right-hand side of the equation becomes minimal
- approximately at the wavelength λ_p for which $\varepsilon'(\lambda_p) = -2\varepsilon_m$, if the imaginary part of the metal dielectric function, $\varepsilon''(\lambda_p)$ *is small*
- the resonance condition implies that the SPR frequency depends on dielectric constant of the medium, ε_m
- it is possible to observe adsorbed layers – **sensing**

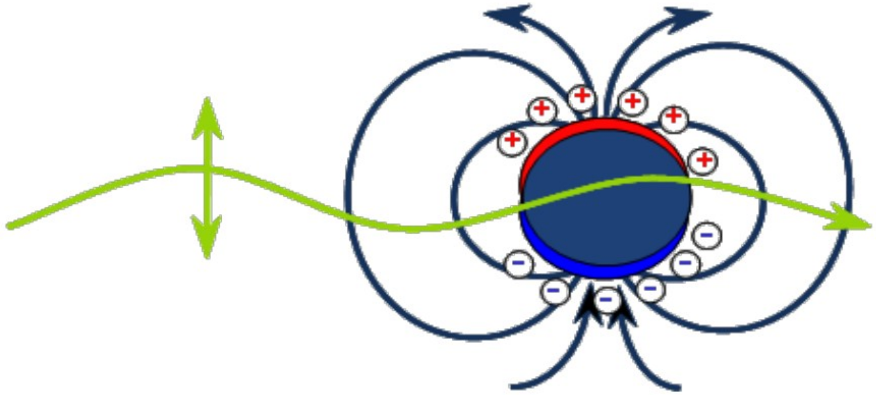
Effect of the size of NPs

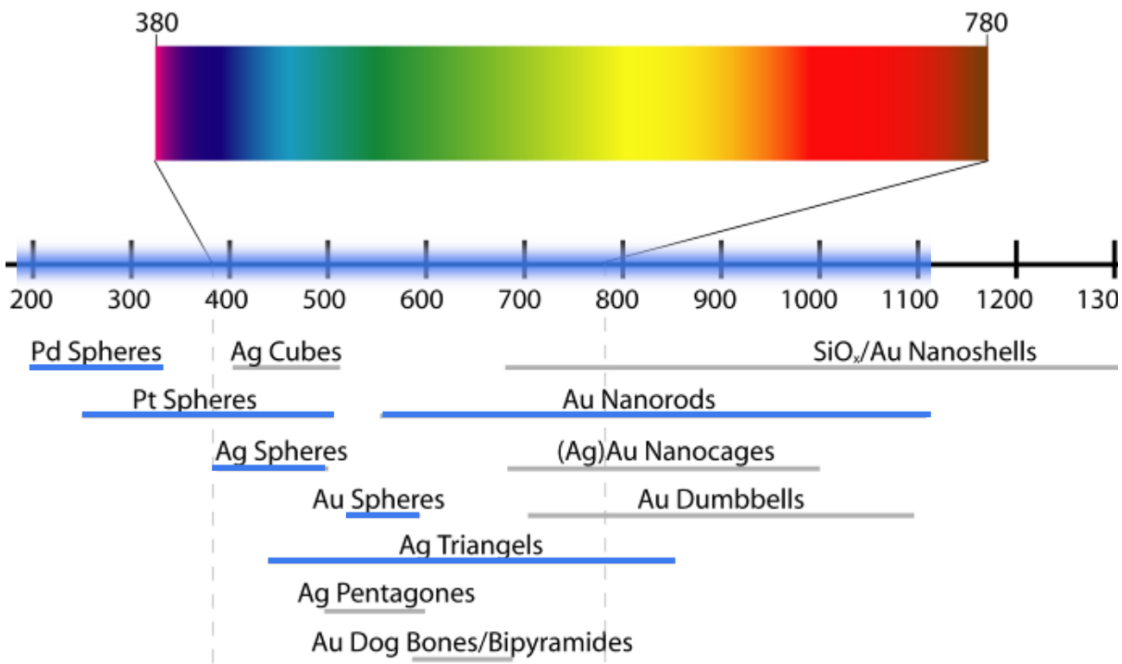
- molar extinction coefficient of gold nanoparticles increases roughly cubically with the particle radius
- size of NPs can be obtained from the absorbance spectra
- very high extinction coefficients, also size-dependent

System	*D* [nm]	ω_M [L (mol × cm)$^{-1}$]
Terphenyl[a]	-	3.3×10^4
Rose Bengal[b]	-	8.0×10^4
1,6-diphenylhexatriene[a]	-	8.0×10^4
Rhodamine B[b]	-	11×10^4
Au NP[c]	3.8	3.6×10^6
Au NP[d]	4.6	8.6×10^6
Au NP[d]	8.6	51×10^6
Au NP[d]	21	88×10^6
Au NP[d]	34	610×10^6

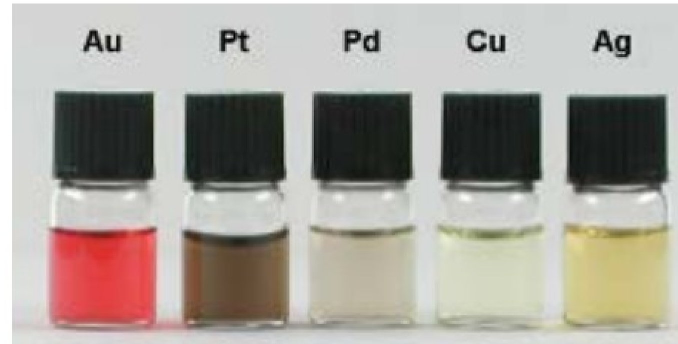


Localised SPR





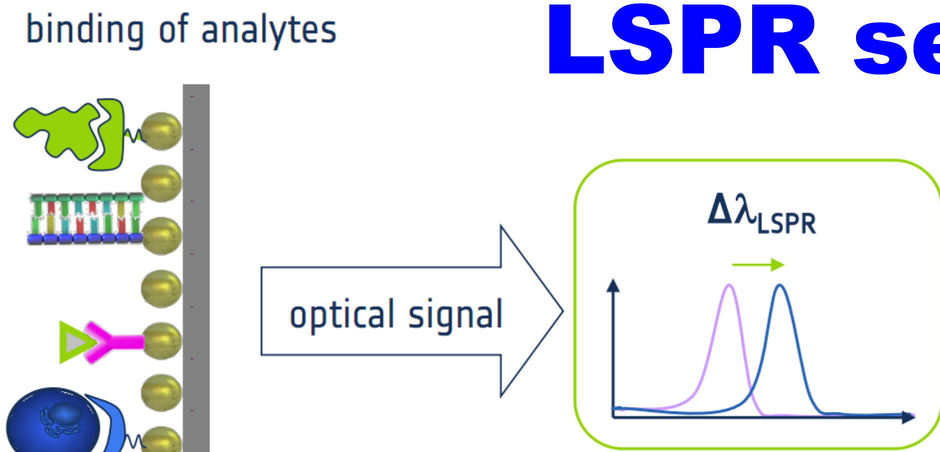
Material/Composition



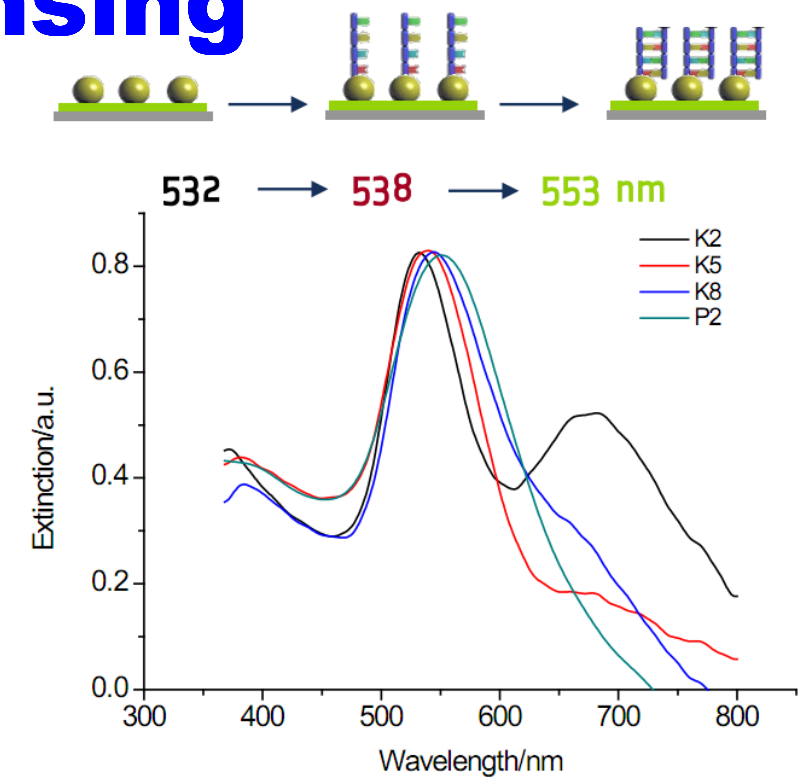
Dimension

Shape

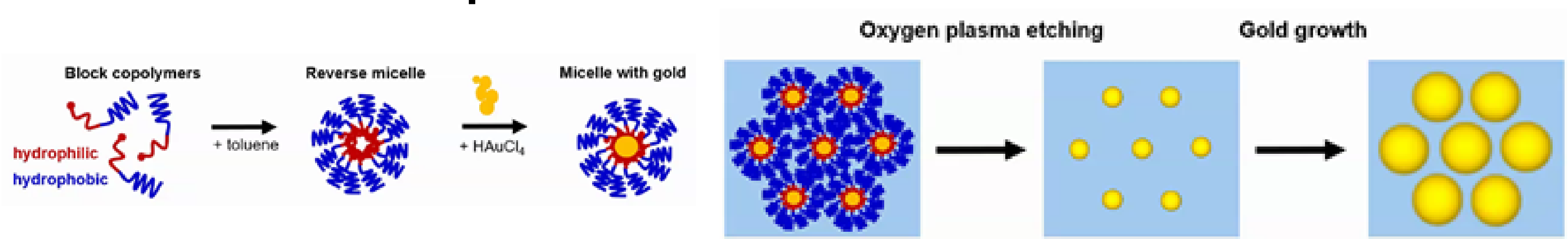
LSPR sensing

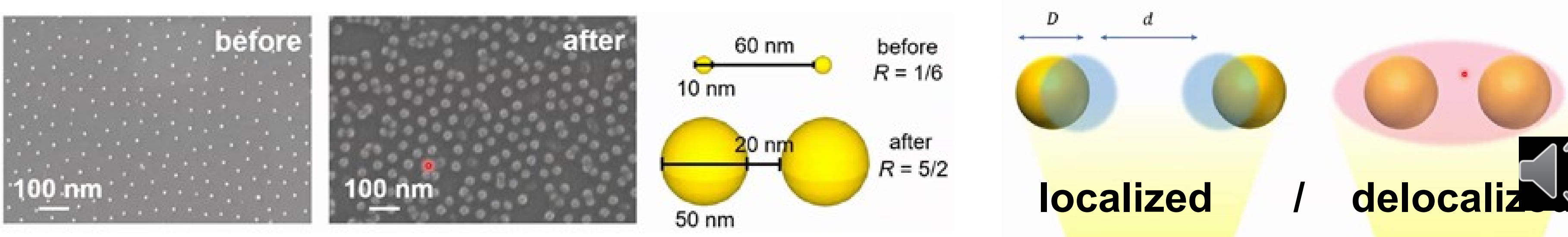


LSPR is sensitive to local change of refractive index around NP



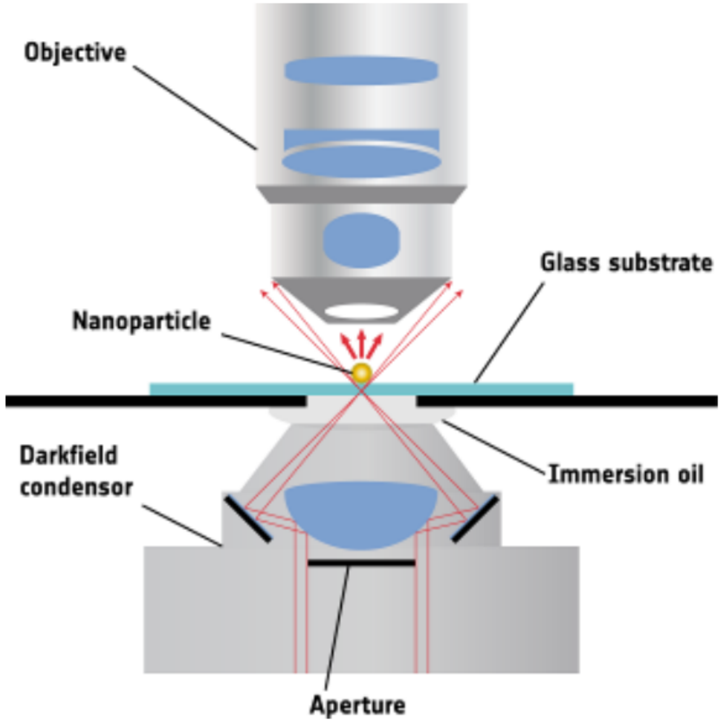
- **binding of target molecules to modified Au NPs results in shift in the absorbance spectrum**



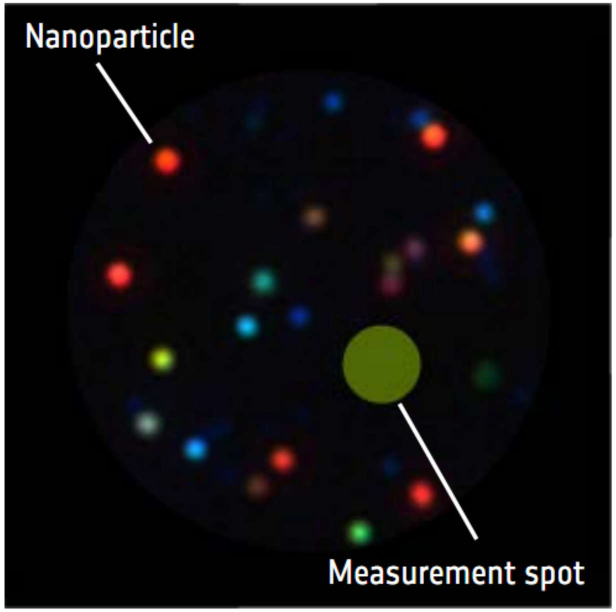


Single NP LSPR sensing

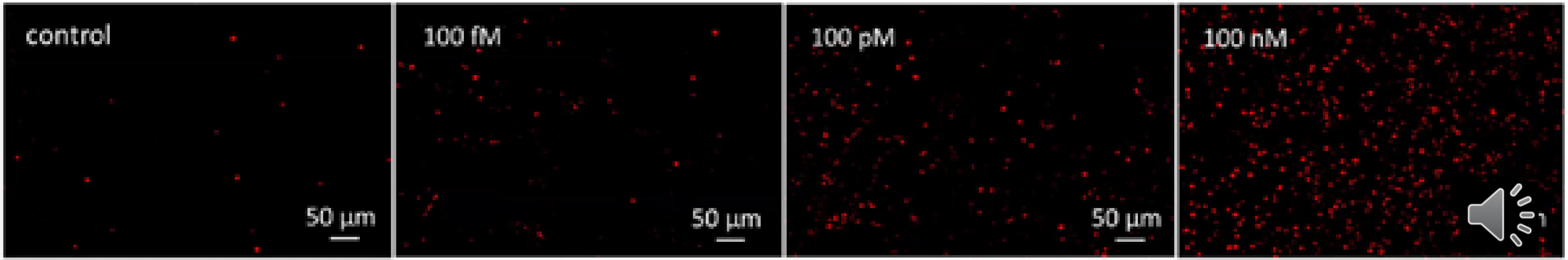
- Ultra small detection volumes
- Detection of small number of molecules
- Possibility of high parallel detection



- Scheme of microspectroscopy

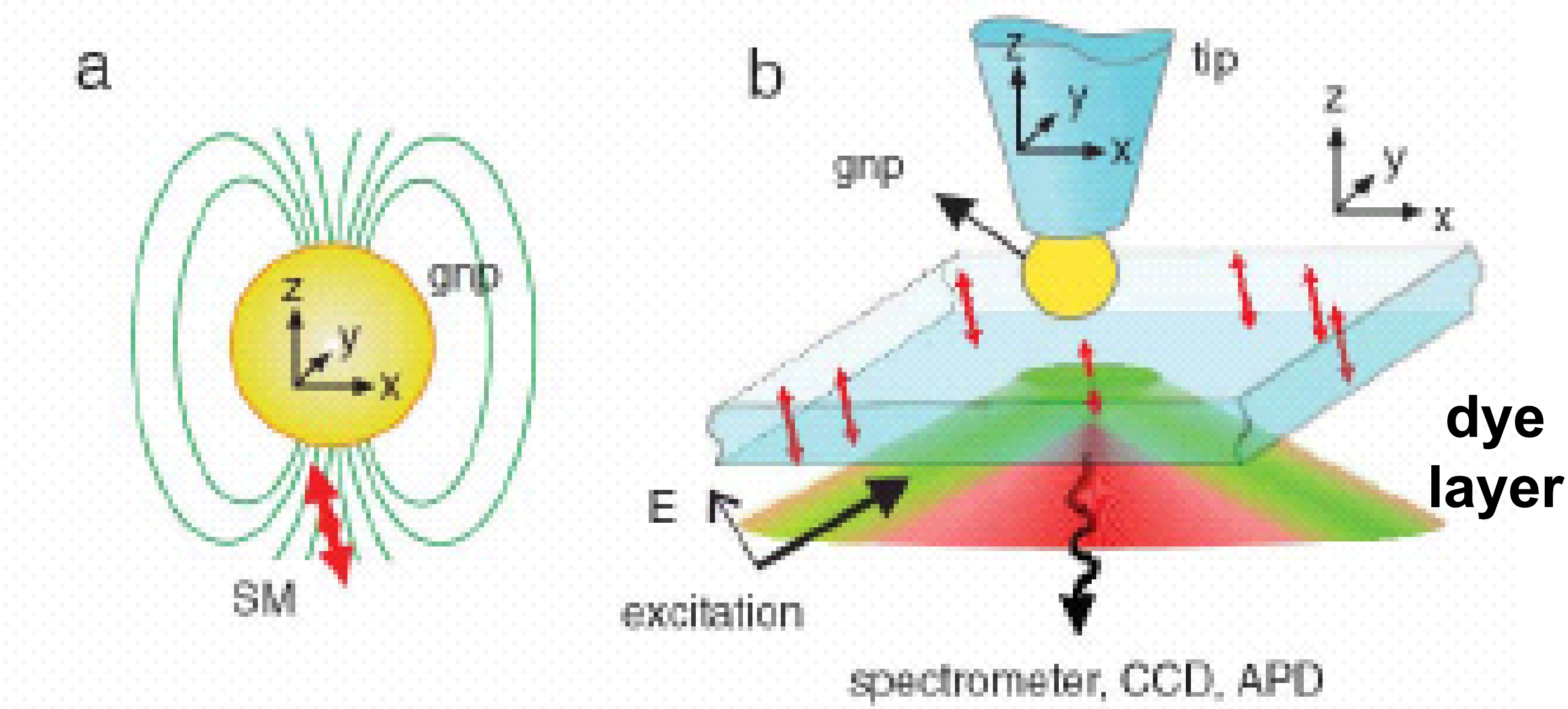


- Microscope image of metal nanoparticles



Plasmon enhanced optical absorption

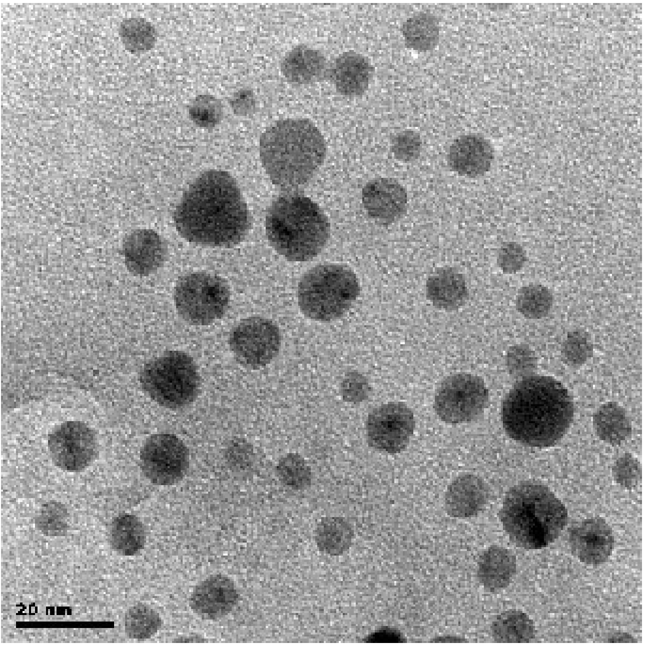
placing a chromophore near a resonant metal nanoparticle – effect of the near field:

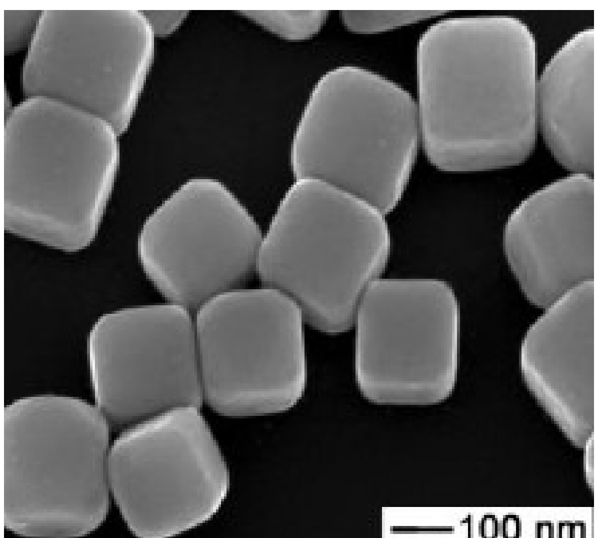


electric field surrounding a resonant nanoparticle ($E=E_z$)

enhanced fluorescence
reduced decay times

Silver nanoparticles (AgNP)





- size between 1 nm and 100 nm
- while frequently described as being 'silver‘, some are composed of a large percentage of silver oxide due to their large ratio of surface to bulk silver atoms.
- synthesis - different routes, physical vapor deposition, ion implantation, and wet chemistry

- monodisperse nanocrystals of silver nanocubes were synthesized in large quantities by reducing silver nitrate with ethylene glycol in the presence of poly(vinylpyrrolidone) (PVP) at 160oC

- t ≠160 … irregular shapes
- [Ag+] < 0.1 M … nanowires

Medical uses of Ag NPs

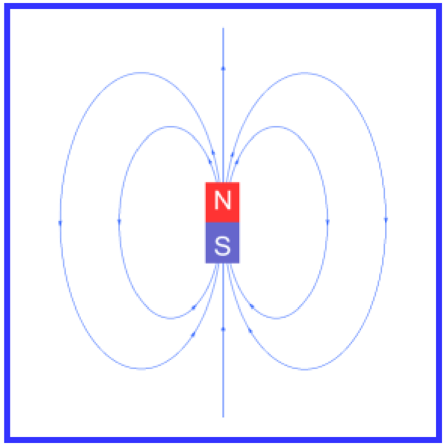
- There is an effort to incorporate silver nanoparticles into a wide range of medical devices

- **bone cement,**
- **surgical instruments,**
- **surgical masks,**
- **wound dressings**
- **treatment of HIV-1.**

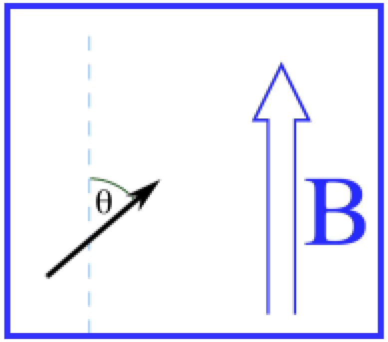
- **Samsung has created and marketed a material called Silver Nano, that includes silver nanoparticles on the surfaces of household appliances**
- **Silver nanoparticles have been used as the cathode in a silver-oxide battery**

- **some local research institute considered addition of silver NPs to fibers for underwear (socks …)**

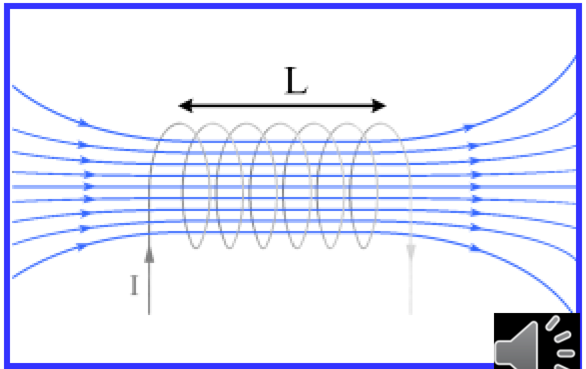
Magnetic NPs



- **permanent magnet has two poles forming the magnetic dipole**
  - represented by an arrow in the S->N direction
  - magnetic field exists between the poles
- **magn. dipole *m* in the magnetic field (gradient *B*) is twisted by a torsion force to be parallel with the magn. field force lines**



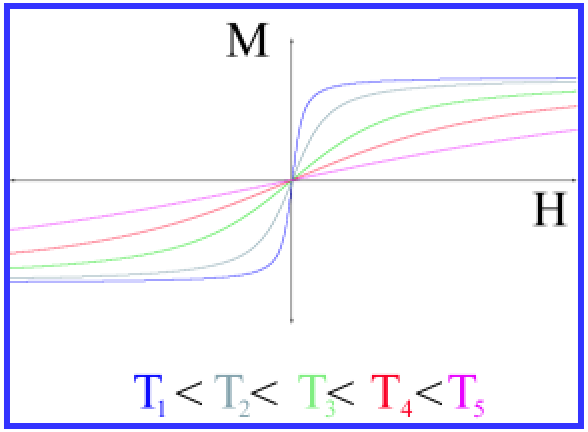
- **magnetic materials have permanent magnetic moment - magnetisation *M*, this depends on:**
  - density of magn. dipoles per unit of volume of the material
  - intensity and mutual orientation of dipoles
  - is due to the non-paired spins of electrons, little bit also due to the movement of electrons within the orbital
- **magn. field can be realised by electromagnet**
  - electric current flowing through a conductive coil (solenoid) forms inside a homogeneous field



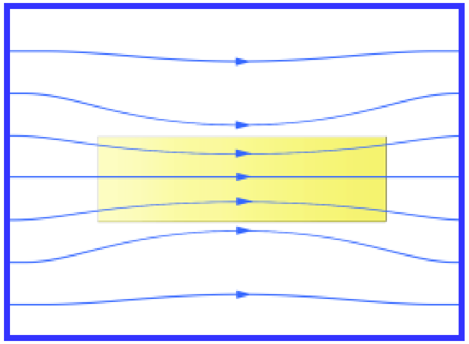
- **density of flow B depends on the intensity H and permeability of vacuum μ_0:**

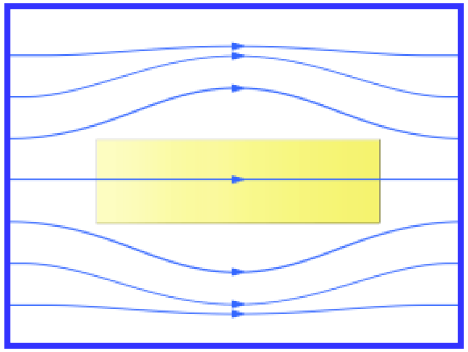
Magnetisation

- **magnetisation M changes in dependence on the intensity of the magn. field H**
  - coefficient is magnetic susceptibility χ
  - size of the change depends on the type of material, temperature and sometimes also on the “history” of the previous magn. field (**hysteresis**)
- **heating of the magentised material decreases its magnetisation M, above the critical temperature T_c (Curie temperature) magnetisation *M* completely dissapears**

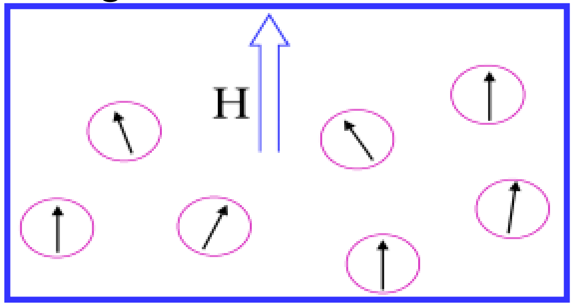


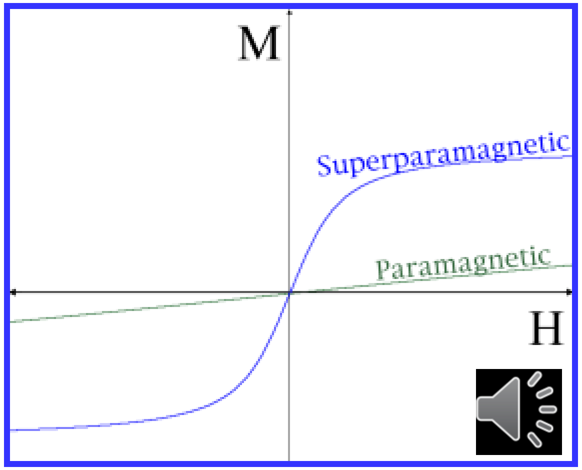
Magnetic materials





- **magnetic** – **exhibit tendency to “concentrate" force lines; magnetisation permanent even in the absence of magn. field**
  - Fe, Co
- **diamagnetic** – **force lines are slightly repelled**
  - proteins, fats, water
  - small negative magn. susceptibility, Larmor diamagnetism
- **paramagnetic**
  - in magn. field their internal magn. dipoles become oriented and the material gains magnetisation; Pauli paramagnetism
- **superparamagnetic**
  - typically nanoparticles 1 to 10 nm
  - become oriented in the magn. field



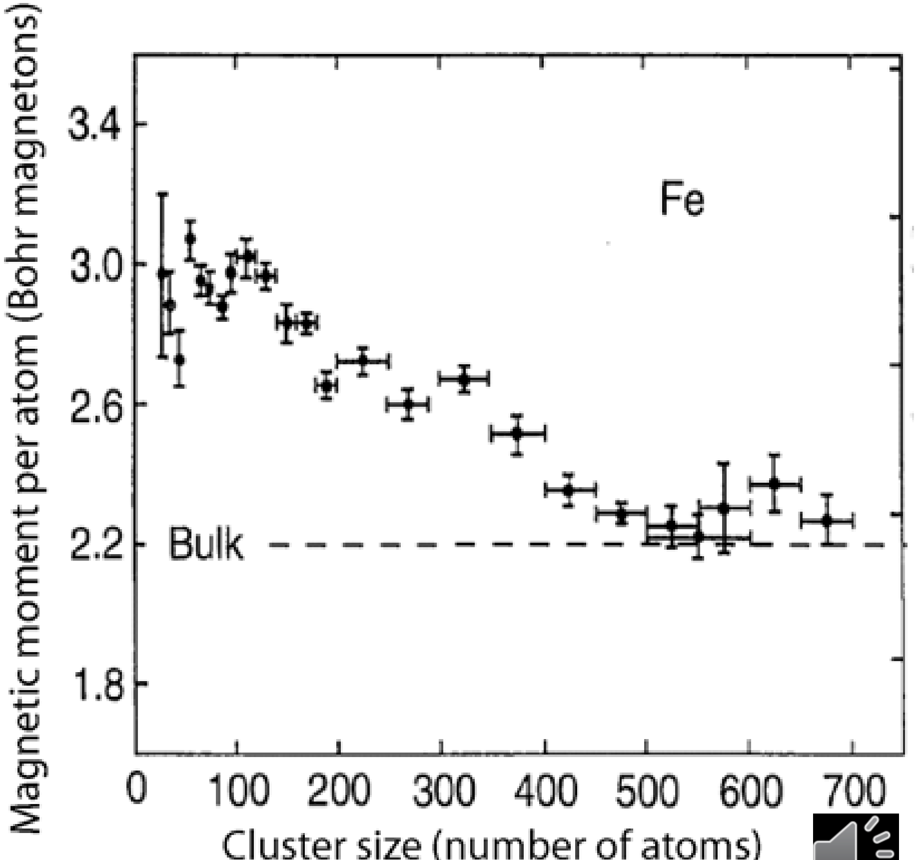


Magnetic interactions / range

- **exchange (electron-electron) interaction (many-particle wavefunction antisymmetry)**
  - **atomic scales**
- **dipole-dipole interactions between locally ordered magnetic regions**
  - dipole interaction energy grows with the volume of the ordered region
  - size of individual domains is set by a competition between volume and surface energy effects
  - **hundreds of atoms to micron scales**
- **magnetic anisotropy energy**
  - magnetization interacts with angular momentum of the atoms in the crystal
  - **many microns**

Super-paramagnetic particles

- ferromagnetic domains, created by d-electrons exchange interactions, develop only when a cluster of iron atoms reaches a critical size (ca. um)
- the magnetic moment per atom decreases toward the bulk value as cluster size is increased
- stable domains cannot be established in crystals that are smaller than the intrinsic domain size
- small particles can have very high magnetic susceptibility with permanent magnetic dipole
- small clusters consisting of a single ferromagnetic domain follow the applied field freely
  - superparamagnetism
- magnetic susceptibility of superparamagnetic particles is orders of magnitude larger than bulk paramagnetic materials

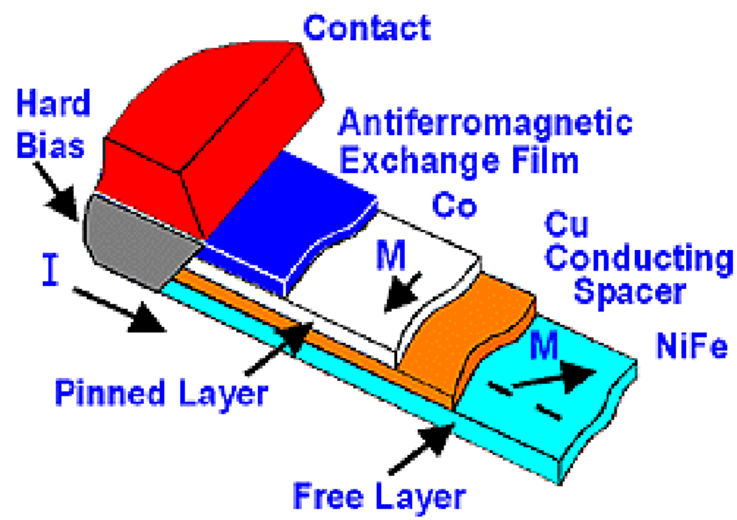


Giant Magnetoresistance

magnetic hard drives are based on a nanostructured device, called **giant magnetoresistance sensor**
Albert Fert, Peter Grünbers Nobel Prize in Physics 2007

Hitachi hard drive reading head

magnetization on the surface of the disk can be read out as fluctuations in the resistance of the conducting layer



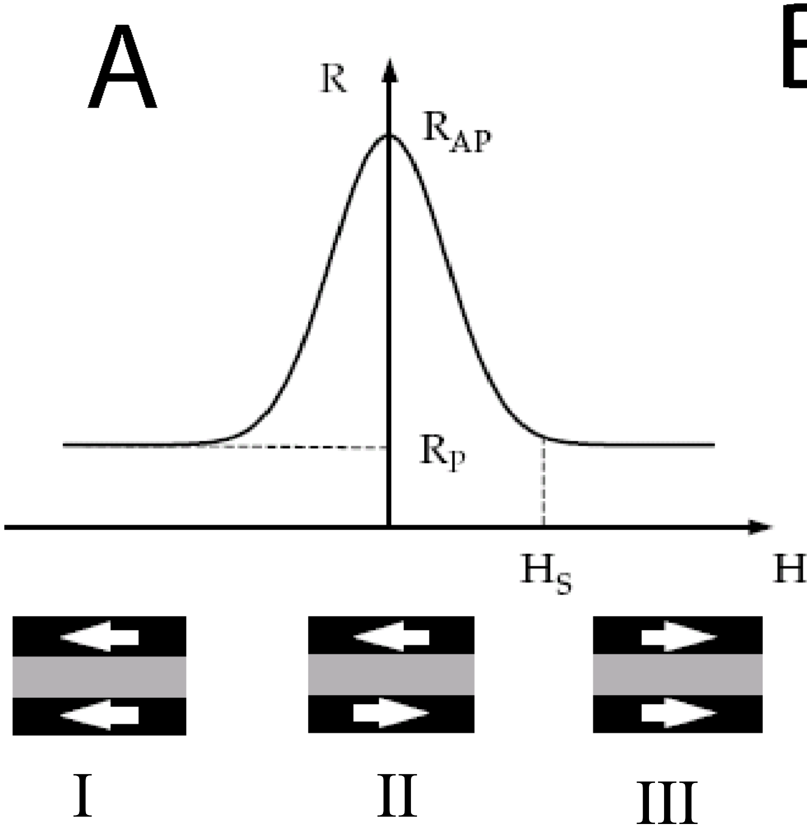
Co, magnetic layer

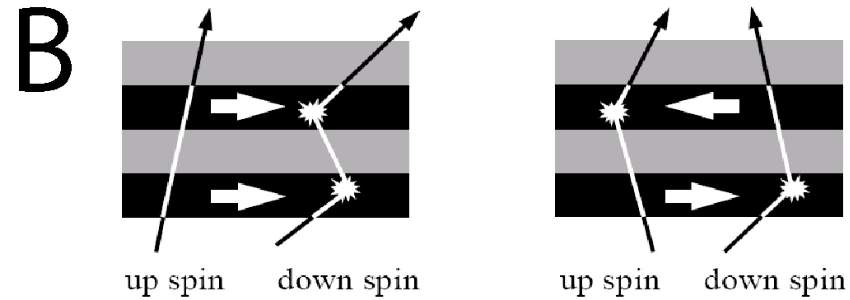
Cu, electrically conducting layer

layers have a width that is smaller than electron scattering length

NiFe alloy, magnetic layer
an easily re-alignable magnetizat

giant magnetoresistance occurs when the magnetic layers above and below the conductor are magnetized in opposite direction





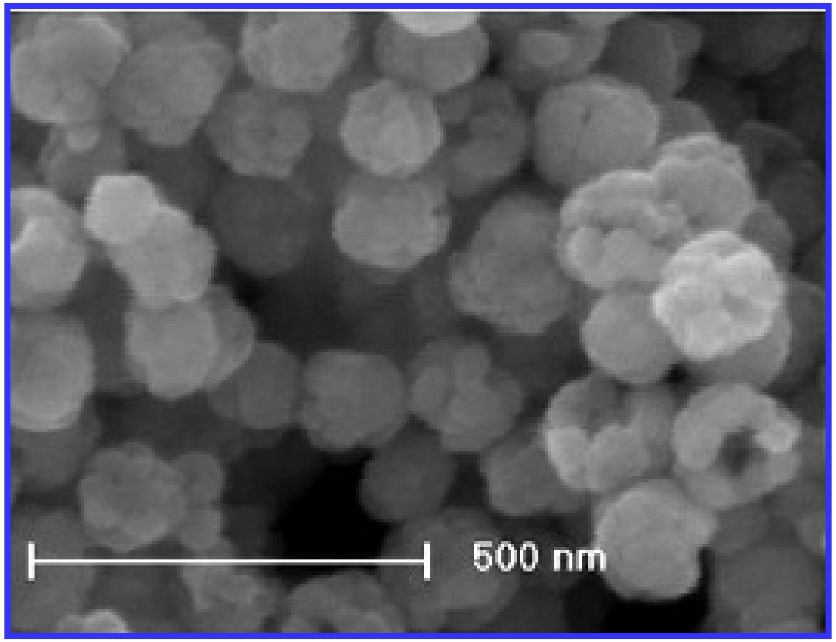
electron scattering in magnetic media is strongly dependent on spin polarization.

when magnetic layers are parallely magnetized, only one spin polarization is scattered (I,III).

for antiparallel magnetic layers both spin polarizations are scattered, giving rise to super-resistance (II)

data storage systems

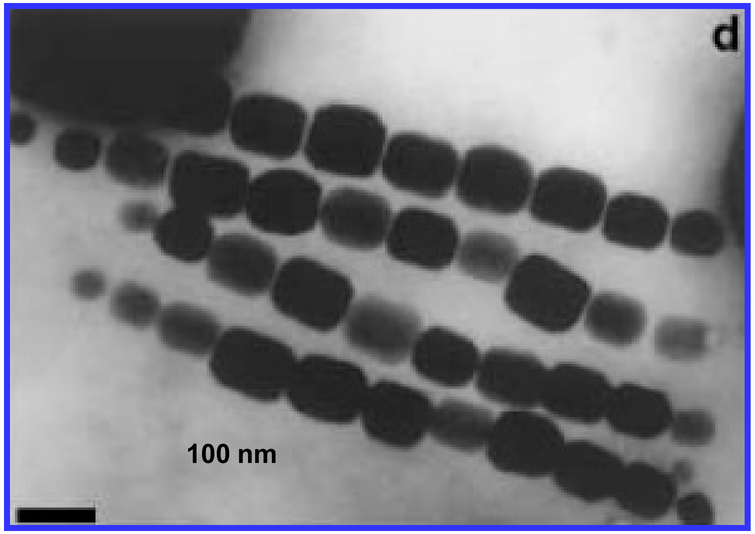
Magnetic NPs



- **wide range of applications:**
  - immunoassays
  - separation of proteins and cells
  - drug, oligonucleotides, … delivery
  - magnetic hypertermia
  - magnetic labels
  - magnetic resonance imaging (MRI)
- **superparamagnetic materials based on maghemite (γ-Fe_2O_3) and magnetite (Fe_3O_4)**
  - good magnetic properties, low toxicity
  - required properties: uniform shape, defined crystalinity, monodispersity, stability in water, surface reactive groups
  - NPs or hollow spheres (higher magn. moment)

Preparation methods

- **deposition from gas phase**
- **termal decomposition**
  - $Fe(CO)_5$, $Fe(oleate)_2$, Fe tris(acetylacetonate)
- **microemulsion precipitation**
- **sonochemical synthesis**
- **hydrolytic reactions**
  - heating up ferric chloride $FeCl_3.6H_2O$ with hexamethylenediamine and sodium acetate in glycol (6 hours, 200 ^oC)
  - resulting particles provide surface aminogroups $-NH_2$
- **bacterial (BMP) production**
  - NPs coated with phospholipids layer (magnetosomes)



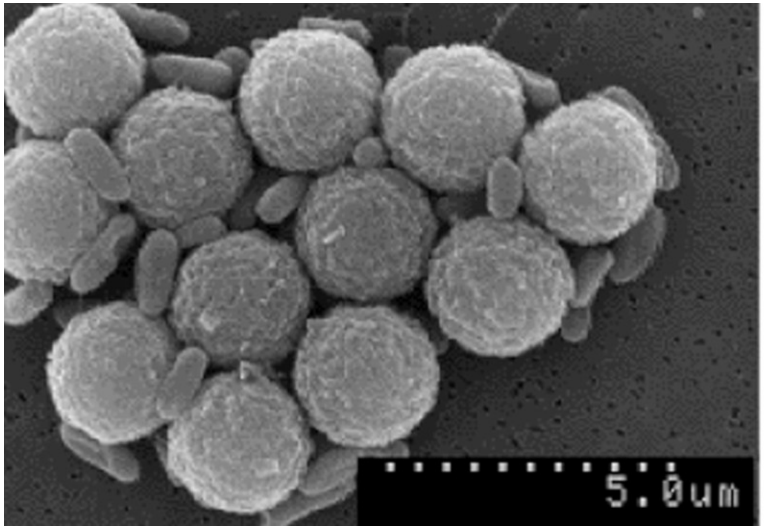
- **surface functionalisation**
  - thin layer of gold (core-shell, also protective)
  - polymer coating with functional groups
  - silanisation using aminopropyltriethoxysilanu (APTES)
  - electrostatic adhesion (over polyamine coating)

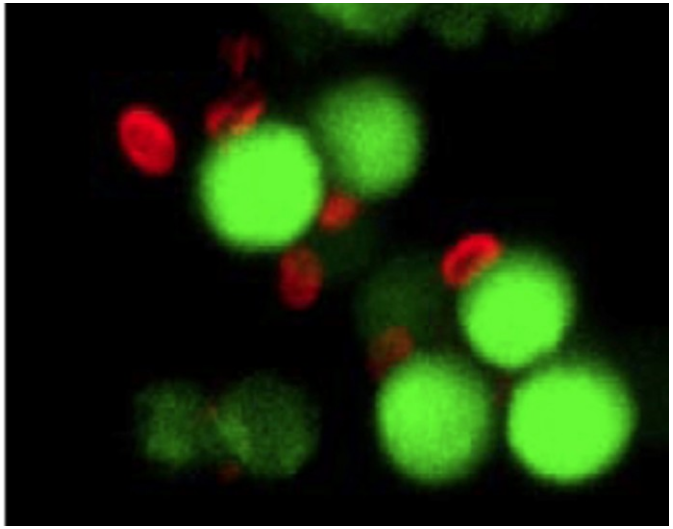
Magn. particles in liquid

- **effect of the magn. field**
  - uniform field orients the particle according to its magn. moment, but no translational movement occurres
  - for translation, the gradient of magn. field is required
- **viscosity effects play significant role**
- **magnetic and electrostatic forces among particles**
  - might result in aggregation and even precipitation
  - electrical repulsion prevents this undesired process – appropriate surface charge

Separation of cells

- **direct method**
  - ligand immobilised at the surface of magn. NPs (up to 50 nm – otherwise mechanically stressful for the cells)
  - added to solution, specifically bound to the surface of target cells
- **indirect method**
  - target cells are labeled with ligand – e.g. antibody (biotinylated …)
  - excess of the label is washed away
  - labeled cells are bound to modified magnetic particles (with streptavidine …)
- **the resulting complex is easily isolated with magnetic separator**
  - a suitable permanent magnet
- **could be either positive or negative isolation**
  - separated are either target or balast cells





Delivery (magnetic targeting)

- **accumulation of active substances (drugs, …) in the chosen target part of the organism**
  - injection to the blood vessel supplying the relevant organ
- **in the presence of external magn. field**
  - should overcome local linear flows (0.05 to 10 cm/s, according to diameter and network of blood vessels)
  - long-term accumulation in the chosen place (~ 70%)
  - local high concentration of the released compound (up to 8x)
  - significantly lower complications for other organs when compared to the system-wide application
- **thermosensitive magnetoliposomes**
  - in the target site, the delivered substance is released by local heating using the magnetic field (alternating – mechanical movement of particles – heat generation)

Hyperthermy using magnetic fluids

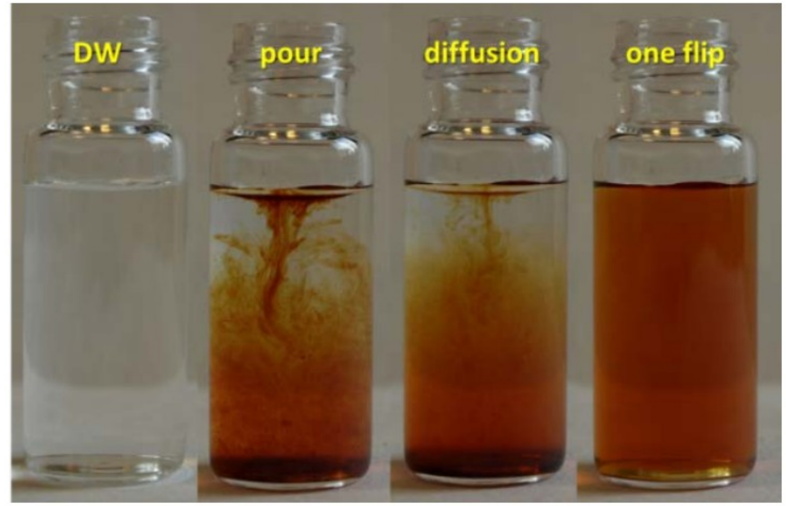
- **damage of tumors using locally increased temperature (42 to 46 ^{o}C)**
  - decreased viability of cells in the tumor, these become more sensitive towards chemo / ratiotherapy, magn. NPs selectively bound to malignant cells

Contrast bioimaging

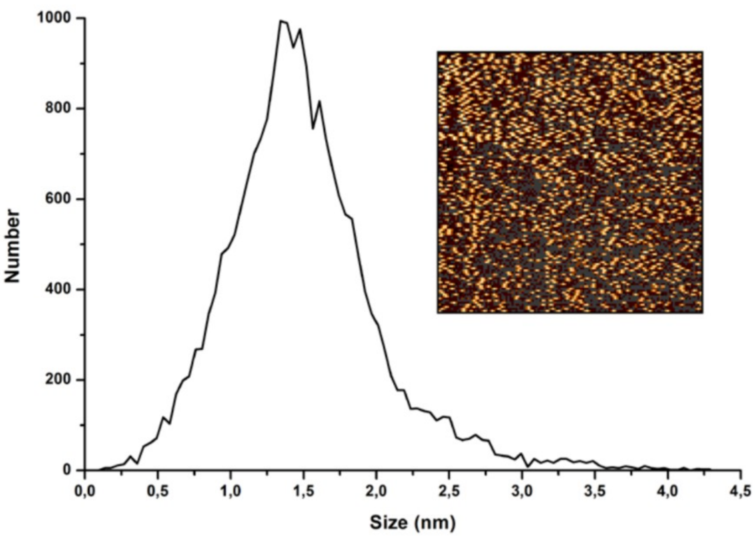
- **MRI, "magnetic resonance imaging" - H-NMR applied on tissues**
- **for MRI, contrast is due to different responses of individual tissues on the applied radiofrequency pulses**
  - density of protons and magn. relaxation times corresponding to the chemical composition, mainly content of water and lipids
- **superparamagnetic NPs (magnetite-dextran) in the target site greatly improve the contrast**
  - more NPs – darker image, effect on the rate of relaxation of protons from the excited state
  - healthy cells accept NPs, damaged or dead cells do not take NPs
- **internal cell label – monitoring of cells added to the organism within cell-based therapies**
  - bone marrow cells tranplantation, stem cells

SPIO

- **superparamagnetic iron oxide .. NPs**

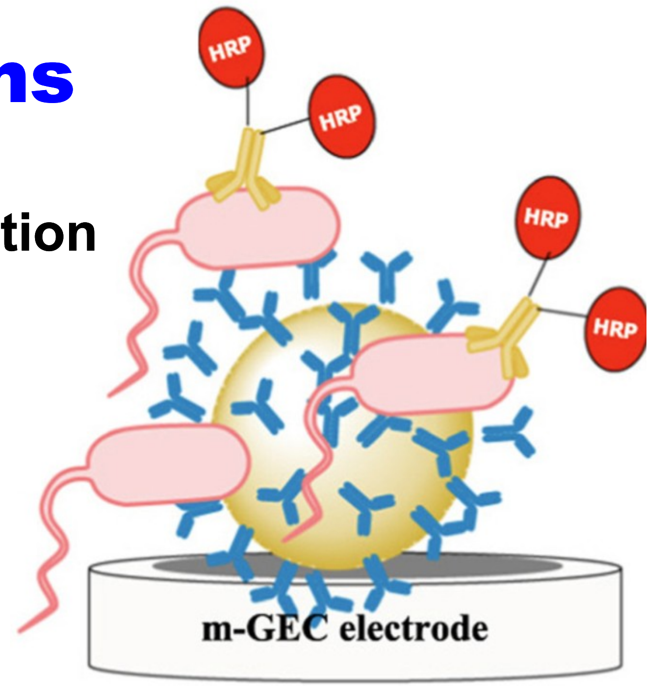


Demonstration of very fast reconstitution of dried SPIO nanoparticles in water. No special conditions (ultrasonication, detergents, etc.) are needed. Only putting of SPIO in water and one flip of vial is sufficient for making stable dispersion.



The histogram of SPIO sizes derived from height profile of AFM scan on square 3 × 4 μm. The section of AFM scan is inserted in the graph showing the square 1 × 1 μm.

Bioanalytical applications



- **immunomagnetic sensors – simple regeneration of the sensing surface**
  - at surface of transducer, magn. particles with immobilized biorecognition element (antibodies) are attached using magnet / electromagnet
  - after completion of the immunoassay, the consumed particles are replaced with fresh ones
  - suitable for complex sample matrices
- **efficient preconcentration of the target analyte from complex samples**
  - simple washing and clean-up procedures
- **enzyme biosensors – regeneration for inhibition-based assays**
- **analysis of DNA**
  - specific extraction of the target sequence from complex sample matrix