Introduction to Physics of Nanosystems

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2007 Nobel Prize in physics:

Albert Fert
(France)

Peter Grunberg
(Germany)

… for discovery of the phenomenon of "giant magnetoresistance", in which weak magnetic changes lead to big differences in electrical resistance.

First Nobel Prize in physics
for nanotechnology!

GMR: discovered in 1988

The discovery has allowed industry to develop sensitive reading tools to pull data off hard drives in computers and other digital devices.

↓

Radical miniaturization of hard disks last years.

Onset of

SPINTRONICS!

Applications:

- **IBM 1997: reading data off CD,**
- **angle, position, velocity spin sensors (ABS: Antiblock Braking System)**
- **Motorola: MRAM (Magnetoresistance Random access Memory)**
- **HDTV, DVD recorders, …**

Microsystems:

- atomic nuclei
- atomic clusters
- carbon nanosystems
- quantum dots
- heterostructures
- Bose-Einstein condensate
- optical lattice

$10^{-15}\ m$

$10^{-9}\ m \longleftarrow$ nano

$10^{-3}\ -10^{-6}\ m$

$10^{-6} = micro$
$10^{-9} = nano$
$10^{-12} = pico$
$10^{-15} = femto$
$10^{-18} = atto$

Related fields and phenomena:

- quantum transport,
- spintronics,
- Hall effect

Techniques:

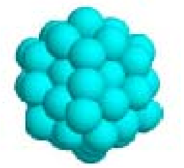
- new generation of lasers (ft, at)
- laser cooling

New

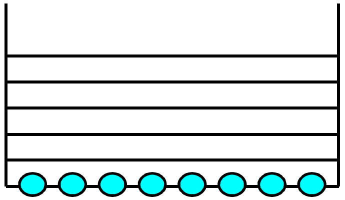
$$\left.\begin{array}{l}\text{systems}\\ \text{phenomena}\\ \text{techniques}\end{array}\right\} \longrightarrow \text{were produced 5 - 20 years ago}$$

Variety of actual micro- and nano-systems

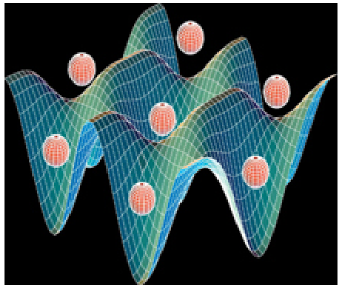
Atomic clusters



Bose-Einstein condensate of atomic trapped dilute gas

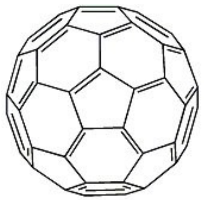


Optical lattice



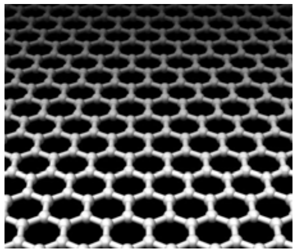
Carbon nanosystems

Fullerenes

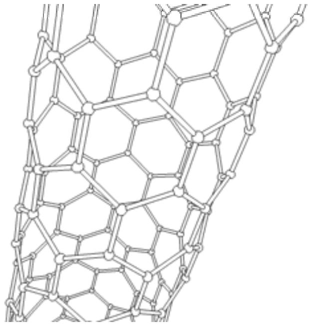


C_{60}
"Buckminster-Fulleren"

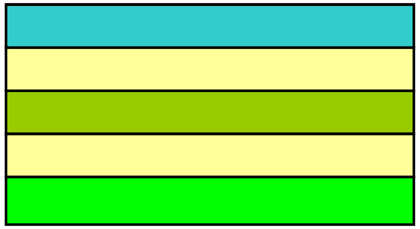
Graphene



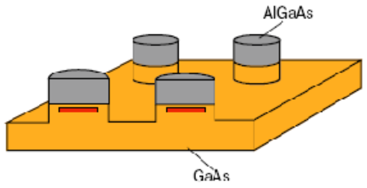
Nanotubes



Hetero-nanostructures

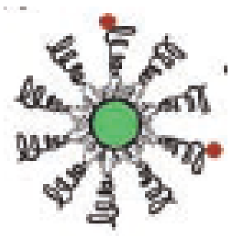


Quantum dots



Quantum transport

Bio-complexes



For every nanosystem:

- definition
- how to produce
- main properties and physical effects
- why it is interesting for:
    - fundamental physics
    - applications

Lecture 1:

Atomic clusters

- metal clusters
- similarity with nuclei
- quantum shells and supershells
- dipole plasmon
- applications

Lecture 2:

Theoretical models

- Kohn-Sham functional

Carbon nanosystems

- fullerenes
- graphene
- nanotubes

Lecture 3:

Quantum dots

- Wigner molecules
- Coulomb blocade
- spintronics

Heterostructures

- Giant Magnetoresistance

(Nobel -2007)

Quantum transport

- different kinds of QT

Biomedical applications

- cancer diagnostic and therapy

Lecture 4:

Bose-Einstein condensate

- amazing laboratory for new physics

Optical lattice

Nano in Russia and Dubna

Conclusions

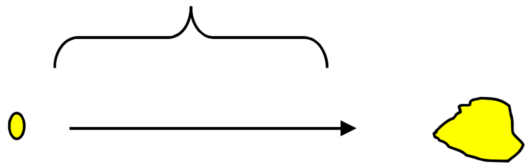
ATOMIC CLUSTERS

- variety of atomic clusters,
- cluster production,
- metal clusters: mean field,
- similarity of atomic clusters and nuclei
- quantum shells, magic numbers,
- super-shells,
- deformation,
- temperature effects,
- phase transitions,
- dipole plasmon, experiment,
- spill-out,
- applications,
- theoretical methods: Kohn-Sham functional, …

Atomic clusters

* Atomic cluster is a bound system of identical atoms.

* Bridge between one atom and bulk:



Atomic clusters

Atom

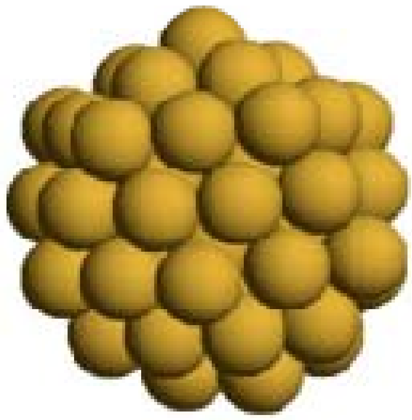
Solid body

* Now it is possible to produce clusters with any number of atoms and for any element of the periodic table.
Fundamental physics + applications!

* The most interesting size interval is $1<N<1000$.

* Applications:

-- creation of new materials by cluster deposition,
-- catalysis of chemical reactions,
-- new alloys,
-- new magnetic materials,
-- cluster nano-electronics,
-- clusters to cure cancer.

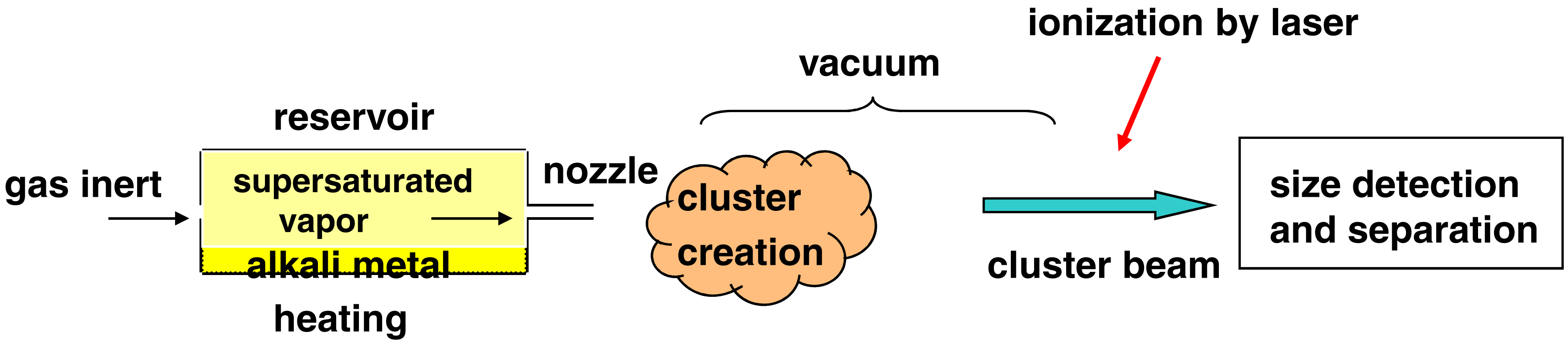


Au_{55}

Cluster production

1. W.D. Knight, et al, PRL 52, 2141 (1984) -- experiment
2. W. Ekardt, PRB, 1558 (1984) -- theory

Seeded supersonic nozzle source

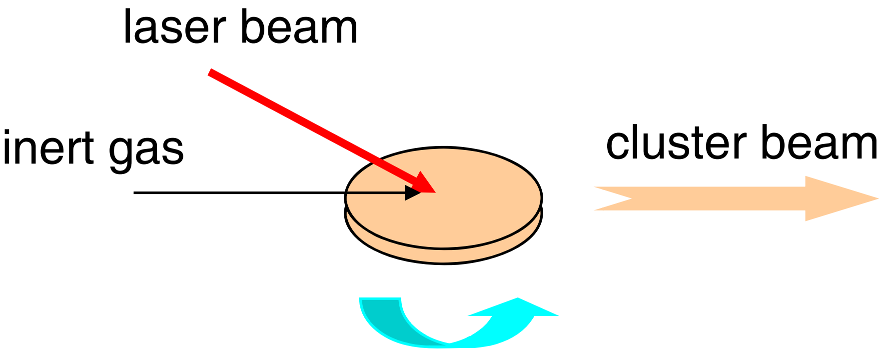


- heating of the material in reservoir to get the supersaturated vapor,
- mixture with a beam of high-pressure inert gas,
- supersonic expansion of the mixture to vacuum,
- sudden expansion, cooling and condensation of atoms into clusters,
- ionization of neutral clusters in beam by laser,
- detection and separation of clusters with a given number of atoms,
- experiments in a beam of size-separated clusters.

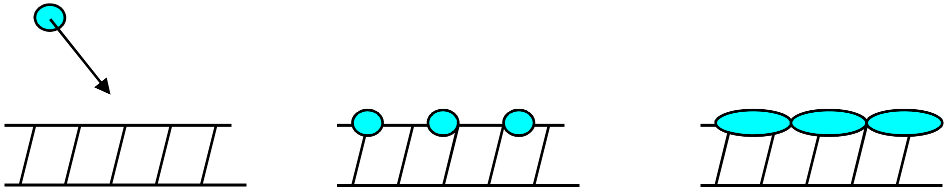
Alternative sources: creation of supersaturated vapor by intense laser, growing cluster in solutions, …

Alternative methods of cluster production

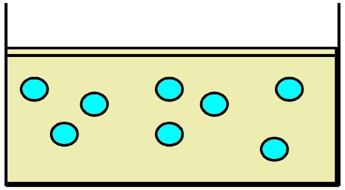
Laser heating:



Epitaxy
(grow on surface):



Colloidal synthesis
(grow in solutions):



Clusters in our life

Colloidal gold: known in ancient Egypt

Gold clusters:

- stained-glass windows in cathedrals:

Metallic micro-grains added to the glass result in various colors of the penetrated light. The light wave length depends on the kind of the metal and grain size.

- British museum, Licurgus cup, IV century AD

The green cup becomes red if to light it from inside (the glass with colloidal gold and silver)

Silver clusters: photography:

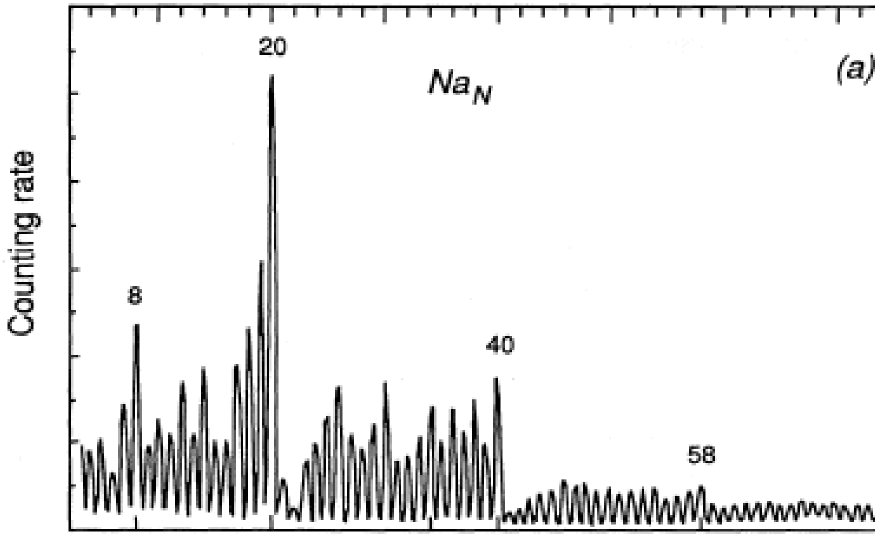
Silver films used in photography consist on silver clusters.

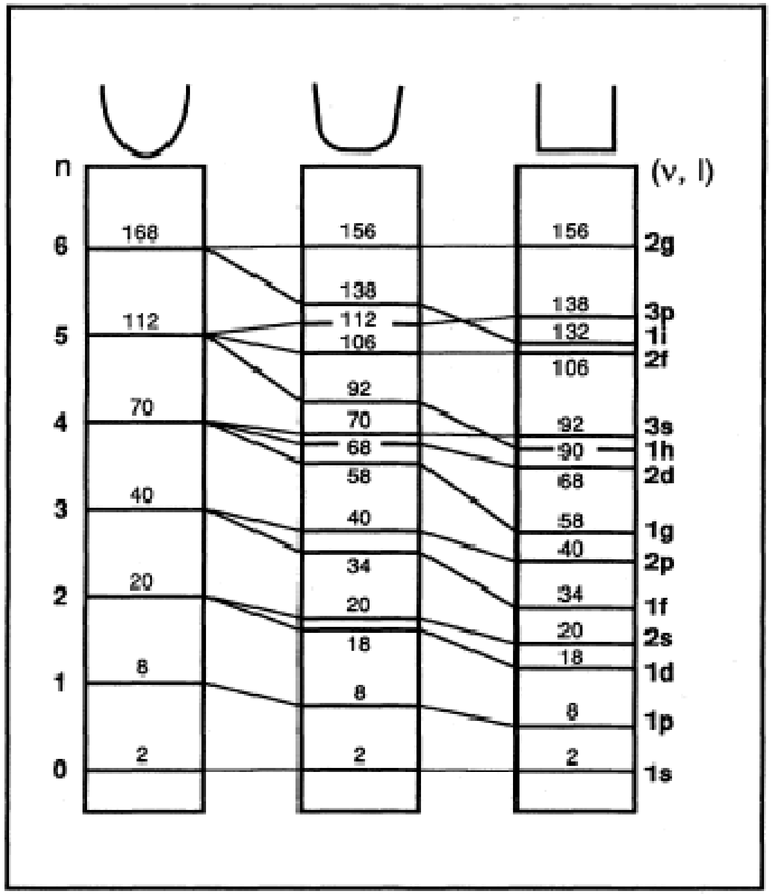
Different kinds of powders.

Clusters as small metal particles are known since ancient times but only ~ 25 years ago we have mastered production of small clusters with given number of atoms .

Metal clusters: mean field, quantum shells, magic numbers

Experiment of Knight et al, 1984





- Magic numbers 8, 20, 40, 58, …
  like in typical quantum wells
  and atomic nuclei (8, 20, 28, 50)!

- The remaining difference in magic numbers is caused by a weak spin-orbital splitting in electronic systems.

Metal clusters

1. W.D. Knight, et al, PRL 52, 2141 (1984) -- experiment
2. W. Ekardt, PRB, 1558 (1984) -- theory

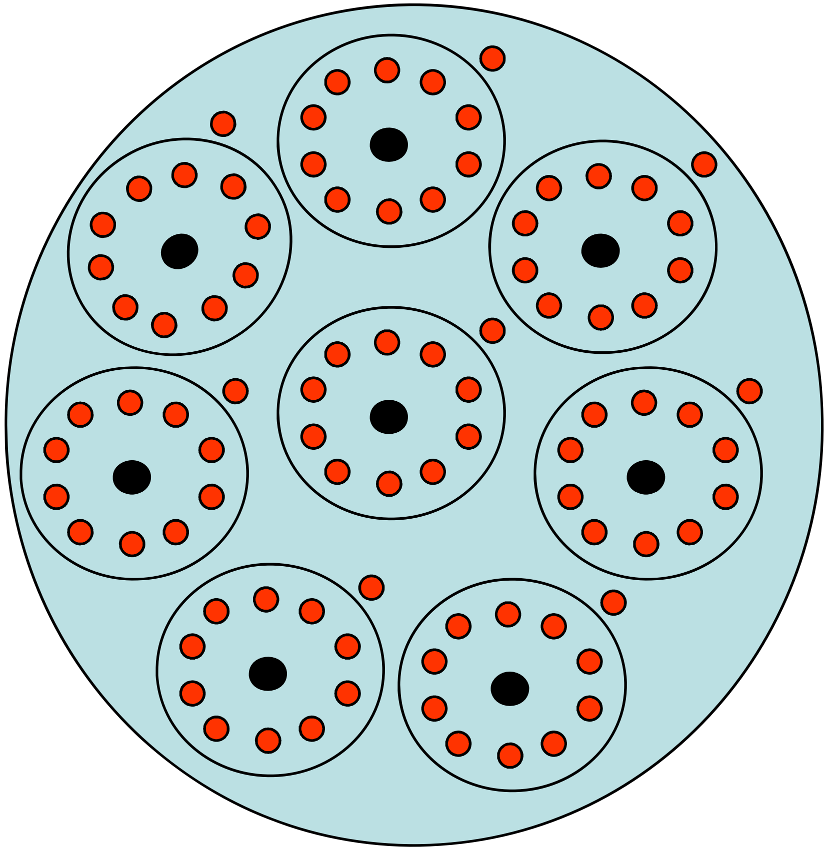
* Clusters of some metals (alkali and noble) are very similar to atomic nuclei.

* Two subsystems in metal clusters:
-- valence electrons (quantum properties),
-- ions (classical particles).

* Mean free path of valence electrons is of the same order of magnitude as the cluster size. So their motion can be quantized and they can create the mean field of the same kind as nucleons do in atomic nuclei.

valence electrons in metal clusters ⟷ nucleons in nuclei

Metal cluster Na_8



Metal clusters vs nuclei

Similarities:

- Mean field, quantum shells, magic numbers
- Various deformations: L=2,3,4,…
- Shape isomerism
- Collective modes:
  plasmons ⟷ giant resonances
- Fission and fusion
- …

and differences

- More quantum shells, **supershells**
- Neutral, negative/positive charges
- Free, supported, embedded, …

} Metal clusters

“Quantum” valence electrons and “classical” ions

$$E = \frac{p^2}{2m} = \frac{\hbar^2}{2m}\left(\frac{\partial}{\partial x}\right)^2 \approx \frac{\hbar^2}{2m}\left(\frac{1}{\Delta x}\right)^2$$

$$Na_{20} : \Delta x \approx D \approx 11\dot{A}$$

$1\text{K}=8.6\cdot10^{-5}\text{eV}$

temperature:	$t \approx 100 - 800\,\text{K} \approx 0.01 - 0.1\,\text{eV}$		
electrons:	$E_e \approx 0.06\,\text{eV} \geq t$	←	**quantum particles**
ions:	$E_i \approx 0.06 \cdot 10^{-3}\,\text{eV} < t$	←	**classical particles**

So, just valence electrons determine quantum properties of clusters while ions can be treated as classical particles.

In metal clusters like Na ones, the ions can be safely replaced by the uniform frozen distribution of the positive charge:

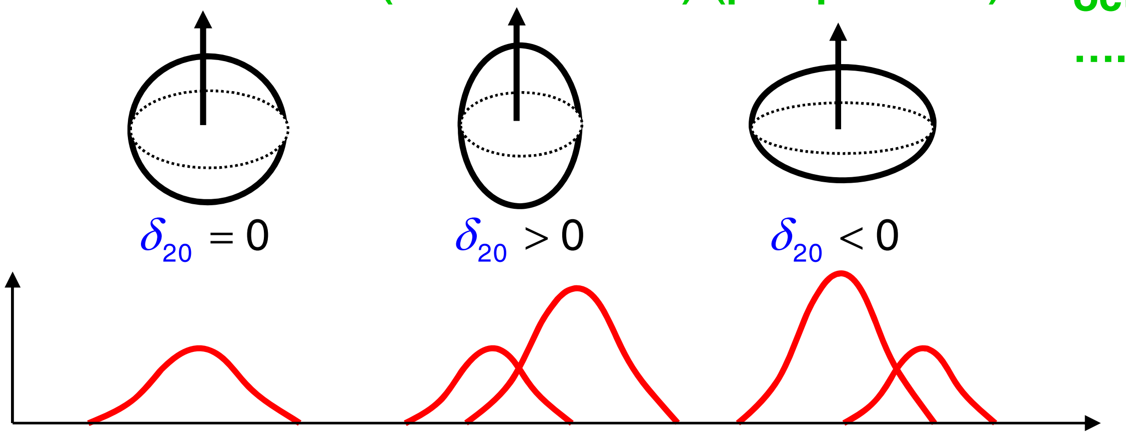
jellium approximation

Metal clusters: deformation

$$R = R_0(\delta_0 + \delta_{20} Y_{20}(\Omega))$$

Like atomic nuclei,
metal clusters with closed (fully occupied) quantum shells are spherical
while clusters with open (partly occupied) quantum shells are deformed.

Deformation in clusters is called as Jahn-Teller effect.



Spherical

Axial prolate
(cucumber-like)

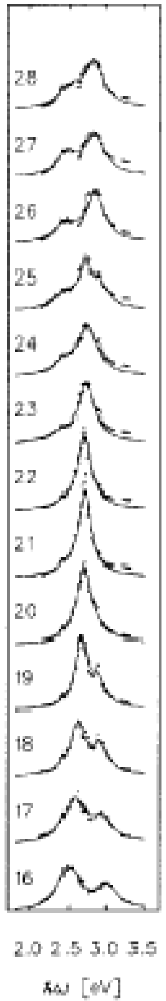
Axial oblate
(pumpkin-like)

Triaxial,
octupole
…..

$\delta_{20} = 0$ $\delta_{20} > 0$ $\delta_{20} < 0$

Splitting of the dipole plasmon:
the only direct evidence and information source
for cluster deformation.

Coexistence of different cluster shapes.



prolate

spherical

oblate

Na clusters,
M. Schmidt
and
H. Haberland,
experiment,
1999.

Limits for the number of quantum shells (1)

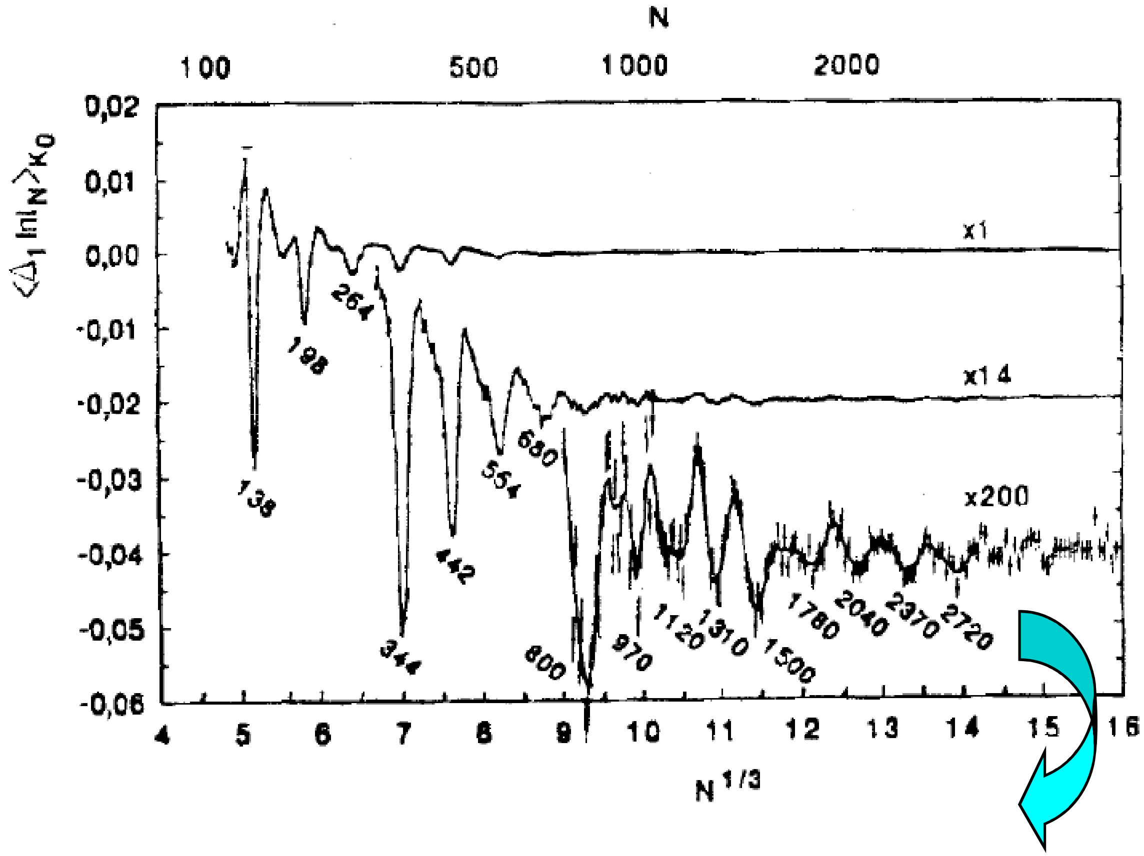
How many quantum shells can exist in metal clusters?

Is there any upper limit?

If yes, then what is a physical reason for the limit?

Limits for the number of quantum shells (2)

Search for most stable clusters → determination of magic numbers.

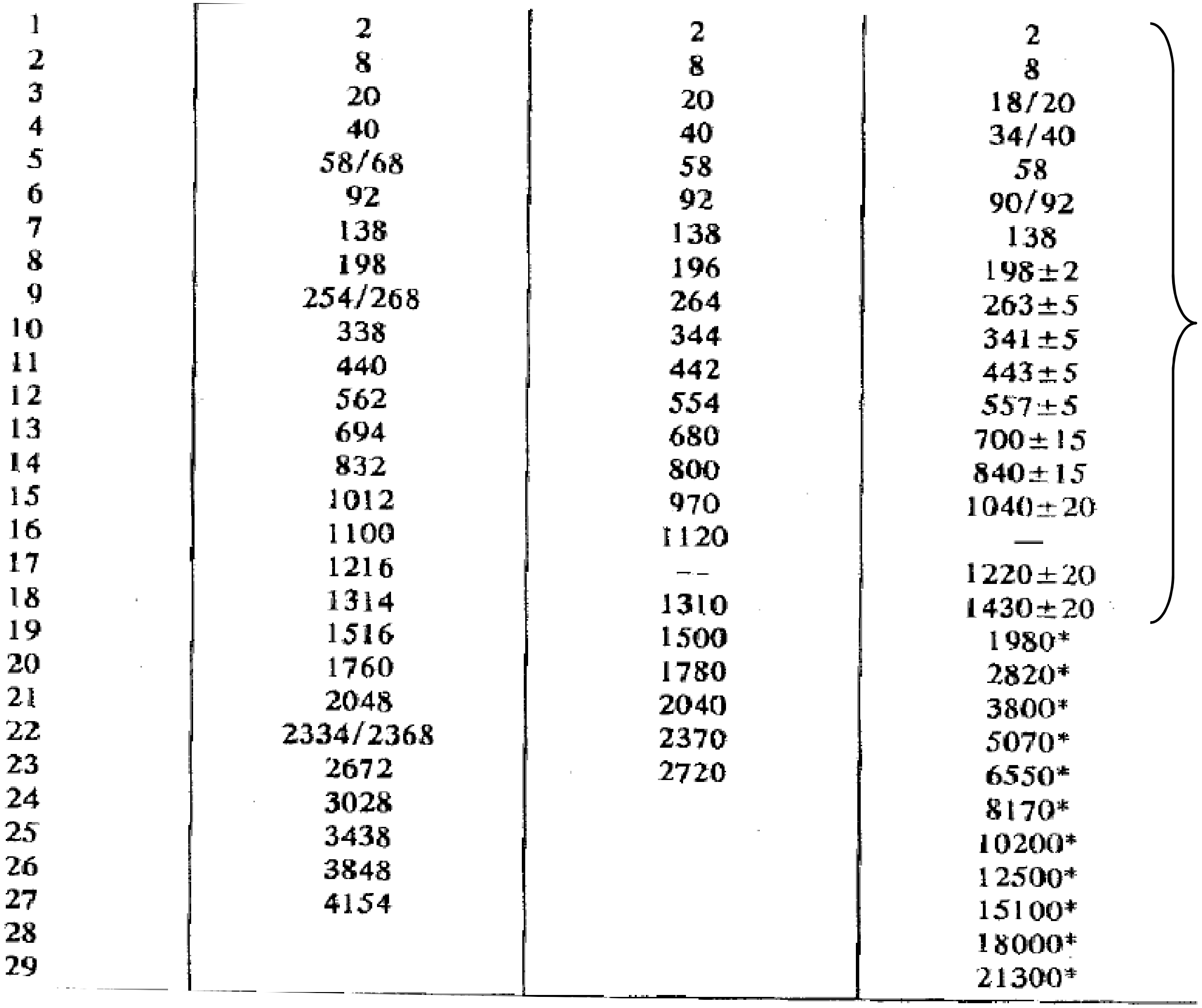


Experiment:
J. Pedersen et al,
Nature, 353 (1991).

There exist at least 23 quantum shells!
Maximal magic number can get ~ 2700!

(Only 8 quantum shells are possible in atomic nuclei.)

Limits for the number of quantum shells (3)



	magic numbers		
Shell number (N)	**Theory (Nishioka)**	**Exper. (Pedersen)**	**Exper. (Schmidt)**
1	2	2	2
2	8	8	8
3	20	20	18/20
4	40	40	34/40
5	58/68	58	58
6	92	92	90/92
7	138	138	138
8	198	196	198±2
9	254/268	264	263±5
10	338	344	341±5
11	440	442	443±5
12	562	554	557±5
13	694	680	700±15
14	832	800	840±15
15	1012	970	1040±20
16	1100	1120	—
17	1216	--	1220±20
18	1314	1310	1430±20
19	1516	1500	1980*
20	1760	1780	2820*
21	2048	2040	3800*
22	2334/2368	2370	5070*
23	2672	2720	6550*
24	3028		8170*
25	3438		10200*
26	3848		12500*
27	4154		15100*
28			18000*
29			21300*

Quantum shells
(best for high T)

Geometrical
(icosahedron)
shells
like in the bulk!
(best for low T)

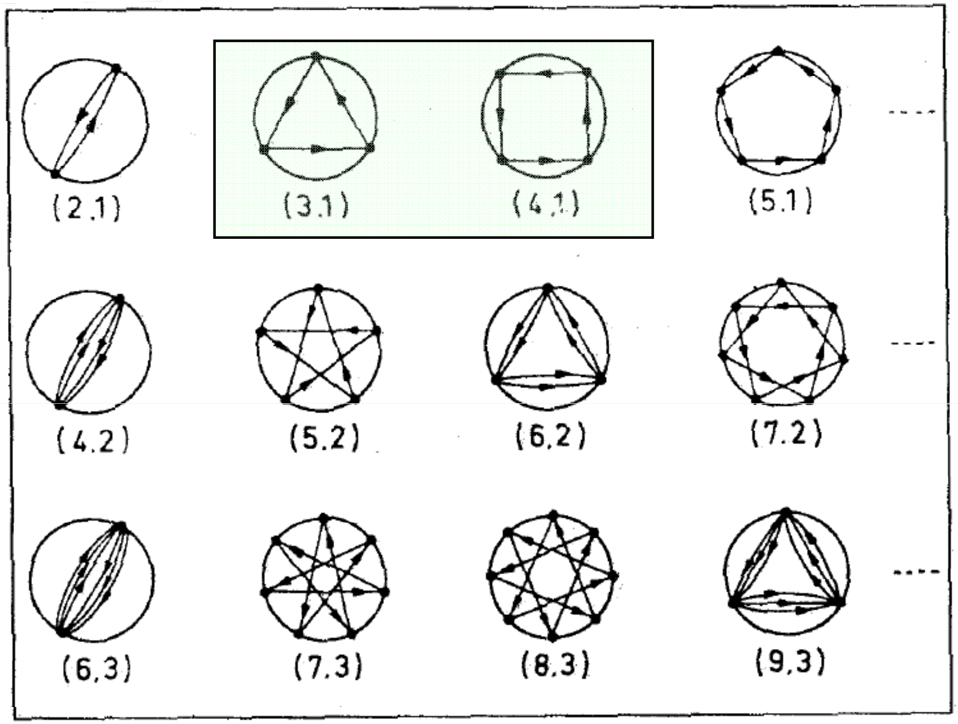
T = 800 K

T = 100 K

Supershells (1)

Theory of periodic orbits

R. Balian and C. Bloch, Ann. Phys., 69 (1971) 430.



Quantum shells in finite systems have a classical analog in the form of periodic closed orbits in the spherical vibrator.

Temperature destroys the orbits so as only a couple of simple orbits with similar characteristics survives: (3,1), (4,1).

$$\cos(\omega_{31}t)+\cos(\omega_{41}t)$$

$$=2\underbrace{\cos(\frac{(\omega_{31}-\omega_{41})t}{2})}_{\text{low frequency}}\underbrace{\cos(\frac{(\omega_{31}+\omega_{41})t}{2})}_{\text{high frequency}}$$

Beating!
Supershells !!!

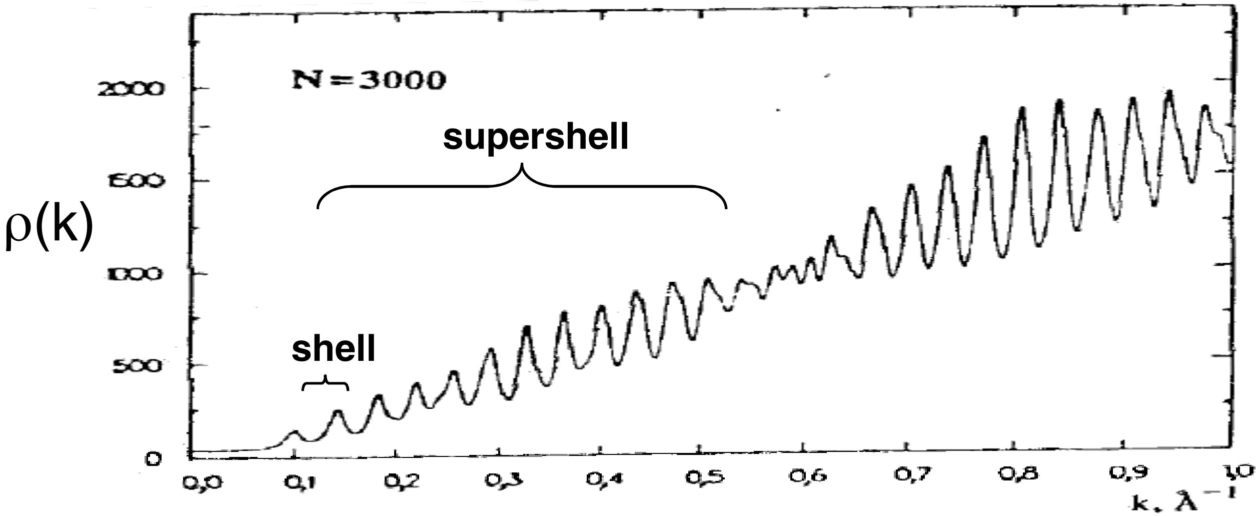
Quantum shell **Periodic orbit**

$$(\Delta l, \Delta n) \Leftrightarrow (k, m)$$

k – number of contacts
m – number of revolutions

Supershells (2)

Density of levels in sodium cluster with 3000 atoms.

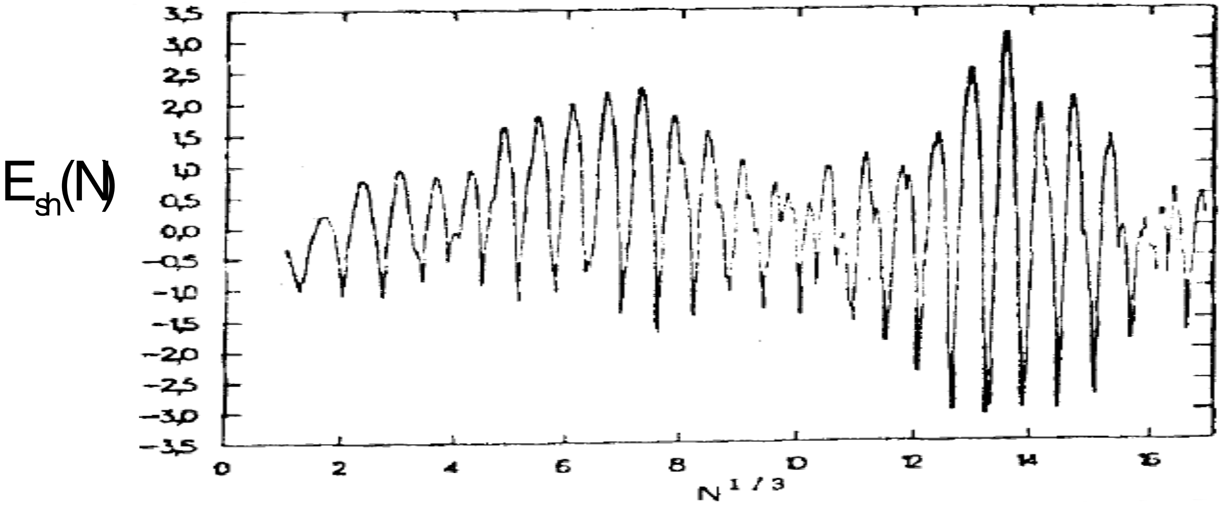


H. Nishioka,
ZPD, 19 (1991) 2331.

WS potential

$$k=\sqrt{2m(E-V_0)}/\hbar$$

Quantum shell energy .



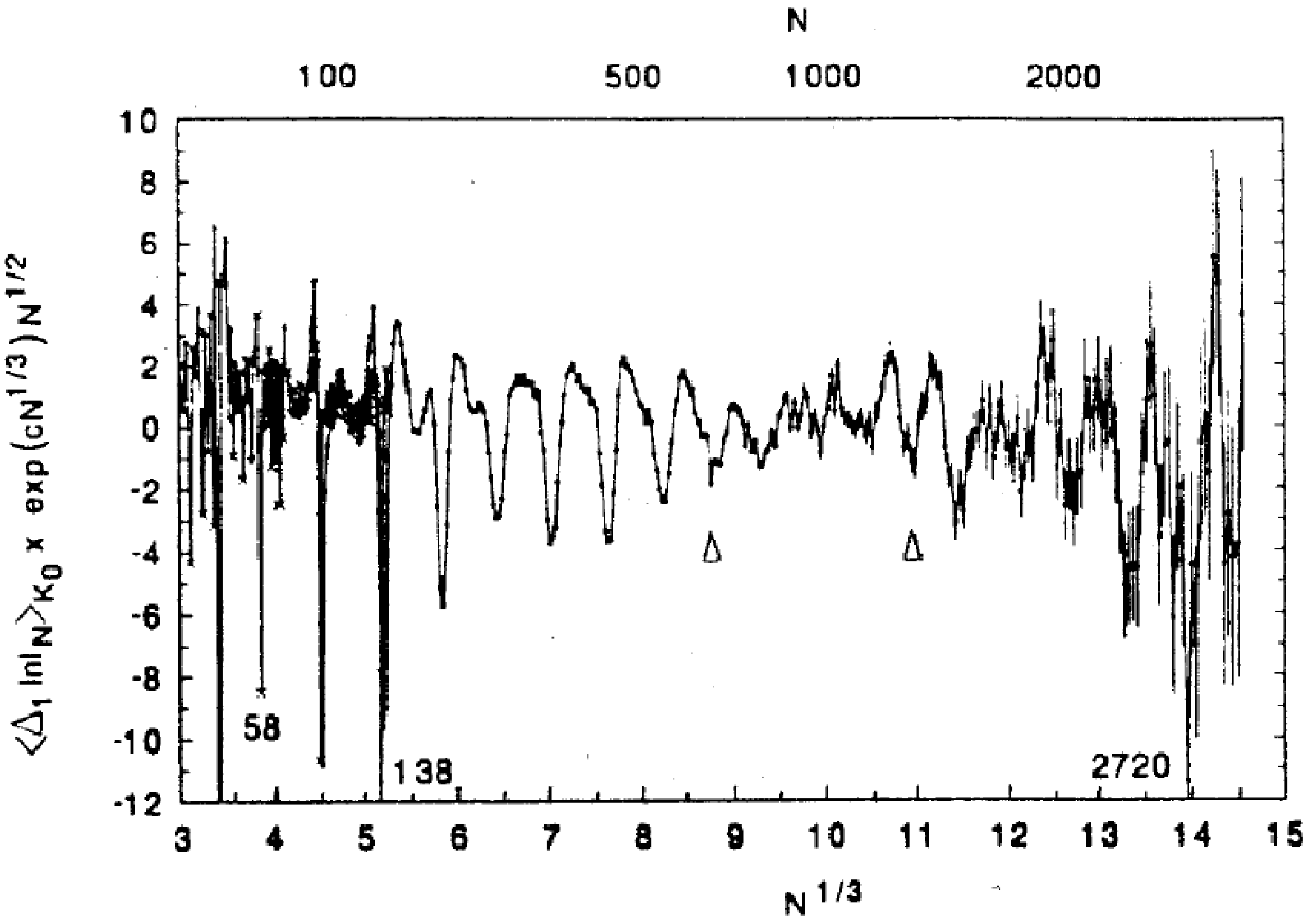
J. Pedersen et al,
Nature, 353 (1991).

$$E_{sh}(N)=E-E_{LD}$$

Supershells (3)

Discovery of supershells in experiment for Na clusters:

J. Pedersen, S. Bjornholm, et al, Nature, 353 (1991).



This discovery leaded to a great progress of TPO, chaos/order studies, etc.

What we have learned from lecture 1:

- definition and variety of atomic clusters
- cluster production
- deformation / Jan-Teller effect
- mean field with quantum shells
- supershells

Similarity with nuclei only for a clusters of alkali and noble metals! For overwhelming majority of other clusters this similarity is absent.

Thank you for your attention!