FLNP JINR 2018

V.Shvetsov

Content

- Introduction;
- FLNP History;
- Neutron Science at the FLNP;
- Applied and Methodical Research;
- FLNP Future Prospects;

Why Neutrons?

Neutrons have No Charge!

- Highly penetrating
- Nondestructive
- Can be used in extremes

Neutrons have a Magnetic Moment!

- Magnetic structure
- Fluctuations
- Magnetic materials

Neutrons have Spin!

- Polarized beams
- Atomic orientation
- Coherent and incoherent scattering

The Energies of neutrons are similar to the energies of elementary excitations!

- Molecular Vibrations and Lattice modes
- Magnetic excitations

The Wavelengths of neutrons are similar to atomic spacing!

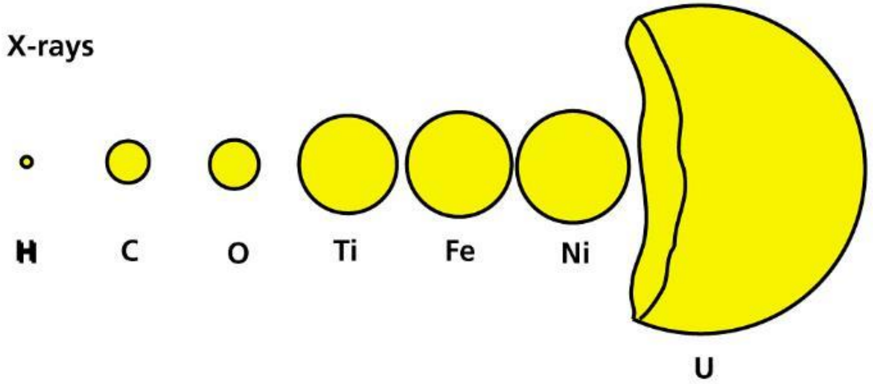
- Sensitive to structure
- Gathers information from 10^{-10} to 10^{-7} m
- Crystal structures and atomic spacings

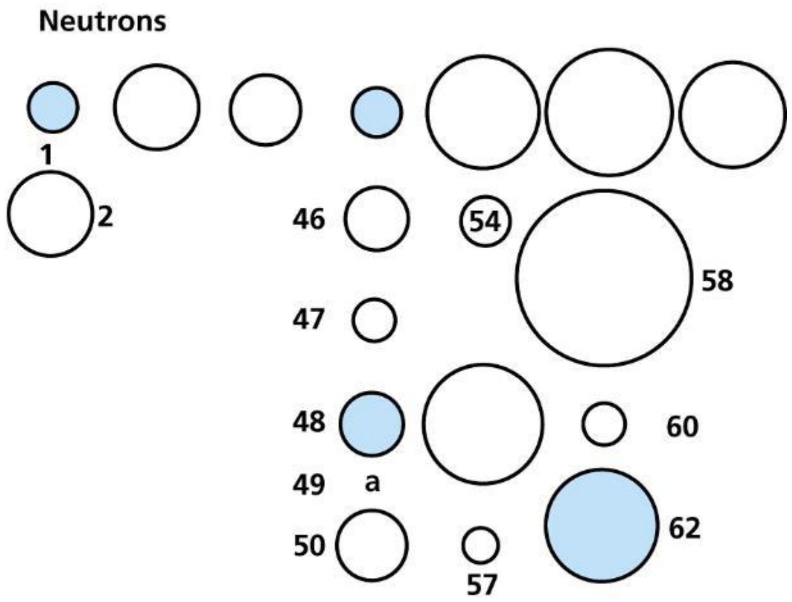
Neutrons probe Nuclei!

- Light atom sensitive
- Sensitive to isotopic substitution

Advantages of neutrons over X-rays

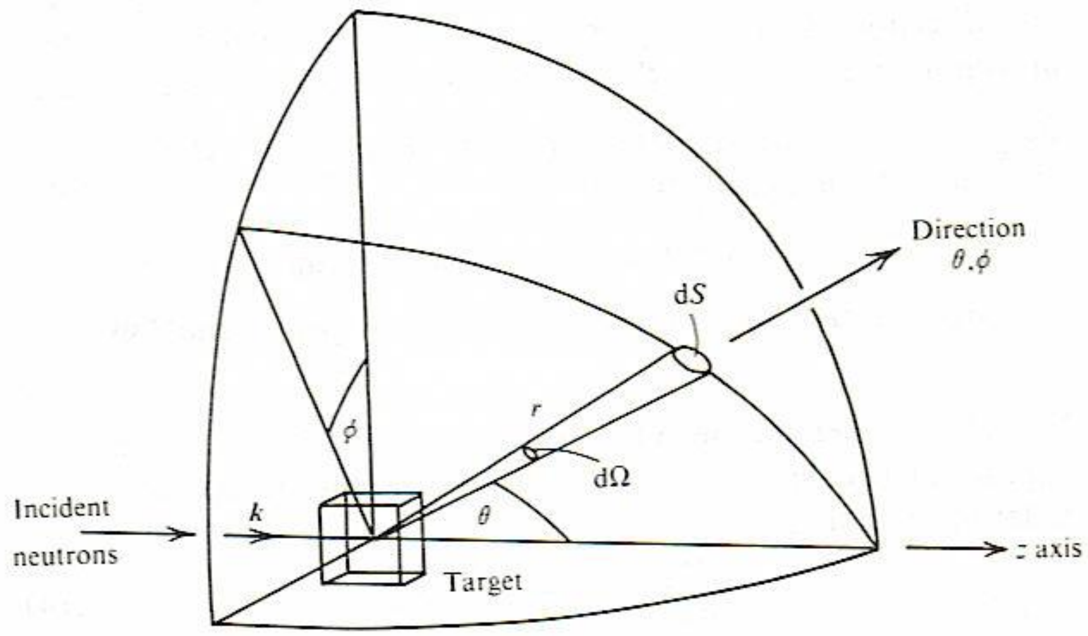
- You can easily work in extreme sample environments H,T,P,...) e.g. ^{4}He cryostat (Shull & Wollan) and penetrate into dense samples
- The magnetic and nuclear cross-sections are comparable, nuclear cross-sections are similar across the periodic table

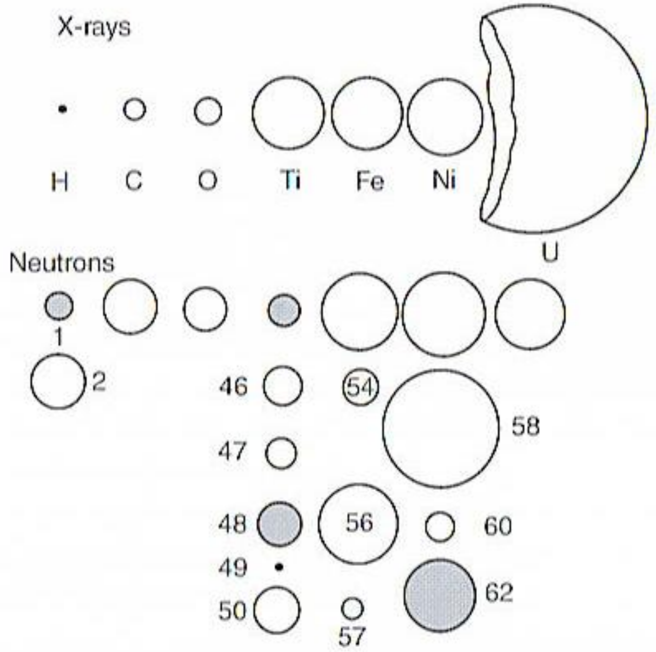




- Sensitivity to a wide a range of properties, both magnetic and structural

Neutrons vs. X-rays!

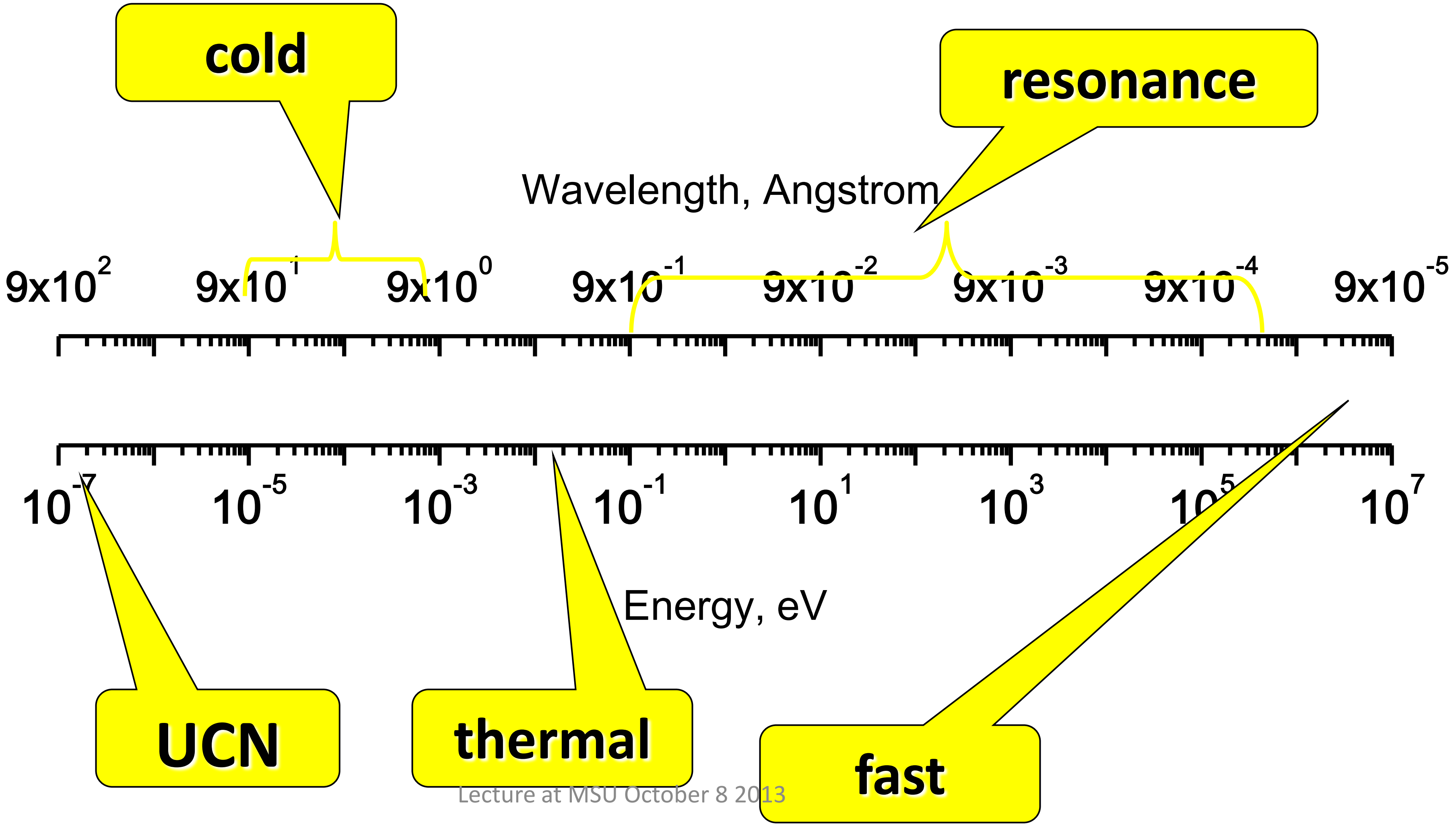




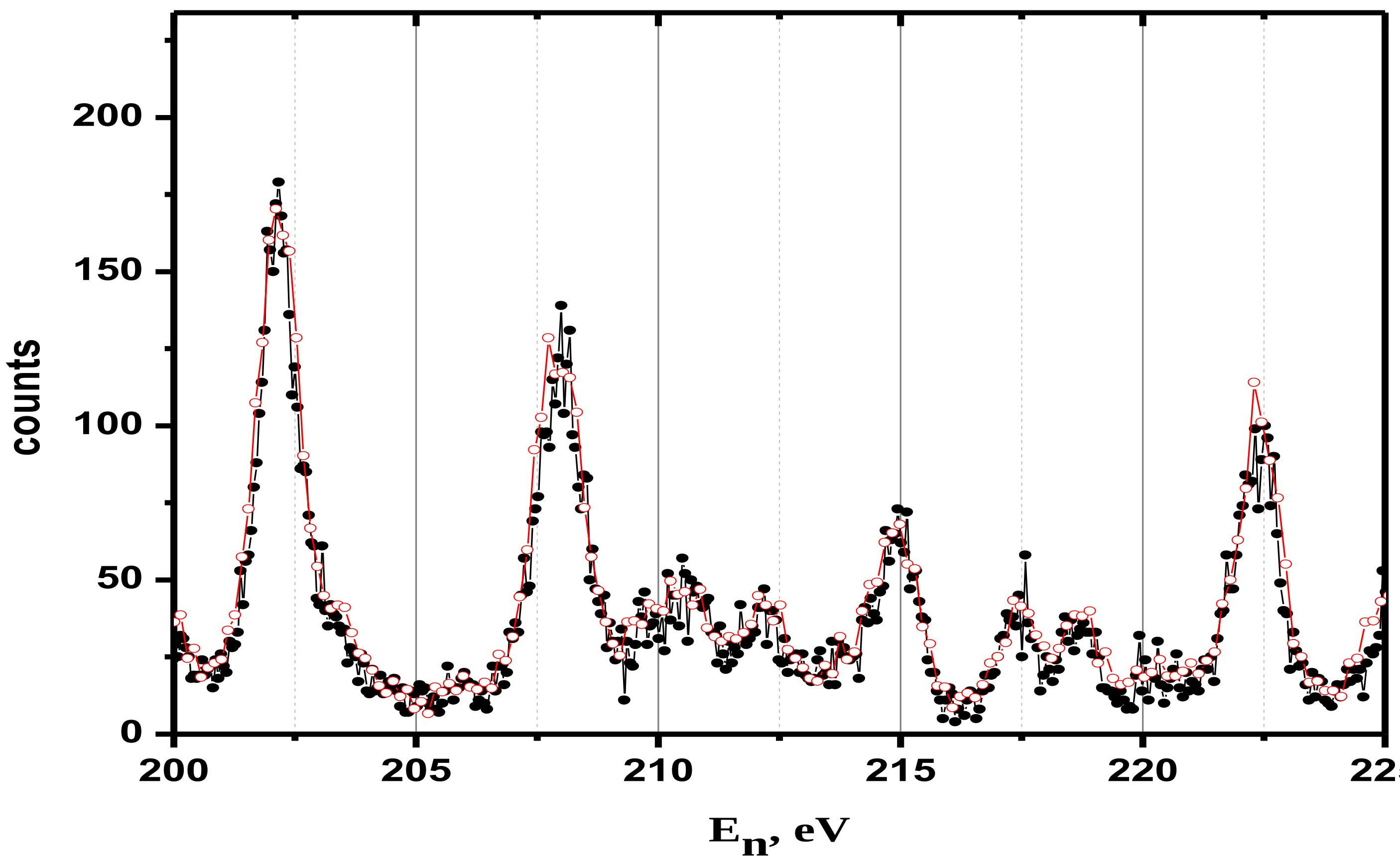
Chatterji, *Neutron Scattering from Magnetic Materials* (2006)

Neutrons allow easy access to atoms that are usually unseen in X-ray Scattering

Neutron – wave and particle



Neutron interaction with condensed matter and nuclei



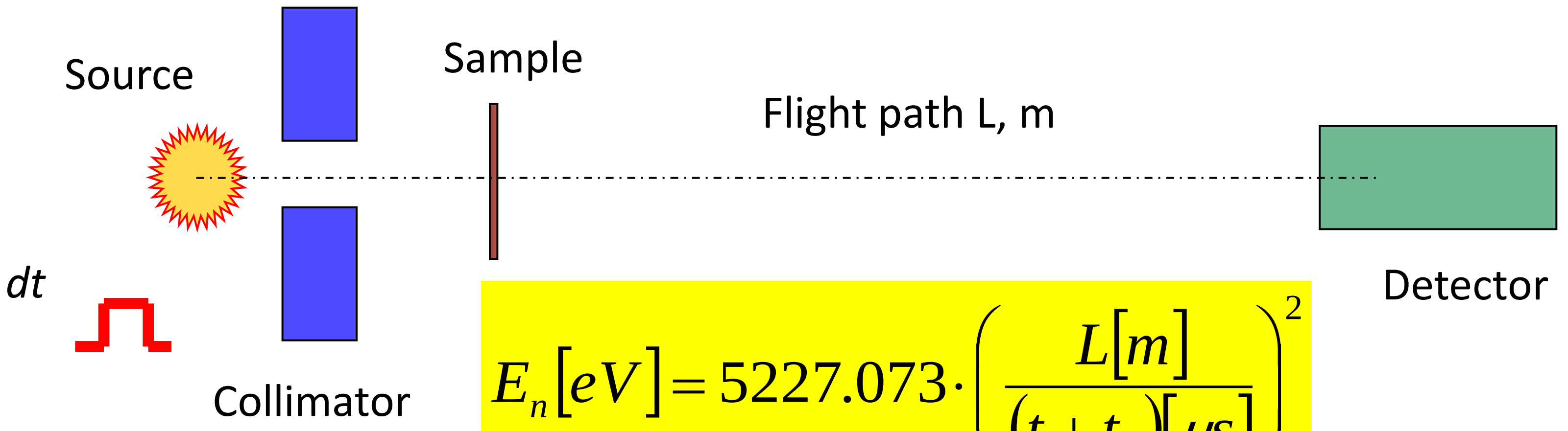
$^{nat}Gd\ (n, \gamma)$

^{152}Gd - 0.20%
^{154}Gd - 2.18%
^{155}Gd - 14.80%
^{156}Gd - 20.47%
^{157}Gd - 15.65%
^{158}Gd - 24.84%
^{160}Gd - 21.86%

Sample:
m_g = 172.8 g
size: 11.2 x 14.5 cm^2
ρ: 1.064039

IREN, Dubna
f = 25 Hz
I_e = 2A; t_e=100ns
L = 58.6m

How to measure the neutron's energy?



$$E_n[eV] = 5227.073 \cdot \left(\frac{L[m]}{(t+t_0)[\mu s]} \right)^2$$

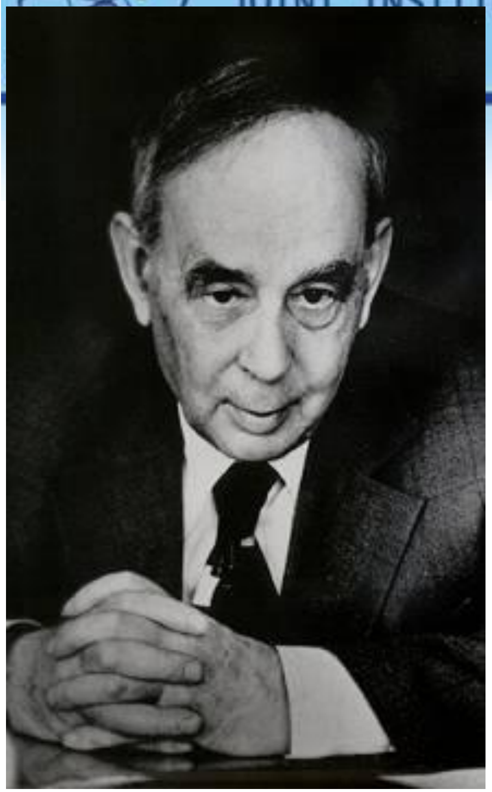
$$E_n[eV] = \left(\frac{72.2985 \cdot L[m]}{(t+t_0)[\mu s]} \right)^2$$

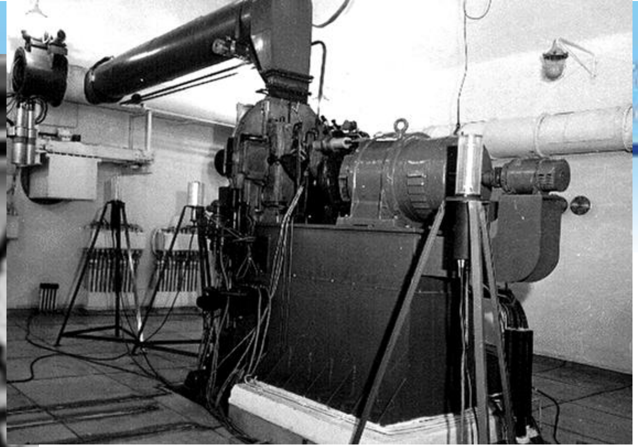
$$\frac{\Delta E_n}{E_n} = \sqrt{\left(\frac{2 \cdot dt}{t} \right)^2 + \left(\frac{2 \cdot dL}{L} \right)^2}$$

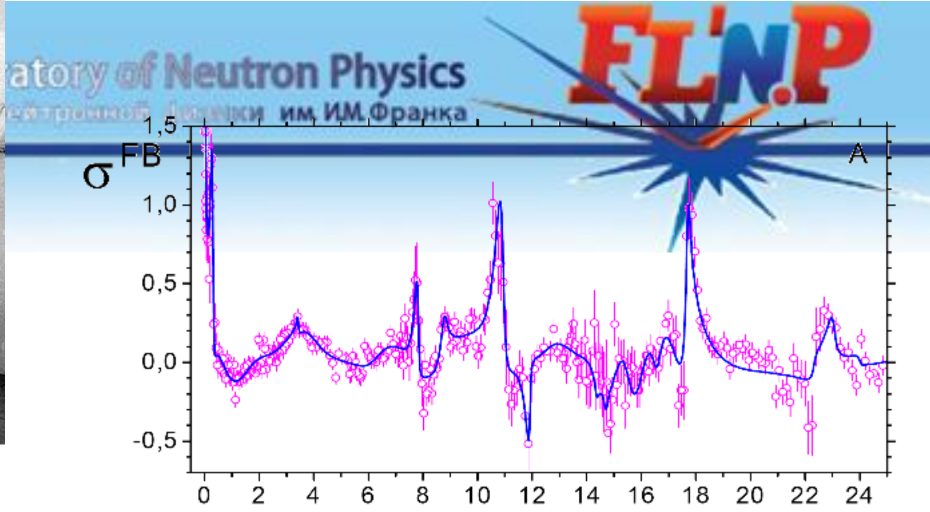
$$\Delta E_n[eV] = 2.8 \cdot 10^{-2} \cdot \frac{dt[\mu s]}{L[m]} \cdot E_n^{3/2}$$

$$dt_{\mathrm{mod}}[\mu s] \approx 1.6 \cdot E_n^{-1/2}$$

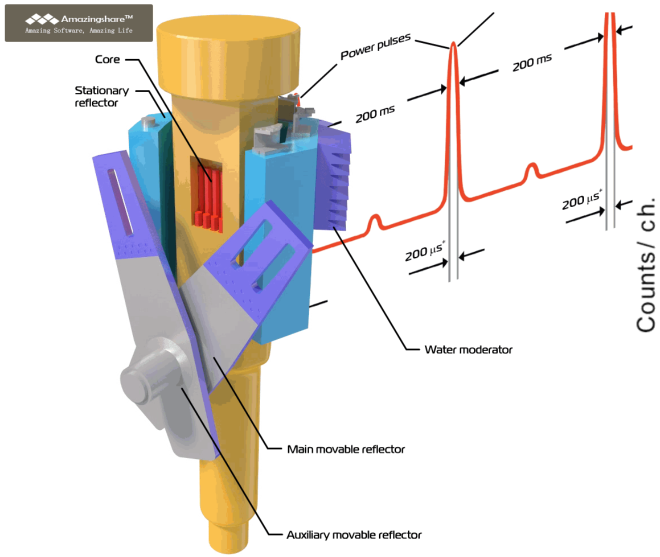
≈50 ns at 1 keV; 500 ns at 10 eV

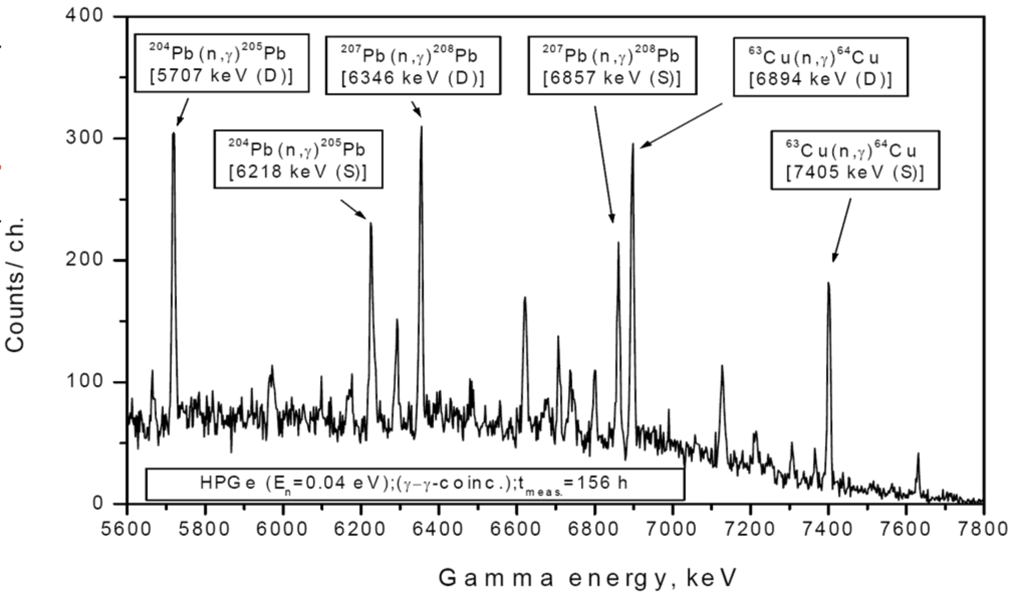






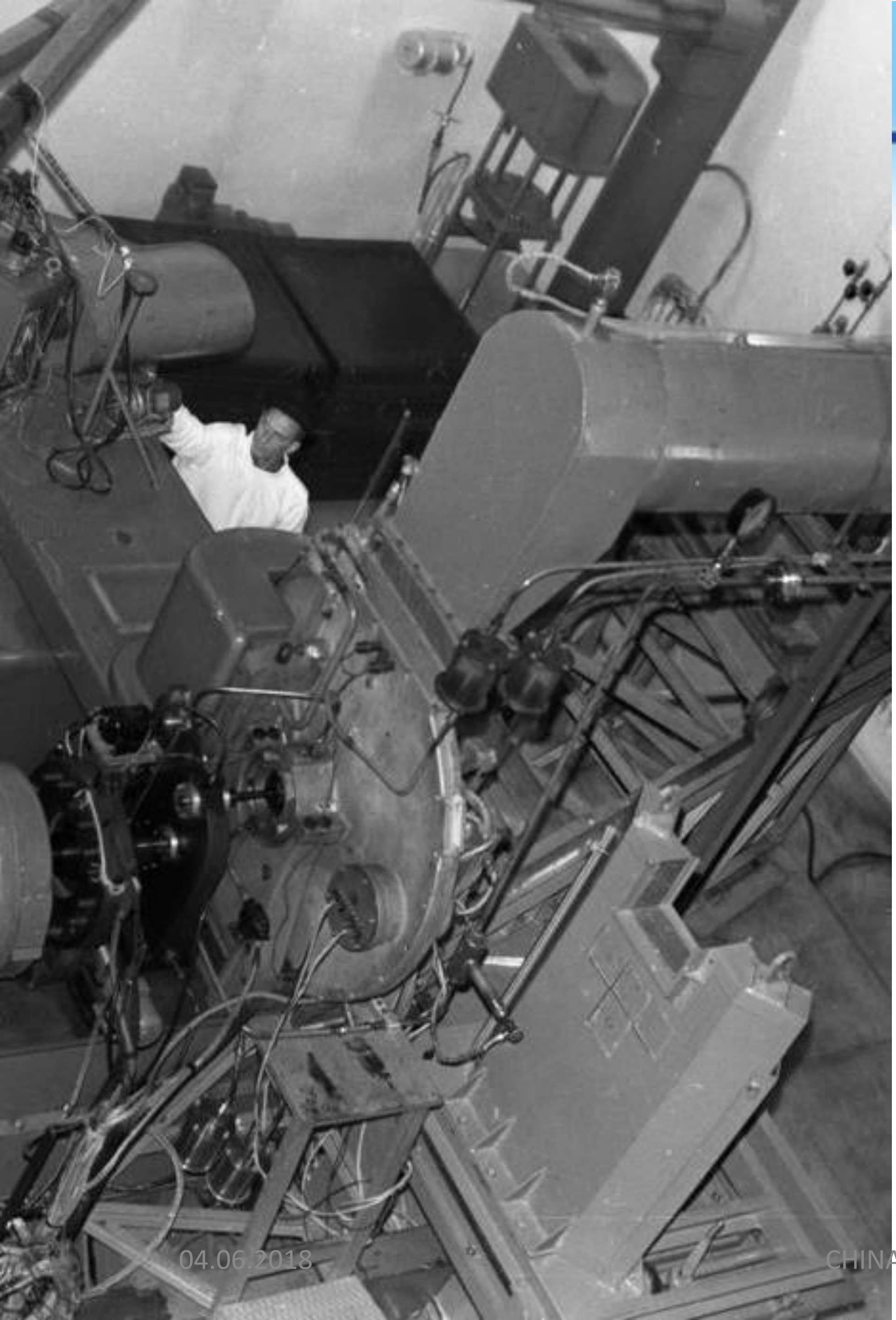
FLNP History





Brief History of IBR reactors

- The first IBR was created chiefly by physicists from IPPE (Obninsk) with the participation of specialists from FLNP JINR under the direction of I.M.Frank.
- To simplify the design of a unique reactor constructed for the first time in the world, the IBR average power was chosen to be rather small 1 kW (but instantaneous power in pulse reached 5 MW). Later on the possibility to raise the reactor average power up to 6 kW with an increase in the consumption of cooling air was substantiated, and since 1964 the reactor worked at a power from 2 to 6 kW.
- In general, rather long pulse of the reactor (50 μs) was more adequate to the tasks of condensed matter physics. To reduce pulse duration, at the suggestion of F.L.Shapiro since 1965 the first IBR started to be used in a neutron pulse multiplication mode of a neutron-producing target of the electron accelerator-microtron. With the start-up of the pulsed booster) the neutron pulse length reduced to 3 μs.



Brief History of IBR reactors cont.

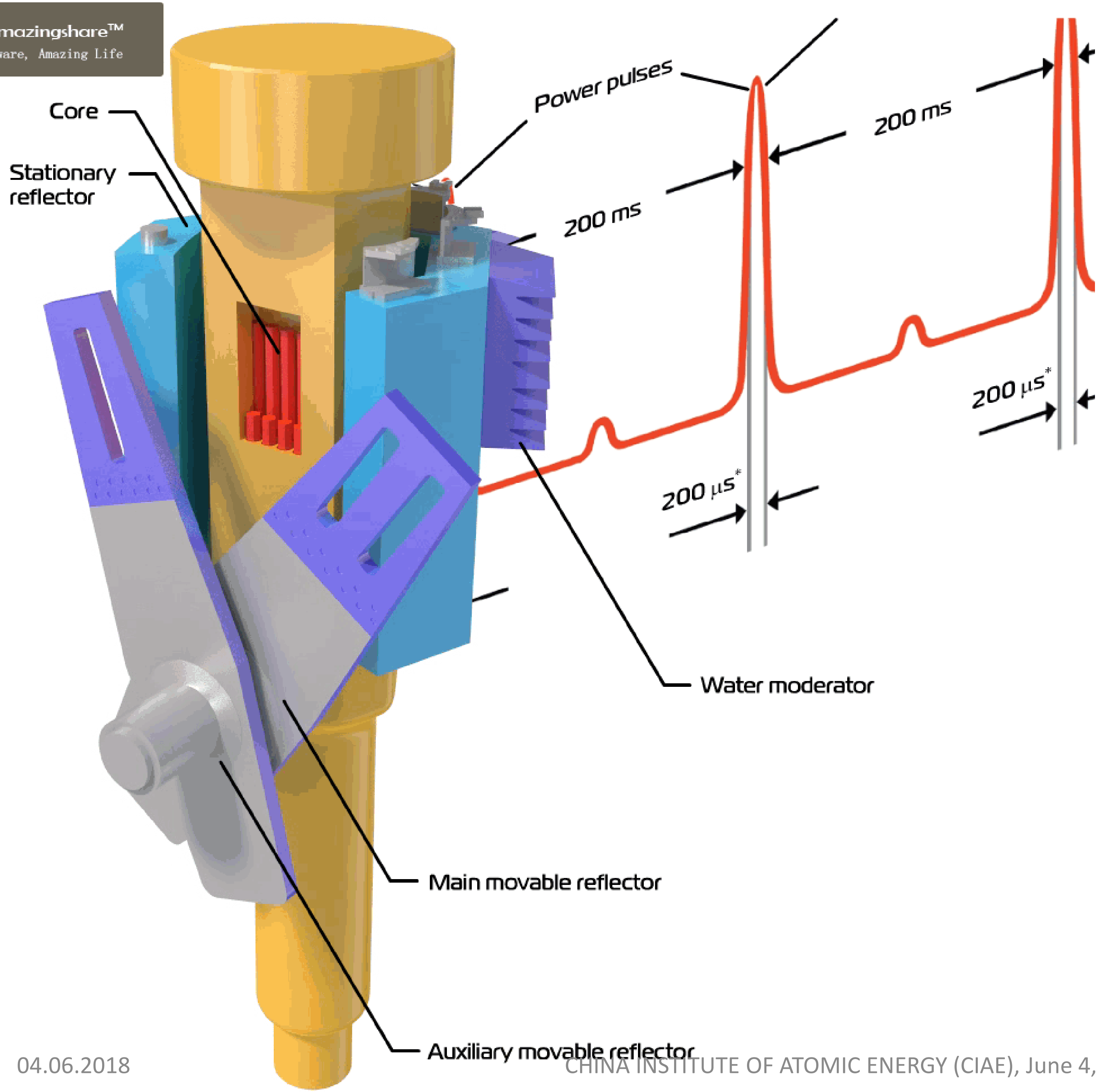
- The first IBR stopped its operation in August 1968. It is particularly remarkable that the last experiment on this reactor was a well-known experiment on the first observation of ultracold neutrons carried out in a rare pulse mode. On June 10, 1969 an advanced analogue of the first IBR – IBR-30 was put into operation. An increase in power was achieved by changing the design of plutonium fuel elements and by introducing two uranium inserts (modulators of reactivity) instead of one in the steel disk.
- The operation in a booster mode (IBR-30 was used in the reactor and booster modes alternately up to 1986, when its operation in the reactor mode was stopped) was carried out with the resonant linear accelerator LUE-40 as an injector with an energy of accelerated electrons of 44 MeV and a pulse current of 0.2 A. An average power in the booster mode was 10 kW at a fast neutron pulse halfwidth of 4 μs. High luminosity of the spectrometer at IBR-30 made it possible to open up a number of entirely new areas in nuclear research and condensed matter physics.

Brief History of IBR reactors cont.

- In 1963 preliminary design works were started to substantiate the possibility to create a much more powerful IBR, which in its neutron characteristics for investigations by slow neutron scattering methods would compare well with 50-100 megawatt stationary reactors (HFR in ILL, Grenoble, SM-2 in RIAR, Dmitrovgrad, PIK in PNPI RAS, Gatchina). In JINR a new reactor with a design power of 4 MW under the name IBR-2 was constructed by 1977 with the participation of NIKIET (A.N.Dollezhal Research and Development Institute of Power Engineering), SSDI (State Specialized Design Institute), VNIINM (A.A.Bochvar All-Russian Research Institute of Inorganic Materials) and other institutes and organizations of the USSR and JINR Member States.
- The physical start-up was in 1978 and the official operation began in April 1984. Later on it was decided to restrict the average power to 2 megawatts to ensure the maximum possible nuclear safety and reliability of the facility, and the pulse duration turned out to be 216 μs instead of design value of 90 μs. But even with these parameters IBR-2 was and still remains to be one of the most effective pulsed sources of slow neutrons for condensed matter investigations. The requirement to obtain high neutron fluxes at short pulse duration also led to the necessity to create a compact zone with high specific heat release and short neutron lifetime. The reactor core of plutonium oxide with sodium cooling was chosen. The sodium cooling system has been functioning successfully and uninterruptedly since its startup in 1981 to the present day both during the reactor cycles and in shutdown periods.

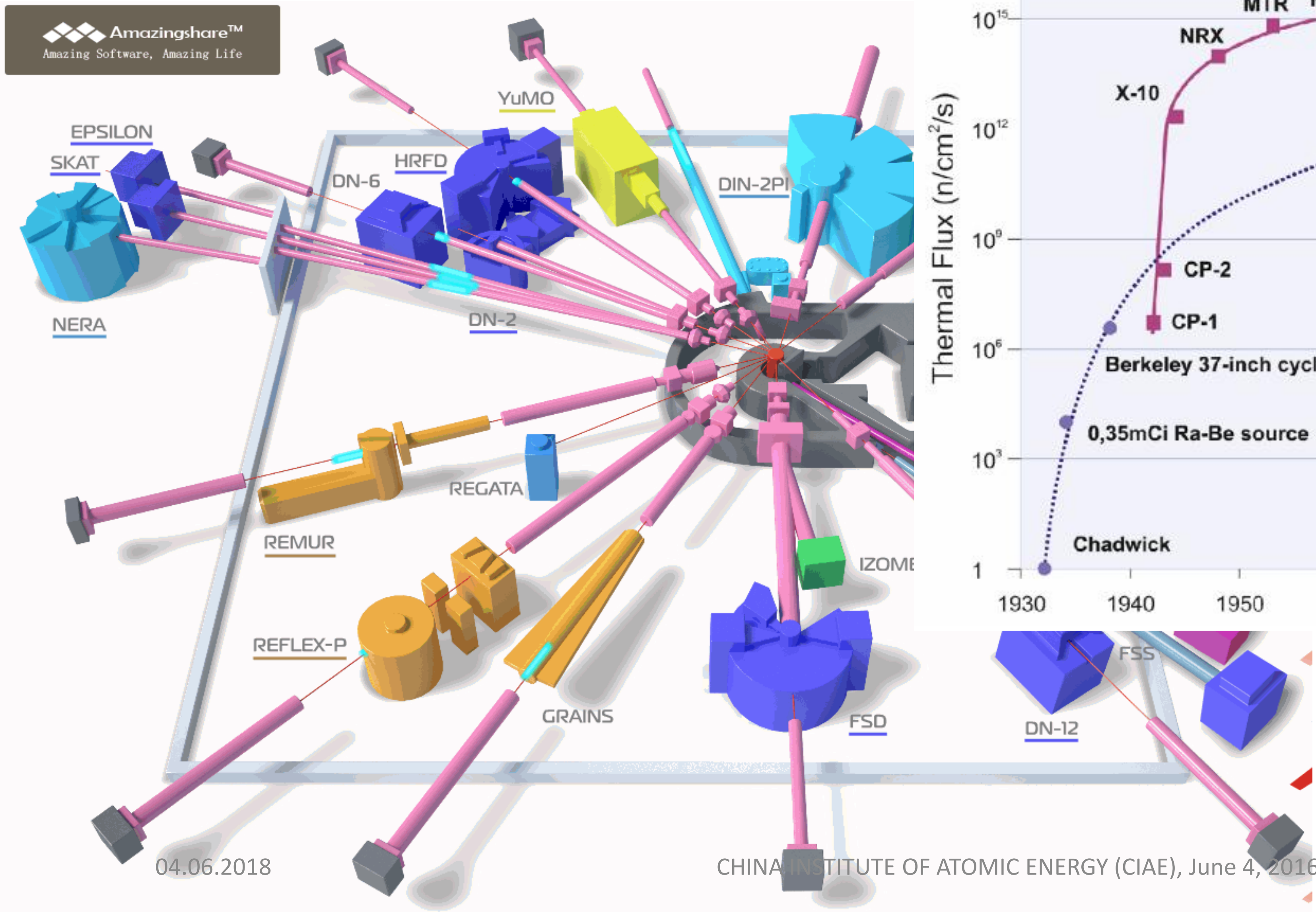
Brief History of IBR reactors cont.

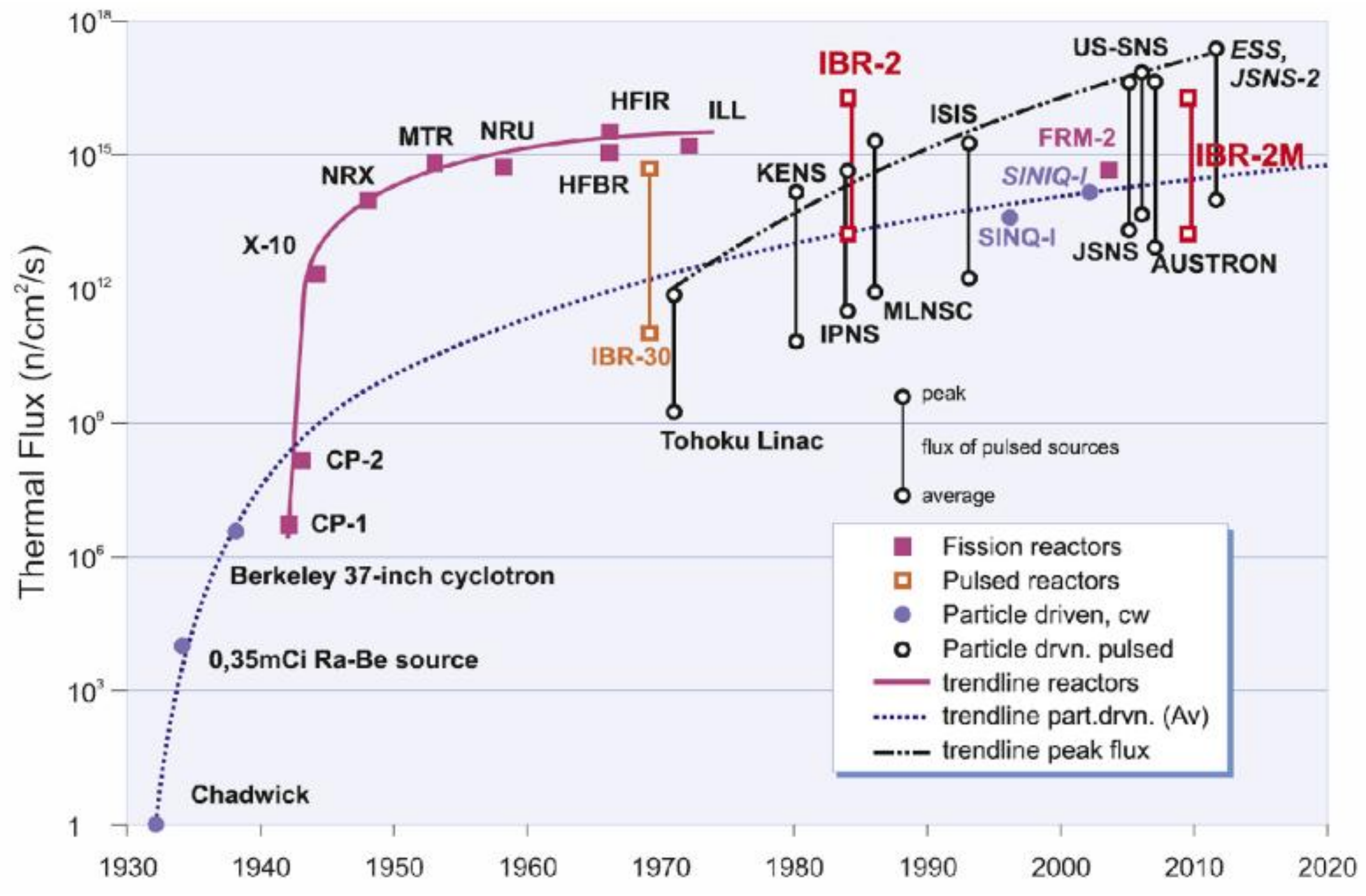
- Any reactor has a limited lifetime because of the development of radiation fatigue of structural materials. In the middle 90s the program of modernization of the IBR-2 was initiated to replace the most part of its units. In 2007, the reactor reached the service life limit on fuel burn up and fluence on the reactor vessel and was shut down for modernization and replacement of the primary reactor equipment. The main objectives of the modernization were to increase safety, reliability and experimental possibilities of the reactor for the next 25 years of operation. By 2010 the installation of new equipment was completed and followed by a successful power startup. Now we have reactor lifetime extended to mid of 2030^{th}.



Average power, MW	2
Burst power, MW	1850
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burnup, %	9
Pulse repetition rate, Hz	5; 10
Pulse half-width, μs: fast neutrons thermal neutrons	 240 320
Rotation rate, rev/min: main reflector auxiliary reflector	 600 300
MMR and AMR material	nickel + steel
MR service life, hours	55000
Background, %	7.5
Thermal neutron flux density from the surface of the moderator**: - time average - burst maximum	 ~10^{13} n/cm²·s ~10^{16} n/cm²·s

* At the mean power 2 MW
** More precise data on the thermal neutron flux density after the modernization will be available when the reactor operates at full power.

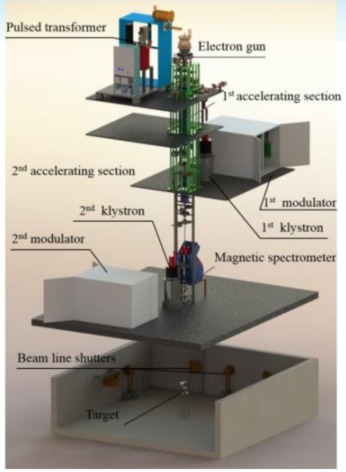

Amazingshare™
Amazing Software, Amazing Life
YuMO
EPSILON
SKAT
HRFD
DN-6
DIN-2PI
NERA
DN-2
REGATA
REMUR
IZOMI
REFLEX-P
GRAINS
FSD
DN-12
FSS

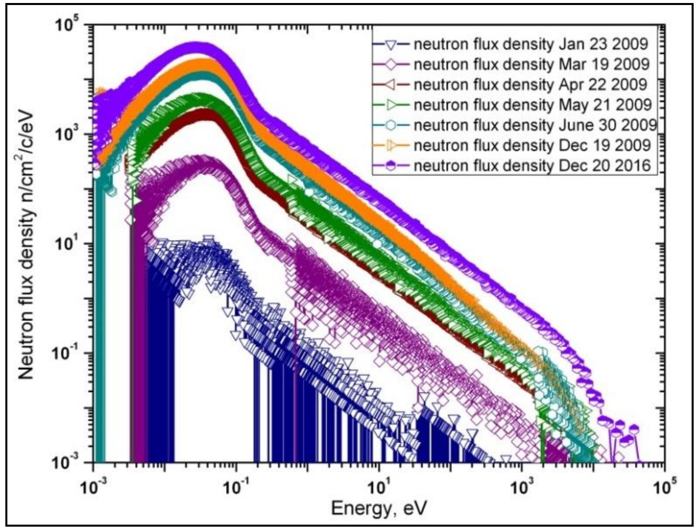

Thermal Flux (n/cm²/s)
1
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Chadwick
0,35mCi Ra-Be source
Berkeley 37-inch cyclotron
CP-1
CP-2
X-10
NRX
MTR
NRU
HFIR
HFBR
ILL
IBR-30
Tohoku Linac
KENS
IBR-2
IPNS
MLNSC
ISIS
FRM-2
SINQ-I
SINQ-I
US-SNS
JSNS
AUSTRON
ESS, JSNS-2
IBR-2M
peak
flux of pulsed sources
average
Fission reactors
Pulsed reactors
Particle driven, cw
Particle drvn. pulsed
trendline reactors
trendline part.drvn. (Av)
trendline peak flux

IREN

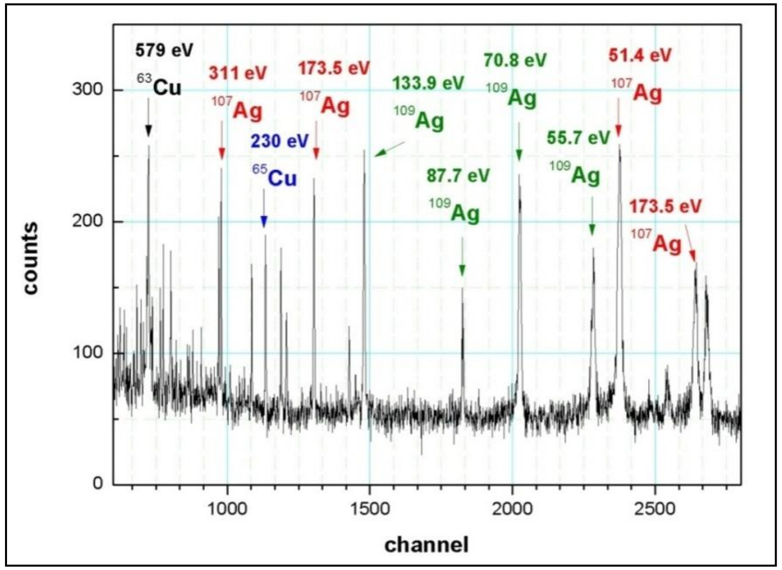
Neutron Resonance Capture Analysis of the archeological samples

Scheme of a new configuration of the accelerator





Spectra of neutron flux density from IREN obtained during the development of the facility



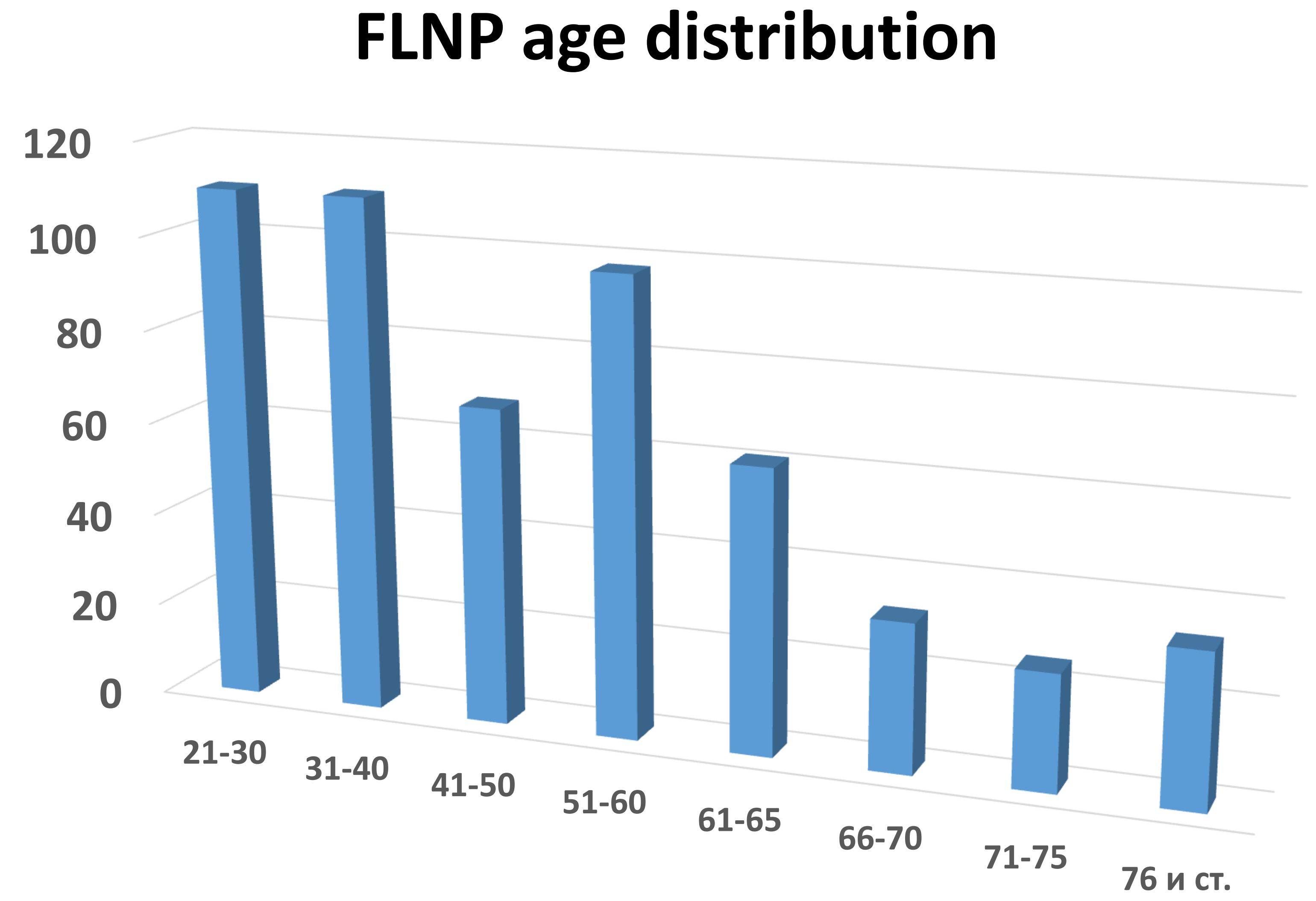
TOF spectrum, obtained from measurement with ancient coins from the Phanagoria's treasure

Personnel & Finances

Frank Laboratory of Neutron Physics

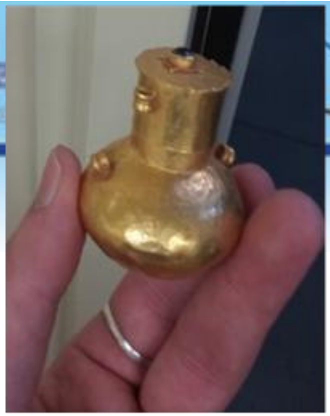
- 556 staff personnel, 111 from non-Russia, average age 47 years;
- 24.362 M$ - 2018 annual budget, 45% - for the research;
- Two scientific directions:
  - Neutron nuclear physics;
  - Condensed matter physics;
- Methodic;
- Basic facilities:
  - IBR-2M;
  - IREN;
- About 250 papers published annually;

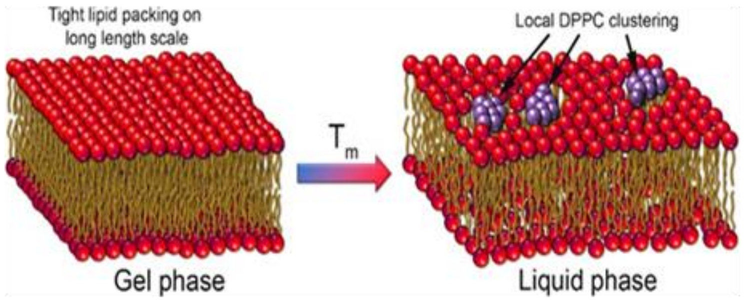
Staff personnel, age

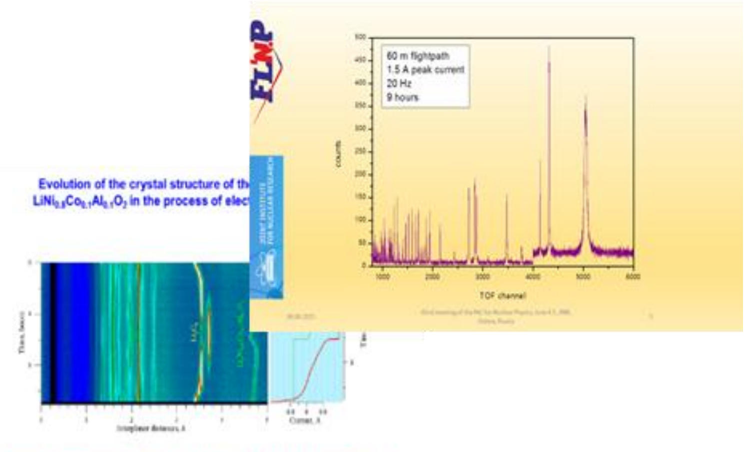


Condensed matter physics

- Physics and Chemistry of Novel Functional Materials;
- Physics of Nanosystems and Nanoscale Phenomena;
- Physics and Chemistry of Complex Liquids and Polymers;
- Molecular Biology and Pharmacology;
- Materials and Engineering Sciences;
- Neutron Radiography and Tomography;





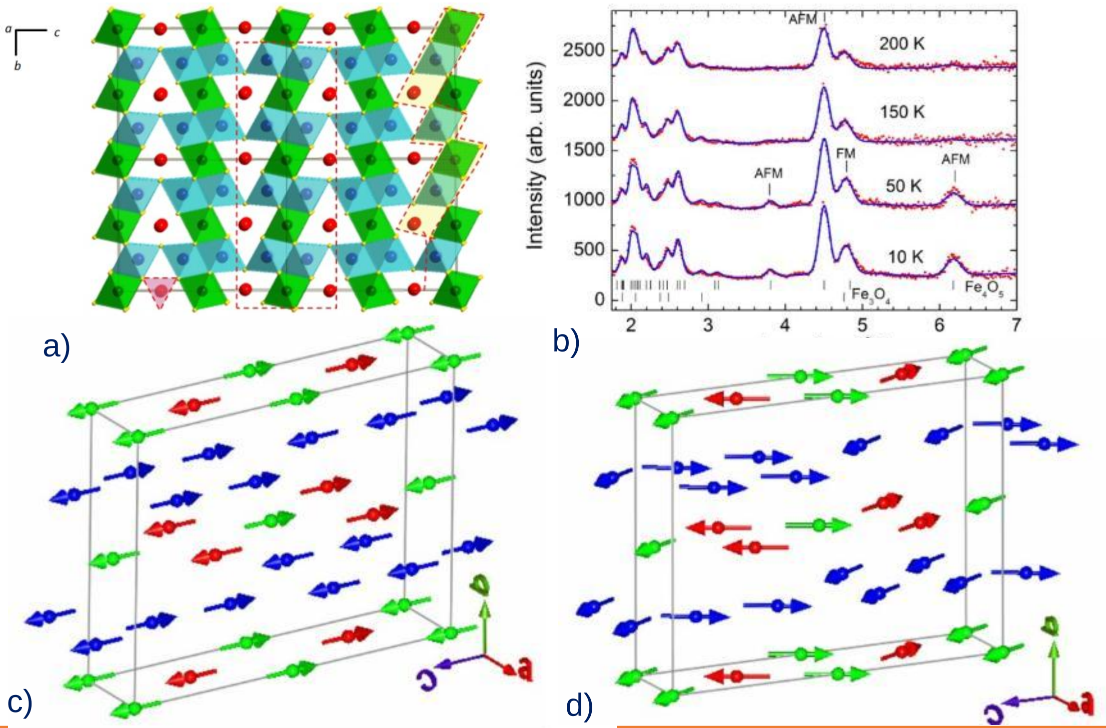


Neutron diffraction patterns of $LiNi_{0.8}Co_{0.1}Al_{0.1}O_2$ obtained in operando regime. The charging-discharging curve of the reloaded electrical current source during the experiment is shown on the right.

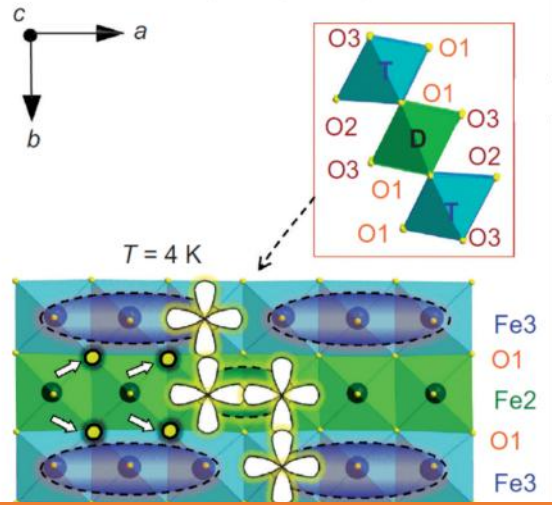
Novel type of the charge ordering state in iron oxide Fe_4O_5 involving competing dimer and trimer formation

Iron oxides:
- important role in the formation of magnetic and other physical properties of the Earth,
- find a wide range of technological applications

Previously known: Fe_3O_4, Fe_2O_3, FeO



Crystal structure of Fe_4O_5 (a), neutron diffraction patterns, measured at different temperatures and processed by the Rietveld method (b), magnetic structures at *T* = 150 K (c), and *T* = 10 K (d).



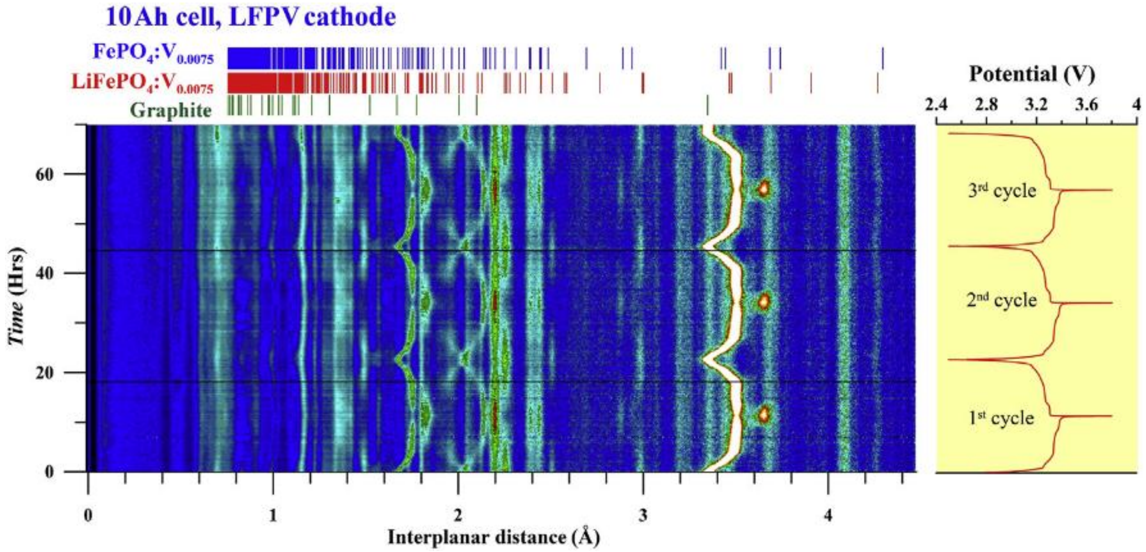
Formation mechanism of the dimeric and trimeric states

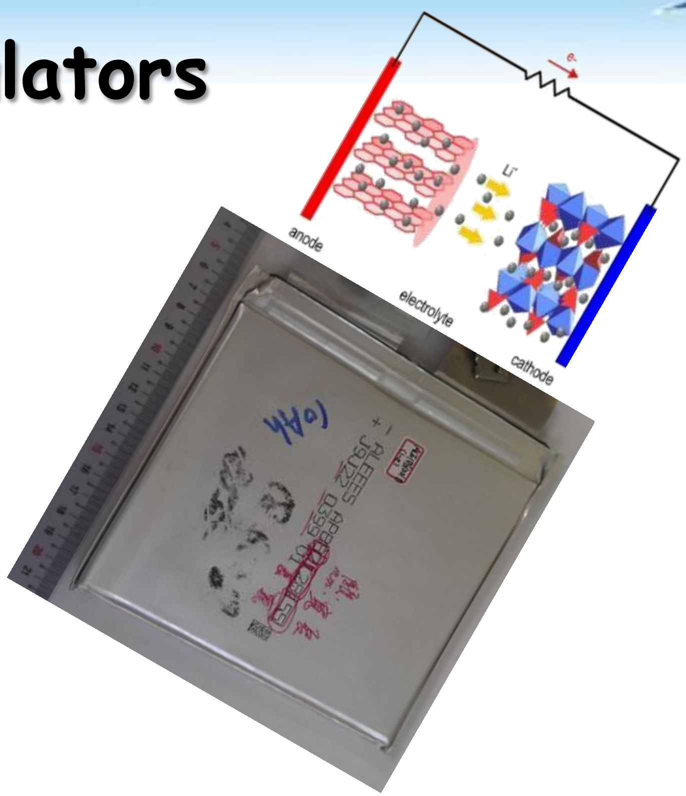
- a new iron oxide, Fe_4O_5, was synthesized under the combined effect of high pressures and temperatures;
- new type of charge-ordering state was revealed.

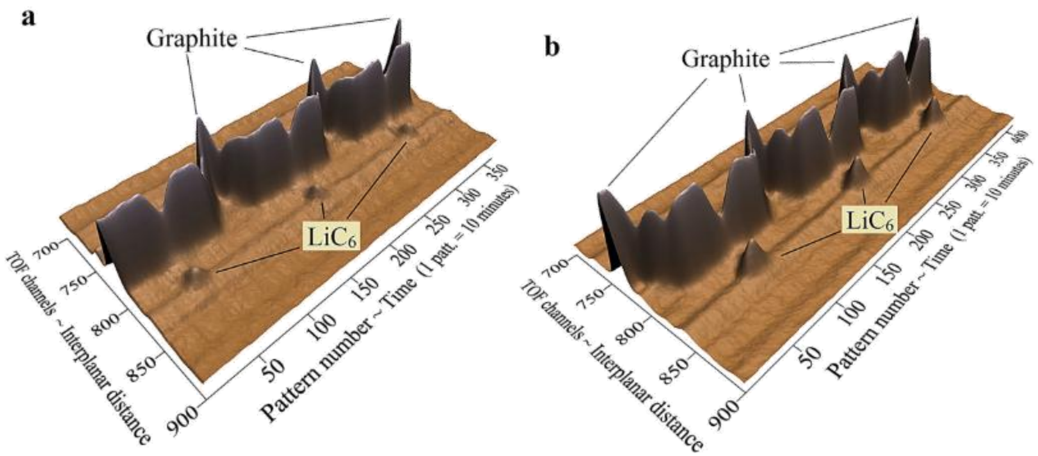
S.V. Ovsyannikov,.., D.P. Kozlenko, et al., Nature Chemistry (2016)

Impact Factor: 27.893

Diffraction Studies of Li-Based Accumulators







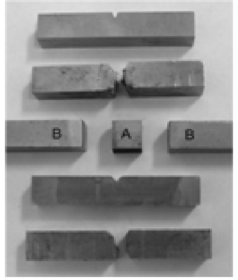
Real-time monitoring of transition processes during charge-discharge cycles revealed 10% increase of LiC_6 phase in anode when cathode was doped with vanadium oxide, which correlates with better electrochemical properties.

I.A.Bobrikov et al., J. Power Sources (2014)

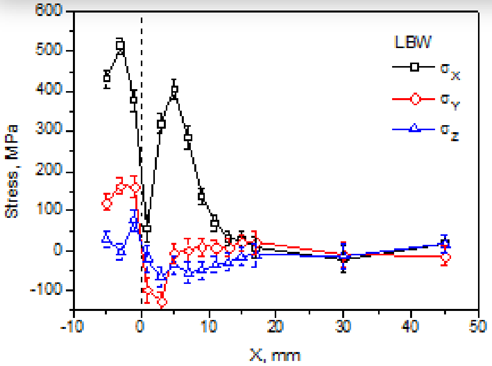
Residual stress in surveillance Charpy specimens, recovered by electron (EBW) and laser (LBW) beam welding

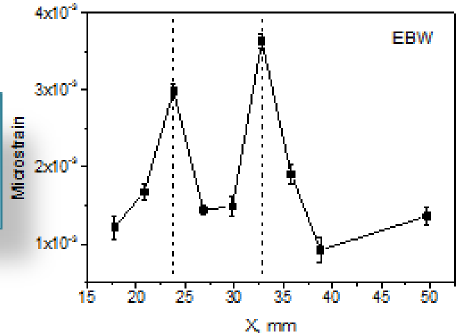
Collaboration: Institute of Electronics of BAS(Sofia, Bulgaria) FLNP JINR (Dubna, Russia), NECSA Ltd. (Pretoria, South Africa)

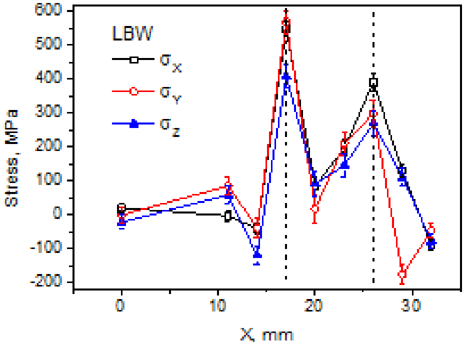
by Gizo Bokuchava (FLNP JINR) with colleagues: submitted to ***Nuclear Engineering and Design***

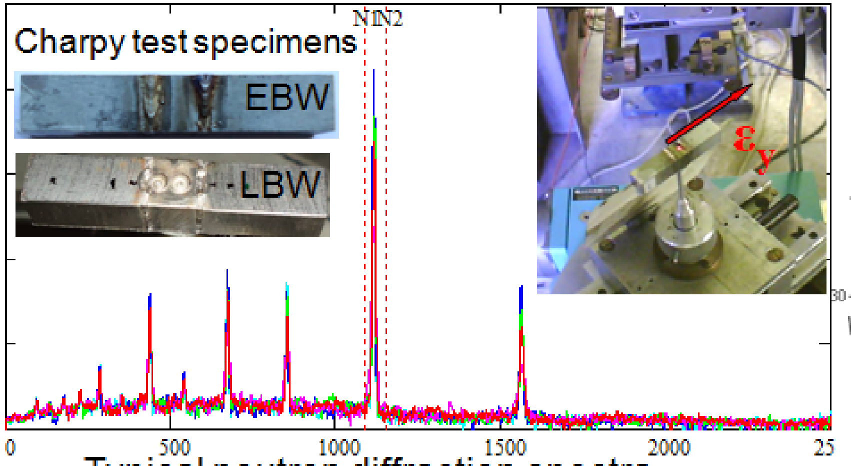


Electron beam welding

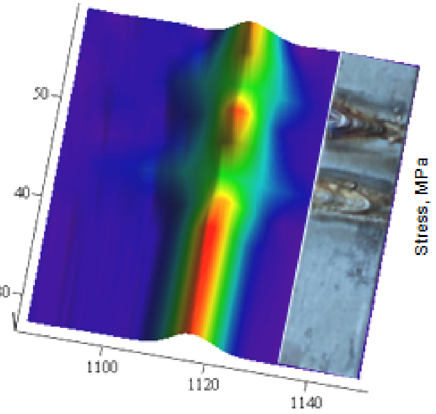


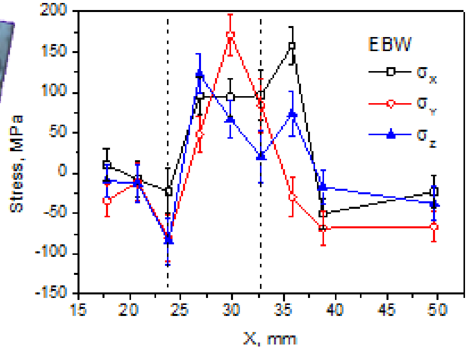






Typical neutron diffraction spectra



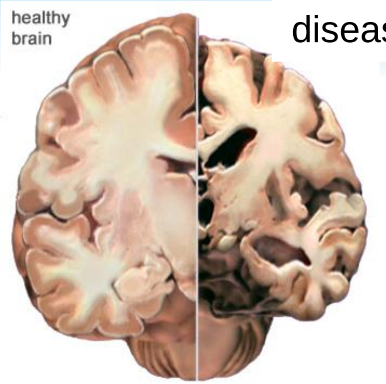


Neutron diffraction (211) reflection broadening at weld seam locations during x-scan

mie

bulgare des sciences (2014).

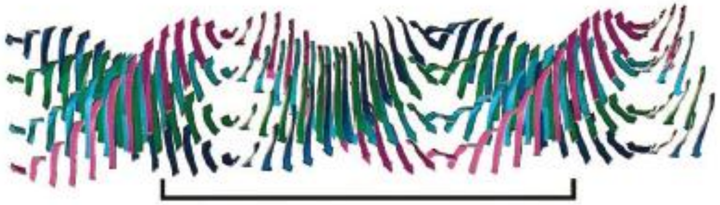
Helical structure of fibril-type amyloidal aggregates



Motivation

Formation of amyloidal aggregates are associated with many aged-related illnesses (e.g. Alzheimer diseases)

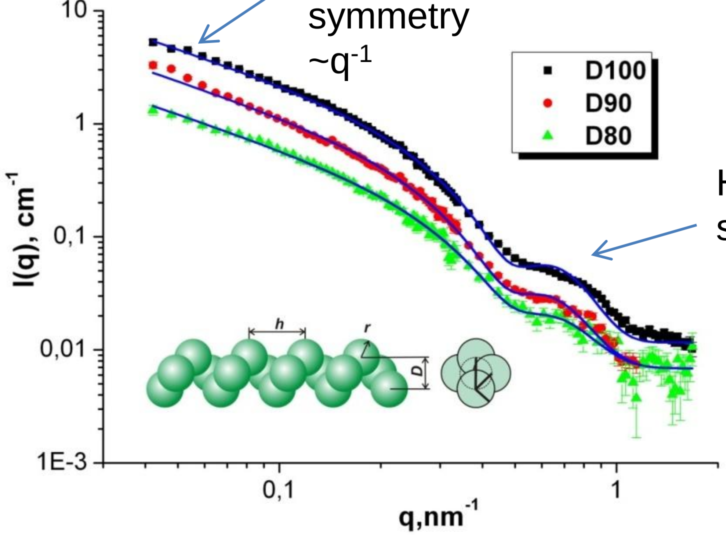
Model of amyloid filament structure from XRD



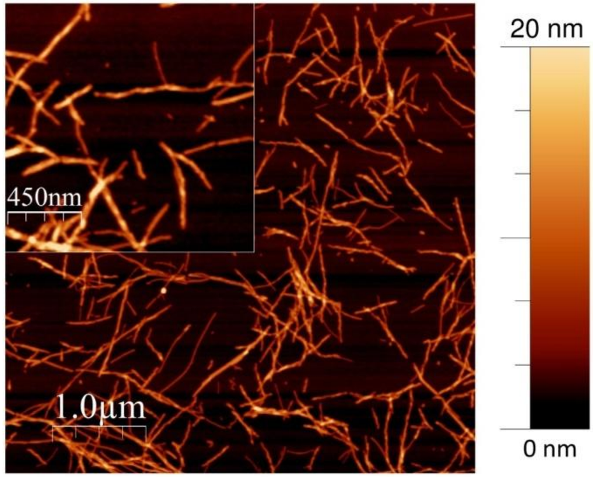
11.5 nm, 24 β-strands

Structure analysis of model lysozyme (hen egg) amyloidal solutions

SANS

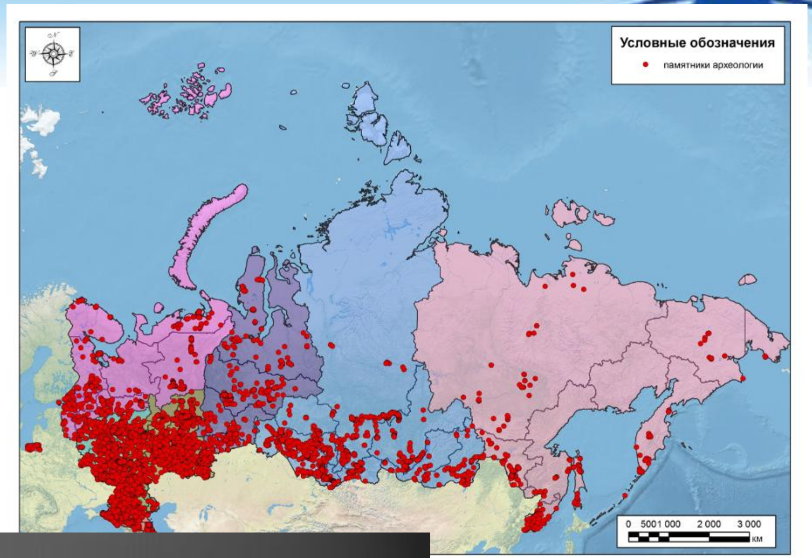


AFM

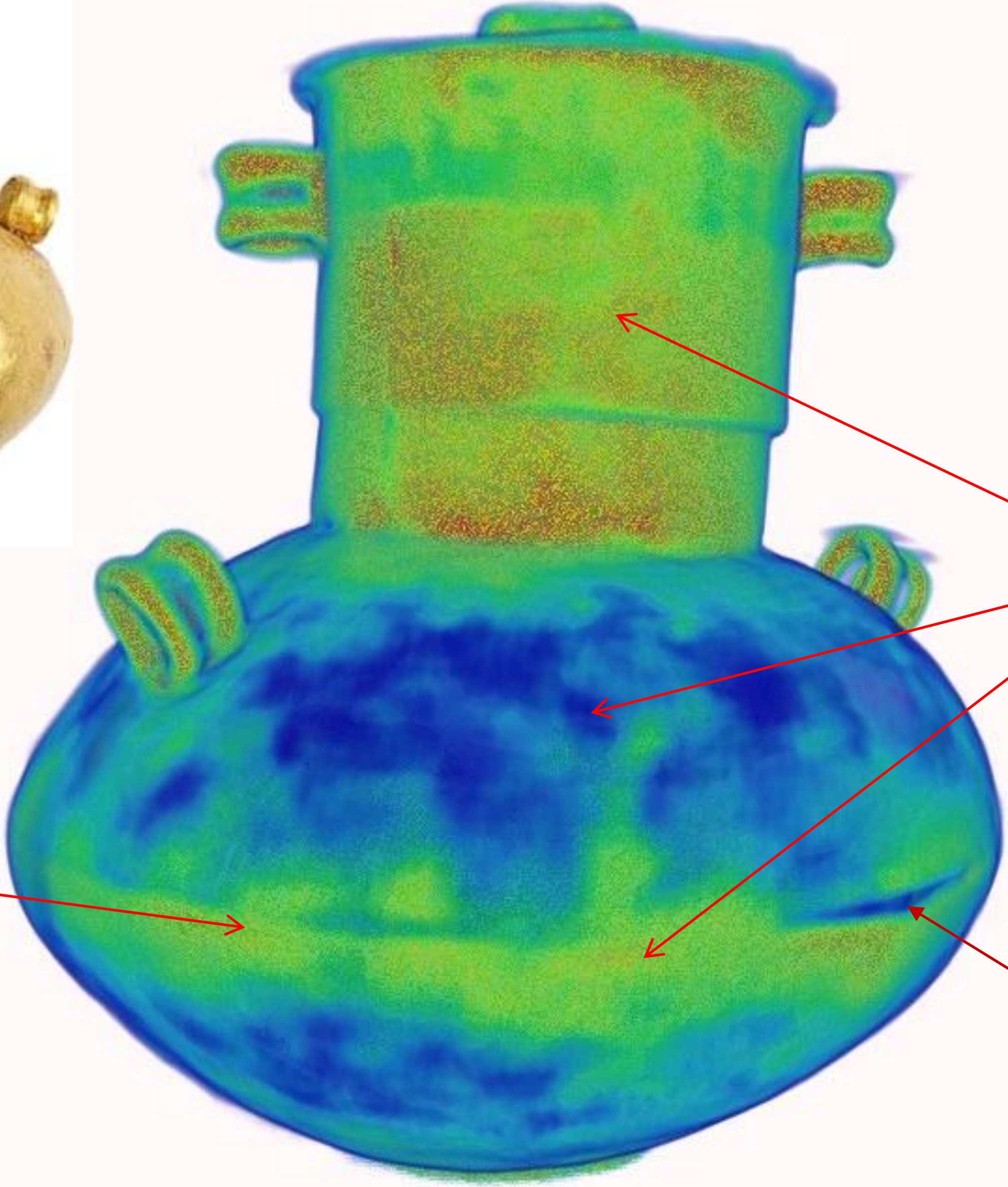


M.V.Avdeev, et al, *J. Appl. Cryst.* (2013)

Neutron radiography and tomography at the Beam #14 are used to study archeological objects, especially metallic artifacts



S. Kichanov

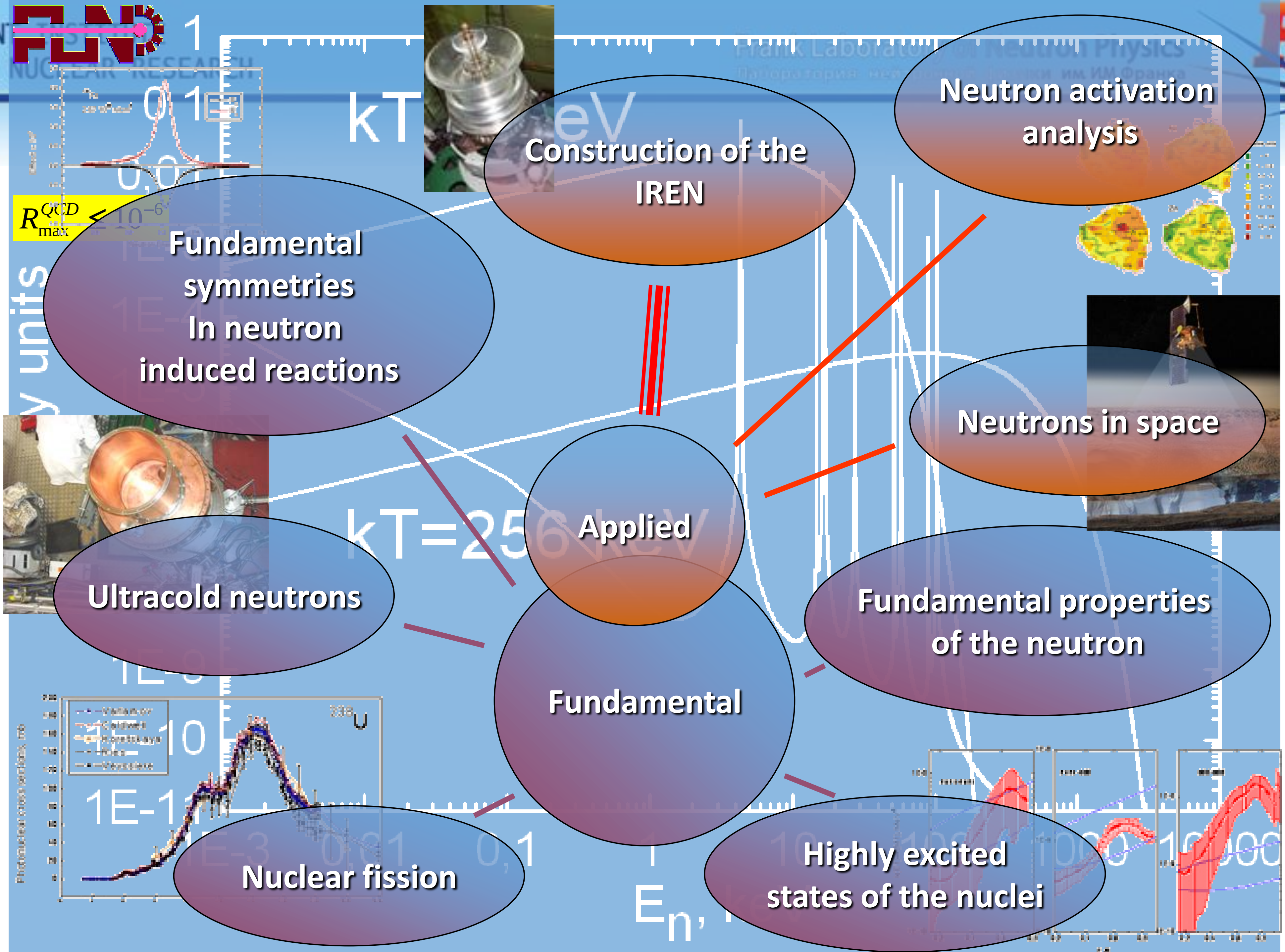


Areas with other composition of gold

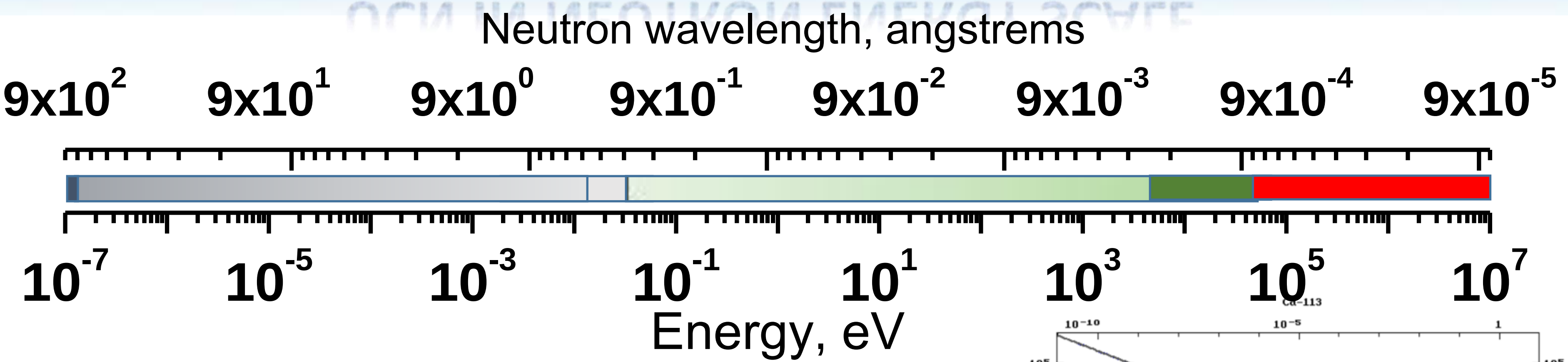
traces of concealment of a joint

Site of dispersed joint

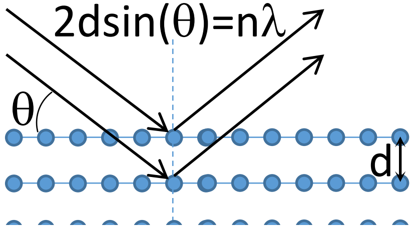
Nuclear Physics

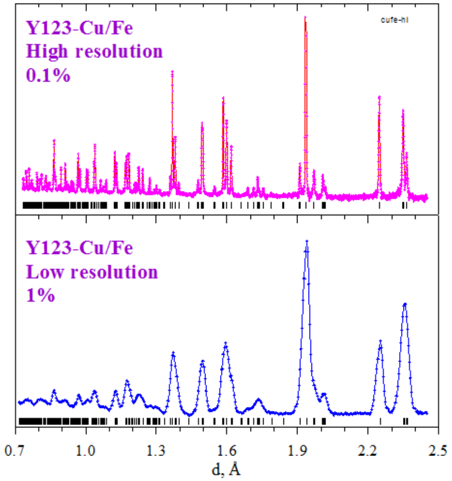


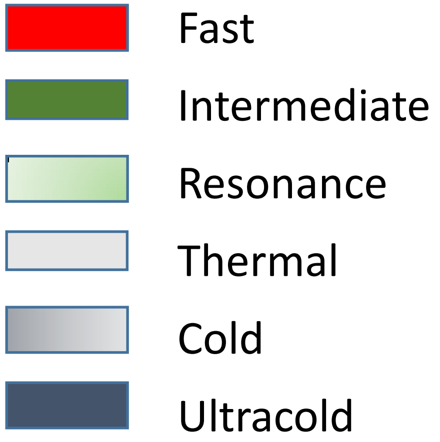
UCN IN NEUTRON ENERGY SCALE

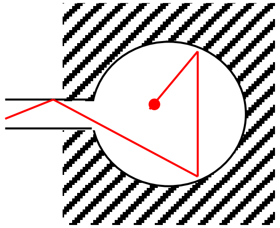


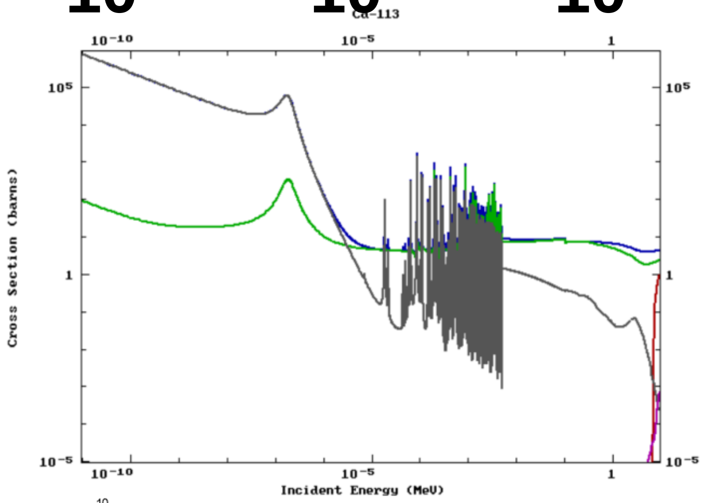
Bragg's low:
$2d\sin(\theta)=n\lambda$

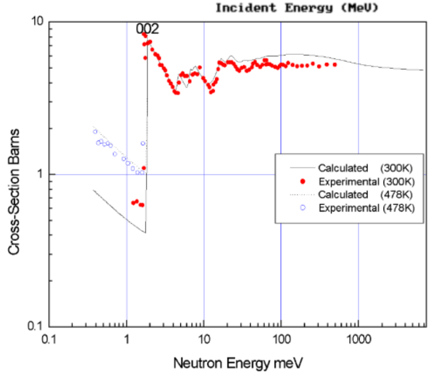




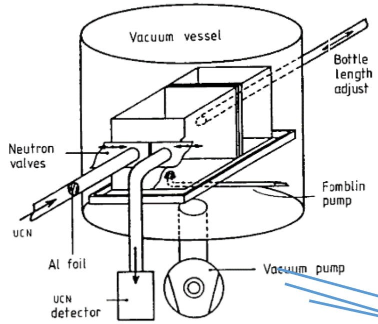


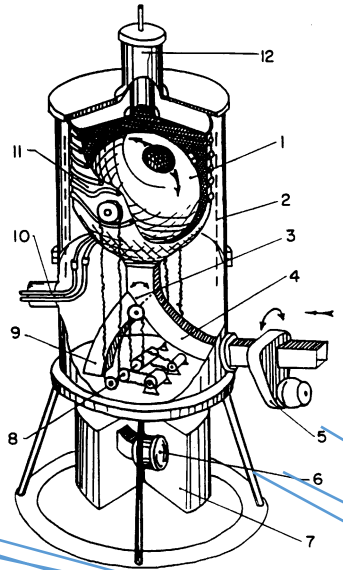




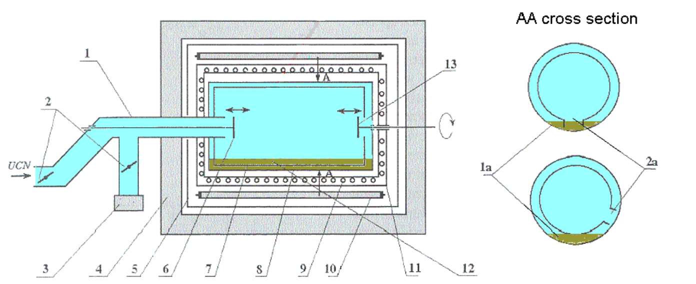


NEUTRON LIFE TIME MEASUREMENTS

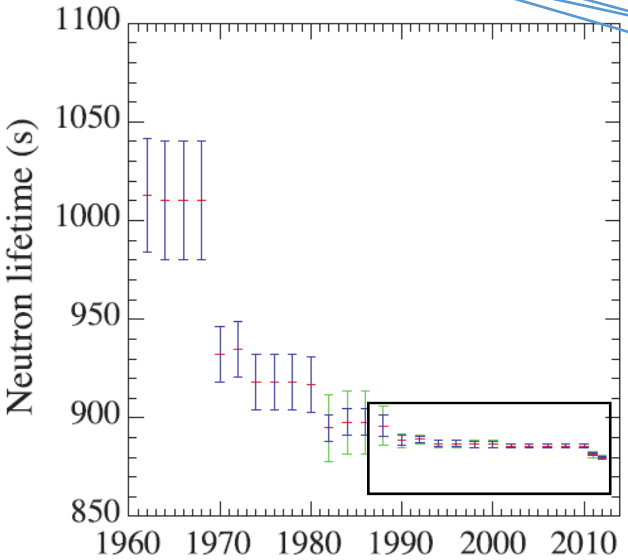


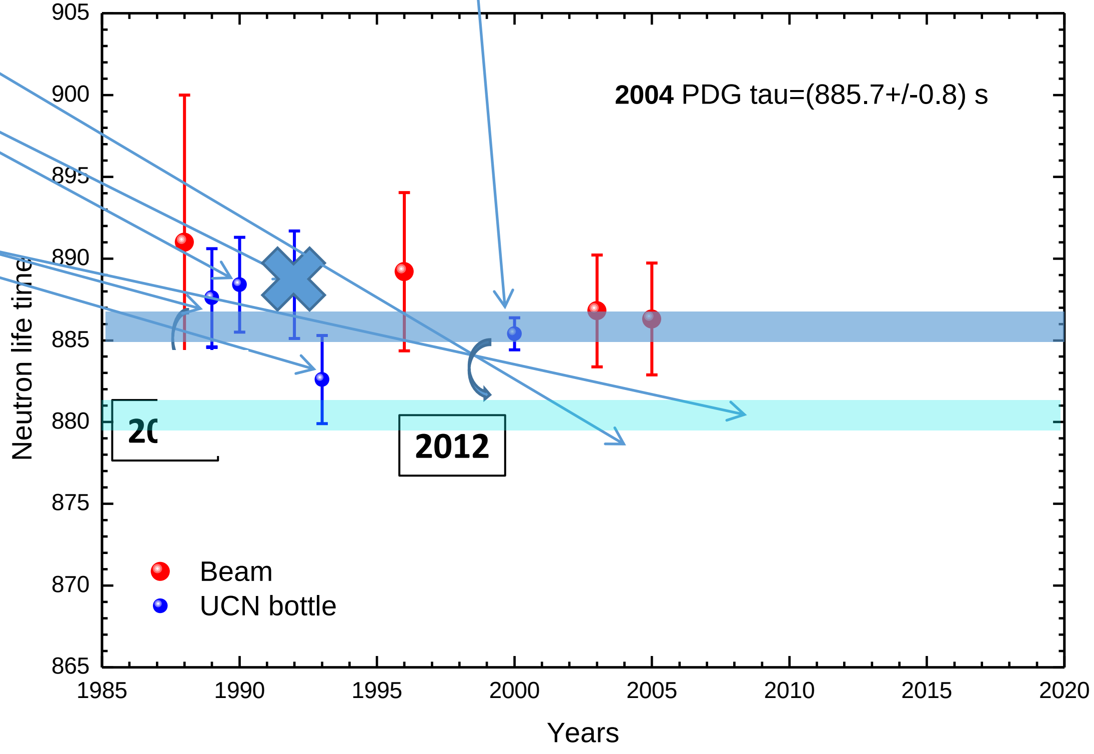


Layout of the experimental set-up



(1) UCN guide; (2) shutters; (3) UCN detector; (4) polyethylene shielding; (5) cadmium housing; (6) entrance shutter of the inner vessel; (7) inner storage vessel; (8) outer storage vessel; (9) cooling coil; (10) thermal neutron detector; (11) vacuum housing; (12) oil puddle; (13) entrance shutter of the annular vessel; (1a) oil puddle; (2a) slit.





Ultracold neutrons and interaction of waves with moving matt

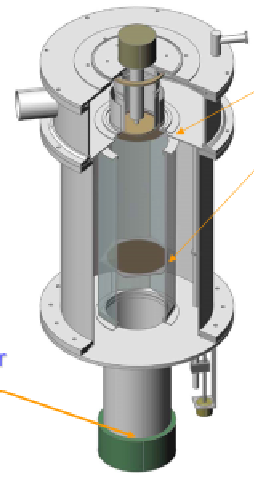
A.I. Frank

FLNP of JINR, Dubna, Russia
frank@nf.jinr.ru

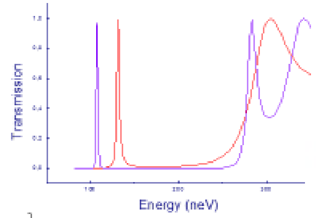
ISINN 25 , 22-26 May, 2017

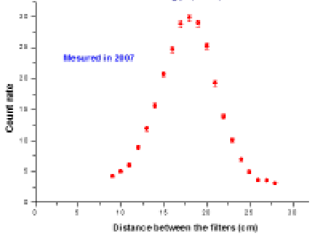
FLNP

UCN spectrometer with Fabry-Perot interferometers



mg=1.02 neV



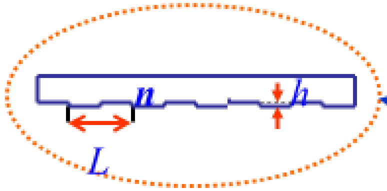


FLNP

FLNP

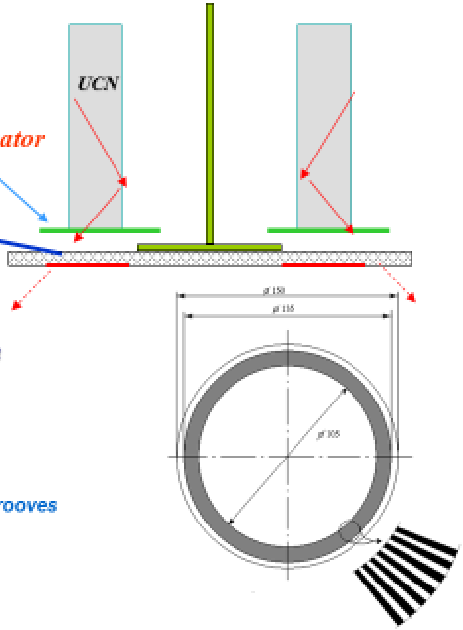
Experimental realization - rotating grating

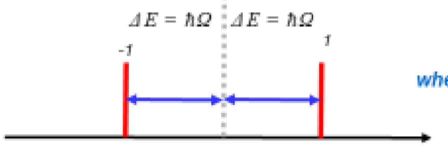
Phase π -grating



$$\Delta\varphi = k(n-1)h = \pi$$

h = 0.14 mkm





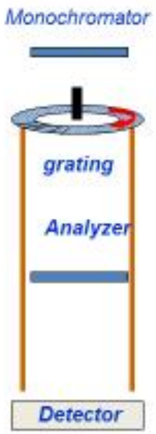
$$\Omega = 2\pi f N$$

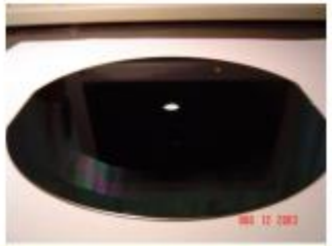
where N is number of grooves

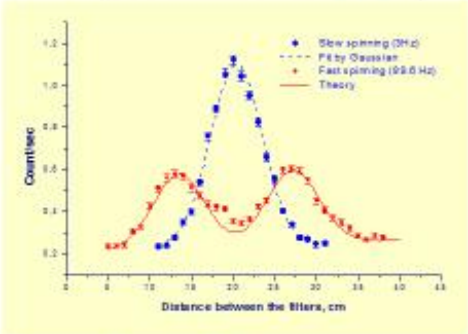
FLNP

First experimental results

Angular period of grating 0.3325mrad (20μ at the middle diameter)

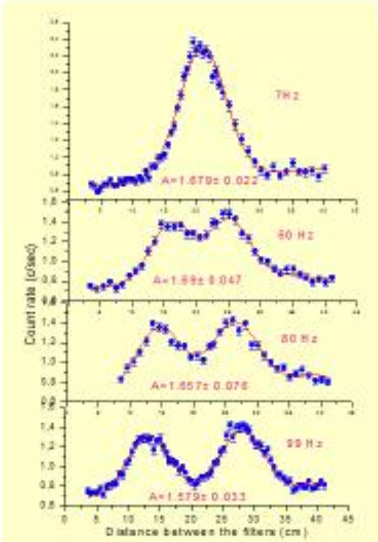






Splitting of the spectrum

A.I.Frank et al. ILL annual report 2001
Phys.Lett.A 311 (2003) 6



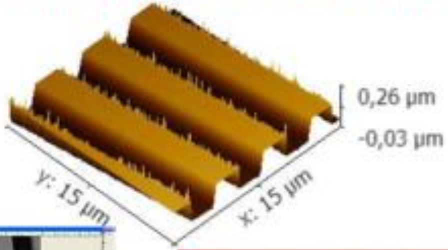
$|a_1|^2_{th} = 0.405$ $|a_1|^2_{exp} = 0.383(8)$

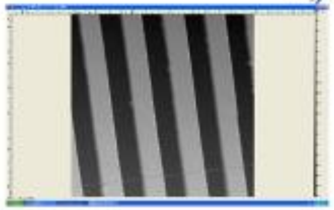
A.I.Frank et al. Jetp Lett, 81 (2005) 427

TOF Fourier spectrometer (2014-2016

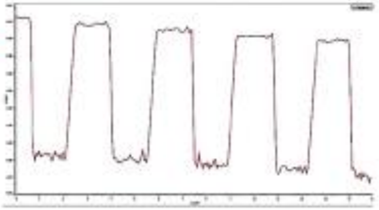
G.V. Kulin, A.I. Frank, S.V. Goryunov et al., NIM A, 869 (2016) 67

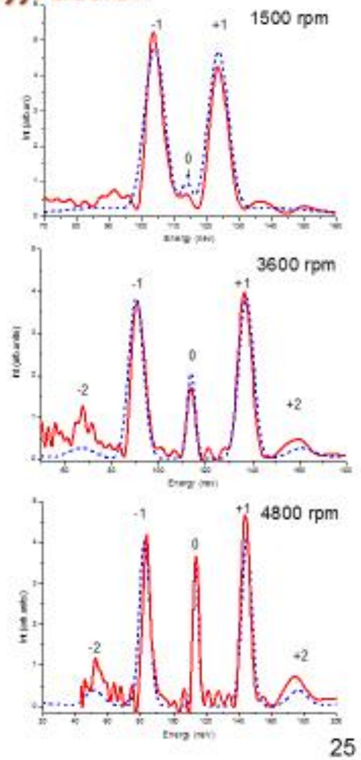
TOF Fourier spectrometry and comparing obtained spectra with dynamic theory of neutron diffraction





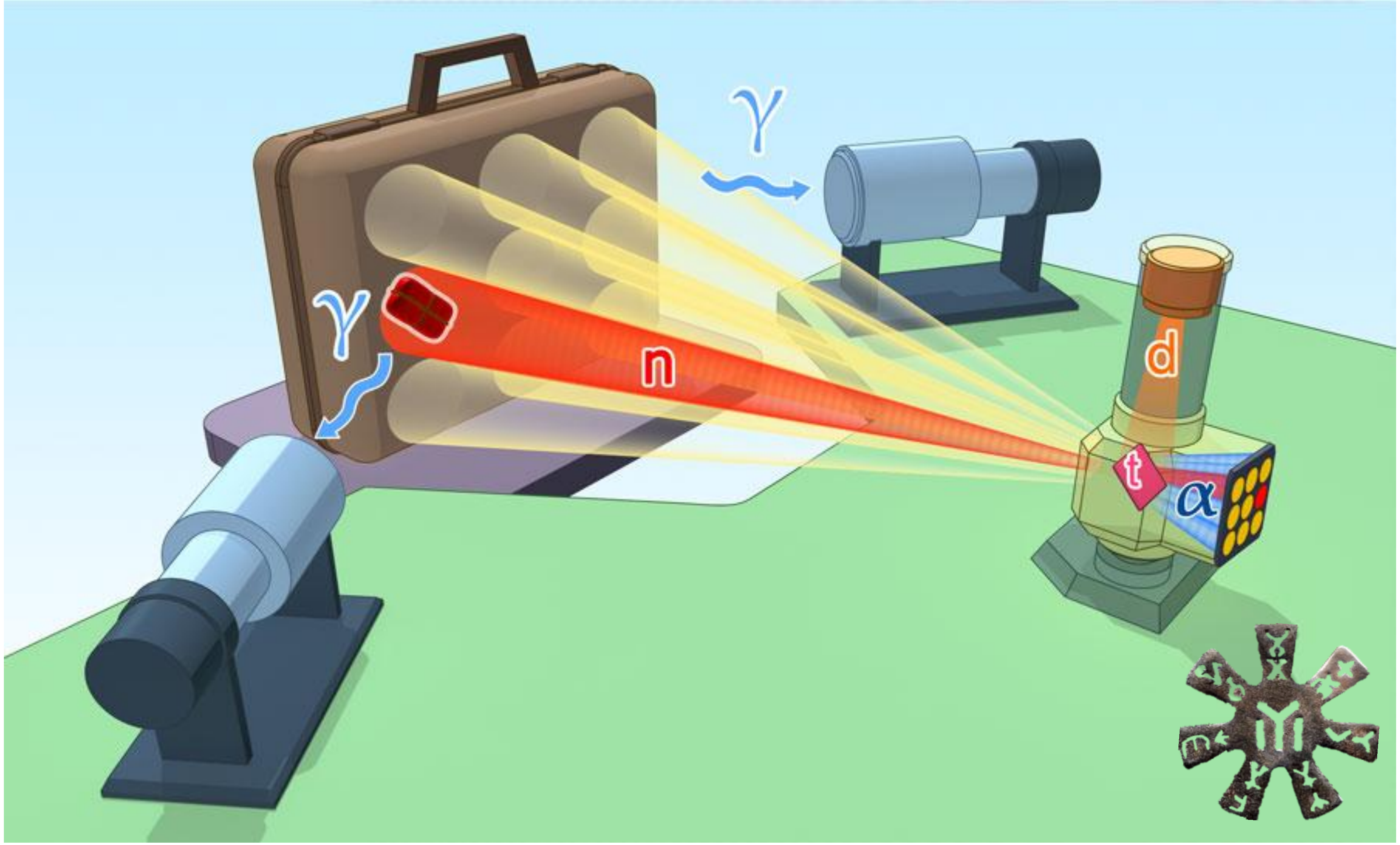
Angular period of grating
0.0665mrad
(4µ at the middle diameter)



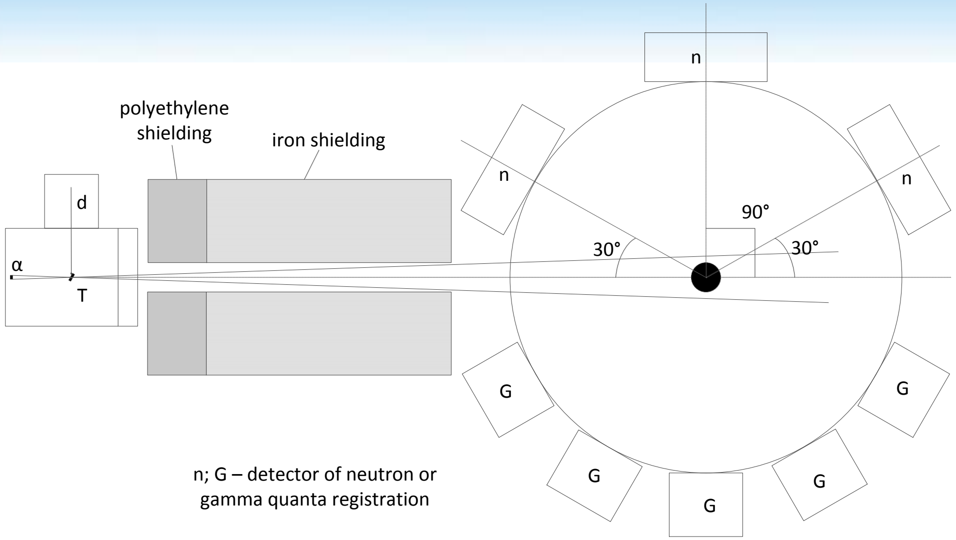


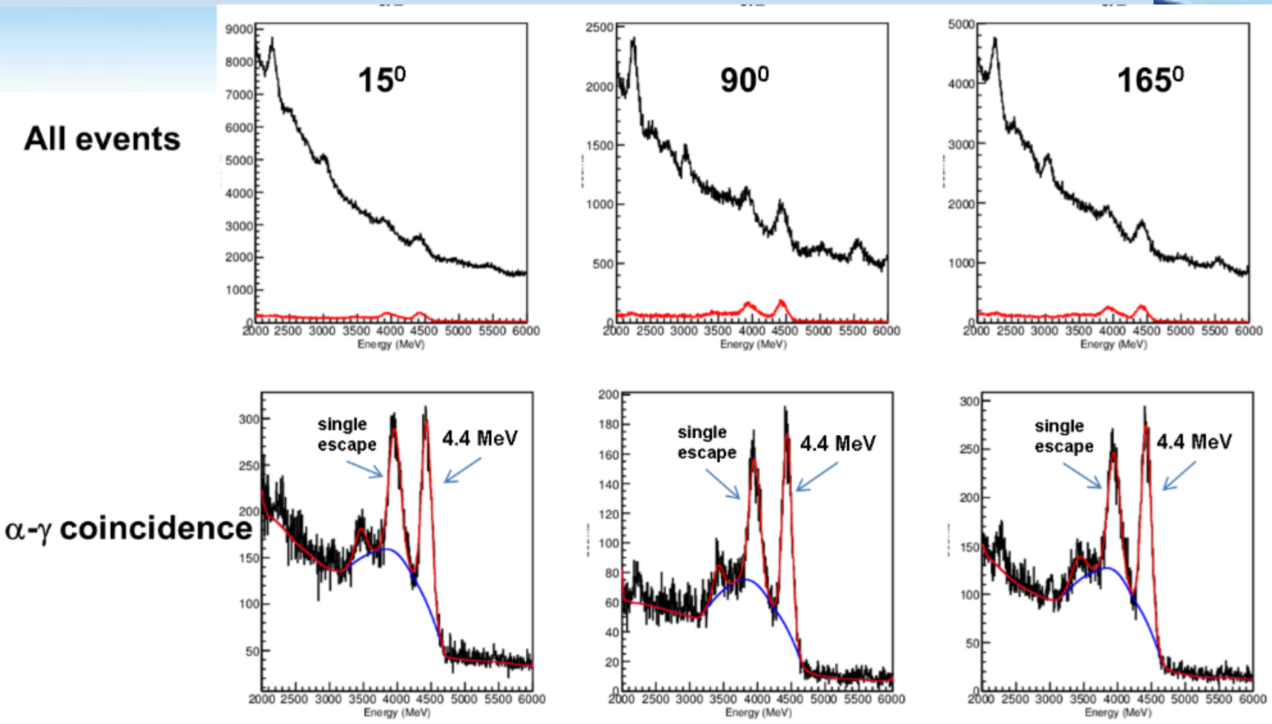
V.A. Bushuev, A.I. Frank, G.V. Kulin. JETP , 122, 32 (2016)
G.V. Kulin, A.I. Frank, S.V. Goryunov, et al. Phys. Rev.A 93033606, (2016)

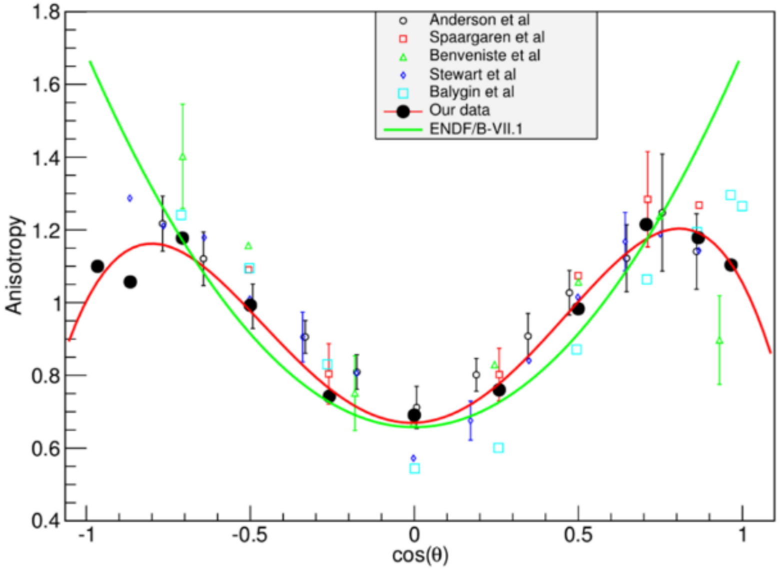
Experiments with tagged neutrons



Experiments with tagged neutrons







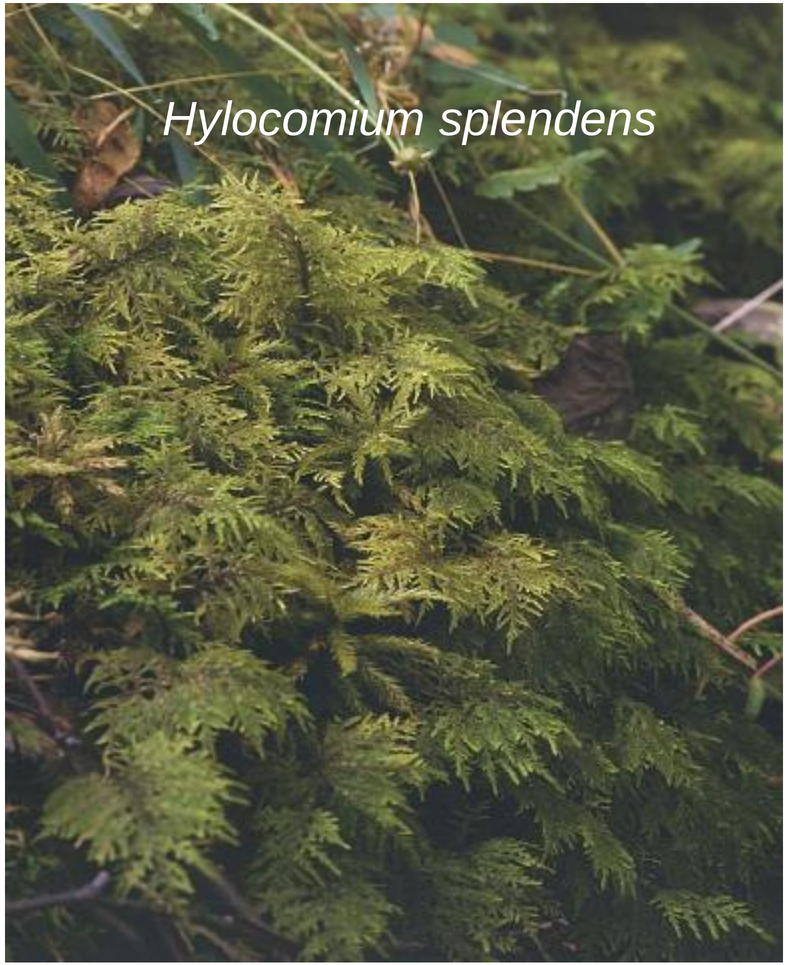
$$w \sim 1 + a \cdot \cos^2 \theta - b \cdot \cos^4 \theta$$

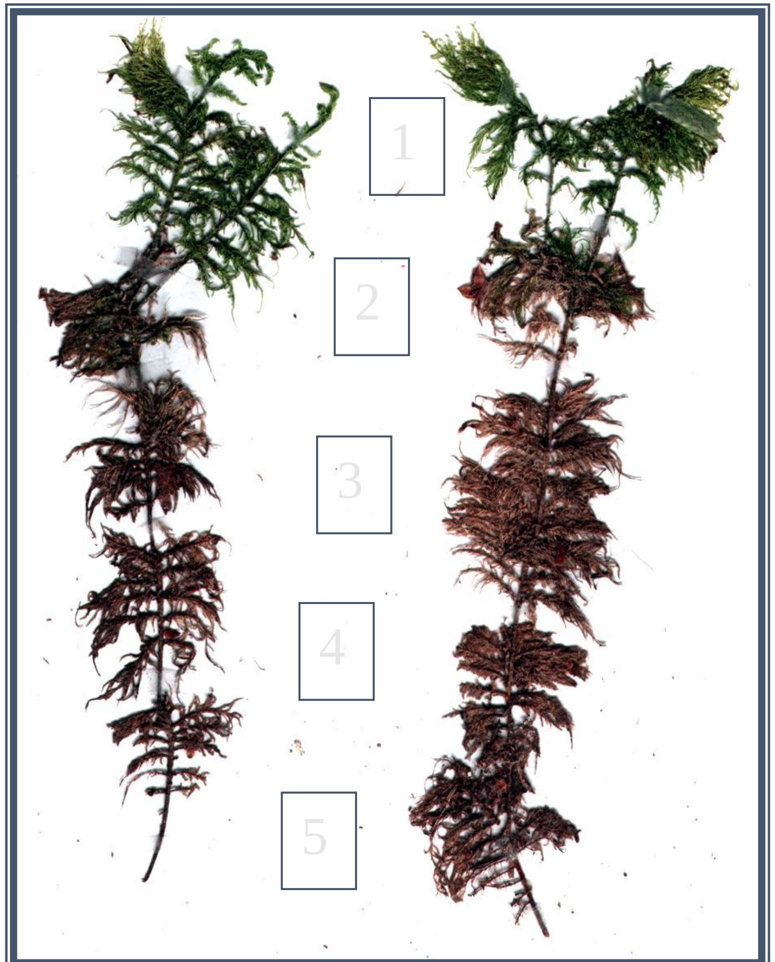
a=1.58±0.04

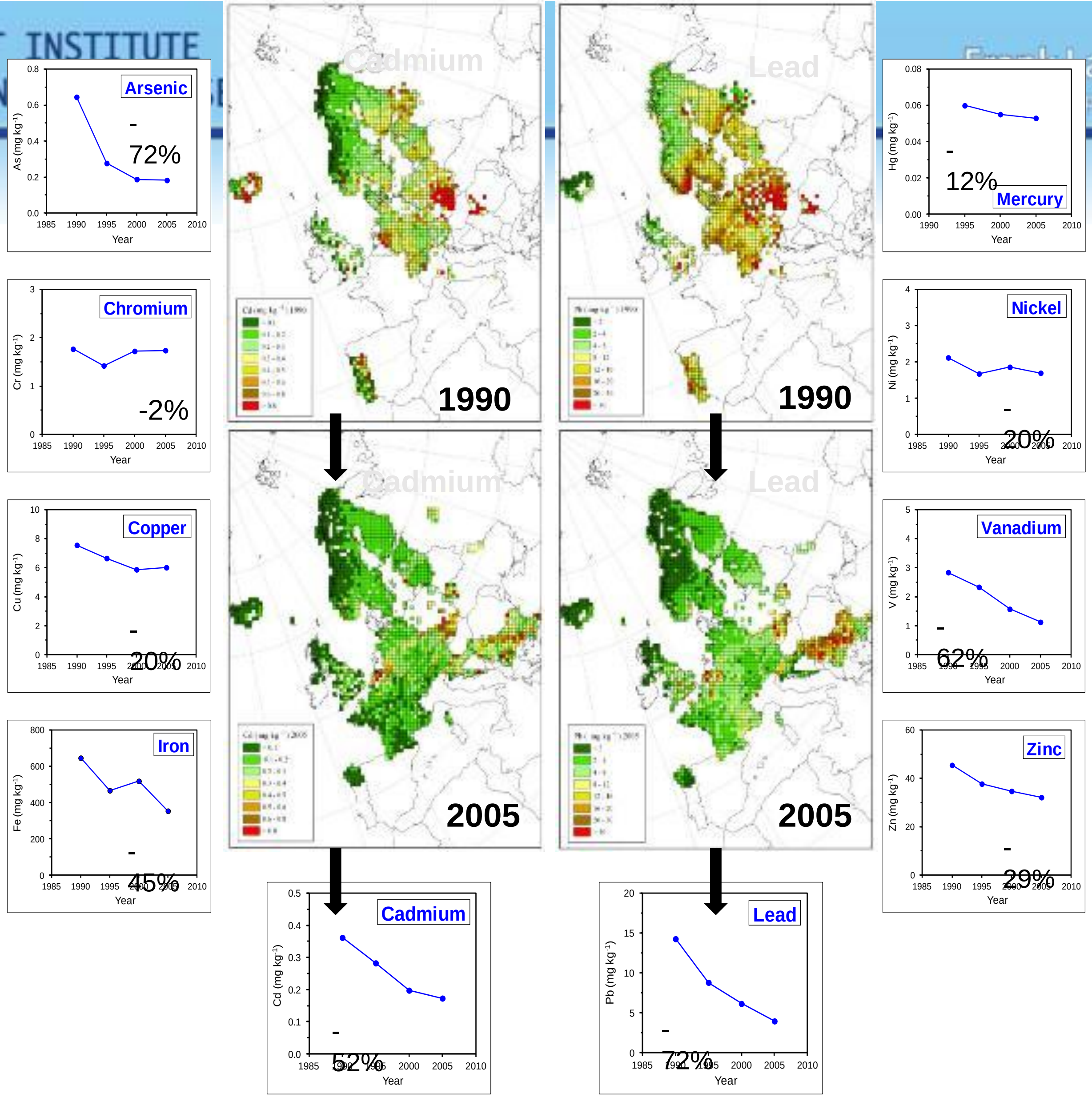
b=1.22 ±0.05

1993: Biomonitoring…

M.V. Frontasyeva, V.M. Nazarov and E. Steinnes. **Mosses as monitors of heavy metal deposition: Comparison of different multi-element analytical techniques.** In R.J. Allan and J.O. Nriagu, eds., *Heavy Metals in the Environment*, Vol.2, pp. 17-20. CEP Consultants, Edinburgh **1993**.







ICP Vegetation Programme Coordination Centre

Mosses provide a complementary method to assess **spatial patterns** and **temporal trends** of atmospheric heavy metal deposition:

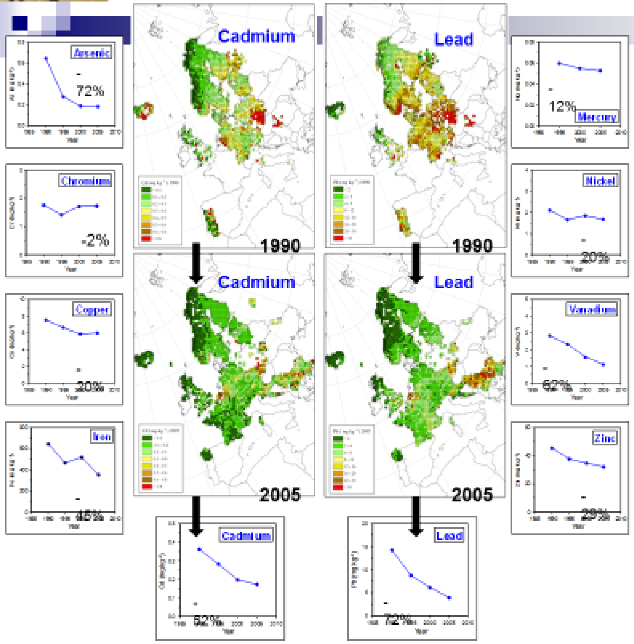
- Carpet forming mosses receive trace elements and nutrients mainly from the atmosphere.
- In recent years, the lowest concentrations of heavy metals in mosses were found generally in northern Europe and the highest concentrations in Belgium and eastern Europe .
- Europe-wide the concentration in mosses of **arsenic, cadmium, lead and vanadium has declined** the most between 1990 and 2010, with hardly any reduction being observed for **chromium and mercury.**
- Temporal trends were country-specific.
- Spatial patterns and temporal trends for cadmium and lead agree quite well with those modelled by the **European Monitoring and Evaluation Programme (EMEP)**.

Department of Neutron Activation Analysis & Applied Research
Division of Nuclear Physics
Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research

STATE-OF-THE-ART AND FUTURE PROSPECTS OF NEUTRON ACTIVATION ANALYSIS AT THE IBR-2 REACTOR OF THE JOINT I[...] RESEARCH IN DUBNA, RUSS[...]

Marina Frontasyeva, Sergey Pavlo[...]
marina@nf.jinr.ru

PAC, June 2018



Mosses provide a complementary method to assess spatial patterns and temporal trends of atmospheric heavy metal deposition:

- Carpet forming mosses obtain trace elements and nutrients directly from the atmosphere.
- In recent years, the lowest concentrations of heavy metals in mosses were found generally in northern Europe and the highest concentrations in Belgium and eastern Europe .
- Europe-wide the concentration in mosses of arsenic, cadmium, lead and vanadium has declined the most between 1990 and 2005, with hardly any reduction being observed for chromium and mercury.
- Temporal trends were country-specific.
- Spatial patterns and temporal trends for cadmium and lead agree quite well with those modelled by the European Monitoring and Evaluation Programme (EMEP).

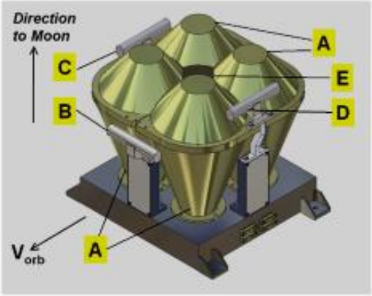
ICP Vegetation Programme Coordination Centre

wge wge wge

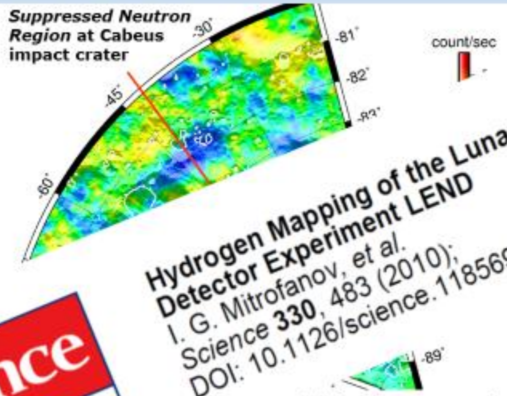
Frank Laboratory of Neutron Physics
Лаборатория нейтронной физики им. И.М. Франка
FLNP

Development of the neutron and gamma detectors for space crafts

- **Cooperation of two JINR Labs with Russian Space Research Institute since 1997;**
- **FLNP and LRB responsibility are: conceptual design, physical and numerical mo deling, physical calibrations;**

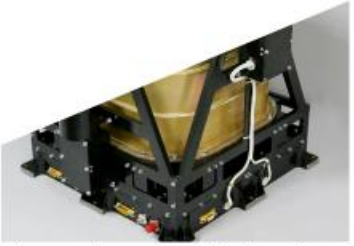


Lunar Exploration Neutron Detector (LEND) at LRO



Hydrogen Mapping of the Lunar South Pole Using the LRO ... Detector Experiment LEND
I. G. Mitrofanov, et al.
Science **330**, 483 (2010);
DOI: 10.1126/science.1185696

Science AAAS

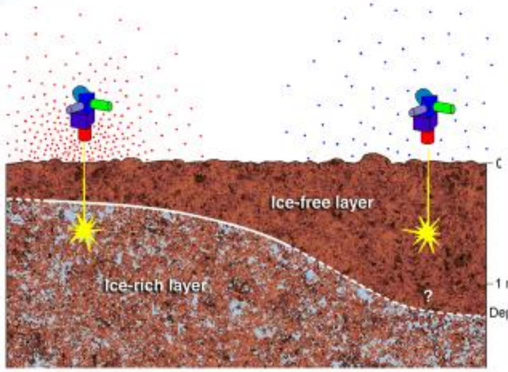


acc... ...ented for the segment of southern polar region with impact crater *Cabeus* (*left*) Hydr... ...tron Detector (*LEND*, *right*). Lower counting rate (*blue*) represents the enhancement of meas... ...er of the surface. Gray shadowing corresponds to the surface relief in accordance to *LOLA* missio... ...ent *Permanently Shadowed Regions* (PSR), as derived from the altimetry data of Japanese *Kaguya*

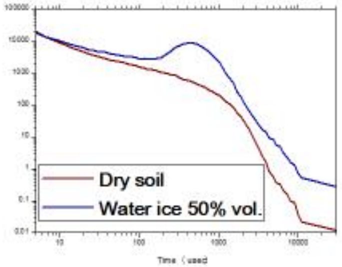
Acc... ...nary analysis of *LEND* data, *PSRs* are not consistent with detected *Suppressed Neutron Regions* (*SNRs*) on the Mo... content of Hydrogen. However, some *PSRs* are positioned inside *SNRs*, like one at the *Cabeus* crater, which is found to ... of the strongest signature of subsurface Hydrogen at the South pole.

Instru... ...nt *LEND* was developed in the Institute for Space Research (Moscow), as the contribution of Federal Space Agency of Russia to the NASA's *Lunar Reconnaissance Orbiter* mission.

Dynamic Albedo of Neutrons (DAN) Russian detector onboard of the Curiosity Rover

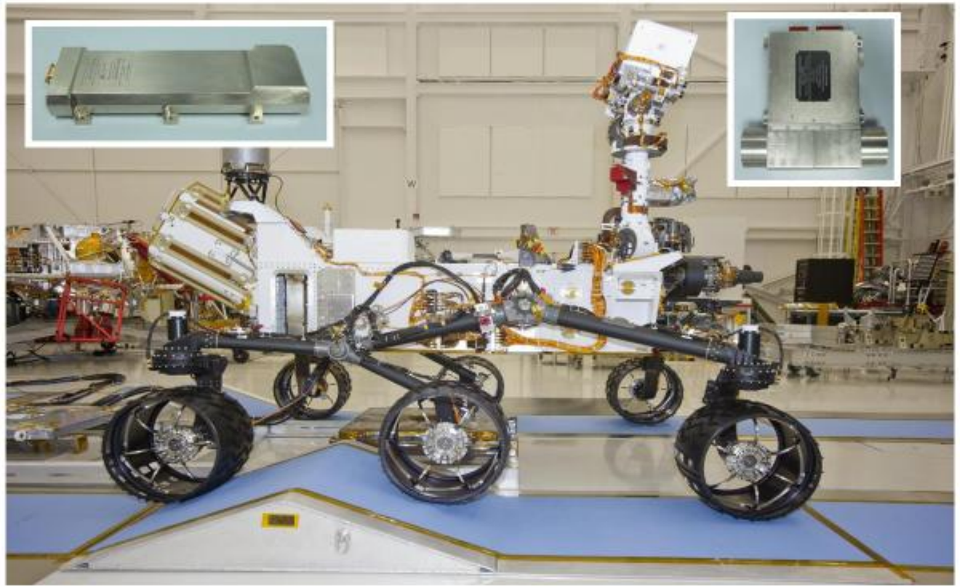


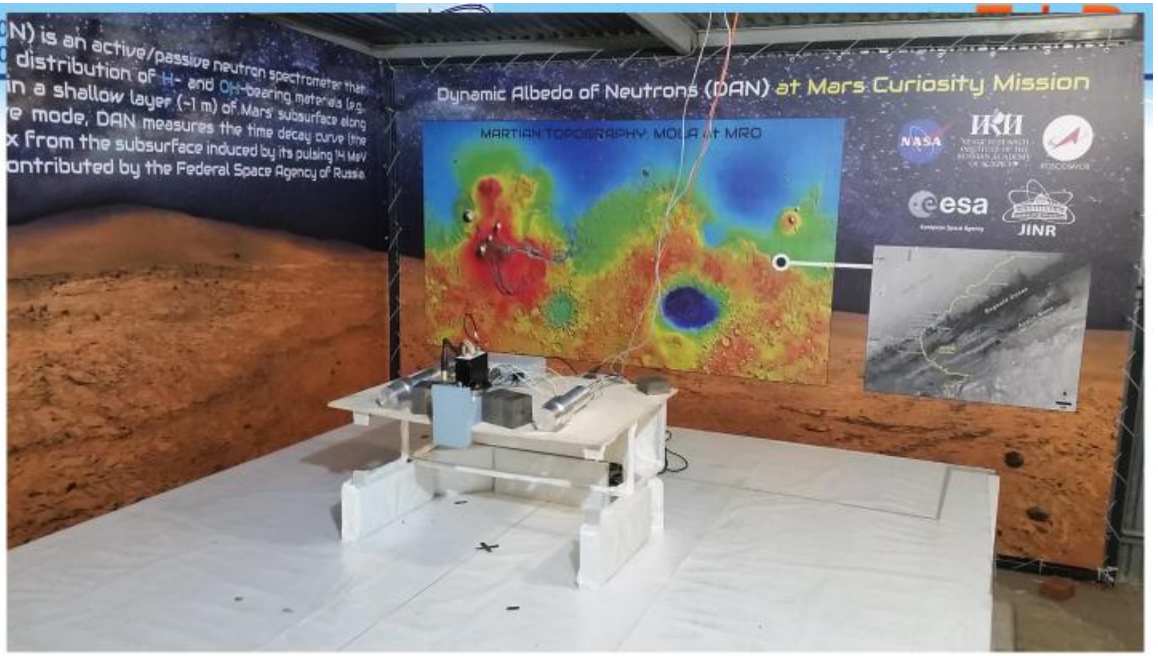
Pulsed neutron Logging: idea belongs to G.N.Flerov. Fast neutrons from generator penetrates into the soil and moderated. Time profile of the slow neutron counter located above the soil drastically depends on the hydrogen content in the soil.



FLNP and LRB of JINR are collaborating with Russian Space Research Institute since 1997. DAN device was proposed in 2003 as one of the scientific instruments onboard of the Mars Science Laboratory and in the beginning of 2004 after non-advocating review was accepted by NASA.

DAN flight unit onboard the NASA Mars rover Curiosity

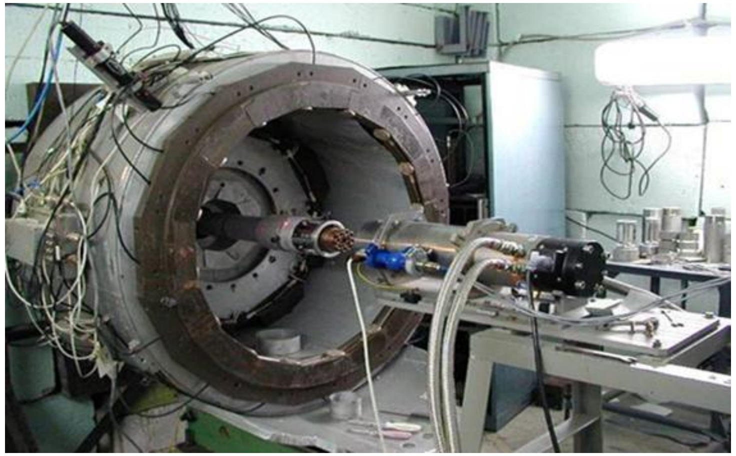


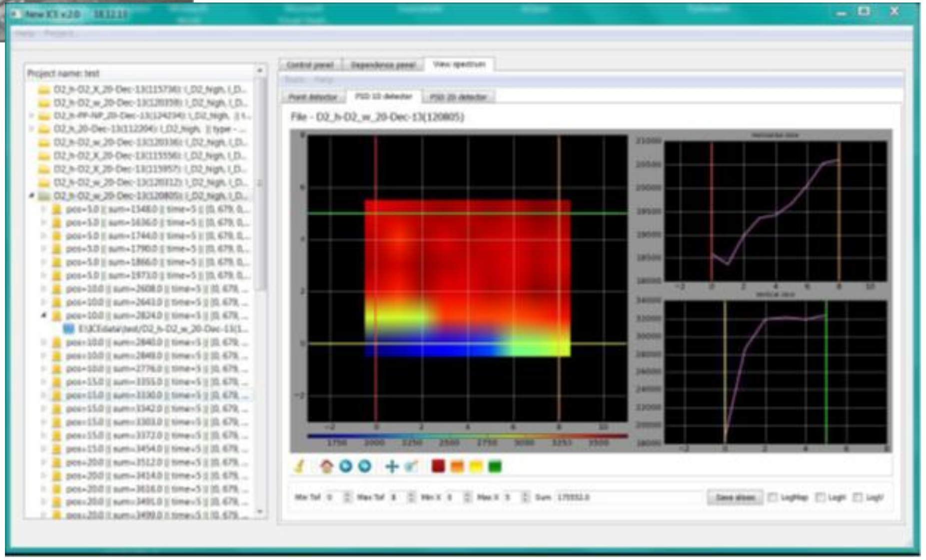


Tagged Neutrons Technique First Testing

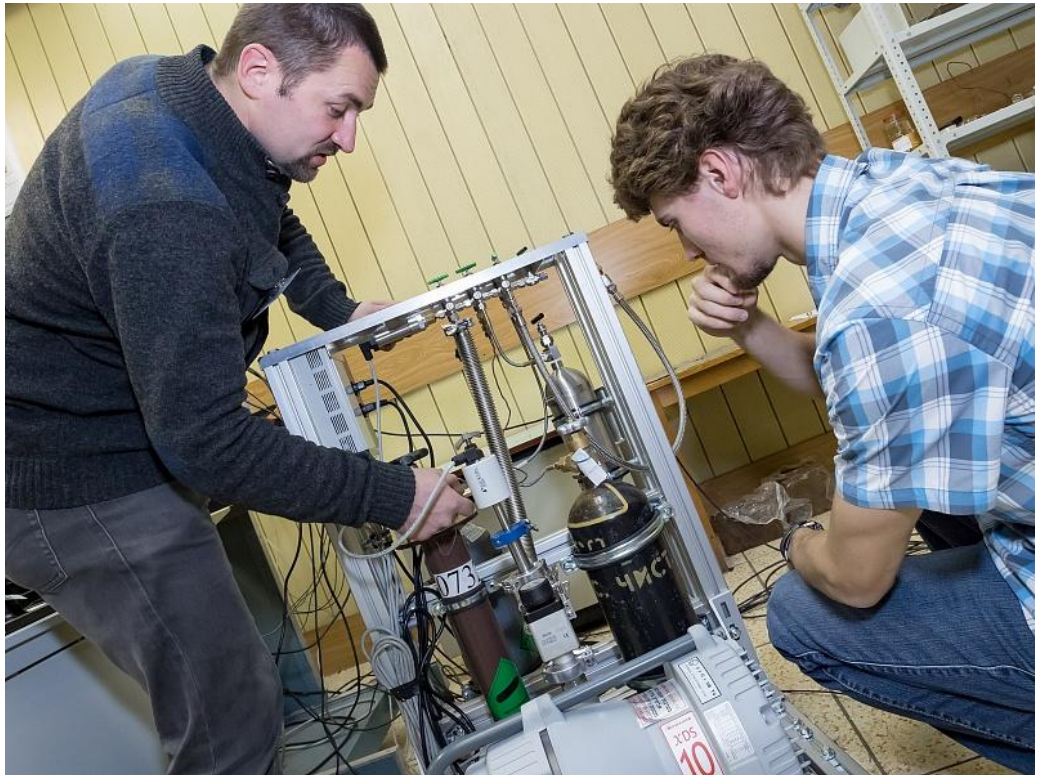
Applied & Methodical Research

- Detectors;
- Experiments Automation;
- Sample Environment;
- Cold Moderators;
- Software & Networking;





International School for Young Scientist and Students «Instruments and Methods of Experimental Nuclear Physics»



FLNP Future

- Short term perspectives:
  - Development and upgrade of the IBR-2 instruments. Already now we have examples of more than 10-fold increase in efficiency;
  - Completion of the CM complex;
  - Startup of the IREN source at designed parameters;
- Long term perspectives – new accelerator based neutron source in order to replace IBR-2 after the end of it's lifetime;

The XXII International Scientific Conference of Young Scientists and Specialists
(AYSS-2018), 23 - 27 April 2018, Dubna

Thank you for your attention!